Module 1

METALLURGY & MATERIAL SCIENCE

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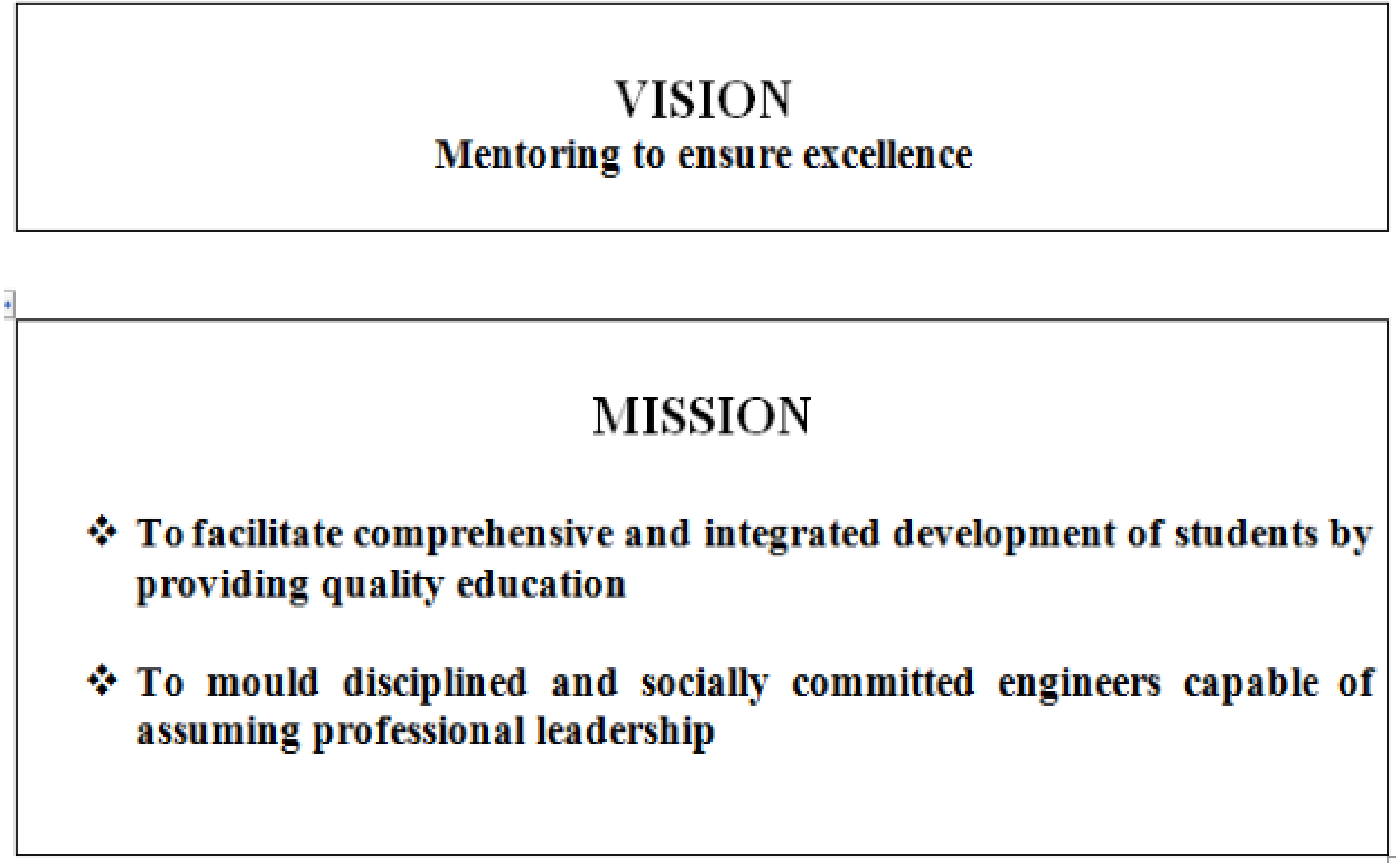


VISION

Mentoring to ensure excellence

MISSION

- To facilitate comprehensive and integrated development of students by providing quality education
- To mould disciplined and socially committed engineers capable of assuming professional leadership

Preamble

- Understanding of the correlation between the chemical bonds and crystal structure of metallic materials to their mechanical properties.

- Recognize the importance of crystal imperfections including dislocations in plastic deformation.

- Learning about different phases and heat treatment methods to tailor the properties of Fe-C alloys.

- Examine the mechanisms of materials failure through fatigue and creep.

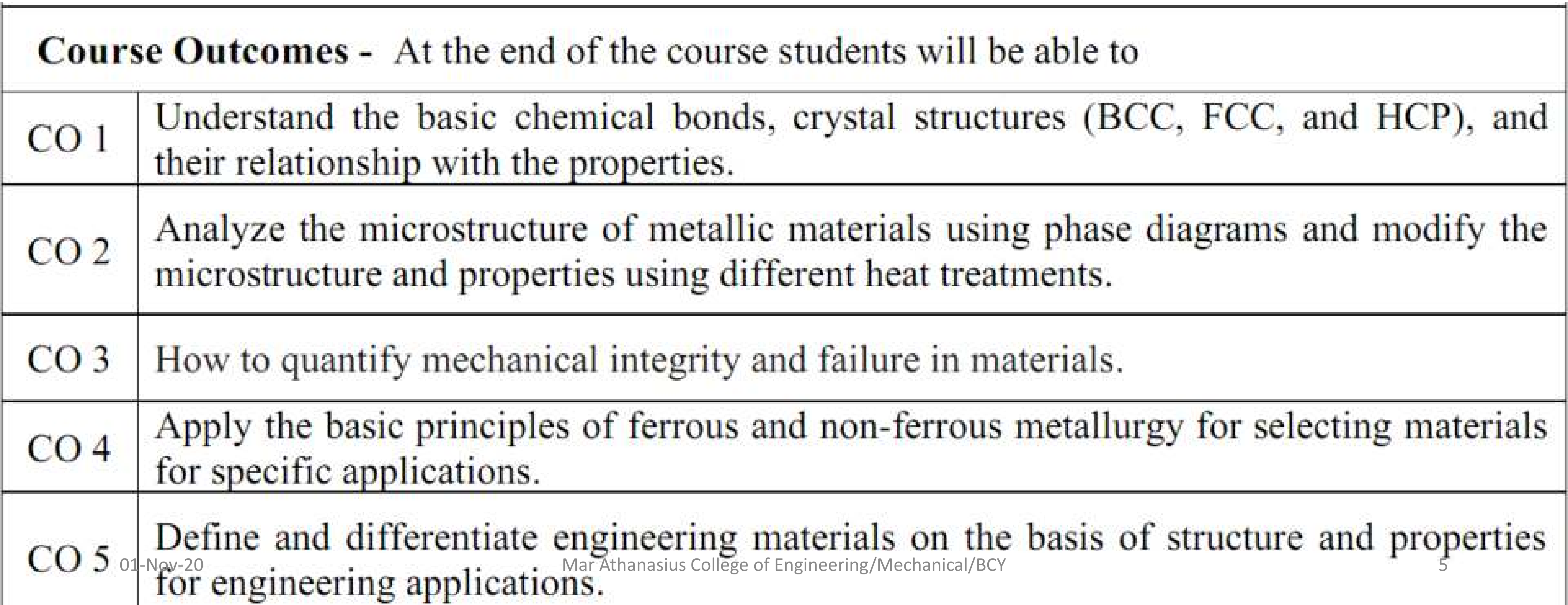
- To determine properties of unknown materials and develop an awareness to apply this knowledge in material design.

Prerequisite

- PHT 110 Engineering Physics
- CYT 100 Engineering Chemistry

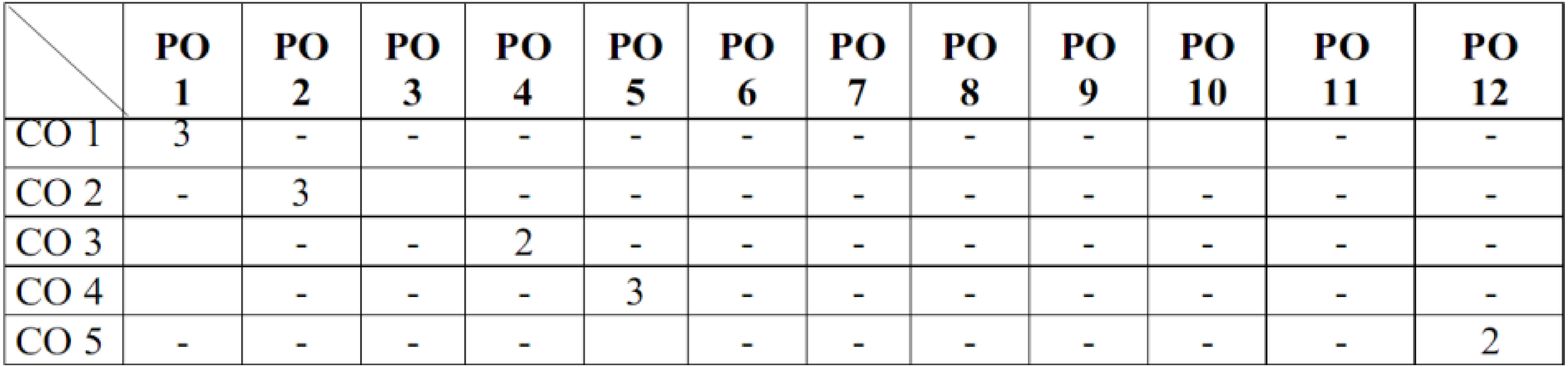
Course Outcomes

At the end of the course students will be able to,



Course Outcomes - At the end of the course students will be able to	
CO 1	Understand the basic chemical bonds, crystal structures (BCC, FCC, and HCP), and their relationship with the properties.
CO 2	Analyze the microstructure of metallic materials using phase diagrams and modify the microstructure and properties using different heat treatments.
CO 3	How to quantify mechanical integrity and failure in materials.
CO 4	Apply the basic principles of ferrous and non-ferrous metallurgy for selecting materials for specific applications.
CO 5	Define and differentiate engineering materials on the basis of structure and properties for engineering applications.

Mapping of course outcomes with program outcomes (Minimum requirements)



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CO 2	-	3		-	-	-	-	-	-	-	-	-
CO 3		-	-	2	-	-	-	-	-	-	-	-
CO 4		-	-	-	3	-	-	-	-	-	-	-
CO 5	-	-	-	-		-	-	-	-	-	-	2

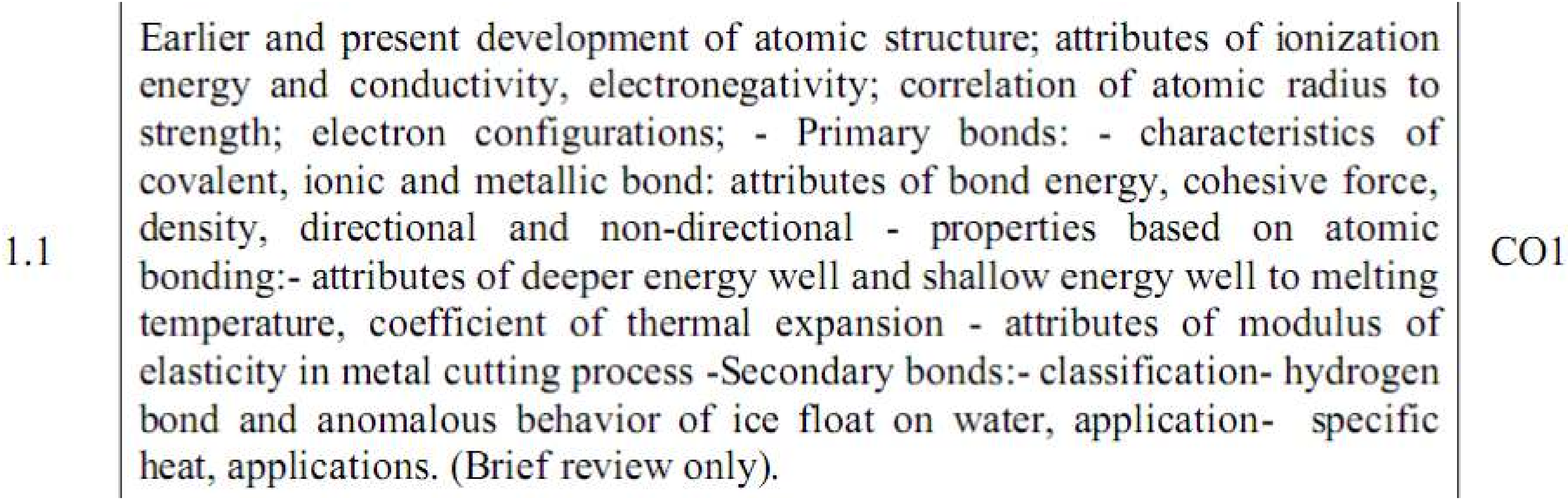
PO 1	Engineering Knowledge
PO 2	Problem Analysis
PO 3	Design & Development of Solutions
PO 4	Investigation of Complex Problem
PO 5	Modern Tools Usage
PO 6	Engineer and Society

PO 7	Environment & Sustainability
PO 8	Ethics
PO 9	Individual & Team work
PO 10	Communication
PO 11	Lifelong Learning
PO 12	Project management & Finance

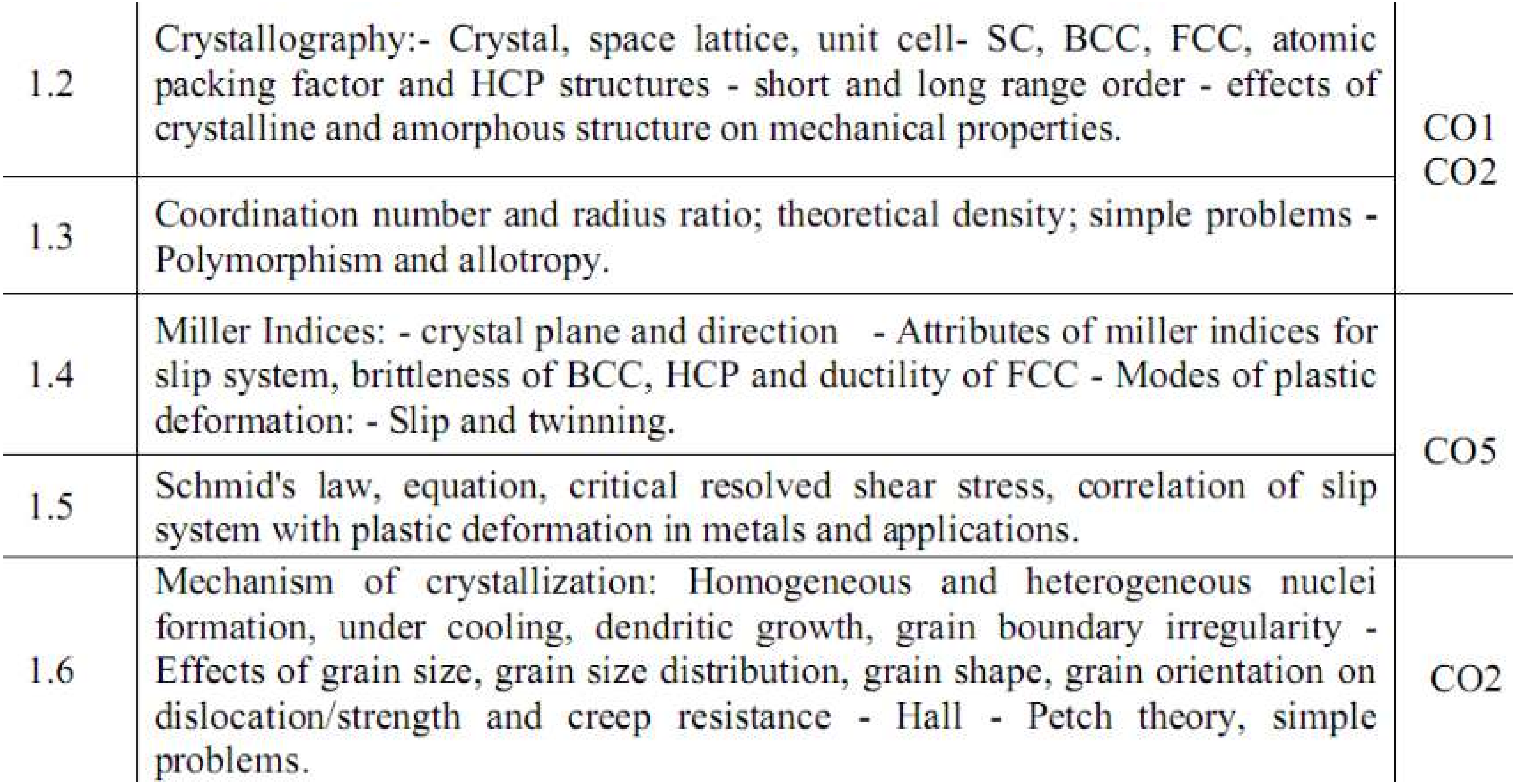
MODULE - 1

- Earlier and present development of atomic structure - Primary bonds: - characteristics of covalent, ionic and metallic bond - properties based on atomic bonding: - Secondary bonds: - classification, application. (Brief review only).
- Crystallography: - SC, BCC, FCC, HCP structures, APF - theoretical density simple problems – Miller Indices: - crystal plane and direction - Modes of plastic deformation: - Slip and twinning -Schmid’s law - Crystallization: Effects of grain size, Hall - Petch theory, simple problems.

COURSE CONTENT



1.1	Earlier and present development of atomic structure; attributes of ionization energy and conductivity, electronegativity; correlation of atomic radius to strength; electron configurations; - Primary bonds: - characteristics of covalent, ionic and metallic bond: attributes of bond energy, cohesive force, density, directional and non-directional - properties based on atomic bonding:- attributes of deeper energy well and shallow energy well to melting temperature, coefficient of thermal expansion - attributes of modulus of elasticity in metal cutting process -Secondary bonds:- classification- hydrogen bond and anomalous behavior of ice float on water, application- specific heat, applications. (Brief review only).	CO1



1.2	Crystallography:- Crystal, space lattice, unit cell- SC, BCC, FCC, atomic packing factor and HCP structures - short and long range order - effects of crystalline and amorphous structure on mechanical properties.	CO1 CO2
1.3	Coordination number and radius ratio; theoretical density; simple problems - Polymorphism and allotropy.	
1.4	Miller Indices: - crystal plane and direction - Attributes of miller indices for slip system, brittleness of BCC, HCP and ductility of FCC - Modes of plastic deformation: - Slip and twinning.	CO5
1.5	Schmid's law, equation, critical resolved shear stress, correlation of slip system with plastic deformation in metals and applications.	
1.6	Mechanism of crystallization: Homogeneous and heterogeneous nuclei formation, under cooling, dendritic growth, grain boundary irregularity - Effects of grain size, grain size distribution, grain shape, grain orientation on dislocation/strength and creep resistance - Hall - Petch theory, simple problems.	CO2

Introduction

History

Historically periods of civilization are divided on the basis of material development

1. Stone Age
2. Bronze Age
3. Iron Age
4. Plastic Age
5. Silicon Age

Importance of Materials

Defense

Inter Continental Ballistic Missile (ICBM)

Nose during re-enrty gets heated to in excess of 1500°C

Material - Reinforced C-C composite

Space

GSLV MK-III

Cryogenic engines require material to hold liquid hydrogen and oxygen

Material - Ti alloys

Popular products

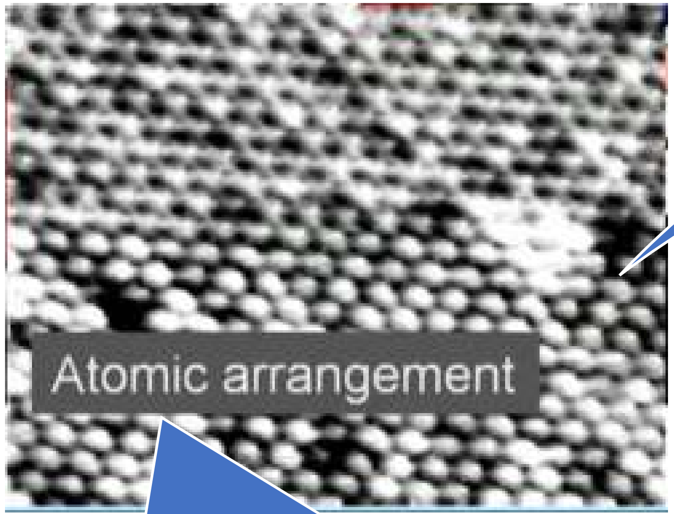
Apple used metallurgy ideas to sell its watch by using Al alloys, gold –ceramics metal matrix composite and stainless steel

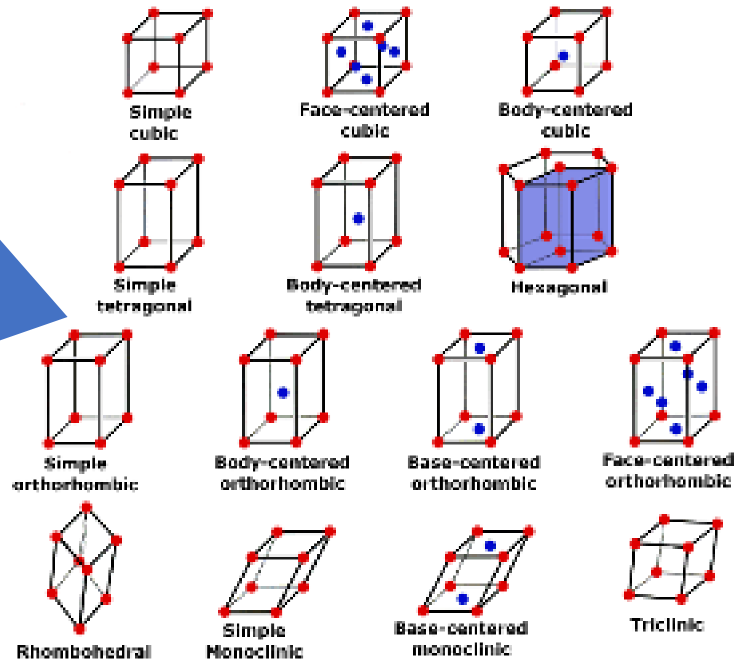
http://gizmodo.com/the-crazy-metallurgy-apple-is-using-to-sell-its-watch-1690388081

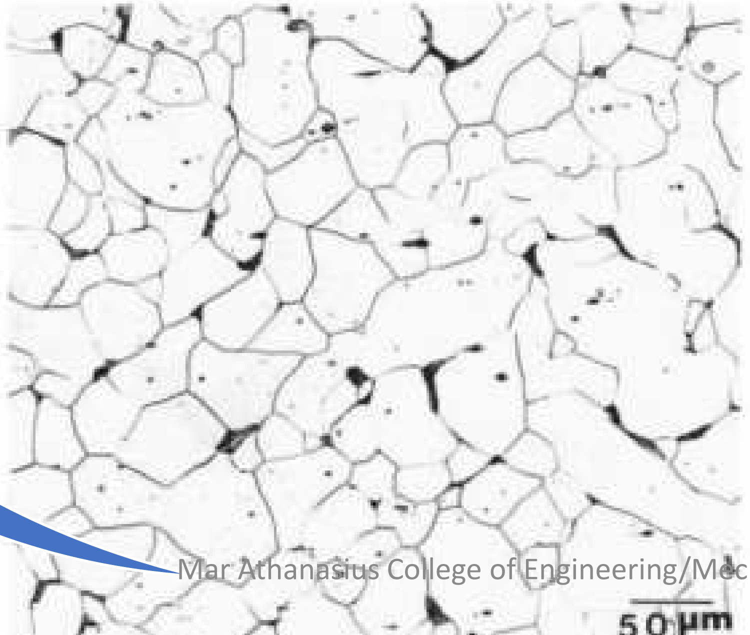
Material Failure

- Poor steel quality, high S and P
- Ductile to brittle transition

Structure at different scale







Atomic Structure

- The atomic structure of an element refers to the constitution of its nucleus and the arrangement of the electrons around it. Primarily, the atomic structure of matter is made up of protons, electrons and neutrons.

- The protons and neutrons make up the nucleus of the atom, which is surrounded by the electrons belonging to the atom. The atomic number of an element describes the total number of protons in its nucleus.

- Neutral atoms have equal numbers of protons and electrons. However, atoms may gain or lose electrons in order to increase their stability and the resulting charged entity is called an ion.

- Atoms of different elements have different atomic structures because they contain different numbers of protons and electrons. This is the reason for the unique characteristics of different elements.

Review of Atomic Structure

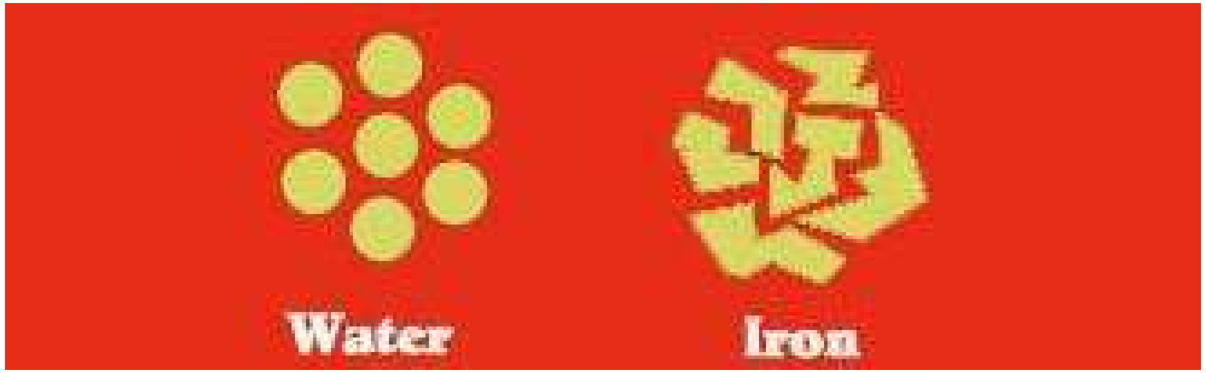
1. Earlier concepts of Atomic Models
2. Present atomic model
3. Chemical bonds
    (a) Primary bonds
        - Ionic bond
        - Covalent bond
        - Metallic bond
    (b) Secondary bonds
4. Mechanical properties

Atomic Structure (Earlier concepts)

1. Democritus
2. Dalton
3. J J Thomson
4. Millikan
5. Rutherford

Democritus (460 –370 BC)

- Greek philosopher
- Can matter be subdivided into fundamental particles?
- Develops the idea of atoms (derived from Greek word atoma - means indivisible)
- All matter can be broken down into indivisible *atoms*.



According to the early theory of atoms developed by Democritus, Water atoms would be round and flow over one another while iron atoms would be jagged and stay solidly together. This is not the modern view.

John Dalton (Dalton's Atomic Theory (1780))

- Suggested that all matter was made up of tiny spheres that were able to bounce around with perfect elasticity and called them ATOMS
- Every matter is made up of atoms.
- Atoms are indivisible.
- Specific elements have only one type of atoms in them.
- Each atom has its own constant mass that varies from element to element.
- Atoms undergo rearrangement during a chemical reaction.
- Atoms can neither be created nor be destroyed but can be transformed from one form to another.

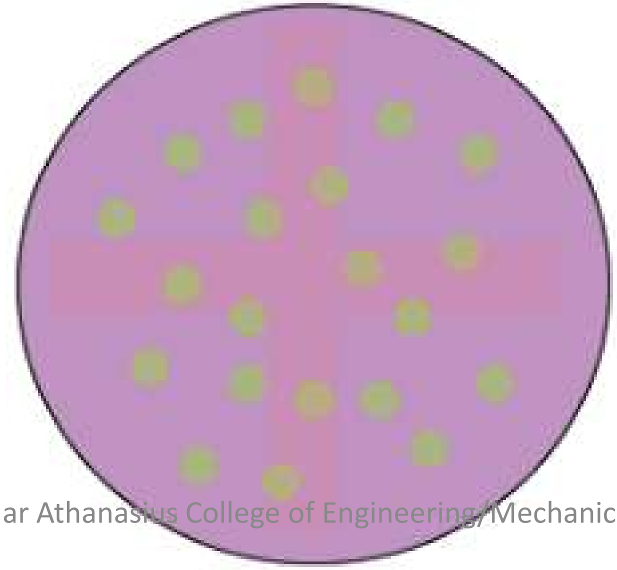
- Dalton's atomic theory successfully explained the Laws of chemical reactions, namely, the Law of conservation of mass, Law of constant properties, Law of multiple proportions and Law of reciprocal proportions.

Demerits of Dalton's Atomic Theory

- The theory was unable to explain the existence of isotopes.
- Nothing about the structure of atom was appropriately explained.
- Later, the scientists discovered particles inside the atom that proved, the atoms are divisible.
- The discovery of particles inside atoms led to a better understanding of chemical species, these particles inside the atoms are called subatomic particles. The discovery of various subatomic particles is as follows:

J J Thompson (1898) (Thomson Atomic Model)

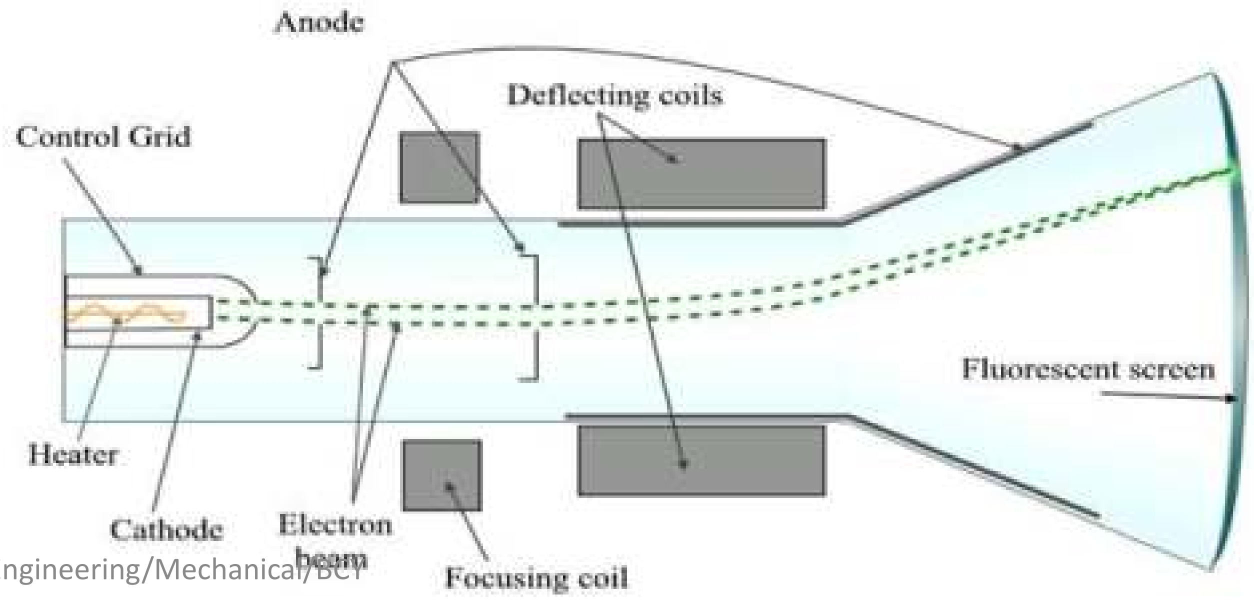
- Thompson pictured atom as uniform spheres of positively charged substance (positive electric fluid) with negative electrons embedded in it
- **Plum Pudding Model**
- His work is based on an experiment called cathode ray experiment
- Electrons were supposed to assume certain stable positions inside atomic body due to – attraction by positive charge and repulsion by other electrons.



Cathode Ray Experiment

- A high voltage power supply is connected using electrodes
- When a high voltage power supply is switched on, there were rays emerging from the cathode towards the anode, called cathode rays
- Thompson concluded that cathode rays are made of negatively charged particles called “electrons”.

- On applying the electric and magnetic field upon the cathode rays (electrons), Thomson found the charge to mass ratio (e/m) of electrons. (e/m) for electron: 17588 × 1011 e/bg.



- Based on conclusions from his cathode ray experiment, Thomson described the atomic structure as a positively charged sphere into which negatively charged electrons were embedded.

- It is commonly referred to as the "plum pudding model" because it can be visualized as a plum pudding dish where the pudding describes the positively charged atom and the plum pieces describe the electrons.

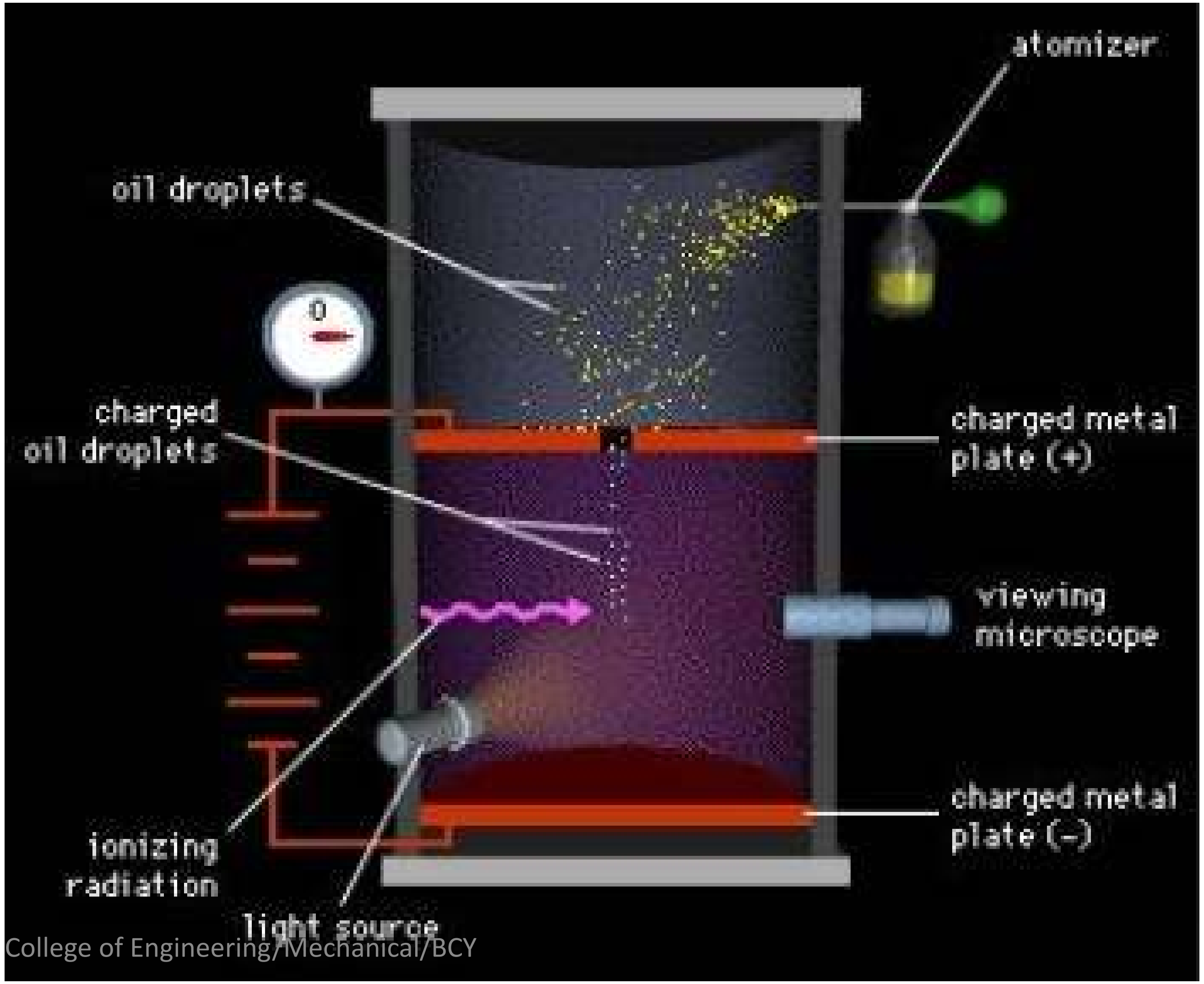
- Thomson's atomic structure described atoms as electrically neutral, i.e. the positive and the negative charges were of equal magnitude.

- Limitations of Thomson's Atomic Structure: Thomson's atomic model does not clearly explain the stability of an atom. Also, further discoveries of other subatomic particles, couldn't be placed inside his atomic model.

Robert Millikan’s Experiment

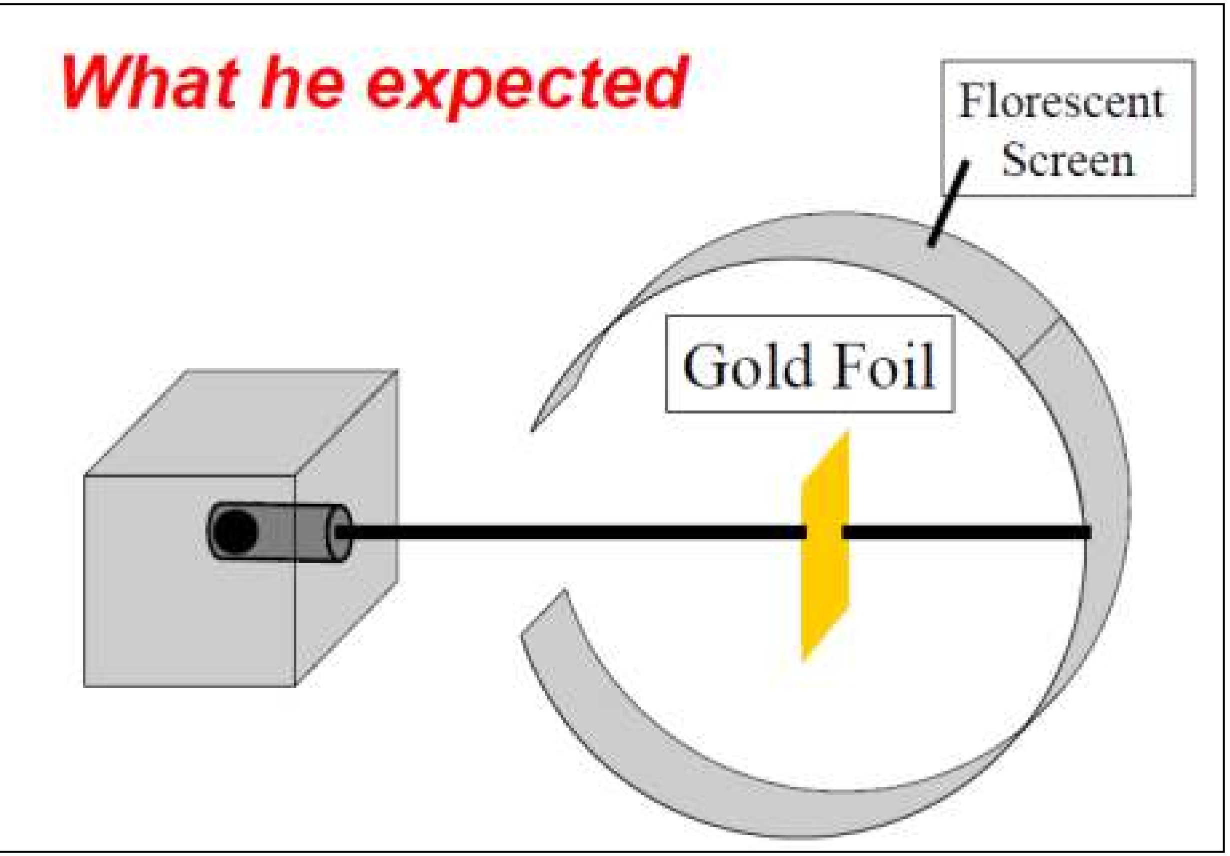
- Thomson found the charge to mass ratio (e/m) of electrons. (e/m) for electron: 17588 × 10^{11} C/Kg.
- From this ratio, the charge of the electron was found by Mullikin through oil drop experiment. [Charge of e^- = 1.6 × 10^{-19} C and Mass of e^- = 9.1093 × 10^{-31} kg].
- Millikan applied electric charge to a tiny drop of oil, and measure how strong an applied electric field had to be in order to stop the oil drop from falling.
- Since he was able to work out the mass of the oil drop, he could calculate the force of gravity on one drop. He could then determine the electric charge that the drop must have.
- By varying the charge on different drops, he noticed that the charge was always a multiple of 1.6x10^{-19} C, the charge on a single electron. This meant that it was electrons carrying this unit charge.

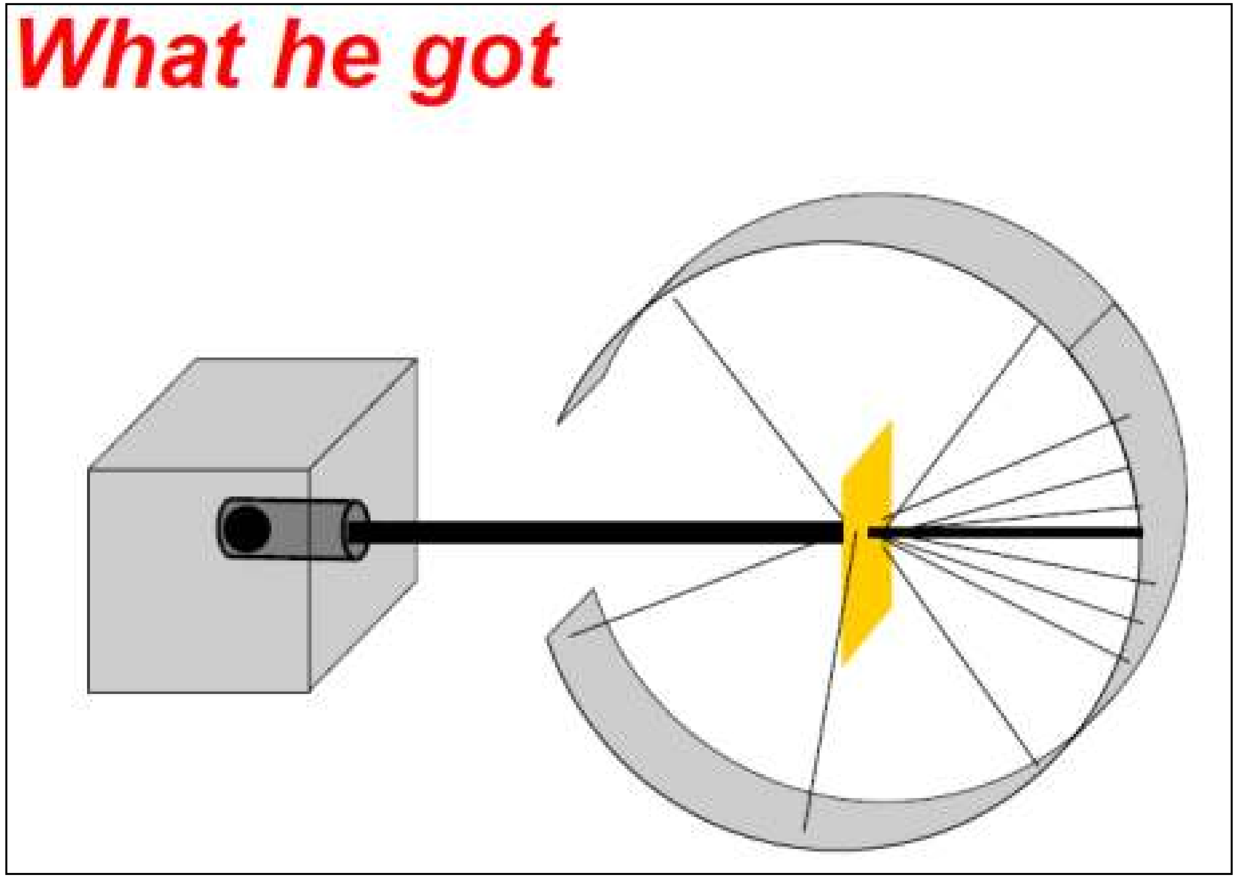
Robert Millikan’s Experiment



(Rutherford Atomic Theory) Ernest Rutherford

- Rutherford modified the atomic structure with the discovery of another subatomic particle called “Nucleus”.
- His atomic model is based on the Alpha ray scattering experiment.
- Fired Helium nuclei on a piece of gold foil which was only a few microns thick.
- Aimed alpha particles at gold foil by drilling a hole in a lead block.
- Expected - Since the mass is evenly distributed in gold atoms, alpha particles should go straight through.


What he expected


What he got

Alpha Ray Scattering Experiment

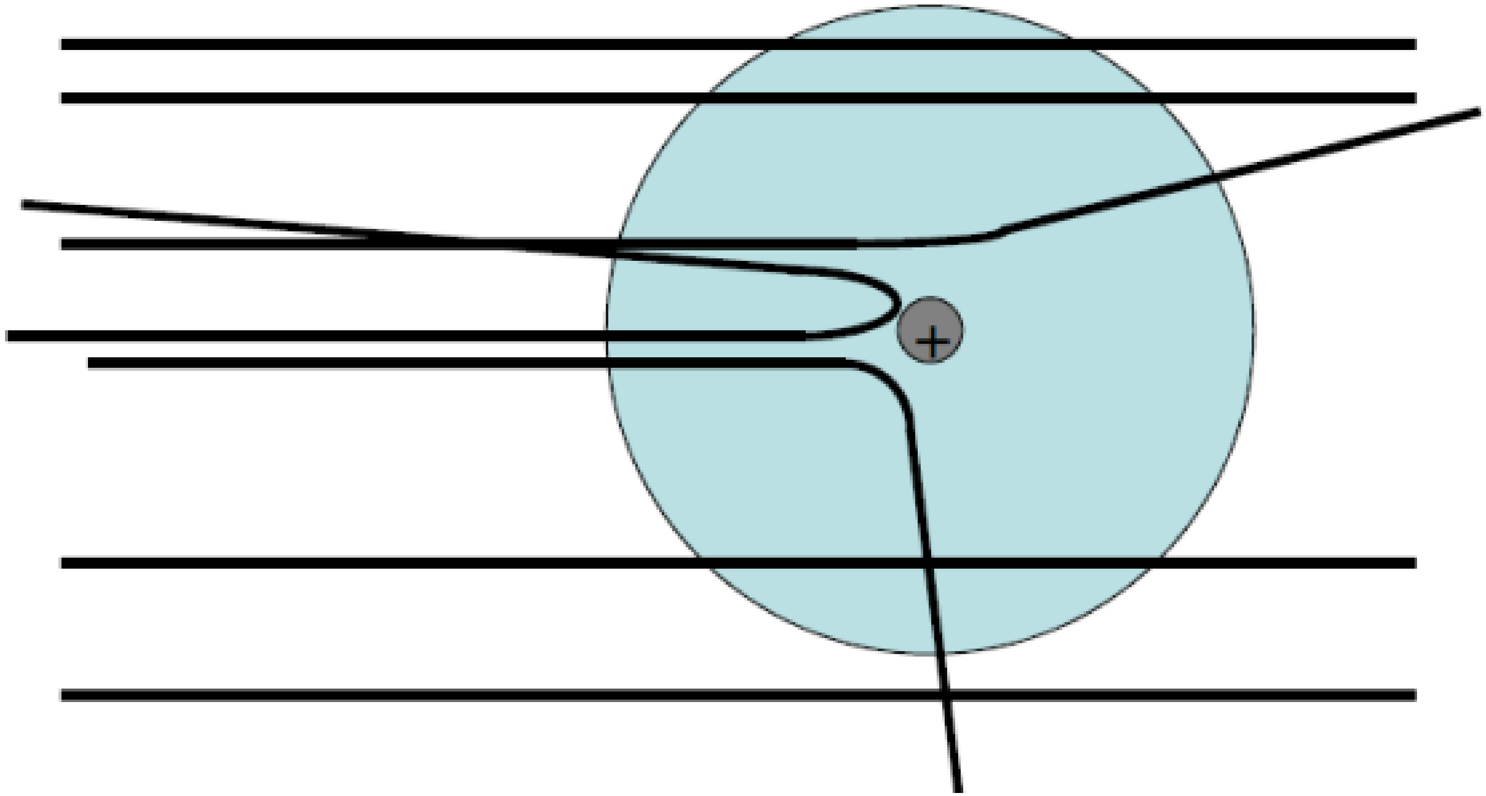
Construction:

- A very thin gold foil of 1000 atoms thick is taken.
- Alpha rays (doubly charged Helium He2+) were made to bombard the gold foil.
- Zn S screen is placed behind the gold foil.

Observations:

- Most of the rays just went through the gold foil making scintillations (bright spots) in the ZnS screen.
- A few rays got reflected after hitting the gold foil.
- One in 1000 rays got reflected by an angle of 180° (retraced path) after hitting the gold foil.

What Rutherford Observed



- Since most rays passed through, Rutherford concluded that most of the space inside the atom is empty.
- Few rays got reflected because of the repulsion of its positive with some other positive charge inside the atom.
- 1/1000th of rays got strongly deflected because of a very strong positive charge in the center of the atom. He called this strong positive charge as "nucleus"
- He said most of the charge and mass of the atom resides in the Nucleus
- Electrons are supposed to move around nucleus in a dynamically stable orbit (planetary model)
- Revolving electric charges radiate energy in the form of electromagnetic waves (electromagnetic theory)

Rutherford’s Structure of Atom

- The nucleus is at the center of an atom, where most of the charge and mass are concentrated.
- Atomic structure is spherical.
- Electrons revolve around the nucleus in a circular orbit, similar to the way planets orbit the sun.

Limitations of Rutherford Atomic Model

- If electrons have to revolve around the nucleus, they will spend energy and that too against the strong force of attraction from the nucleus, a lot of energy will be spent by the electrons and eventually, they will lose all their energy and will fall into the nucleus so the stability of atom is not explained.
- If electrons continuously revolve around the ‘nucleus, the type of spectrum expected is a continuous spectrum. But in reality, what we see is a line spectrum.

Summary

Democritus – Concepts of atoms

Dalton – Atoms have certain properties

- Elements are made of atoms
- Atoms of one element are all the same
- Atoms of one element are different from those of another
- The number of different atoms and way atoms combine determine the identity of a substance
- Only whole atoms can combine to form substances

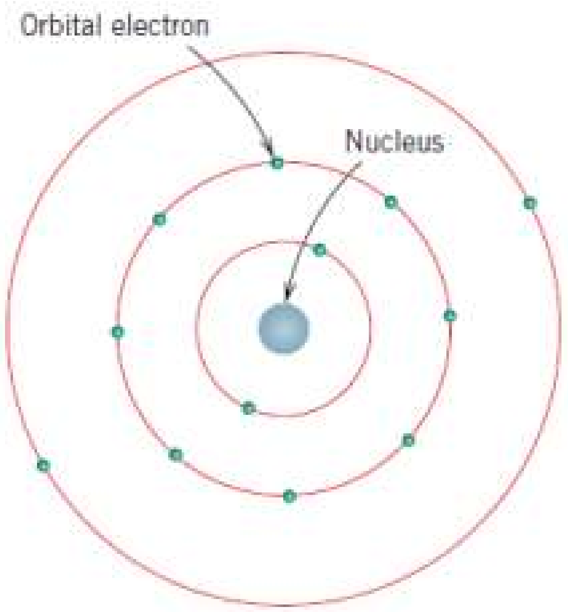
JJ Thomson – Atoms have electrons

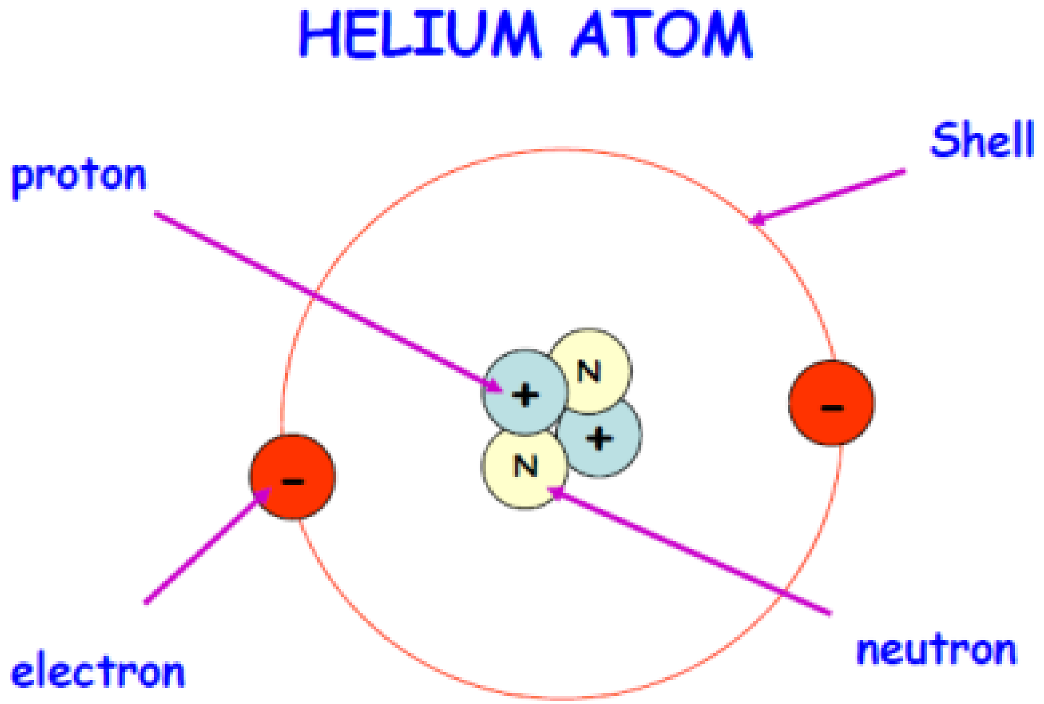
Millikan – Proved electrons exist

Rutherford – Discovered the nucleus

Niels Bohr 1915 (Bohr atomic model)

- Bohr refined Rutherford's idea by adding that the electrons are like planets orbiting the sun.
- Electrons are assumed to revolve around the atomic nucleus in discrete orbitals, and the position of any particular electron is more or less well defined in terms of its orbital.

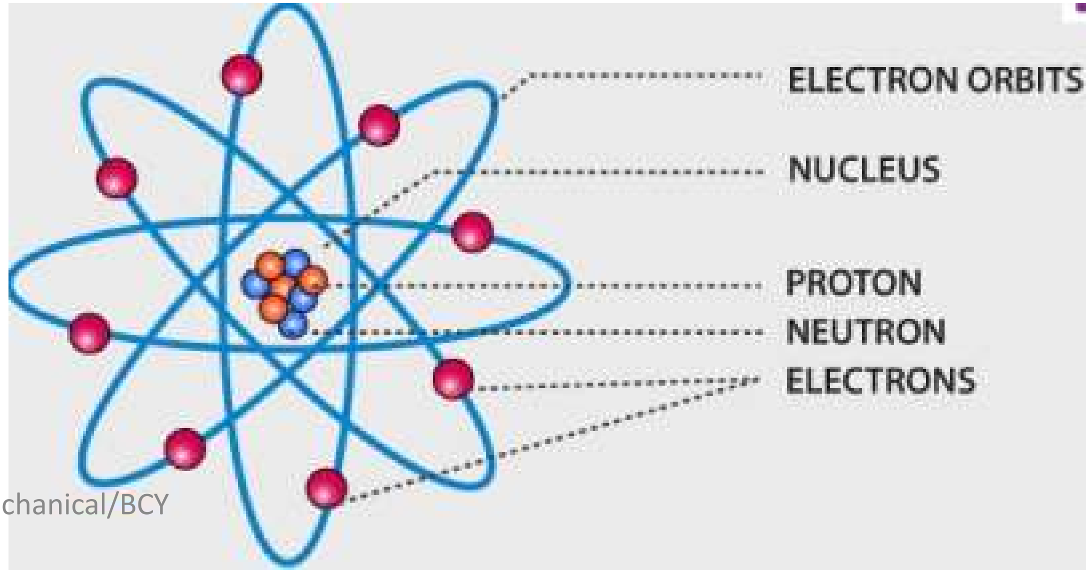




- **Nucleus** In the center, contains protons & neutrons
- **Protons** positive, one atomic mass unit (amu)
- **Neutrons** neutral, one amu

The structure of the nucleus has little or no effect on the chemical and physical properties of an element , we shall not study further.

- **Shells** energy levels around nucleus
- **Electrons** negative, no effective mass



1. The Atomic Number of an atom = number of protons in the nucleus.

2. The Atomic Mass of an atom = number of Protons + Neutrons in the nucleus.

3. The number of Protons = Number of Electrons.

4. **ISOTOPE**: **Atoms with the same number of protons, but different numbers of neutrons.**

ATOMIC STRUCTURE

Particle	Charge	Mass
proton	+ ve charge	1
neutron	No charge	1
electron	-ve charge	nil

ATOMIC STRUCTURE

He

2 Atomic number

the number of protons in an atom

4 Atomic mass

the number of protons and neutrons in an atom

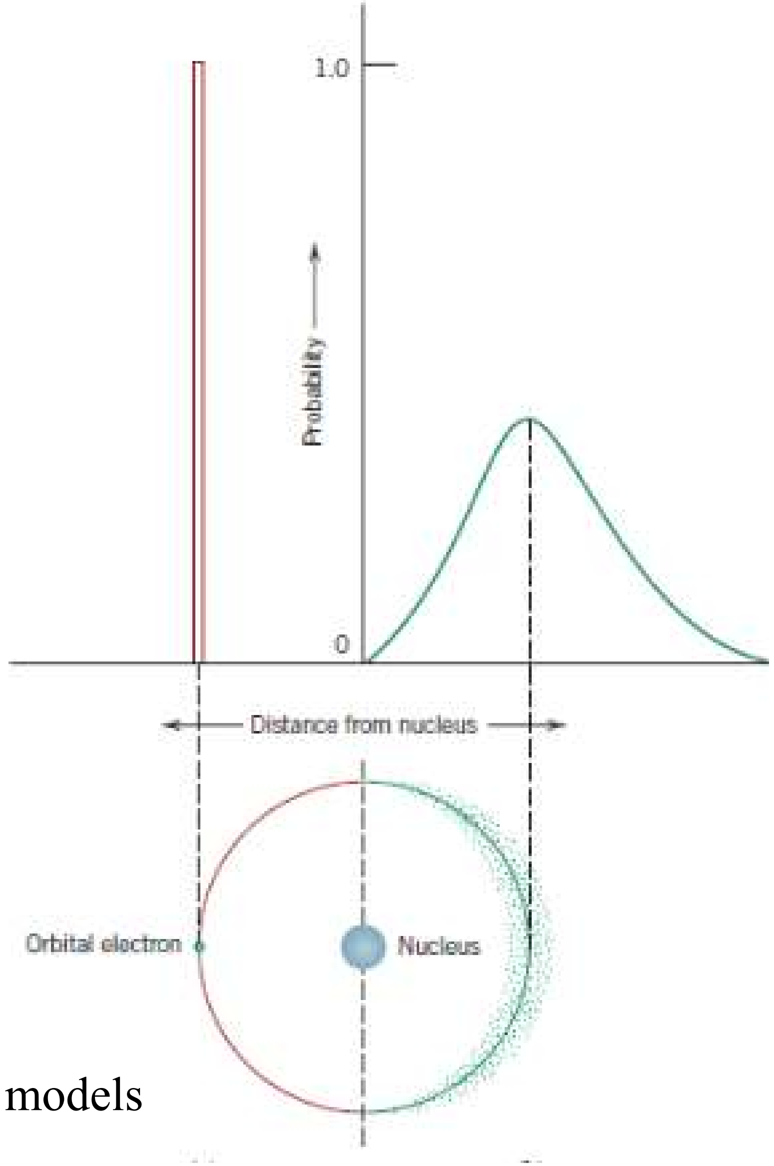
number of electrons = number of protons

Strength and Atomic Radius…?

- As the atomic number increases, the number of electrons increases, the number of shells increases therefore atomic radius increases.
- As a result the valence shell and valence electrons become away from the nucleus reducing the attraction between outer shell and nucleus which in turn reduces the strength.
- Thus, as atomic number increases, strength decreases and as atomic number decreases strength increases.

Wave Mechanical Model

- Electron is considered to exhibit both wave-like and particle-like characteristics.
- An electron is no longer treated as a particle moving in a discrete orbital rather, position is considered to be the probability of an electron's being at various locations around the nucleus.



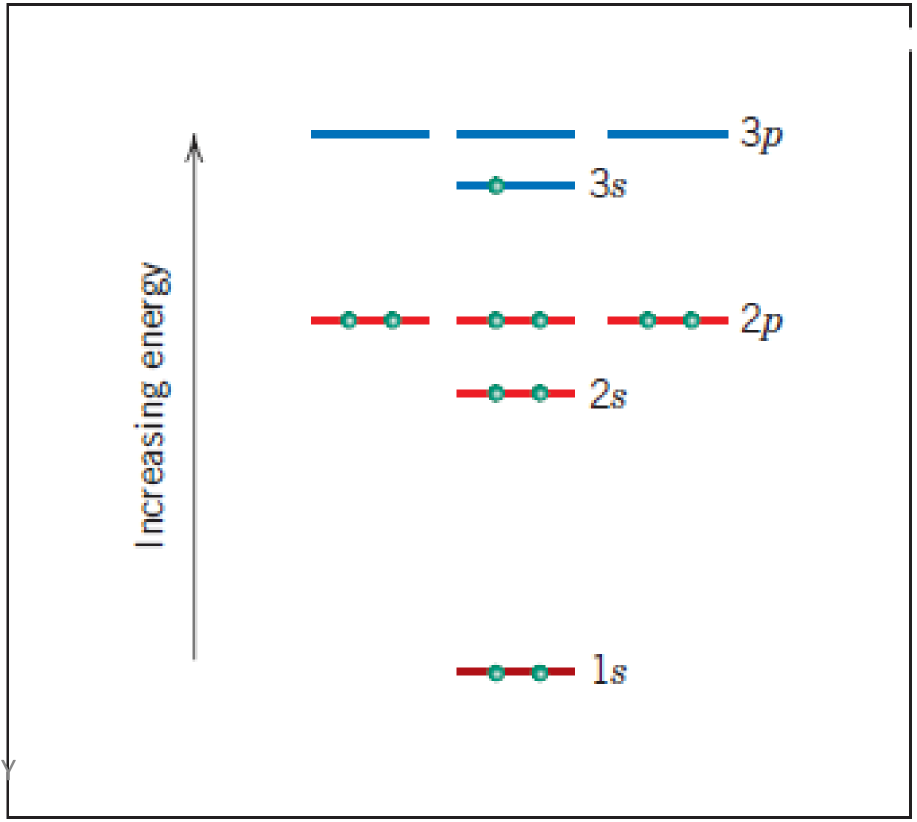
Comparison of
the (*a*) Bohr and (*b*) wave mechanical atom models
in terms of electron distribution.

Quantum Numbers

- Using wave mechanics, every electron in an atom is characterized by four parameters called quantum numbers.
- The size, shape, and spatial orientation of an electron's probability density are specified by three of these quantum numbers.
- Principal quantum number *n*
- Shells are designated by the letters *K, L, M, N, O,* and so on, which correspond, respectively, to n = 1, 2, 3, 4, 5, . . . ,
- This quantum number is related to the distance of an electron from the nucleus, or its position.
- The second quantum number, *l*, signifies the subshell, which is denoted by a lowercase letter—an s, p, d, or f; it is related to the shape of the electron subshell.

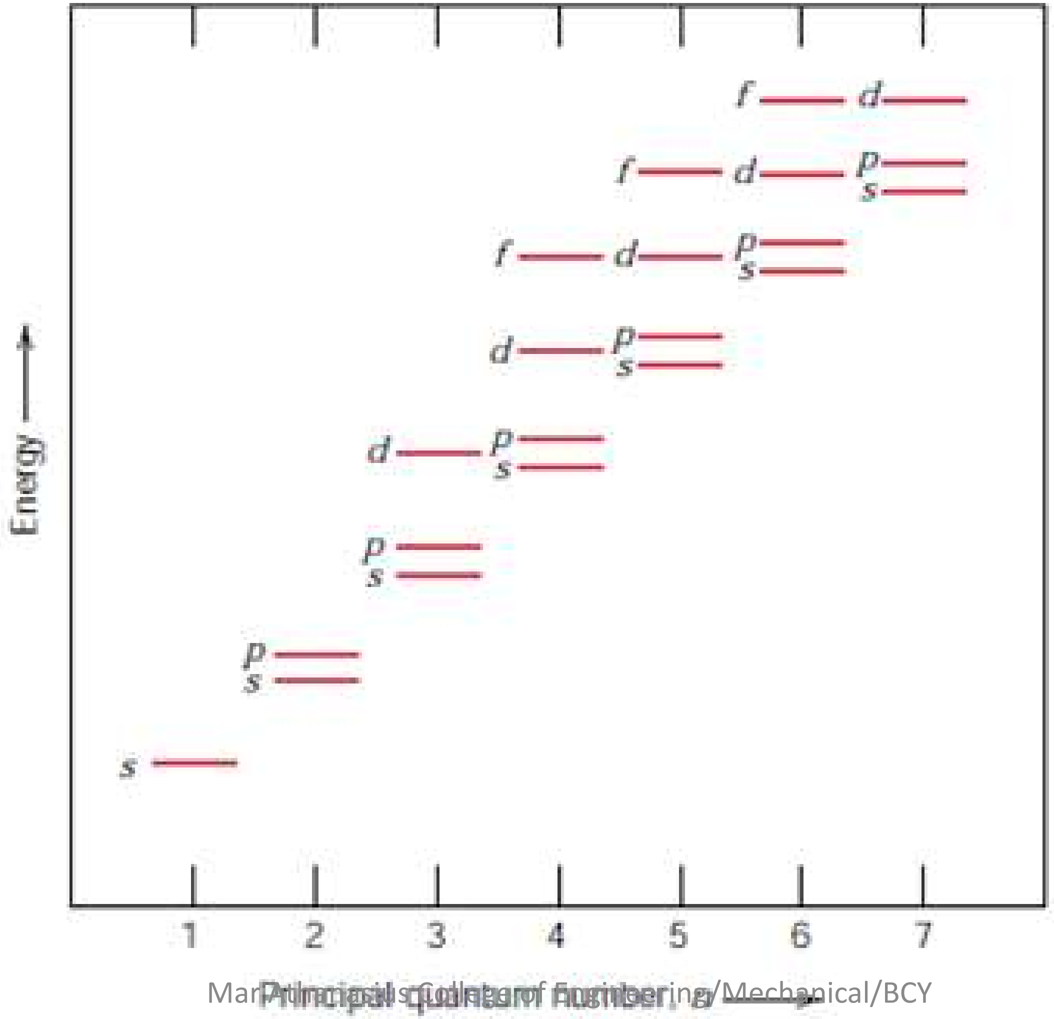
- The number of these subshells is restricted by the magnitude of n.
- Third quantum number m_l.
- The number of energy states for each subshell is determined by the third quantum number.
- For an s subshell, there is a single energy state, whereas for p, d, and f subshells, three, five, and seven states exist, respectively.

- Fourth quantum number ms. Related to this spin moment
- Each electron in a subshell has a spin moment, which must be oriented either up or down
- Two values are possible (+1/2 and -1/2), one for each of the spin orientations



Sodium Atom

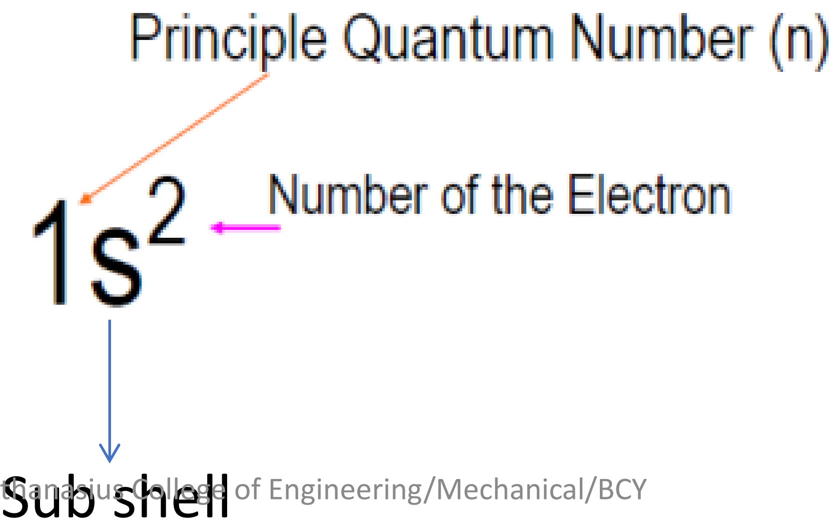
Schematic representation of the relative energies of the electrons for various shells and subshells



Electron Configurations

- Is used to determine the manner in which atoms are filled with electrons.
- The 4 sub shells are s, p, d & f.
- s, p, d and f sub shells accommodates a total of 2, 6, 10, and 14 electrons respectively.

Notation for Quantum Numbers



Principle Quantum Number (n)

$1s^2$

Number of the Electron

Sub shell

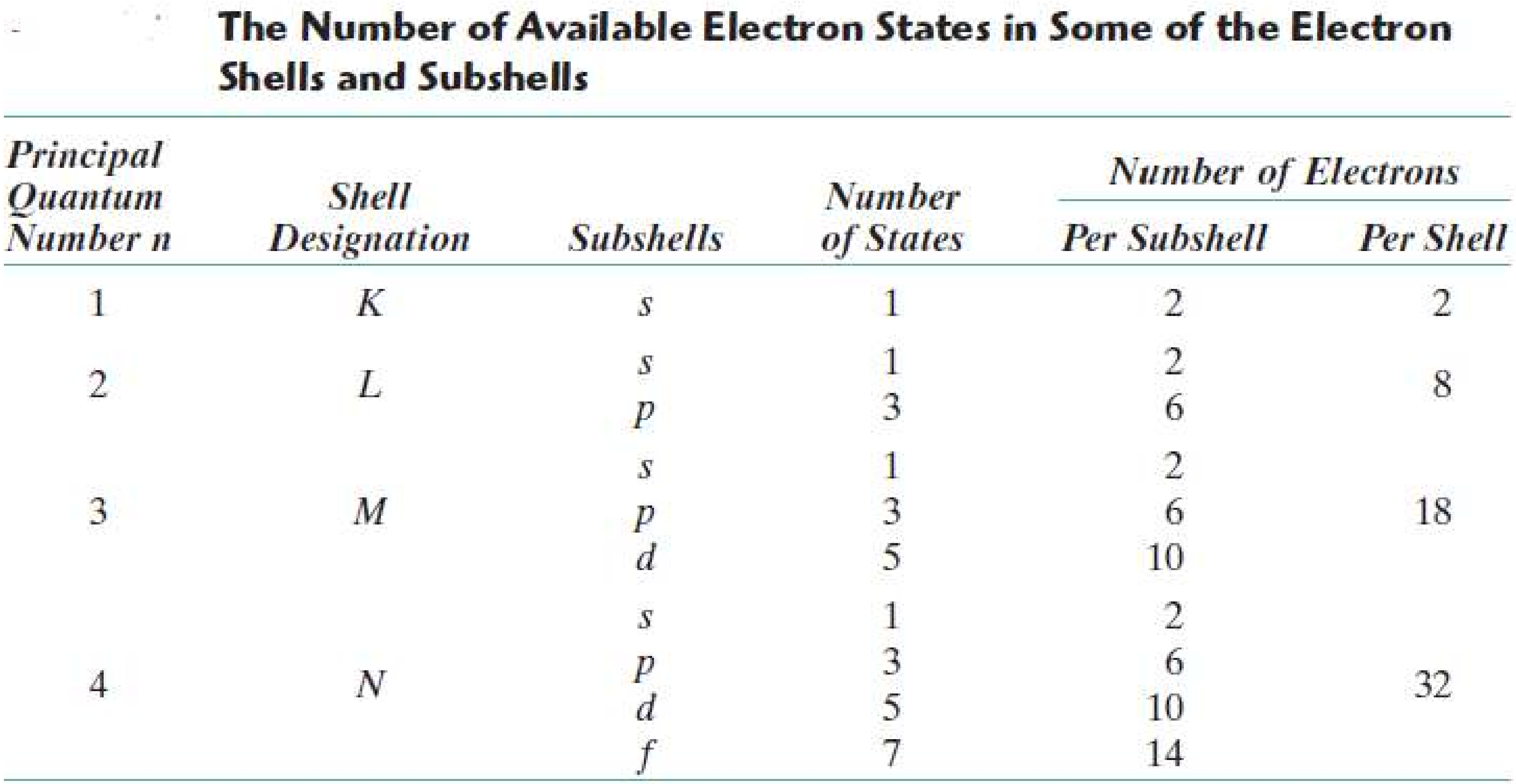
- Valence electrons are those that occupy the outermost shell
- They participate in the bonding between atoms to form atomic and molecular aggregates.
- Many of the physical and chemical properties of solids are based on these valence electrons.
- Stable electron configurations.
- The states within the outermost or valence electron shell are completely filled.
- These elements (ne, ar, kr, and he) are the inert, or noble, gases, which are virtually unreactive chemically. Some atoms of the elements that have unfilled valence shells assume stable electron configurations by gaining or losing electrons to form charged ions, or by sharing electrons with other atoms.

Aufbau's principle

- According to Afbau principle, electrons fill orbitals starting at the lowest available (possible) energy states before filling higher states. (e.g. 1s before 2s)

Pauli exclusion principle

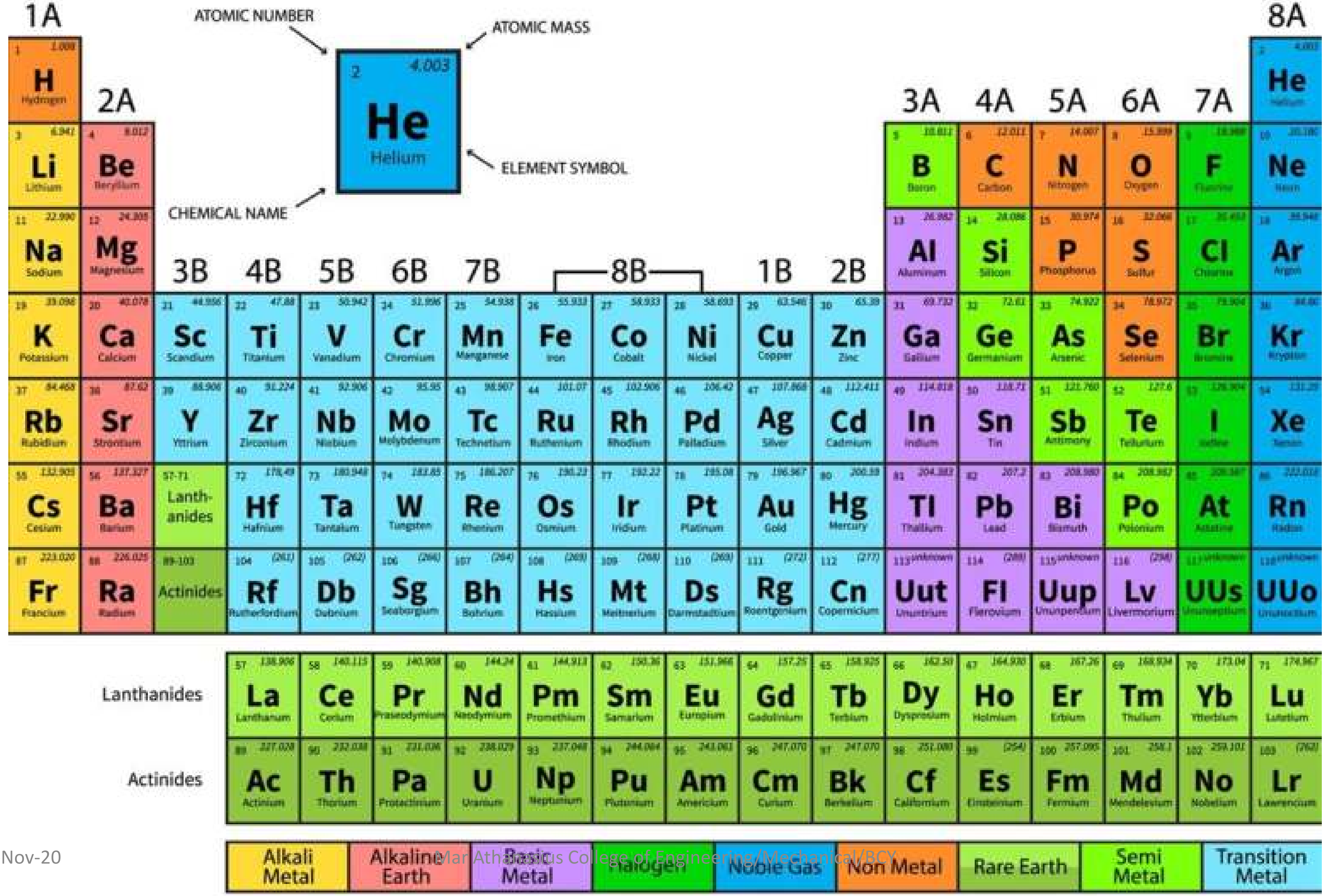
- No two electrons can have all the four quantum numbers to be the same or, if two electrons have to placed in an energy state they should be placed with opposite spins.
- The number of electrons that can occupy each orbital is limited by the Pauli exclusion principle.
- This principle stipulates that each electron state can hold no more than two electrons, which must have opposite spins. Thus, s, p, d, and f subshells may each accommodate, respectively, a total of 2, 6, 10, and 14 electrons.



The Number of Available Electron States in Some of the Electron Shells and Subshells

Principal Quantum Number n	*Shell Designation*	*Subshells*	*Number of States*	*Number of Electrons*	
				Per Subshell	*Per Shell*
1	*K*	*s*	1	2	2
2	*L*	*s*	1	2	8
		p	3	6	
3	*M*	*s*	1	2	18
		p	3	6	
		d	5	10	
4	*N*	*s*	1	2	32
		p	3	6	
		d	5	10	
		f	7	14	

Element	Symbol	N	Electron Configuration
Hydrogen	H	1	$1s^1$
Helium	He	2	$1s^2$
Lithium	Li	3	$1s^22s^2$
Boron	**B**	**5**	$1s^22s^22p^1$
Carbon	**C**	**6**	$1s^22s^22p^2$
Nitrogen	**N**	**7**	$1s^22s^22p^3$
Oxygen	**O**	**8**	$1s^22s^22p^4$



1A	2A	3B	4B	5B	6B	7B	8B			1B	2B	3A	4A	5A	6A	7A	8A
1 1.008 H Hydrogen																	2 4.003 He Helium
3 6.941 Li Lithium	4 9.012 Be Beryllium											5 10.811 B Boron	6 12.011 C Carbon	7 14.007 N Nitrogen	8 15.999 O Oxygen	9 18.998 F Fluorine	10 20.180 Ne Neon
11 22.990 Na Sodium	12 24.305 Mg Magnesium											13 26.982 Al Aluminum	14 28.086 Si Silicon	15 30.974 P Phosphorus	16 32.066 S Sulfur	17 35.453 Cl Chlorine	18 39.948 Ar Argon
19 39.098 K Potassium	20 40.078 Ca Calcium	21 44.956 Sc Scandium	22 47.88 Ti Titanium	23 50.942 V Vanadium	24 51.996 Cr Chromium	25 54.938 Mn Manganese	26 55.933 Fe Iron	27 58.933 Co Cobalt	28 58.693 Ni Nickel	29 63.546 Cu Copper	30 65.39 Zn Zinc	31 69.732 Ga Gallium	32 72.61 Ge Germanium	33 74.922 As Arsenic	34 78.972 Se Selenium	35 79.904 Br Bromine	36 84.80 Kr Krypton
37 84.468 Rb Rubidium	38 87.62 Sr Strontium	39 88.906 Y Yttrium	40 91.224 Zr Zirconium	41 92.906 Nb Niobium	42 95.95 Mo Molybdenum	43 98.907 Tc Technetium	44 101.07 Ru Ruthenium	45 102.906 Rh Rhodium	46 106.42 Pd Palladium	47 107.868 Ag Silver	48 112.411 Cd Cadmium	49 114.818 In Indium	50 118.71 Sn Tin	51 121.760 Sb Antimony	52 127.6 Te Tellurium	53 126.904 I Iodine	54 131.29 Xe Xenon
55 132.905 Cs Cesium	56 137.327 Ba Barium	57-71 Lanthanides	72 178.49 Hf Hafnium	73 180.948 Ta Tantalum	74 183.85 W Tungsten	75 186.207 Re Rhenium	76 190.23 Os Osmium	77 192.22 Ir Iridium	78 195.08 Pt Platinum	79 196.967 Au Gold	80 200.59 Hg Mercury	81 204.383 Tl Thallium	82 207.2 Pb Lead	83 208.980 Bi Bismuth	84 208.982 Po Polonium	85 209.987 At Astatine	86 222.018 Rn Radon
87 223.020 Fr Francium	88 226.025 Ra Radium	89-103 Actinides	104 (261) Rf Rutherfordium	105 (262) Db Dubnium	106 (266) Sg Seaborgium	107 (264) Bh Bohrium	108 (269) Hs Hassium	109 (268) Mt Meitnerium	110 (269) Ds Darmstadtium	111 (272) Rg Roentgenium	112 (277) Cn Copernicium	113 unknown Uut Ununtrium	114 (289) Fl Flerovium	115 unknown Uup Ununpentium	116 (298) Lv Livermorium	117 unknown UUs Ununseptium	118 unknown UUo Ununoctium

Lanthanides	57 138.906 La Lanthanum	58 140.115 Ce Cerium	59 140.908 Pr Praseodymium	60 144.24 Nd Neodymium	61 144.913 Pm Promethium	62 150.36 Sm Samarium	63 151.966 Eu Europium	64 157.25 Gd Gadolinium	65 158.925 Tb Terbium	66 162.50 Dy Dysprosium	67 164.930 Ho Holmium	68 167.26 Er Erbium	69 168.934 Tm Thulium	70 173.04 Yb Ytterbium	71 174.967 Lu Lutetium
Actinides	89 227.028 Ac Actinium	90 232.038 Th Thorium	91 231.036 Pa Protactinium	92 238.029 U Uranium	93 237.048 Np Neptunium	94 244.064 Pu Plutonium	95 243.061 Am Americium	96 247.070 Cm Curium	97 247.070 Bk Berkelium	98 251.080 Cf Californium	99 (254) Es Einsteinium	100 257.095 Fm Fermium	101 258.1 Md Mendelevium	102 259.101 No Nobelium	103 (262) Lr Lawrencium

Alkali Metal
Alkaline Earth
Basic Metal
Halogen
Noble Gas
Non Metal
Rare Earth
Semi Metal
Transition Metal

Atomic Bonding in Solids

BONDING FORCES AND ENERGIES

- The bonding energy for these two atoms, E_0, corresponds to the energy at this minimum point. it represents the energy that would be required to separate these two atoms to an infinite separation.

- At a state of equilibrium, The centers of the two atoms will remain separated by the equilibrium spacing r_0

- The magnitude of this bonding energy and the shape of the energy-versus interatomic separation curve vary from material to material, and they both depend on the type of atomic bonding.

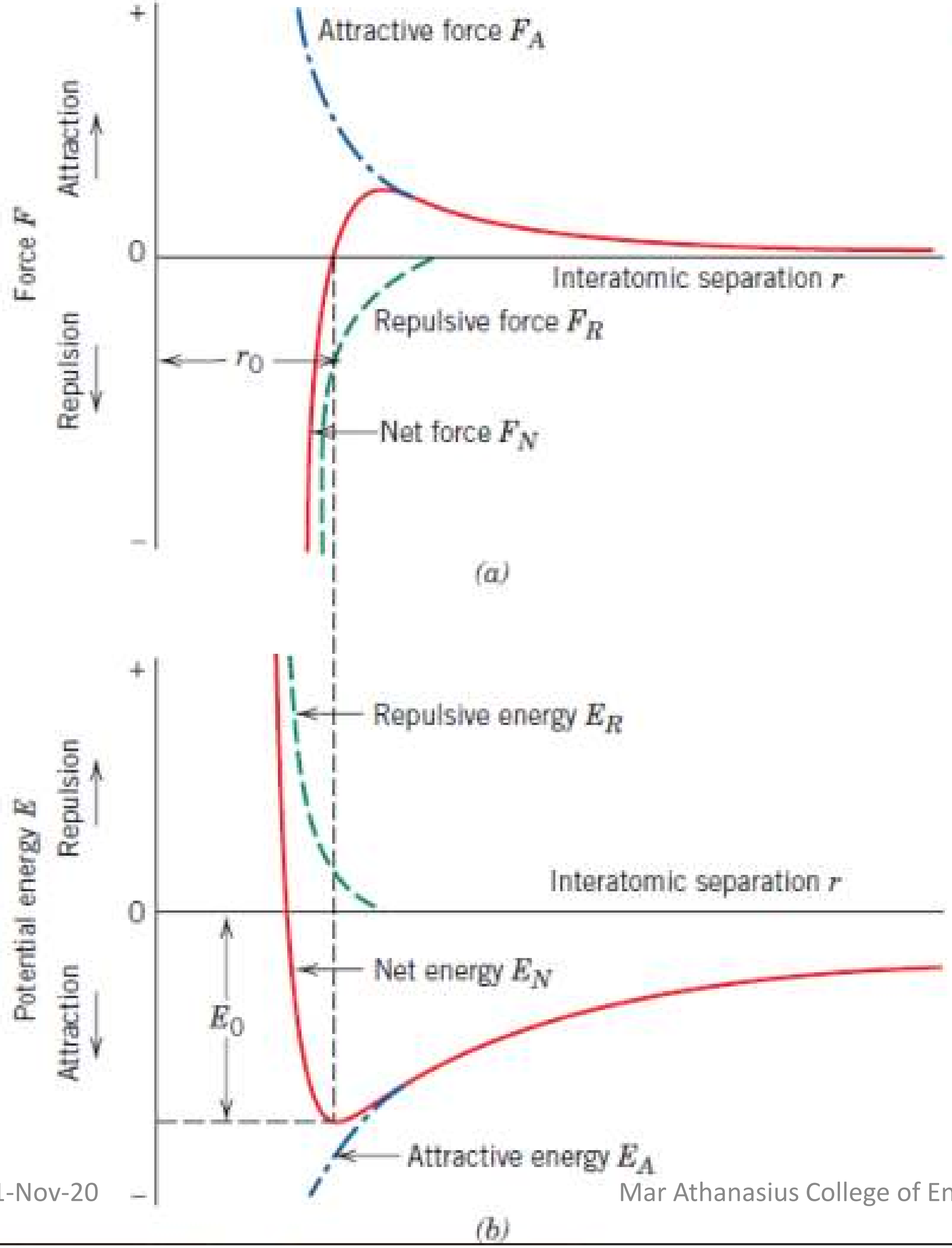
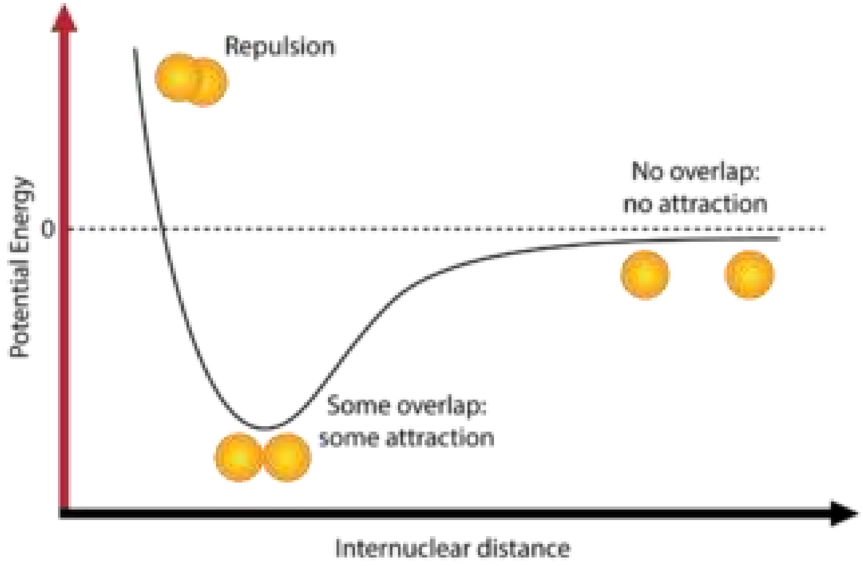
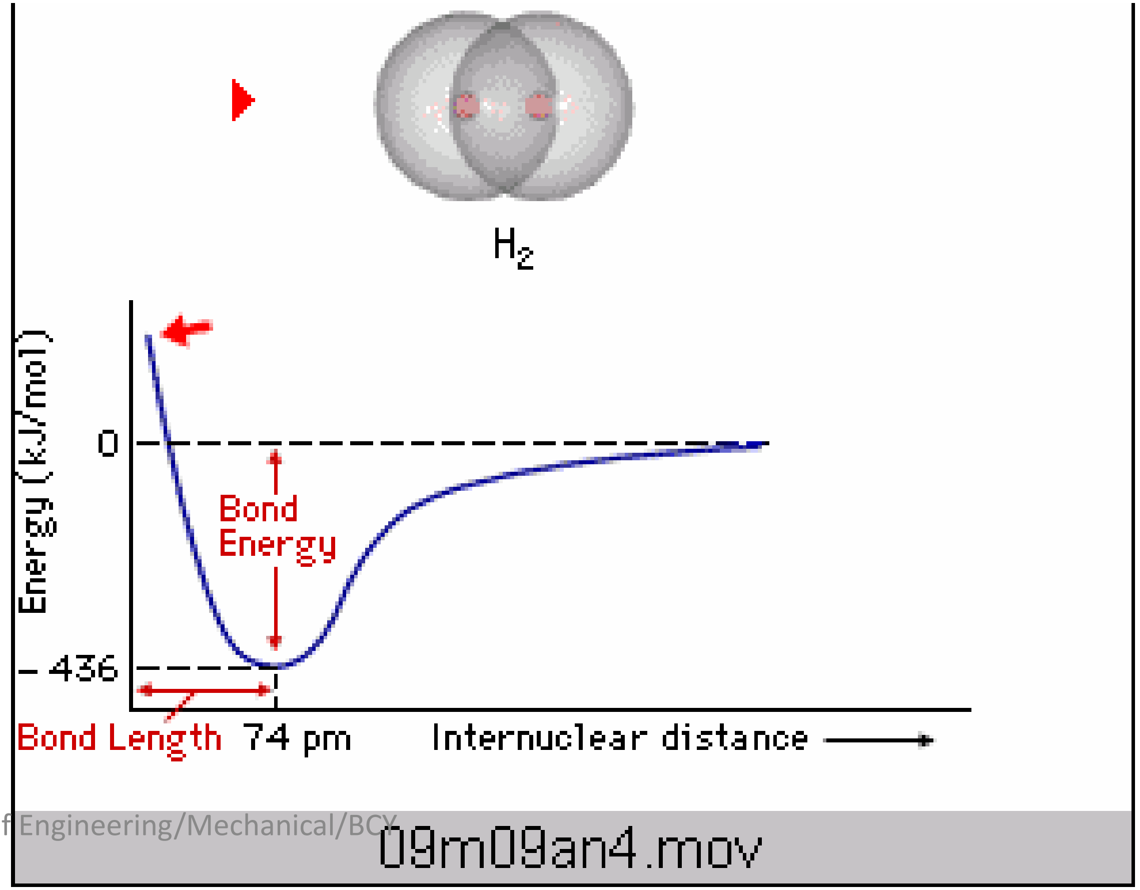


Figure 2.8 (*a*) The dependence of repulsive, attractive, and net forces on interatomic separation for two isolated atoms. (*b*) The dependence of repulsive, attractive, and net potential energies on interatomic separation for two isolated atoms.

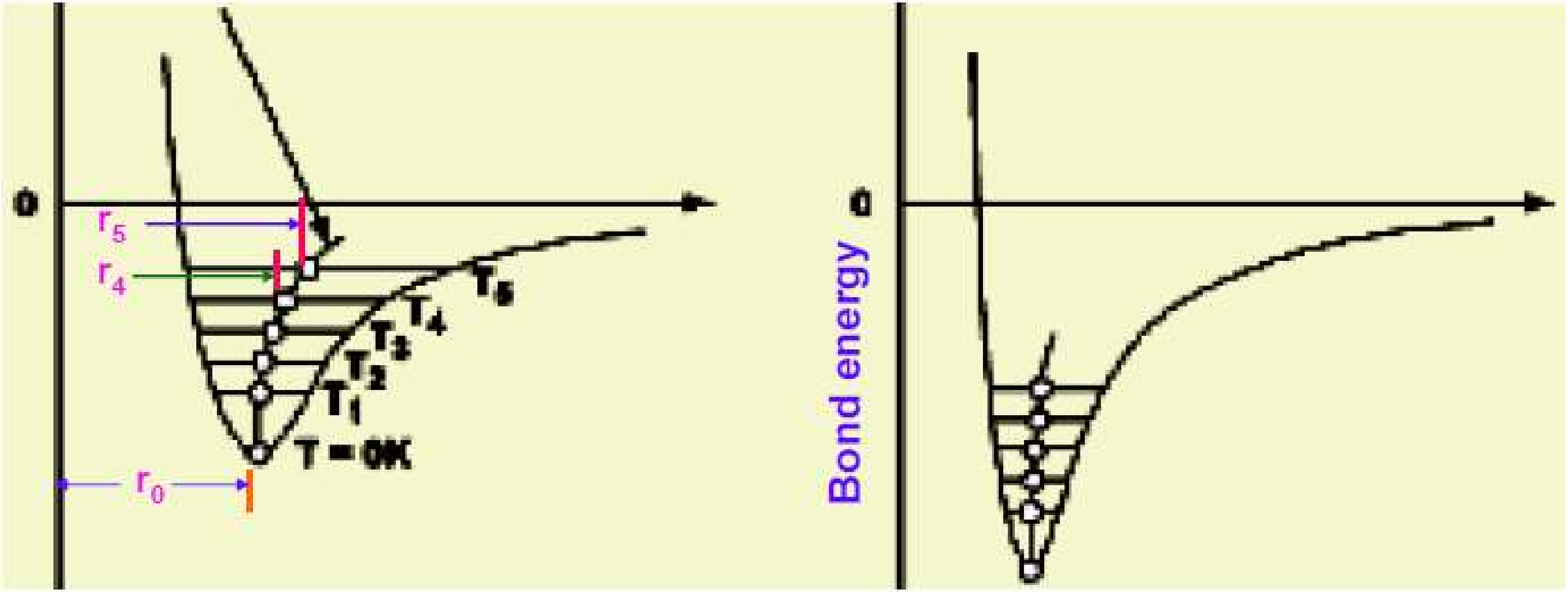


Bond Length (r_o)

- Bond length is the distance between nuclei of two bonded atoms. ro = 1-2 Å – primary bonds; 2-5 Å–secondary bonds
- Bond length increases & bond energy reduces with increase in atomic number / radius.



Deeper energy well bond and shallow energy well bond



Shallow well

Weakly bonded solid

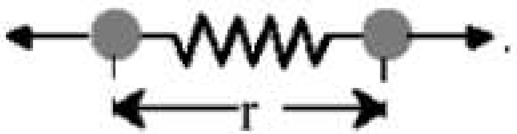
Deep well

Strongly bonded solid

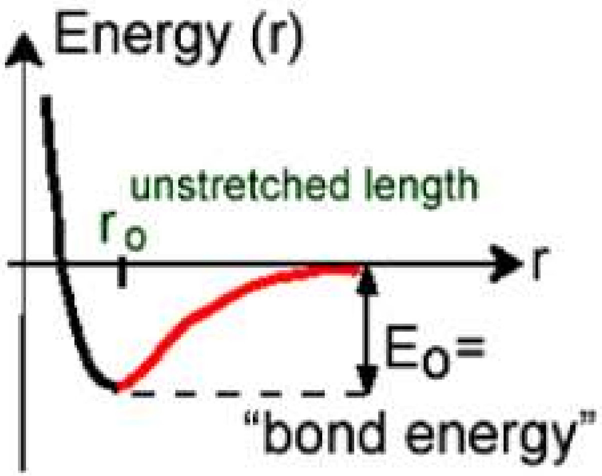
Properties of bonding

1. Melting Temperature (Tm)

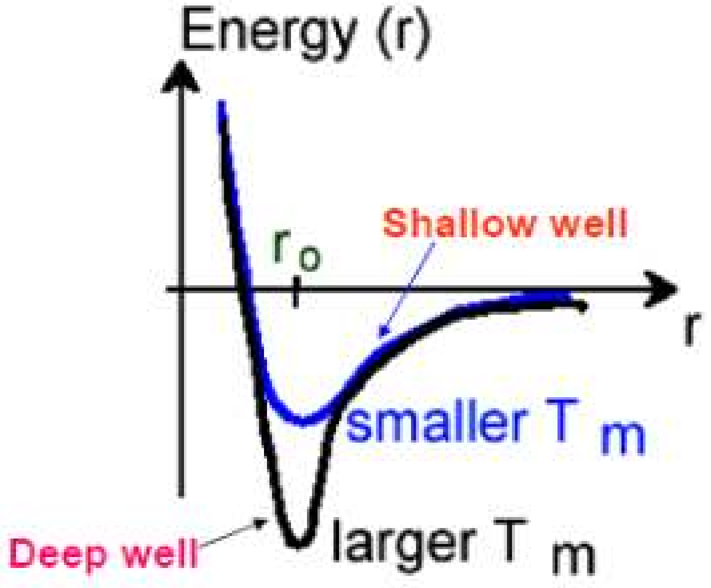
- Bond length, r



- Bond energy, E_o



- Melting Temperature, T_m

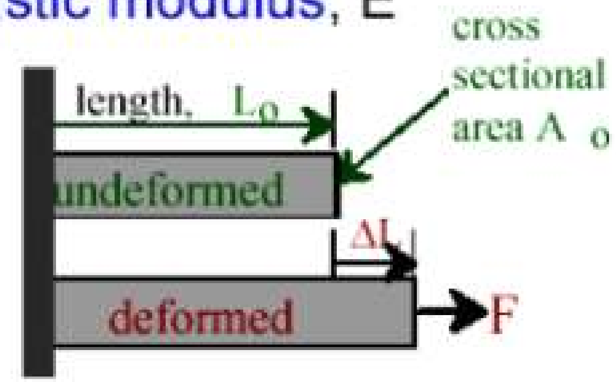


T_m is larger if E_o is larger.

Properties of bonding

2. Modulus of Elasticity (E)

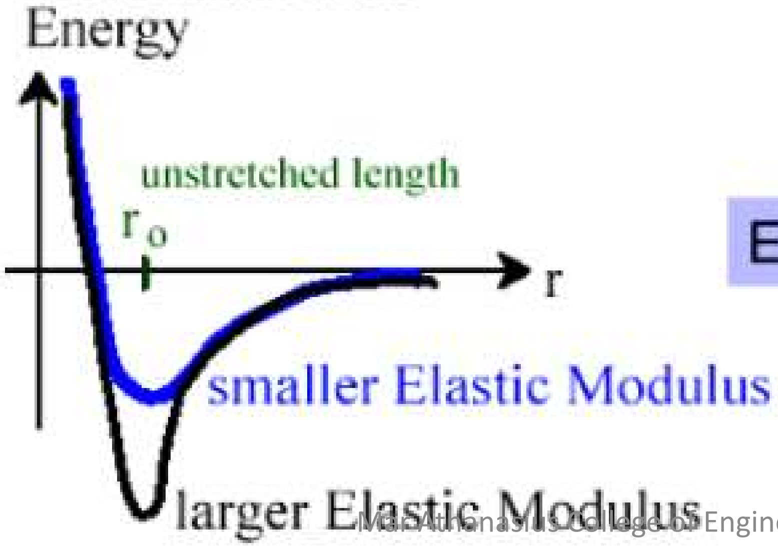
- Elastic modulus, E



Elastic modulus

$$\frac{F}{A_o} = E\frac{\Delta L}{L_o}$$

- E ~ curvature at r_o

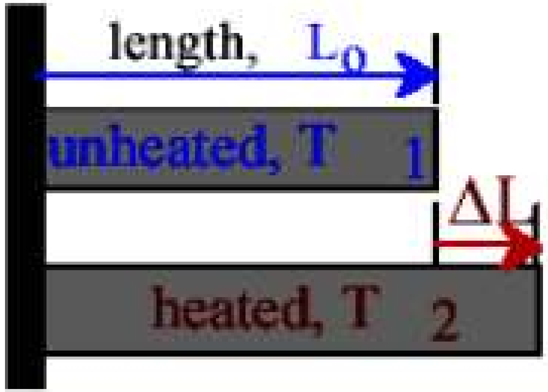


E is larger if E_o is larger.

Properties of bonding

3. Coefficient of Thermal Expansion (α)

- Coefficient of thermal expansion, α



coeff. thermal expansion

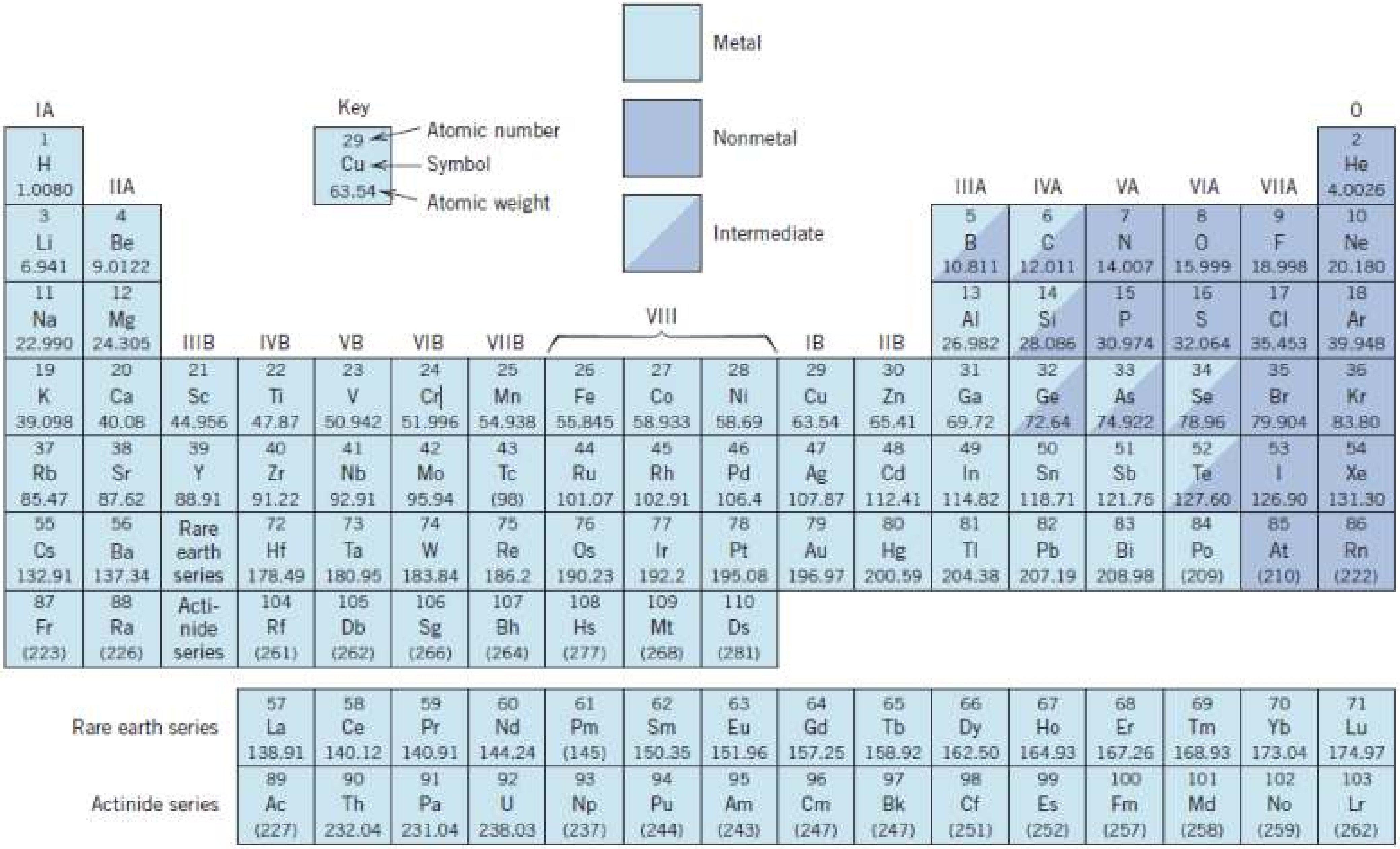
$$\frac{\Delta L}{L_o} = \alpha\,(T_2 - T_1)$$

α is larger if E_o is smaller.

material	**CTE (ppm/°C)**
silicon	3.2

Chemical Bonding

- Chemical Bonding refers to the formation of a chemical bond between two or more atoms, molecules, or ions to give rise to a chemical compound. These chemical bonds are what keep the atoms together in the resulting compound.
- Atoms of all elements has a tendency to acquire an electronic configuration similar to that of inert gases, because it represents the most stable electronic configuration. (Lewis Octect Rule)
- It is this tendency of atoms to complete and hence stabilize their outermost orbit of electrons, which is mainly responsible for chemical combination between atoms.
- The attractive force which holds various constituents (atom, ions, etc.) together and stabilizes them by the overall loss of energy is known as chemical bonding.
- According to a more general rule of electron pairing, atoms of elements have a tendency to get their electrons paired in all the occupied orbits and thus attain greater stability.



Key

29 ← Atomic number Cu ← Symbol 63.54 ← Atomic weight

Metal

Nonmetal

Intermediate

IA	IIA	IIIB	IVB	VB	VIB	VIIB	VIII			IB	IIB	IIIA	IVA	VA	VIA	VIIA	0
1 H 1.0080																	2 He 4.0026
3 Li 6.941	4 Be 9.0122											5 B 10.811	6 C 12.011	7 N 14.007	8 O 15.999	9 F 18.998	10 Ne 20.180
11 Na 22.990	12 Mg 24.305											13 Al 26.982	14 Si 28.086	15 P 30.974	16 S 32.064	17 Cl 35.453	18 Ar 39.948
19 K 39.098	20 Ca 40.08	21 Sc 44.956	22 Ti 47.87	23 V 50.942	24 Cr 51.996	25 Mn 54.938	26 Fe 55.845	27 Co 58.933	28 Ni 58.69	29 Cu 63.54	30 Zn 65.41	31 Ga 69.72	32 Ge 72.64	33 As 74.922	34 Se 78.96	35 Br 79.904	36 Kr 83.80
37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.94	43 Tc (98)	44 Ru 101.07	45 Rh 102.91	46 Pd 106.4	47 Ag 107.87	48 Cd 112.41	49 In 114.82	50 Sn 118.71	51 Sb 121.76	52 Te 127.60	53 I 126.90	54 Xe 131.30
55 Cs 132.91	56 Ba 137.34	Rare earth series	72 Hf 178.49	73 Ta 180.95	74 W 183.84	75 Re 186.2	76 Os 190.23	77 Ir 192.2	78 Pt 195.08	79 Au 196.97	80 Hg 200.59	81 Tl 204.38	82 Pb 207.19	83 Bi 208.98	84 Po (209)	85 At (210)	86 Rn (222)
87 Fr (223)	88 Ra (226)	Actinide series	104 Rf (261)	105 Db (262)	106 Sg (266)	107 Bh (264)	108 Hs (277)	109 Mt (268)	110 Ds (281)								

Rare earth series	57 La 138.91	58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm (145)	62 Sm 150.35	63 Eu 151.96	64 Gd 157.25	65 Tb 158.92	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.04	71 Lu 174.97
Actinide series	89 Ac (227)	90 Th 232.04	91 Pa 231.04	92 U 238.03	93 Np (237)	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (252)	100 Fm (257)	101 Md (258)	102 No (259)	103 Lr (262)

Classification of Chemical Bonding

(a) **Primary bonds** (Strong Bonds :100 -1500 kJ/mole, bond length = 1-2 Å)

- Ionic bond (METAL+ NON METAL)
- Covalent bond (NON METAL+ NON METAL)
- Metallic bond (METAL+ METAL)

(b) **Secondary bonds** (Weak Bonds :1-50 kJ/mole, bond length = 2-5 Å)

– Inter molecular, gases and liquids

– Feeble and less stable

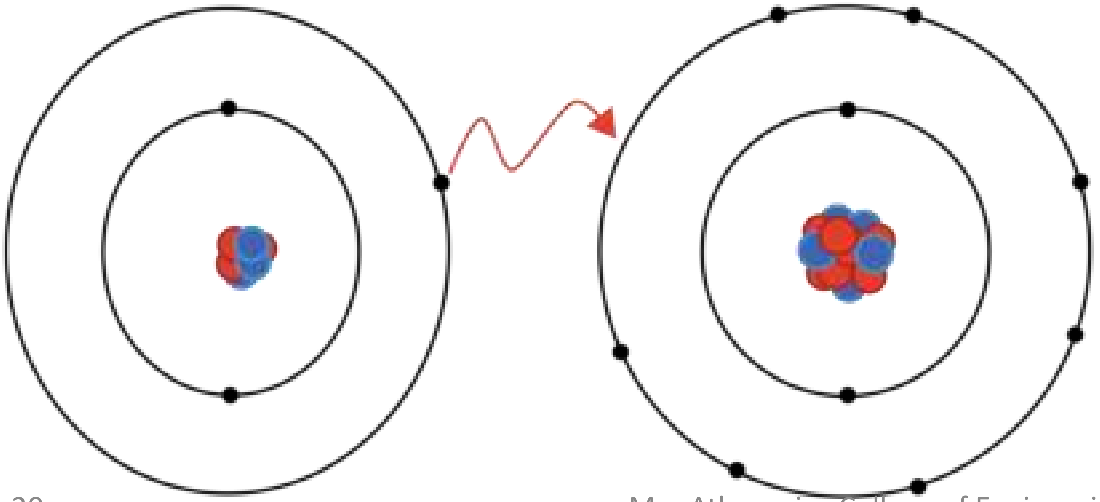
- Di-pole bond
- Hydrogen bond
- Vander Waals bond

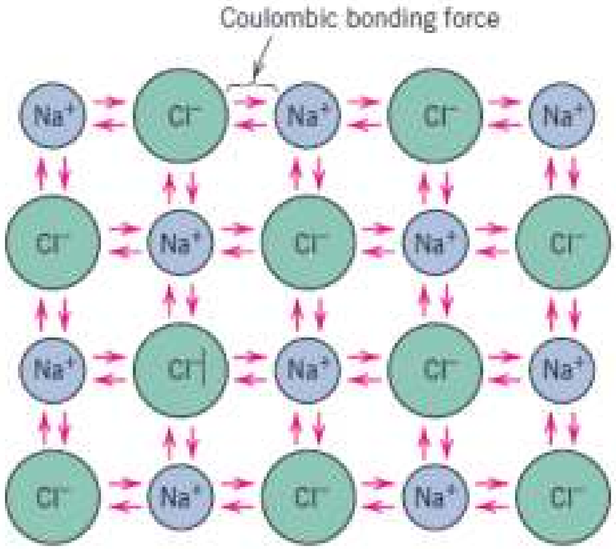
Ionic Bonding

- Bonding between **Metal + Non metal**
- Transfer of electrons - easily exchange/ transfer electrons so as to stabilize their outer shells (i.e. become more inert gas-like)
- **Non Directional** – over lapping of electrons - magnitude of the bond equal in all directions around an ion OR bond posses equal strength in all directions.
- Bond energies : 600 –1500 kJ/mol (6-15 eV/ atom)
- High melting temperature, hard, brittle, electrically and thermally insulative.
- Example : NaCl

Properties of Ionic Compounds

- Crystalline structure.
- A regular repeating arrangement of ions in the solid.
- Ions are strongly bonded.
- Structure is rigid.
- High melting points-because of strong forces between ions.



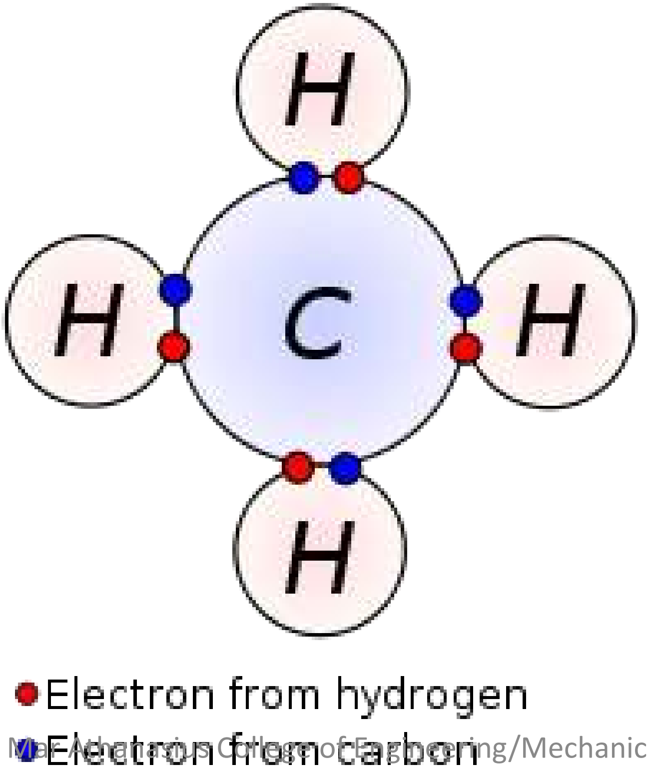


Covalent bonding

- Bonding **Non Metal + Non Metal**
- Covalent bond- A bond formed when atoms share electrons equally
- Two atoms share one or more pairs of outer shell electrons
- Strongest of all chemical bonds
- Good overlap of orbital-bring shared electrons close both the nuclei
- Overlapping orbitals are directionally oriented and not spherically symmetric.

Covalent bonding

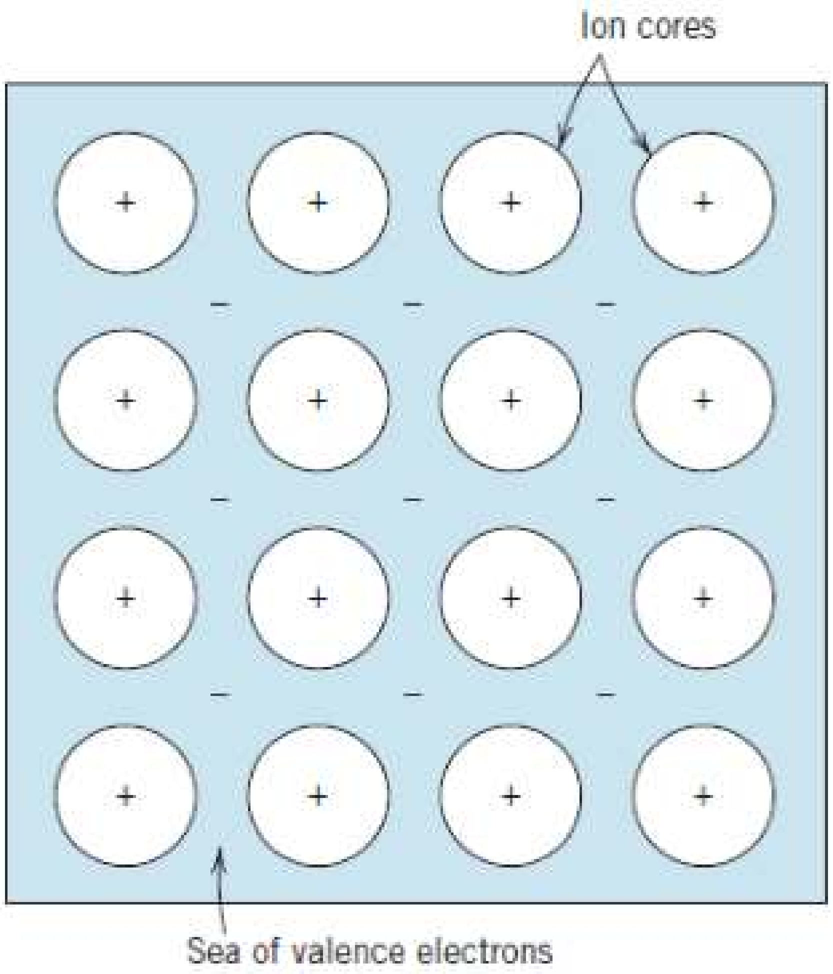
- **Directional** – magnitude of the bond is not equal in all directions
- Bond energies : 100 –1000 kJ/mol (1-10 eV/ atom)
- High melting temperature, hard, brittle, electrically and thermally insulative

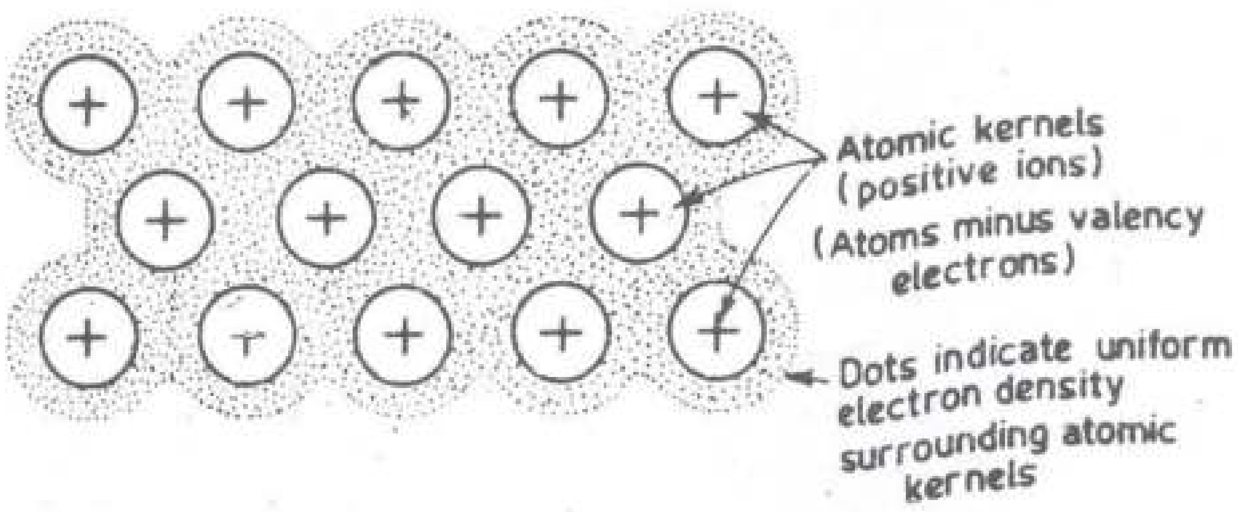


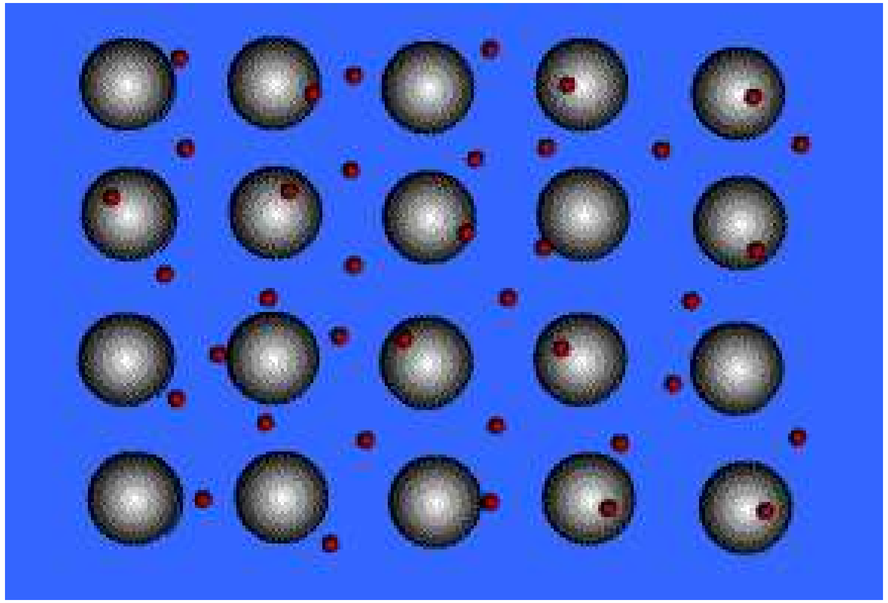
Metallic Bonding

- Bonding **Metal + Metal**
- Delocalized electrons/electron cloud/sea of electrons
- **Non directional** – over lapping of electrons orbitals are spherically symmetric. Magnitude of the bond equal in all directions around an ion OR bond posses equal strength in all directions
- Bond energy: wide range:-E (Hg) = 0.7eV/atom to E (W) = 8.8 eV/atom
- Metals are lustrous, Ductile, electrically and thermally conductive

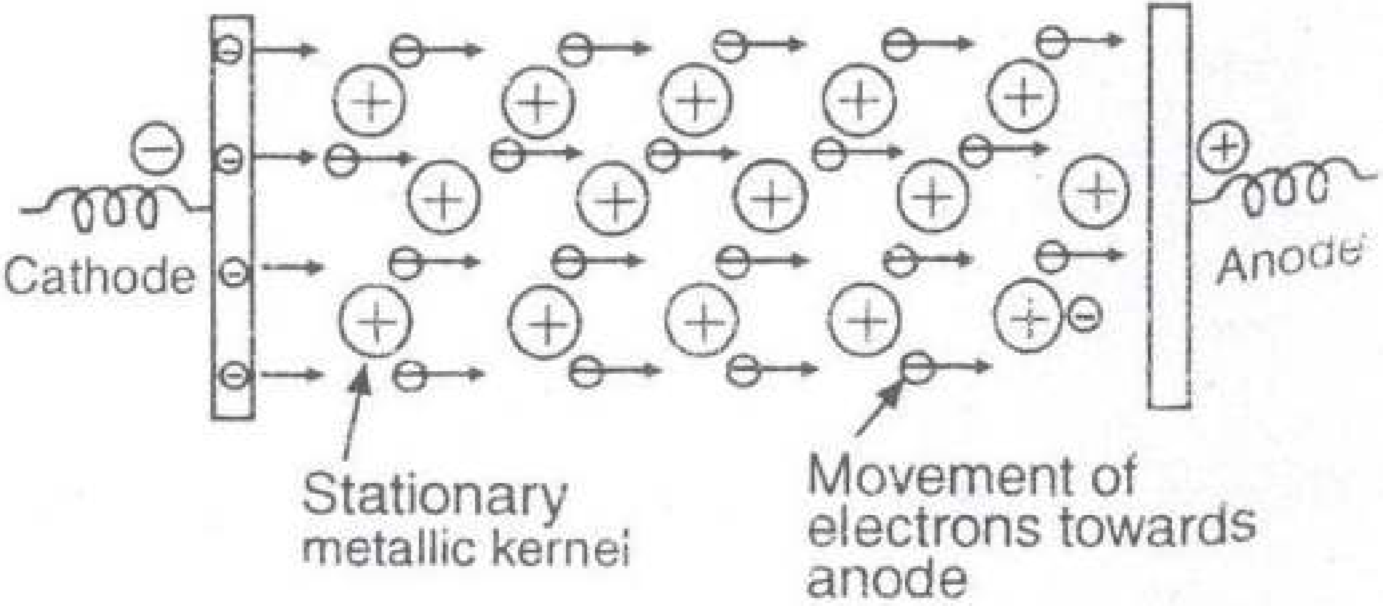
Metallic bond





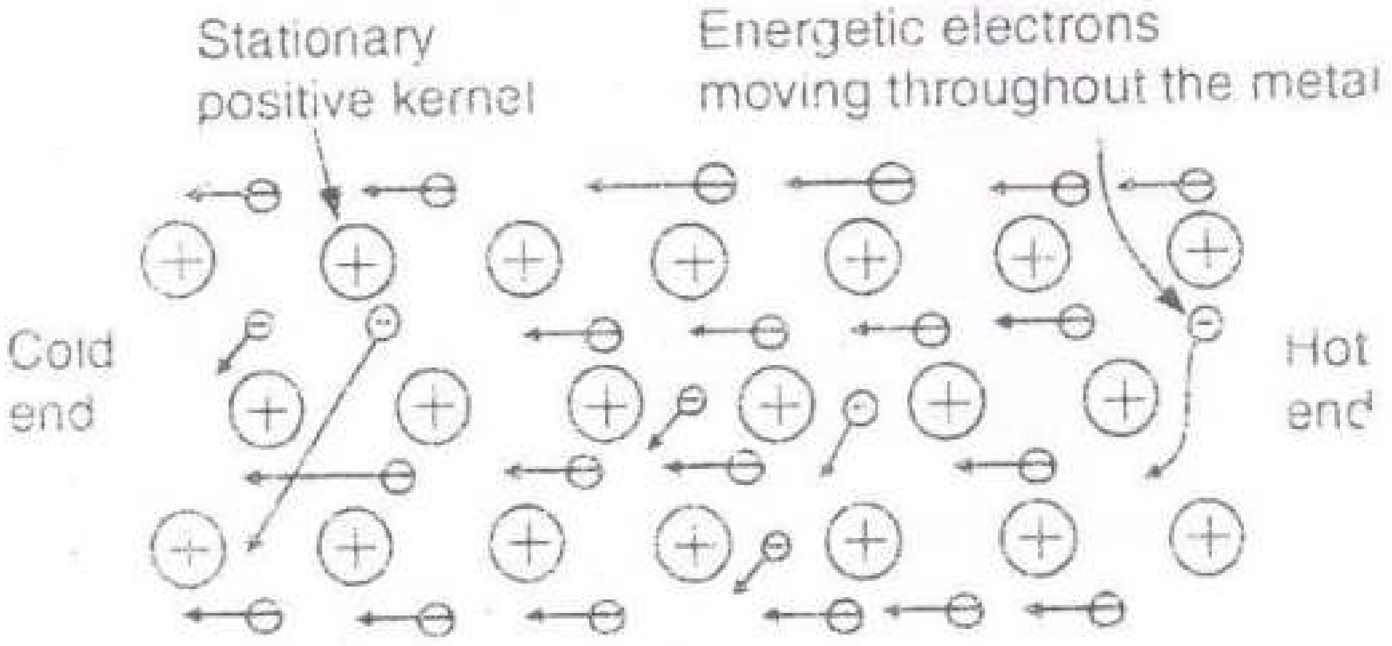


Why metals have high electrical conductivity…?



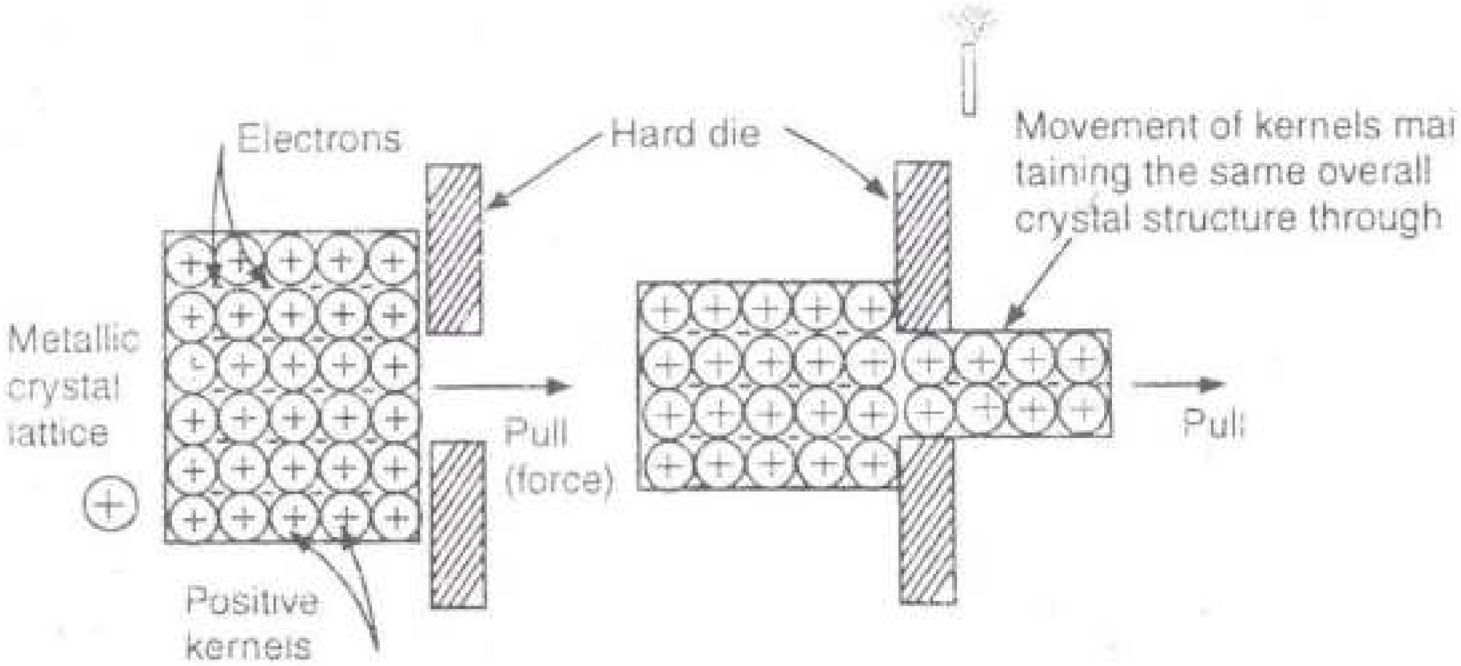
Metals are good conductors of electricity. This is due to the mobility of electrons.

Why metals have high thermal conductivity…?



Metals are good conductors of heat. This is also due to the mobility of electrons.

Why metals are malleable & ductile…?



- Metals are malleable (can be flattened to thin sheets) and ductile (can be drawn into wires).
- This is because positive kernals and electrons can "flow" around each other, without breaking the crystal structure.

Why metals are lustrous & opaque…?

- Metals are lustrous - This is due to the uniform way that the valence electrons of the metal absorb and re-emit light energy.
- Metals are opaque - The free electrons oscillate in the alternating electric field of the incident light beam, absorbing energy at all wavelengths and so making the metal opaque.
- In turn the oscillating electrons emit waves and in this way produce the reflected beam.

Primary bonds, bond energies & melting temperatures.

Bond	substance	kJ/mol	eV/atom	M.T. (^{o}C)
Ionic	NaCl	640	3.3	801
	MgO	1000	5.2	2800
Covalent	Si	450	4.7	1410
	C (Diam.)	713	7.4	> 3550
Metallic	Hg	68	0.7	- 39
	Al	324	3.4	660
	Fe	406	4.2	1538

Secondary Bonding

Secondary / Van der Waals / Physical bonds.

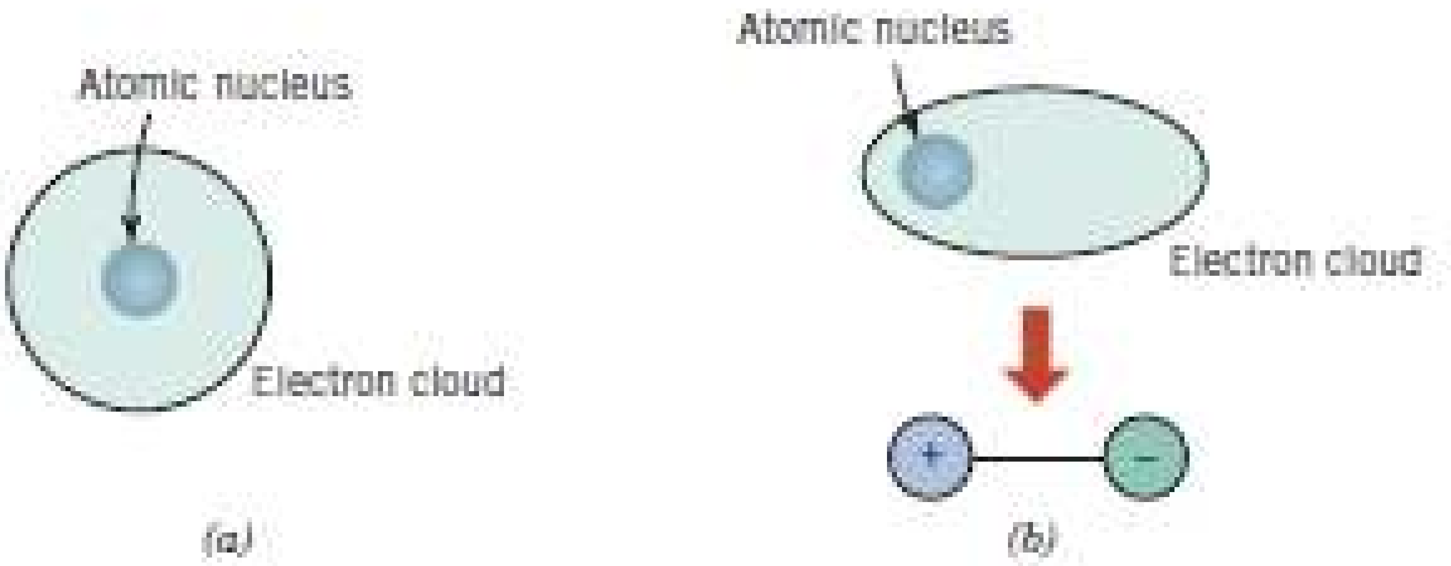
- They are due to van der waals force or inter molecular attractive forces, which acts between all molecules when they are close to each other.
- They are weak in comparison to the primary bond - bonding energies are typically in the order of only 10 kJ/mol.
- Secondary bond exists between all atoms or molecules

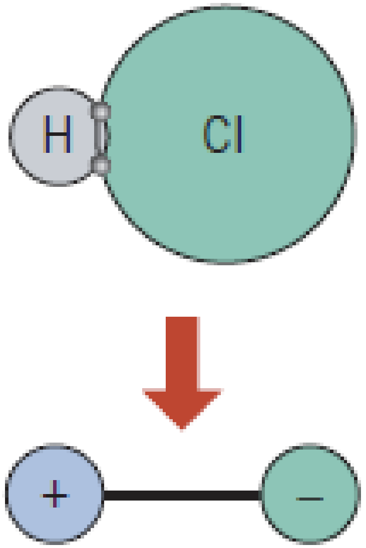
Secondary Bonding

1. Dipole – dipole attraction
2. Hydrogen bond

Polar Molecule / Induced Dipole Bonds

- Permanent dipole moments exist in some molecules by virtue of an asymmetrical arrangement of positively and negatively charged regions, such molecules are termed as **polar molecules.**

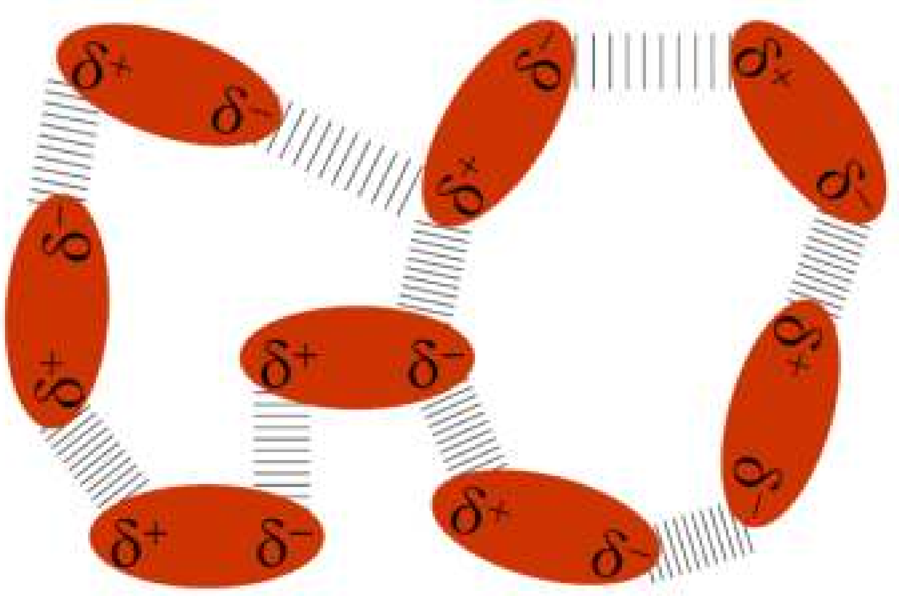


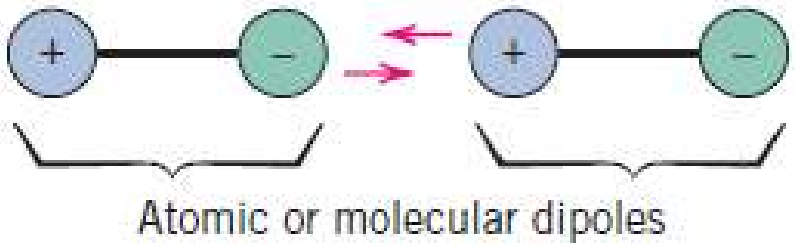


Schematic representations of (a) an electrically symmetric atom and (b) an induced atomic dipole.

Dipole – dipole attraction / bonding

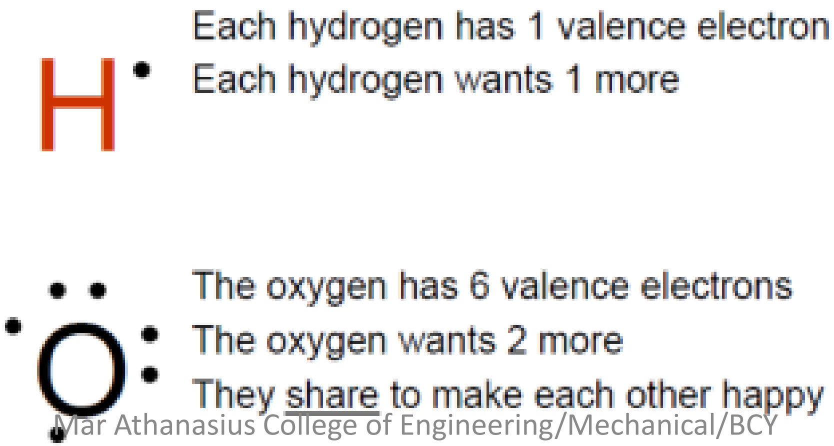
The bonding results from the attraction between the positive end of one dipole and the negative region of an adjacent one.





Hydrogen bond

- Hydrogen bonding, a special type of secondary bonding, is found to exist between some molecules having hydrogen as one of the constituents.
- It is a type of polar covalent bonding between oxygen and hydrogen wherein the hydrogen develops a partial positive charge. This implies that the electrons are pulled closer to the more electronegative oxygen atom.
- This creates a tendency for the hydrogen to be attracted towards the negative charges of any neighboring atom.

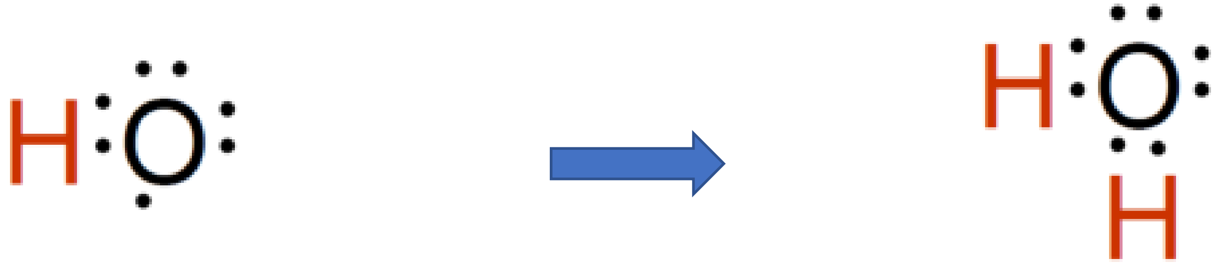


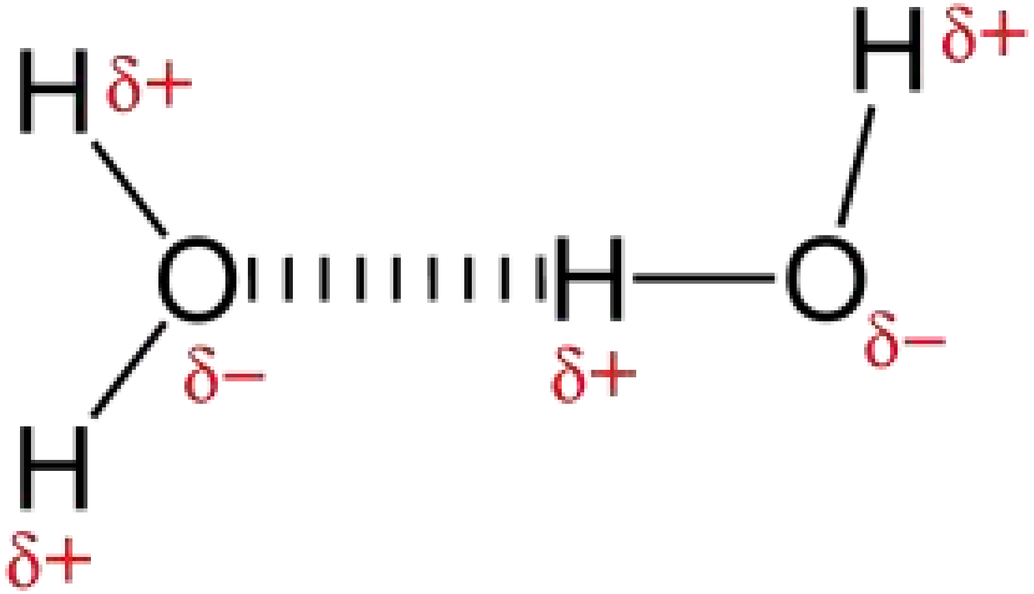
Each hydrogen has 1 valence electron
Each hydrogen wants 1 more

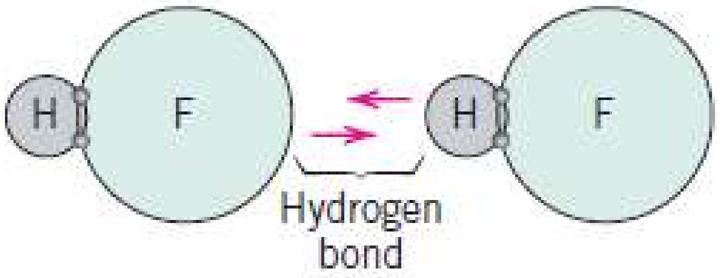
The oxygen has 6 valence electrons
The oxygen wants 2 more
They share to make each other happy

Water

As the second hydrogen atom attaches, now every atom has full energy levels.







Types of bonding

Classification based on no. of pairs of electrons being shared.

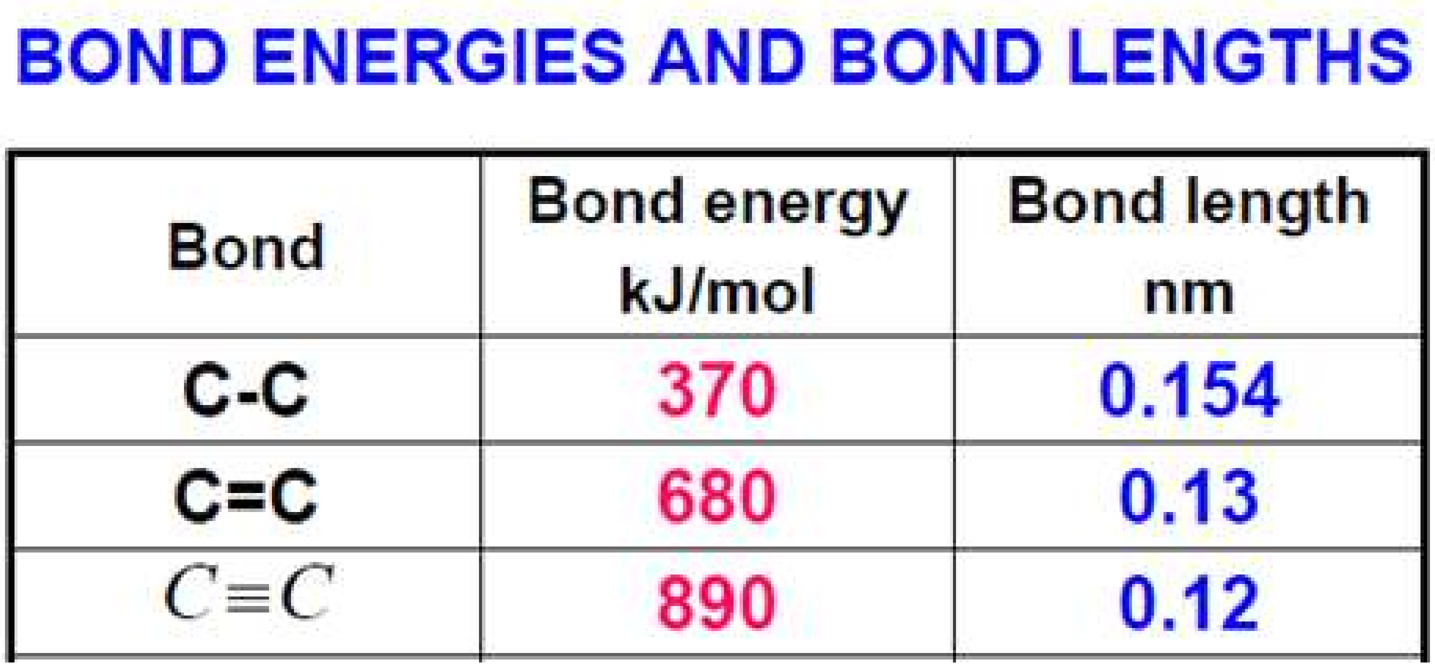
- **Single bond:** one pair of electrons are shared between two atoms
- **Double bond:** two pairs of electrons are shared between two atoms
- **Triple bond:** three pairs of electrons are shared between two atoms

Bond energy: the amount of energy required to break a bond holding two atoms together.

triple bond > double bond > single bond

Bond length: the distance separating the nuclei

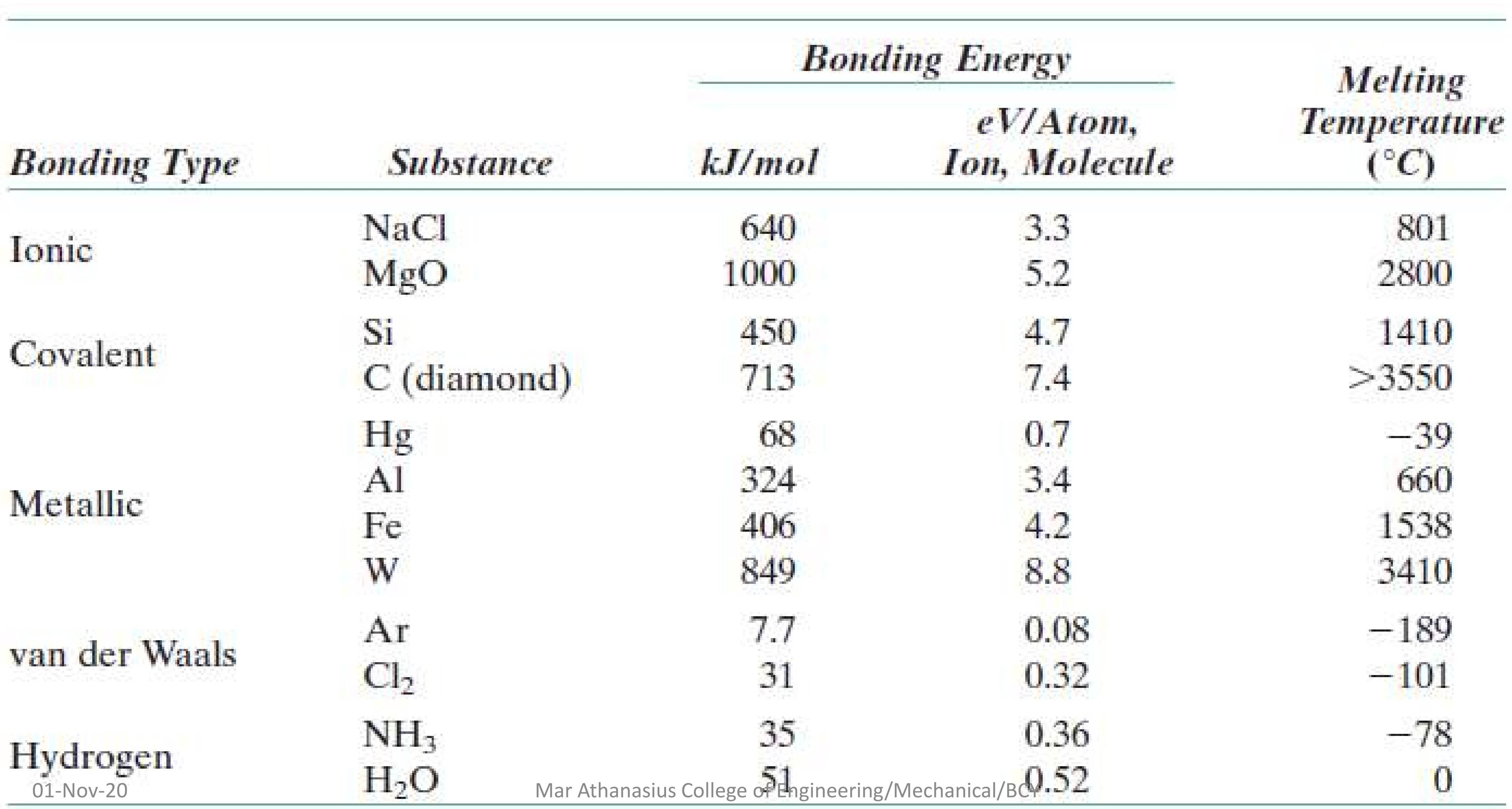
single bond > double bond > triple bond



BOND ENERGIES AND BOND LENGTHS

Bond	Bond energy kJ/mol	Bond length nm
C-C	370	0.154
C=C	680	0.13
$C \equiv C$	890	0.12

Bonding Type, Energies and Melting Temperatures for Various Substances



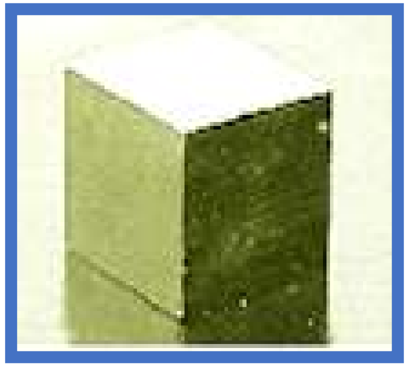
Bonding Type	Substance	Bonding Energy		Melting Temperature (°C)
		kJ/mol	eV/Atom, Ion, Molecule	
Ionic	NaCl	640	3.3	801
	MgO	1000	5.2	2800
Covalent	Si	450	4.7	1410
	C (diamond)	713	7.4	>3550
Metallic	Hg	68	0.7	−39
	Al	324	3.4	660
	Fe	406	4.2	1538
	W	849	8.8	3410
van der Waals	Ar	7.7	0.08	−189
	Cl_2	31	0.32	−101
Hydrogen	NH_3	35	0.36	−78
	H_2O	51	0.52	0

Crystallography

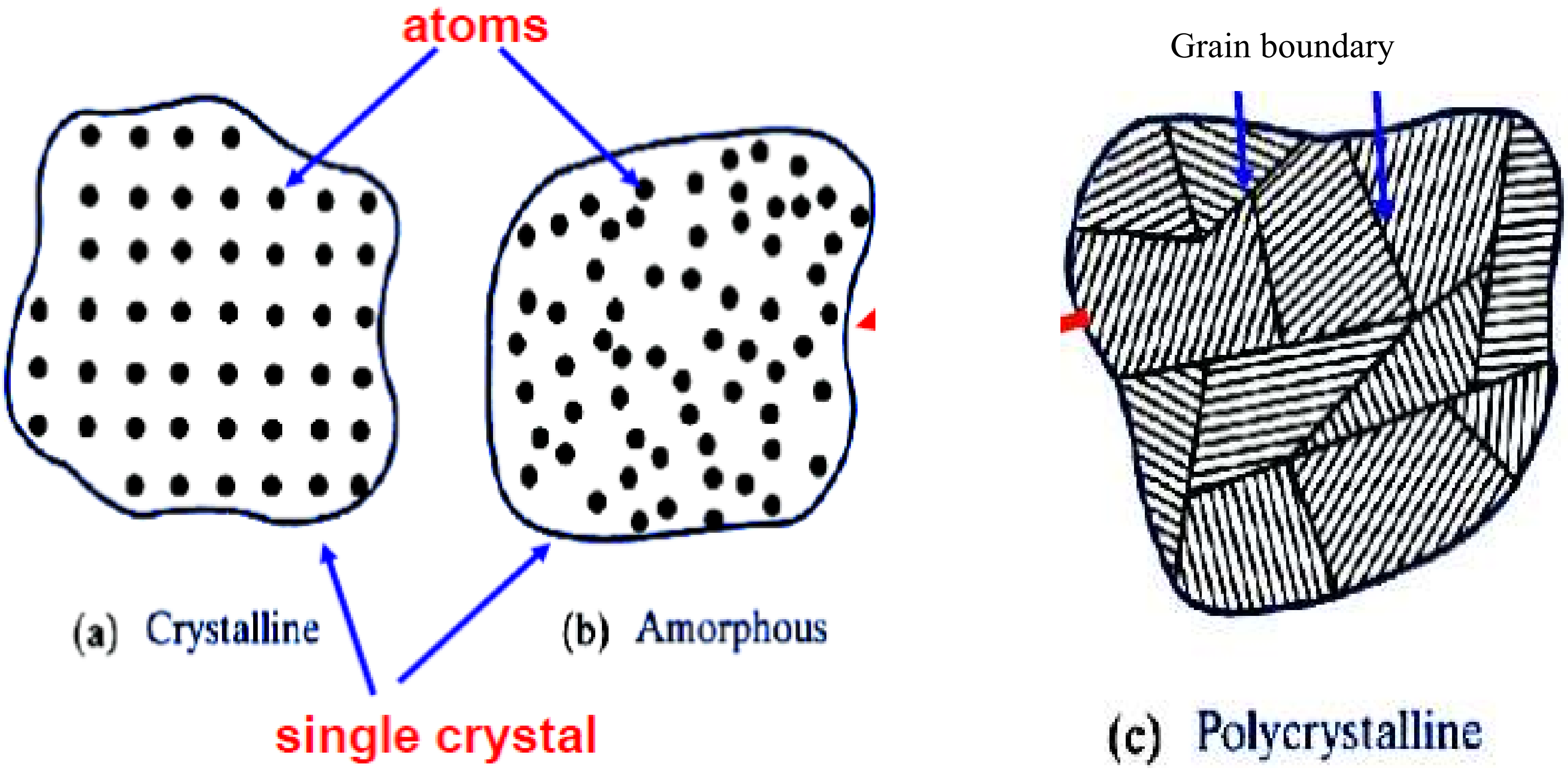
The structure of materials

SOLID MATERIALS

- **CRYSTALLINE**
  - **Single Crystal**
- **POLYCRYSTALLINE**
- **AMORPHOUS (Non-crystalline)**
- **Quasi crystal**



Crystal Structure



(a) Crystalline (b) Amorphous (c) Polycrystalline

Classification of Solid materials

Solid materials may be classified according to the regularity with which atoms or ions are arranged with respect to one another.

1. **Crystalline**

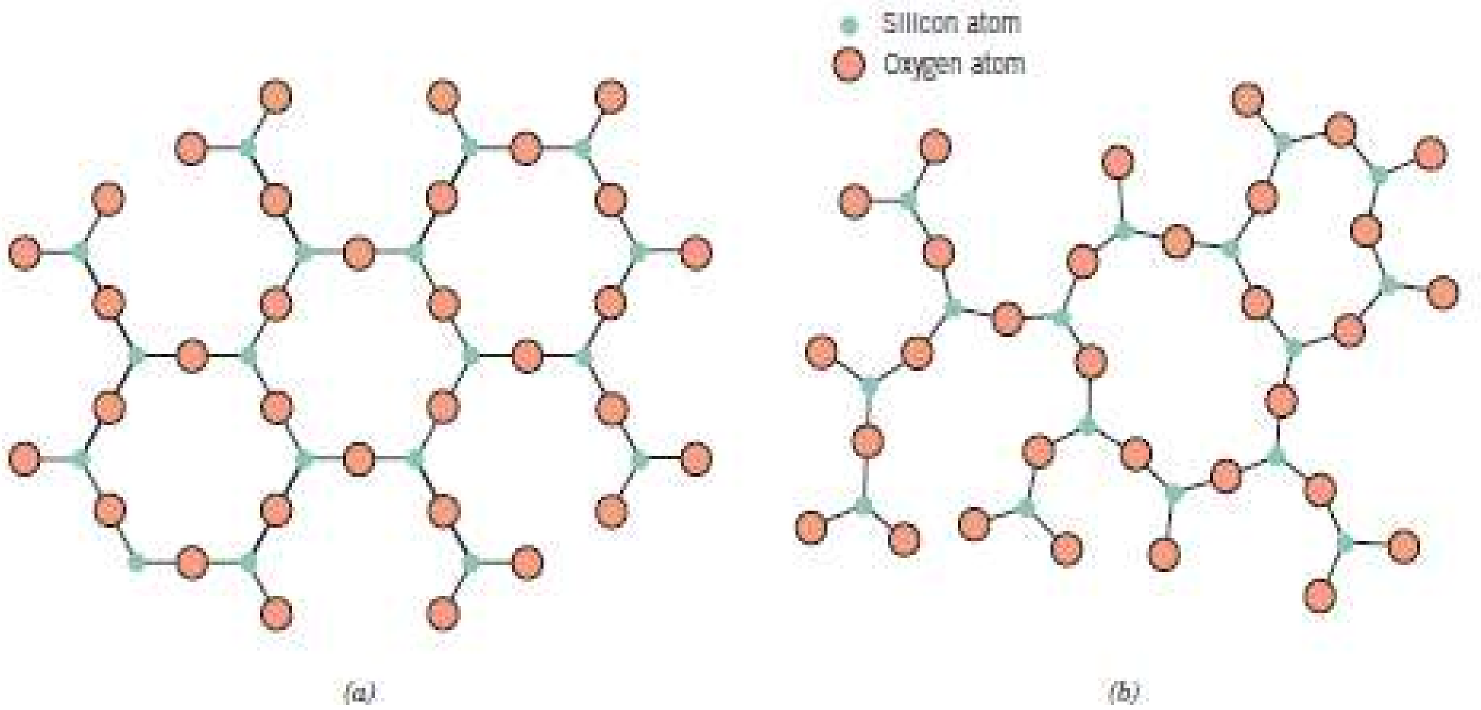
- A **crystalline solid** is one in which the atoms are regularly arranged in a repeating or periodic array over large atomic distances, that is, long-range order exists.
- Upon solidification, the atoms will position themselves in a repetitive three-dimensional pattern, in which each atom is bonded to its nearest / neighbour atom.
- All metals, many ceramic materials, and certain polymers form crystalline structures under normal solidification conditions.
- Crystalline solid have the order of 10^{28} atoms/m^3

Figure 3.16
Photograph of a garnet single crystal that was found in Tongbei, Fujian Province, China. (Photograph courtesy of Irocks.com, Megan Foreman photo.)

2. Amorphous

- Non crystalline solids lack systematic and regular arrangement of atoms over relatively large atomic distances or they have short range order. Such materials are also called amorphous (meaning literally without form)
- Atomic density is almost similar to that of crystalline solids.

Crystalline Vs Amorphous



Two-dimensional structure of (a) Crystalline silicon dioxide and (b) Non crystalline silicon dioxide.

3. Poly crystalline

- A polycrystalline solid is one in which portions of solid are perfect crystals, but not all of these crystals have the same axis of symmetry.
- Each of the crystals (or grains) have slightly different orientations with boundaries bordering each other. This borders are called grain boundaries.

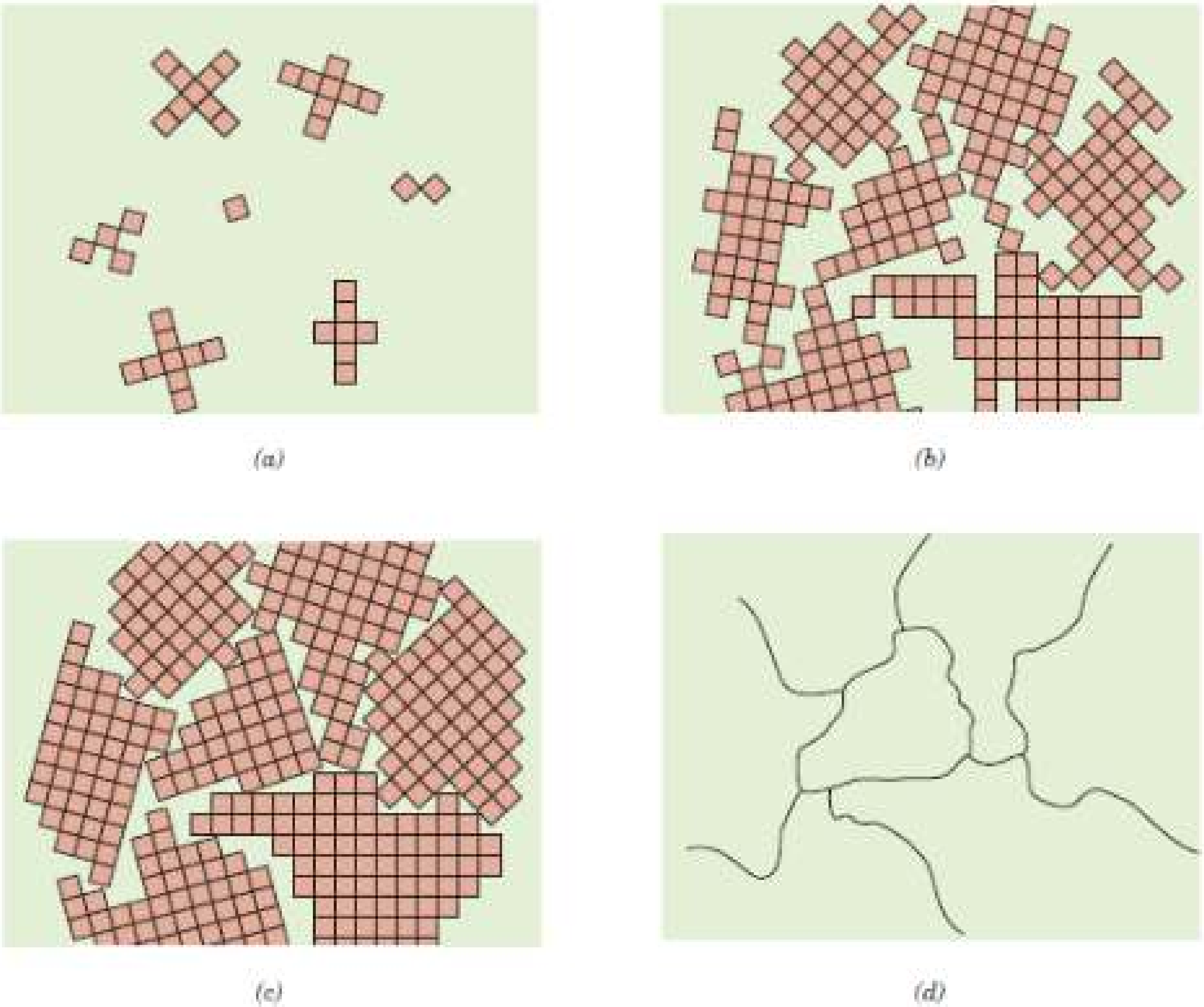
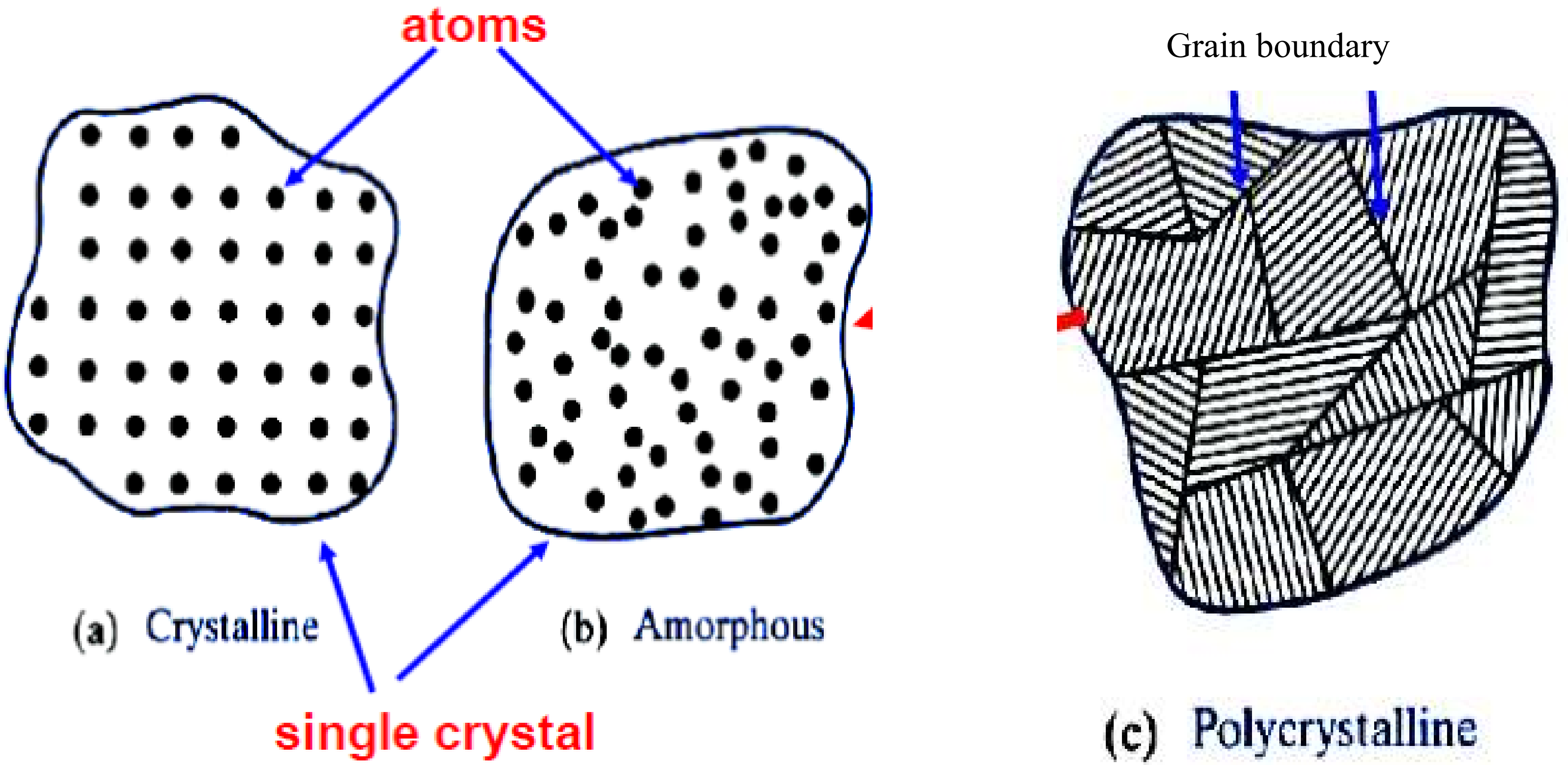


Figure 3.17 Schematic diagrams of the various stages in the solidification of a polycrystalline material; the square grids depict unit cells. (*a*) Small crystallite nuclei. (*b*) Growth of the crystallites; the obstruction of some grains that are adjacent to one another is also shown. (*c*) Upon completion of solidification, grains having irregular shapes have formed. (*d*) The grain structure as it would appear under the microscope; dark lines are the grain boundaries. (Adapted from W. Rosenhain, *An Introduction to the Study of Physical Metallurgy*, 2nd edition, Constable & Company Ltd., London, 1915.)

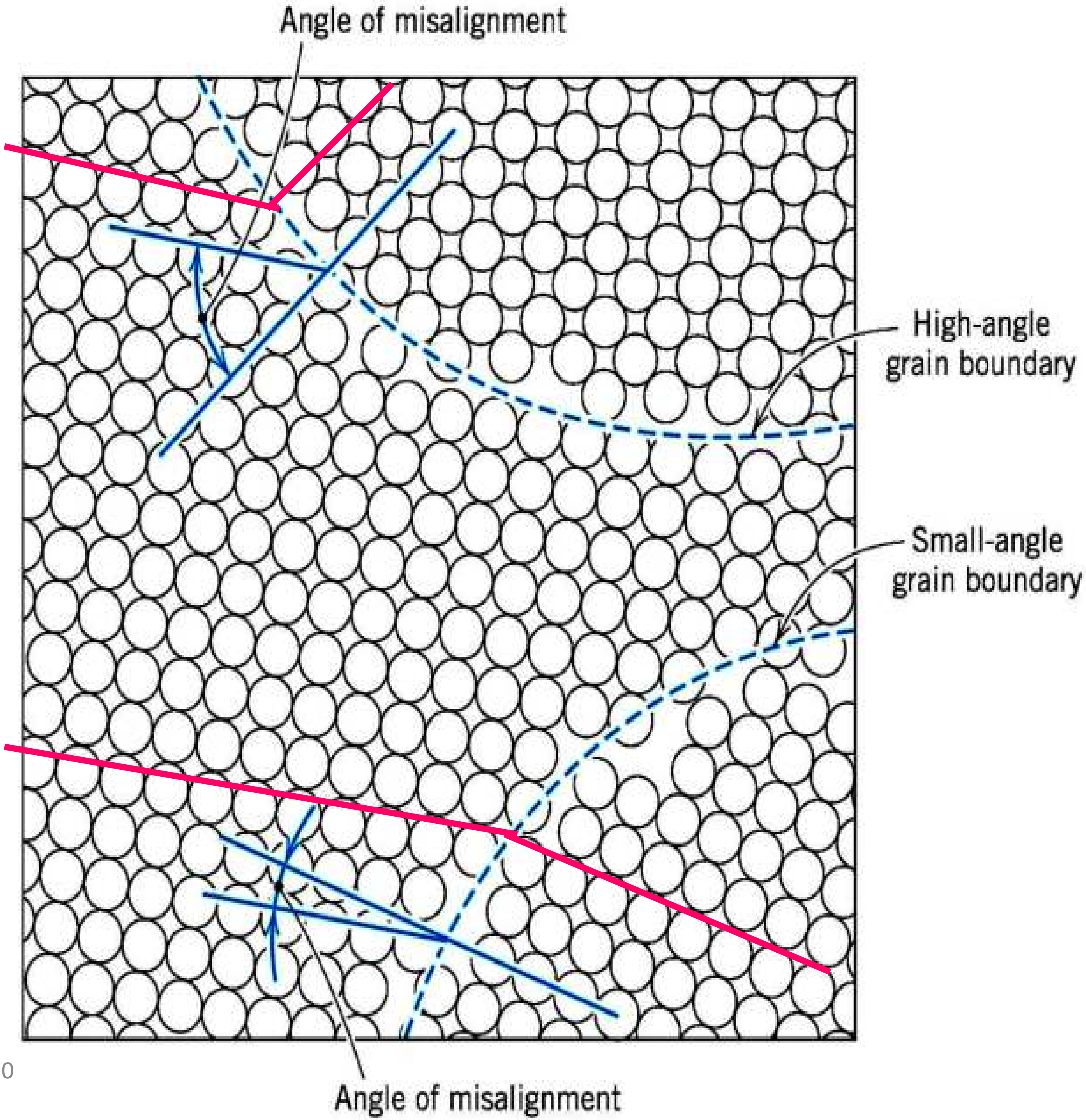
Crystal Structure



(a) Crystalline

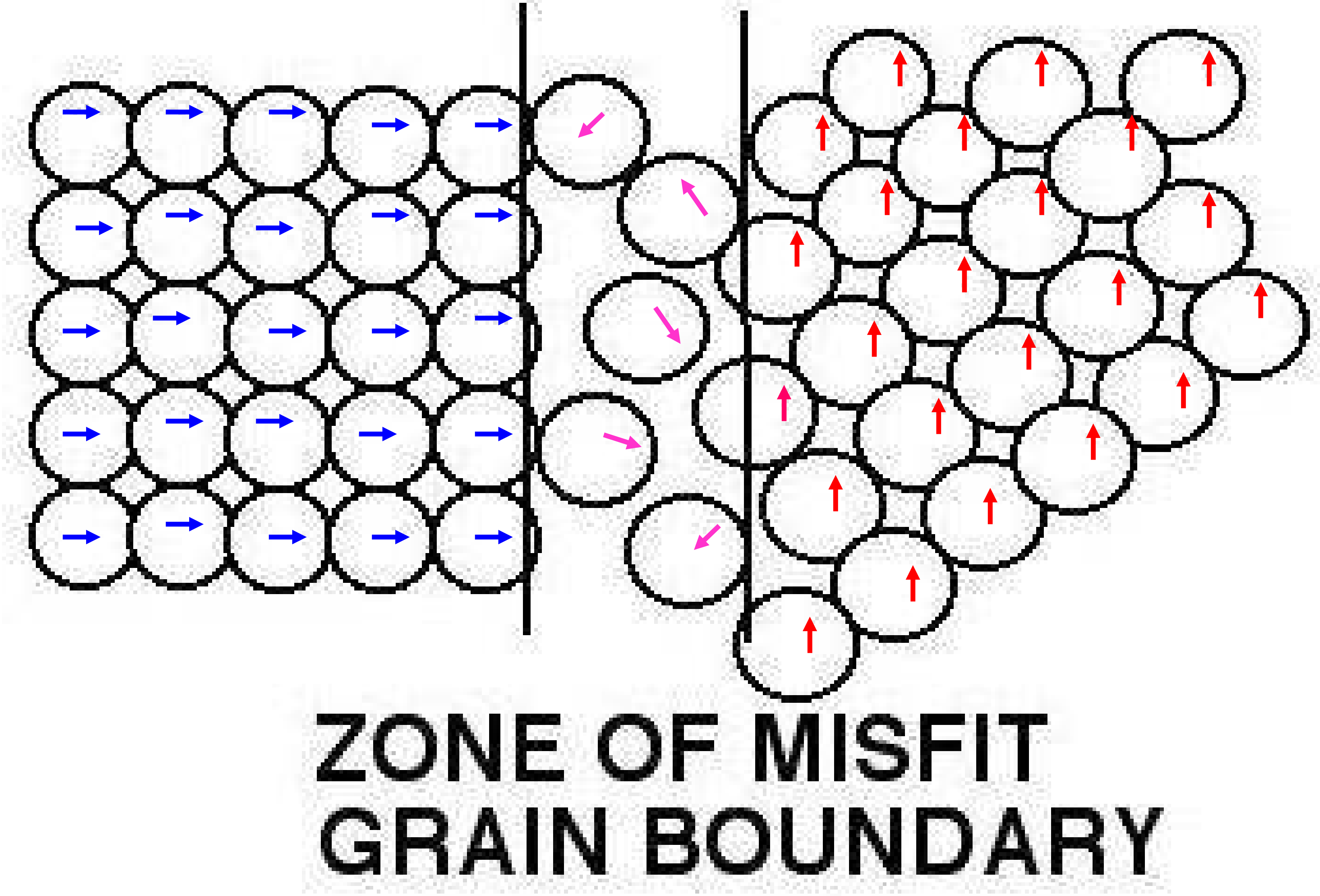
(b) Amorphous

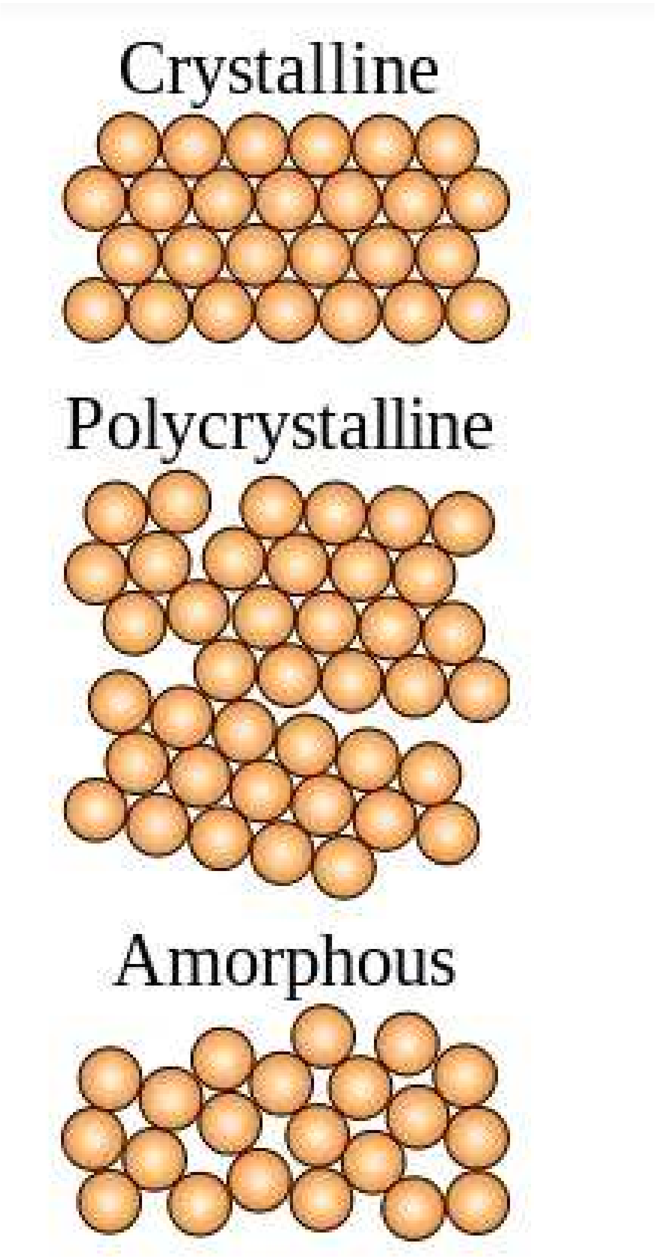
(c) Polycrystalline

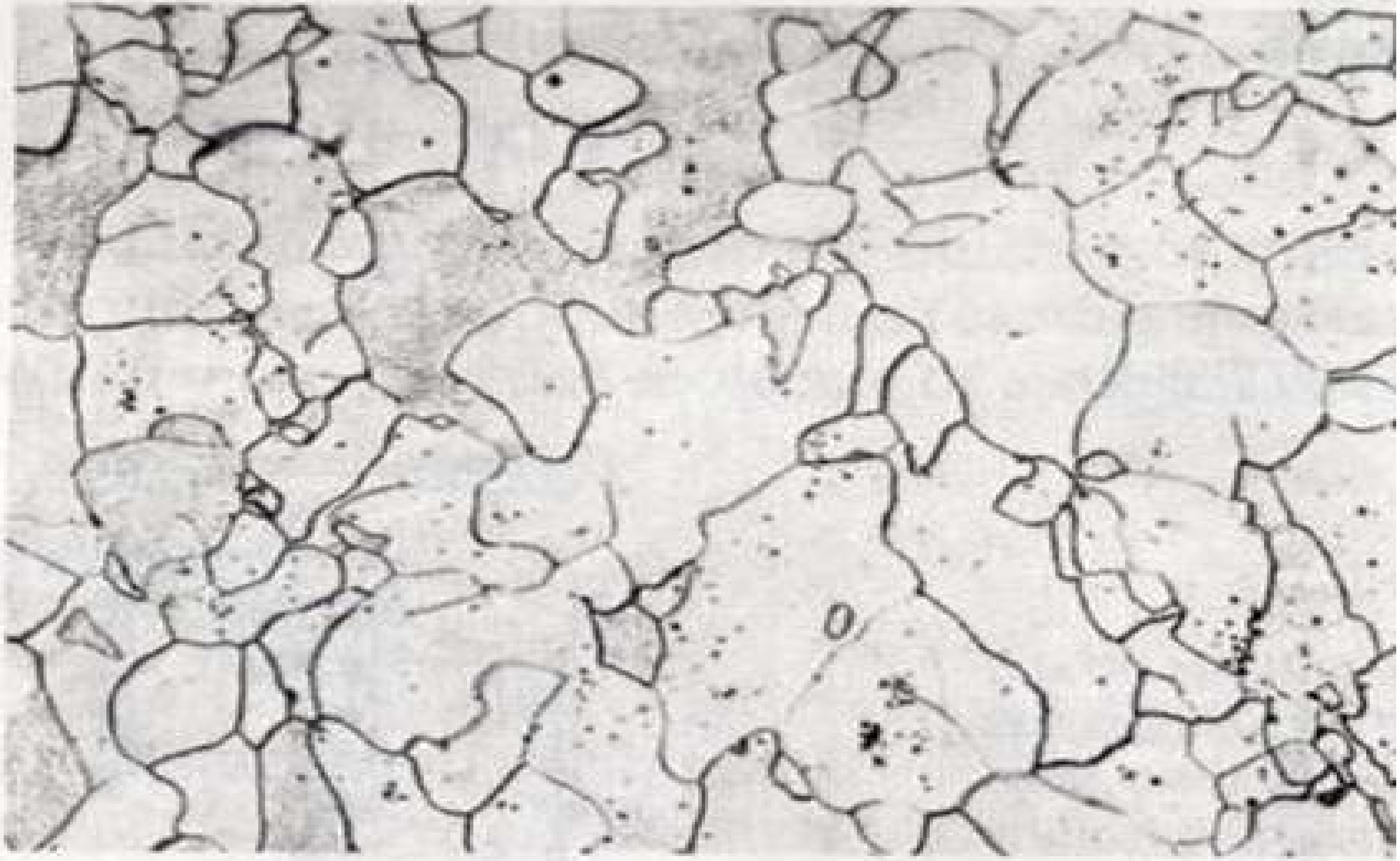


Schematic diagram showing small- and high-angle grain boundaries and the adjacent atom positions.

Depending on which planes are brought together, the angle of alignment will vary.

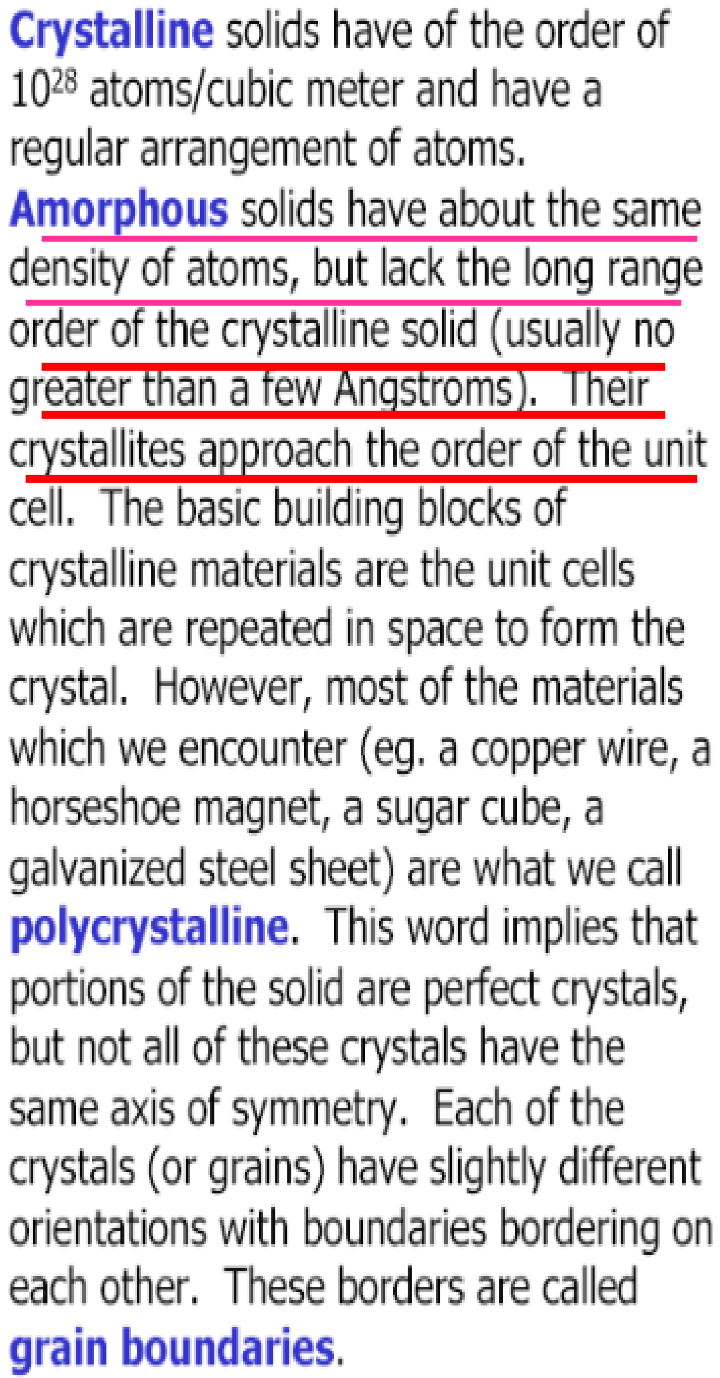

ZONE OF MISFIT
GRAIN BOUNDARY


Crystalline
Polycrystalline
Amorphous



Microstructure of pure iron (×100). Dark areas are grain boundaries. Each grain is a crystal.

<u>CRYSTALLINE</u>	<u>AMORPHOUS</u>
10^{28} atoms/m^3	Crystallites approach size of unit cell, i.e. A (10^{-10} m)
Regular arrangement Basic building blocks are unit cells	~~NO LONG RANGE ORDER~~ Short range order
Portions perfect-- polycrystalline-- grain boundaries Long range order	



Crystalline solids have of the order of 10^{28} atoms/cubic meter and have a regular arrangement of atoms. **Amorphous** solids have about the same density of atoms, but lack the long range order of the crystalline solid (usually no greater than a few Angstroms). Their crystallites approach the order of the unit cell. The basic building blocks of crystalline materials are the unit cells which are repeated in space to form the crystal. However, most of the materials which we encounter (eg. a copper wire, a horseshoe magnet, a sugar cube, a galvanized steel sheet) are what we call **polycrystalline**. This word implies that portions of the solid are perfect crystals, but not all of these crystals have the same axis of symmetry. Each of the crystals (or grains) have slightly different orientations with boundaries bordering on each other. These borders are called **grain boundaries**.

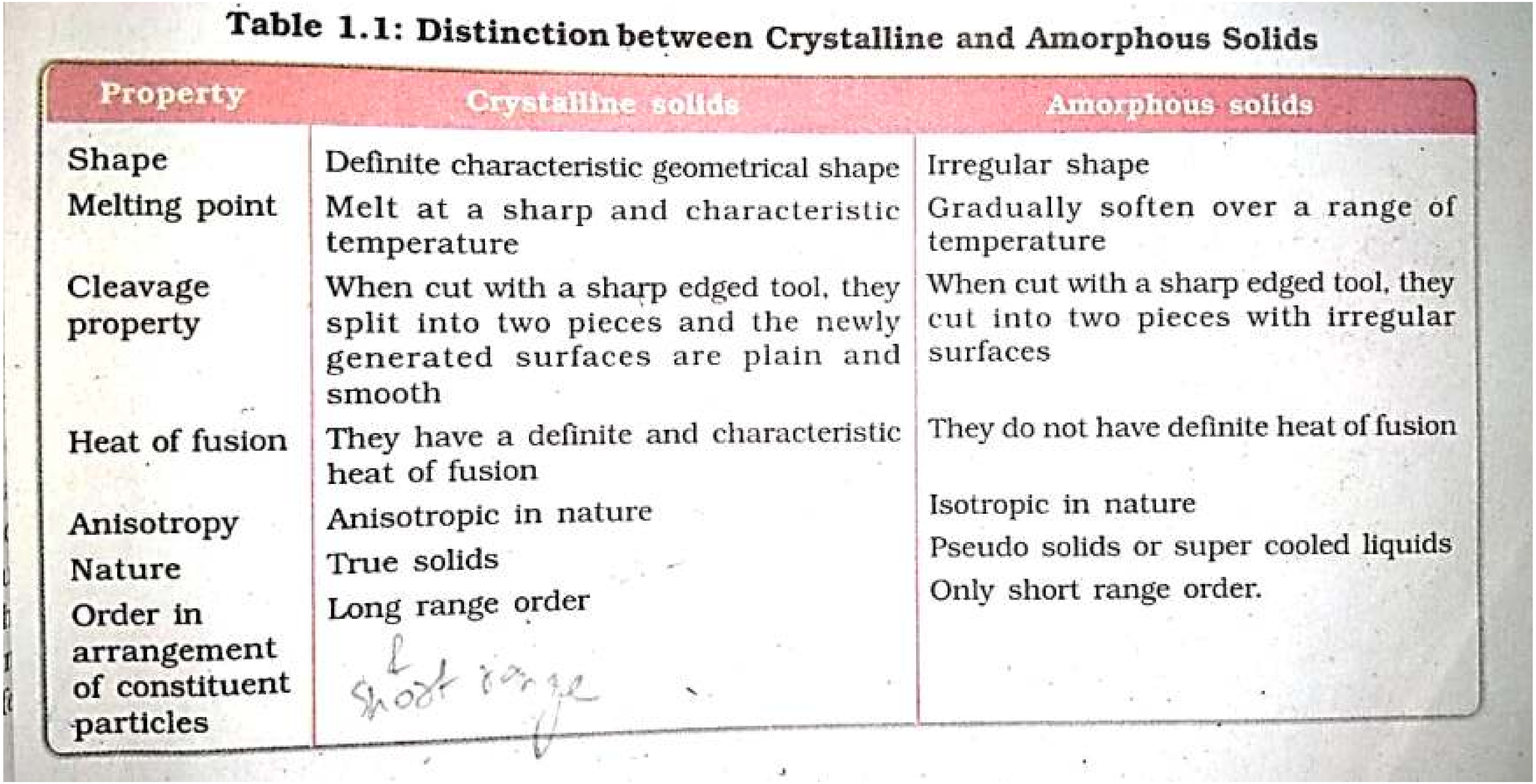
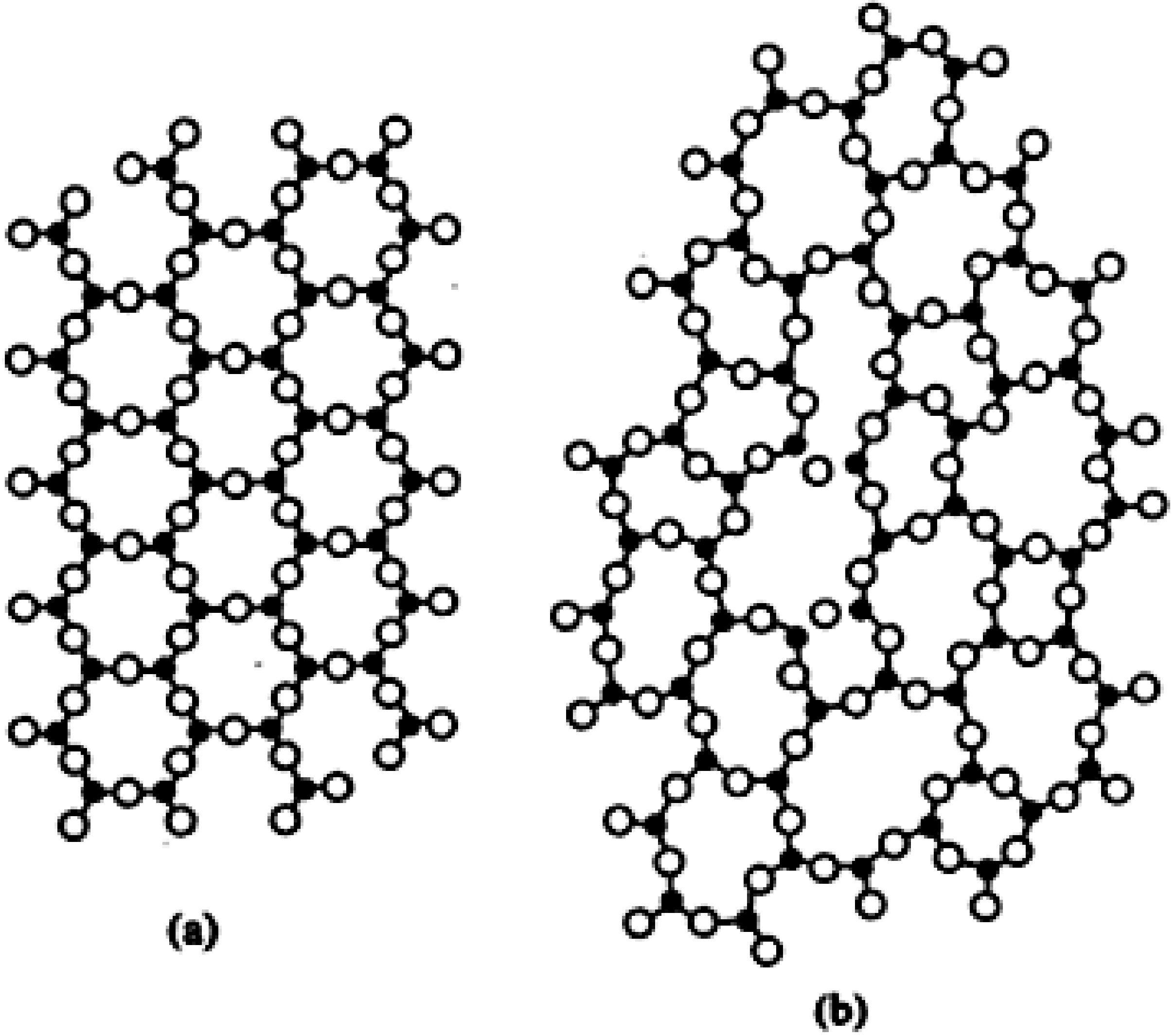


Table 1.1: Distinction between Crystalline and Amorphous Solids

Property	Crystalline solids	Amorphous solids
Shape	Definite characteristic geometrical shape	Irregular shape
Melting point	Melt at a sharp and characteristic temperature	Gradually soften over a range of temperature
Cleavage property	When cut with a sharp edged tool, they split into two pieces and the newly generated surfaces are plain and smooth	When cut with a sharp edged tool, they cut into two pieces with irregular surfaces
Heat of fusion	They have a definite and characteristic heat of fusion	They do not have definite heat of fusion
Anisotropy	Anisotropic in nature	Isotropic in nature
Nature	True solids	Pseudo solids or super cooled liquids
Order in arrangement of constituent particles	Long range order & short range	Only short range order.



[redacted]

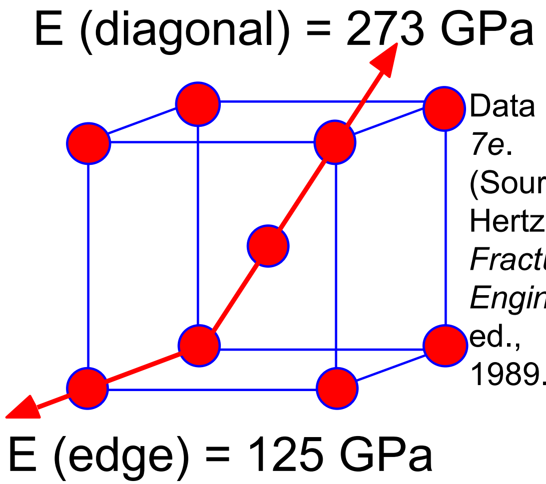
Structures of (a) Crystalline silica, and (b) Silica glass (From W. H. Zachariasen, 'J. Am. Ceram. Soc', Vol. 54, 1932, p. 3841. Printed with the permission of the American Ceramic Society, Copyright 1932).

Single vs Polycrystals

- **Single Crystals**

- Properties vary with direction: anisotropic.

-Example: the modulus of elasticity (E) in BCC iron:



Data from Table 3.3, *Callister 7e*.
(Source of data is R.W. Hertzberg, *Deformation and Fracture Mechanics of Engineering Materials*, 3rd ed., John Wiley and Sons, 1989.)

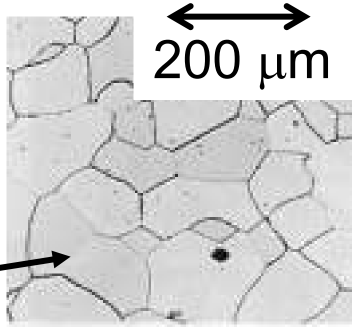
- **Polycrystals**

- Properties may/may not vary with direction.

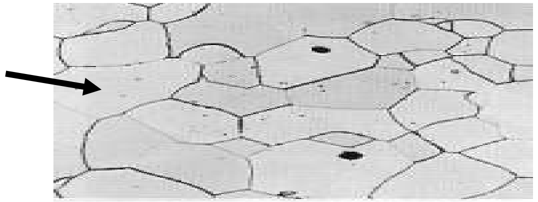
- If grains are randomly oriented: isotropic.

($E_{\text{poly iron}}$ = 210 GPa)

- If grains are textured, anisotropic.



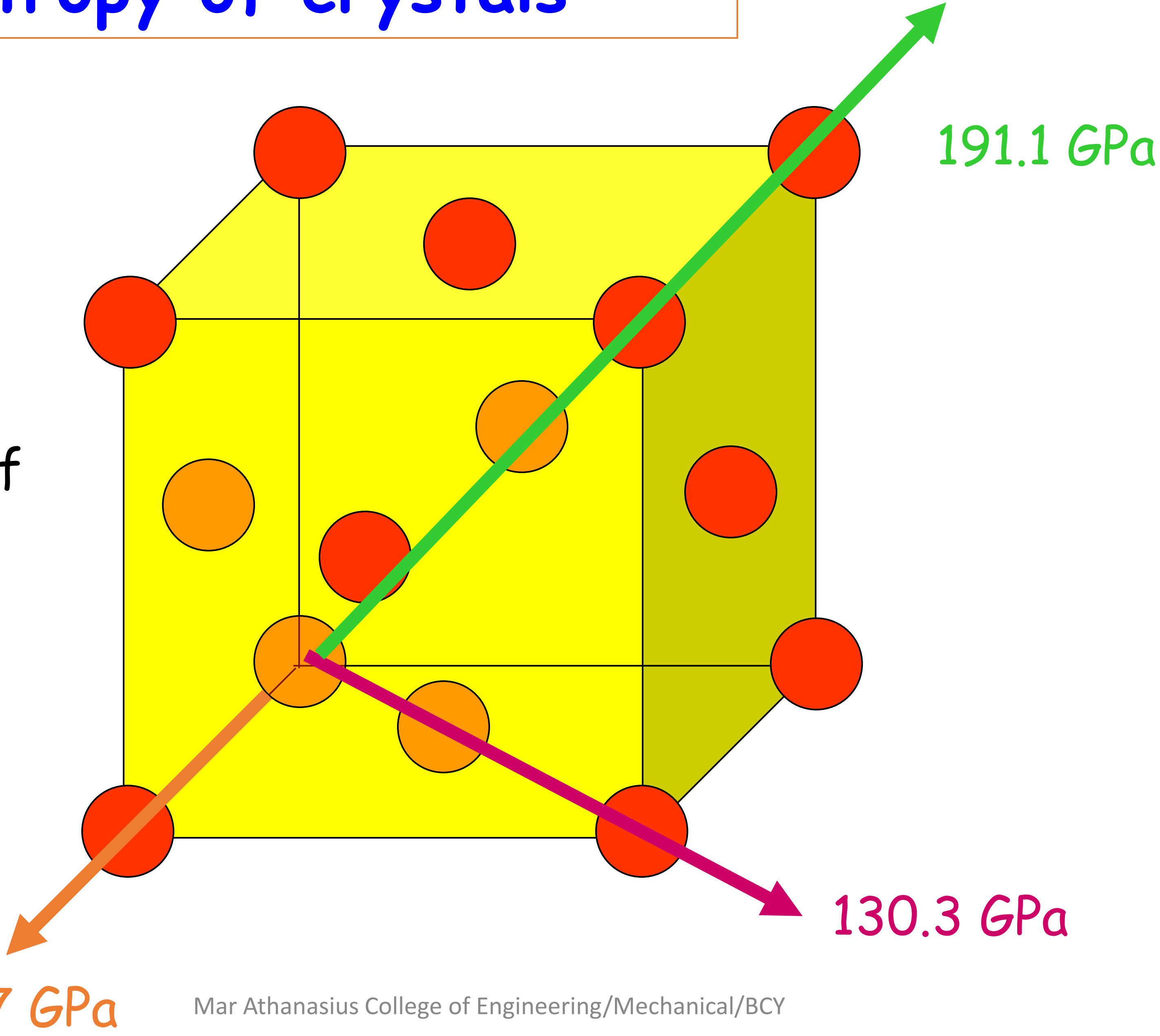
Adapted from Fig. 4.14(b), *Callister 7e*.
(Fig. 4.14(b) is courtesy of L.C. Smith and C. Brady, the National Bureau of Standards, Washington, DC [now the National Institute of Standards and Technology, Gaithersburg, MD].)



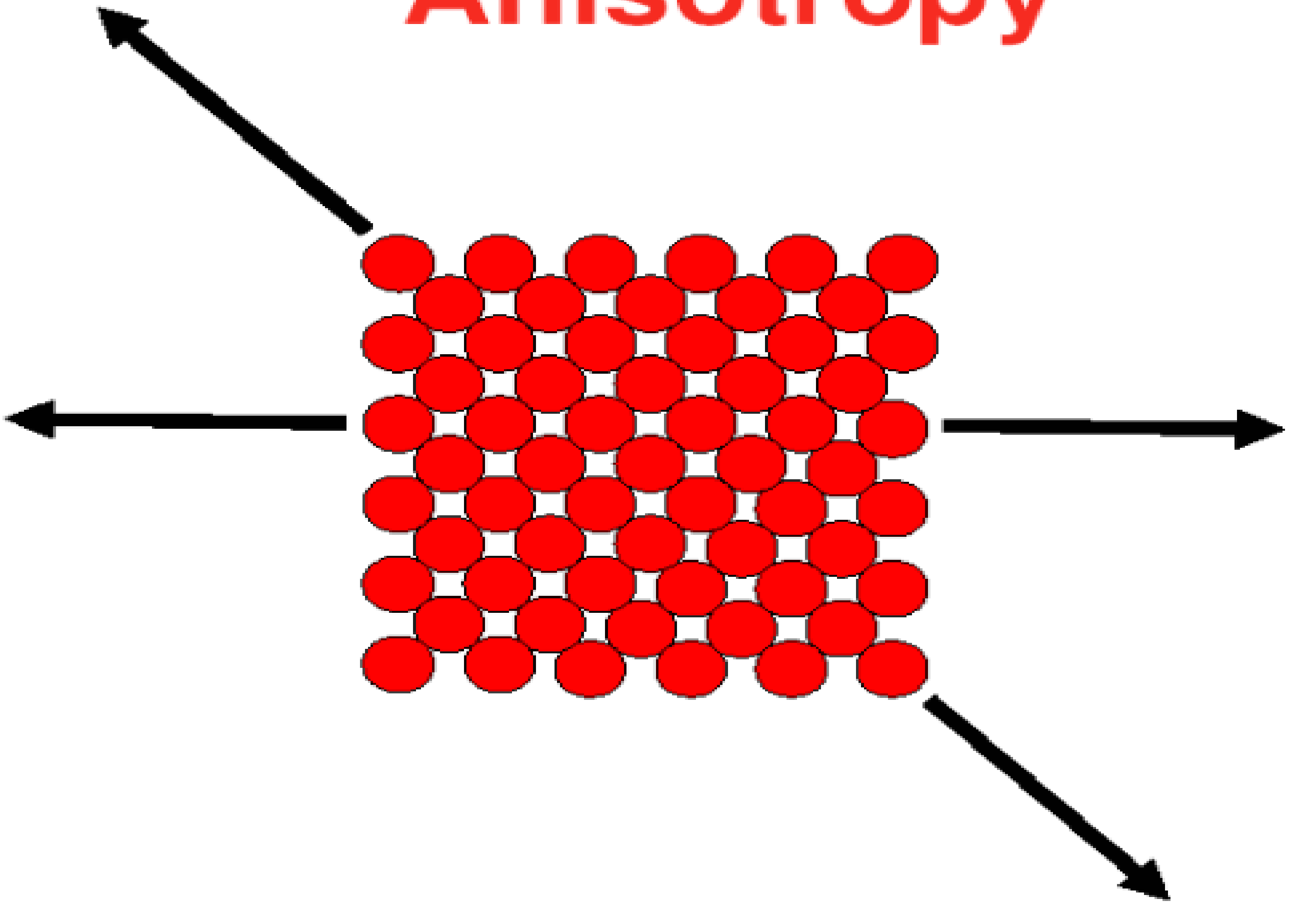
Amorphous Glass - crystalline glass

Anisotropy of crystals

Young's modulus of FCC Cu



Anisotropy



Single crystals are *anisotropic* → properties vary with direction. In polycrystalline materials, the grains are generally randomly orientated → *isotropic* behaviour.

WHY POLYCRYSTALLINE MATERIALS ARE ISOTROPIC & SINGLE CRYSTALS ARE ANISOTROPIC? NARRATE.

Explain why single crystals are generally anisotropic while poly-crystals are usually isotropic.

- In a single crystal, the orientation of the crystal structure is uniform throughout the specimen. Since the properties of the crystal (e.g. linear and planar atomic densities) vary with the crystallographic plane or direction considered, the macroscopic properties of a single crystal specimen also vary with direction; that is, they are anisotropic.

- On the other hand, the many different crystals in a polycrystalline specimen are all oriented differently, so that the measured properties at a macroscopic scale represent the average of the properties in all different crystallographic directions. It doesn't matter what direction is considered, the average property is the same, so the polycrystalline specimen will be isotropic.

Polycrystals

- ***Most*** **engineering materials are polycrystals.**

Anisotropic

Isotropic

Adapted from Fig. K, color inset pages of *Callister 5e*. (Fig. K is courtesy of Paul E. Danielson, Teledyne Wah Chang Albany)

- Each "grain" is a single crystal.
- **If grains are randomly oriented, overall component properties are not directional.**
- Grain sizes, range from 1 nm to 2 cm – (normal range 5 - 200 µm) (i.e., from a few to millions of atomic layers).

Nb-Hf-W plate with an electron beam weld.

- **Each "grain" is a single crystal.**

Crystals as Building Blocks

- ***Some* engineering applications require single crystals:**

--diamond single crystals for abrasives

(Courtesy Martin Deakins, GE Superabrasives, Worthington, OH. Used with permission.)

--**turbine blades**

Fig. 8.33(c), *Callister 7e.* (Fig. 8.33(c) courtesy of Pratt and Whitney).

--semiconductor

- **Properties of crystalline materials often related to crystal structure/direction.**

--Ex: Quartz fractures more easily along some crystal planes than others.

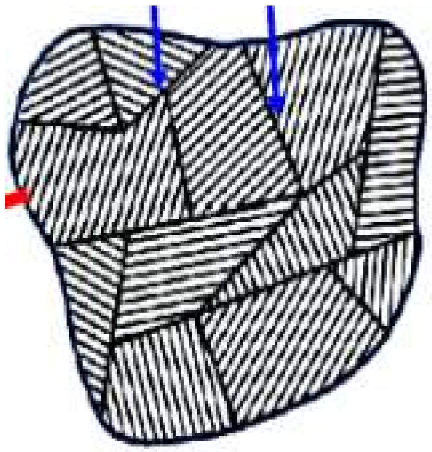
(Courtesy P.M. Anderson)

Single crystal- polycrystalline Structure

Crystalline solid can be **single crystal**. Where the solid consist of only one crystal.

An aggregate of many crystals separated by well defined grain boundaries **(irregularly shaped)** is said to be **polycrystalline**.

WHAT IS THE DIFFERENCE BETWEEN - GRAIN AND CRYSTAL?



(c) Polycrystalline

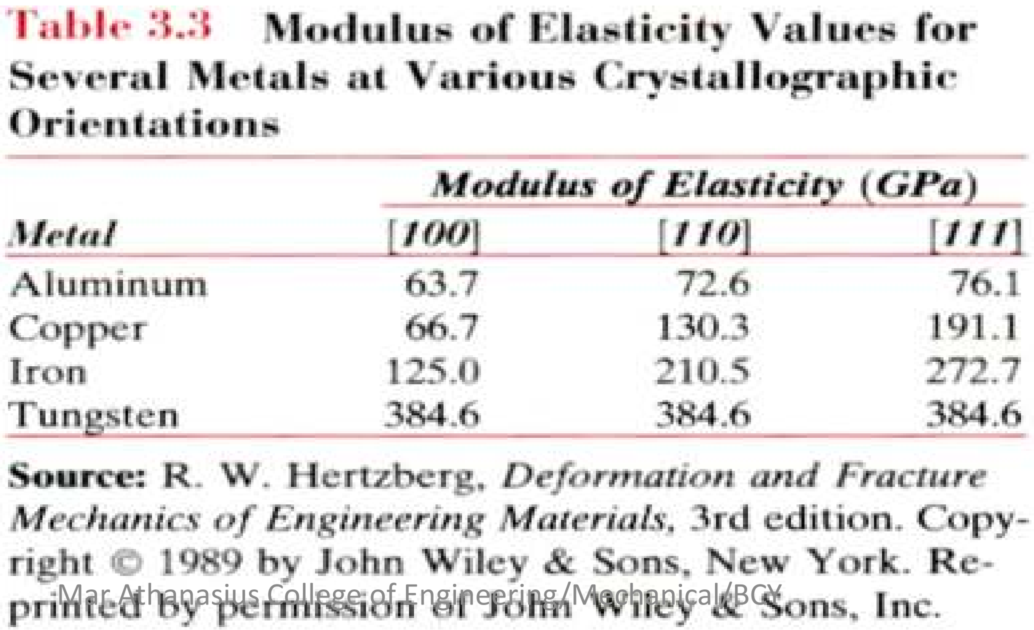
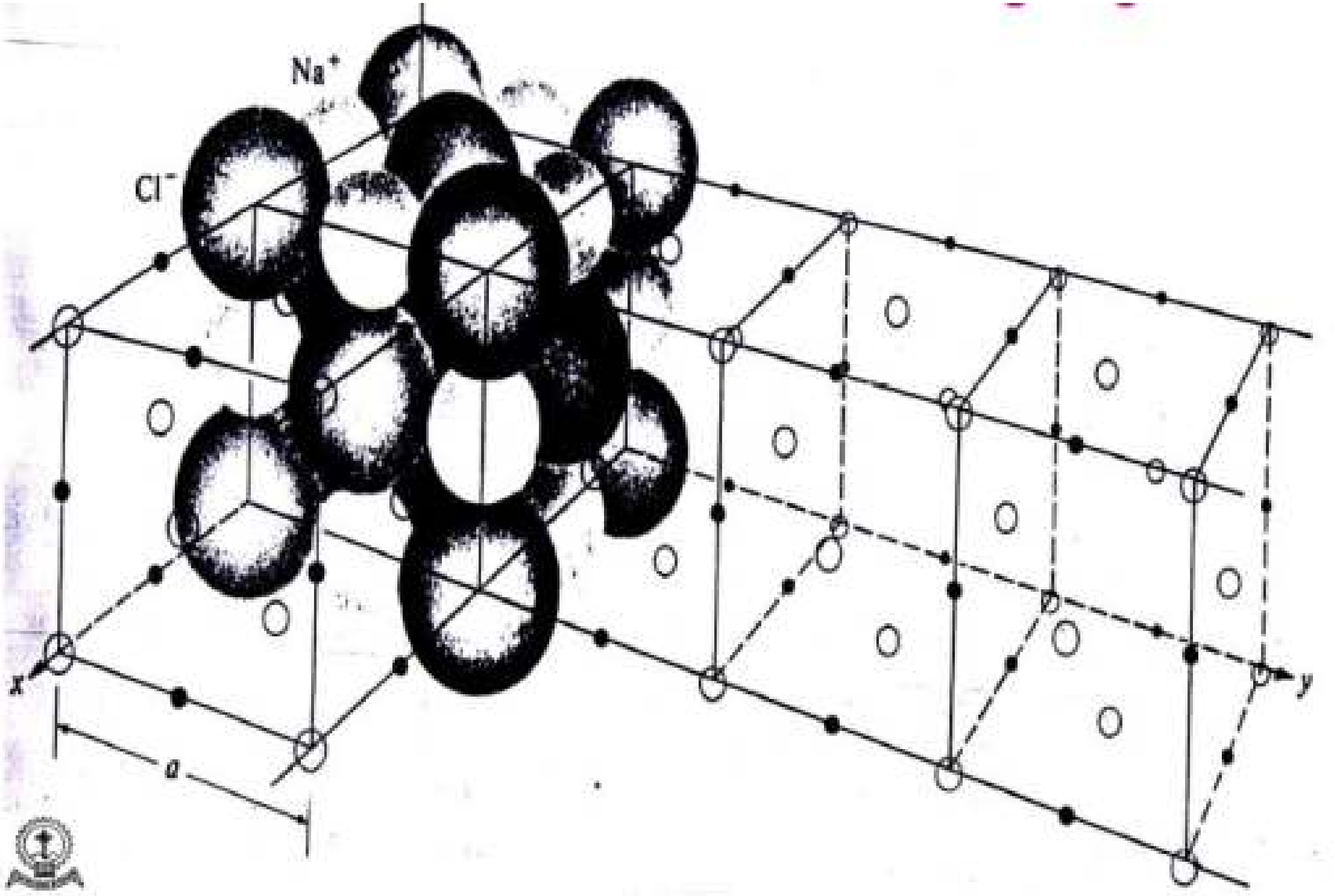


Table 3.3 **Modulus of Elasticity Values for Several Metals at Various Crystallographic Orientations**

	Modulus of Elasticity (GPa)		
Metal	*[100]*	*[110]*	*[111]*
Aluminum	63.7	72.6	76.1
Copper	66.7	130.3	191.1
Iron	125.0	210.5	272.7
Tungsten	384.6	384.6	384.6

Source: R. W. Hertzberg, *Deformation and Fracture Mechanics of Engineering Materials*, 3rd edition. Copyright © 1989 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.

Order of atoms

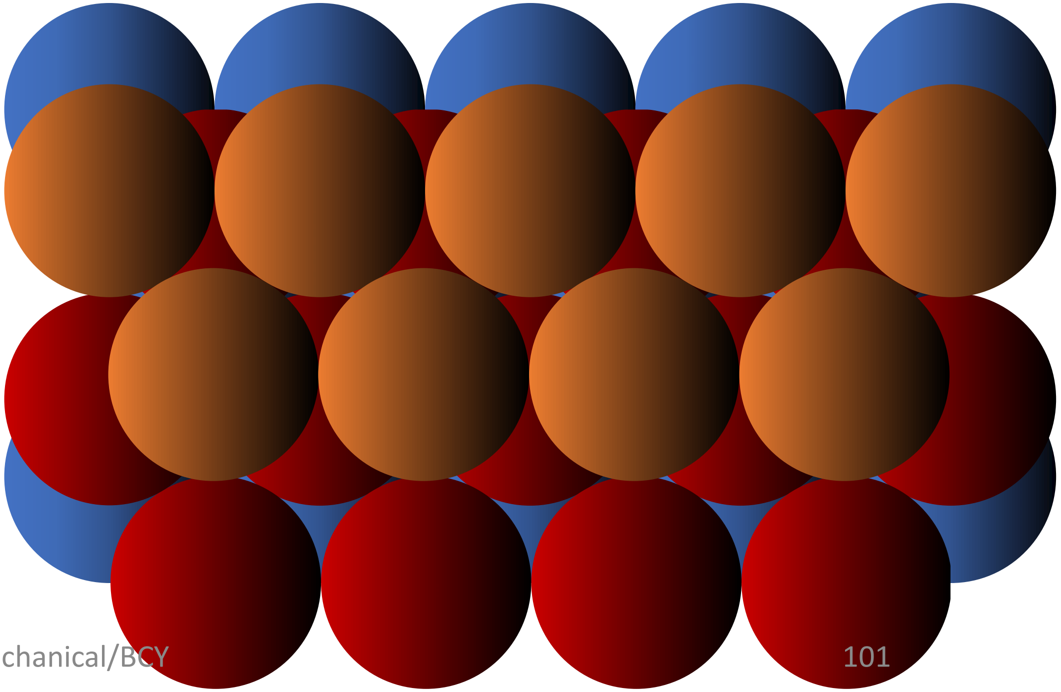


Crystalline solids – Long range order exists

Amorphous solids – Only Short range order exists

Close packing of atoms

- Closed electron shell that is created when an ionic or metallic bond is formed can be regarded roughly as a rigid sphere, so that adjacent atoms in a solid pack together like solid balls.
- The radius of the equivalent rigid sphere is called the *ionic radius* of the element.



Important Terms

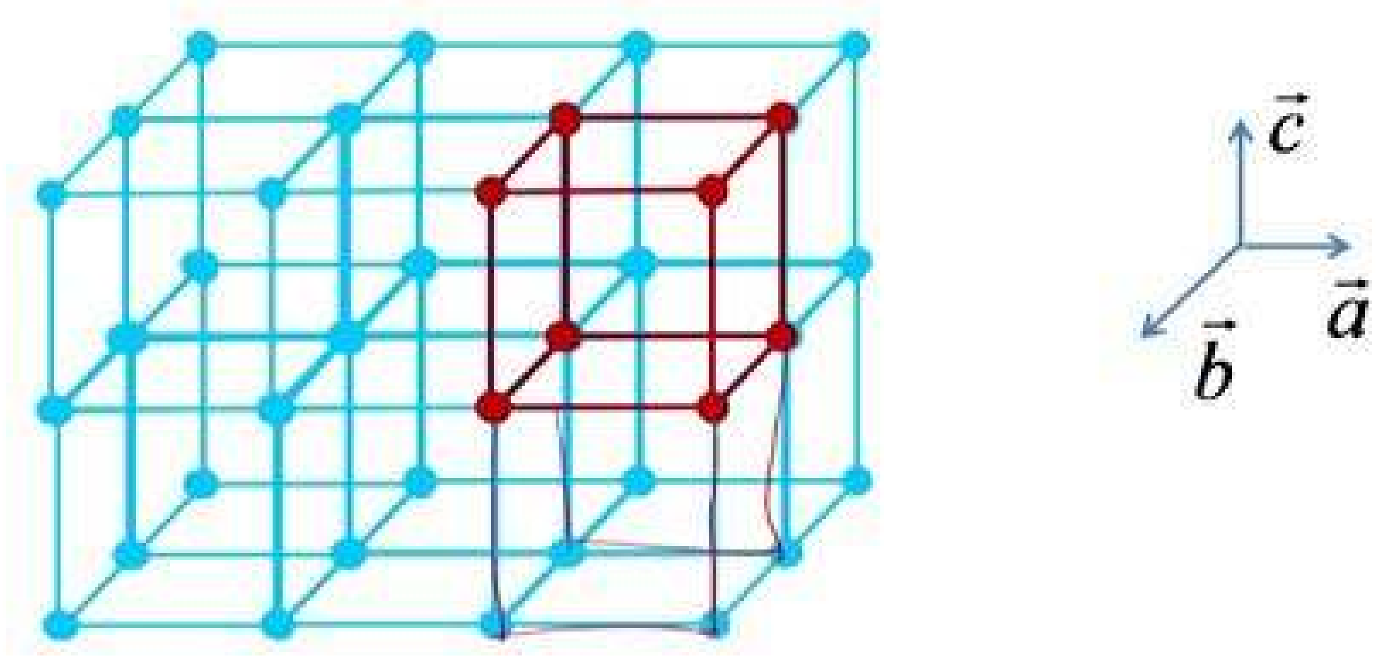
- *SPACE LATTICE*:- its an infinitely regularly spaced array of lattice points in 3 Dimension with translational and rotational symmetry.
- Crystal = lattice + basis
- The location and pattern/ arrangement of atoms in a crystal described by the term space lattice. There are 14 space lattices possible.
- It's a 3-dimensional network of lines, the intersection which generates a 3 dimensional array of points which are occupied by the atoms or group of atoms or about which a group of atoms are clustered, forming the crystalline material.
- *UNIT CELL*:- While describing crystals structure, it is convenient to subdivide the structure into small groups of atoms from a repetitive pattern called unit cell.
- Unit cell is the smallest group of atoms that, by repeated translation in three dimensions, builds up the whole crystal
- Unit cell is the smallest unit which when repeated in space indefinitely will generate the space lattice.

3D- lattice

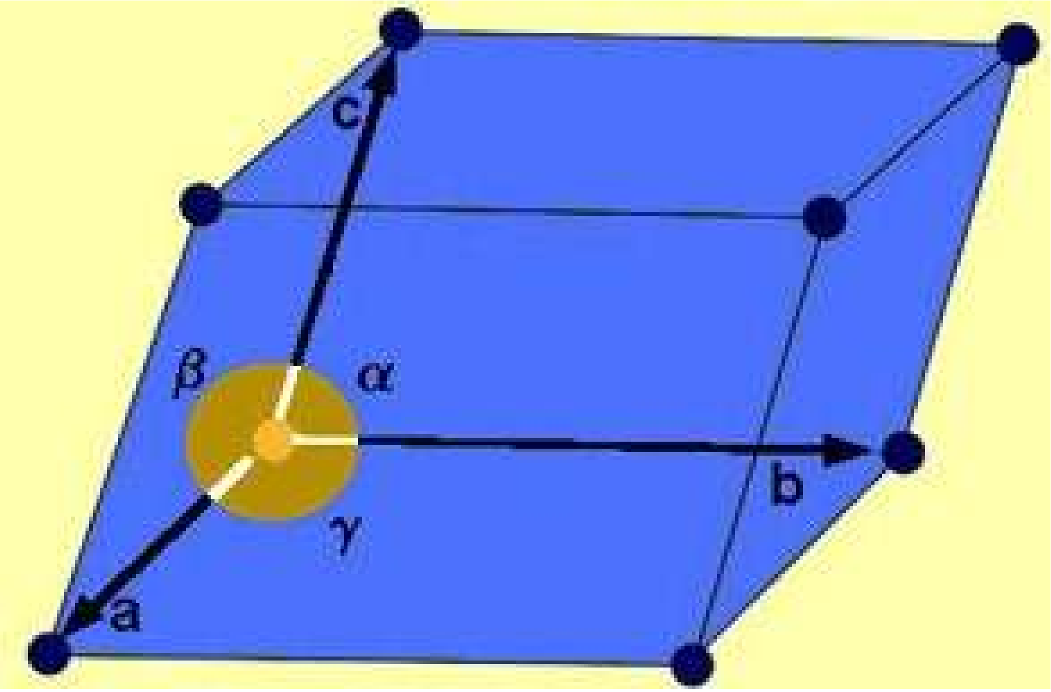
Unit cell

$$\vec{T} = m\vec{a} + n\vec{b} + o\vec{c}$$

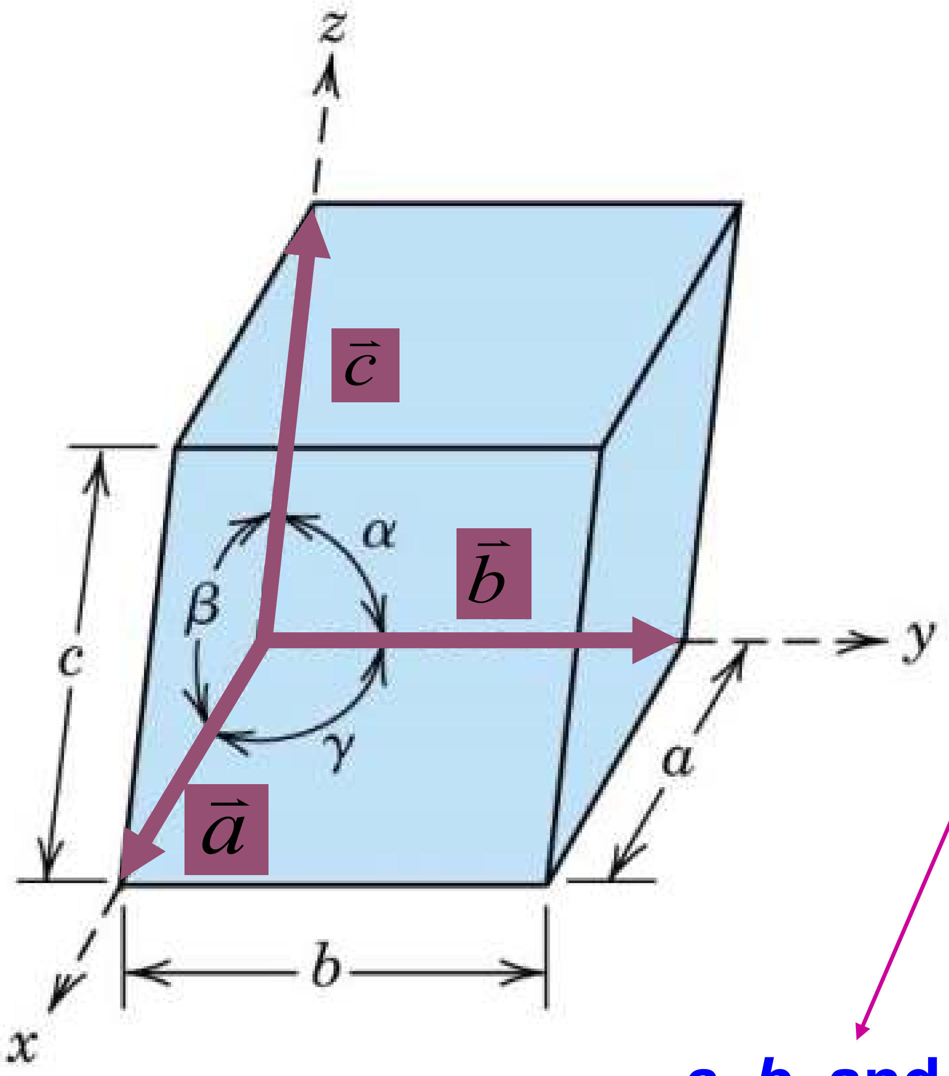
An infinite regularly spaced array of points in three dimensions



The Unit Cell



- Crystal: 3D order structure
- Unit cell: smallest repetitive volume which contains the complete lattice pattern of a crystal.
- The size and shape of the unit cell are described by three lattice vectors *a,b,c,* originating from one corner of the unit cell.
- The axial lengths *a,b,c* and the inter axial angles *α, β,* and γ are lattice CONSTANTS of the unit cell.



Lattice parameters

axial lengths: a, b, c

interaxial angles: α, β, γ

unit vectors: $\vec{a}\ \ \vec{b}\ \ \vec{c}$

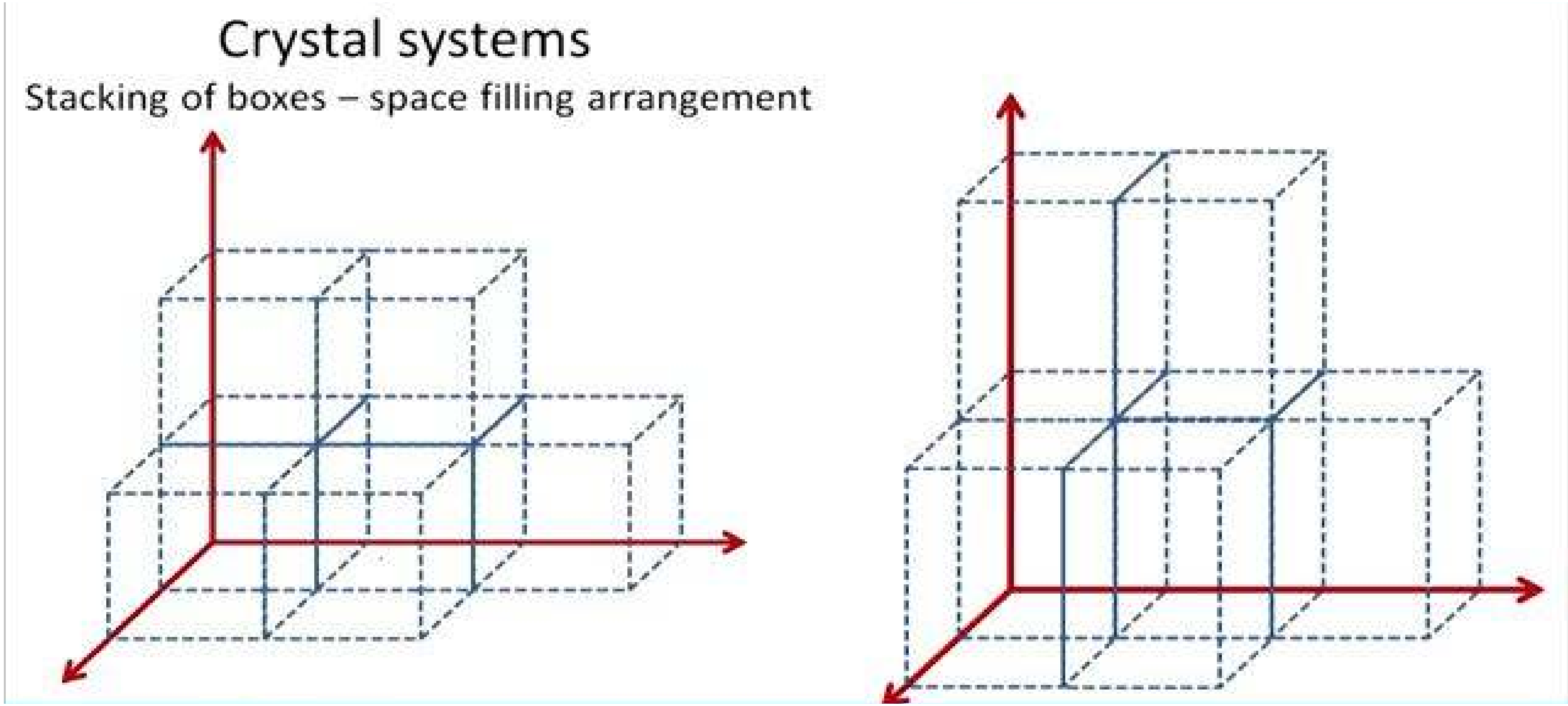
In general: $a \neq b \neq c$

$\alpha \neq \beta \neq \gamma$

7 crystal systems

14 crystal structures

***a*, *b*, and *c* are the lattice constants**

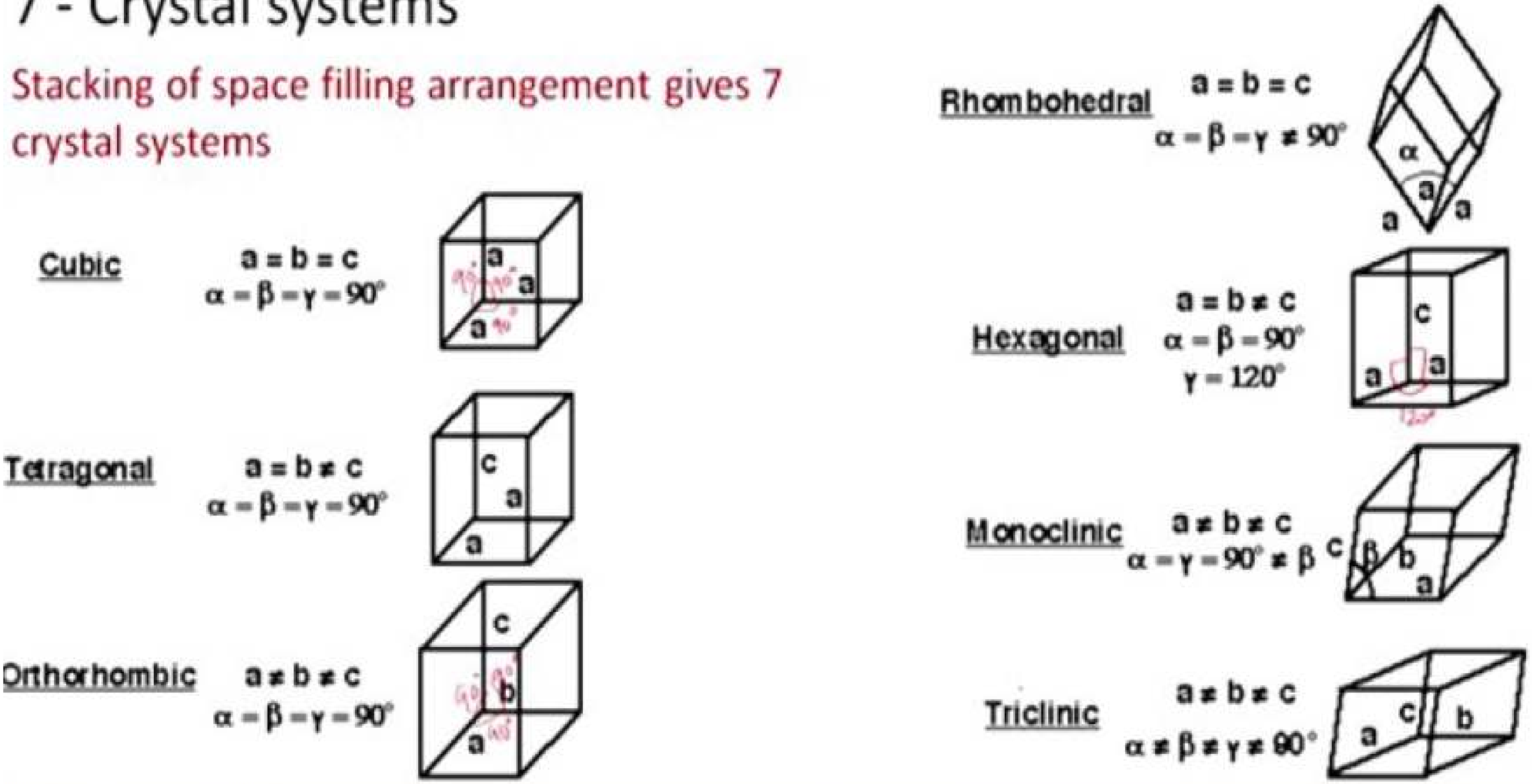


Crystal systems

Stacking of boxes – space filling arrangement

7 - Crystal systems

Stacking of space filling arrangement gives 7 crystal systems



Cubic $a = b = c$, $\alpha = \beta = \gamma = 90^\circ$

Tetragonal $a = b \neq c$, $\alpha = \beta = \gamma = 90^\circ$

Orthorhombic $a \neq b \neq c$, $\alpha = \beta = \gamma = 90^\circ$

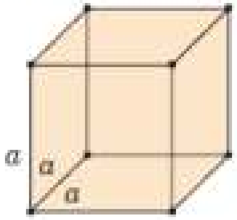
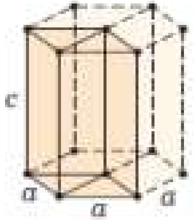
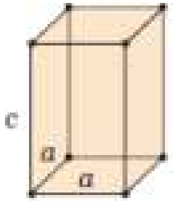
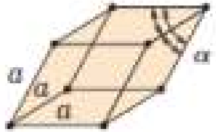
Rhombohedral $a = b = c$, $\alpha = \beta = \gamma \neq 90^\circ$

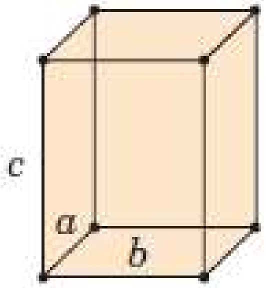
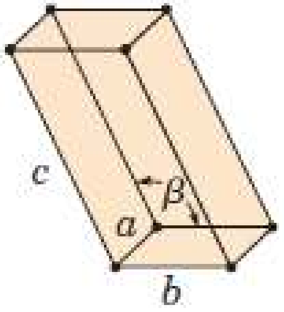
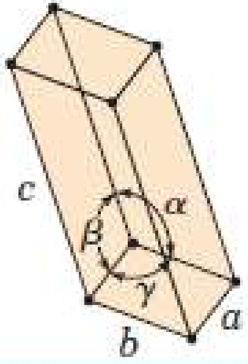
Hexagonal $a = b \neq c$, $\alpha = \beta = 90^\circ$, $\gamma = 120^\circ$

Monoclinic $a \neq b \neq c$, $\alpha = \gamma = 90^\circ \neq \beta$

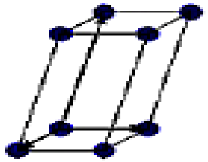
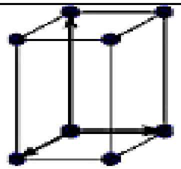
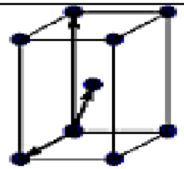
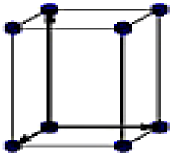
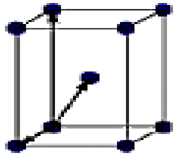
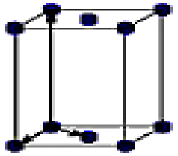
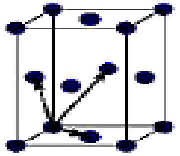
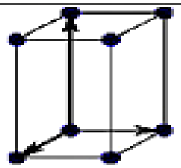
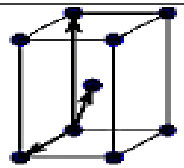
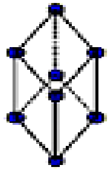
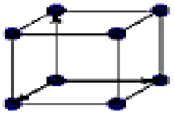
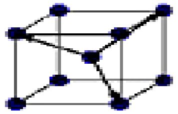
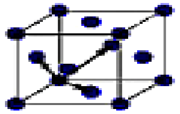
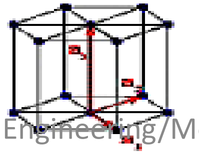
Triclinic $a \neq b \neq c$, $\alpha \neq \beta \neq \gamma \neq 90^\circ$

Unit Cells: Bravais Lattices

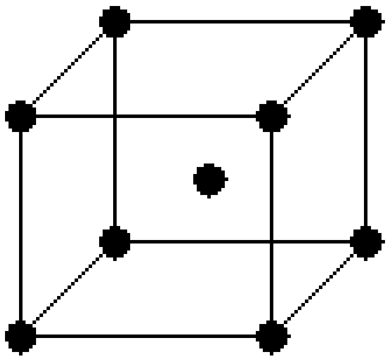
Crystal System	*Axial Relationships*	*Interaxial Angles*	*Unit Cell Geome*
Cubic	$a = b = c$	$\alpha = \beta = \gamma = 90°$	
Hexagonal	$a = b \neq c$	$\alpha = \beta = 90°, \gamma = 120°$	
Tetragonal	$a = b \neq c$	$\alpha = \beta = \gamma = 90°$	
Rhombohedral (Trigonal)	$a = b = c$	$\alpha = \beta = \gamma \neq 90°$	

Orthorhombic	$a \neq b \neq c$	$\alpha = \beta = \gamma = 90^\circ$	
Monoclinic	$a \neq b \neq c$	$\alpha = \gamma = 90^\circ \neq \beta$	
Triclinic	$a \neq b \neq c$	$\alpha \neq \beta \neq \gamma \neq 90^\circ$	

The fourteen Bravais lattices

Bravais lattice	Parameters	Simple (P)	Volume centered (I)	Base centered (C)	Face centered (F)
Triclinic	$a_1 \neq a_2 \neq a_3$ $\alpha_{12} \neq \alpha_{23} \neq \alpha_{31}$				
Monoclinic	$a_1 \neq a_2 \neq a_3$ $\alpha_{23} = \alpha_{31} = 90°$ $\alpha_{12} \neq 90°$				
Orthorhombic	$a_1 \neq a_2 \neq a_3$ $\alpha_{12} = \alpha_{23} = \alpha_{31} = 90°$				
Tetragonal	$a_1 = a_2 \neq a_3$ $\alpha_{12} = \alpha_{23} = \alpha_{31} = 90°$				
Trigonal	$a_1 = a_2 = a_3$ $\alpha_{12} = \alpha_{23} = \alpha_{31} < 120°$				
Cubic	$a_1 = a_2 = a_3$ $\alpha_{12} = \alpha_{23} = \alpha_{31} = 90°$				
Hexagonal	$a_1 = a_2 \neq a_3$ $\alpha_{12} = 120°$ $\alpha_{23} = \alpha_{31} = 90°$				

Principal Metallic Crystal Structure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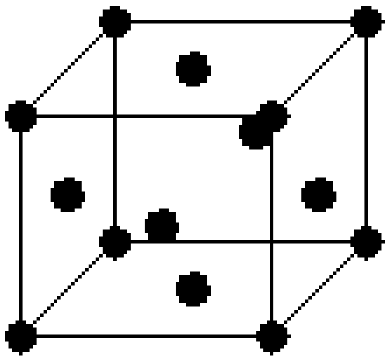
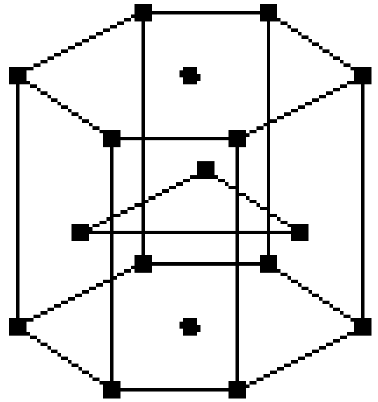

fcc


hcp

90% of metals crystallize into 3 densely packed crystal structures:

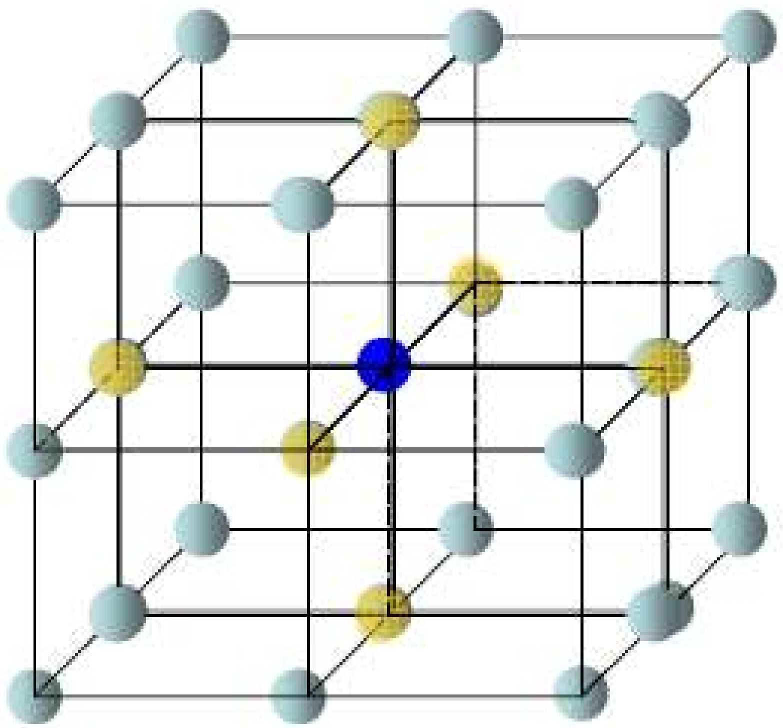
- Body-Centered Cubic
- Face-Centered Cubic
- Hexagonal Close-Packed

It is important to understand how small the unit cell really is. The cube side of BCC Iron is 0.287nm. How many unit cells would there be if you had 1mm of units cells of pure iron lined up?

Coordination Number

- The number of nearest neighbours surrounding any one atom, ion or molecule is called co-ordination number.
- It depends upon the radii of the atoms or ions in the structure.
- Eg: Simple cubic (SC) – co-ordination number = 6

- Large atoms tend to have large CN, small atoms usually have small CN
- it’s easier to surround a big atom with lots of atoms than a smaller one.



Ion element A surrounding a smaller ion element C CN	Range radius ratio for which CN is expected to be stable (r_C/r_A)	Coordination polyhedron	Packing
2	0 to 0.155	line	Linear
3	0.155 to 0.225	Triangle	Triangular
4	0.225 to 0.414	Tetrahedron	Tetrahedral
6	0.414 to 0.732	Octahedron	Octahedral
8	0.732 to 1.0	Cube	Cubic
12	1.0	Twinned Cubo Octahedron	HCP
12	1.0	Cubo Octahedron	FCC

CN calculated as a function of radius ratio

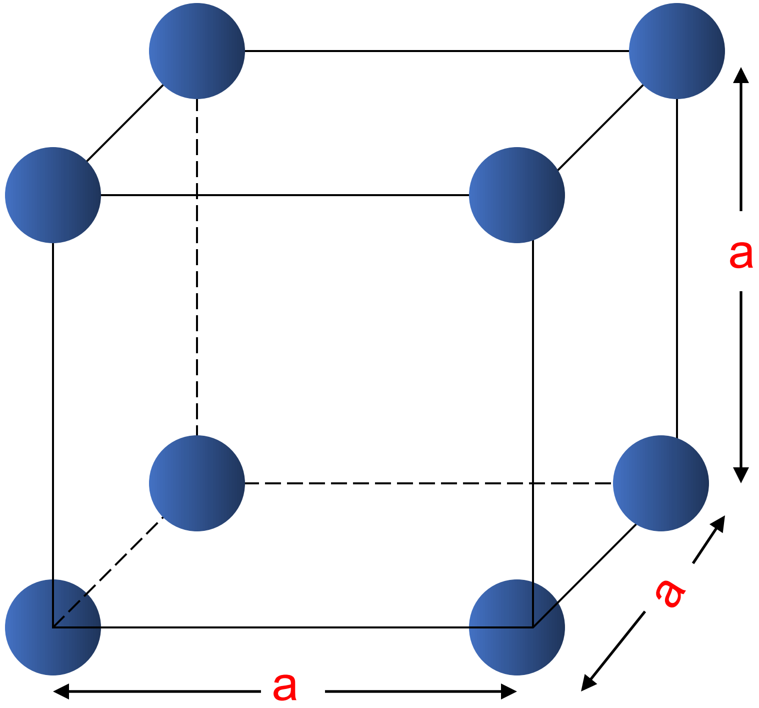
Atomic Packing Factor (APF)

$$APF = \frac{\text{Vol. of atom/s in unit cell}}{\text{Vol. of unit cell}}$$

Depends on:

- Crystal structure.
- How “close” packed the atoms are.
- In simple close-packed structures with hard sphere atoms, independent of atomic radius

Number of atoms in a unit cell



Simple cubic (no metals except Polonium Po – N is 84)

8 atoms **but** each atom is shared by 8 unit cells.

In each cubic unit cell has 8 octants. ie,1/8 x 8 =1 atom

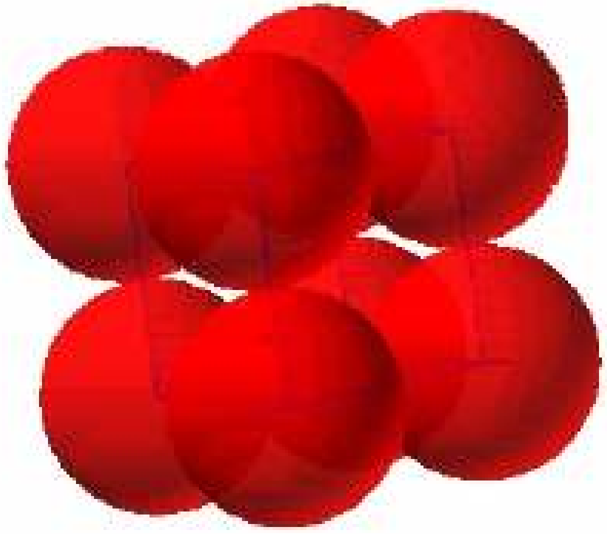
→ **1 atom per unit cell**

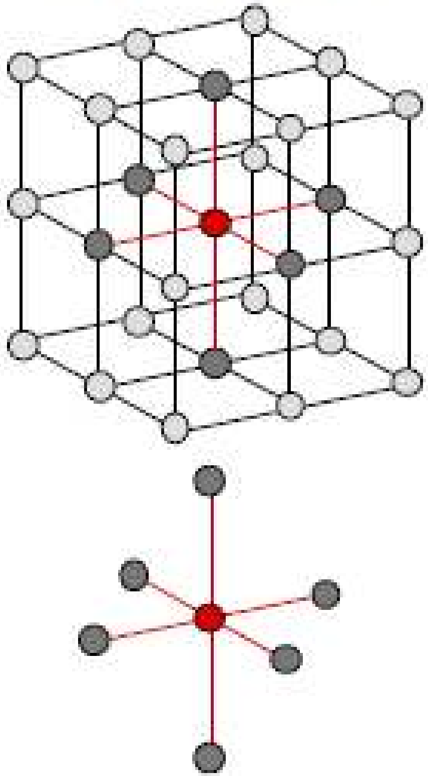
Simple Cubic (SC)

- Rare due to low packing density (only Po has this structure)
- **Close-packed directions** are cube edges.

Eight atoms situated at the eight corners.The corner atoms touch each other

- Coordination # = 6
  (# nearest neighbors)



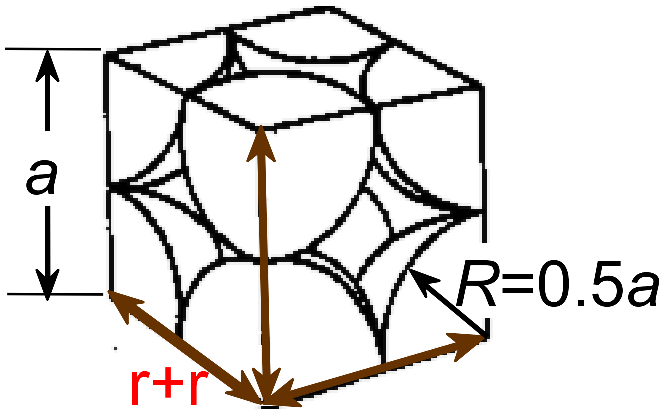


Atomic Packing Factor (APF) – Simple Cubic

$$\mathrm{APF} = \frac{\text{Volume of atoms in unit cell*}}{\text{Volume of unit cell}}$$

- APF for a simple cubic structure = **0.52**

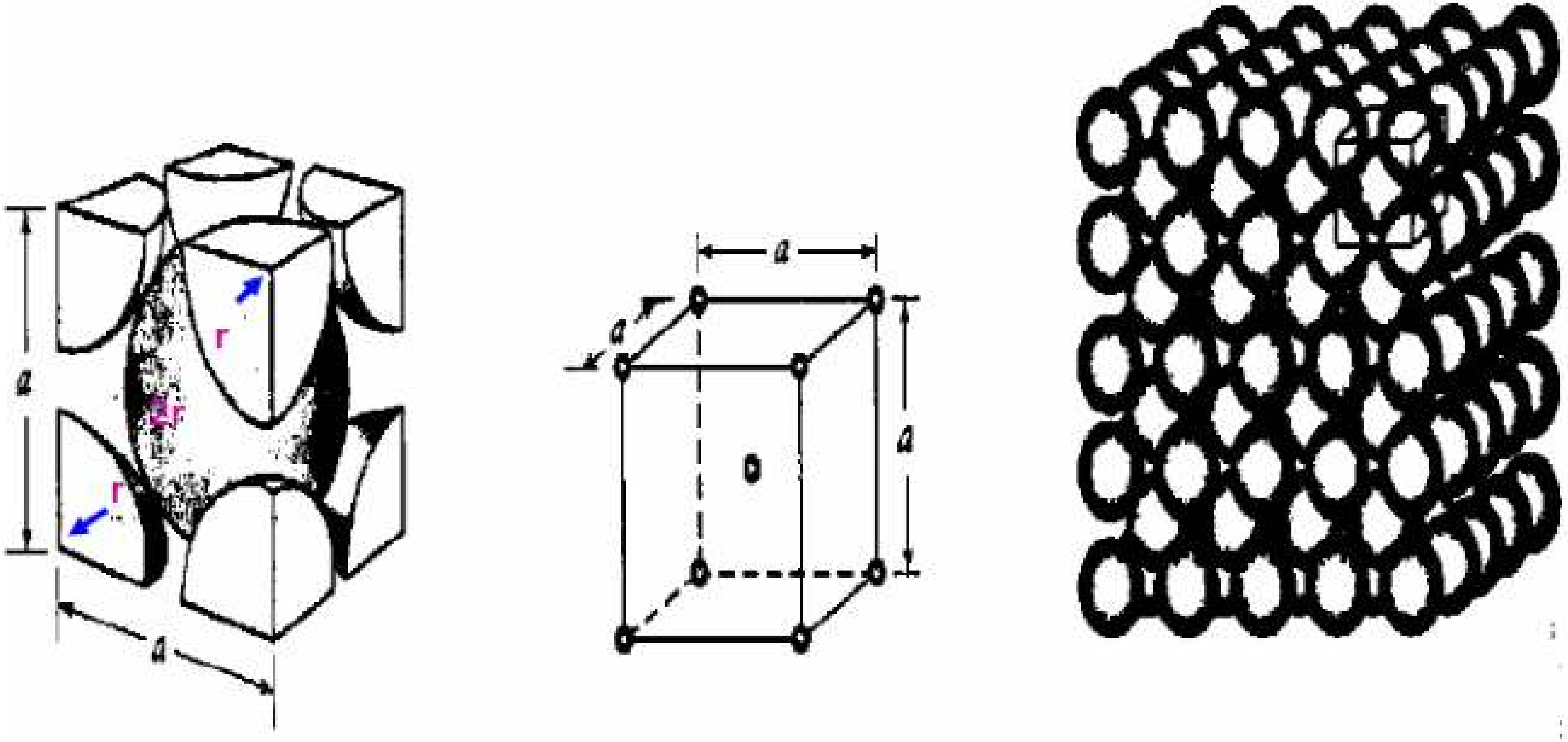
a = 2r



contains 8 x 1/8 = **1 atom/unit cell**

$$\mathrm{APF} = \frac{\overset{\frac{\text{atoms}}{\text{unit cell}}}{1}\ \overset{\frac{\text{volume}}{\text{atom}}}{\frac{4}{3}\pi(0.5a)^3}}{\underset{\frac{\text{volume}}{\text{unit cell}}}{a^3}}$$

Body Centered Cubic (bcc)- BRITTLE

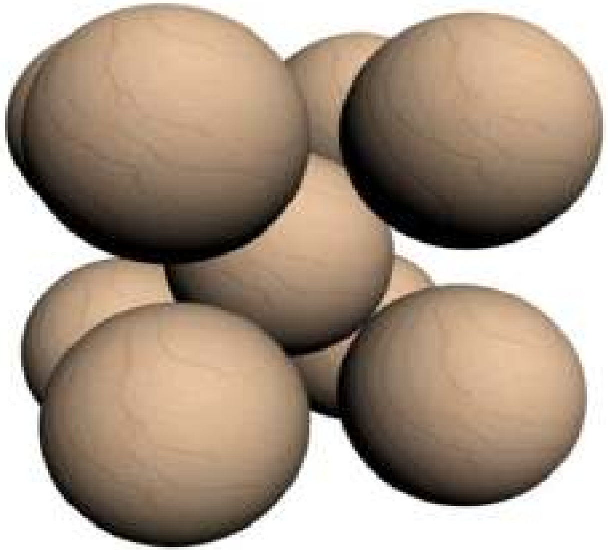


(a) (b) (c)

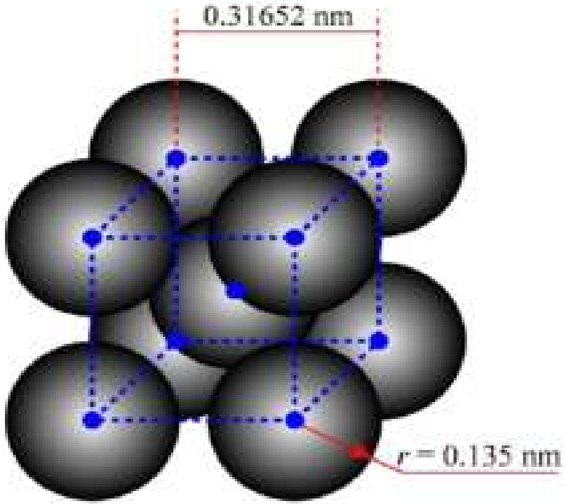
- Eight corner atoms and one atom at center.
- Corner atoms do not touch each other, but each corner atoms touches the center atom.

Body centered cubic lattice (*bcc*)

Body centered cubic lattice (*bcc*)



Unit cell of W (Tungsten)



Unit cell of W (Tungsten)

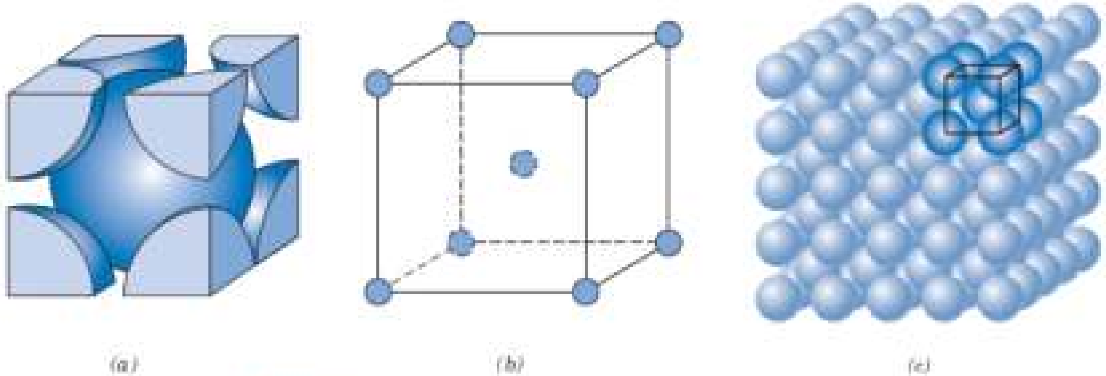
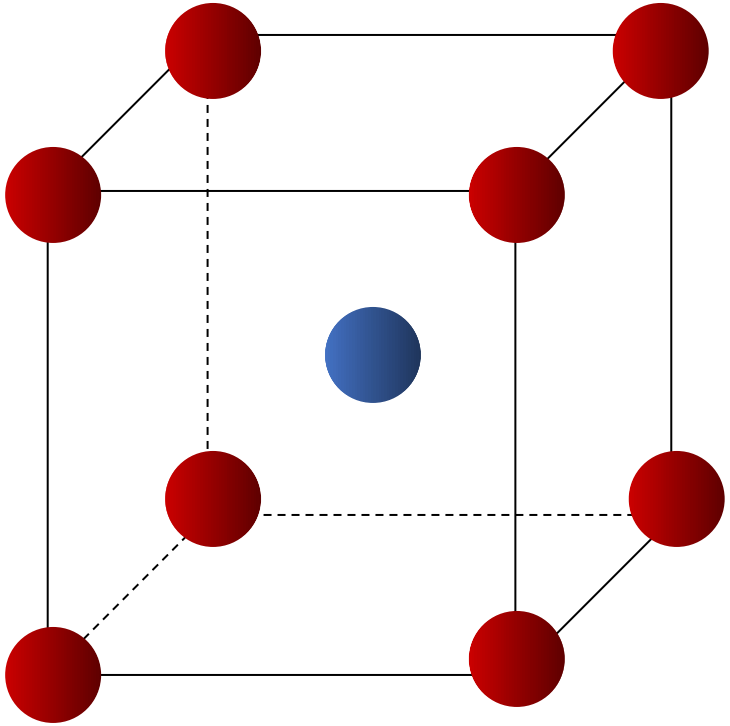
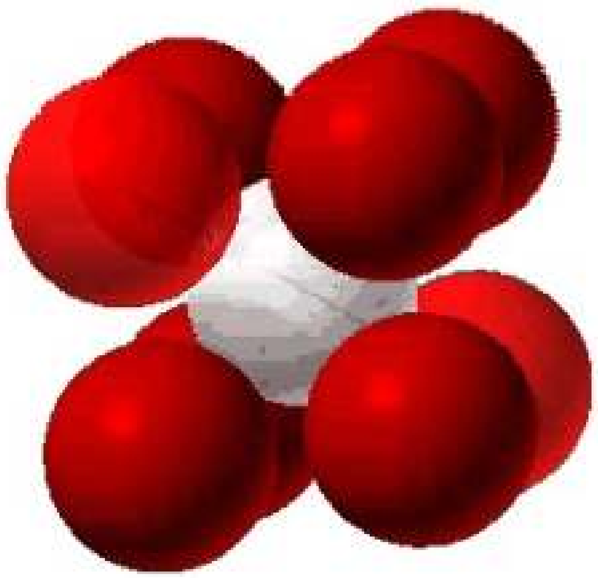


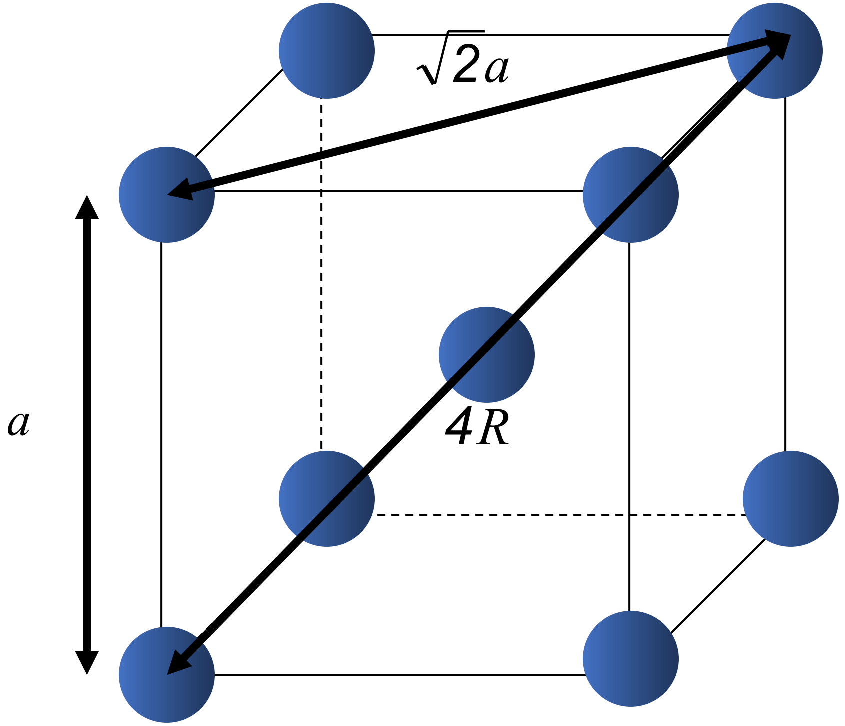
Figure 3.2 For the body-centered cubic crystal structure, (*a*) a hard sphere unit cell representation, (*b*) a reduced-sphere unit cell, and (*c*) an aggregate of many atoms. [Figure (*c*) from W. G. Moffatt, G. W. Pearsall, and J. Wulff, *The Structure and Properties of Materials*, Vol. I, *Structure*, p. 51. Copyright © 1964 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.]





From Callister 6e resource CD.

Body-Centered Cubic (BCC)



LATTICE CONSTANT (a) = Atoms at the corners of the cube

+

Atom at the center of the cube

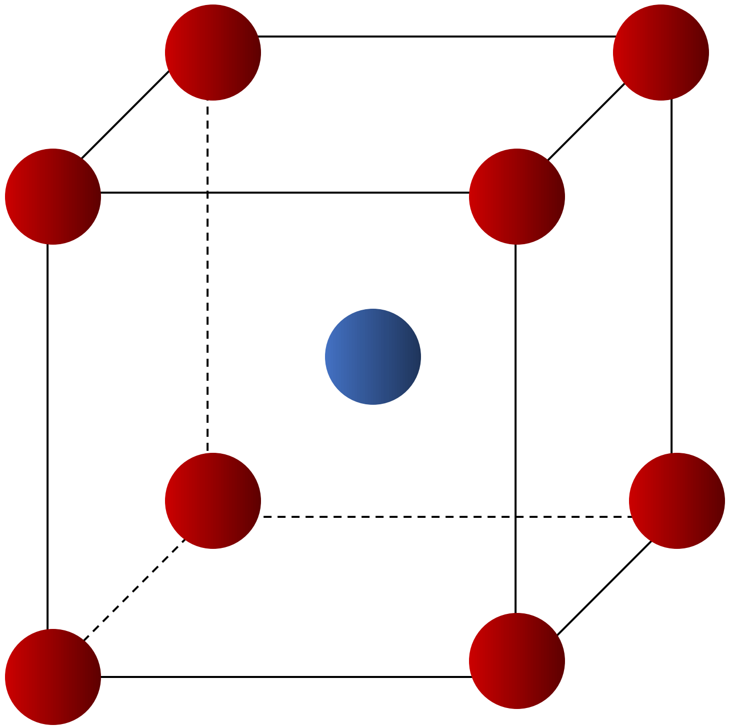
$$a^2 + \left(\sqrt{2}a\right)^2 = (4R)^2$$

Pythagoras theorem

$$a = \frac{4R}{\sqrt{3}}$$

Body diagonal (b.d) of the unit cell = 4R = $a_{bcc}\sqrt{3}$

Number of atoms in a BCC unit cell

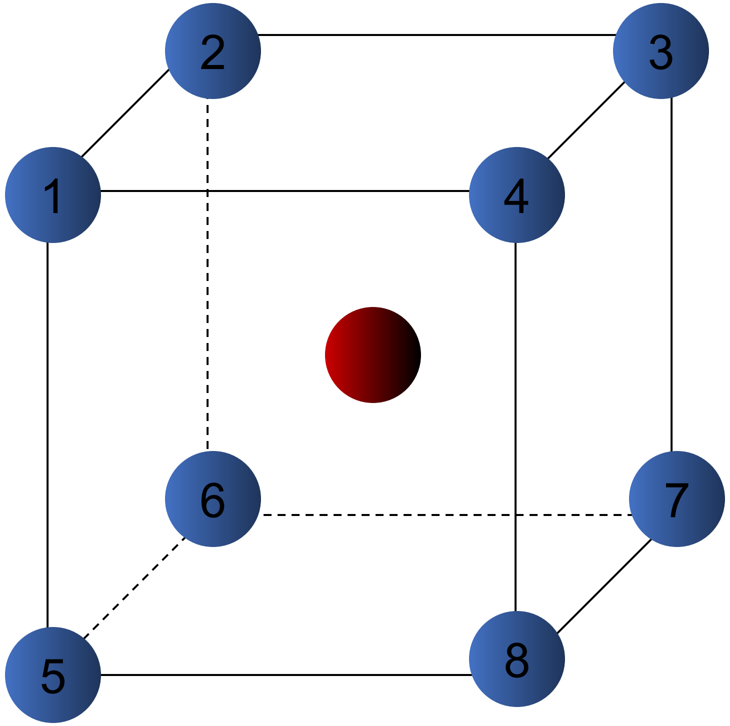


- Each corner atom contributes as **1/8**.
  There are **8** corner atoms in an FCC unit cell.

- **The center atom contributes as 1.**
  There is only 1 center atom.

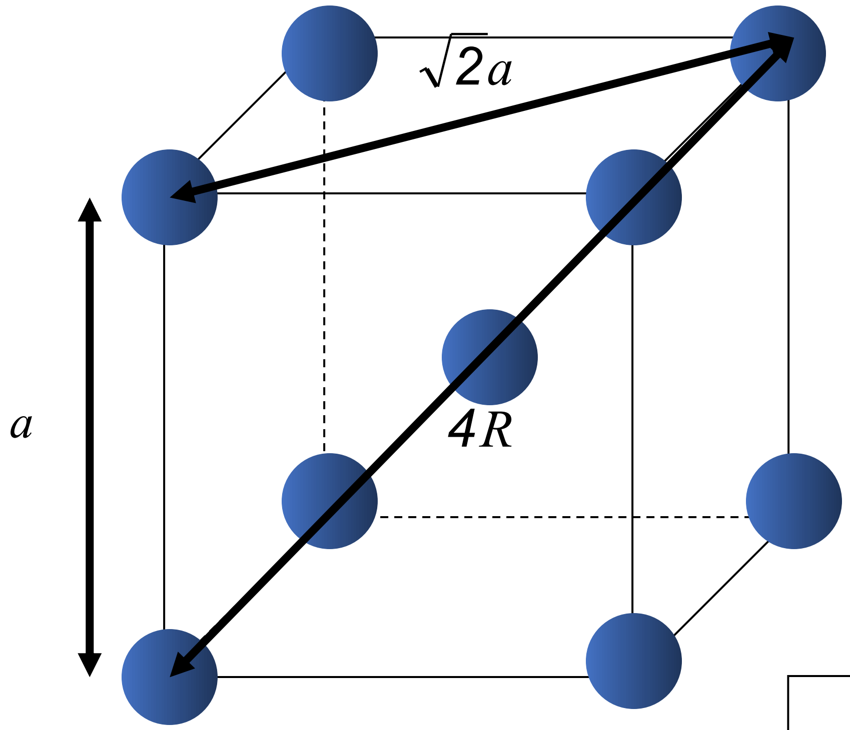
$$\frac{1}{8}\times 8(corner\_atoms)+1\times 1(center\_atom)=2atoms/unit\_cell$$

Coordination number for BCC



Total 8 nearest neighbor atoms
Coordination number = 8

Atomic packing factor (APF) for BCC



$$V_{atoms} = 2\left(\frac{4}{3}\pi R^3\right)$$

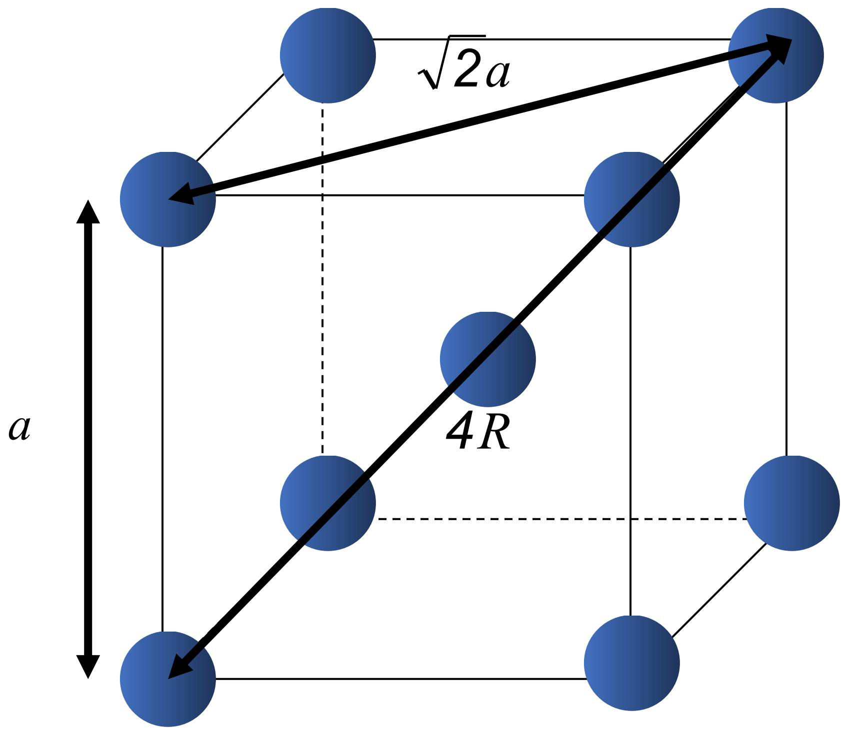
$$a^2 + (\sqrt{2}a)^2 = (4R)^2$$

$$a = \frac{4R}{\sqrt{3}}$$

$$V_{unit\_cell} = a^3 = (\frac{4R}{\sqrt{3}})^3 = \frac{64R^3}{3\sqrt{3}}$$

$$\boxed{APF = \frac{V_{atoms}}{V_{unit\_cell}} = \frac{\left(\frac{8}{3}\pi R^3\right)}{\frac{64R^3}{3\sqrt{3}}} = \frac{\sqrt{3}\pi}{8} = 0.68}$$

Summary for BCC



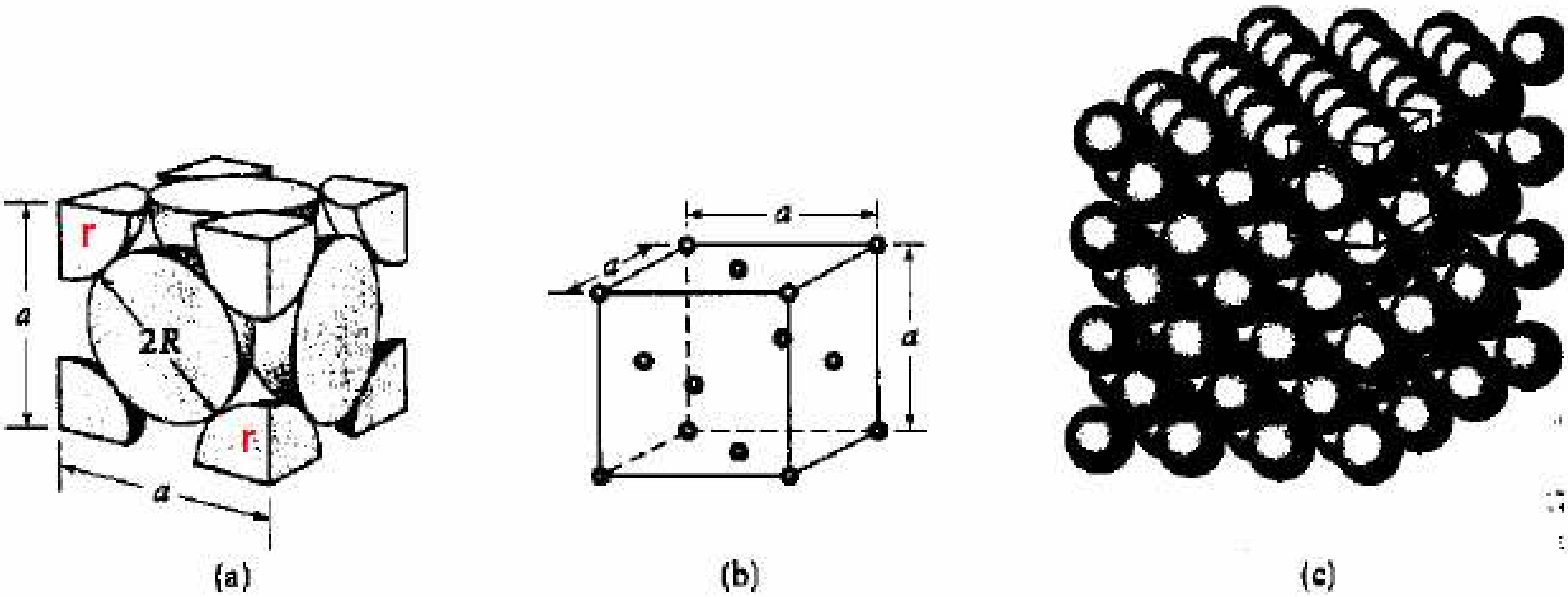
||unit vector|| = $a = \frac{4R}{\sqrt{3}}$

2 atoms/unit cell

Coordination number = **8 = CN**

APF = 0.68

Face Centered Cubic (fcc)



(a) (b) (c)

Eight corner atoms and one atom at the center of each face. Corner atoms do not touch each other, but each corner atoms touches the center atom of each face.

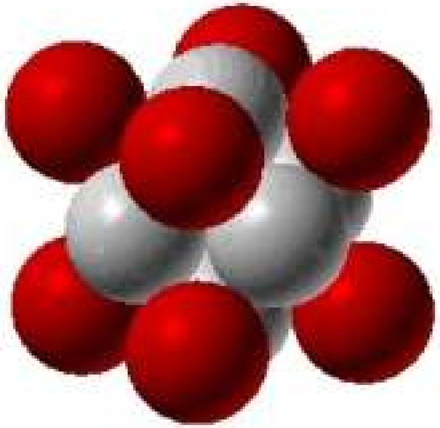
Face Centered Cubic (FCC)

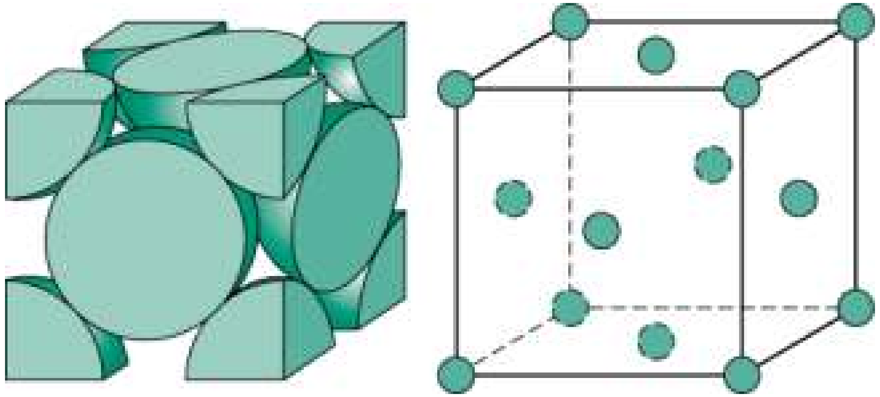
- **Atoms touch each other along face diagonals.**

--Note: All atoms are identical; the face-centered atoms are shaded differently only for ease of viewing.

ex: **Al, Cu, Au, Pb, Ni, Pt, Ag - DUCTILE**

- Coordination no. = 12

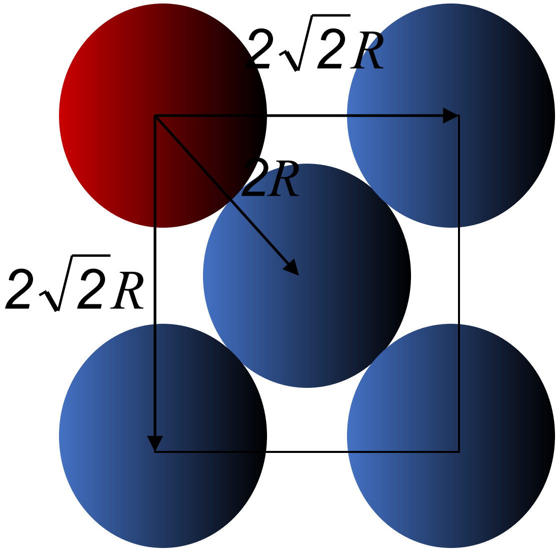


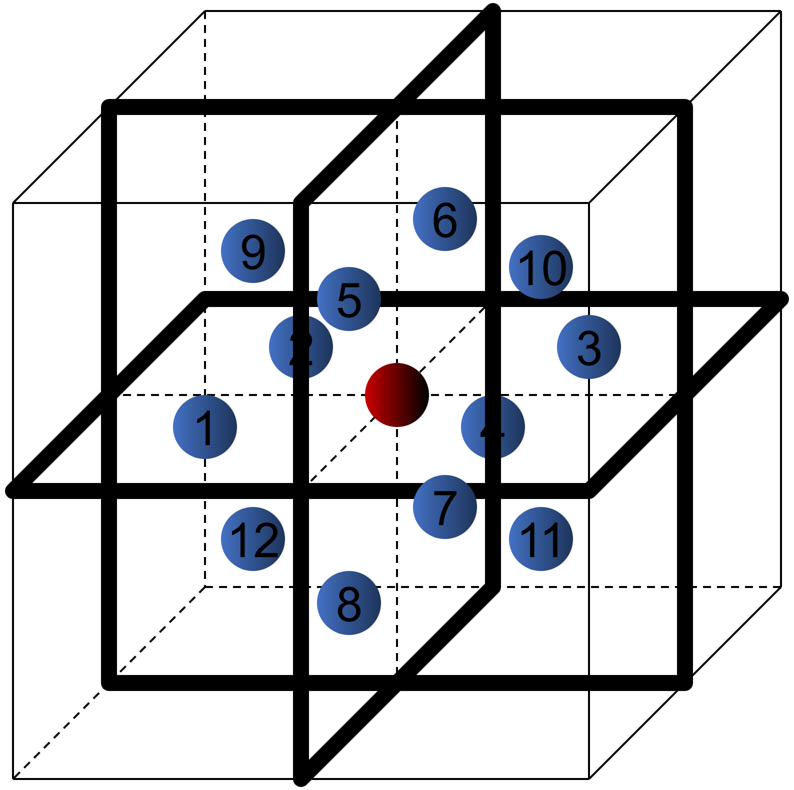


Adapted from Fig. 3.1, *Callister 7e.*

4 atoms/unit cell: 6 face x 1/2 + 8 corners x 1/8

Coordination number for FCC

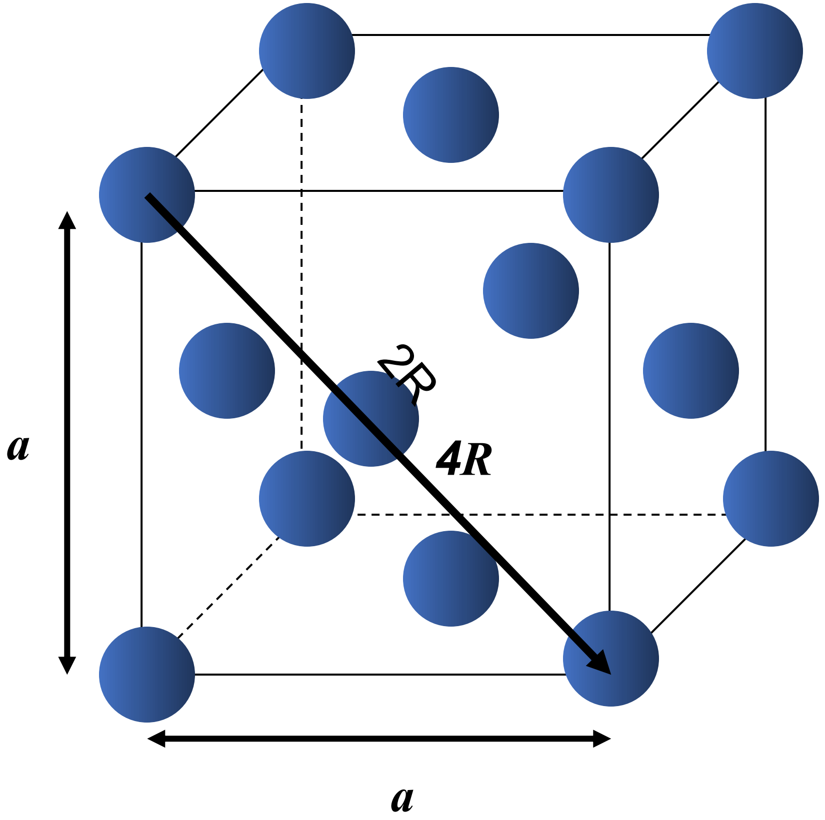




Total 12 nearest neighbor atoms

Coordination number = 12

Face-Centered Cubic (FCC)



Atoms at the corners of the cube

+

Atoms at the center of each face

***a* = ||unit vector||**

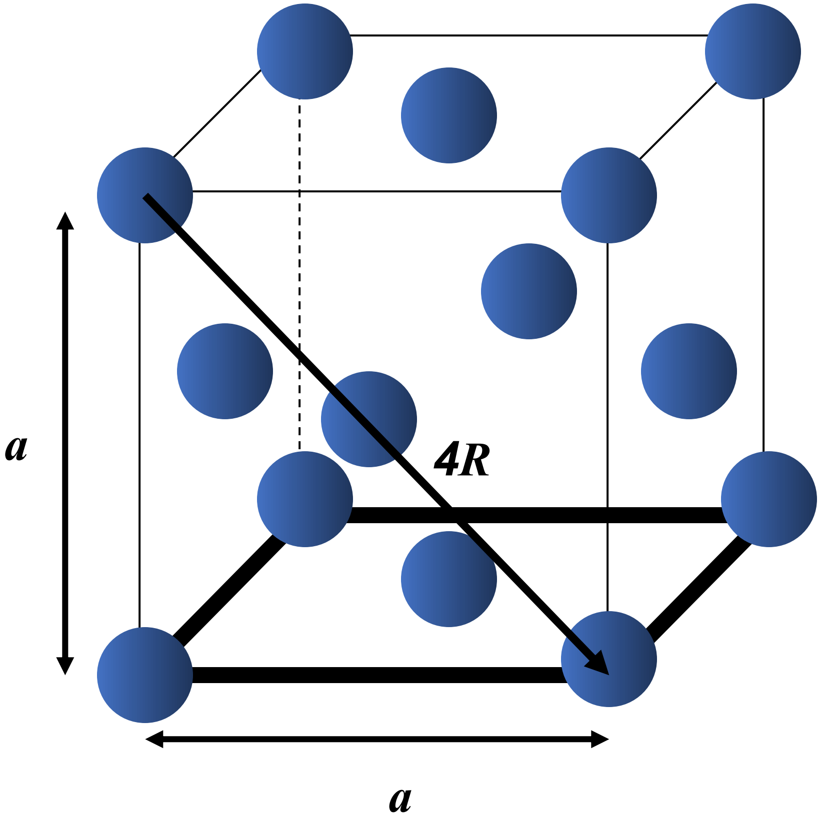
R = atomic radius

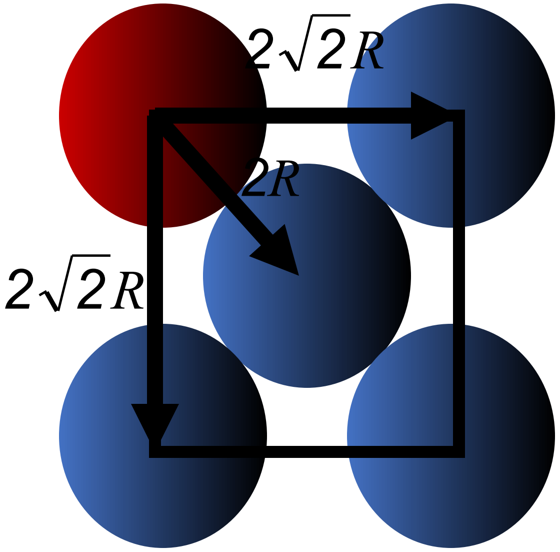
$$a^2 + a^2 = (4R)^2$$

$$a = 2\sqrt{2}R$$

Pythagoras theorem

Atomic packing factor (APF) for FCC





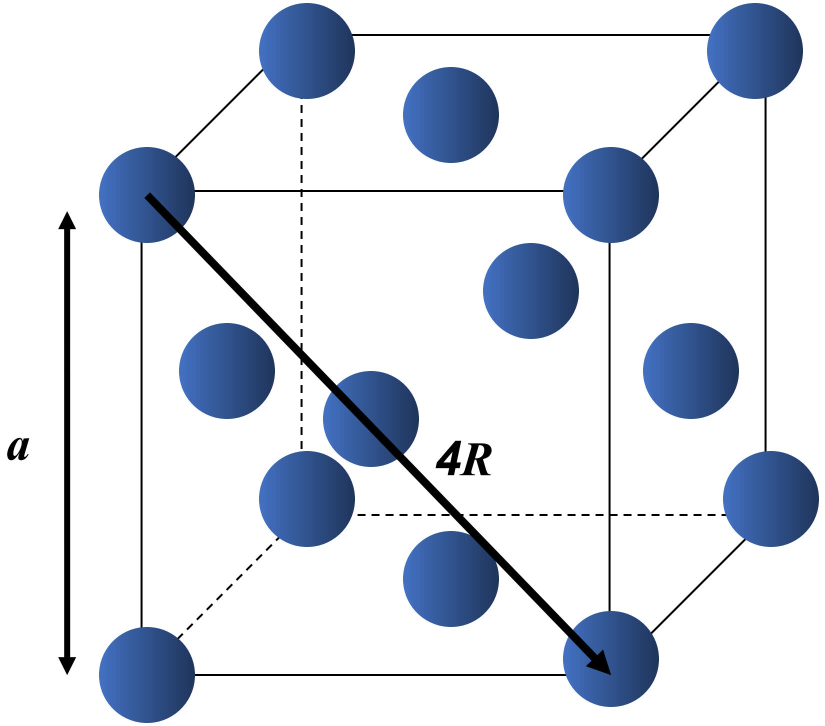
$$V_{atoms} = 4\left(\frac{4}{3}\pi R^3\right)$$

$$V_{unit\_cell} = a^3 = (2\sqrt{2}R)^3 = 16\sqrt{2}R^3$$

$$APF = \frac{V_{atoms}}{V_{unit\_cell}} = \frac{\left(\frac{16}{3}\pi R^3\right)}{16\sqrt{2}R^3} = \frac{\pi}{3\sqrt{2}} = 0.74$$

Independent of *R* and *a*!

Summary for FCC



||unit vector|| = $a = 2\sqrt{2}R$

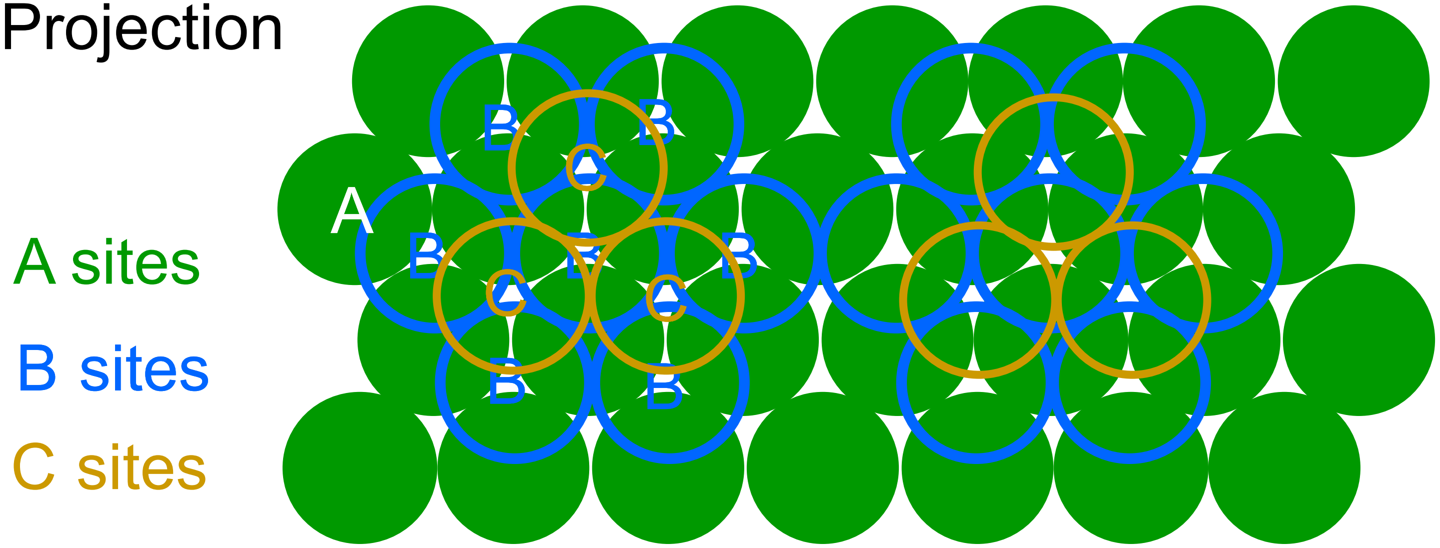
4 atoms/unit cell

Coordination number = **12 =N**

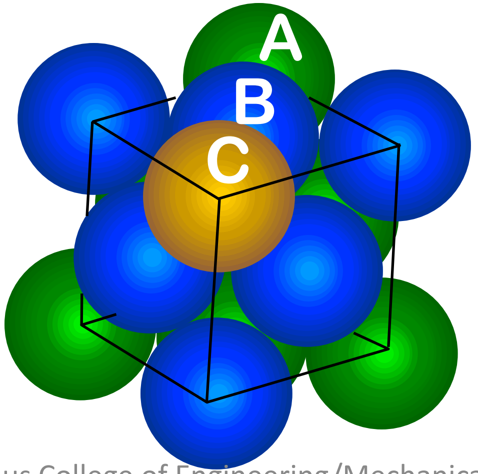
APF = 0.74

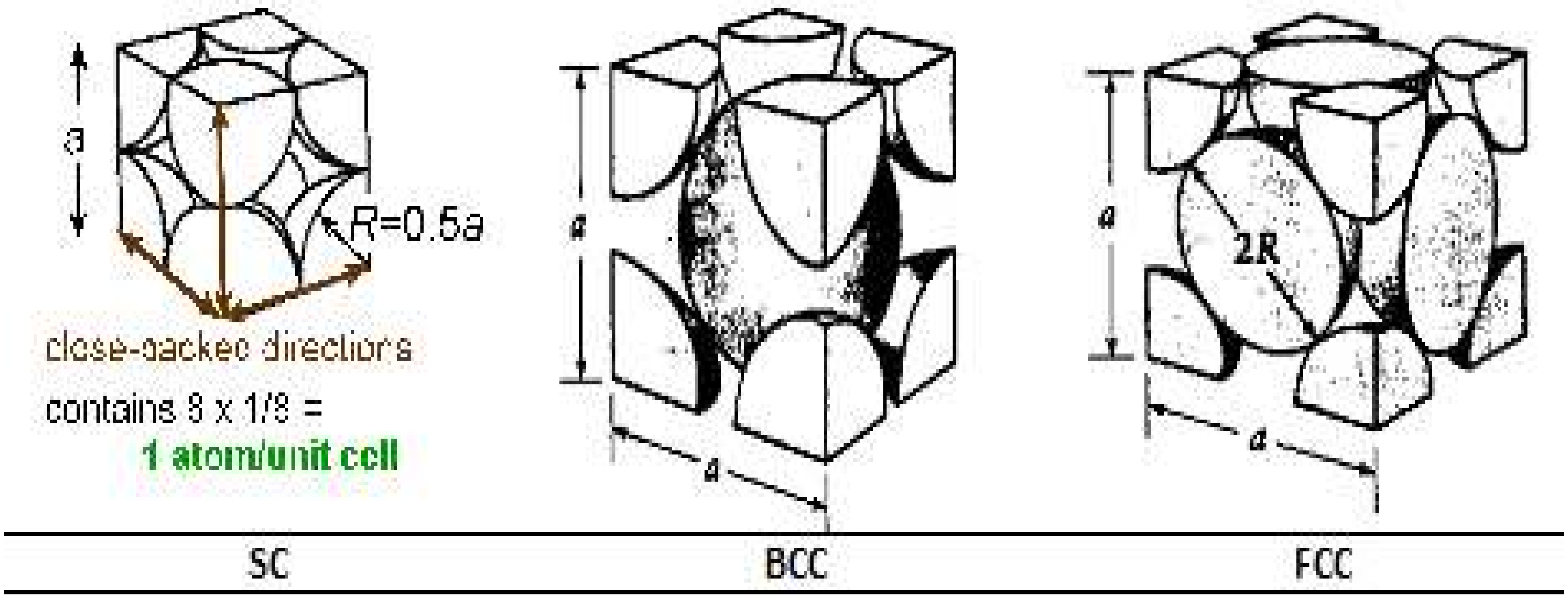
FCC Stacking Sequence

- ABCABC... Stacking Sequence
- 2D Projection



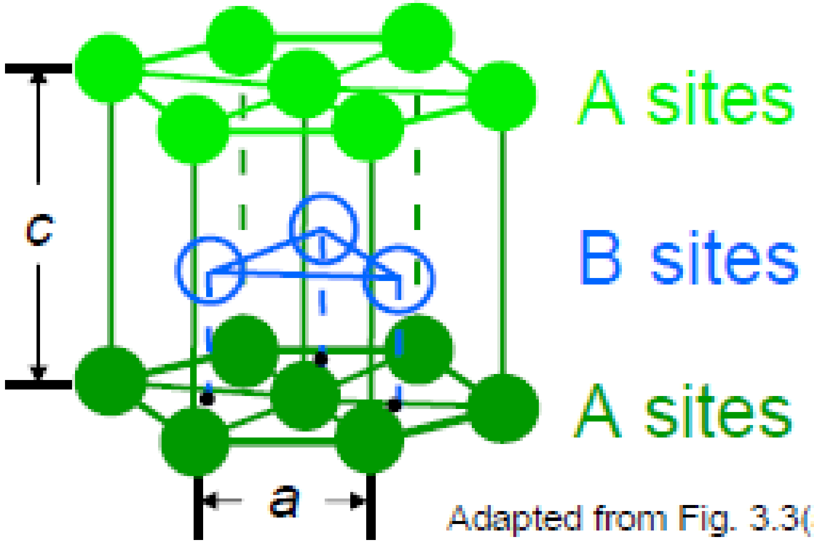
- FCC Unit Cell




a
R=0.5a
close-packed directions
contains 8 x 1/8 =
1 atom/unit cell
a
a
a
2R
a
SC
BCC
FCC

Hexagonal Close-Packed (HCP) –Brittle – AB, AB…

- ABAB... Stacking Sequence
- 3D Projection



Adapted from Fig. 3.3(a), *Callister 7e.*

- 2D Projection

6 atoms/unit cell

- Coordination # = 12
- APF = 0.74

ex: Cd, Mg, Ti, Zn

Hexagonal Close-Packing (HCP)

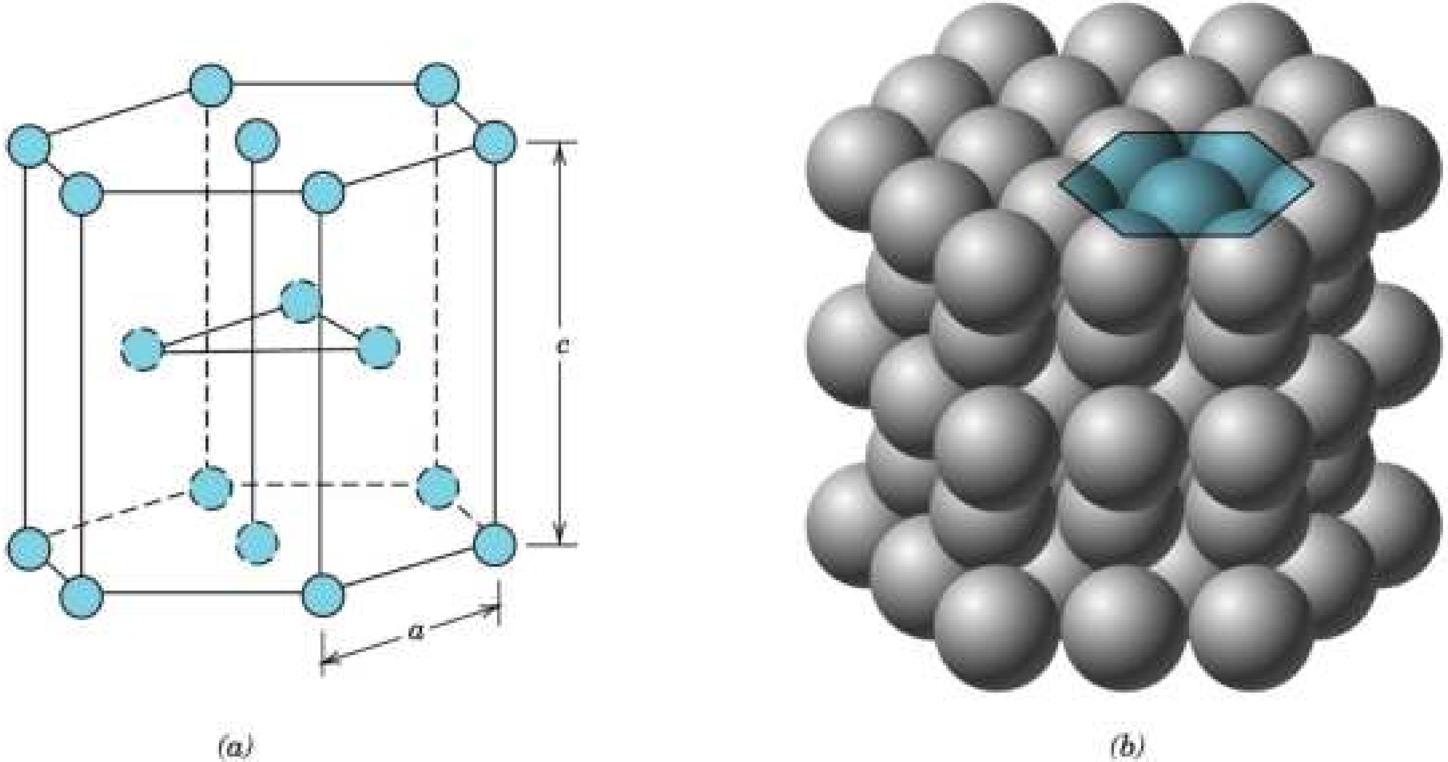


FIGURE 3.3 For the hexagonal close-packed crystal structure, (*a*) a reduced-sphere unit cell (*a* and *c* represent the short and long edge lengths, respectively), and (*b*) an aggregate of many atoms. (Figure *b* from W. G. Moffatt, G. W. Pearsall, and J. Wulff, *The Structure and Properties of Materials*, Vol. I, *Structure*, p. 51. Copyright © 1964 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)

Middle layer = 3 atoms

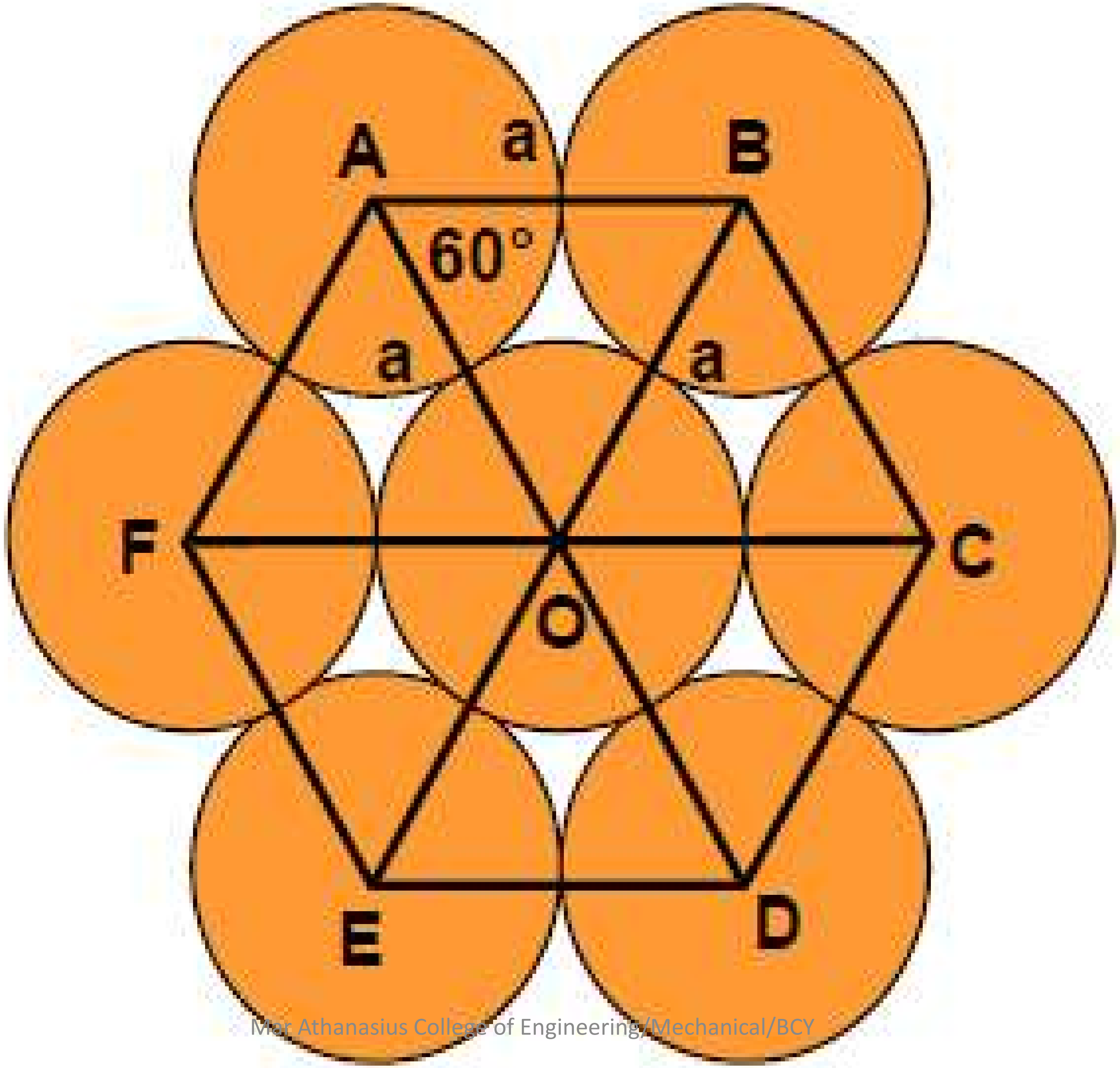
Top layer = ½ x 1 = ½ atom

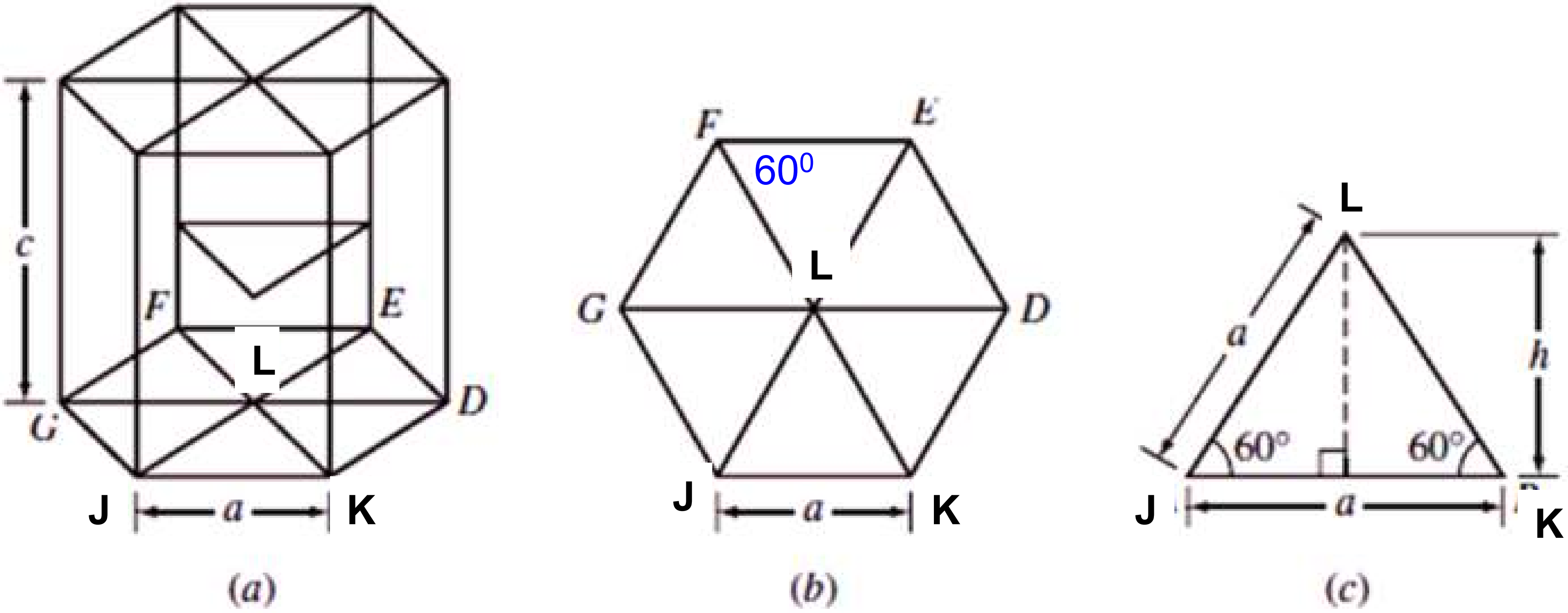
= 1/6 x 6 = 1 atom = 1 ½ atom

Bottom layer = ½ x 1 = ½ atom

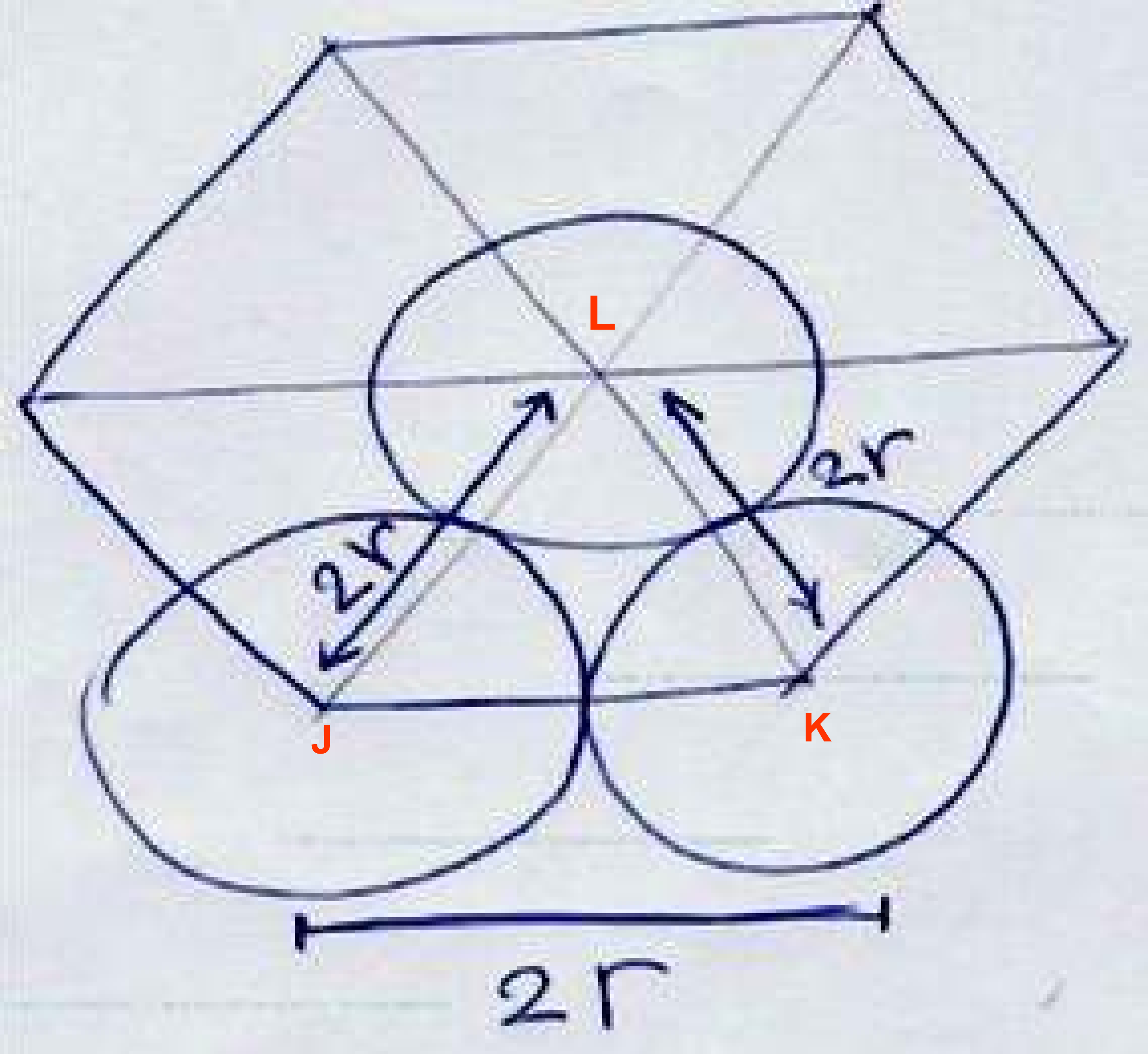
= 1/6 x 6 = 1 atom = 1 ½ atom

Total atoms in HCP = 6 atoms


A
a
B
60°
a
a
F
C
O
E
D



Diagrams for calculating the volume of an HCP unit cell. (*a*) HCP unit cell. (*b*) Base of HCP unit cell. (*c*) Triangle **JKL** removed from base of unit cell.


L
2r
2r
J
K
2r

$$\text{Area } \Delta\, \text{JKL} = \frac{1}{2} \times \text{base} \times \text{height}$$

$$= \frac{1}{2} \times 2\text{r} \times \text{a} \sin 60$$

$$= \frac{1}{2} \times 2\text{r} \times 2\text{r} \sin 60$$

$$\text{Total base area} = 6 \times \frac{1}{2} \times 2\text{r} \times 2\text{r} \cos 60$$

$$= 6 \times 2\text{r}^2 \sin 60$$

$$\text{Total volume of HCP unit cell} = \text{total base area} \times \text{height}$$

$$= 6 \times 2\text{r}^2 \sin 60 \times \text{c}$$

$$= 6 \times 2\text{r}^2 \sin 60 \times 1.633 \times 2\text{r}$$

Lattice parameter a and c of HCP unit cell related by c=1.633a =1.633 x 2r

$$\text{APF} = \frac{6 \times \frac{4}{3} \pi \text{r}^3}{6 \times 2 \times \text{r}^2 \sin 60 \times 1.633 \times 2\text{r}} = 0.74$$

Structures of Elemental Metals [Ref.Callister 3.4]

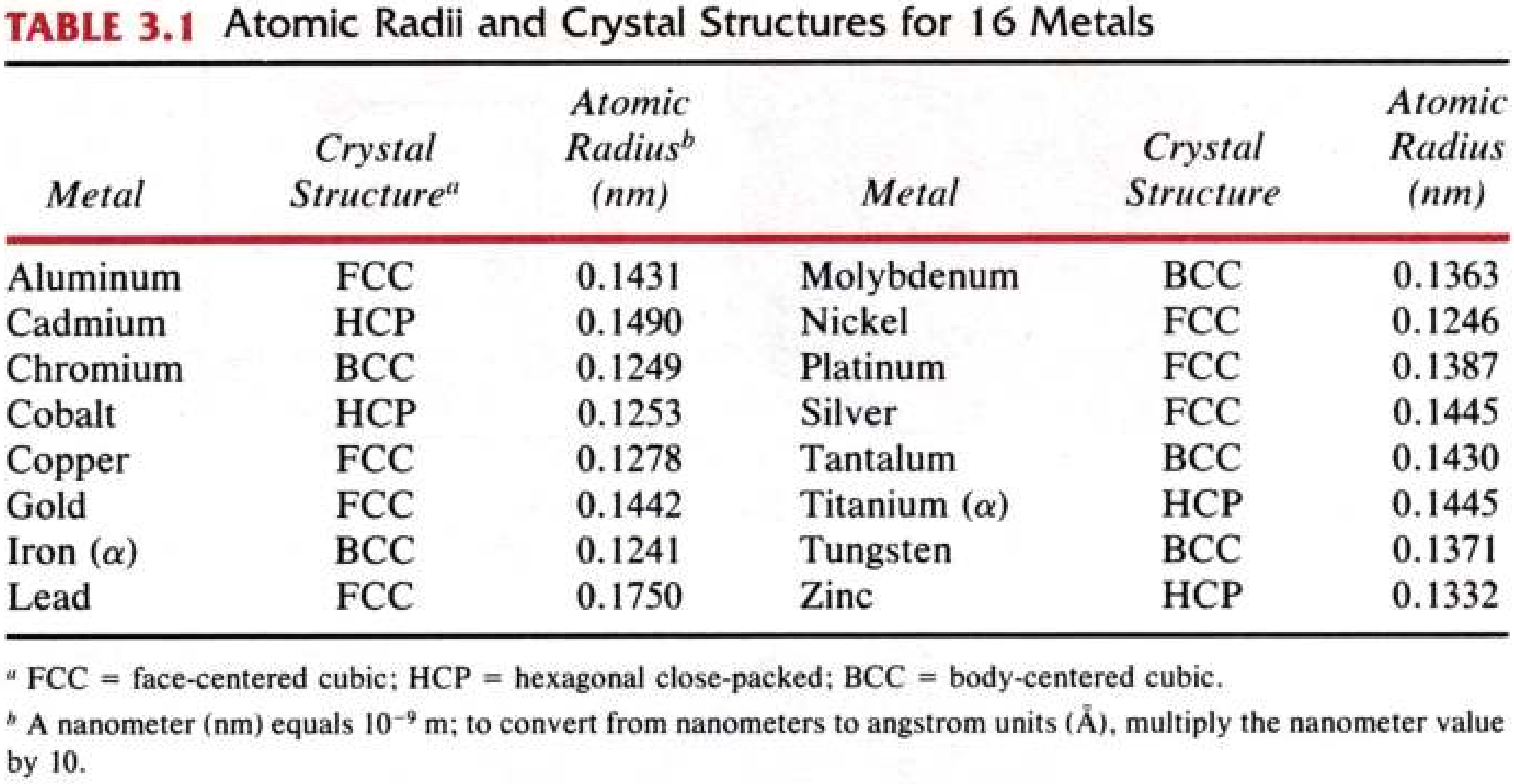


TABLE 3.1 Atomic Radii and Crystal Structures for 16 Metals

Metal	*Crystal Structure*[a]	*Atomic Radius*[b] *(nm)*	*Metal*	*Crystal Structure*	*Atomic Radius (nm)*
Aluminum	FCC	0.1431	Molybdenum	BCC	0.1363
Cadmium	HCP	0.1490	Nickel	FCC	0.1246
Chromium	BCC	0.1249	Platinum	FCC	0.1387
Cobalt	HCP	0.1253	Silver	FCC	0.1445
Copper	FCC	0.1278	Tantalum	BCC	0.1430
Gold	FCC	0.1442	Titanium (α)	HCP	0.1445
Iron (α)	BCC	0.1241	Tungsten	BCC	0.1371
Lead	FCC	0.1750	Zinc	HCP	0.1332

[a] FCC = face-centered cubic; HCP = hexagonal close-packed; BCC = body-centered cubic.

[b] A nanometer (nm) equals 10^{-9} m; to convert from nanometers to angstrom units (Å), multiply the nanometer value by 10.

Polymorphism and Allotropy

- Existence of more than one equilibrium crystallographic form for elements or compounds at different conditions of temperature and pressure is called Polymorphism.
- i.e., two or more different crystal structures for the same material exists…
- If the change in in crystal structure is reversible, then the polymorphic change is called Allotropy.
- Polymorphisam :- more than one element or compound eg. Fe3C
- Allotropy:- only one element
- eg. C - Diamond (sp3), graphite (sp2), polymer(sp1), fullerene (C66).

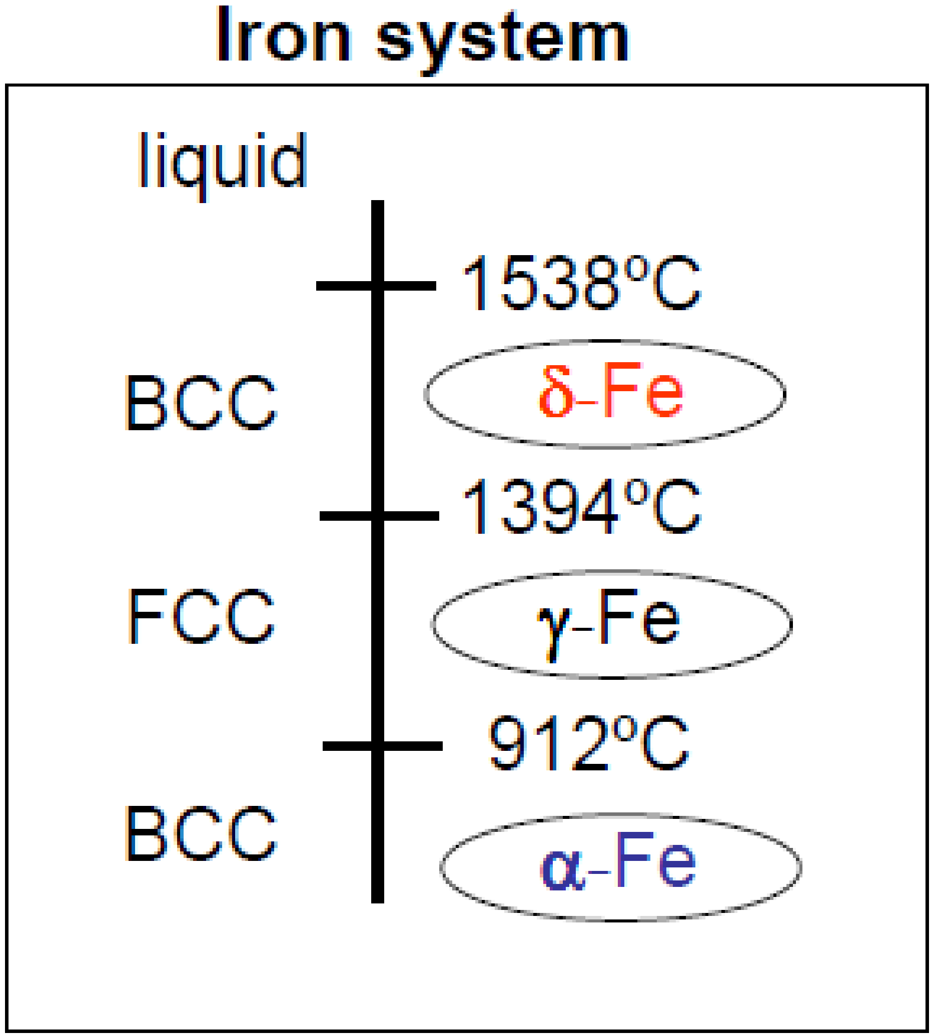
Example: Polymorphism

- Iron is liquid above 1539ºC

➢δ- Iron (BCC) between 1394 and 1539ºC

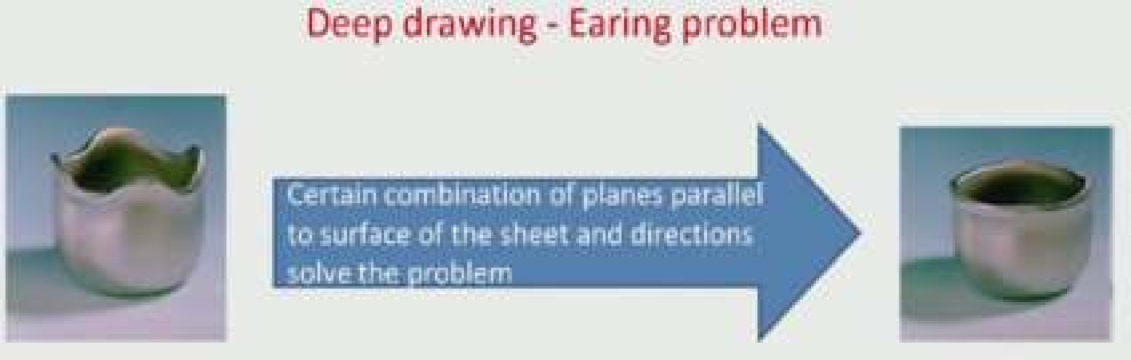
➢γ- Iron (FCC) between 912 and 1394ºC

➢α- Iron (BCC) between -273 and 912ºC



Crystallographic Points,Directions, and Planes

- When dealing with crystalline materials, it often becomes necessary to specify a particular point within a unit cell, a crystallographic direction, or some crystallographic plane of atoms.
- Three numbers or indices are used to designate point locations, directions, and planes.



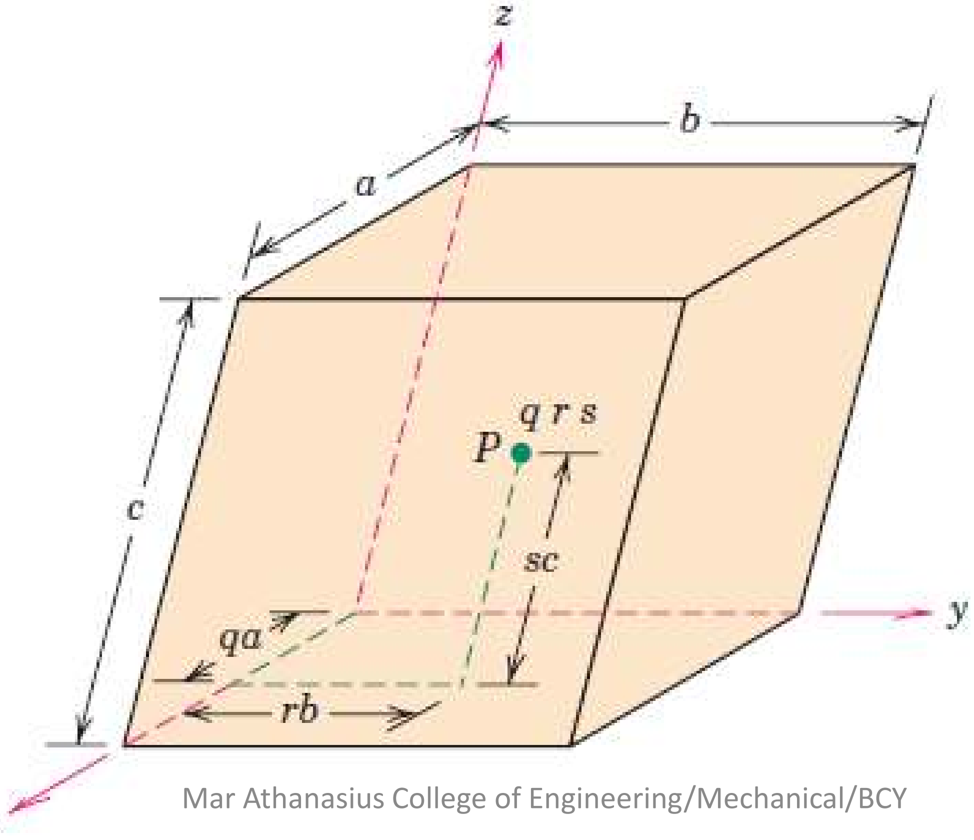
Deep drawing - Earing problem

Certain combination of planes parallel to surface of the sheet and directions solve the problem

POINT COORDINATE

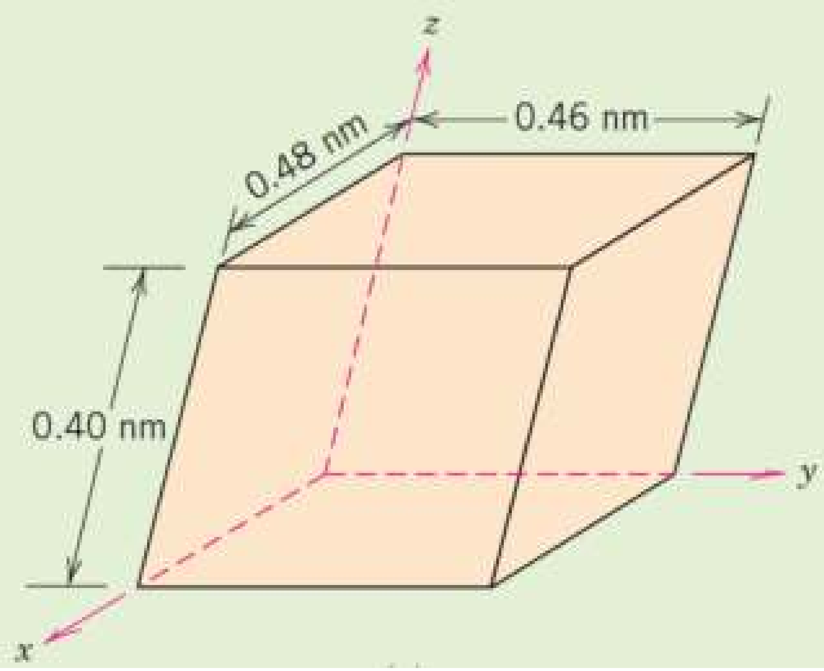
- The position of any point located within a unit cell may be specified in terms of coordinates as fractional multiples of the unit cell edge lengths (i.e., in terms of a, b, and c).

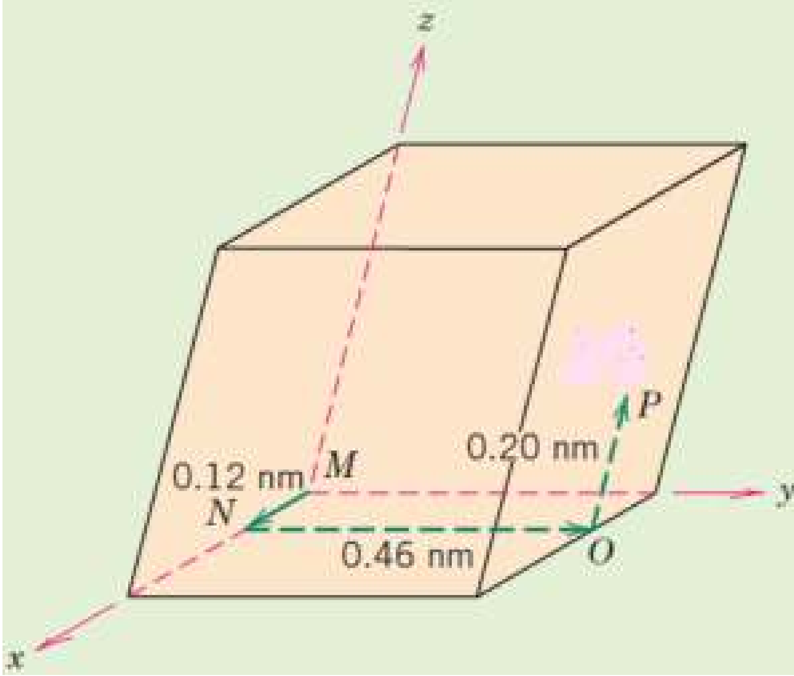
- Position of P in terms of the generalized coordinates q, r, and s where q is some fractional length of *a* along the x axis, r is some fractional length of *b* along the y axis, and similarly for s.
- Thus, the position of P is designated using coordinates q r s with values that are less than or equal to unity.



- For the unit cell shown in the accompanying sketch, locate the point P coordinates.
  - a=0.48 nm , b= 0.46 nm, c = 0.40 nm
  - For point P , x coordinate = 0.12 nm, y coordinate = 0.46 nm, z coordinate = 0.20 nm
- q = 0.12/.48 = ¼
- r = 0.46/.46 = 1
- s = 0.20/0.40= 1/2

$$\frac{1}{4}\ 1\ \frac{1}{2}$$





CRYSTALLOGRAPHIC DIRECTIONS (Miller Indices of Directions)

- Certain directions and planes within a unit cell carry particular significance
- Ex, crystallographic directions are used to indicate a particular orientation of a crystal.
- A crystallographic direction is defined as a line or a vector between two points.
- Following are the steps for determination of the Miller Indices of Directions.
  - Determine the coordinates of two points that lie on the direction , using a right handed coordinate system.
  - Subtract the coordinates of tail point from those of the head point and express the same in terms of the unit cell dimensions.
  - Multiply or divide these numbers by a common factor to reduce them to the smallest integer
  - The three indices are enclosed in square brackets as [uvw]. A negative integer is represented with a bar over the number.

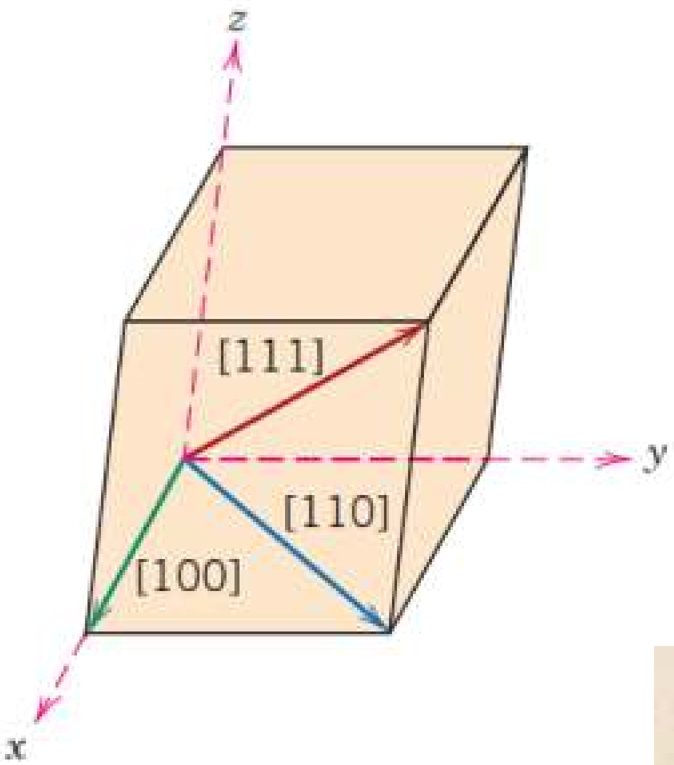
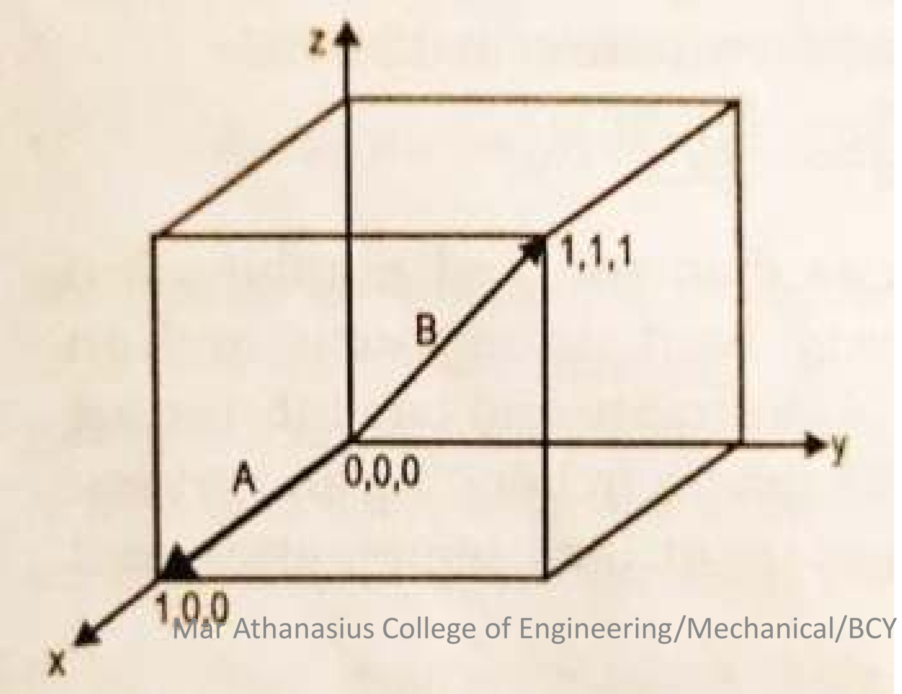
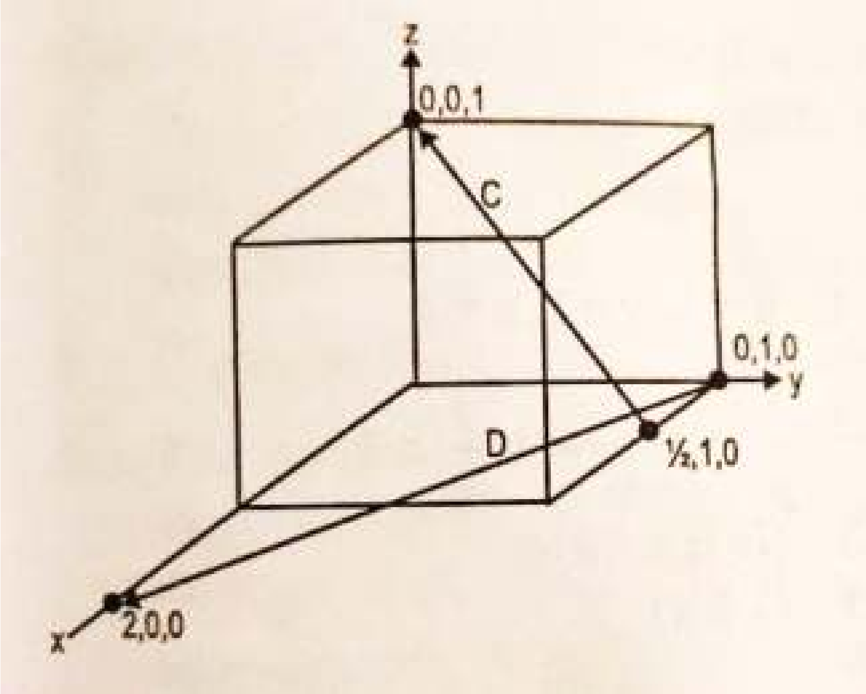
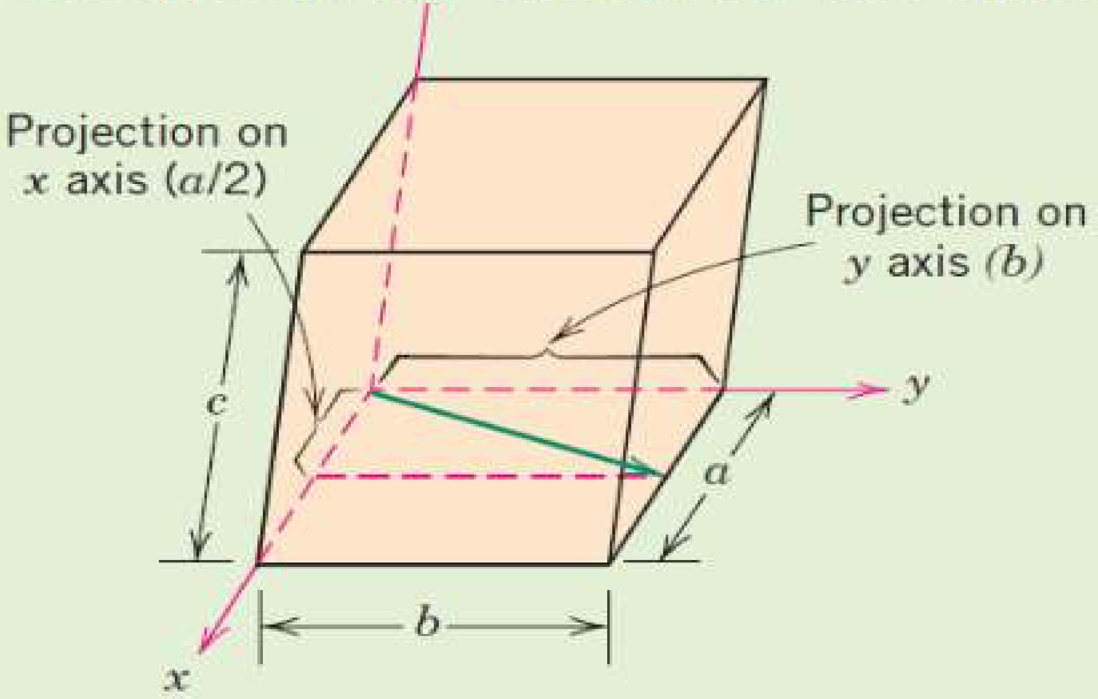


Figure 3.6 The [100], [110], and [111] directions within a unit cell.



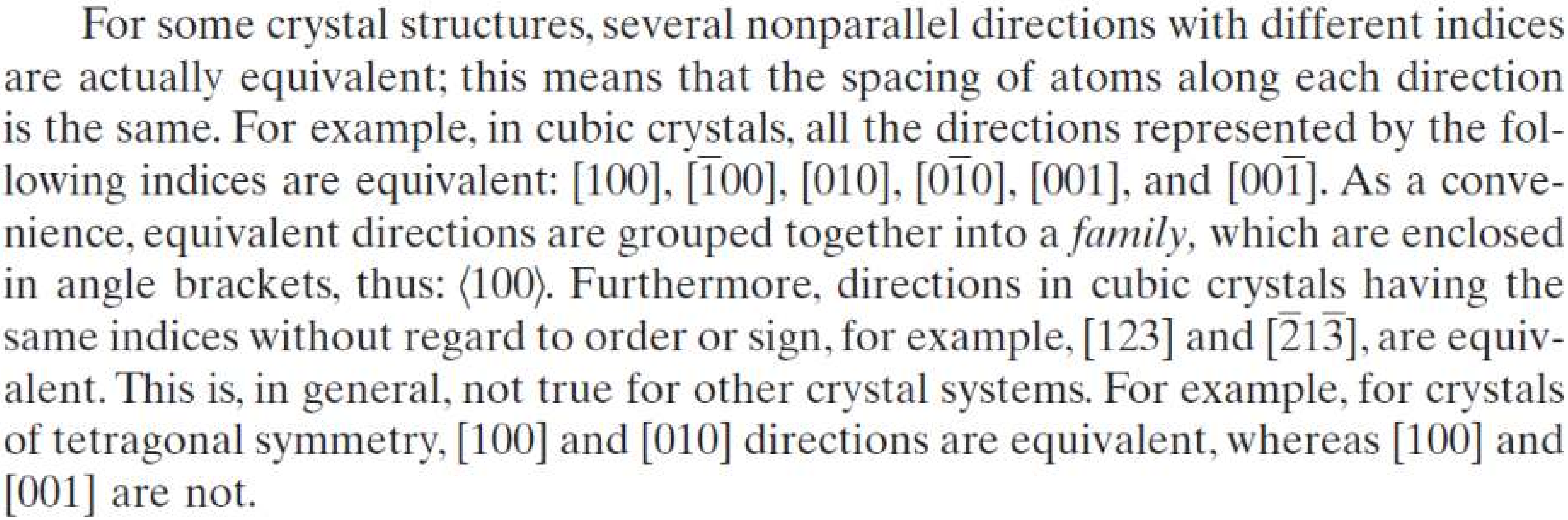


Determine the indices for the direction shown in the accompanying figure.



This procedure may be summarized as follows:

	x	y	z
Projections	$a/2$	b	$0c$
Projections (in terms of a, b, and c)	$\frac{1}{2}$	1	0
Reduction	1	2	0
Enclosure		[120]	

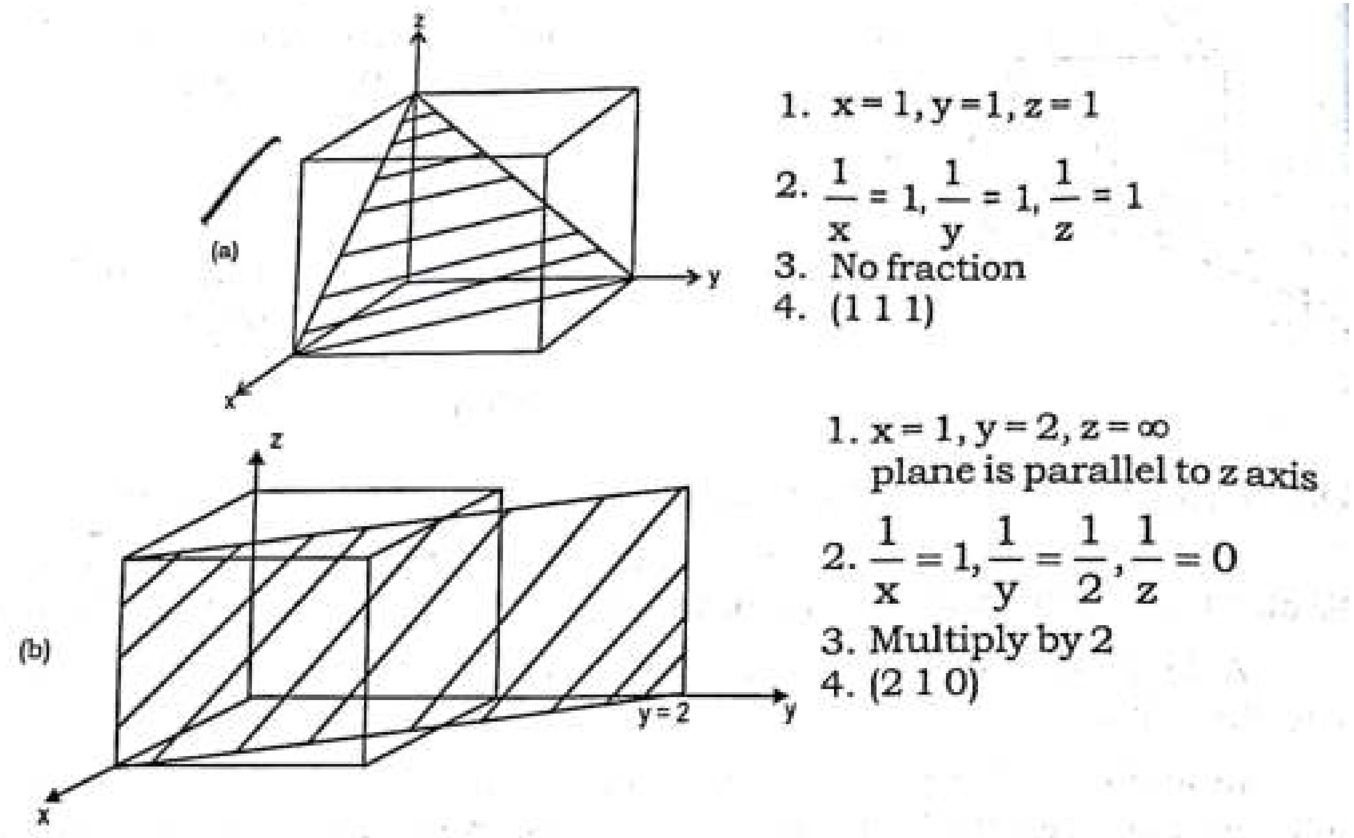


For some crystal structures, several nonparallel directions with different indices are actually equivalent; this means that the spacing of atoms along each direction is the same. For example, in cubic crystals, all the directions represented by the following indices are equivalent: [100], $[\bar{1}00]$, [010], $[0\bar{1}0]$, [001], and $[00\bar{1}]$. As a convenience, equivalent directions are grouped together into a *family*, which are enclosed in angle brackets, thus: ⟨100⟩. Furthermore, directions in cubic crystals having the same indices without regard to order or sign, for example, [123] and $[\bar{2}1\bar{3}]$, are equivalent. This is, in general, not true for other crystal systems. For example, for crystals of tetragonal symmetry, [100] and [010] directions are equivalent, whereas [100] and [001] are not.

(CRYSTALLOGRAPHIC PLANES) Miller Indices

- Metals deform along the planes of atoms which are most tightly packed.
- Miller Indices are a symbolic vector representation for the orientation of an atomic plane in a crystal lattice.
- It is defined as the reciprocals of the fractional intercepts which the plane makes with the crystallographic axes.
- Miller indices are represented by a set of 3 integer numbers (hkl).
- Any two planes parallel to each other are equivalent and have identical indices. The procedure employed in determination of the h, k, and l index numbers is as follows:
  - If the plane passes thorough the origin of coordinate system , the origin must be moved to another corner of unit cell
  - Identify the points at which the plane intercepts the x,y,z axis and express the intercepts in terms of the lattice parameters

- Take reciprocals of these numbers. Intercepts for a plane parallel to an axis to be taken as infinity with reciprocal equal to zero.
- Change the number to a set of smallest integer by multiplication or division by a common factor.
- Enclose the integer indices within parentheses as (hkl)



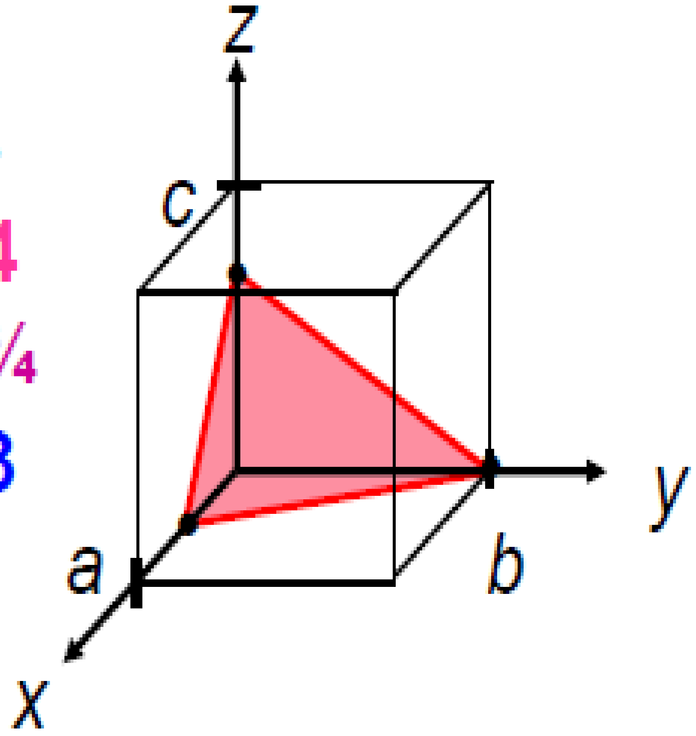
1. $x = 1, y = 1, z = 1$
2. $\frac{1}{x} = 1, \frac{1}{y} = 1, \frac{1}{z} = 1$
3. No fraction
4. (1 1 1)

1. $x = 1, y = 2, z = \infty$
   plane is parallel to z axis
2. $\frac{1}{x} = 1, \frac{1}{y} = \frac{1}{2}, \frac{1}{z} = 0$
3. Multiply by 2
4. (2 1 0)

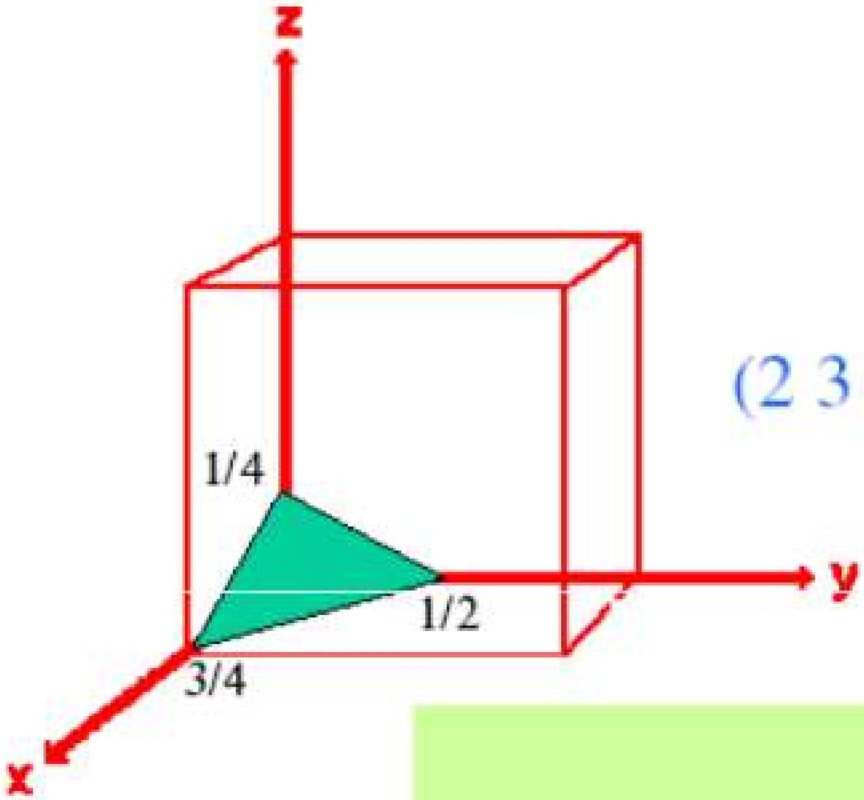
Miller Indices

example	a	b	c
1. Intercepts	1/2	1	3/4
2. Reciprocals	1/½	1/1	1/¾
	2	1	4/3
3. Reduction	6	3	4

4. Miller Indices (634)

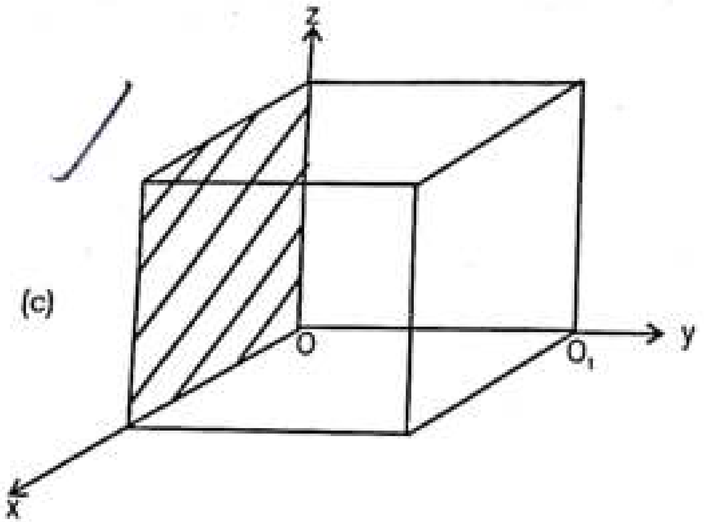


Miller Indices



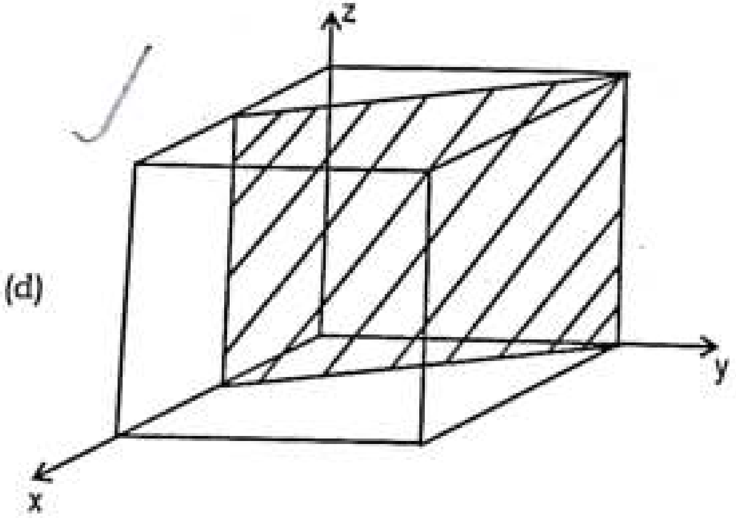
(2 3 6)

	x	y	z
Intercepts	¾	½	1/4
Reciprocal	4/3	2	4
As integer	4	6	12
Common fac.	2	3	6



Origin to be moved from O to O_1

1. $x = \infty, y = -1, z = \infty$
2. $\frac{1}{x} = 0, \frac{1}{y} = -1, \frac{1}{z} = 0$
3. No fractions to clear
4. $(0\,\bar{1}\,0)$



1. $x = \frac{1}{2}, y = 1, z = \infty$
2. $\frac{1}{x} = 2, \frac{1}{y} = 1, \frac{1}{z} = 0$
3. No fraction
4. $(2\ 1\ 0)$

- Following are some important aspects of the Miller indices for planes.
  - Planes and their negatives are identical; (0 1 0) = (0 1 0) unlike the case of directions. By Changing the signs of all the indices of a plane, we obtain a Plane located at the same distance on the other side of the origin.
  - Planes and their multiples are not identical (unlike the case of directions)
  - The planes defined by Miller indices obtained by changing the order and sign of indices represent a family of planes. This group of similar planes are denoted with curly brackets. Eg., The family {1 1 0 } in cubic system.
  - In cubic system, a plane and a direction having the same indices are perpendicular to each other. Hence the direction [110] is perpendicular to the plane (1 1 0), in a cubic unit cell.
  - Parallel planes have the same Miller indices. Distance between two adjacent parallel planes with same Miller index (hkl) is called interplanar spacing. Interplanar spacing in cubic crystals is given by

$$\mathrm{d} = \frac{a}{\sqrt{h^2 + k^2 + l^2}}$$

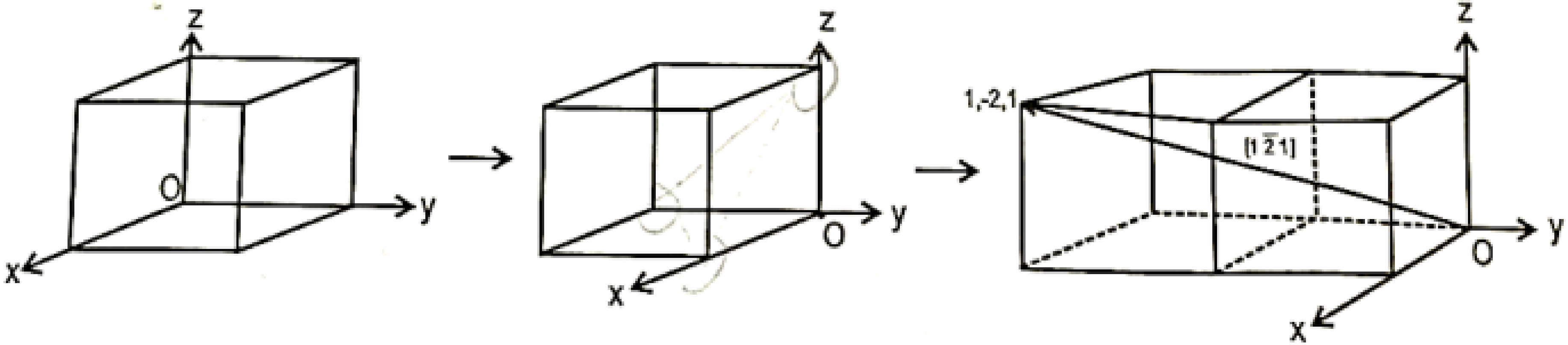
EXAMPLE 1.6

Draw the $[1\bar{2}1]$ direction and the plane $(\bar{2}01)$ in a cubic unit cell.

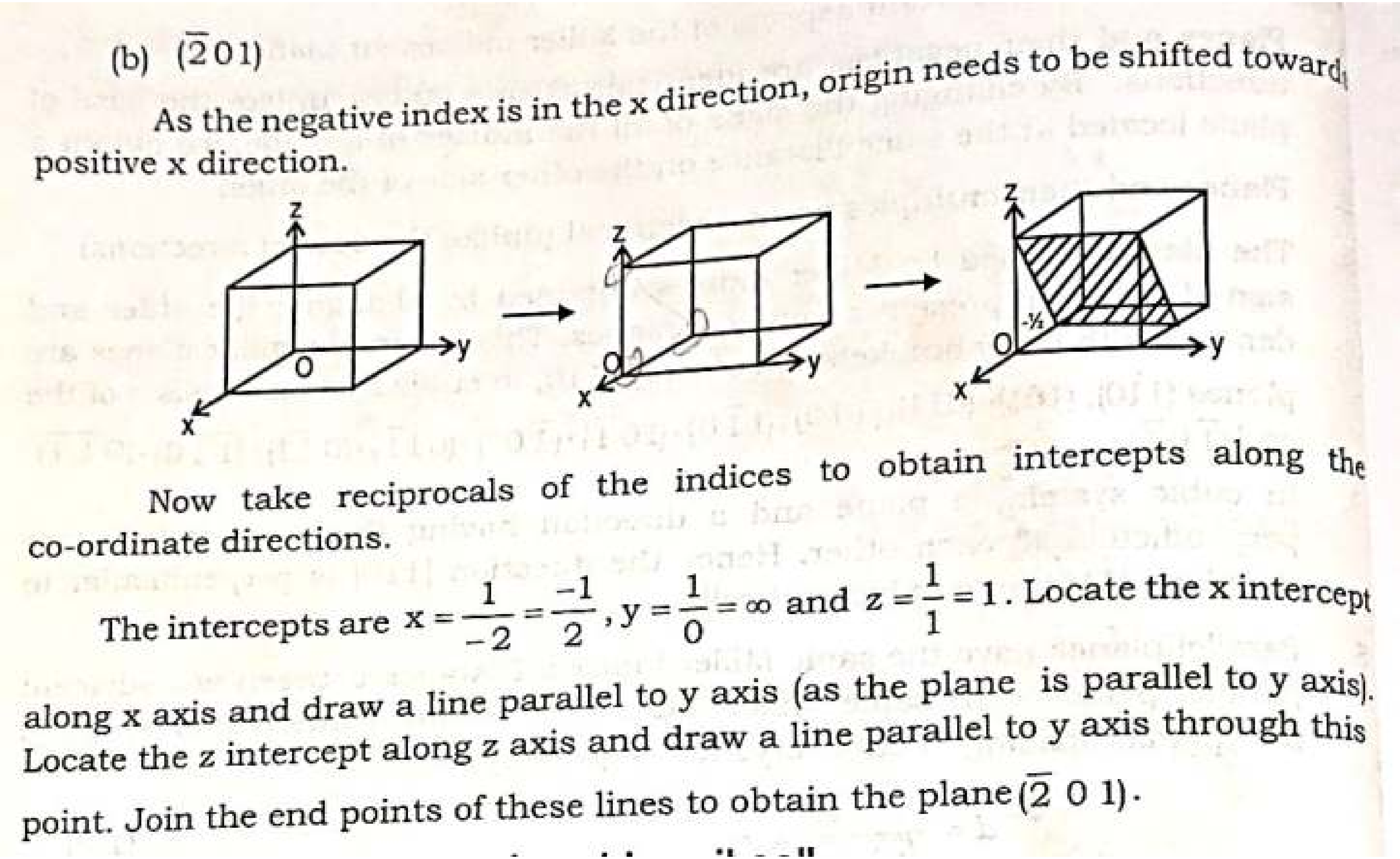
Solution.

(a) $[1\bar{2}1]$

Since a negative index is involved, the origin needs to be shifted towards the positive y-direction.



Locate the 'tail' of direction at the origin, and move +1 in x direction, -2 in y- direction and +1 in z-direction to obtain the other point. Join these points to represent $[1\bar{2}1]$ direction.



(b) $(\bar{2}01)$

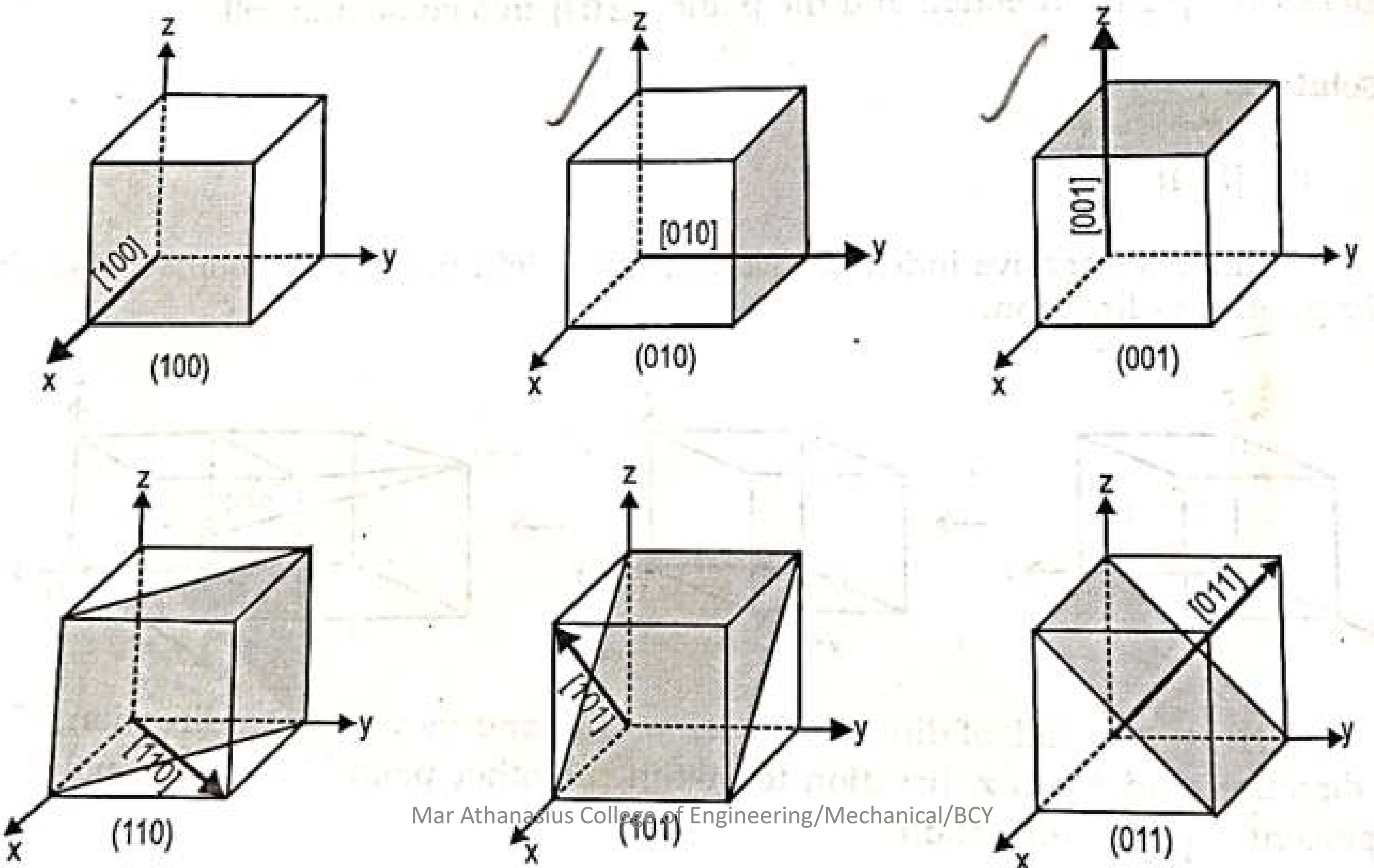
As the negative index is in the x direction, origin needs to be shifted towards positive x direction.

Now take reciprocals of the indices to obtain intercepts along the co-ordinate directions.

The intercepts are $x = \frac{1}{-2} = \frac{-1}{2}$, $y = \frac{1}{0} = \infty$ and $z = \frac{1}{1} = 1$. Locate the x intercept along x axis and draw a line parallel to y axis (as the plane is parallel to y axis). Locate the z intercept along z axis and draw a line parallel to y axis through this point. Join the end points of these lines to obtain the plane $(\bar{2}\ 0\ 1)$.

1.5.2 Directions and planes in cubic unit cell

The cube edges in the unit cell are represented by the family of directions <100>, the face diagonals by <110> and the body diagonals by <111>. Faces of the cube are denoted by {100}. Figure 1.20 shows the important planes and directions in a cubic unit cell. The thick lines with arrows indicate the directions.



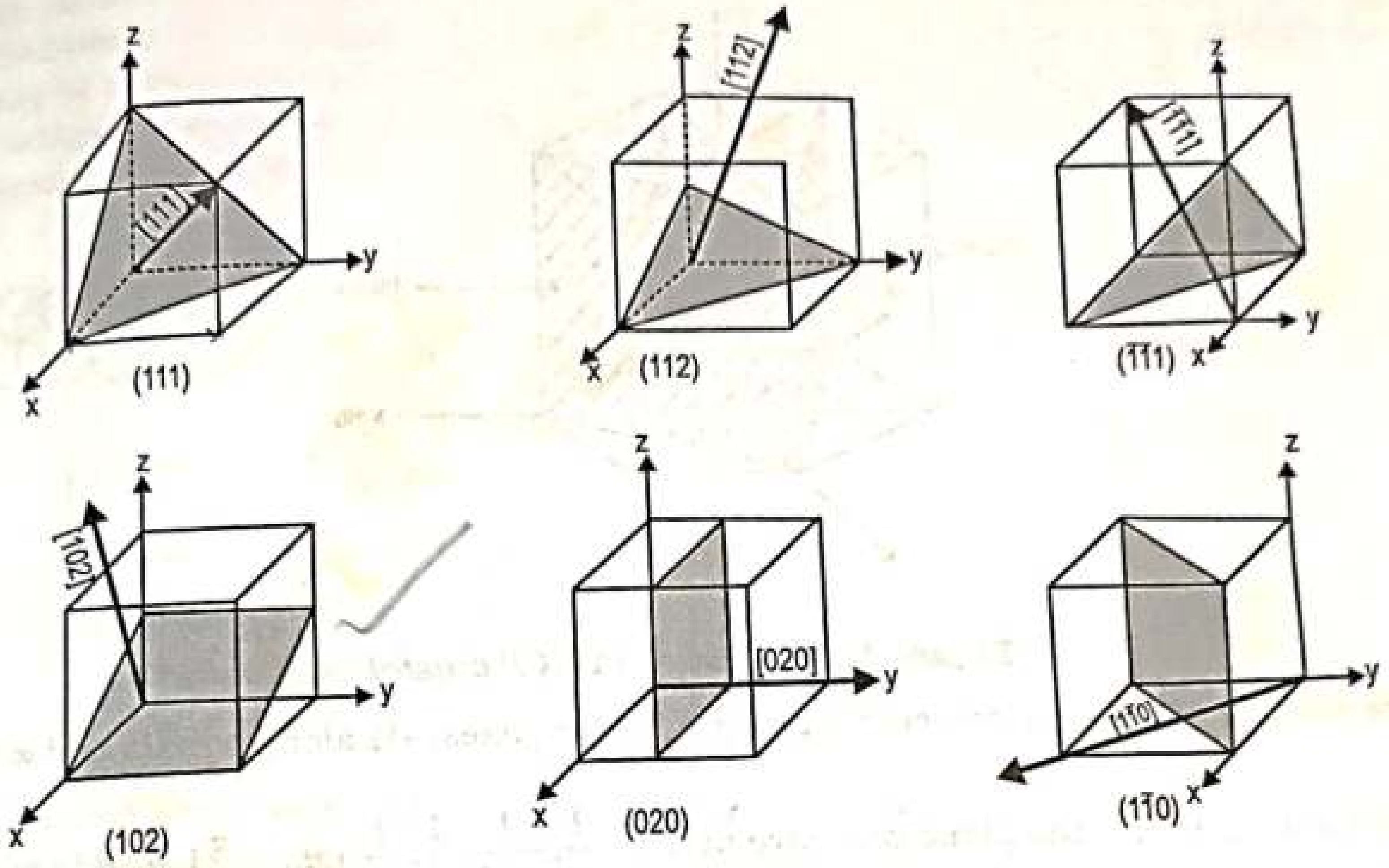


Figure 1.20 *Important planes and directions in a cubic unit cell*

Atomic Arrangements

- The atomic arrangement for a crystallographic plane, which is often of interest, depends on the crystal structure.
- The (110) atomic planes for FCC and BCC crystal structures are represented in Figures, Note that the atomic packing is different for each case.

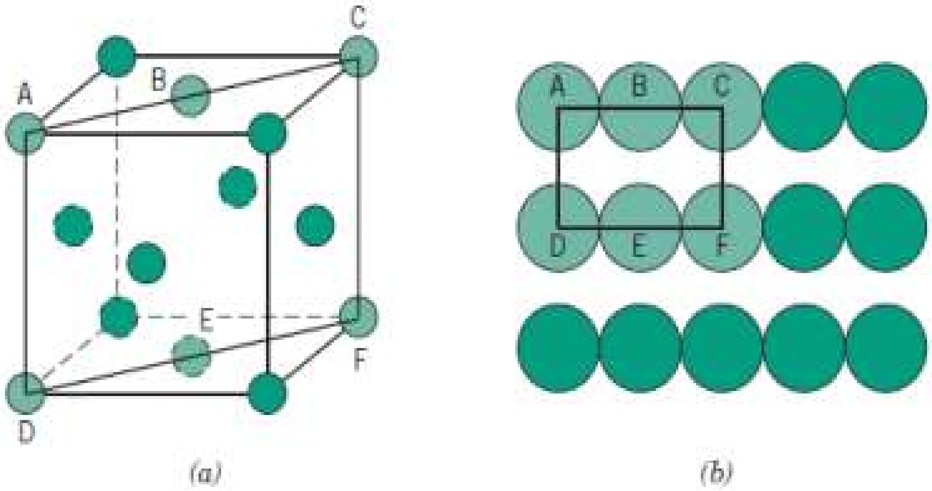


Figure 3.10 (*a*) Reduced-sphere FCC unit cell with (110) plane. (*b*) Atomic packing of an FCC (110) plane. Corresponding atom positions from (*a*) are indicated.

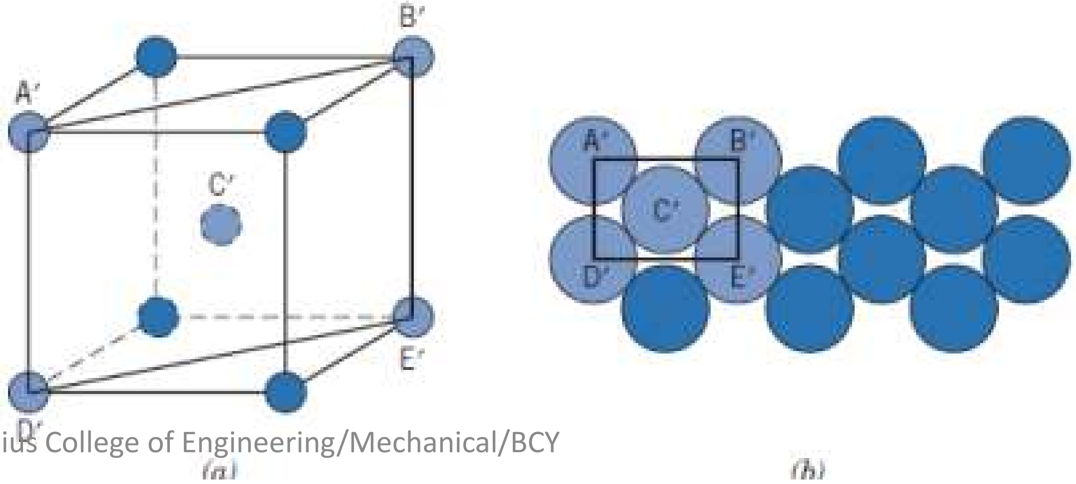


Figure 3.11 (*a*) Reduced-sphere BCC unit cell with (110) plane. (*b*) Atomic packing of a BCC (110) plane. Corresponding atom positions from (*a*) are indicated.

- A “family” of planes contains all those planes that are crystallographically equivalent—that is, having the same atomic packing.

LINEAR AND PLANAR DENSITIES

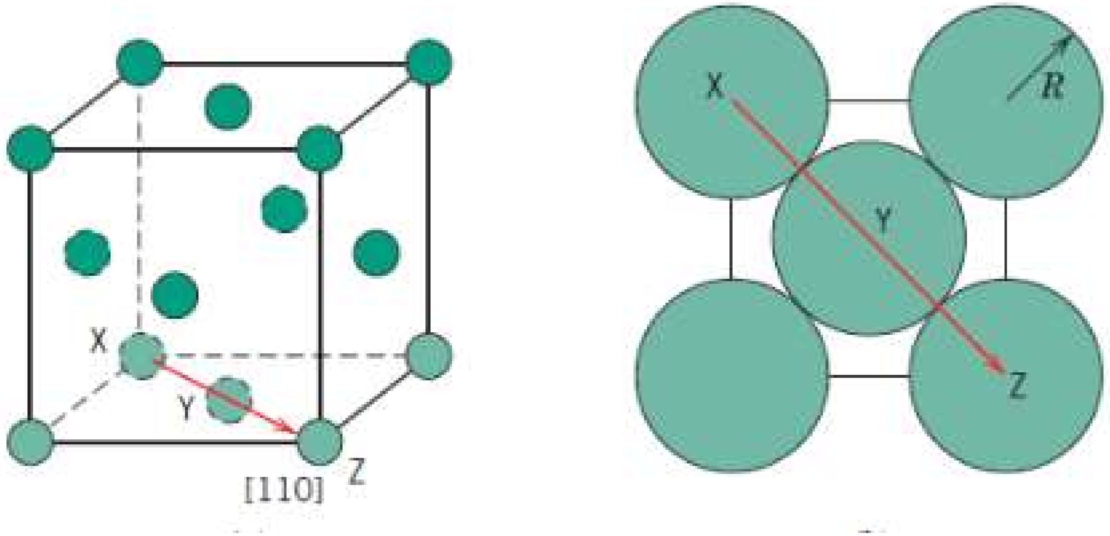
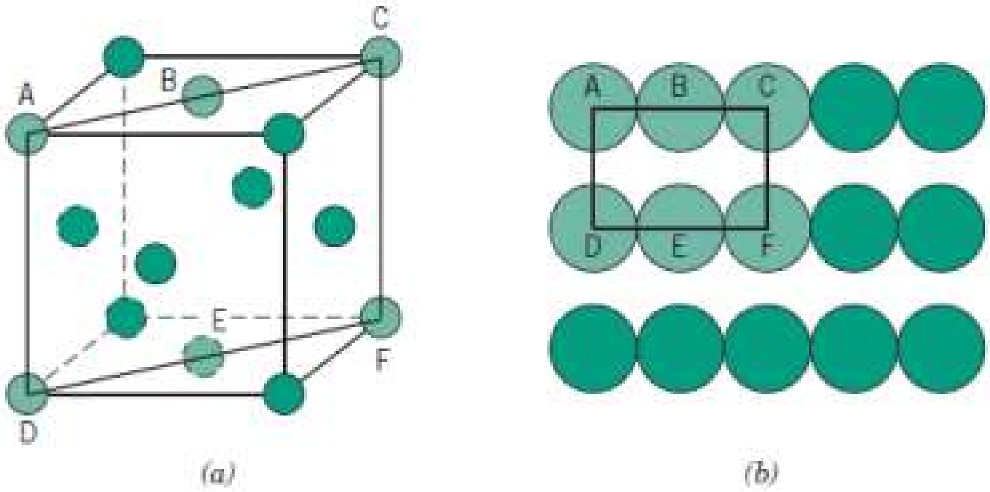


Figure 3.12 (*a*) Reduced-sphere FCC unit cell with the [110] direction indicated. (*b*) The bottom face-plane of the FCC unit cell in (*a*) on which is shown the atomic spacing in the [110] direction, through atoms labeled X, Y, and Z.

$$\mathrm{LD}_{110} = \frac{2\ \text{atoms}}{4R} = \frac{1}{2R}$$

In an analogous manner, planar density (PD) is taken as the number of atoms per unit area that are centered on a particular crystallographic plane, or

$$\mathrm{PD} = \frac{\text{number of atoms centered on a plane}}{\text{area of plane}}$$



(a) (b)

Figure 3.10 (*a*) Reduced-sphere FCC unit cell with (110) plane. (*b*) Atomic packing of an FCC (110) plane. Corresponding atom positions from (*a*) are indicated.

$$\mathrm{PD}_{110} = \frac{2\ \text{atoms}}{8R^2\sqrt{2}} = \frac{1}{4R^2\sqrt{2}}$$

Deformation in Metals

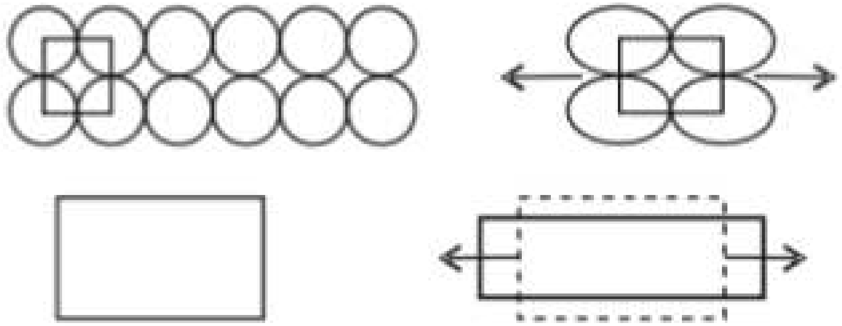
- When a material is subjected to an external force or load, the material suffers a change in shape, which is called deformation.
- If the deformation is temporary, (if the deformation disappears on removal of the load) it is elastic deformation
- if permanent, (if the deformation persists even after removal of the load), it is called plastic deformation.
- Both deformations take place due to adjustments or displacement in atomic arrangement within the crystal.
- The mechanical behavior of a material reflects the relationship between its response or deformation to an applied load or force.
- Factors to be considered, while evaluating the properties are nature of the applied load and its duration, as well as the environmental conditions.

Elastic Deformation

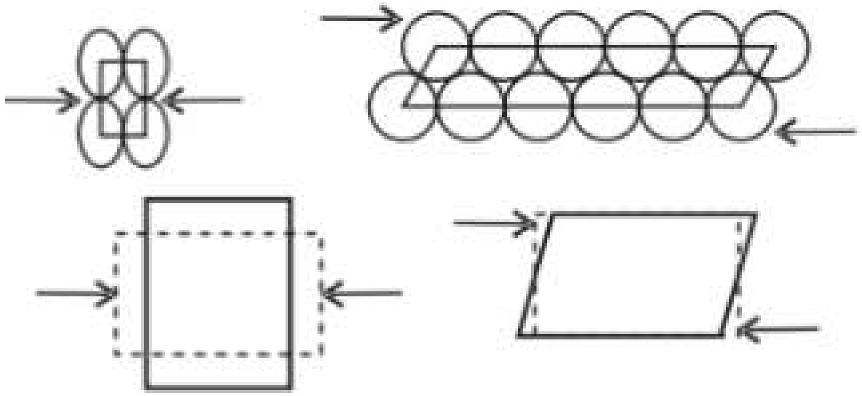
- When a solid material is subjected to an applied force, the atoms within the crystal are displaced from their normal positions of equilibrium.

- Thus, when a solid bar is loaded axially in tension, it becomes slightly longer. If, on removal of the load, the bar returns to its original dimensions, the deformation is elastic in nature.

- This is because the displacement of the atoms is by relatively small amounts and the removal of the applied load allows the atoms to return to their normal equilibrium positions. Thus the elastic deformation is reversible.

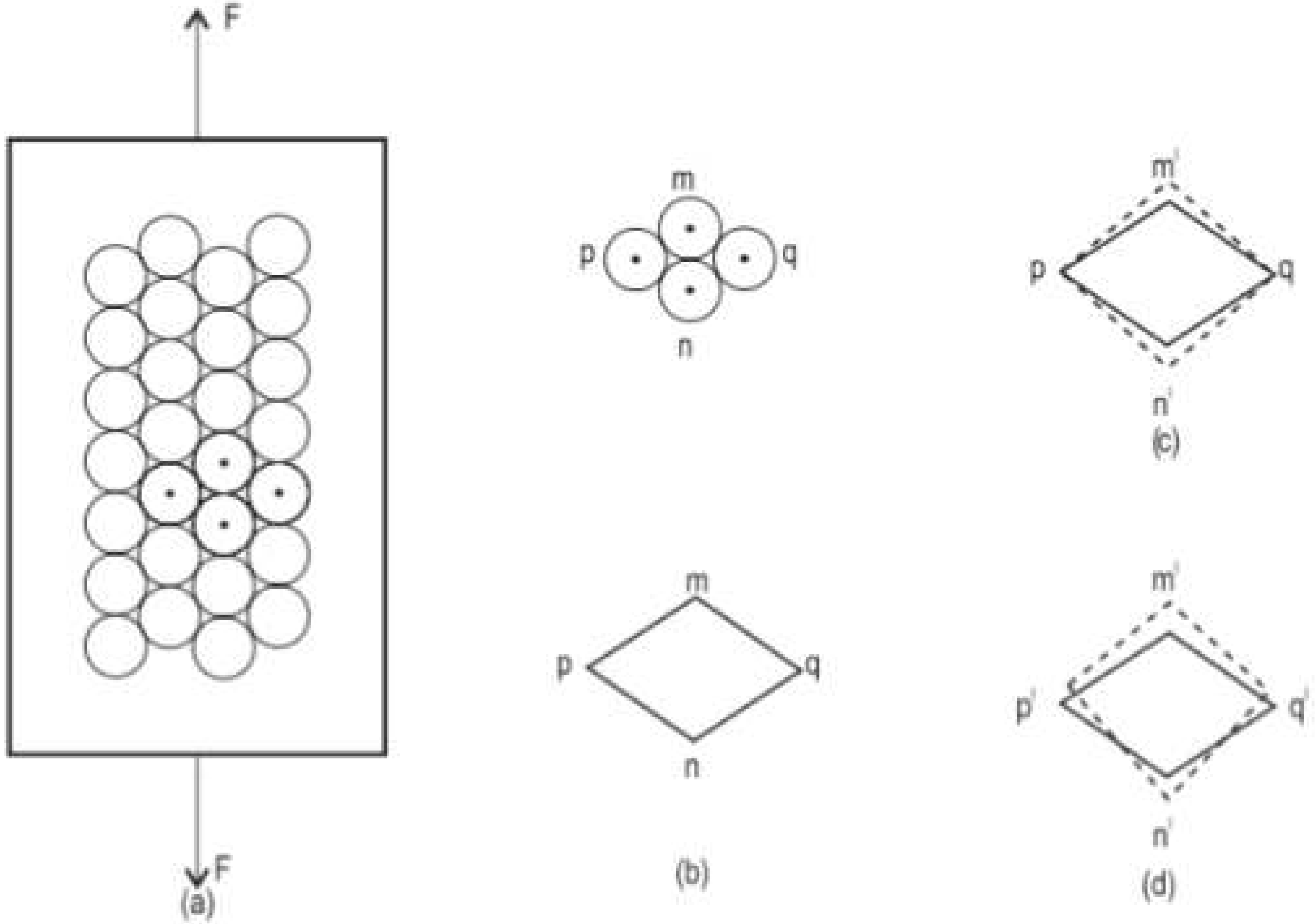


a) Before Loading   b) Under Tension



c) Under Compression   d) Under shear

Elastic Deformation



a) Bar subjected to an external load
b) Four neighbouring atoms
c) Elongation assuming pq fixed
d) Deformation assuming free atomic displacement

Plastic deformation

- Yielding involves the possibility that some of the atoms, under the distortion produced by the applied load, move to new equilibrium positions.
- Since the atoms form new bonds in their new positions, the material is not weakened and also there is no tendency for the atoms to return to their original positions.
- Thus the deformation is inelastic or irrecoverable. Such a deformation is permanent and known as plastic deformation. There are two common mechanisms of plastic deformation
  - (i) by slip and
  - (ii) by twinning.

Plastic deformation by slip

- Most metals are significantly weaker in shear than in tension or compression and hence yielding or plastic deformation occurs under the action of a shear force.

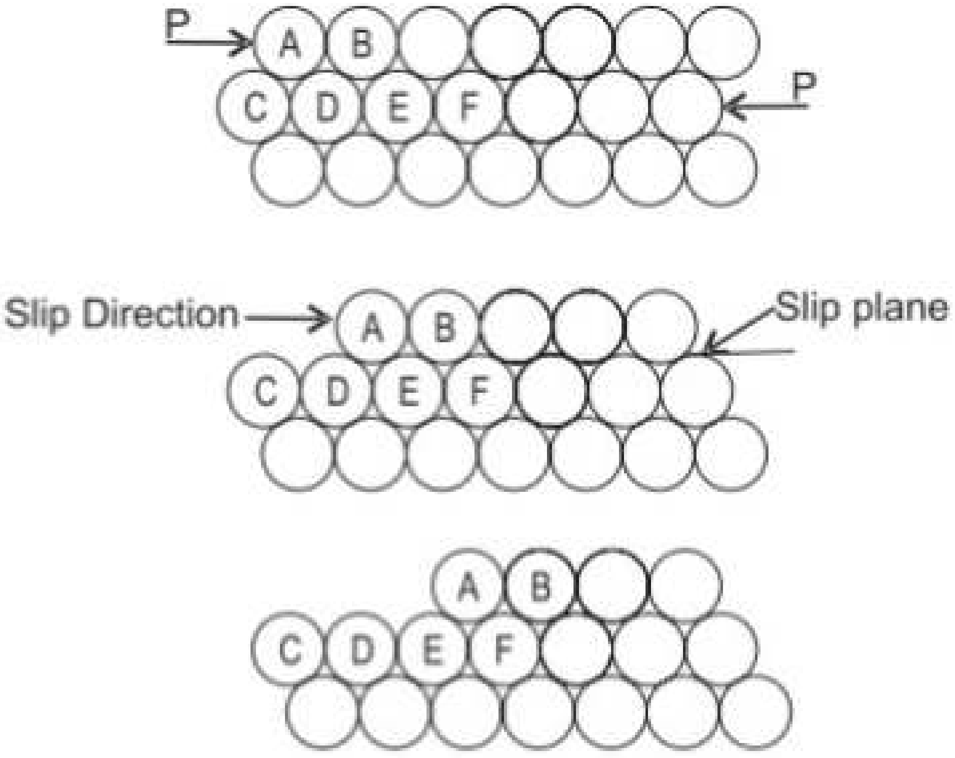


Figure 1.25 *Mechanism of slip*

Plastic deformation by slip

- Under the influence of a shear force, atoms move relative to each other on certain planes from one position of equilibrium to another position of equilibrium, causing a permanent deformation.
- Some atoms are said to have slipped past the other atoms on a certain plane in a certain direction. This process is called slip, the plane on which slip takes place is known as the slip plane and the direction along which the atoms move is known as the slip direction.
- Even when the material is subjected to a tensile or compressive load, it is the shear component that causes plastic deformation.
- Slip occurs more readily along certain crystal directions and planes within the crystal. A set of such favored plane and direction together is called a slip system.

Plastic deformation by slip

- For a particular crystal structure, the slip plane is the plane that has the most dense atomic packing—that is, has the greatest planar density.
- The slip direction corresponds to the direction, in this plane, that is most closely packed with atoms—that is, has the highest linear density.

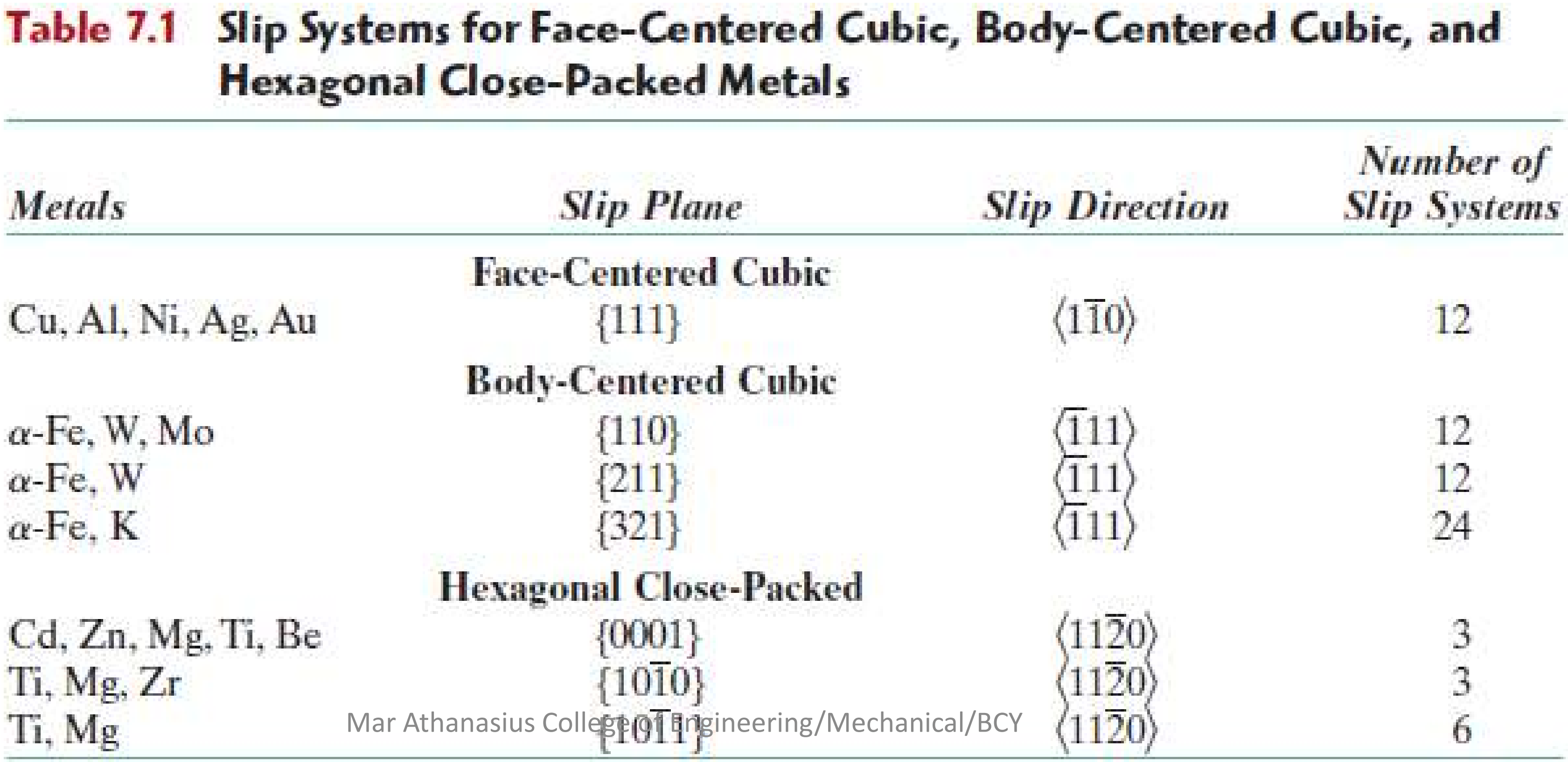


Table 7.1 Slip Systems for Face-Centered Cubic, Body-Centered Cubic, and Hexagonal Close-Packed Metals

Metals	*Slip Plane*	*Slip Direction*	*Number of Slip Systems*
	Face-Centered Cubic		
Cu, Al, Ni, Ag, Au	$\{111\}$	$\langle 1\bar{1}0\rangle$	12
	Body-Centered Cubic		
α-Fe, W, Mo	$\{110\}$	$\langle \bar{1}11\rangle$	12
α-Fe, W	$\{211\}$	$\langle \bar{1}11\rangle$	12
α-Fe, K	$\{321\}$	$\langle \bar{1}11\rangle$	24
	Hexagonal Close-Packed		
Cd, Zn, Mg, Ti, Be	$\{0001\}$	$\langle 11\bar{2}0\rangle$	3
Ti, Mg, Zr	$\{10\bar{1}0\}$	$\langle 11\bar{2}0\rangle$	3
Ti, Mg	$\{10\bar{1}1\}$	$\langle 11\bar{2}0\rangle$	6

Brittleness and Ductility

- When stressed, some materials are capable of undergoing extensive plastic deformation before breakage or rupture occurs. Such materials are said to be ductile.
- Some other materials break up abruptly with very little or no plastic deformation. Such materials are termed brittle.
- In crystalline materials dominant mode of plastic deformation is slip, which is dependent on the available number of slip systems within the crystal.
- Slip occurs easily on planes and in directions of maximum atomic density.
- In FCC crystals the {111} planes and <110> directions have maximum atomic density and there are 12 easy slip systems available in FCC crystals. These slip systems are well distributed in space and therefore it is possible to have at least one slip system oriented in a favorable position for slip to take place. Hence, slip and thereby plastic deformation is initiated easily in FCC crystals. Materials having FCC structure are therefore ductile in nature.

Brittleness and Ductility

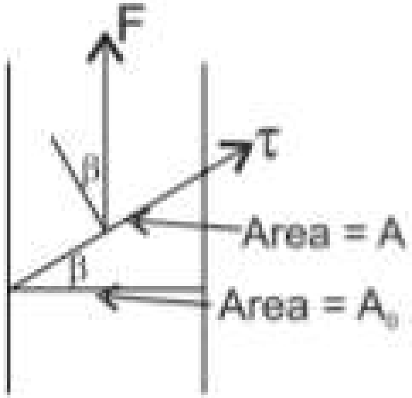
- BCC crystals also have 12 easy slip systems with the {110} planes and <111> directions. However, the {110} planes of BCC have lesser atomic density compared to the {111} planes of FCC. Therefore, the stress required to cause unit atomic displacement will be more in BCC crystals. So BCC materials are less plastic (or less ductile) compared to FCC.

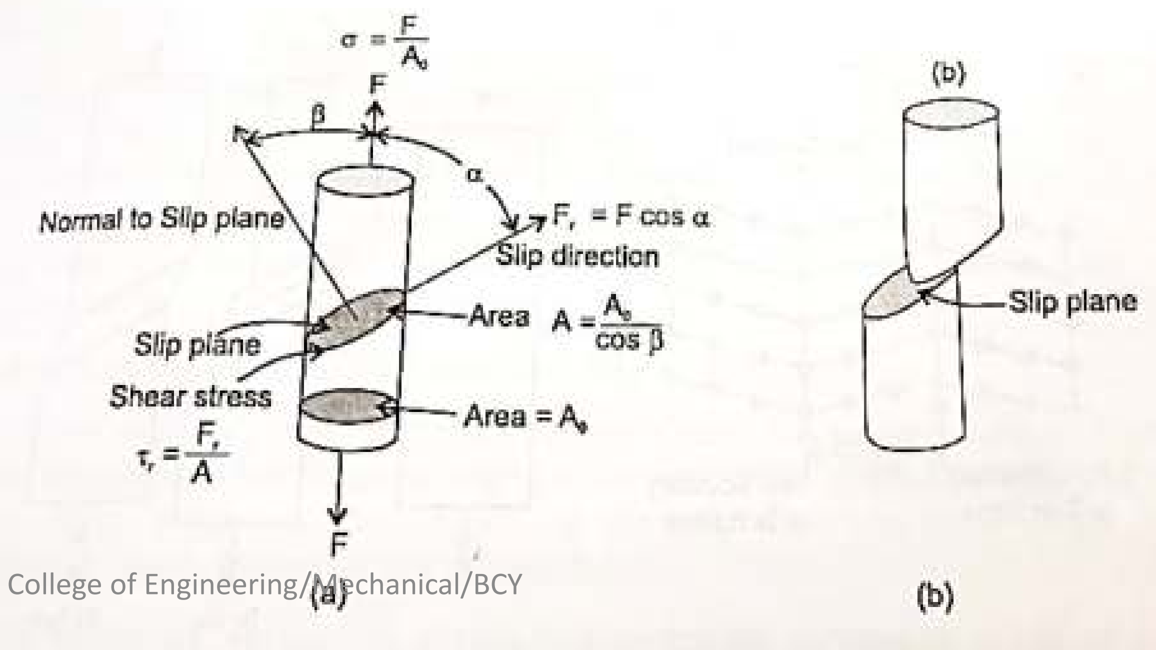
- In HCP crystals, the planes having maximum atomic density are the basal planes {0001} and the directions <1120>. Only 3 common slip systems are available in HCP. Having only a few active slip systems, HCP materials are normally brittle.

Resolved Shear Stress and Critical Resolved Shear Stress (Schmid's Law)

- Consider a single crystal cylindrical bar as shown in to which an axial load F is applied.
- Let the angle between slip direction and applied force be α , inclination of the normal to slip plane with the applied force be β.
- For the dislocation to move along its slip system, a shear force acting along the slip direction must be produced by the applied force.

Shear force $F_r = F \cos \alpha$





- If the area of the cross section of the cylindrical bar is A0, then area of the slip plane is,

$$A = \frac{A_0}{\cos\beta}$$

Resolved shear stress along the slip direction can be written as

$$\tau_r = \frac{F_r}{A} = \frac{F\cos\alpha}{A_0 / \cos\beta} = \frac{F\cos\alpha\cos\beta}{A_0}$$

Since $\frac{F}{A_0} = \sigma$, the normal stress applied to the bar,

$$\tau_r = \sigma\cos\alpha\cos\beta$$

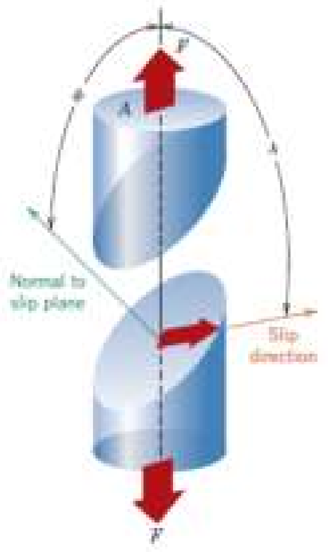


Figure 7.7 Geometrical relationships between the tensile axis, slip plane, and slip direction used in calculating the resolved shear stress for a single crystal.

- This equation is called Schmid's Law
- τ_r is called resolved shear stresses, and their magnitudes depend not only on the applied force, but also on the orientation of both the slip plane and direction within that plane.

- A metal single crystal has a number of different slip systems that are capable of operating. The resolved shear stress normally differs for each one because the orientation of each relative to the stress axis (β and α angles) also differs
- However, one slip system is generally oriented most favorably—that is, has the largest resolved shear stress,

$$\tau_r\ (\max) = \sigma\ (\cos\alpha\ \cos\beta\ )_{\max}$$

- In response to an applied tensile or compressive stress, slip in a single crystal commences on the most favorably oriented slip system when the resolved shear stress reaches some critical value, termed the **critical resolved shear stress** τ_{cr}; it represents the minimum shear stress required to initiate slip, and is a property of the material that determines when yielding occurs.
- The single crystal plastically deforms or yields when

Condition for yielding, $\tau_r\ (\max) = \tau_{cr}$

- And the magnitude of the applied stress required to initiate yielding (i.e., the yield strength σ_y)

$$\sigma_y = \frac{\tau_{crss}}{(\cos\phi\ \cos\lambda)_{\max}}$$

- The minimum stress necessary to introduce yielding occurs when a single crystal is oriented such that (β and α = 450 under these conditions,

$$\sigma_y = 2\,\tau_{cr}$$

- For a single-crystal specimen that is stressed in tension, deformation will be as in Figure, where slip occurs along a number of equivalent and most favorably oriented planes and directions at various positions along the specimen length.
- This slip deformation forms as small steps on the surface of the single crystal that are parallel to one another and loop around the circumference of the specimen.

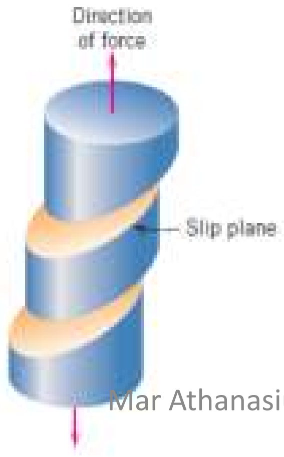


Figure 7.9 Slip in a zinc single crystal. (From C. F. Elam, *The Distortion of Metal Crystals*, Oxford University Press, London, 1935.)

Plastic deformation by twinning.

- In certain materials, when a shear stress is applied, planes of atoms in the lattice move parallel to a specific plane so that the lattice is divided into two symmetrical parts which are differently oriented. This phenomenon is known as twinning .
- Planes parallel to which atomic movement has taken place are known as twinning planes. The differently oriented region within the crystal and between the twinning planes is known as the twinned region.

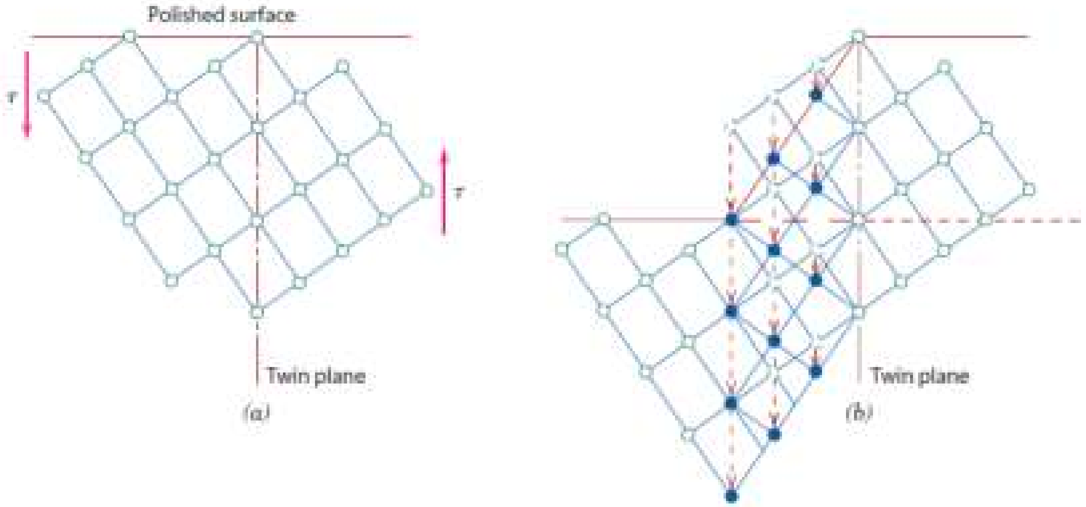
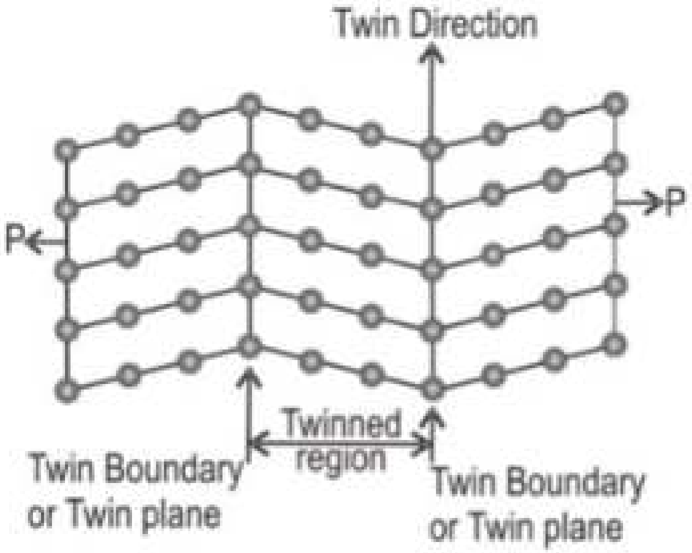


Figure 7.12 Schematic diagram showing how twinning results from an applied shear stress τ. In (b), open circles represent atoms that did not change position; dashed and solid circles represent original and final atom positions, respectively. (From G. E. Dieter,



Plastic deformation by twinning.

- Twinning is produced suddenly (within a few micro seconds) and is accompanied with sound. In both slip and twinning the lattice is sheared.
- In slip, the deformation or shear is uniformly distributed over a volume, rather than localized on a discrete number of slip planes.
- In contrast to slip, here the atoms move only a fraction of an interatomic distance relative to each other.
- The amount of movement of each plane of atoms in the twinned region is proportional to its distance from the twinning plane, so that a mirror image is formed across the twin plane.
- Twinning is not a significant deformation mechanism for cubic metals. However, it is a significant mode of deformation in HCP crystals.

Deformation by slip & twinning

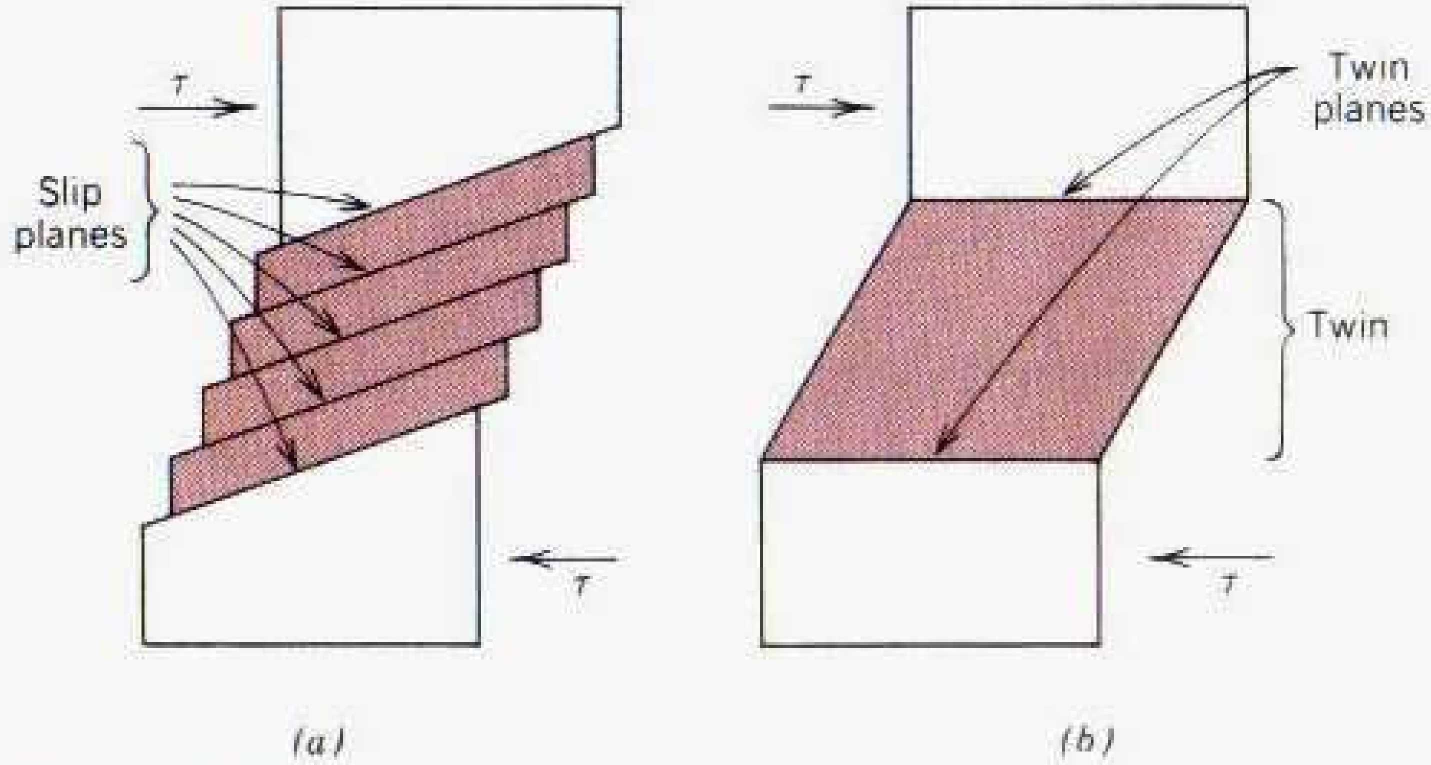
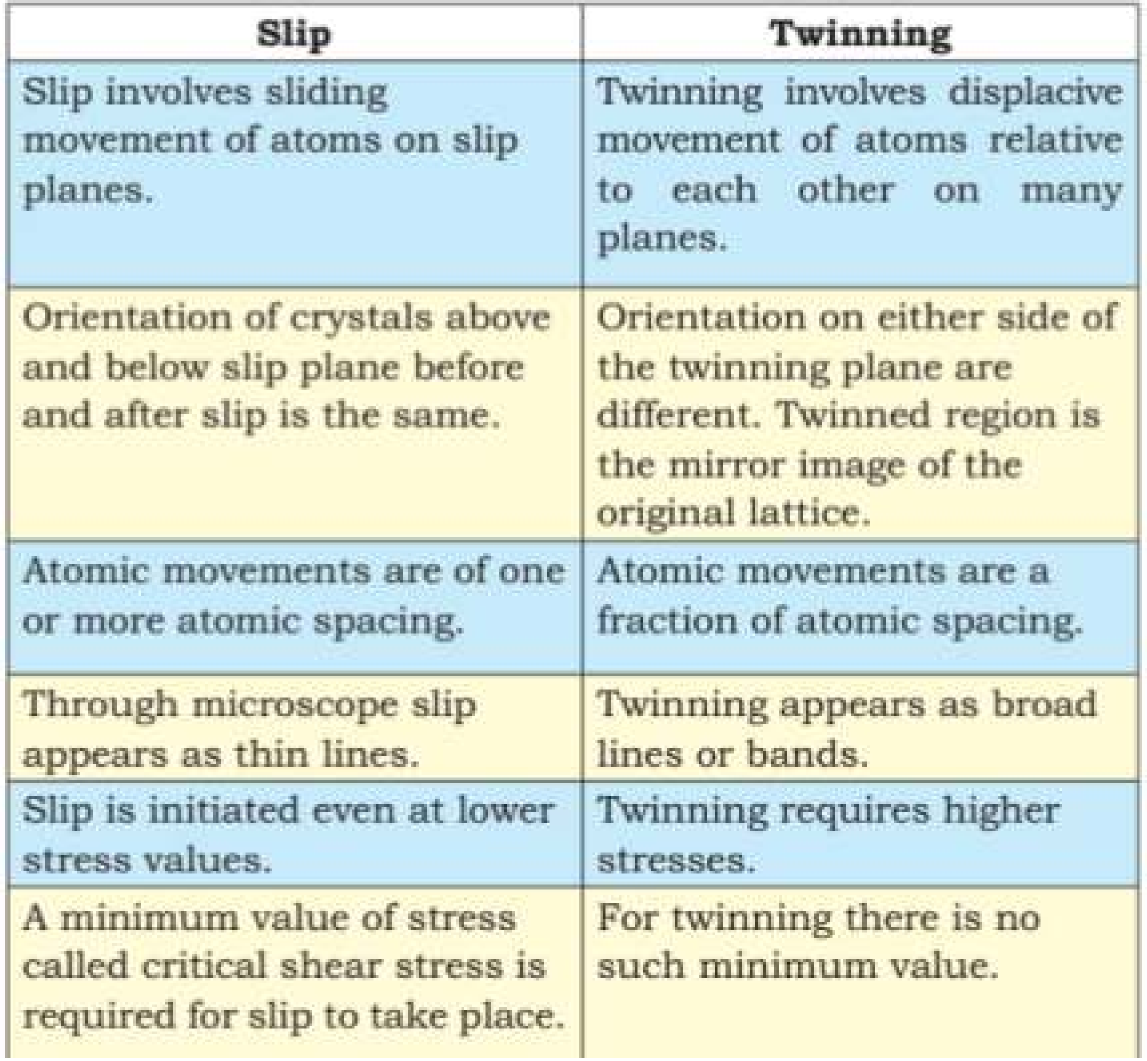
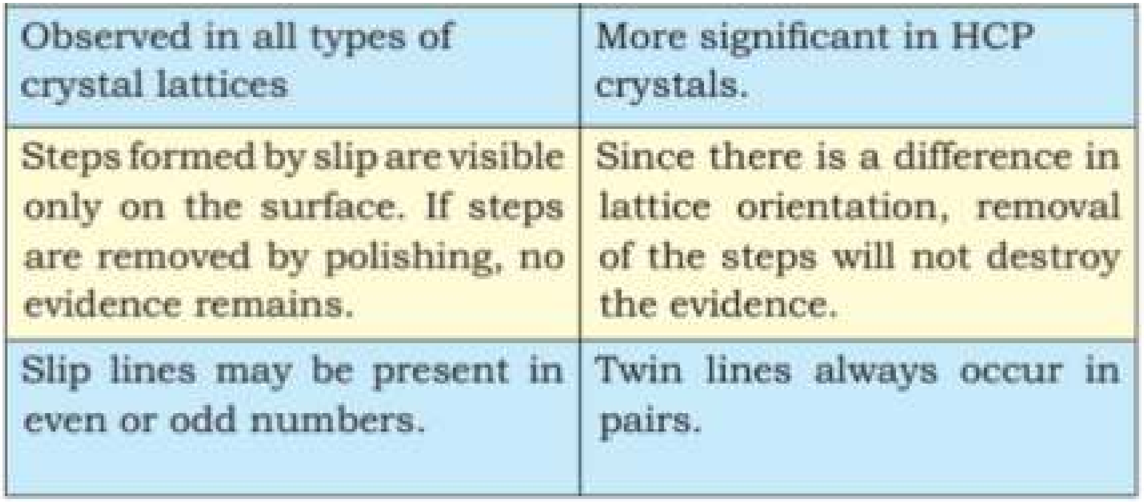


Figure 7.13 For a single crystal subjected to a shear stress τ, (*a*) deformation by slip; (*b*) deformation by twinning.

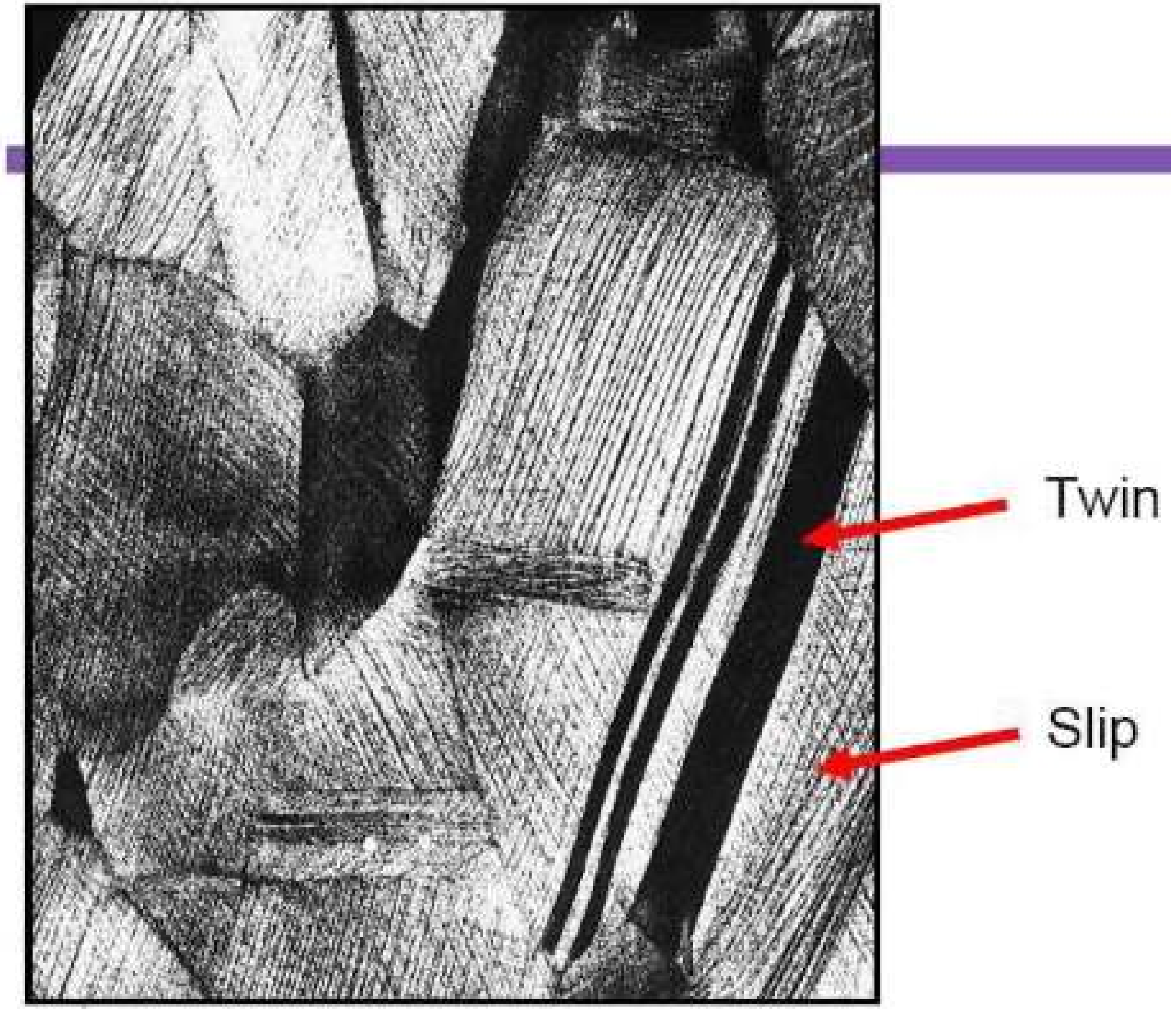
Table 1.6 *Comparison between slip and twinning*

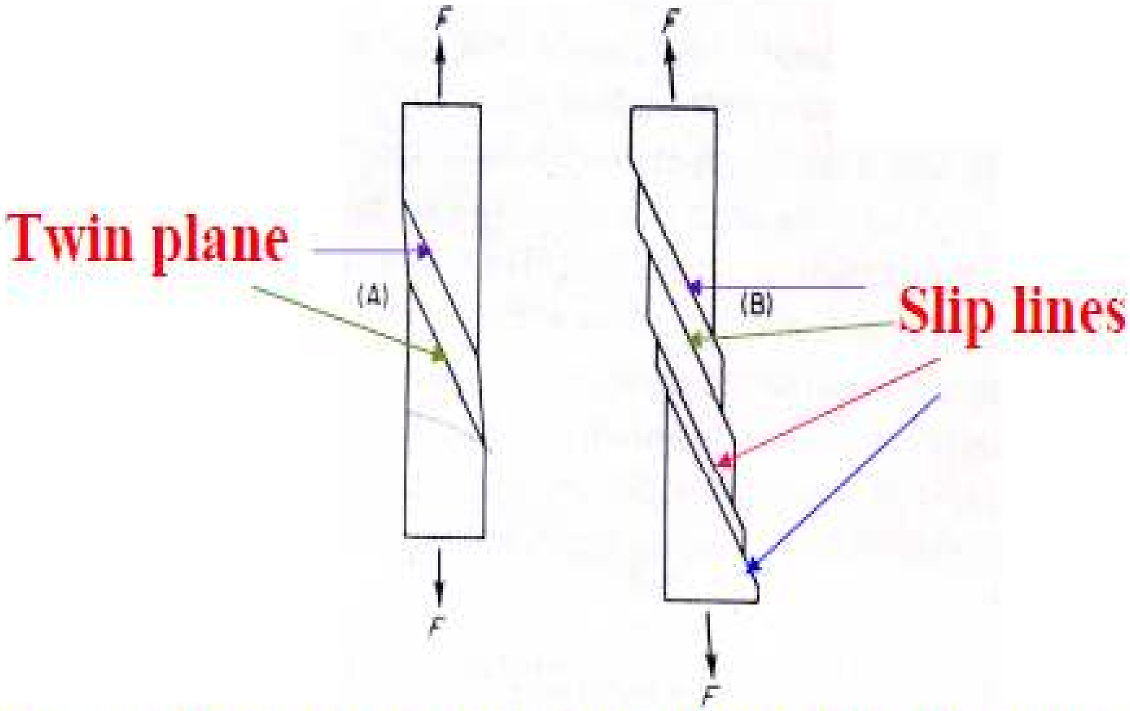




Slip	Twinning
Slip involves sliding movement of atoms on slip planes.	Twinning involves displacive movement of atoms relative to each other on many planes.
Orientation of crystals above and below slip plane before and after slip is the same.	Orientation on either side of the twinning plane are different. Twinned region is the mirror image of the original lattice.
Atomic movements are of one or more atomic spacing.	Atomic movements are a fraction of atomic spacing.
Through microscope slip appears as thin lines.	Twinning appears as broad lines or bands.
Slip is initiated even at lower stress values.	Twinning requires higher stresses.
A minimum value of stress called critical shear stress is required for slip to take place.	For twinning there is no such minimum value.
Observed in all types of crystal lattices	More significant in HCP crystals.
Steps formed by slip are visible only on the surface. If steps are removed by polishing, no evidence remains.	Since there is a difference in lattice orientation, removal of the steps will not destroy the evidence.
Slip lines may be present in even or odd numbers.	Twin lines always occur in pairs.

Slip & Twinning



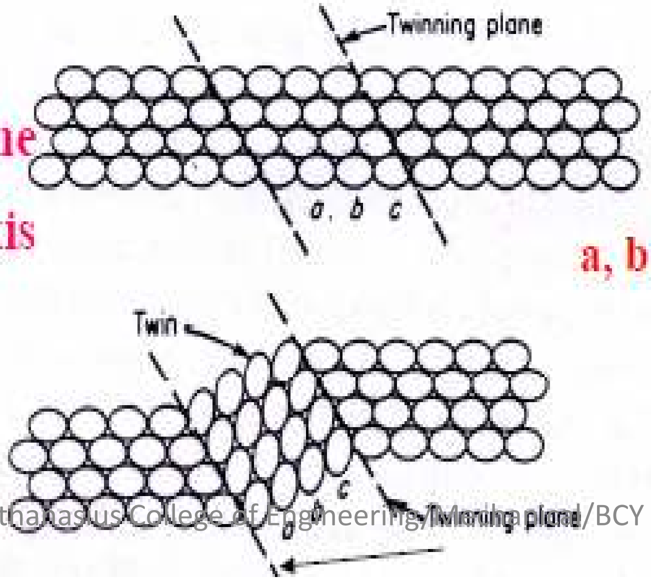


Twin plane

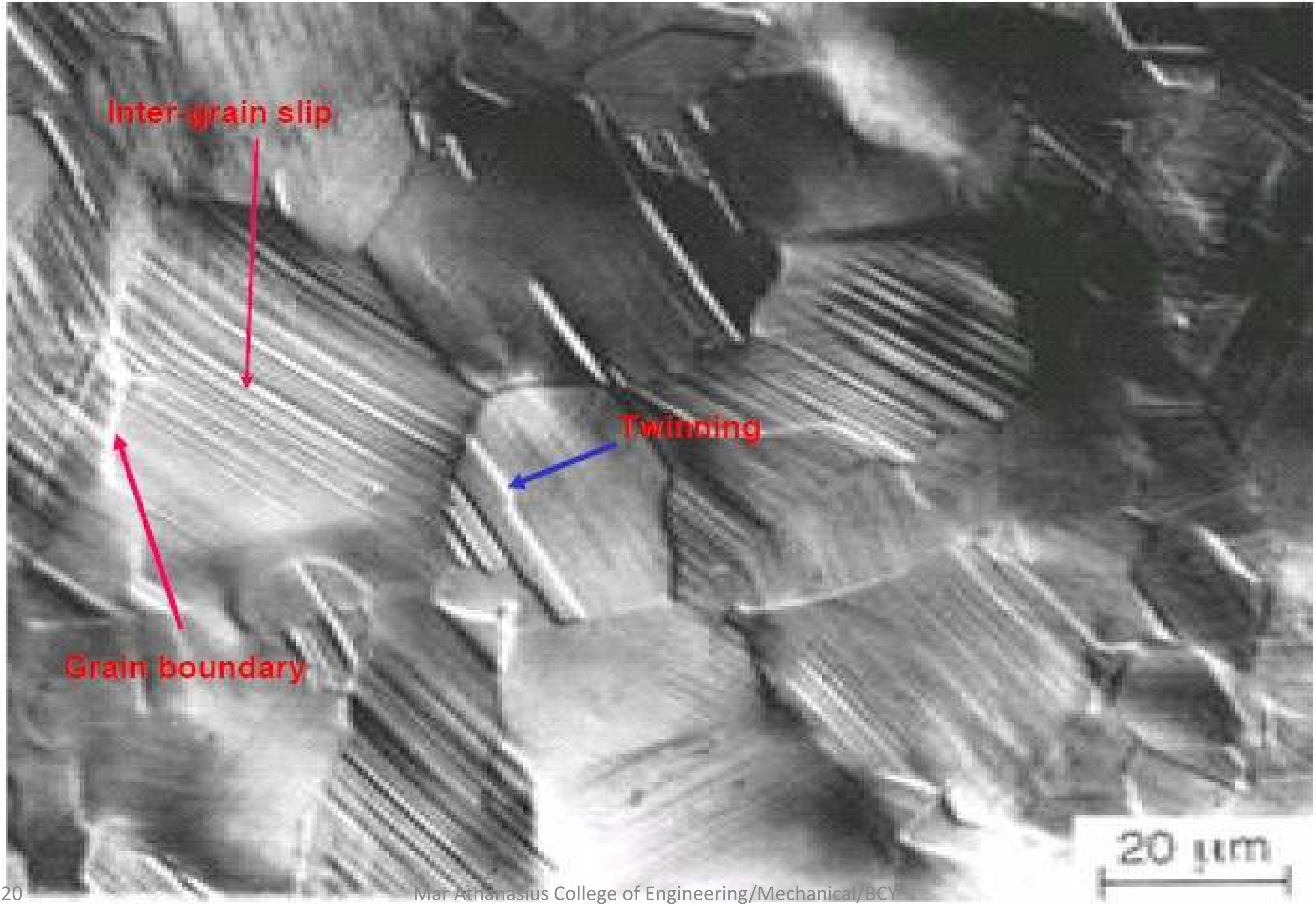
Slip lines

The difference between the shears associated with twinning (A), and slip (B)

The twin is formed by the rotation of each atoms in the deformed area about an axis through its center and perpendicular to the plane of the paper



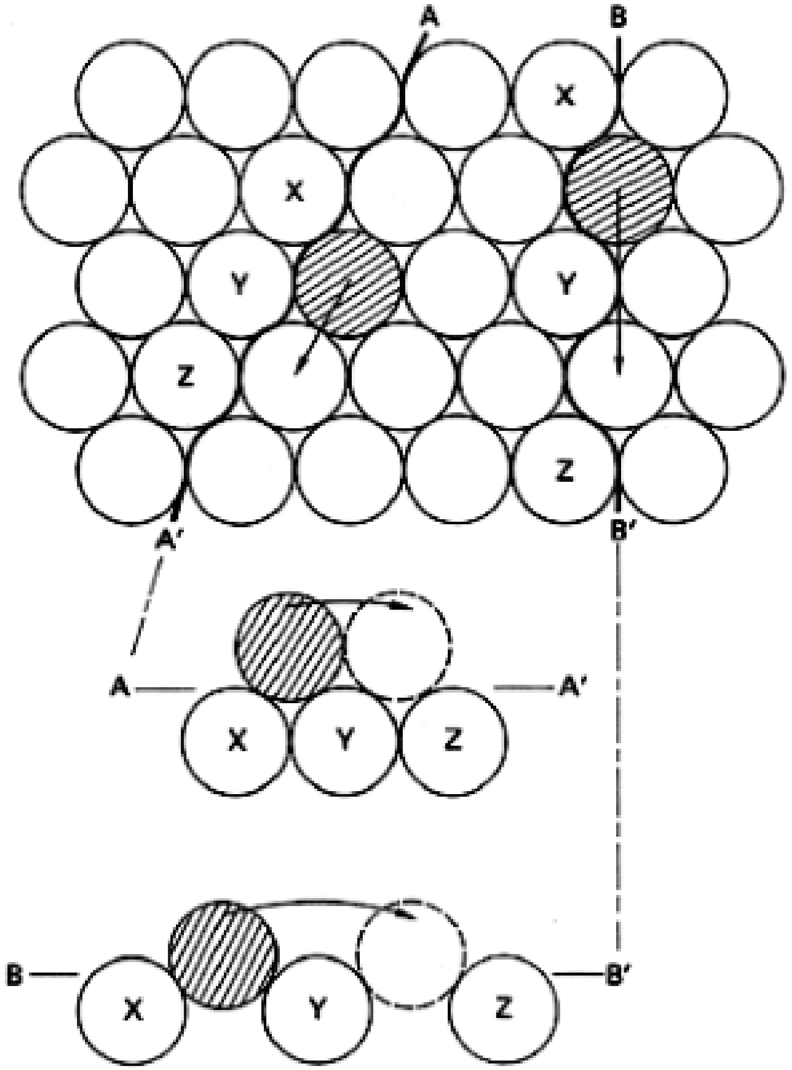
a, b, c – atoms


Inter-grain slip
Twinning
Grain boundary
20 μm

Slip systems

Along which direction (AA' or BB') will atoms move easier?

FCC {111}
close packed plane



Dislocations move along preferred **direction** in preferred **planes**!

MECHANISM OF CRYSTALLISATION

Solidification

- CASTING - One of the oldest manufacturing processes – **4000 B.C.** with stone and metal molds for casting **copper**

- Single crystal.
- Crystalline solids are composed of a collection of many small crystals known as **grains**. Such materials are termed polycrystalline.
- Grain structure and the defects develop during solidification of the liquid material.
- Solidification of pure metals, also known as **Crystallisation** is the transition from liquid state to solid state.
- **Crystallization is a** Phase Transformation process.
- The stages of Phase Transformation divided in to two,
  - Nucleation
    - Homogeneous nucleation
    - Heterogeneous nucleation
  - Growth

Mechanism of Crystallization

1. Nuclei formation
   - Nuclei – not center of an atom, is the center of few atoms together

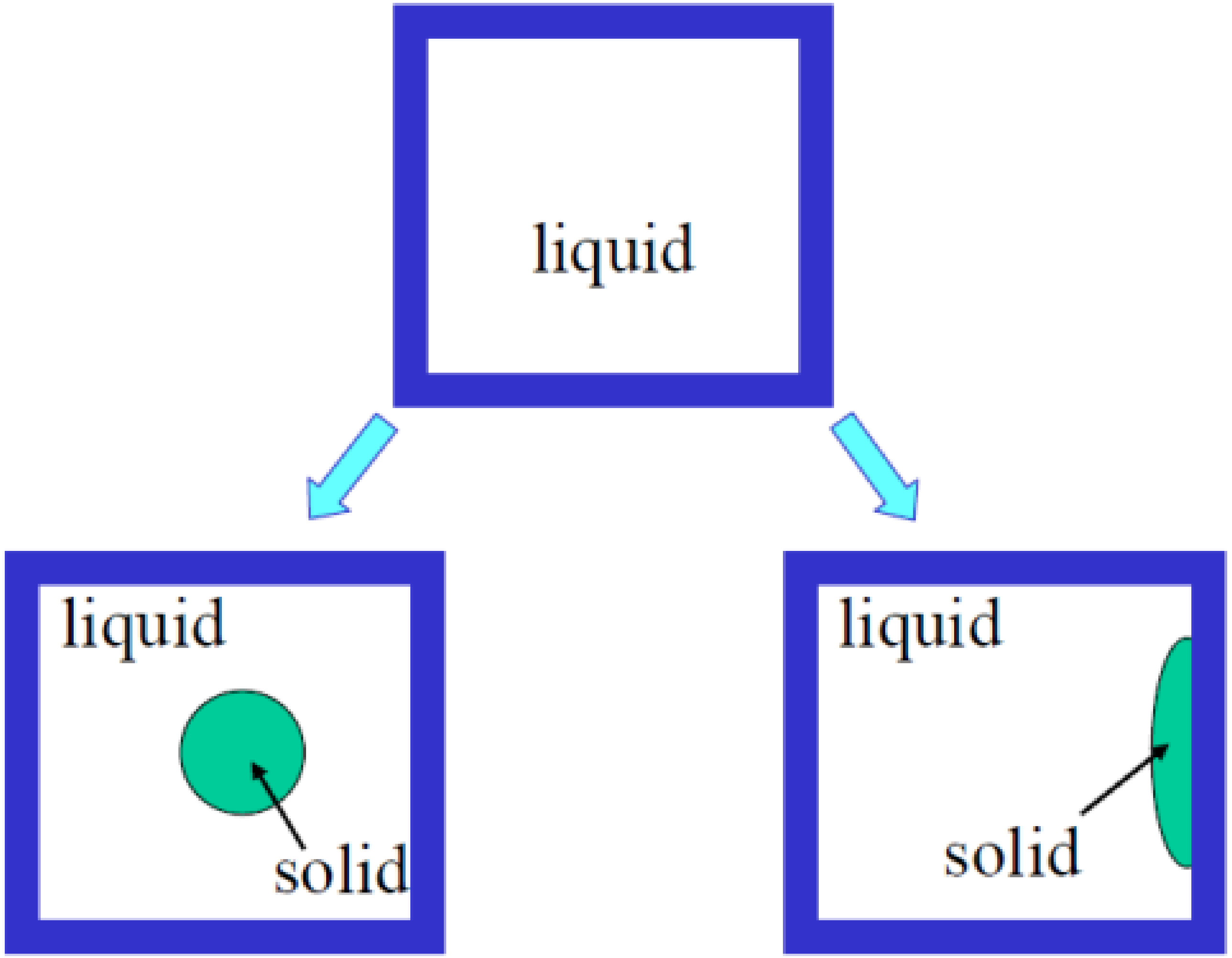
2. Crystal growth

- At freezing point B, K.E (L) = K.E. (S)
- = ∫ (TEMPERATURE)
- But P.E (L) ≠ P.E (S) = AVERAGE DISTANCE BETWEEN ATOMS

Ref:- Avner

Nucleation

- Two Type
    - Homogeneous nucleation
    - Heterogeneous nucleation
- Homogeneous nucleation
    - No preferred nucleation sites
    - Spontaneous
    - Random
- Heterogeneous nucleation
    - Those of preferred sites
    - Boundary, mould walls,
    - Surface, interface
    - Inclusion, impurity
    - Multiphase



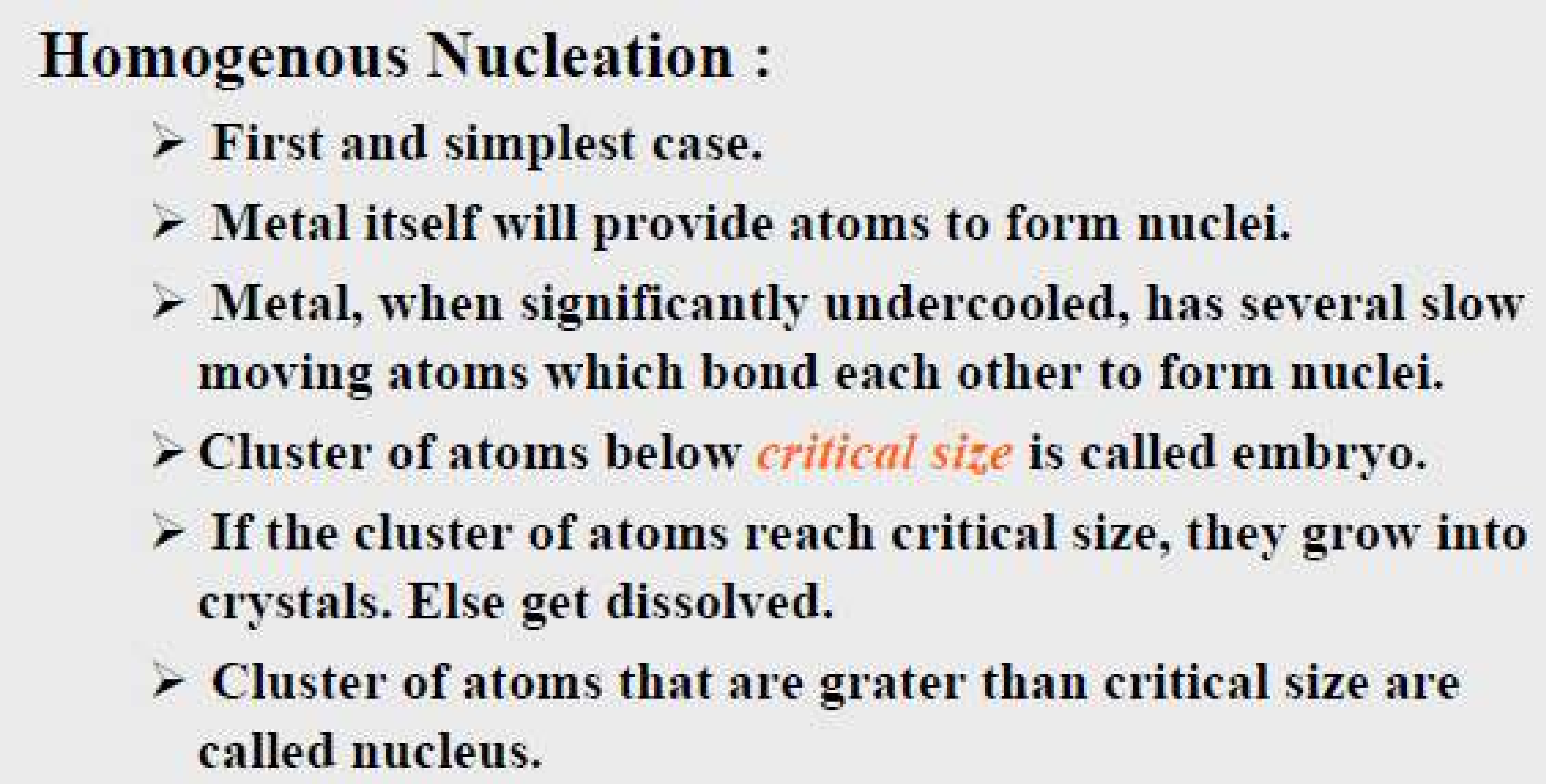
homogeneous nucleation

heterogeneous nucleation

Homogeneous nucleation

- In the liquid state, atoms of any material will be in constant motion due to their high **kinetic energy**
- The atoms do not have any definite arrangement in liquid state.
- When the temperature of the molten metal is brought down, it is possible that some atoms, at any given instant, may group together in positions exactly corresponding to the space lattice.
- These chance aggregates or groups are not permanent; but continually, break up and regroup at other points. How long they last is determined by the temperature and the size of the group.
- When the temperature of liquid is sufficiently decreased, the atomic movement also decreases. This lengthens the life of the group and also promotes the formation of more groups within the liquid. Such groups are known as embryos.

- As the temperature of the liquid metal drops, a stage is reached where the embryos (more like solid) and the surrounding liquid co-exist. This temperature is known as the solidification point or freezing point.
- At this point, both the liquid and solid states are at the same temperature and hence have the same kinetic energy for the respective atoms. But there is significant difference in the potential energy.
- The atoms in the solid are much closer together resulting in lowering of potential energy. Thus, solidification occurs with release of energy. The difference in potential energy between the liquid and solid states is known as latent heat (heat of fusion or heat of solidification).
- At the freezing point, energy is required to establish a surface between the solid and the liquid.
- In pure materials, at freezing point, insufficient energy is released by the heat of fusion to create a stable boundary surface. Hence some undercooling (super cooling) is necessary to form a stable solid region.

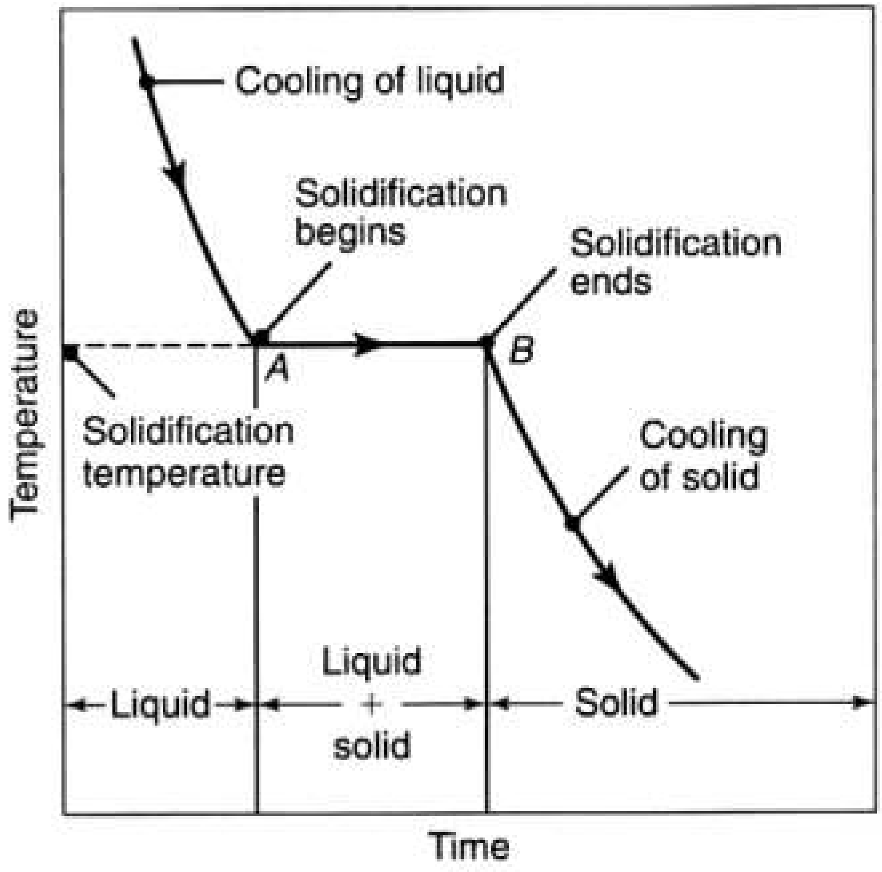


Homogenous Nucleation :

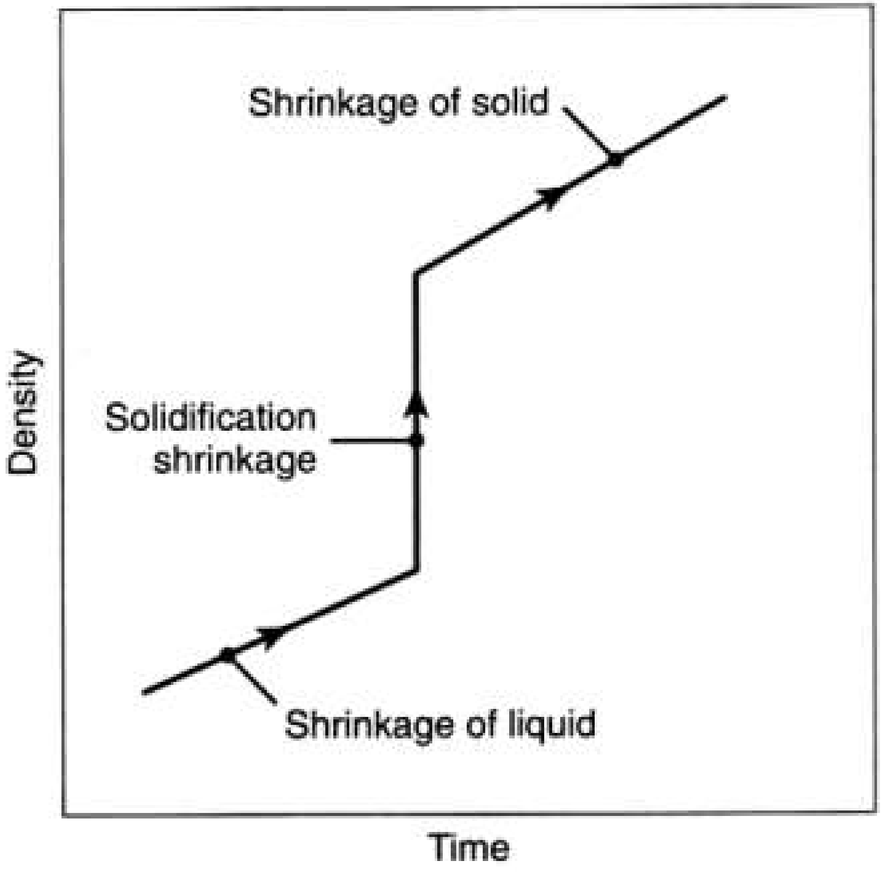
- First and simplest case.
- Metal itself will provide atoms to form nuclei.
- Metal, when significantly undercooled, has several slow moving atoms which bond each other to form nuclei.
- Cluster of atoms below *critical size* is called embryo.
- If the cluster of atoms reach critical size, they grow into crystals. Else get dissolved.
- Cluster of atoms that are grater than critical size are called nucleus.

Homogeneous nucleation: very pure metal, nuclei form **uniformly** throughout the parent phase; requires considerable **supercooling** (typically 80-300°C/ **0.2Tm).**

Solidification of Pure Metals

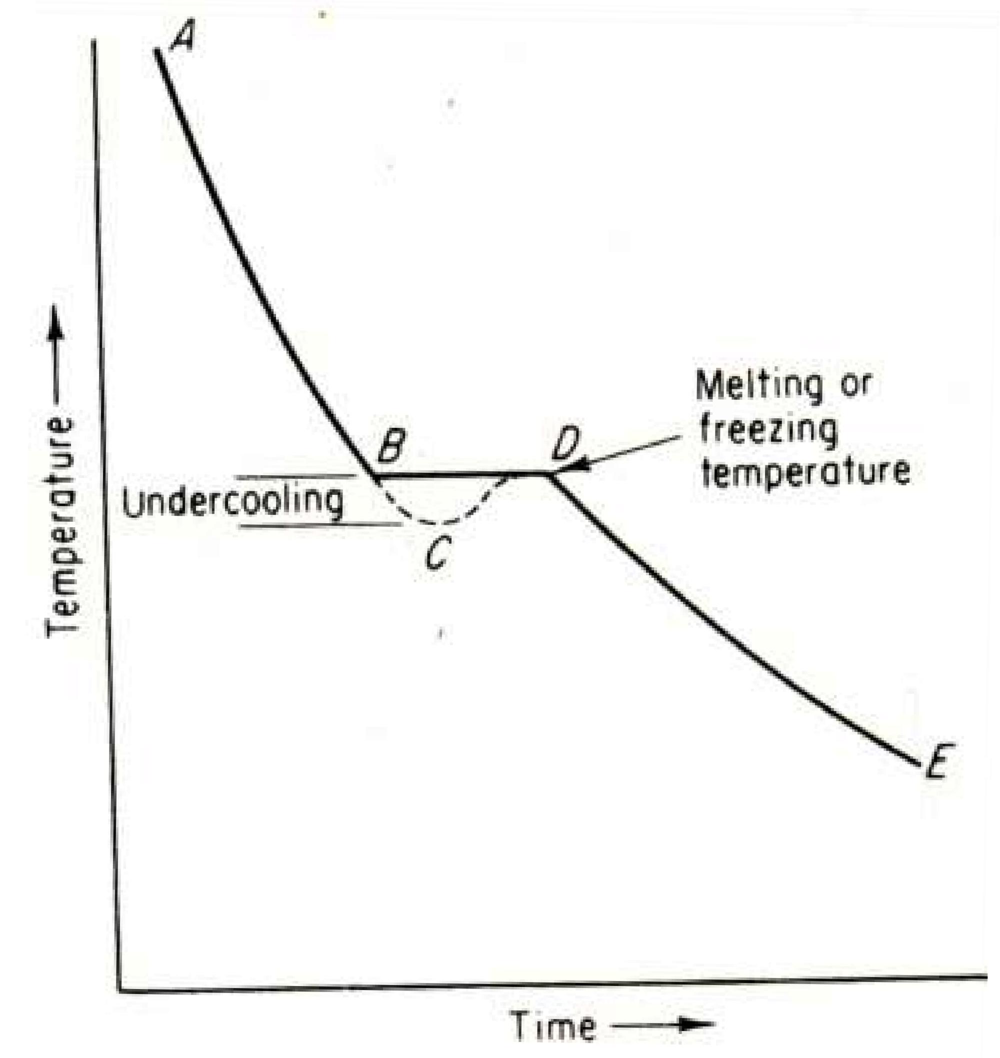


(a)



(b)

Pure metals solidify at a constant temperature. During freezing the latent heat of solidification is given off. Most metals shrink on solidification and shrink further (Ice) as the solid cools to room temperature.



Cooling curve for a pure metal; ABDE ideal, ABCDE actual.

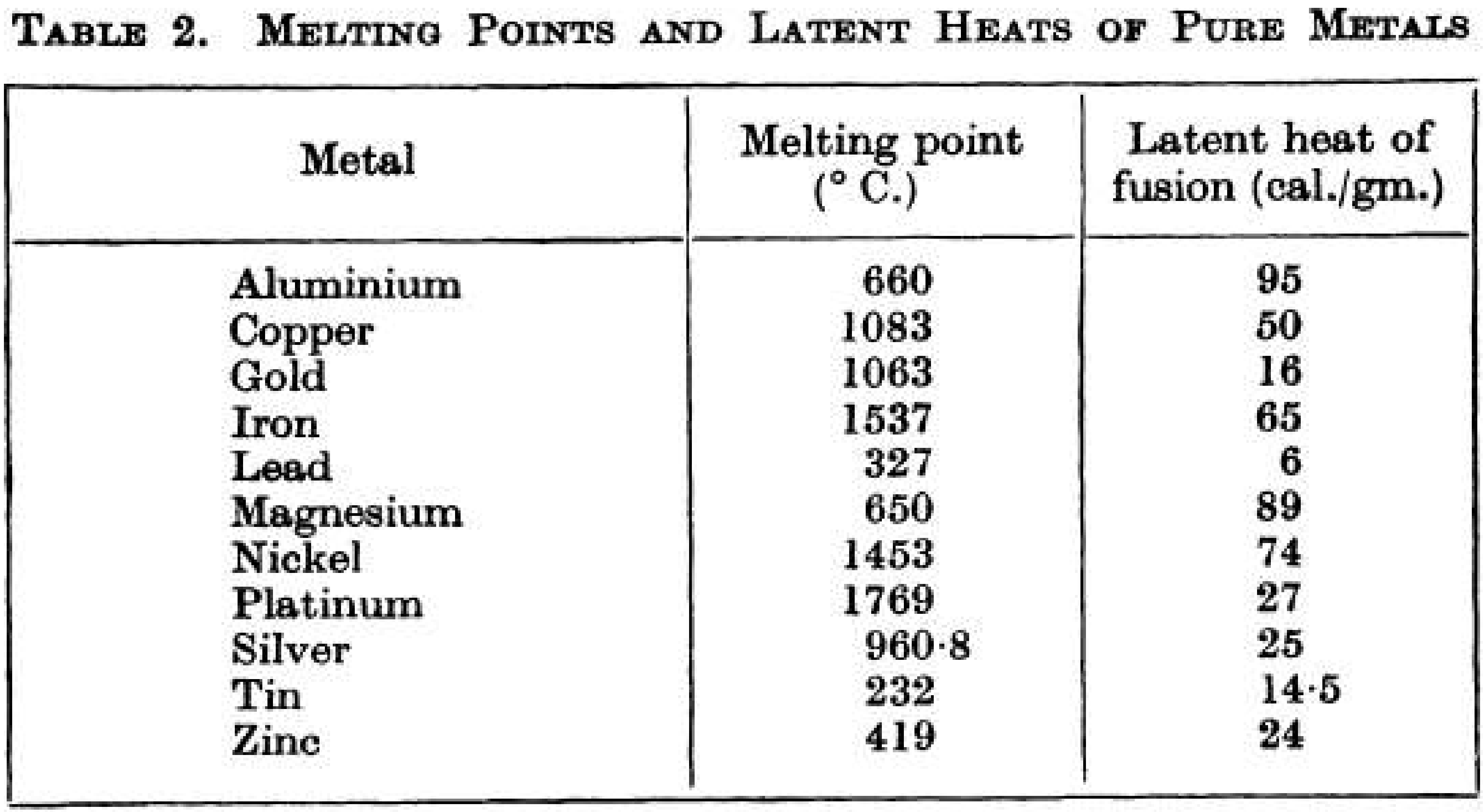
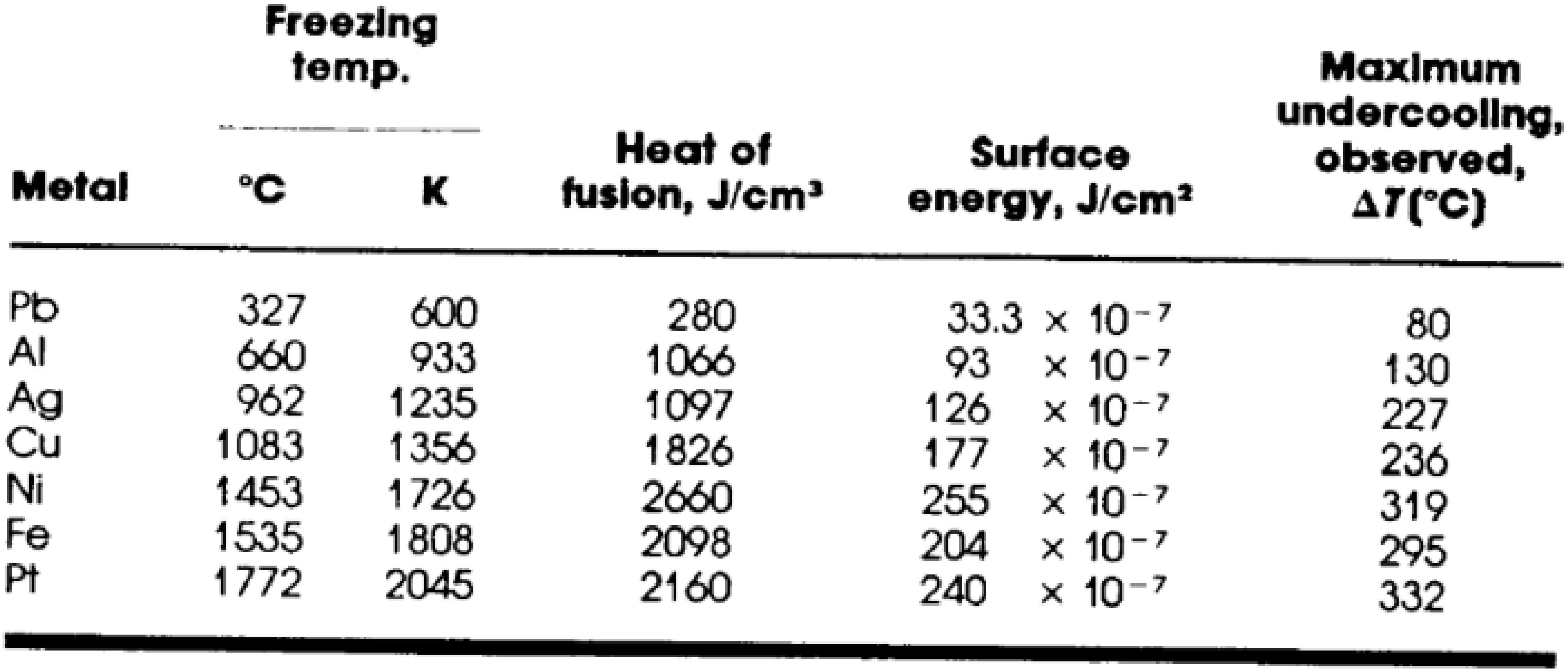


TABLE 2. MELTING POINTS AND LATENT HEATS OF PURE METALS

Metal	Melting point (° C.)	Latent heat of fusion (cal./gm.)
Aluminium	660	95
Copper	1083	50
Gold	1063	16
Iron	1537	65
Lead	327	6
Magnesium	650	89
Nickel	1453	74
Platinum	1769	27
Silver	960·8	25
Tin	232	14·5
Zinc	419	24

Ref.-Bailey

- This kind of nucleation occurs uniformly throughout the liquid. The nucleus grows further by adding more and more atoms to it which leads to a small solid region.
- Such stable solid regions within the liquid are known as nuclei.
- Subsequent to the formation of nuclei, release of heat of fusion takes place and the temperature will be raised to the freezing point again. But loss of heat to the surroundings lowers the temperature again making more atoms to freeze.
- These atoms may attach themselves to already existing nuclei or form new nuclei of their own. Thus the process of solidification continues apparently at constant temperature till the entire liquid is transformed into solid.



Metal	Freezing temp.		Heat of fusion, J/cm³	Surface energy, J/cm²	Maximum undercooling, observed, ΔT(°C)
	°C	K			
Pb	327	600	280	33.3×10^{-7}	80
Al	660	933	1066	93×10^{-7}	130
Ag	962	1235	1097	126×10^{-7}	227
Cu	1083	1356	1826	177×10^{-7}	236
Ni	1453	1726	2660	255×10^{-7}	319
Fe	1535	1808	2098	204×10^{-7}	295
Pt	1772	2045	2160	240×10^{-7}	332

Source: B. Chalmers, "Solidification of Metals," Wiley, 1964.

Energies involved in homogenous nucleation.

Volume free energy G_v

- Released by liquid to solid transformation.
- ΔG_v is change in free energy per unit volume between liquid and solid.
- free energy change for a spherical nucleus of radius r is given by

$$r = \frac{4}{3}\pi r^3 \Delta G_v$$

Surface energy Gs

- Required to form new solid surface
- ΔG_s is energy needed to create a surface.
- γ is specific surface free energy.

Then $\Delta G_s = 4\pi r^2 \gamma$

- ΔG_s is retarding energy.

Total Free Energy

- Total free energy is given by $\Delta G_T = \frac{4}{3}\pi r^3 \Delta G_v + 4\pi r^2 \gamma$

Since when r=r*, $d(\Delta G_T)/dr = 0$ $$r^* = -\frac{2\gamma}{\Delta G_V}$$

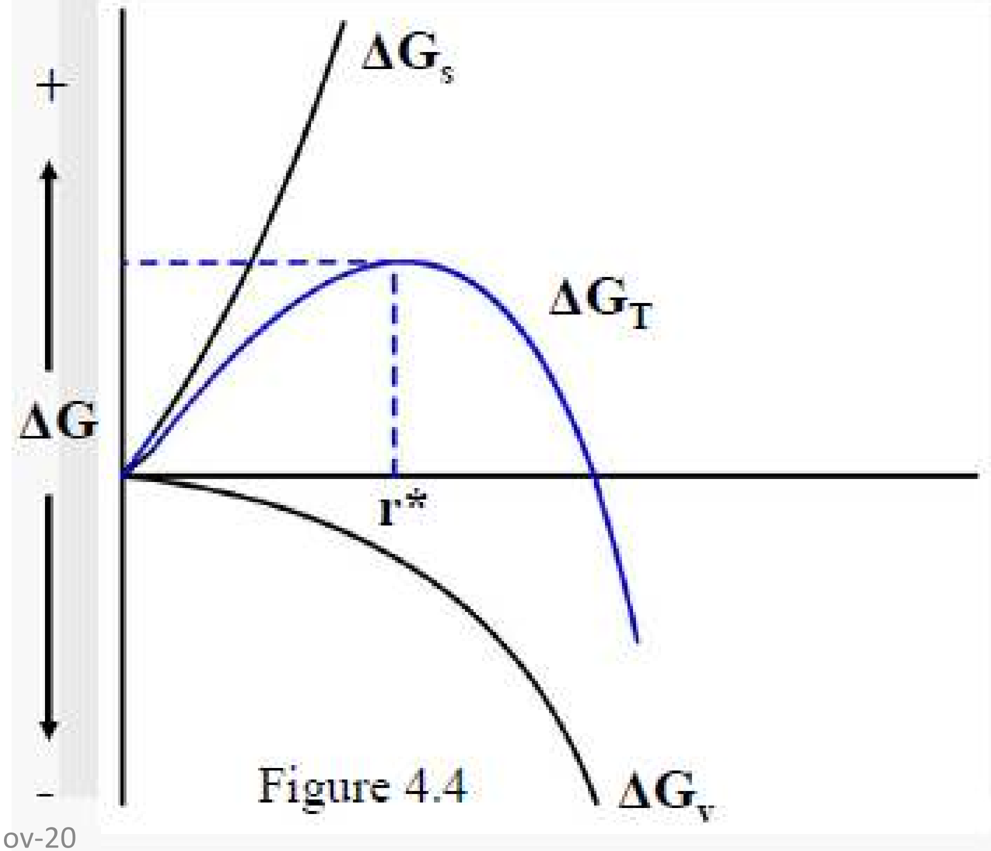
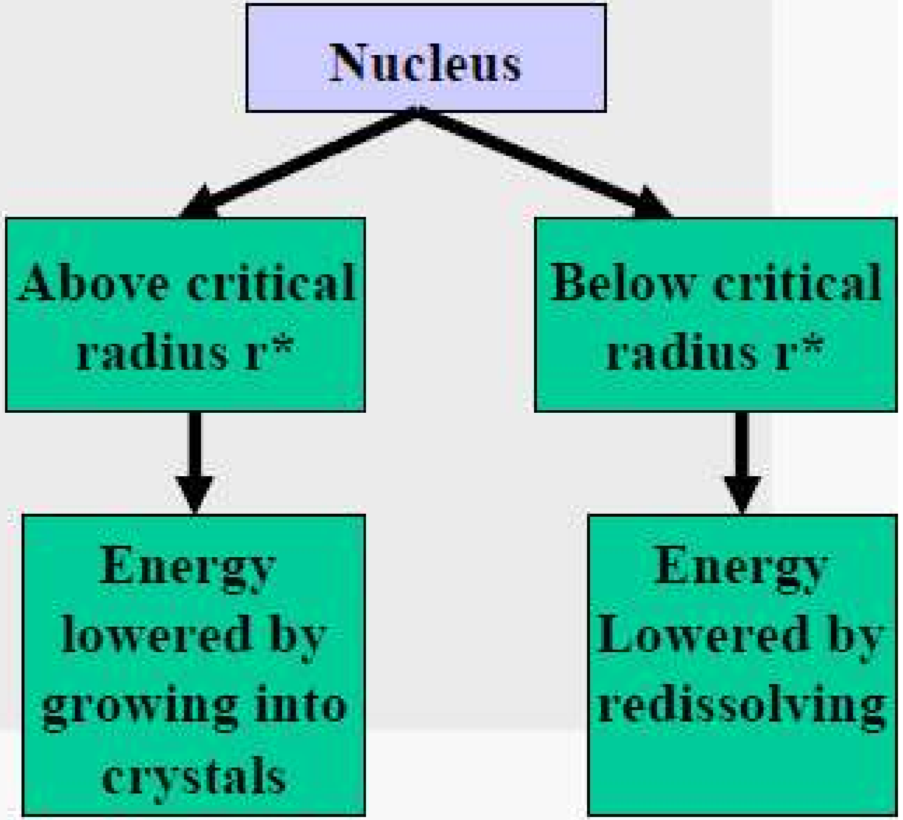


Figure 4.4



Nucleus

Above critical radius r* → **Energy lowered by growing into crystals**

Below critical radius r* → **Energy Lowered by redissolving**

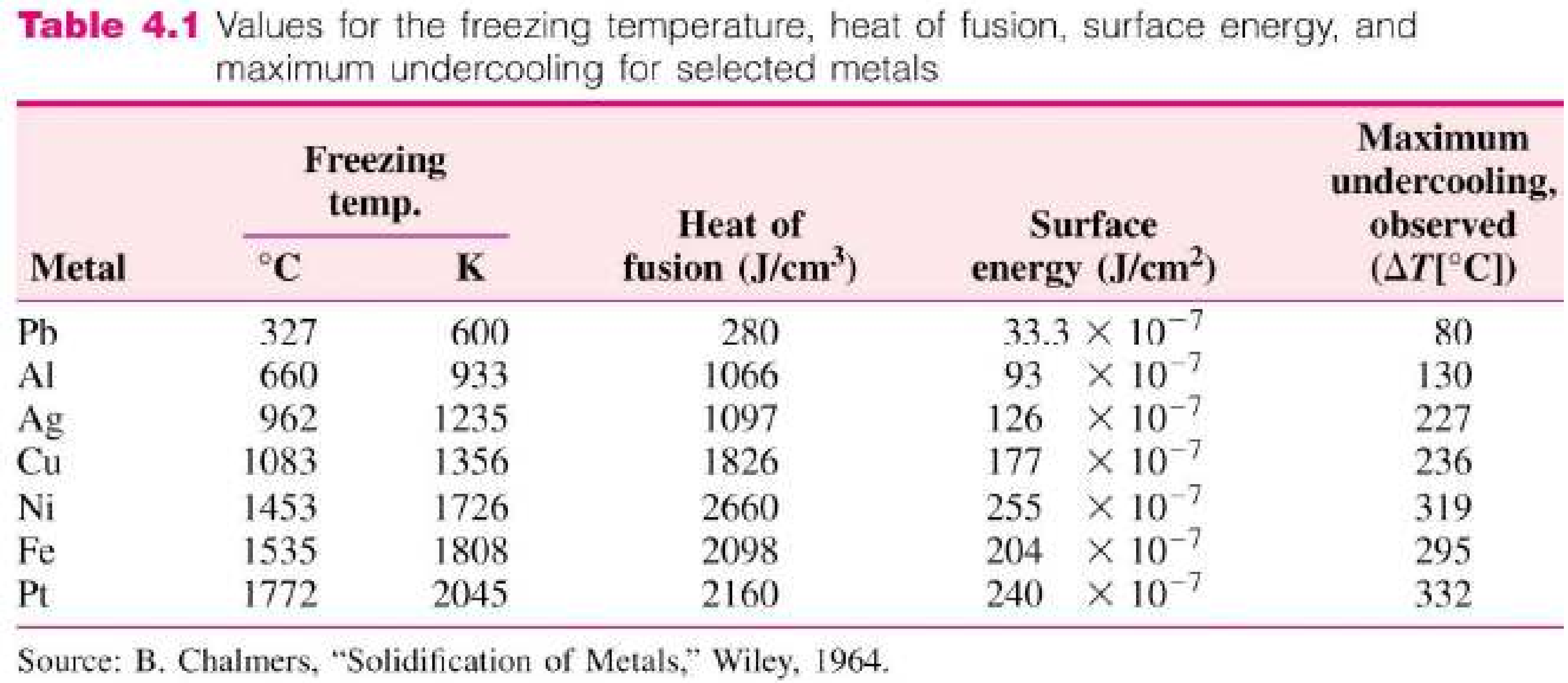


Table 4.1 Values for the freezing temperature, heat of fusion, surface energy, and maximum undercooling for selected metals

Metal	Freezing temp. °C	Freezing temp. K	Heat of fusion (J/cm^3)	Surface energy (J/cm^2)	Maximum undercooling, observed (ΔT[°C])
Pb	327	600	280	33.3×10^{-7}	80
Al	660	933	1066	93×10^{-7}	130
Ag	962	1235	1097	126×10^{-7}	227
Cu	1083	1356	1826	177×10^{-7}	236
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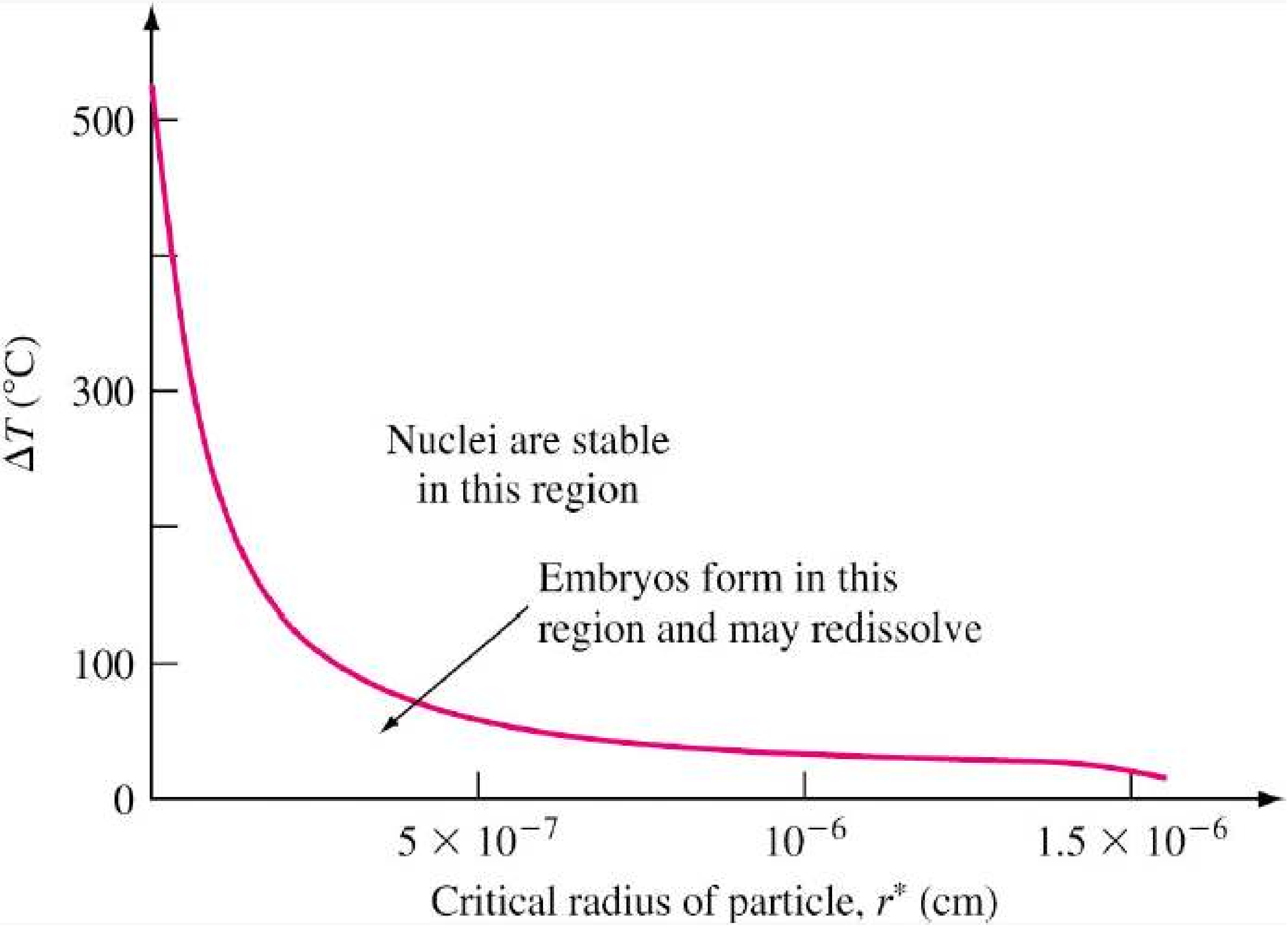
Source: B. Chalmers, "Solidification of Metals," Wiley, 1964.


500
300
100
0
ΔT (°C)
Nuclei are stable in this region
Embryos form in this region and may redissolve
5 × 10⁻⁷
10⁻⁶
1.5 × 10⁻⁶
Critical radius of particle, r* (cm)

Critical Radius Versus Undercooling

Greater the degree of undercooling, greater the change in volume free energy ΔG_v

ΔG_s does not change significantly.

As the amount of undercooling ΔT increases, critical nucleus size decreases.

Critical radius is related to undercooling by relation

$$r^* = \frac{2\gamma T_m}{\Delta H_f \Delta T}$$

r^* = critical radius of nucleus

γ = Surface free energy

ΔH_f = Latent heat of fusion

ΔT = Amount of undercooling.

Supercooling

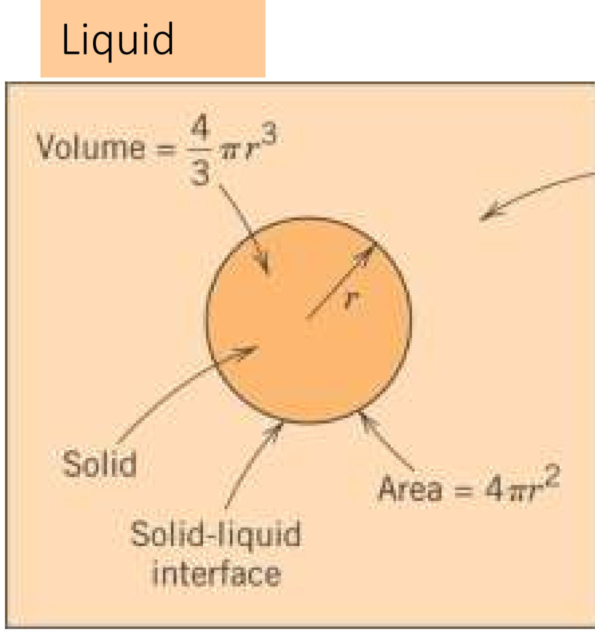
- During the cooling of a liquid, solidification (nucleation) will begin only after the temperature has been lowered below the equilibrium solidification (or melting) temperature T_m. This phenomenon is termed supercooling (or undercooling.

- The driving force to nucleate increases as ΔT increases
- Small supercooling → slow nucleation rate - few nuclei - large crystals

- Large supercooling → rapid nucleation rate - many nuclei - small crystals

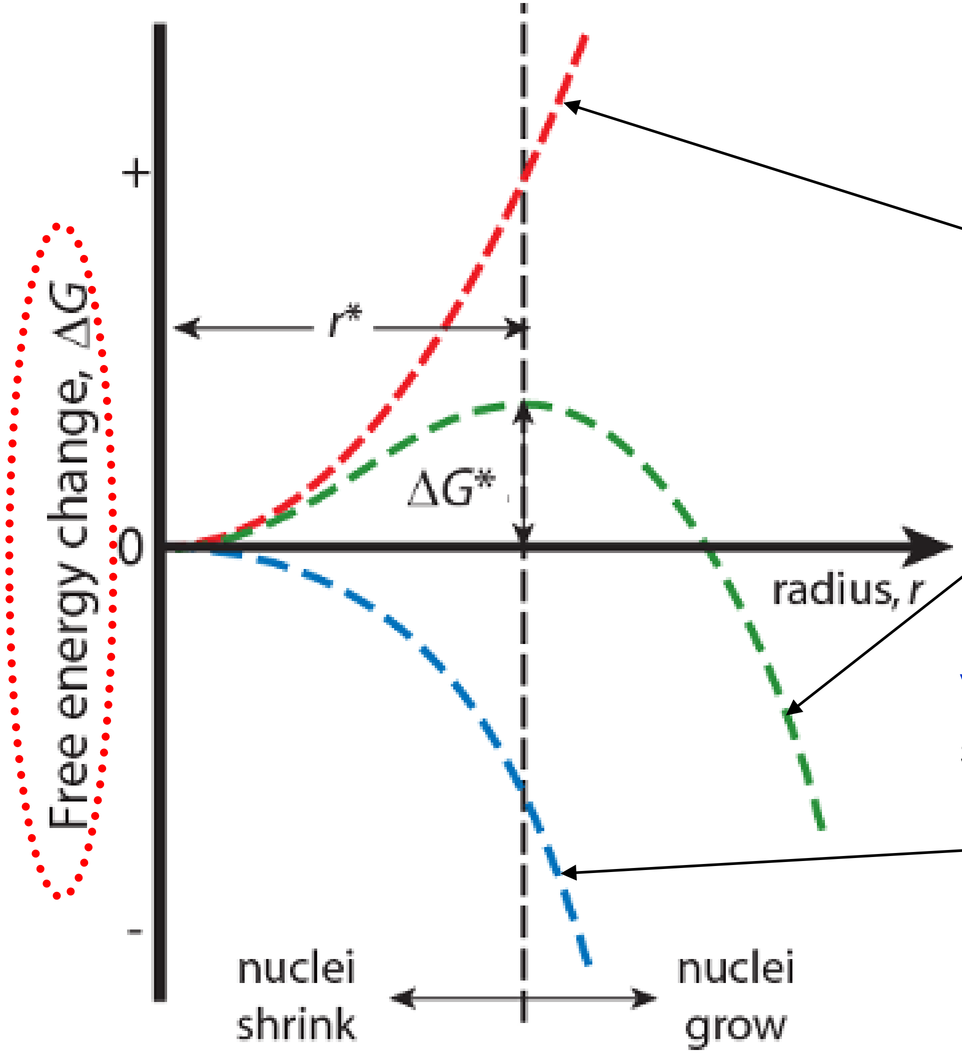
Nucleation of a spherical solid particle in a liquid

- The change in free energy DG (a function of the internal energy and enthalpy of the system) must be negative for a transformation to occur.
- Assume that nuclei of the solid phase form in the interior of the liquid as atoms cluster together-similar to the packing in the solid phase.
- Also, each nucleus is spherical and has a radius r.
- Free energy changes as a result of a transformation: 1) the difference between the solid and liquid phases (volume free energy, DG_V); and 2) the solid-liquid phase boundary (surface free energy, DG_S).
- Transforming one phase into another takes time.



$$\Delta G = \Delta G_S + \Delta G_V$$

Homogeneous Nucleation & Energy Effects



Surface Free Energy- destabilizes the nuclei (it takes energy to make an interface)

$$\Delta G_S = 4\pi r^2 \gamma$$

γ = surface tension

ΔG_T = Total Free Energy

$= \Delta G_S + \Delta G_V$

Volume (Bulk) Free Energy – stabilizes the nuclei (releases energy)

$$\Delta G_V = \frac{4}{3}\pi r^3 \Delta G_\upsilon$$

$$\Delta G_\upsilon = \frac{\text{volume free energy}}{\text{unit volume}}$$

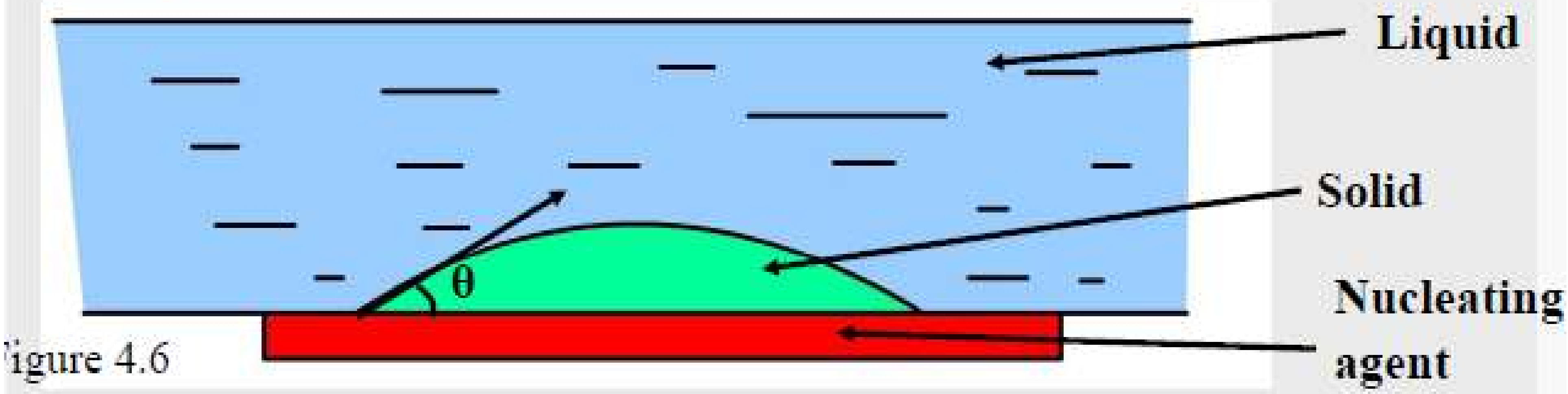
*r** = critical nucleus: for *r* < *r** nuclei shrink; for *r* >*r** nuclei grow (to reduce energy)

Heterogeneous nucleation

- Nucleation is also facilitated by the presence of some impurity atoms, an inoculant (grain refiner), an imperfection or a grain boundary. This type of preferential nucleation is called heterogeneous nucleation.
- Form at structural inhomogeneities (container surfaces, impurities, grain boundaries, dislocations) in liquid phase much easier since stable "nucleating surface" is already present; requires slight supercooling (0.1-10ºC).
- A much lower level of undercooling is sufficient for this type of nucleation to occur. Even the wall of the container promotes heterogeneous nucleation.
- Addition of a grain refiner to molten metal can produce fine grained grains. Nb
- The grain refiners solidify earlier and form a large number of small solid particles in the liquid.
- Solidification of the liquid is initiated by heterogeneous nucleation around these solid particles.

Heterogeneous Nucleation

- Nucleation occurs in a liquid on the surfaces of structural materials Eg:- Insoluble impurities.
- These structures, called *nucleating agents*, lower the free energy required to form stable nucleus.



igure 4.6

- Nucleating agents also lower the critical size.
- Smaller amount of undercooling is required to solidify.
- Used excessively in industries.

Growth (Dendritic Growth)

- During the process of solidification, each nucleus grows by attracting atoms from the liquid into the space lattice.
- Crystal growth continues in three dimensions, the atoms attaching themselves in certain preferred directions, usually along the axes of the crystal. This gives rise to the characteristic treelike structure which is called a **dendrite.**
- Since each nucleus is formed by chance, the crystal axes are pointed at random, and dendrites growing from them will grow in different directions in each crystal.

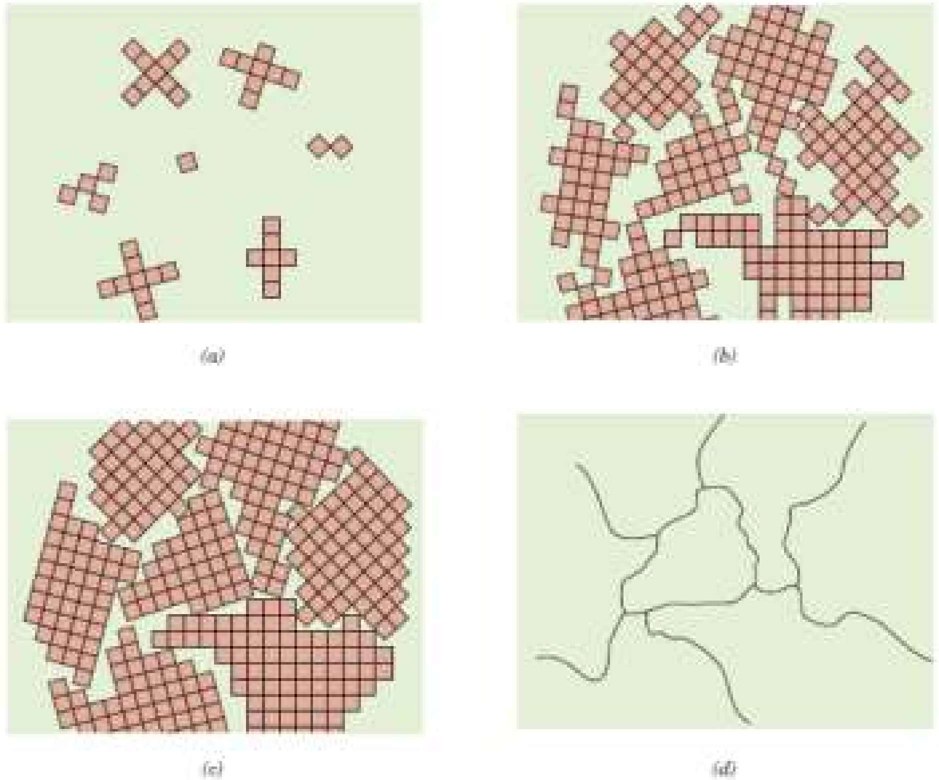
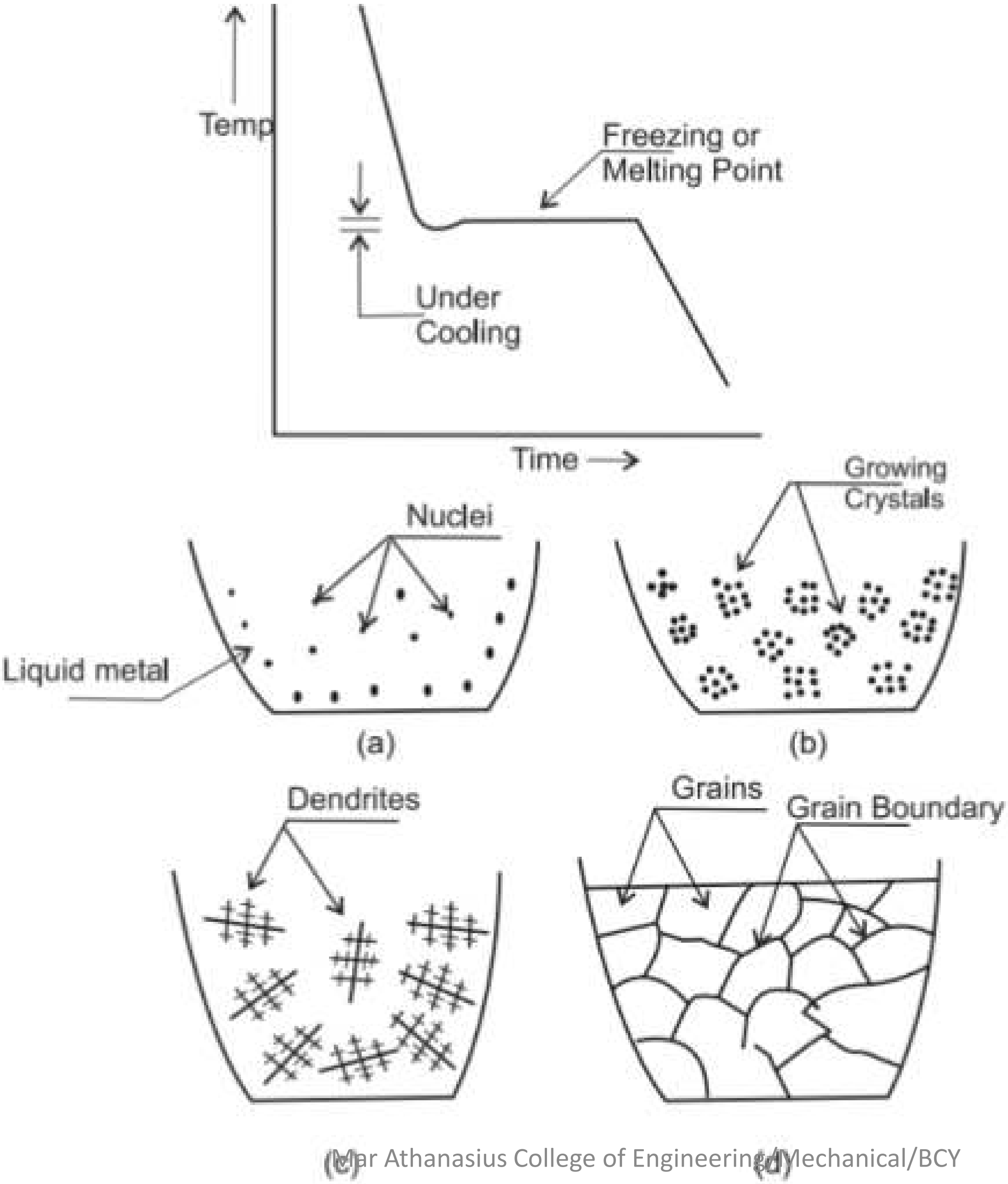
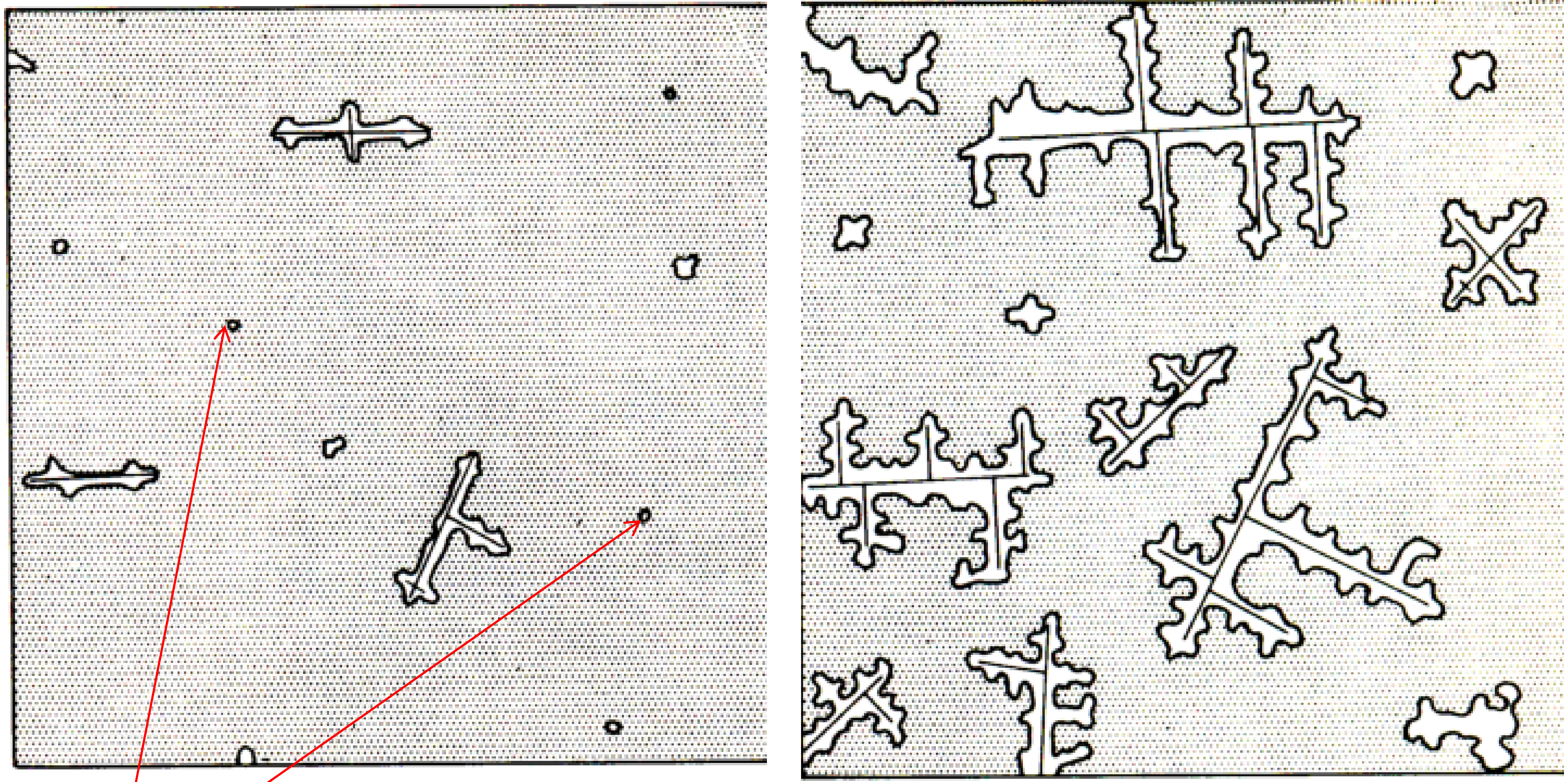


Figure 3.17 Schematic diagrams of the various stages in the solidification of a polycrystalline material; the square grids depict unit cells. (*a*) Small crystallite nuclei. (*b*) Growth of the crystallites; the obstruction of some grains that are adjacent to one another is also shown. (*c*) Upon completion of solidification, grains having irregular shapes have formed. (*d*) The grain structure as it would appear under the microscope; dark lines are the grain boundaries. (Adapted from W. Rosenhain, *An Introduction to the Study of Physical Metallurgy*, 2nd edition, Constable & Company Ltd., London, 1915.)

- This is a sort of crystal skeleton from which arms begin to grow in all directions depending upon the lattice pattern.
- From the primary arms, secondary, tertiary etc. arms begin to sprout, somewhat similar to branches and twigs growing out of the trunk of a tree, leading to the formation of a rather elongated skeleton.
- In the case of metallic dendrites, these branches and twigs conform to a rigid geometrical pattern. The dendritic arms continue to grow and thicken at the same time, until ultimately the space between them will become filled with solid.
- Meanwhile the outer arms of one dendrite begin to make contact with those of neighboring dendrites, which have been developing independently at the same time.

- If the material is pure, there shall be no evidence of dendritic growth once the solidification is complete, since all the atoms are identical.
- If the material is impure, dissolved impurities will often tend to remain in the molten portion of the metal, which ultimately solidifies in the spaces between the dendrites.
- Since their presence will often cause a slight alteration in colour of the parent metal, the dendritic structure will be easily revealed on microscopical examination.
- The areas containing impurity will appear as patches between the dendrite arms.

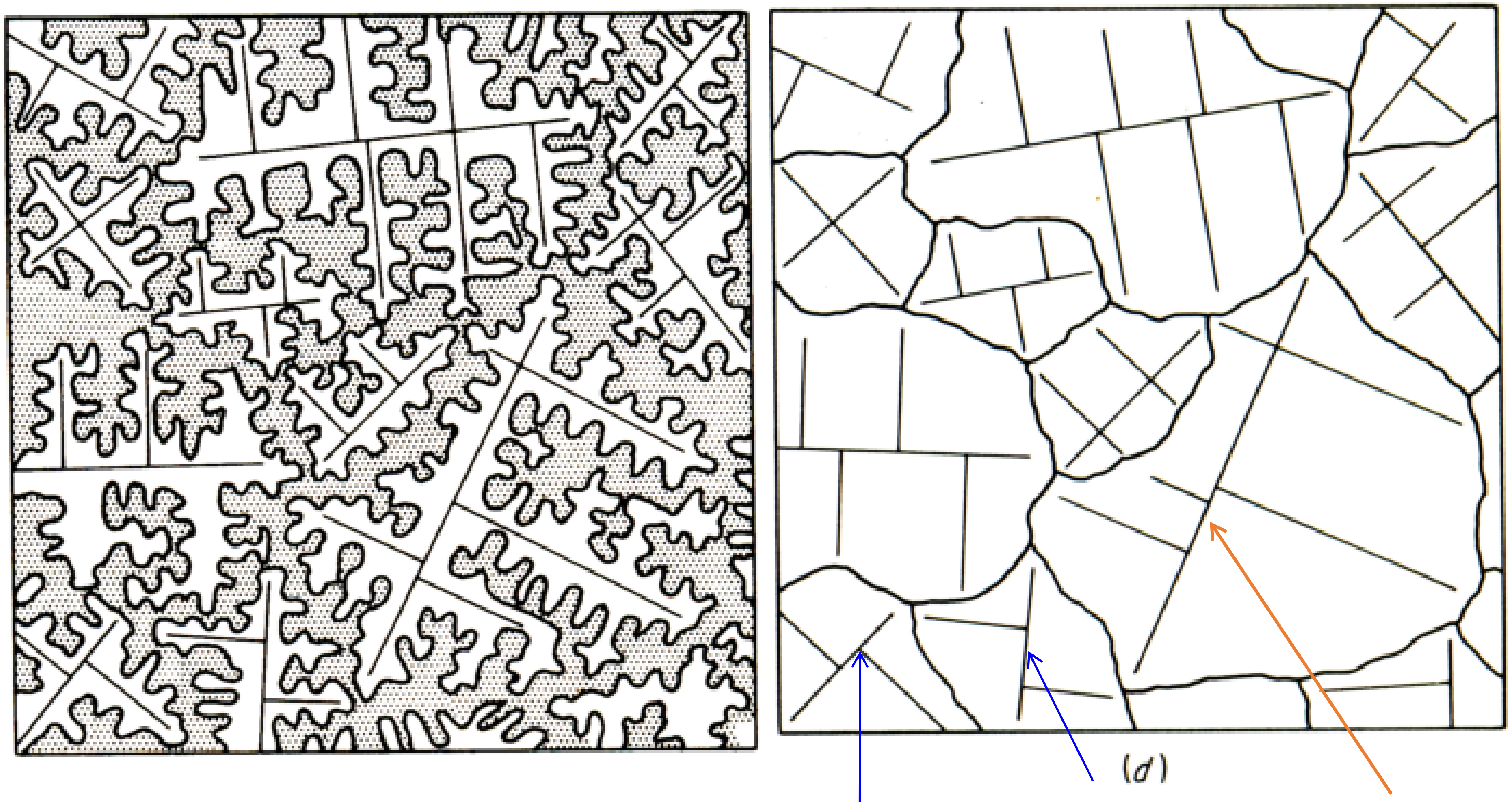

Temp
Freezing or Melting Point
Under Cooling
Time
Nuclei
Liquid metal
(a)
Growing Crystals
(b)
Dendrites
Grains
Grain Boundary
(c)
(d)



(a) **(b)**

Nuclei **– not center of an atom, is the center of few atoms together**

Schematic representation of the process of crystallization by nucleation and dendrite growth.

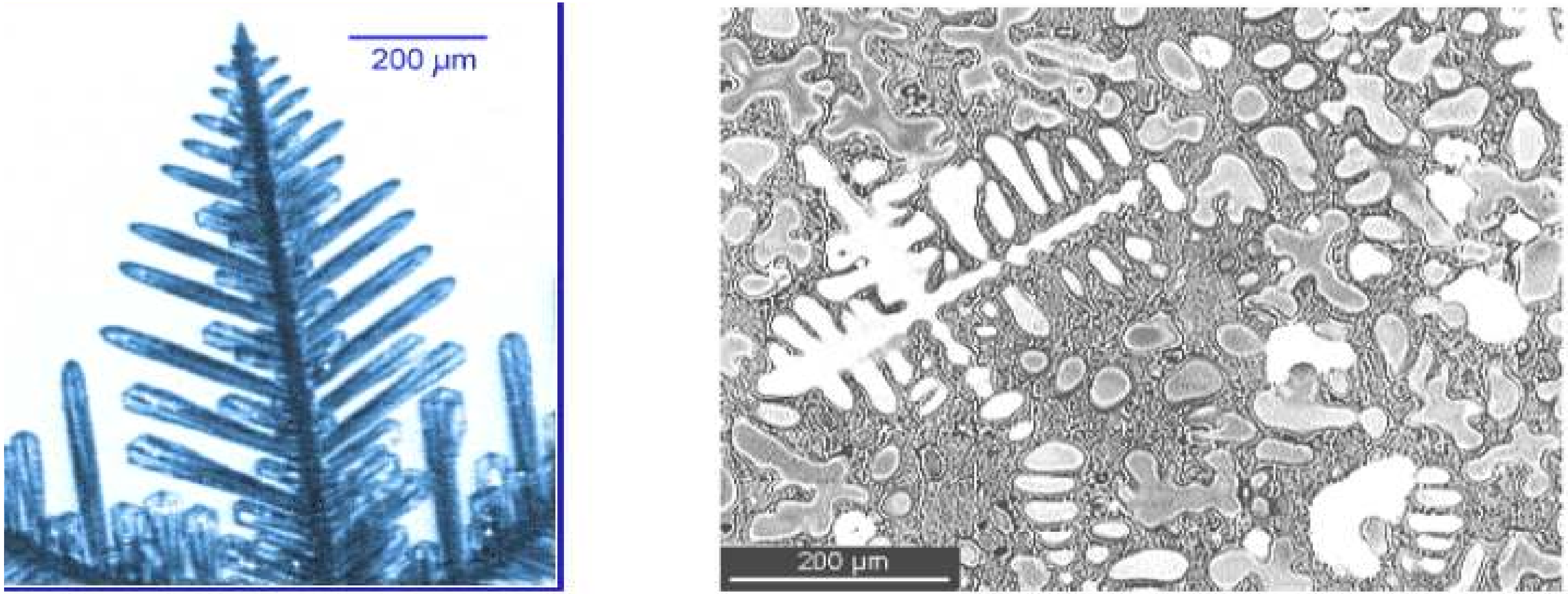


(c)

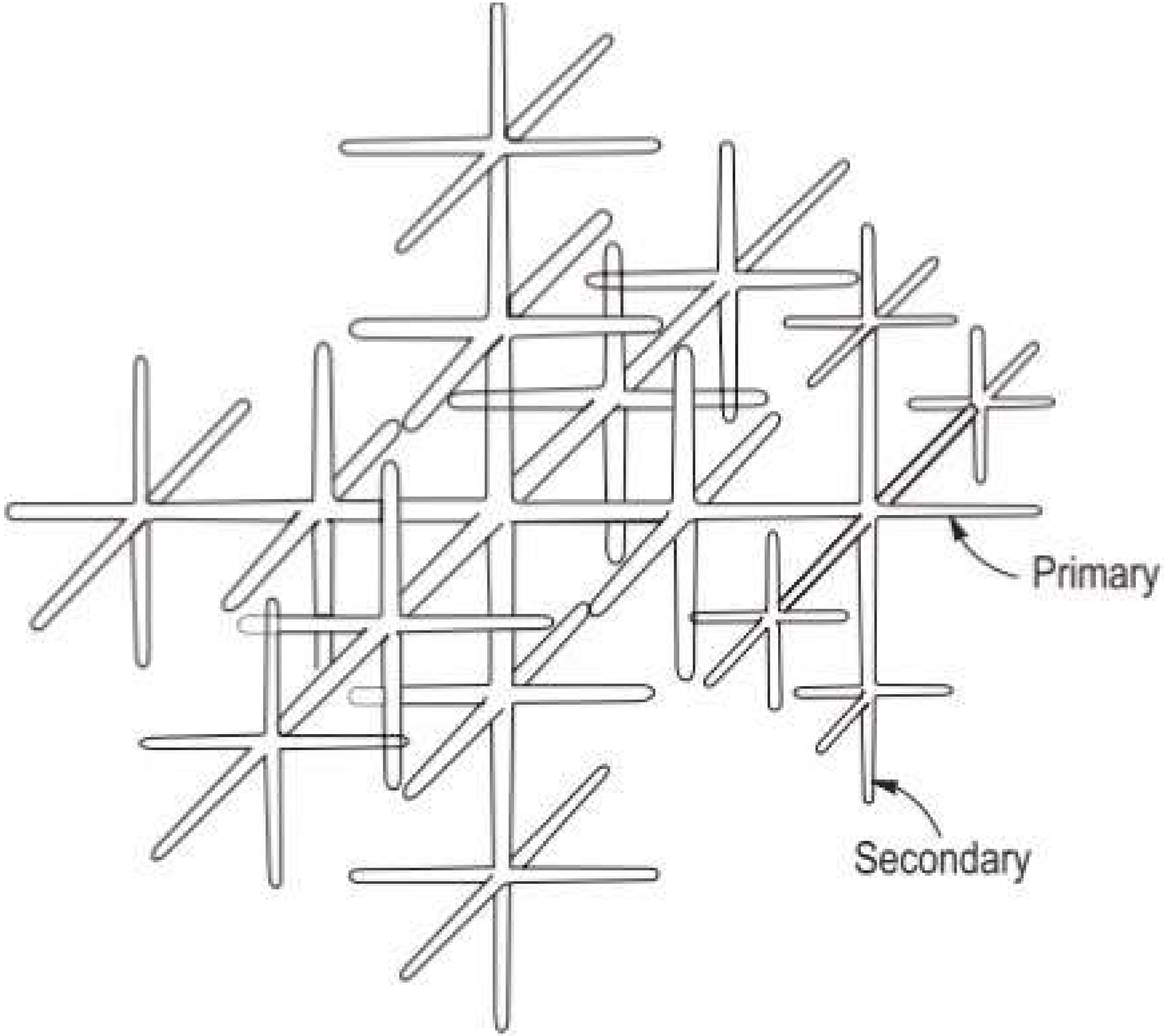
Orientation of atoms in each crystal

Schematic representation of the process of crystallization by nucleation and dendrite growth.

Why grain boundaries are irregular?



Dendrites in water (left) and in a Cu-P alloy (right).


Primary
Secondary

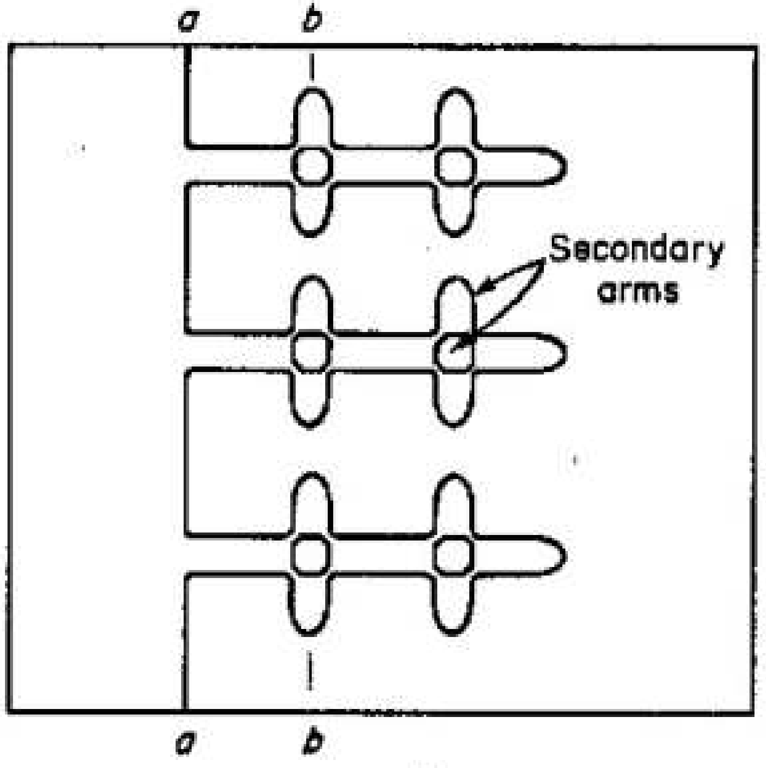
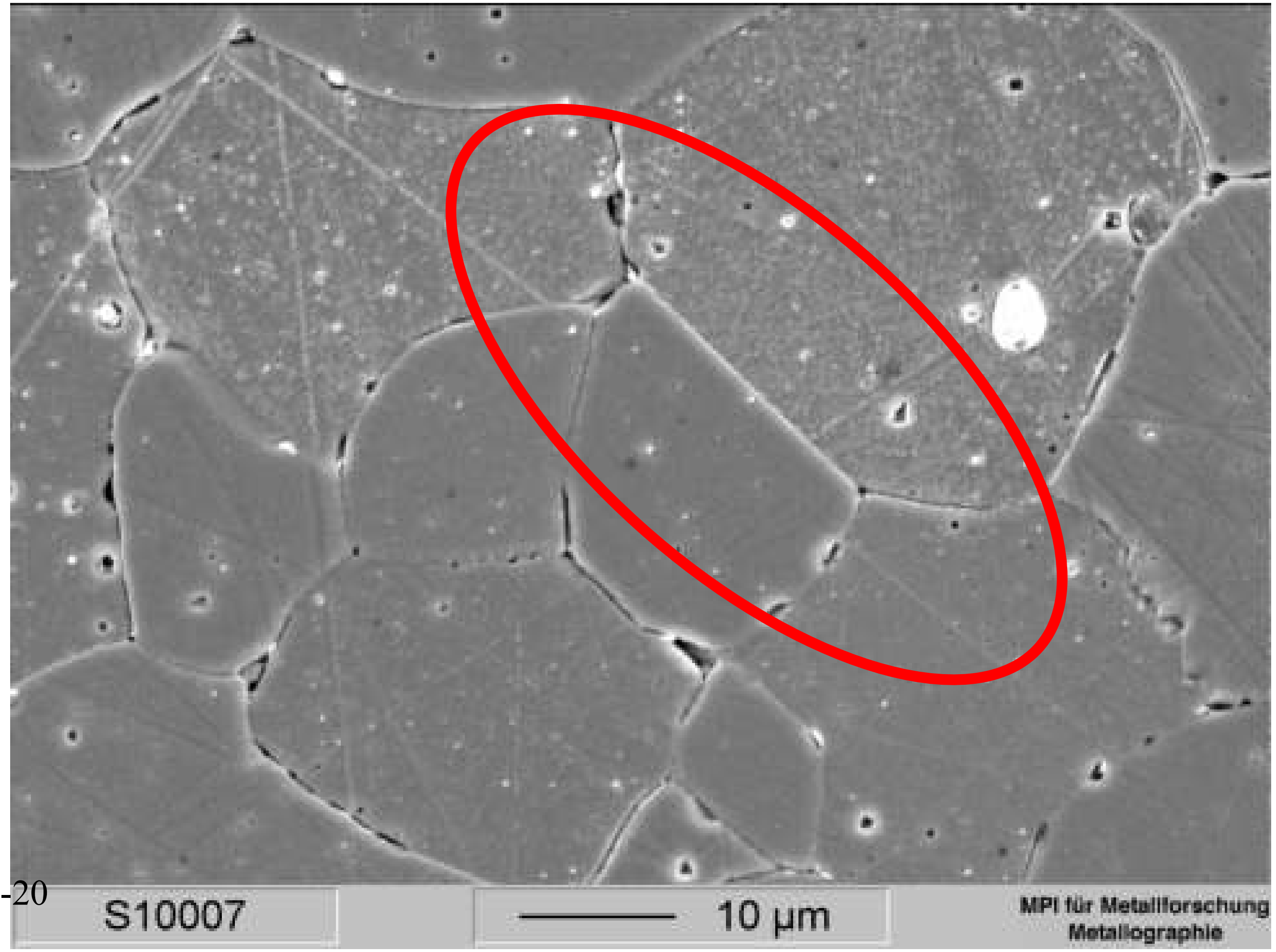


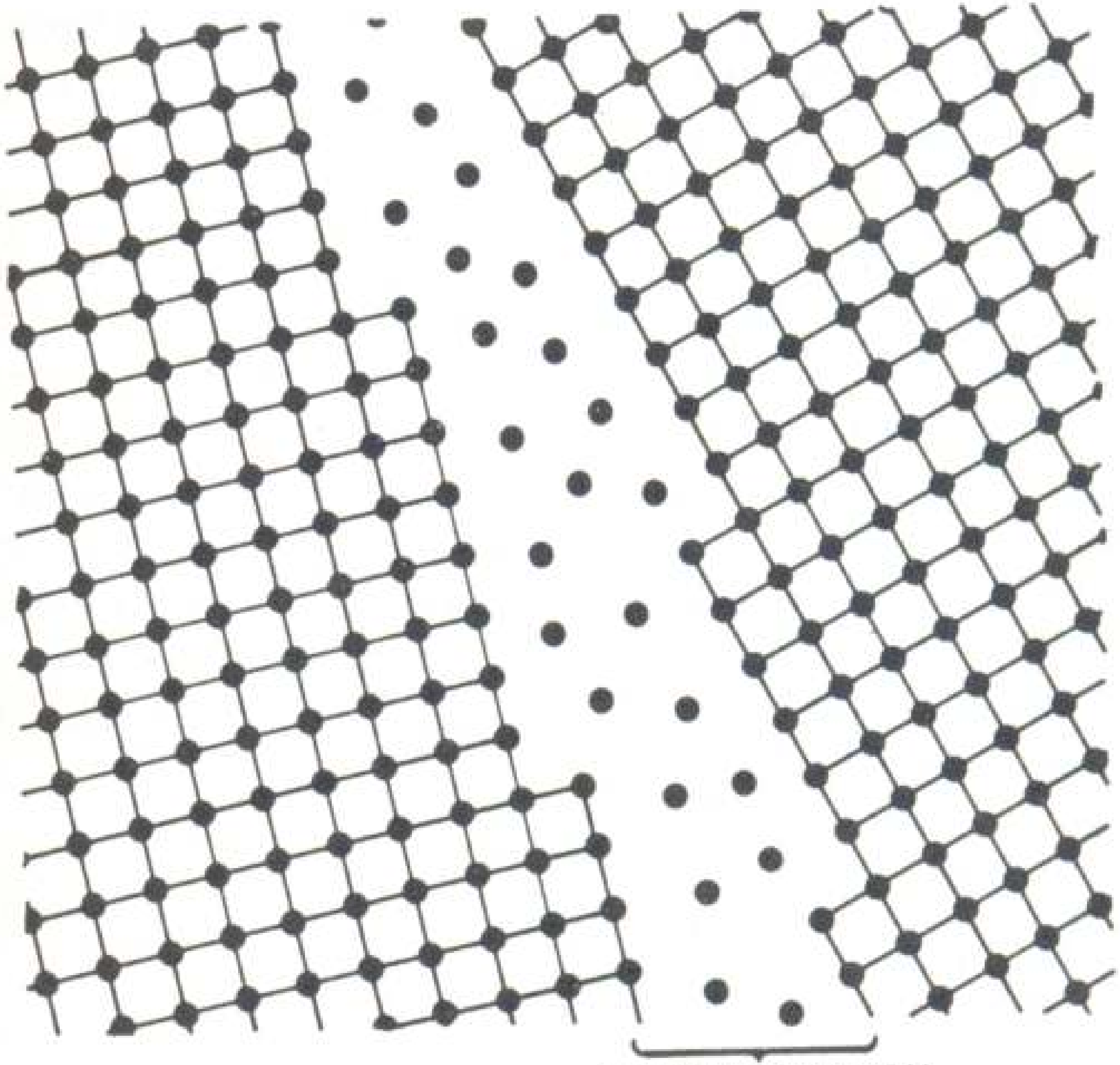
Fig. 15.14 In a cubic crystal, the dendrite arms form along ⟨100⟩ directions. Primary and secondary arms are thus normal to each other.

The **secondary dendrite arm spacing controls strength**, very similar to the Hall Petch relation (1/sqrt d) in the case of grain size strengthening. Thus, in castings, this is an **important microstructural parameter to consider**. The **arm spacing is proportional to cooling rate.**

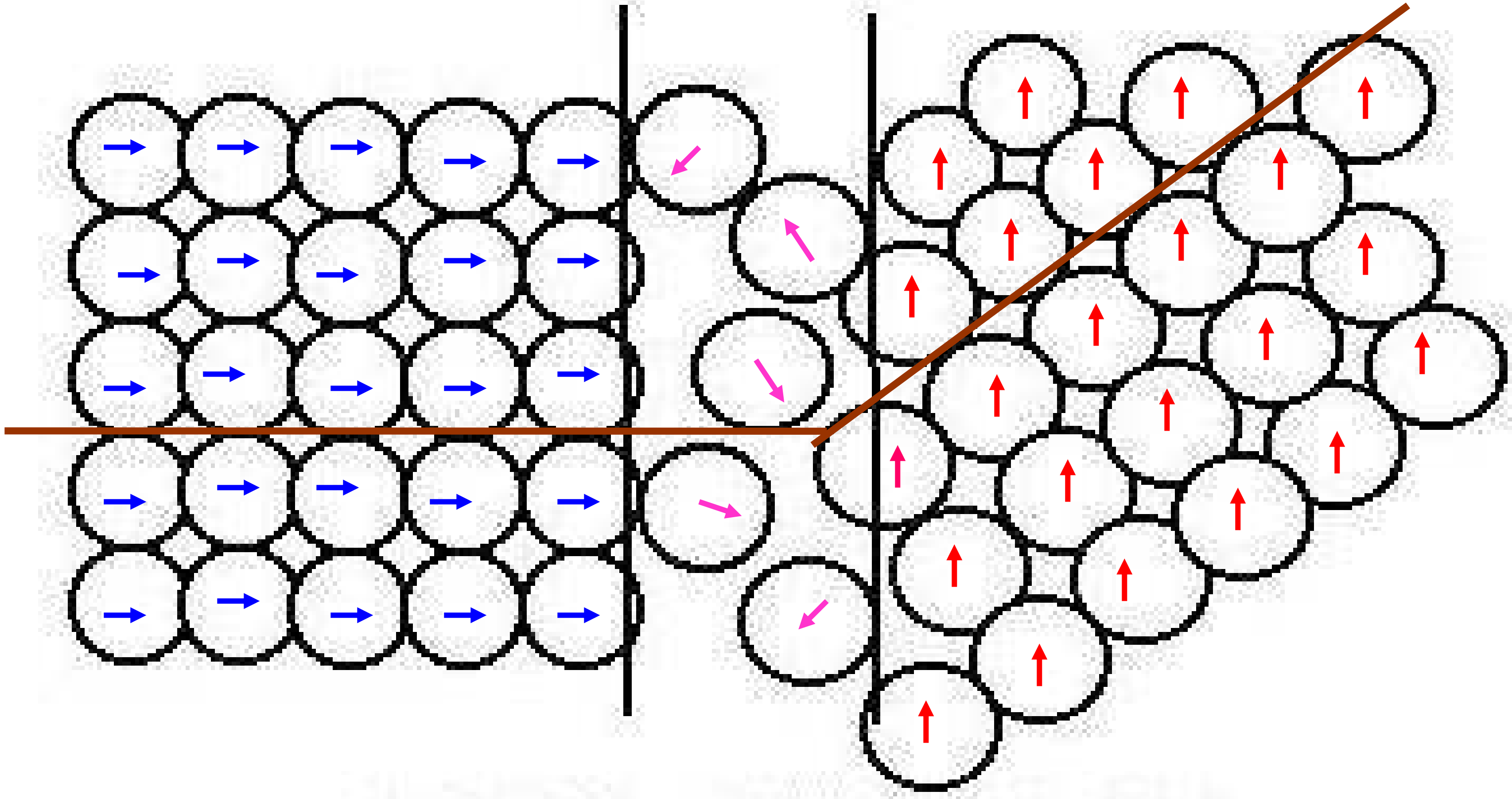
Type of boundary	**Energy (J/m^2)**
Grain boundary between BCC crystals	0.89
Grain boundary between FCC crystals	0.85
Interface between BCC and FCC crystals	0.63



Grain boundaries in $SrTiO_3$



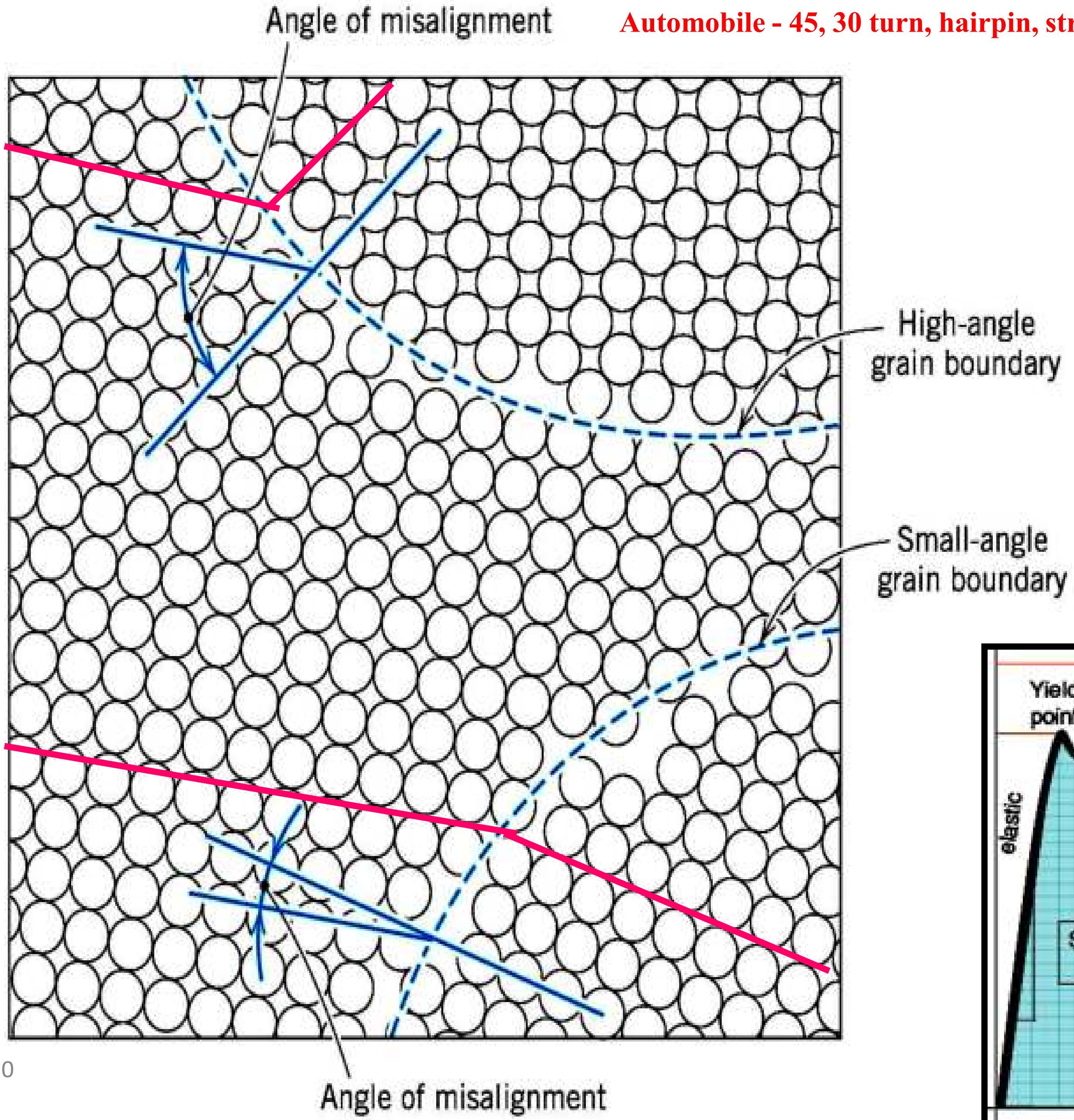
GRAIN BOUNDARY
(ABOUT 3 ATOMS THICK)



ZONE OF MISFIT

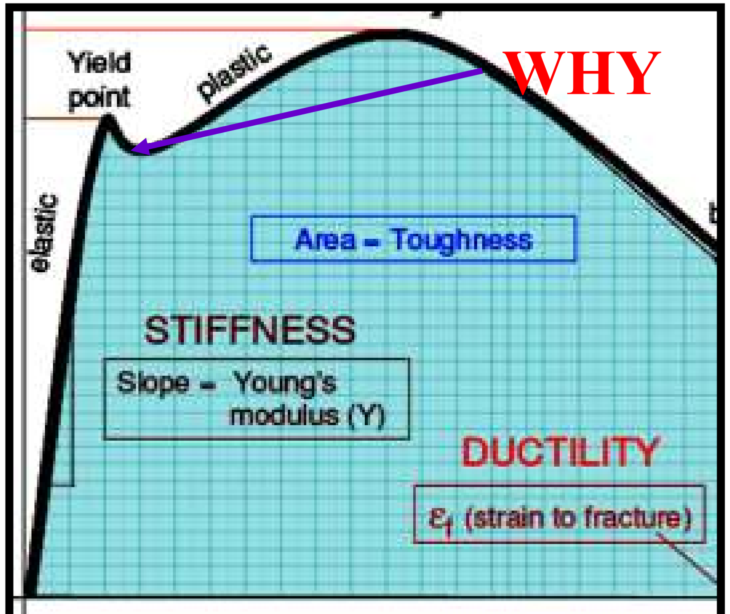
GRAIN BOUNDARY

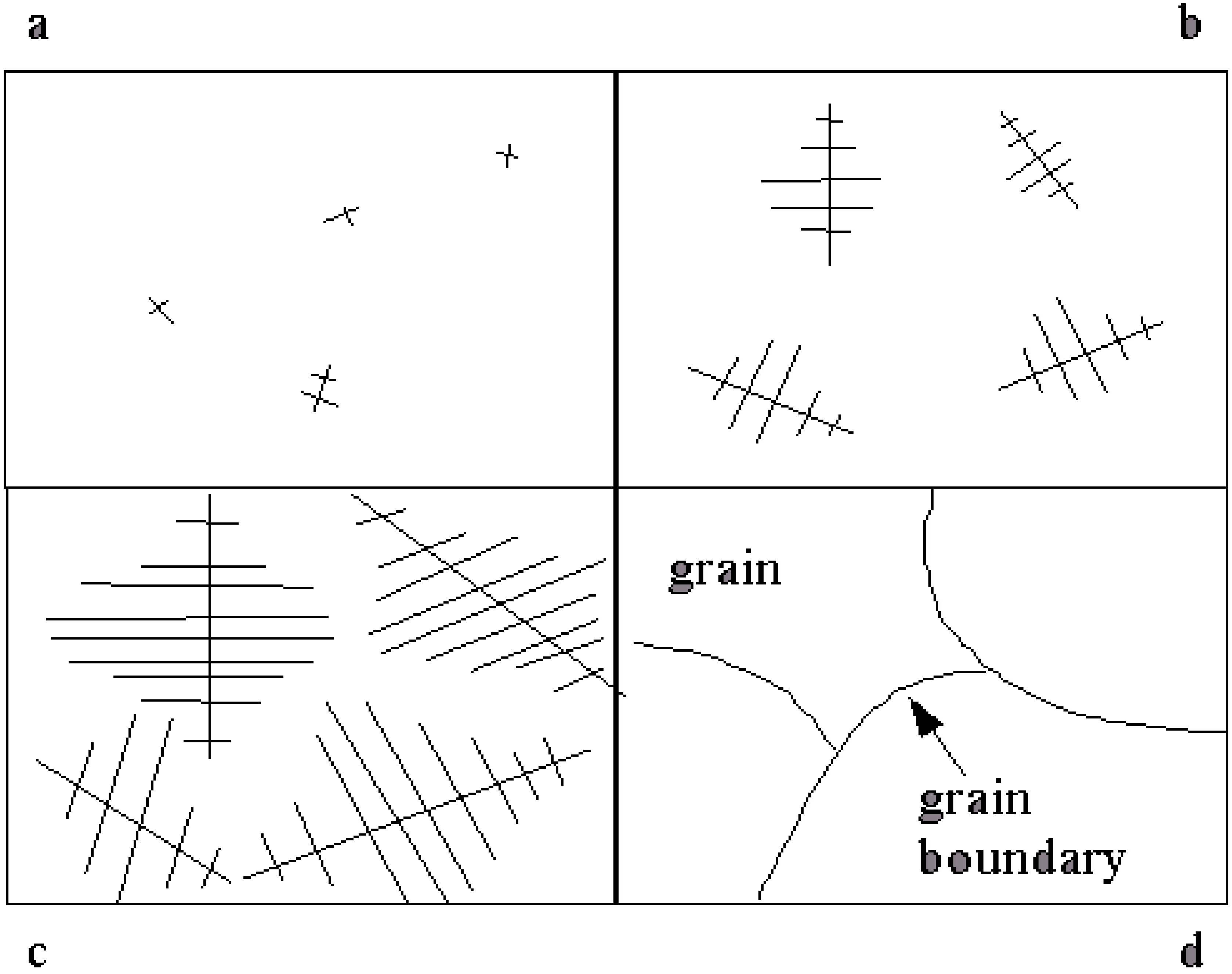
Automobile - 45, 30 turn, hairpin, straight



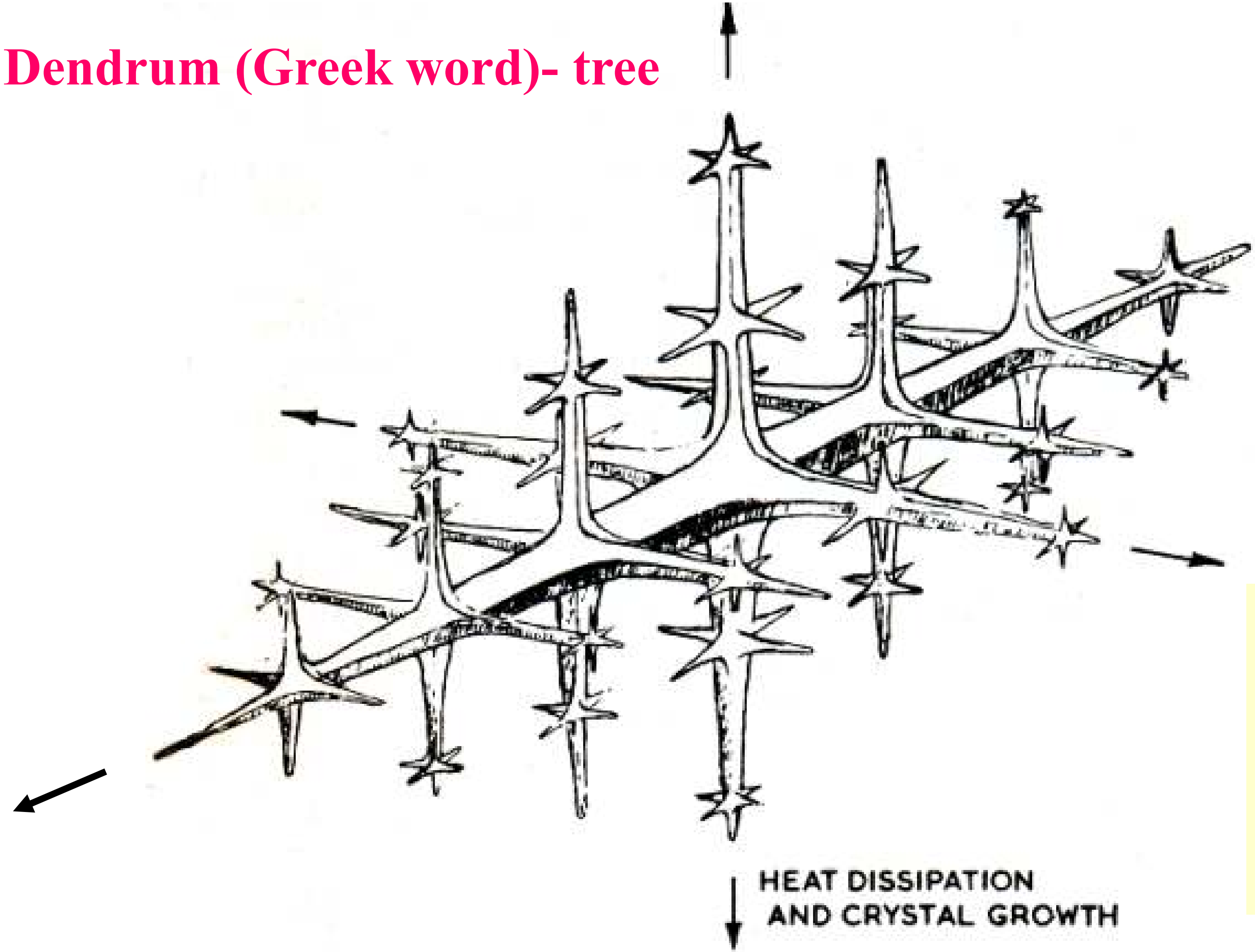
Schematic diagram showing small- and high-angle grain boundaries and the adjacent atom positions.

Depending on which planes are brought together, the angle of alignment will vary.




a
b
grain
grain boundary
c
d

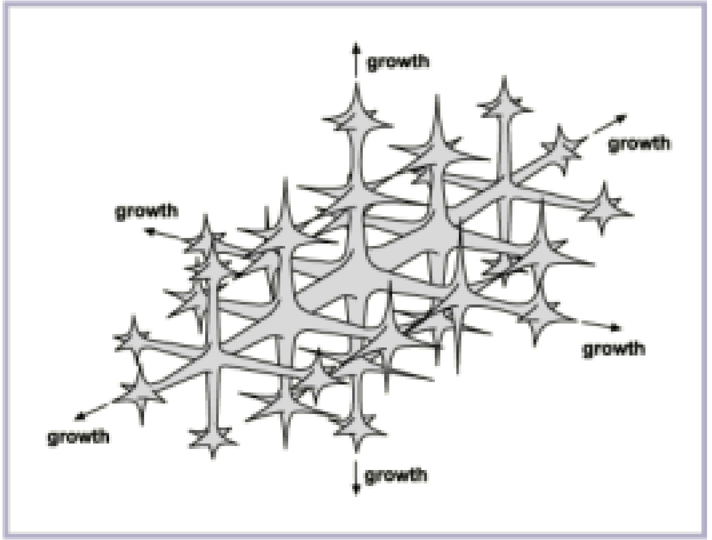
Dendrite – Dendrum (Greek word)- tree



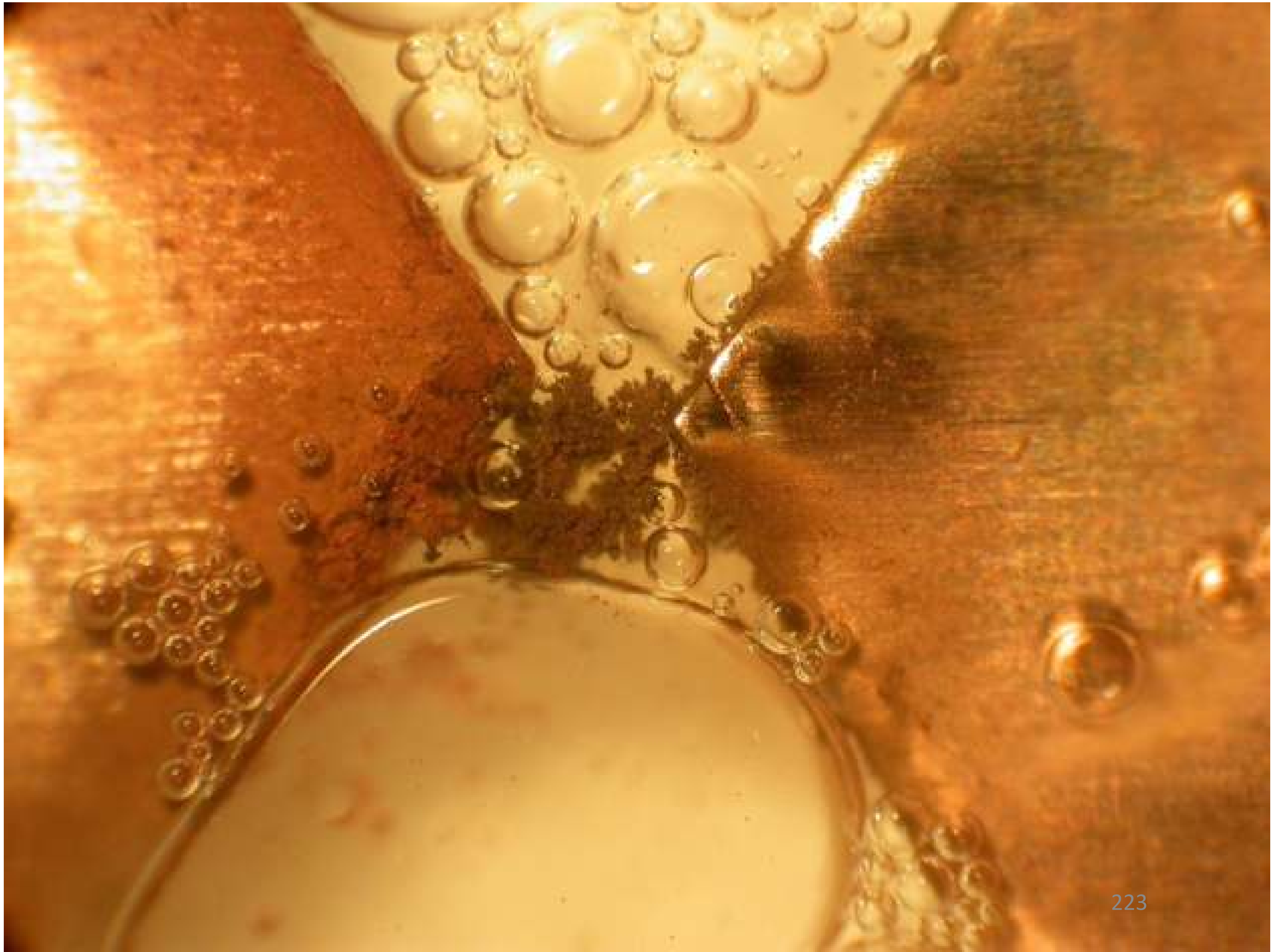
Direction of dendrite growth shows direction of cooling

The early stages in the growth of a metallic dendrite

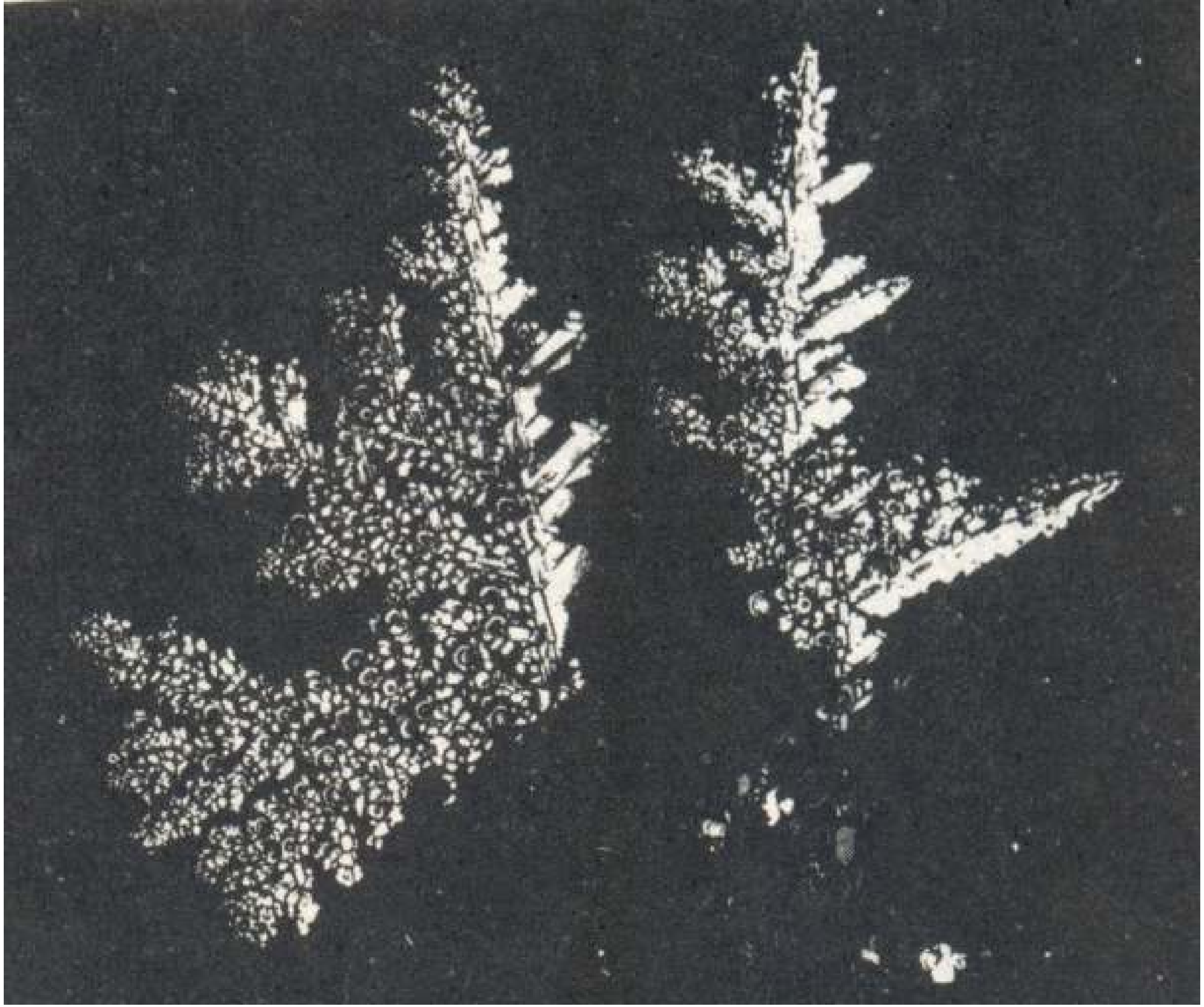
Metallic Structures



Growth of metal dendrite



Copper dendrites



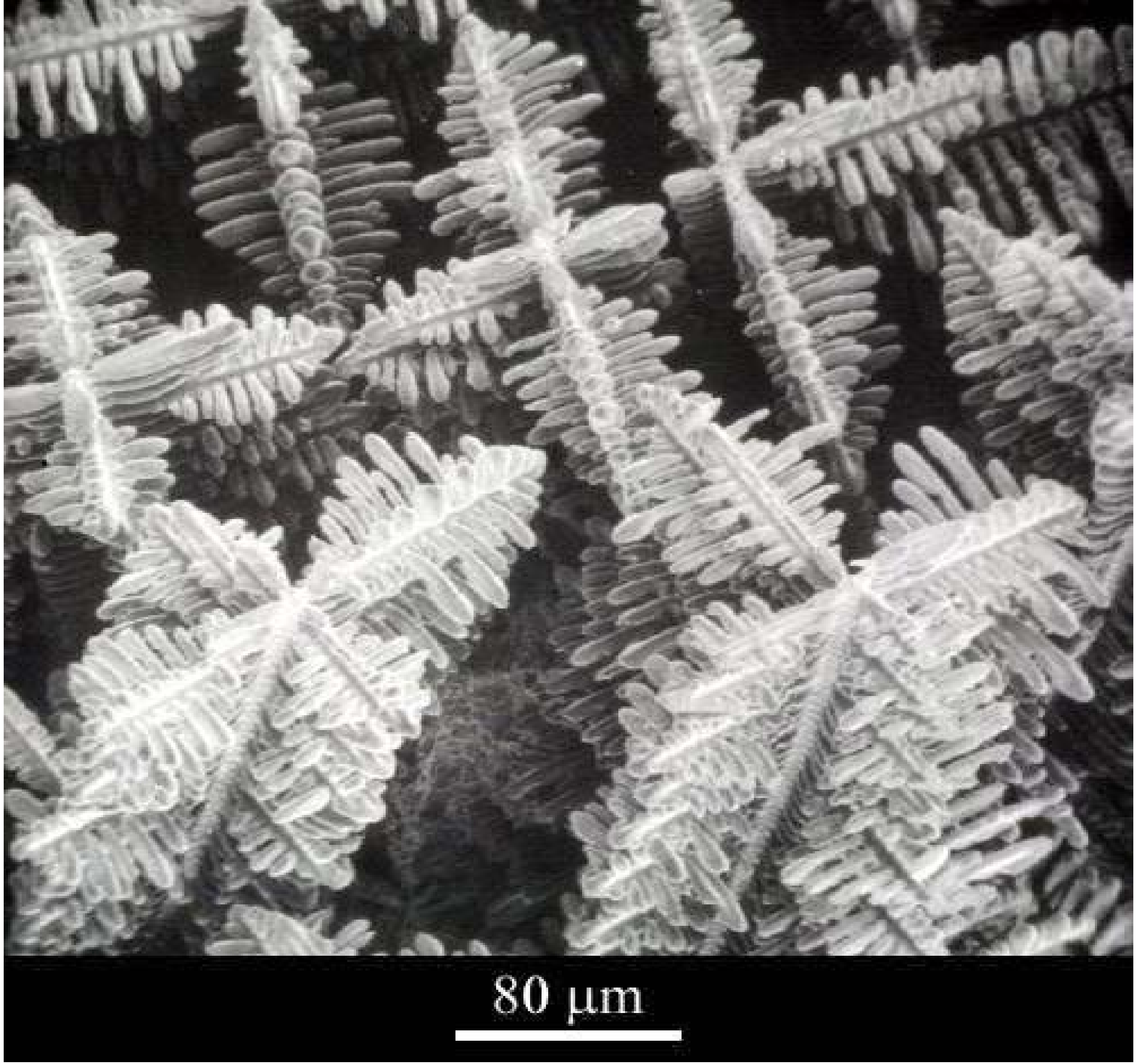
Magnesium dendrites growing from liquid

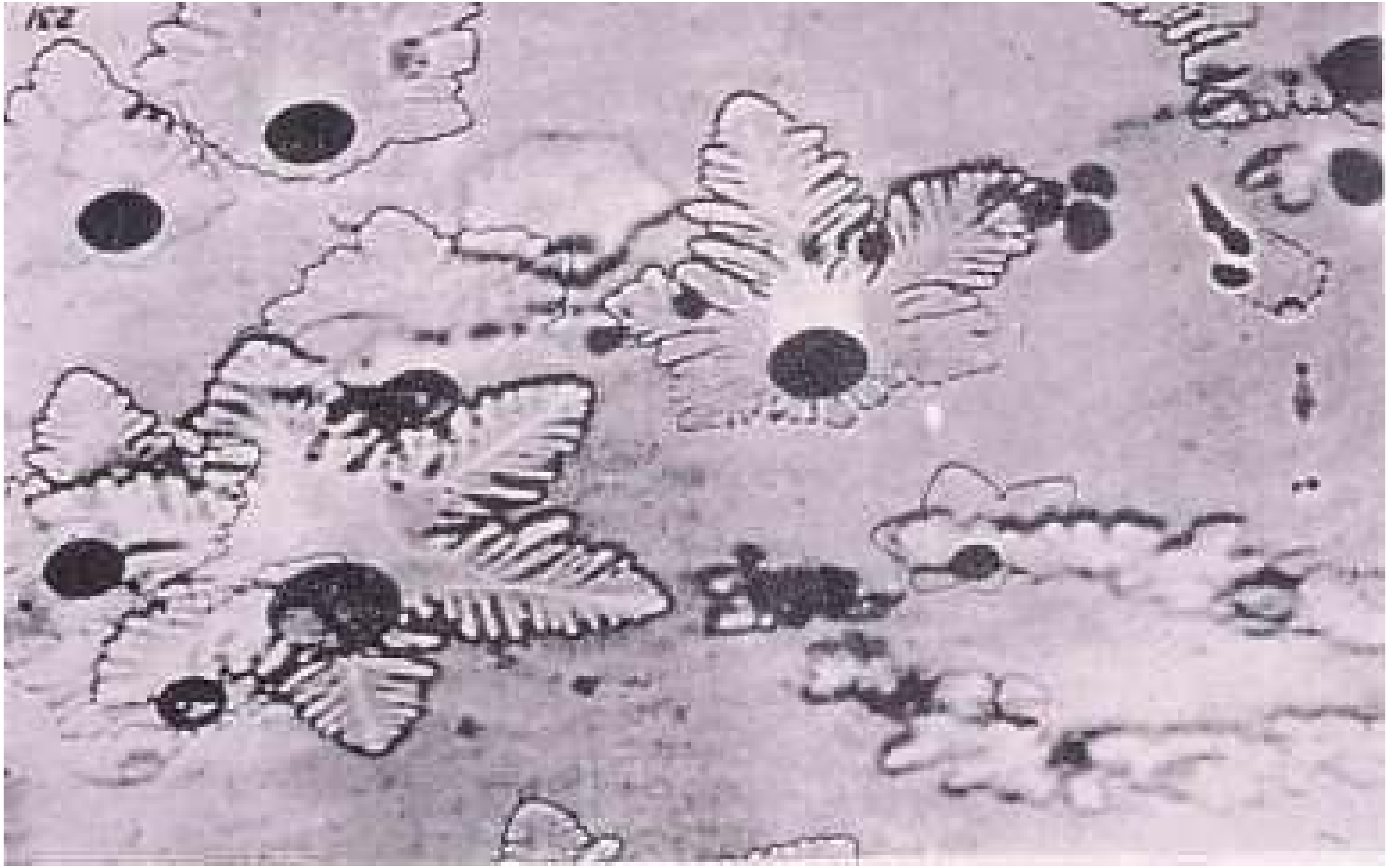
Dendrites in a

Cobalt-Samarium-Copper alloy

-SEM

-Why grain boundaries are irregular shape?



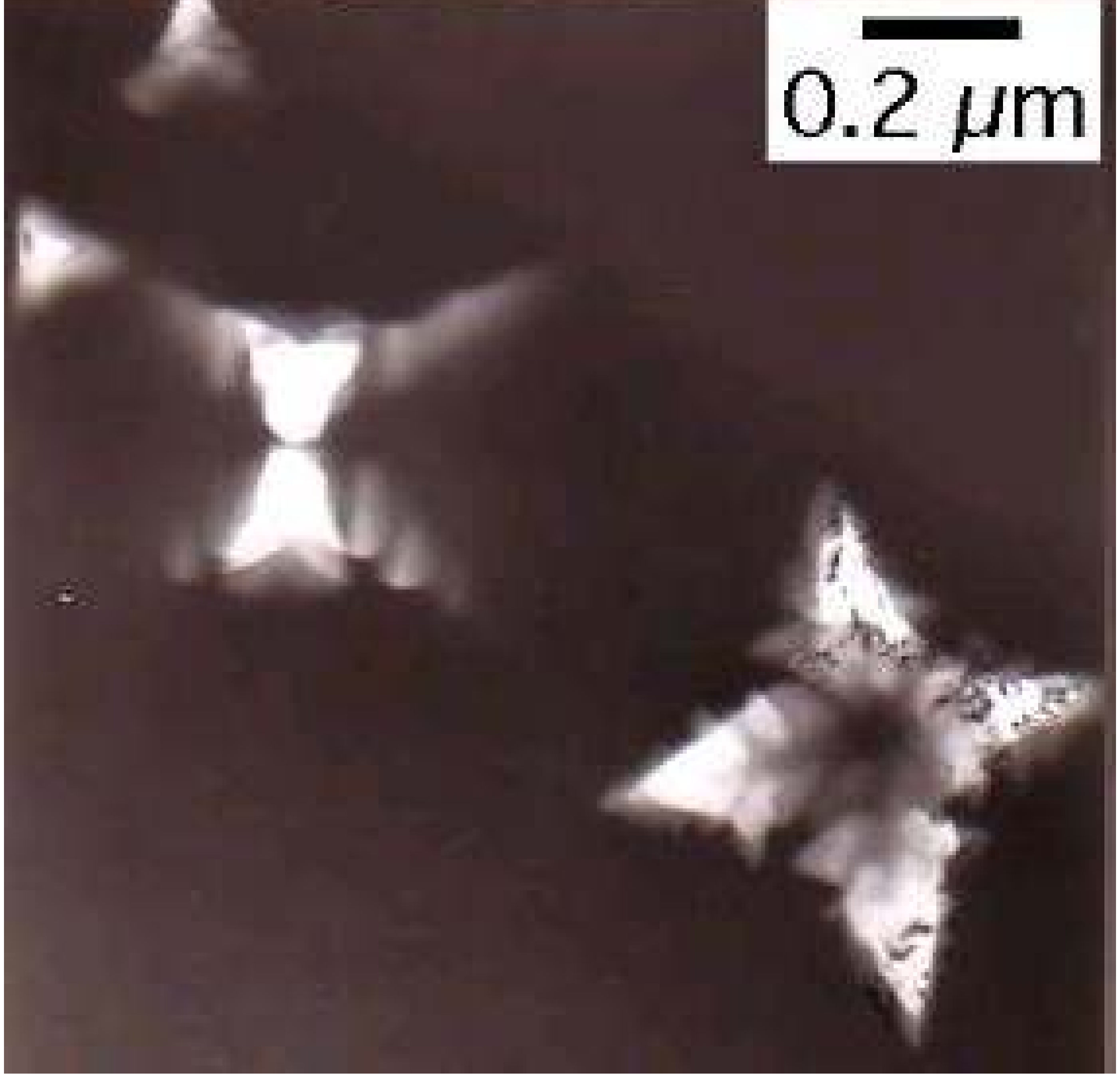


Dendrites of water in ice

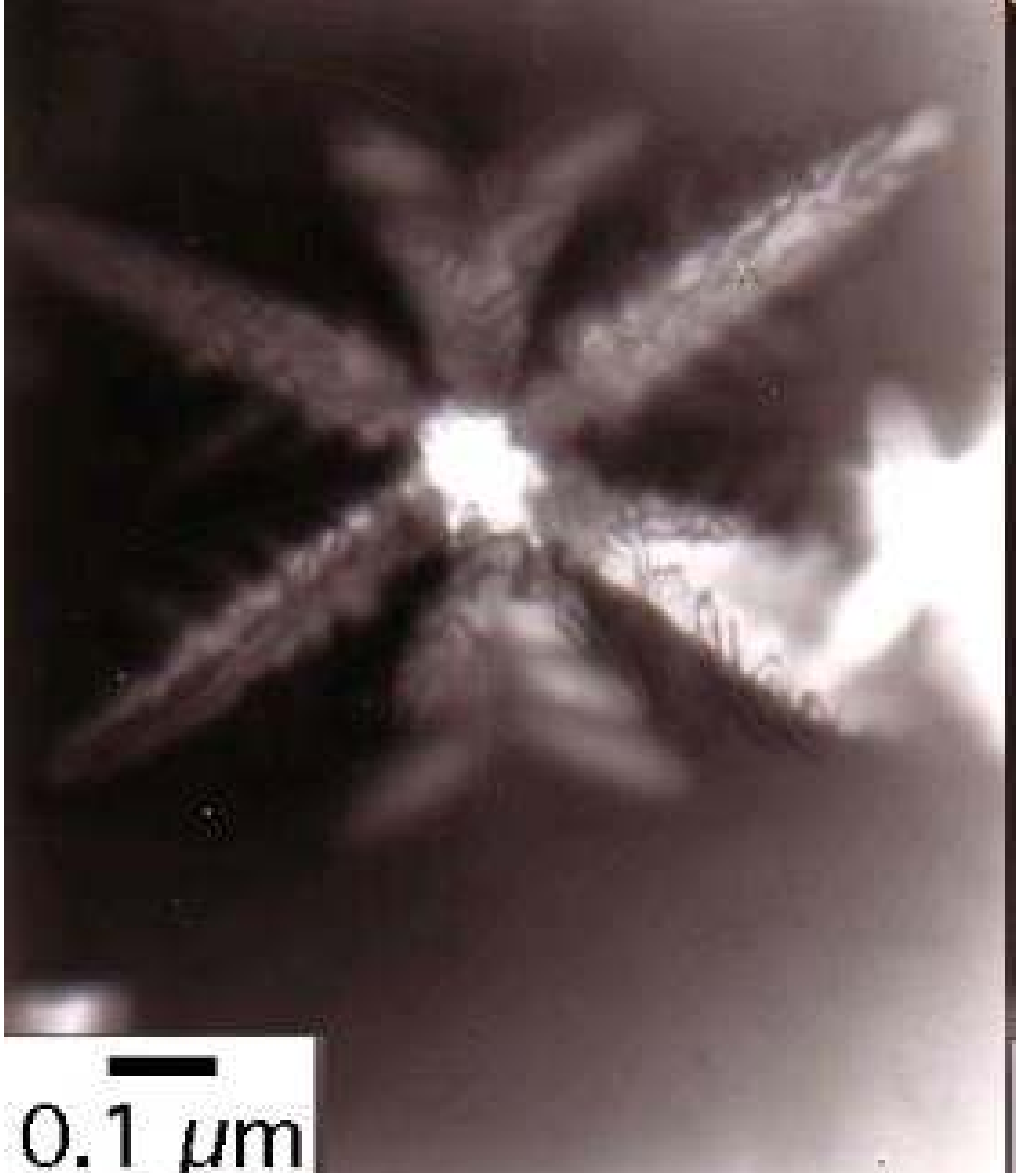
Dendrites of zinc rescued from partially solidified melt

Dendrites of ice on window, Harbin, China (-25 ^{o}C)

Dendrites forming in Fe82Si4B14 metallic glass.



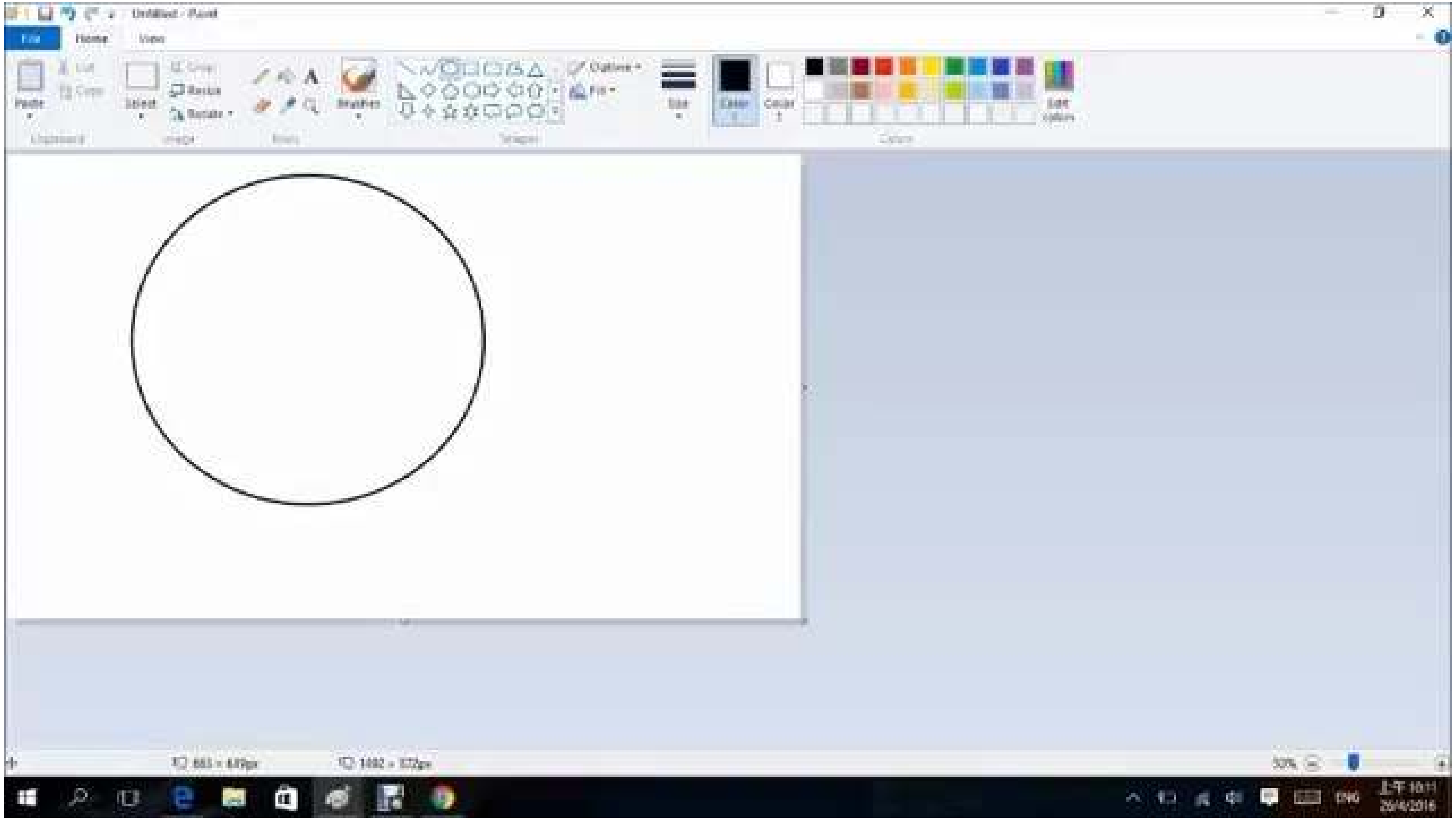
Dendrites forming in $Fe_{82}Si_4B_{14}$ metallic glass



Dendrites forming in Fe82Si4B14 metallic glass

Grain

- The randomly formed nuclei will be having different crystallographic orientations. The nuclei grow into crystals by the successive addition of atoms from the surrounding liquid.
- All these neighboring crystals (or grains) will be oriented differently due to their independent formation.
- As these grow, the outer arms of the neighboring crystals meet similar extremities of other neighboring grains. Finally at a certain stage, further growth outwards becomes impossible, the remaining liquid is used up in thickening the existing dendrite arms and solidification will be completed.
- This independent formation of each crystal leads to the irregular shape of the crystal. These crystals are commonly called grains.
- **A grain is a portion of the material within which the atomic arrangement is nearly identical. But the orientation of the atomic arrangement may be different for adjoining grains.**
- The area, along which the grains meet is known as grain boundary, is a region of mismatch, because atoms at the grain boundary are irregularly placed.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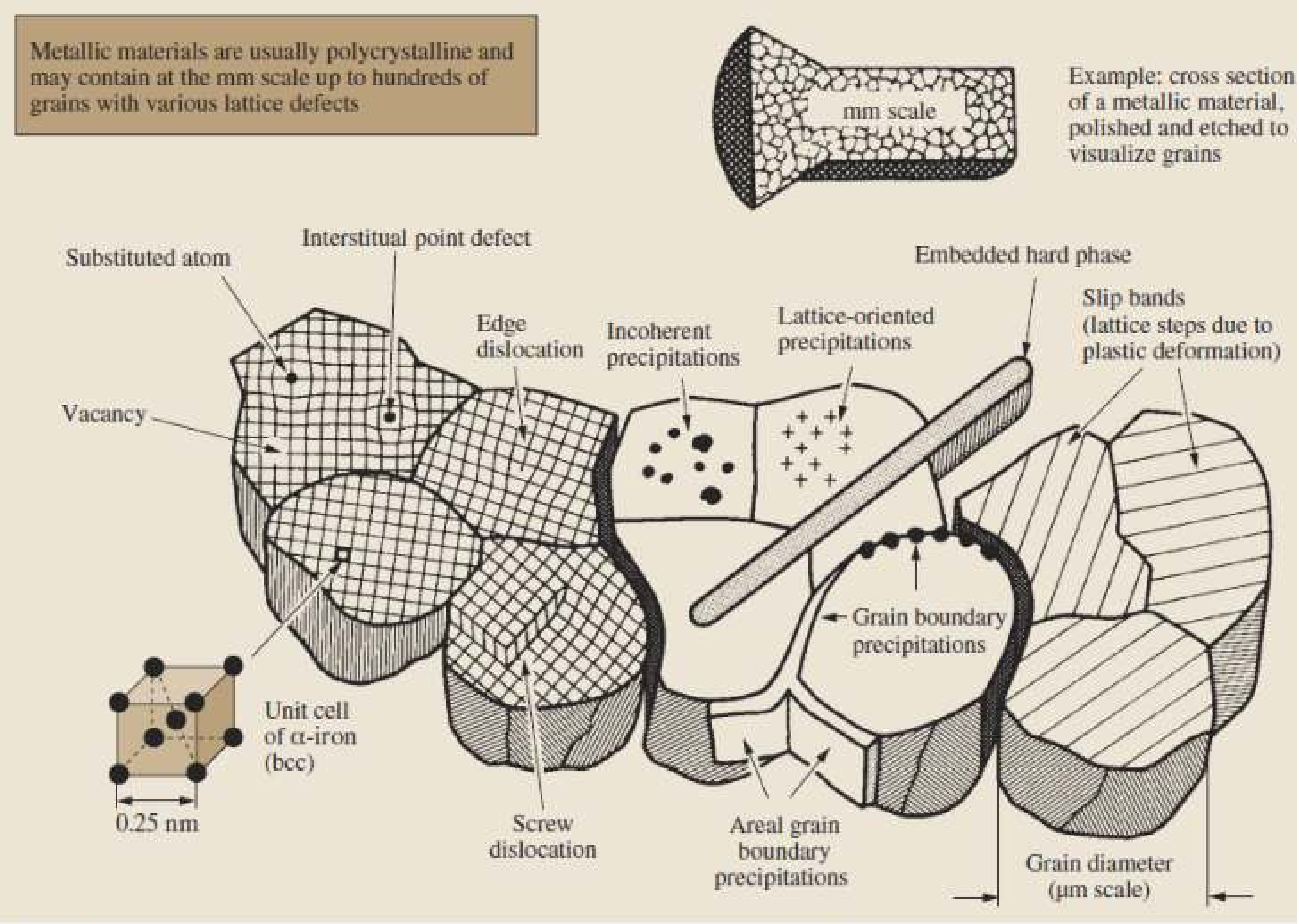


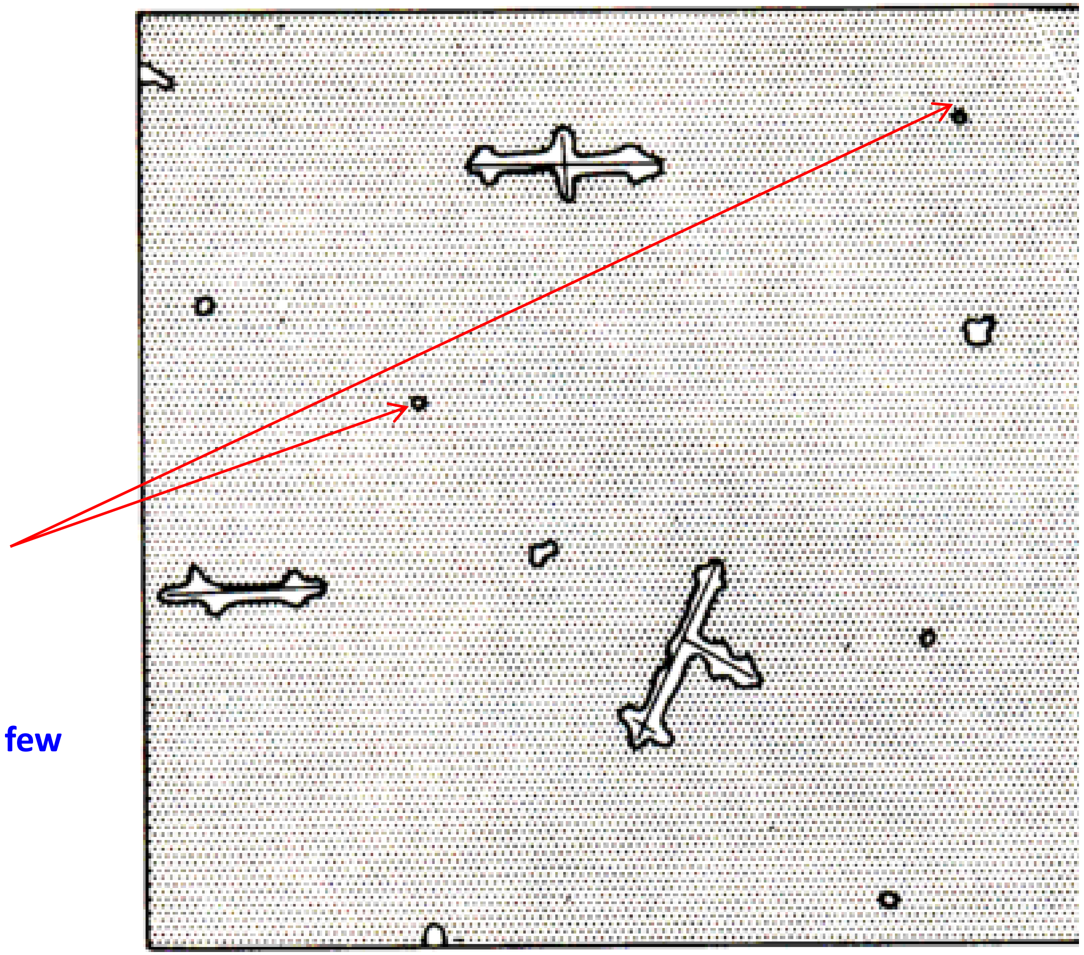
Fig. 1.9 Schematic overview on the microstructural features of metallic materials and alloys

Metallic Structures

- This **crystalline structure** gives metals their **properties** (strength, stiffness, ductility, conductivity & toughness).
- Each **dendrite** grows in a **geometric pattern** consistent with the lattice structure until each one touches its neighbour. At this point the dendrites begin to thicken to form a totally solid **grain** of metal.
- The grain boundaries between are visible under a microscope, each grain having the same structure but a different orientation. This boundary is a narrow zone (perhaps three atoms) in which the atoms are not properly spaced according to the lattice structure.

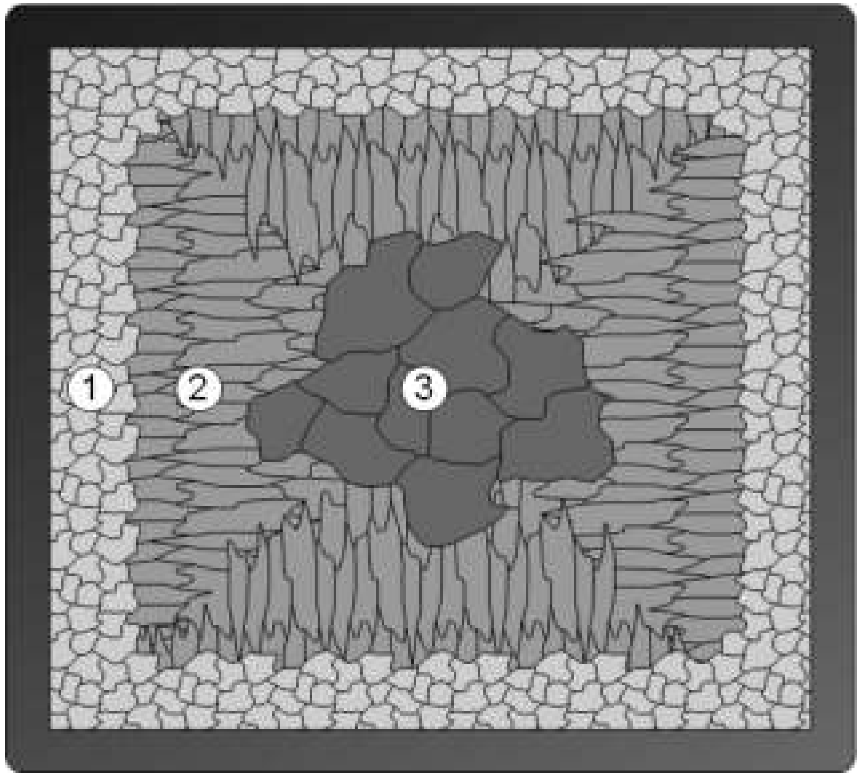
Single Crystal & Poly crystals

- When a liquid is cooled slowly in equilibrium with the surroundings, the solid that form contains tiny crystals called grains.
- The number of grains formed during solidification depends on the number of nuclei formed.
- If all nucleation sites except one are suppressed, the liquid solidifies into a **single grain**. Even the orientation of grain can be engineered to be in a specific direction. Single crystals show excellent high temperature properties because of the absence of grain boundaries.
- When the liquid is normally cooled under equilibrium condition, there would be abundant nucleation sites and the liquid solidifies into a large number of small grains.
- Although these grains look alike, the crystallographic orientations are different and the orientation changes randomly from one grain to other. Such a solid is called polycrystalline.



Nuclei – not center of an atom, is the center of few atoms together

Microstructure of a casting



- Polygonal crystal growth also explains the typical three-zone microstructure of a solidified casting block (primary microstructure). Such a casted block is also called ingot.
- In the vicinity of the mold wall, a very fine-grained structure with roundish grains (globulites) forms due to the strong isotropic undercooling caused by the cool mold wall **(zone I).**
- Subsequently, a zone with elongated grains (columnar crystals) is obtained due to the strongly directed, anisotropic heat dissipation towards the mold wall (transcrystalline zone II).
- The relatively low (isotropic) cooling or undercooling inside the casting block produces a very coarse-grained microstructure (zone III).
- By subsequent heat treatment, this heterogeneous structure can be transformed into a homogeneous structure with the desired properties (secondary microstructure).

Growth of Crystals and Formation of Grain Structure

- Nucleus grow into crystals in different orientations.
- Crystal boundaries are formed when crystals join together at complete solidification.
- Crystals in solidified metals are called grains.
- Grains are separated by grain boundaries.
- More the number of nucleation sites available, more the number of grains formed.

Nuclei growing into grains
Forming grain boundaries

Types of Grains

- **Equiaxed Grains**:
  - Crystals, smaller in size, grow equally in all directions.
  - Formed at the sites of high concentration of the nuclie.
  - Example:- Cold mold wall

- **Columnar Grains**:
  - Long thin and coarse.
  - Grow predominantly in one direction.
  - Formed at the sites of slow cooling and steep temperature gradient.
  - Example:- Grains that are away from the mold wall.

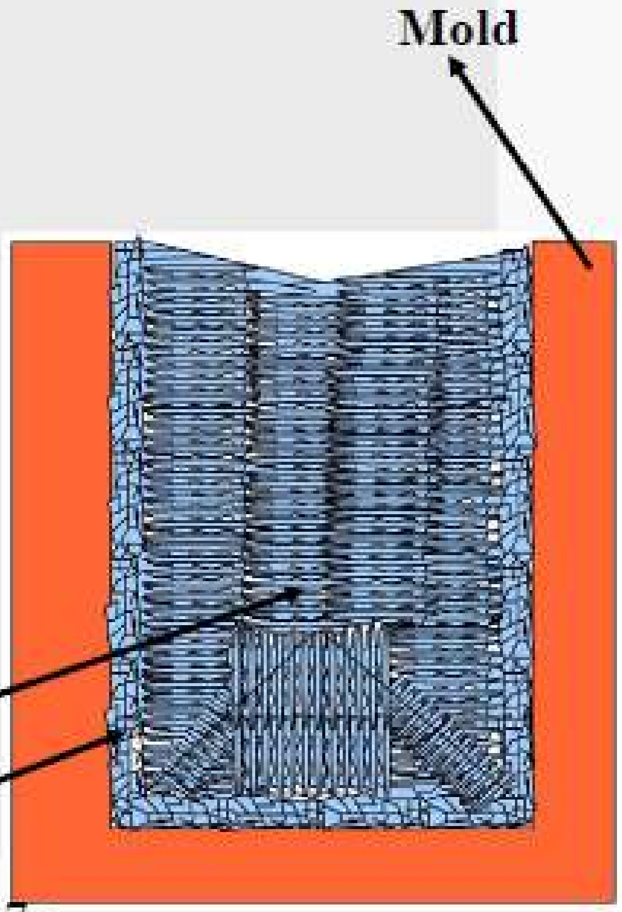


Figure 4.7a

Grain Structure in Industrial castings

- To produce cast ingots with fine grain size, *grain refiners* are added.
- Example:- For aluminum alloy, small amount of Titanium, Boron or Zirconium is added.

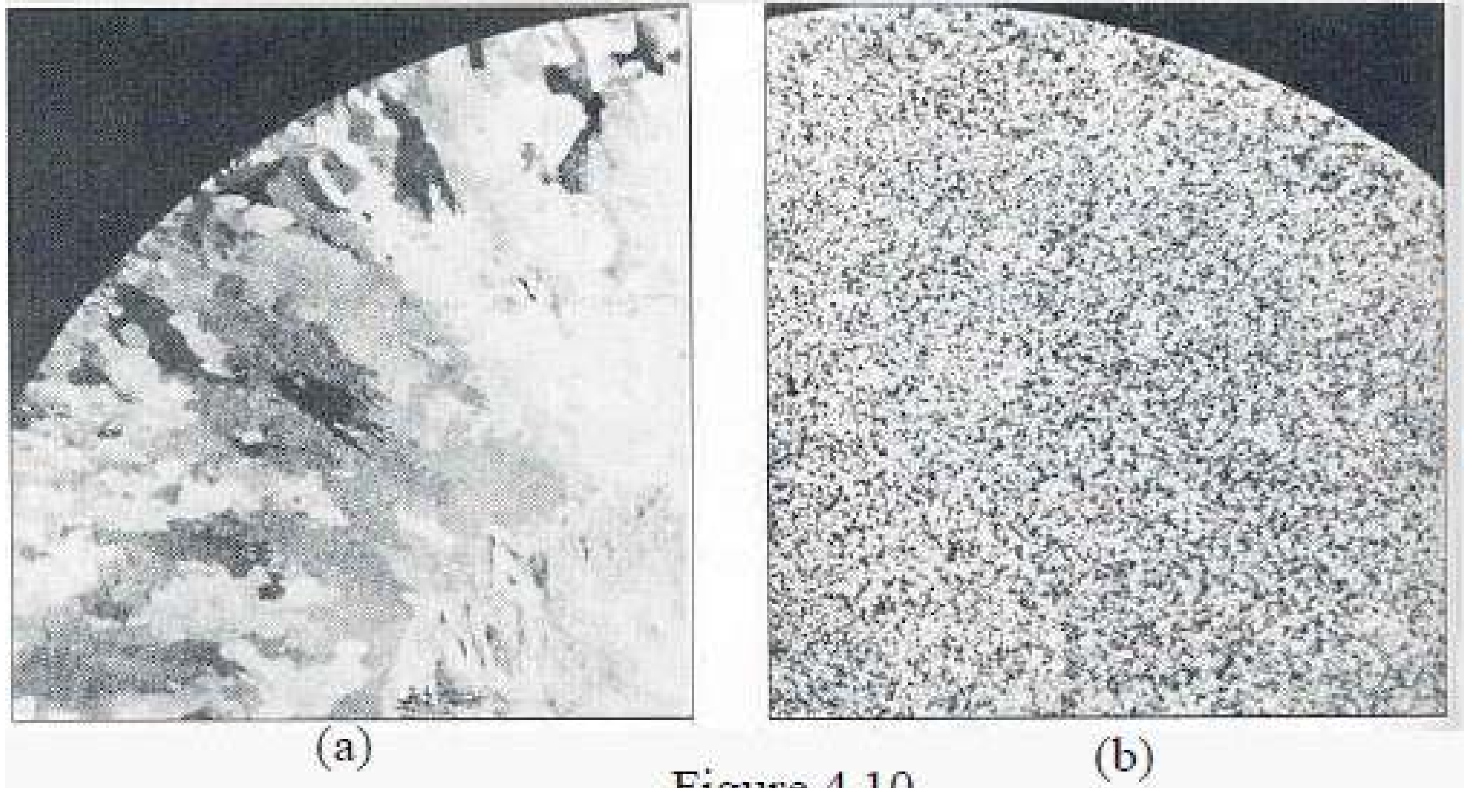

(a) (b)

Figure 4.10

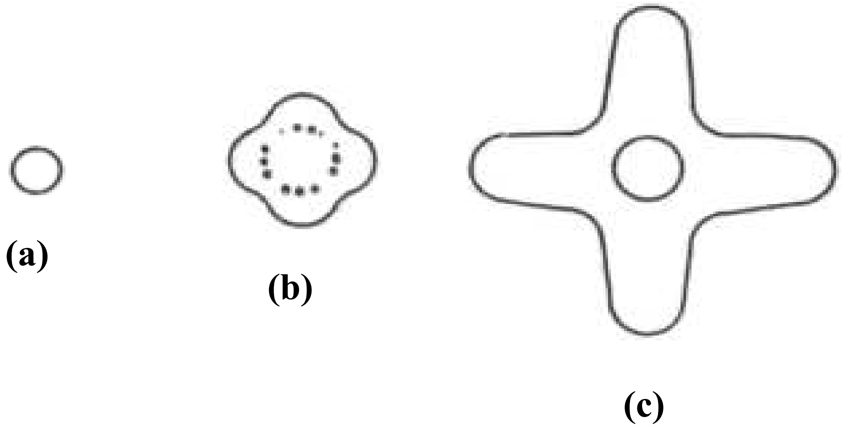
Grain structure of Aluminum cast with (a) and without (b) grain refiners.

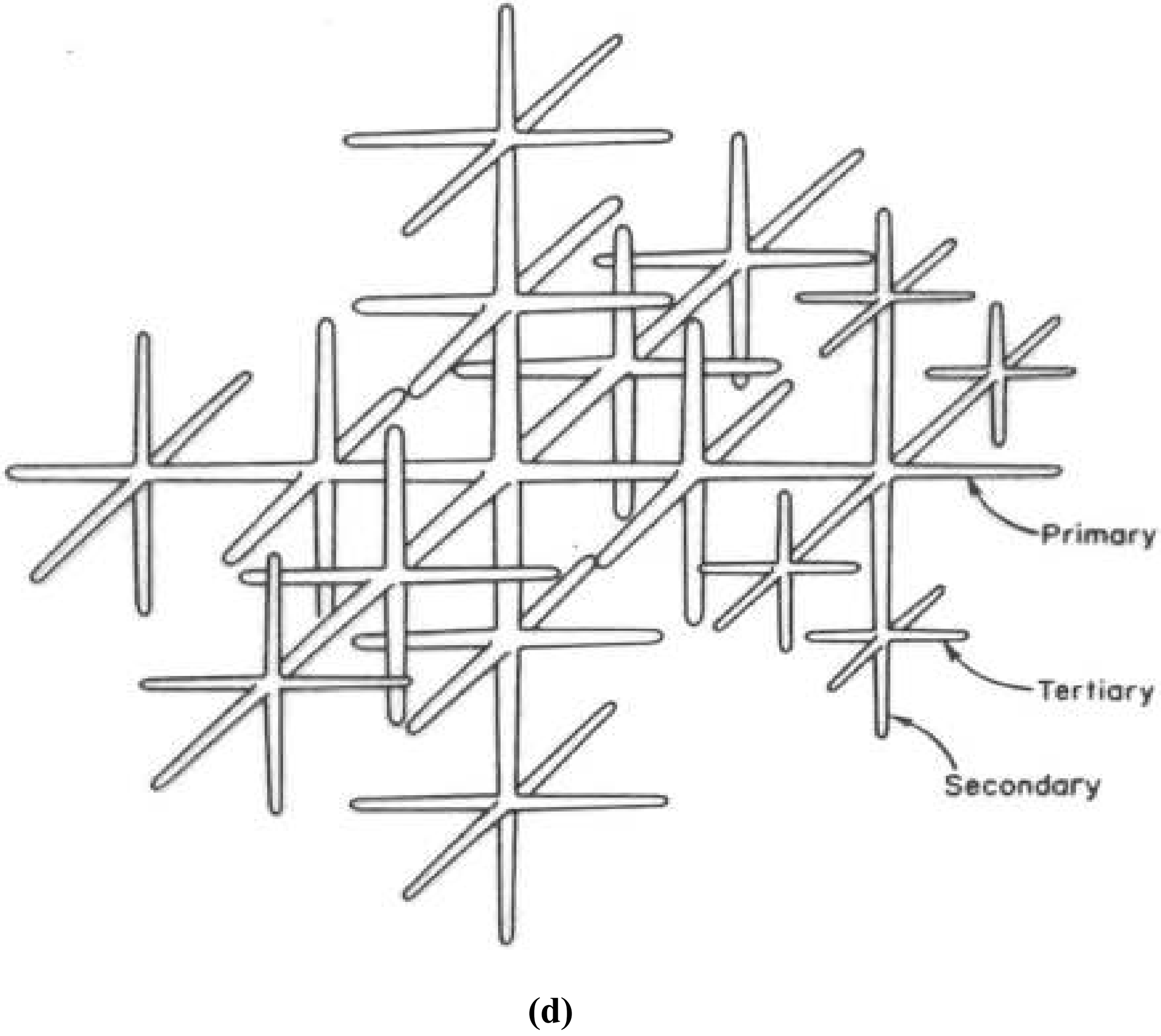
The grain refiners solidify earlier and form a large number of small solid particles in the liquid.

Solidification of the liquid is initiated by heterogeneous nucleation around these solid particles.

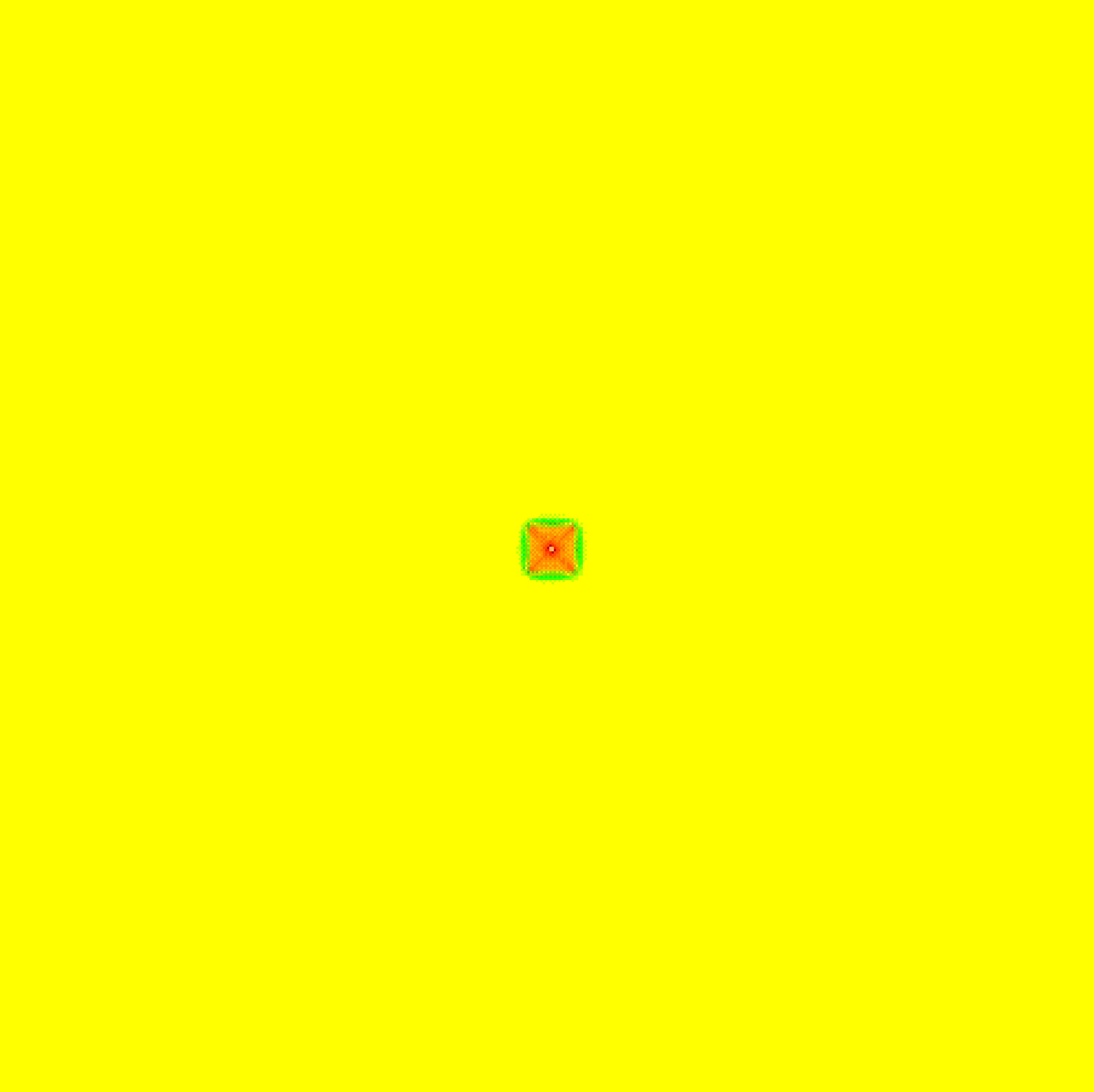
After "Metals Handbook" vol. 8, 8th ed., American Society of Metals, 1973, p.164)

Heat Flow, Interface Stability and Dendritic Growth





The development of dendrites: (a) a spherical nucleus; (b) the interface becomes unstable; (c) primary arms develop in crystallographic directions (<100> in cubic crystals); (d) secondary and tertiary arms develop (after R.E. Reed-Hill, *Physical Metallurgy Principles*, 2nd. Edn., Van Nostrand, New York, 1973.)



Modification of grain size

- The rate of cooling and the amount of impurities in the molten metal will affect grain size:
- Gradual cooling - a few nuclei are formed – leads to large grain size
- Rapid cooling - many nuclei formed - small grain size.
- Reheating a solid metal / alloy allows the grain structure to re-align itself.
- Directional cooling in a structure is achieved by selectively cooling one area of a solid.
- The effect of impurities (or additives) in a molten metal can induce a large number of fine grains that will give a stronger and harder metal. This addition must be carefully controlled as too many impurities may cause an accumulation at the grain boundaries, which will weaken the material.

- Walls of mold is cold - large under cooling - fine grains form at walls of the mold.
- Cubic lattice – some grains grows faster than other grains – Easy grow direction -cooling rate is faster in <100> / fastest growth direction - <100> is parallel to heat flow – coarse structure - columnar structure.
- Presence of dirt particles at center portion of molten pool lead to form equiaxed structure.

Features of Grains

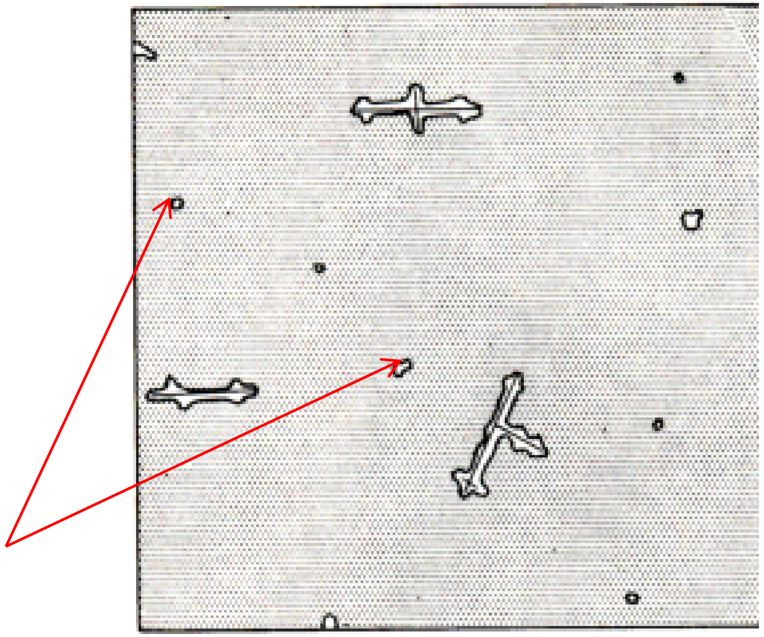
GRAIN SIZE DISTRIBUTION;

GRAIN SHAPE and

GRAIN ORIENTATION

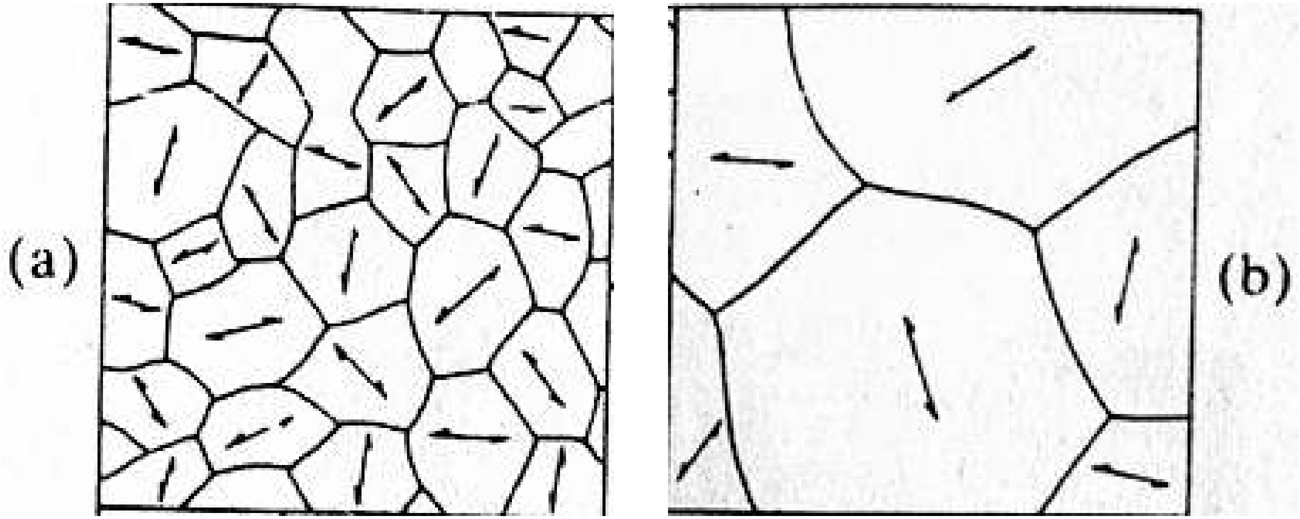
GRAIN SIZE

- Size of the crystal formed depends on the rate at which a molten metal is cooled.
- A slow fall in temperature, which leads to a small degree of undercooling at the onset of solidification, promotes the formation of relatively few nuclei, so that the resultant crystal size will be large.



Nuclei – not center of an atom, is the center of few atoms together

- Grain size is having effect on material properties
- There are methods to control the nucleation process and thereby the material properties.
- Grain size in materials is also controlled by the combination of controlled deformation and thermal treatments, called thermo mechanical treatments.



(a) grain size *(20 - 50μm – small* (b) *100 - 200μm - large)*

Orientation of grains –Random

Equiaxed (approximately equal dimensions in the three coordinate directions)

EFFECT OF GRAIN SIZE

Hall – Petch equation

The Hall-Petch equation gives a general relationship between the yield stress and grain size of a material.

$$\sigma_y = \sigma_0 + K d^{-1/2}$$

where σ_y is the yield strength (the stress needed to cause plastic deformation), d is the average diameter of grains, σ_i and K are constants for the material. It is to be noted that the dislocation density has been experimentally observed as an inverse function of grain size.

Constants indicating the extent to which dislocations are piled up at barriers (such as grain boundaries)

σ_0 Basic yield stress that can be regarded as the stress opposing the motion of dislocations

Valid for many materials but not for nano-structures and very large grain material !!

- Hall-Petch equation finds application in design of components made of metallic materials.
- Using this relationship, yield stress, σ_y of a material for a given grain size or the grain size to be developed for obtaining a required yield stress can be evaluated.
- An estimation of the yield stress for the materials can be made by determining the grain size using a micrograph.

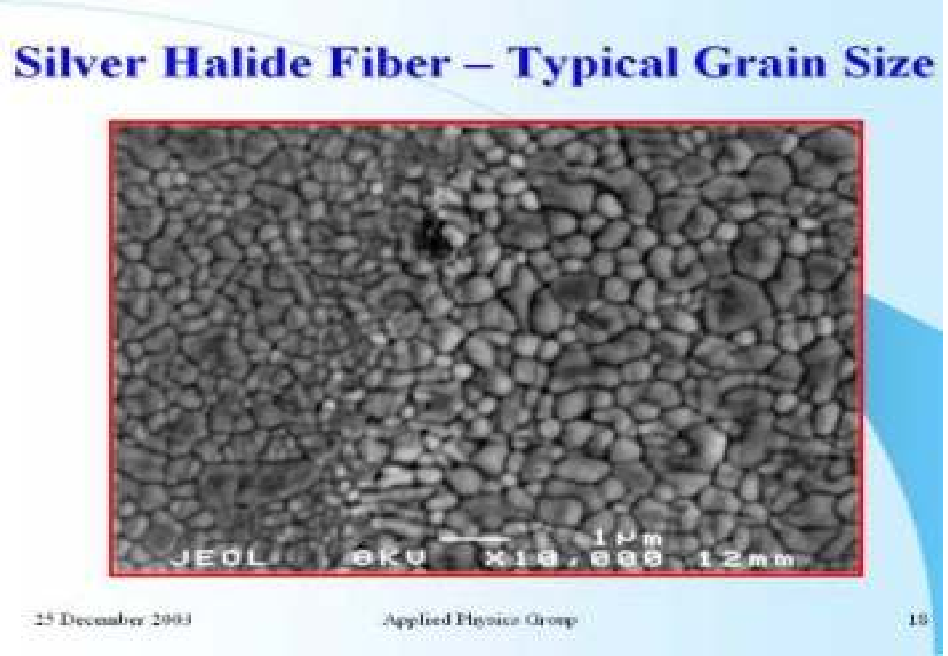
Effect of Grain size on Material Strength

- Smaller grain size – *More number of grains*!!!
- More number of grains – *More barriers for slip*!!!
- More barriers for slip - *Increased material strength*!!!

- Influence of grain boundaries in dislocation movement - restricting or hindering dislocation motion makes material harder and stronger.

How is grain size measured?

1. Counting the grains in a given area
2. Counting number of grains that intersect a length of a line (microscopic)
3. Determined by comparing to a standard chart (ASTM Chart)

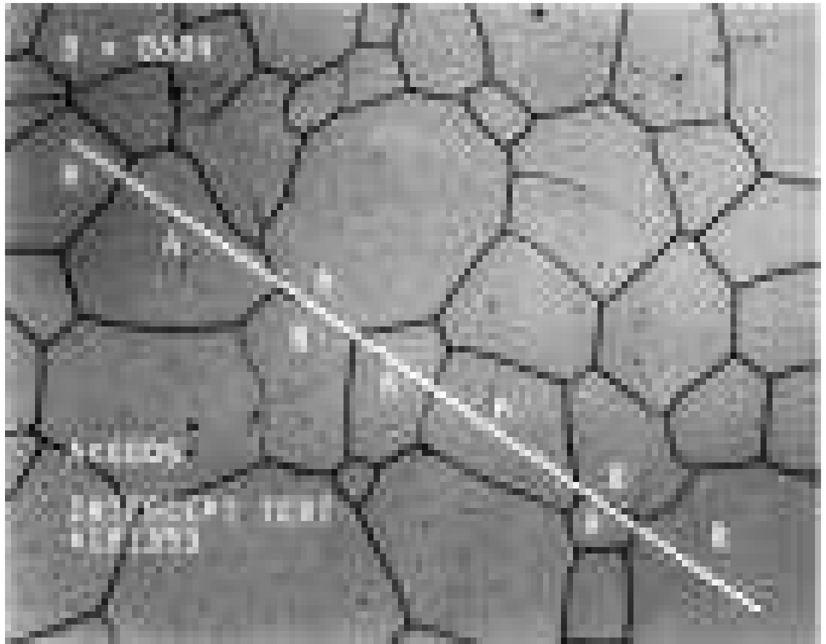


Silver Halide Fiber – Typical Grain Size

25 December 2003

Applied Physics Group

18



Grain Size

ASTM Grain size number

- Calculated as:

$$N = 2^{n-1}$$

where:

n=ASTM grain size

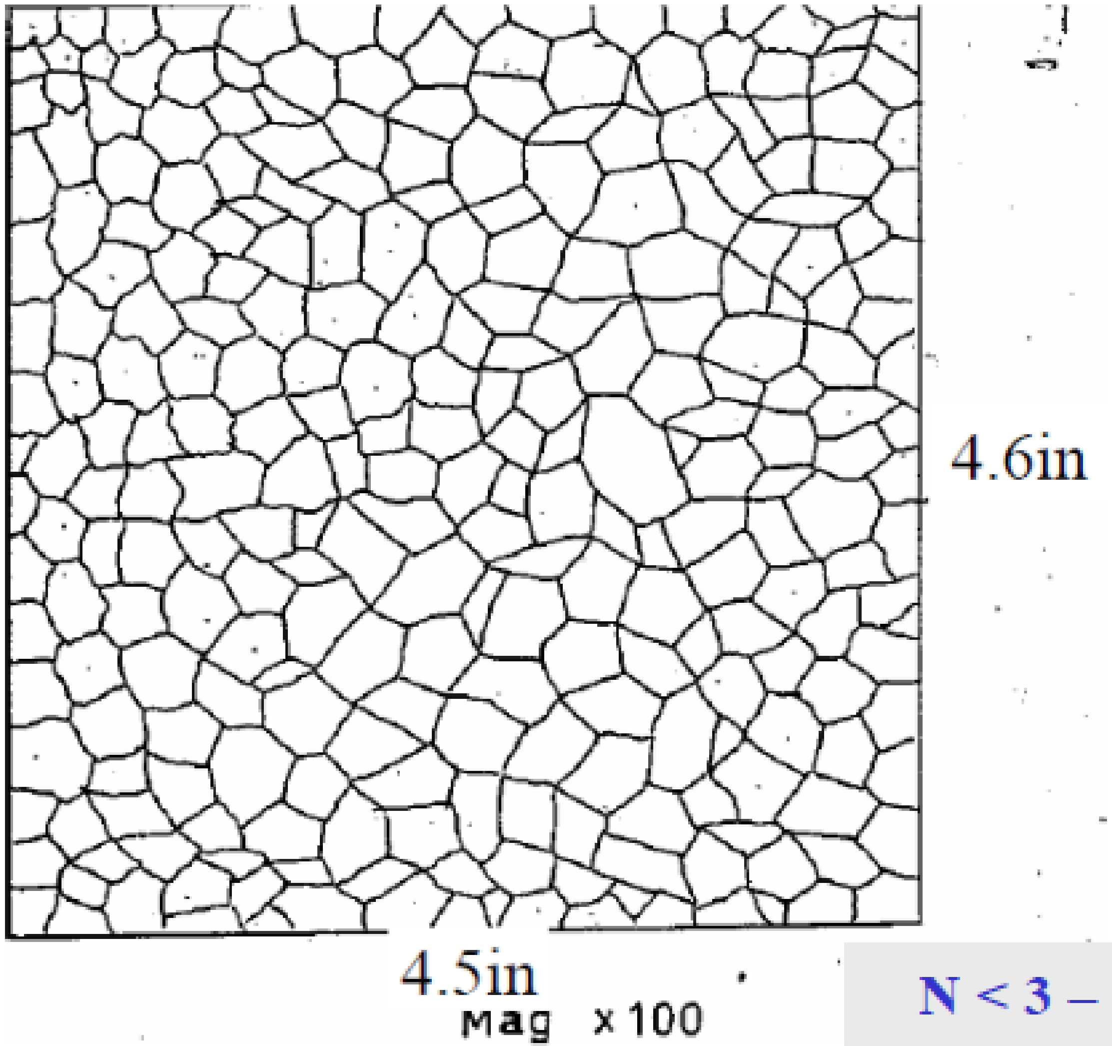
N=grains/in^2 at 100x

$$N = \frac{274}{4.5 \times 4.6} = 13.2$$

$$N = 2^{n-1}$$

$$\log N = (n-1)\log 2$$

$$n = 1 + \frac{\log N}{\log 2} = 4.7$$



$N < 3$ – Coarse grained

$4 < n < 6$ – Medium graine

$7 < n < 9$ – Fine grained

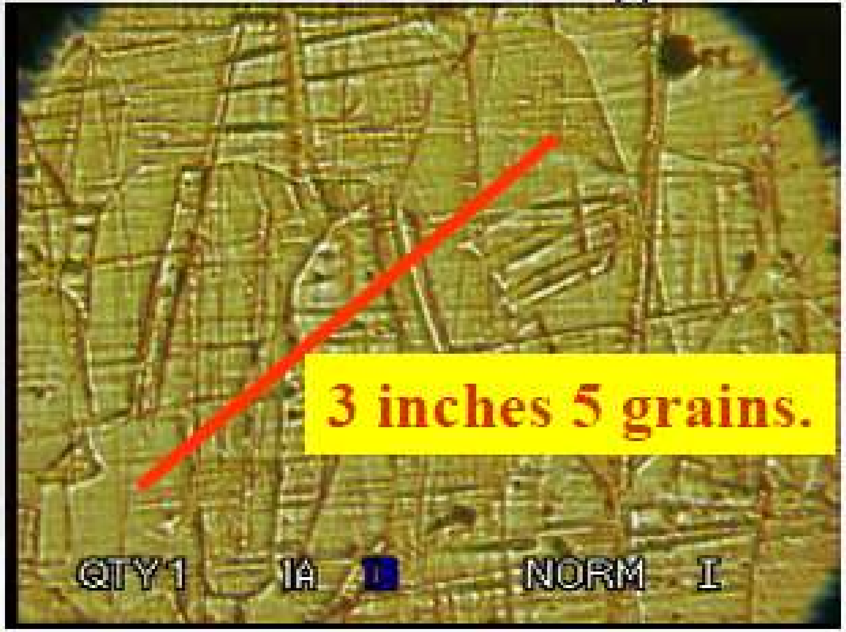
$N > 10$ – ultrafine grained

Average Grain Diameter

- **Average grain diameter** more directly represents grain size.
- Random line of known length is drawn on photomicrograph.
- Number of grains intersected is counted.
- Ratio of number of grains intersected to length of line, n_L is determined.

$$d = C/n_L M$$

C=1.5, and M is magnification


3 inches 5 grains.

Measuring Grain Size

- Mean Intercept Method
  - Draw random line
  - Count g.b. intersections

$$d = \frac{Length/Mag.}{n}$$

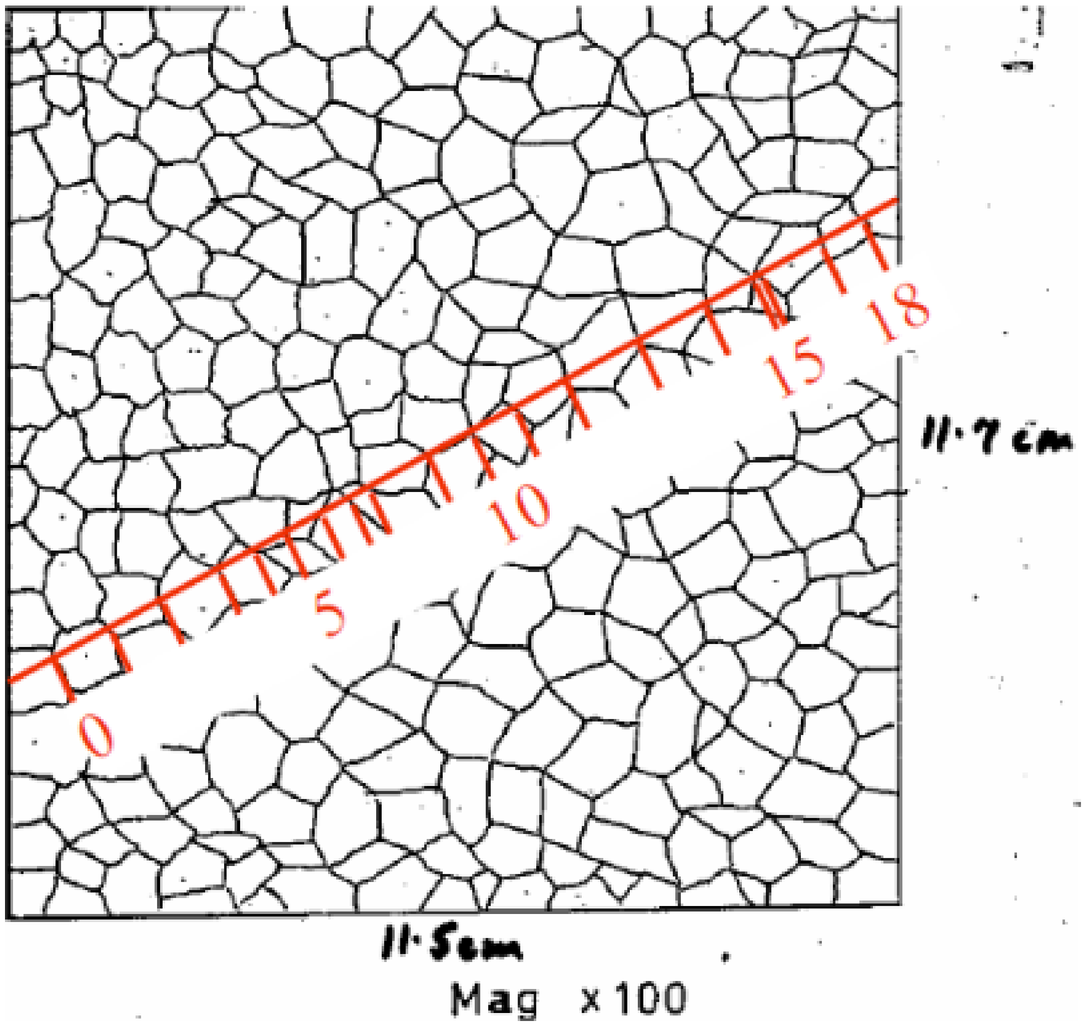
$$L = 11.6cm$$

$$M = 100; \quad n = 18$$

$$d = \frac{11.6/100}{18}$$

$$= 6.4 \times 10^{-3} cm$$

$$= 64 \mu m$$

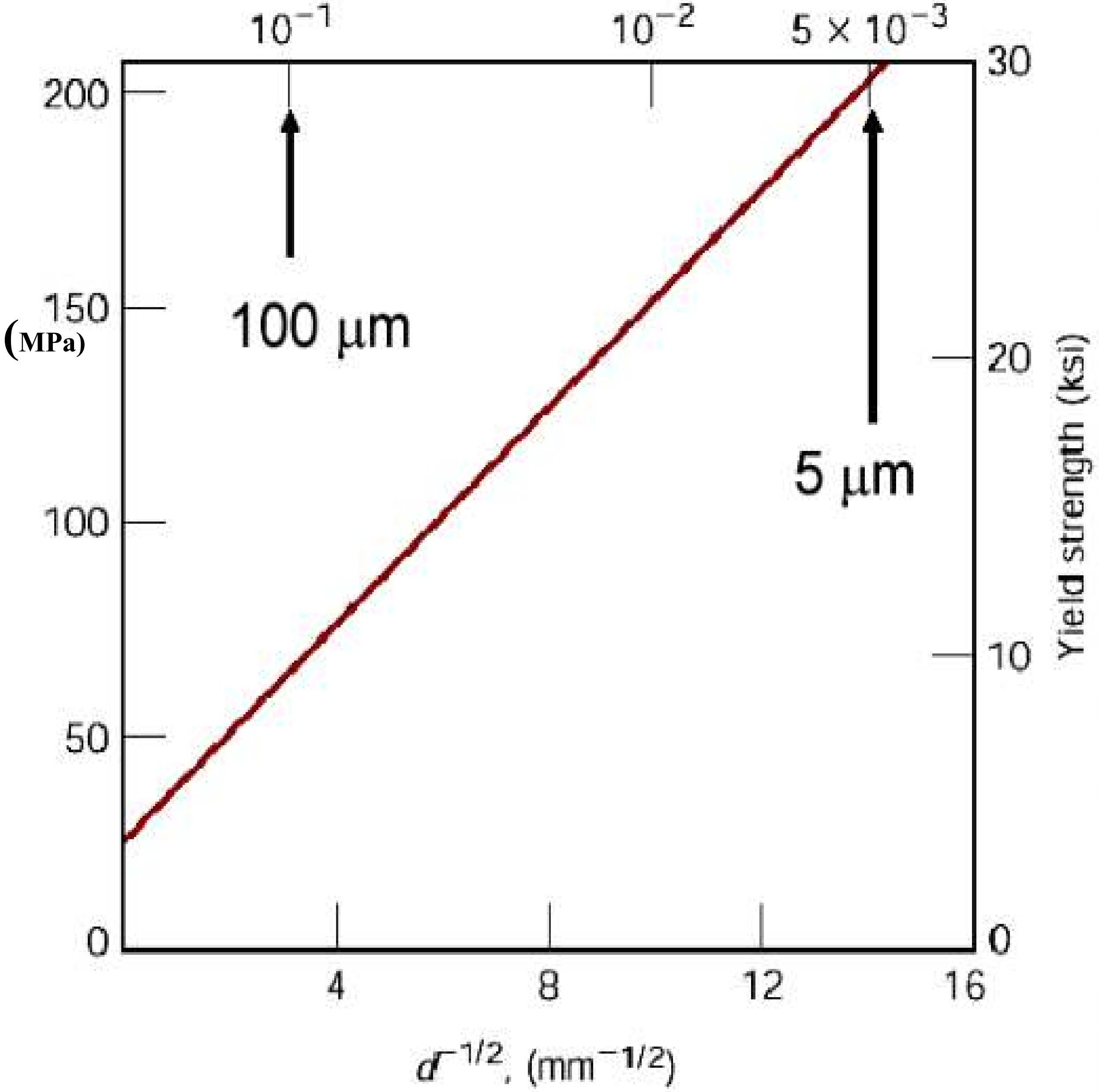


The effects of grain size on yield strength

- A change in grain size affects the yield strength due to the dislocations interacting with the grain boundary as they move.
- The boundaries act as obstacles, hindering the dislocation glide along the slip planes. As subsequent dislocations move along the same slip plane the dislocations pile-up at the grain boundaries.
- The dislocations repel each other, so as the number of dislocations in the pile-up increases the stress on the grain boundary increases.
- In a larger grain there will be more dislocations within the grain, so there will be more dislocations in the pile-up.
- Therefore a lower applied stress is required to produce a local stress great enough to cause the grain boundary to collapse.

- A fine-grained material (one that has small grains) is harder and stronger than one that is coarse grained, since the former has a greater total grain boundary area to impede dislocation motion.

- A fine grain size in shaped castings ensures the following:
  (i) Mechanical properties that are uniform throughout the material
  (ii) Distribution of second phases and microporosity on a fine scale
  (iii) Improved machinability because of (ii)
  (iv) Improved ability to achieve a uniformly anodizable surface
  (v) Better strength, toughness, and fatigue life, and
  (vi) Better corrosion resistance



Strength triples as grain size goes from 100 μm to 5 μm.

As d⇓, σ_{ys}⇑ and the ductility or ⇑ or it is constant

Grain Size Effect

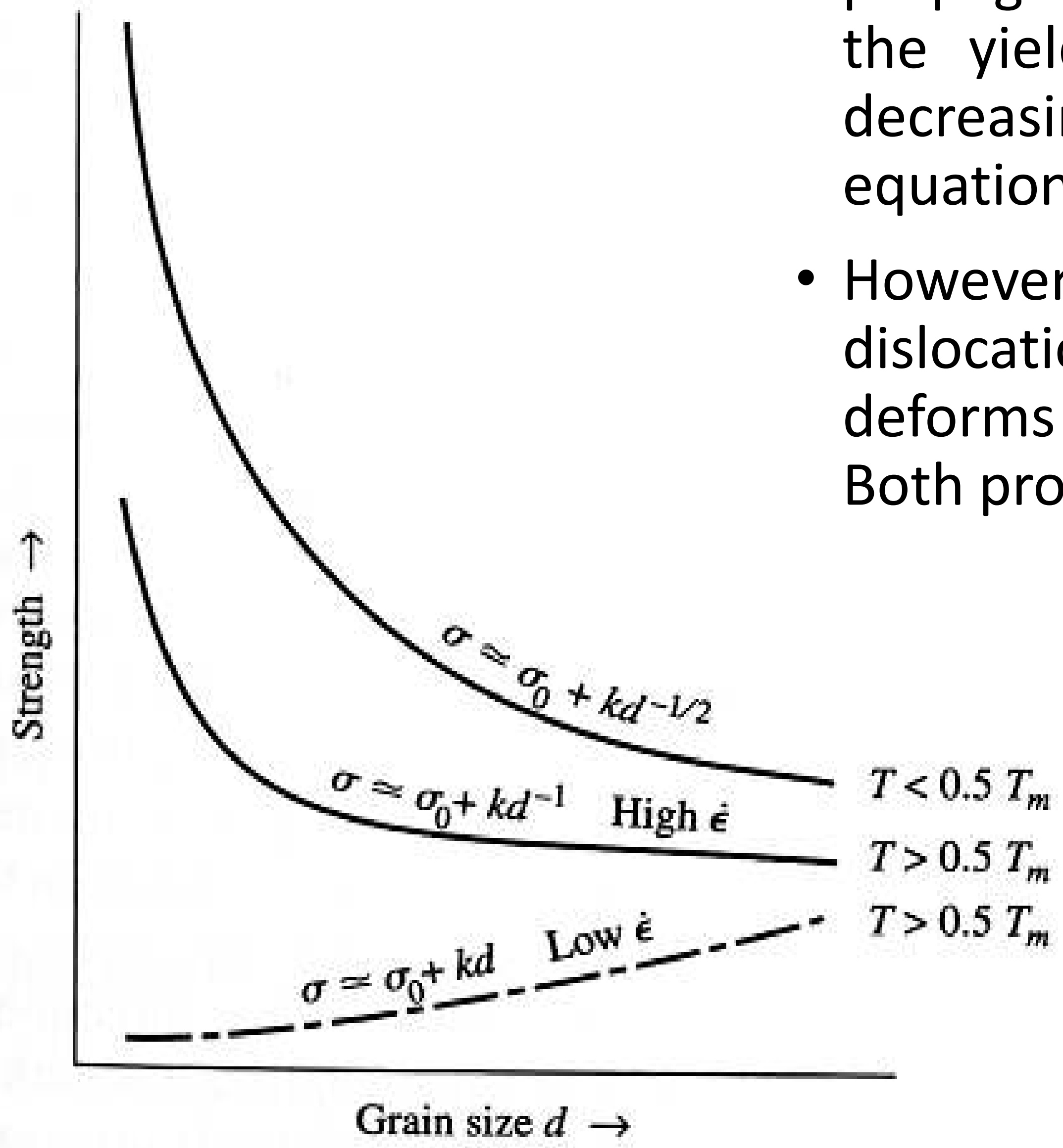


Figure 6–18 The strength of metals increases with

- Grain boundaries present obstacles to dislocation propagation. Therefore, it is generally found that the yield strength of a material increase with decreasing grain size according to the Hall-Petch equation.
- However at low strain rate and close to Tm, dislocation is resolved by diffusion. Material deforms by sliding of grains or reshaping of grains. Both processes are easier if grain size is small.

WORKED EXAMPLE

The strengthening of a polycrystalline metal is provided by grain refinement. The tensile yield stress of the metal is 4×10^8 N m^{-2} when the grain size is 0.36 mm, and 3×10^8 N m^{-2} when it is 0.81 mm. Calculate the strength when the grain size is 0.5 mm.

Solution

Hall–Petch: $\sigma_y = \sigma_0 + k_y d^{-1/2}$.

The two conditions give: $4 = \sigma_0 + k_y/\sqrt{0.36}$ and $3 = \sigma_0 + k_y/\sqrt{0.81}$.

Solving gives: $k_y = 1.8 \times 10^8$ Pa mm$^{1/2}$, $\sigma_0 = 1 \times 10^8$ Pa.

For a grain size of 0.5 mm, $\sigma_y = (1 + 1.8/\sqrt{0.5}) \times 10^8$ Pa $= 3.5 \times 10^8$ Pa.

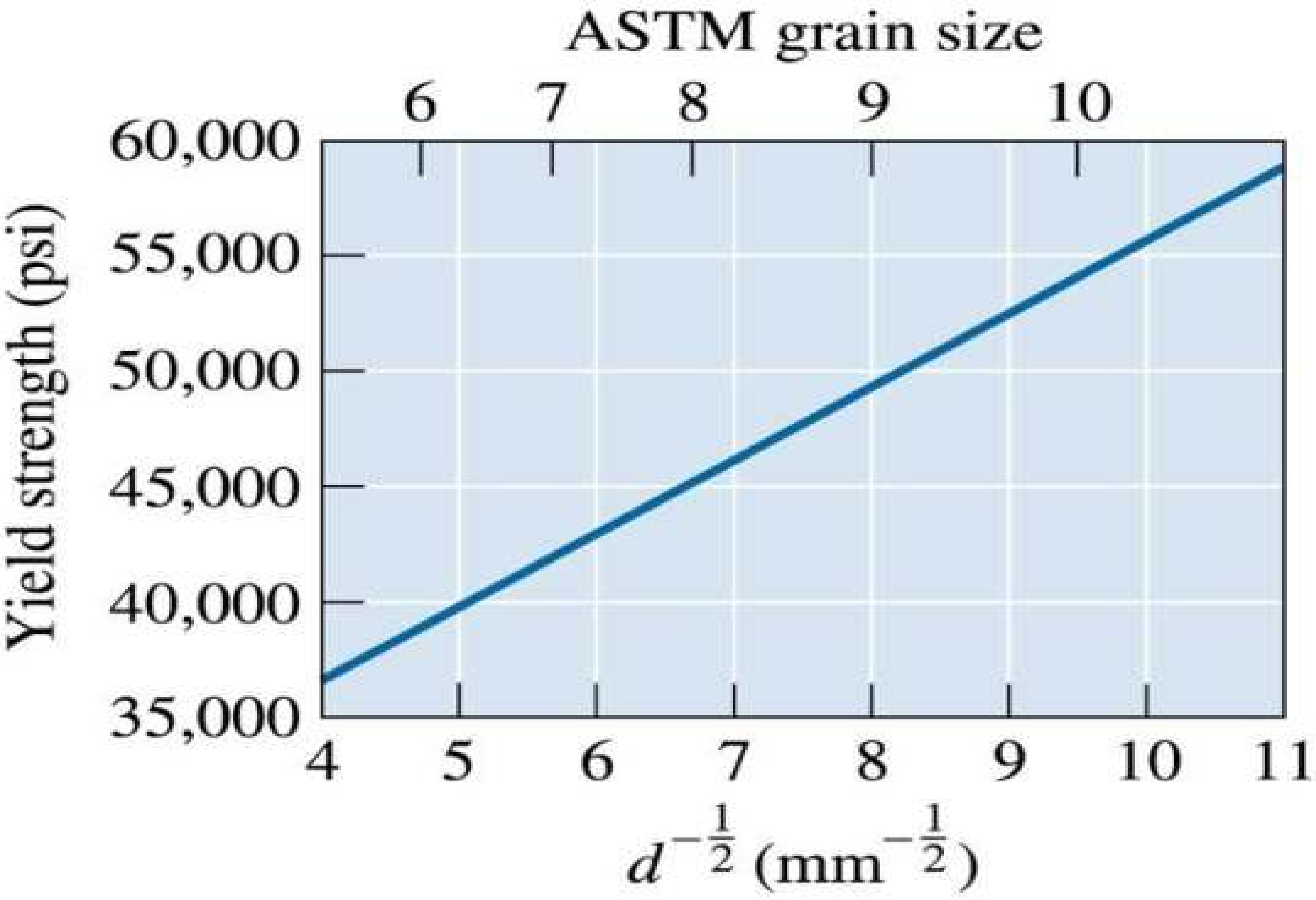


Figure 4.17 The effect of grain size on the yield strength of steel at room temperature.

Example 1 Design of a Mild Steel

The yield strength of mild steel with an average grain size of 0.05 mm is 20,000 psi. The yield stress of the same steel with a grain size of 0.007 mm is 40,000 psi. What will be the average grain size of the same steel with a yield stress of 30,000 psi? Assume the Hall-Petch equation is valid and that changes in the observed yield stress are due to changes in dislocation density.

Example 1 SOLUTION

$$\sigma_y = \sigma_0 + Kd^{-1/2}$$

Thus, for a grain size of 0.05 mm the yield stress is

20 × 6.895 MPa = 137.9 MPa.

(Note:1,000 psi = 6.895 MPa). Using the Hall-Petch equation

Example 1 SOLUTION (Continued)

$$137.9 = \sigma_0 + \frac{K}{\sqrt{0.05}}$$

For the grain size of 0.007 mm, the yield stress is 40 × 6.895 MPa = 275.8 MPa. Therefore, again using the Hall-Petch equation:

$$275.8 = \sigma_0 + \frac{K}{\sqrt{0.007}}$$

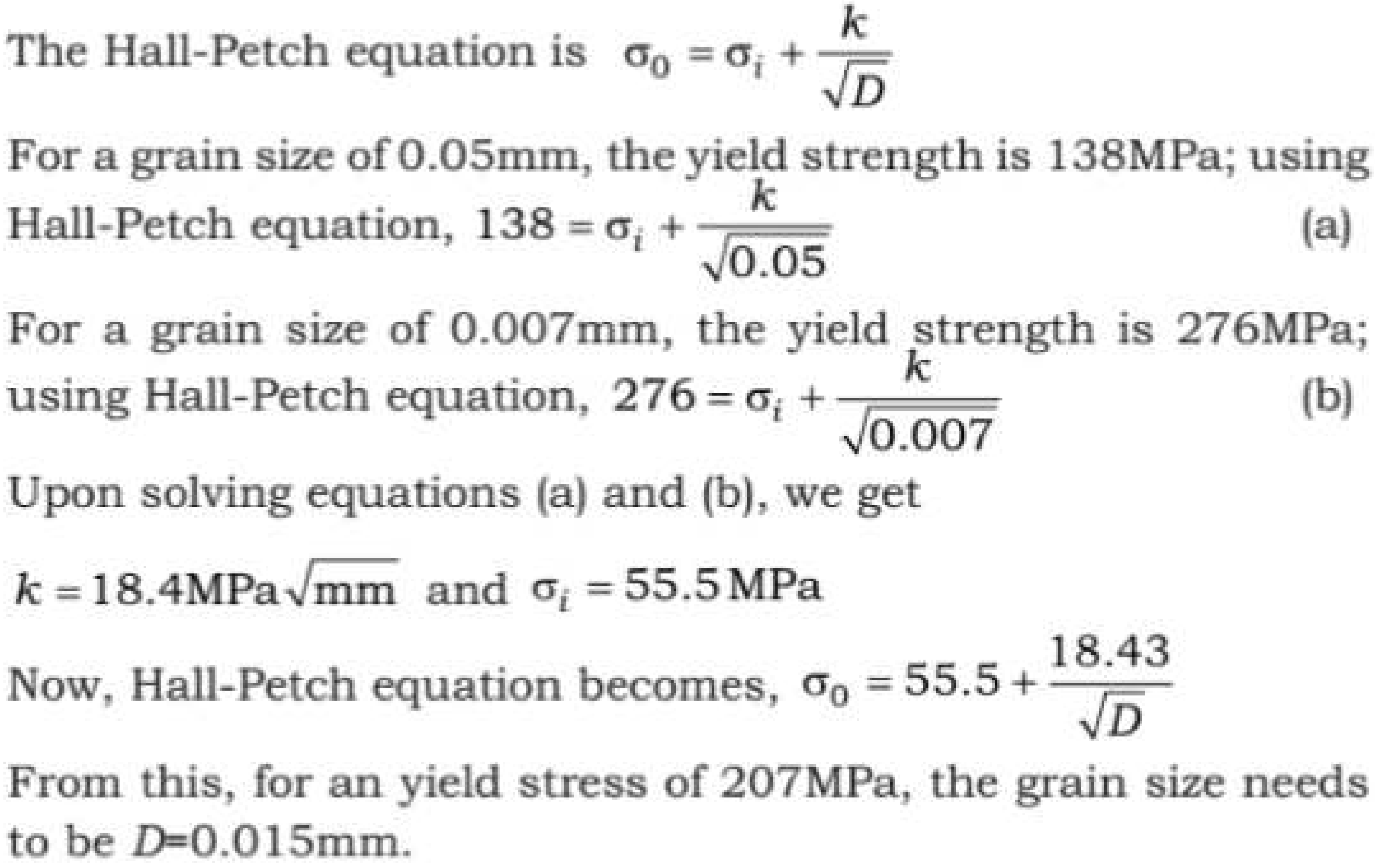
Solving these two equations K = 18.43 MPa-mm$^{1/2}$, and $\boldsymbol{\sigma}_0 = 55.5$ MPa. Now we have the Hall-Petch equation as

$$\boldsymbol{\sigma}_y = 55.5 + 18.43\ d^{-1/2}$$

If we want a yield stress of 30,000 psi or 30 × 6.895 = 206.9 MPa, the grain size will be 0.0148 mm.

Example 2

The yield strength of mild steel with an average grain size of 0.05mm is 138MPa. The yield strength of the same steel with a grain size of 0.007mm is 276MPa. What will be the grain size of the same steel with a yield stress of 207MPa. Assume the HallPetch equation is valid and that the changes in yield stress are due to changes in grain size.



The Hall-Petch equation is $\sigma_0 = \sigma_i + \frac{k}{\sqrt{D}}$

For a grain size of 0.05mm, the yield strength is 138MPa; using Hall-Petch equation, $138 = \sigma_i + \frac{k}{\sqrt{0.05}}$ (a)

For a grain size of 0.007mm, the yield strength is 276MPa; using Hall-Petch equation, $276 = \sigma_i + \frac{k}{\sqrt{0.007}}$ (b)

Upon solving equations (a) and (b), we get

$k = 18.4\text{MPa}\sqrt{\text{mm}}$ and $\sigma_i = 55.5\,\text{MPa}$

Now, Hall-Petch equation becomes, $\sigma_0 = 55.5 + \frac{18.43}{\sqrt{D}}$

From this, for an yield stress of 207MPa, the grain size needs to be D=0.015mm.

Example 3

- Assume that a metal has a yield stress of 20 ksi if the grain size is 10^{-4} mm, and 32 ksi if the grain size is 10^{-6} mm. What will be the yield stress if the grain size was 10^{-5} mm, all other things being equal?

$$20 = \sigma_0 + k\sqrt{10000}$$

$$32 = \sigma_0 + k\sqrt{1000000}$$

Solving, we find that k=0.01333 and σ_0 = 18.67

$$\sigma_y = 18.67 + 0.01333\sqrt{100000} = 22.9\,ksi$$

Example 4 Calculation of ASTM Grain Size Number

Suppose we count 16 grains per square inch in a photomicrograph taken at magnification × 250. What is the ASTM grain size number?

Example 4 SOLUTION

If we count 16 grains per square inch at magnification × 250, then at magnification × 100 we must have:

$$N = (250/100)^2\,(16) = 100 \text{ grains/in.}^2 = 2^{n\text{-}1}$$

$$\text{Log } 100 = (\text{n} - 1) \log 2$$

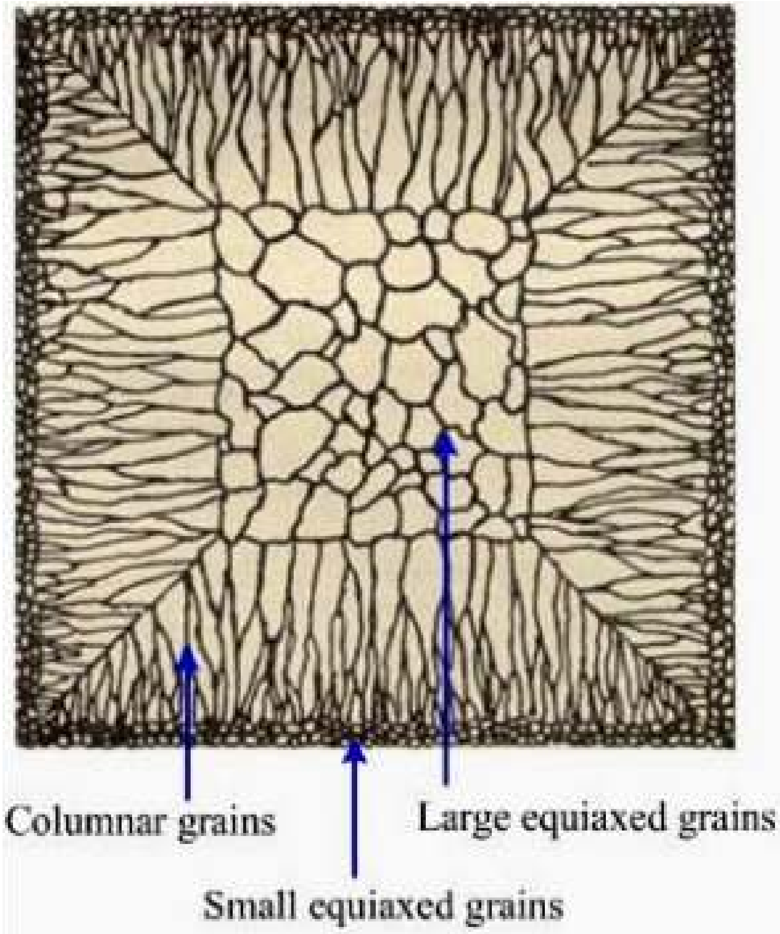
$$2 = (n - 1)(0.301)$$

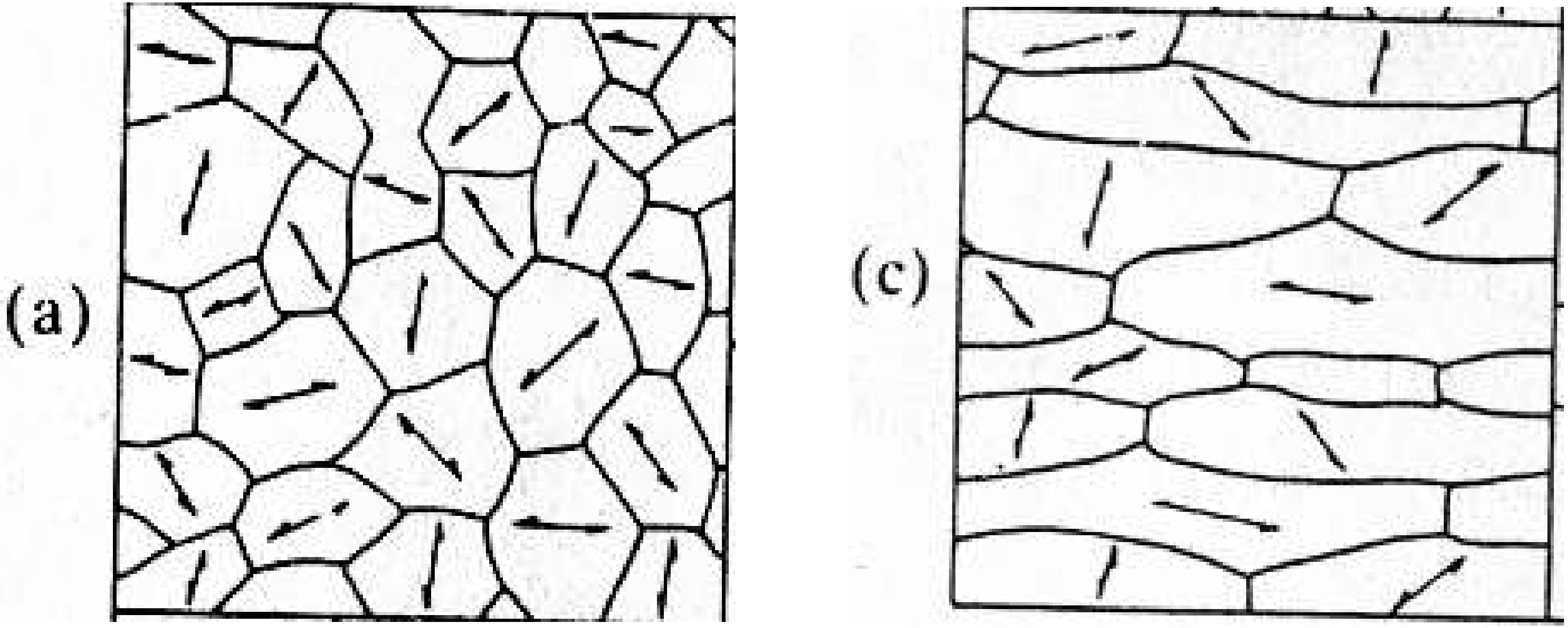
$$n = 7.64$$

Grain Shape

- Three separate zones can be distinguished in an ingot solidified in a large mould.
  - First zone is near to the mould walls where fine grains are observed,
  - Followed by a zone of long columnar grains
  - At the center of mould having coarse, equi-axed grains.
- Nature of the container in which the liquid metal cools, will affect the shape and number of grains

Microstructure of ingots



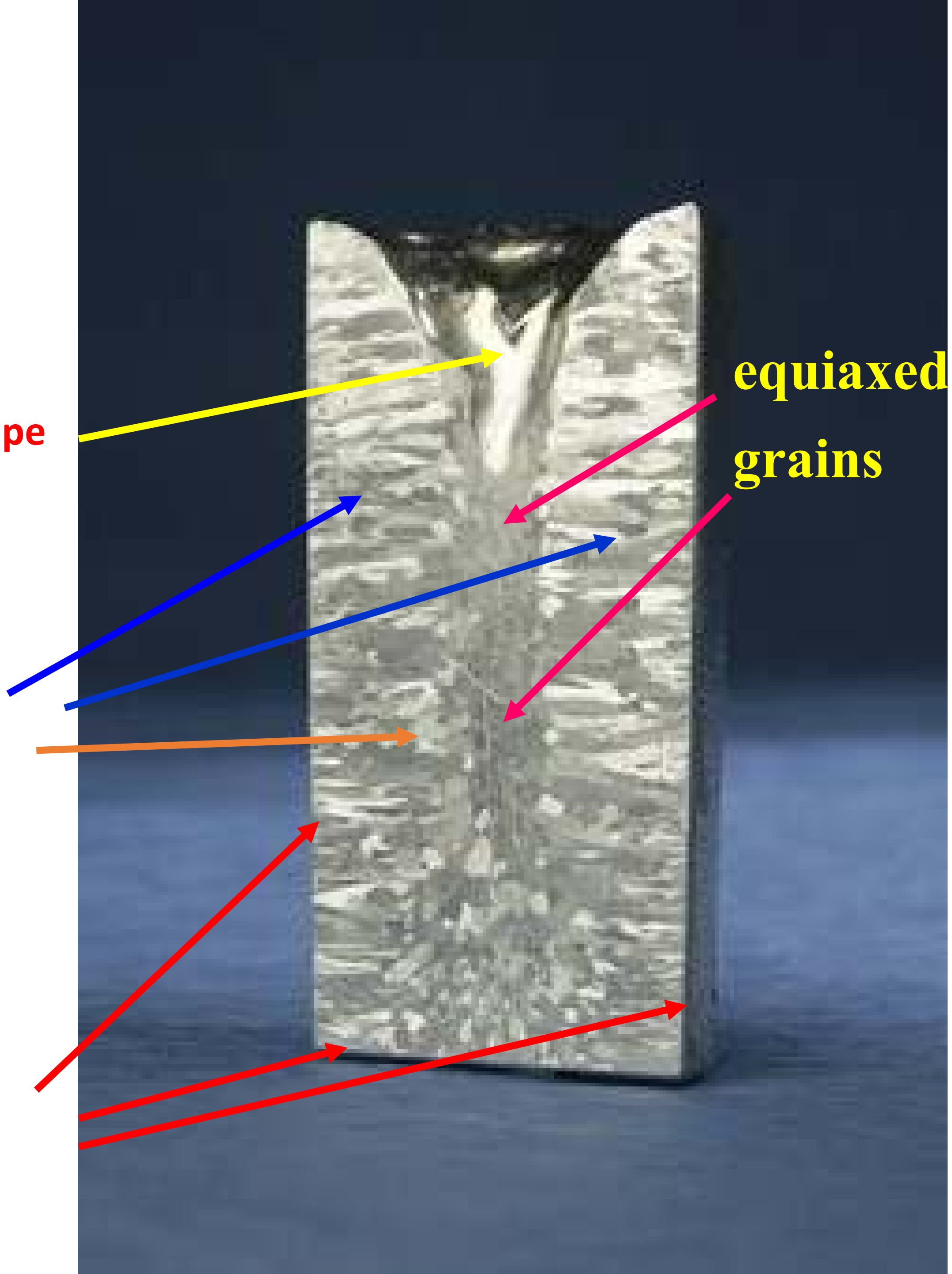


(a) Equiaxed (c) Columnar shape

Grain shape – equiaxed (approximately equal dimensions in the three coordinate Directions therefore properties are same in all directions)

- When the molten metal first strike the mould, the mould is cold and has a chilling effect. This results in the formation of a large number of nuclei and consequently large number of fine grains along the surface of the solidifying metal.
- As the mould is warmed up, the chilling effect is reduced, so that nuclei formation is retarded as the solidification progresses. Thus the crystals formed towards the center of the mould will be larger in size.
- In the intermediate portion, the rate and nature of cooling are favorable to the formation of elongated columnar grains.
- Metallic mould tends to produce a fine grained structure, while sand mould a coarse grained structure.
- Thin sections are subjected to relatively larger rate of cooling, resulting in fine grains.

Al. Ingot

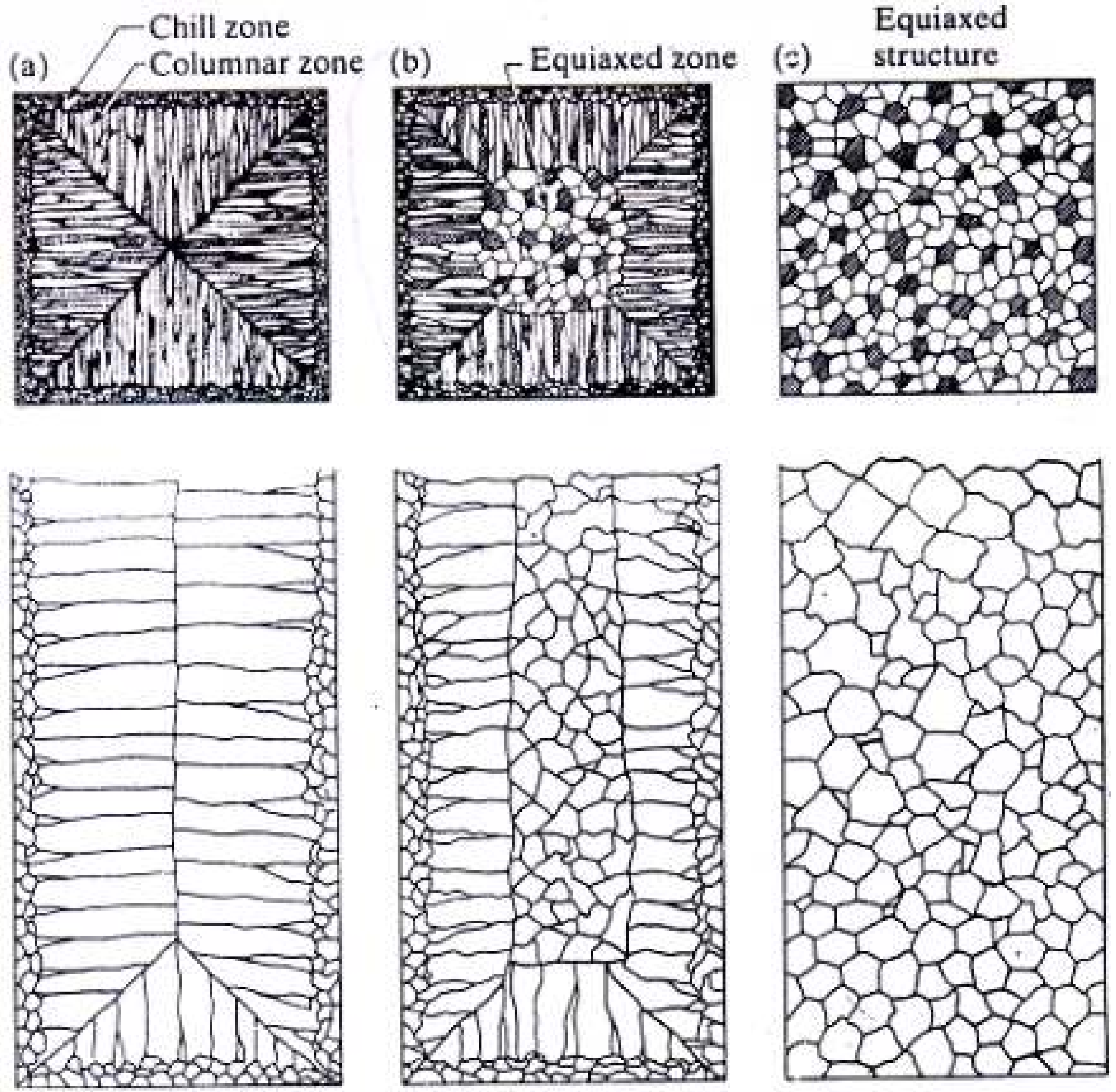


pipe

equiaxed grains

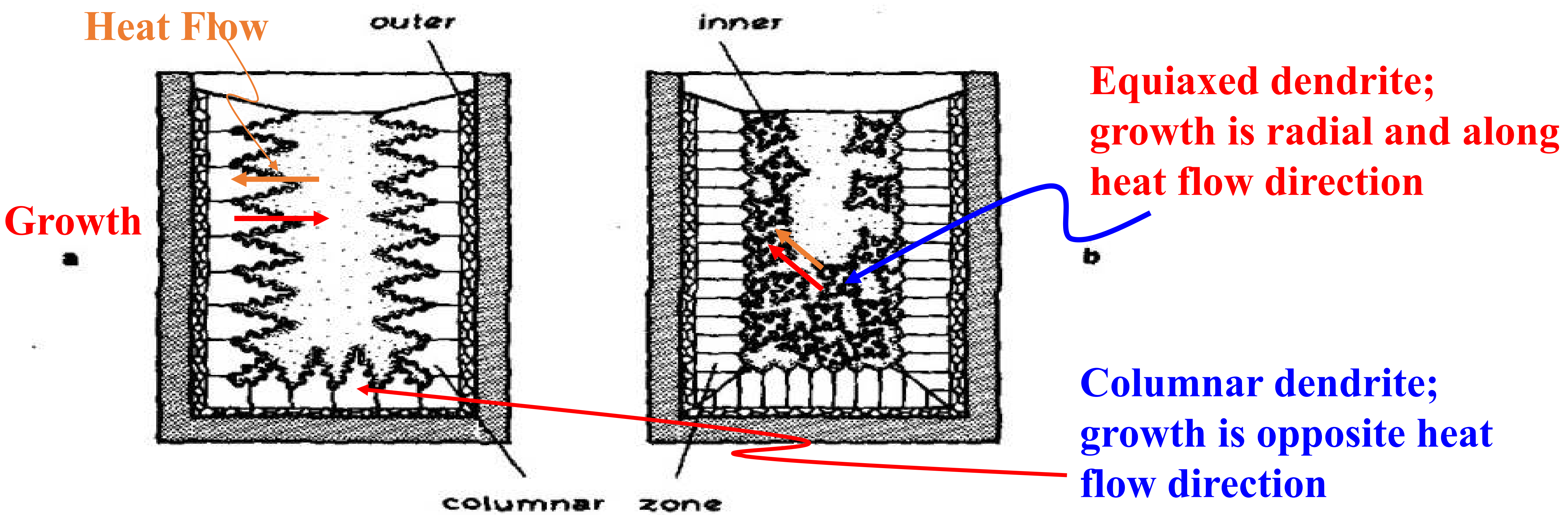
coarse grains

Fine grains



Schematic illustration of three cast structures of metals solidified in a square mold (a) pure metals (b) solid solution alloys (c) structure obtained by using nucleating agents.

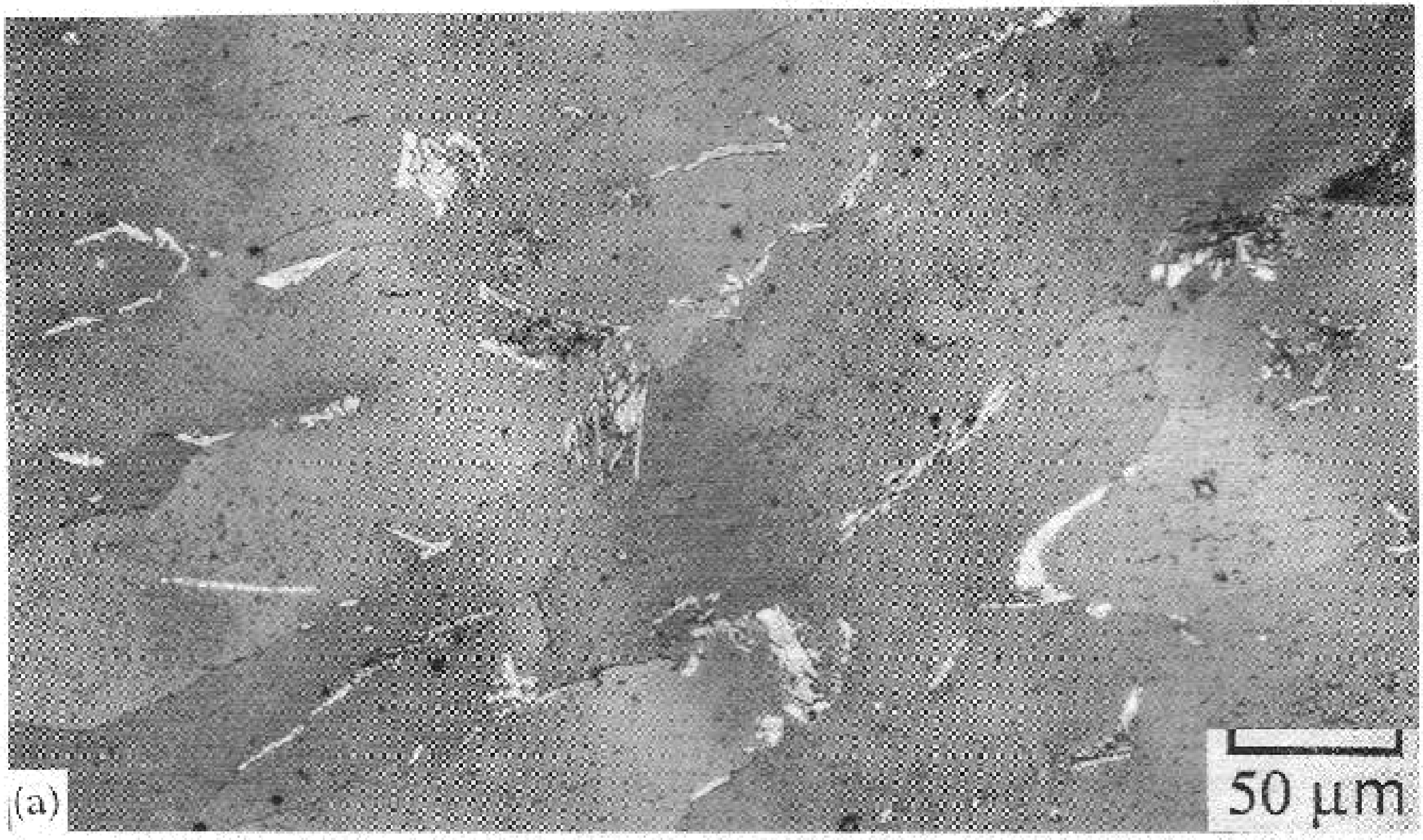
MORPHOLOGY OF SOLIDIFICATION



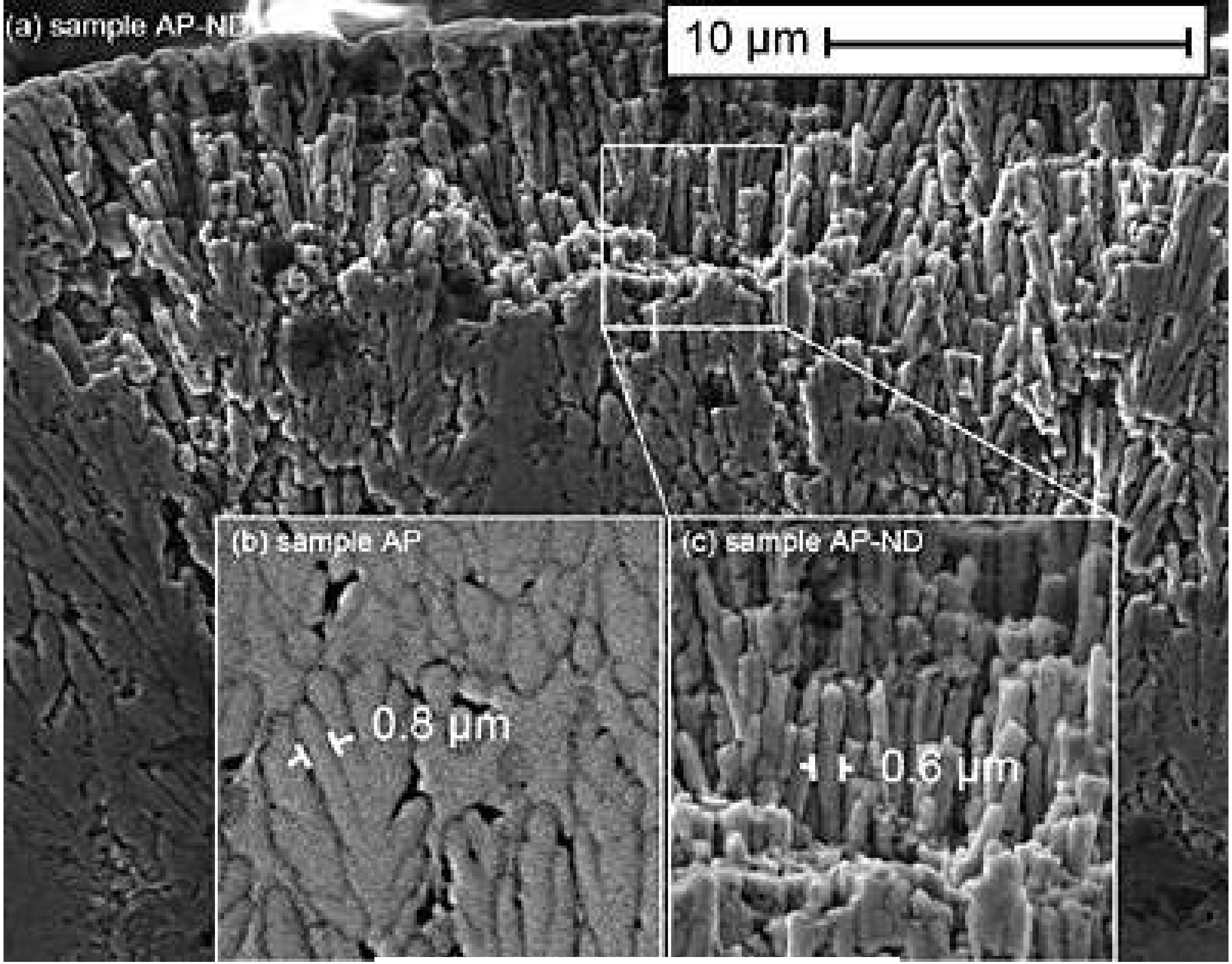
Equiaxed dendrite; growth is radial and along heat flow direction

Columnar dendrite; growth is opposite heat flow direction

Initially, small nuclei nucleate near mold walls, and mutual competition makes them grow in an equiaxed manner. Then, those crystals (dendrites) which can grow parallel and opposite to the heat flow direction become dominant, and produce the columnar structure. With time, some of the dendrite branches break off. These are then forced to grow into an undercooled melt, with growth along the direction of heat flow. The heat flow is now radial and forces these crystals to take on an equiaxed morphology. Stirring is often used, such as in continuous casting, to break of the columnar branches and produce more equiaxed structure.



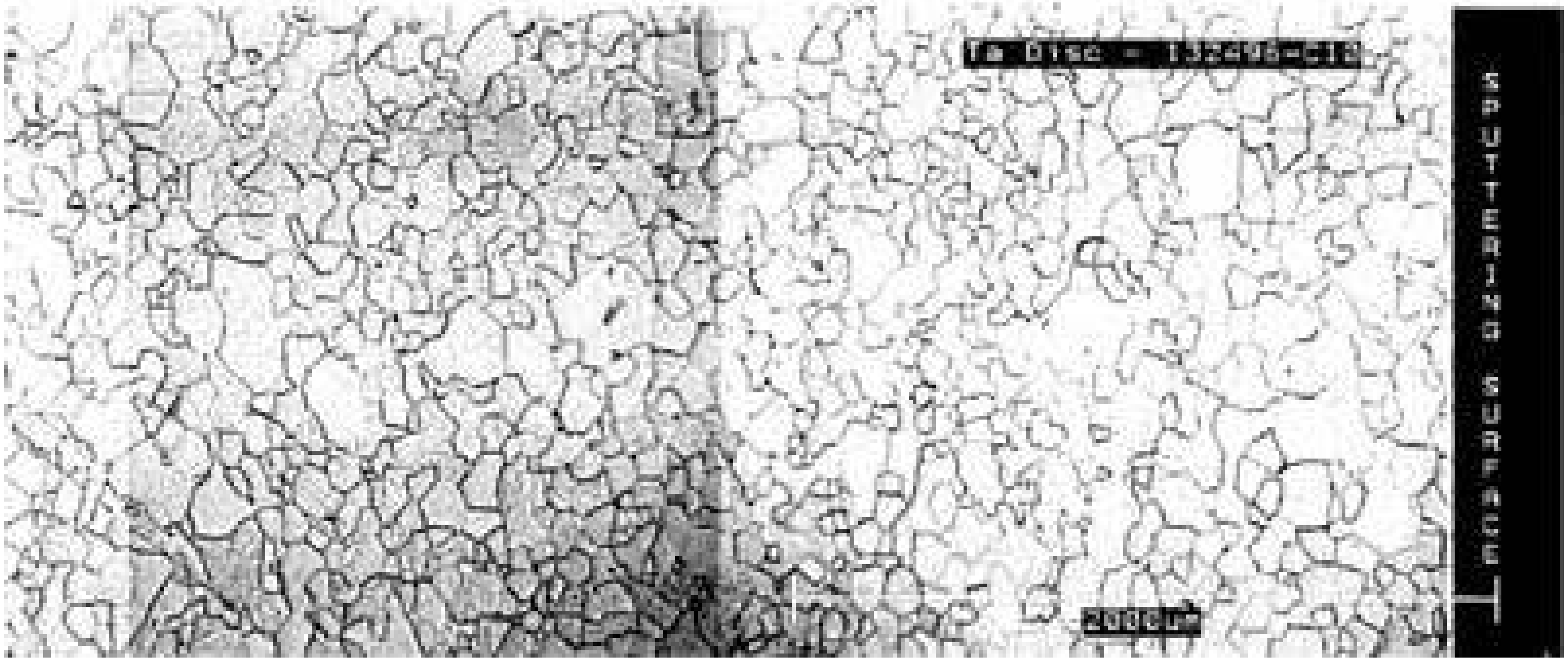
Columnar -ferrite grains, with austenite (light phase) allotriomorphs growing at the grain boundaries.



Columnar microstructure

Plate-like W,
8mm/h

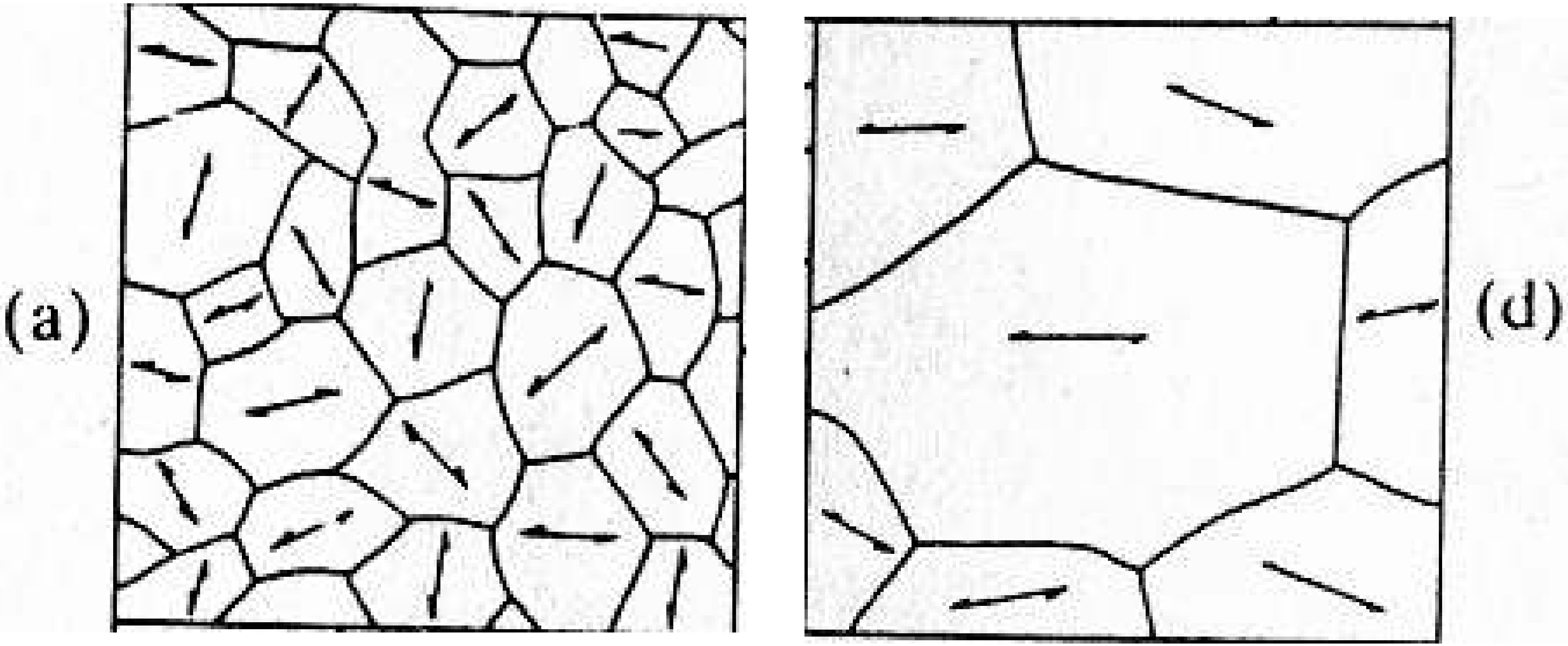
Microstructure of unidirectionally solidified Ni-W alloy Kagami Memorial Research Institute for Materials Science and Technology,Waseda University, since 1882, private independent University, Tokyo.



Microstructure of Ta target fabricated by thermomechanical processing of 300 mm ingot revealing a uniform and equiaxed grain structure. Metallurgical homogeneity is desirable for consistent performance through the life of the tantalum sputtering target.

Orientation of Grains

- Usually, the grains formed are having random crystallographic orientations. But there are metallurgical techniques with which the grains can be made oriented along some specified direction.
- As an example, the [100] directions of iron have a higher magnetic permeability (ability of a magnetic material to support magnetic field development) than do the other directions. Therefore, if the grains within a polycrystalline transformer sheet are not random, but are processed to have preferred orientation such that the [100] direction is preferentially aligned with magnetic field, the transformer will operate with greater efficiency. The metallurgist has learned how to develop this orientation, with the result of billions of dollars worth of savings in electrical-power distribution



(a) Orientation of grains are random (d) preferred orientation (atoms are arranged to a desired direction)

[100] of iron - high magnetic permeability- Transformer efficiency – high Savings.

Grain Boundary

- The grain boundary region may be distorted with atoms belonging to neither crystal
- The thickness may be of the order of few atomic diameters
- The crystal orientation changes abruptly at the grain boundary
- Orientation difference of atoms in adjacent grains are the grain boundary.
- Grain boundary are area of mismatch.
- Along the grain boundary imperfections, impurities are present therefore grain boundary area are considered as area of weakness.
- Grain boundary has 2 to 3 atomic thickness
- Grain boundary containing atoms are randomly oriented and these atoms are not belongs to adjacent neither of grains.
- In an low angle boundary the orientation difference is $< 10^{\circ}$
- Grain boundary energy is responsible for grain growth on heating ~ ($>0.5T_m$)
- Large grains grow at the expense of smaller ones

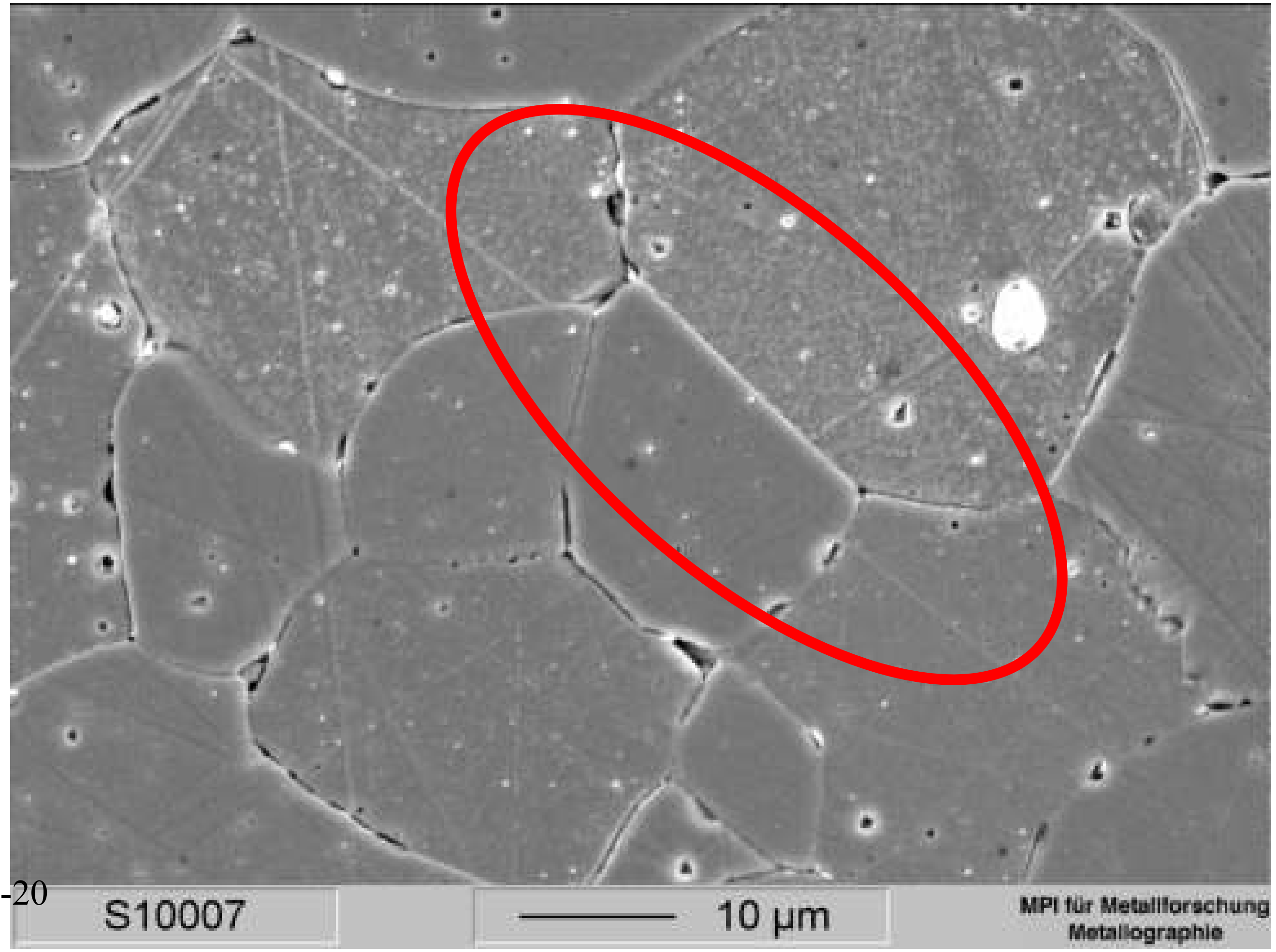
Grain boundaries are barriers to slip:

- Owing to misalignment of the slip planes in adjacent grains, a dislocation passing the grain boundary have to change its direction and thus lose its energy.

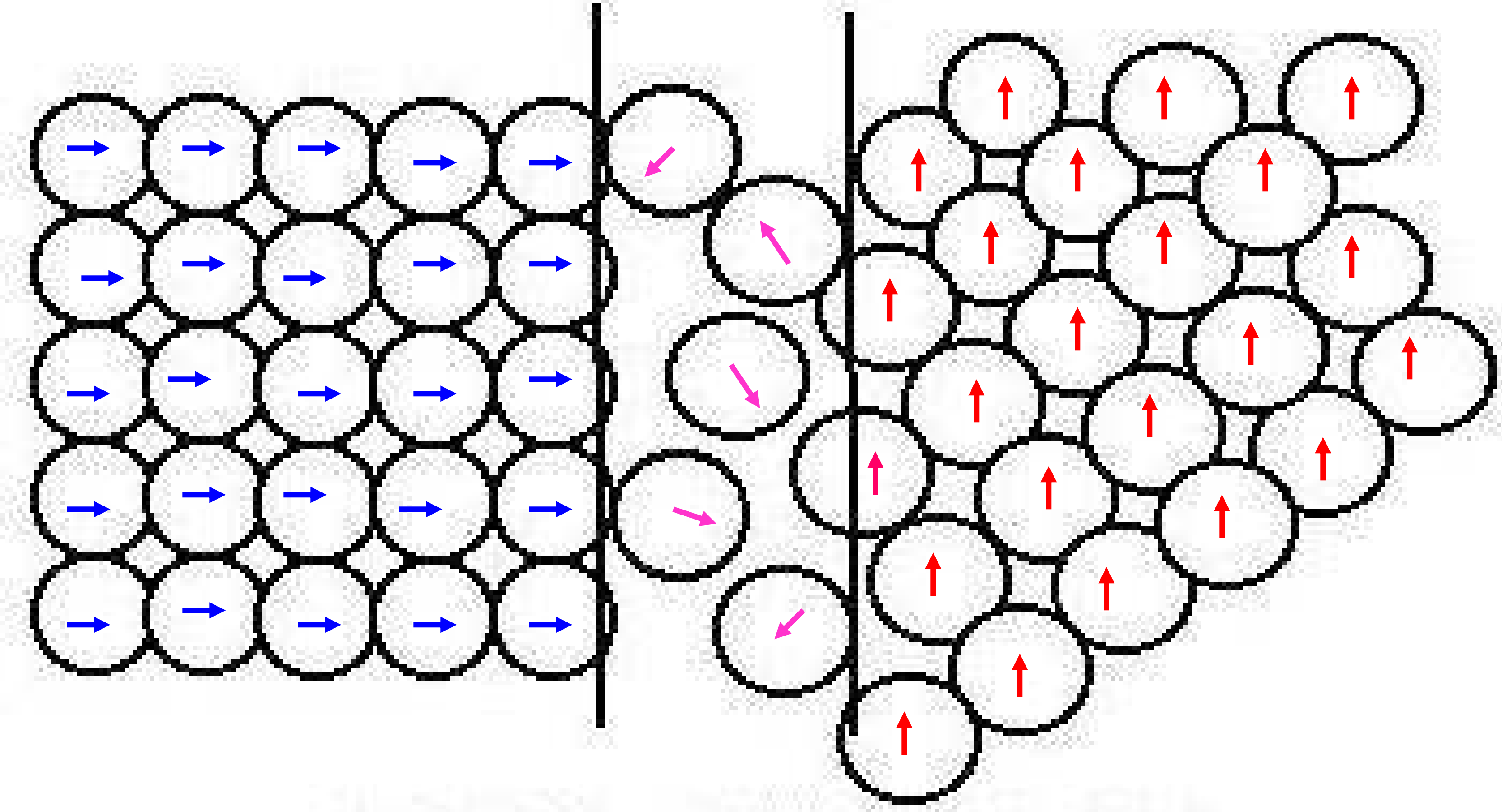
-low angle boundaries are less effective in blocking than high angle ones.

-How strength is related to fine and coarse grain?

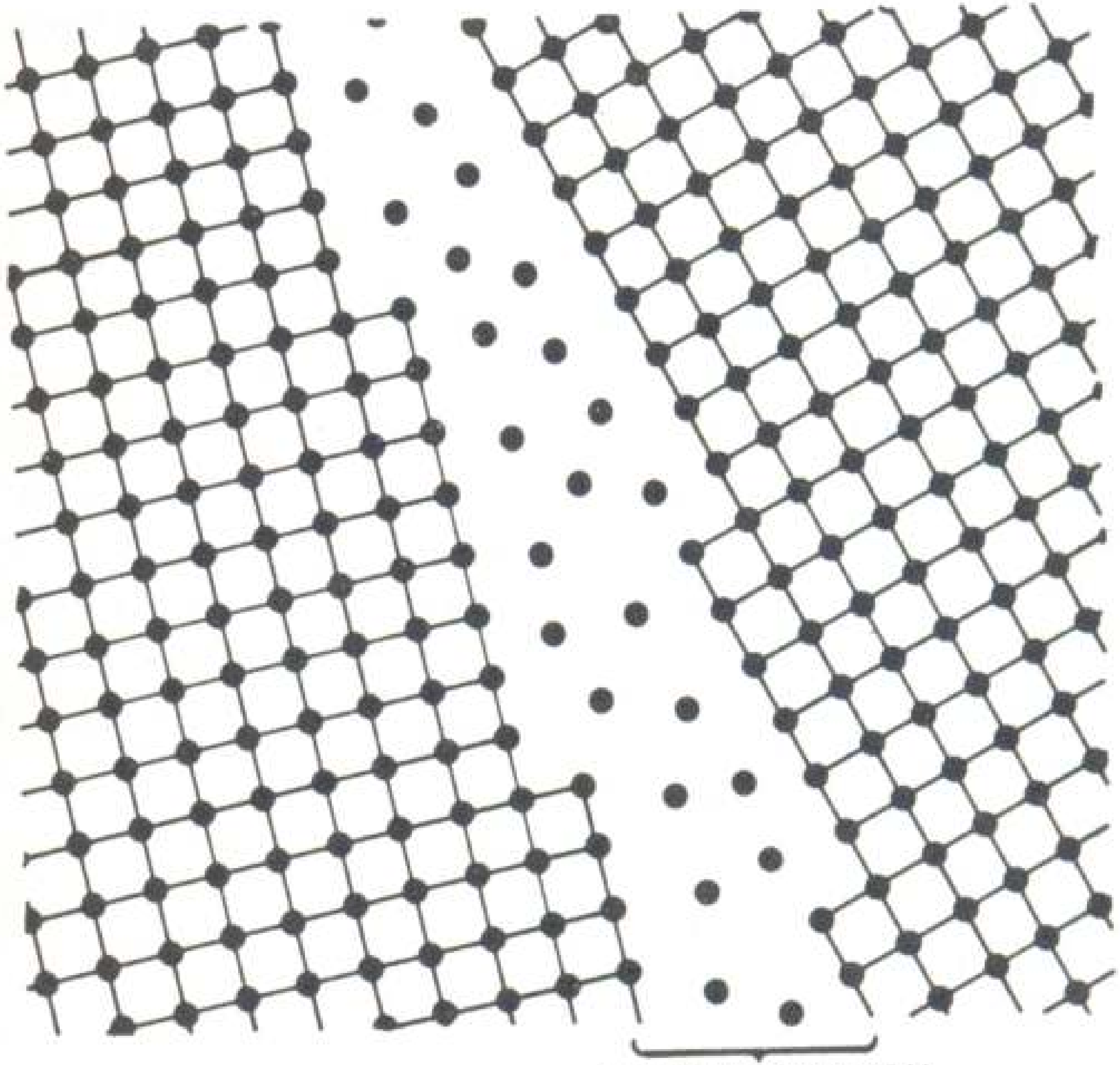
Type of boundary	Energy (J/m^2)
Grain boundary between BCC crystals	0.89
Grain boundary between FCC crystals	0.85
Interface between BCC and FCC crystals	0.63

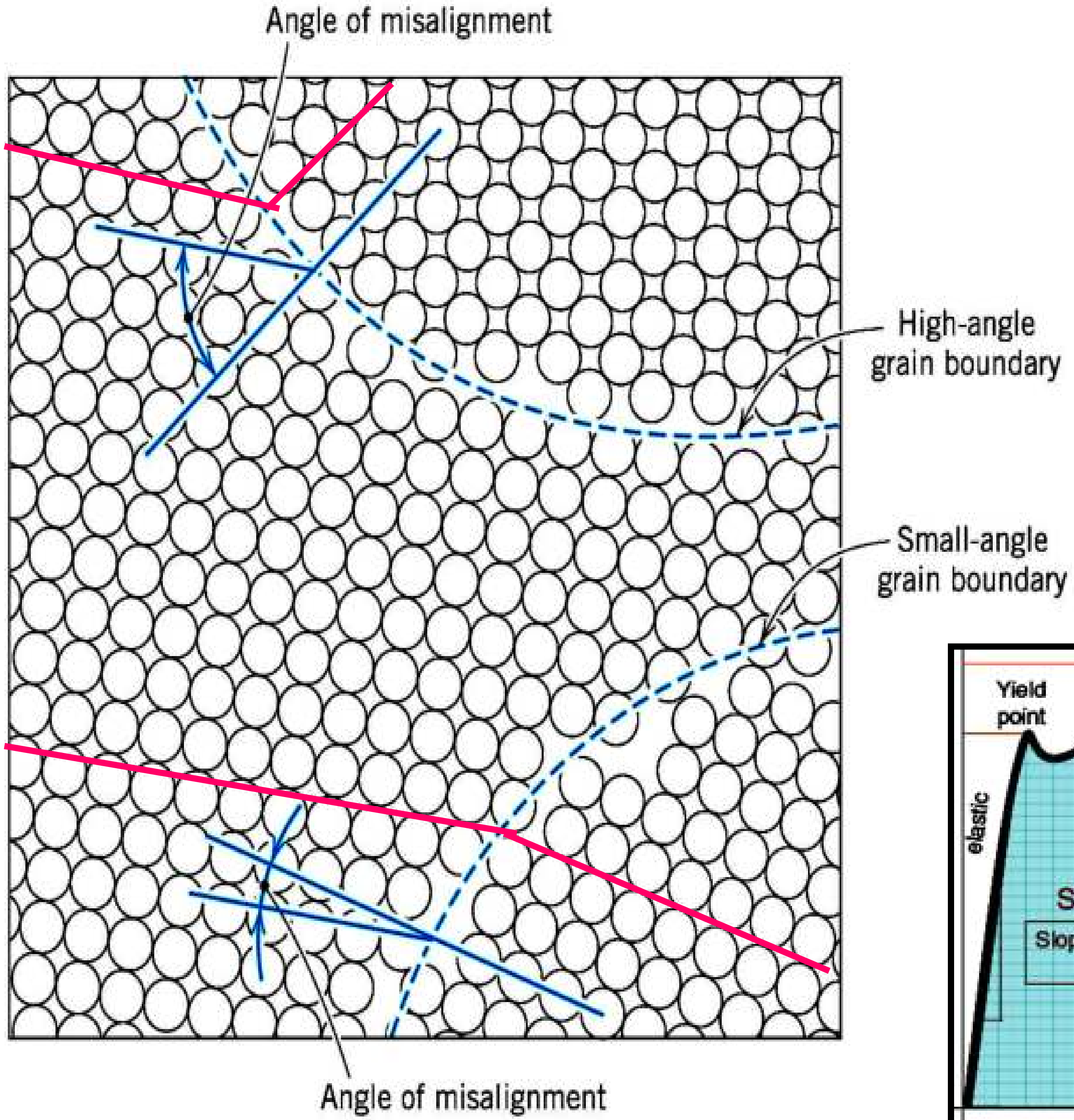


Grain boundaries in $SrTiO_3$



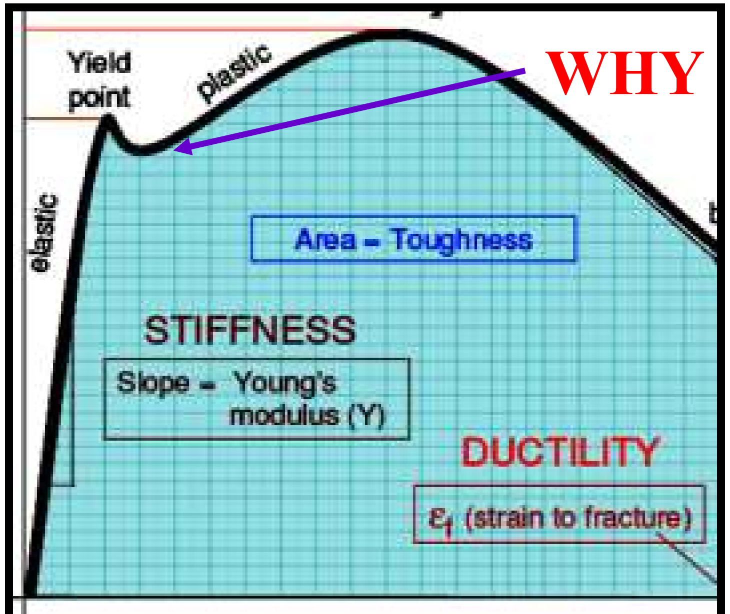
ZONE OF MISFIT
GRAIN BOUNDARY

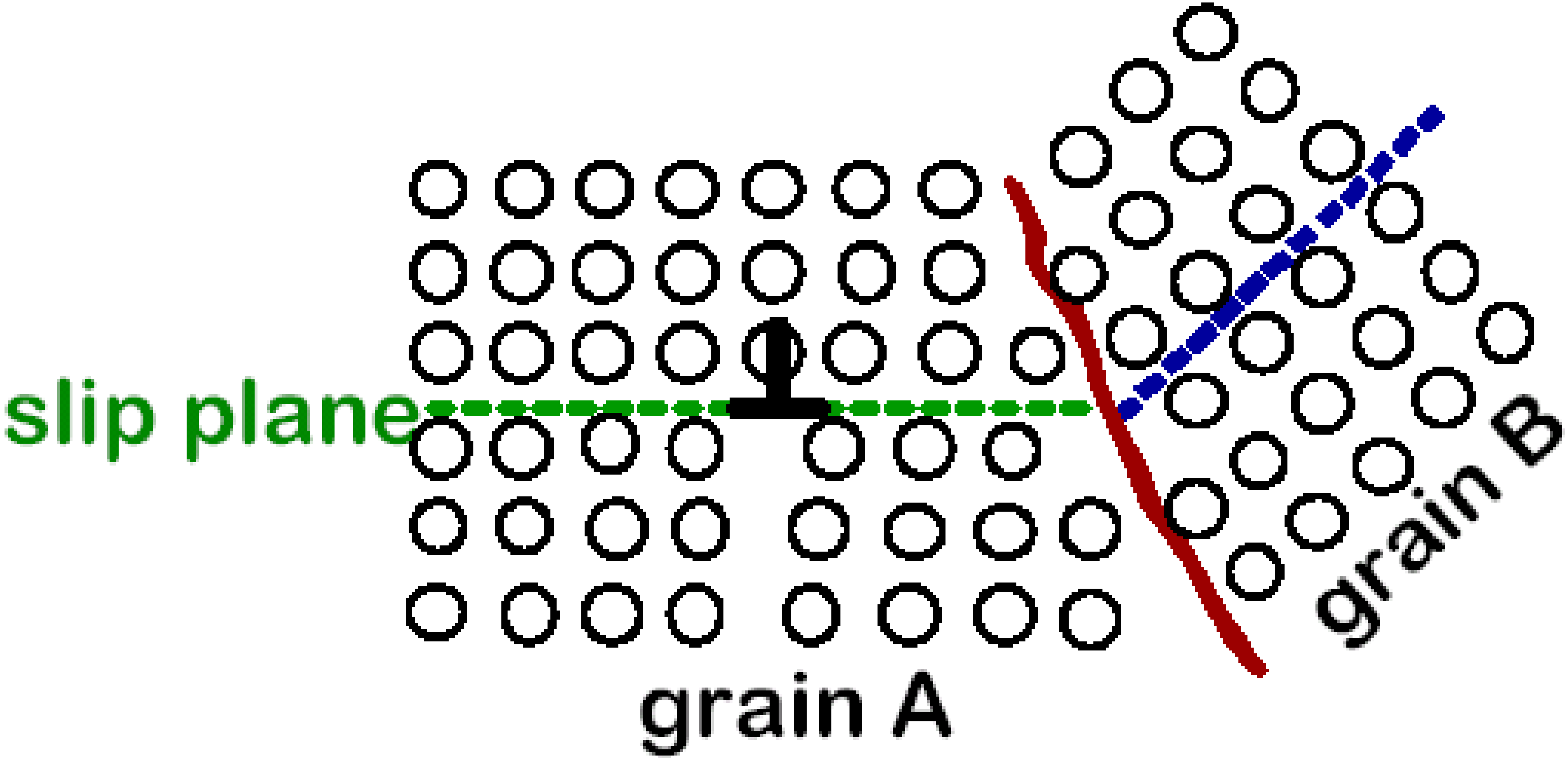

GRAIN BOUNDARY
(ABOUT 3 ATOMS THICK)

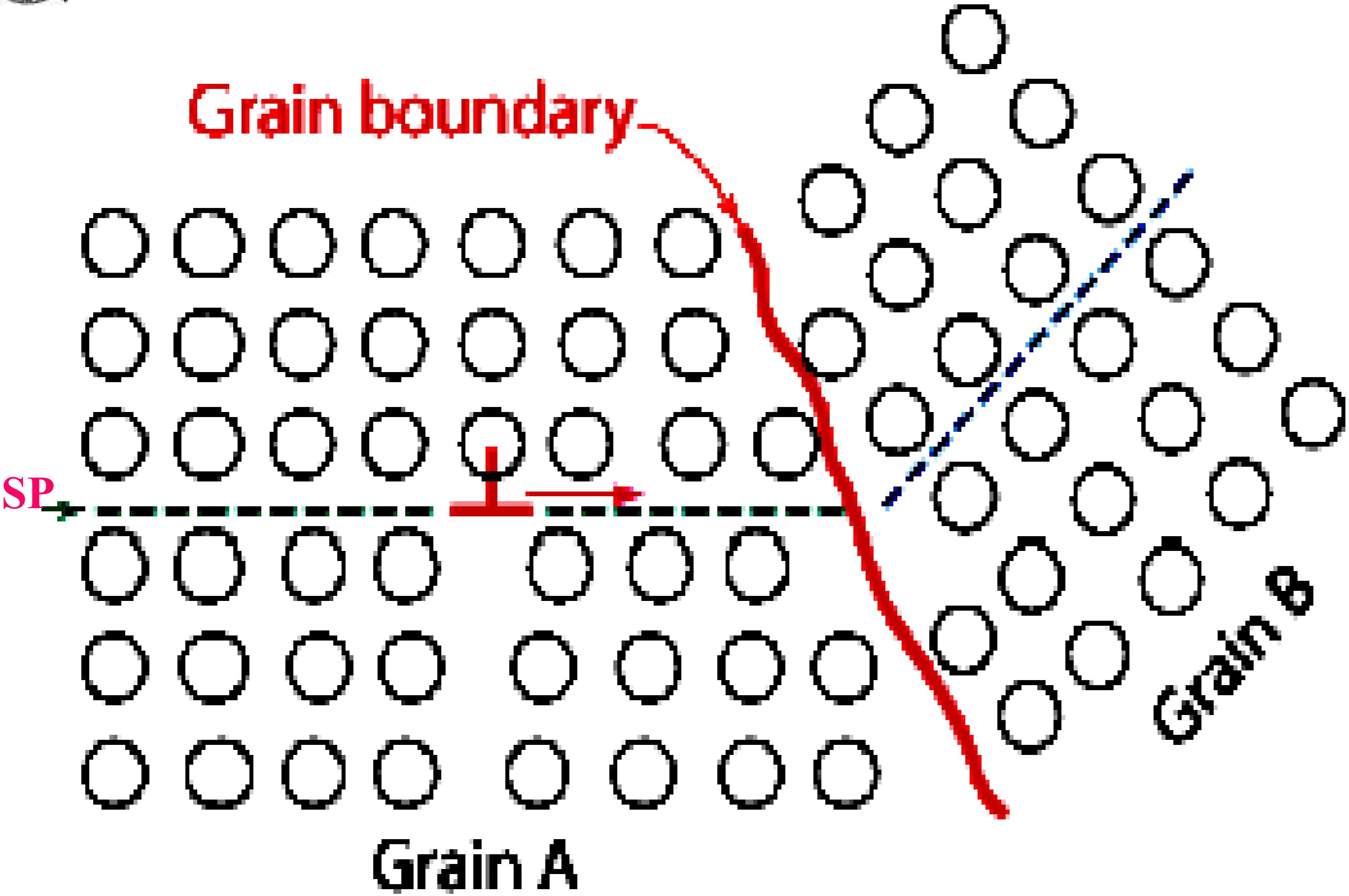


Schematic diagram showing small- and high-angle grain boundaries and the adjacent atom positions.

Depending on which planes are brought together, the angle of alignment will vary.




slip plane
grain A
grain B


Grain boundary
SP
Grain A
Grain B

MODULE 2

Imperfections in Solids

Reference : CALLISTER

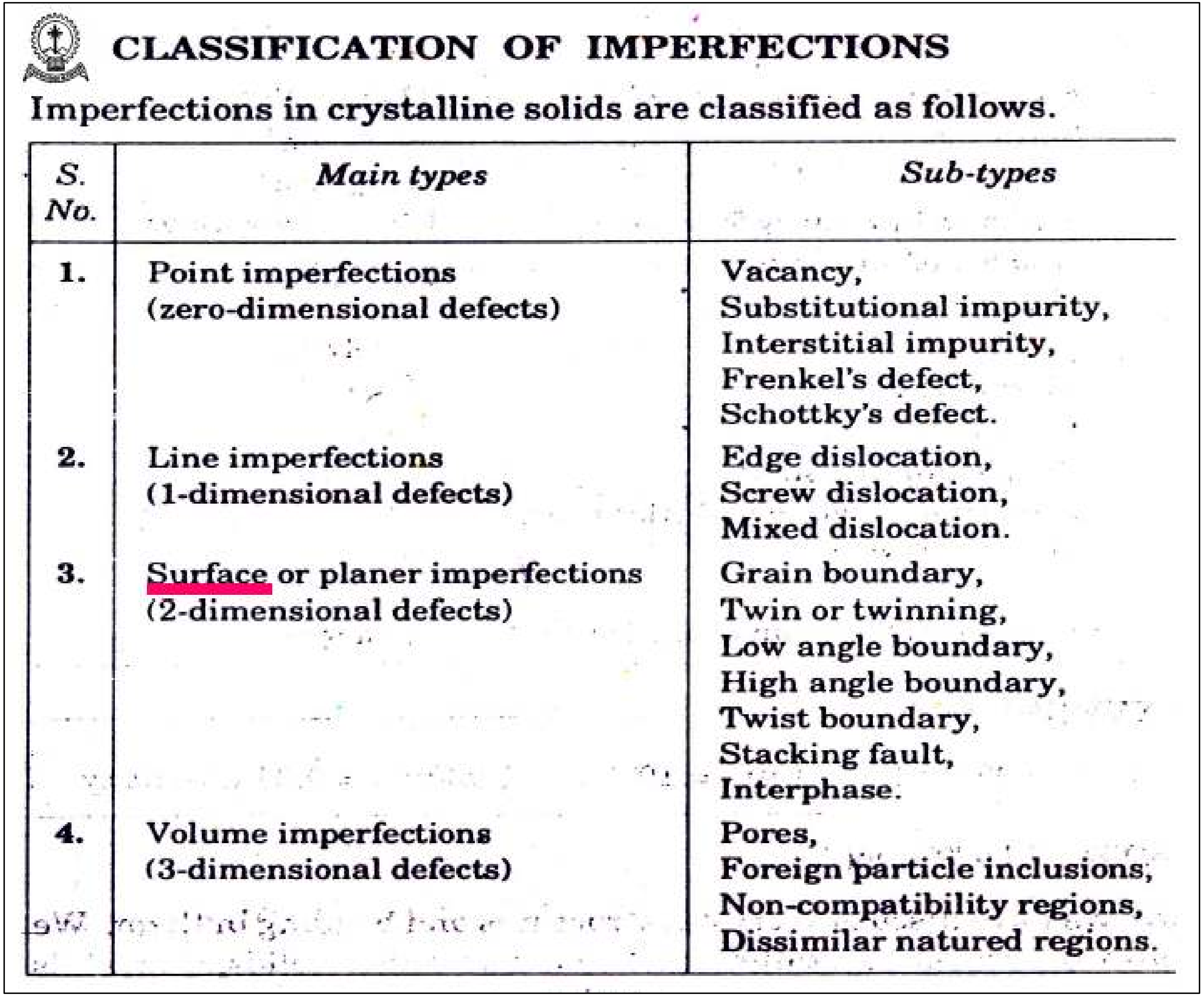
Crystal Imperfections

Definition

- A perfect crystal is a solid composed of atoms, ions or molecules arranged in a pattern which is repetitive in 3 dimensions
- But real crystals are never perfect; lattice distortion & irregularities are generally present in them. These defects are called crystal imperfections

Why study Imperfections in Solids?

- The properties of some materials are profoundly influenced by the presence of imperfections.
- Mechanical properties of pure metals experience significant *alterations when alloyed* i.e., when impurity atoms are added
- Eg. **brass** (70% copper–30% zinc) is much harder and stronger than pure copper
- Eg. Integrated Circuit devices with **doped semiconducting materials**



CLASSIFICATION OF IMPERFECTIONS

Imperfections in crystalline solids are classified as follows.

S. No.	*Main types*	*Sub-types*
1.	Point imperfections (zero-dimensional defects)	Vacancy, Substitutional impurity, Interstitial impurity, Frenkel's defect, Schottky's defect.
2.	Line imperfections (1-dimensional defects)	Edge dislocation, Screw dislocation, Mixed dislocation.
3.	Surface or planer imperfections (2-dimensional defects)	Grain boundary, Twin or twinning, Low angle boundary, High angle boundary, Twist boundary, Stacking fault, Interphase.
4.	Volume imperfections (3-dimensional defects)	Pores, Foreign particle inclusions, Non-compatibility regions, Dissimilar natured regions.

Types of lattice defects

Crystalline defect can be classified in to,

- *Point defects (Zero dimensional)*
- *Line defects (one dimensional)*
- *Surface defects (two dimensional)*
- *Volume defects (three dimensional)*

Point defects/imperfections (Zero dimensional defects)

Point defects are localized disruptions or it is one which is having completely local effect.

Types of point defects

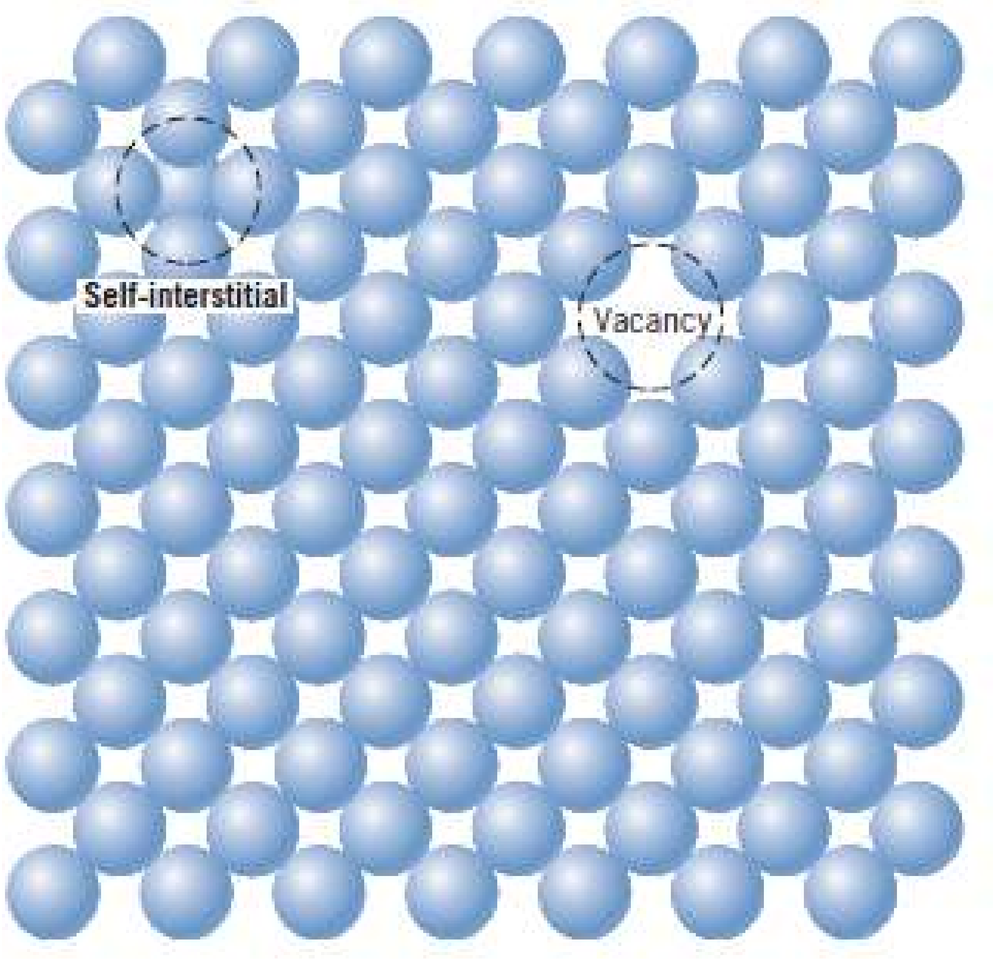
1. Vacancies
2. Interstitialcies
3. Impurities
4. Electronic defects

Point defects

- ***Vacancy*** – An *atom or an ion missing* from regular lattice position.
- Vacancies are present invariably in all materials.

- ***Self-interstitial*** – An *atom trapped in the interstitial point* (a point intermediate between regular lattice points) is called an interstitialcy.

- An impurity atom at the regular or interstitial position in the lattice is another type of point defect.



- In metals, a self-interstitial introduces *relatively large distortions* in the surrounding lattice because the atom is substantially larger than the interstitial position in which it is situated.

- The formation of this defect is *not highly probable*, and it exists in very *small concentrations*, which are significantly lower than for vacancies.

Impurities in Solids

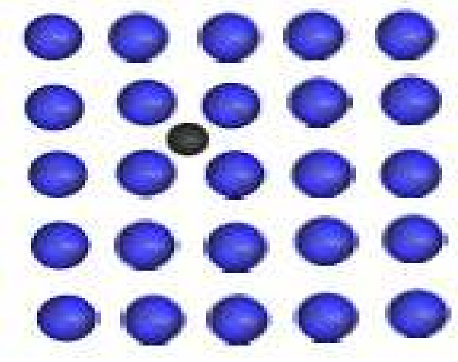
- A pure metal consisting of only one type of atom just isn’t possible; *impurity or foreign atoms will always be present*

- **Alloys**-impurity atoms have been added *intentionally* to impart specific characteristics to the material

- Eg. *sterling silver* is a 92.5% silver 7.5 % copper alloy.

- In normal ambient environments, pure silver is highly corrosion resistant, but also very soft.

- Alloying with copper *significantly enhances the mechanical strength* without depreciating the corrosion resistance appreciably.



Impurity

Solid Solution

- Addition of *impurity atoms* to a metal will result in the formation of a *solid solution and/ or a new second phase depending on the*
  - *kinds of impurity,*
  - *their concentrations, and*
  - *the temperature of the alloy.*

- A solid solution forms when, as the solute atoms are added to the host material, the *crystal structure is maintained*, and no new structures are formed.

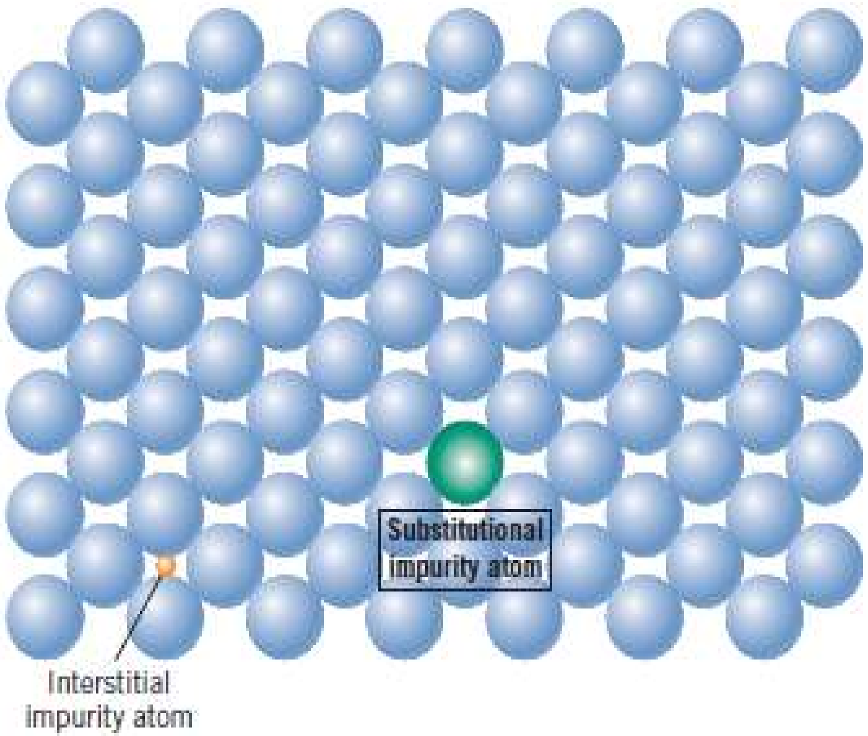
- "**Solvent / *host atoms***"- represents the element or compound that is present in the greatest amount.

- ***"Solute(inpurity)"*** *is used to denote an* element or compound present in a minor concentration.

- A solid solution is also compositionally homogeneous; the impurity atoms are randomly and uniformly dispersed within the solid.

- Ex, Steel is an example of a solid–solid solution. It is an iron solvent with a carbon solute.

- Impurity point defects are found in solid solutions, of which there are two types:
  - ***substitutional***
  - ***interstitial.***



Substitutional solid solution

- Solute or impurity atoms *replace or substitute* for the host atoms
- Degree to which the former dissolves in the latter and to form a completely soluble substitutional solid solution depends on **Home Rothery 's Rule**

1. The atomic size difference between parent atom and solute atom must be less than ±15%.
2. Electronegativity difference between metals must be small.
3. Crystal structure of metals should be same.
4. Valancy Other factors being equal, a metal will have more of a tendency to dissolve another metal of higher valency than one of a lower valency.

- Eg. ***solid solution for copper and nickel*****.** **(**These two elements are completely soluble in one another at all proportions)
- These two elements are completely soluble in one another at all proportions.
- Atomic radii for copper and nickel are 0.128 and 0.125 nm, respectively
- Both have the FCC crystal structure,
- Their electro negativities are 1.9 and 1.8
- Most common valences are for copper are +1 or +2 and for nickel its +2.
- Another Eg. Tin in bronze

Interstitial Solid Solutions

- Impurity atoms fill the *voids or interstices* among the host atoms.

- For metallic materials that have relatively high atomic packing factors, these interstitial positions are *relatively small*

- Atomic diameter of an interstitial impurity must be substantially smaller than that of the host atoms.

- Even very small impurity atoms are ordinarily larger than the interstitial sites, and as a consequence they introduce some ***lattice strains on the adjacent host atoms***

- Maximum allowable concentration of interstitial impurity atoms is low (less than 10%).

Example

- *Carbon forms an interstitial solid solution when added to iron (Steel)*
- The maximum concentration of carbon is about 2%.
- The atomic radius of the carbon atom (0.071 nm)is much less than that for iron (0.124 nm.)

IMPERFECTIONS IN CERAMICS

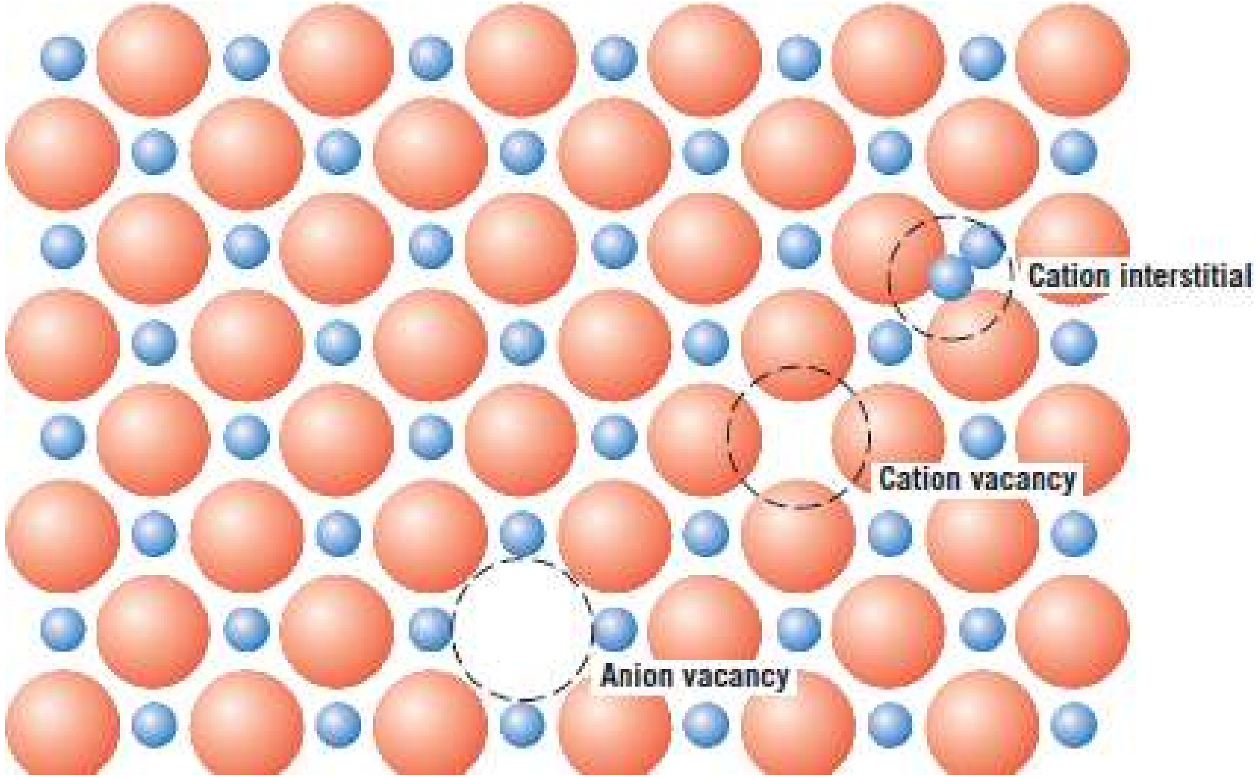
Atomic Point Defects

- Since ceramic materials contain ions of at least two kinds, defects for each ion type may occur.

  Eg. - In NaCl, Na interstitials and vacancies and Cl interstitials and vacancies may exist.

- The anion is relatively large, and to fit into a small interstitial position, substantial strains on the surrounding ions must be introduced.

- It is highly improbable that there would be appreciable concentrations of anion interstitials.



- In ceramic materials point defects occur in *pair to maintain the electro neutrality.*
- Electroneutrality is the state that exists when there are *equal numbers of positive and negative charges* from the ions.
- As a consequence, defects in ceramics do not occur alone.

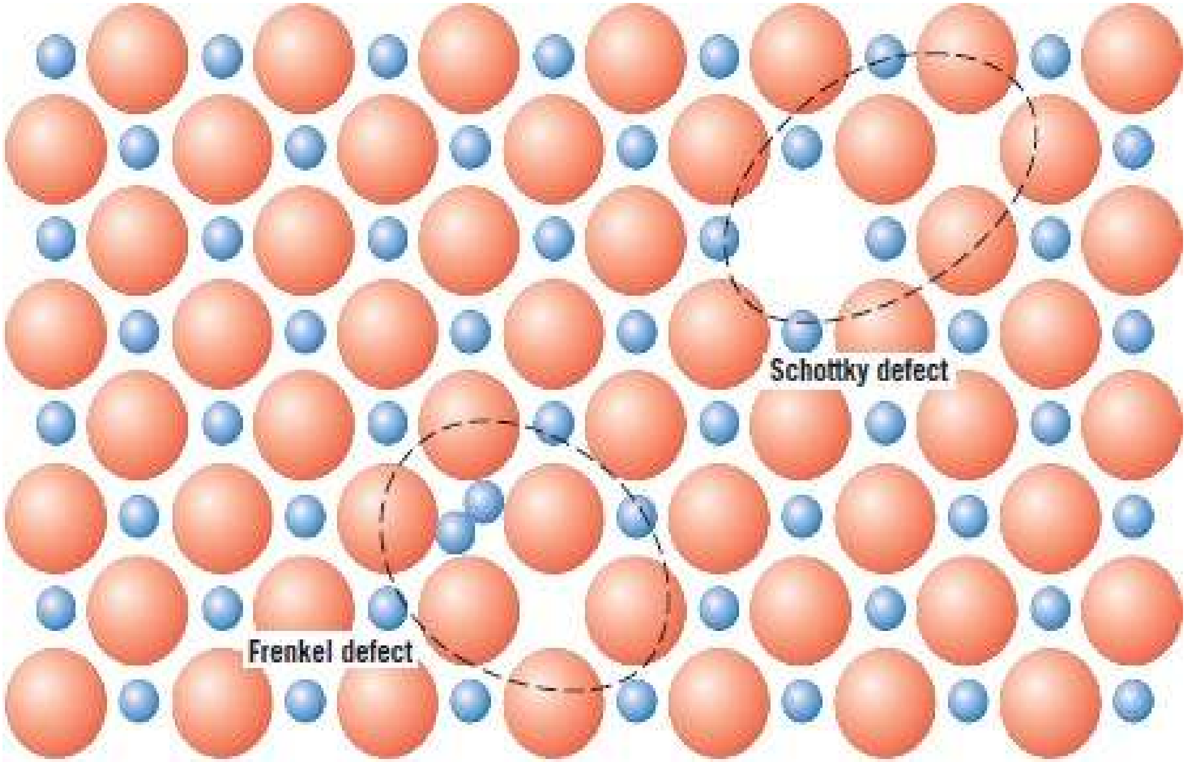
Frenkel defect

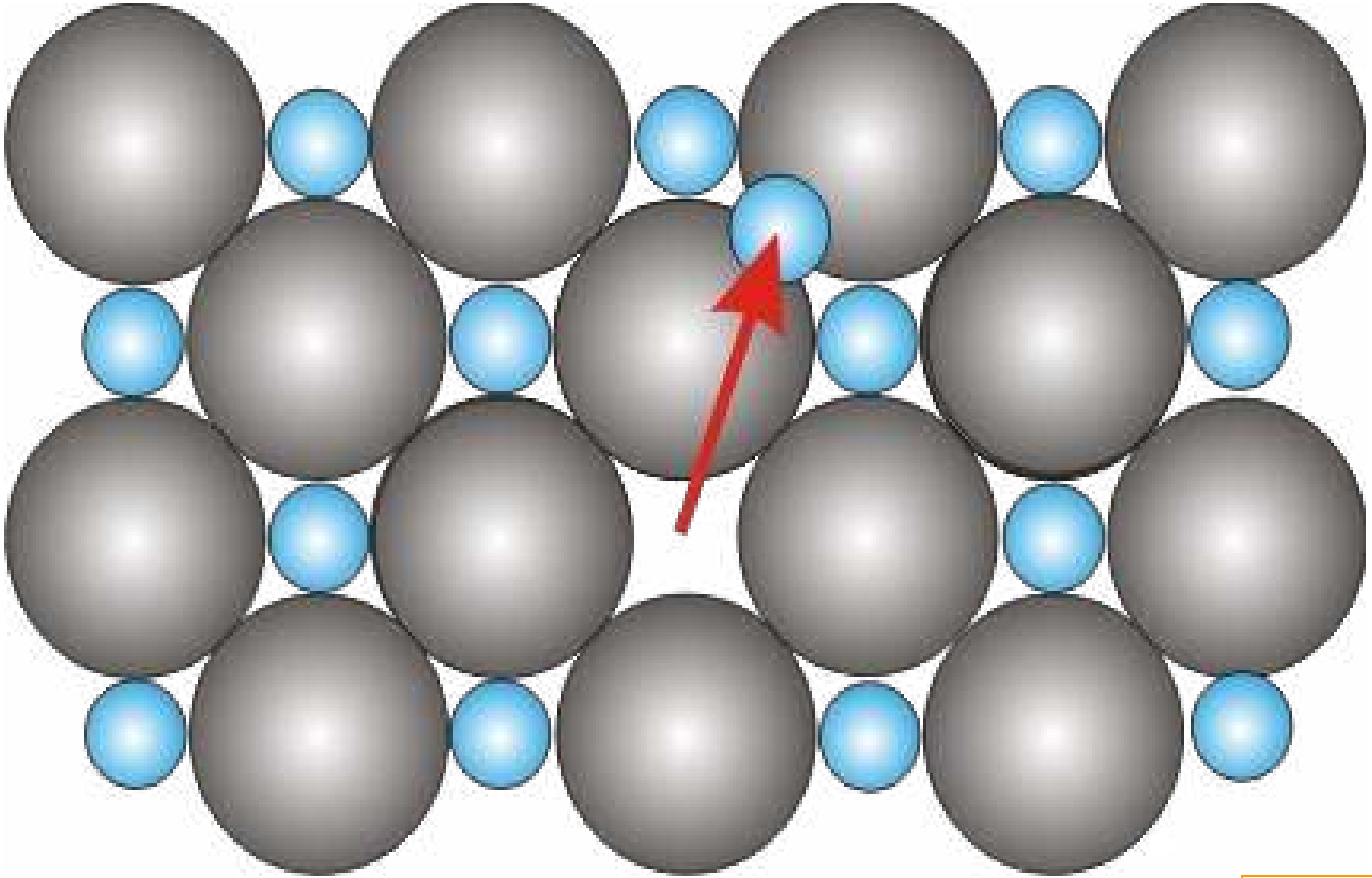
- A *cation-vacancy and a cation-interstitial pair* is known as **Frenkel defect**.
- Formed by a cation leaving its normal position and *moving into an interstitial site.*
- No change in charge because the cation maintains the same positive charge as an interstitial

Cation vacancy

+

Cation interstitial





Frenkel defect

Cation vacancy

+

Cation interstitial

Schottky defect

- A *cation vacancy-anion vacancy* pair is known as a **Schottky defect**.

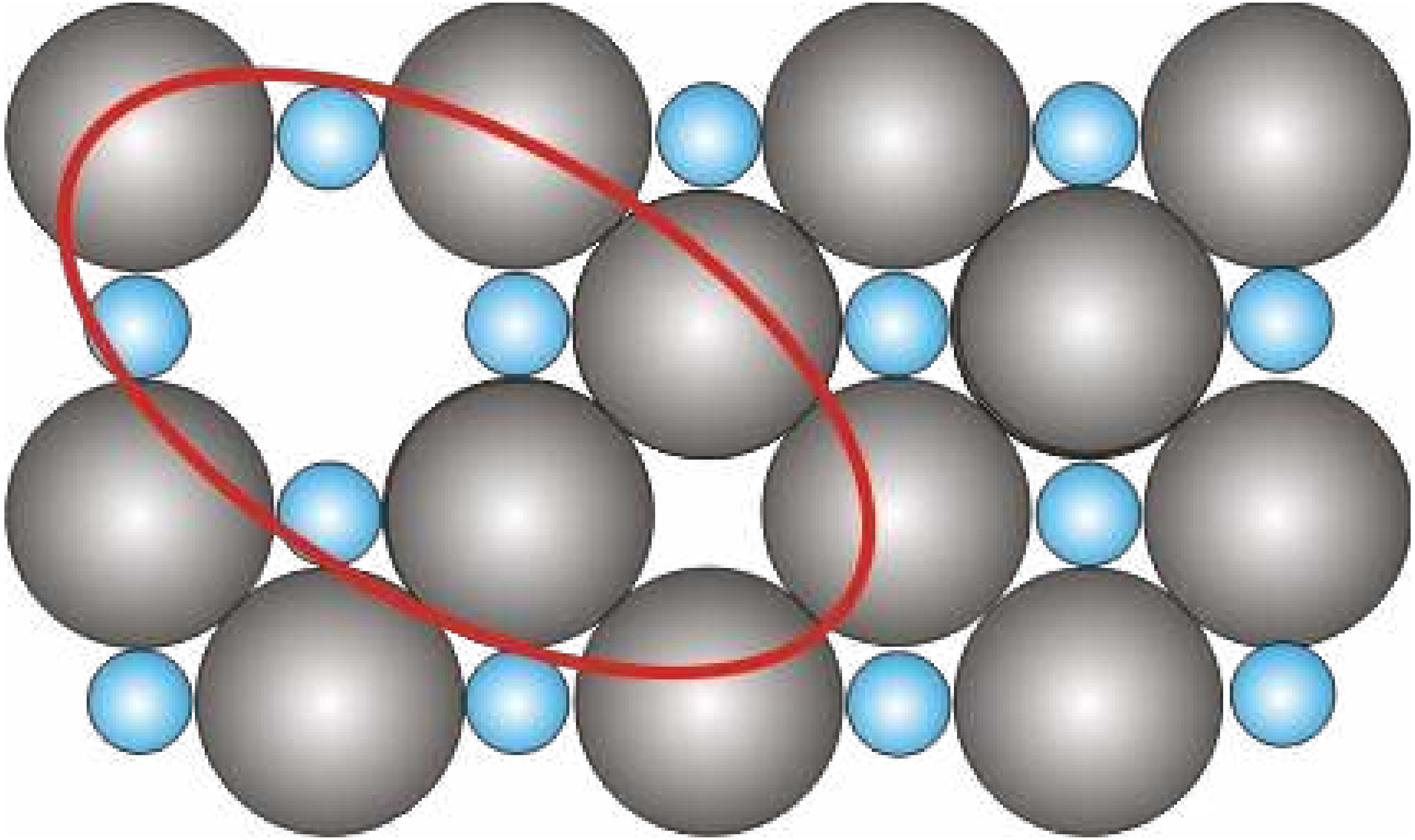
- *Created by removing one cation and one anion from the interior* of the crystal and then placing them both at an external surface.

- Both cations and anions have the same charge, and since for every anion vacancy there exists a cation vacancy, the *charge neutrality* of the crystal is maintained.

- The *ratio of cations to anions is not altered* by the formation of either a Frenkel or a Schottky defect.

Schottky defect

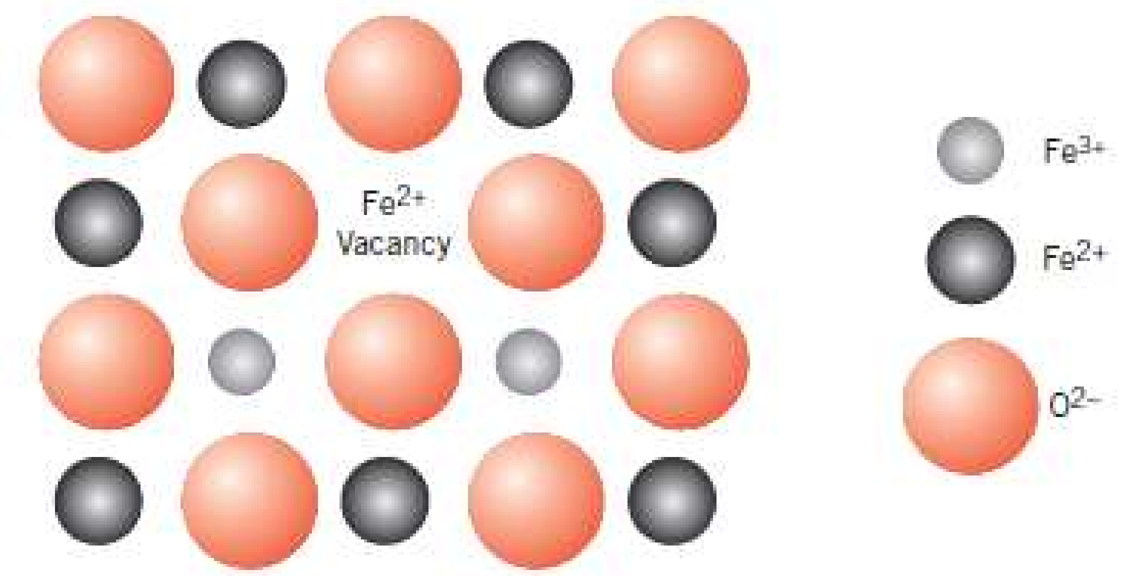
Cation vacancy
+
Anion vacancy



Stoichiometry

- Defined as a state for ionic compounds wherein there is the *exact ratio of cations to anions as predicted by the chemical formula.*
- NaCl is stoichiometric if the ratio of Na^+ ion and Cl^+ ion in exactly 1:1
- Non-stoichiometry may occur for some ceramic materials in which *two valence* (or ionic) states exist for one of the ion types. Eg. FeO (Iron oxide, iron can be present in both Fe^+ and Fe^- states).

Eg . Iron Oxide



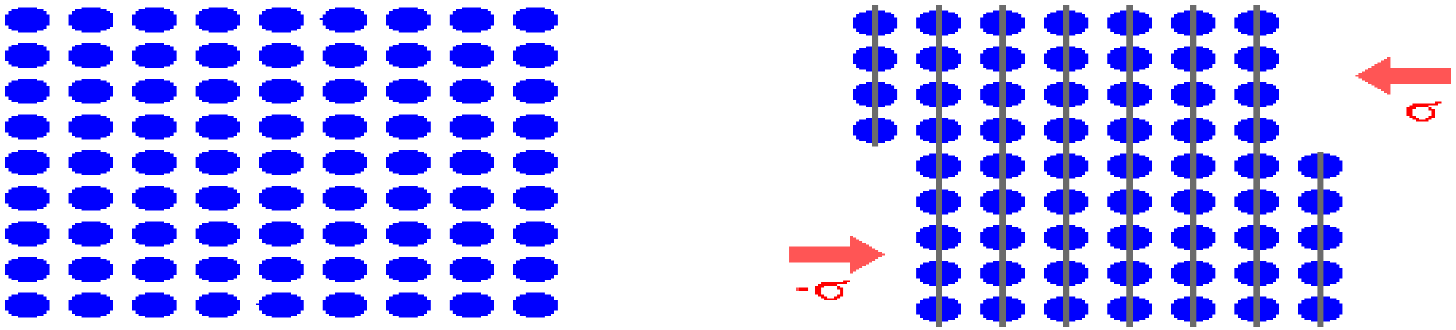
How do metals plastically deform?

Why does forging change properties?

Why deformation occurs at stresses smaller than those for perfect crystals?

Plastic deformation due to motion of large number of dislocations.

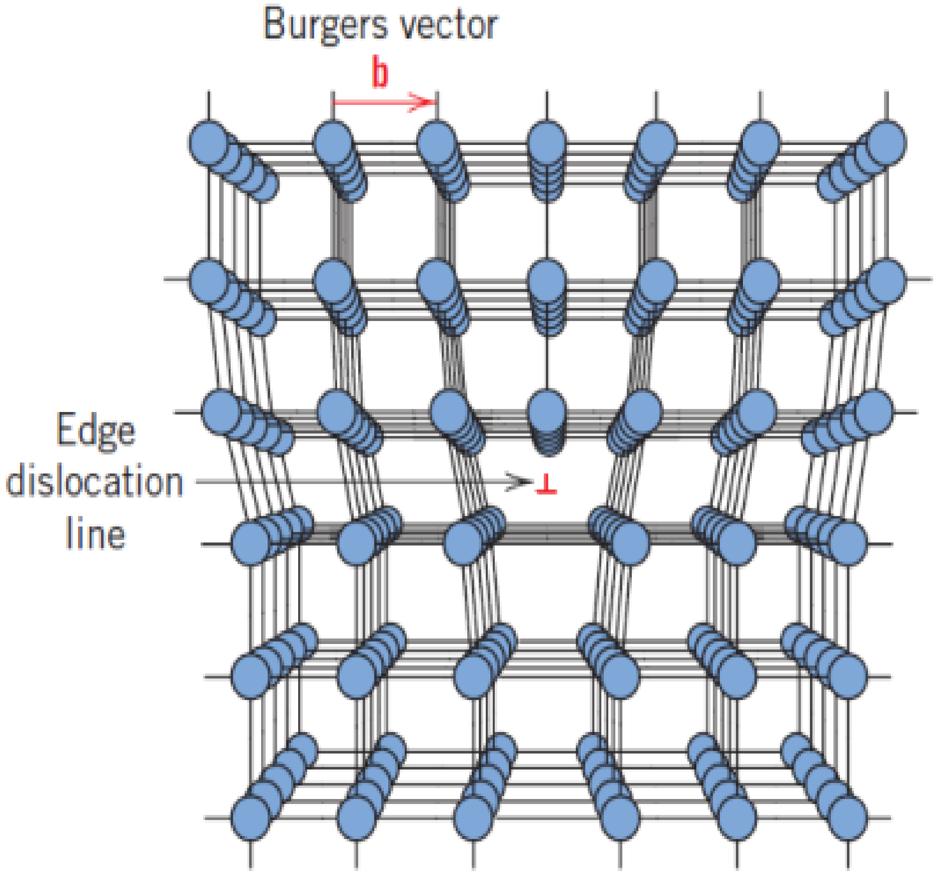
Plastic deformation under shear stress



DISLOCATIONS—LINEAR DEFECTS

Edge dislocation

- A dislocation is a **linear or one-dimensional defect** around which some of the atoms are misaligned.
- An *extra portion of a plane of atoms*, or half-plane, the edge of which terminates within the crystal.
- Line that is defined along the end of the extra half-plane of atoms is called dislocation line (Tangent vector).
- Within the region around the dislocation line there is some localized lattice distortion.



- The atoms above the dislocation line are squeezed together, and those below are pulled apart; this is reflected in the slight curvature for the vertical planes of atoms as they bend around this extra half-plane.

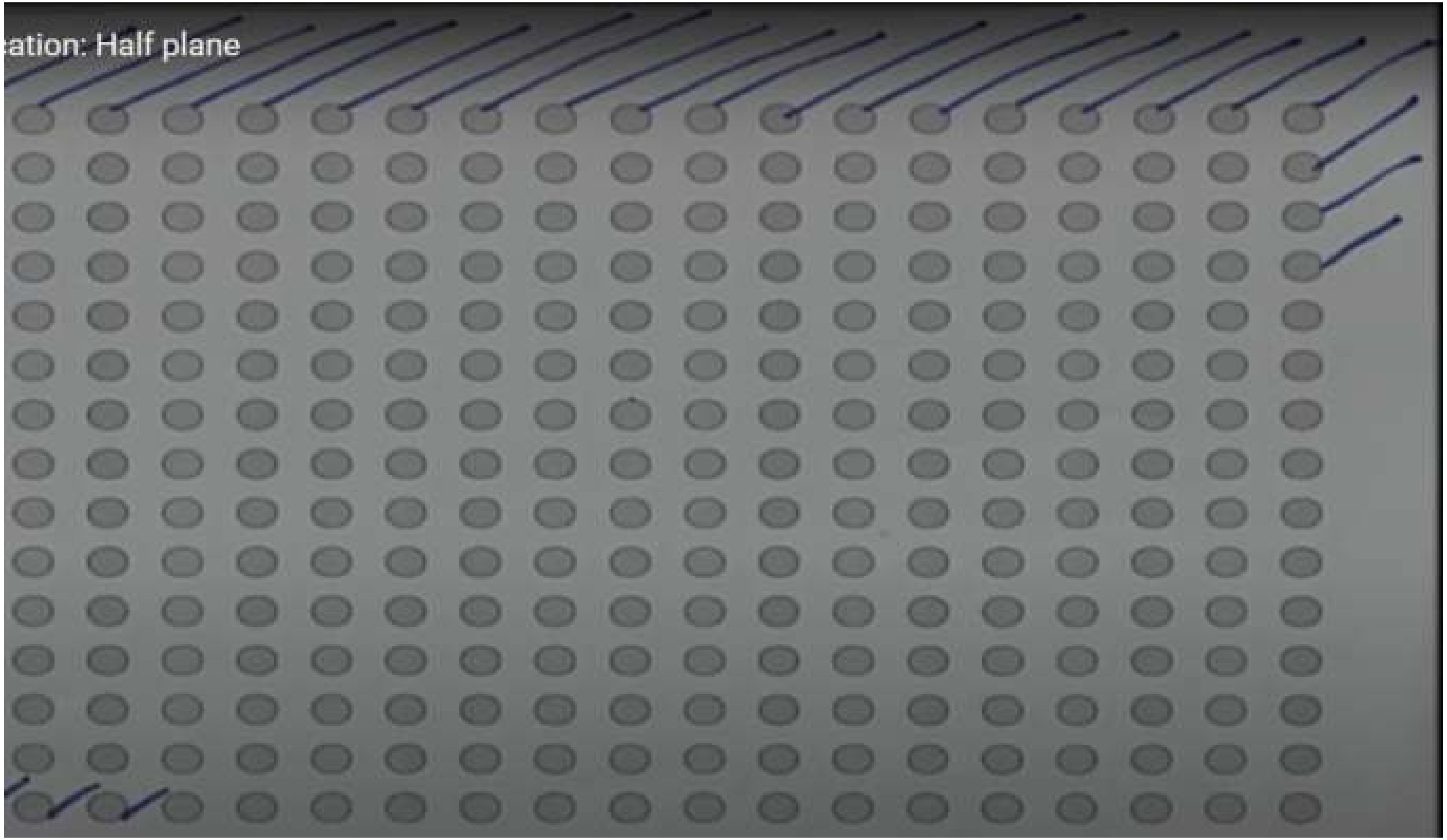
- The magnitude of this distortion decreases with distance away from the dislocation line.

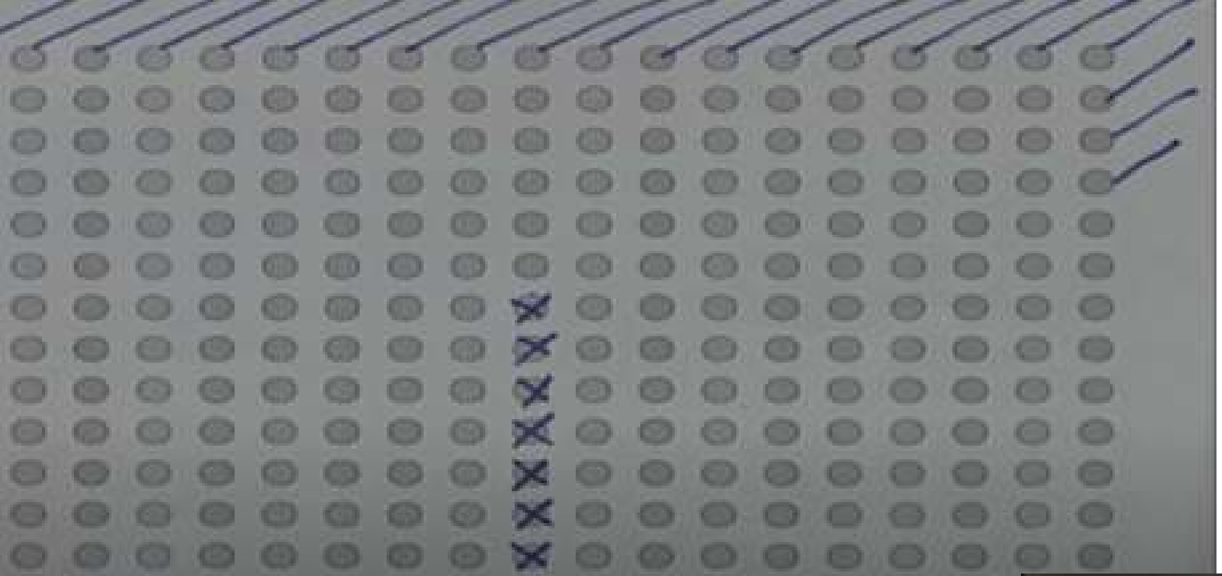
- An edge dislocation may also be formed by an extra half-plane of atoms that is included in the bottom portion of the crystal.

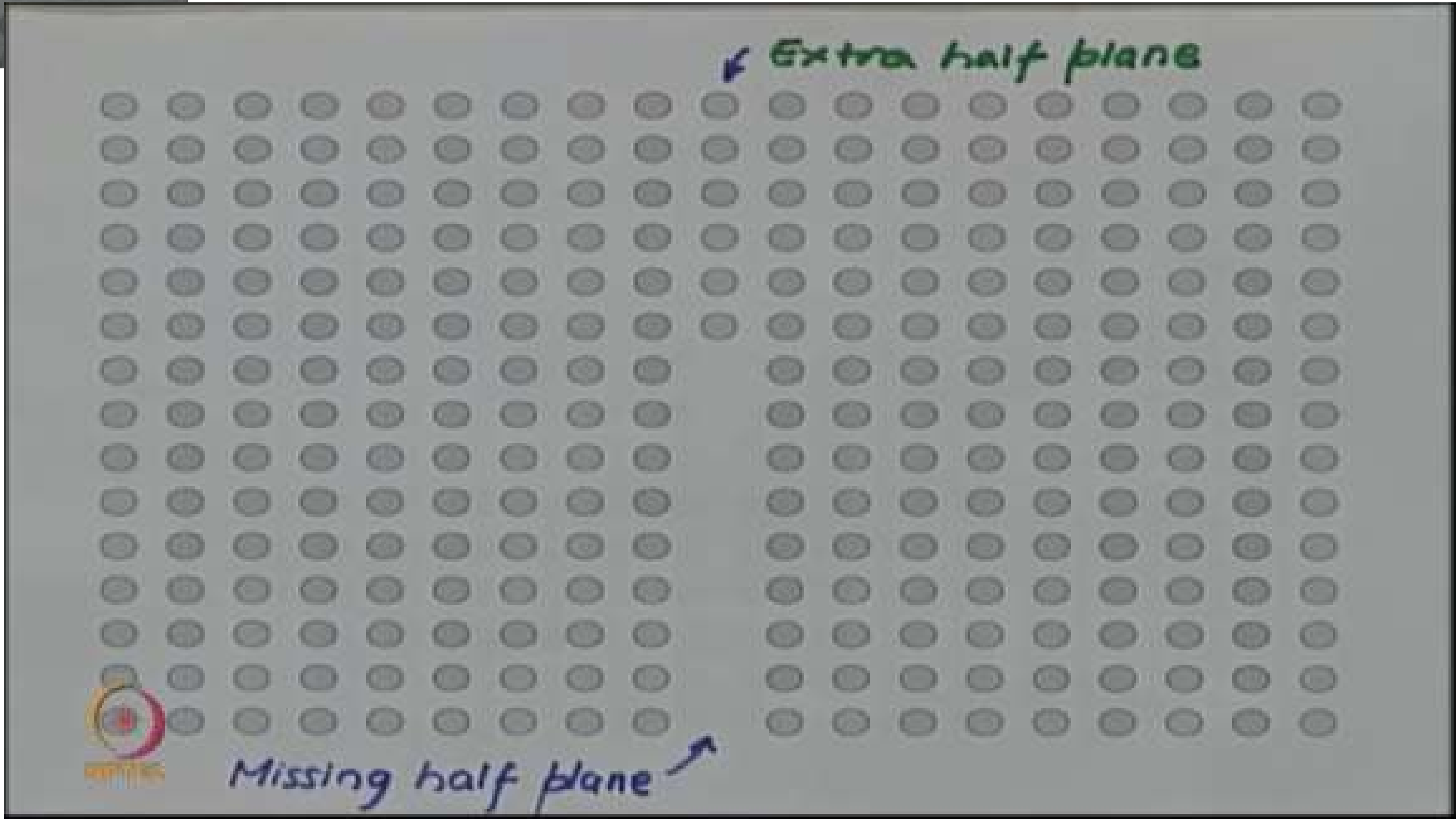
- The magnitude and direction of the lattice distortion associated with a dislocation is expressed in terms of a **Burgers vector,** denoted by **b.**

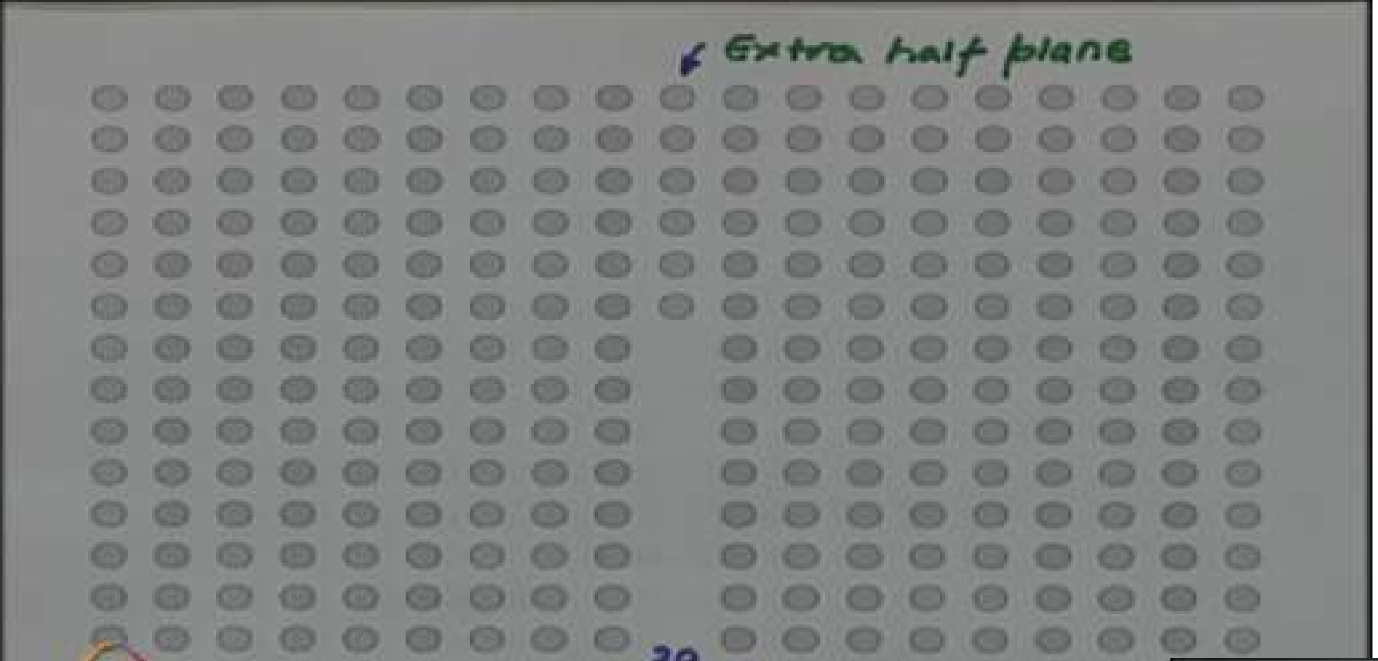
- Nature of a dislocation (i.e., edge, screw, or mixed) is defined by the *relative orientations of dislocation line and Burgers vector*

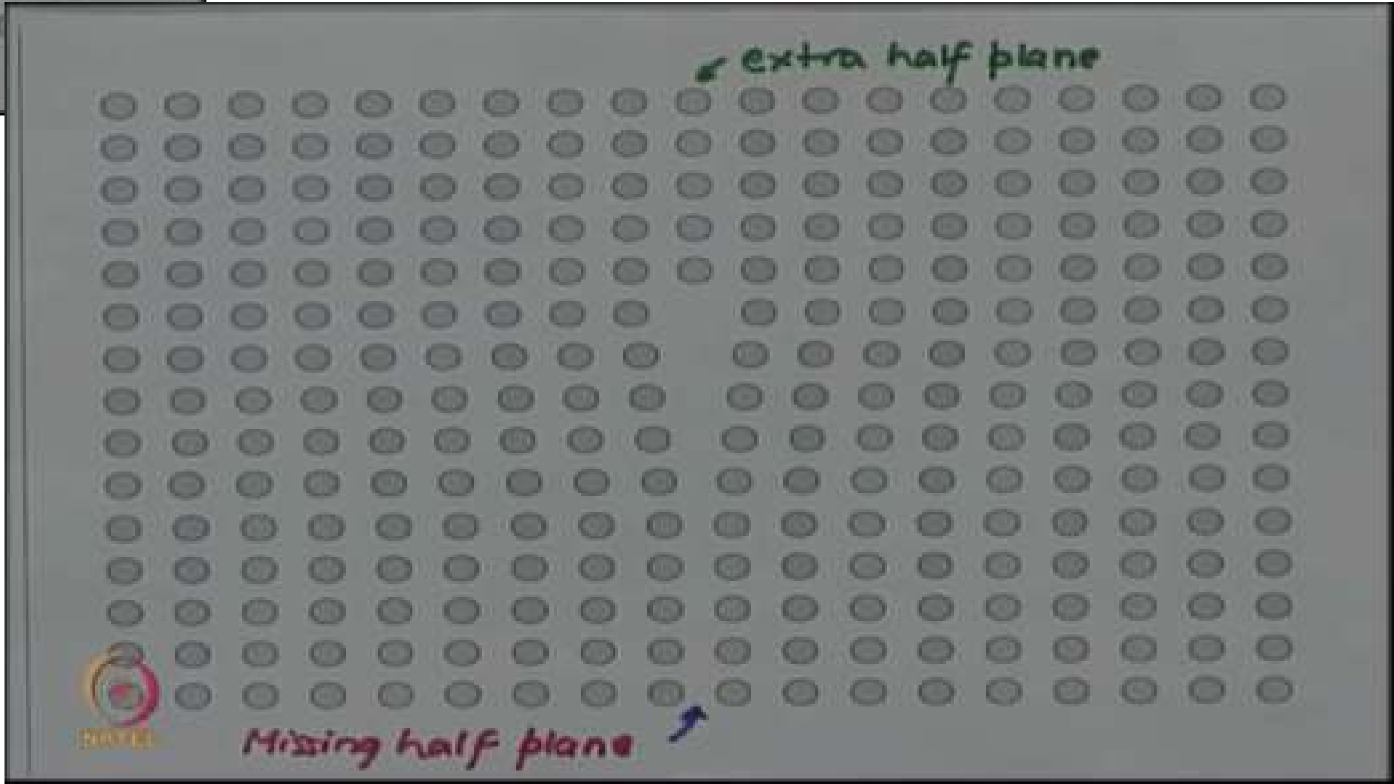
- Edge dislocation line is *perpendicular to burgers vector*

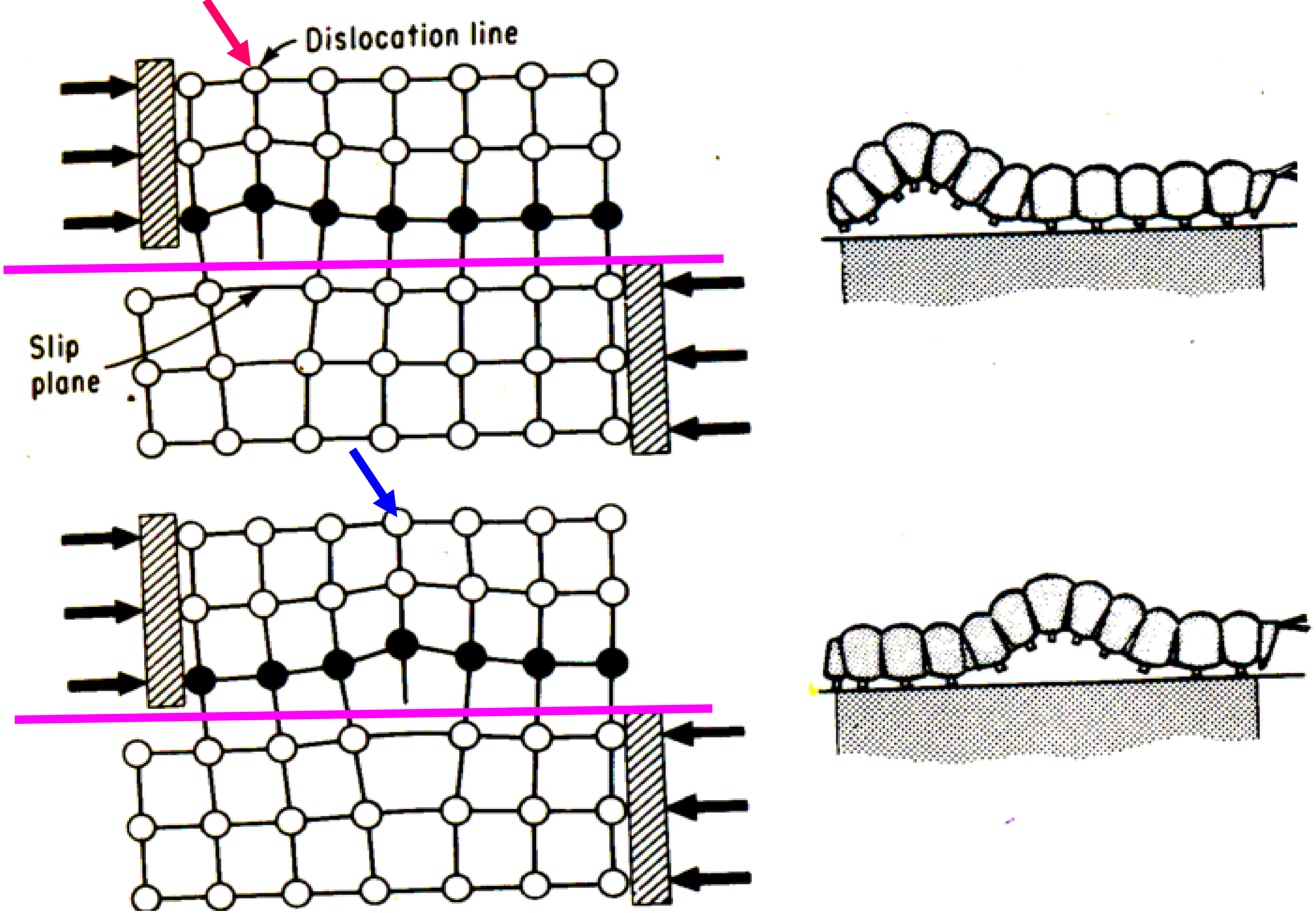

ation: Half plane



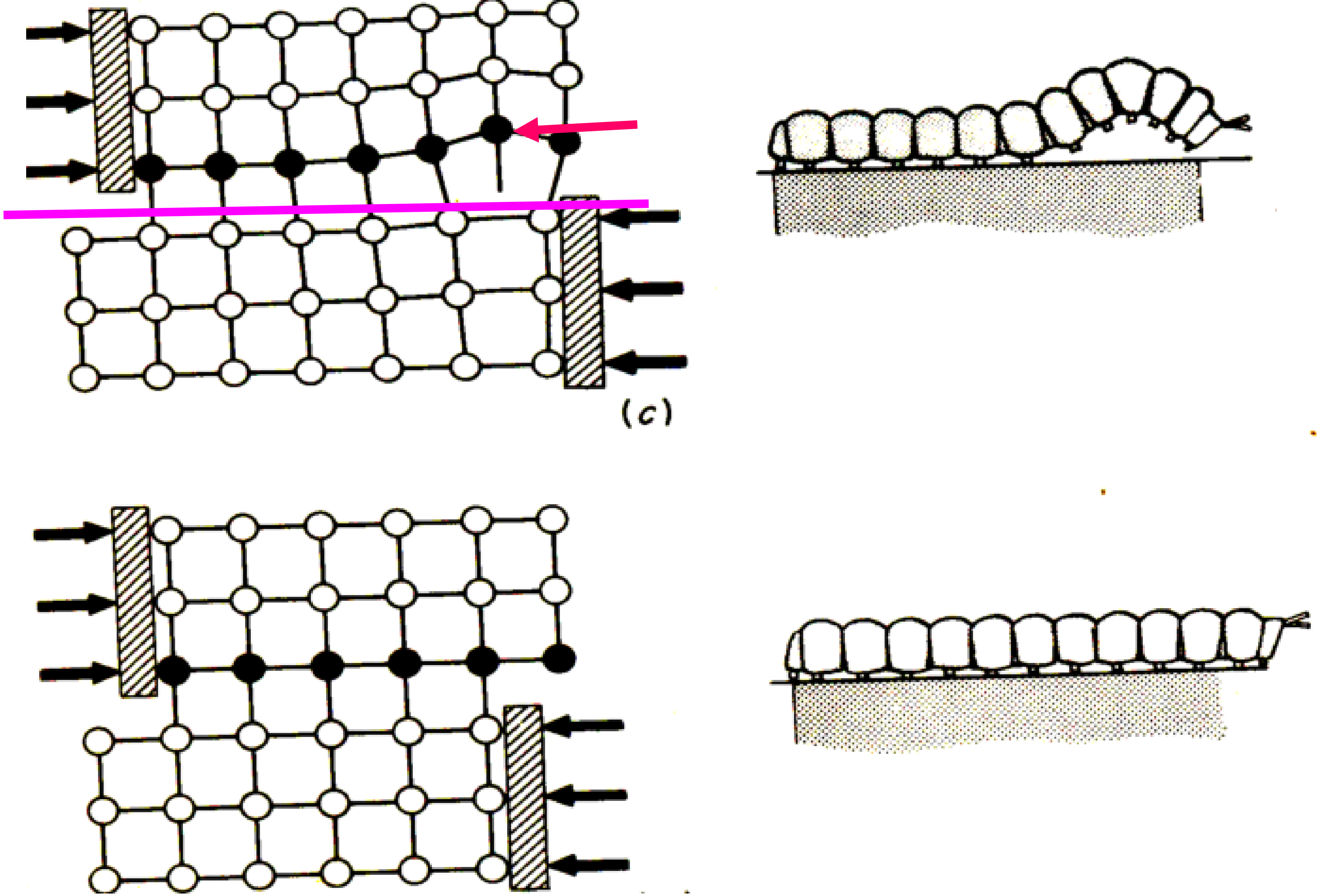

Extra half plane
Missing half plane


Extra half plane
2a
Missing half plane

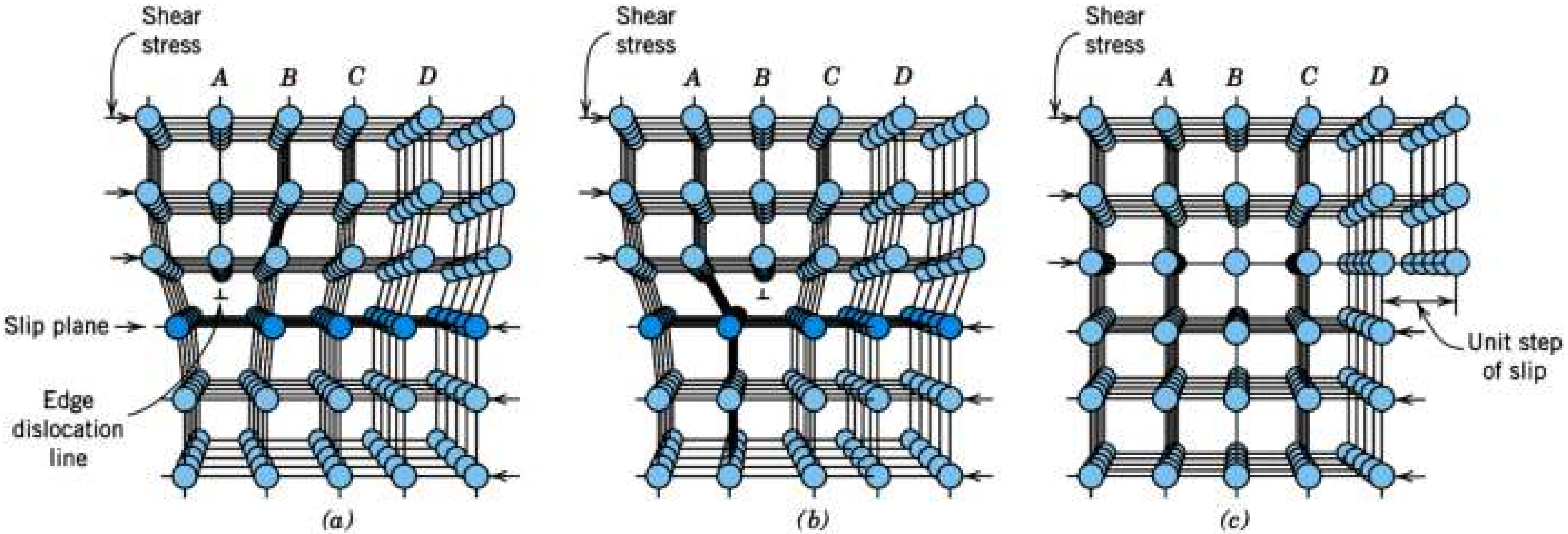

extra half plane
Missing half plane



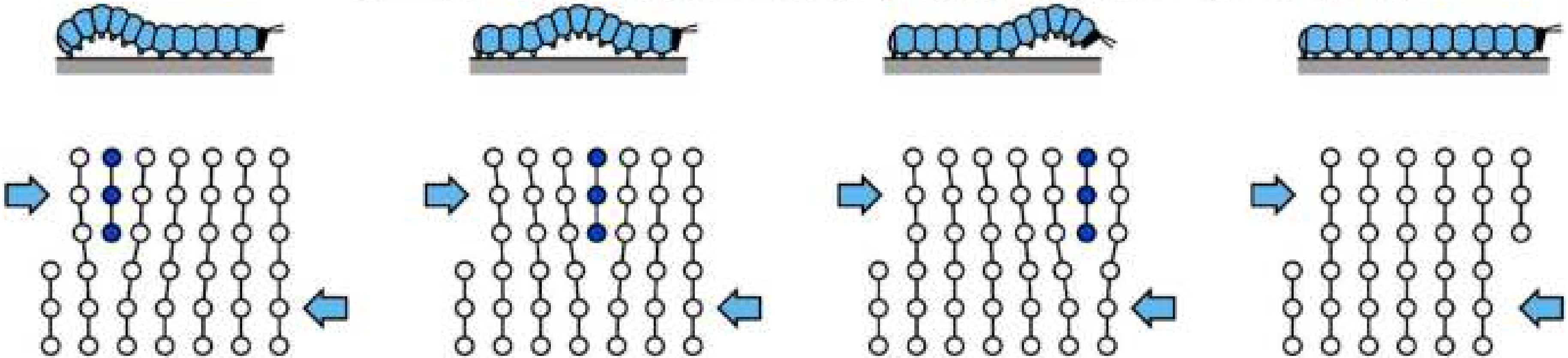
Analogy between the movement of a dislocation through a crystal and the movement of an earthworm as it arches its back while going forward.



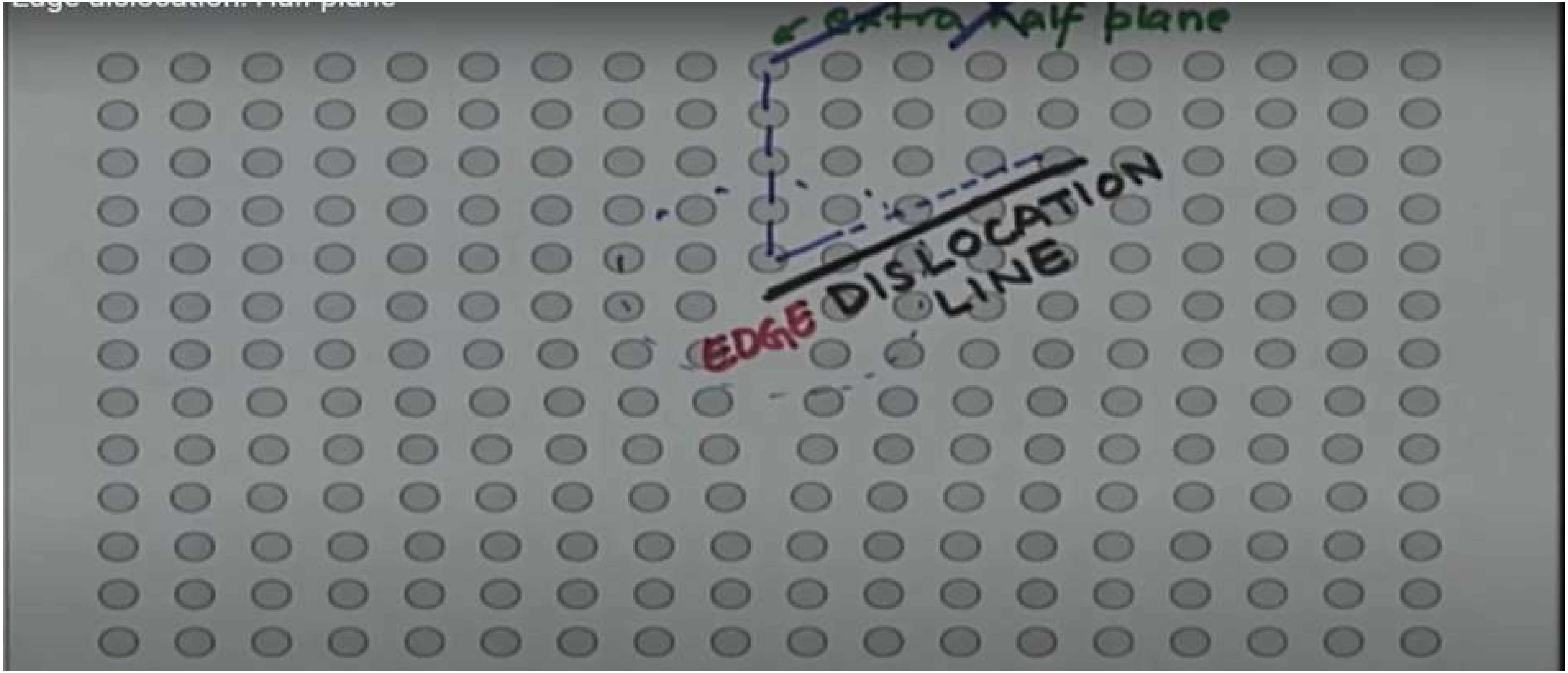
Analogy between the movement of a dislocation through a crystal and the movement of an earthworm as it arches its back while going forward.



Atomic rearrangements that accompany the motion of an edge dislocation as it moves in response to an applied shear stress. (*a*) The extra half-plane of atoms is labeled *A*. (*b*) The dislocation moves one atomic distance to the right as *A* links up to the lower portion of plane *B*; in the process, the upper portion of *B* becomes the extra half-plane. (*c*) A step forms on the surface of the crystal as the extra half-plane exits. (Adapted from A. G. Guy,

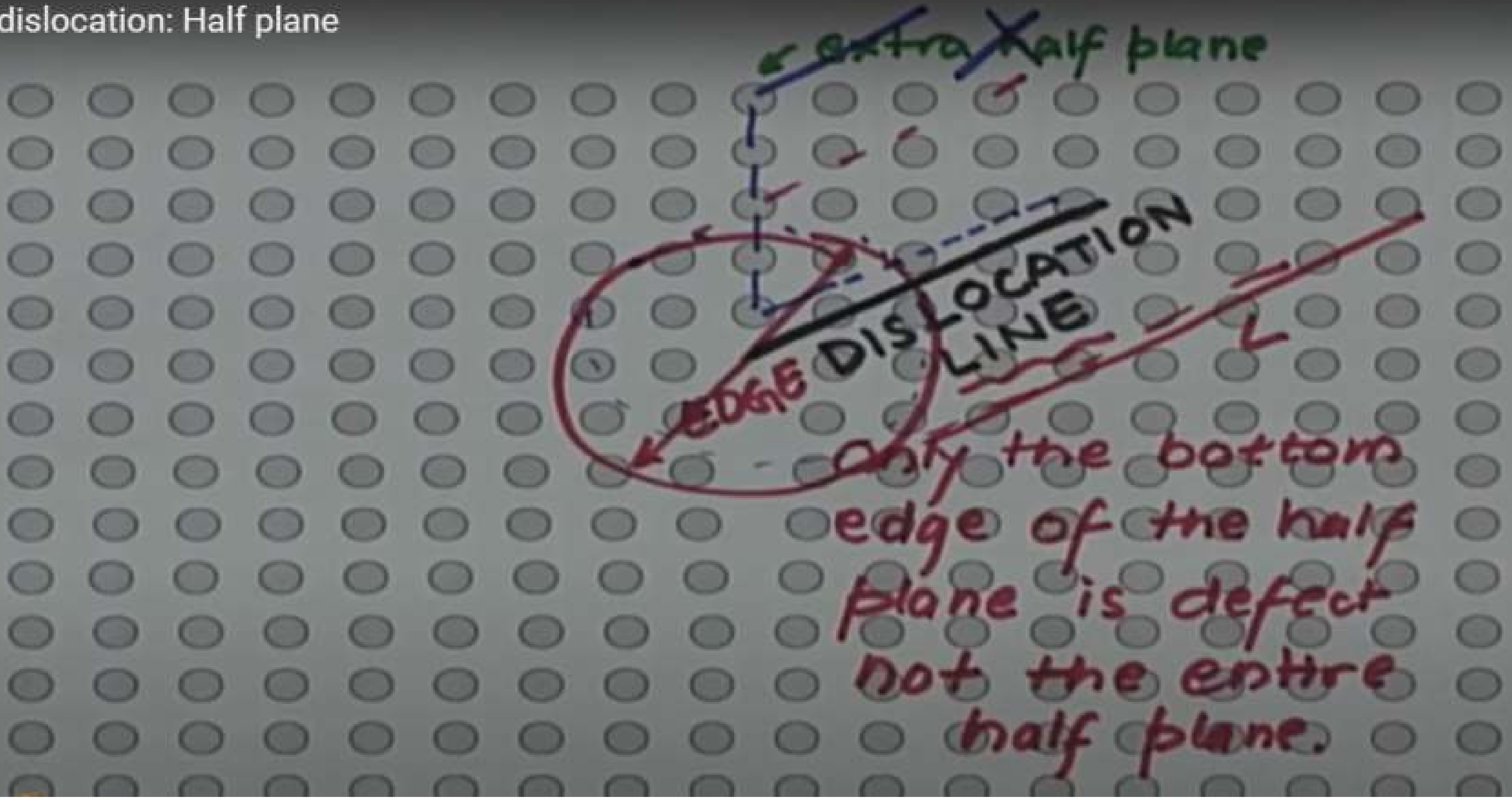


Representation of the analogy between caterpillar and dislocation motion.

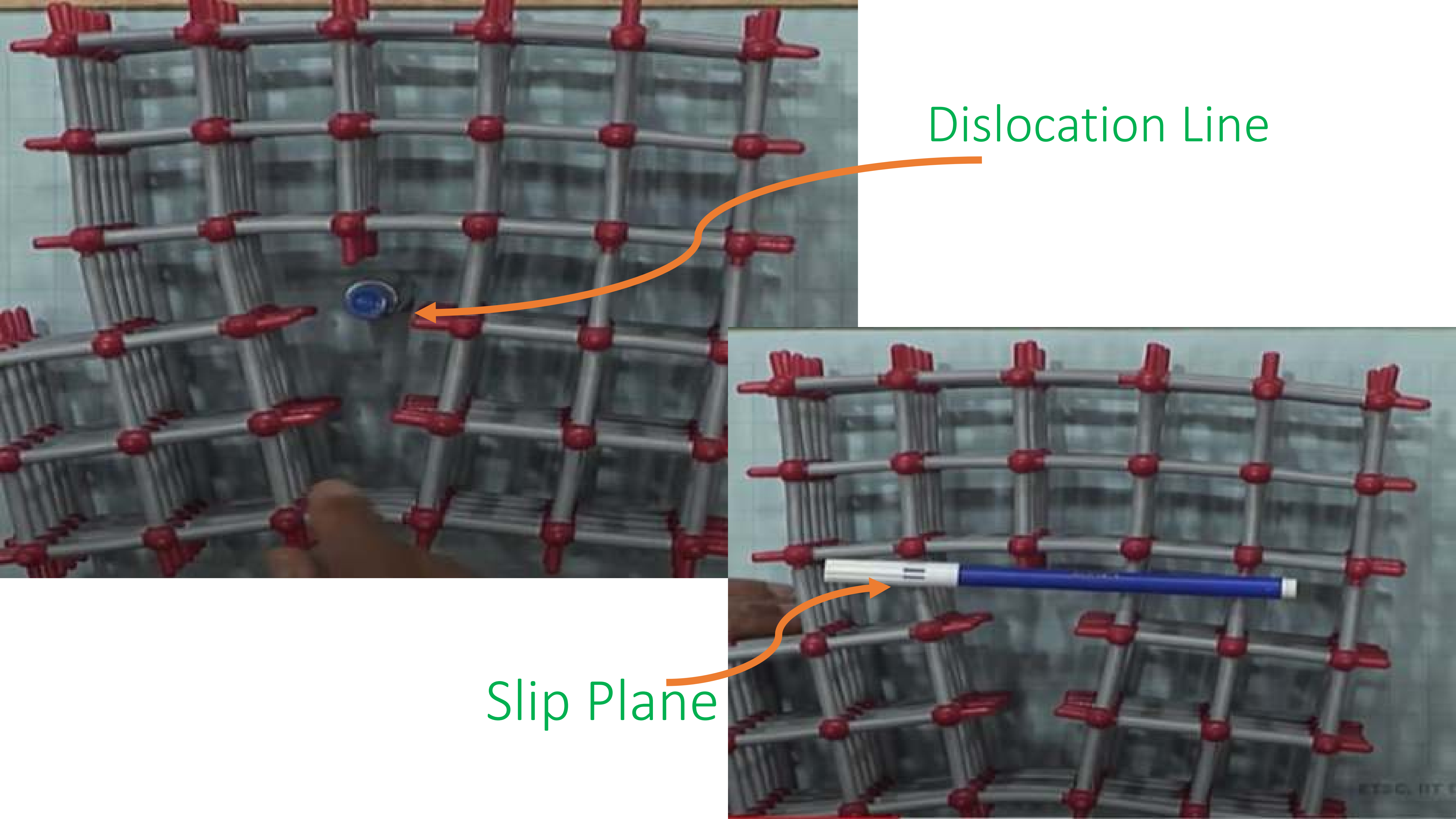


Edge dislocation: Half plane

Edge dislocation: Half plane

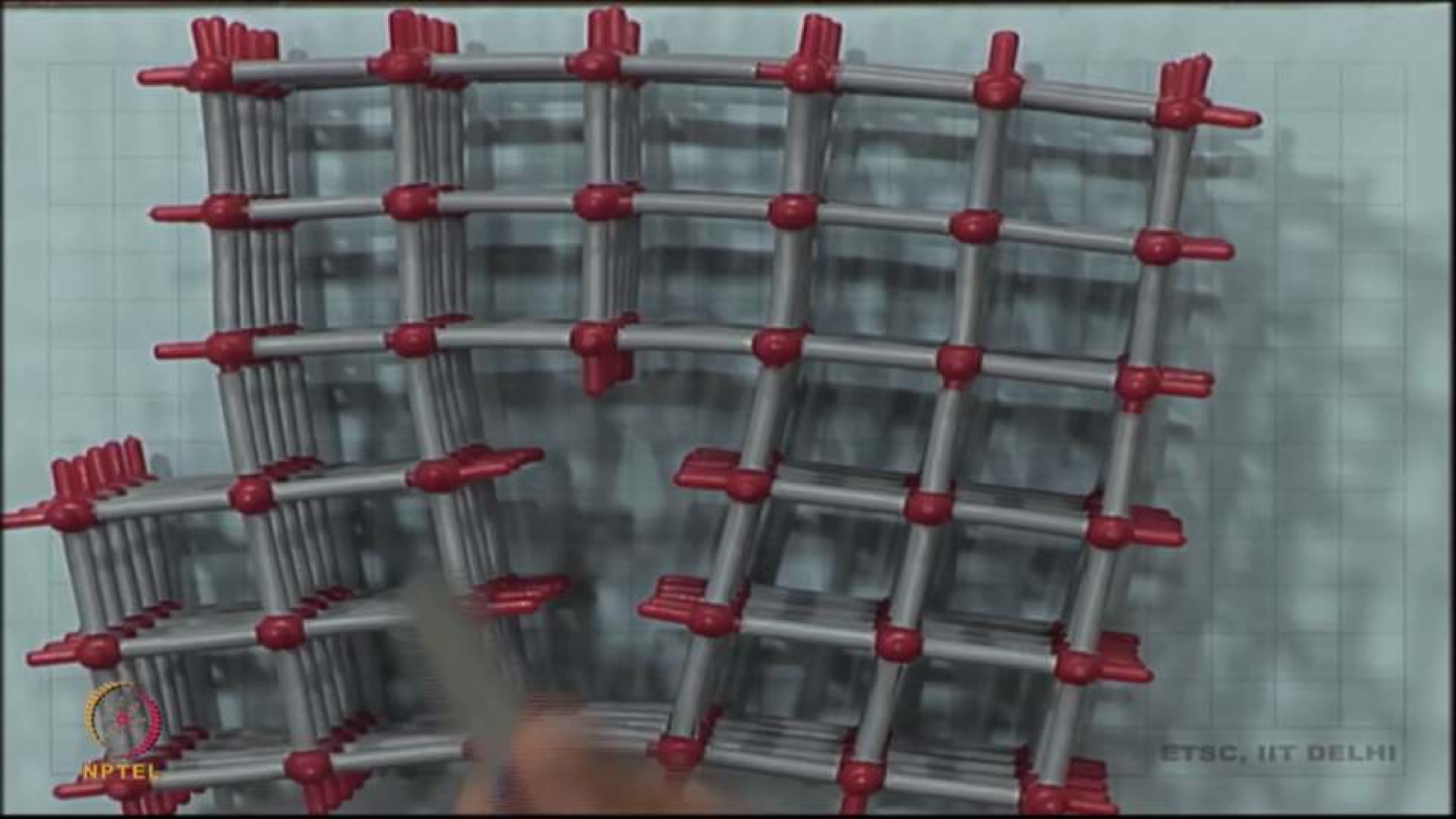


Only the bottom edge of the half plane is defect not the entire half plane.



Dislocation Line

Slip Plane



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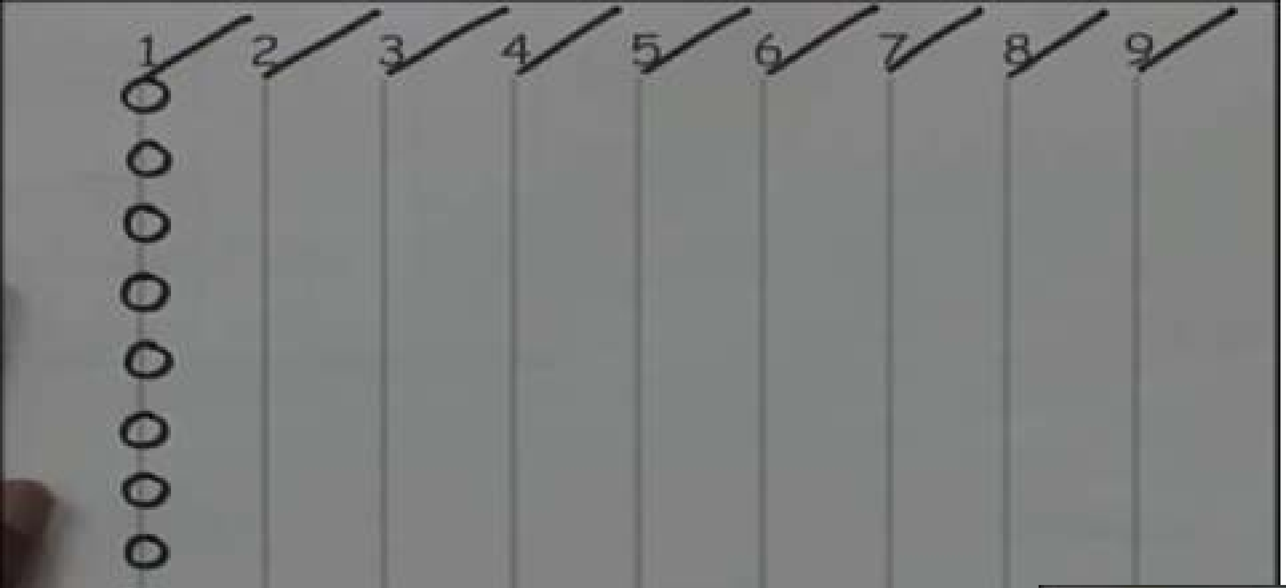
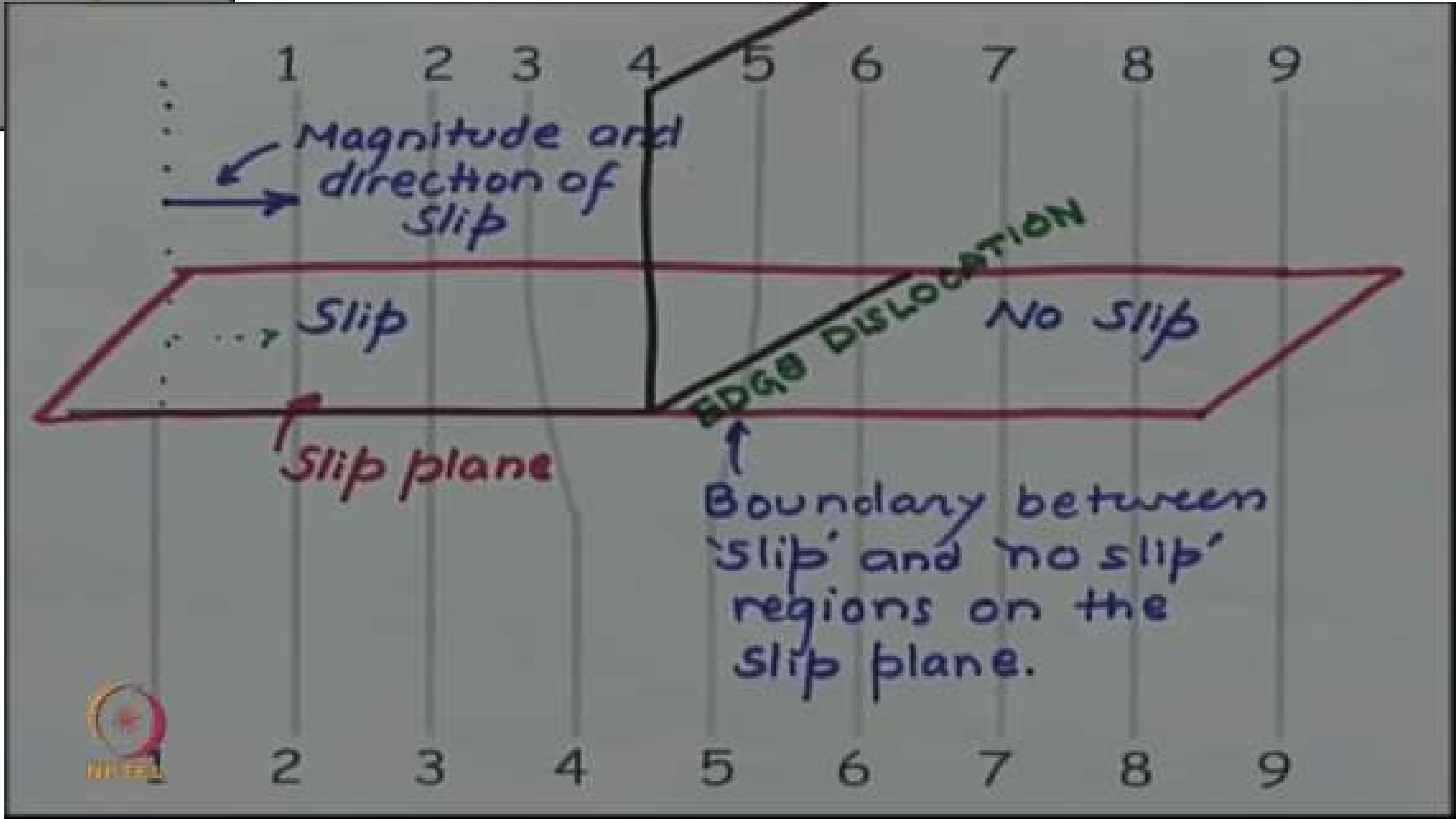
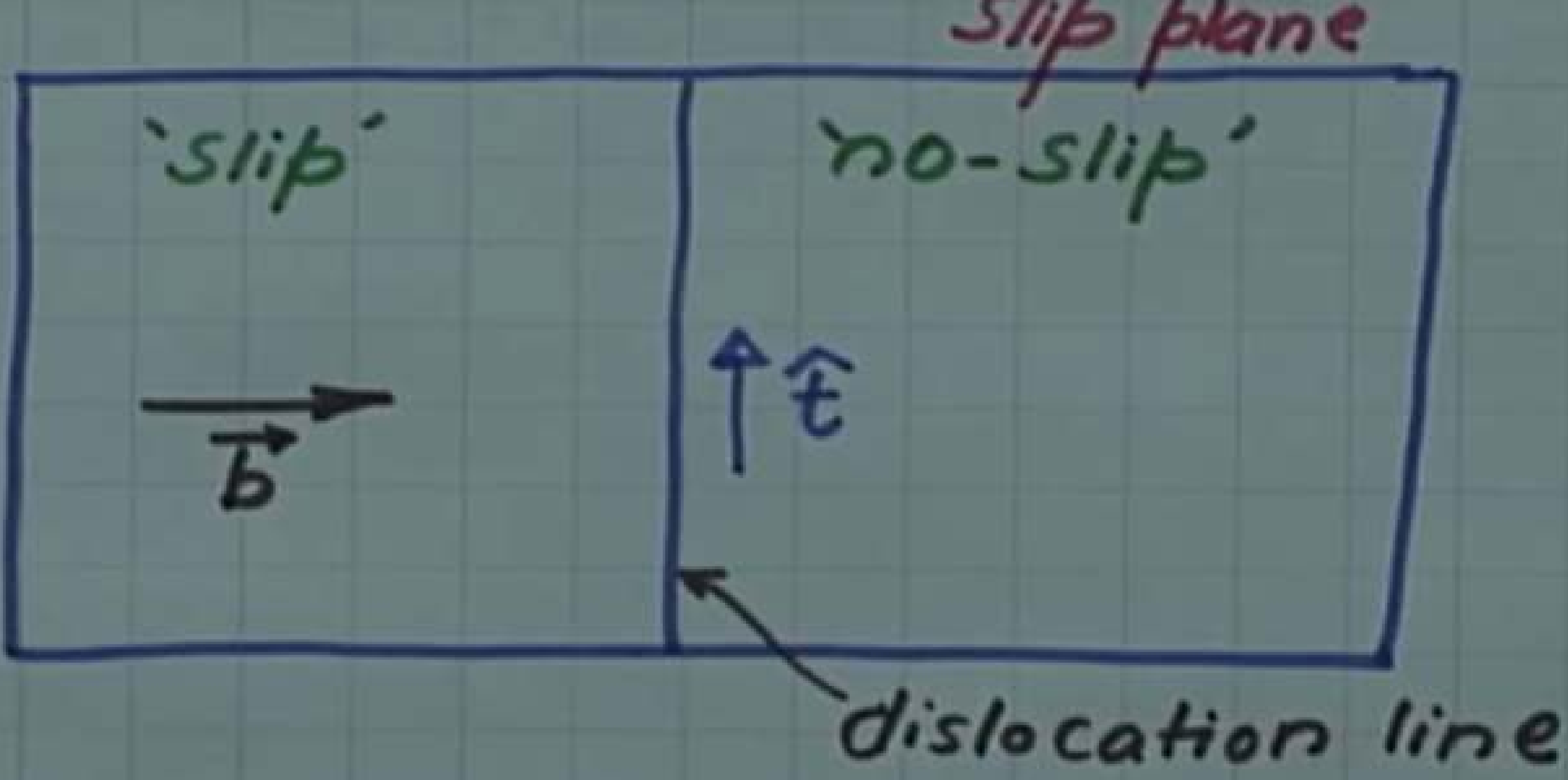
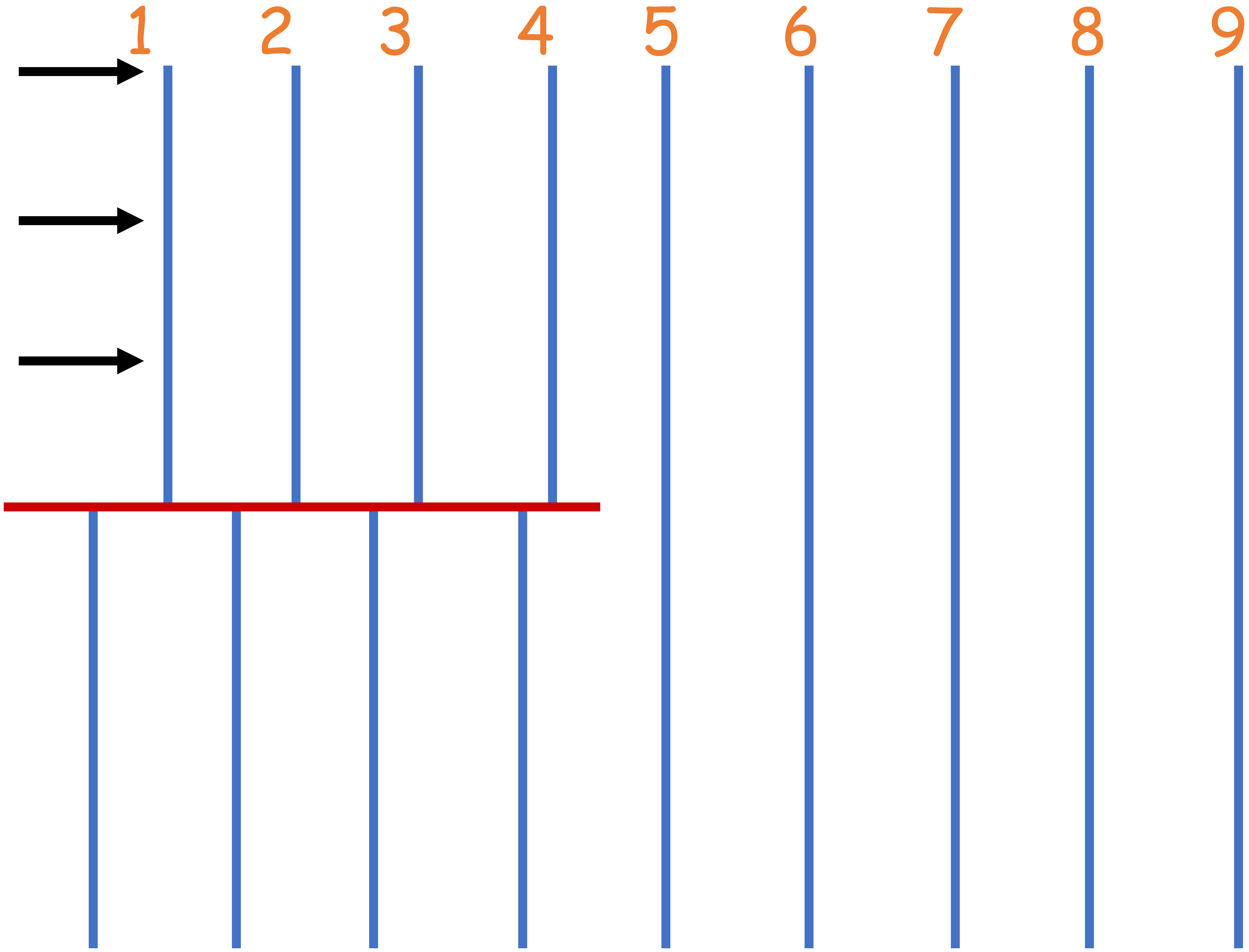

1 2 3 4 5 6 7 8 9
1 2 3 4 5 6 7 8


1 2 3 4 5 6 7 8 9
Magnitude and direction of Slip
Slip
No Slip
EDGE DISLOCATION
Slip plane
Boundary between 'Slip' and 'no slip' regions on the slip plane.
1 2 3 4 5 6 7 8 9



$\hat{t}$: tangent vector (line vector)
unit vector parallel or tangent to the dislocation line.

$\vec{b}$: Burgess vector : Magnitude & direction of slip


1
2
3
4
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8
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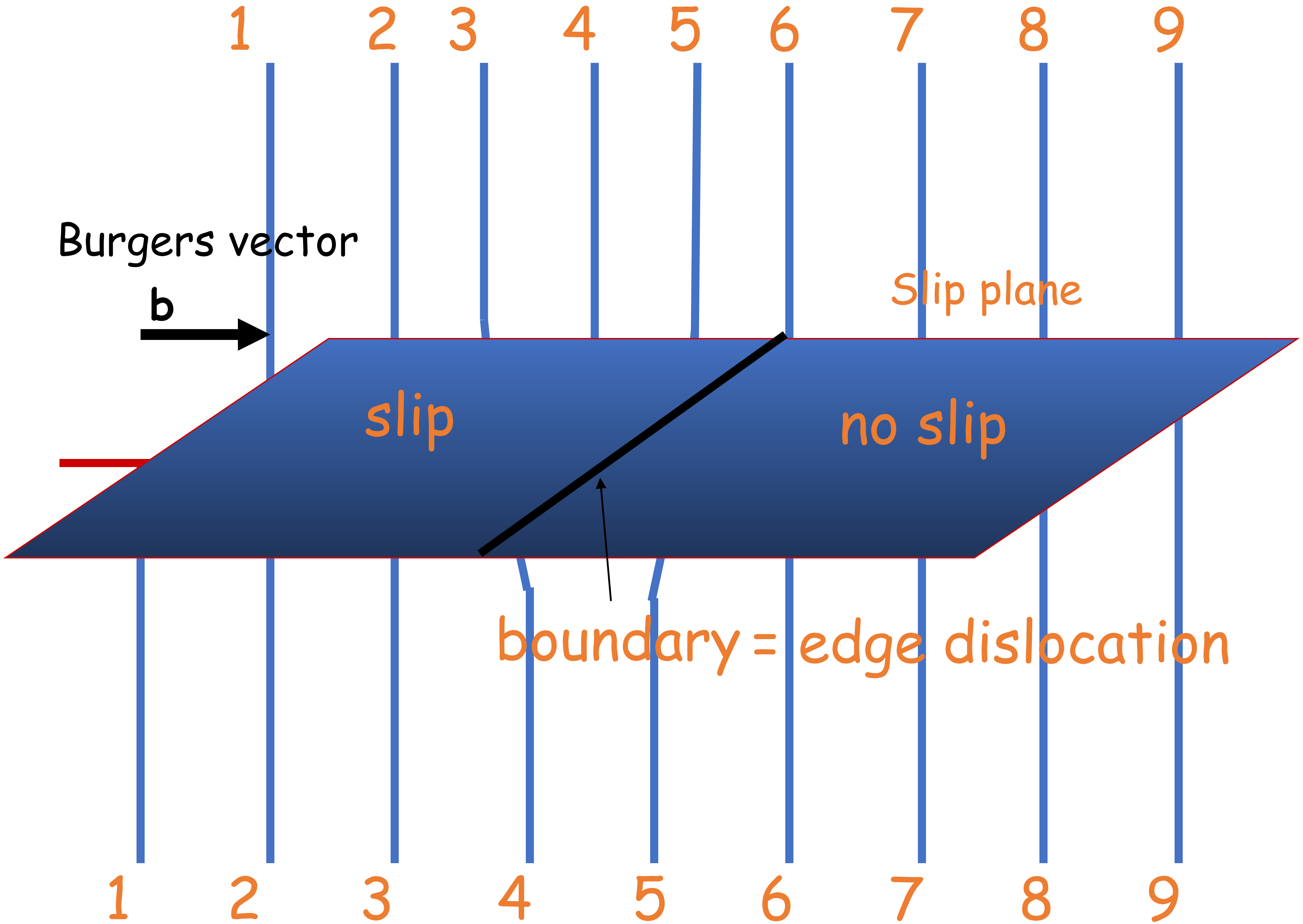
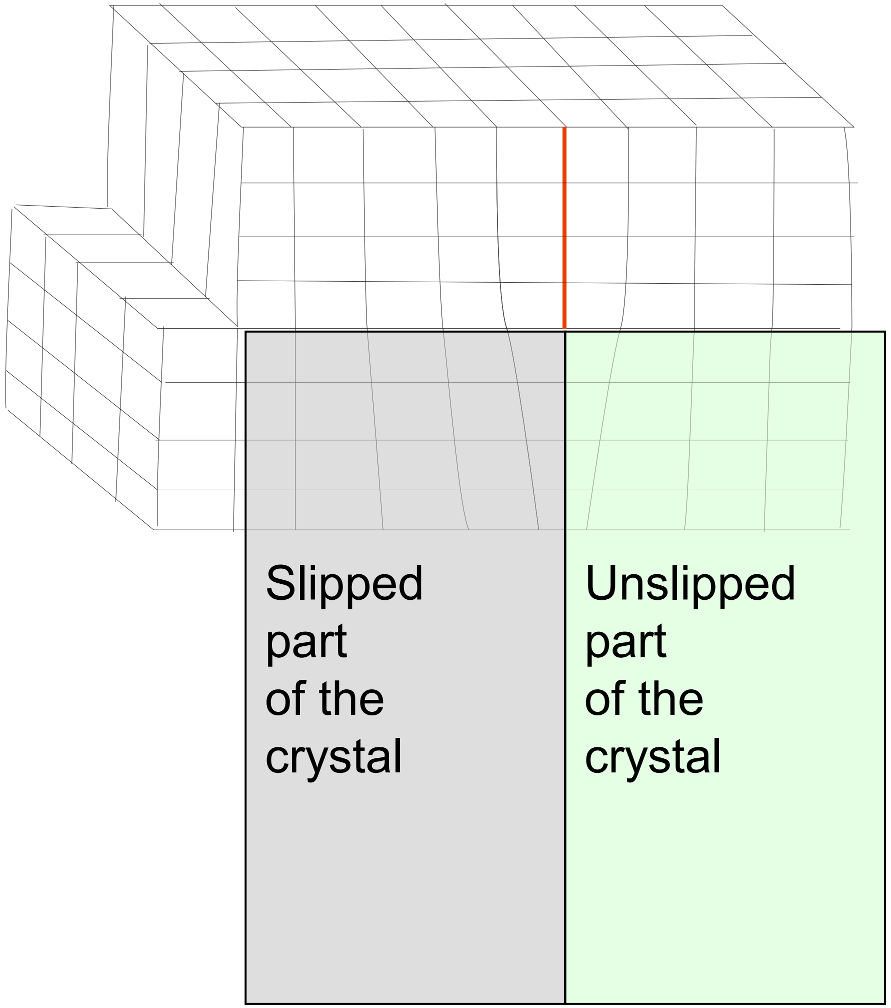
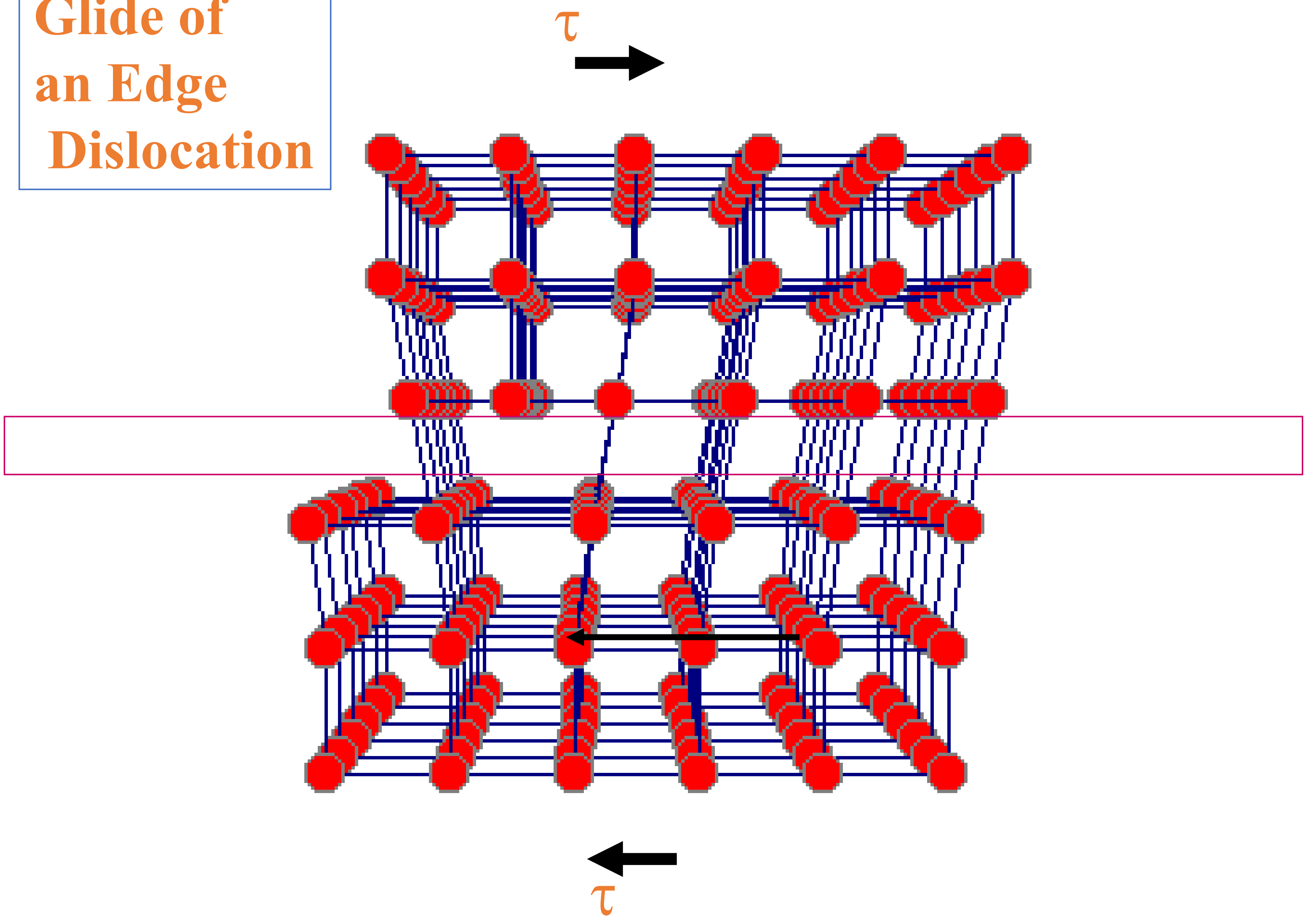

1 2 3 4 5 6 7 8 9
Burgers vector
b
Slip plane
slip
no slip
boundary = edge dislocation
1 2 3 4 5 6 7 8 9



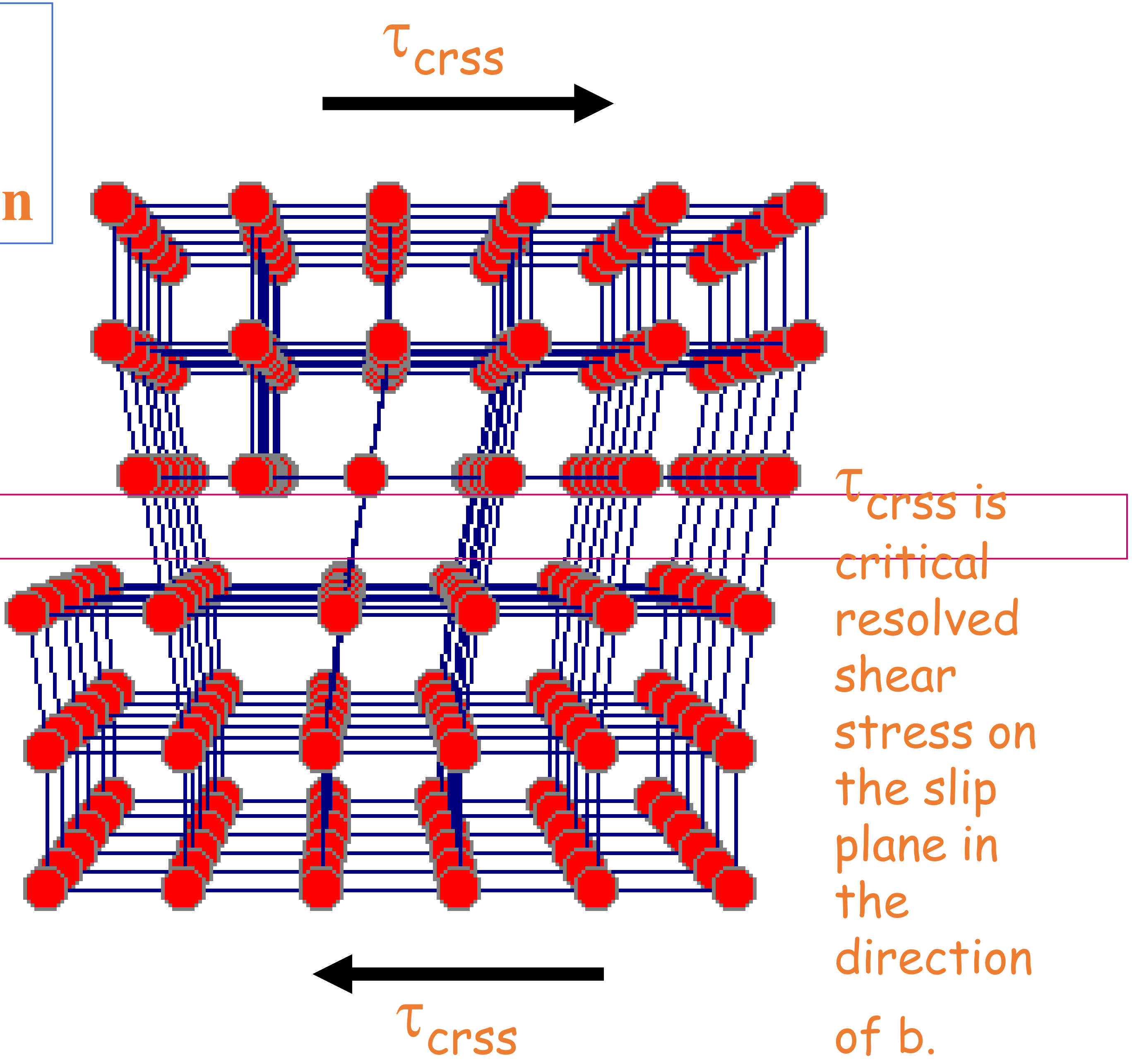
Dislocation can be considered as a boundary between the slipped and the unslipped parts of the crystal lying over a slip plane*

** this is just a way of visualization and often the slipped and unslipped regions may not be distinguished*

Glide of an Edge Dislocation

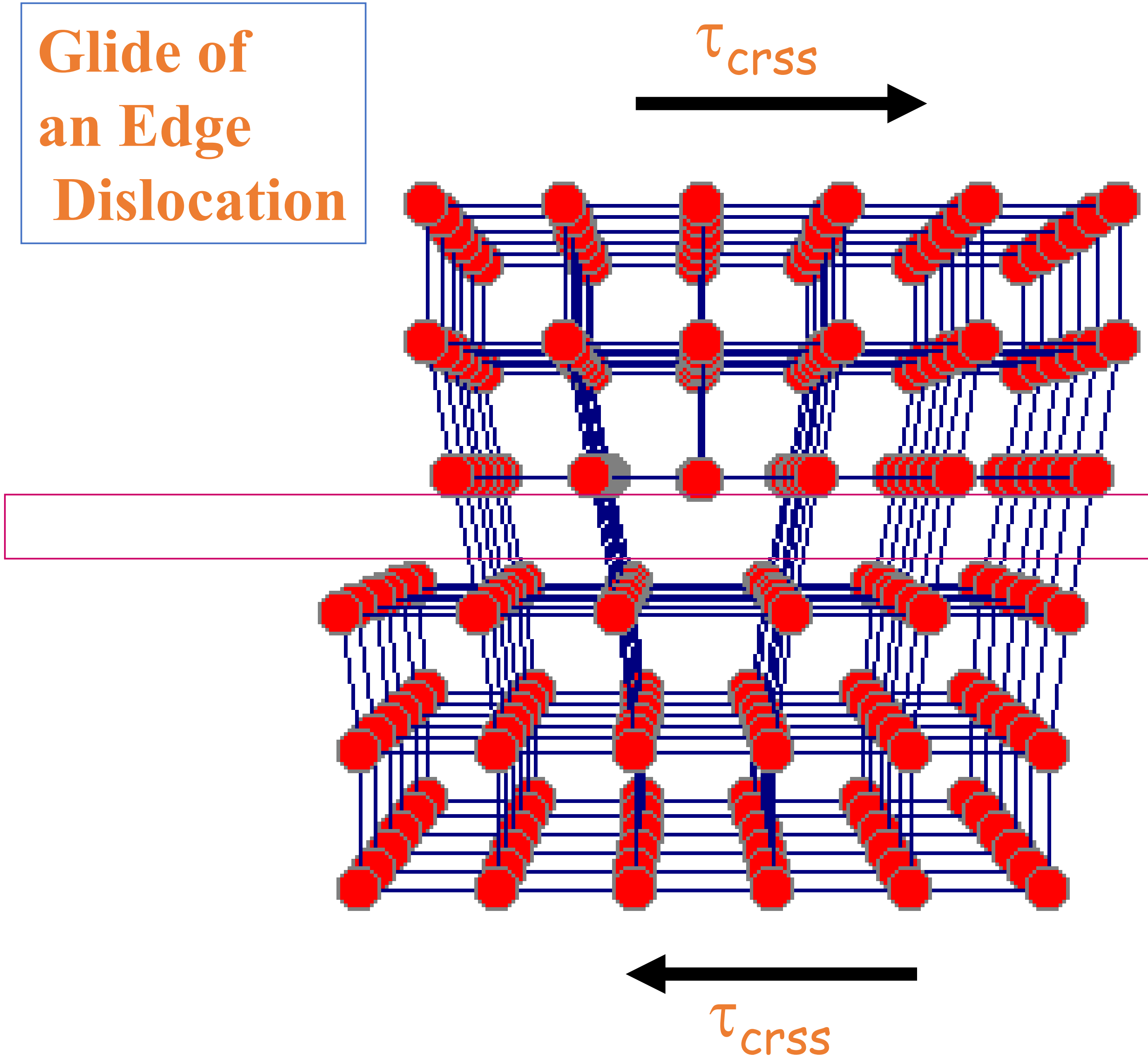


Glide of an Edge Dislocation



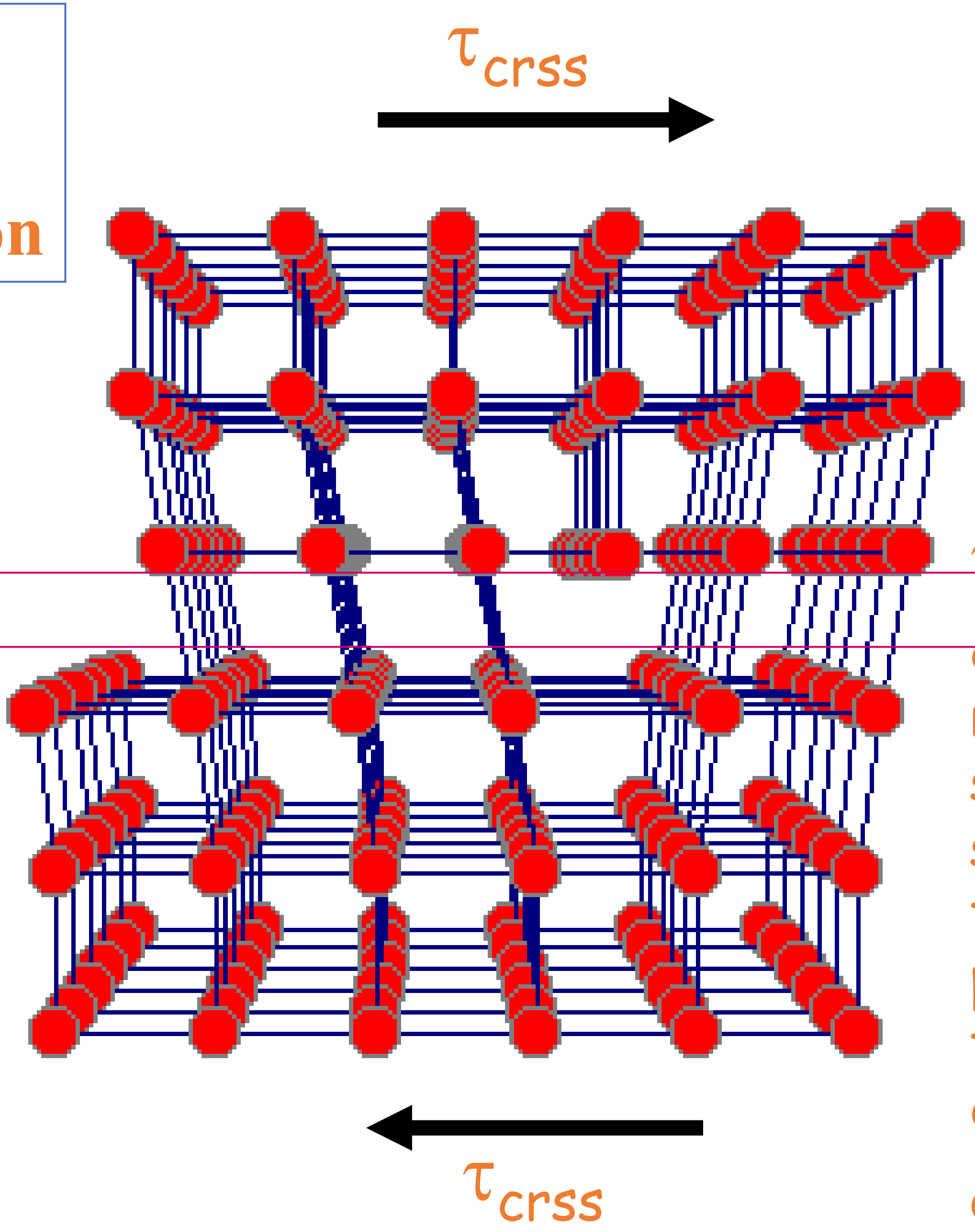
τ_{crss} is critical resolved shear stress on the slip plane in the direction of b.

Glide of an Edge Dislocation



τ_{crss} is critical resolved shear stress on the slip plane in the direction of b.

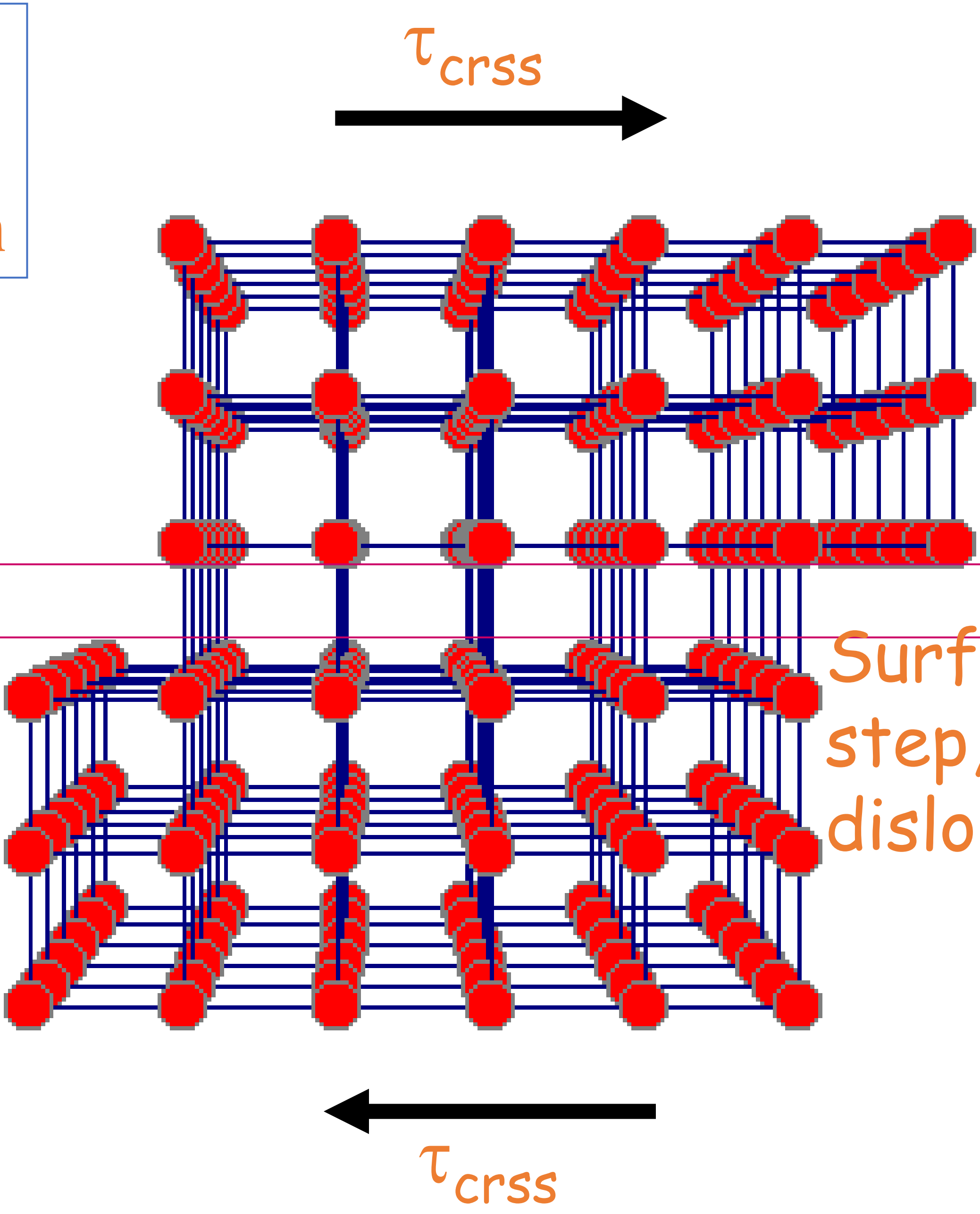
Glide of an Edge Dislocation



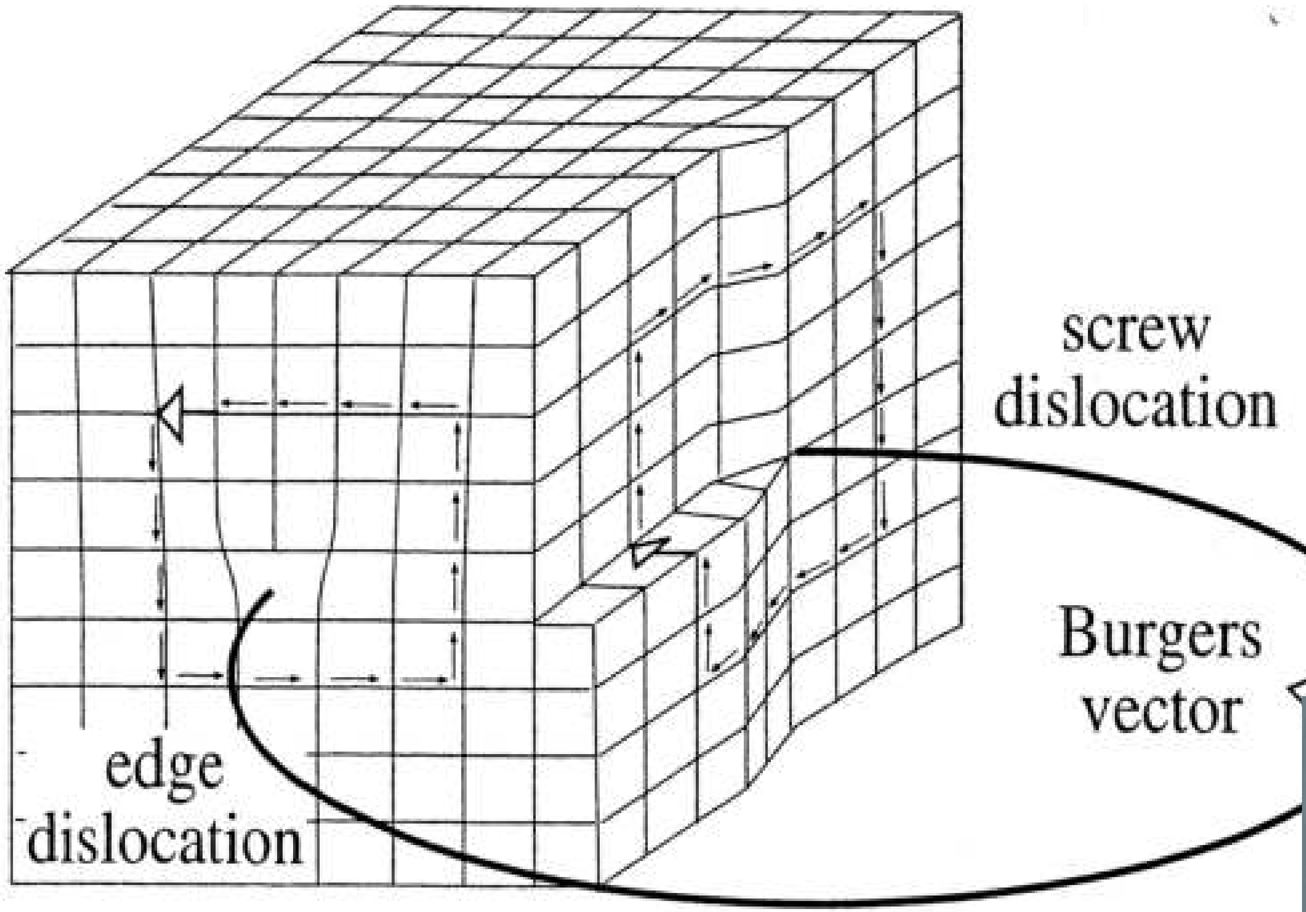
τ_{crss} is critical resolved shear stress on the slip plane in the direction of b.

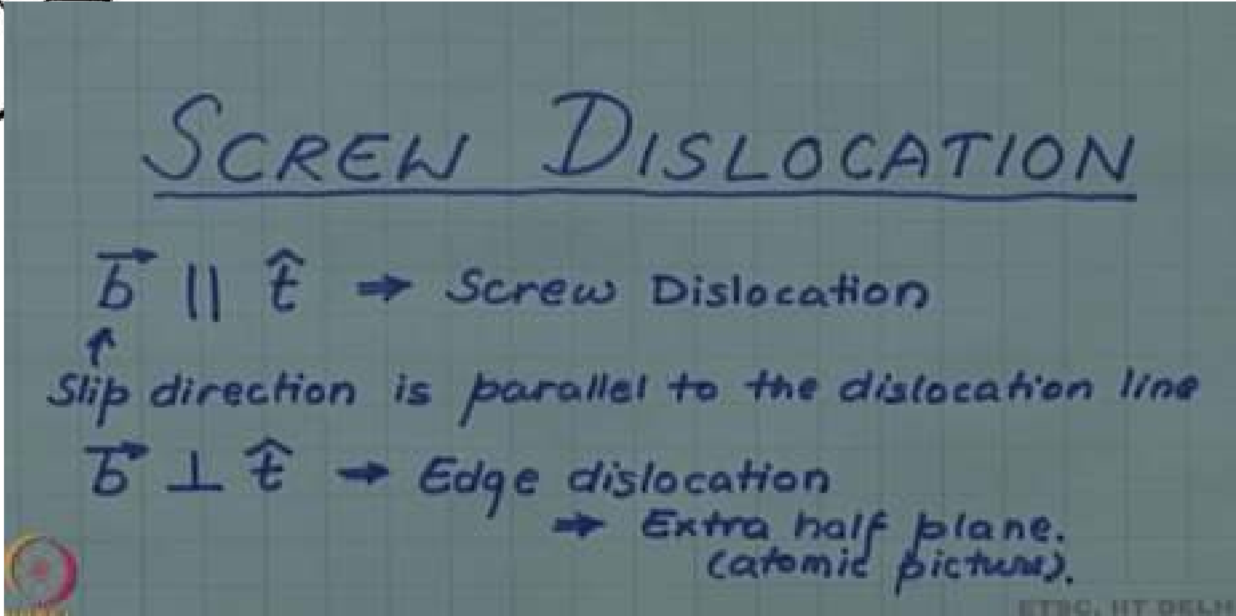
Glide of an Edge Dislocation

A surface step of b is created if a dislocation sweeps over the entire slip plane



Surface step, not a dislocation





SCREW DISLOCATION

$\vec{b} \parallel \hat{t}$ → Screw Dislocation

↑

Slip direction is parallel to the dislocation line

$\vec{b} \perp \hat{t}$ → Edge dislocation

→ Extra half plane.
(atomic picture).

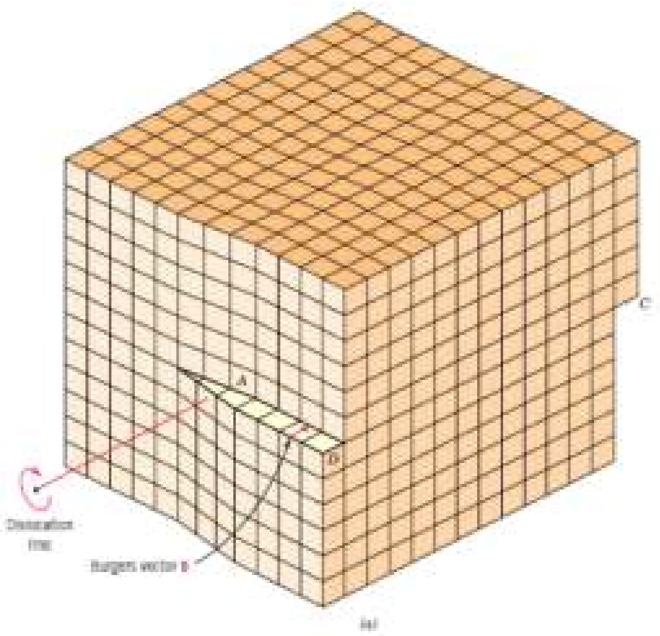
Screw dislocation

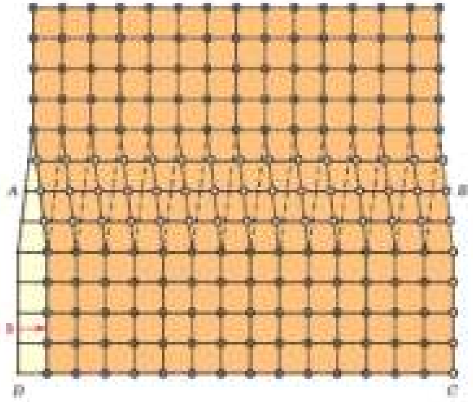
- Formed by a *shear stress* that is applied to produce the distortion.

- The upper front region of the crystal is *shifted one atomic distance* to the right relative to the bottom portion.

- The screw dislocation derives its name from the *spiral or helical path or ramp that is traced around the dislocation line* by the atomic planes of atoms.

- Burger vector is *parallel to dislocation line.*





$\vec{b} \parallel \hat{t} \Rightarrow$ screw dislocation

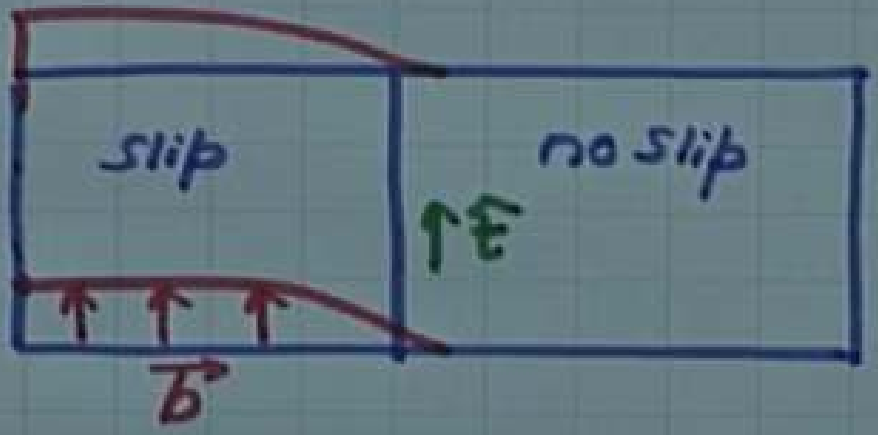
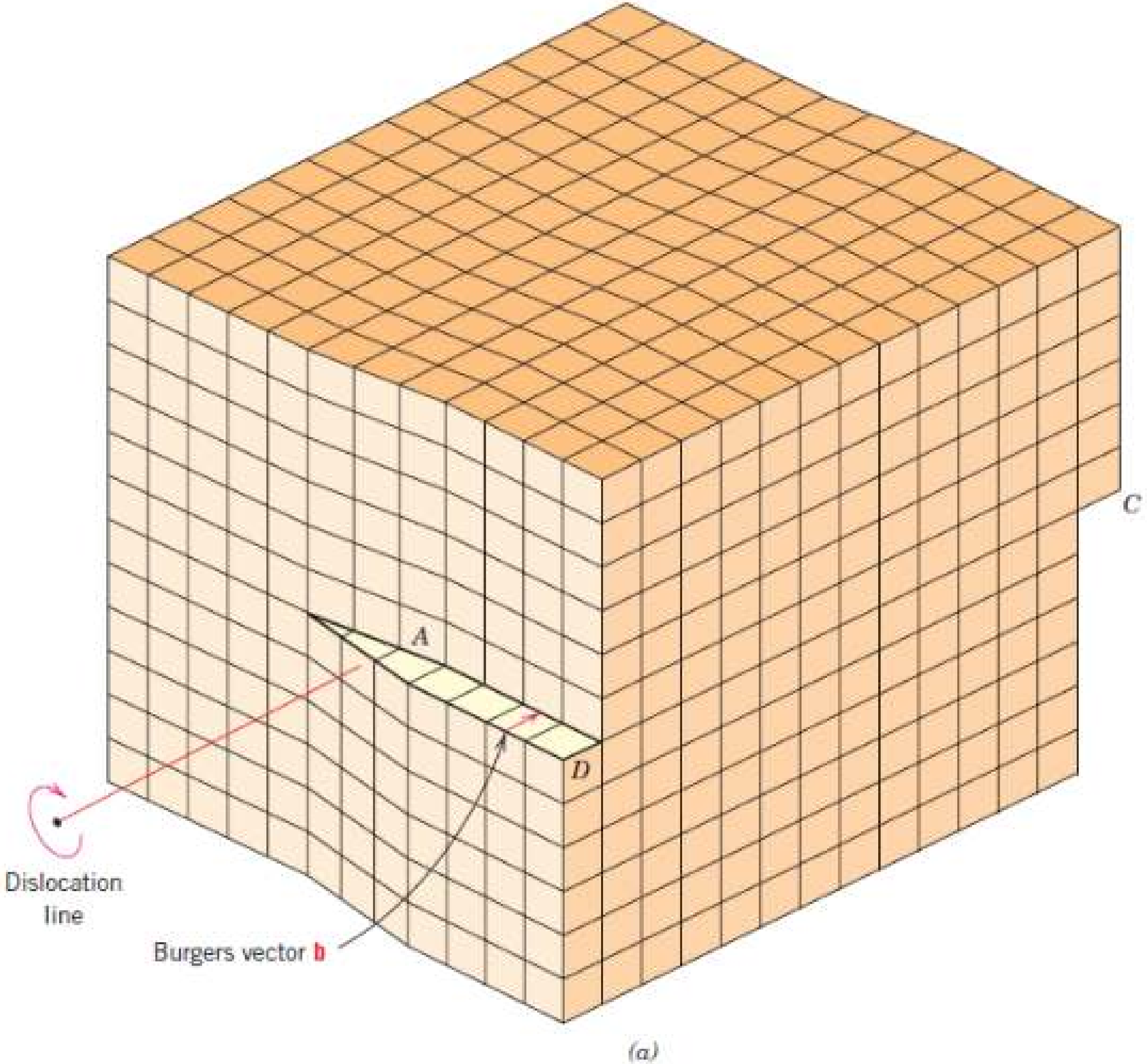
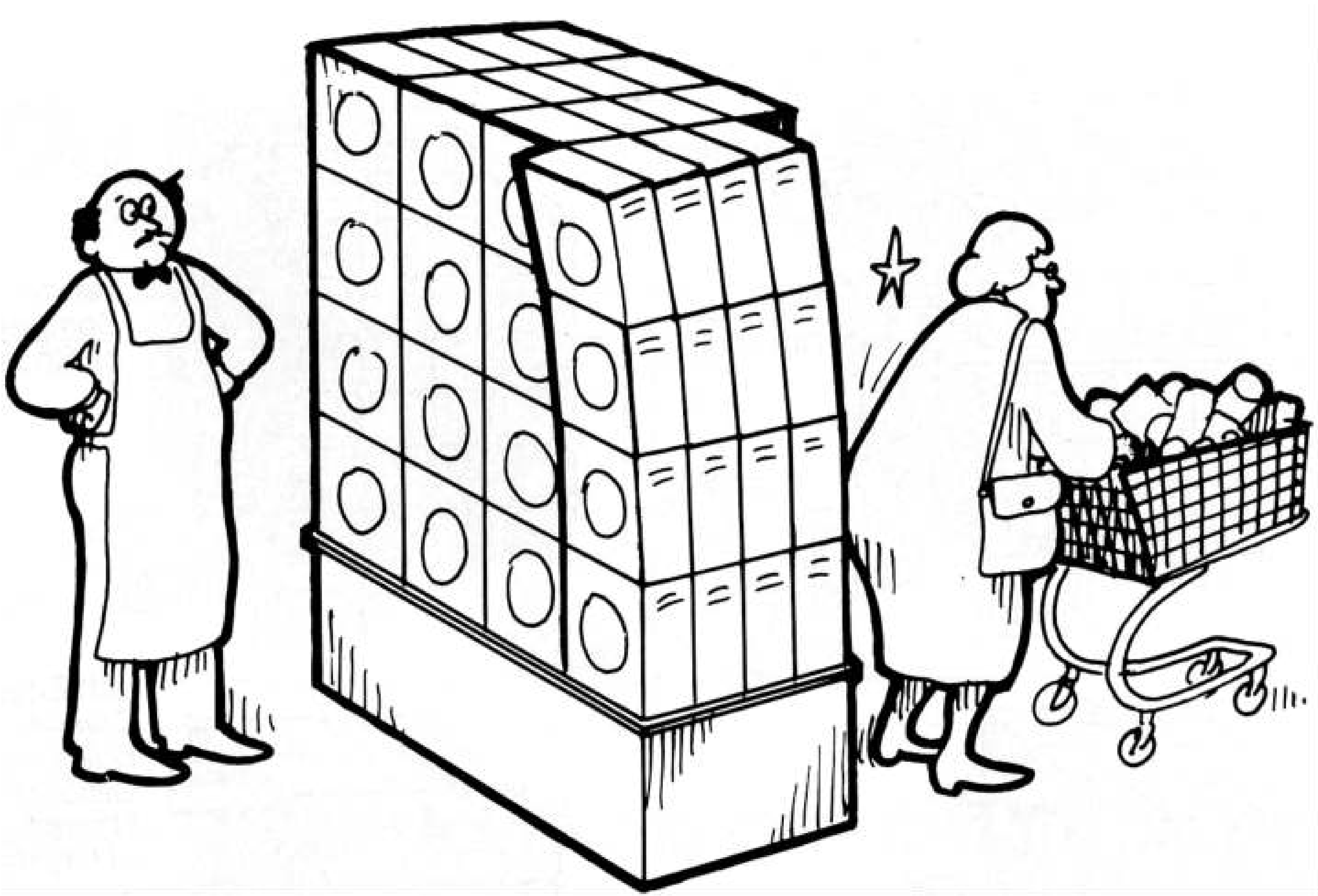
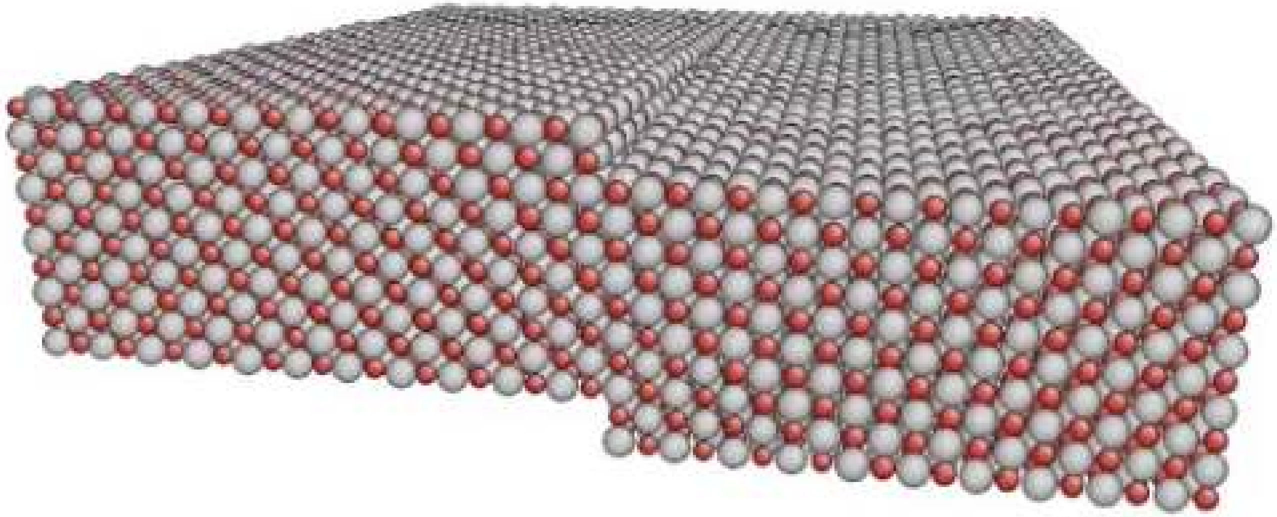


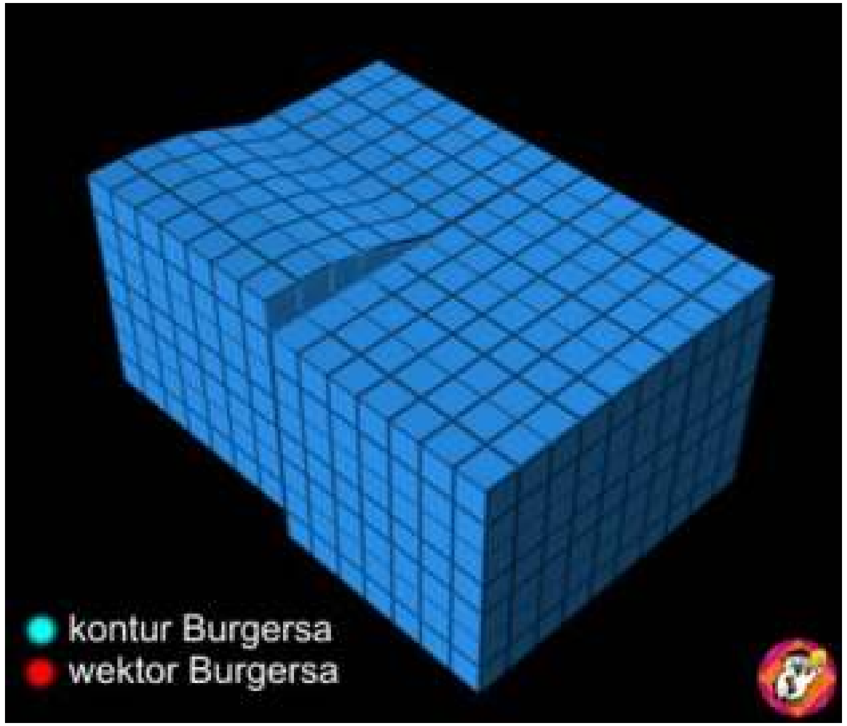
Figure 4.4 (*a*) A screw dislocation within a crystal. (*b*) The screw dislocation in (*a*) as viewed from above. The dislocation line extends along line *AB*. Atom positions above the slip plane are designated by open circles, those below by solid circles. [Figure (*b*) from W. T. Read, Jr., *Dislocations in Crystals,* McGraw-Hill Book Company, New York, 1953.]

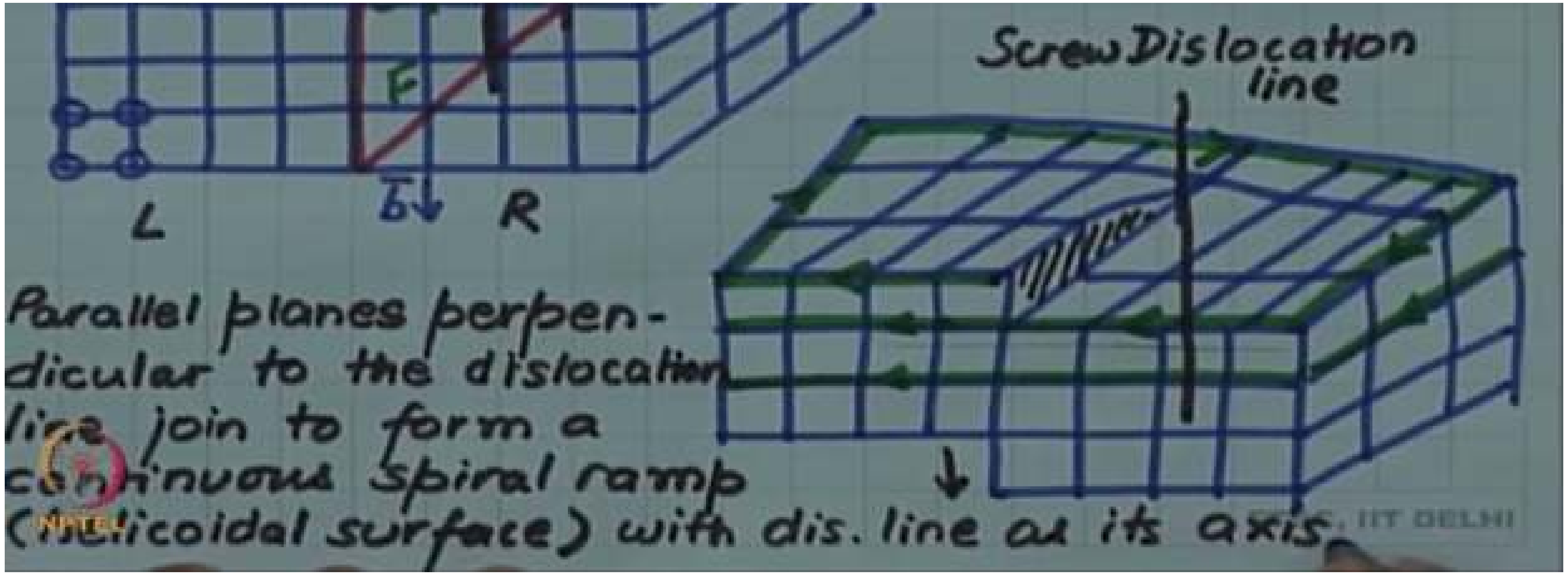


think of screw dislocation this way:

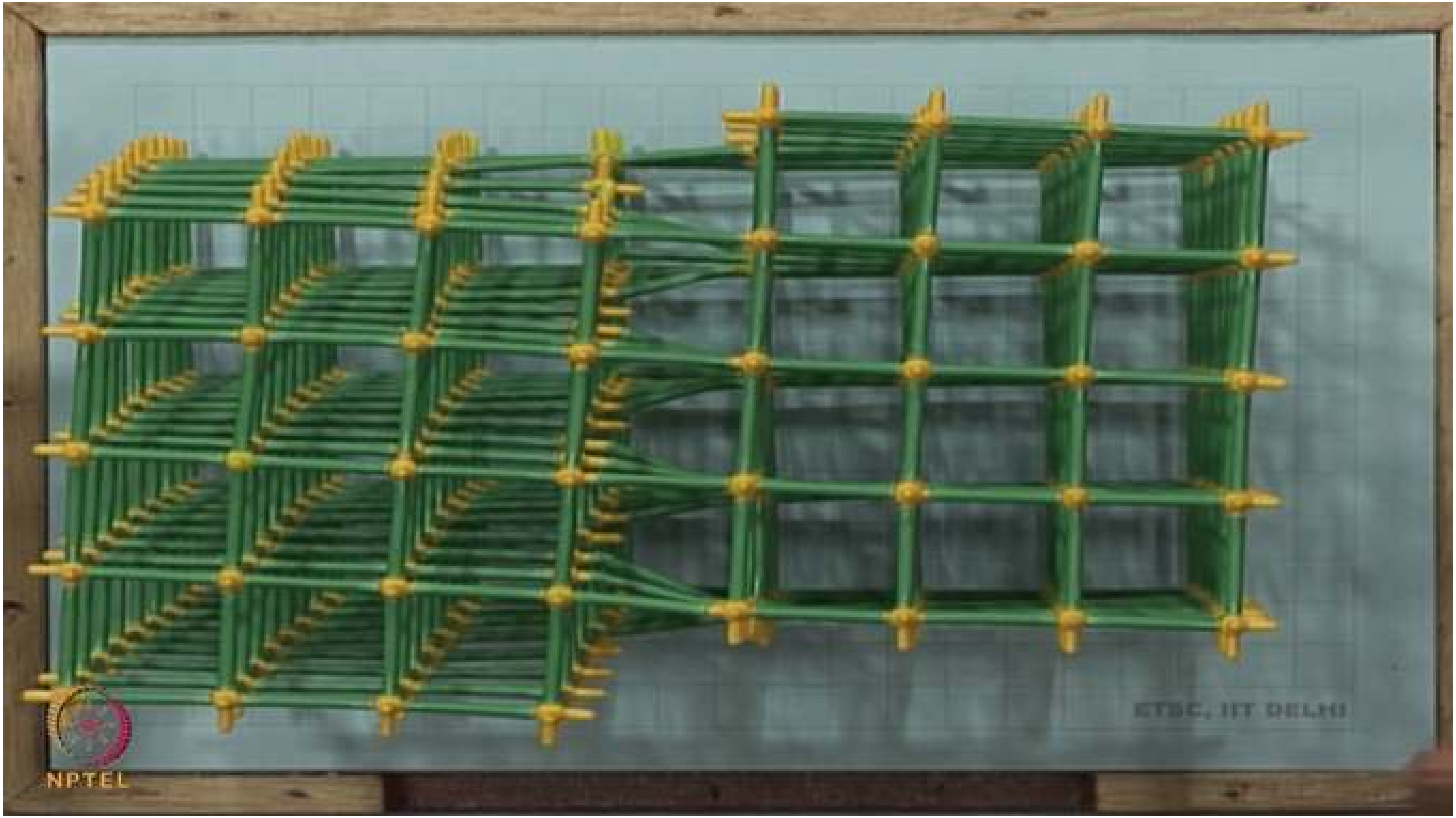





● kontur Burgersa
● wektor Burgersa



Parallel planes perpendicular to the dislocation line join to form a continuous spiral ramp (helicoidal surface) with dis. line as its axis.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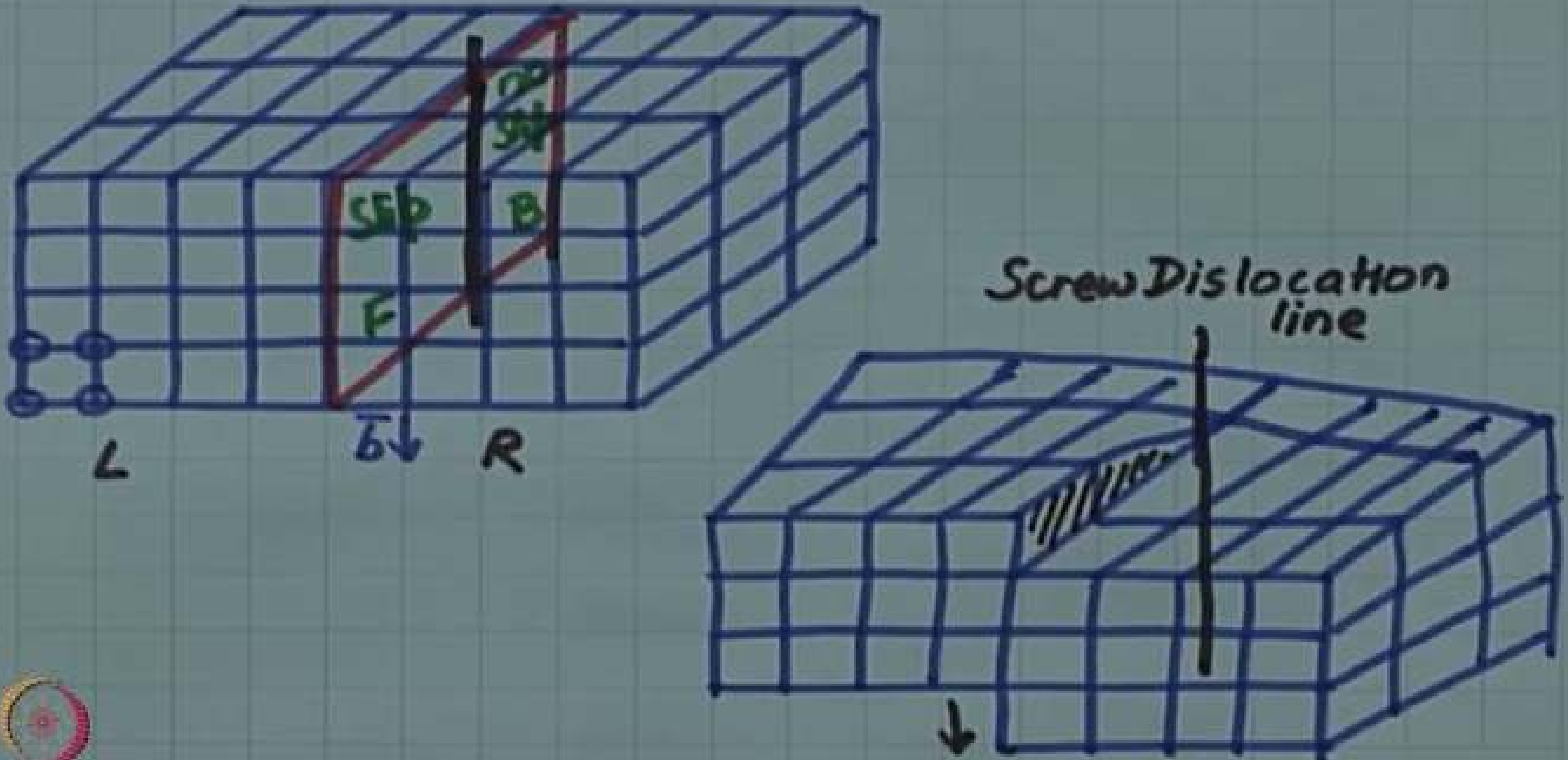
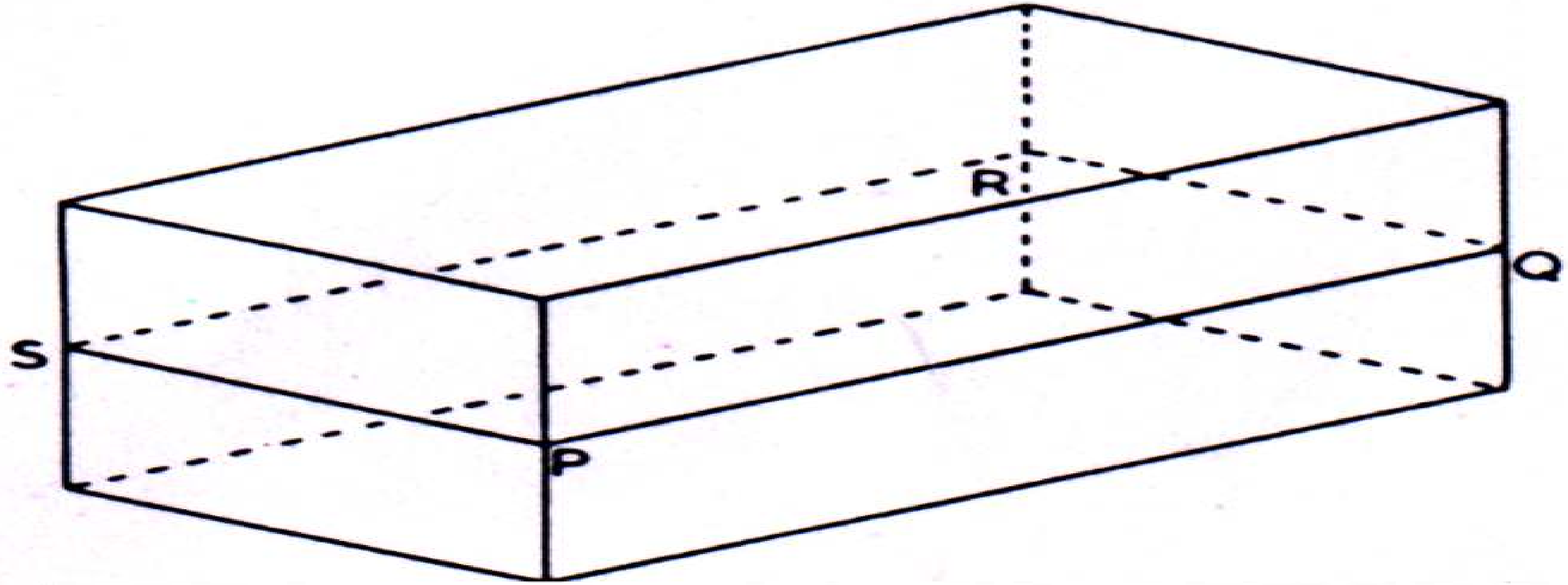
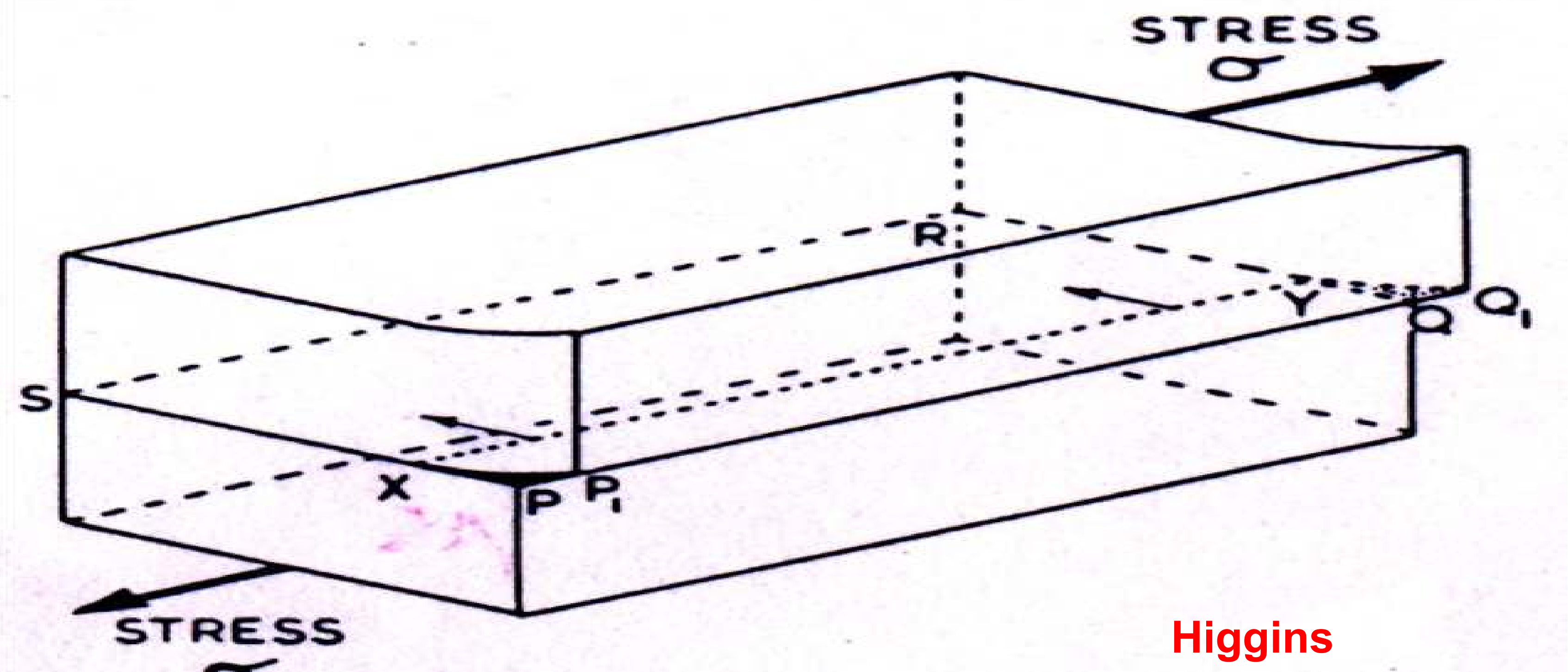
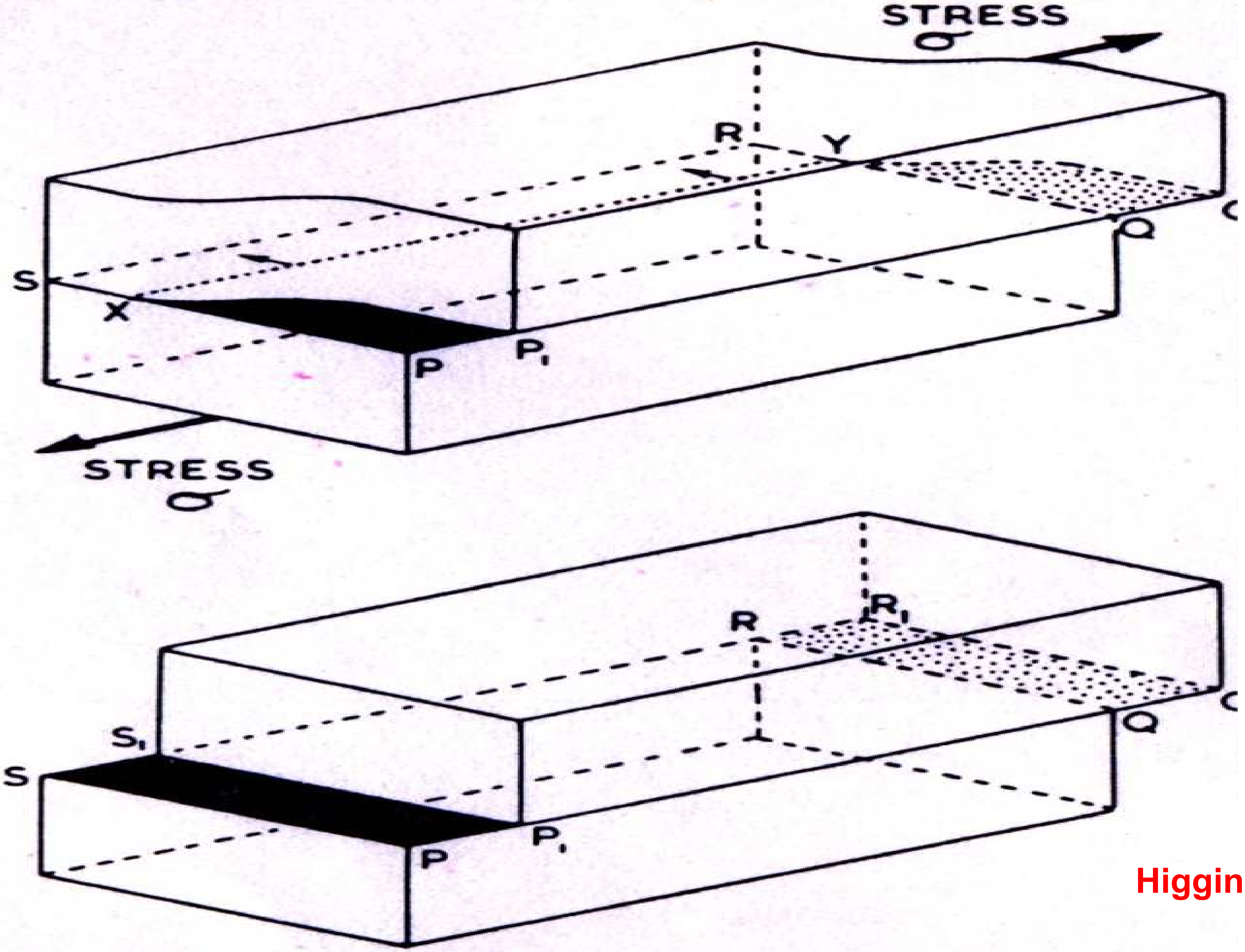
NPTEL


F
B
$\bar{b}$
L
R
Screw Dislocation line



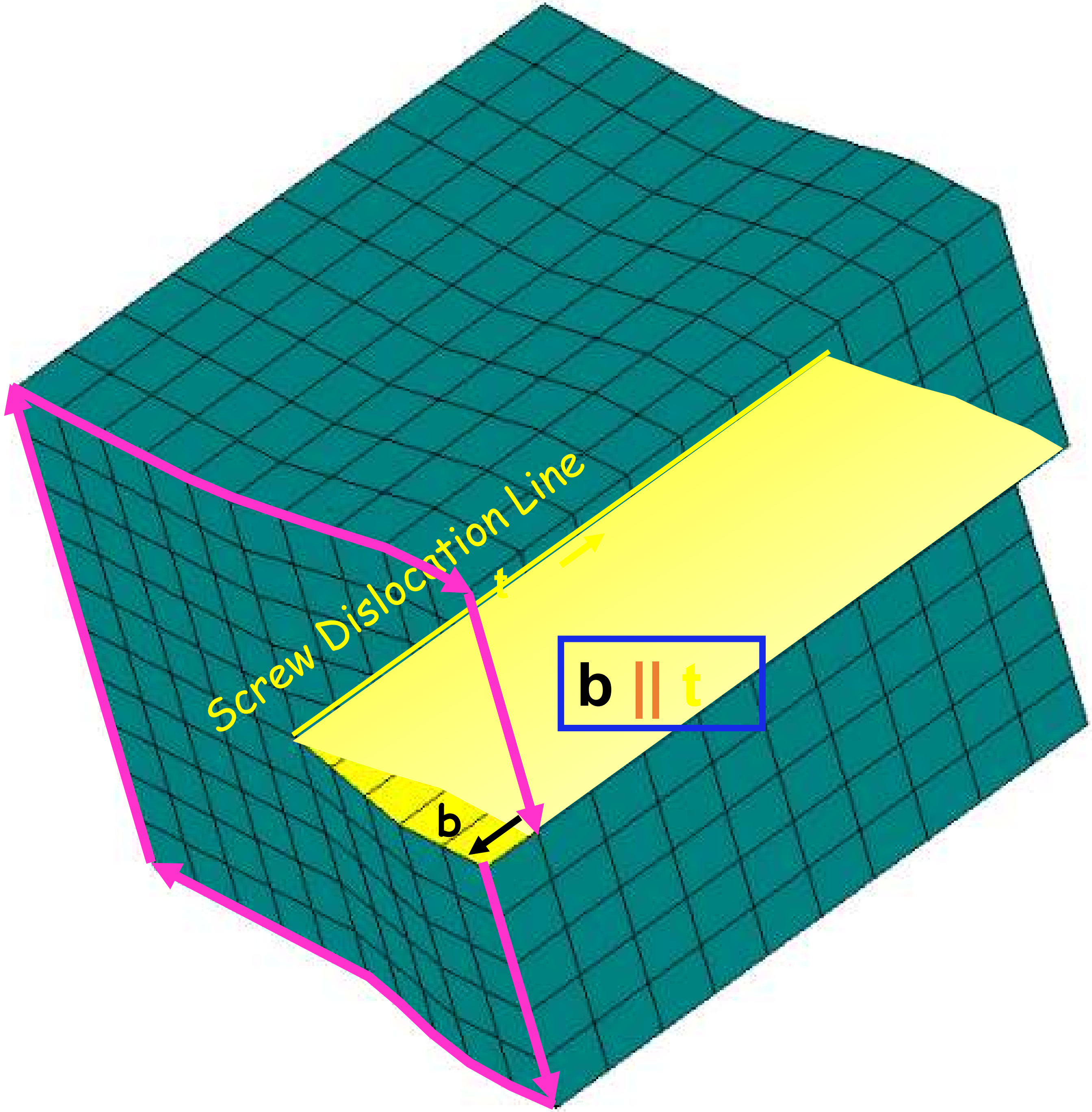


Higgins

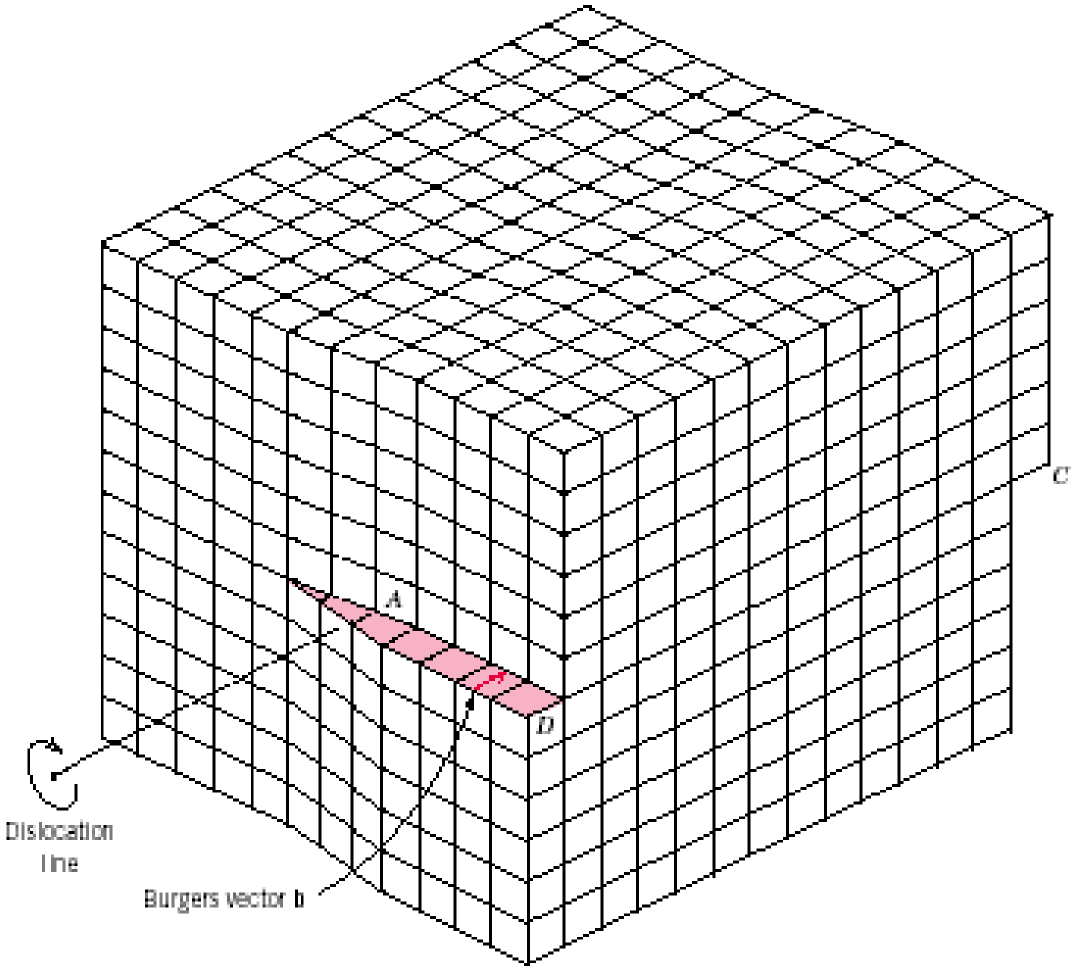


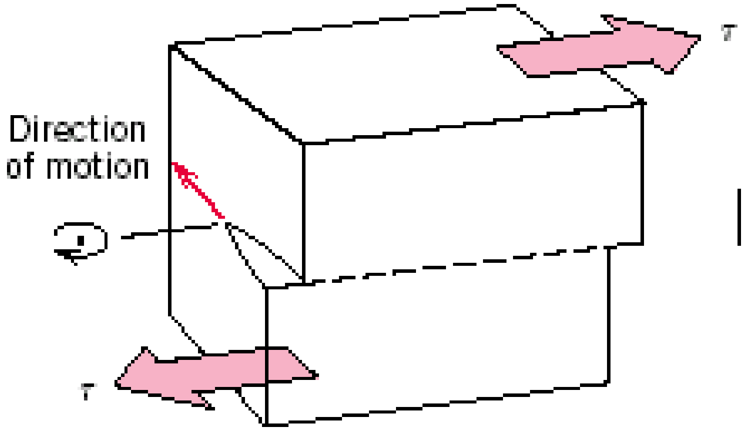
Higgins

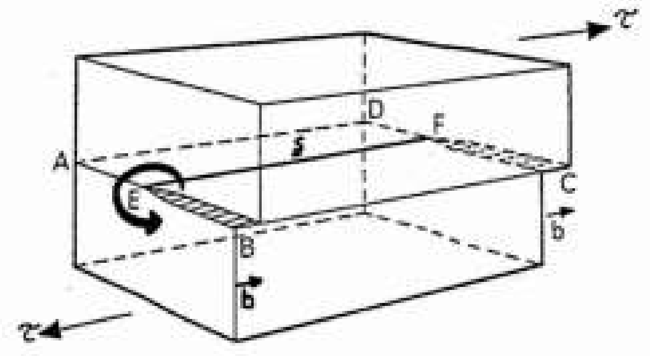
The movement of a screw dislocation

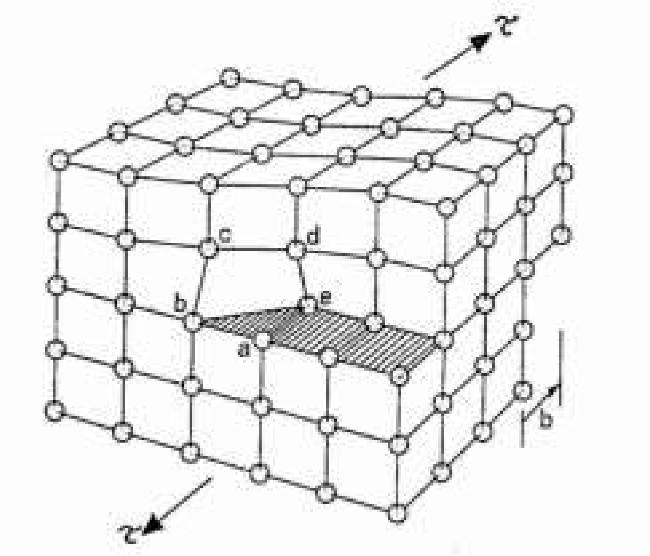

Screw Dislocation Line
t
b || t
b

Screw Dislocation



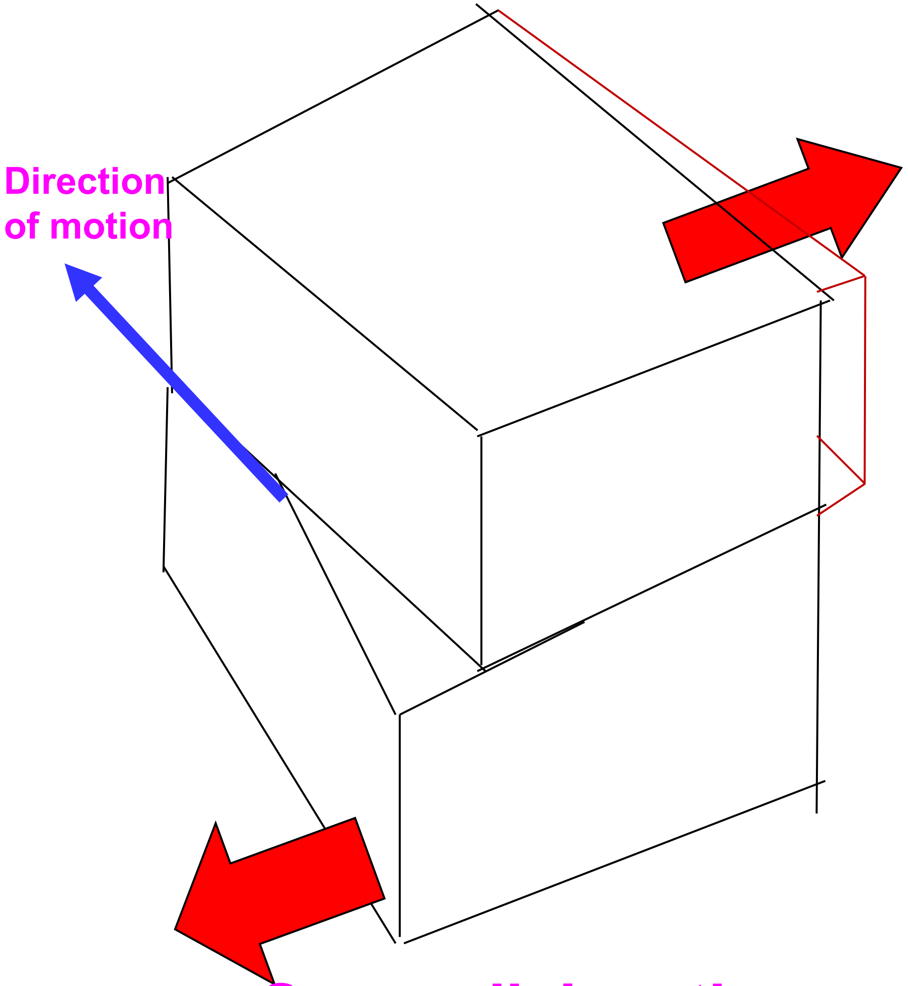




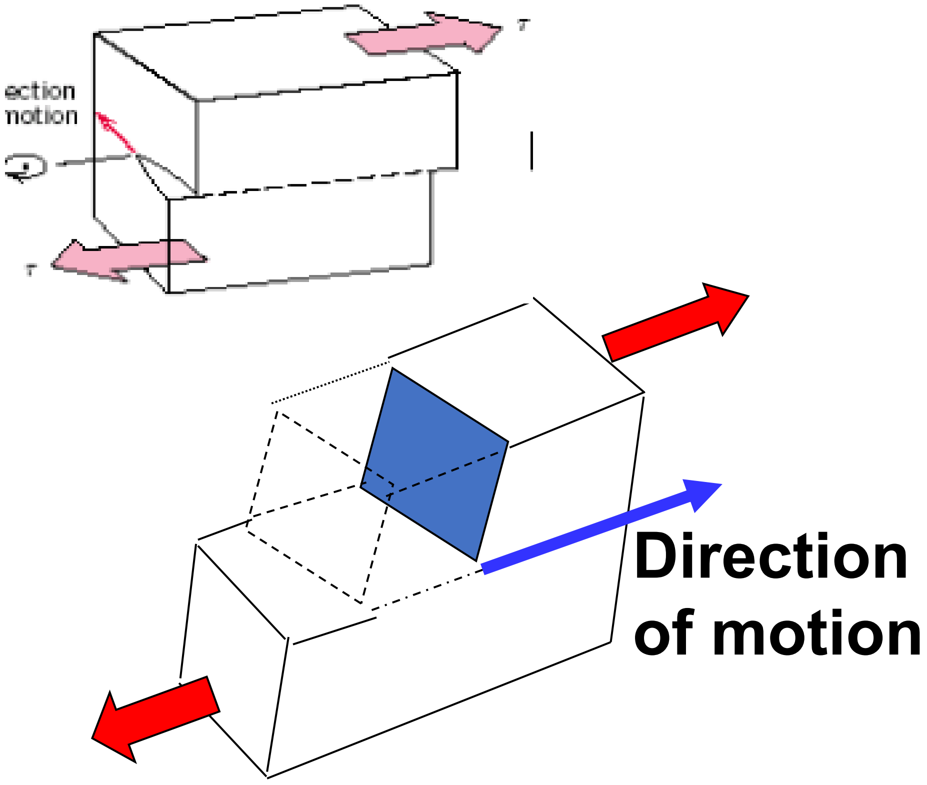


- **Burgers vector b ǀǀ Dislocation line**

In an edge dislocation, the direction of motion of the dislocation is parallel to the shear stress whereas in a screw dislocation, the direction of motion is perpendicular to the shear stress.



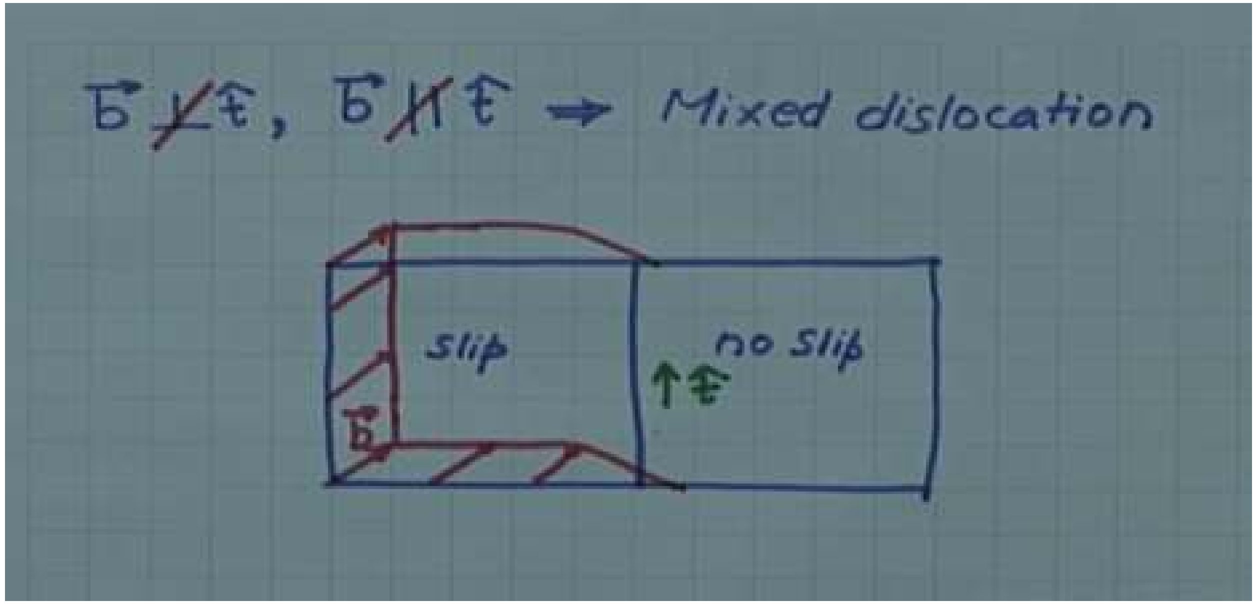
Screw dislocation



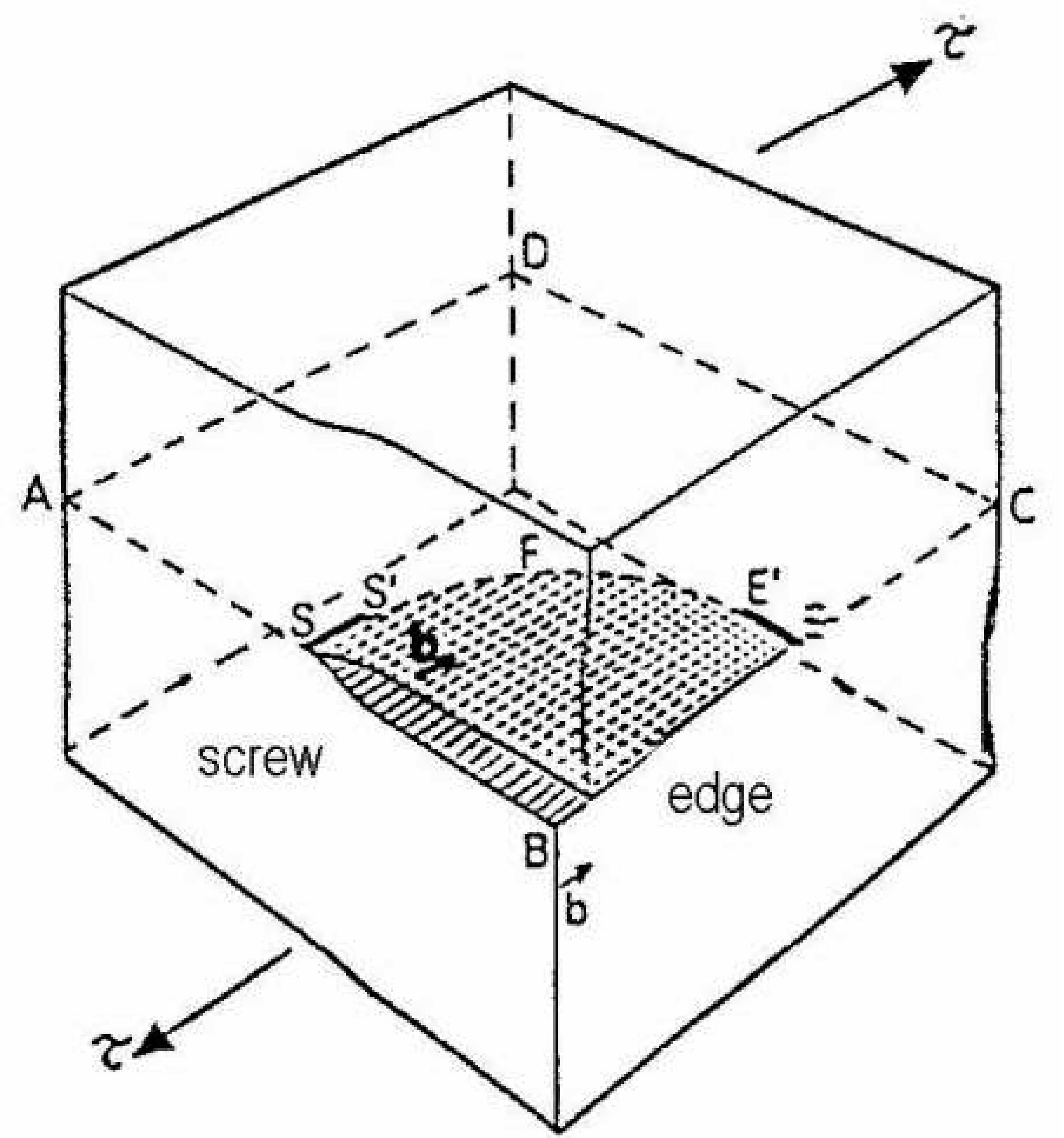
Edge dislocation

Mixed dislocation

- Most dislocations found in crystalline materials are probably neither pure edge nor pure screw, but exhibit components of both types; these are termed mixed dislocations.
- The lattice distortion that is produced away from the two faces is mixed, having varying degrees of screw and edge character.



Mixed Dislocation



Dislocation line

Burgers vector

Dislocation Line:

A dislocation line is the boundary between slip and no slip regions of a crystal

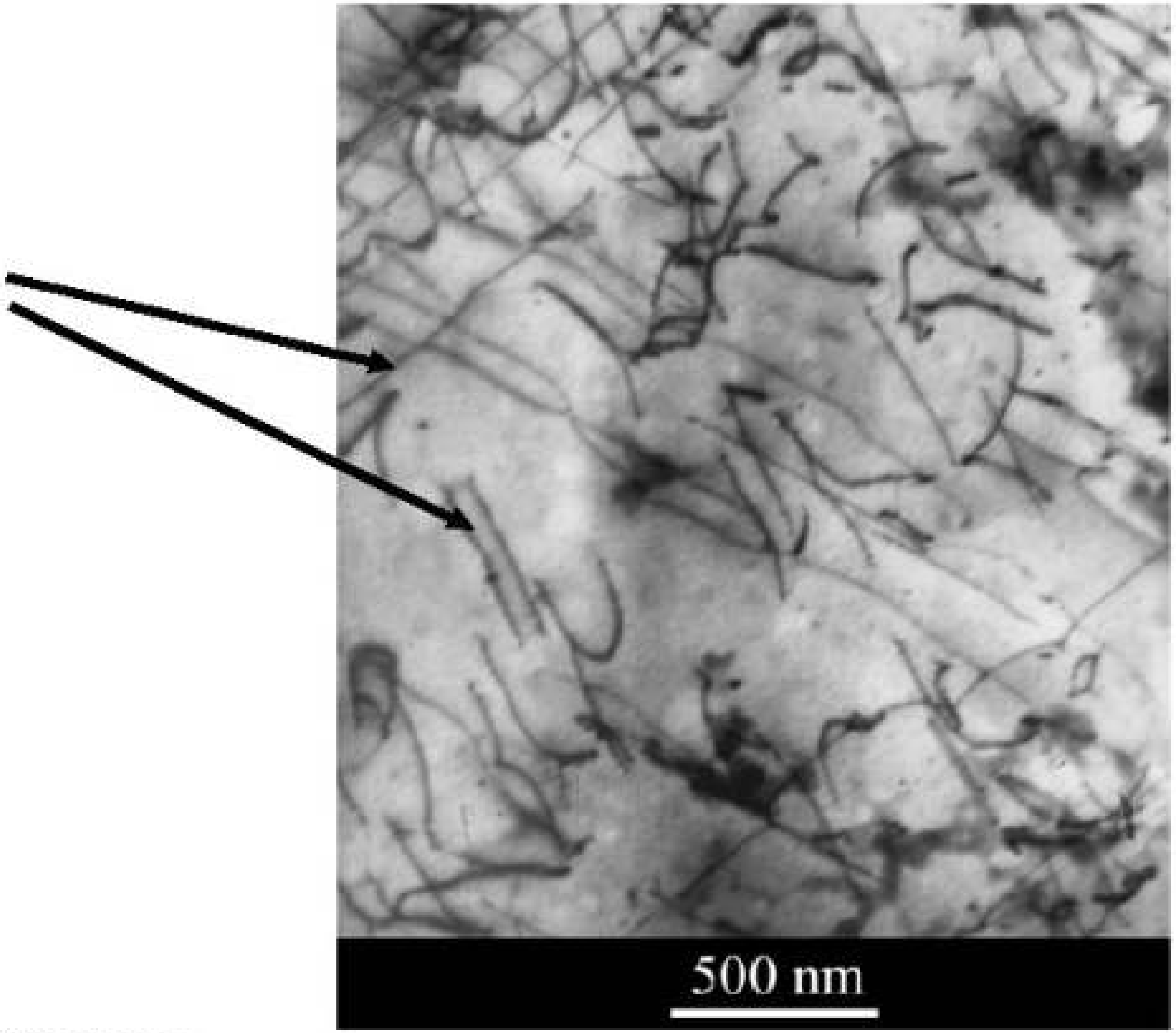
Burgers vector:

The magnitude and the direction of the slip is represented by a vector b called the Burgers vector,

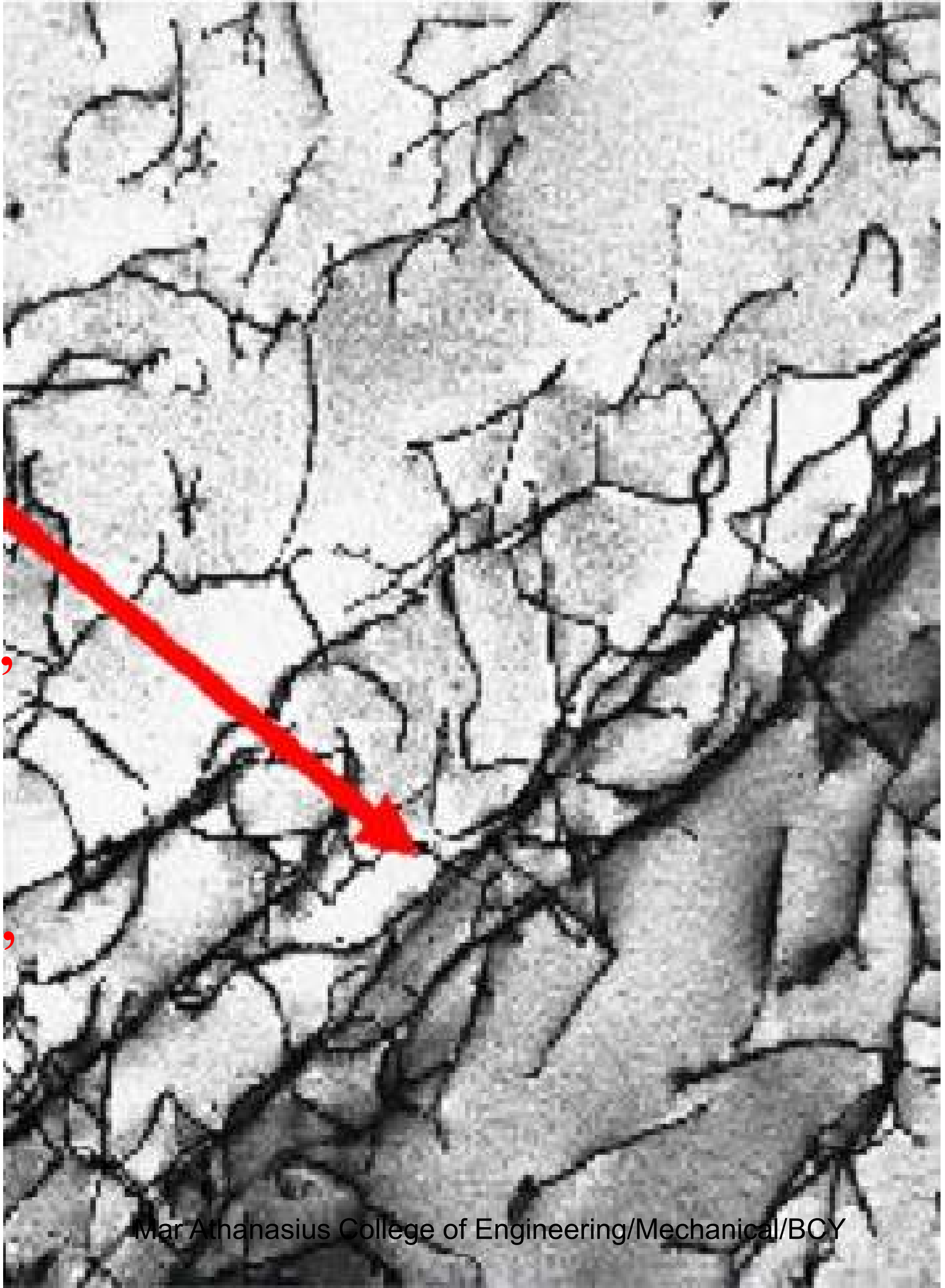
Line vector:

A unit vector t tangent to the dislocation line is called a tangent vector or the line vector.

Transmission electron microscopy



RWK Honeycombe, University of Cambridge



Dislocation forest

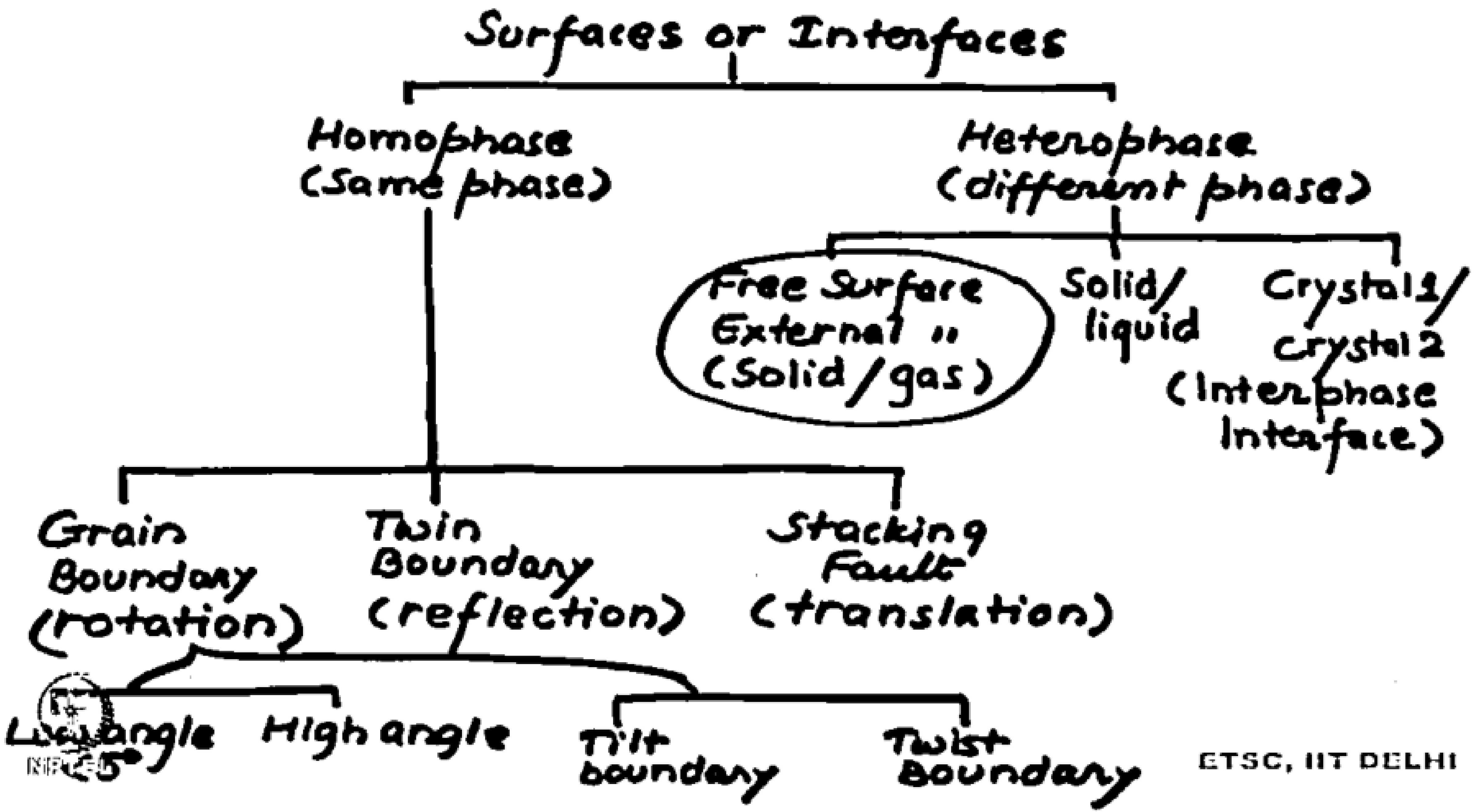
(stacking fault, Dislocations pile up, defects, misalignments, disordered atoms etc.)

TEM of dislocations (dark lines) in titanium alloy-51,450X

INTERFACIAL DEFECTS / SURFACE DEFECTS

- Are boundaries that normally separate regions of the materials that have different crystallographic orientations or different phases.

1. *External Surfaces*
2. *Grain Boundaries*
3. *Twin Boundaries*
4. *Stacking faults*
5. *Phase boundaries*
6. *Ferromagnetic domain walls*



Surfaces or Interfaces

- Homophase (Same phase)
  - Grain Boundary (rotation)
    - Low angle <15°
    - High angle
    - Tilt boundary
    - Twist Boundary
  - Twin Boundary (reflection)
  - Stacking Fault (translation)
- Heterophase (different phase)
  - Free Surface External " (Solid / gas)
  - Solid/ liquid
  - Crystal 1/ crystal 2 (Interphase Interface)

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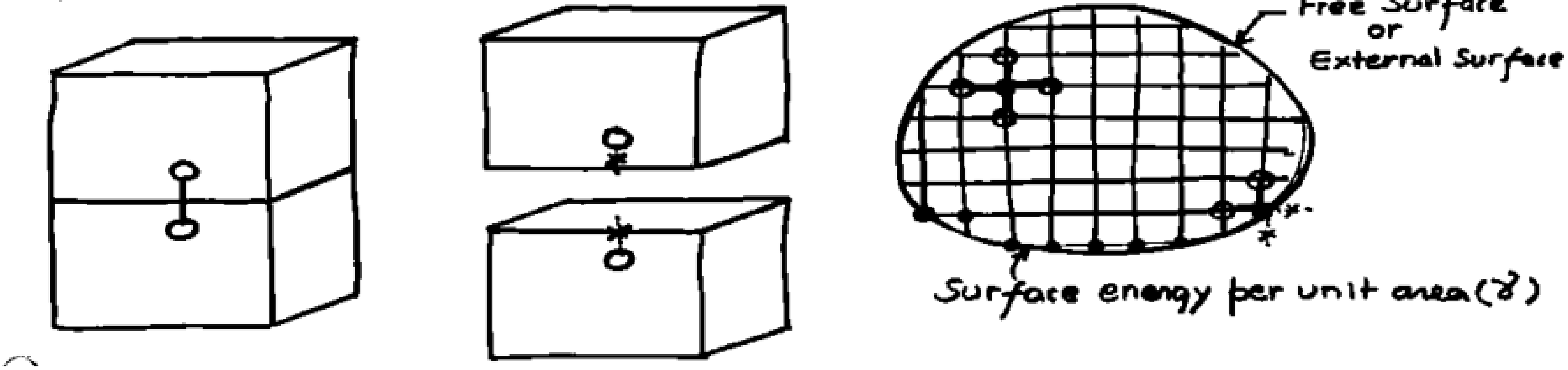
- **External surface** are *boundaries along* which the crystal structure *terminates*.
- Surface atoms are *not bonded* to the maximum number of nearest neighbours, and are therefore in a *higher energy state* than the atoms at interior positions.
- To reduce this *surface energy*, materials tend to *minimize the total surface area* but *not possible* with solids, which are mechanically rigid.

Surface energy in terms of bond breaking model



Grain Boundaries

- Introduced in *boundary separating two small grains* or crystals having different crystallographic orientations in polycrystalline materials

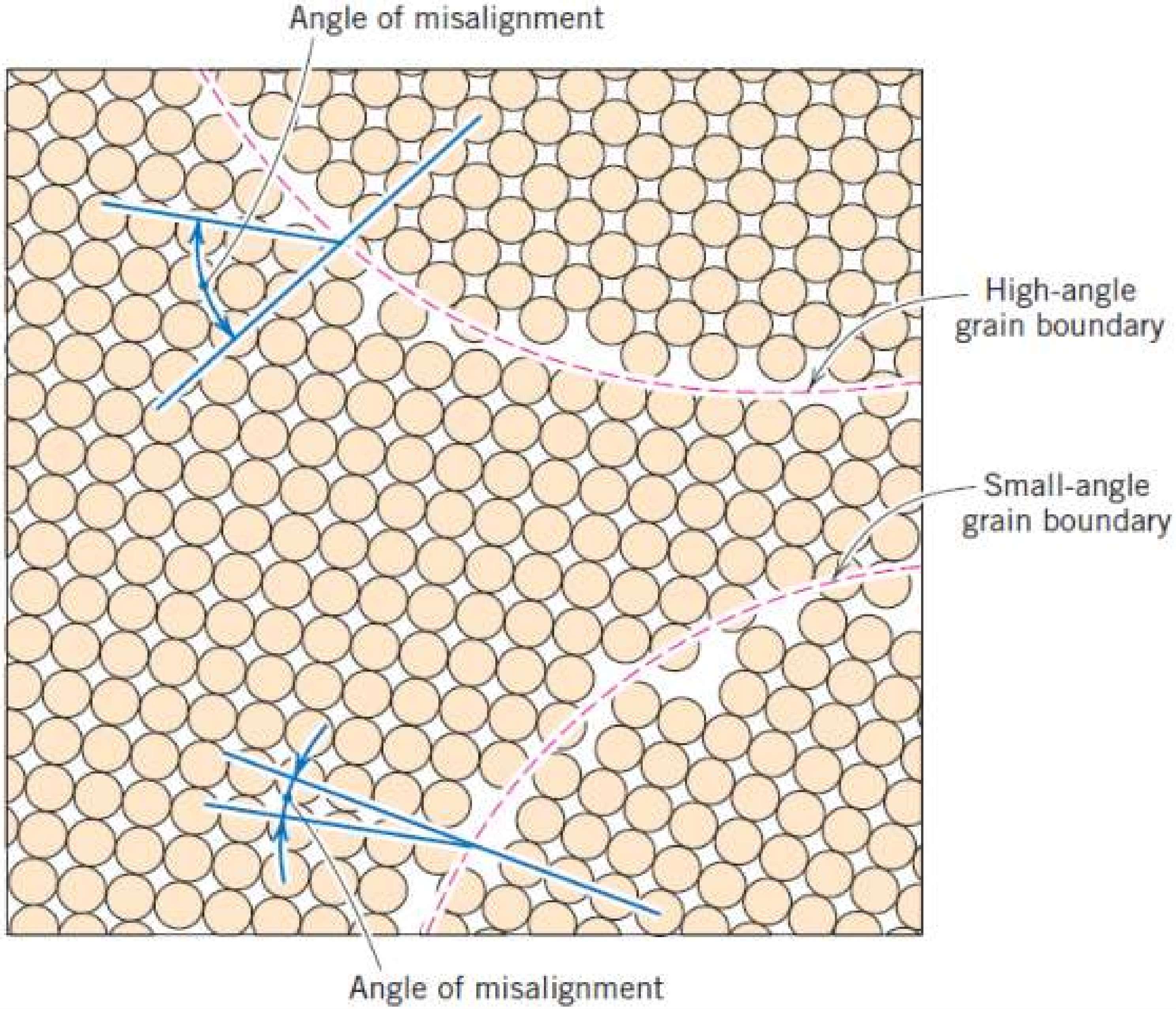
- Various degrees of crystallographic misalignment between adjacent grains are possible.

- When this orientation mismatch is slight, on the order of a few degrees, termed as ***small (low) angle grain boundary.***

- If orientation mismatch is large it is called ***high angle grain boundary.***

- Atoms are bonded less regularly along a grain boundary – result in interfacial or *grain boundary energy* which is a *function of the degree of misorientation*

- The atoms are bonded less regularly along a grain boundary (e.g., bond angles are longer), and consequently, there is an interfacial or grain boundary energy similar to the surface energy.
- The magnitude of this energy is a function of the degree of misorientation, being larger for high-angle boundaries.
- Grain boundaries are more chemically reactive than the grains themselves as a consequence of this boundary energy.
- Impurity atoms often preferentially segregate along these boundaries because of their higher energy state.
- The total interfacial energy is lower in large or coarse-grained materials than in fine-grained ones, since there is less total boundary area in the former.
- Grains grow at elevated temperatures to reduce the total boundary energy

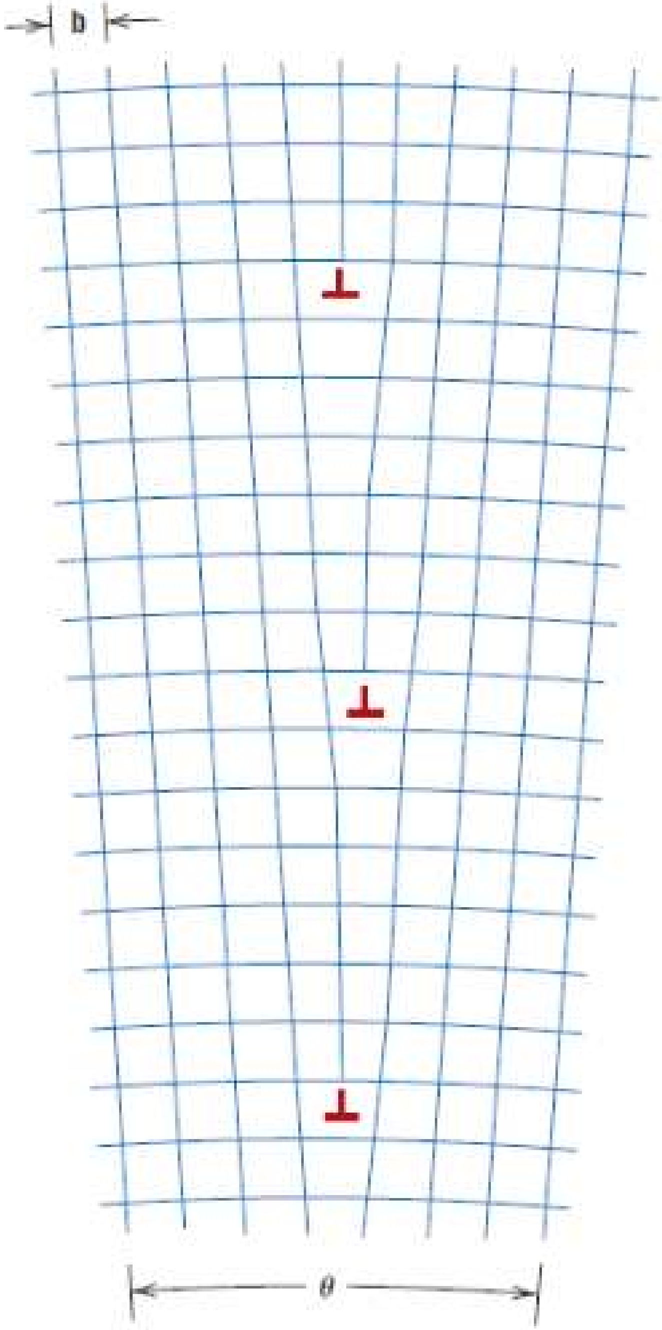

Angle of misalignment
High-angle grain boundary
Small-angle grain boundary
Angle of misalignment

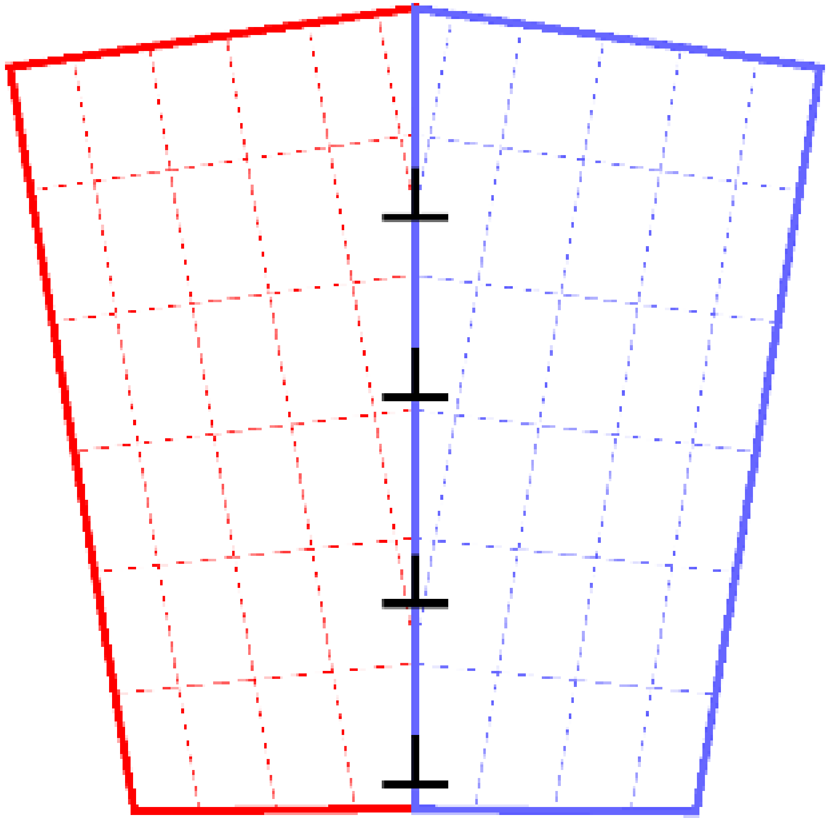
Tilt boundary

- Small angle grain boundary formed when *edge dislocations are in aligned manner shown in fig.*

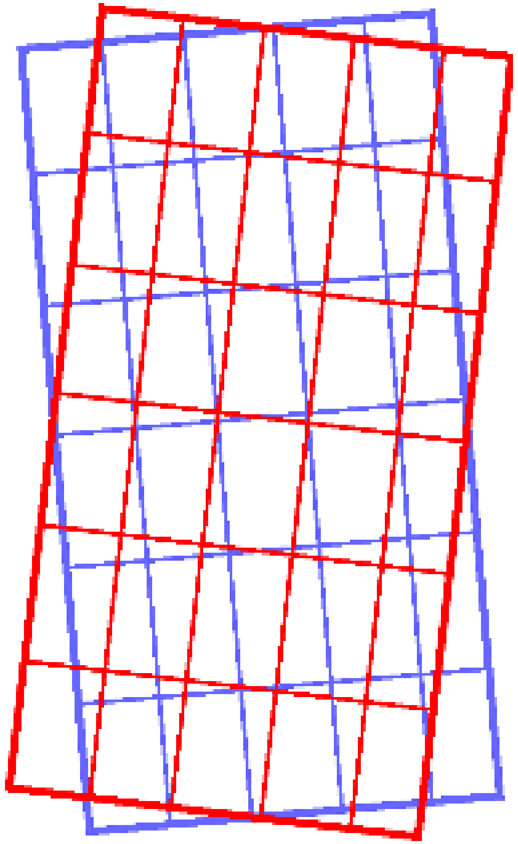
Twist boundary

- When the *angle of misorientation is parallel to the boundary.*
- Can be described by an *array of screw dislocations.*

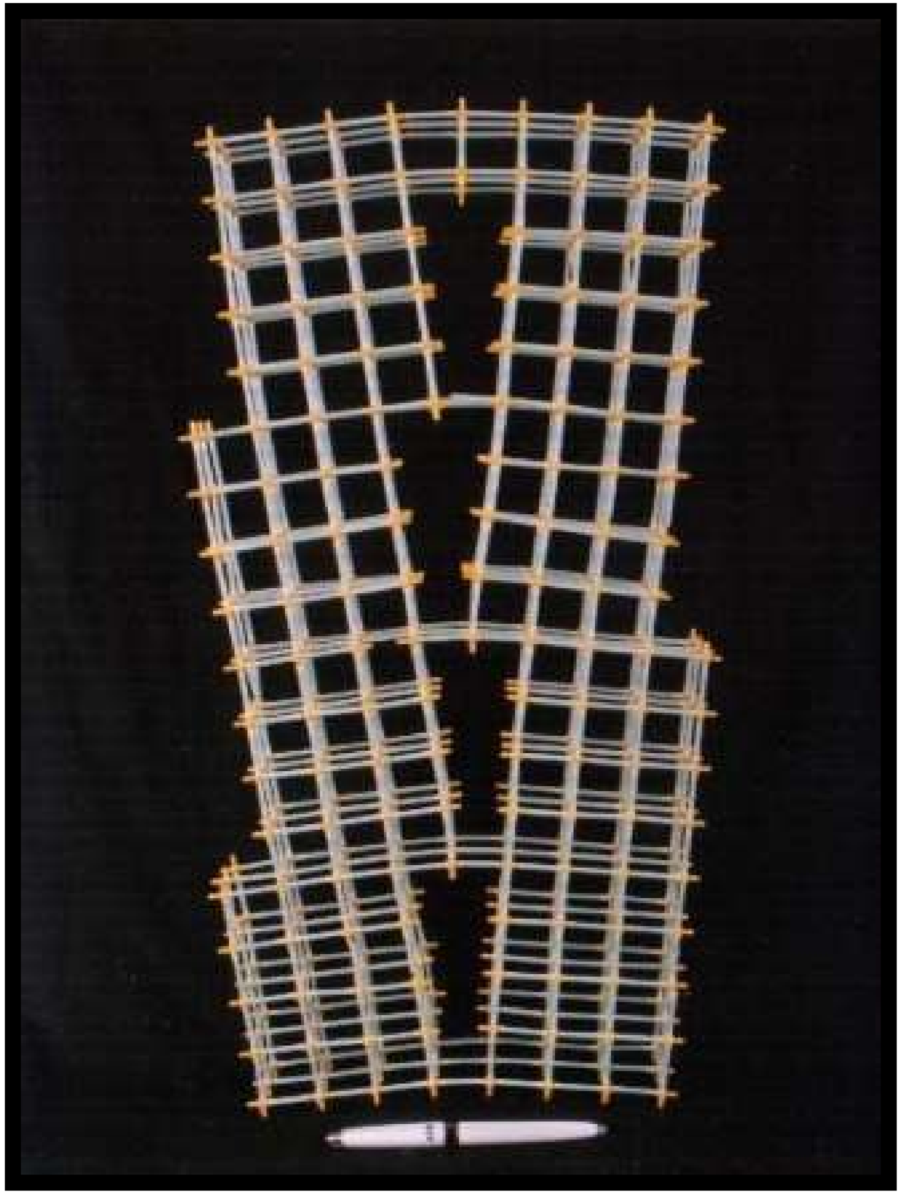




Tilt



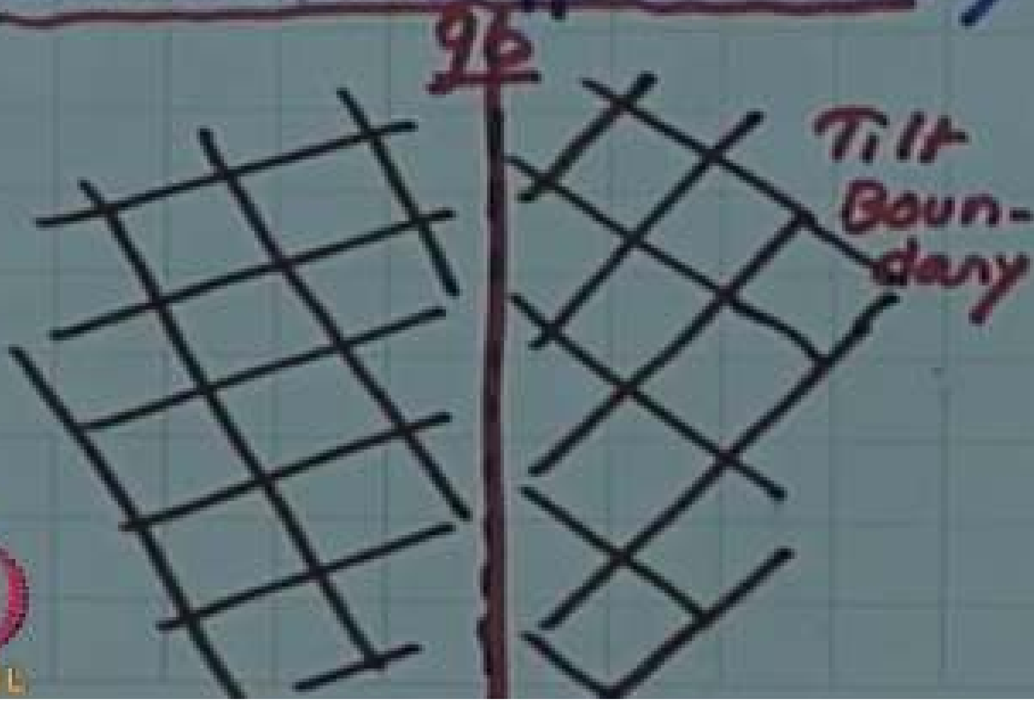
Twist



Classification of GB based on relationship of the Rotation axis wrt the boundary plane:

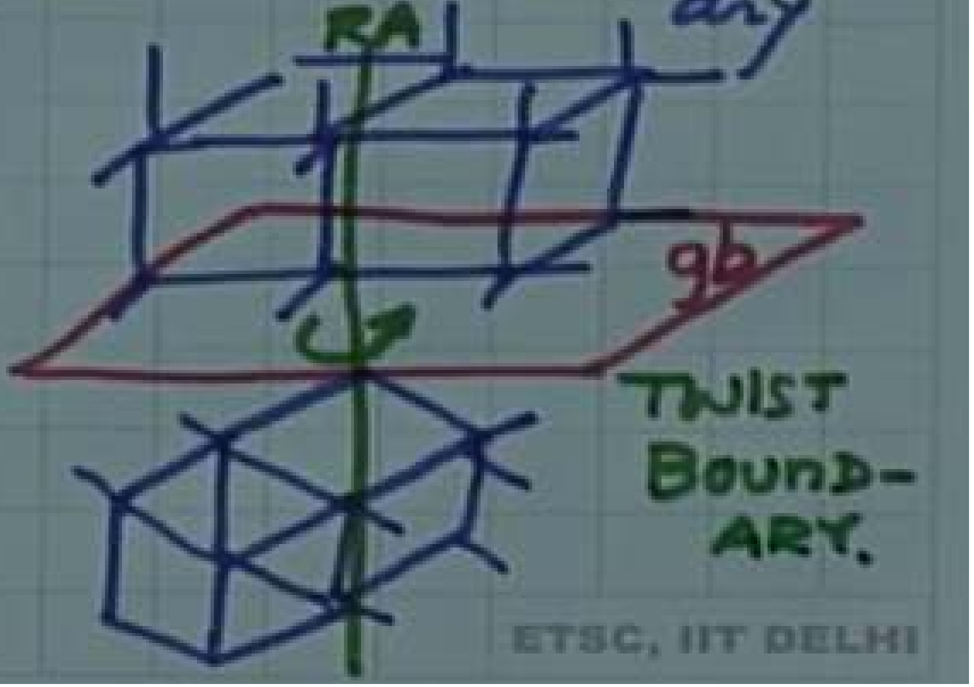
TILT BOUNDARY

Rotation Axis $\parallel$ Boundary



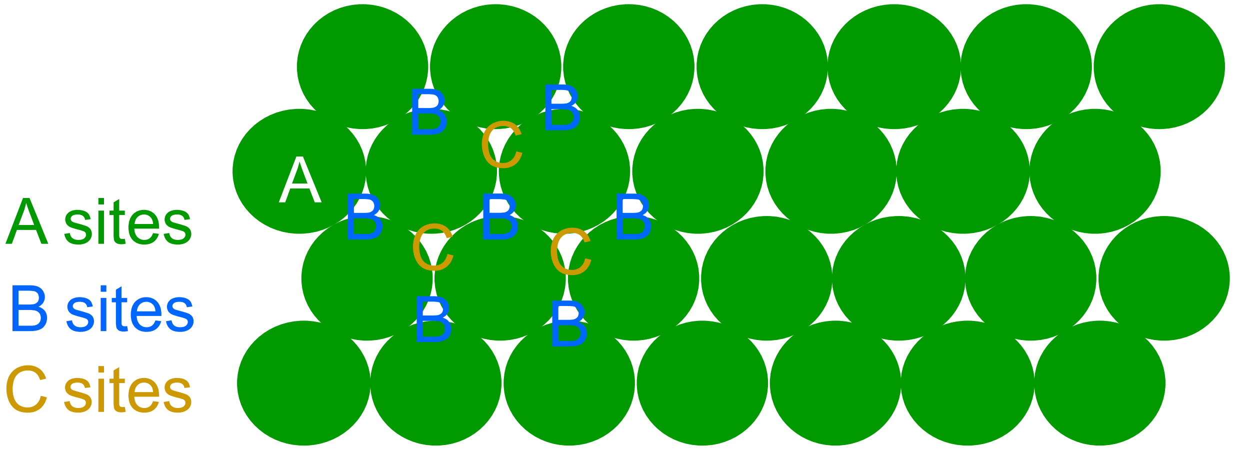
TWIST Boundary

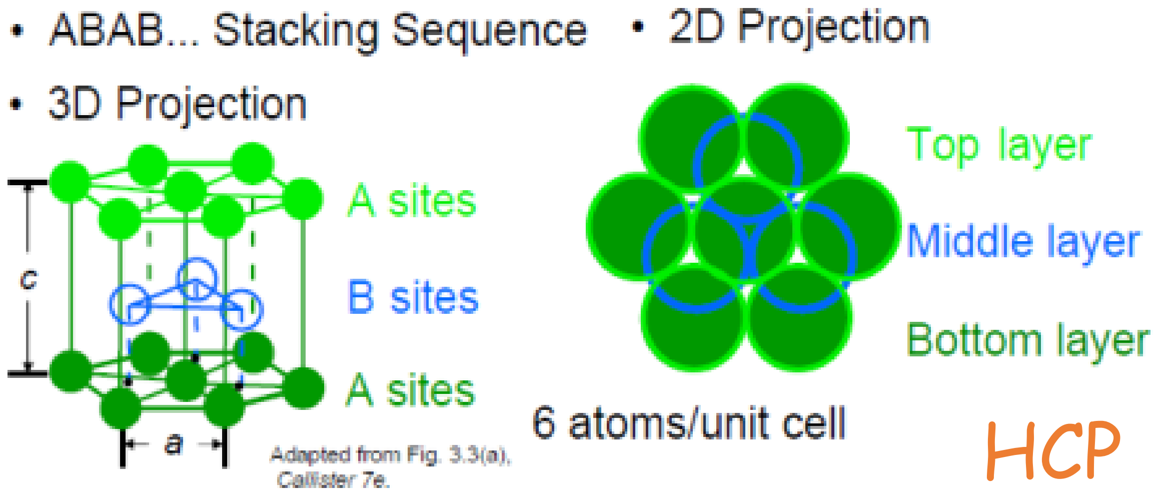
Rotation Axis $\perp$ Boundary



Stacking faults

- Found in FCC metals when there is an *interruption in the ABCABCABC . . . stacking sequence* of close-packed planes

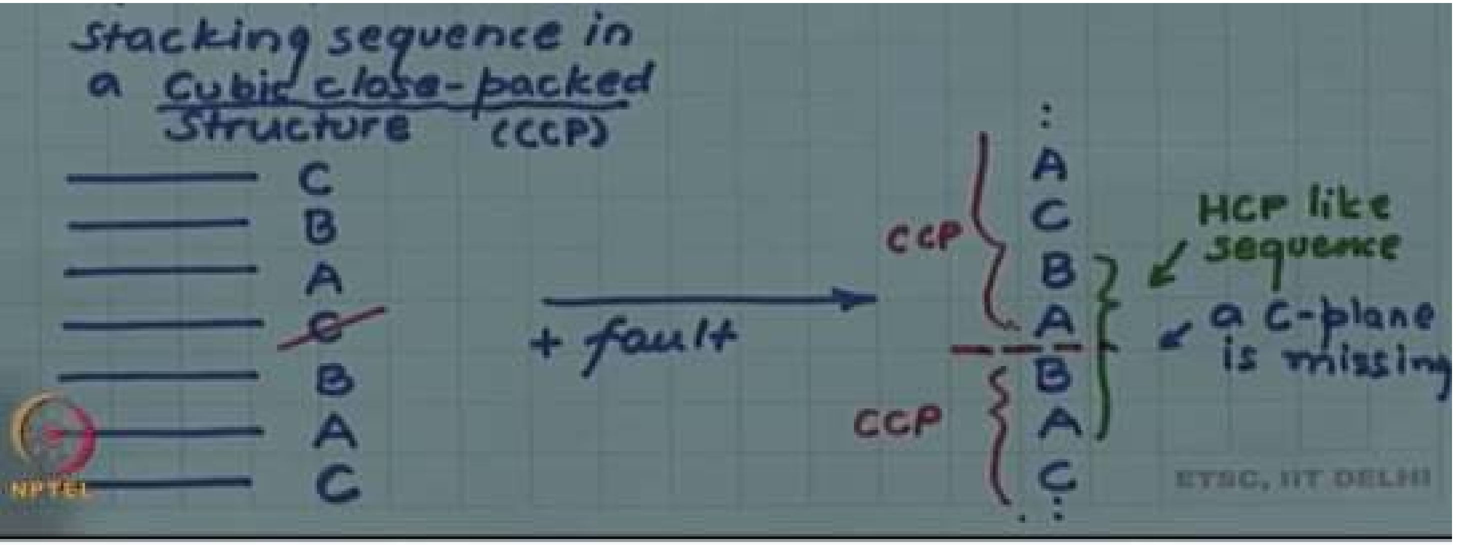




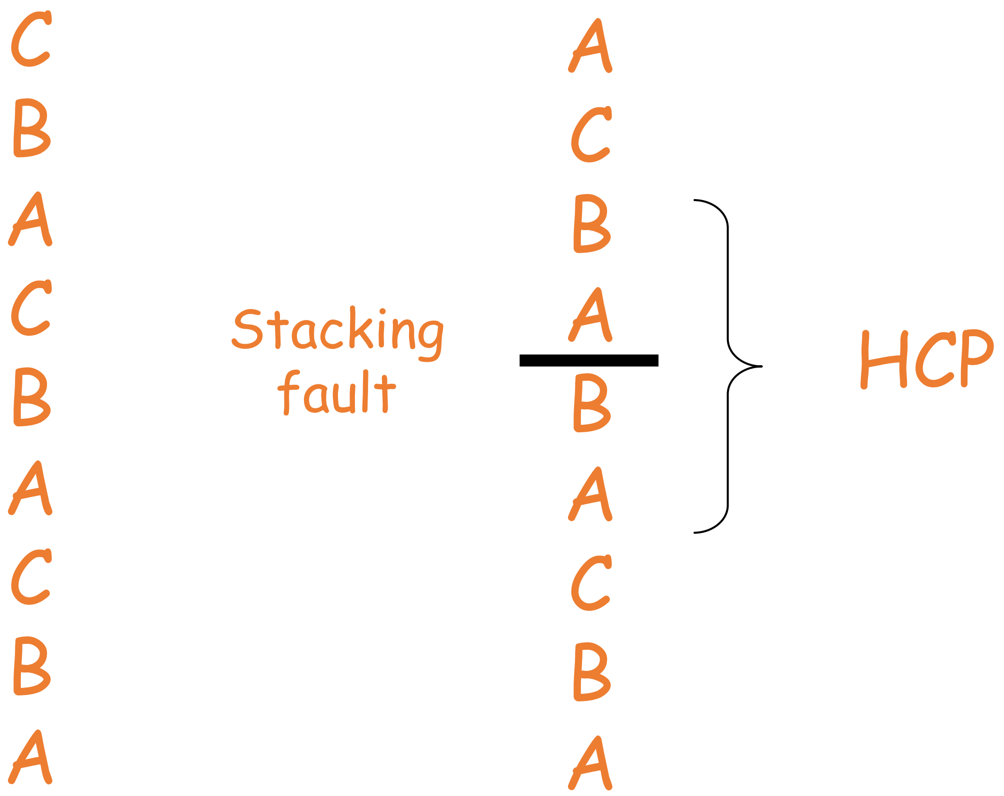
- ABAB... Stacking Sequence
- 2D Projection
- 3D Projection

6 atoms/unit cell

Adapted from Fig. 3.3(a), Callister 7e.



Stacking fault



C
B
A
C
B
A
C
B
A

Stacking fault

A
C
B
A
B
A
C
B
A

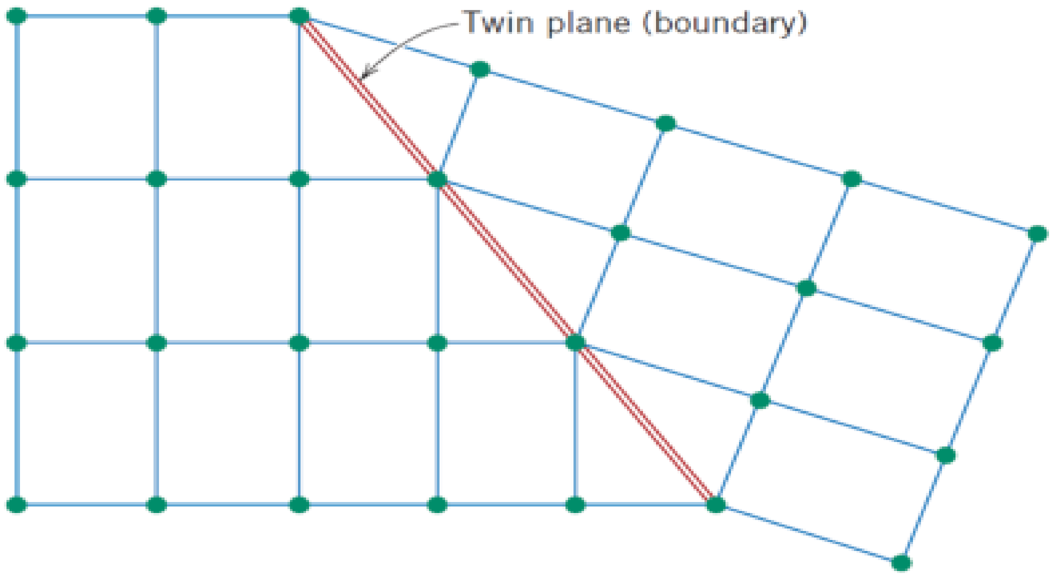
HCP

Twin Boundaries

- A *twin boundary* is a special type of *grain boundary across which there is a specific mirror lattice symmetry*

- Atoms on one side of the boundary are located in mirror-image positions of the atoms on the other side

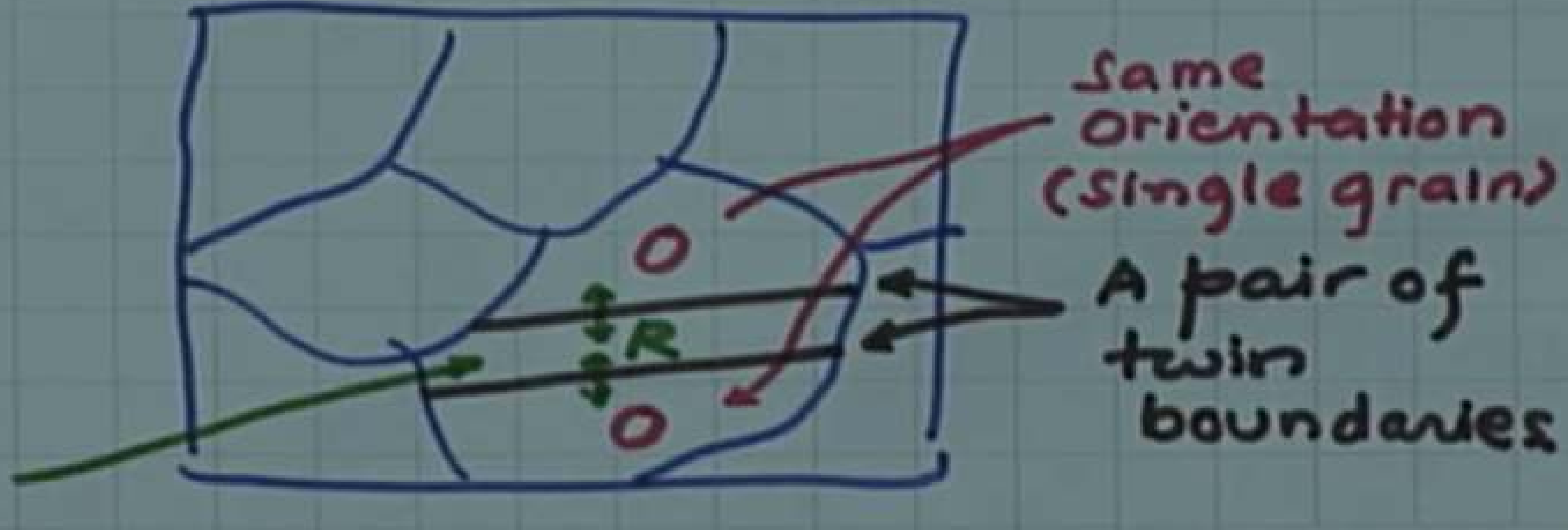
- The region of material between these boundaries is appropriately termed a ***twin***.



Twin Boundary in CCP structure

CCP (Perfect)		CCP with a twin Boundary	
C		C	
B		B	
A		A	original crystal
C		C	
B		B	
A		A	Mirror plane [TWIN PLANE]
C		B	
B	Different	C	Mirror image
A	orientation	A	of the crystal
C		B	above the TWIN PLANE
B		C	
A		A	

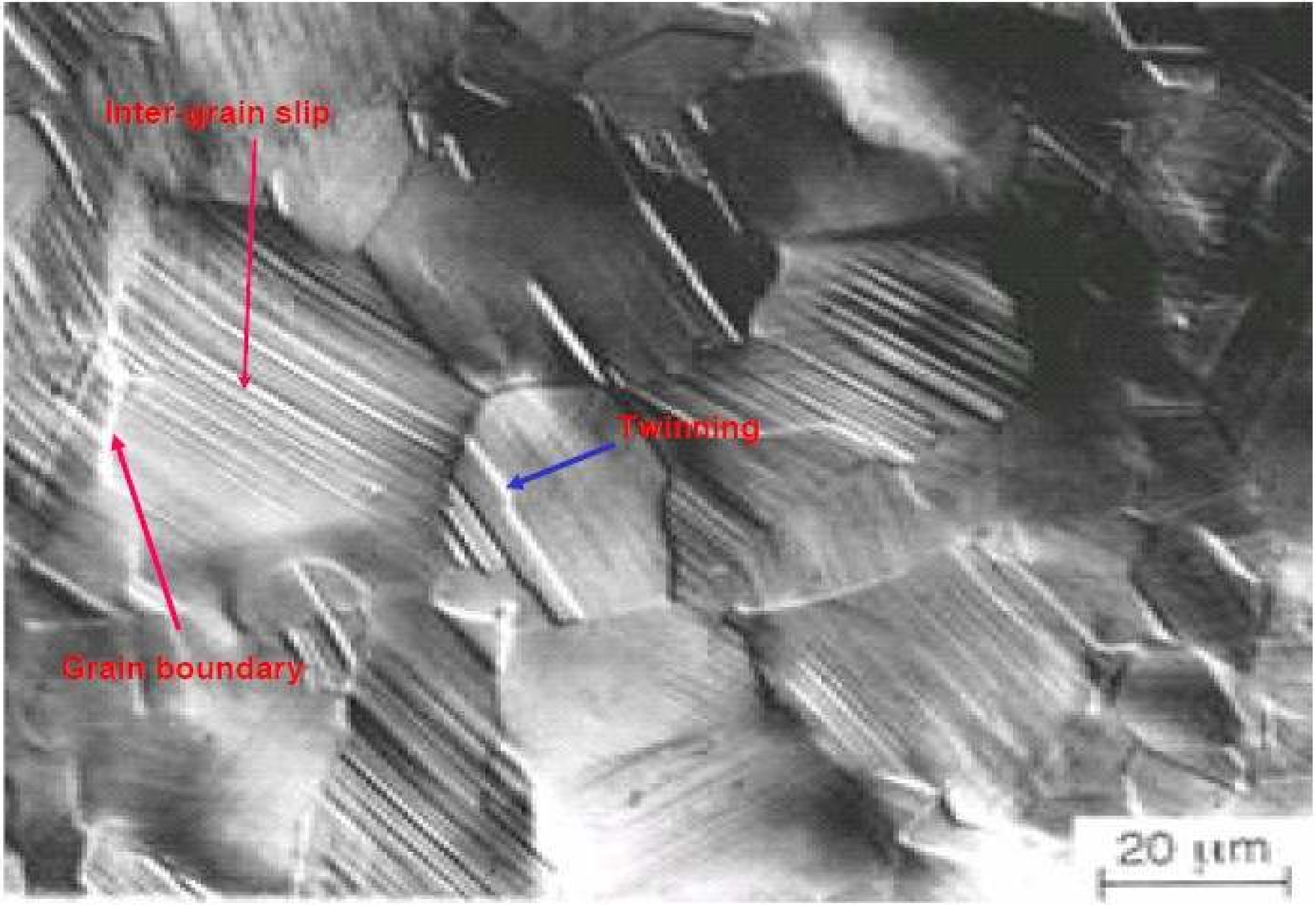
Twin Boundary: Boundary in a crystal such that crystals on either side are mirror images of each other.



Same orientation (single grain)

A pair of twin boundaries

TWIN


Inter-grain slip
Twinning
Grain boundary
20 μm

Mechanical twins

- Twins result from atomic displacements that are produced from applied *mechanical shear forces*
- Mechanical twins are observed in BCC and HCP metals

Annealing twins

- Formed during annealing *heat treatment*
- Annealing twins are typically found in metals that have the FCC crystal structure

Phase boundaries

- Exist in multiphase materials across which there is a *sudden change* in physical and/or chemical *characteristics.*

Ferromagnetic domain walls

- For ferromagnetic and ferrimagnetic materials, the *boundary* that separates regions having *different directions of magnetization (magnetic moments of the atoms are aligned)* is termed a domain wall.

BULK OR VOLUME DEFECTS

- These *defects form during manufacturing processes* for various reasons and are harmful to the material.
- Volume defects in crystals are three-dimensional aggregates of atoms or vacancies.
- Second phase particles or dispersants, which vary in size from a fraction of a micron to the normal grain size (10-100μm), but are intentionally introduced into the microstructure
- Inclusions, which vary in size from a few microns to macroscopic dimensions, and are relatively large, undesirable particles that entered the system as dirt or formed by precipitation
- Voids, which are holes in the solid formed by trapped gases or by the accumulation of vacancies.
- *Cracks*
- All these defects are capable of acting as stress raisers, and thus deleterious to parent metal's mechanical behavior. Pores are detrimental because they reduce effective load bearing area and act as stress concentration sites

- *Casting blow holes, porosity* – Gas entrapment during melting and pouring.
- *Shrinkage cavity -* due to improper riser
- *Non-metallic inclusions* – Slag, oxide particles or sand entrapment
- *Cracks* – Uneven heating/cooling, thermal mismatch, constrained expansion/contraction all leading to stress development

Weld defect

Casting defect

Shrinkage cavity

Comparison of Energy of Various 2D Defects

Type of boundary	**Energy (J/m^2)**
Surface	~ 0.89
Grain boundary	~0.85
Twin Boundary	~ 0.63 0.498 (Cu)
Stacking Fault	0.08 (Cu) 0.2 (Al)

Role of surface defects on crack initiation

- Atoms located near grain boundaries have distorted surroundings – higher energy levels
- Every atom at an exterior surface is also having
- same situation
- Exterior surface is usually rough and contains tiny notches
- These notches initiates cracks that propagate along grain boundaries – intergranular failure…

Factors affecting plastic deformation

1. **Crystal Structure:**
   - Materials with crystal structure having easy slip system are more plastic.
   - FCC crystals are more plastic compared to BCC and HCP

2.Grain Size:

- Fine grained metals are more stronger and tougher
- With larger grains plasticity of a metal get enhanced

3.Type of metal:

- Pure metals and single phase alloys have better plasticity compared to alloys with more than one phase
- Presence of intermetallic compounds reduce plasticity

4.Strain rate:

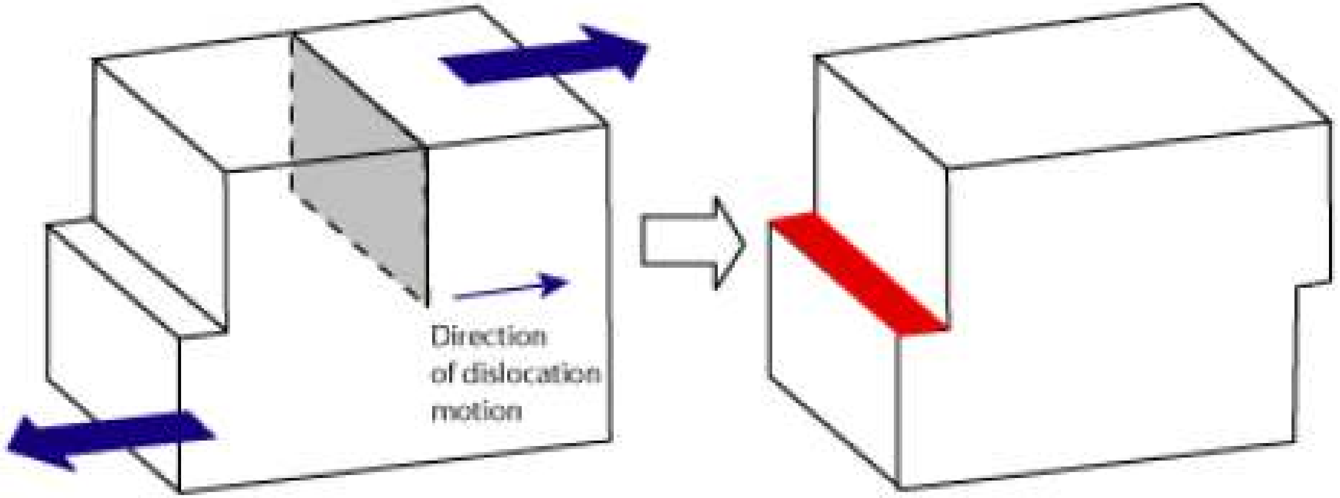
- Deformation at higher strain rate reduces plasticity

5.Presence of crystal defect:

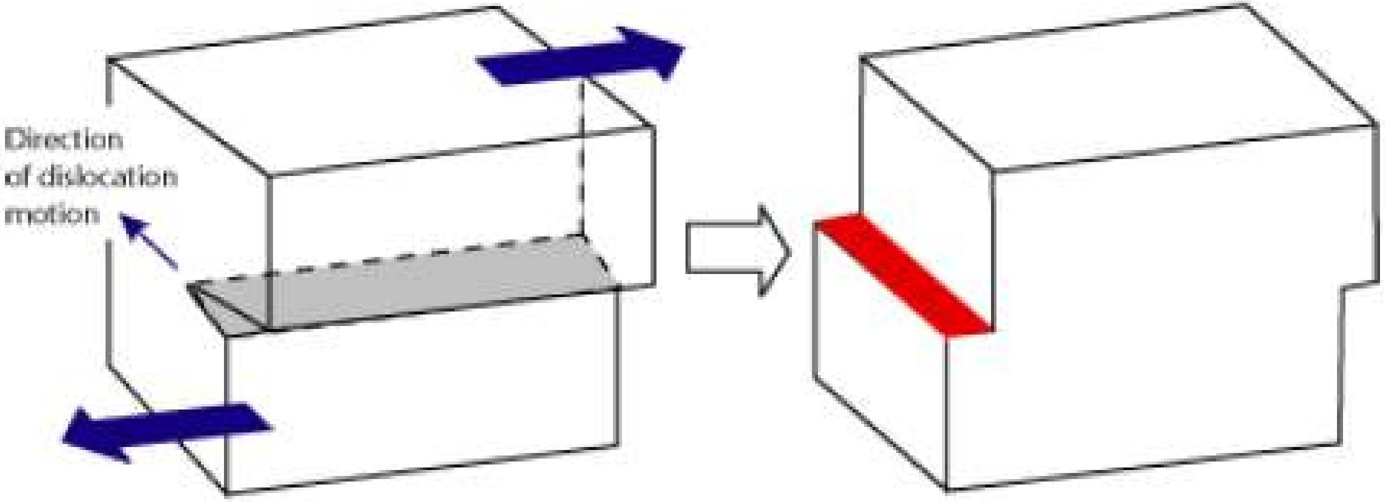
- If the defects behave so as to activate slip systems plasticity is enhanced
- During plastic deformation by slip ,the atomic bonds at one point are broken and re established at another point.
- Presence of defects in real crystals causes yielding to take place at lower value of shear stress

6. Presence of dislocation

- The defect that has significant influence on plastic deformation is dislocation
- In crystals where dislocations present atomic movement can be affected easily.



Edge Dislocation



Screw Dislocation

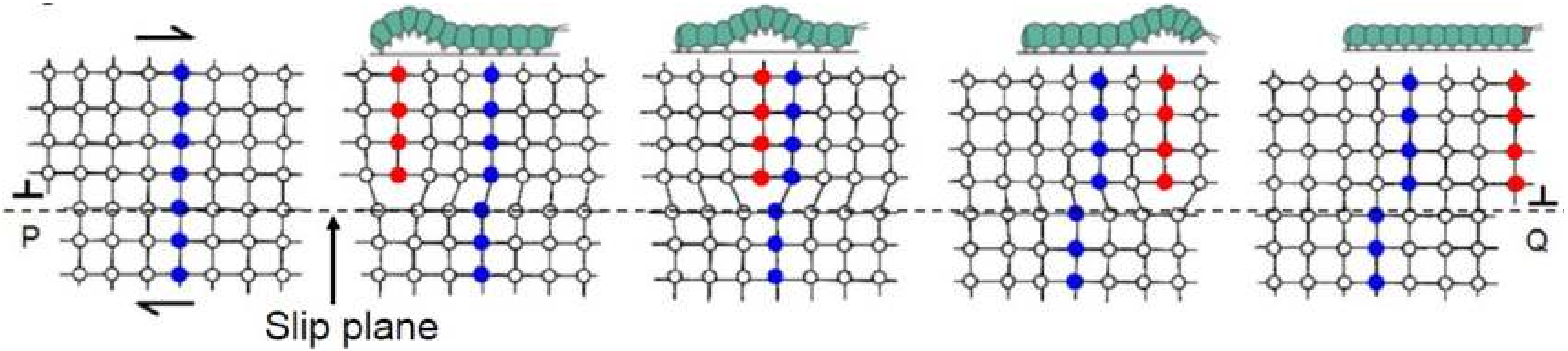
Dislocation Motion

- Glide (for edge , screw or mixed dislocation)
- Cross- slip (for screw dislocation)
- Climb (for edge dislocation)

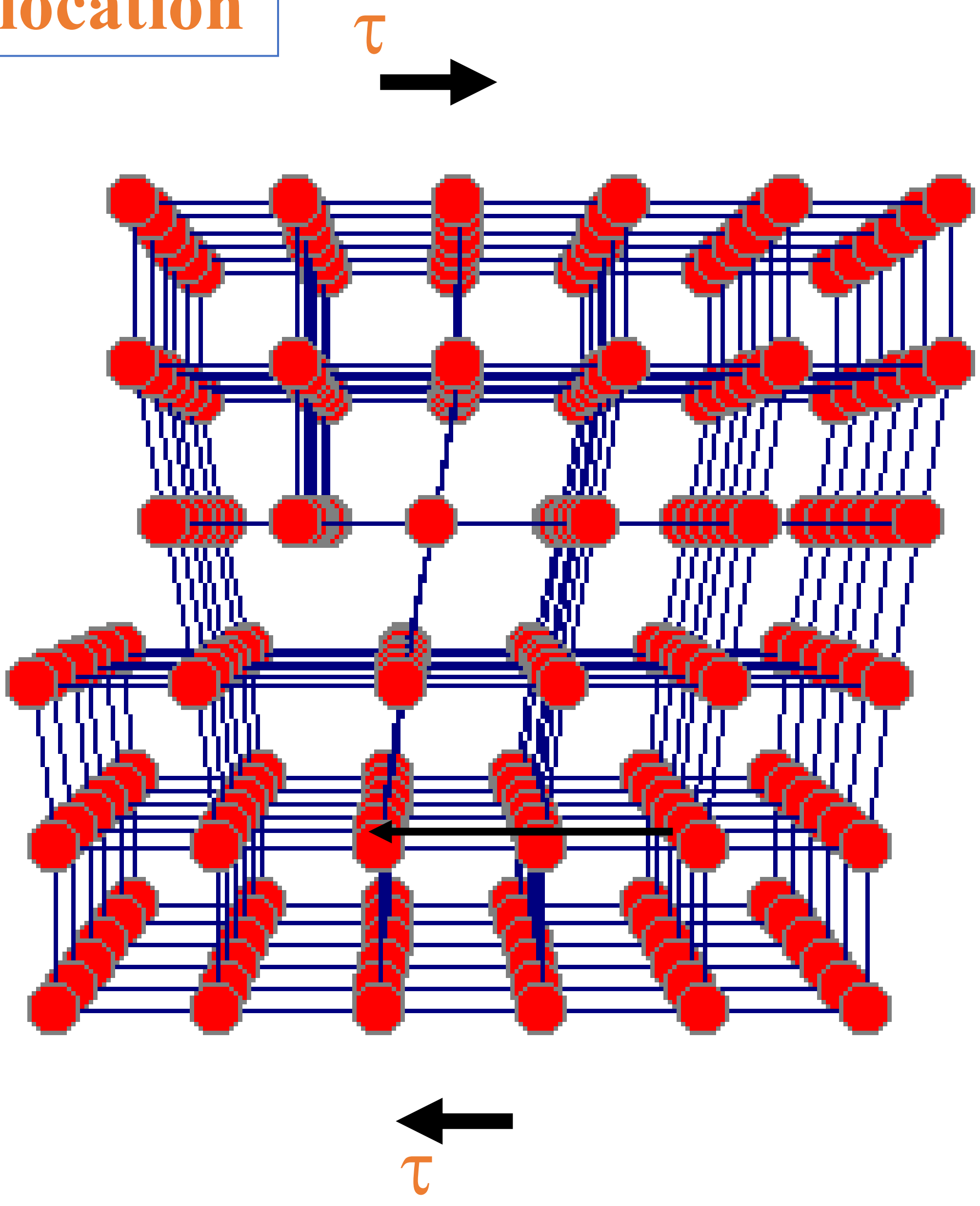
- Edge dislocation move by slip or glide and climb while screw dislocation can be moved by slip or glide and cross-slip.
- Atomic bonds at one point are broken and reestablished at another point
- During the motion, dislocations will tend to interact among themselves. Dislocation interaction is very complex as number of dislocations moving on number of slip planes in various directions.
- When they are in the same plane, they repel each other if they have the same sign, and annihilate if they have opposite signs (leaving behind a perfect crystal).

Glide Dislocation Motion

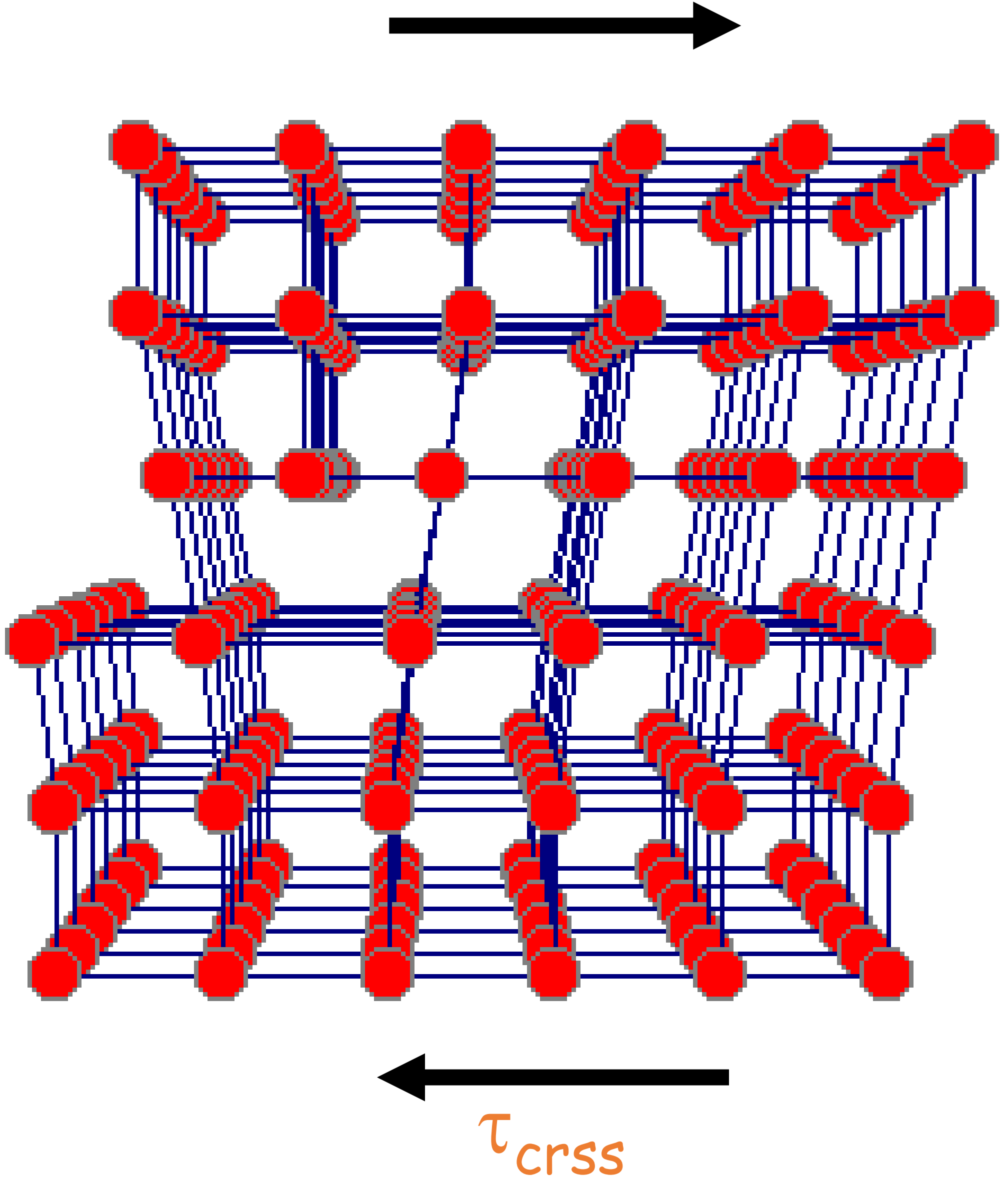
- Glide is a motion of a dislocation in its own slip plane
- Dislocations move in steps. The edge dislocation at P moves to Q in steps
- This movement is *analogous to movement of a caterpillar.*
- When the half-plane reaches a free surface it produces a slip step.
- Since plastic deformation takes place by movement of dislocations, any hindrance to their motion will increase the strength of metals.



Glide of an Edge Dislocation

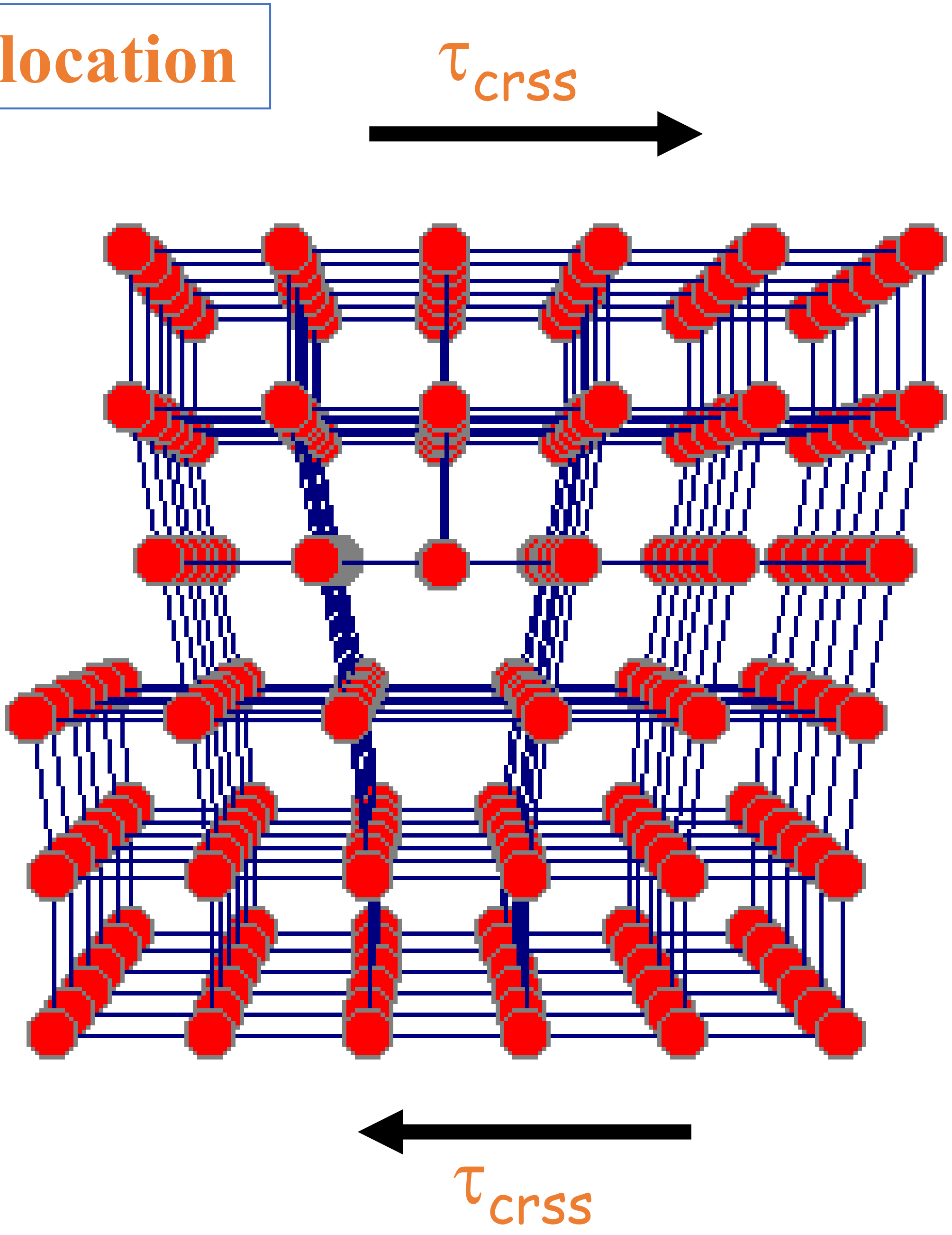


Glide of an Edge Dislocation



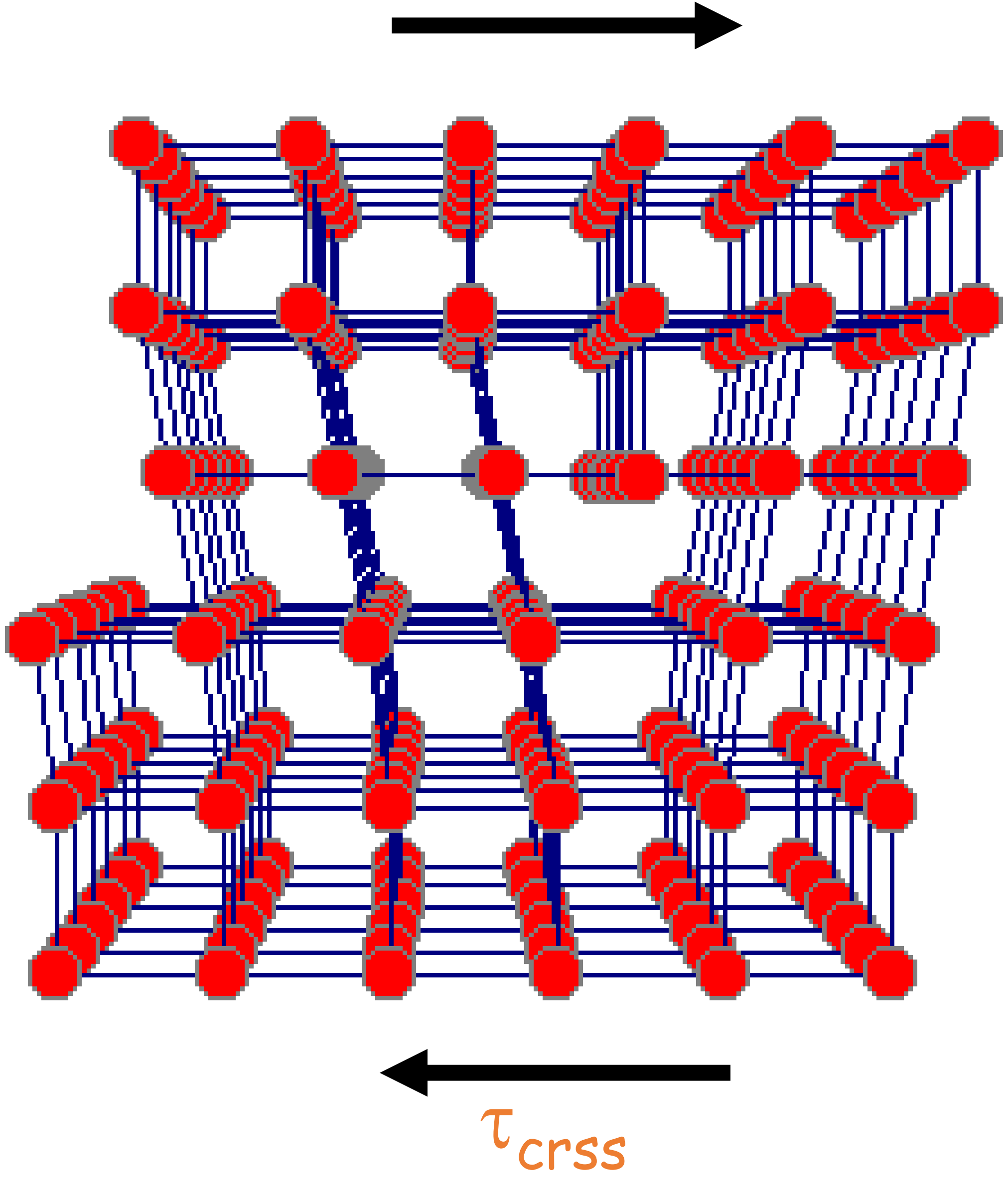
τ_{crss} is critical resolved shear stress on the slip plane in the direction of b.

Glide of an Edge Dislocation



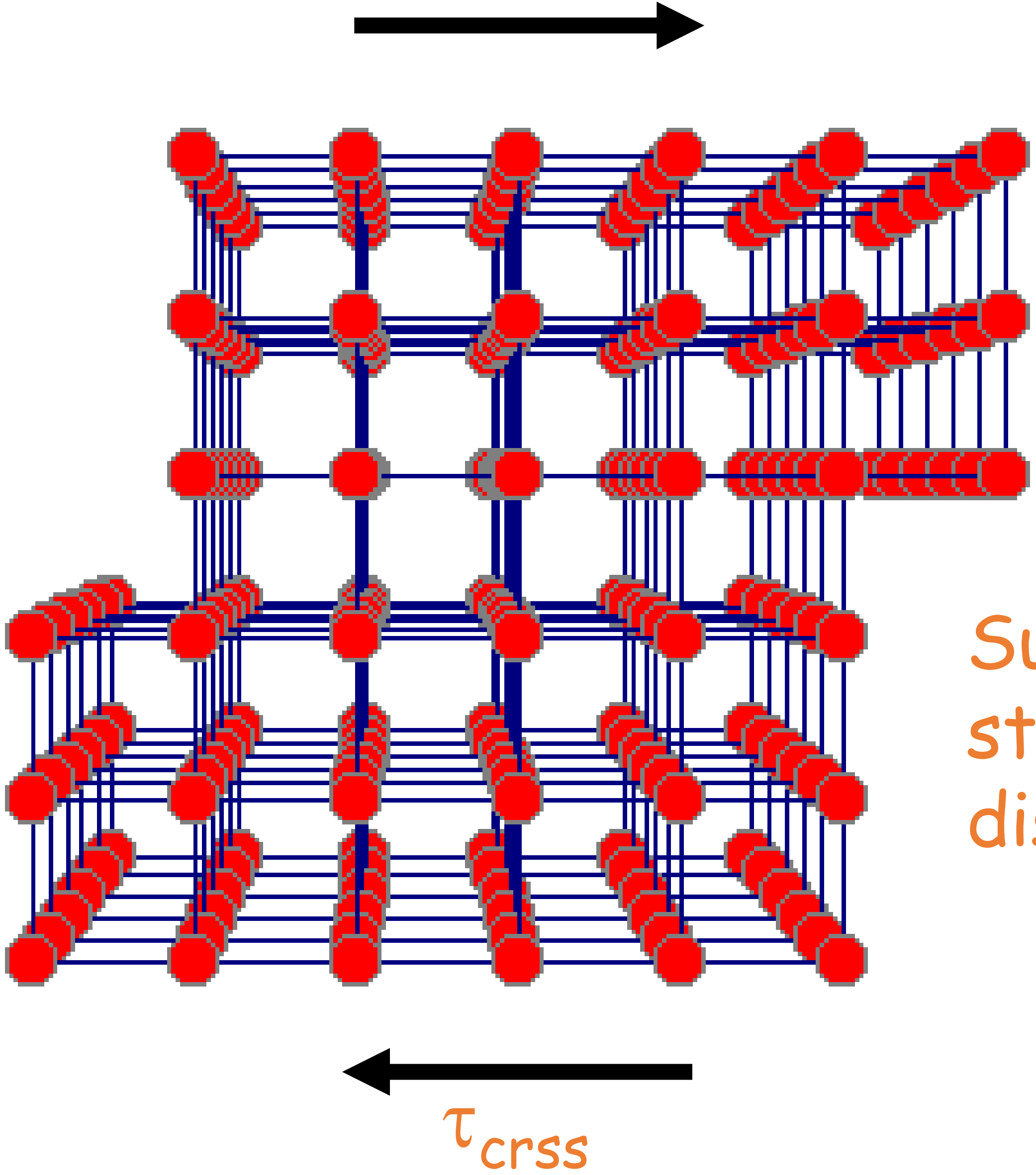
τ_{crss} is critical resolved shear stress on the slip plane in the direction of b.

Glide of an Edge Dislocation



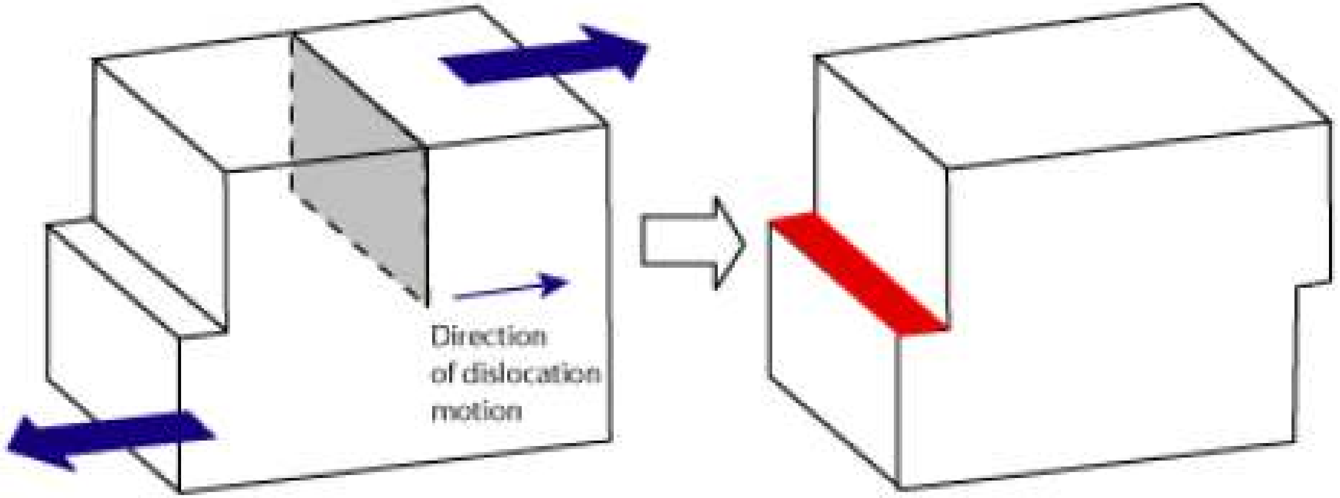
τ_{crss} is critical resolved shear stress on the slip plane in the direction of b.

Glide of an Edge Dislocation

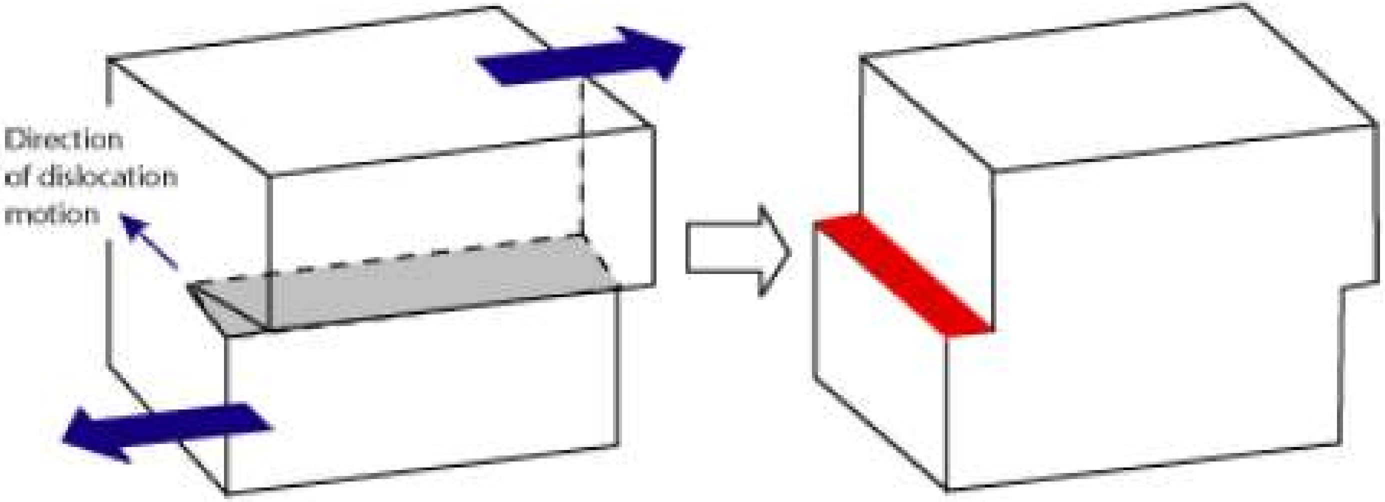


A surface step of b is created if a dislocation sweeps over the entire slip plane

Surface step, not a dislocation



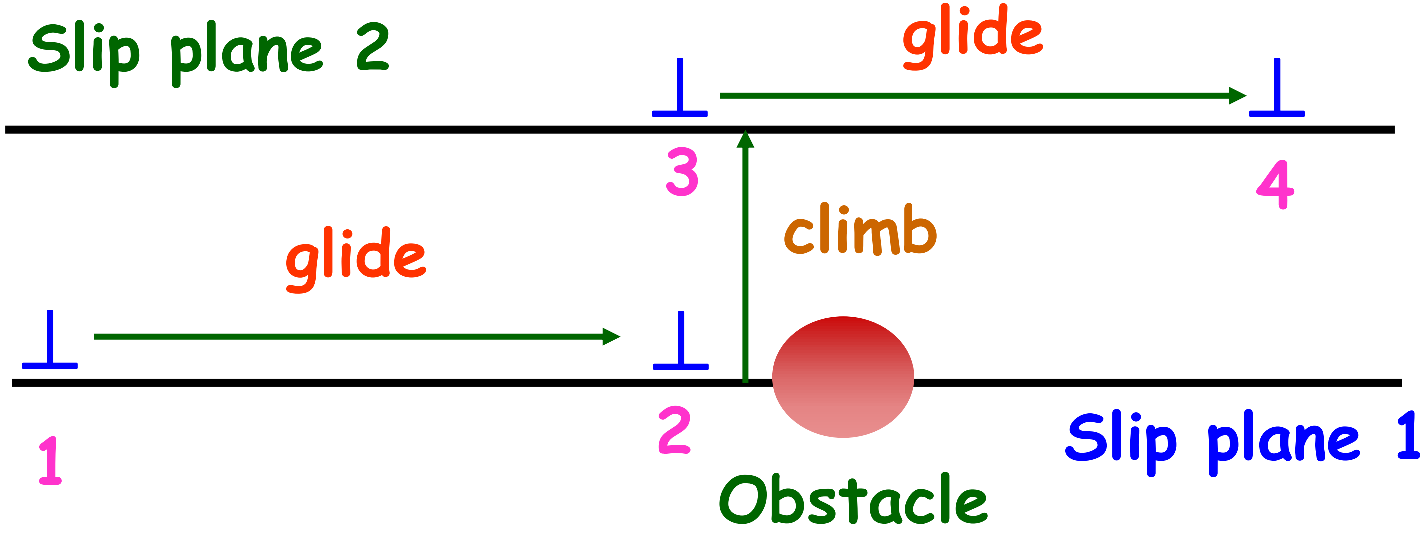
Edge Dislocation



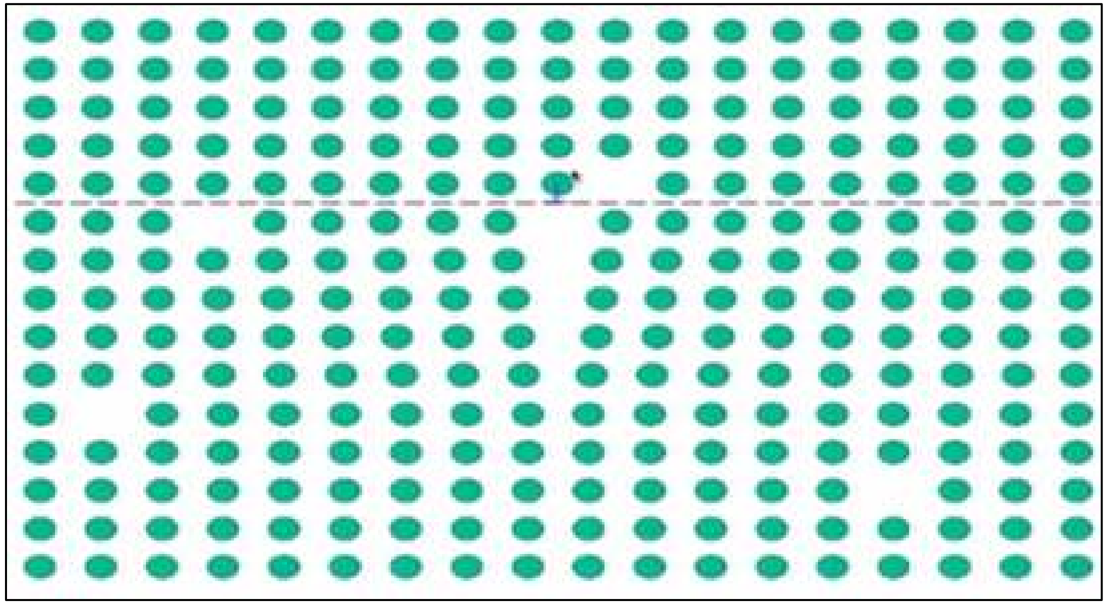
Screw Dislocation

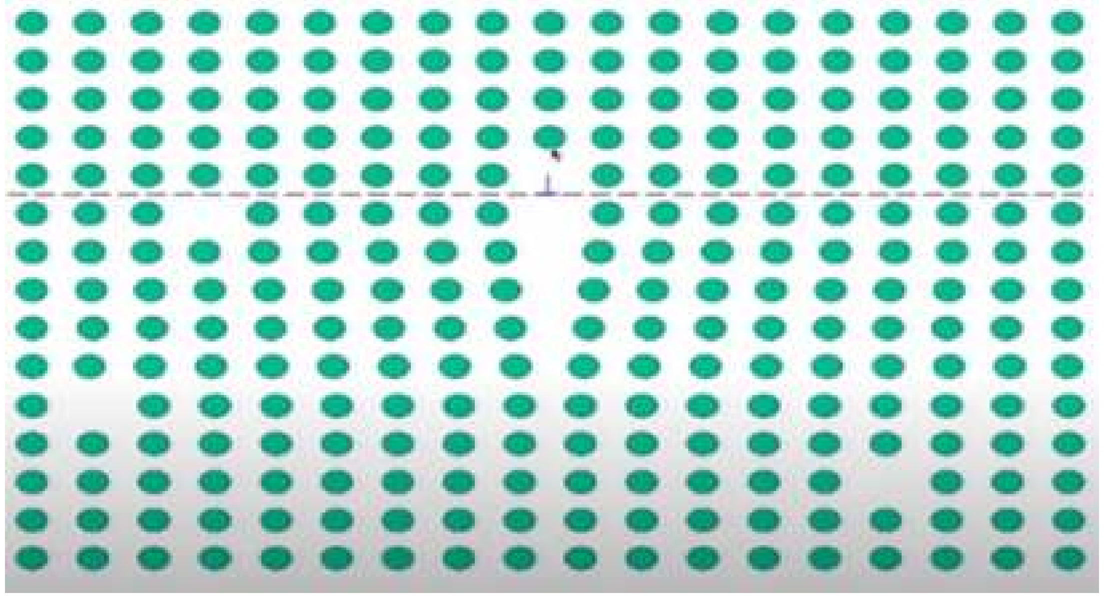
Climb of a Edge Dislocation

The motion of an edge dislocation from its slip plane to an adjacent parallel slip plane is called CLIMB

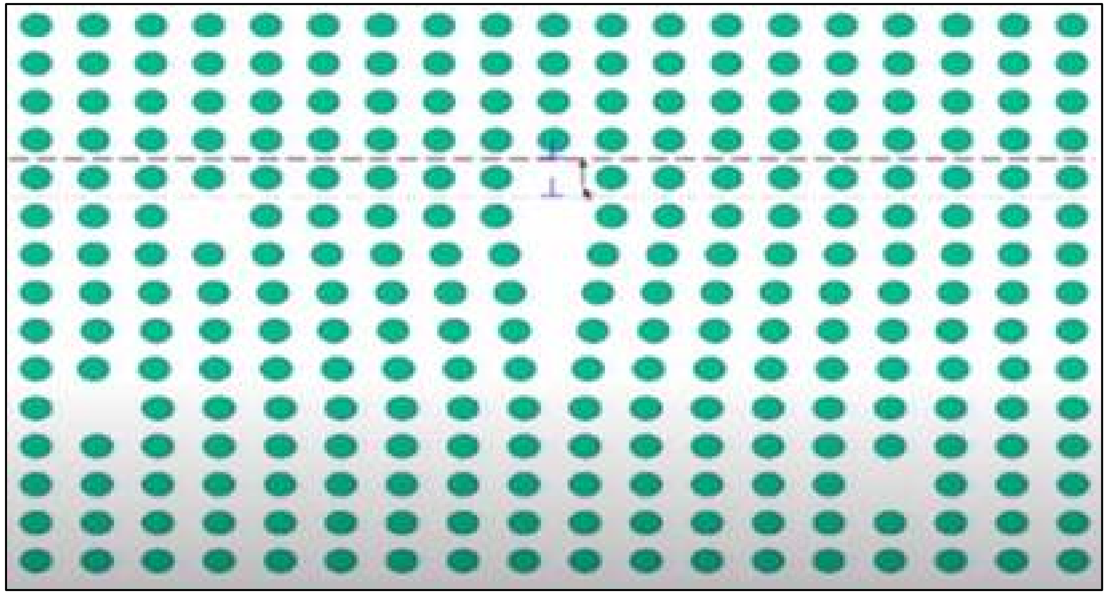


Climb of a Edge Dislocation





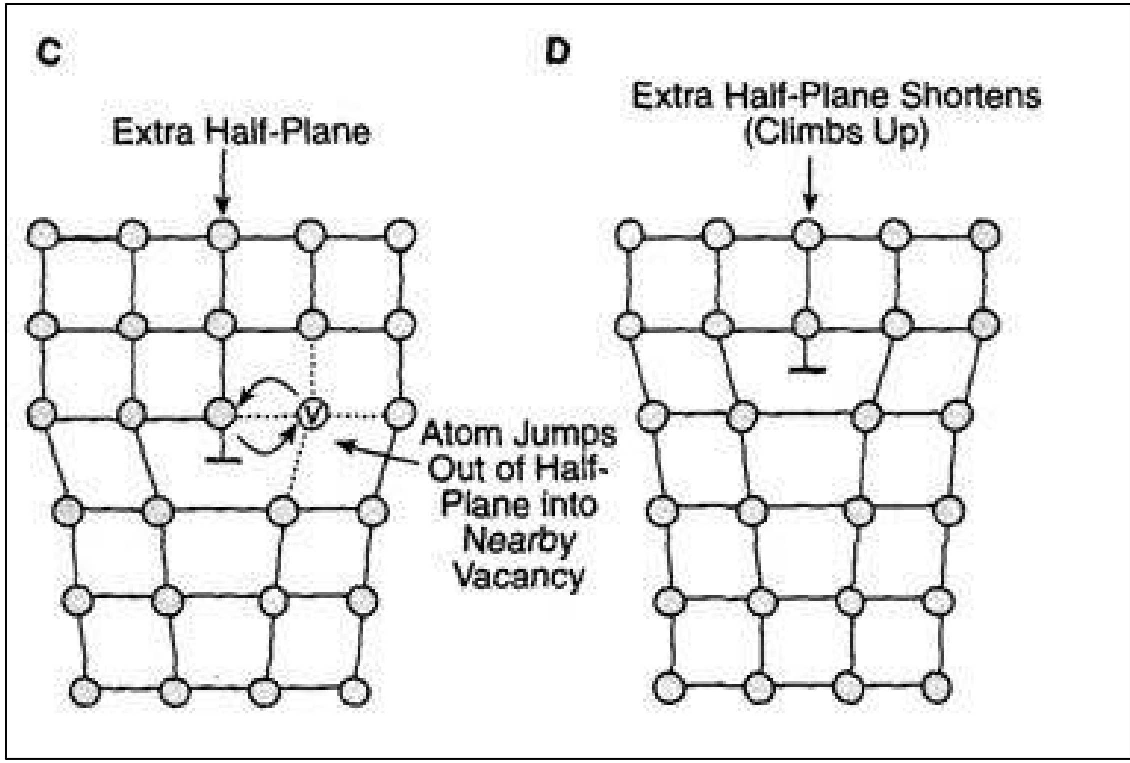
Climb Up



Climb Up

a. Edge dislocation (Extra plane of atoms)
b. A vacancy diffuses to right side of bottom of extra plane
c. Vacancy and bottom atom of extra plane exchange their places

- Dislocation climbs up by *motion of vacancy to dislocation line*
- A compressive stress perpendicular to extra half plane helps in dislocation climb up as it reduces the extra plane

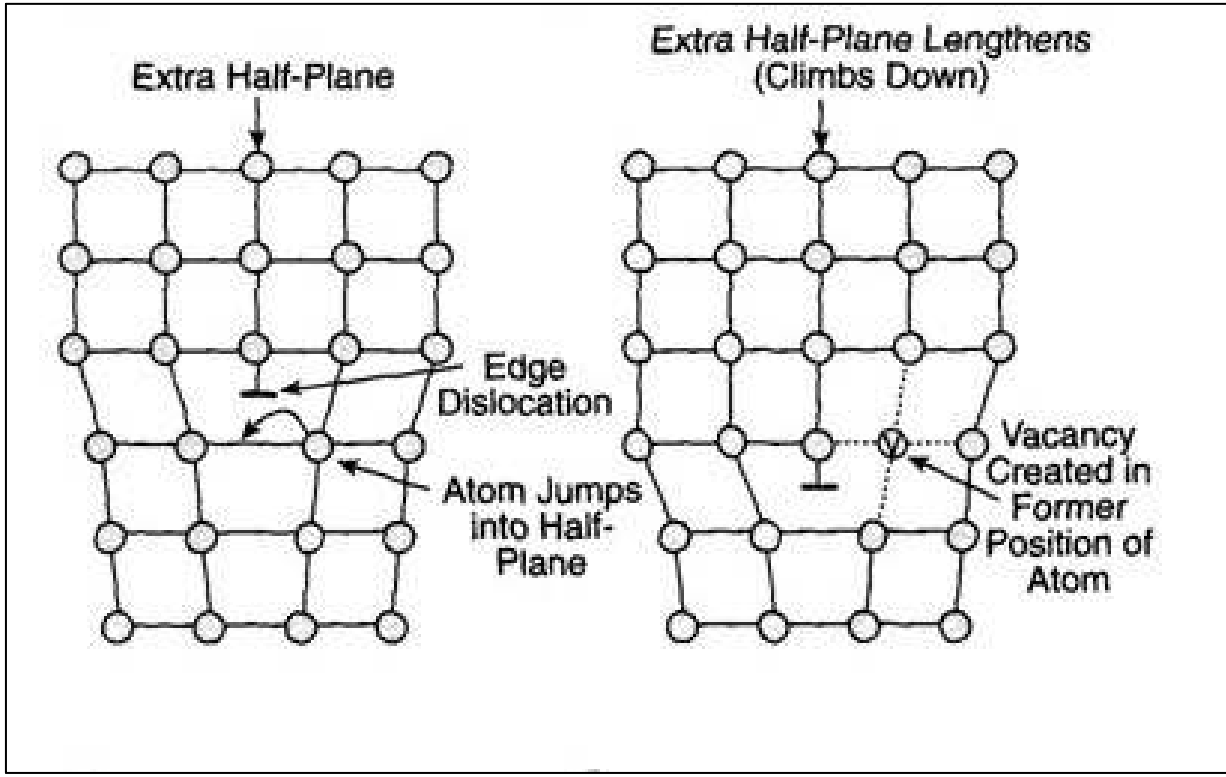


Climb down

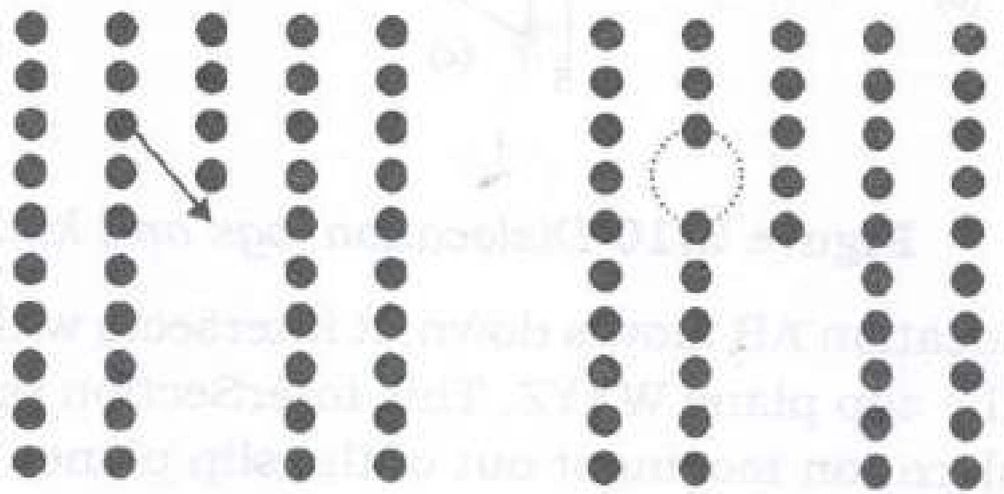
a. Edge dislocation (Extra plane of atoms)

b. Atom jump to left and replaced by vacancy

c. c. Vacancy moves away from dislocation line

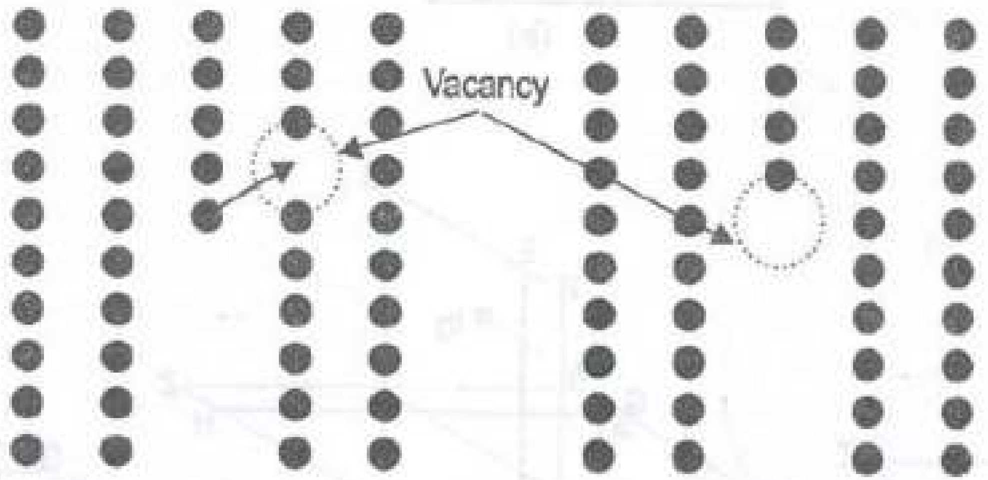


- Dislocation climbs down by motion of vacancy away from dislocation line.
- A tensile stress perpendicular to extra half plane helps in dislocation climb down as it grows the extra plane.



An atom diffuses into dislocation

Dislocation Climbs down (Negative Climb)



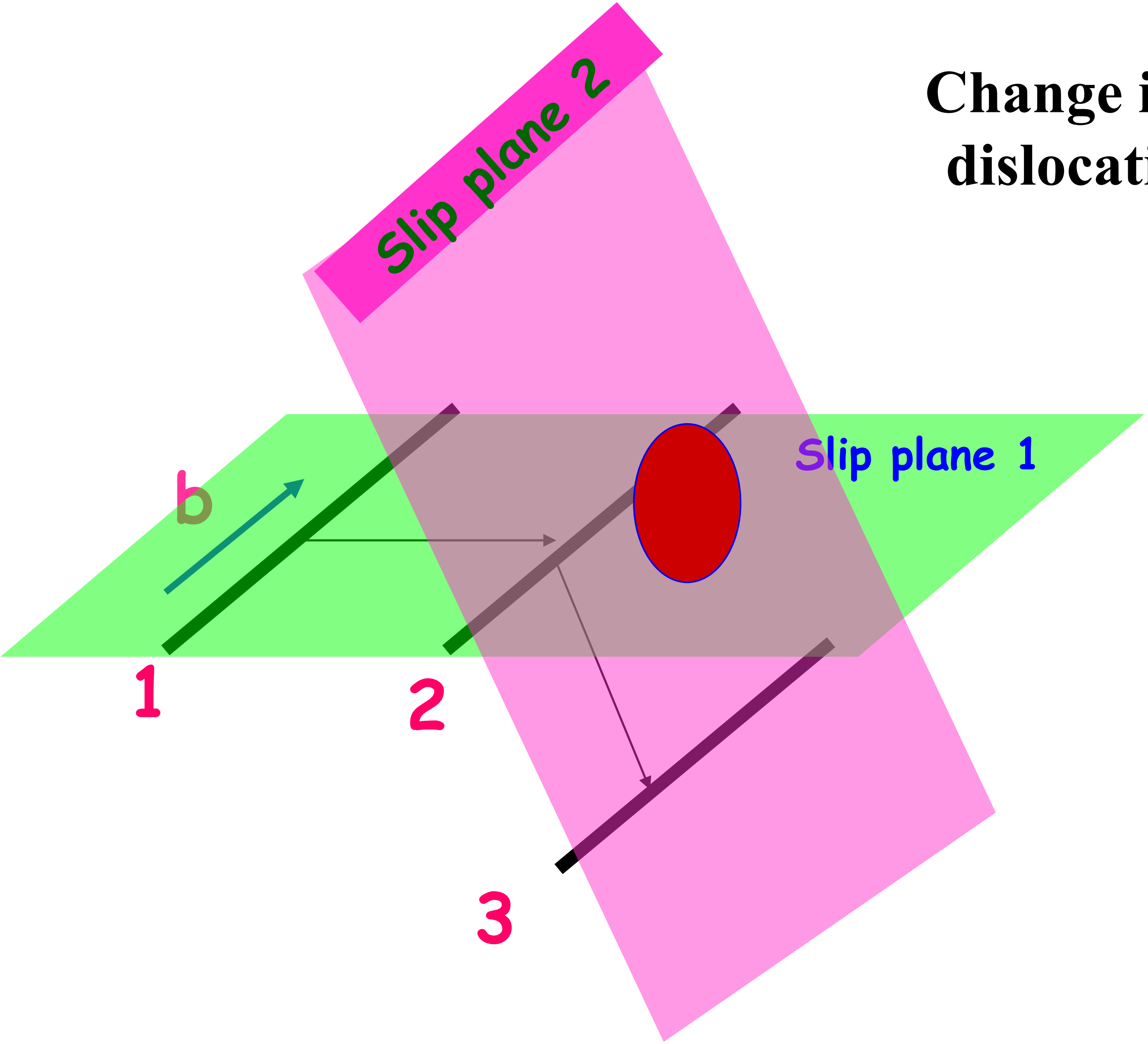
Vacancy diffuses to edge dislocation

Dislocation Climbs up (Positive Climb)

Climb of an edge dislocation

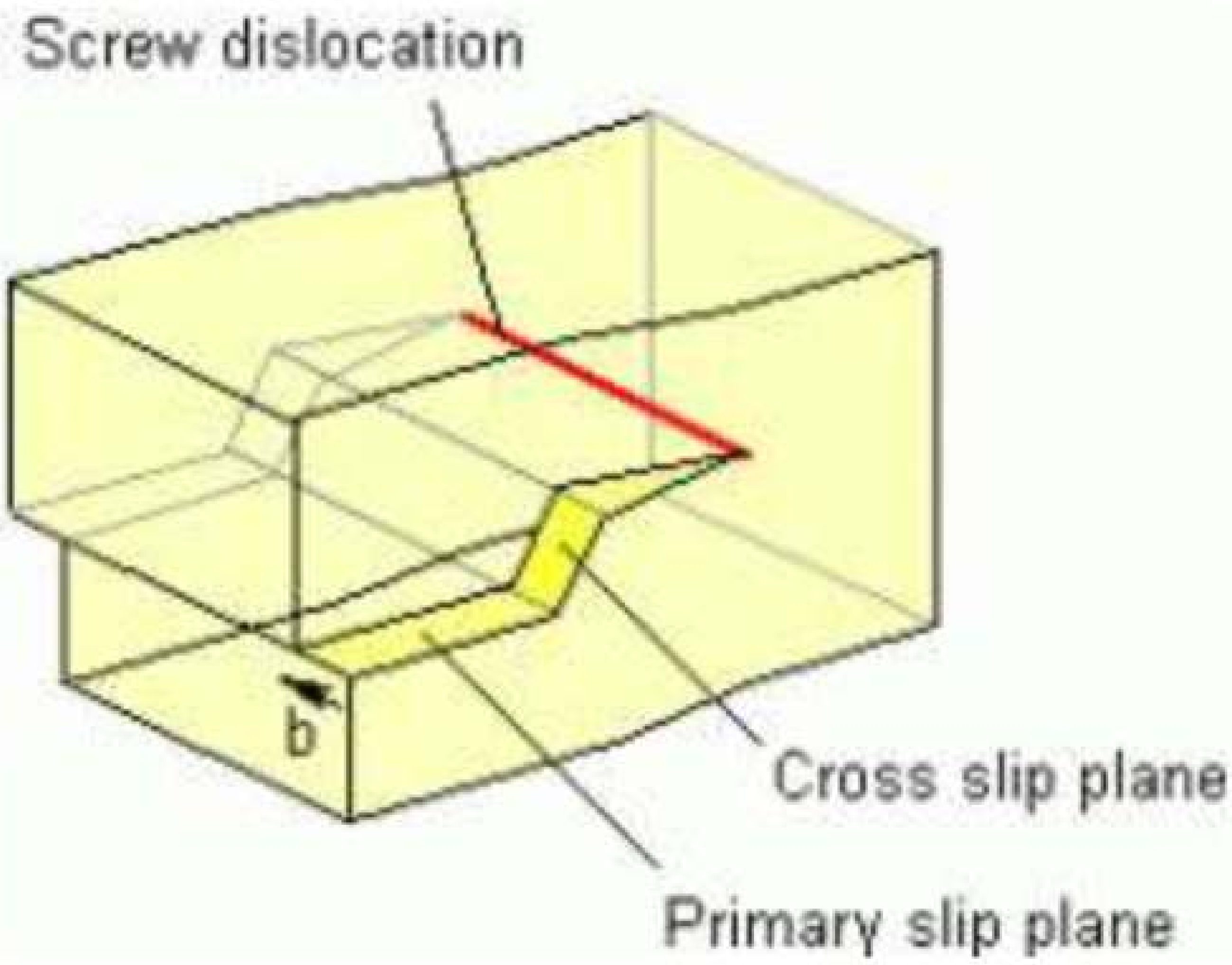
Climb up	Climb down
Half plane shrinks	Half plane stretches
Atoms move away from the edge to nearby vacancies	Atoms move toward the edge from nearby lattice sites
Vacancy concentration goes down	Vacancy concentration goes up

Cross Slip of a Screw Dislocation



Change in slip plane of a screw dislocation is called cross-slip

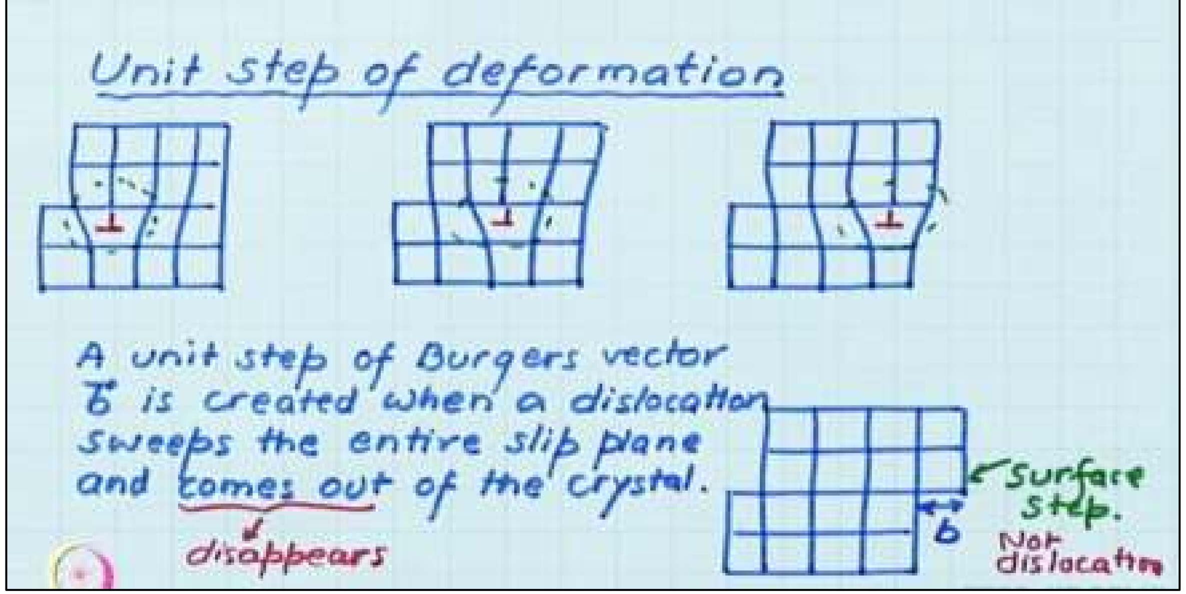
Movement of a screw dislocation from one slip plane to a non parallel slip plane is called cross-slip


Screw dislocation
b
Cross slip plane
Primary slip plane

Dislocation Density

- The dislocation density is a measure of how many dislocations are present in a quantity of a material.
- Dislocation is a line defect, this is defined as the total length of dislocation per unit volume. Total dislocation length per unit volume (mm/mm^3)
- It can also be defined as number of dislocation lines intersecting a unit area.
- Temperature change below R.C.T will not affect dislocation density
- Annealing(heat treatment) increases dislocation density ($10^4 – 10^6$ mm^{-2})
- Cold working / strain hardening increases dislocation density (10^{12} - 10^{16} mm^{-2})

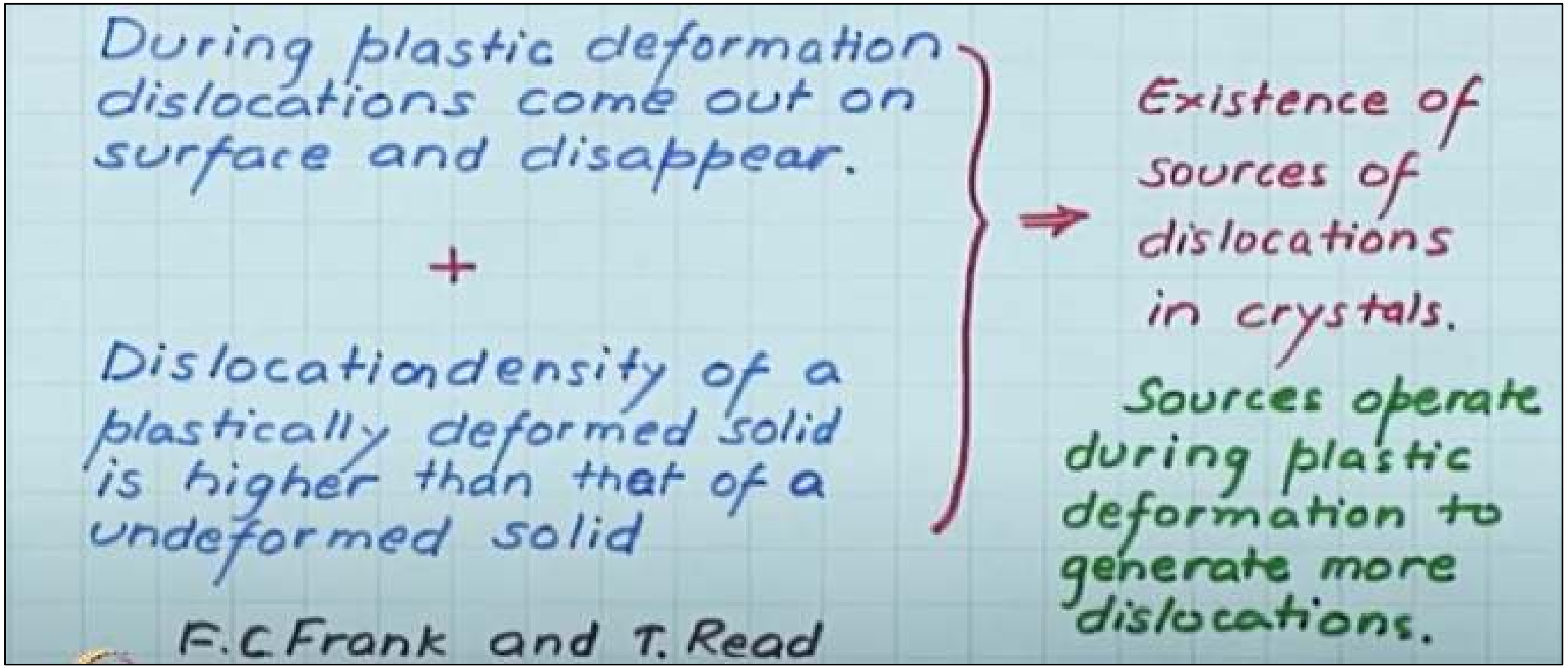
By plastic deformation dislocation density must come down but actually it is increasing , why**?**



Unit step of deformation

A unit step of Burgers vector $\vec{b}$ is created when a dislocation sweeps the entire slip plane and comes out of the crystal.

disappears



During plastic deformation dislocations come out on surface and disappear.

+

Dislocationdensity of a plastically deformed solid is higher than that of a undeformed solid

⇒ Existence of sources of dislocations in crystals.

Sources operate during plastic deformation to generate more dislocations.

F.C. Frank and T. Read

Dislocation Sources

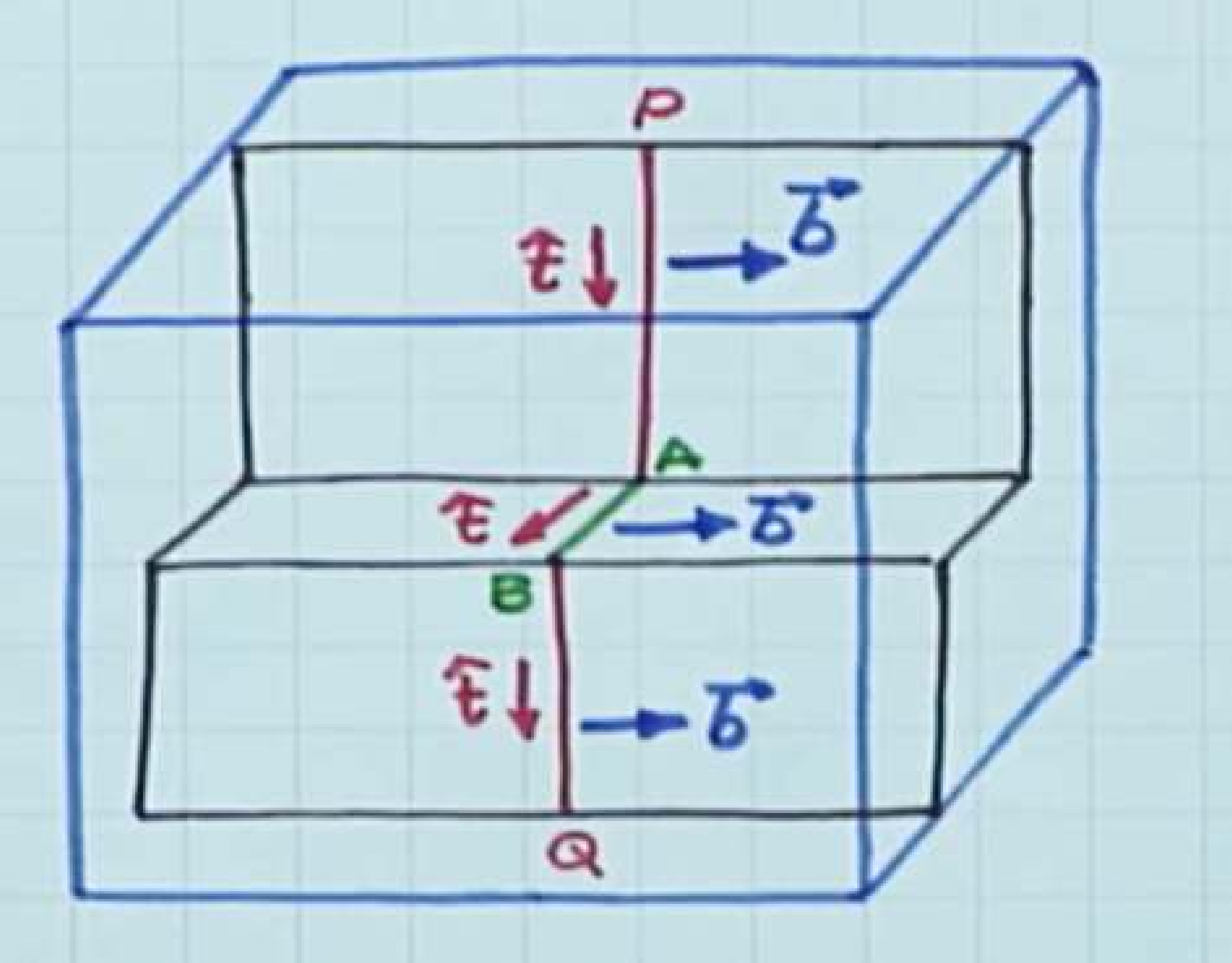
Existence of source of dislocations in crystals , there are sources which operates during the plastic deformation create more and more dislocations .

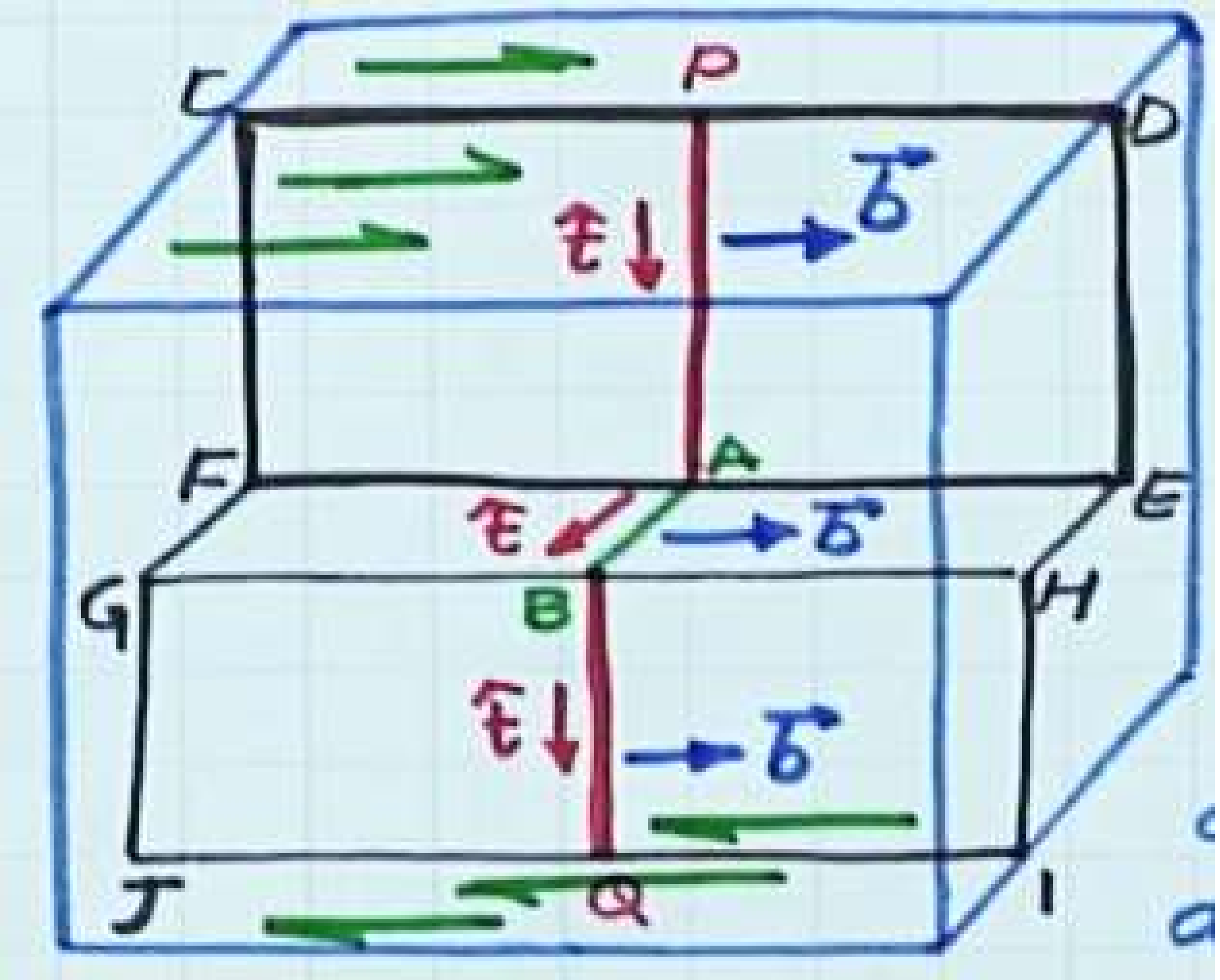
- Irregularities in grain boundary (grain boundary steps and ledges are responsible for emitting dislocation in polycrystalline materials)
- Small surface steps that act as stress raisers can act as dislocation source in single crystals.
- Dislocation can also form by aggregation and collapse of vacancies that forms a loop .

  Eg. Frank partials formed on {111} plane in fcc crystals.
- Heterogeneous nucleation of dislocation by high local stresses at second phase particles.
- Heterogeneous nucleation of dislocation by high local stresses due to phase transformation.

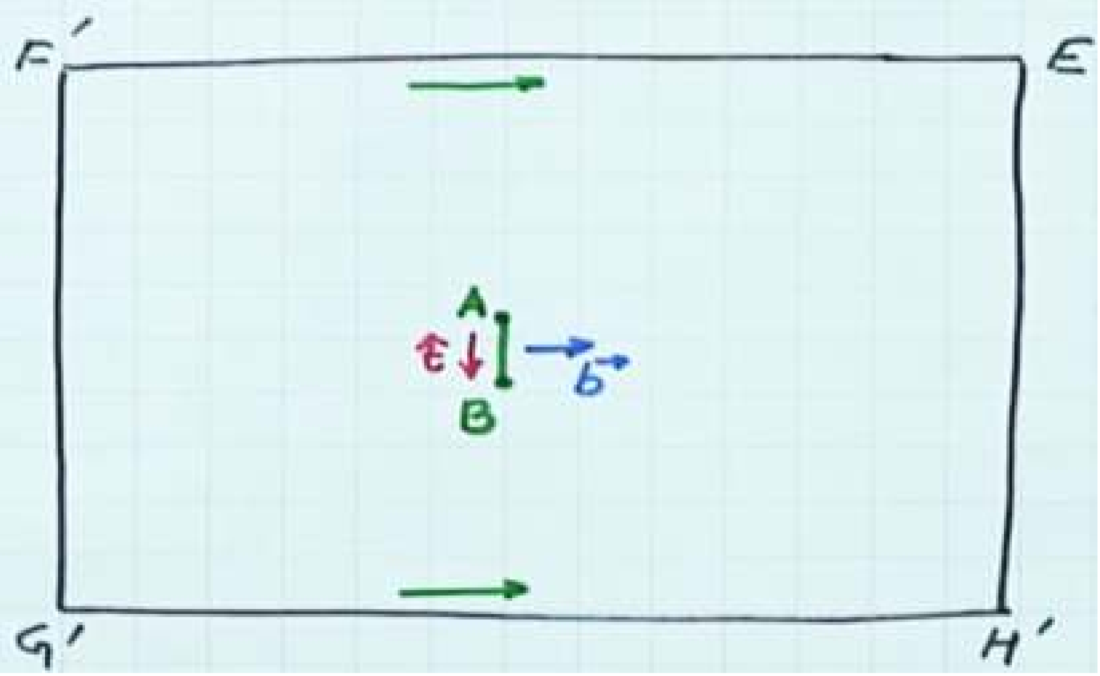
Dislocation Sources (Frank-Read Source)

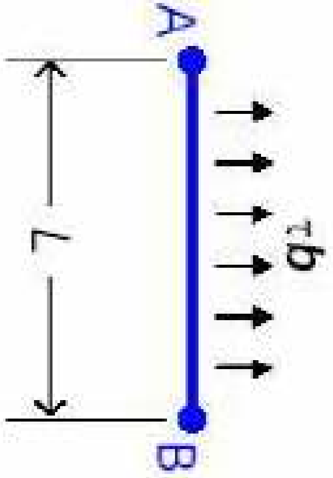
Existence of source of dislocations in crystals , there are sources which operates during the plastic deformation create more and more dislocations .





- For the applied shear stress as shown, there will be no shear stress on the vertical planes CDEF and GHIJ. There will be shear on horizontal plane EFGH

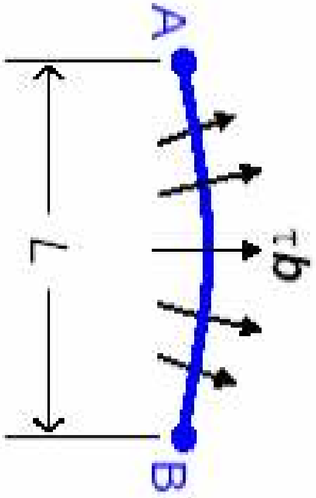


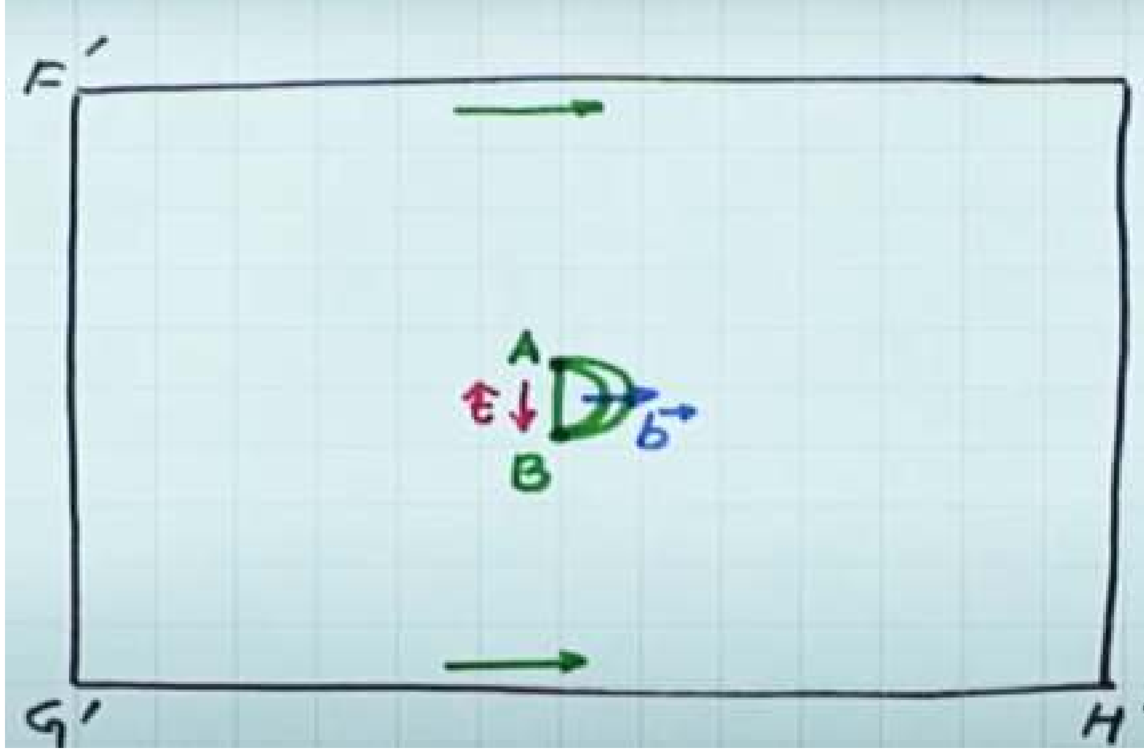


1. Segment of moving dislocation is pinned at points A and B.
2. Applied shear stress causes the segment to bow out between points A and B with a radius of:

$$\tau \propto \frac{Gb}{R}$$

where R is the radius of curvature.



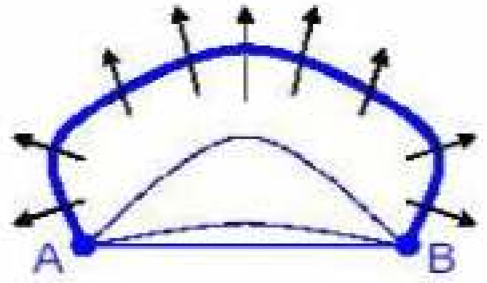


$$\tau = \frac{Gb}{L}$$

L = length of AB.

G = Shear modulus

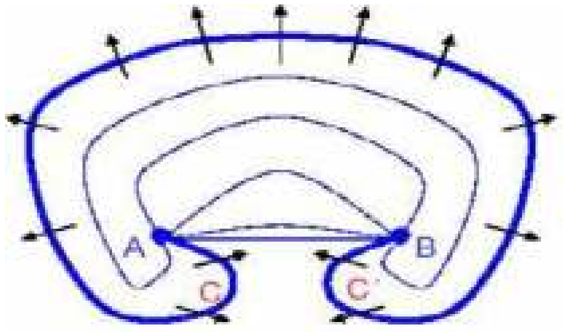
b = Burgers vector.



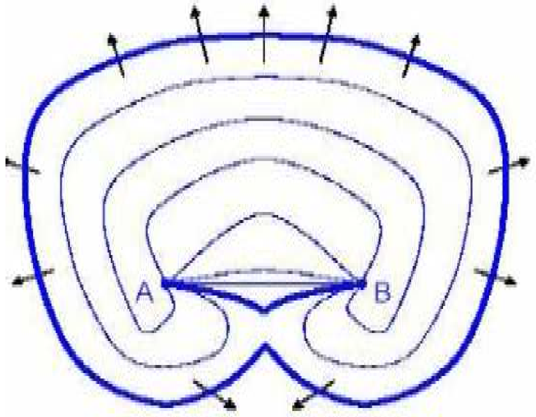
3. Bowing continues until R= $L/2$. At this point the loop becomes unstable and begins to bend around upon itself. This occurs when:

$$\tau \approx \frac{Gb}{L}$$

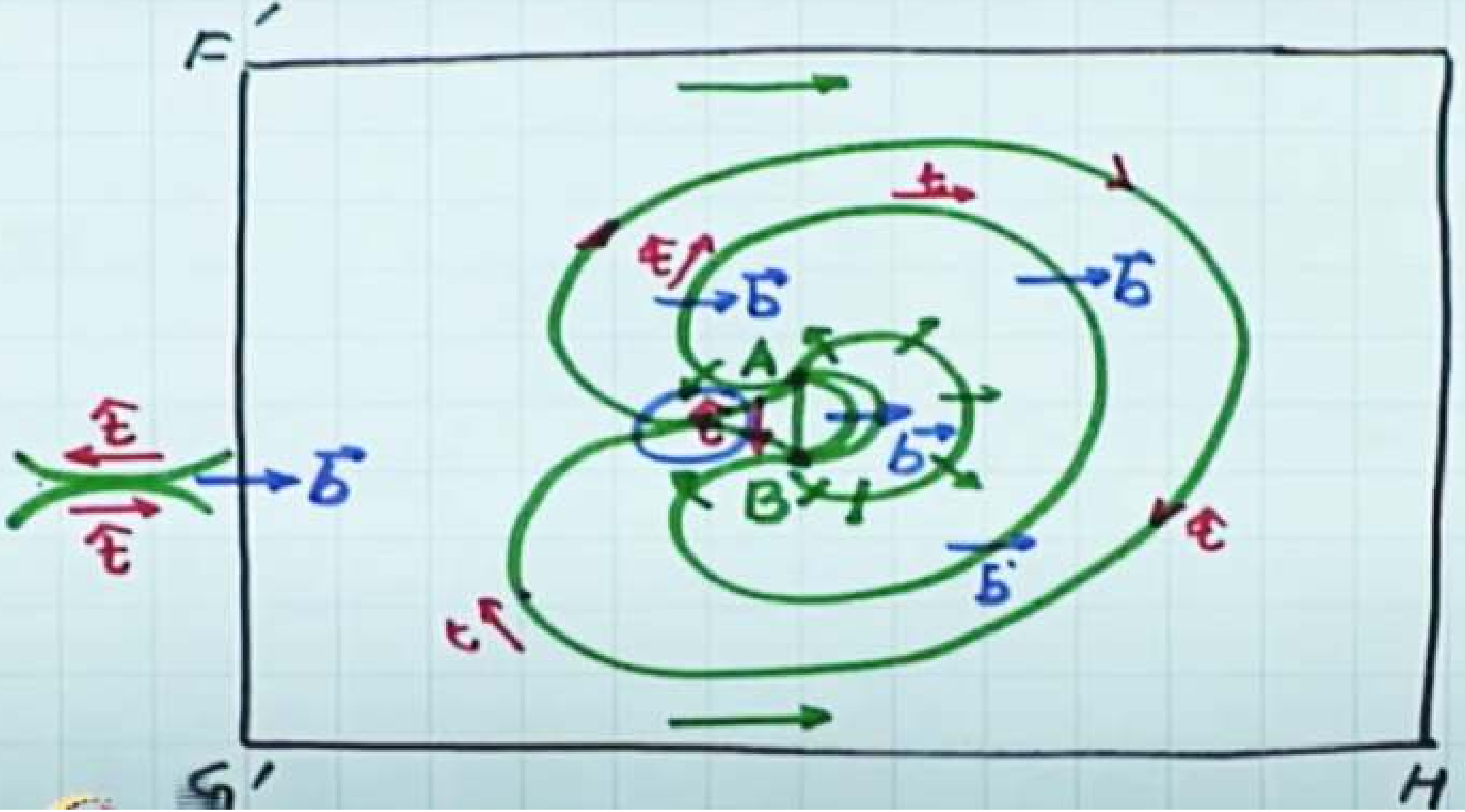
G = modulus of rigidity
b = burger vector
L = length of dislocation



4. This continues until the loop pinches off at point CC', which are screw dislocations of opposite sign.



The loop continues to grow. New dislocation will repeat if applied stress is sufficient.

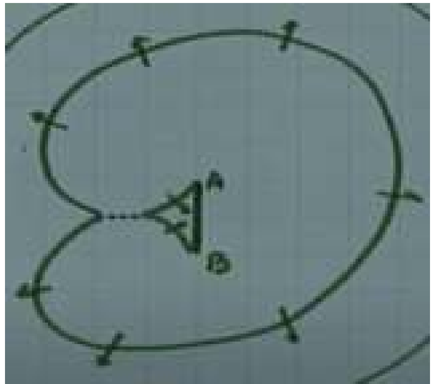


$$\tau = \frac{Gb}{L}$$

$L \equiv$ length of AB.

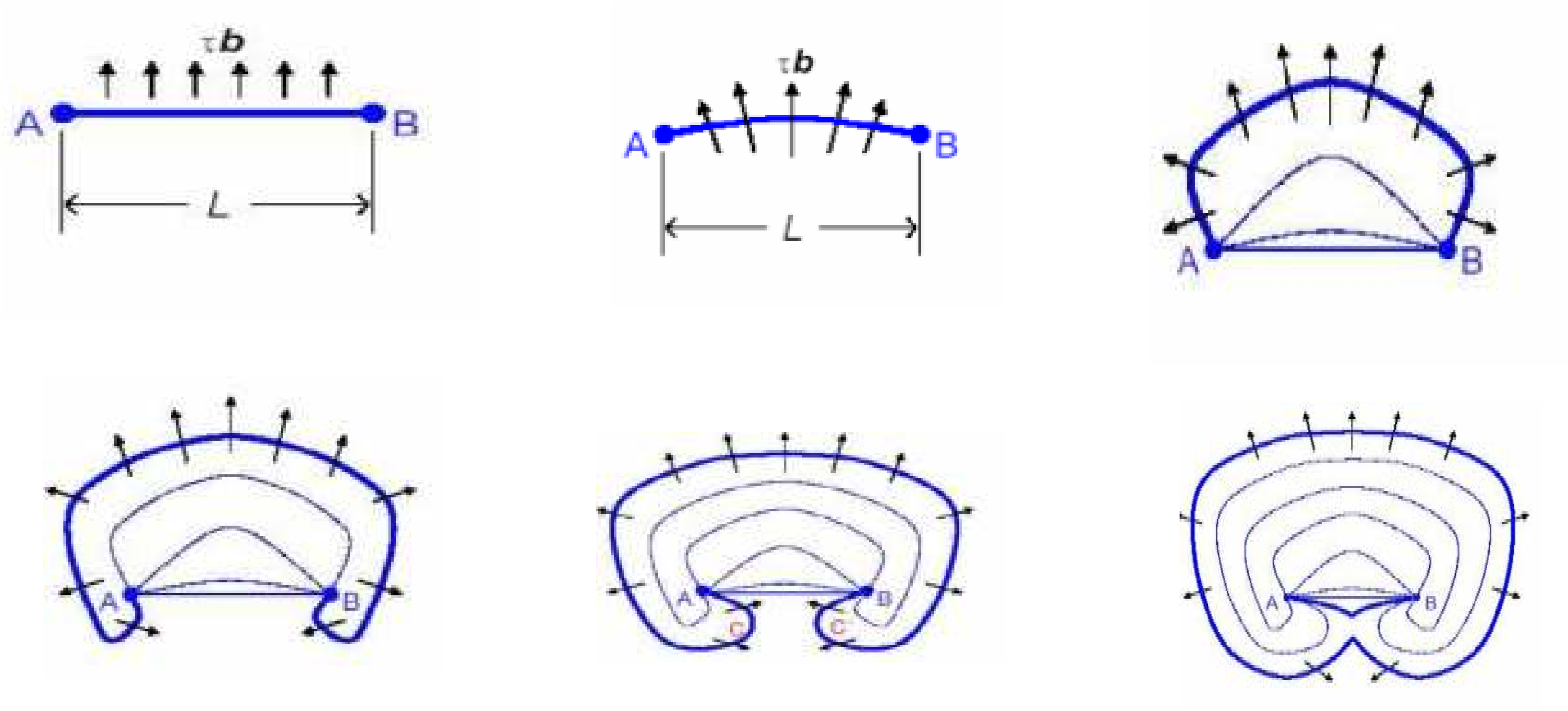
G = Shear modulus

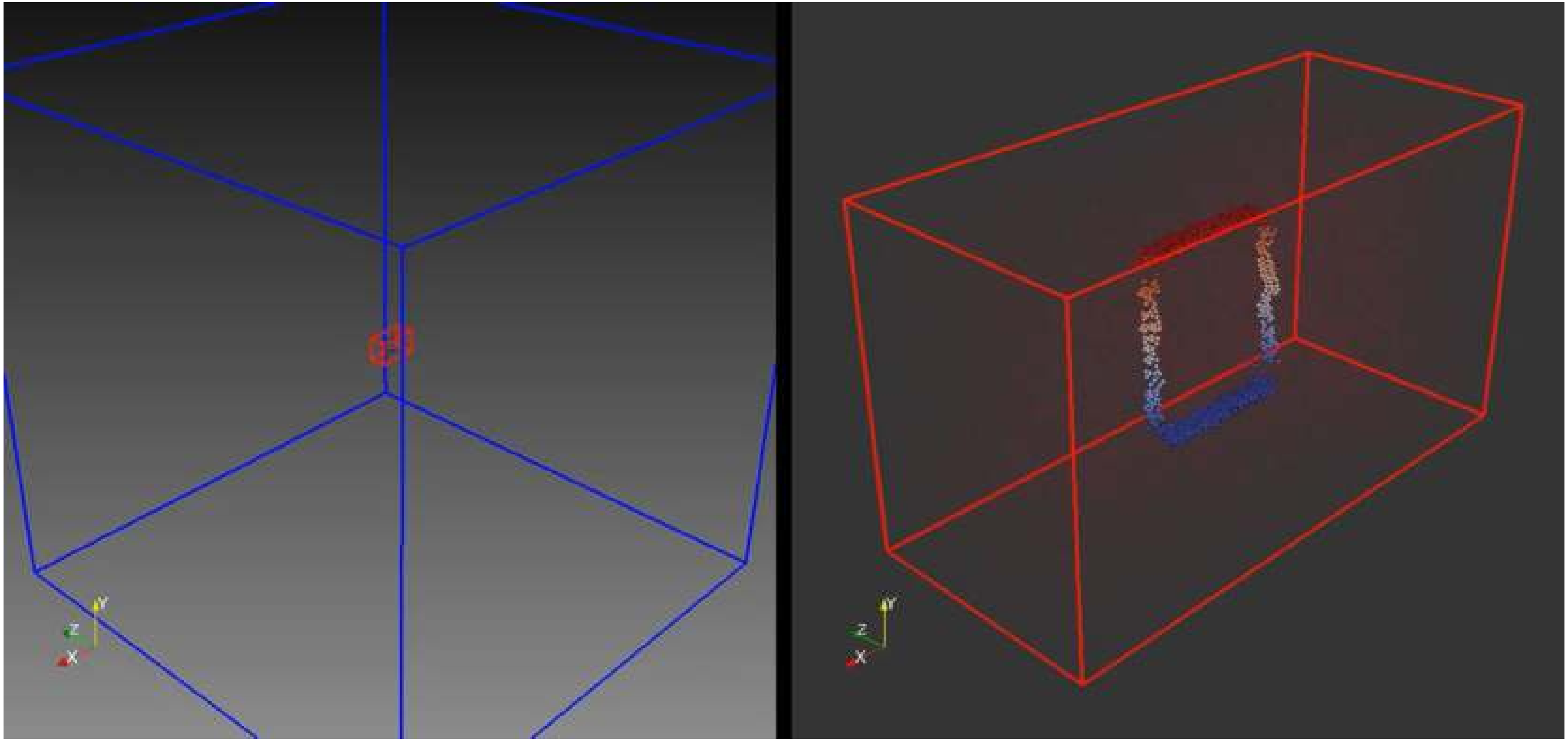
b = Burgers vector.

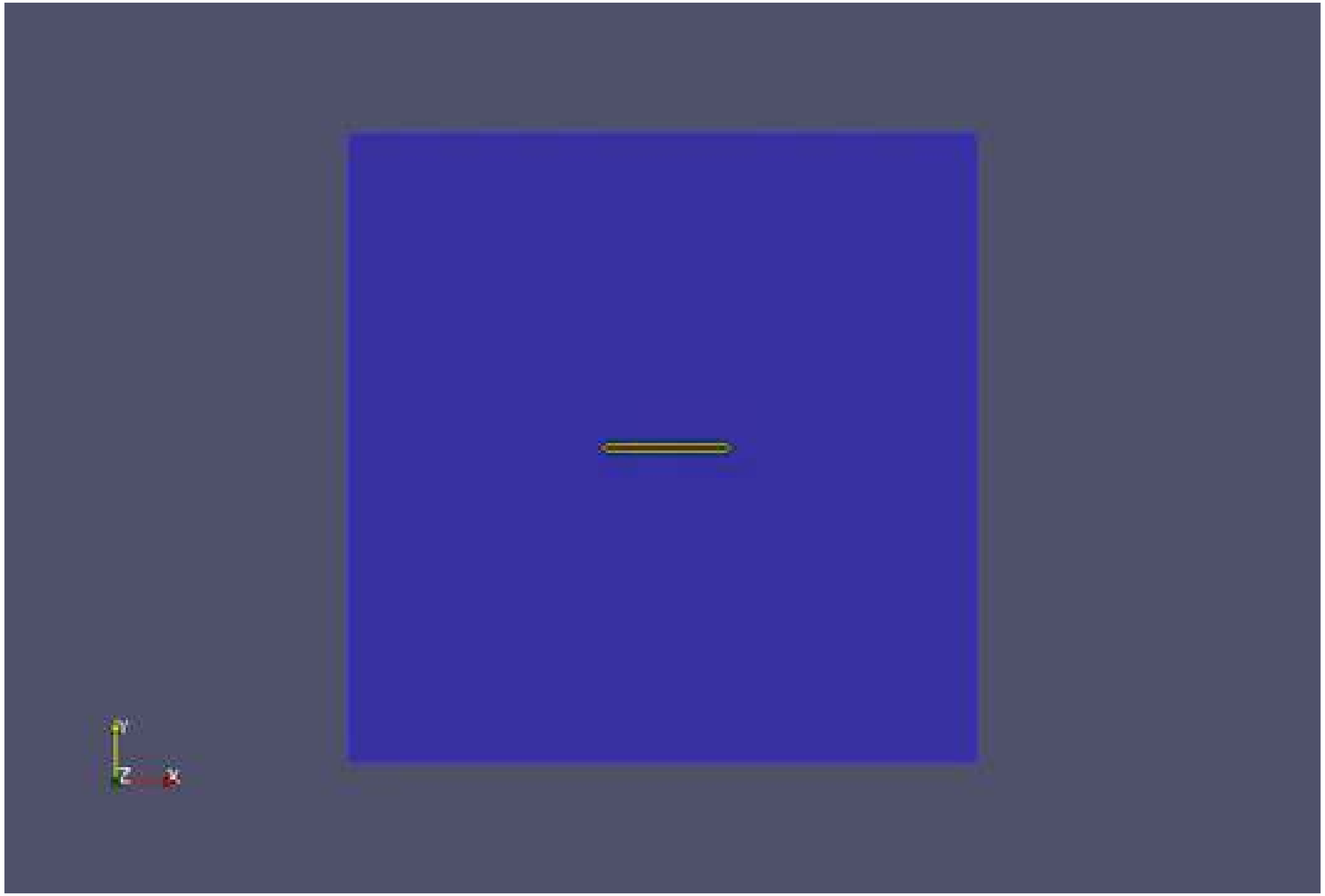


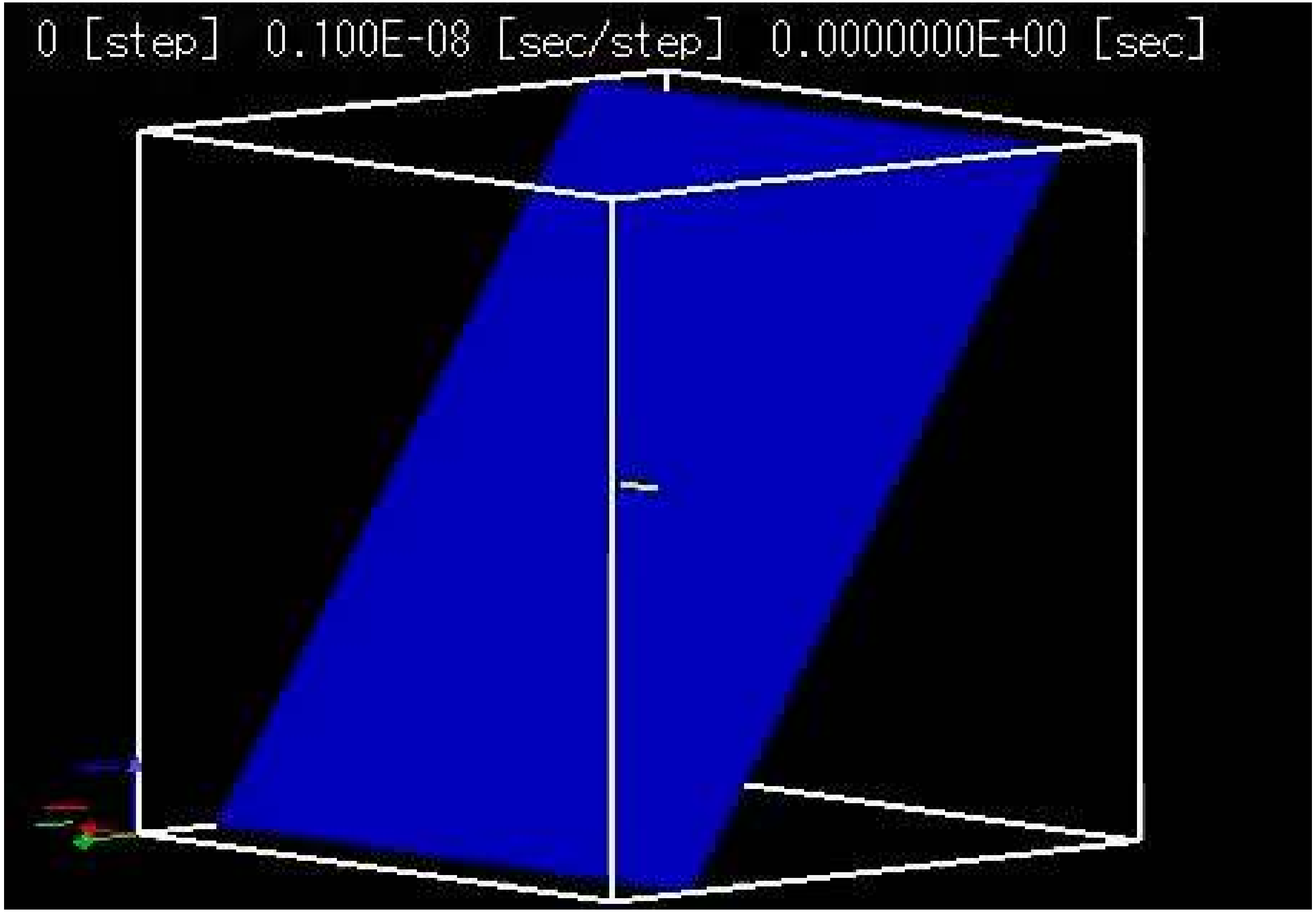
Multiplication of Dislocation Frank-Read Source

- ***Frank-Read Source*** is the mechanism by which dislocation multiply during plastic deformation

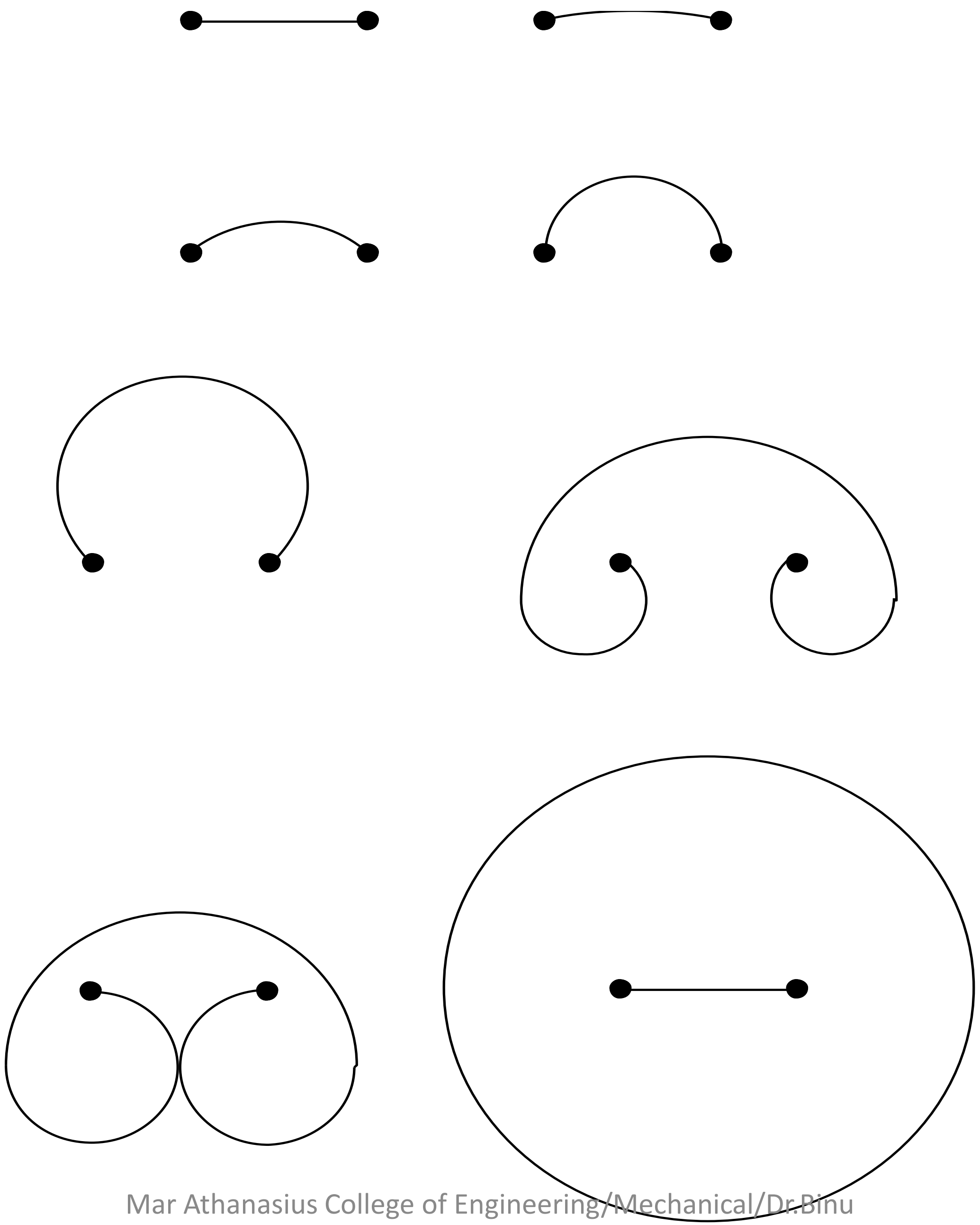


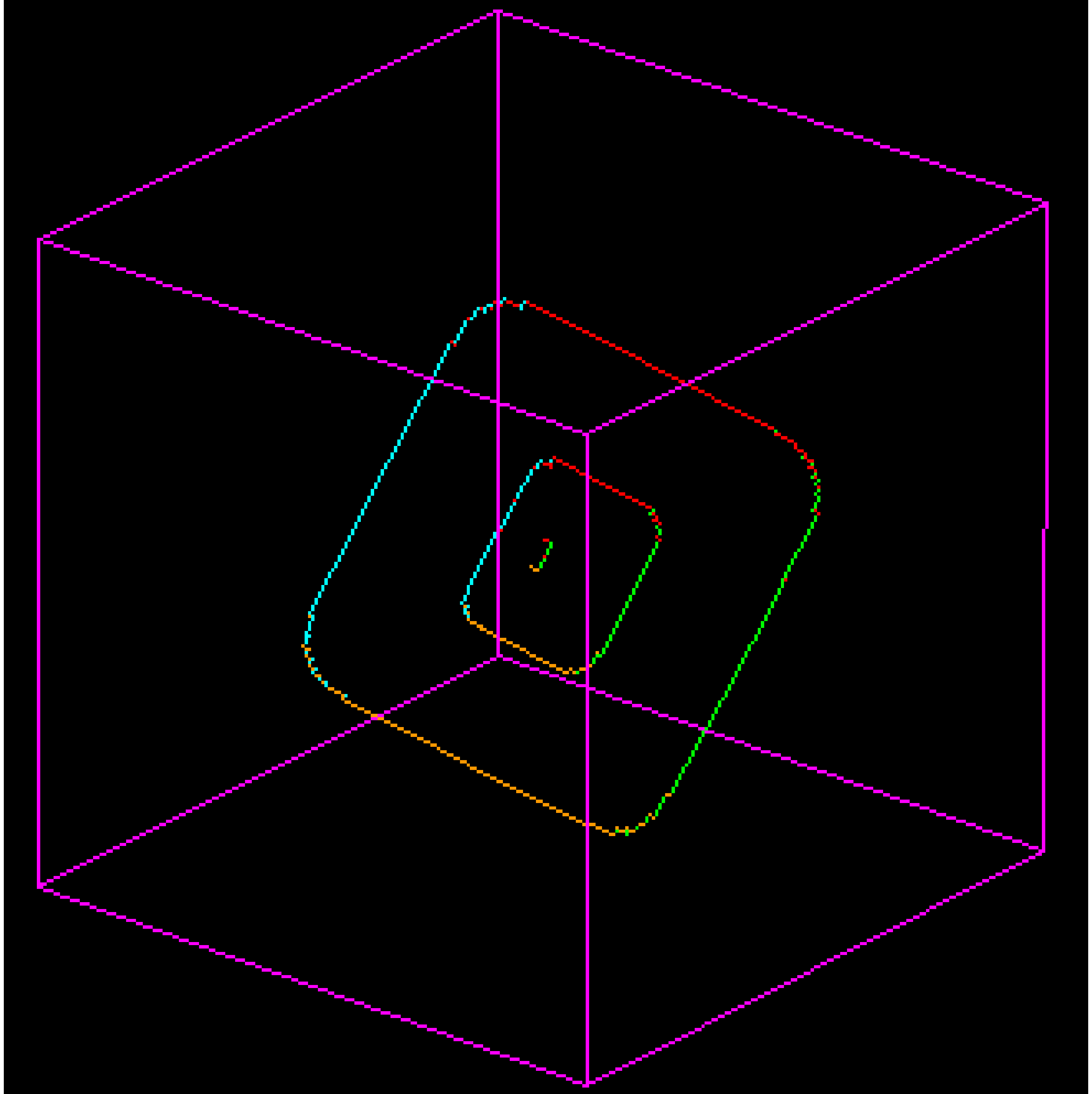

Y
Z
X
Y
Z
X

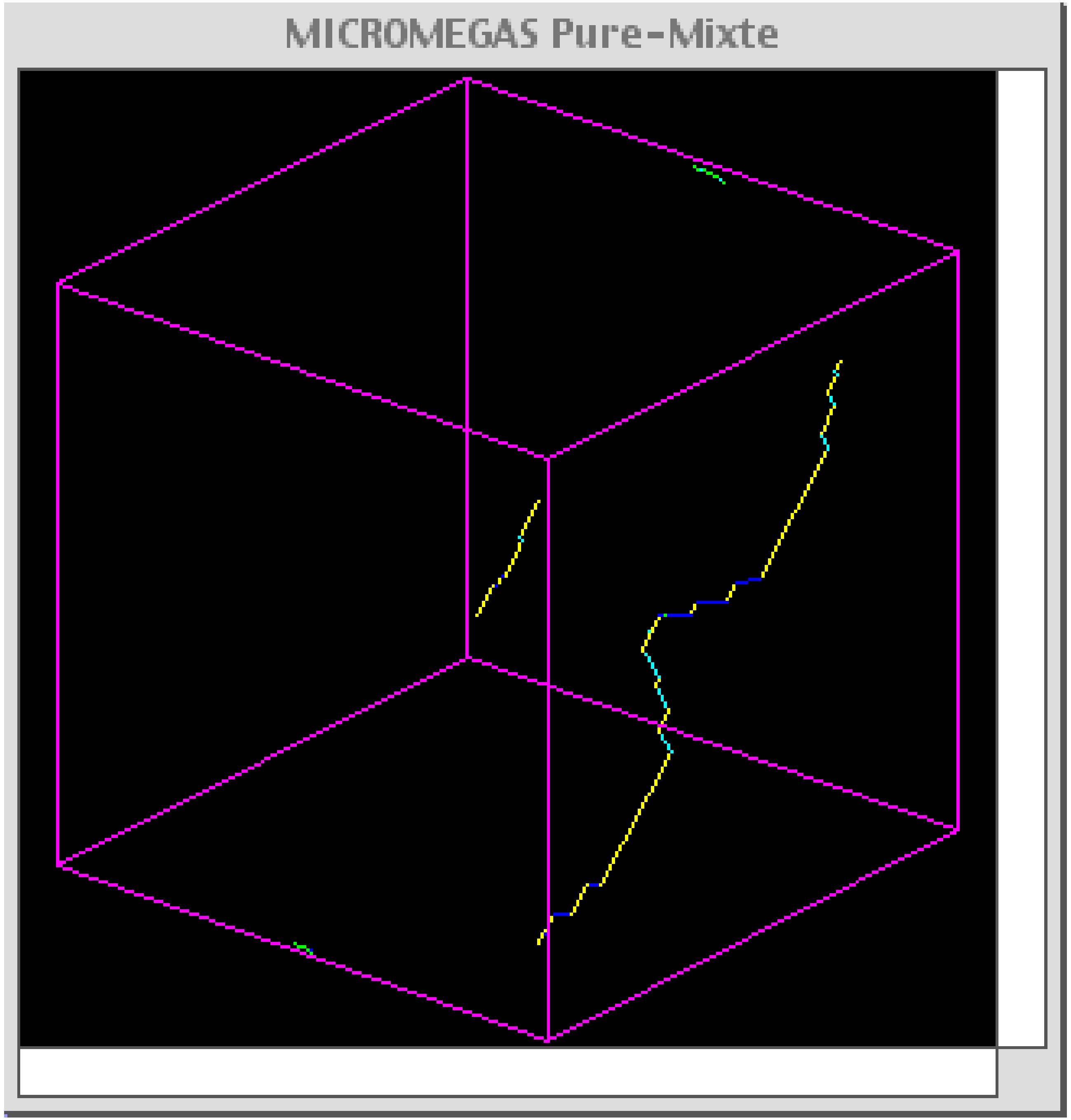

Y
Z
X

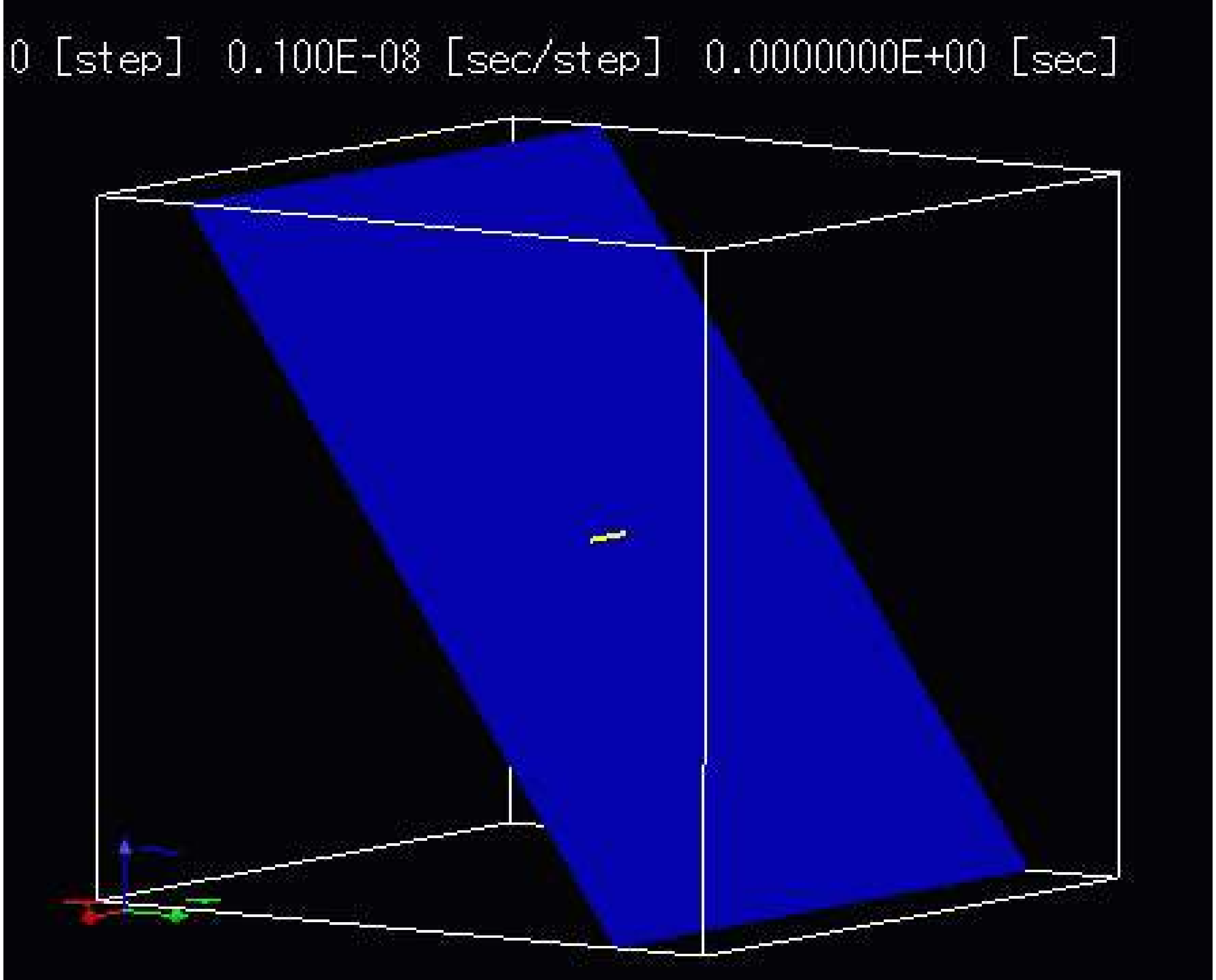


0 [step] 0.100E-08 [sec/step] 0.0000000E+00 [sec]






MICROMEGAS Pure-Mixte



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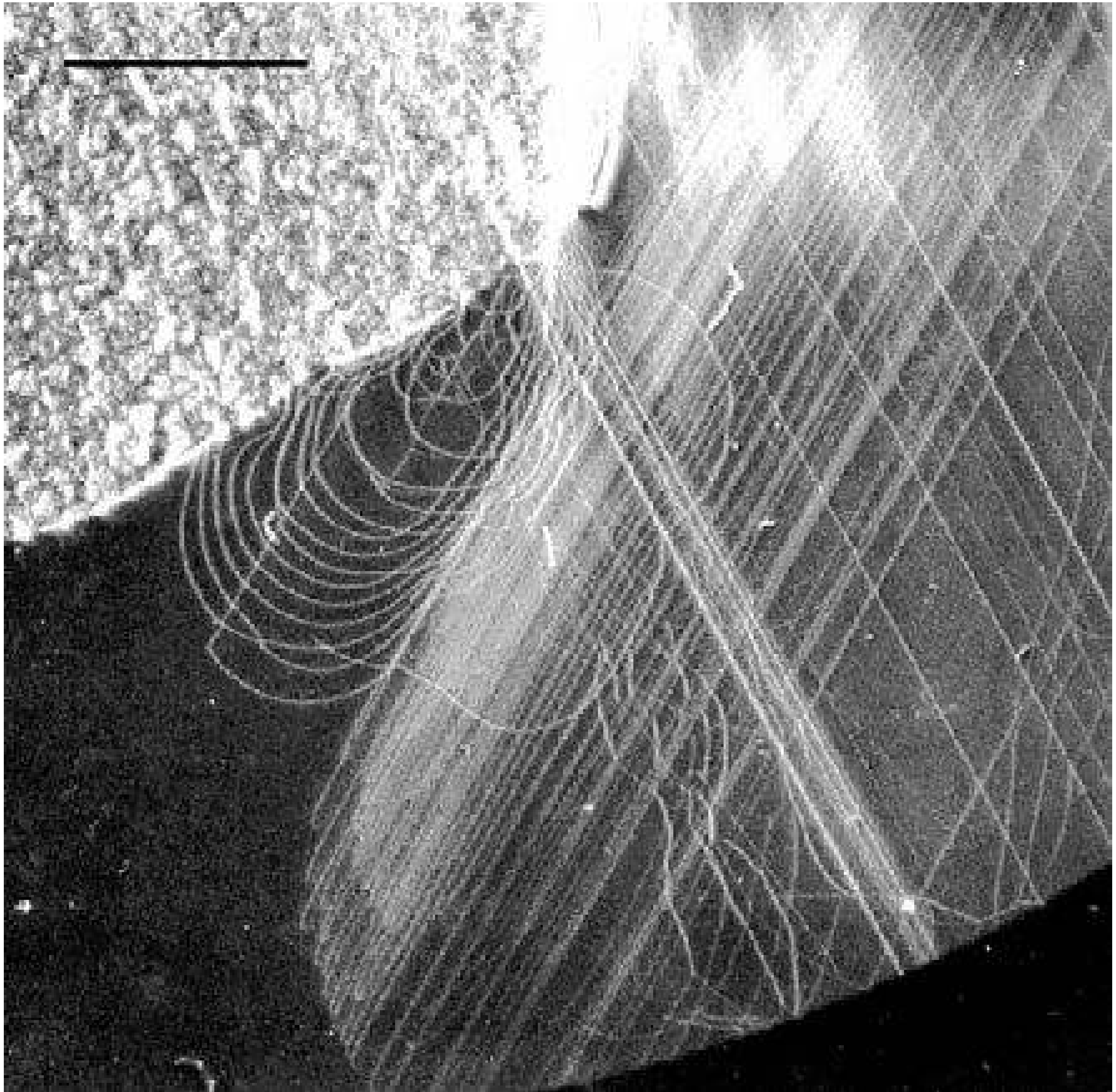
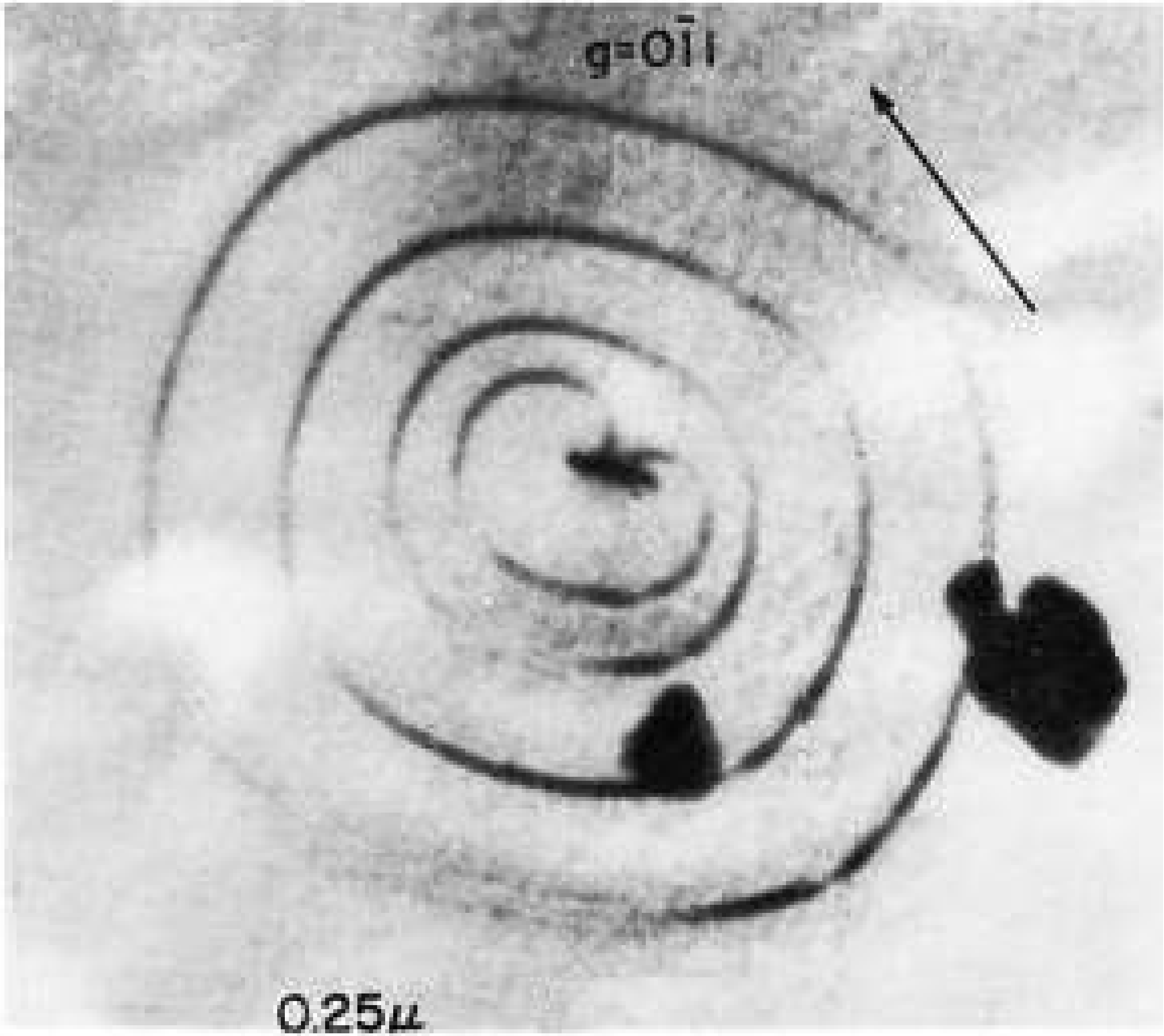




The Frank-Read source can generate dislocations. Electron micrograph of a Frank-Read source (3,30,000 X).

(Adapted from Brittain, J., ''Climb Sources in Beta Prime-NiAl,'' Metallurgical Transactions, Vol. 6A, April 1975.)

Why actual values of shear stress in metals to produce plastic deformation is much lower than theoretical shear stress ?

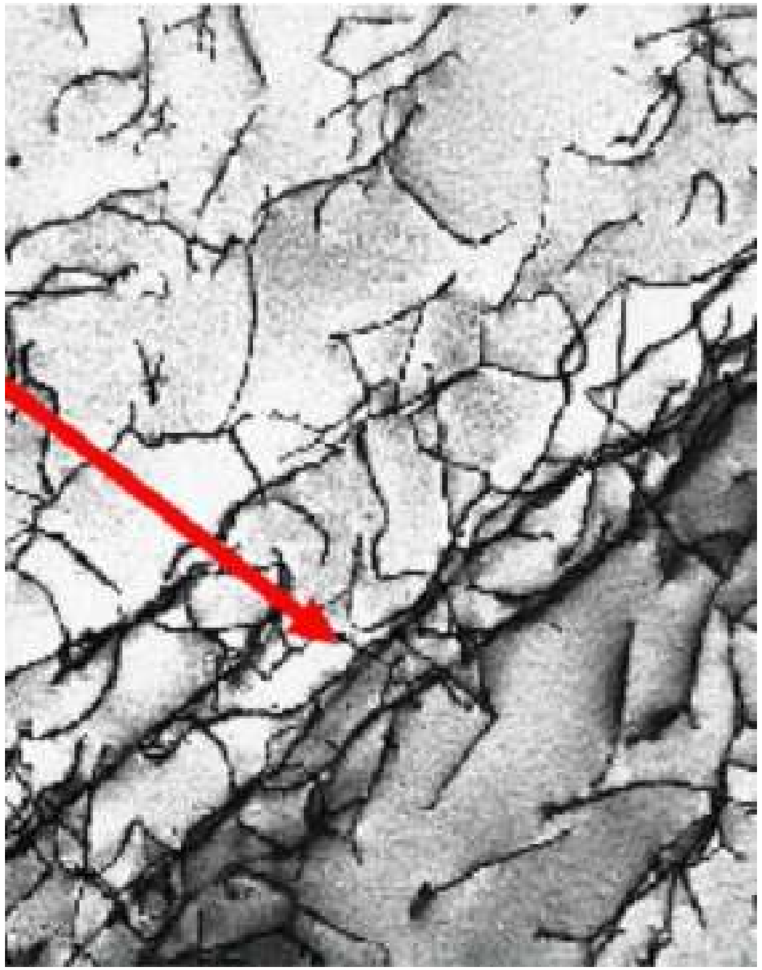
- This difference can be explained by the presence of ***dislocations*** in the lattice.
- Dislocations assist in plastic deformation since it is easier to move the atoms at the dislocations core.
- Weakening of a crystal by the presence of dislocations or increasing dislocation density?
- The movement of dislocations produces a slip step of one Burger vector or one interatomic distance.
- Cumulative movement of dislocations leads to the gross plastic deformation.
- During plastic deformation, dislocation come out the surface and disappear.
- **For example: pure aluminum**
  - **Theoretical shear strength approx. 7000 MPa**
  - **Actual shear strength approx. 40 MPa**

Correlation of dislocation density with strength

- Cold working / strain hardening increases dislocation density.
- Strain hardening – increasing strength of a material with strain
- Strength of a material is inversely proportional to mobility of dislocation
- When dislocation density increase with strain hardening , moving dislocations get interlocked with each other. (**dislocation lines interfere with other dislocation motion).**
- This prevent dislocation movement and strength increase.
- Foreign atoms also block dislocation motion and solution strengthen crystals
- Second phase precipitates block dislocations and further strengthen crystals.

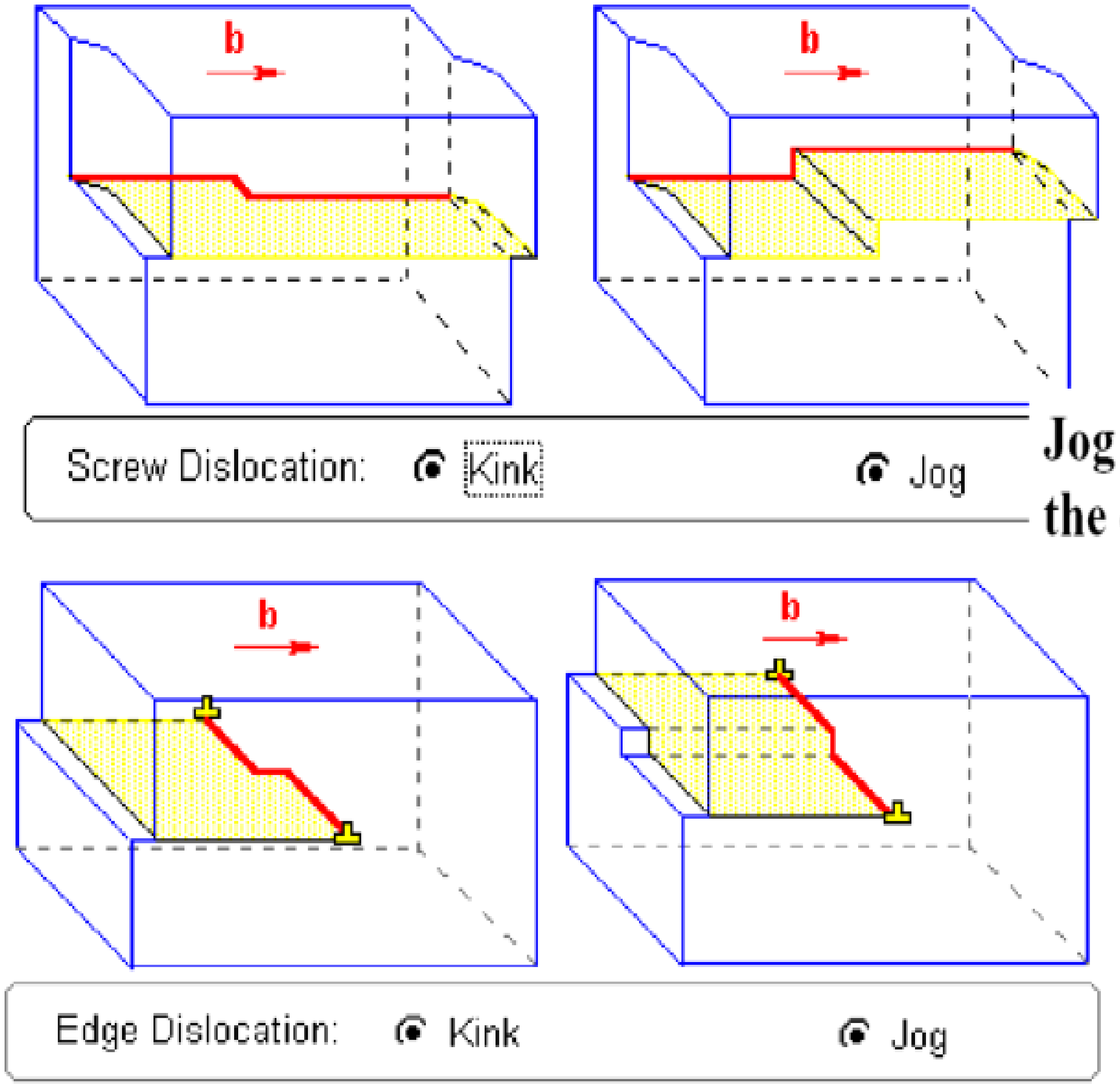
Dislocation Forest

- Movement of dislocation one behind other active slip plane is called Dislocation Forest
- When dislocation forest intersect jogs and kinks are formed which restrict movement of dislocation.
- Intersection of two dislocations results in a sharp break in the dislocation line. These breaks can be of two kinds:
    - A jog is break in dislocation line moving it out of slip plane.
    - A kink is break in dislocation line that remains in slip plane.



Jogs and Kinks (Dislocation-Dislocation Interactions) (Defect in a defect!)

- A straight dislocation line can have a break in it of two types:
- A jog moves it out of the current slip plane *(→ to a parallel one)*
- A kink leaves the dislocation on the slip plane
- The Jog and the Kink can be considered as a defect in a dislocation line *(which itself is a defect → hence these are defects in a defect)*
- Jogs and Kinks can be produced by intersection of straight dislocations
- Two straight dislocation can intersect to leave Jogs and Kinks in the dislocation line.
- These extra segments in a dislocation line cost energy and hence require work done by the external force ⇒ lead to hardening of the material (Additional stress as compared to the stress required to glide the dislocation line is required to form the Jog/Kink)



Jog and kink: a part of the dislocation line

Kinks and Jogs

- A straight dislocation can have a sharp break of a few atomic spacing in length or a short segment that can connect one straight portion of dislocation with other offset by a small distance

- There are two kind of such sharp breaks.

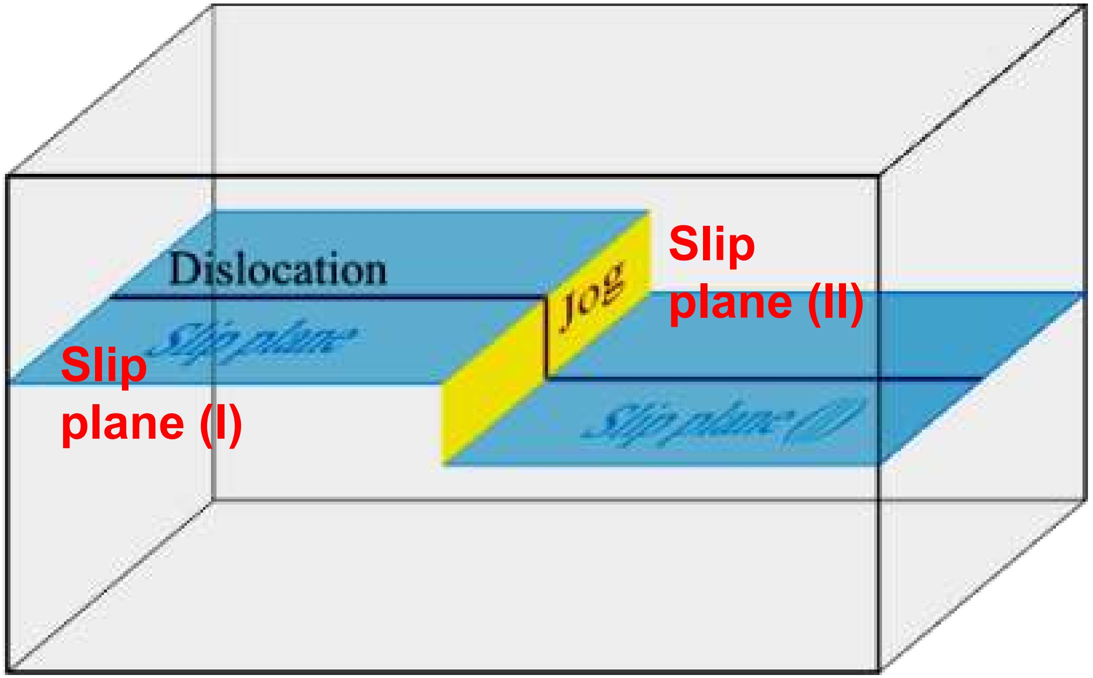
- Kink – connecting segment , if offset part of dislocation line lies in original slip plane

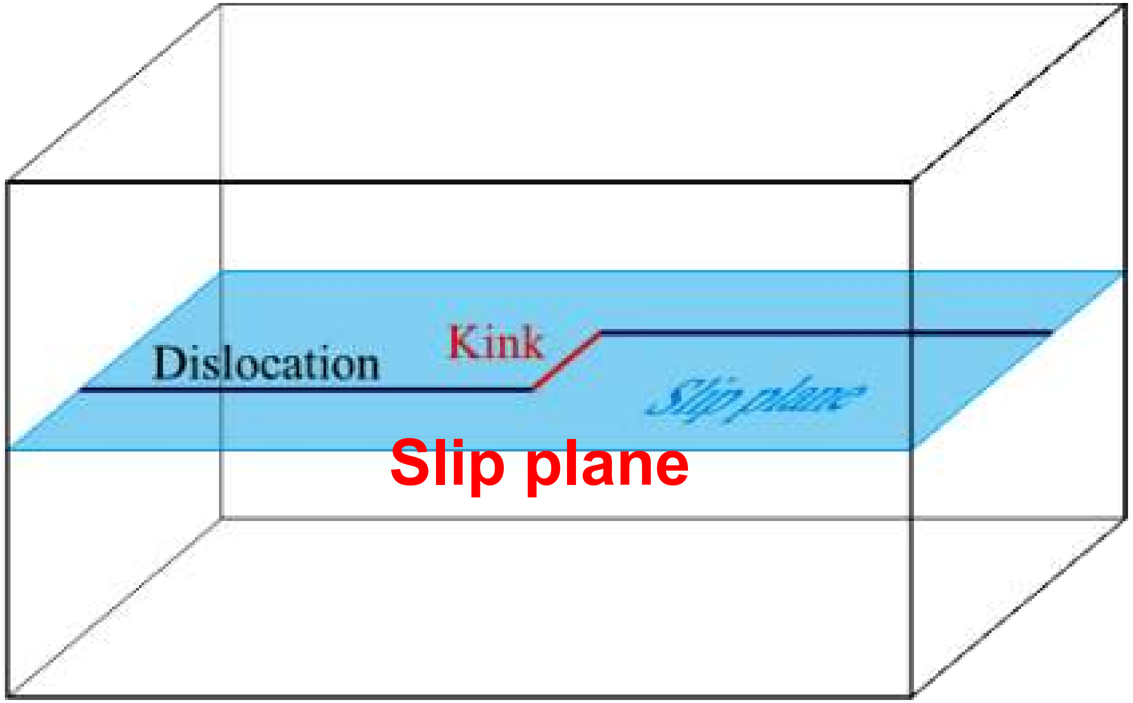
- Jogs- connecting segment if offset part of dislocation line lies not in original plane , but in a parallel slip plane

- Kinks and jogs are formed by the intersection of moving dislocation with other dislocation in the crystal or by the intersection of dislocation forest

- Jog is Edge nature as it is perpendicular to burger vector

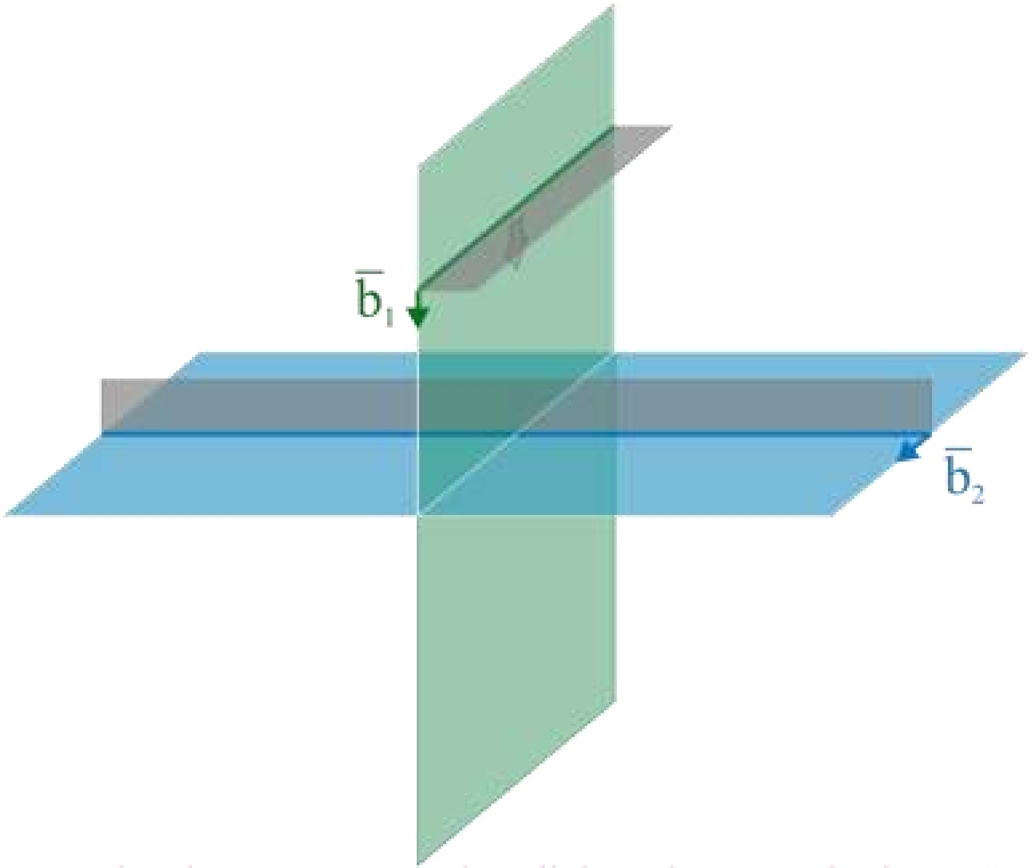
- Kink is Screw nature as it is parallel to burger vector


Dislocation
Jog
Slip plane (II)
Slip plane
Slip plane (I)
Slip plane (II)

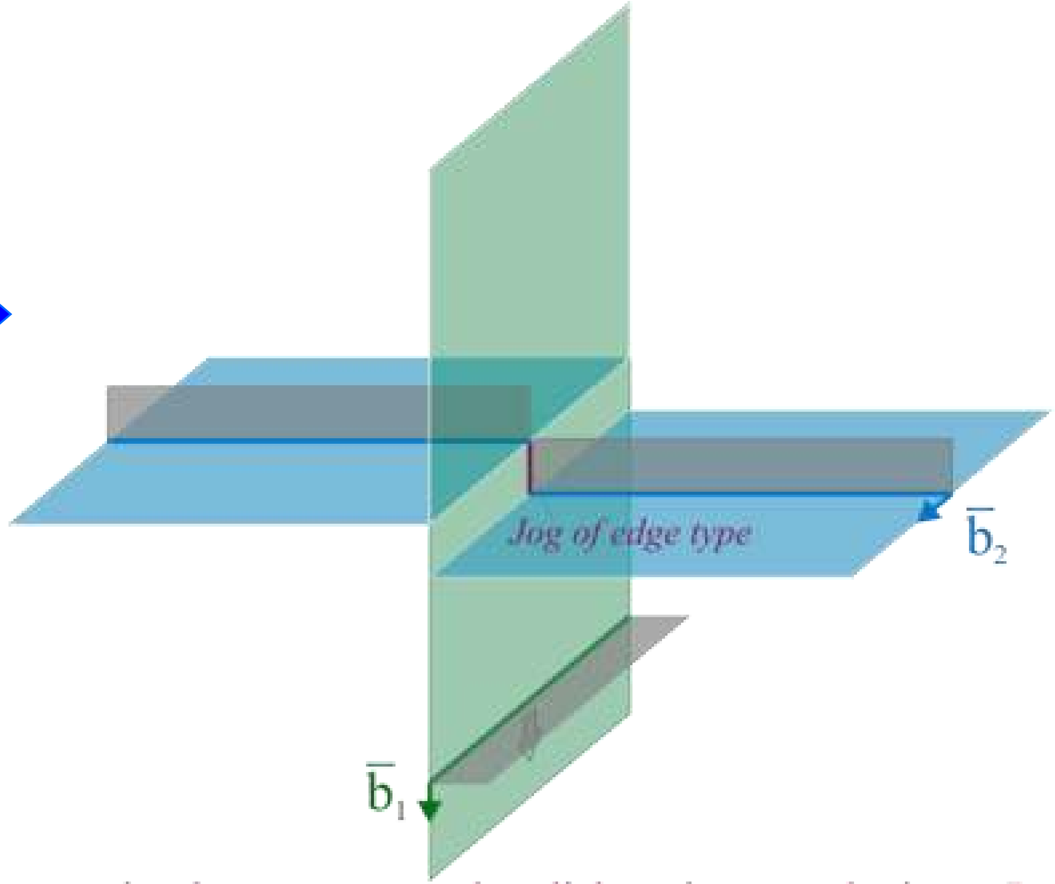

Kink
Dislocation
Slip plane
Slip plane

Edge-Edge Intersection *(Perpendicular Burgers vector)*

- The jog has edge character and can glide *(with Burgers vector = $\boldsymbol{b}_2$)*
- The length of the jog = $\mathbf{b}_1$
- Edge Dislocation-1 *(Burgers vector* $\mathbf{b}_1$*)* → Unaffected as $\mathbf{b}_2$ is || $\mathbf{t}_1$ *(line vector)*
- Edge Dislocation-2 *(Burgers vector* $\mathbf{b}_2$*)* → Jog (Edge character) → Length $|\mathbf{b}_1|$



Intersection between two edge dislocations producing a Jog

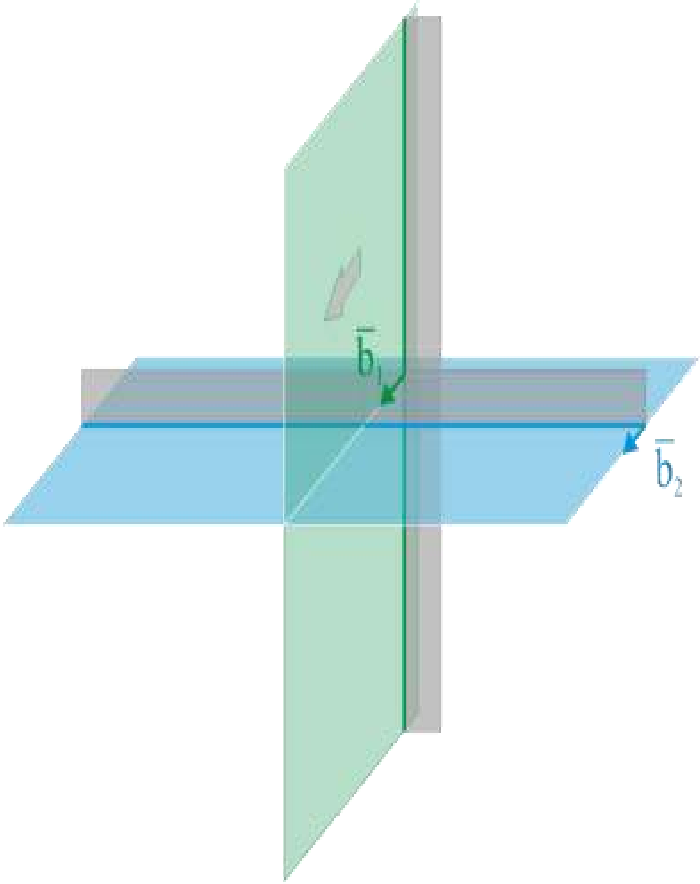


Intersection between two edge dislocations producing a Jog

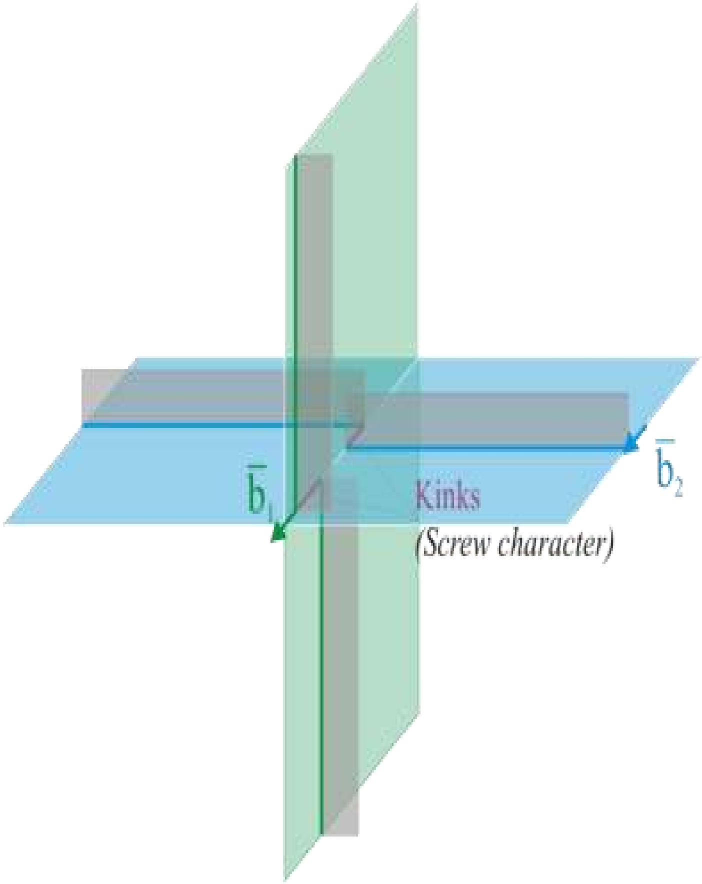
Edge-Edge Intersection

(Parallel Burgers vector)

- Both dislocations are kinked
- Edge Dislocation-1 *(Burgers vector* $\mathbf{b}_1$*)* → Kink (Screw character) → Length $|\mathbf{b}_2|$
- Edge Dislocation-2 *(Burgers vector* $\mathbf{b}_2$*)* → Kink (Screw character) → Length $|\mathbf{b}_1|$
- The kinks can glide



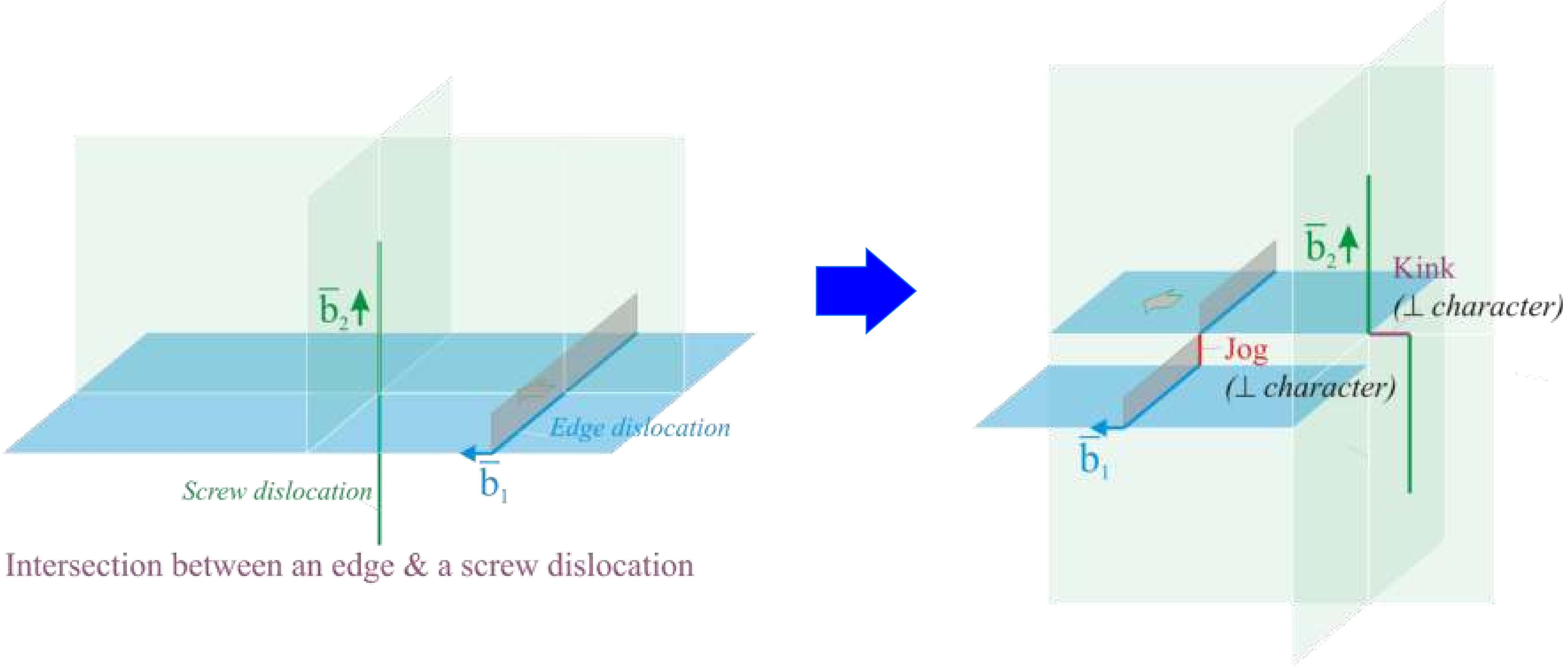
Intersection between two edge dislocations



Intersection between two edge dislocations

Edge-Screw Intersection *(Perpendicular Burgers vector)*

- Edge Dislocation *(Burgers vector* $\mathbf{b}_1$*)* → Jog (Edge Character) → Length $|\mathbf{b}_2|$
- Screw Dislocation *(Burgers vector* $\mathbf{b}_2$*)* → Kink (Edge Character) → Length $|\mathbf{b}_1|$



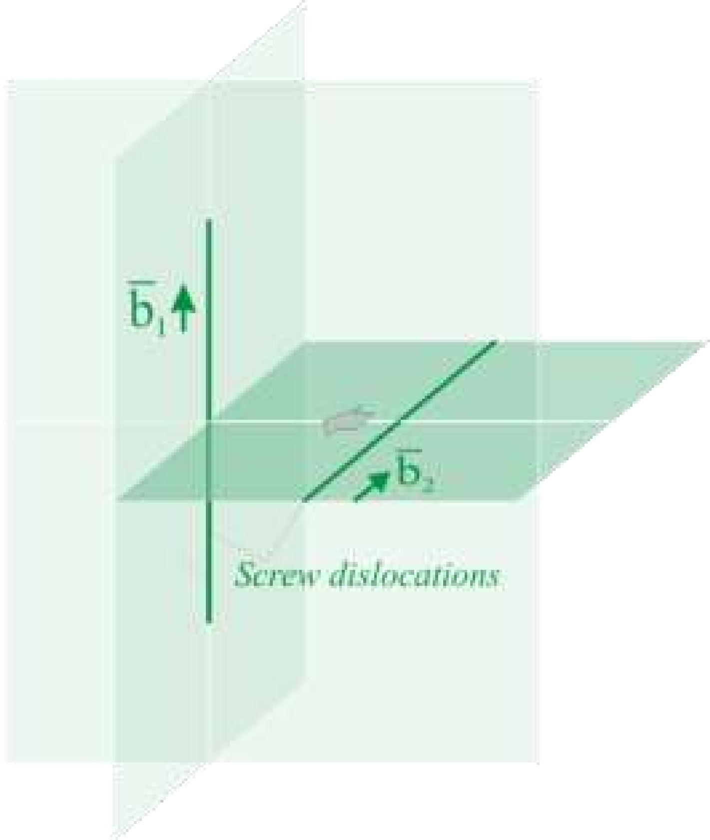
Intersection between an edge & a screw dislocation

Screw -Screw Intersection

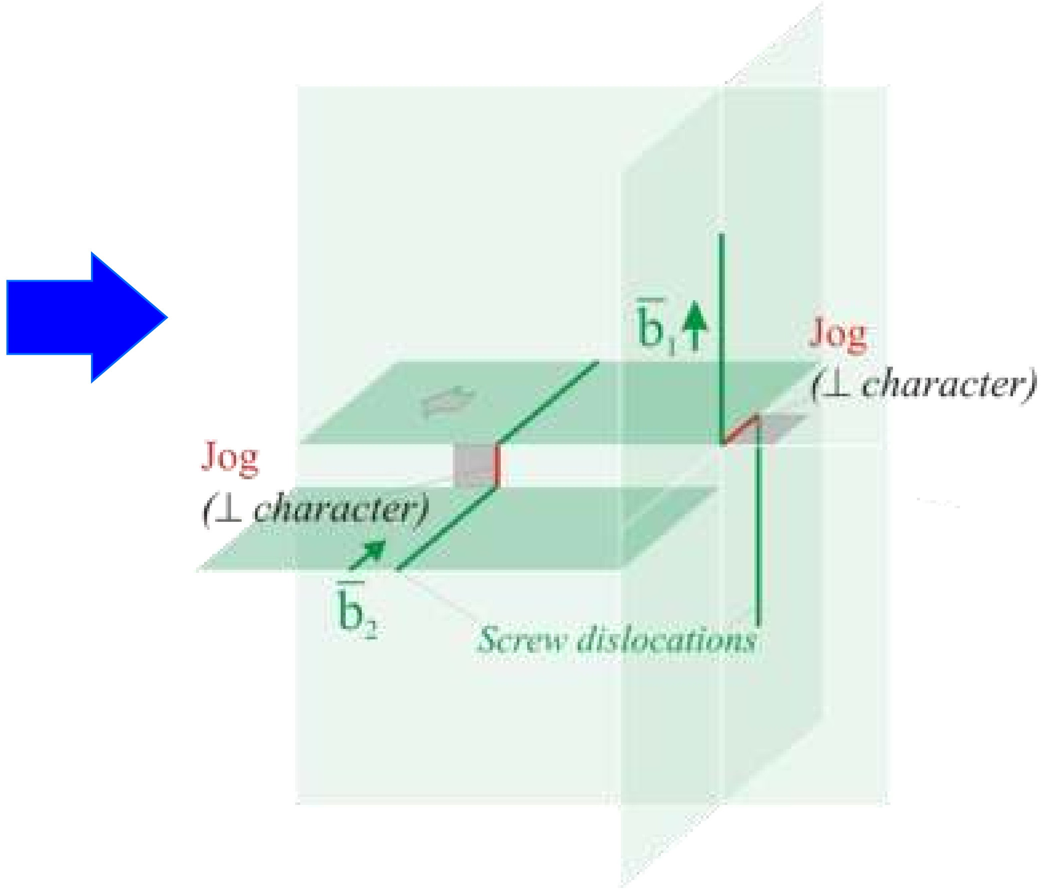
Perpendicular Burgers vector

- Important from plastic deformation point of view
- Screw Dislocation *(Burgers vector* $\mathbf{b}_1$*)* → Jog (Edge Character) → Length $\mathbf{b}_2$
- Screw Dislocation *(Burgers vector* $\mathbf{b}_2$*)* → Jog (Edge Character) → Length $\mathbf{b}_1$
- Both the jogs are non conservative

  (i.e. cannot move with the dislocations by glide)



Intersection between two screw dislocations



Strength in nano-materials

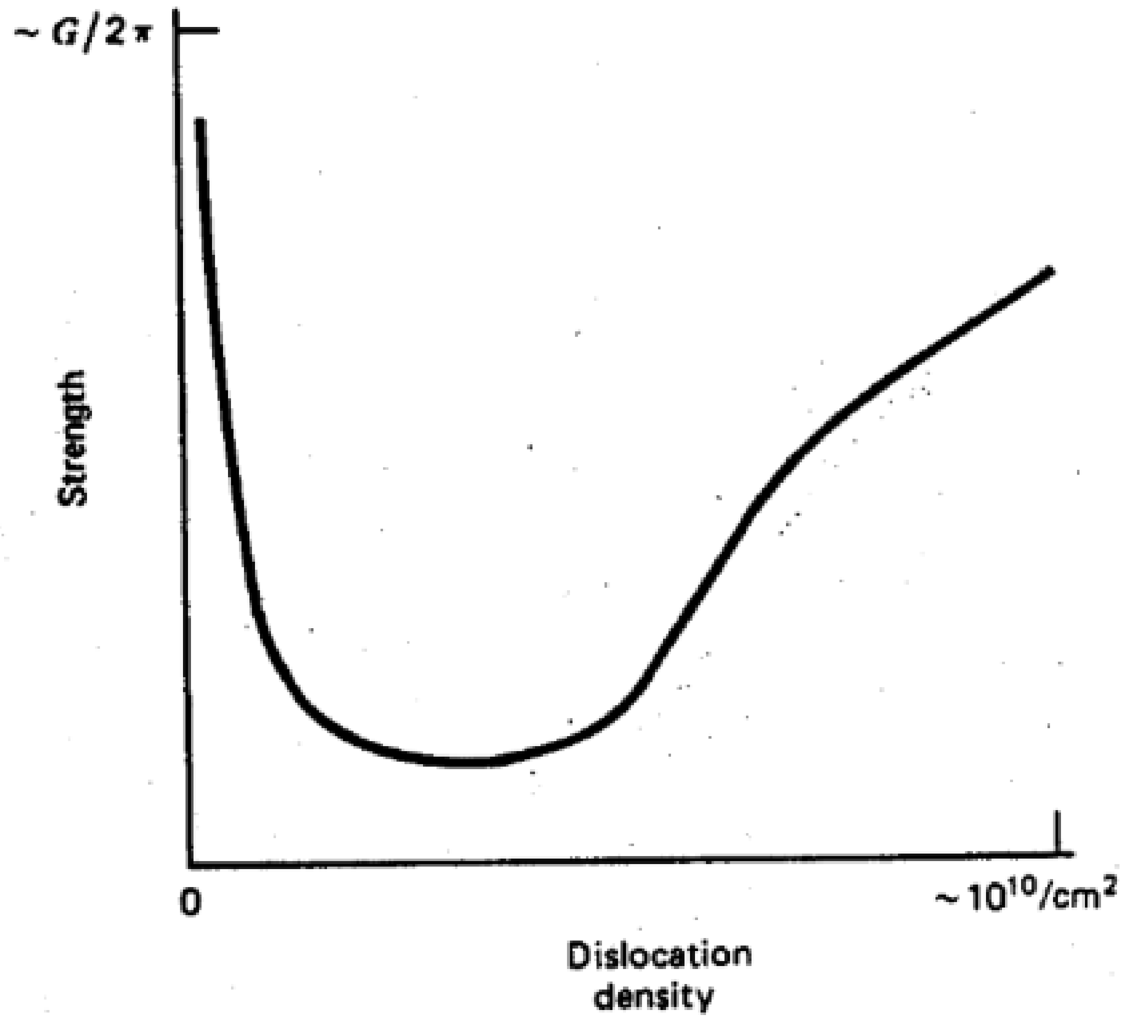
- Dislocation density is lower in nano material
- In nanocrystal one or more free surfaces may be in proximity to the dislocation.
- As the dislocation is positioned closer and closer to a free surface. The dislocation can spontaneously leave the crystal without the application of any external stresses
- In nanocrystals the proximity of multiple free surfaces may lead to all dislocations leaving the crystal when: (for all dislocations)
- Hence, nanocrystals can become completely dislocation free.
- For single crystals of Al and Ni this size is the order of a few tens of nanometers.
- Thus the strength of such a nanocrystal may approach the theoretical strength of the crystal.

- Inverse Hall-Petch effect. It is well established that decreasing the grain size results in an increased hardness and strength as grain boundaries pose an impediment to dislocation motion (dislocation 'pile- up mechanism- the usually accepted mechanism!).
- When grain size reduces to tens of nanometers (< 15 nm) the grain is not able to support a dislocation pile-up. Hence the trend of increasing hardness/strength with a decrease in grain size is broken in the nanocrystalline materials.
- The are even reports in literature of decreasing strength with decreasing grain size at very small grain sizes (< 5 nm).
- Drastic change in properties may be observed on approaching the nanoscale
- Example, Fracture strength of Ni has shown to increase from 100 MPa to 900 MPa once the nanometer-sized grains are obtained.

Nanocrystalline Metals

- Average grain diameter < 100 nm
- Results in high strength and hardness, and Superplasticity
- If grain diameter reduces from 10 microns to 10 nm, yield strength of copper increases 31 times.
- Very difficult to produce nanocrystalline metals.
- If $d < 5$ nm, elastic modulus drops as more atoms are in grain boundary
- Hall-Petch equation is invalid in lower nanocrystalline range.
- Negative Hall-Petch effect might take place

Strength vs. Dislocation Density



About Ductility?

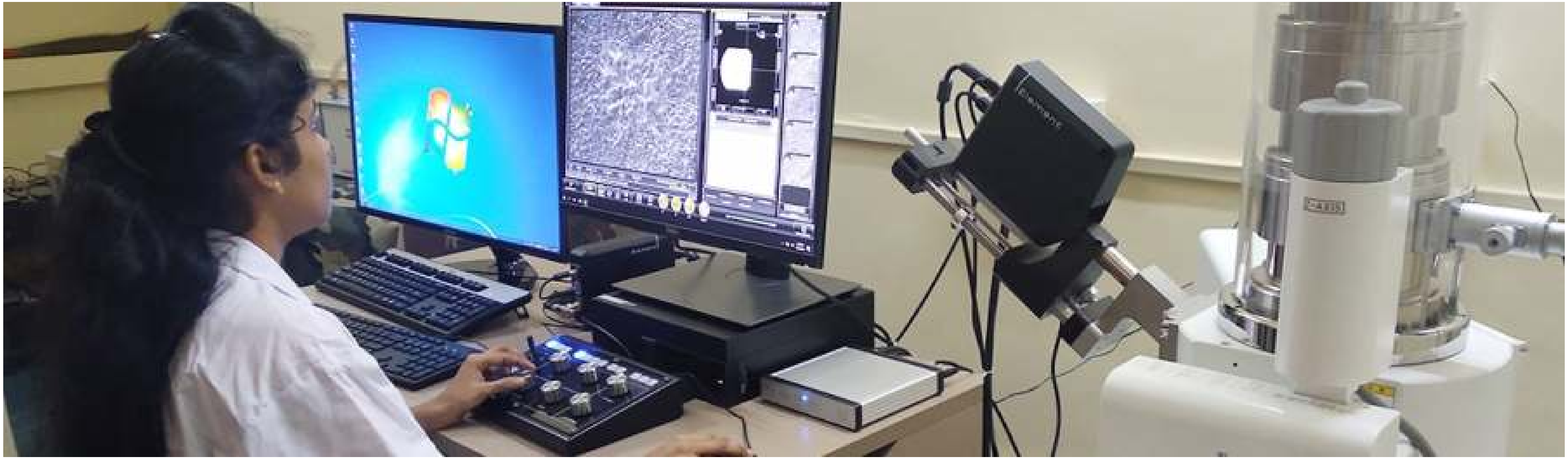
- As we block dislocations, and the material gets stronger, we lose the capacity for plastic deformation. In other words, the ductility is decreased.

- AS WE BLOCK DISLOCATIONS, STRENGTH INCREASES AND DUCTILITY DECREASES.

- Exception: Fine grain size gives strength without significant decrease in ductility.

Microstructure Determination

- Study of microstructure of metals by microscopic examination using optical or electron microscopes – Metallography
- Reveal the structure of grains, grain boundaries, line and surface defects etc.
- Their effect on material behaviour can also be studied
- Specimen preparation



Surface Preparation

Various stages of Surface preparation are,

- *Selection & Cutting of specimen*
- *Rough Grinding*
- *Intermediate and Fine grinding*
- *Polishing*
- *Etching*

Selection & Cutting of specimen

- True representative of the material being studied
- Specimen should be from the regions of specific interest
- Cut the specimen using a saw or abrasive wheel
- Ensure, specimen is not heated up
- Specimen of approximately 10 to 15 mm diameter or square will be convenient
- For smaller sized specimens mounding is done on thermoplastic resins *e.g.. Bakelite mounting*

Specimen moulding machine

Moulded specimens

Rough Grinding

- To make the surface absolutely flat
- Ensure, specimen is not heated up
- Wash – to remove coarse filings and abrasive particles
- Using file , rotating grinding wheel or motor driven belt grinder

Fine grinding

- Intermediate and Fine grinding
- Intermediate- Done using sets of emery papers in sequence of grit size as 220 , 320 , 400 , 600
- Sequence of emery papers of progressively finer abrasive grit
- Rubbing against emery paper
- One direction Grinding process
- OR m/c grinding
- Wash
- Fine grinding – fine grit emery papers (1/0, 2/0, 3/0, 4/0)
- Shining and scratch free surface

Polishing

- Fine grinding of specimen would leave series of very small parallel groves
- Polishing removes this grooves by burnishing operation
- Specimen surface are polished by means of rotating cloth pad impregnated with suitable polishing medium
- Specimen is held against rotating cloth pad with sufficient pressure.
- Harder specimens (iron, steel) – 2 stage polishing
- 1st stage using polishing agents with particle size 6 microns
- 2nd with 0.5 to 1 microns

Alumina polishing *- polishing medium is alumina paste*

Diamond polishing *- polishing medium is diamond paste*

Etching

- The specimen surface must first be ground and polished to a smooth and mirror like finish.
- The microstructure is revealed by a surface treatment using an appropriate chemical reagent in a procedure termed *etching*.
- The chemical reactivity of the grains depends on crystallographic orientation.
- Since atoms along grain boundary regions are more chemically active, they dissolve at a greater rate than those within the grains
- Enchants are chosen depending on material composition.
- An etchant is used to dissolve this layer and remove it
- Cleaning before etching and drying
- Dip and agitate the specimen in etching reagent for a few to several seconds
- Quickly washed in running water

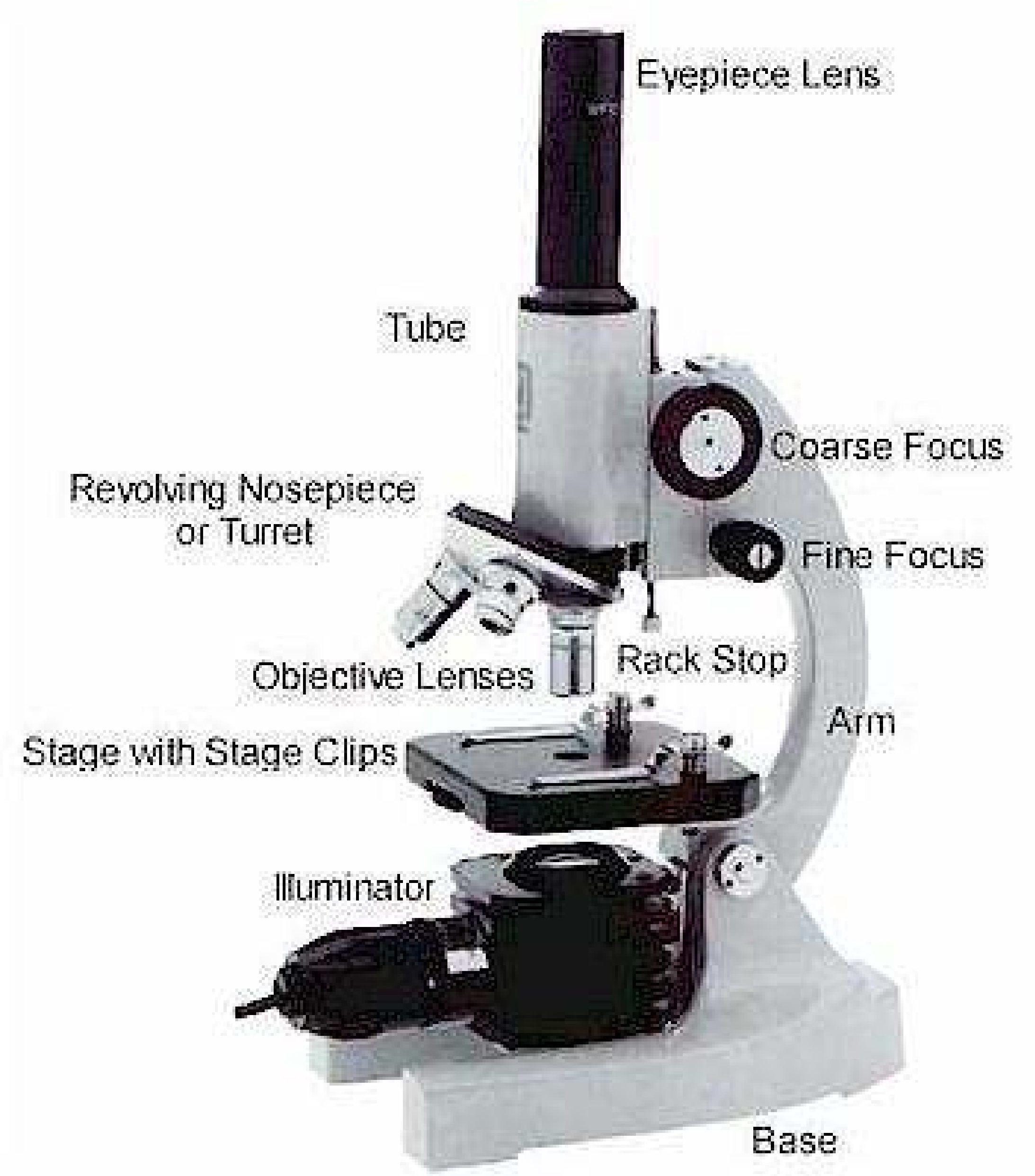
- Examined with naked eye
  Bright appearance is lost and become uniformly dull
  If not successful, repolishing and etching again
  Examined immediately before oxidation

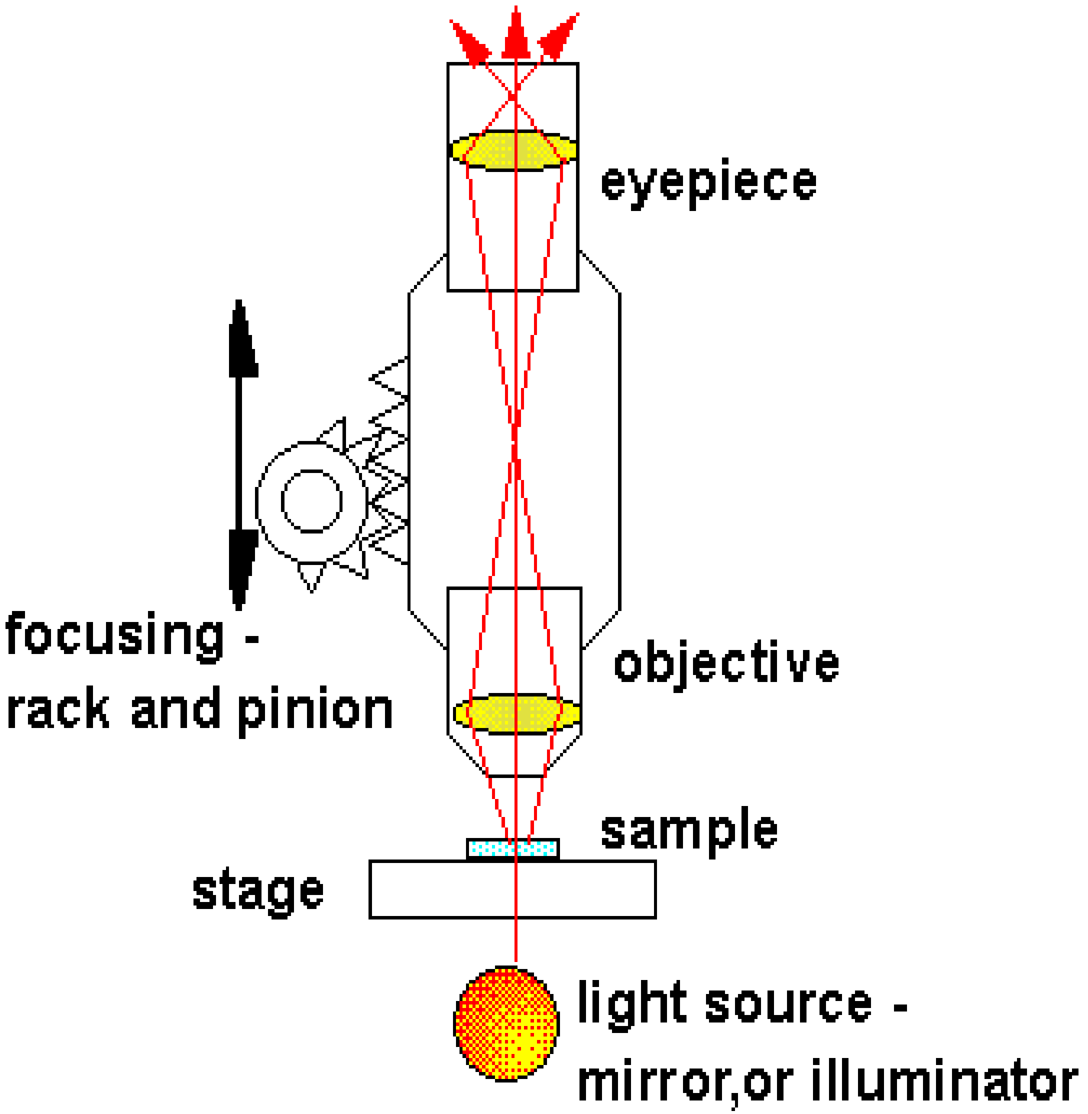
Etchant	Composition	Use	Etching time
Nital	2% nitric acid 98% methyl alcohol	Ferrous materials	30s to 1 min.
Picral	5% picric acid 95% methyl alcohol	High carbon steels , Cast Iron	10s to 30s
Keller's Reagent	1ml HF 1.5ml HCl 2.5ml HNO_3 95ml water	Duralumin alloys	10s to 20s
Dilute Hydrofluoric acid	0.5 ml HF 99.5 ml water	Aluminium alloys	30s to 60s

Optical Microscopy

- Light microscope is used to study the microstructure
- Optical and illumination systems are its basic elements
- Careful surface preparations are necessary to reveal the important details of the microstructure
- Light microscope must be used in a reflecting mode.
- Contrasts in the image produced result from *differences in reflectivity of the various regions* of the microstructure.
- 3 optical systems
  - illuminating system
  - objective lens
  - eye piece
- Max: magnification 1000x

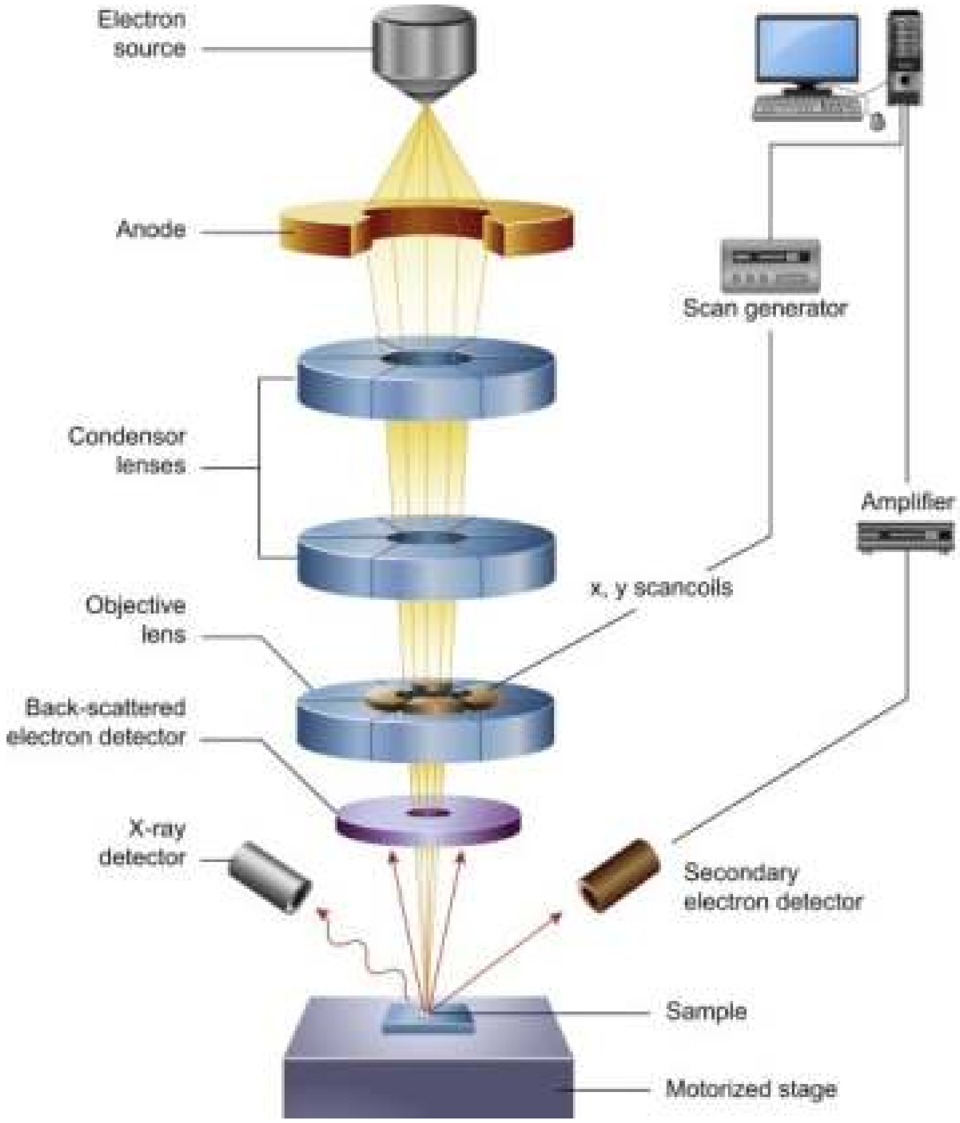
Light Microscope





Electron Microscopy

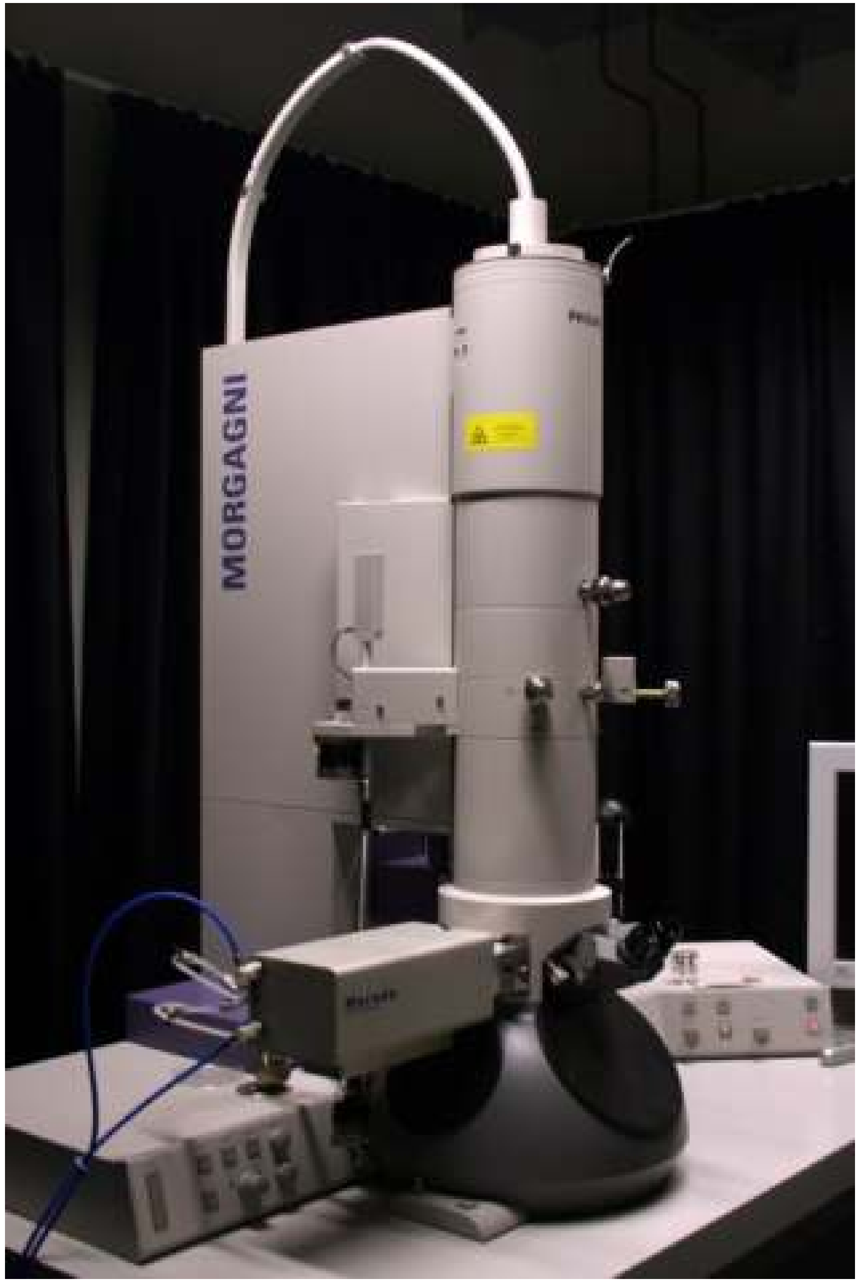
- The upper limit to the magnification possible with an optical microscope is approximately 2000 times.
- Electron microscope is used for higher magnification.
- An image of the structure under investigation is formed using beams of electrons instead of light radiation.
- High magnifications and resolving powers of these microscopes are consequences of the short wavelengths of electron beams.
- Both transmission and reflection beam modes of operation are possible for electron microscopes.
- Specimens need not be polished or etched but should be electrically conductive

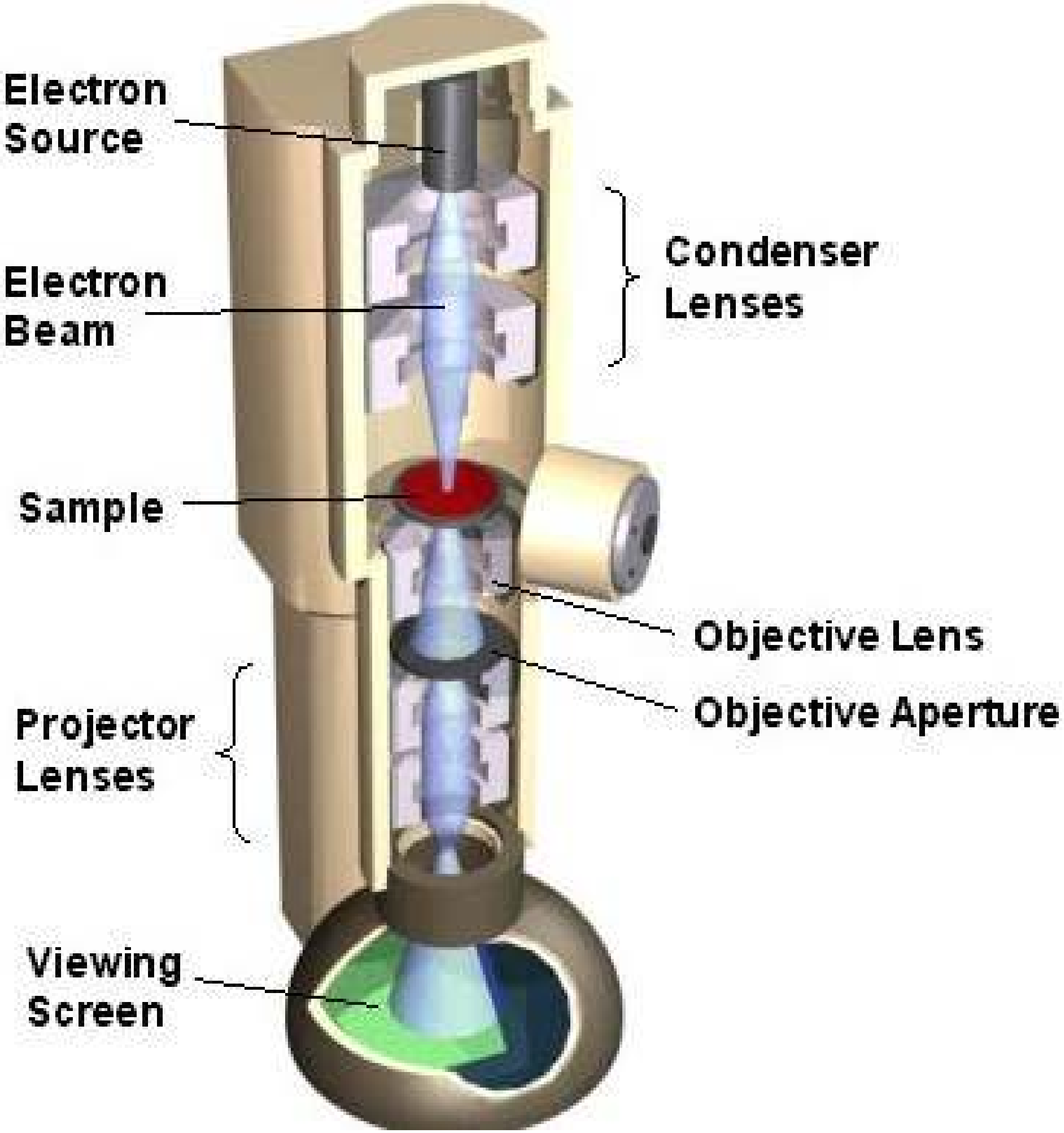

Electron source
Anode
Condensor lenses
Objective lens
Back-scattered electron detector
X-ray detector
Scan generator
x, y scancoils
Amplifier
Secondary electron detector
Sample
Motorized stage

Transmission Electron Microscopy (TEM)

- The image seen with a **transmission electron microscope (TEM)** is formed by an electron beam that passes through the specimen.
- Details of internal microstructural features are accessible to observation
- Contrast in the image are produced by differences in beam scattering
- Since solid materials are highly absorptive to electron beams, a specimen to be examined must be prepared in the form of a very thin foil.

- The transmitted beam is projected onto a fluorescent screen or a photographic film so that the image may be viewed.
- Magnifications up to 20,00,000 X are passible
- TEM frequently utilized in the study of dislocations.

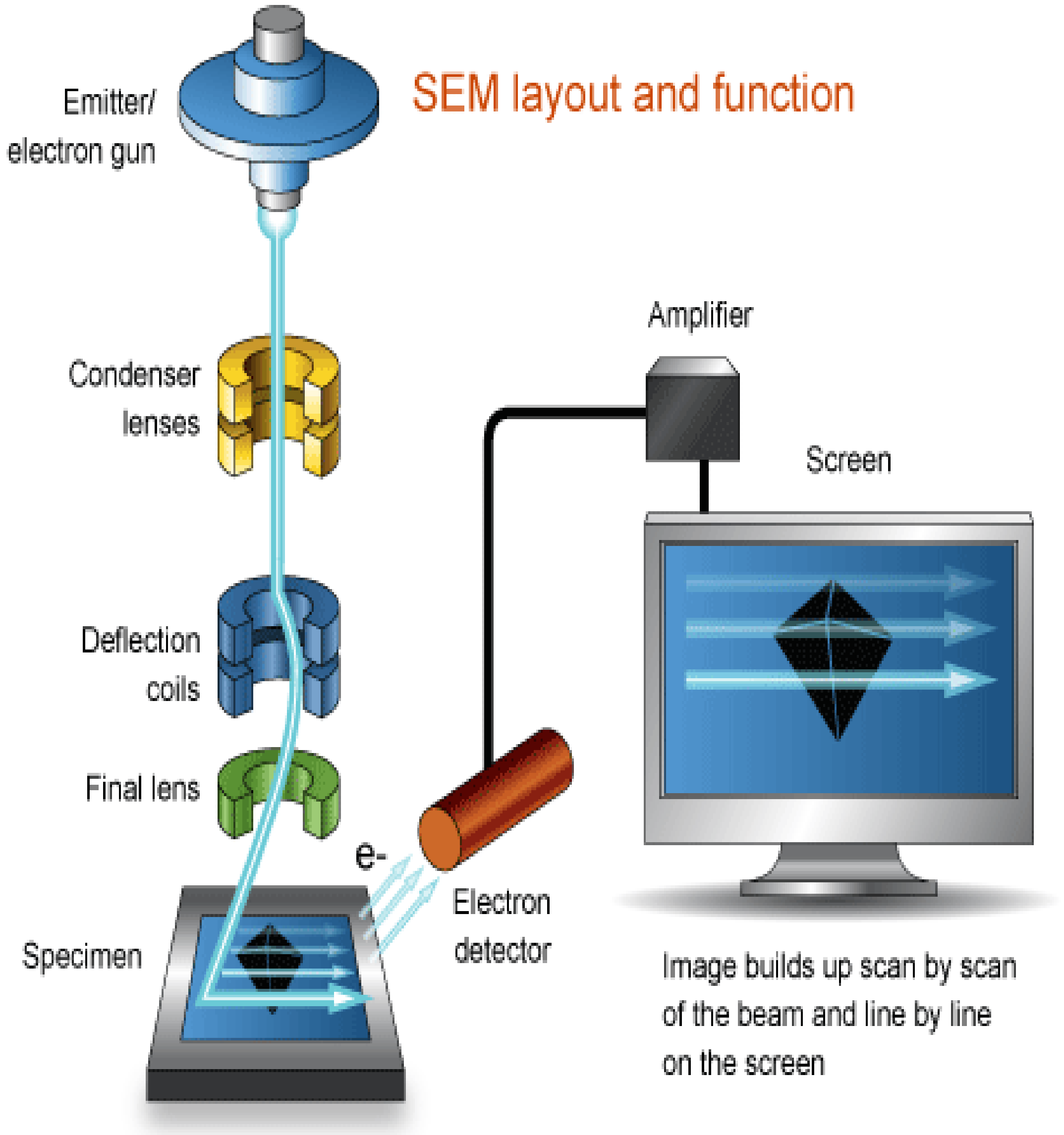

MORGAGNI


Electron Source
Condenser Lenses
Electron Beam
Sample
Objective Lens
Objective Aperture
Projector Lenses
Viewing Screen

Scanning Electron Microscopy

- The surface of a specimen to be examined is scanned with an electron beam, and the reflected (or back-scattered) beam of electrons is collected
- Collected beam is displayed on a cathode ray tube (similar to a CRT television screen)
- The surface may or may not be polished and etched, but it must be electrically conductive
- a very thin metallic surface coating must be applied to nonconductive materials
- Magnifications ranging from 10 to in excess of 50,000 times are possible


HITACHI
S-3000N


SEM layout and function
Emitter/ electron gun
Condenser lenses
Deflection coils
Final lens
e-
Specimen
Electron detector
Amplifier
Screen
Image builds up scan by scan of the beam and line by line on the screen

Sr. No.	SCANNING ELECTRON MICROSCOPY (SEM)	TRANSMISSION ELECTRON MICROSCOPY (TEM)
1	SEM provides information on the sample's surface and its composition. SEMs use a specific set of coils to scan the beam in a raster-like pattern and collect the scattered electrons.	TEM use the transmitted electrons; the electrons which are passing through the sample before they are collected. So, TEM offers invaluable information on the inner structure of the sample, such as crystal structure, morphology and stress state information.
2	SEM resolution is limited to ~0.5 nm.	TEM has resolution of even less than 50 pm.
3	If you want to get information on the surface of your sample, like roughness or contamination detection, then you should choose a SEM.	If you would like to know what the crystal structure of your sample is, or if you want to look for possible structural defects or impurities, then using a TEM is the only way to do so.

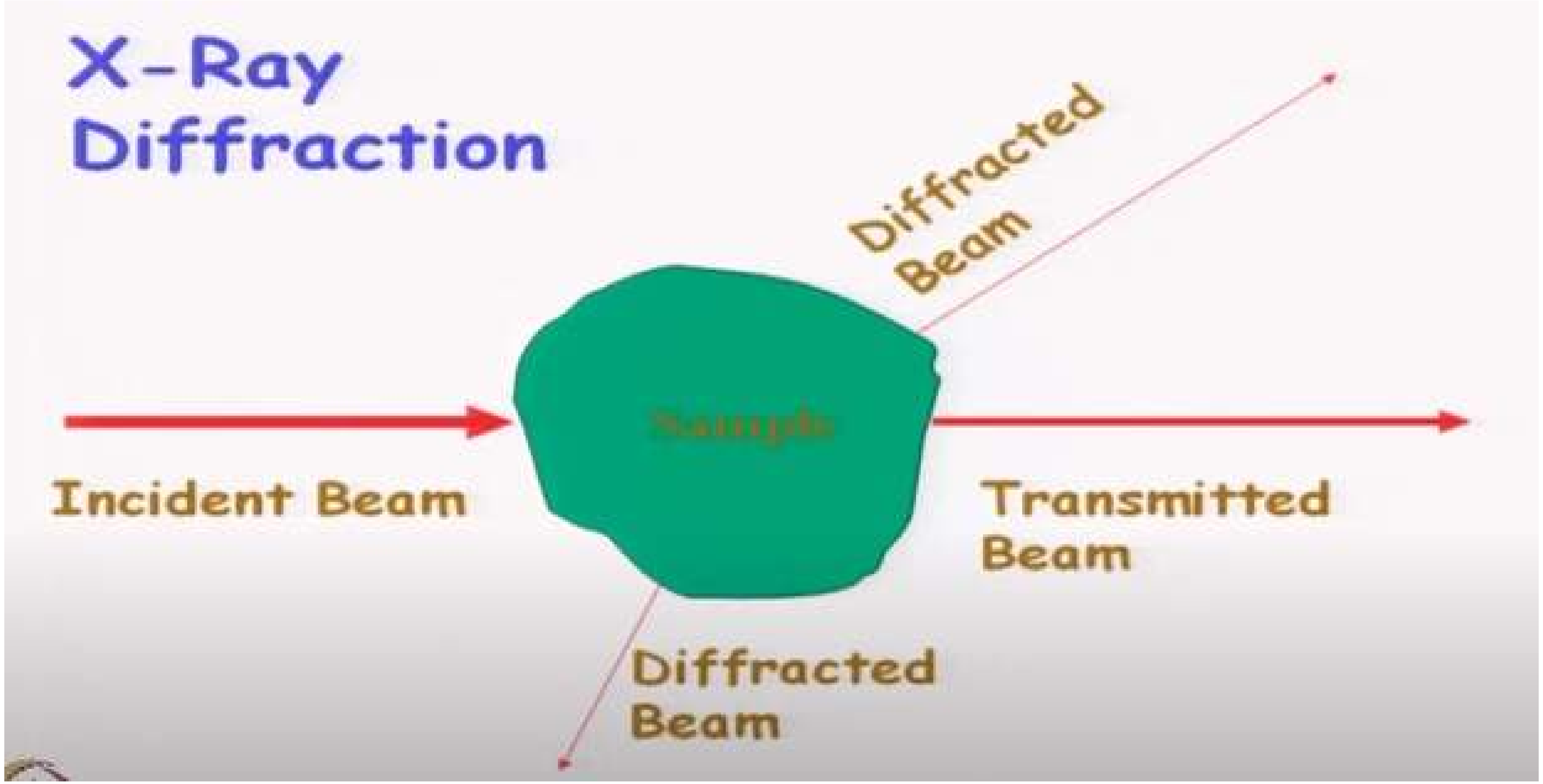
Sr. No.	SCANNING ELECTRON MICROSCOPY (SEM)	TRANSMISSION ELECTRON MICROSCOPY (TEM)
4	SEMs provide a 3D image of the surface of the sample.	TEM images are 2D projections of the sample, which in some cases makes the interpretation of the results more difficult for the operator.
5	SEM imaging there is no specific requirement of sample preparation.	Due to the requirement for transmitted electrons, TEM samples must be very thin, generally below 150 nm, and in cases that high-resolution imaging is required, even below 30 nm.
6	SEM samples require little or no effort for sample preparation and can be directly imaged by mounting them on an aluminum stub.	TEM sample preparation is a quite complex and tedious procedure that only trained and experienced users can follow successfully. The samples need to be very thin, as flat as possible, and the preparation technique should not induce any artefacts (such as precipitates or amorphisation) to the sample. Many methods have been developed, including electro polishing, mechanical polishing and focused ion beam milling. Dedicated grids and holders are used to mount the TEM samples.

Sr. No.	SCANNING ELECTRON MICROSCOPY (SEM)	TRANSMISSION ELECTRON MICROSCOPY (TEM)
7	SEMs usually use acceleration voltages up to 30 kV.	TEM uses it in the range of 60 – 300 kV.
8	The magnifications for the SEM is limited up to 1-2 million times.	The magnifications that TEMs is much higher compared to SEMs. TEM users can magnify their samples by more than 50 million times,
9	However, the maximum Field of View (FOV) that SEMs can achieve is far larger than TEMs, Similarly, the depth of field of SEM systems are much higher than in TEM systems.	Users can only use to image a very small part of their sample.

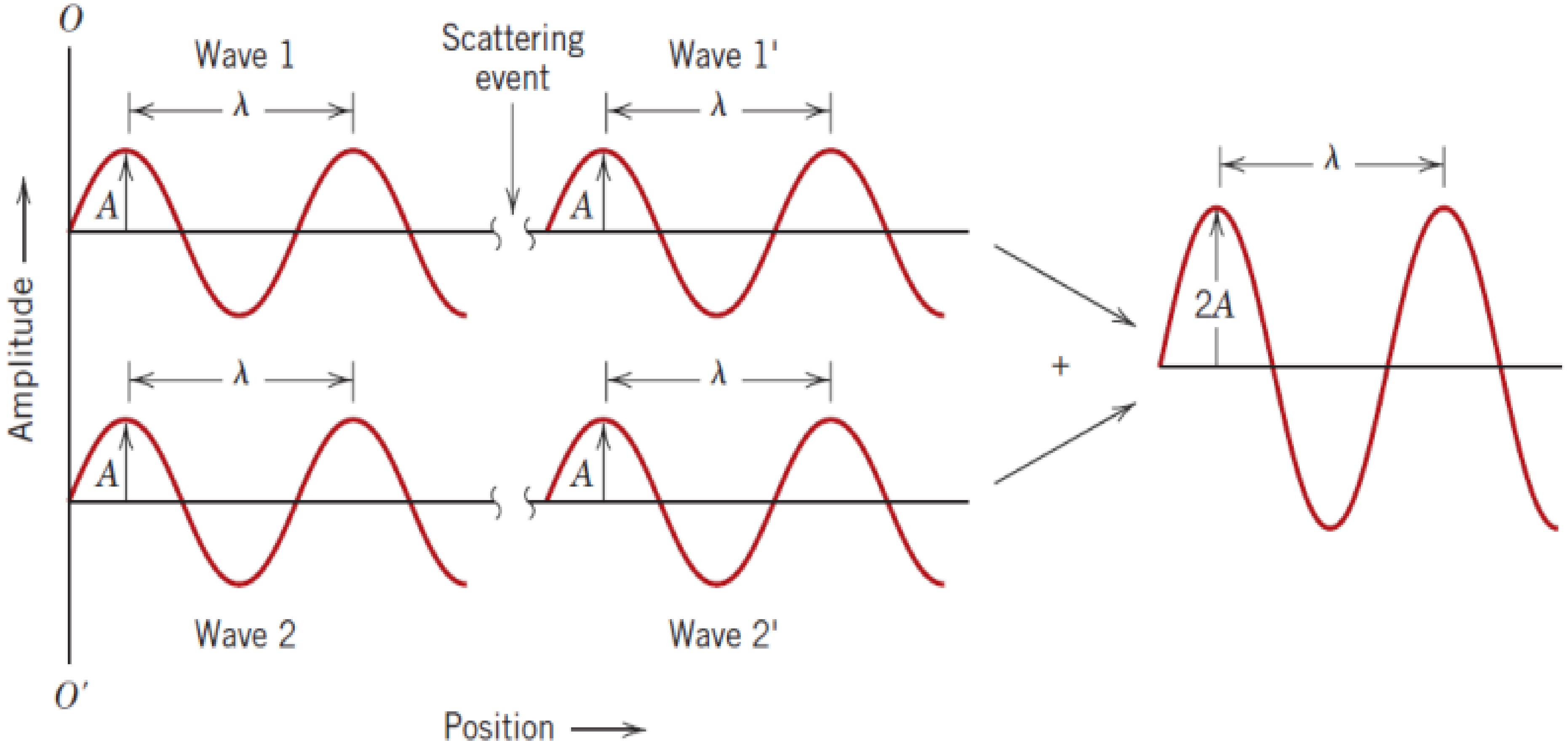
Sr. No.	SCANNING ELECTRON MICROSCOPY (SEM)	TRANSMISSION ELECTRON MICROSCOPY (TEM)
10	In addition, the way images are created are different in the two systems. In SEMs, samples are positioned at the bottom of the electron column and the scattered electrons (back-scattered or secondary) are captured by electron detectors. Photomultipliers are then used to convert this signal into a voltage signal, which is amplified and gives rise to the image on a PC screen.	In a TEM microscope, the sample is located in the middle of the column. The transmitted electrons pass through it, and through a series of lenses below the sample (intermediate and projector lenses). An image is directly shown on a fluorescent screen or via a charge-coupled device (CCD) camera, onto a PC screen.

Sr. No.	SCANNING ELECTRON MICROSCOPY (SEM)	TRANSMISSION ELECTRON MICROSCOPY (TEM)
11	Relatively simple to operate	Generally, TEMs are more complex to operate. TEM users require intensive training before being able to operate them. Special procedures need to be performed before every use, with several steps included that ensure that the electron beam is perfectly aligned.
12	Relatively simple	TEMs may enable much more resolving power and versatility to the user, but they are much more expensive and larger than SEMs and require more effort in order to acquire and interpret results.

X-RAY DIFFRACTION:
DETERMINATION OF CRYSTAL STRUCTURES

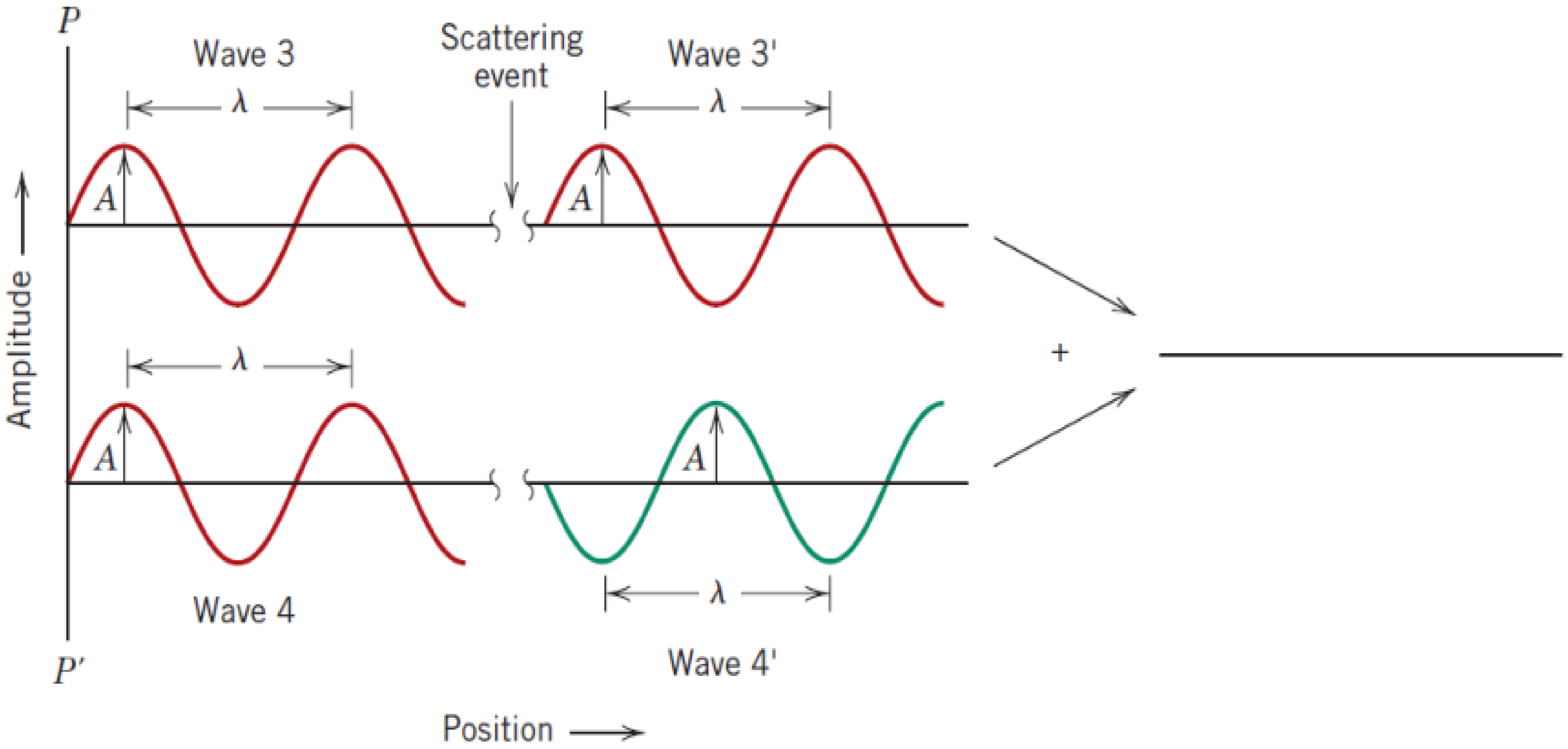


Constructively Interfere



(a)

Destructive Interference



The Diffraction Phenomenon

Diffraction is a consequence of specific *phase relationships established between two or more waves* that have been scattered by the obstacles.

- Diffraction occurs when a wave encounters a series of regularly spaced obstacles that

  (1) are capable of scattering the wave, and

  (2) have spacing that are comparable in magnitude to the wavelength.

- The phase relationship between the scattered waves, will depend upon the difference in ***path length***

- When this path length difference is an integral number of wavelengths , scattered waves are ***still in phase***

- They are said to be mutually reinforce (or *constructively interfere* with) one another; and, their amplitudes are added

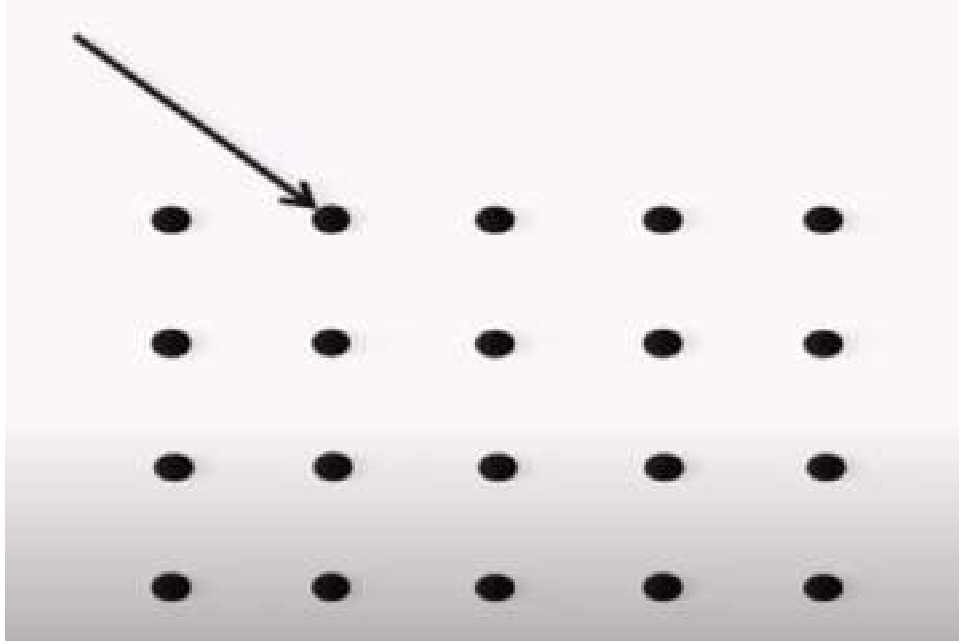
- Diffracted beam is one composed of a *large number of scattered waves that mutually reinforce one another.*

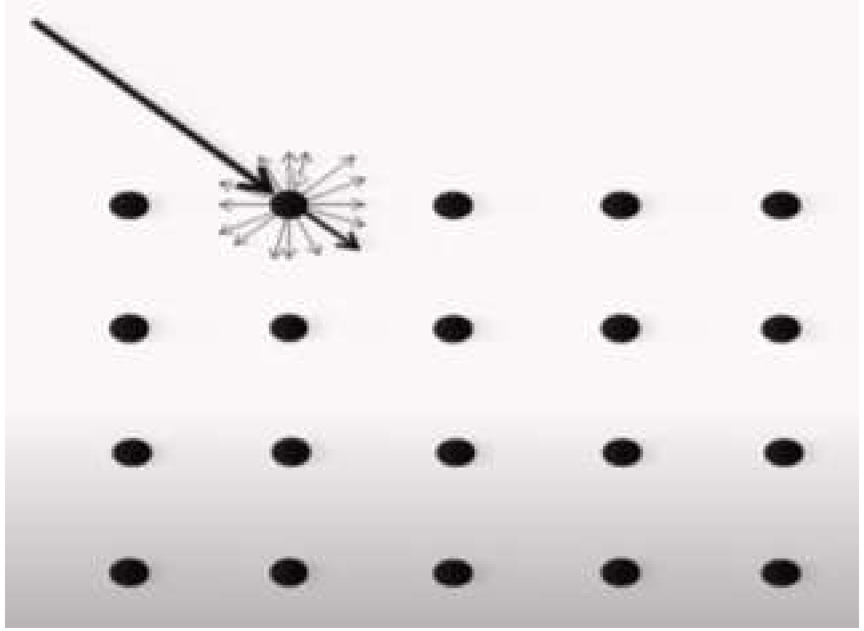
X-Ray Diffraction and Bragg's Law

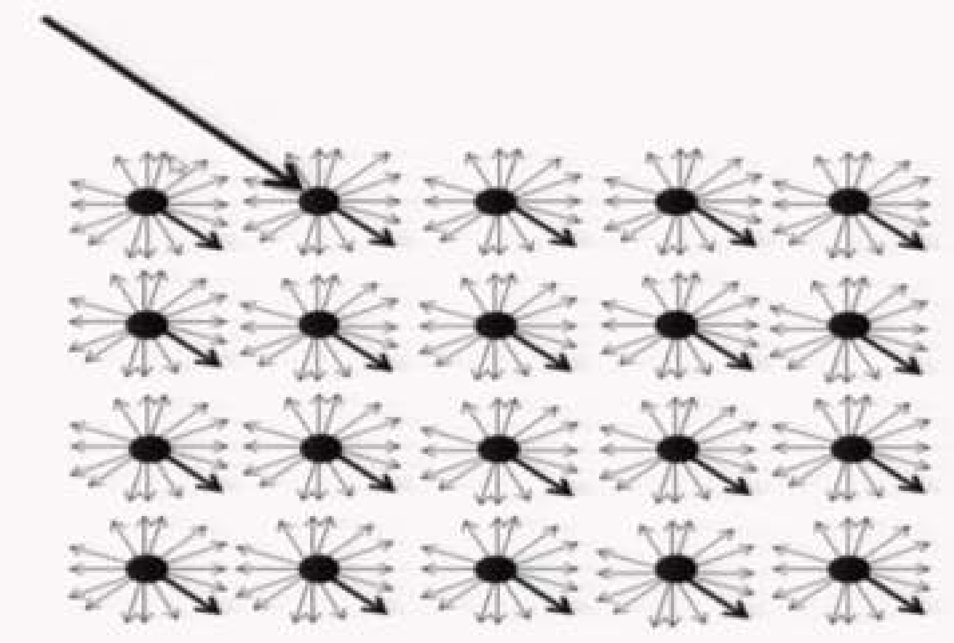
- X-rays are a form of ***electromagnetic radiation*** that have *high energies and short wavelengths*

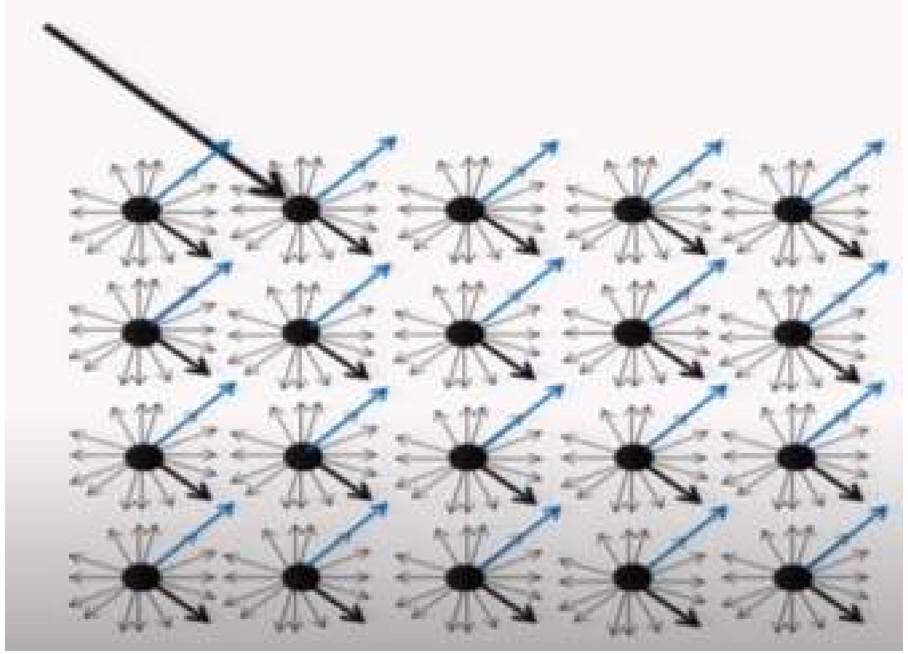
- Wavelengths of X-ray are of *order of the* ***atomic spacings*** for solids.

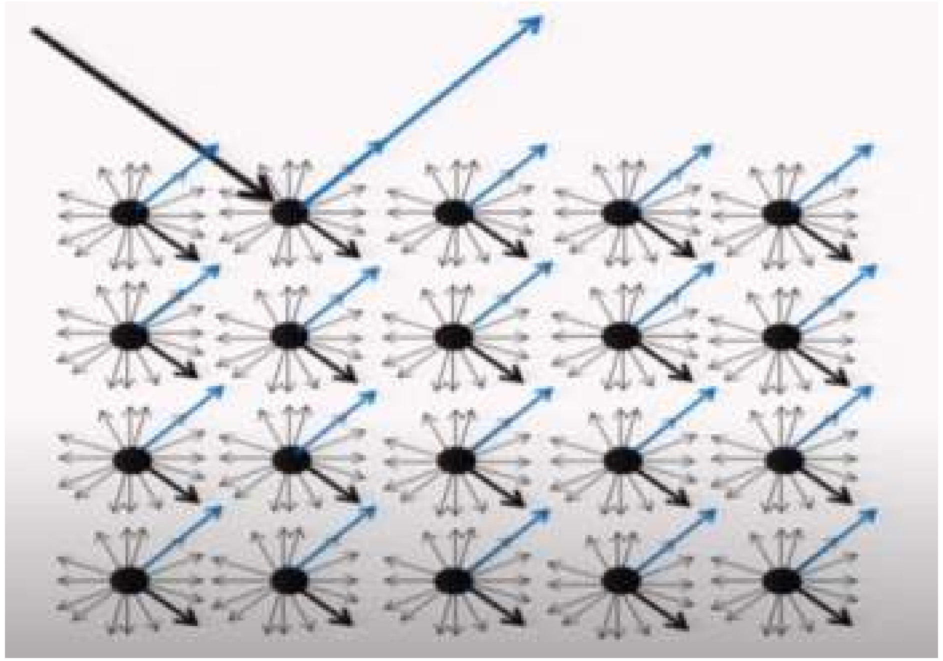
- When a beam of x-rays impinges on a solid material, a portion of this beam will be scattered in all directions by the electrons associated with each atom or ion that lies within the beam's path.

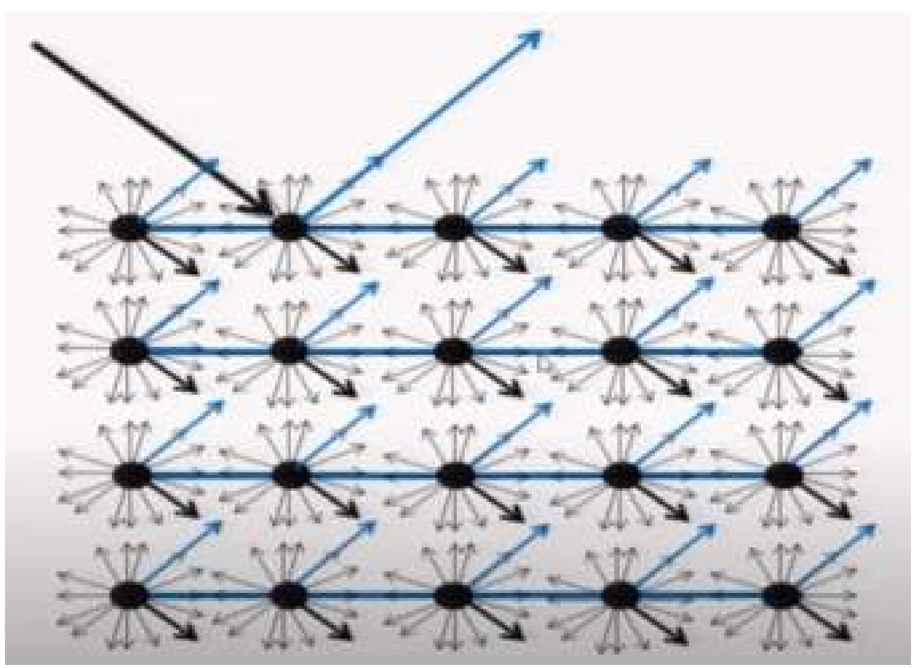


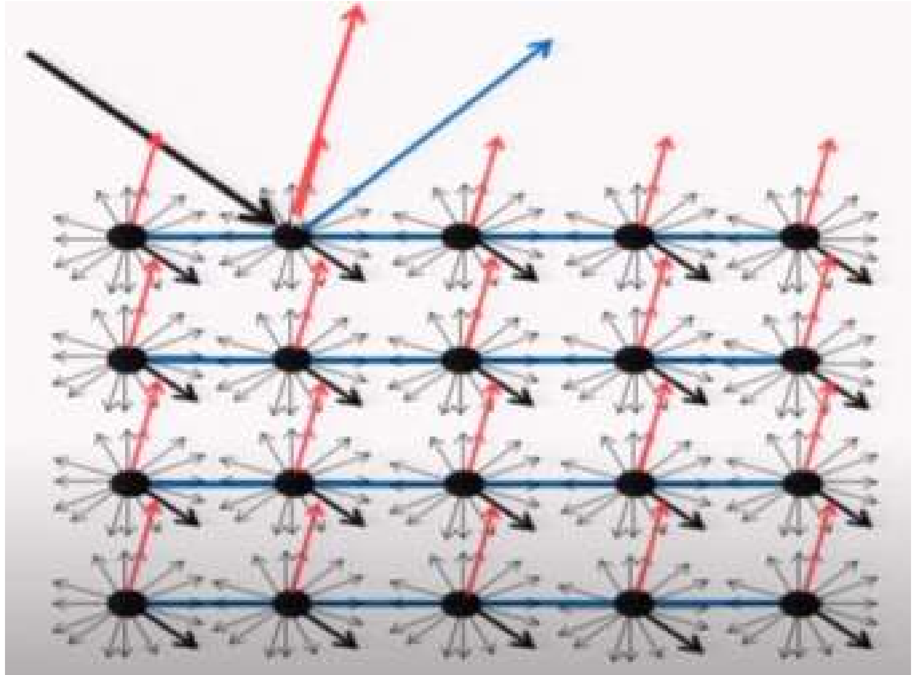


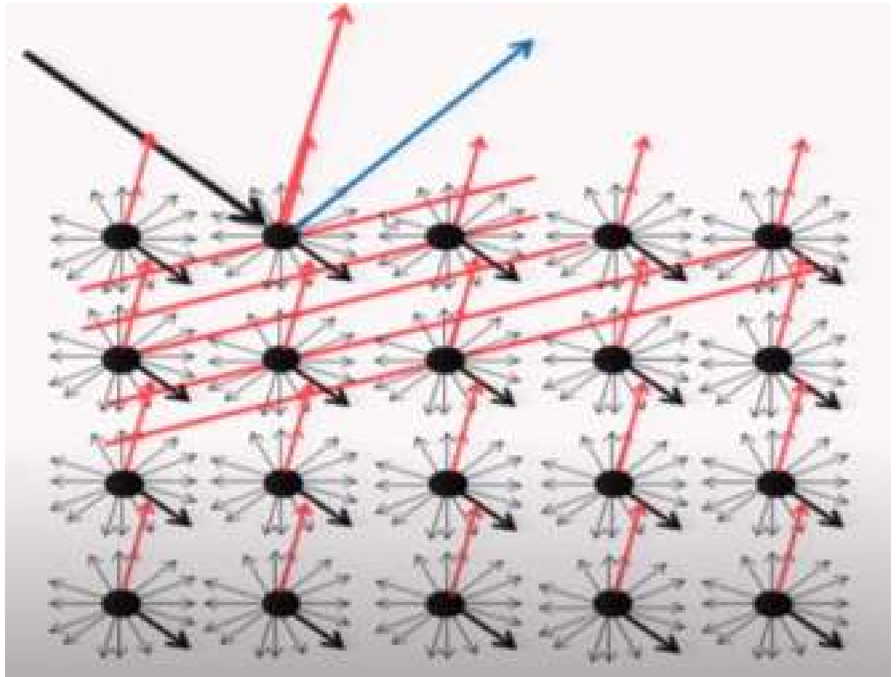




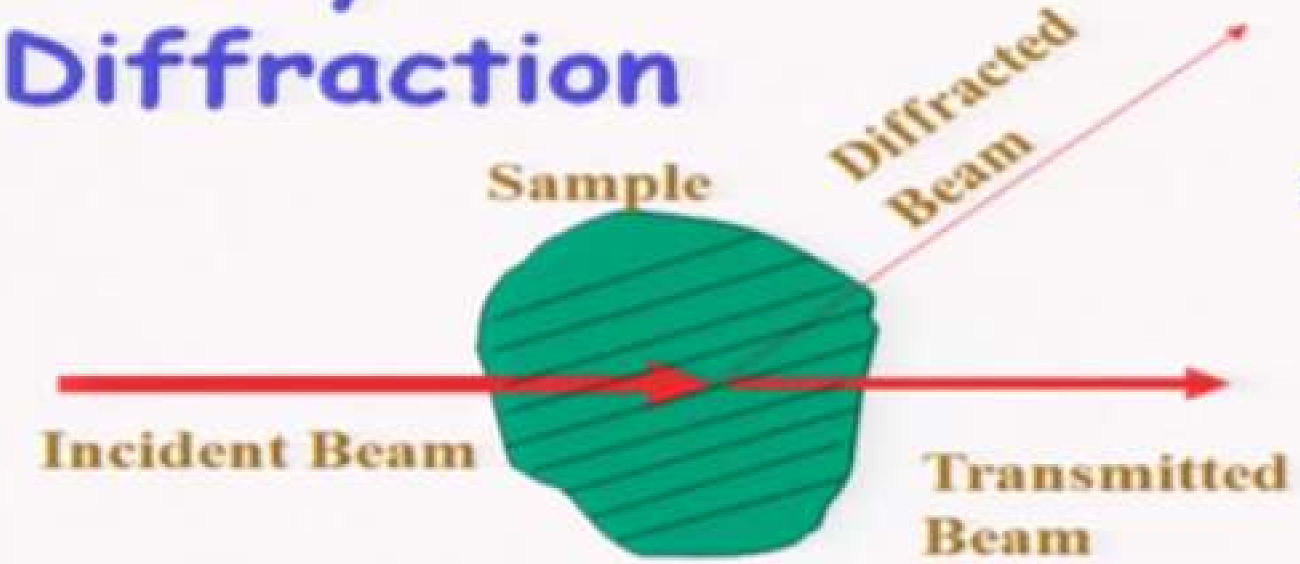








X-Ray Diffraction



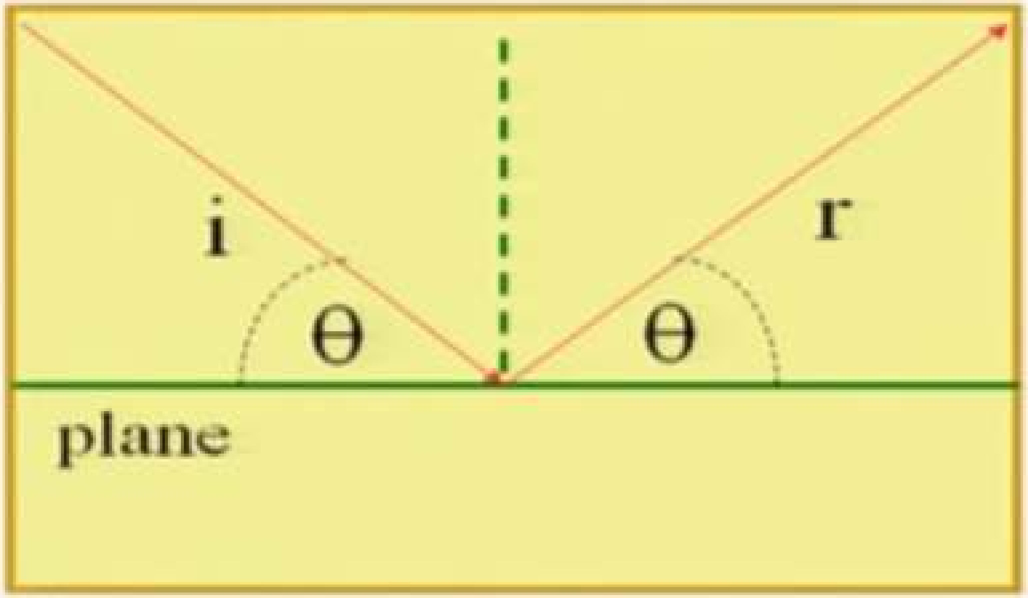
≡ **Bragg Reflection**

Bragg's Law (Part I): For every diffracted beam there exists a set of crystal lattice planes such that the diffracted beam appears to be specularly reflected from this set of planes.

X-Ray Diffraction

Bragg's Law (Part 1): the diffracted beam appears to be **specularly** reflected from a set of crystal lattice planes.

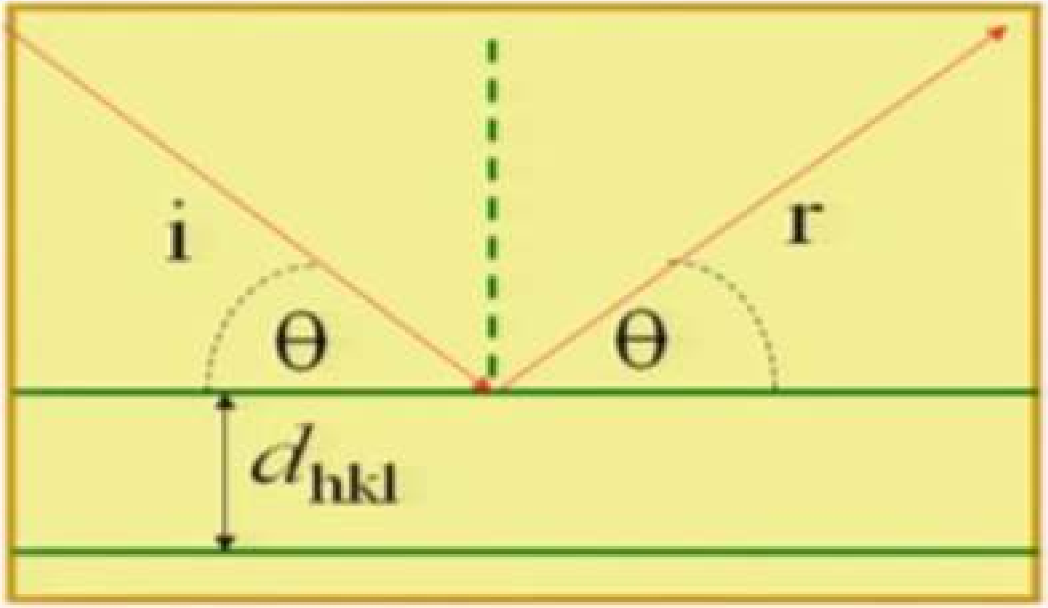
Specular reflection:



(A) Angle of incidence
=Angle of reflection
(both measured from the plane and not from the normal)

(B) The incident beam, the reflected beam and the plane normal lie in one plane

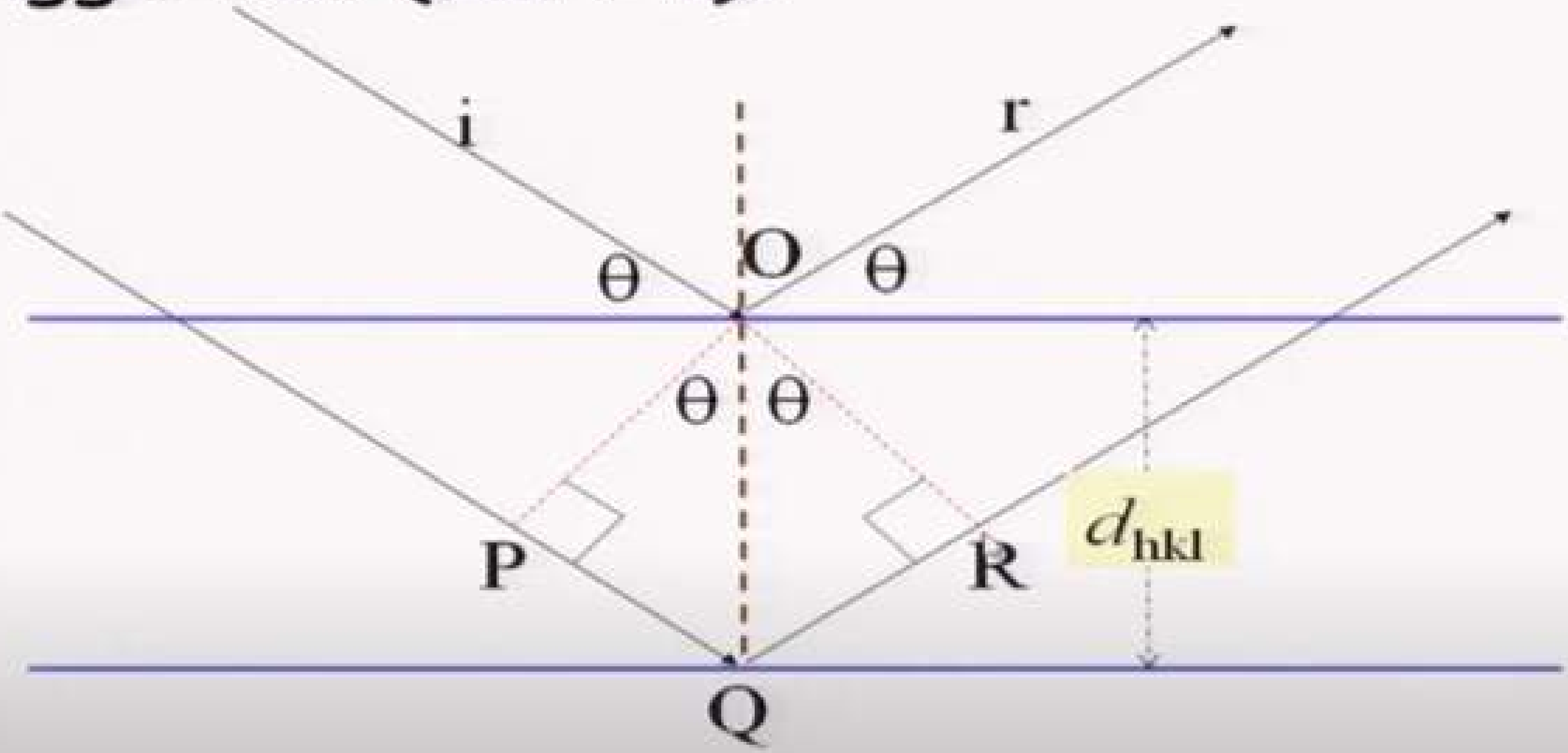
X-Ray Diffraction



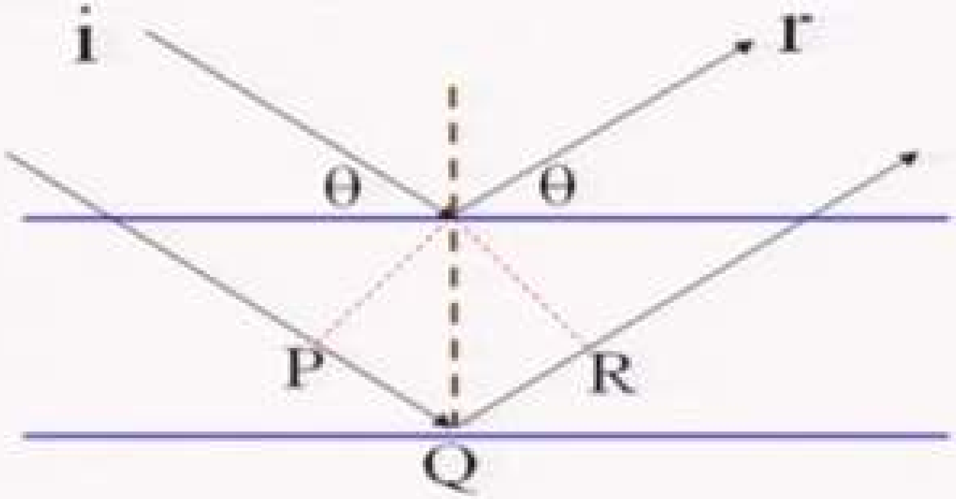
Bragg's law (Part 2):

$$\boxed{n\lambda = 2d_{hkl}\sin\theta}$$

Bragg's law (Part 2):



Path Difference =PQ+QR $= 2d_{hkl} \sin\theta$



Path Difference =PQ+QR $= 2d_{hkl}\sin\theta$

Constructive inteference

$$n\lambda = 2d_{hkl}\sin\theta$$

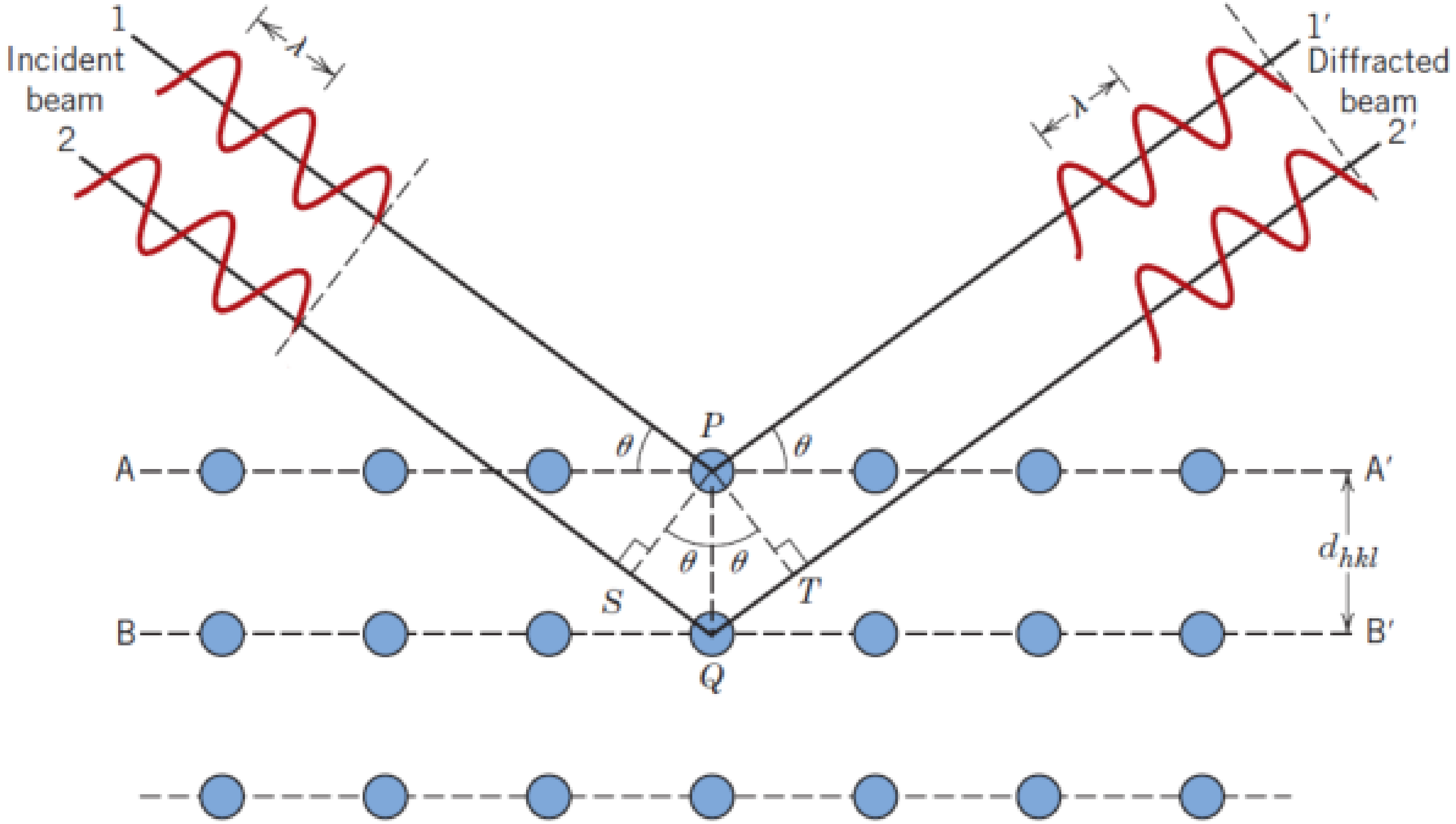
Bragg's law Part II

X-Ray Diffraction

Braggs' recipe for Nobel prize?

Call the diffraction a reflection!!!

- Necessary conditions for diffraction of x-rays by a periodic arrangement of atoms is given by **Braggs Law .**



- Constructive interference of the scattered rays and occurs, if the path length difference is equal to a whole number, n, of wavelengths.

$$n\lambda = d_{hkl}\sin\theta + d_{hkl}\sin\theta$$

$$= 2d_{hkl}\sin\theta$$

- *n* may be any integer (1, 2, 3, . . .)

- If Bragg’s law is not satisfied, then the interference will be non-constructive and diffraction will not occur

Interplanar spacing

- The magnitude of interplanar spacing is a function of the Miller indices (*h*, *k*, and *l*) *as well as the lattice parameter*
- For crystal structures that have cubic symmetry

$$d_{hkl} = \frac{a}{\sqrt{h^2 + k^2 + l^2}}$$

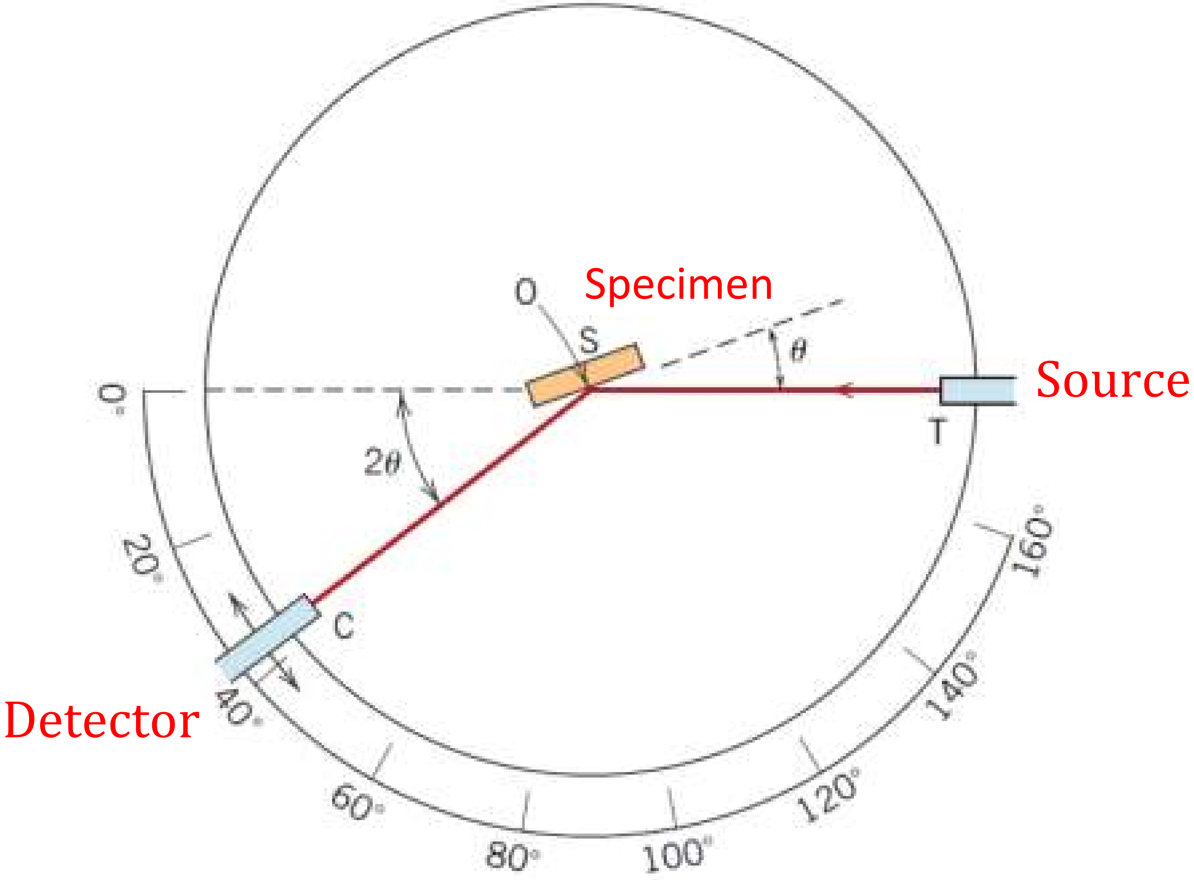
- Bragg's law, Equation is a necessary but ***not sufficient condition*** for diffraction by real crystals.

- For the **BCC** crystal structure, *h+k+l must be even* if diffraction is to occur, whereas

- For **FCC**, *h, k, and l must all be either odd or even.*

Diffractometer

- The *diffractometer is an apparatus used to determine the angles at which diffraction* occurs
- *Counter* is mounted on a movable carriage that to obtain angular position
- *Collimators* are incorporated within the beam path to produce a well-defined and focused beam.
- *filter* provides a near-monochromatic beam.



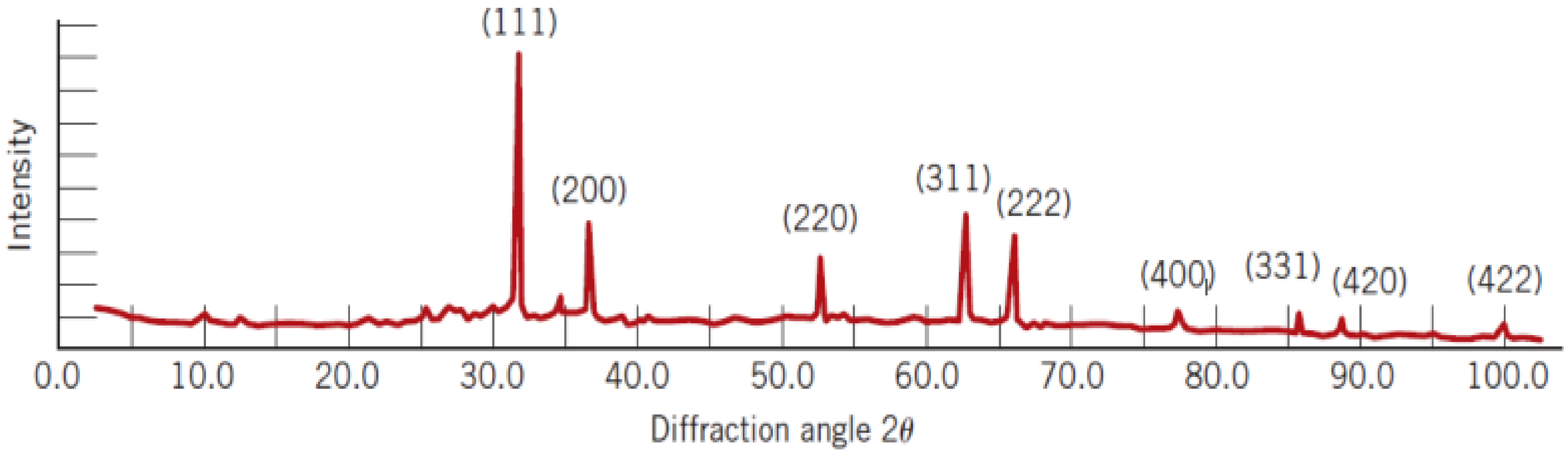
Two Measurements are made by diffractometer

1. Angle of diffracted beam
2. Intensity of diffracted beam

If specimen is rotated at an angle : $\boldsymbol{\theta}$

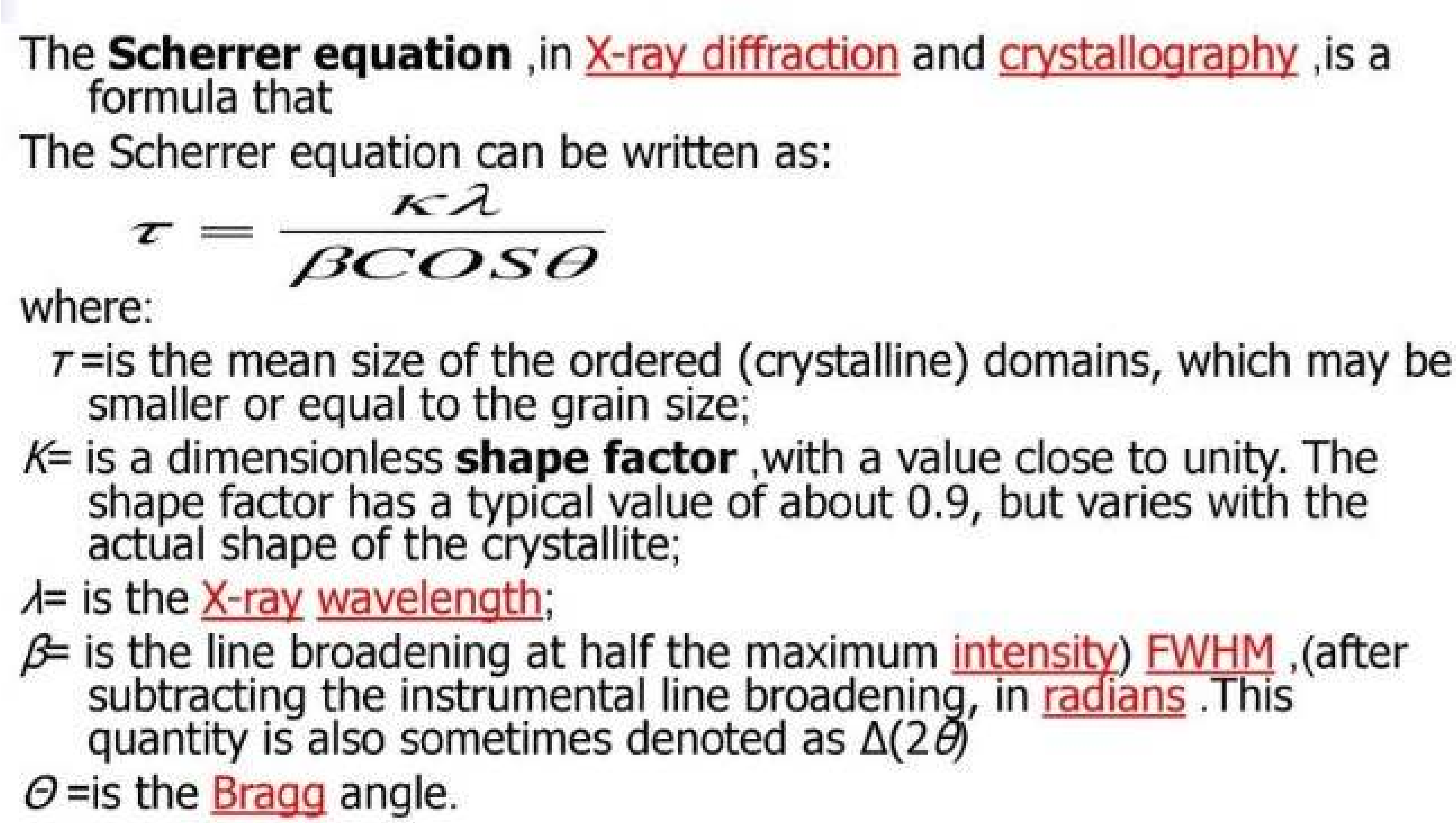
Counter is made to rotate at an angle : $\boldsymbol{2\theta}$

This $\boldsymbol{2\theta}$ is the diffraction angle



diffraction pattern for a powdered specimen of lead.

Crystallite / Grain size Measurement using XRD



The **Scherrer equation** ,in X-ray diffraction and crystallography ,is a formula that

The Scherrer equation can be written as:

$$\tau = \frac{\kappa\lambda}{\beta \cos\theta}$$

where:

τ =is the mean size of the ordered (crystalline) domains, which may be smaller or equal to the grain size;

K= is a dimensionless **shape factor** ,with a value close to unity. The shape factor has a typical value of about 0.9, but varies with the actual shape of the crystallite;

λ= is the X-ray wavelength;

β= is the line broadening at half the maximum intensity) FWHM ,(after subtracting the instrumental line broadening, in radians .This quantity is also sometimes denoted as $\Delta(2\theta)$

Θ =is the Bragg angle.

Application of XRD

- *Determination of Crystal structure*
- *Determination of Crystallite / Grain size*
- *Determination of Phases*
- *Identification of unknown crystalline materials*
- *To find the whether materials is crystalline or amorphous – degree of crystallinity*
- *To find the phase fractions*

Interplanar Spacing and Diffraction Angle Computations

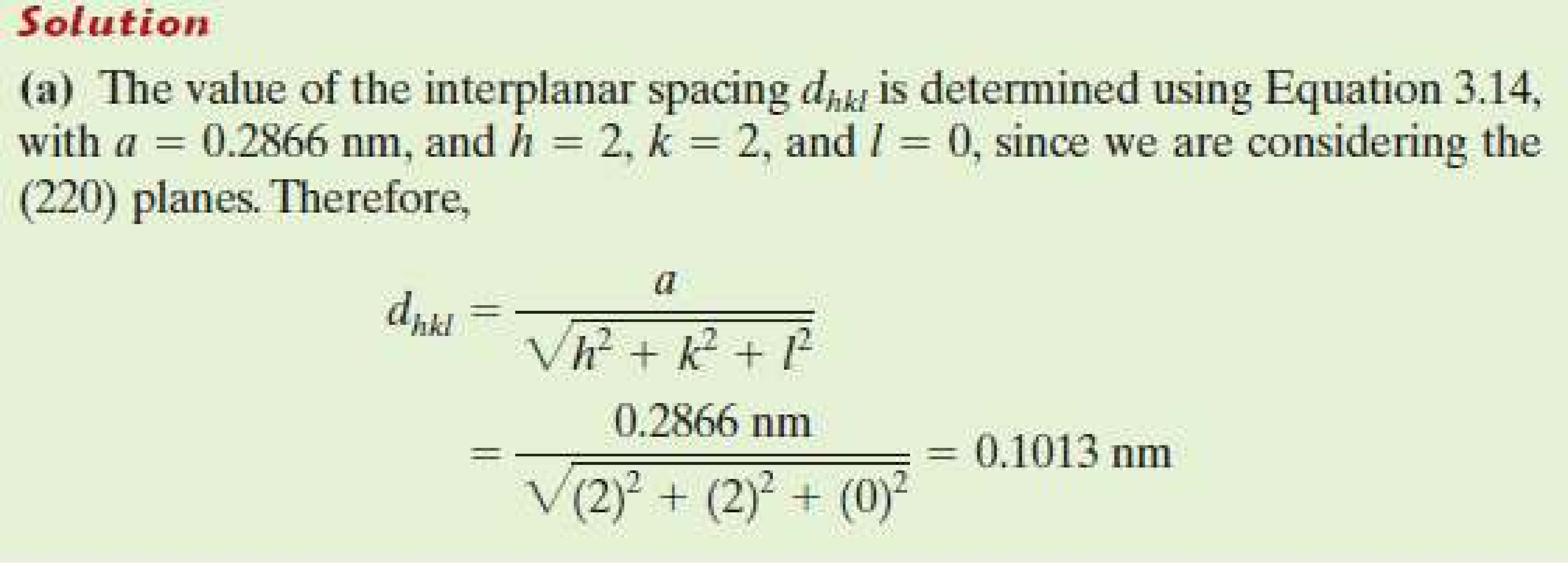
Question?

For BCC iron, compute

(a) the interplanar spacing, and

(b) the diffraction angle for the (220) set of planes.

The lattice parameter for Fe is 0.2866 nm. Also, assume that monochromatic radiation having a wavelength of 0.1790 nm is used, and the order of reflection is 1.



Solution

(a) The value of the interplanar spacing d_{hkl} is determined using Equation 3.14, with $a = 0.2866$ nm, and $h = 2$, $k = 2$, and $l = 0$, since we are considering the (220) planes. Therefore,

$$
\begin{aligned}
d_{hkl} &= \frac{a}{\sqrt{h^2 + k^2 + l^2}} \\
&= \frac{0.2866 \text{ nm}}{\sqrt{(2)^2 + (2)^2 + (0)^2}} = 0.1013 \text{ nm}
\end{aligned}
$$

$= 2d_{hkl} \sin\theta$

$n\lambda$

(b) The value of θ may now be computed using Equation 3.13, with $n = 1$, since this is a first-order reflection:

$$\sin\theta = \frac{n\lambda}{2d_{hkl}} = \frac{(1)(0.1790\text{ nm})}{(2)(0.1013\text{ nm})} = 0.884$$

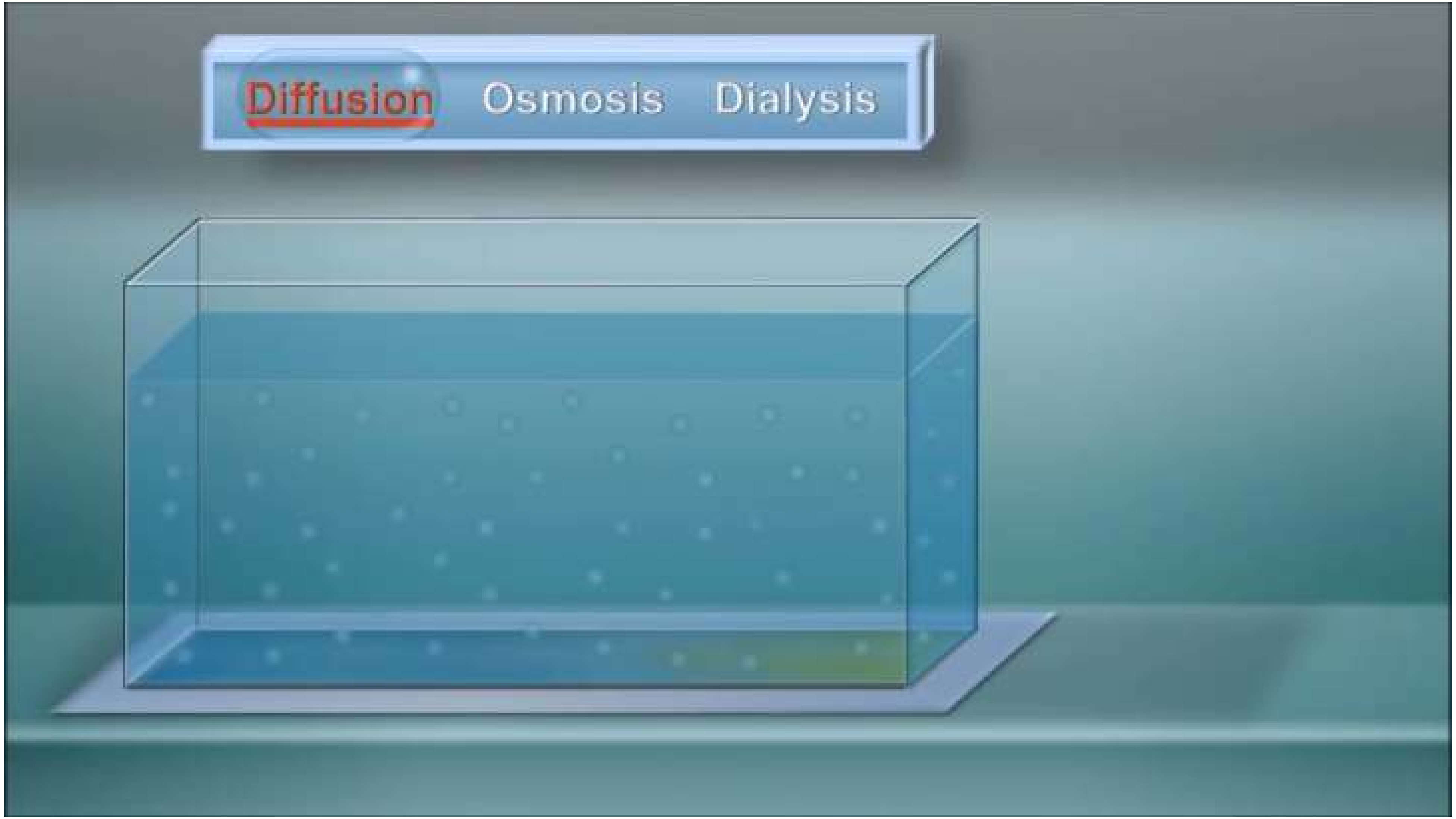
$$\theta = \sin^{-1}(0.884) = 62.13^\circ$$

The diffraction angle is 2θ, or

$$2\theta = (2)(62.13^\circ) = 124.26^\circ$$

DIFFUSION

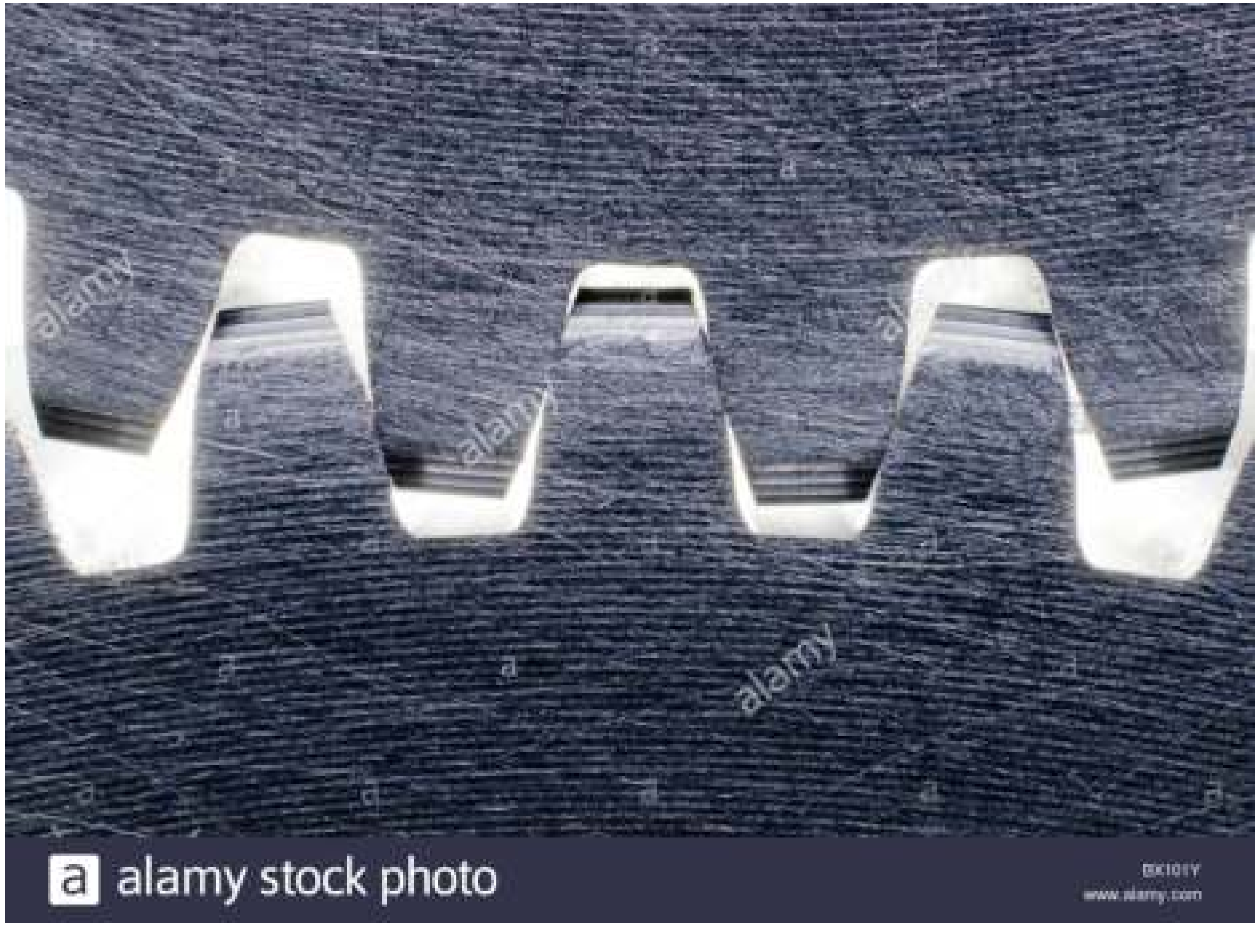
- Diffusion is the phenomenon of material transport by atomic movement.
- Microstructure is controlled by Phase transformation and it involves Diffusion.
- Mass Transfer
- Solid state diffusion

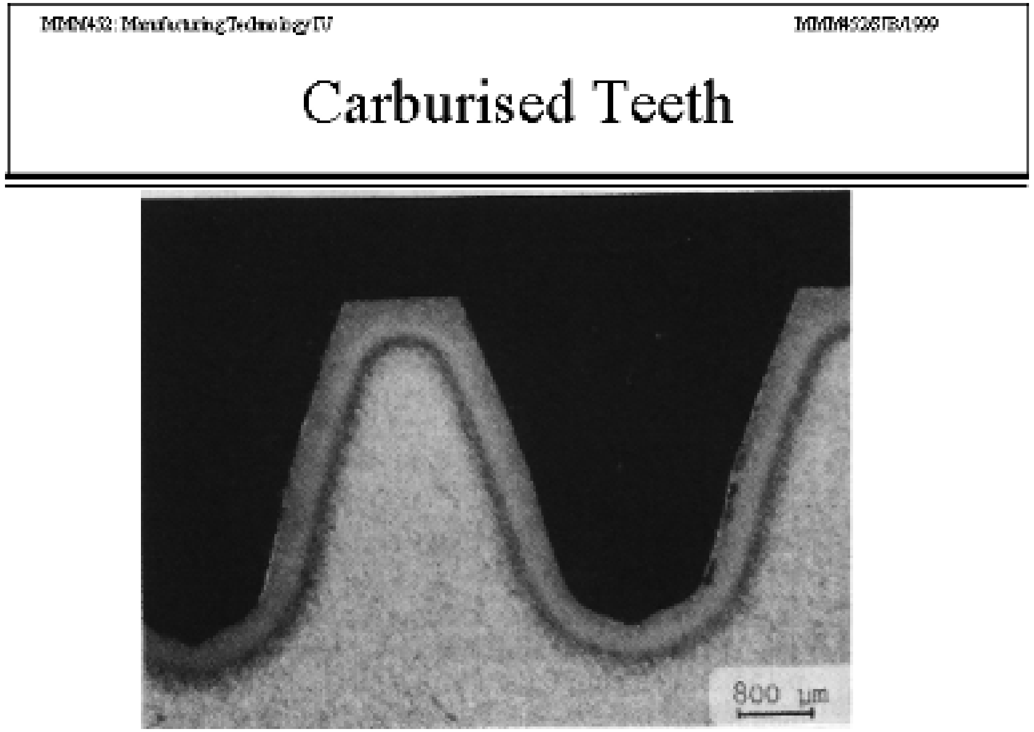

Diffusion
Osmosis
Dialysis

Importance of Diffusion in Material Science

- Many reactions and processes that are important in the treatment of materials rely on diffusion.

Eg,.




MMM432: Manufacturing Technology IV MMM432/STB/1999

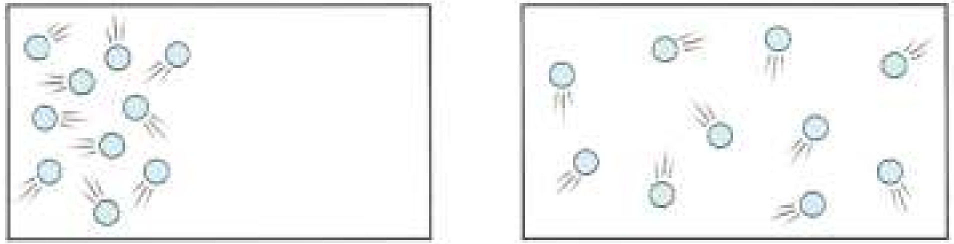
Carburised Teeth

DIFFUSION

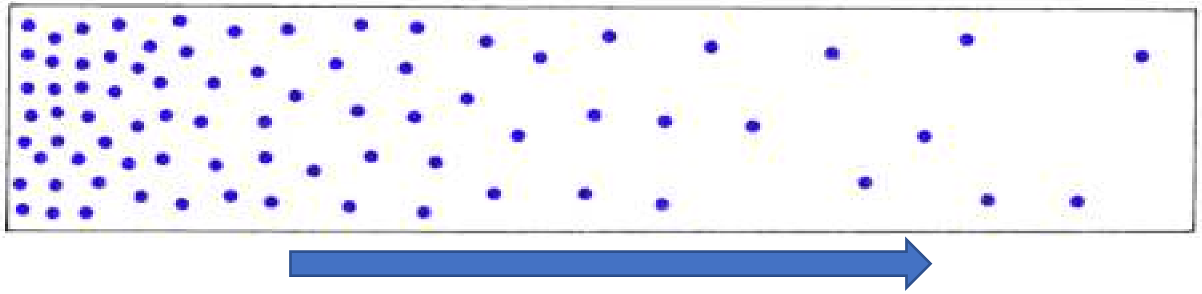
Diffusion is the process by which atoms move in a material.

Diffusion can be defined as the mass flow process in which atoms change their positions relative to neighbours in a given phase under the influence of a gradient and thermal energy.

Diffusion gradient



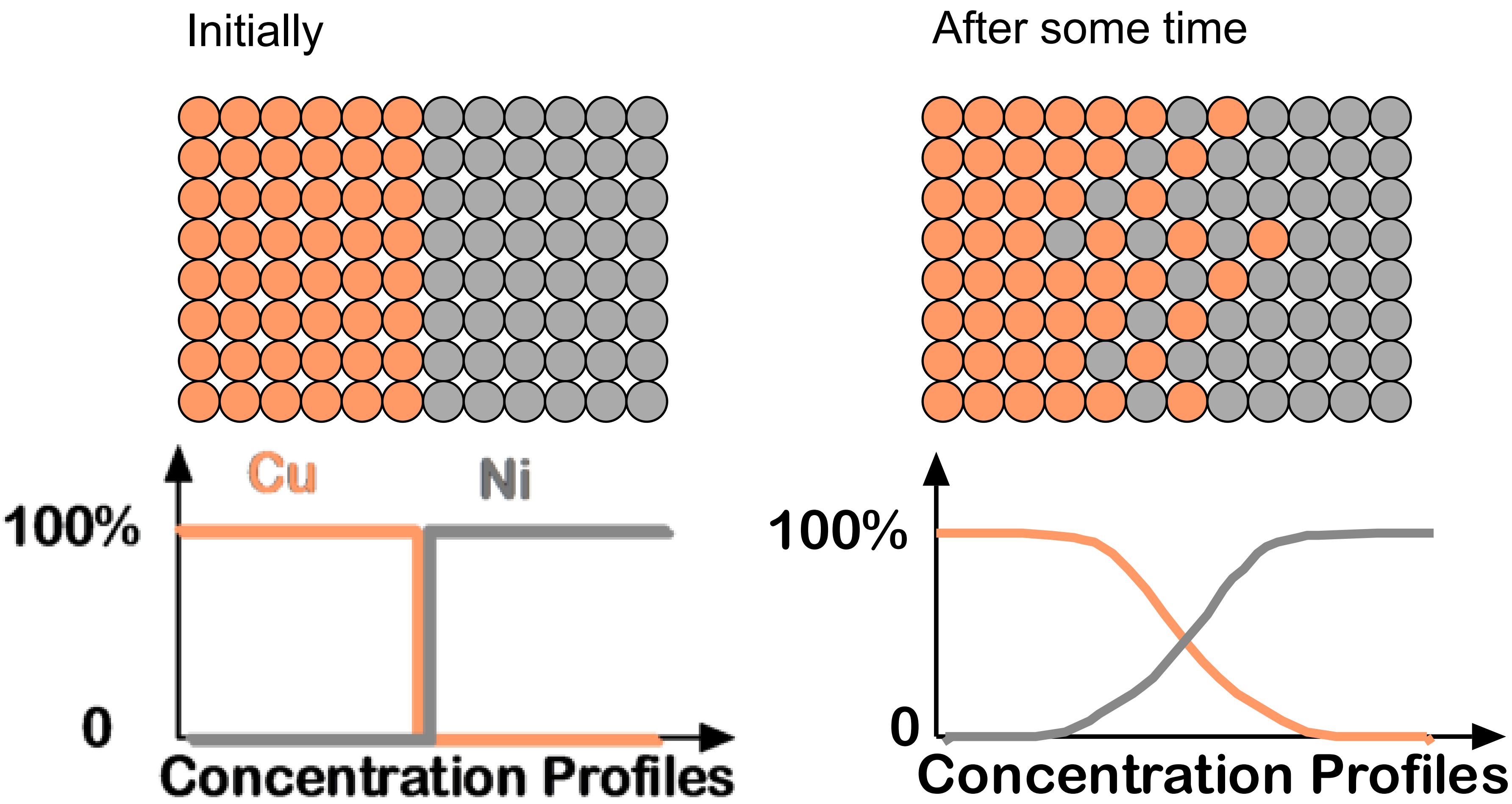
The molecules are more densely packed on the left and so they tend to diffuse into the space on the right. This is a diffusion gradient.



Inter-diffusion

The process by which atoms of one metal diffuse into another is called inter-diffusion or impurity diffusion.

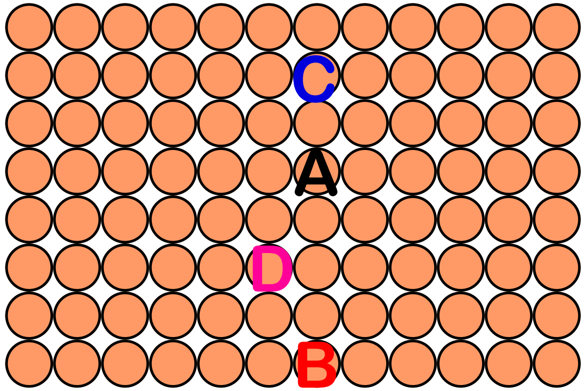
This is a diffusion couple.



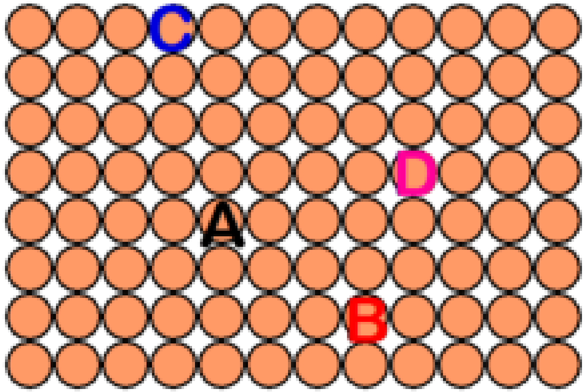
Self-diffusion

Diffusion occurring in *pure metals* is called self-diffusion, Where atoms of the metal *exchange* their positions.

Label some atoms



After some time



Self-diffusion does not contribute any significant effects on the properties of the material

Mechanisms of diffusion

For an atom to move from its lattice site, two conditions are to be satisfied

- there must be an adjacent *empty site.*
- atom must have sufficient energy to break bonds with its neighbours and migrate to adjacent site ("*activation*" energy)

Higher the temperature, higher is the probability that an atom will have sufficient energy

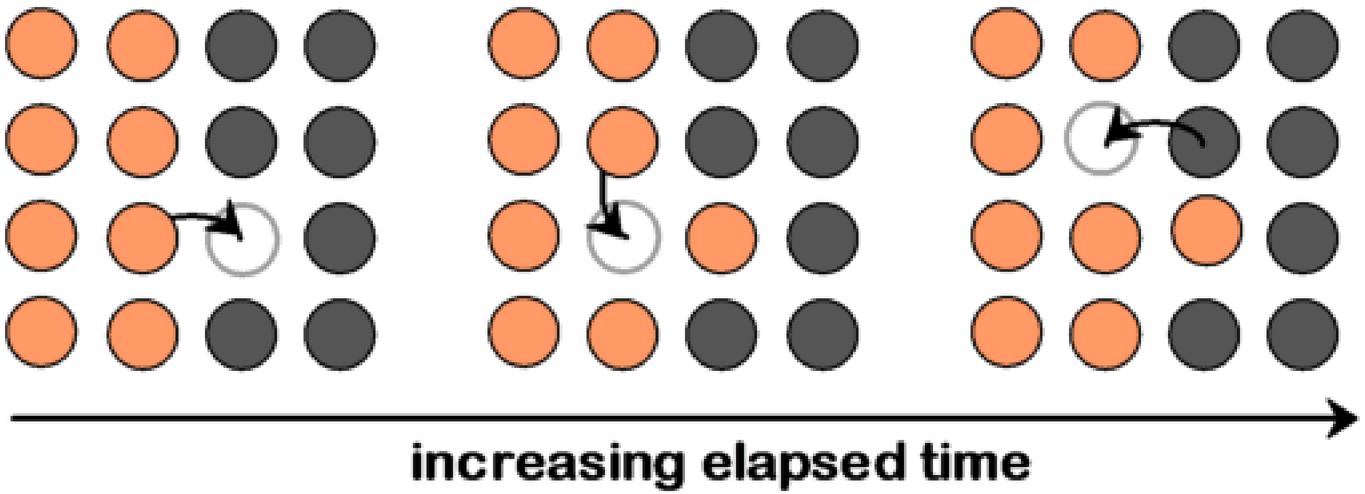
➔ hence, diffusion rates *increase with temperature*

Types of atomic diffusion mechanisms:

- Vacancy diffusion
- Interstitial diffusion
- Substitutional Diffusion
- Self diffusion
- Self-interstitial diffusion

Vacancy diffusion

This mechanism involves the interchange of an atom from a normal site to an adjacent vacant site or a vacancy. When this happens, a vacancy is created at another site, to which another atom can move creating a vacancy else where.

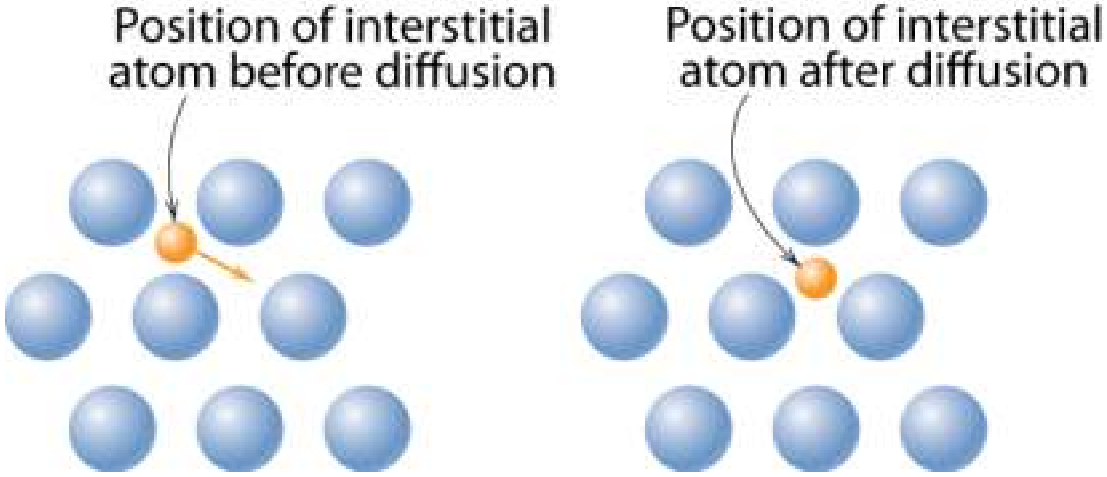


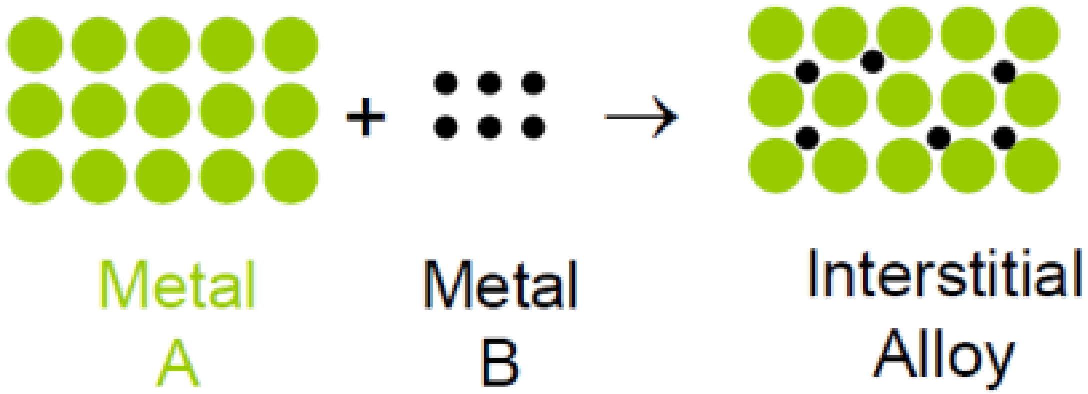
Rate of diffusion depends on:

- Number of vacancies
- Temperature
- Activation energy to exchange.

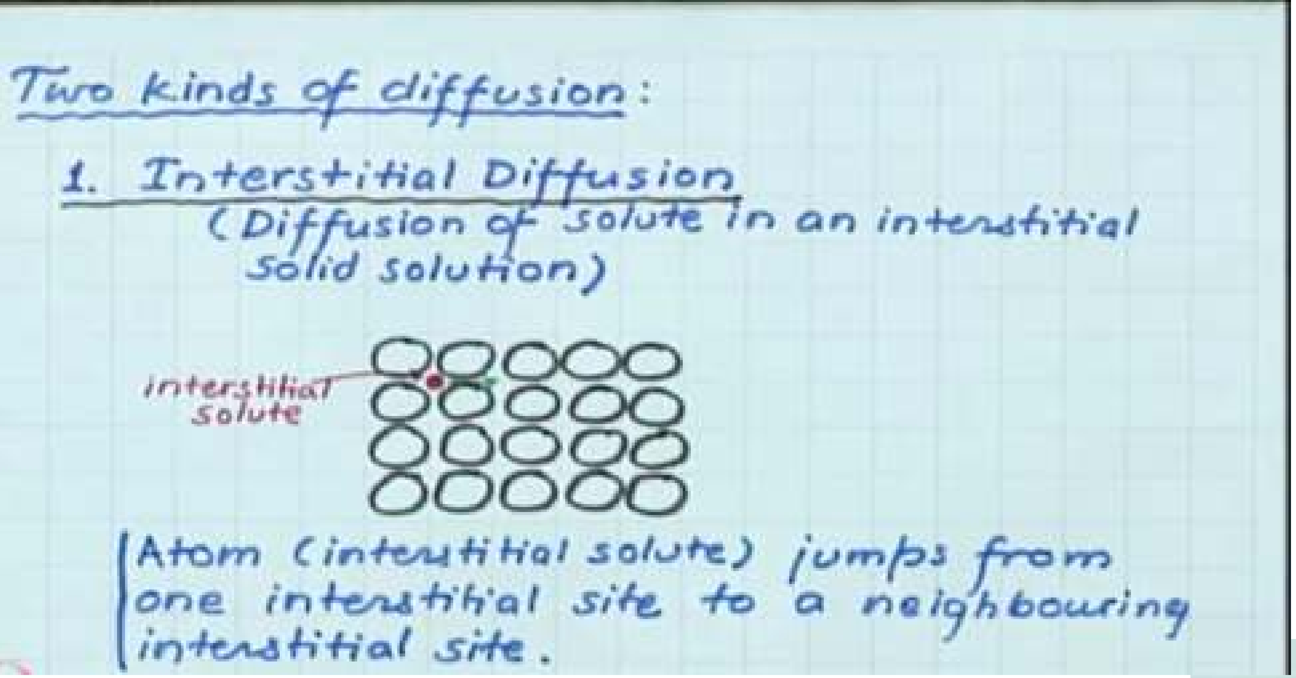
Interstitial diffusion

Migration of atom from one interstitial position to a neighboring one that is empty.





- Smaller atoms diffuse between atoms.
- More rapid than vacancy diffusion, since there are more empty interstitial positions than vacancies.
- Probability of having interstitial diffusion is more than that of vacancy diffusion

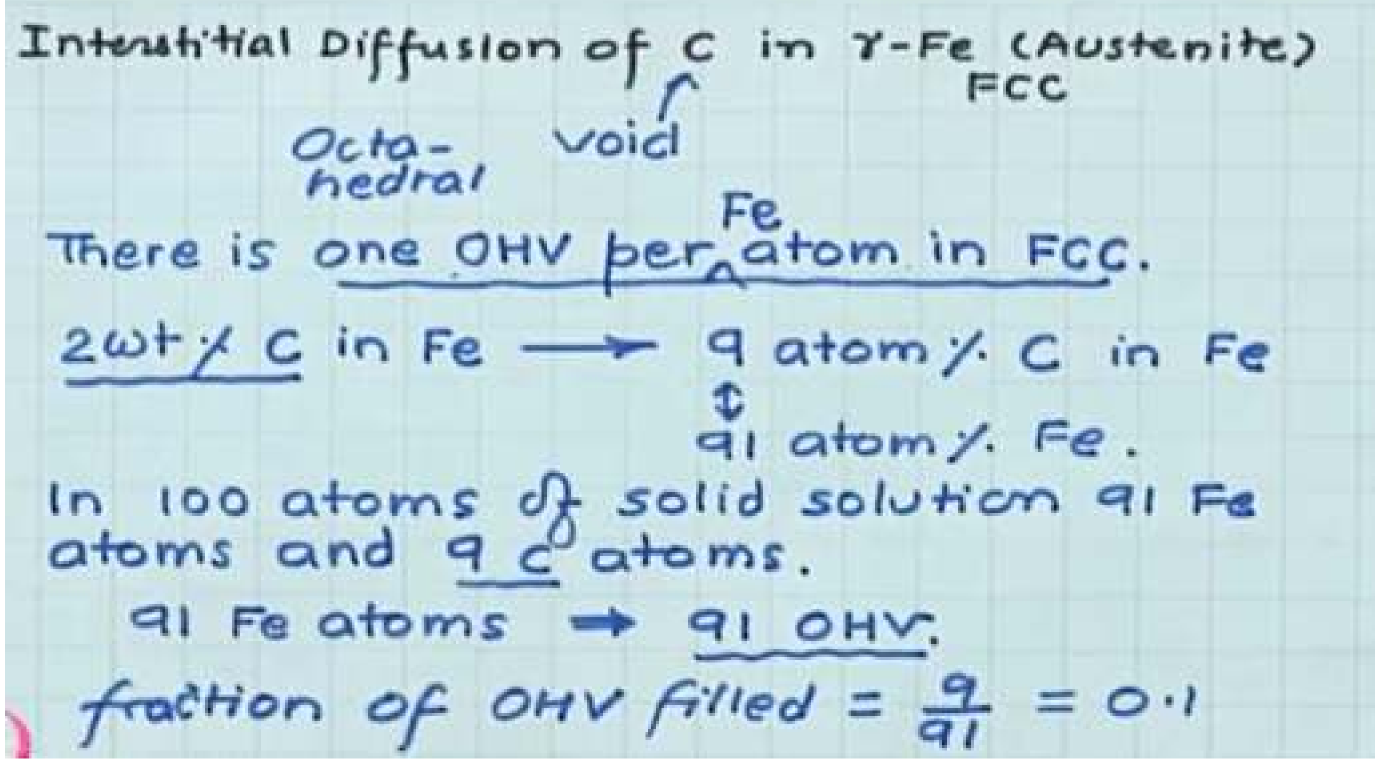


Two kinds of diffusion:

1. Interstitial Diffusion

(Diffusion of solute in an interstitial solid solution)

Atom (interstitial solute) jumps from one interstitial site to a neighbouring interstitial site.



Interstitial Diffusion of C in γ-Fe (Austenite)

FCC

Octa-hedral void

There is one OHV per Fe atom in FCC.

2wt% C in Fe → 9 atom% C in Fe

↕

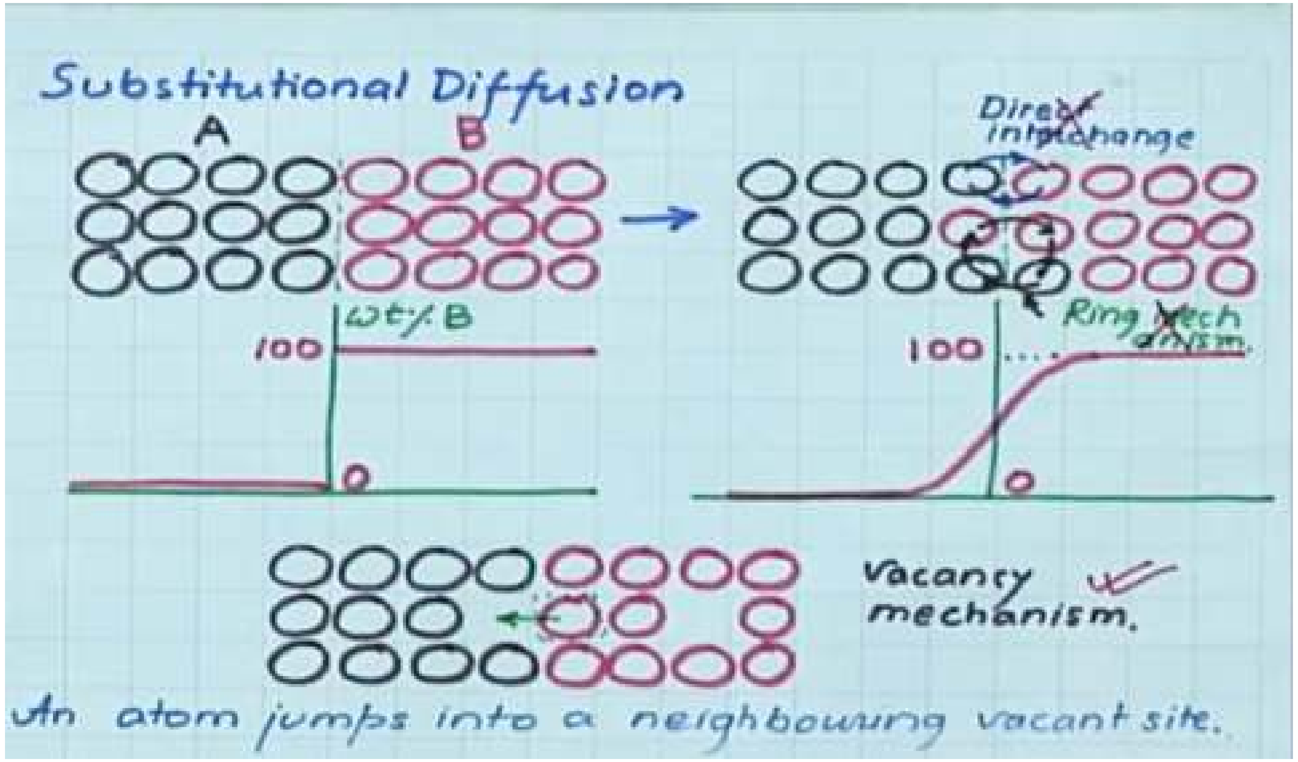
91 atom% Fe.

In 100 atoms of solid solution 91 Fe atoms and 9 C atoms.

91 Fe atoms → 91 OHV.

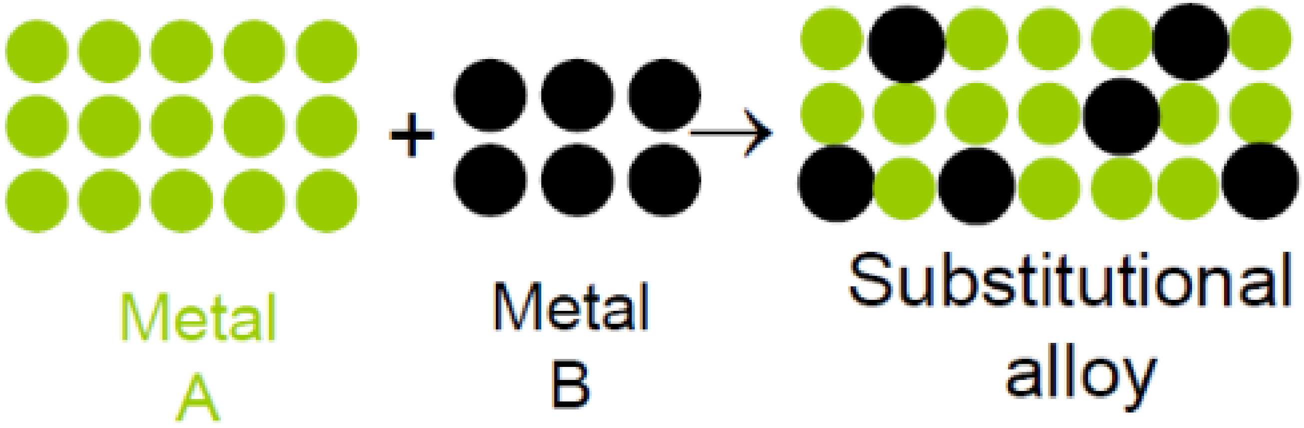
fraction of OHV filled = $\frac{9}{91}$ = 0.1

Substitutional Diffusion



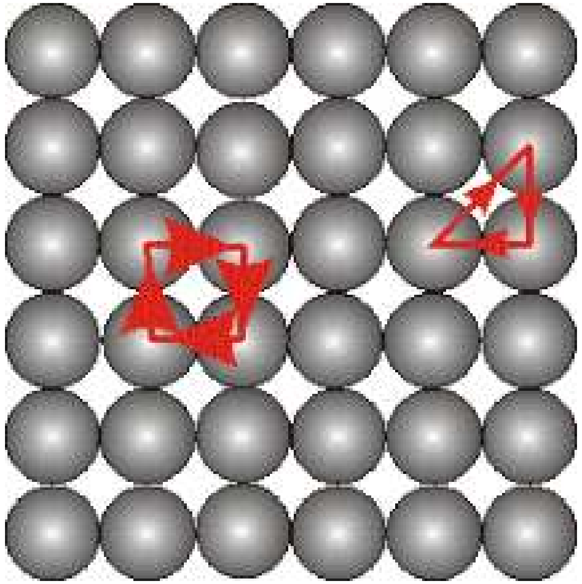
An atom jumps into a neighbouring vacant site.

Substitutional diffusion generally proceeds by the vacancy mechanism. Thus interstitial diffusion is faster than substitutional diffusion by the vacancy mechanism.



Self diffusion

Two or more adjacent atoms jump past each other and exchange position

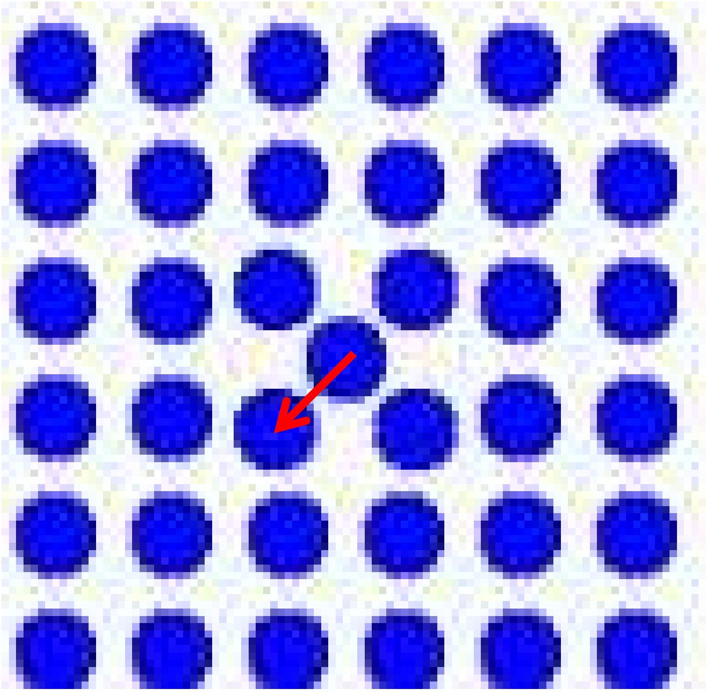


During self-diffusion or ring mechanism or direct-exchange mechanism, three or four atoms in the form of a ring move simultaneously round the ring, thereby interchanging their positions.

- Takes place between 2, 3 or 4 atoms.
- Also known as *Ring diffusion or Zenner* ring diffusion
- Results in severe local lattice distortion.
- Requires much more energy for the atoms to jump.

Self-interstitial diffusion

An atom occupying an interstitial site forces a regular atom to leave its site to an interstitial site. Continuation of this result in interstitial diffusion



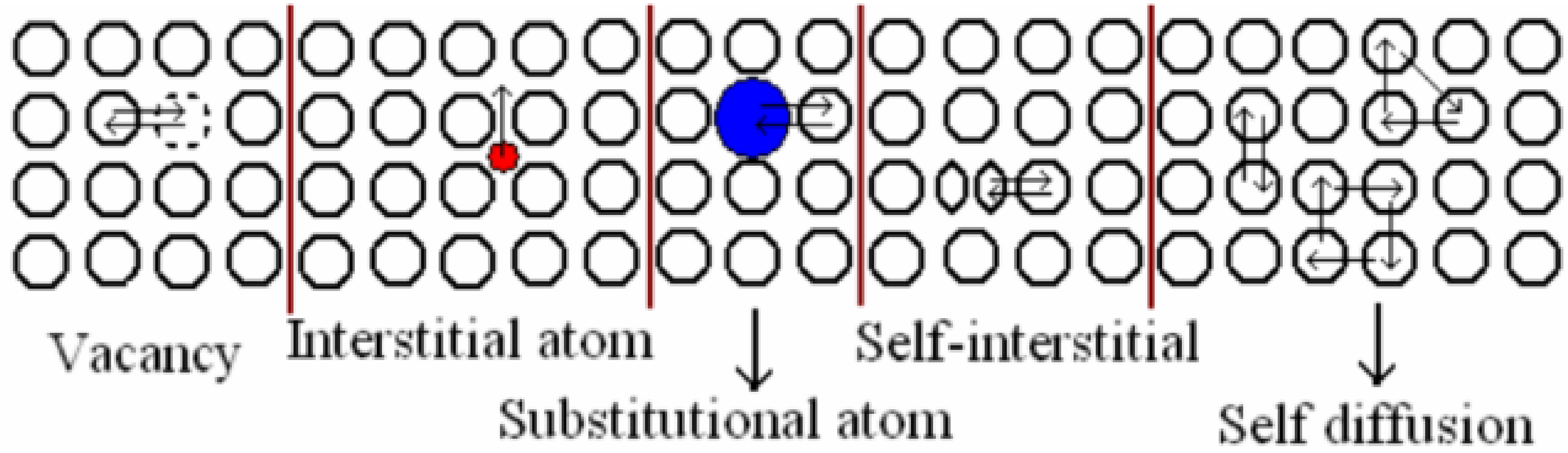
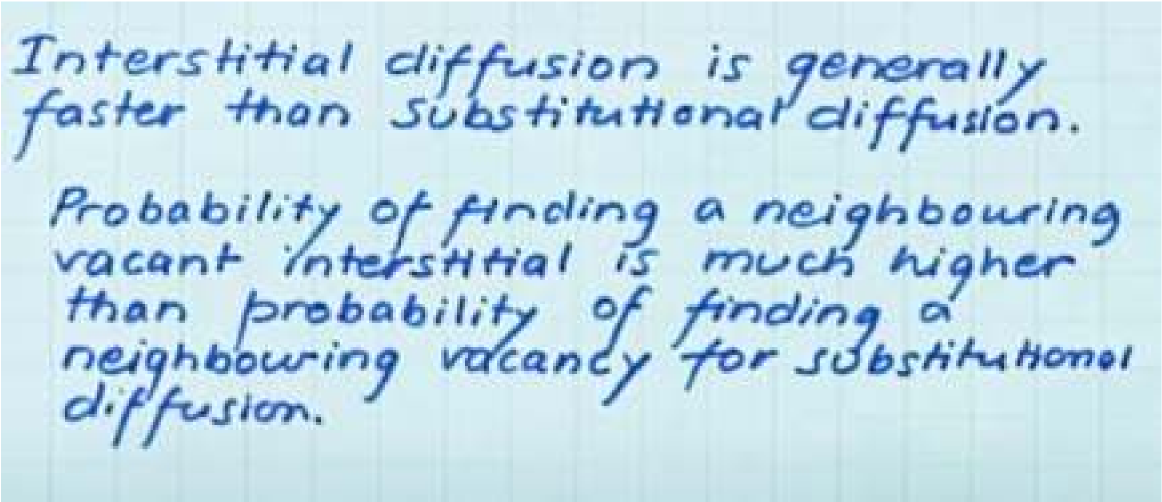


Figure-5.1: *Diffusion mechanisms.*

Diffusion in most ionic solids occurs by a vacancy mechanism. In ionic crystals, Schottky and Frankel defects assist the diffusion process.



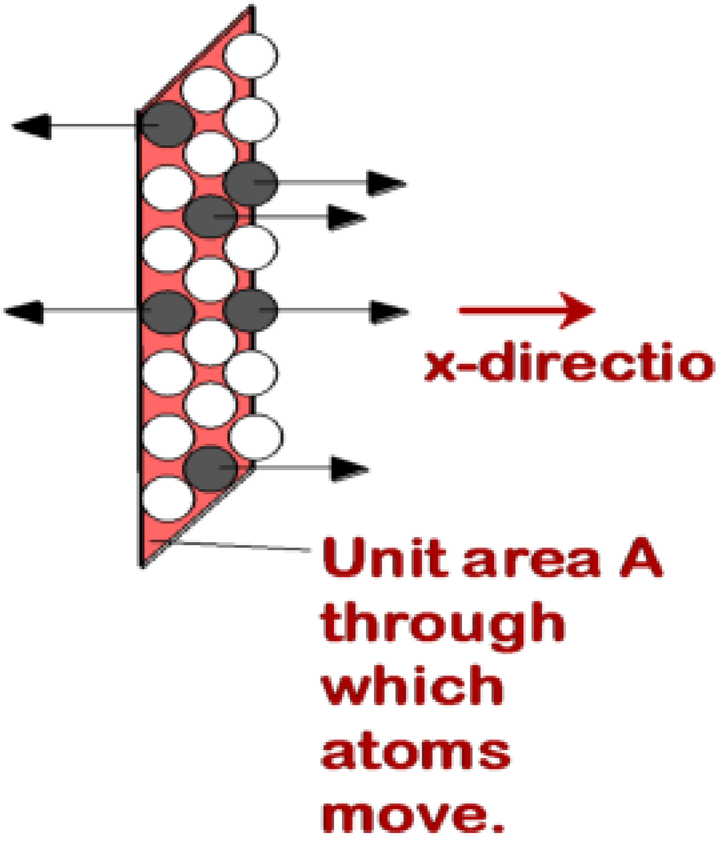
Interstitial diffusion is generally faster than substitutional diffusion.

Probability of finding a neighbouring vacant interstitial is much higher than probability of finding a neighbouring vacancy for substitutional diffusion.

Terms associated with diffusion

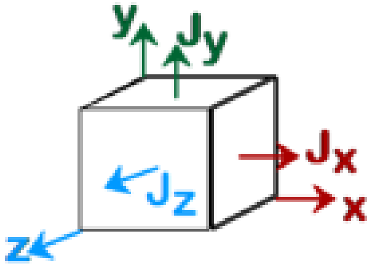
Diffusion flux (J) : Amount of material or atoms moving past a unit area in unit time

$$J = \frac{1}{A}\frac{dM}{dt} \Rightarrow \left[\frac{\mathrm{kg}}{\mathrm{m^2 s}}\right] \text{ or } \left[\frac{\mathrm{atoms}}{\mathrm{m^2 s}}\right]$$



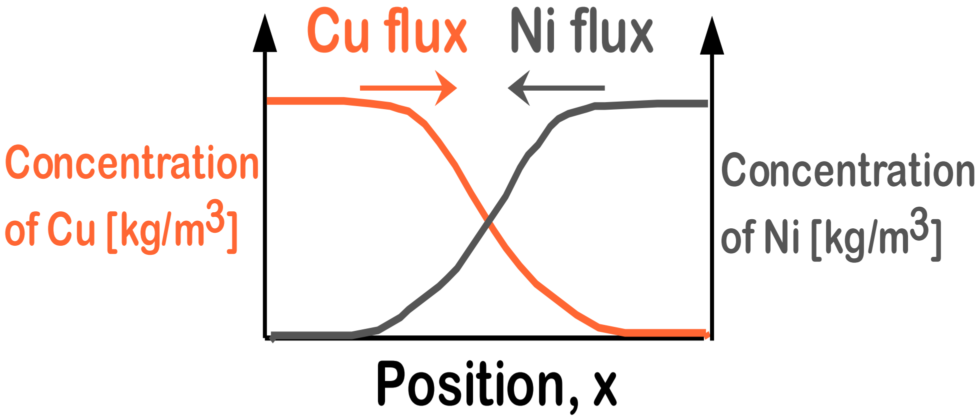
- Flux can be measured for:

  --Vacancies
  --Host (A) atoms
  --Impurity (B) atoms



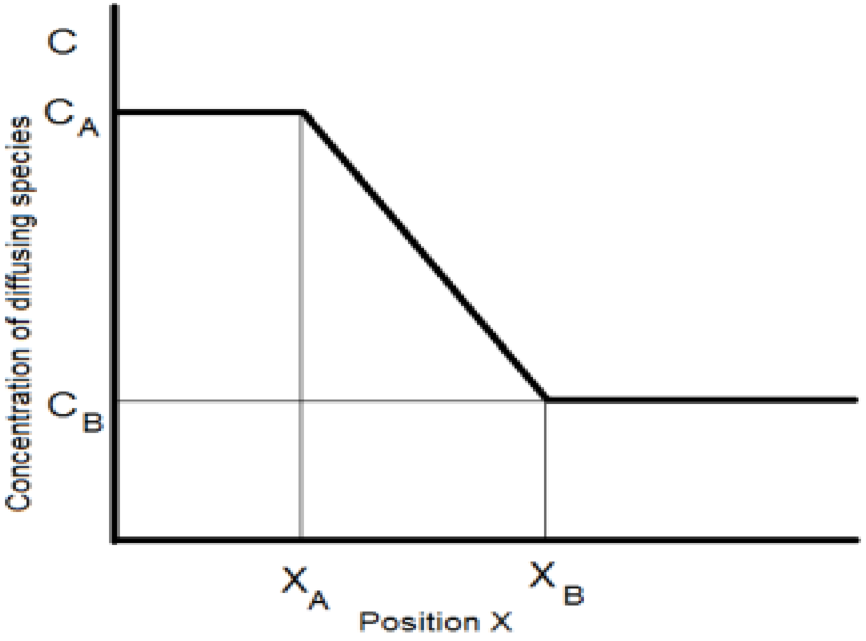
Terms associated with diffusion

Concentration Gradient : Concentration (C) of the diffusing element is plotted versus position (or distance) within the solid, the resulting curve is known as concentration profile and slope of curve is termed as concentration gradient



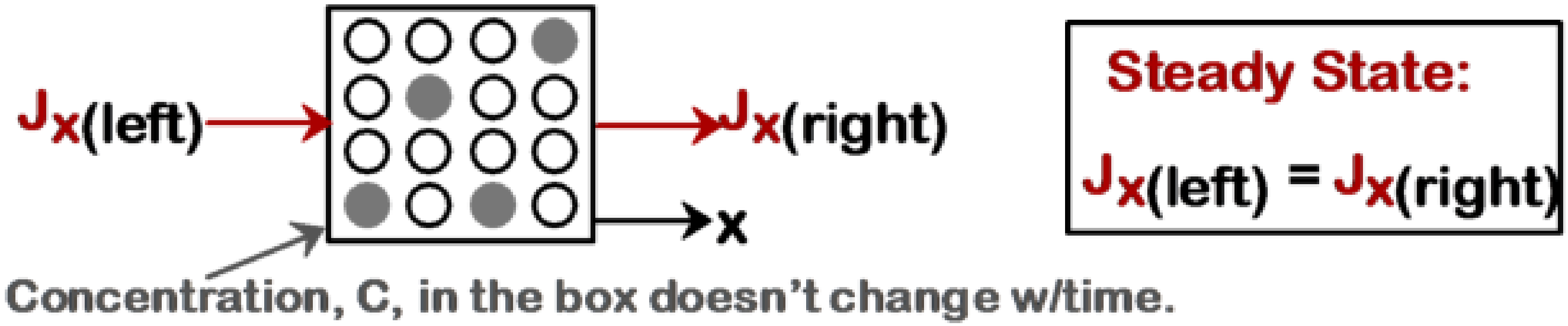
$$\frac{dC}{dt}$$

$$\frac{\Delta C}{\Delta X} = \frac{C_A - C_B}{X_A - X_B}$$



Terms associated with diffusion

Steady state : Steady rate of diffusion from one end to the other.
Implies that the concentration profile doesn't change with time



Result: the slope, dC/dx, must be constant

(i.e., slope doesn't vary with position)!

Non Steady state diffusion :
Implies that the concentration profile change with time

Terms associated with diffusion

Diffusion co-efficient or diffusivity (D): Intensity at which the atom diffuse

It is a material property which depends upon

- (i) the diffusing species
- (ii) the composition of the medium into which diffusion occurs
- (iii) the temperature

Diffusion co-efficient can also be considered as a measure of how fast one species can diffuse into another

Activation energy: Atoms will have to overcome the resistance and barriers to their movement and, some energy is required for this.

So energy required to overcome the barrier is known as activation energy

Factors affecting diffusion process

(1) Nature of the diffusing species - atomic diameter, bonding, melting point etc.

(2) Concentration of the medium into which diffusion takes place

(3) Crystal structure – atomic packing factor, atomic density along diffusion direction, distortion of crystal lattice etc.

(4) Presence of crystal imperfections – provides paths for diffusion.

(5) Grain size – fine grains means more grain boundaries and hence more diffusion paths.

(6) Temperature – higher the temperature faster the diffusion.

(7) Impurities – presence of impurities slows down diffusion.

Fick’s Laws of Diffusion

Fick’s First Law of Diffusion

Statement :

Fick’s first law states that diffusion flux is proportional to the concentration gradient.

$$\boxed{J \propto \frac{dc}{dx}}$$

$$J \equiv atoms/area/time \propto concentration\ gradient$$

Fick’s first law states that flux, *J, is proportional to the concentration gradient.*

$$J \propto \frac{dc}{dx}$$

$$J = -D\frac{dc}{dx}$$

The constant of proportionality is called diffusion coefficient (diffusivity), *D (cm^2/sec)*

$$J = \frac{1}{A}\frac{dn}{dt} = -D\frac{dc}{dx}$$

$$\frac{dn}{dt} = -DA\frac{dc}{dx}$$

Fick’s first law

No. of atoms crossing area A per unit time

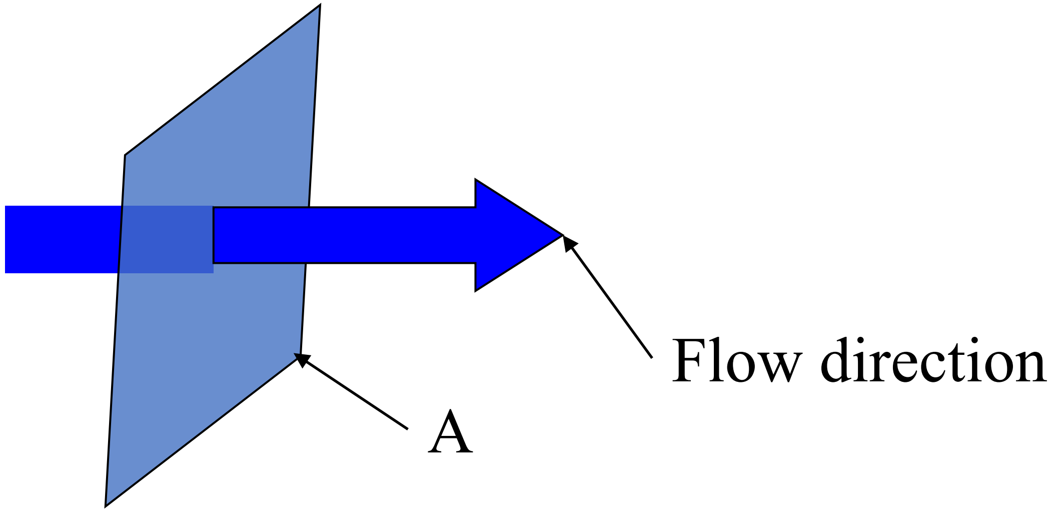
$$\frac{dn}{dt} = -DA\frac{dc}{dx}$$

Diffusion coefficient/ diffusivity

Cross-sectional area

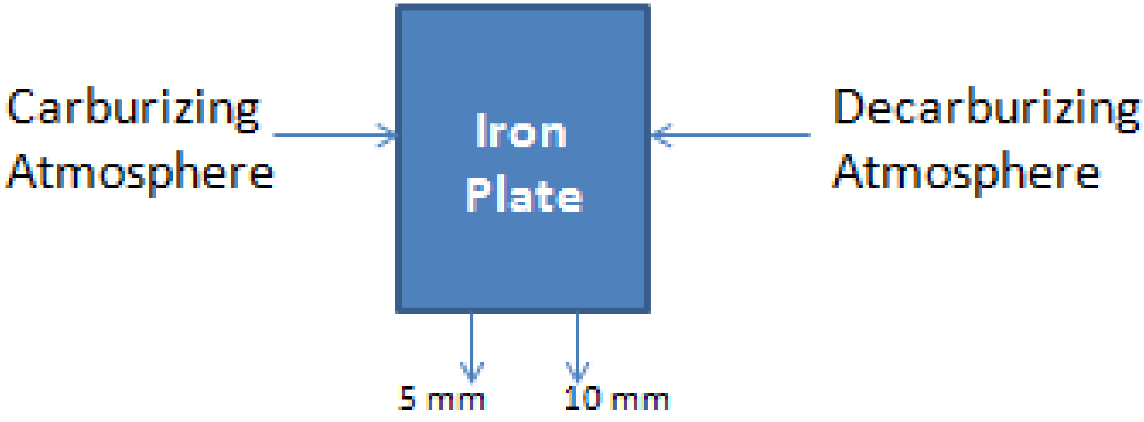
Concentration gradient

Matter transport is down the concentration gradient



Fick’s First Law - Problem

- A plate of iron is exposed to a Carburizing (carbon-rich) atmosphere on one side and a decarburizing (carbon-deficient) atmosphere on the other side at 700 Degree Celsius. If a condition of steady state is achieved, calculate the diffusion flux of carbon through the plate if the concentrations of carbon at positions of 5 and 10 mm beneath the carburizing surface are 1.2 and 0.8 kg/m^3, respectively. Assume a diffusion coefficient of 3x10^{-11} m^2/s at this temperature.



Carburizing Atmosphere

Iron Plate

Decarburizing Atmosphere

5 mm

10 mm

$$J = -D\frac{C_A - C_B}{x_A - x_B}$$

$$J = -D\frac{C_A - C_B}{x_A - x_B} = -(3 \times 10^{-11}\ \mathrm{m^2/s})\frac{(1.2 - 0.8)\ \mathrm{kg/m^3}}{(5 \times 10^{-3} - 10^{-2})\ \mathrm{m}}$$

$$= 2.4 \times 10^{-9}\ \mathrm{kg/m^2\text{-}s}$$

Fick's Second Law of Diffusion

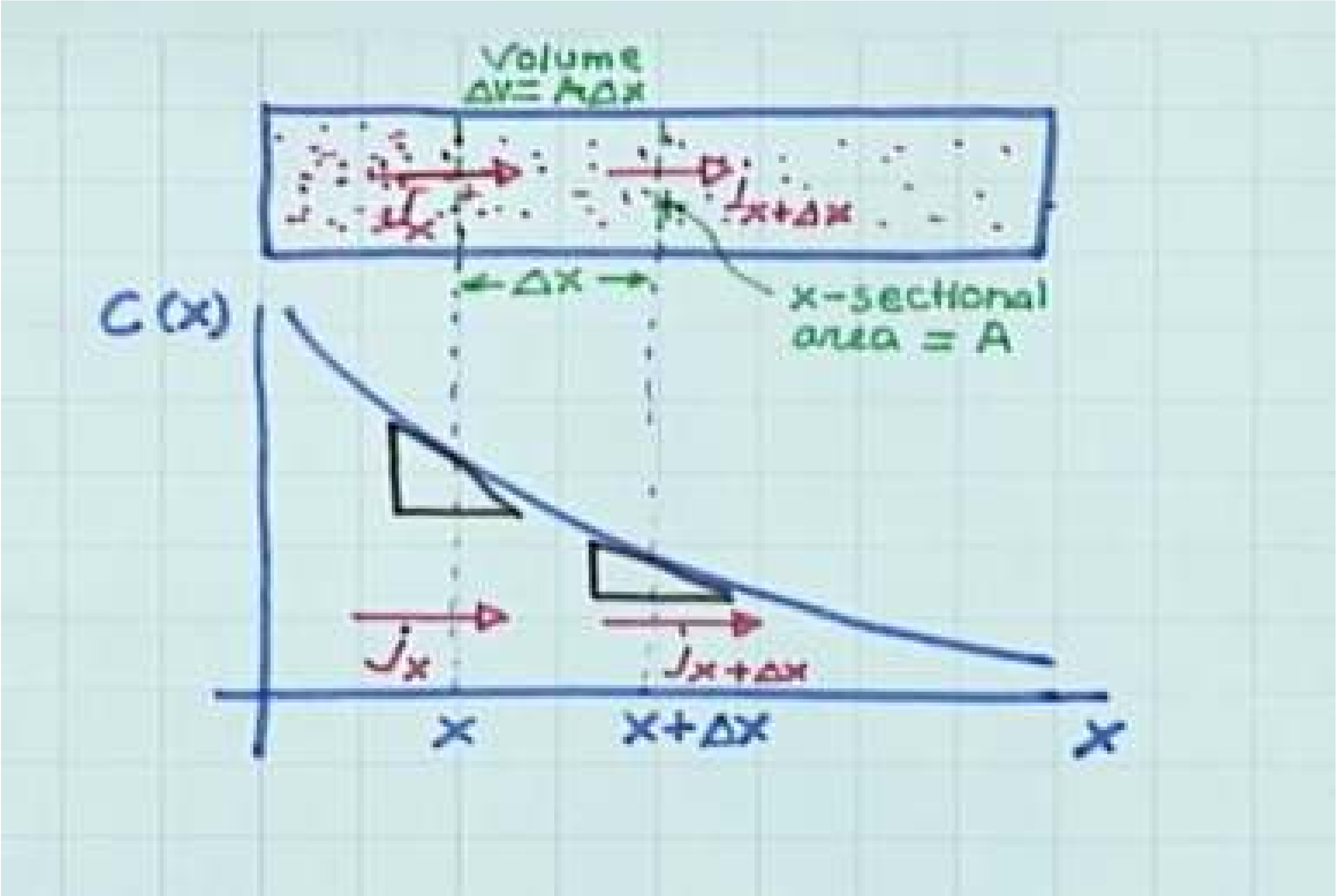
Fick's second law

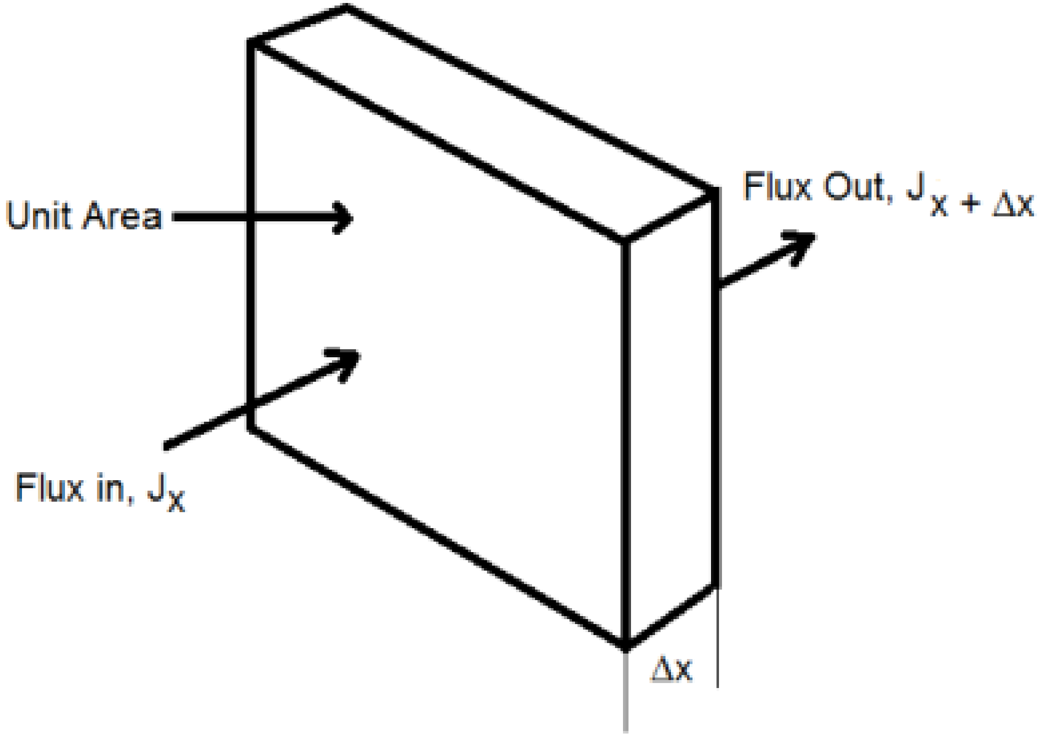
The changes of the concentration profile can be described in this case by a differential equation, **Fick's second law**

Statement :

Fick's second law states that rate of accumulation of concentration within a volume is proportional curvature of concentration gradient

Fick's Second Law of Diffusion





Fick’s law is used in the study and analysis of various transformations and heat treatment process

$$\frac{\partial c}{\partial t}\Delta x = J_x - J_{x+\Delta x}$$

$$\left(\frac{\partial c}{\partial t}\right)\Delta x = J_x - \left\{J_x + \frac{\partial J}{\partial x}\Delta x\right\}$$

$$\left(\frac{\partial c}{\partial t}\right)\Delta x = -\frac{\partial J}{\partial x}\Delta x$$

$$\left(\frac{\partial c}{\partial t}\right) = -\frac{\partial}{\partial x}\left(-D\frac{\partial c}{\partial x}\right)$$

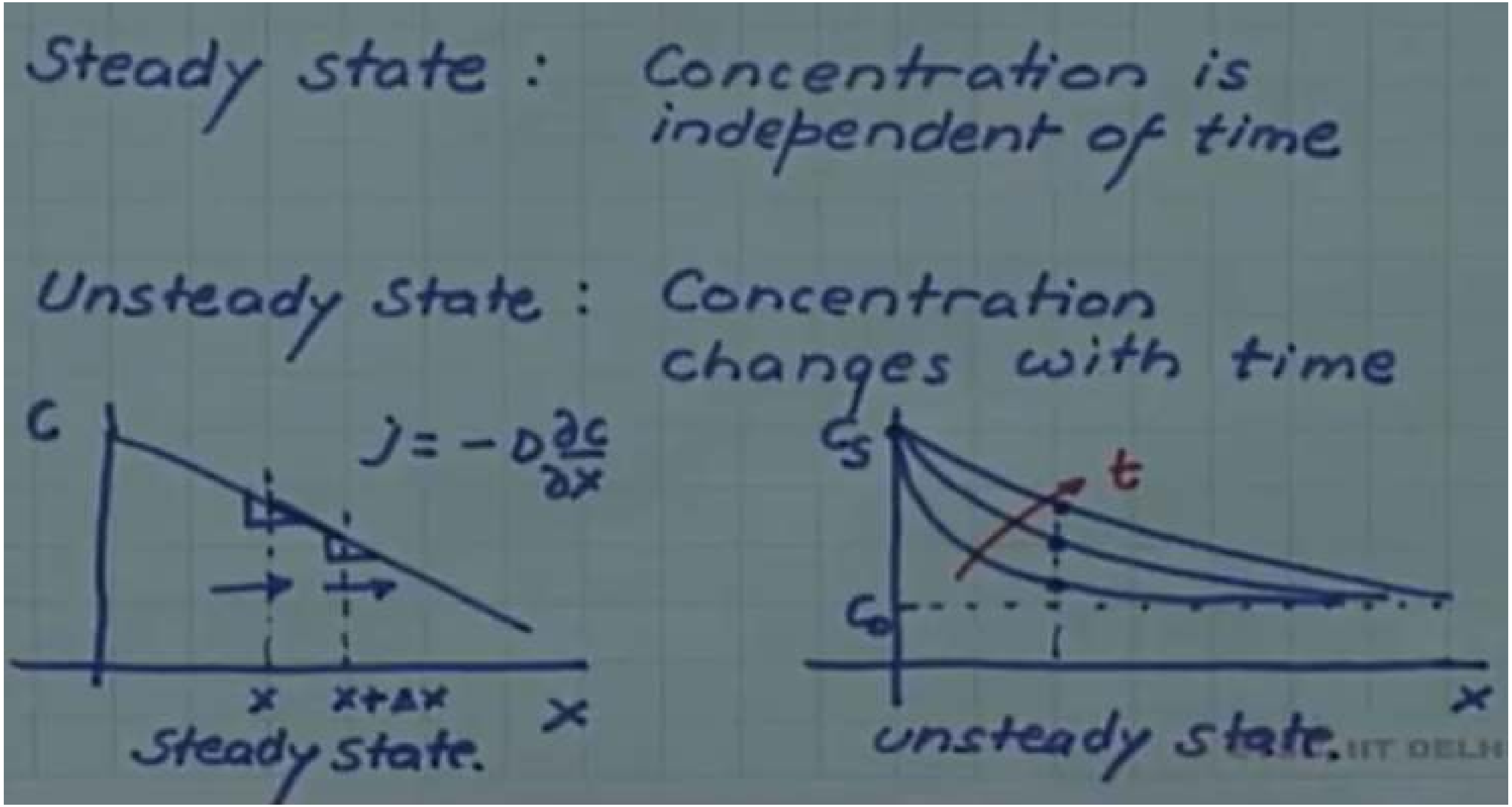
$$J = -D\frac{dc}{dx}$$

Fick’s first law

$$\left(\frac{\partial c}{\partial t}\right) = \frac{\partial}{\partial x}\left(D\frac{\partial c}{\partial x}\right) \longrightarrow \left(\frac{\partial c}{\partial t}\right) = D\frac{\partial^2 c}{\partial x^2}$$

Fick’s second law

Steady and unsteady state of Diffusion



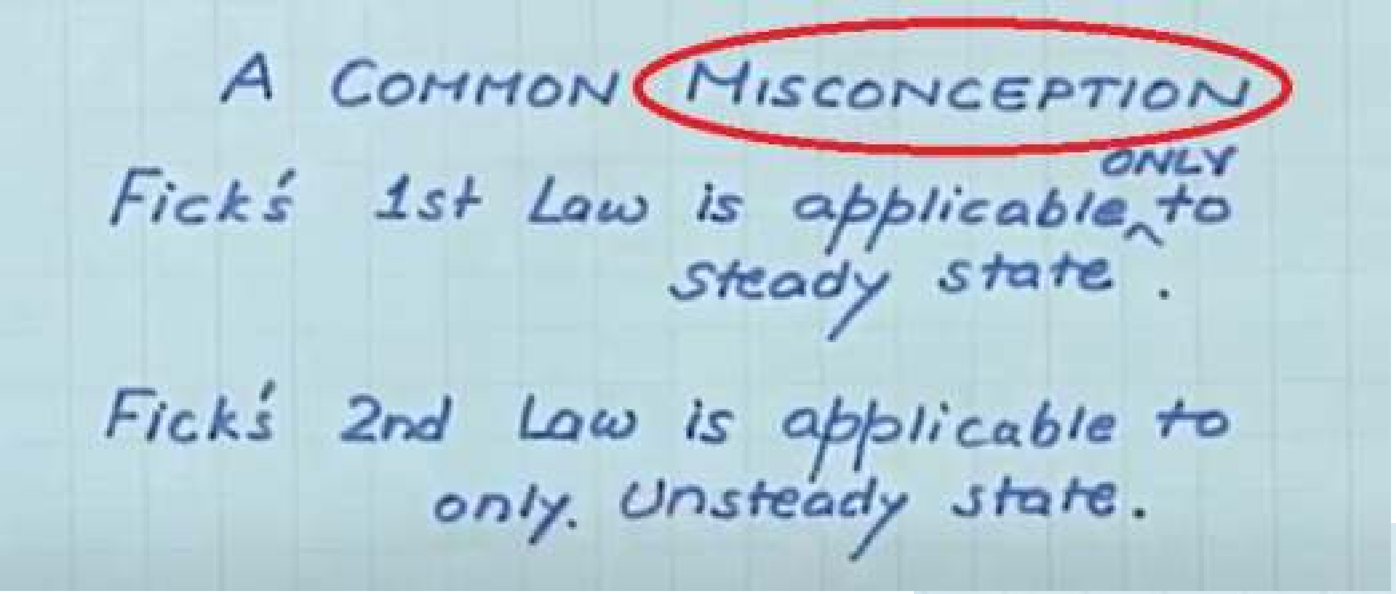
Steady state : Concentration is independent of time

Unsteady State : Concentration changes with time

$J = -D\frac{\partial c}{\partial x}$

Steady State.

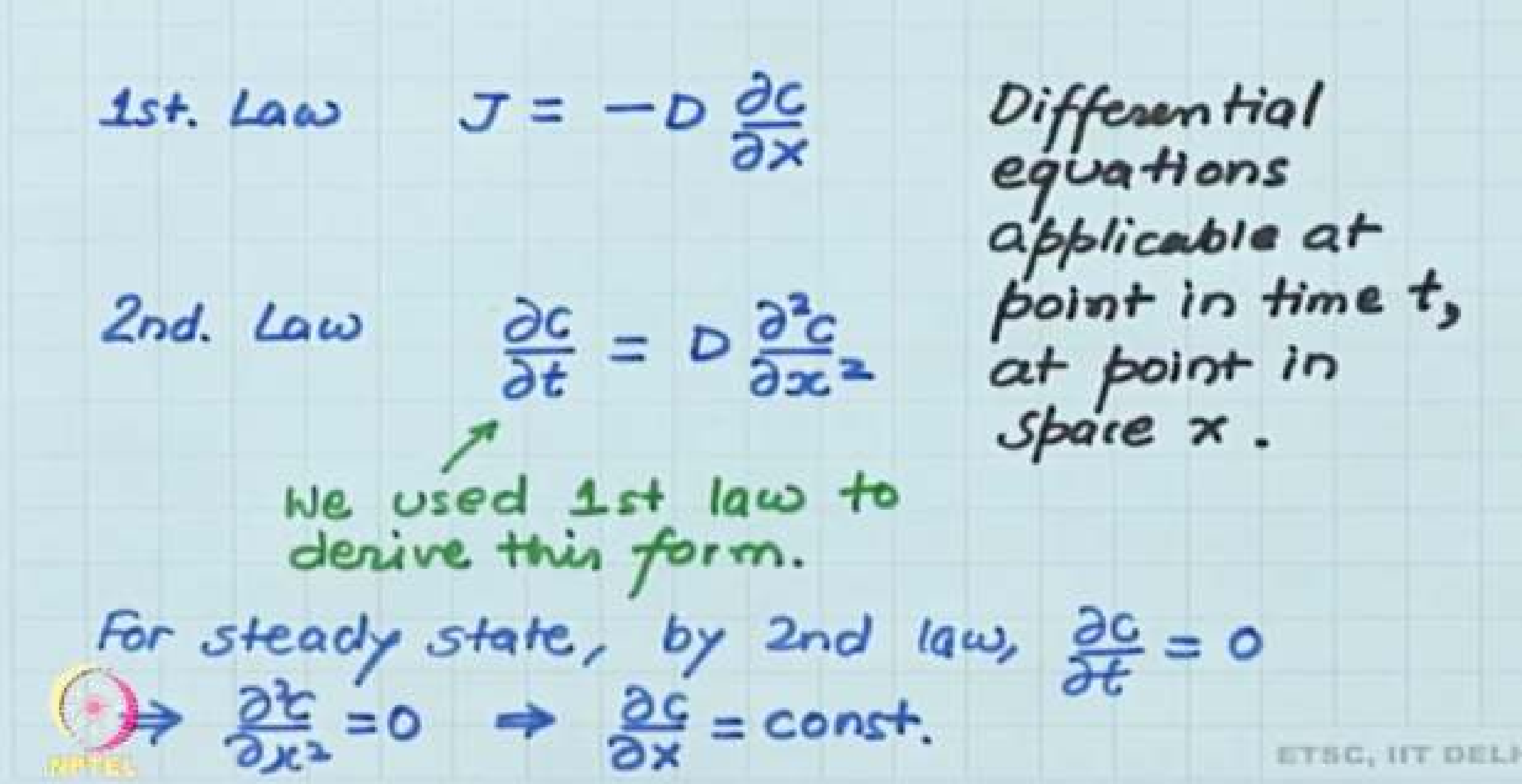
unsteady state.



A COMMON MISCONCEPTION

Fick's 1st Law is applicable ONLY to steady state.

Fick's 2nd Law is applicable to only Unsteady state.



1st. Law $J = -D \frac{\partial c}{\partial x}$

2nd. Law $\frac{\partial c}{\partial t} = D \frac{\partial^2 c}{\partial x^2}$

We used 1st law to derive this form.

Differential equations applicable at point in time t, at point in Space x.

For steady state, by 2nd law, $\frac{\partial c}{\partial t} = 0$

$\Rightarrow \frac{\partial^2 c}{\partial x^2} = 0 \Rightarrow \frac{\partial c}{\partial x} = \text{const.}$

Application of Diffusion

Diffusion plays important role when materials are processed at *higher temperature*

1. Melting and Casting – Diffusion play an important role in solidification of metals and alloy
2. Sintering - Diffusion play an important role in materials processed using powder metallurgy
3. Surface Hardening of Steels – case hardening by carburization , nitriding…..
4. Doping of semiconductors – Doping P ,As, B … in to Si atom
5. Oxidation of Aluminum – By formation of protective layer of Alumina
6. Beverage Bottles – PET bottle used for carbonated beverages

Module 3

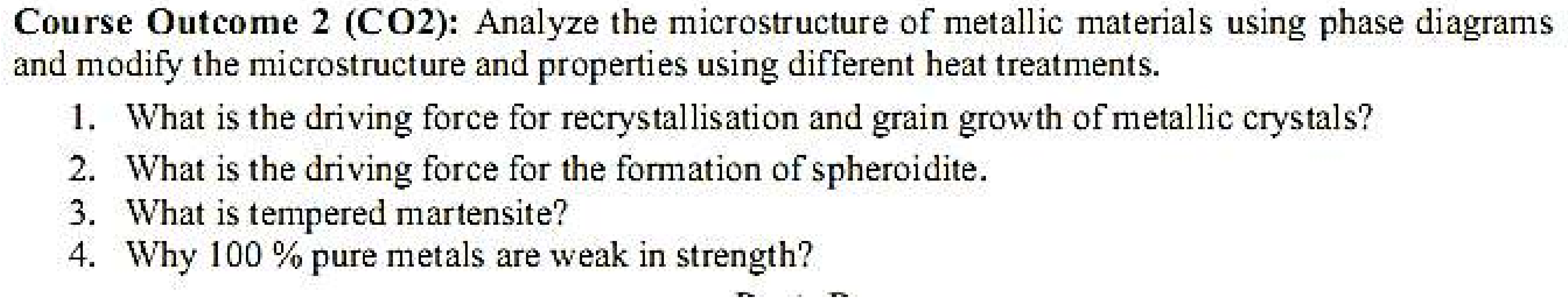
SYLLABUS

Phase diagrams: - need of alloying - classification of alloys - Hume Rothery`s rule – equilibrium diagram of common types of binary systems: five types - Coring - lever rule and Gibb`s phase rule – Reactions - Detailed discussion on Iron-Carbon equilibrium diagram with microstructure and properties -Heat treatment: - TTT, CCT diagram, applications - Tempering- Hardenability, Jominy end quench test, applications- Surface hardening methods.

Course Outcome 2

At the end of the Module students will be able to,

Analyze the microstructure of metallic materials using phase diagrams and modify the microstructure and properties using different heat treatments.



Course Outcome 2 (CO2): Analyze the microstructure of metallic materials using phase diagrams and modify the microstructure and properties using different heat treatments.

1. What is the driving force for recrystallisation and grain growth of metallic crystals?
2. What is the driving force for the formation of spheroidite.
3. What is tempered martensite?
4. Why 100 % pure metals are weak in strength?

PHASE DIAGRAMS

Solid Solution

- If two liquids, soluble in each other (such as water and alcohol) are combined, a liquid solution is produced as the molecules intermix, and its composition is homogeneous throughout.

- A solid solution has two components,
  - Solvent
  - Solute

- Solvent represents the element or compound that is present in the greatest amount in a solid solution.

- Solute is used to denote an element or compound present in a minor concentration.

- In alloy formation, The addition of impurity atoms to a metal will result in the formation of a **solid solution** and/or a new *second phase,* depending on the kinds of impurity, their concentrations, and the temperature of the alloy.

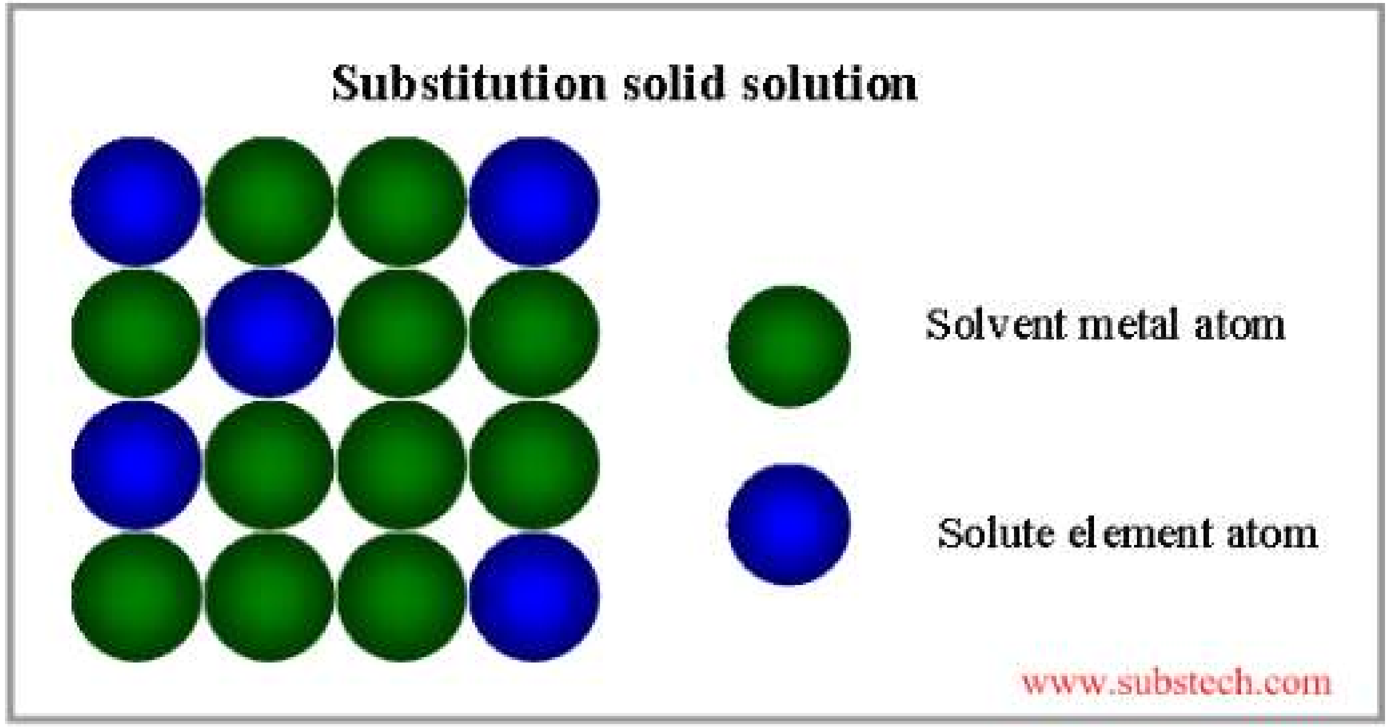
- A solid solution forms when, as the solute atoms (impurity) are added to the host material, the crystal structure is maintained, and no new structures are formed.

- A solid solution is also compositionally homogeneous; the impurity atoms are randomly and uniformly dispersed within the solid.

- A solid solution consists of atoms of at least two different types; the solute atoms occupy either substitutional or interstitial positions in the solvent lattice, and the crystal structure of the solvent is maintained.

Substitutional Solid solutions

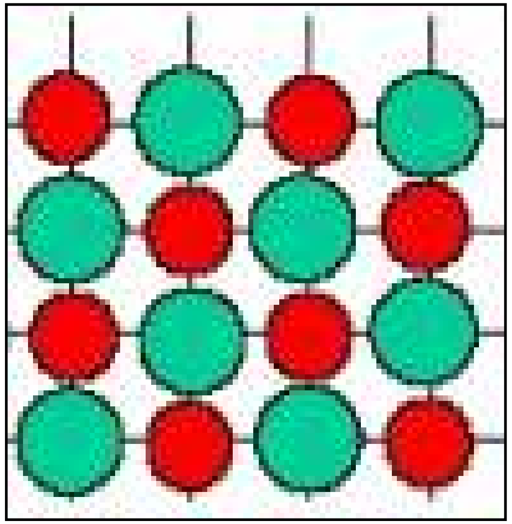
Here there is direct substitution of one type of atom for another



In a Cu-Ni solid solution

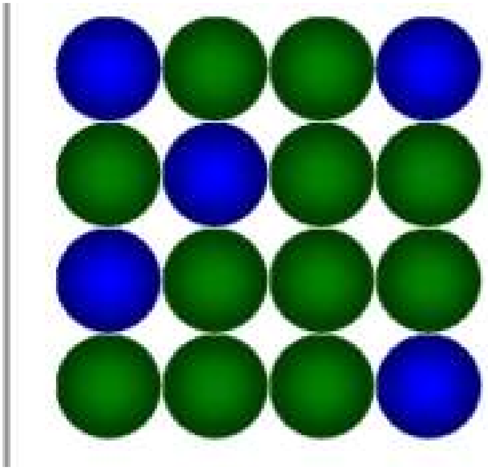
The solute atom (Ni) takes the position normally occupied by solvent (Cu) atoms.

Substitutional Solid solutions



Ordered substitutional solid solution

Solute and solvent atoms are arranged in a regular fashion on the atomic sites

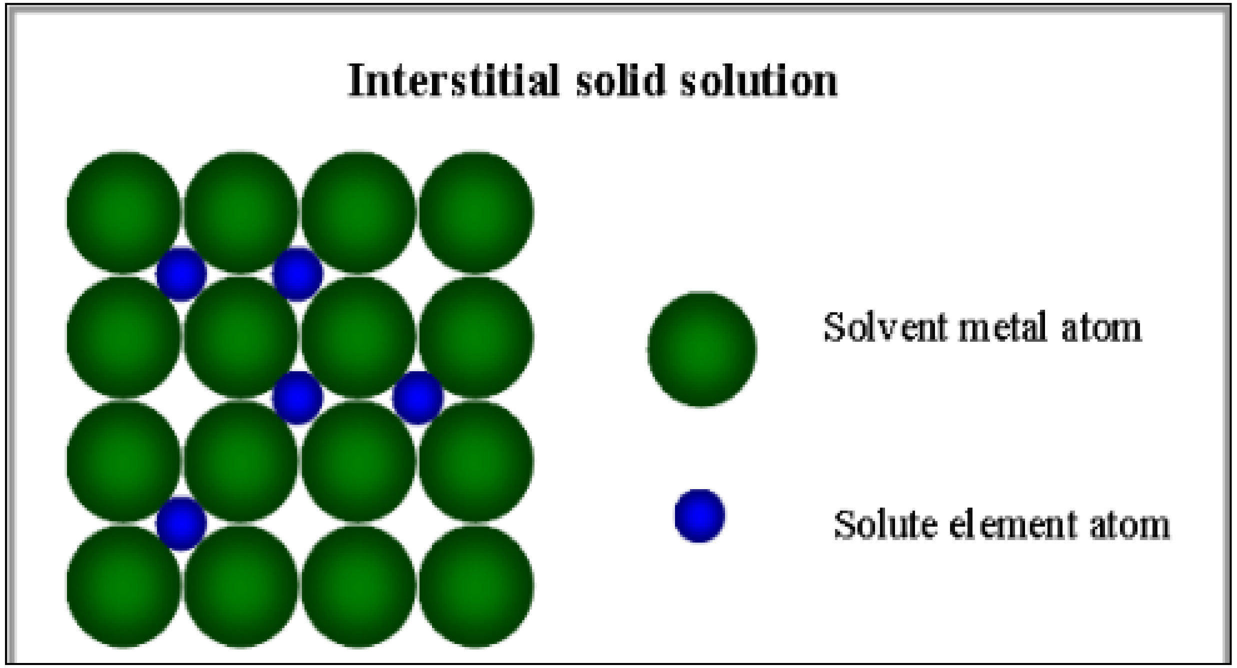


Random substitutional solid solution

Solute and solvent atoms are arranged in a random fashion on the atomic sites

Interstitial Solid solutions

When the solute atoms are much smaller than solvent atoms, they may occupy the interstitial voids between the solvent atoms.



Note:
In some case both interstitial and substitutional solid solutions are formed

Example

- Carbon forms an interstitial solid solution when added to iron
- The maximum concentration of carbon is about 2%.
- The atomic radius of the carbon atom (0.071 nm)is much less than that for iron (0.124 nm.)

Hume – Rothery's Rule

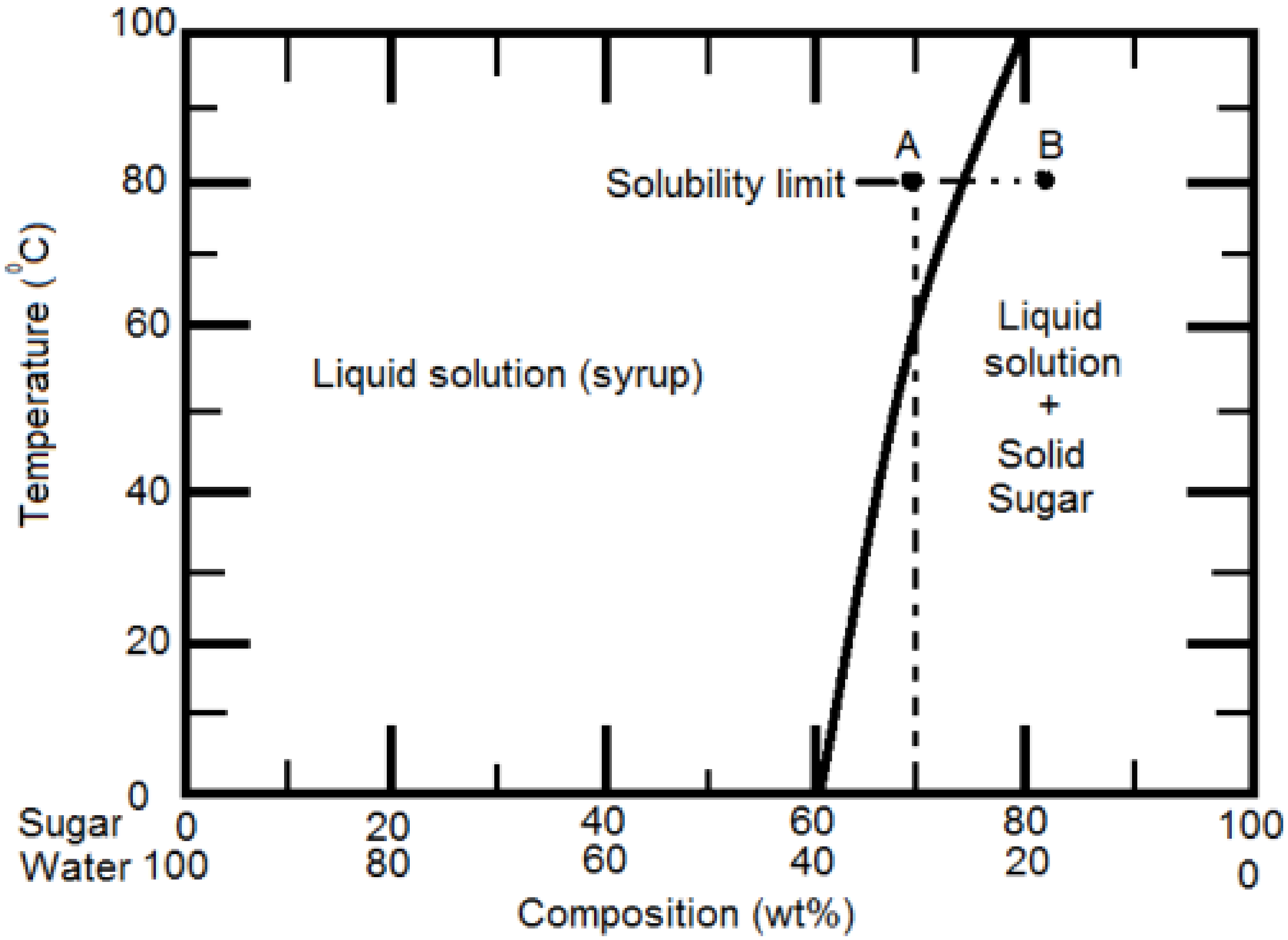
Four conditions that governs the Substitutional solid solubility

1. The size difference between the solvent and solute atoms must be less than 15%
2. The crystal structure of both the metals must be the same
3. The difference in electro negativity of the two metals must be small.
4. The valencies of the atoms must be nearly the same.

- Eg. ***solid solution for copper and nickel*.**
- These two elements are completely soluble in one another at all proportions.
- Atomic radii for copper and nickel are 0.128 and 0.125 nm, respectively
- Both have the FCC crystal structure,
- Their electro negativities are 1.9 and 1.8
- Most common valences are for copper are +1 , +2 and for nickel its +1.

Solubility of sugar and water

$C_{12}H_{22}O_{11}$ –H2O



Left of solubility curve – single phase of sugar syrup

Right side of curve – liquid syrup and solid crystal co-exist

- For many alloy systems and at some specific temperature, there is a maximum concentration of solute atoms that may dissolve in the solvent to form a solid solution; this is called a solubility limit.

- As more sugar is introduced, the solution becomes more concentrated, until the solubility limit is reached, or the solution becomes saturated with sugar.

- At this time the solution is not capable of dissolving any more sugar, and further additions simply settle to the bottom of the container.

- Thus, the system now consists of two separate substances: a sugar–water syrup liquid solution and solid crystals of undissolved sugar.

- This solubility limit of sugar in water depends on the temperature of the water and Sugar

Alloys

Alloy is a substance composed of two or more elements.

The element present in largest proportion is called base metal and other elements present are known as alloying elements

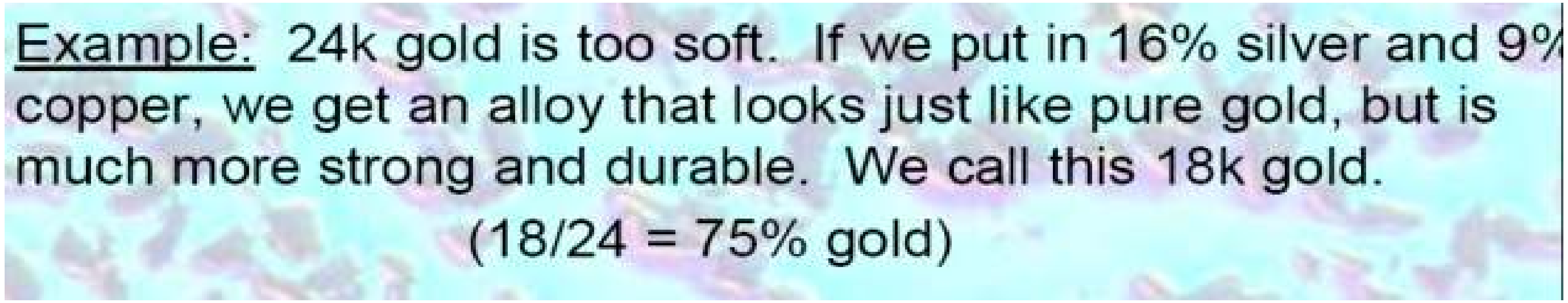
Alloying elements are added to base metal in order to improve,

- Physical properties
- Chemical properties
- Mechanical properties and
- Electrical properties

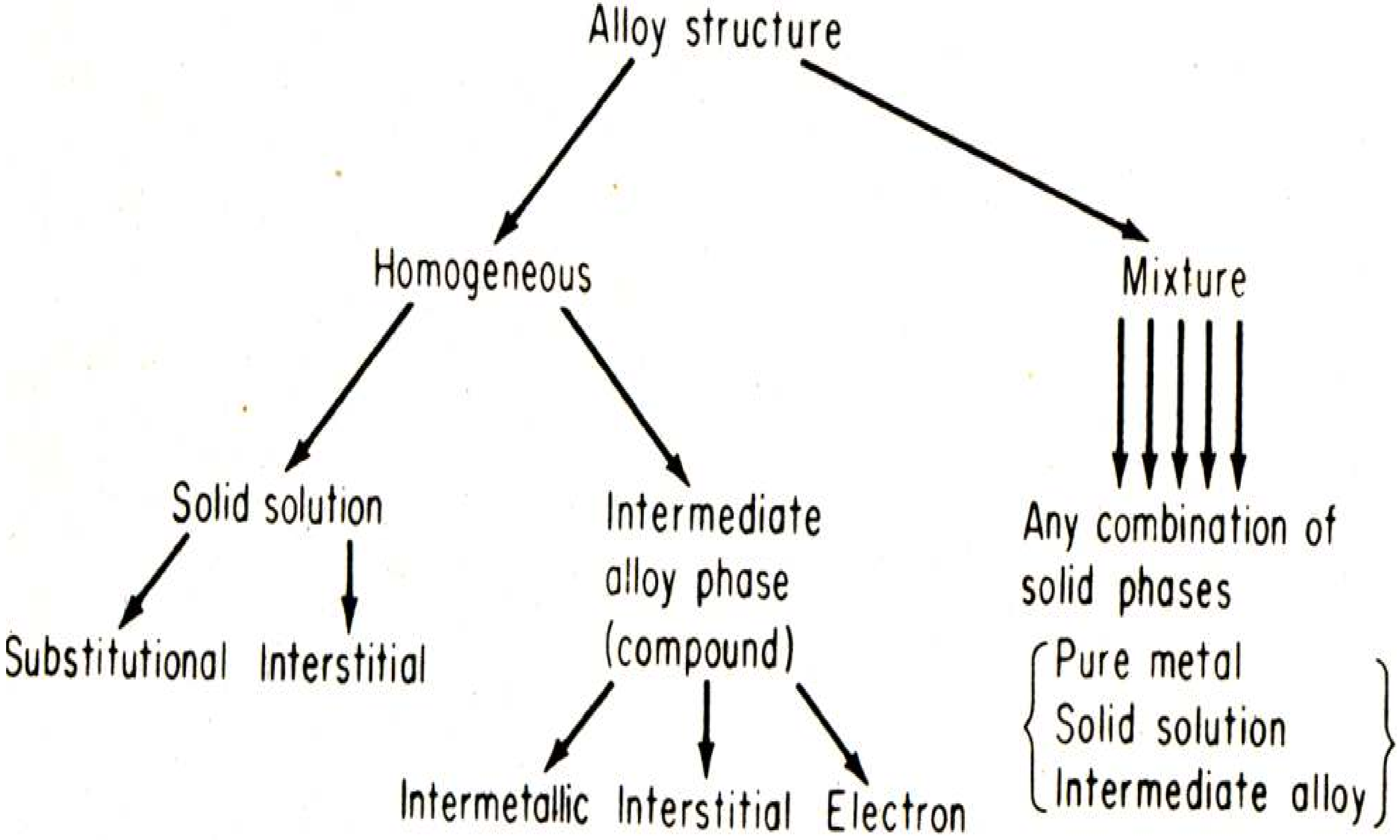
PRIMARY FUNCTION OF ALLOYING

- Alloying elements prevents dislocation movements
- An alloy is a substance that has metallic properties and is composed of two or more chemical elements, of which at least one is metal.
- System made up of two elements – Binary alloy system.
- Three elements- ternary alloy system.

Why 100% pure metals are weak?



Example: 24k gold is too soft. If we put in 16% silver and 9% copper, we get an alloy that looks just like pure gold, but is much more strong and durable. We call this 18k gold.
(18/24 = 75% gold)



Possible alloy structures.

Definitions: Components and Phases

Phase

A phase may be defined as a homogeneous portion of a system that has uniform physical and chemical characteristics. Every pure material is considered to be a phase.

Two distinct phases in a system have distinct physical or chemical characteristics

Three phases of matter : Liquid, Solid, Gas.

- Solid phases : different crystal structures will be considered different phases.
- Eg, Fe has BCC(α) and CCP (γ)

e.g. Water and ice – distinct physical characteristics
Polymorphic forms - distinct physical characteristics
sugar solution and sugar – distinct physical and chemical

- If more than one phase is present in a given system, each will have its own distinct properties, and a boundary separating the phases will exist across which there will be a discontinuous and abrupt change in physical and/or chemical characteristics.

- When two phases are present in a system, it is not necessary that there be a difference in both physical and chemical properties; a disparity in one or the other set of properties is sufficient.

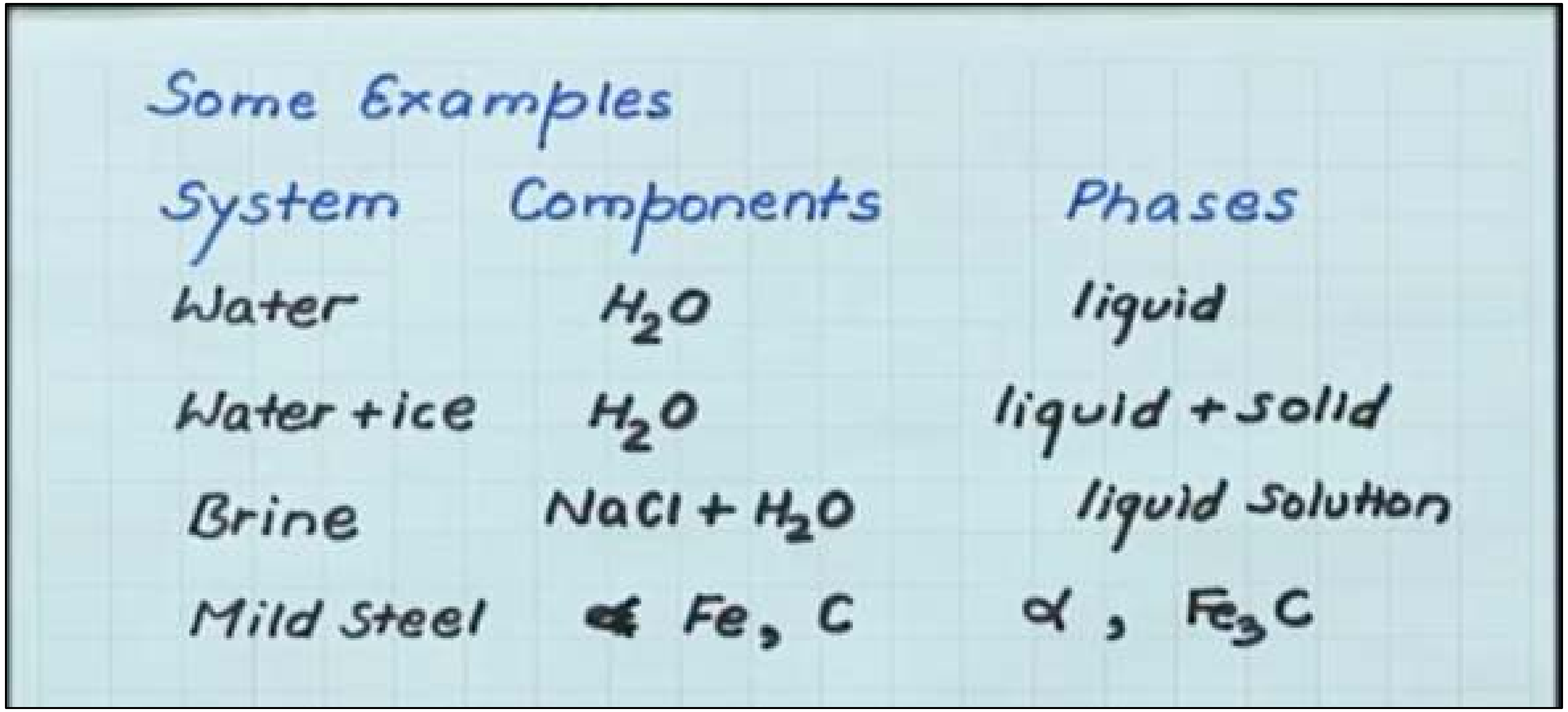
- A single-phase system is called homogeneous
- Systems with two or more phases are mixtures or heterogeneous systems.

- Most metallic alloys and, for that matter, ceramic, polymeric, and composite systems are heterogeneous. Ordinarily, the phases interact in such a way that the property combination of the multiphase system is different from, and more attractive than, either of the individual phases.

Definitions: Components and Phases

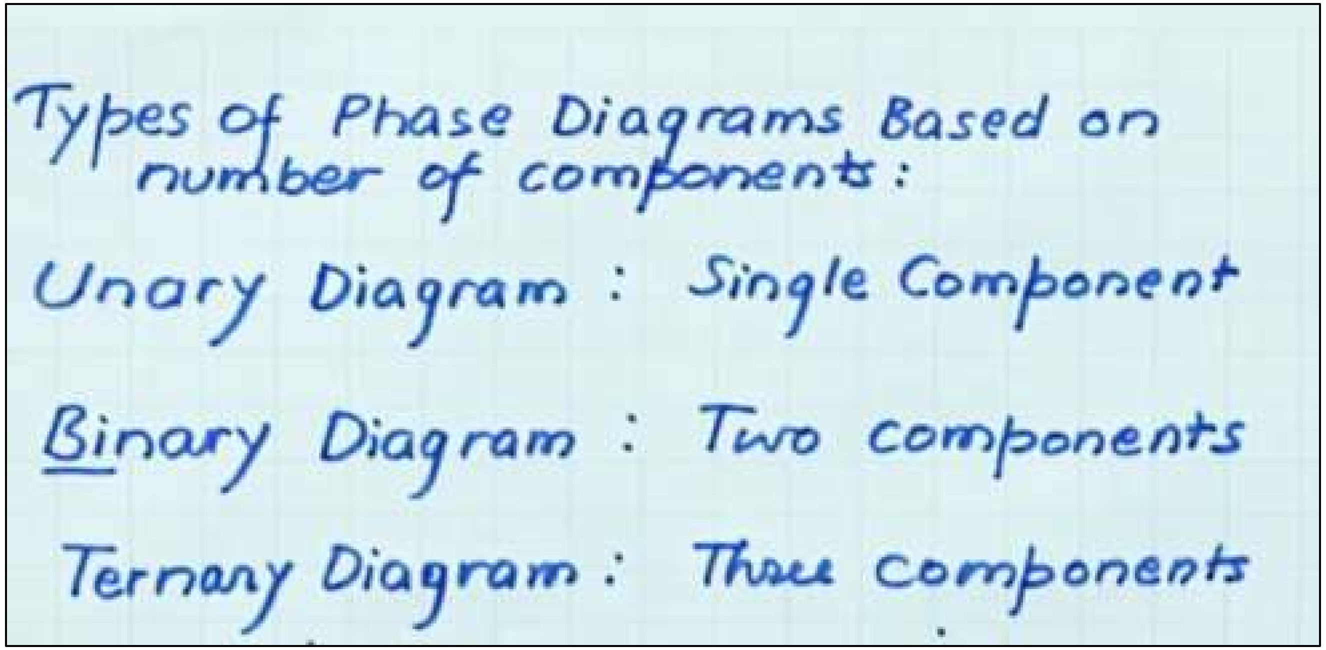
Component

- The independent chemical species (element, compound) in terms of which the composition of a system is specified is/are called components.
- Chemically recognizable species (Fe and C in carbon steel, H2O and NaCl in salted water).
- A binary alloy contains two components, a ternary alloy – three, etc.



Some Examples

System	Components	Phases
Water	H_2O	liquid
Water + ice	H_2O	liquid + solid
Brine	NaCl + H_2O	liquid solution
Mild Steel	~~α~~ Fe, C	α, Fe_3C



Types of Phase Diagrams Based on number of components:

Unary Diagram : Single Component

Binary Diagram : Two components

Ternary Diagram : Three components

Classification of Alloy

- Practically all structural metals in use today are alloys that are obtained by melting two or more different metals together.
- When two metals are melted together and solidified, any of the following three different things can happen:
  - the alloy is formed as a solid solution,
  - as a mixture of separate phases or
  - as an inter metallic compound.
- If X and Y are the two component metals, a solid solution will be formed when the strength of X-Y bond is intermediate between those of X-X and Y-Y bonds. Here the atoms of the metals X and Y randomly occupy the lattice positions in the crystal. Cu-Ni alloy is an example.
- A multi-phase mixture is formed when the X-Y bond is weaker than the X-X bond and Y-Y bond. The alloy solidifies by separating out into two distinct phases. One phase will be rich in X and the other rich in Y. Here the solubility of X in Y and Y in X are relatively low. An example is the Sn-Pb alloy.

Classification of Alloy

- An inter metallic compound is formed when the X-Y bond is stronger than the X-X bond and the Y-Y bonds. Fe3C is an inter metallic compound formed in the Fe-C alloy system.
- The term, alloy system refers to all the different compositions of the particular alloy. This does not mean that all the alloys behave in any one of the above ways in all compositions.
- In some alloy systems, the components are completely soluble in each other at solid state; meaning solid solutions are formed at all compositions. In some other alloy systems, the components are partially soluble in solid state. Here solid solutions are formed at some compositions and phase mixtures at other compositions.
- When the components are completely insoluble in solid state, phase mixtures are formed at all compositions. In some alloy systems, inter metallic compounds are also formed corresponding to certain range of compositions along with solid solutions and/or phase mixtures at some other compositions. As an example, in Fe-C alloy system.

Gibb’s Phase Rule

This rule establishes the relationship between the number of components, the number of phases and number of degree of freedom in a system.

Maximum number of phases P which may co-exist under equilibrium conditions is equal to the sum of the number of components C and between the number of degrees of freedom in the system(number of variable factors)

$$P + F = C + n$$

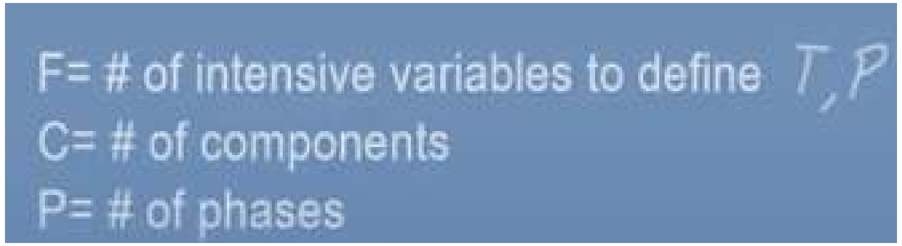
$$P + F = C + 2$$

$$F = C - P + 2$$

$$F = C - P + 2$$

if both temperature and pressure are variable

Where F = no. of degrees of freedom
C = no. of components
P = no. of phases in the system



F= # of intensive variables to define T, P
C= # of components
P= # of phases

The parameter F is termed the number of degrees of freedom or the number of externally controlled variables (e.g., temperature, pressure, composition) which must be specified to completely define the state of the system.

Pressure is usually ignored in the case of liquids and solids.(pressure is kept constant)

So phase rule can be written as,

$$F = C - P + 1$$

- No of **degree of freedom** is the quantity of independent external or internal variables (Pressure , temperature & concentration) which may be altered with out changing the phases in equlibrium.
- No. of phases in a system cant exceed number of components plus one.
- When maximum possible phases are in equilibrium , number of degrees of freedom will be zero – **invariant equilibrium.**
- A system in invariant equilibrium exits at constant temperature and definite composition of all phases.
- Eg. – A pure metal at solidification temperature

- If no of phases is less than max possible number by one then F=1 – called ***Monovariant system***
- If no of phases is less than max possible number by two then F=2 – called ***Bivariant system***

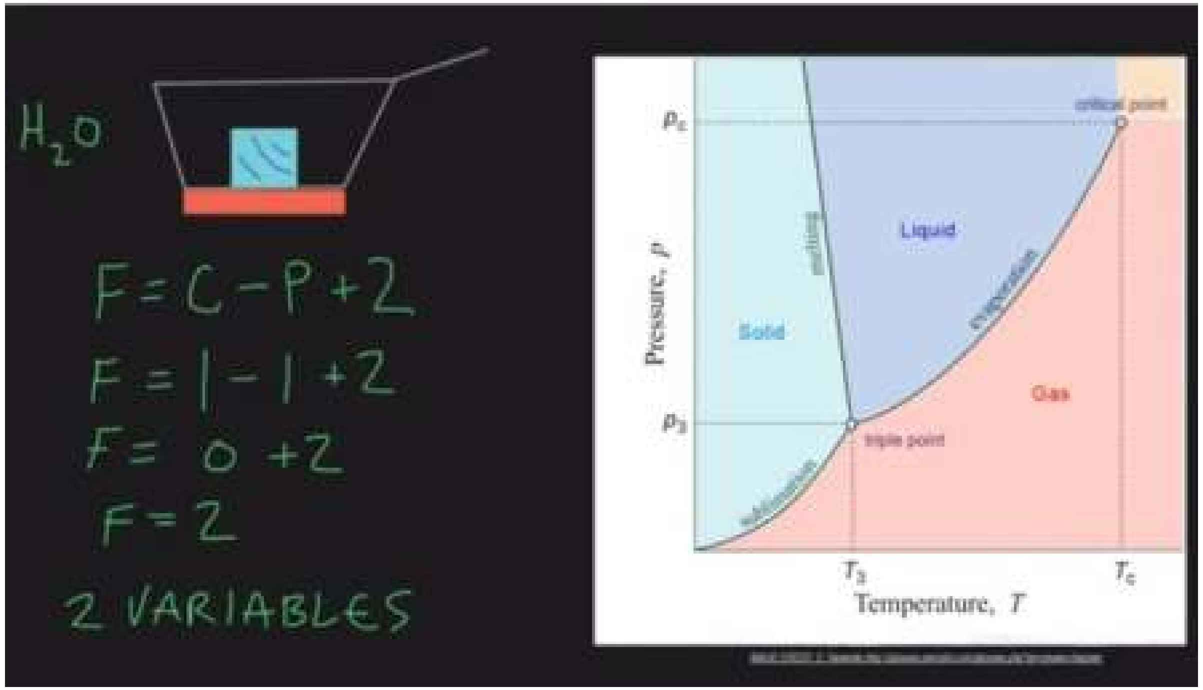
Q? Determine dof of a 2 component system when no of phases is one ,two and three

$$\boxed{F = C - P + 2}$$

If pressure and temperature both are variables

$$\boxed{F = C - P + 1}$$

If pressure is held constant


H_2O

$F = C - P + 2$

$F = 1 - 1 + 2$

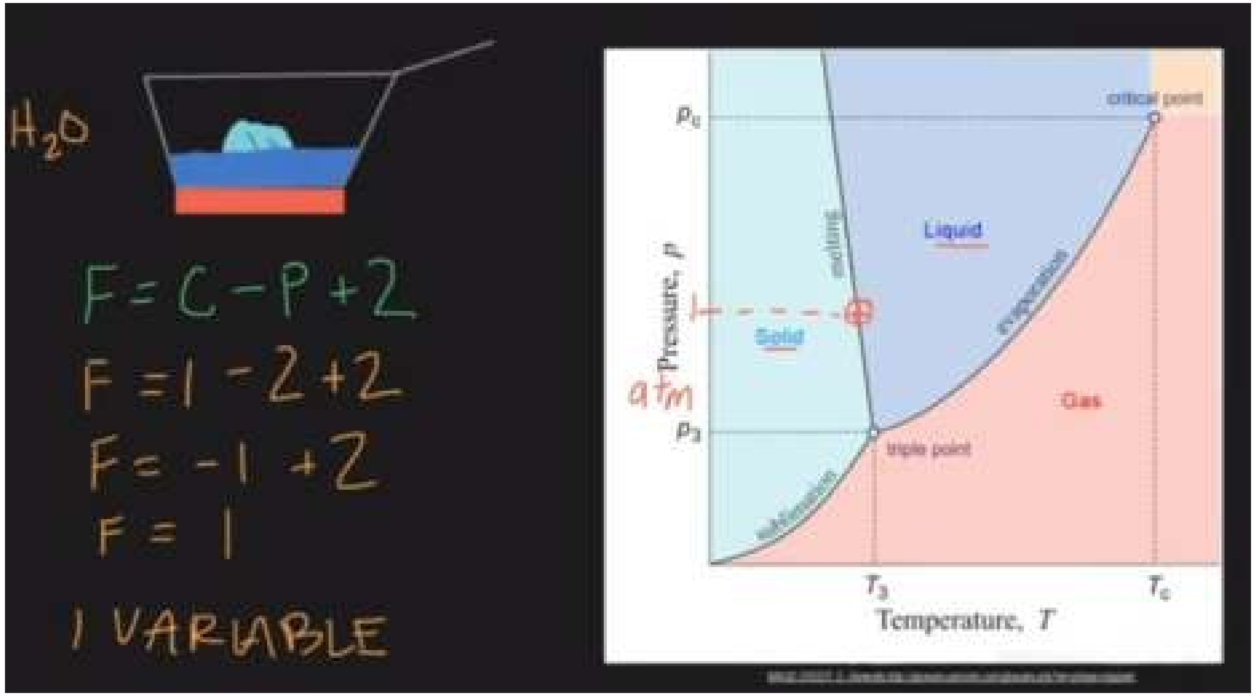
$F = 0 + 2$

$F = 2$

2 VARIABLES

This means that to completely describe the characteristics of solid phase fields, we must specify two parameters (Pressure and temperature here); which locate, respectively, the horizontal and vertical positions of the alloy on the phase diagram.

It is necessary to specify either temperature or the composition of one of the phases to completely define the state of system


H_2O

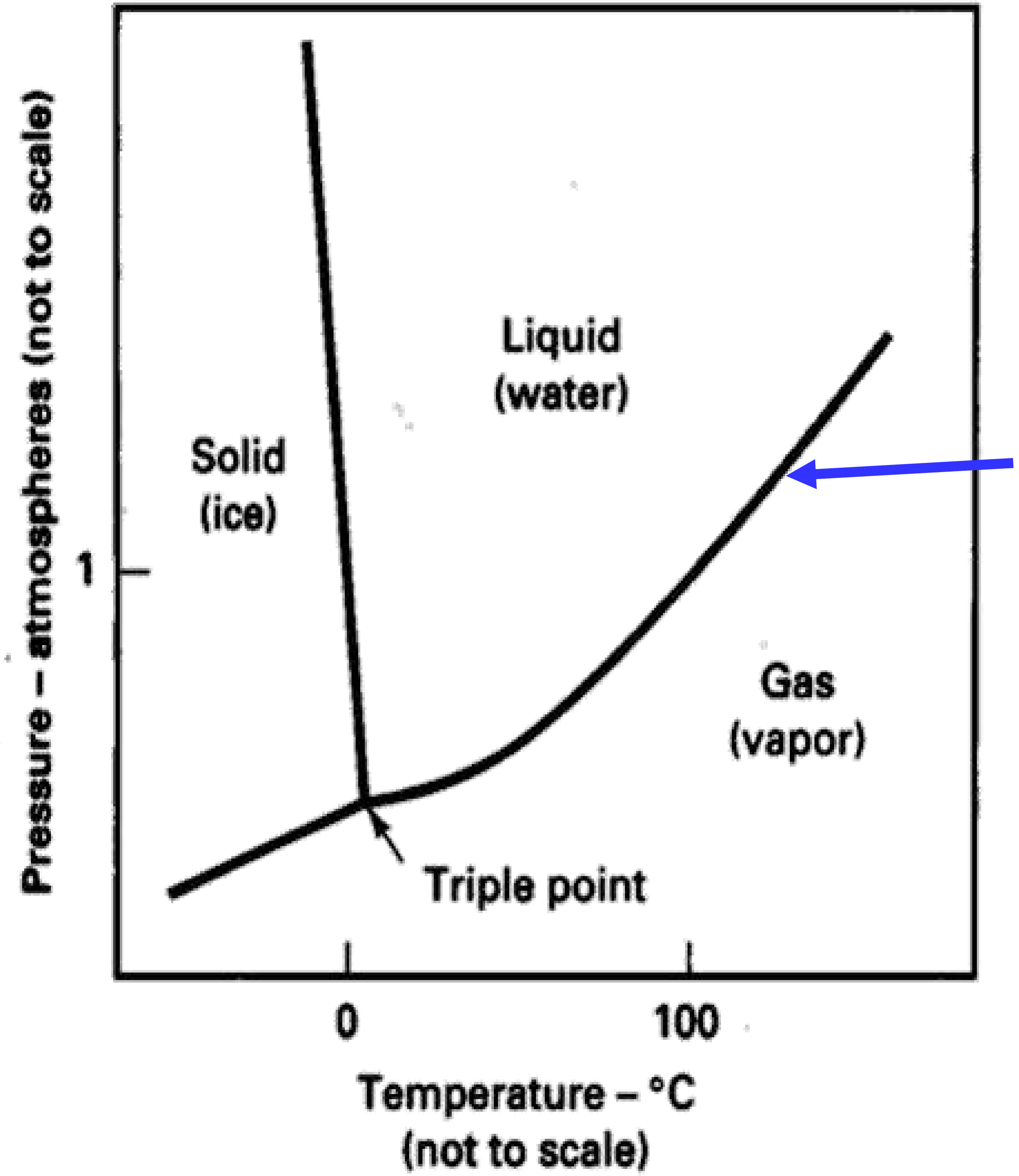
$F = C - P + 2$

$F = 1 - 2 + 2$

$F = -1 + 2$

$F = 1$

1 VARIABLE

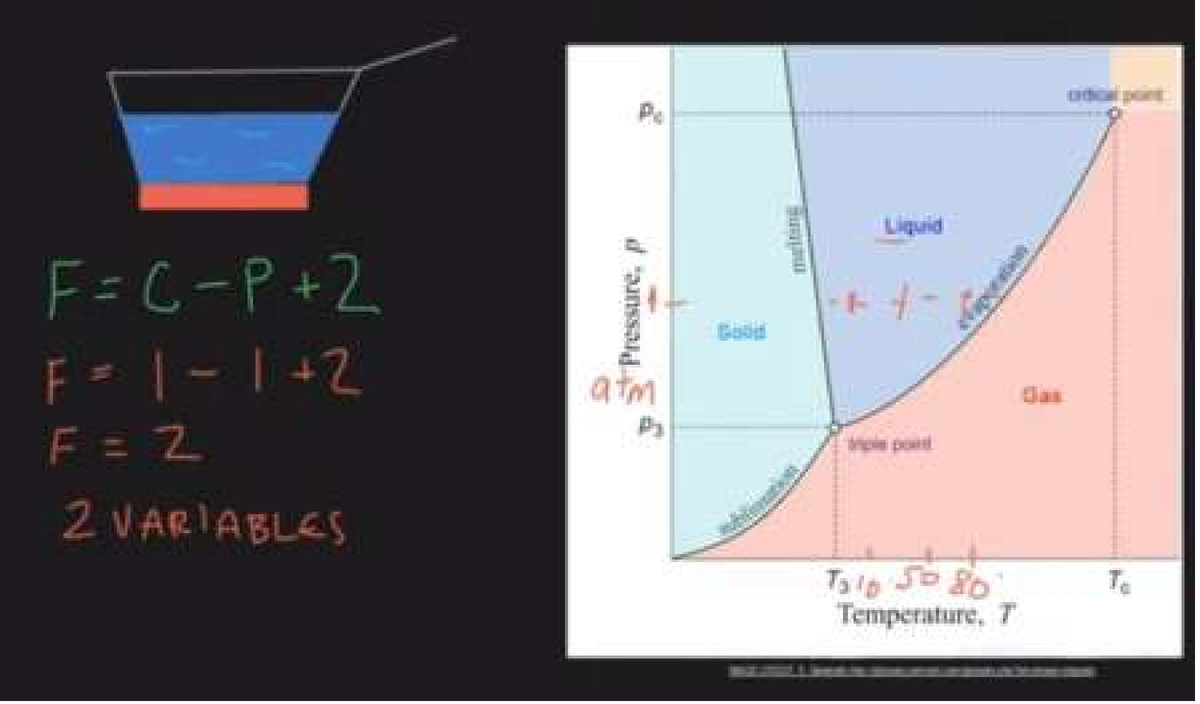


$P + F = C + 2$

$2 + F = 1 + 2$

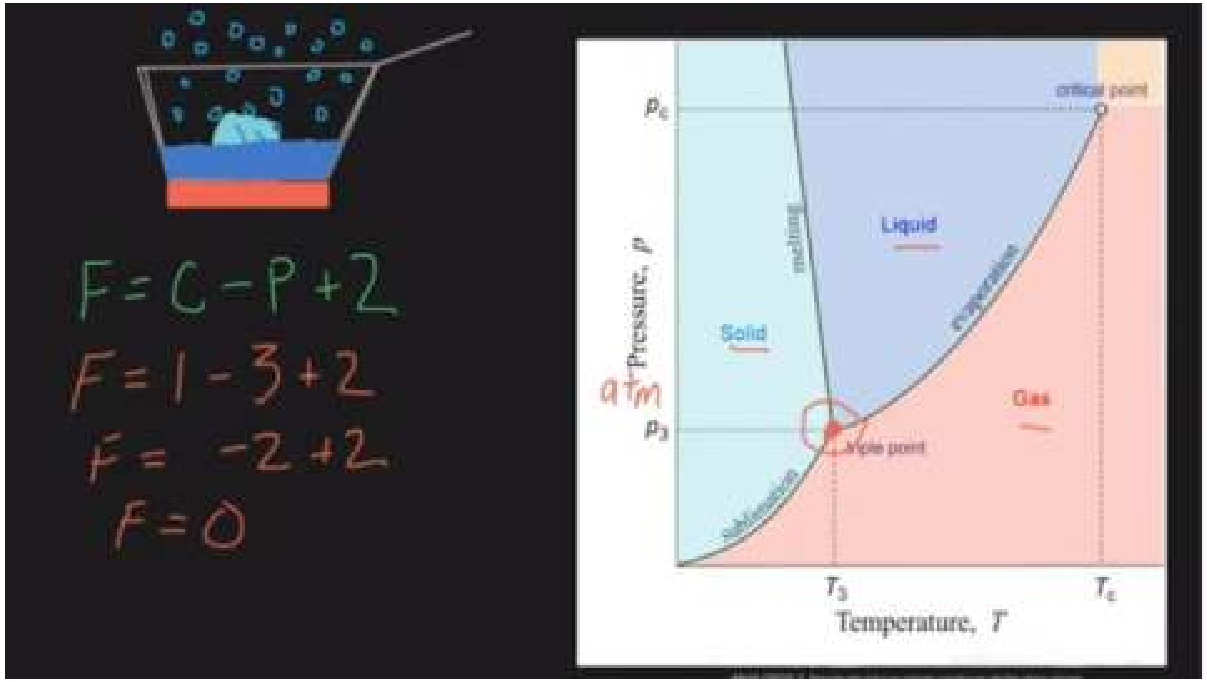
$F = 1$

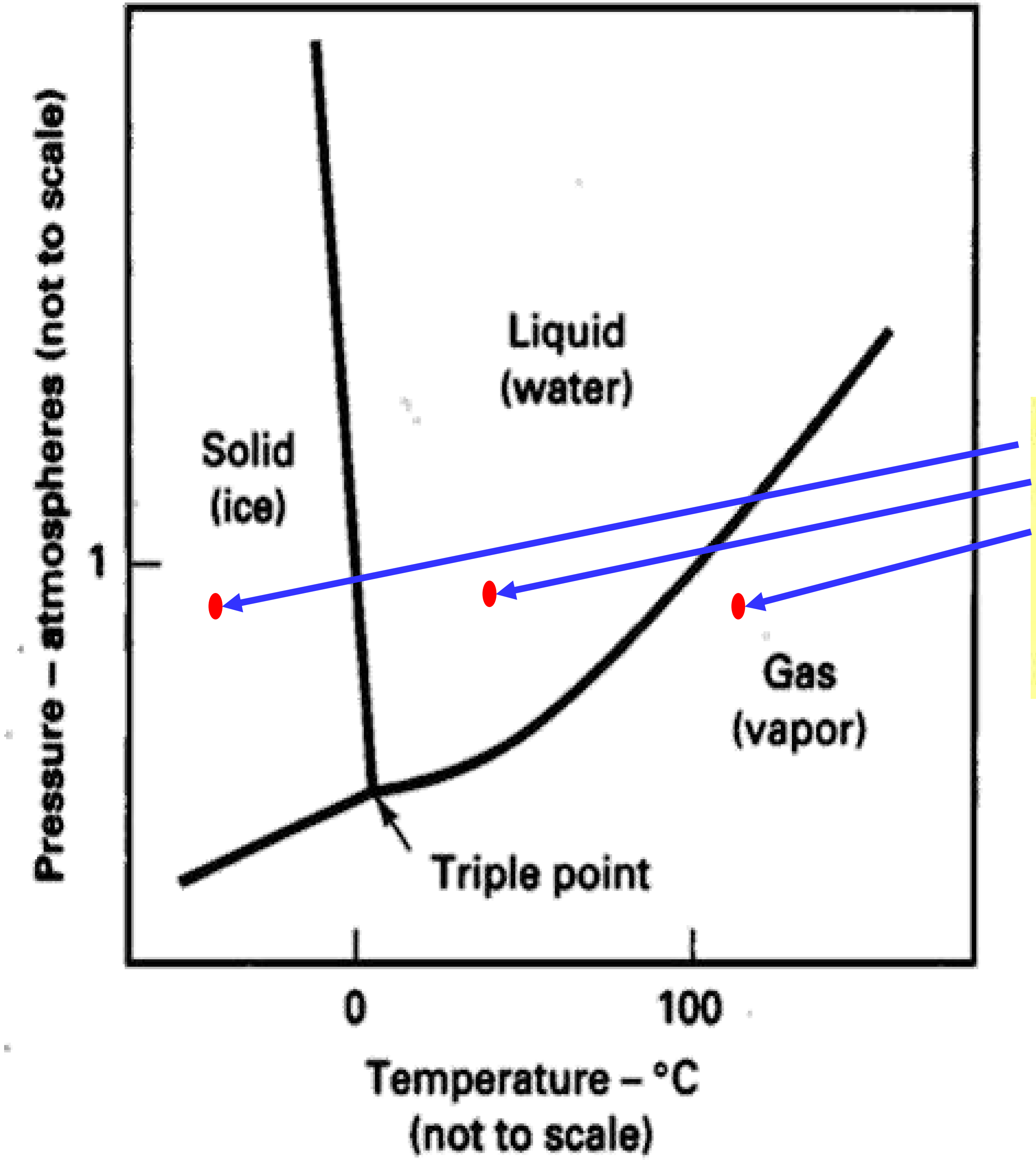
(one degree of freedom)



This means that to completely describe the characteristics of liquid phase fields, we must specify two parameters (Pressure and temperature here); which locate, respectively, the horizontal and vertical positions of the alloy on the phase diagram.

Any alteration of temperature or pressure, then one of phase will disappear OR no need to specify Pressure and temperature define the state of system





$P + F = C + 2$

$1 + F = 1 + 2$

$F = 2$

(two degree of freedom)

Solubility Limit

Solubility Limit: of a component in a phase is the maximum amount of the component that can be dissolved in it.

Example:

- Alcohol has unlimited solubility in water
- Sugar has a limited solubility
- Oil is insoluble

The same concepts can be applied to solid phases: Cu and Ni are mutually soluble in any amount (unlimited solid solubility), while C has a limited solubility in Fe.

PHASE DIAGRAMS OR EQUILIBRIUM DIAGRAMS

- **A diagram** – in the space of relevant thermodynamic variables (eg. Pressure, Temperature and composition) indicating phases in equilibrium is called a **phase diagram**

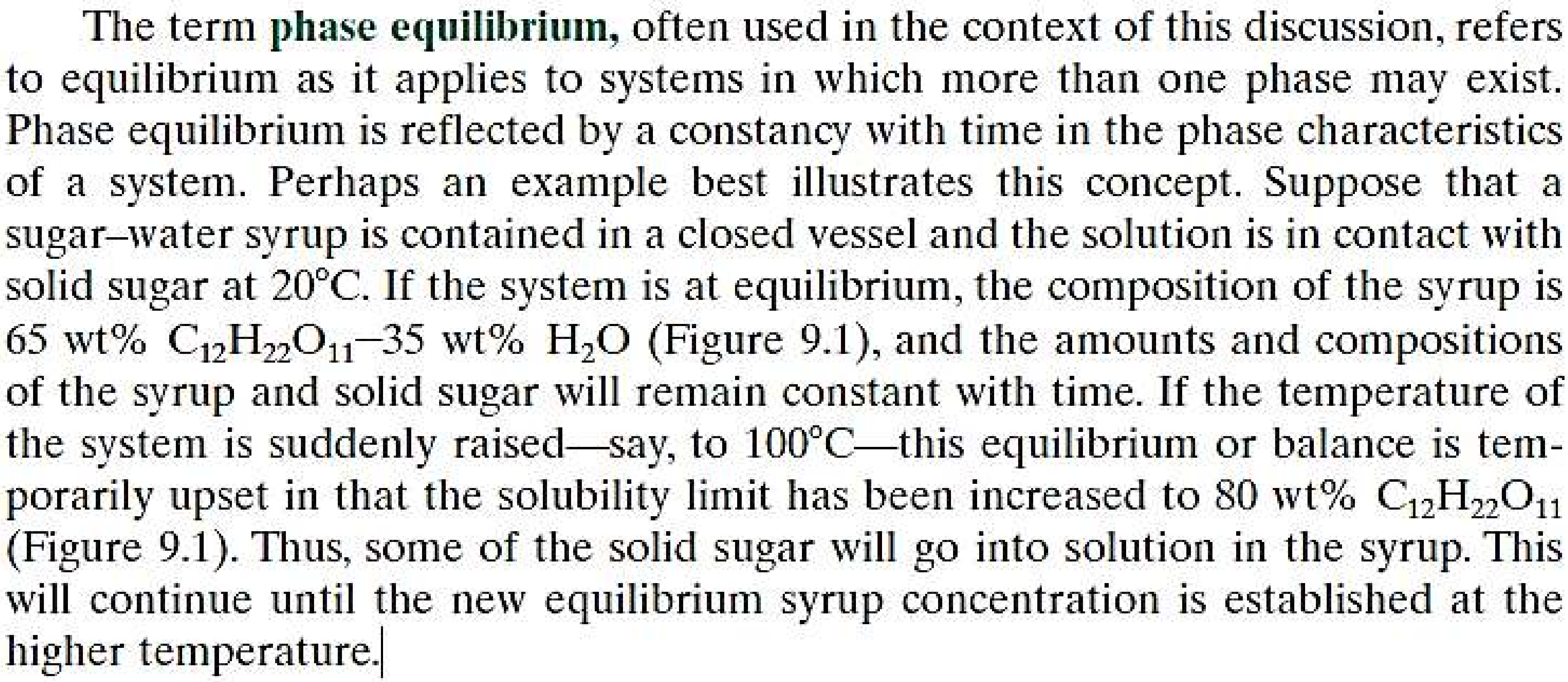
- **A phase diagram** - graphical representation of the combinations of temperature, pressure, composition, or other variables for which specific phases exist at equilibrium.

- Diagram or map representing the relationship between phases in equilibrium in a system as a function of any two among temperature, pressure and composition

- Also called **equilibrium diagram** or constitutional diagrams

- The phase diagram thus shows the phases which exist in **equilibrium** corresponding to any combination of temperature and composition of an alloy.

PHASE EQUILIBRIUM



The term **phase equilibrium,** often used in the context of this discussion, refers to equilibrium as it applies to systems in which more than one phase may exist. Phase equilibrium is reflected by a constancy with time in the phase characteristics of a system. Perhaps an example best illustrates this concept. Suppose that a sugar–water syrup is contained in a closed vessel and the solution is in contact with solid sugar at 20°C. If the system is at equilibrium, the composition of the syrup is 65 wt% $C_{12}H_{22}O_{11}$–35 wt% H_2O (Figure 9.1), and the amounts and compositions of the syrup and solid sugar will remain constant with time. If the temperature of the system is suddenly raised—say, to 100°C—this equilibrium or balance is temporarily upset in that the solubility limit has been increased to 80 wt% $C_{12}H_{22}O_{11}$ (Figure 9.1). Thus, some of the solid sugar will go into solution in the syrup. This will continue until the new equilibrium syrup concentration is established at the higher temperature.

Types of Phase Diagrams

Three externally controllable parameters that will affect the structure of a system are temperature, pressure and composition

Phase diagrams are constructed showing the variation in any two of these parameters in comparison with the others

Unary Diagram : Single component
Binary Diagram : Two component
Ternary diagram :Three component

1. Unary Phase Diagram or One Component Phase diagram

When the parameter composition (a pure component or one component system) is held constant, Pressure and temperature are the variables

The phase diagram thus formed is ***Unary*** phase diagram

1. Unary Phase diagram for water

- The simplest phase diagram is the water which is a one component system.

- It is also known as pressure-temperature or P-T diagram.

- Two phases exist along each of the three phase boundaries.

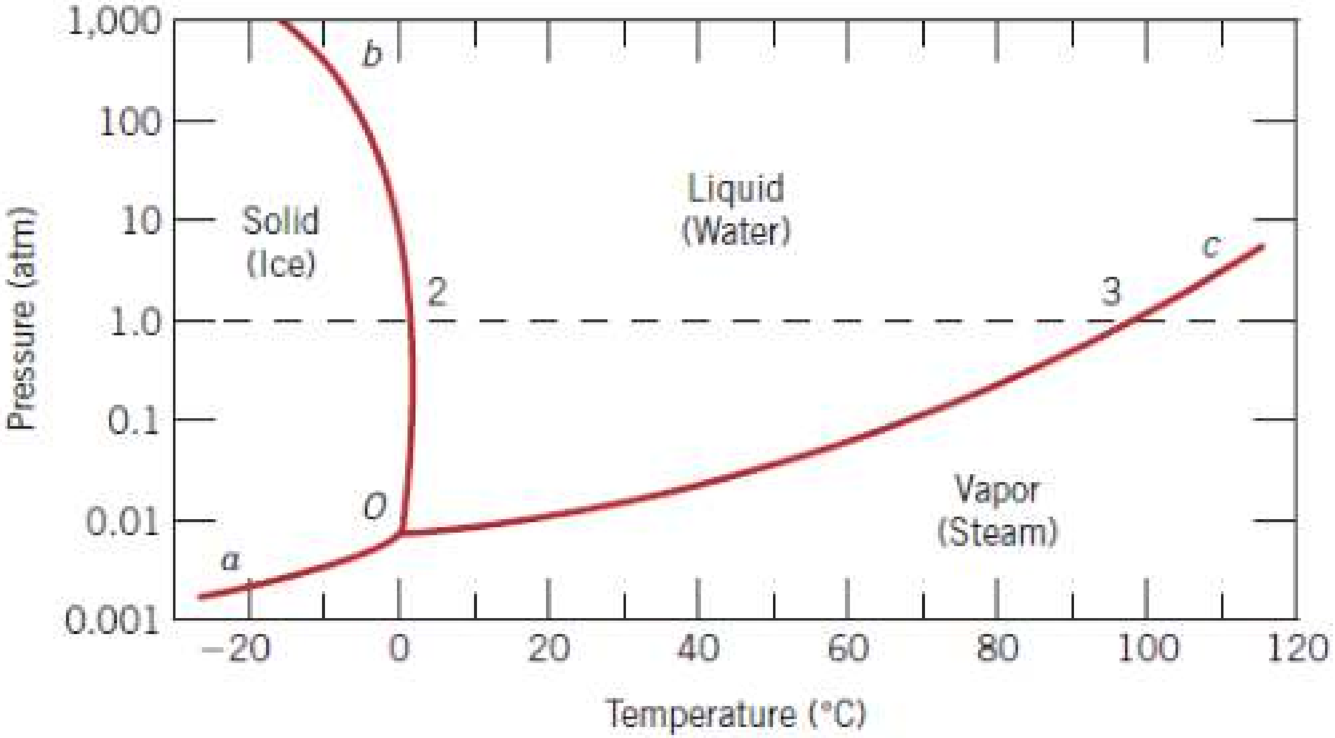
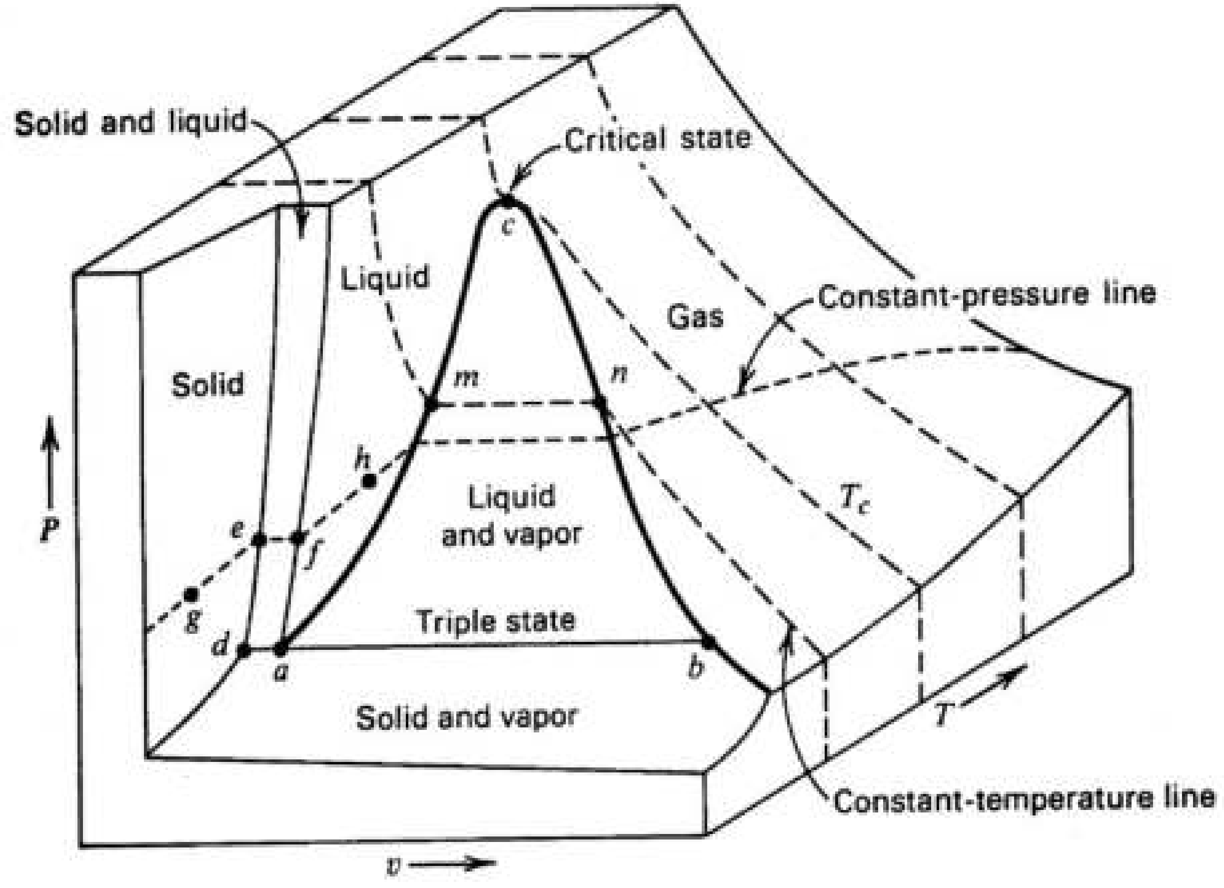
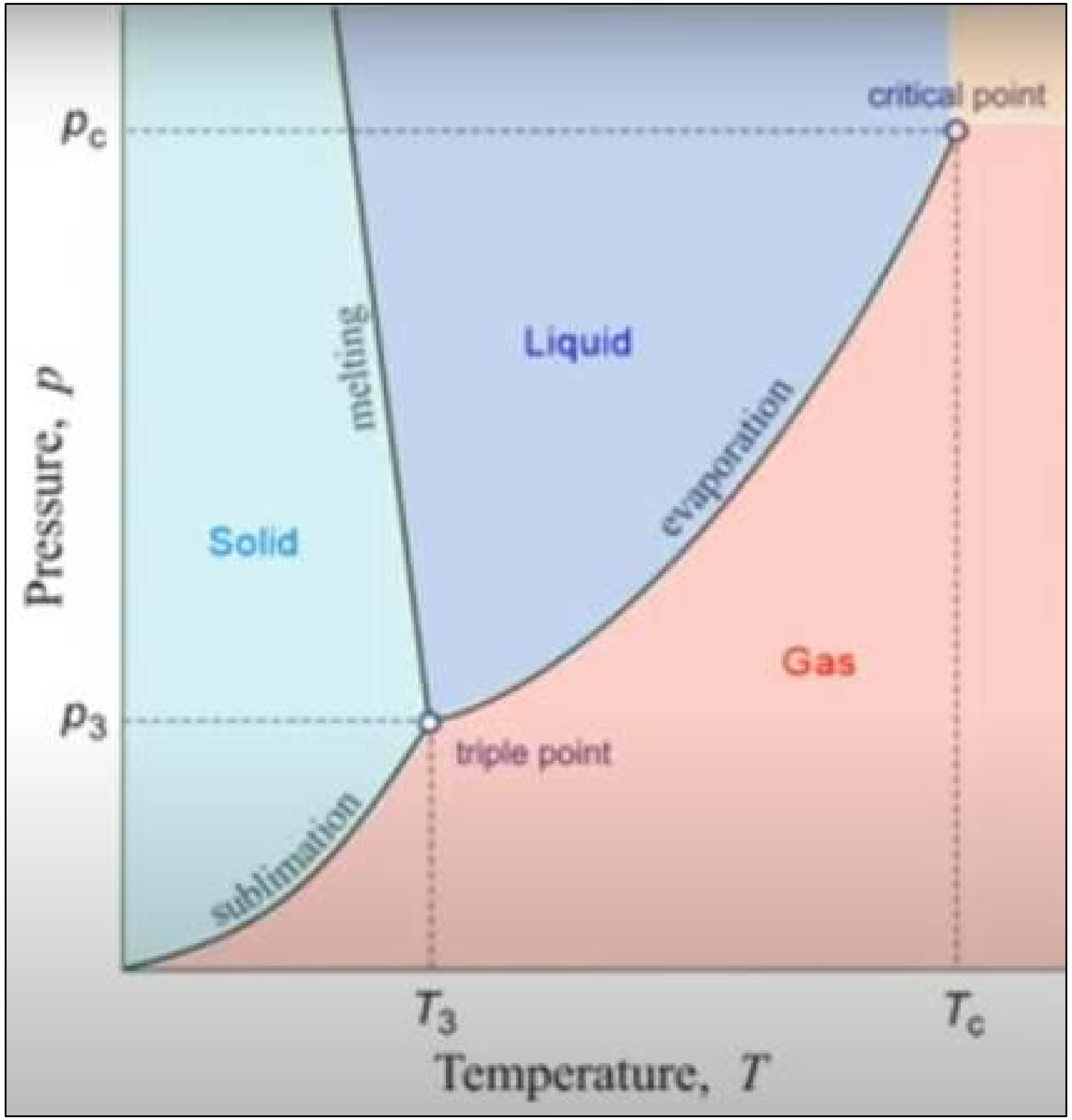


Figure 9.2 Pressure–temperature phase diagram for H_2O. Intersection of the dashed horizontal line at 1 atm pressure with the solid-liquid phase boundary (point 2) corresponds to the melting point at this pressure (T = 0°C). Similarly, point 3, the intersection with the liquid-vapor boundary, represents the boiling point (T = 100°C).

- At low pressure (6.04 x 10 $^{-3}$ atm) and temperature (0.01 Degree C or 273.16 K) all the three phases coexist at a point called triple point.



The *PvT* surface for a substance which contracts on freezing.



2. Binary Phase Diagrams

- Phase diagram is one in which temperature and composition are variable parameters, and **pressure is held constant—normally 1 atm.**
- There are several different varieties; in the present discussion, we will concern ourselves with binary alloys—those that contain two components.
- Binary phase diagrams are maps that represent the relationships between temperature and the compositions and quantities of phases at equilibrium, which influence the microstructure of an alloy.
- Many microstructures develop from phase transformations, the changes that occur when the temperature is altered (ordinarily upon cooling).
- This may involve the transition from one phase to another, or the appearance or disappearance of a phase.
- Binary phase diagrams are helpful in predicting phase transformations and the resulting microstructures, which may have equilibrium or nonequilibrium character.

Classification of Binary Phase Diagrams

Isomorphous system

When components are Completely soluble in liquid state as well as in solid state.

Eutectic Systems

When components are not completely soluble in the solid state

Criteria for Solid Solubility

Simple system (e.g., Ni-Cu solution)

Element	**Crystal Structure**	**Electroneg.**	***r*** **(nm)**
Ni	**FCC**	**1.9**	**0.1246**
Cu	**FCC**	**1.8**	**0.1278**

- Both have the same crystal structure (FCC) and have similar electronegativities and atomic radii (W. Hume – Rothery rules) suggesting high mutual solubility.

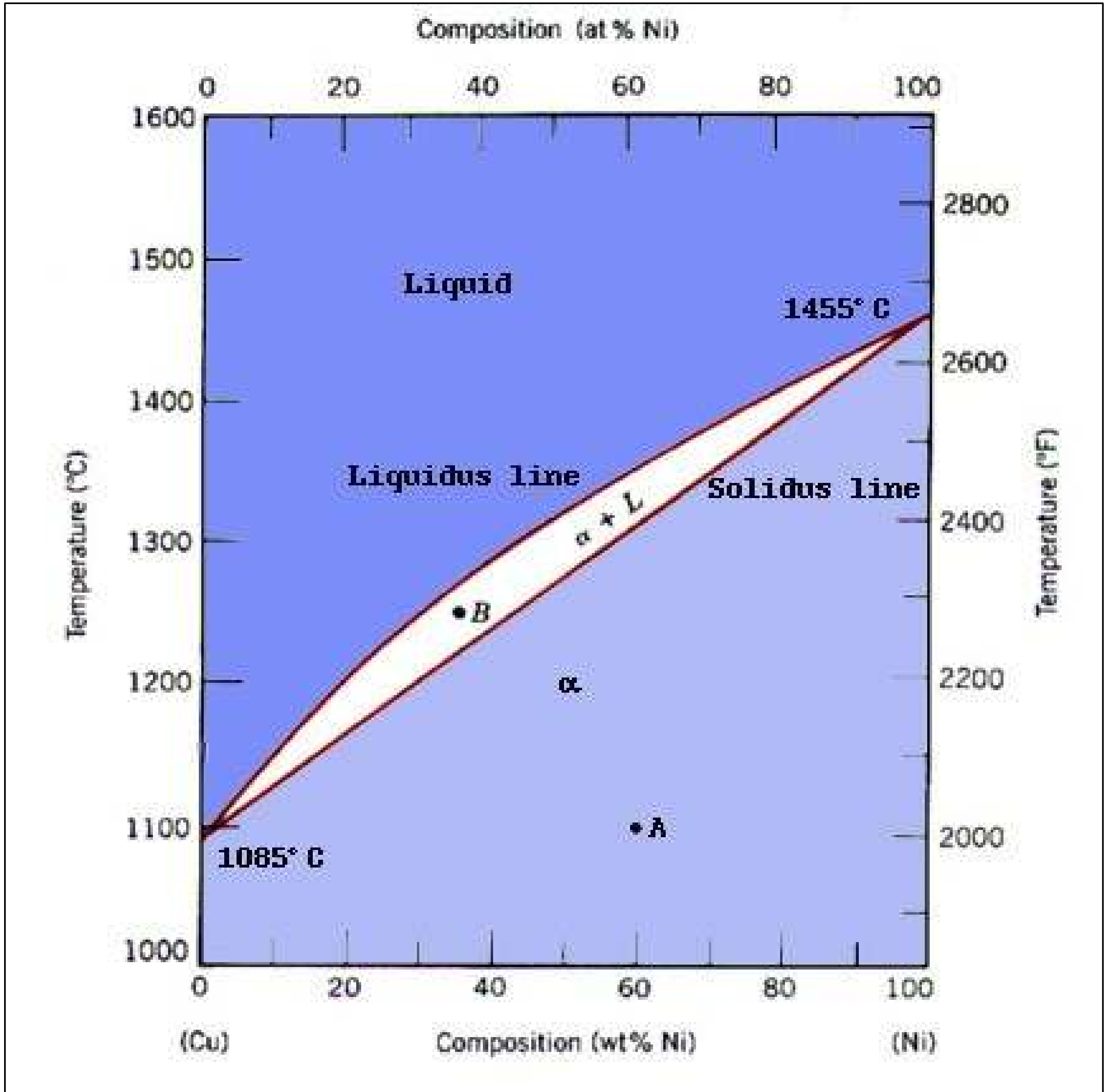
Ni and Cu are totally soluble in one another for all proportions.

Classification of Binary Phase Diagrams

1.Binary-Isomorphous Phase diagram

When two components are mixed, they could be **completely soluble in liquid state as well as in solid state.** Such a binary system is called isomorphous system

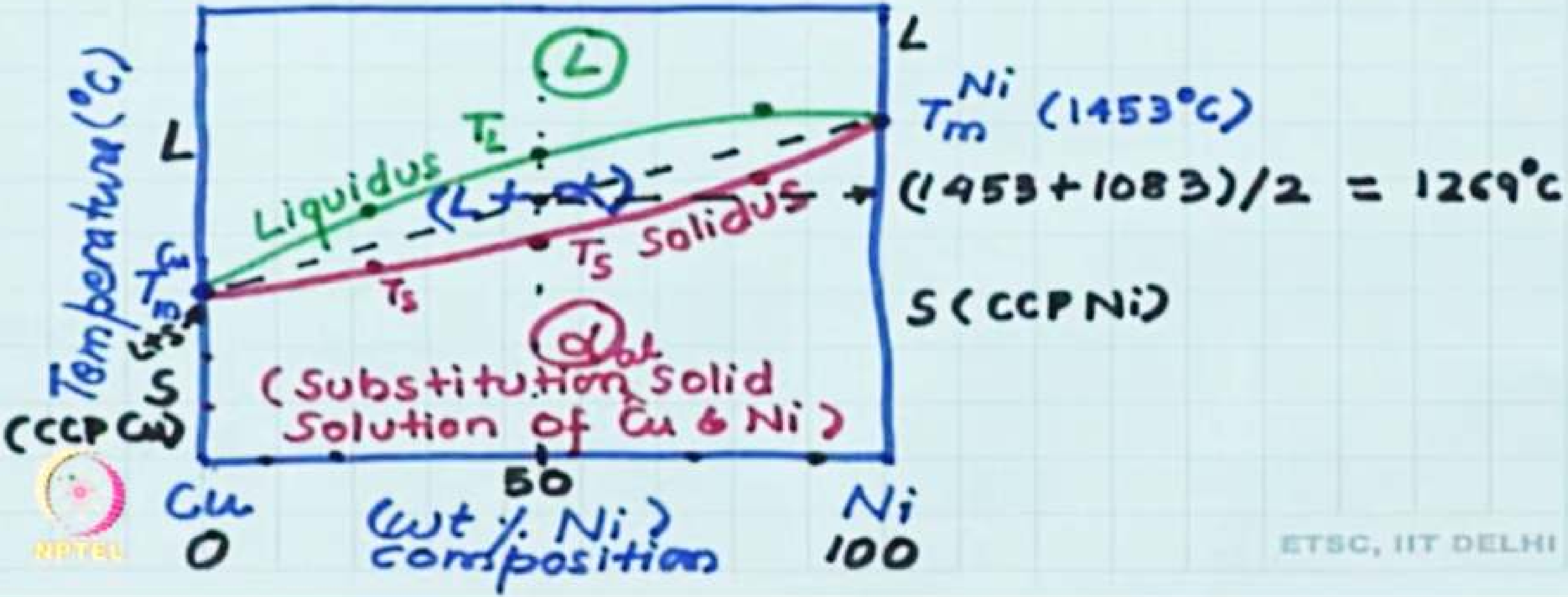
Eg; Cu-Ni, Ge-Si, Ag-Cu etc…



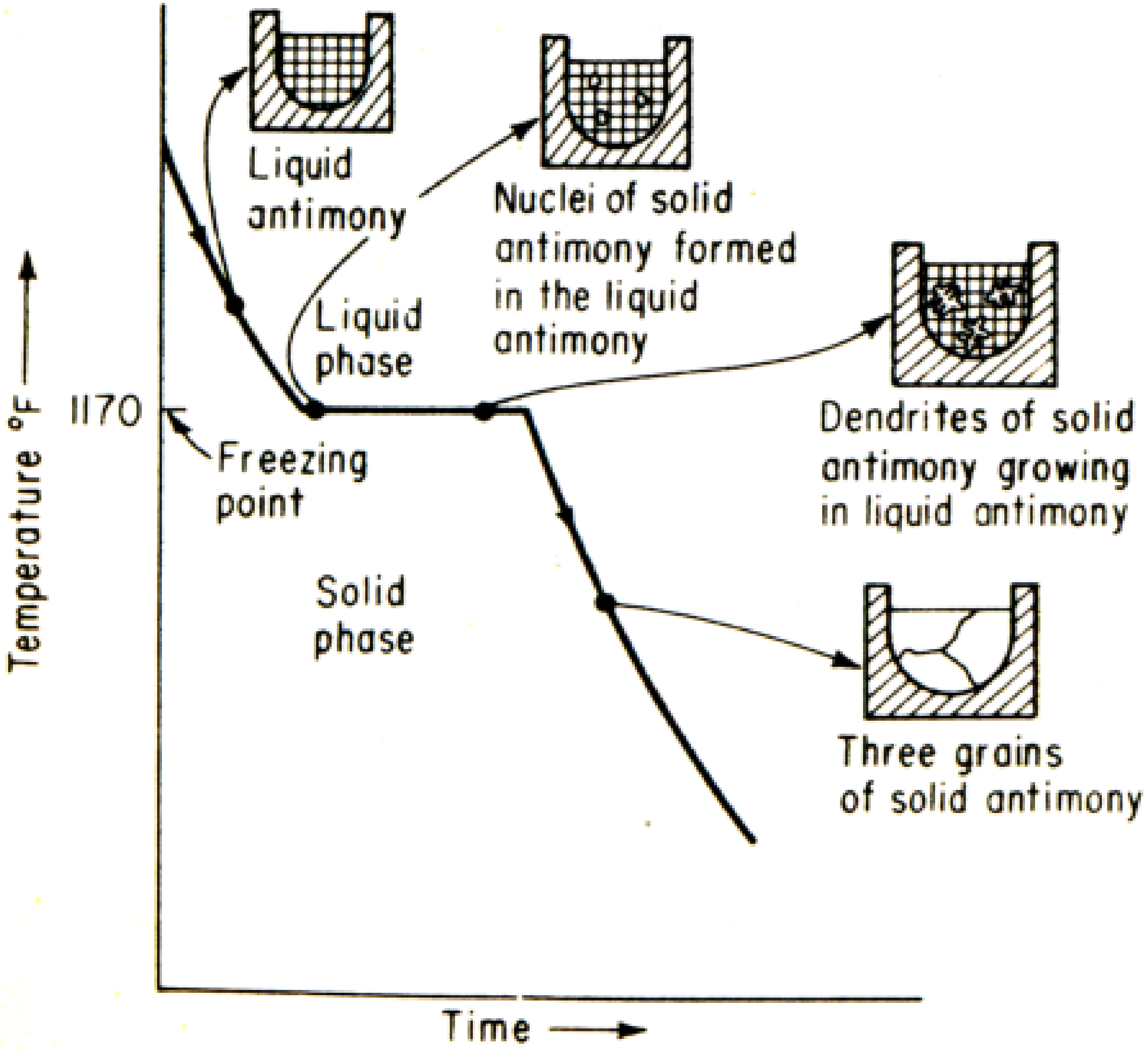
Cu-Ni Alloy (Cu-Ni System)

Cu (CCP) $T_m^{Cu} = 1085°C$

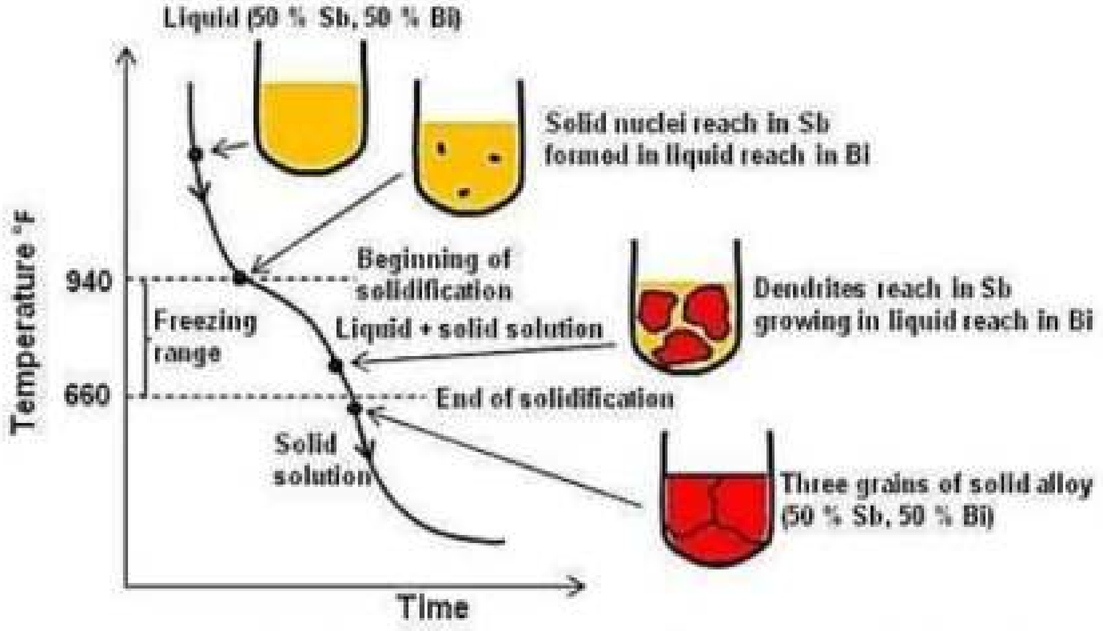
Ni (CCP) $T_m^{Ni} = 1453°C$



$(1453 + 1083)/2 = 1269°C$



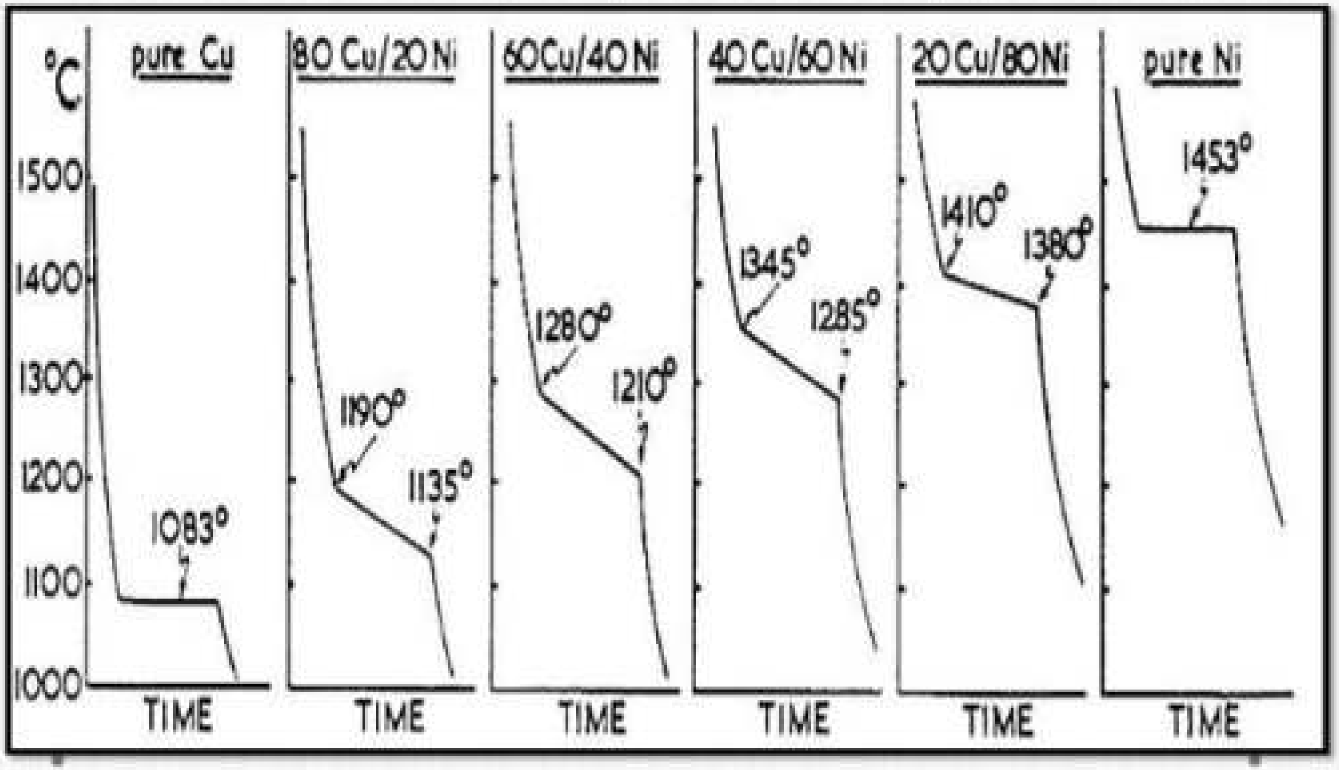
Cooling Curve

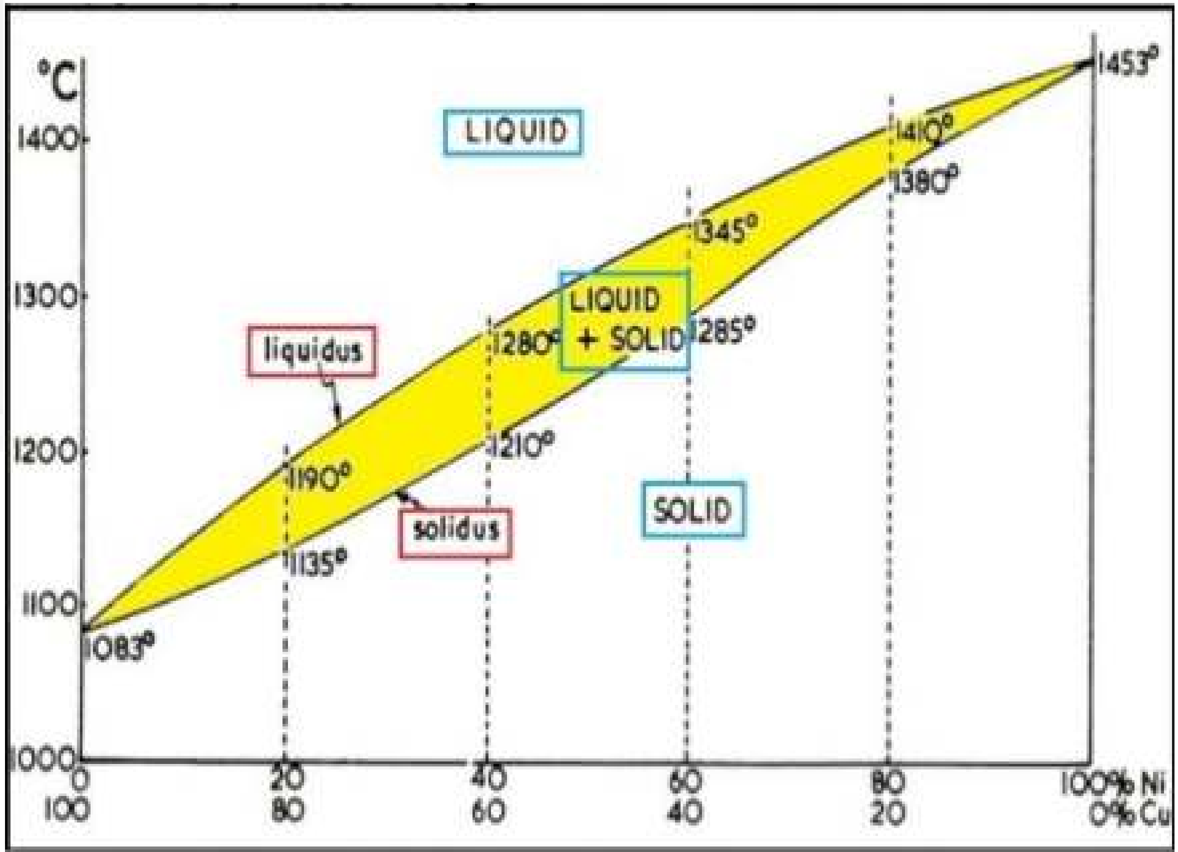


Cooling Curve for the solidification of 50 % antimony and 50 % bismuth alloy

(Cooling Curve for an Alloy)

Cooling Curve for Cu-Ni System





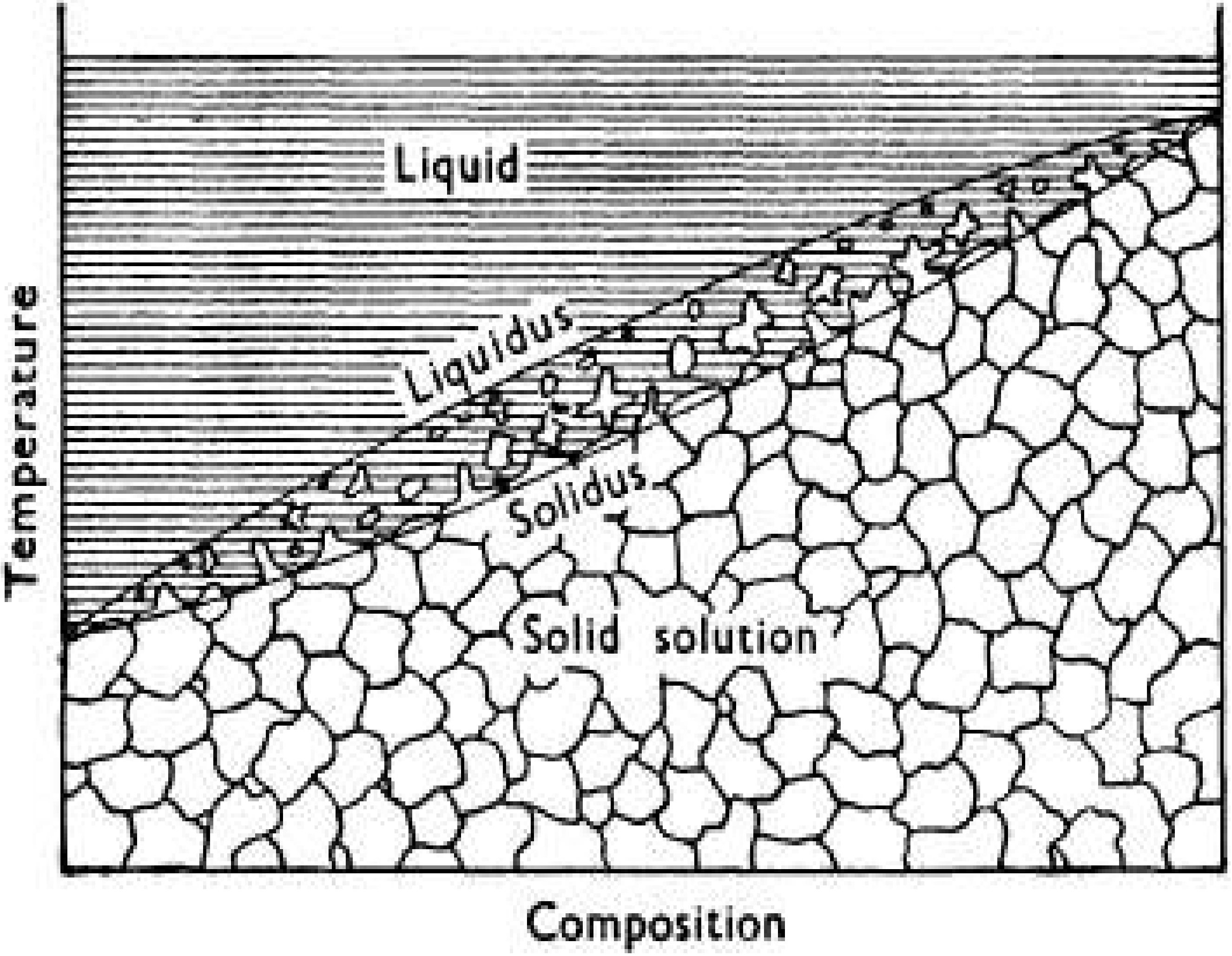
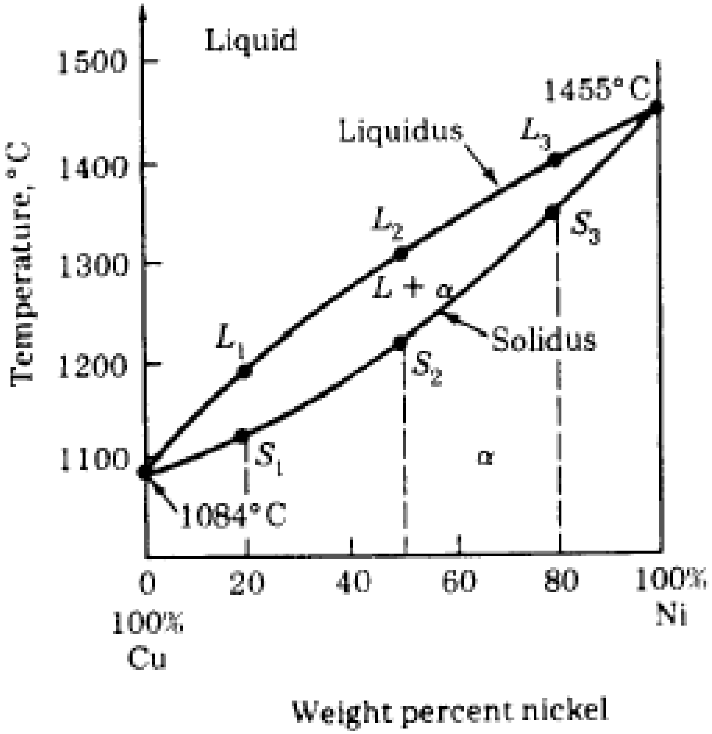
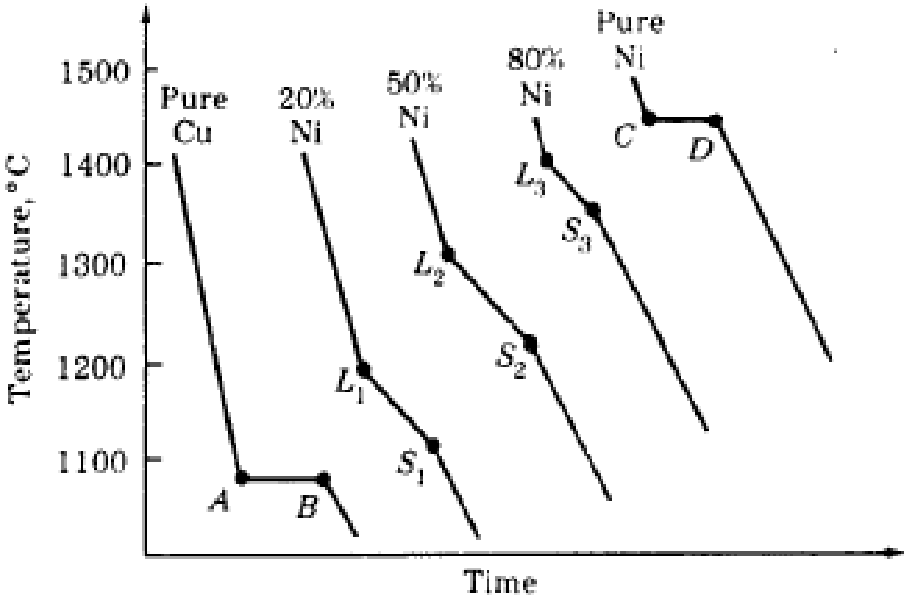


FIG. 37. Sketch illustrating microstructures in solid solution alloys.

Construction of Binary Phase Phase diagram

Thermal analysis- begin with preparation of number of samples of the binary alloys with different composition. All these samples are separately melted and then allowed to solidify.





Cooling curves are recorded and the points corresponding to solid- liquid transition is noted.

These points are plotted corresponding to composition of alloys. By joining all the solid-liquid transition temperature for various compositions we get the continuous curve indicating phase boundaries

In Graph, composition of Ni-Cu

---- Ni ranges from 0% wt. at left extreme to 100% wt at right extreme
---- Cu ranges from 100% wt. at left extreme to 0% wt at right extreme

Three different phase region exist

1. Liquid (L)
2. Solid (α)
3. Two phase region(α + L)

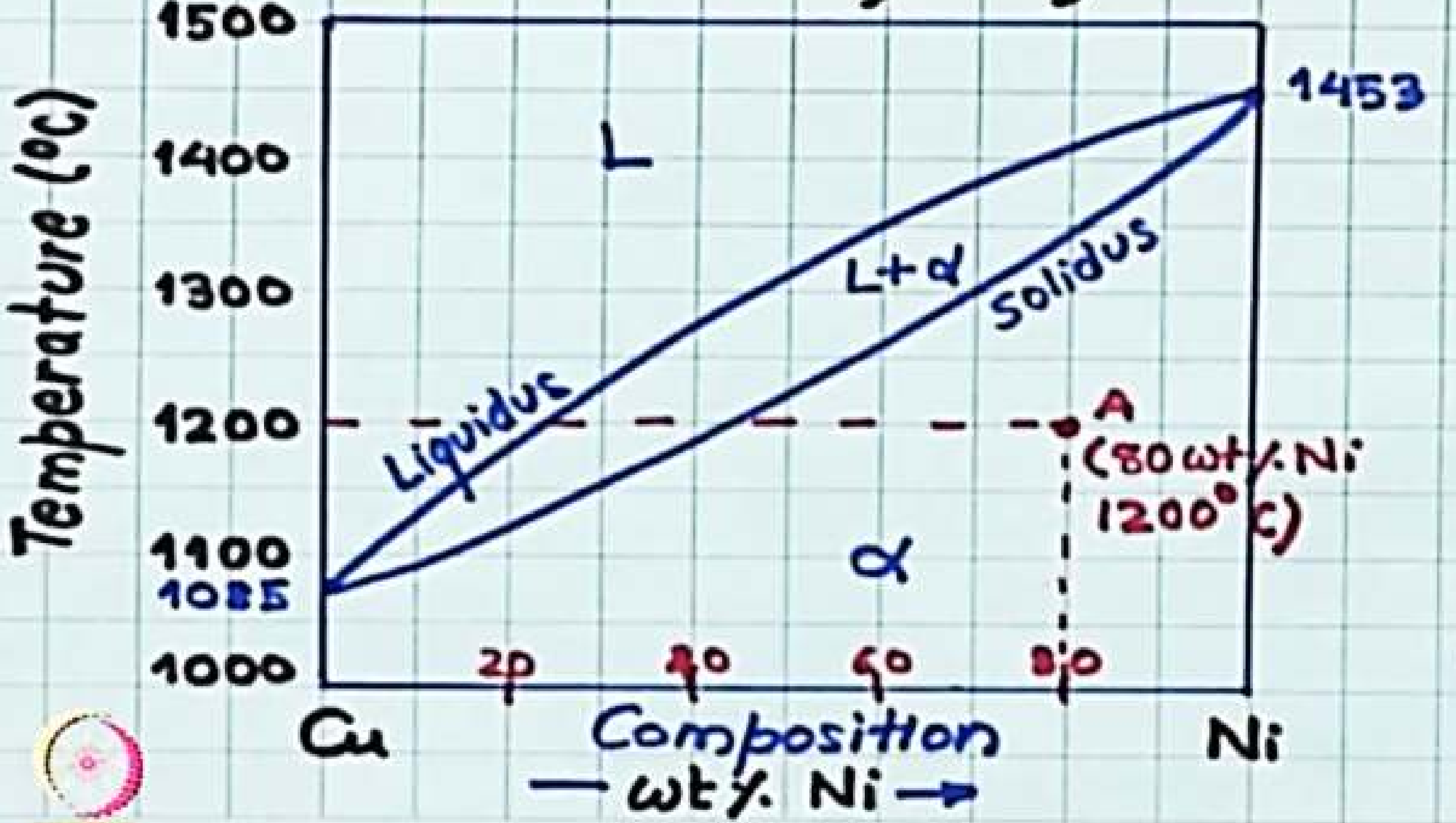
Boundary b/w two phase region and liquid is the liquidus curve
Boundary b/w two phase region and solid is the solidus curve

Three kinds of information's are available from a phase diagram corresponding to specific composition and temperature.

1. **The phases that are present?**
2. **The composition of these phases ?**
3. **The relative percentage of phases ?**

"Constitution Point"

Cu-Ni "Binary Diagram"



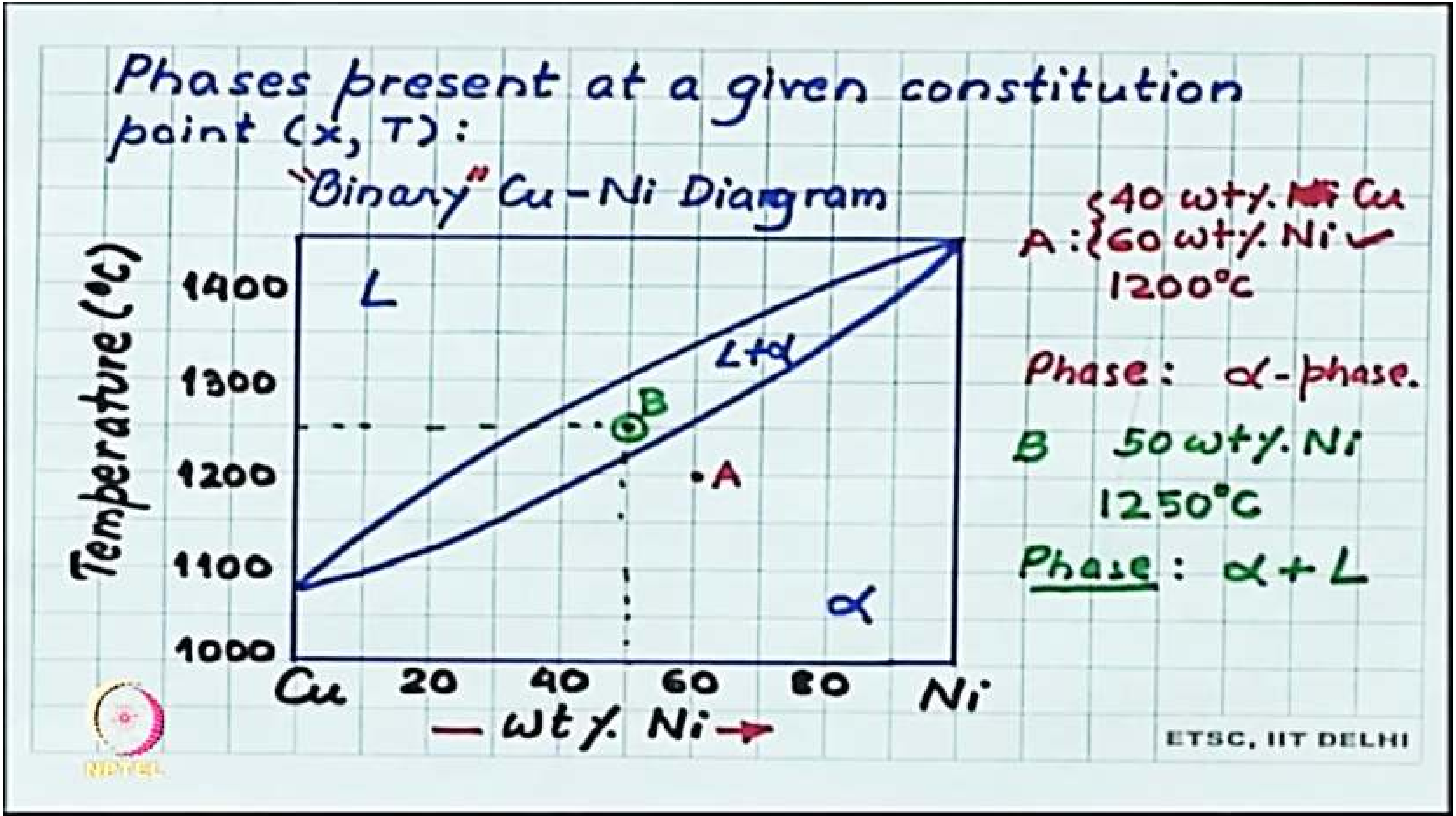
Temp

Composition

A point (x, T) on the phase diagram represents an alloy of composition x held in equilibrium at temp. T.

ETSC, IIT DELHI

(1) What are the phases that are present?



Phases present at a given constitution point (x, T):

"Binary" Cu-Ni Diagram

A : {40 wt%. Cu
{60 wt%. Ni ✓
1200°C

Phase : α-phase.

B 50 wt%. Ni
1250°C

Phase : α + L

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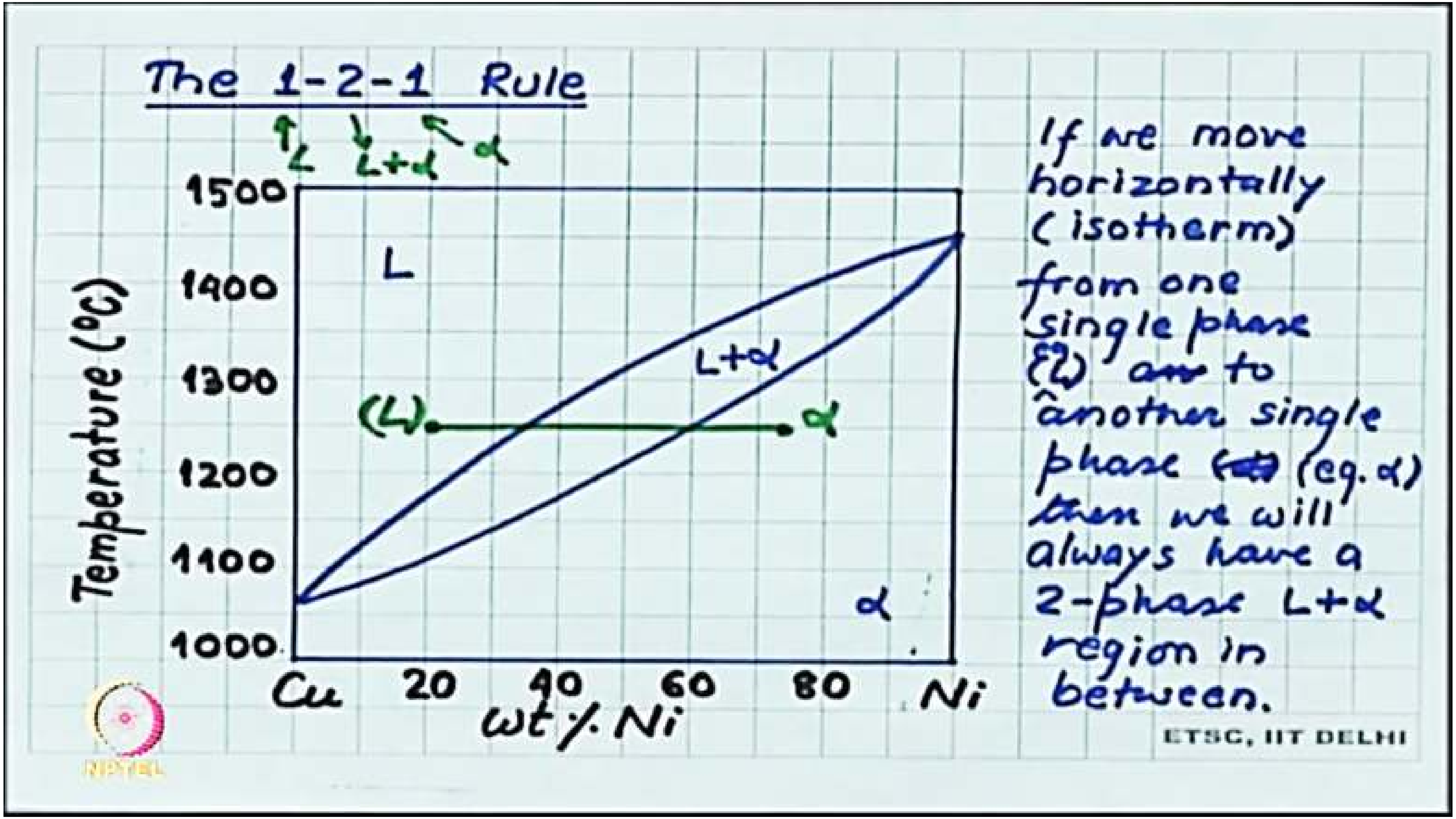

The 1-2-1 Rule

If we move horizontally (isotherm) from one single phase (eg. L) ~~am~~ to another single phase ~~(α)~~ (eg. α) then we will always have a 2-phase L+α region in between.

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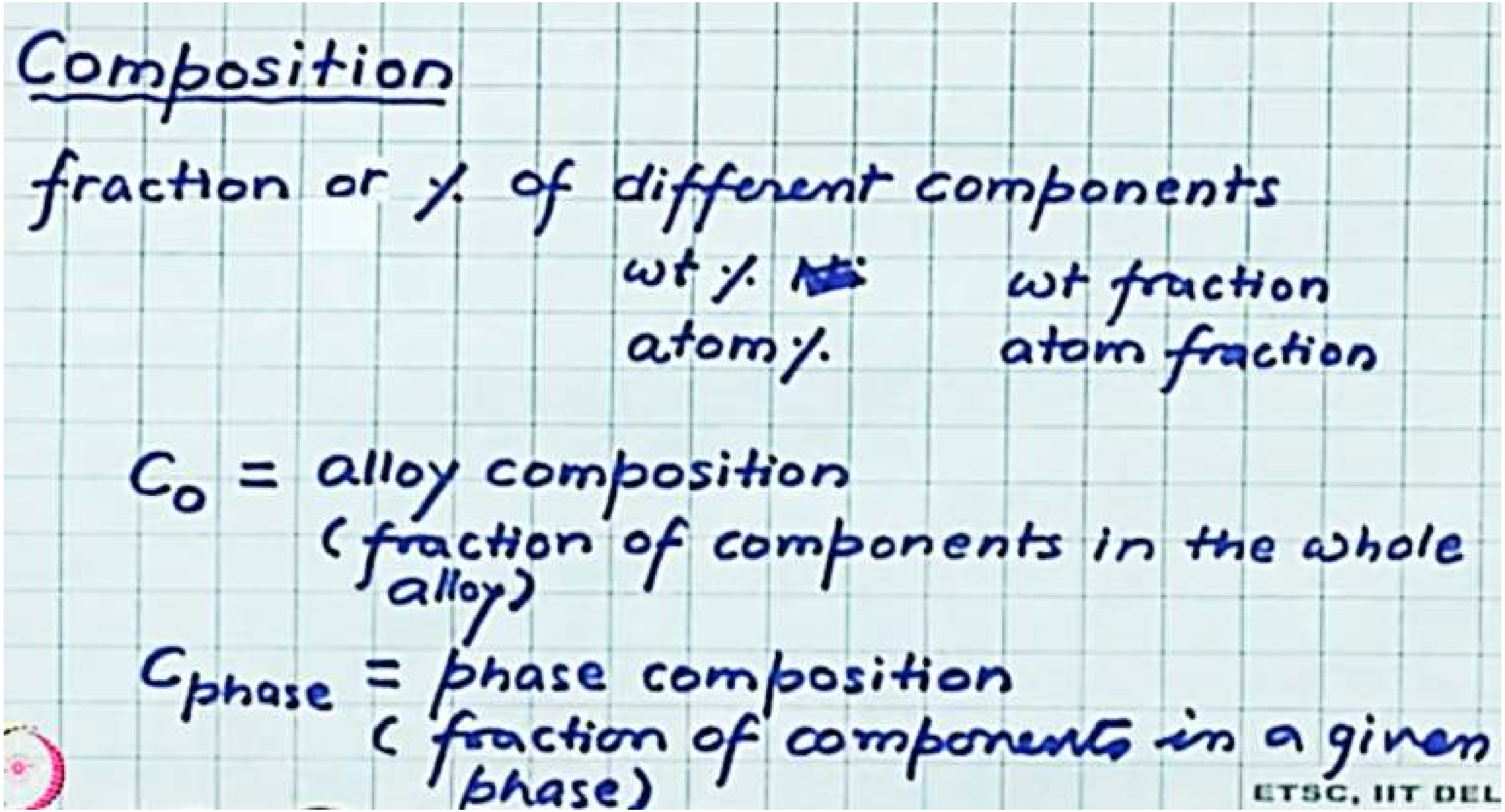
Every Binary phase diagram follow 1-2-1 Rule

2. What are the composition of these phases Present?



Composition

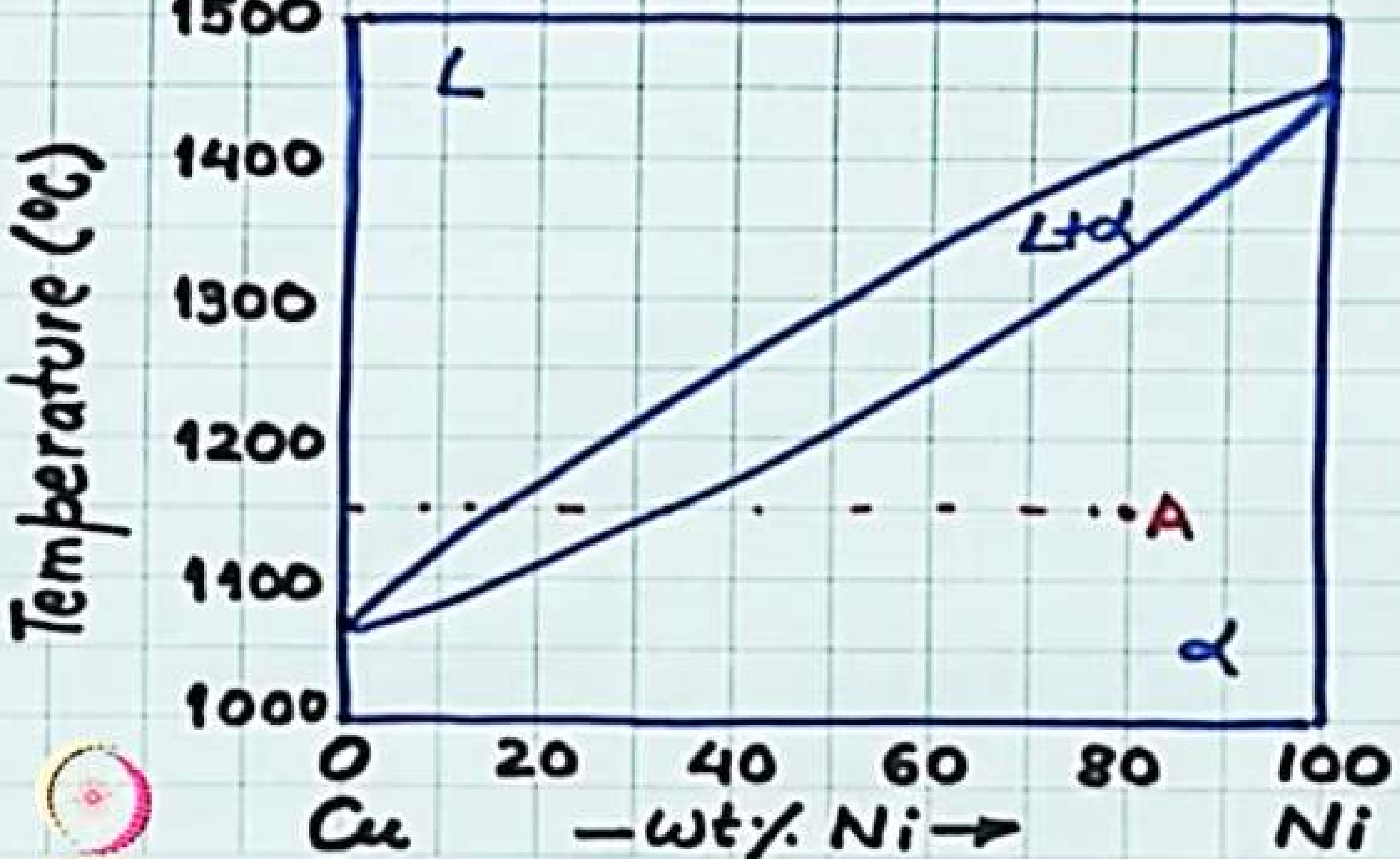
fraction or % of different components

wt %	wt fraction
atom %	atom fraction

C_o = alloy composition
(fraction of components in the whole alloy)

C_{phase} = phase composition
(fraction of components in a given phase)

Composition for the constitution Point A



C_o

A $\frac{80 \text{ wt\% Ni}}{1150°C}$

Phase : α

C_α = 80 wt% Ni
= C_o

For single phase

Phase Composition

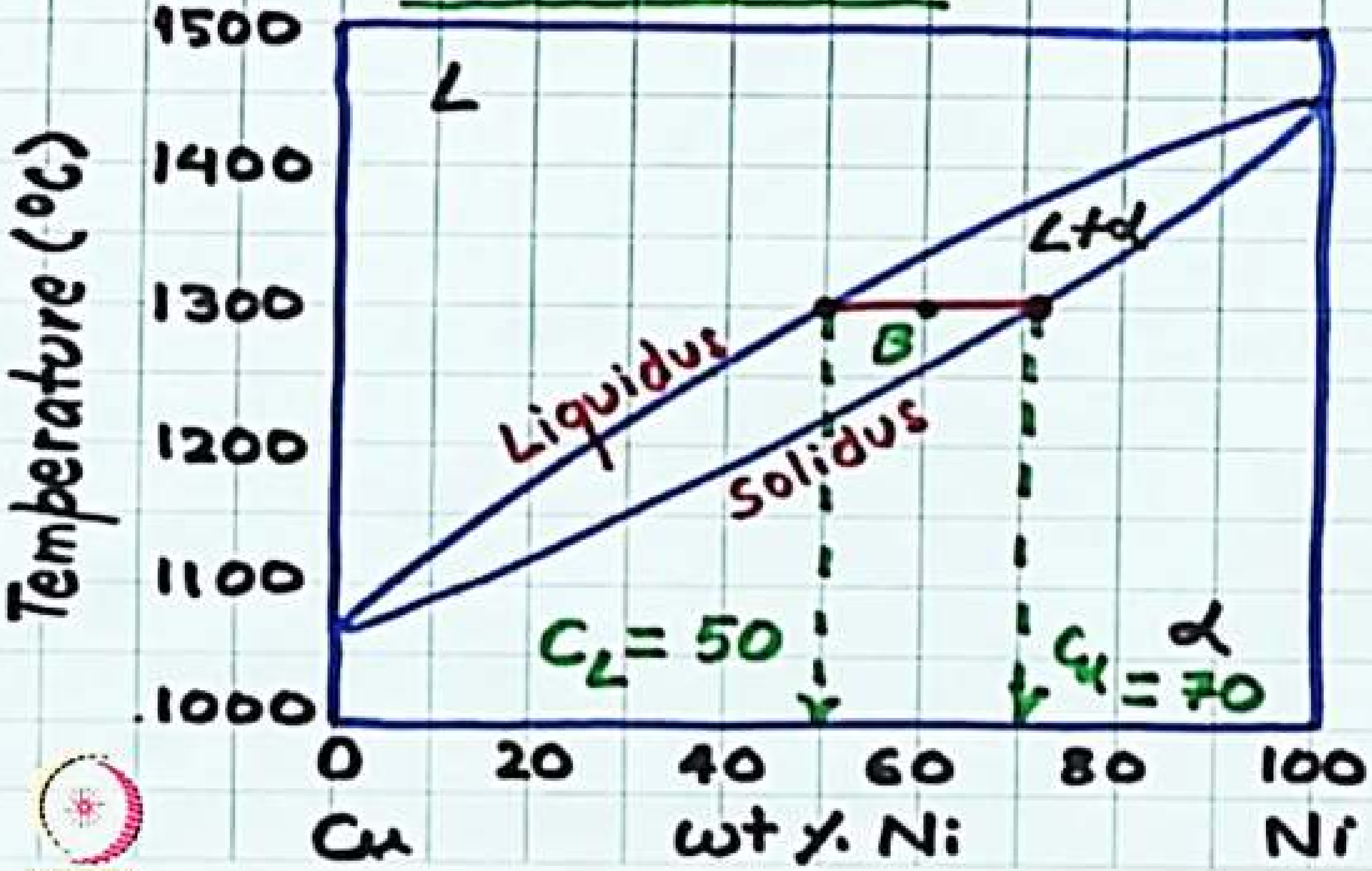
= Alloy Composition

ETSC, IIT DELHI

Determination of composition of Phases – **Tie Line Rule**

Composition of phases in the 2-phase region

Tie-Line Rule



• B $C_0 = 60$ wt% Ni

$T = 1300°C$

Phases : $L + \alpha$

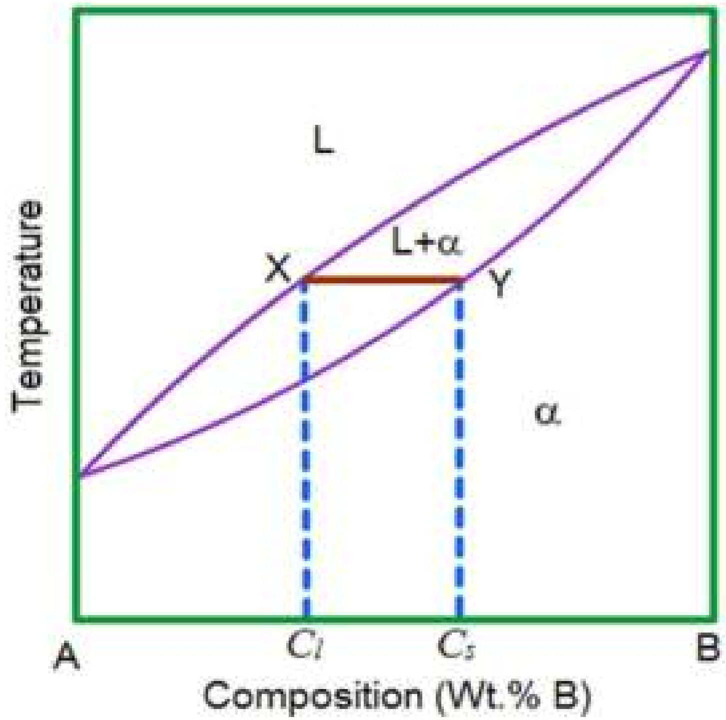
C_α , C_L ?

Tie Line

An Isotherm in the 2-phase region running from one boundary to the other.

ETSC, IIT DELHI

Determination of composition of Phases – **Tie Line Rule**

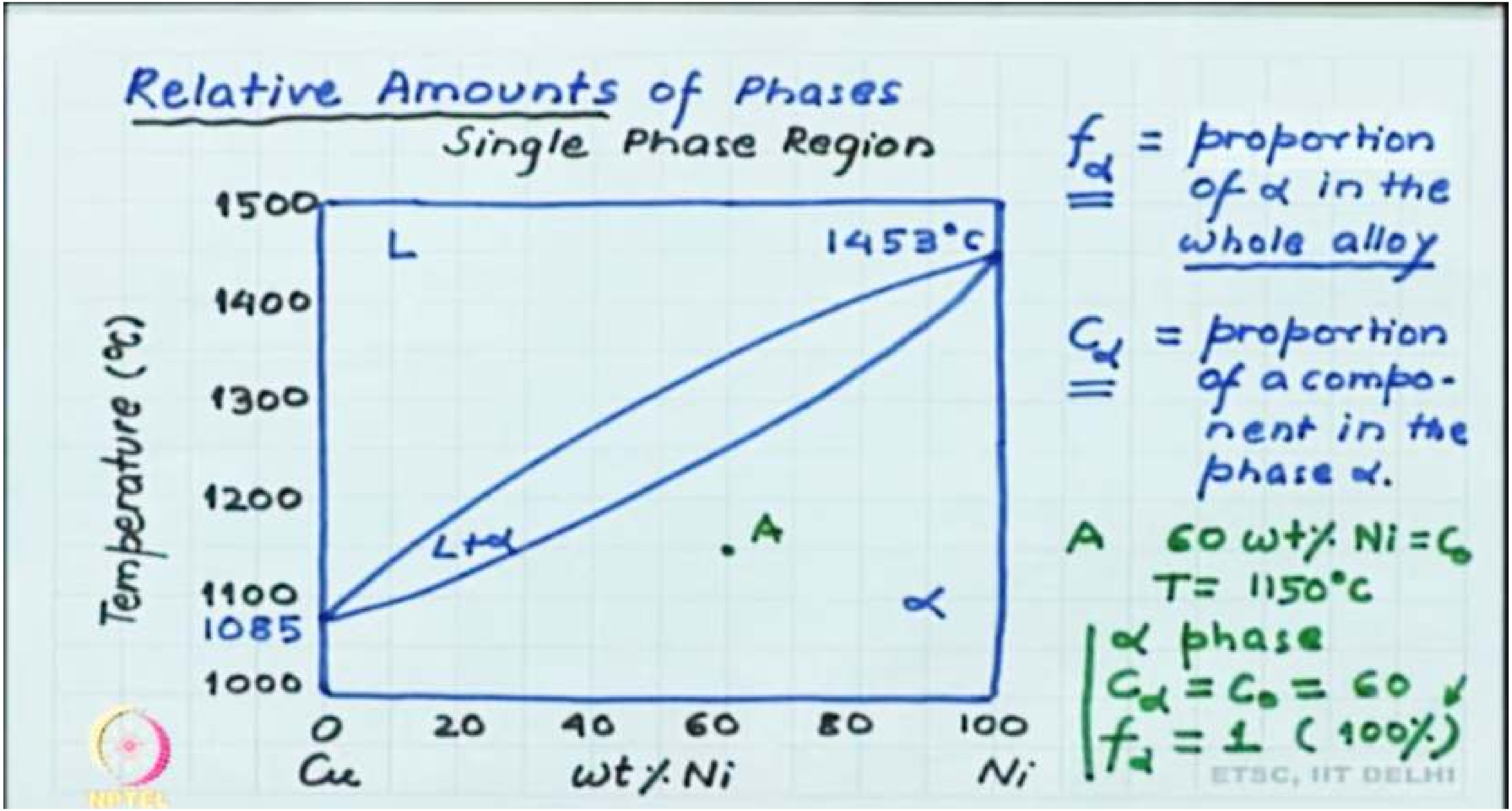


(a) A tie-line is drawn horizontally across the two phase region corresponding to the selected temperature

(b) The intersection of the tie line with phase boundaries on both sides are noted.

(c) Vertical lines are drawn downwards from the intersecting points to the composition axis, from which the composition of phases is obtained.

3. What are the relative amount or Proportion of phases present in the system?



Relative Amounts of Phases

Single Phase Region

f_α = proportion of α in the whole alloy

C_α = proportion of a component in the phase α.

A 60 wt% Ni = C_0

T= 1150°C

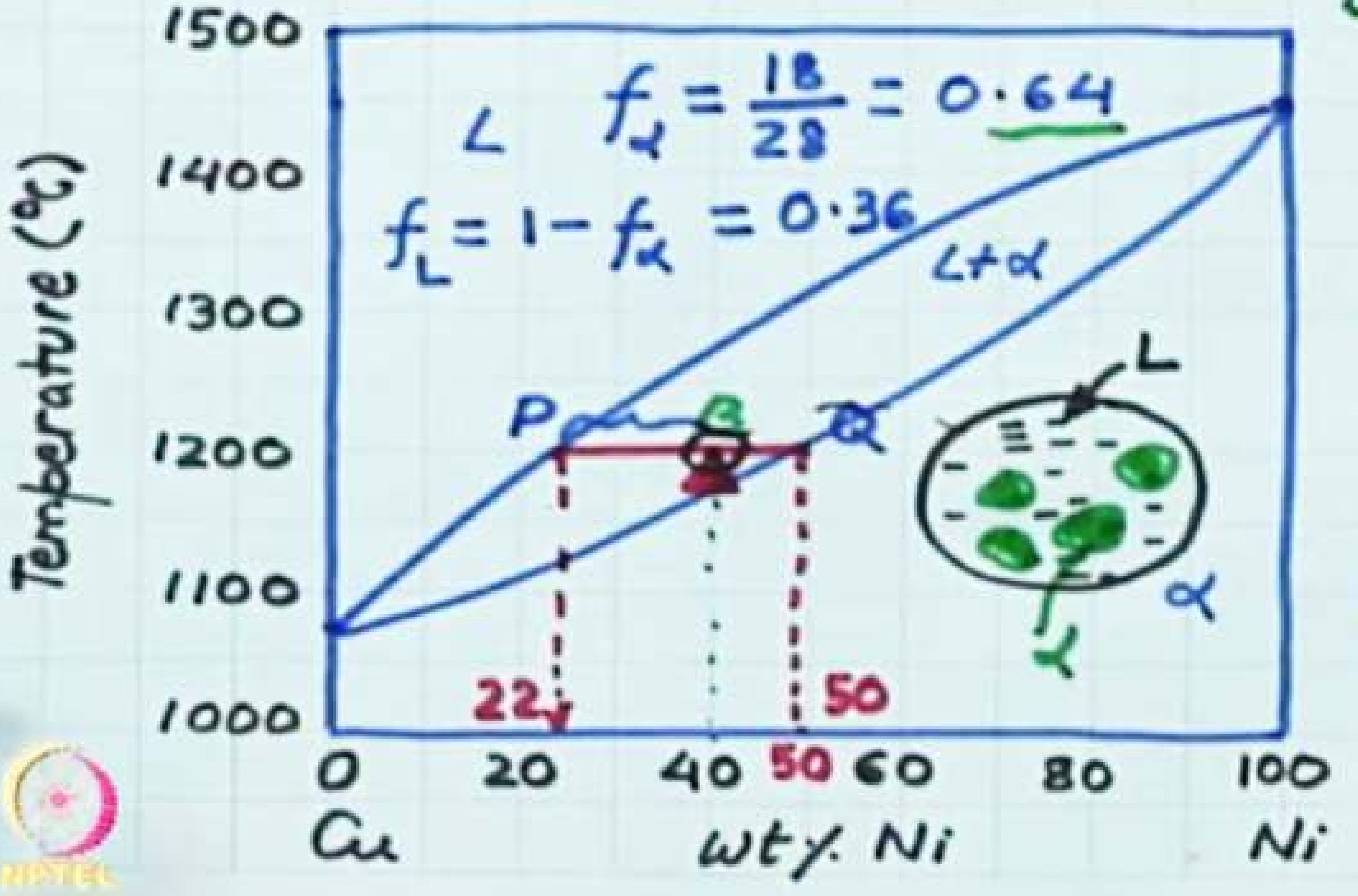
α phase

$C_\alpha = C_0 = 60$ ✓

$f_\alpha = 1$ (100%)

Determination of relative amounts of phases – Lever Line Rule

Relative Amount of Two Phases Region



$f_\alpha = \frac{18}{28} = 0.64$

$f_L = 1 - f_\alpha = 0.36$

B · $C_0 = 40$ wt% Ni

L + α

$C_L = 22$

$C_\alpha = 50$

LEVER RULE
for relative proportions.

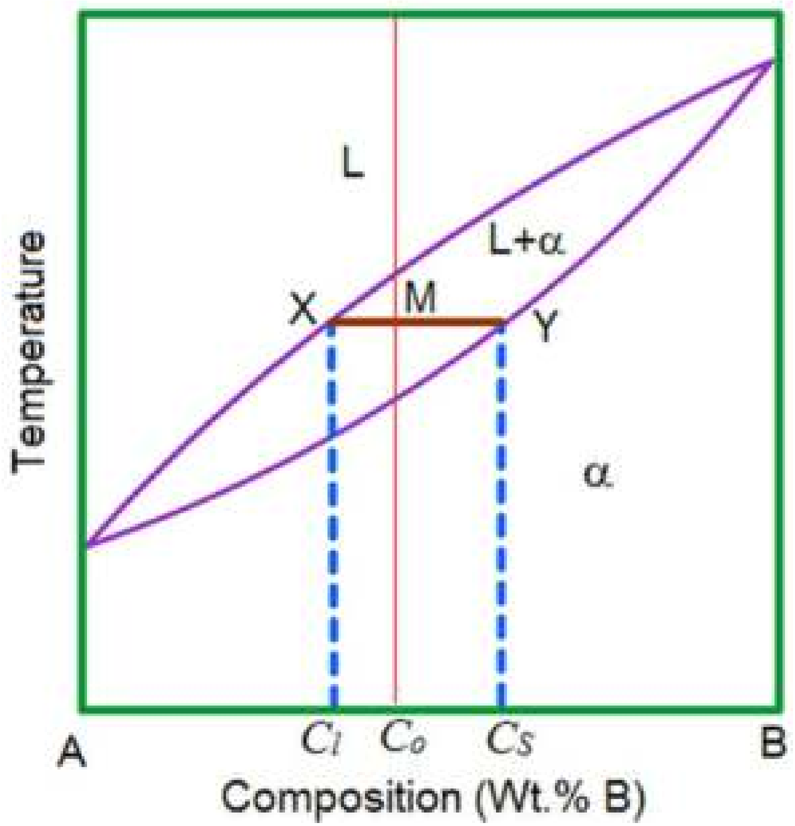
$$f_\alpha = \frac{\text{opp arm}}{\text{total arm}}$$

$$= \frac{PB}{PQ} = \frac{40-22}{50-22}$$

Determination of relative amounts of phases – **Lever Line Rule**

(1) A tie-line is constructed across the two phase region at the temperature of the alloy to intersect the region boundaries.

(2) The relative amount of a phase is computed by taking the length of tie line from overall composition to the phase boundary for the other phase, and dividing by the total tie-line length.



$F_L = MY / XY = (C_s - C_o) / (C_s - C_L)$

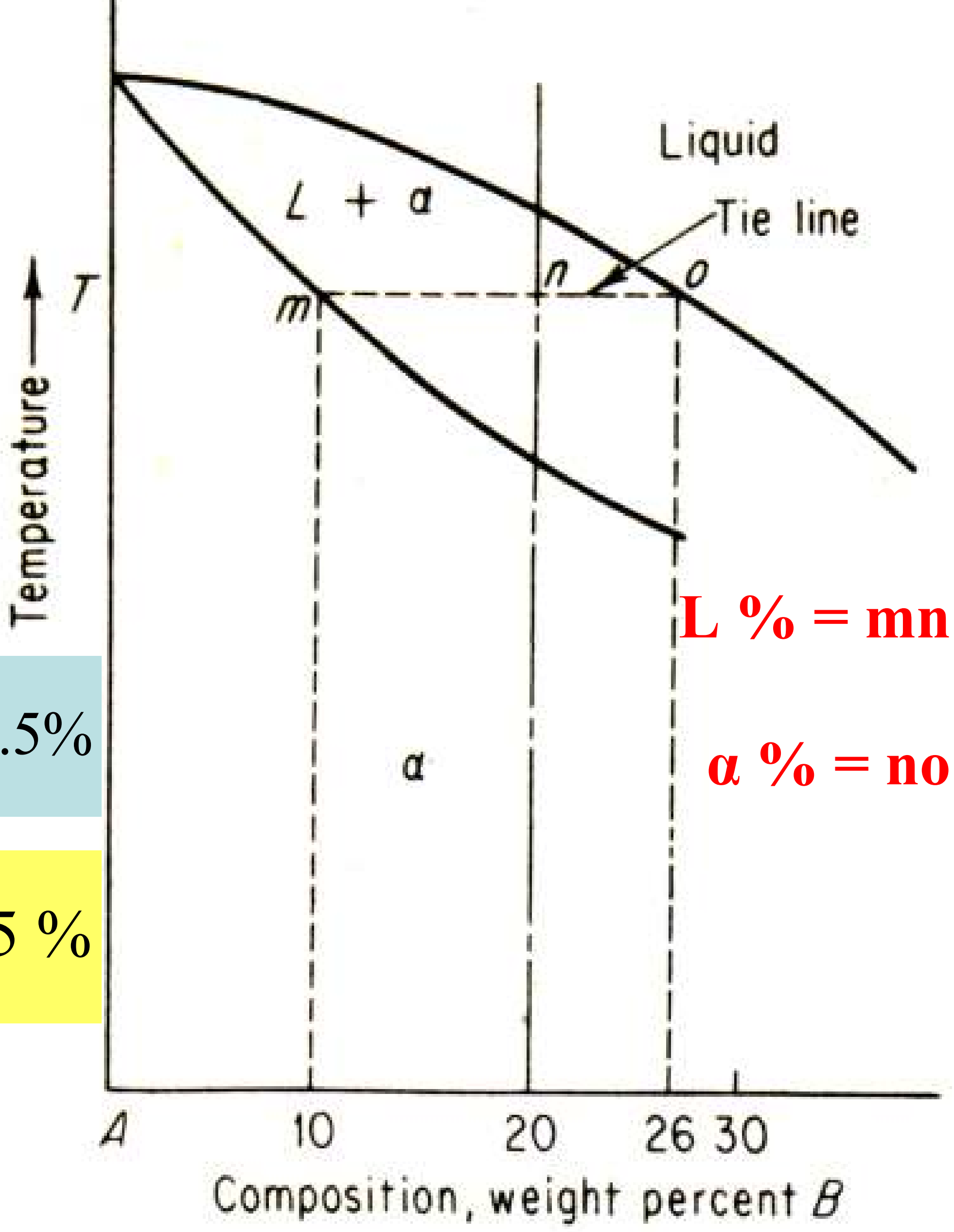
$F_s = MX / XY = (C_o - C_L) / (C_s - C_L)$

Lever Phase Rule

Constant temperature line – Tie line

$$\text{Liquid } \% = \frac{10}{16} \text{x} 100 = 62.5\%$$

$$\alpha \ \% = \frac{6}{16} \text{ x } 100 = 37.5 \ \%$$



L % = mn /mo x 100

α % = no /mo x 100

Fig. 6·3 Diagram showing the tie line *mo* drawn in the two-phase region at temperature *T*.

It is easy to confuse the foregoing procedures for the determination of phase compositions and fractional phase amounts; thus, a brief summary is warranted. *Compositions* of phases are expressed in terms of weight percents of the components (e.g., wt% Cu, wt% Ni). For any alloy consisting of a single phase, the composition of that phase is the same as the total alloy composition. If two phases are present, the tie line must be employed, the extremities of which determine the compositions of the respective phases. With regard to *fractional phase amounts* (e.g., mass fraction of the α or liquid phase), when a single phase exists, the alloy is completely that phase. For a two-phase alloy, on the other hand, the lever rule is utilized, in which a ratio of tie line segment lengths is taken.

DEVELOPMENT OF MICROSTRUCTURE IN ISOMORPHOUS ALLOYS (EQUILIBRIUM COOLING)

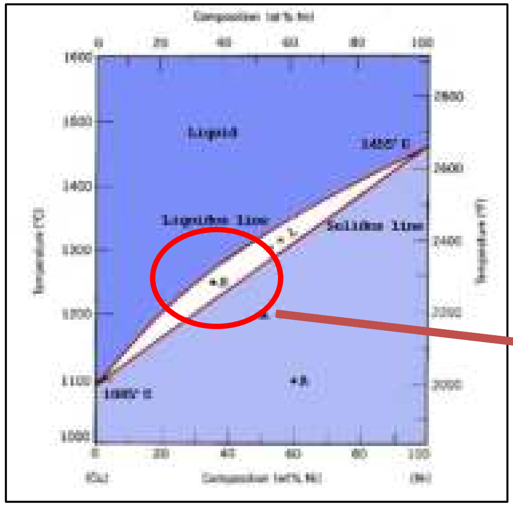
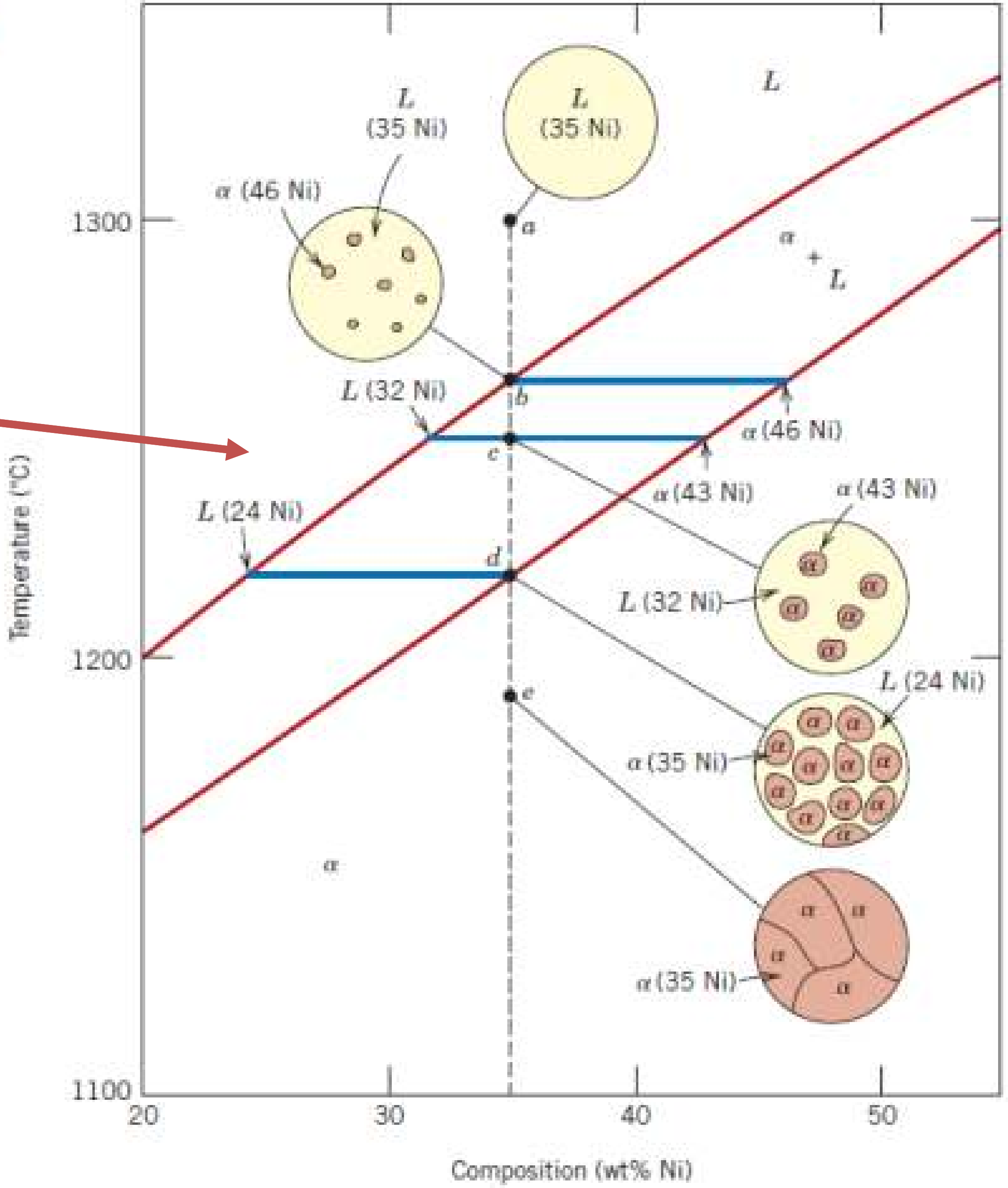


Figure 9.4 Schematic representation of the development of microstructure during the equilibrium solidification of a 35 wt% Ni–65 wt% Cu alloy.



- Here cooling occurs very slowly, in that phase equilibrium is continuously maintained.
- 35 wt% Ni–65 wt% Cu as it is cooled from 1300 ^{0}C.
- At 1300 ^{0}C point *a*, the alloy is completely liquid
- At point b , 1260 ^{0}C point, the first solid begins to form.
- The solidification process is virtually complete at about 1220 ^{0}C. point *d*
- Upon crossing the solidus line, this remaining liquid solidifies; the final product then is a polycrystalline -phase solid solution that has a uniform 35 wt% Ni–65 wt% Cu composition

DEVELOPMENT OF MICROSTRUCTURE IN ISOMORPHOUS ALLOYS (NONEQUILIBRIUM COOLING)

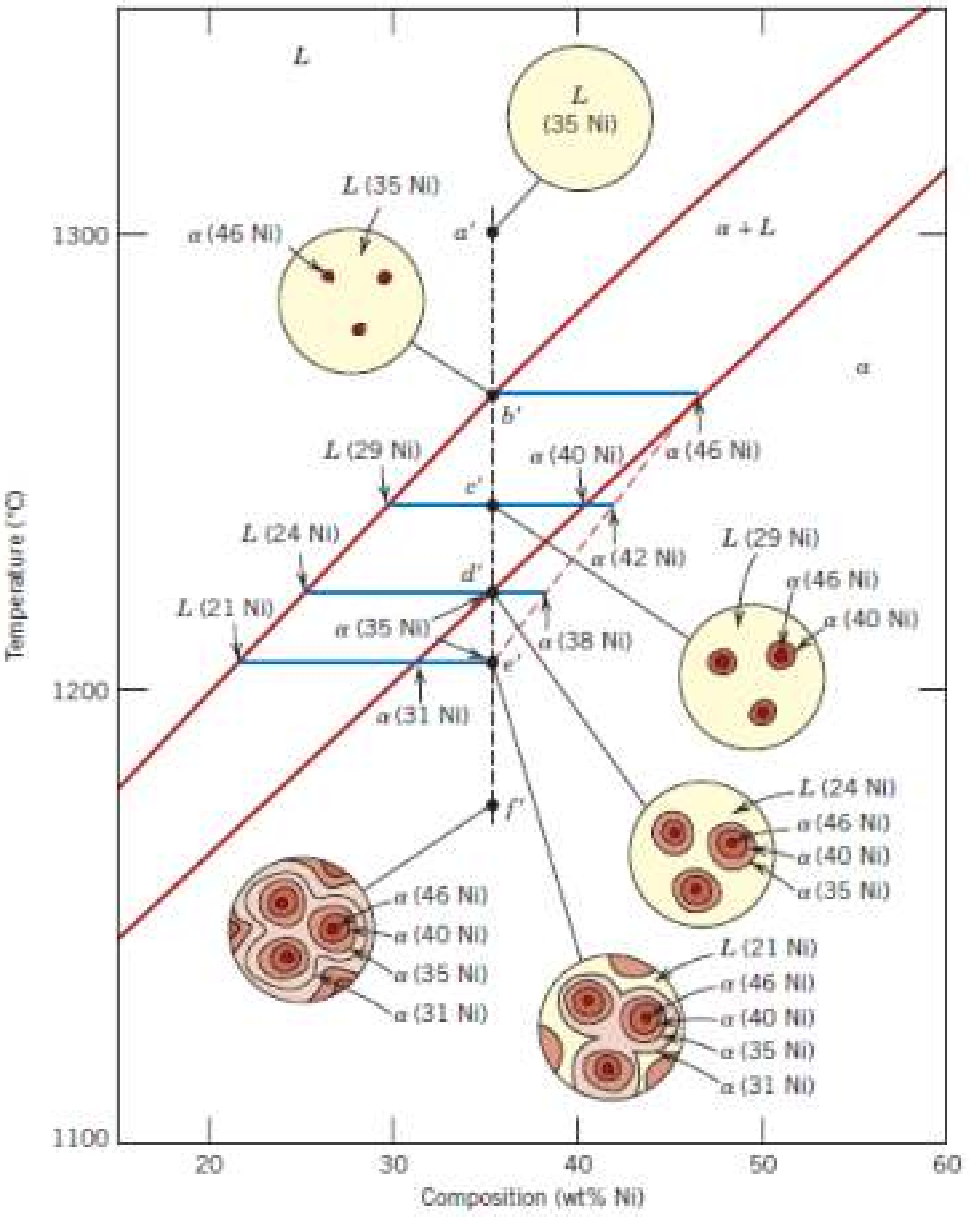


Figure 9.5 Schematic representation of the development of microstructure during the nonequilibrium solidification of a 35 wt% Ni–65 wt% Cu alloy.

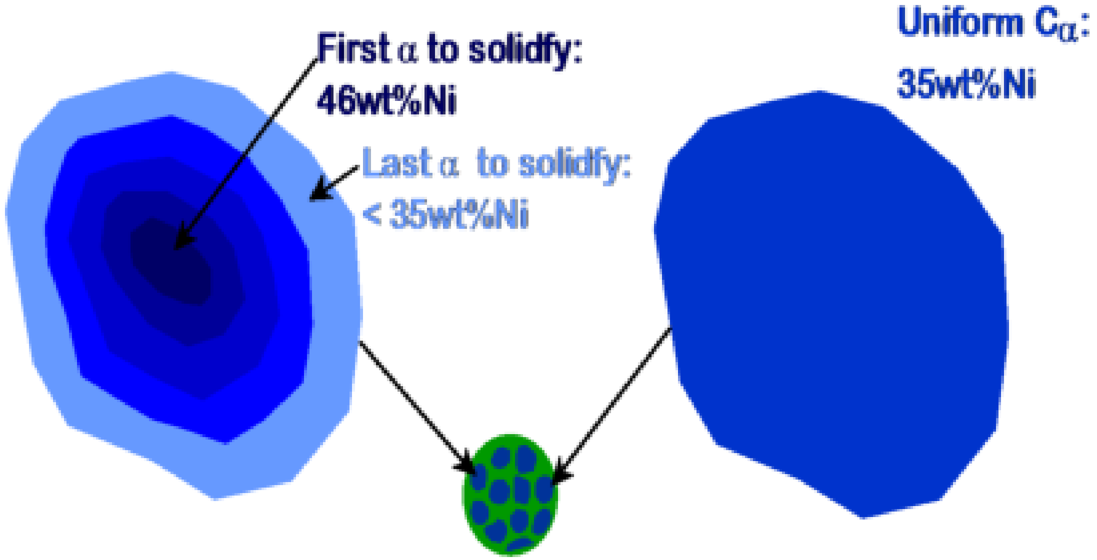
Cored structure (**Coring**) form by Nonequilibrium cooling

There are some important consequences for isomorphous alloys that have solidified under nonequilibrium conditions. As discussed above, the distribution of the two elements within the grains is nonuniform, a phenomenon termed *segregation;* that is, concentration gradients are established across the grains that are represented by the insets of Figure 9.5. The center of each grain, which is the first part to freeze, is rich in the high-melting element (e.g., nickel for this Cu–Ni system), whereas the concentration of the low-melting element increases with position from this region to the grain boundary. This is termed a *cored* structure, which gives rise to less than the optimal properties. As a casting having a cored structure is reheated, grain boundary regions will melt first inasmuch as they are richer in the low-melting component. This produces a sudden loss in mechanical integrity due to the thin liquid film that separates the grains. Furthermore, this melting may begin at a temperature below the equilibrium solidus temperature of the alloy. Coring may be eliminated by a homogenization heat treatment carried out at a temperature below the solidus point for the particular alloy composition. During this process, atomic diffusion occurs, which produces compositionally homogeneous grains.

- The center region of the each grain, which is rich in the high melting element, whereas the low melting elements increases with position from the region to the grain boundary. Thus concentration gradients across the grains are established, which is shown in figure. This is often termed a cored structure.
- A cored structure is reheated, grain boundary regions will melt first as they are richer in the low melting component. This produces a sudden loss mechanical integrity due to the thin liquid film that separates the grains.

Fast cooling
Non-equilibrium phases

Slow cooling
Equilibrium phases



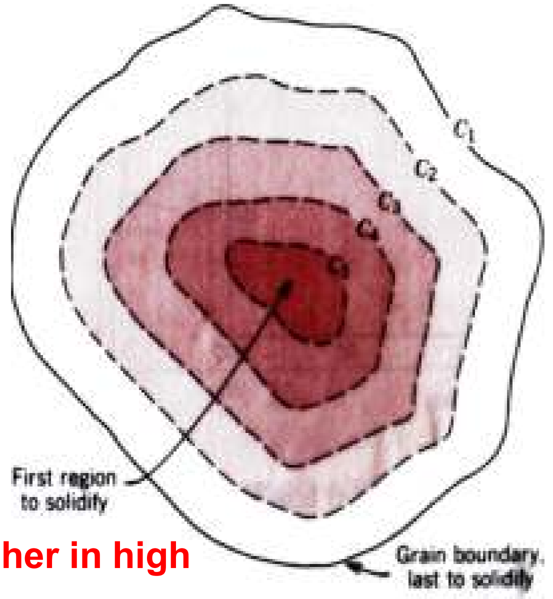


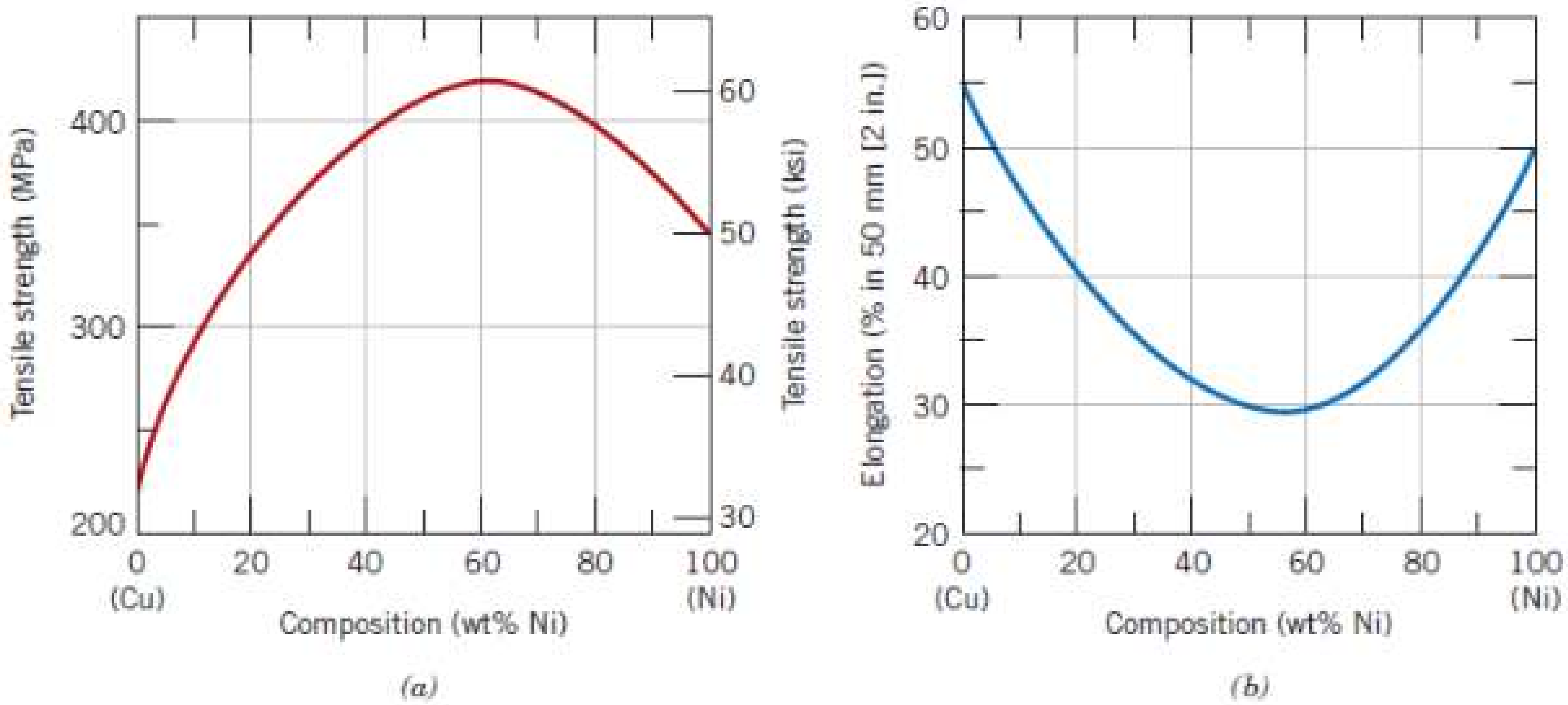
Figure 9.4 Schematic representation of coring in a single grain. For a cored structure, concentration gradients are established across the grains; dashed lines indicate constant concentration contours (C_1, C_2, C_3, etc.).

Richer in high melting element

Richer in low melting element

MECHANICAL PROPERTIES OF ISOMORPHOUS ALLOYS

- Each component will experience solid-solution strengthening , or an increase in strength and hardness by additions of the other component.



(a) *(b)*

Figure 9.6 For the copper–nickel system, (*a*) tensile strength versus composition, and (*b*) ductility (%EL) versus composition at room temperature. A solid solution exists over all compositions for this system.

Eutectic Systems

When components are not completely soluble in the solid state, it is known as eutectic System

This usually results in two different categories of eutectic system.

(a) Components are completely soluble in liquid state and completely insoluble in solid state

(b) Components have complete solubility in liquid state, but limited solubility in the solid state.

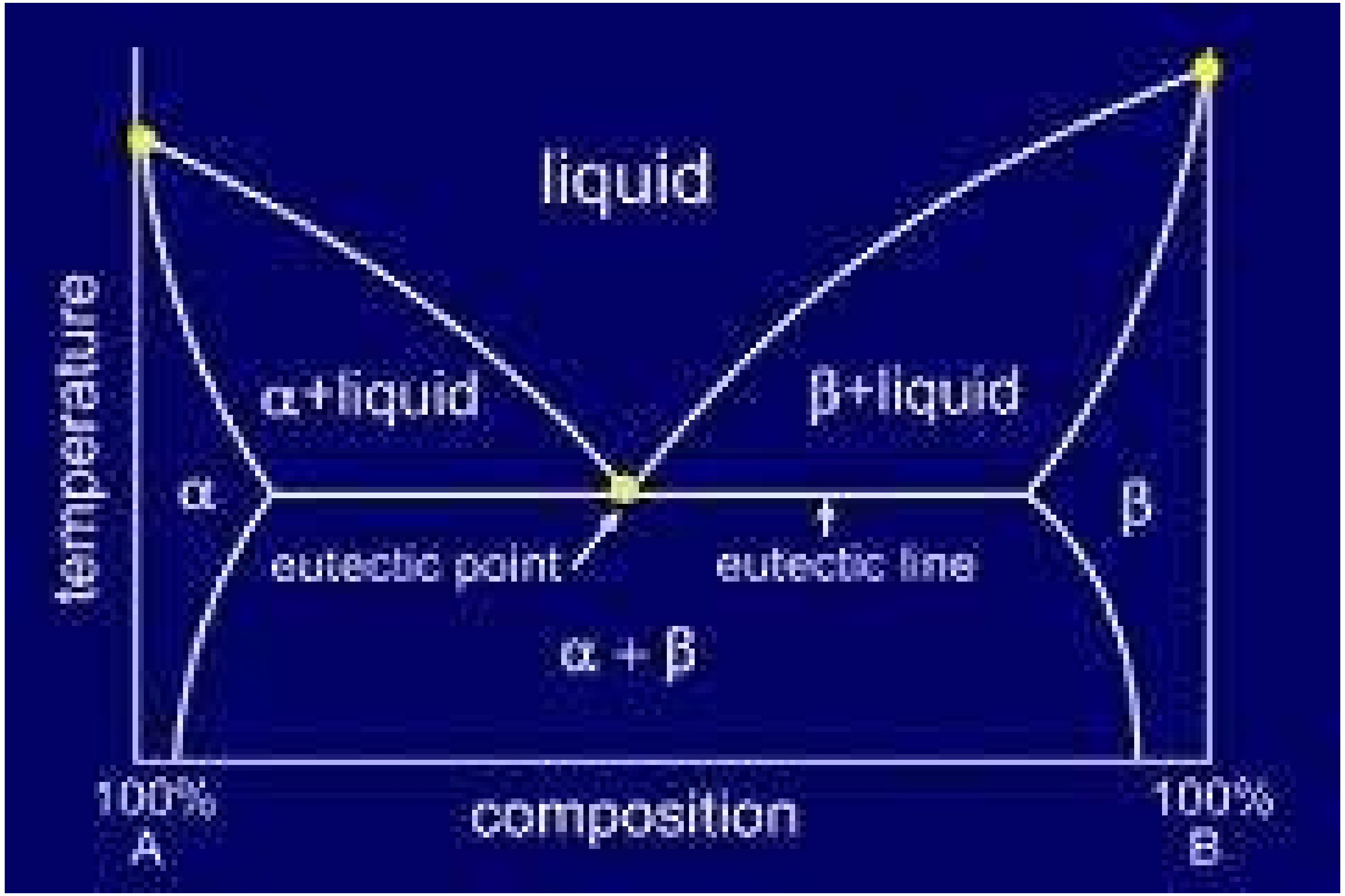
The word eutectic means easy to melt

Eutectic reaction: When a liquid solution of definite composition solidifies at a fixed temperature, two separate phases are formed.

$$Liquid \xrightarrow[cooling]{eutectic\ temperature} \alpha\ solid\ solution + \beta\ solid\ solution$$

Eutectic temperature: In a eutectic system, there is always an alloy of a specific composition which solidifies at a fixed lower temperature than alloys of all other composition. This temperature is known as eutectic temperature.

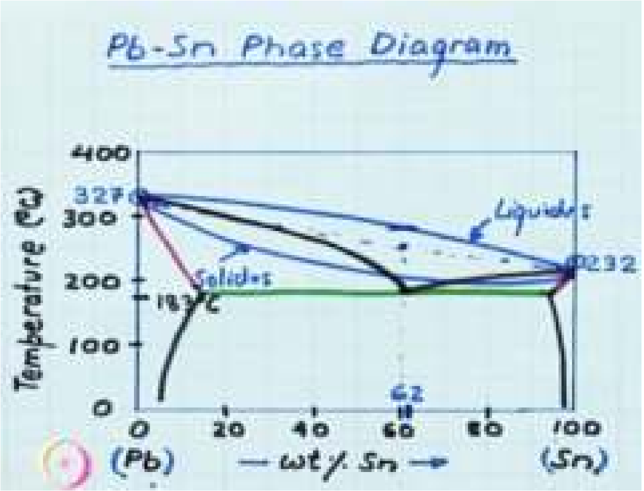
On a phase diagram the intersection of the eutectic temperature and the eutectic composition gives the **eutectic point**.



(a) Components are completely soluble in liquid state and limited solubility in solid state

- *Eg., Copper–Silver system; a binary eutectic phase diagram.*

Melting temperature of pure copper, point *A* 1085 ^{0}C
Melting temperature of pure Silver, point *B* 961.8 °C



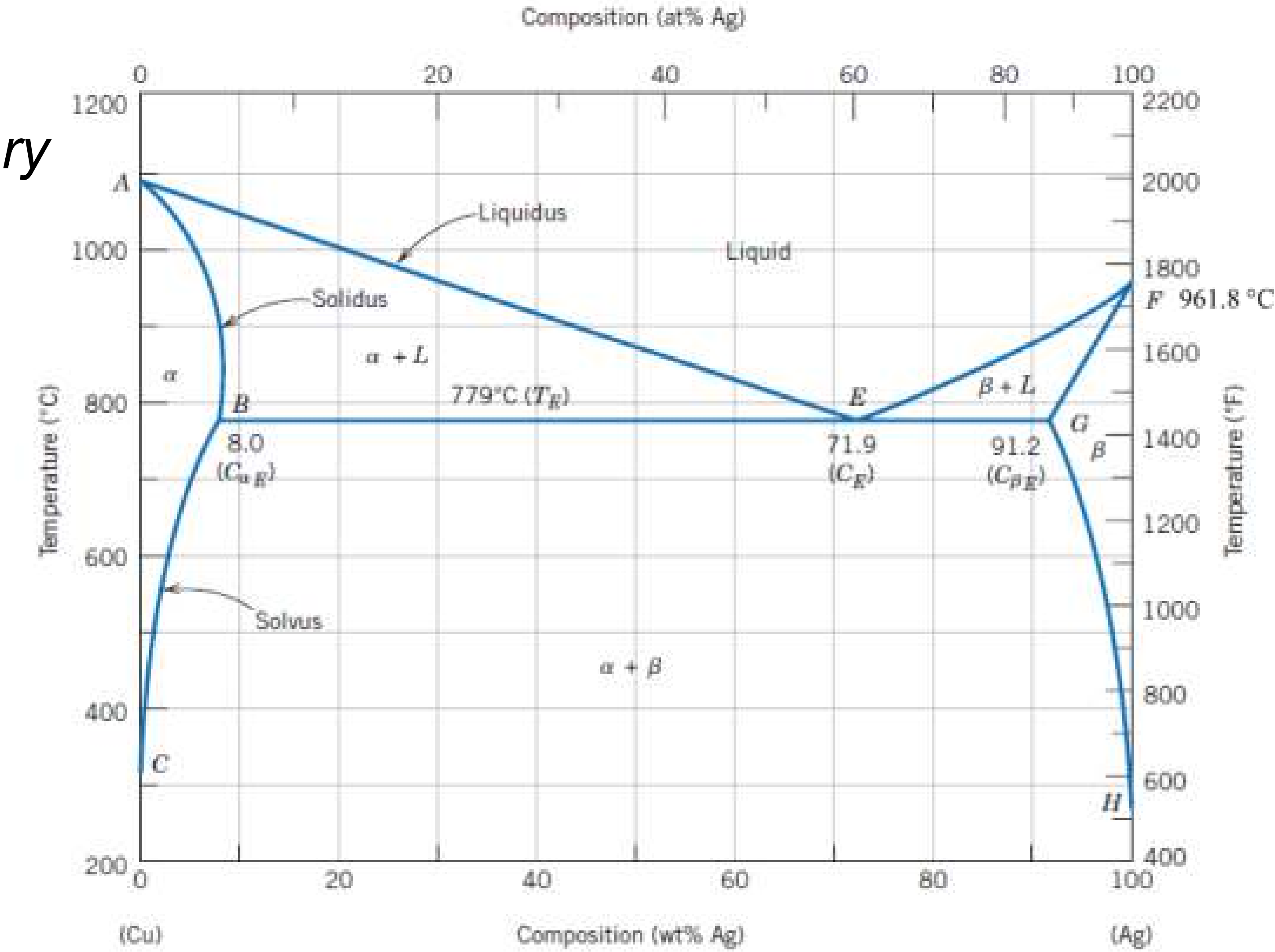
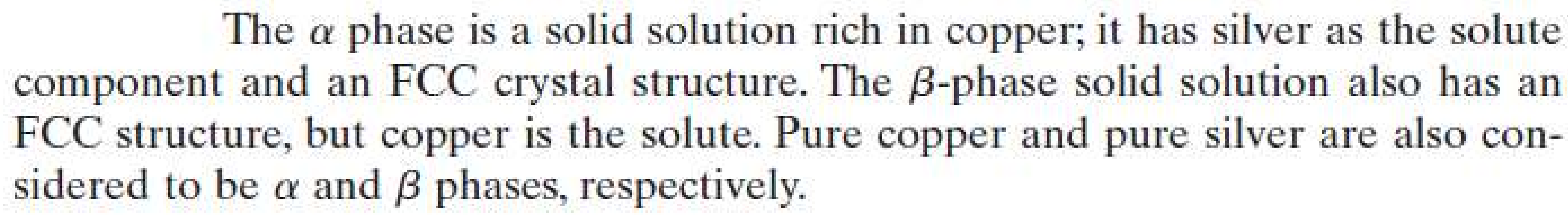


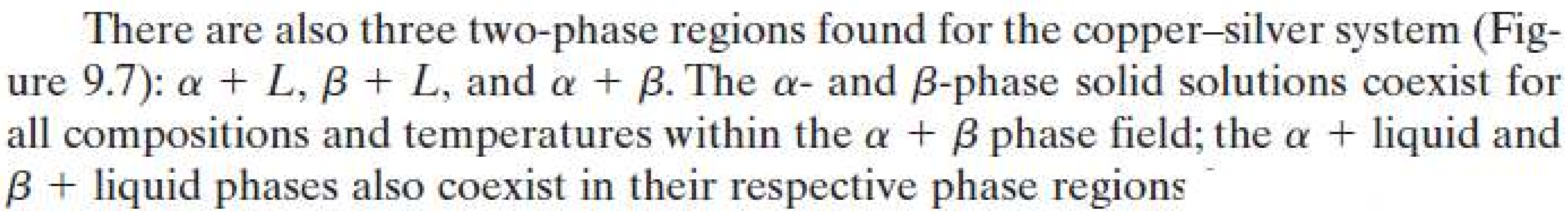
Figure 9.7 The copper–silver phase diagram. [Adapted from *Binary Alloy Phase Diagrams*, 2nd edition, Vol. 1, T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of ASM International, Materials Park, OH.]

- Three single phase regions
  - *α - solid solution of Ag in Cu matrix,*
  - *β - solid solution of Cu in Ag matrix,*
  - *L - liquid*



The α phase is a solid solution rich in copper; it has silver as the solute component and an FCC crystal structure. The β-phase solid solution also has an FCC structure, but copper is the solute. Pure copper and pure silver are also considered to be α and β phases, respectively.

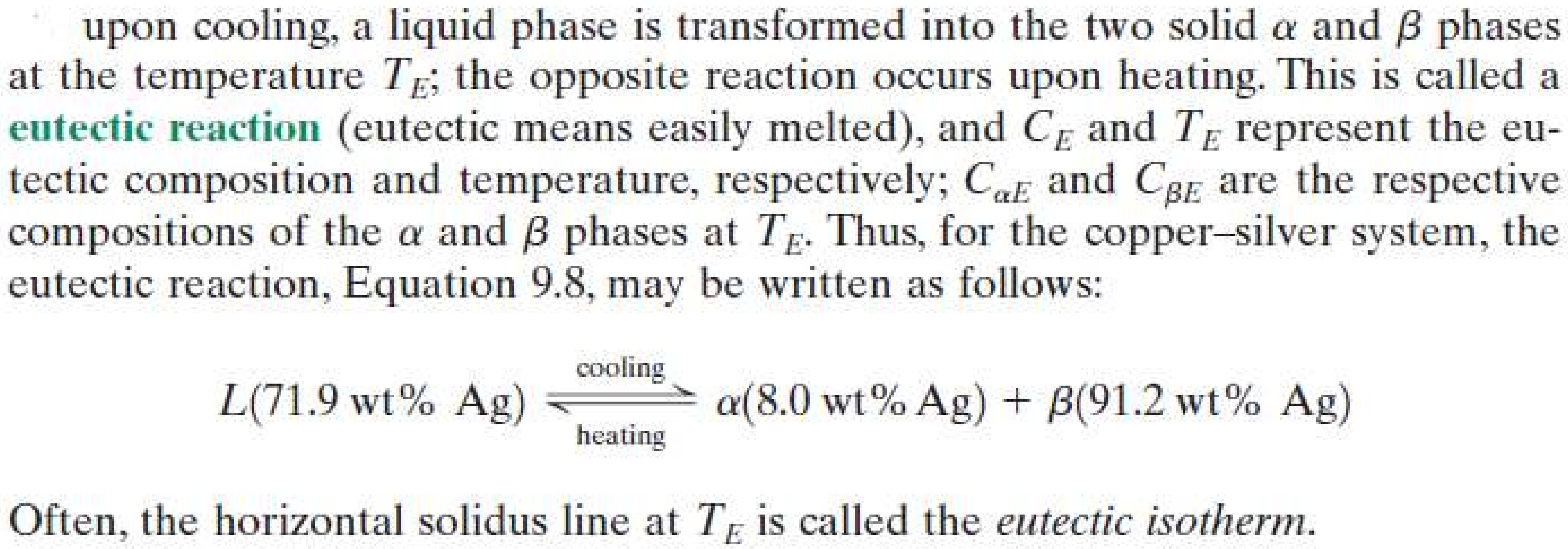
- Three two-phase regions
  - *α + L*
  - *β +L*
  - *α +β*



There are also three two-phase regions found for the copper–silver system (Figure 9.7): $\alpha + L$, $\beta + L$, and $\alpha + \beta$. The α- and β-phase solid solutions coexist for all compositions and temperatures within the $\alpha + \beta$ phase field; the α + liquid and β + liquid phases also coexist in their respective phase regions

Boundaries

- Liquidus Boundary (AE and EF) : Liquid (L) Changes to (Liquid + α) **or** Liquid (L) Changes to (Liquid + β)
- Solidus Boundary (AB and GF) : Solid (α) Changes to (α + Liquid) **or** Solid (β) Changes to (β + Liquid)
- Solvus Boundary (CB and GH) : Solid (α) Changes to (α + β) **or** Solid (β) Changes to (α + β)
- Eutectic horizontal isotherm (BG) : Liquid (L) Changes to (α + β) solid



upon cooling, a liquid phase is transformed into the two solid α and β phases at the temperature T_E; the opposite reaction occurs upon heating. This is called a **eutectic reaction** (eutectic means easily melted), and C_E and T_E represent the eutectic composition and temperature, respectively; $C_{\alpha E}$ and $C_{\beta E}$ are the respective compositions of the α and β phases at T_E. Thus, for the copper–silver system, the eutectic reaction, Equation 9.8, may be written as follows:

$$L(71.9\text{ wt\% Ag}) \underset{\text{heating}}{\overset{\text{cooling}}{\rightleftharpoons}} \alpha(8.0\text{ wt\% Ag}) + \beta(91.2\text{ wt\% Ag})$$

Often, the horizontal solidus line at T_E is called the *eutectic isotherm*.

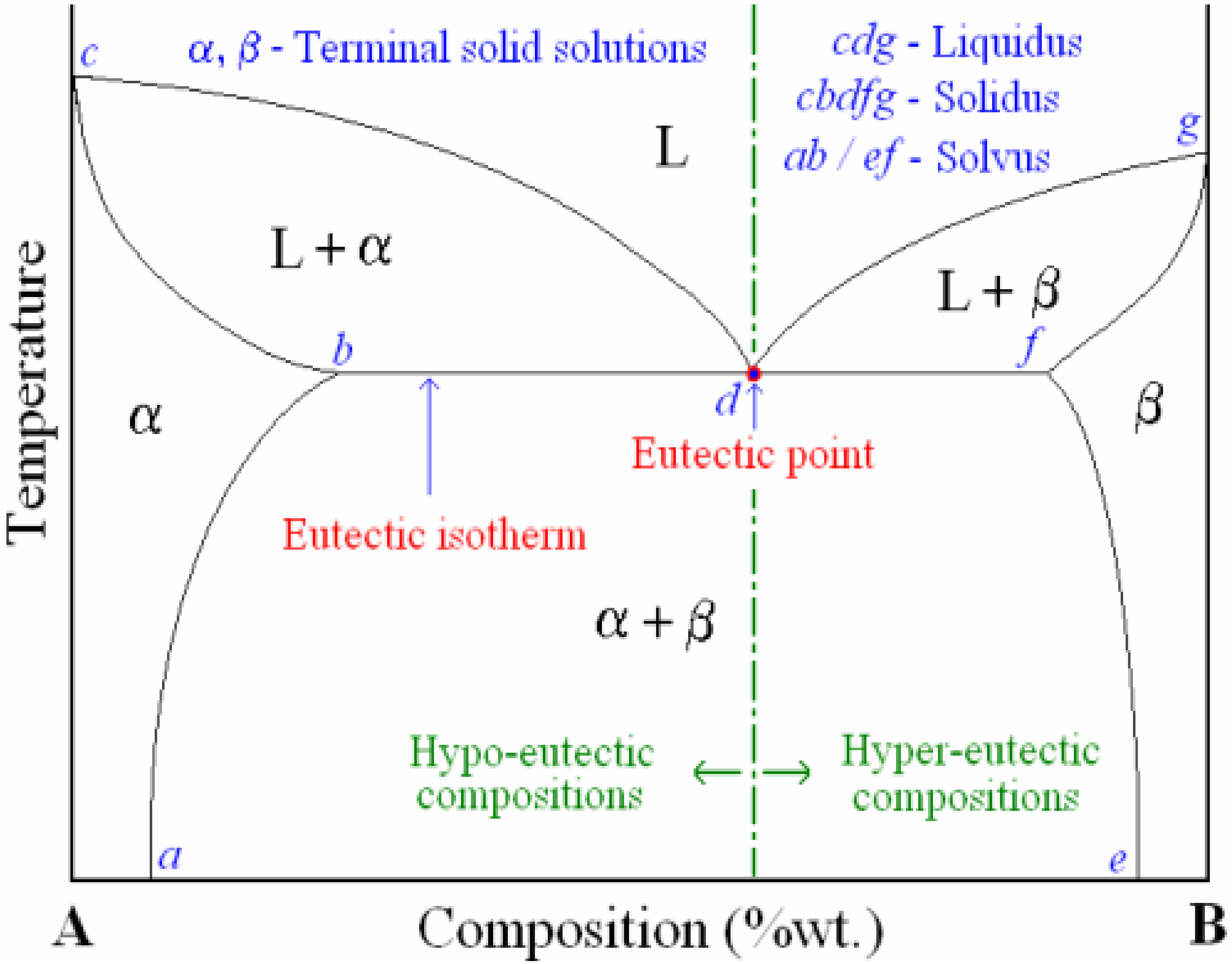
Eutectic reaction is a invariant reaction with fixed temperature and concentration, and corresponding point also called invariant point.

Solvus line separates one solid solution from a mixture of solid solutions. Solvus line shows limit of solubility

Alloy in the ***eutectic composition called eutectic alloy***

Compositions that are on left-hand-side of the eutectic composition are known as ***hypo-eutectic compositions or (hypo-eutectic alloy)*** while compositions on right-hand-side of the eutectic composition are called ***hyper-eutectic compositions or (hyper-eutectic alloy)*** *.*

The regions of limited solid solubility at each end of a phase diagram are called ***terminal solid solutions***



(a) Components are completely soluble in liquid state and limited solubility in solid state

Eutectic system : Eg. 2 , Lead –Tin Phase Diagram

- *Another common eutectic system is that for lead and tin; the phase diagram.*

- *Soldering Process requirements are,*
  - *Low melting point*
  - *Strength (allow stronger than that of alloy)*
- *Pb Melting Point : 327 ^{0}C*
- *Sn Melting Point : 232 ^{0}C*

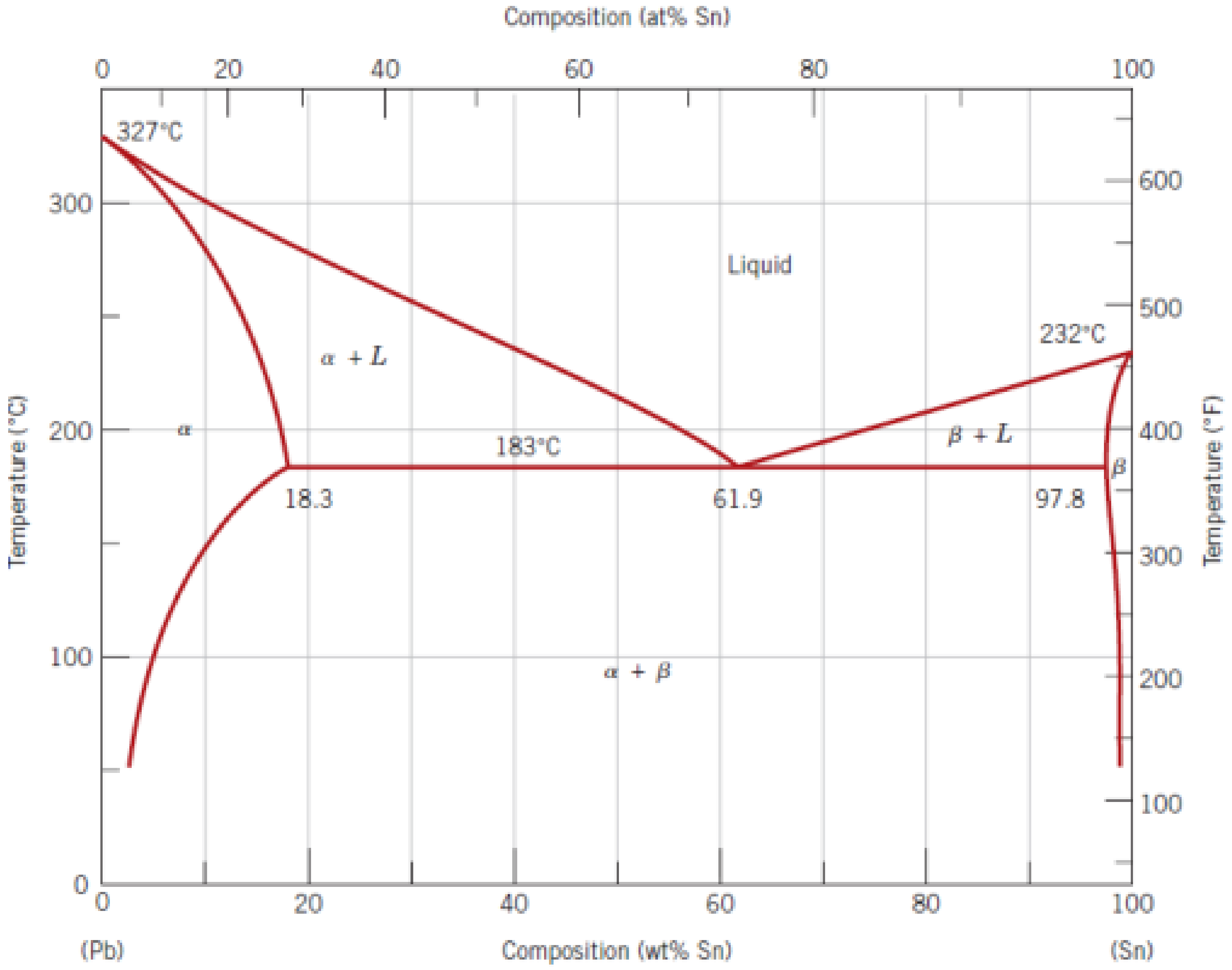


Figure 9.8 The lead–tin phase diagram. [Adapted from *Binary Alloy Phase Diagrams*, 2nd edition, Vol. 3, T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of

Micro-structure development for eutectic alloy that passes mainly through terminal solid solution

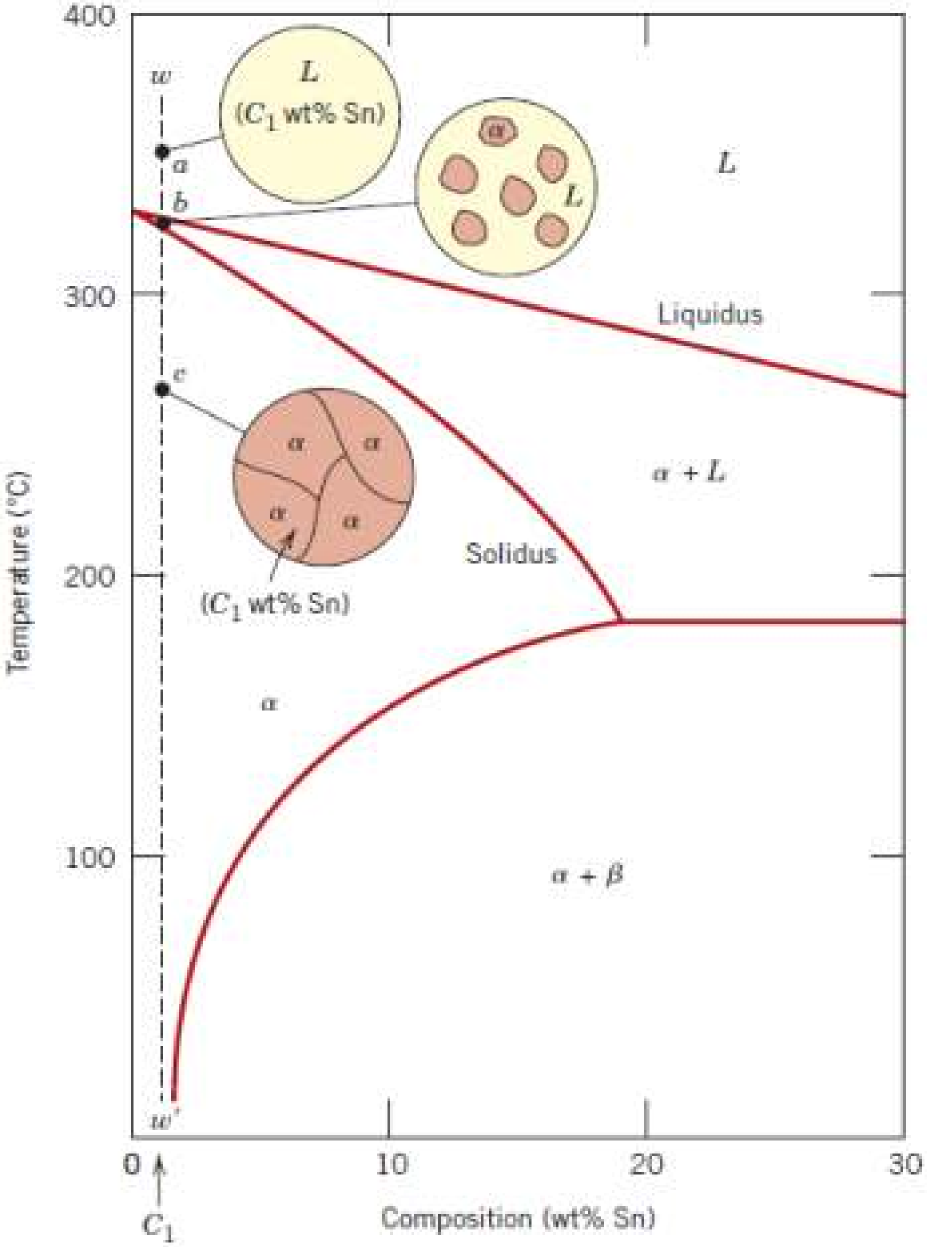


Figure 9.11 Schematic representations of the equilibrium microstructures for a lead–tin alloy of composition C_1 as it is cooled from the liquid-phase region.

Cooling curve and micro-structure development for eutectic alloy that passes through terminal solid solution and Multi without formation of eutectic solid.

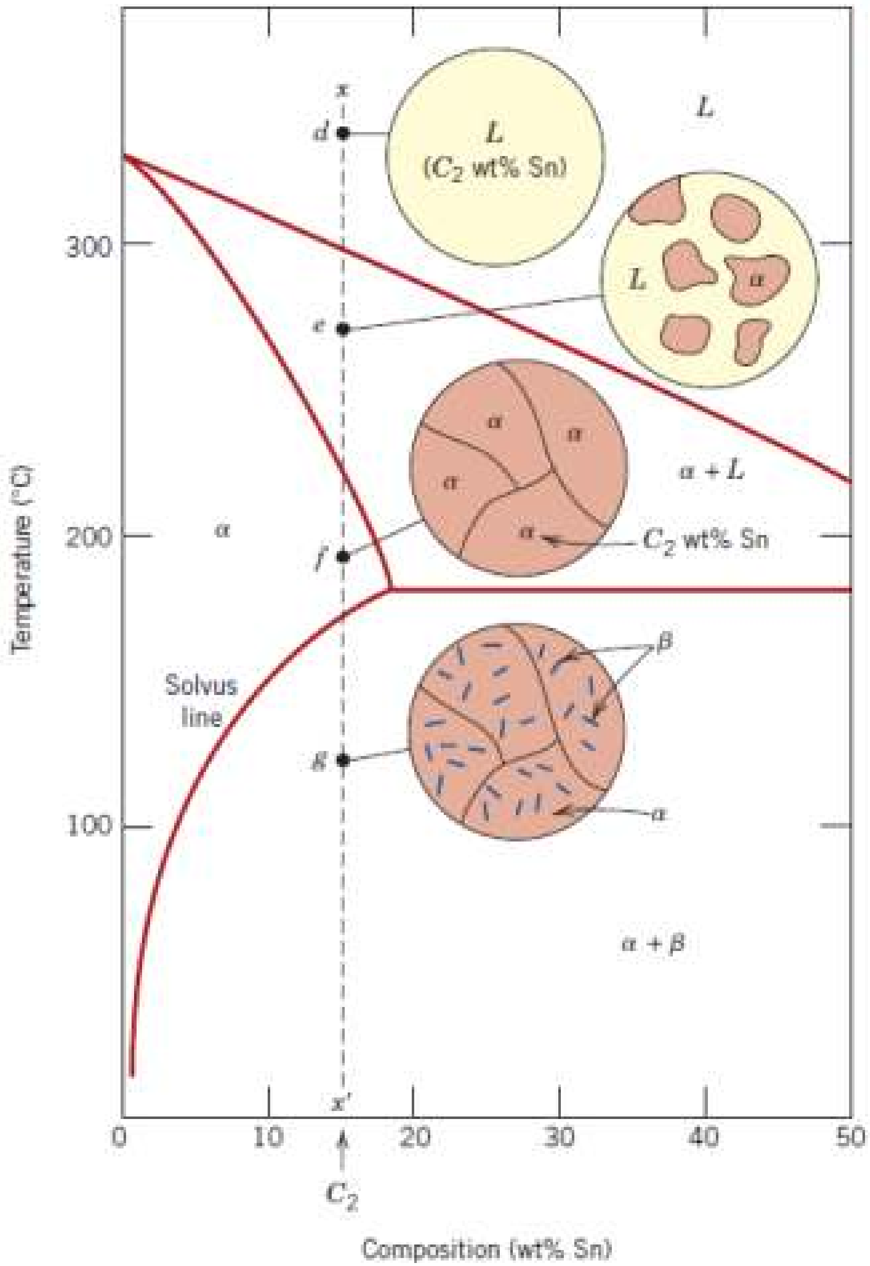
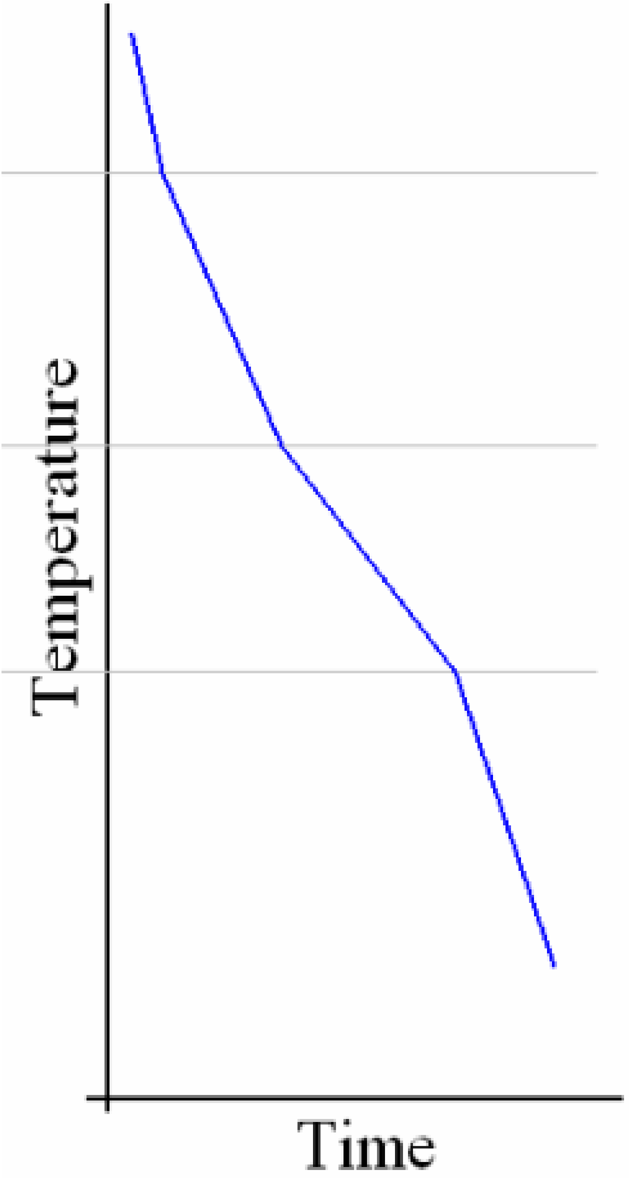
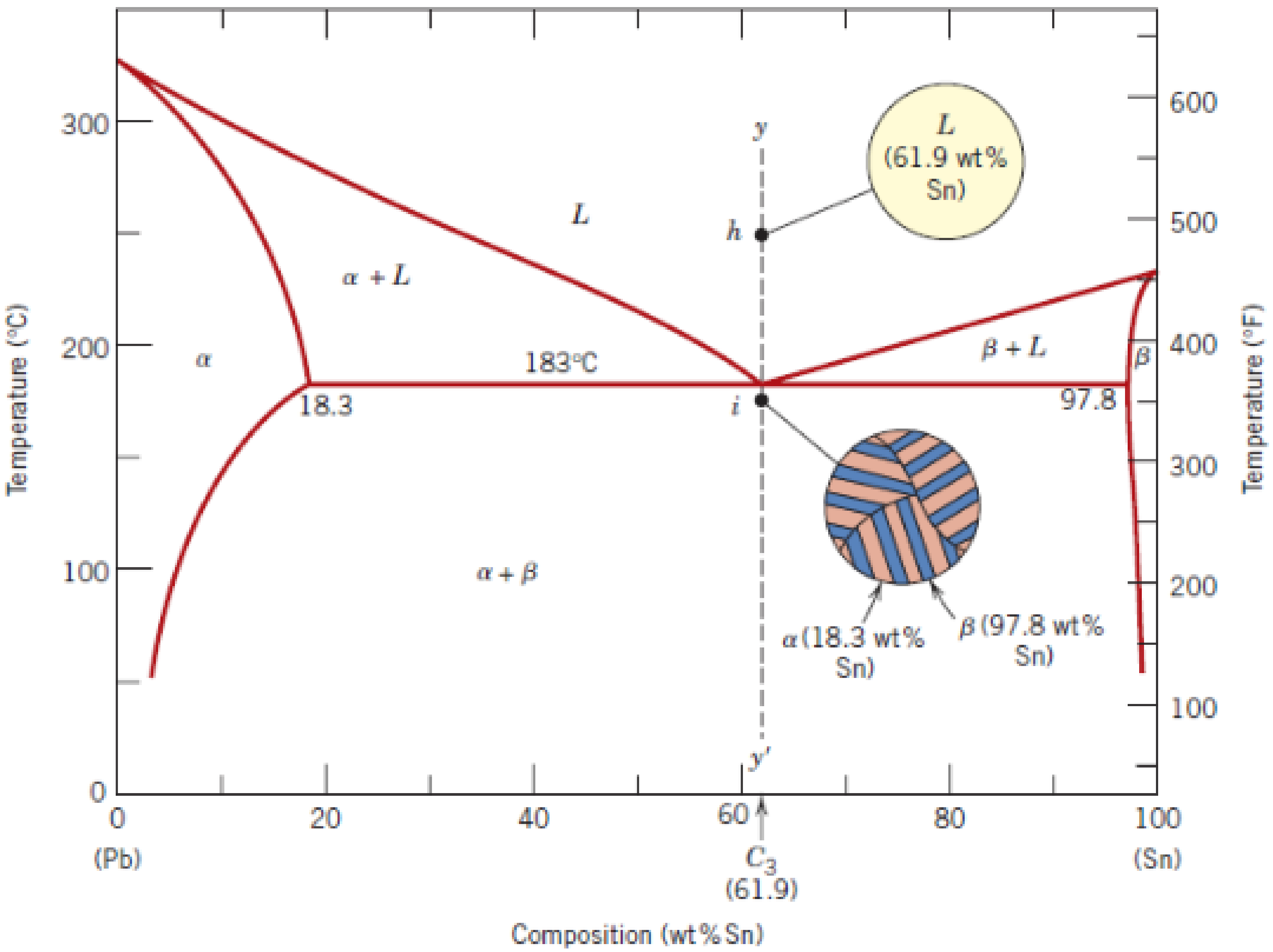


Figure 9.12 Schematic representations of the equilibrium microstructures for a lead–tin alloy of composition C_2 as it is cooled from the liquid-phase region.



Cooling curve and micro-structure development for eutectic alloy that passes through eutectic-point

Figure 9.13 Schematic representations of the equilibrium microstructures for a lead–tin alloy of eutectic composition C_3 above and below the eutectic temperature.



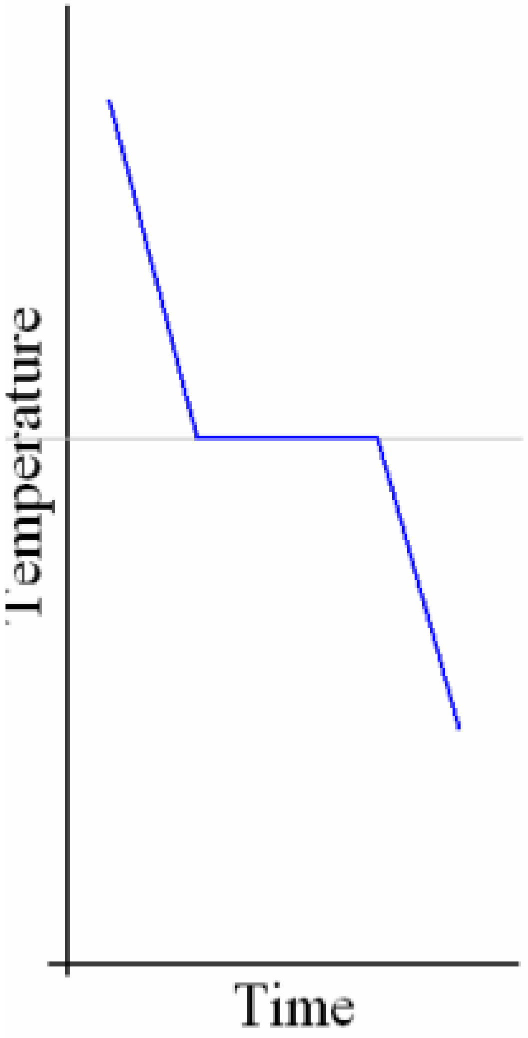


Figure 9.14 Photomicrograph showing the microstructure of a lead–tin alloy of eutectic composition. This microstructure consists of alternating layers of a lead-rich α-phase solid solution (dark layers), and a tin-rich β-phase solid solution (light layers). 375×. (Reproduced with permission from *Metals Handbook,* 9th edition, Vol. 9, *Metallography and Microstructures,* American Society for Metals, Materials Park, OH, 1985.)

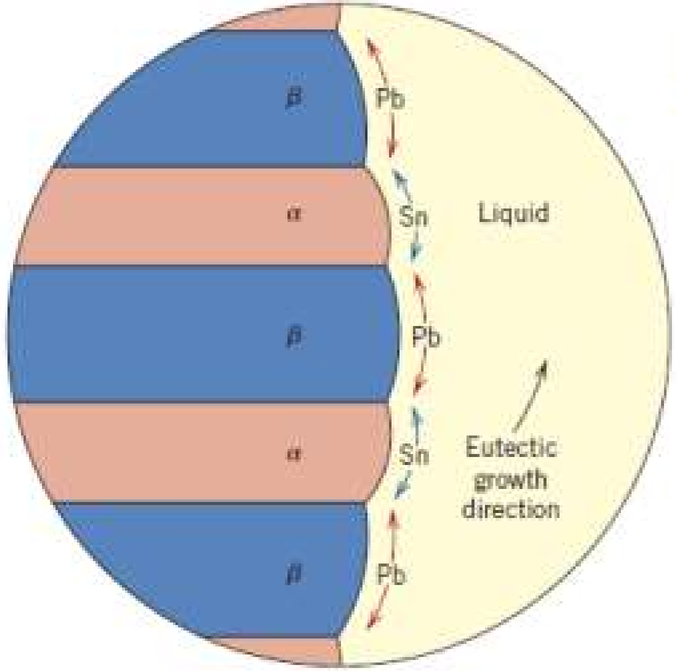


Figure 9.15 Schematic representation of the formation of the eutectic structure for the lead–tin system. Directions of diffusion of tin and lead atoms are indicated by blue and red arrows, respectively.

Micro-structure development for two phase region

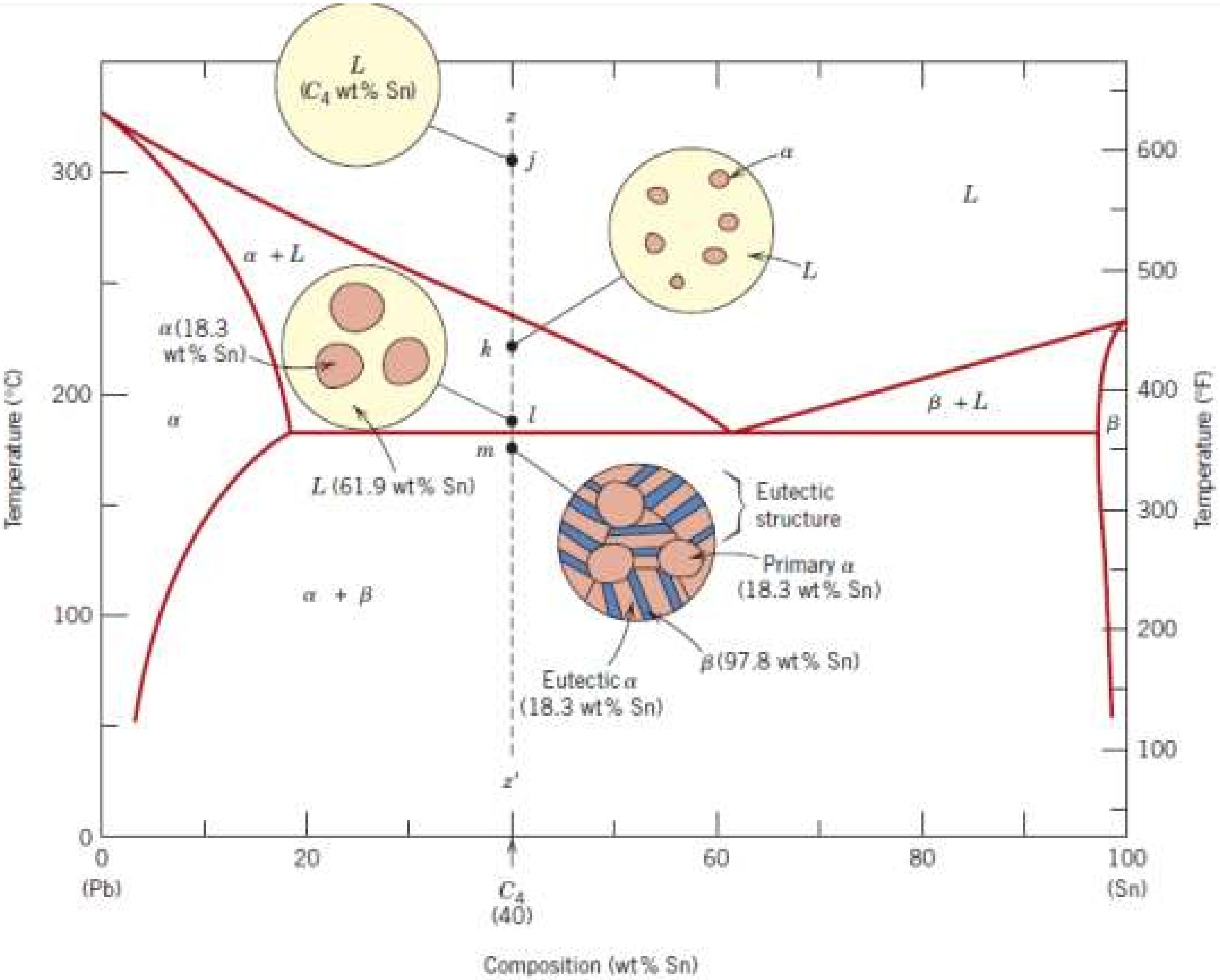


Figure 9.16 Schematic representations of the equilibrium microstructures for a lead–tin alloy of composition C_4 as it is cooled from the liquid-phase region.

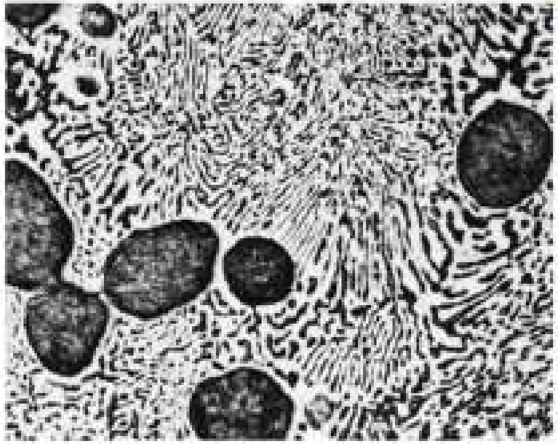
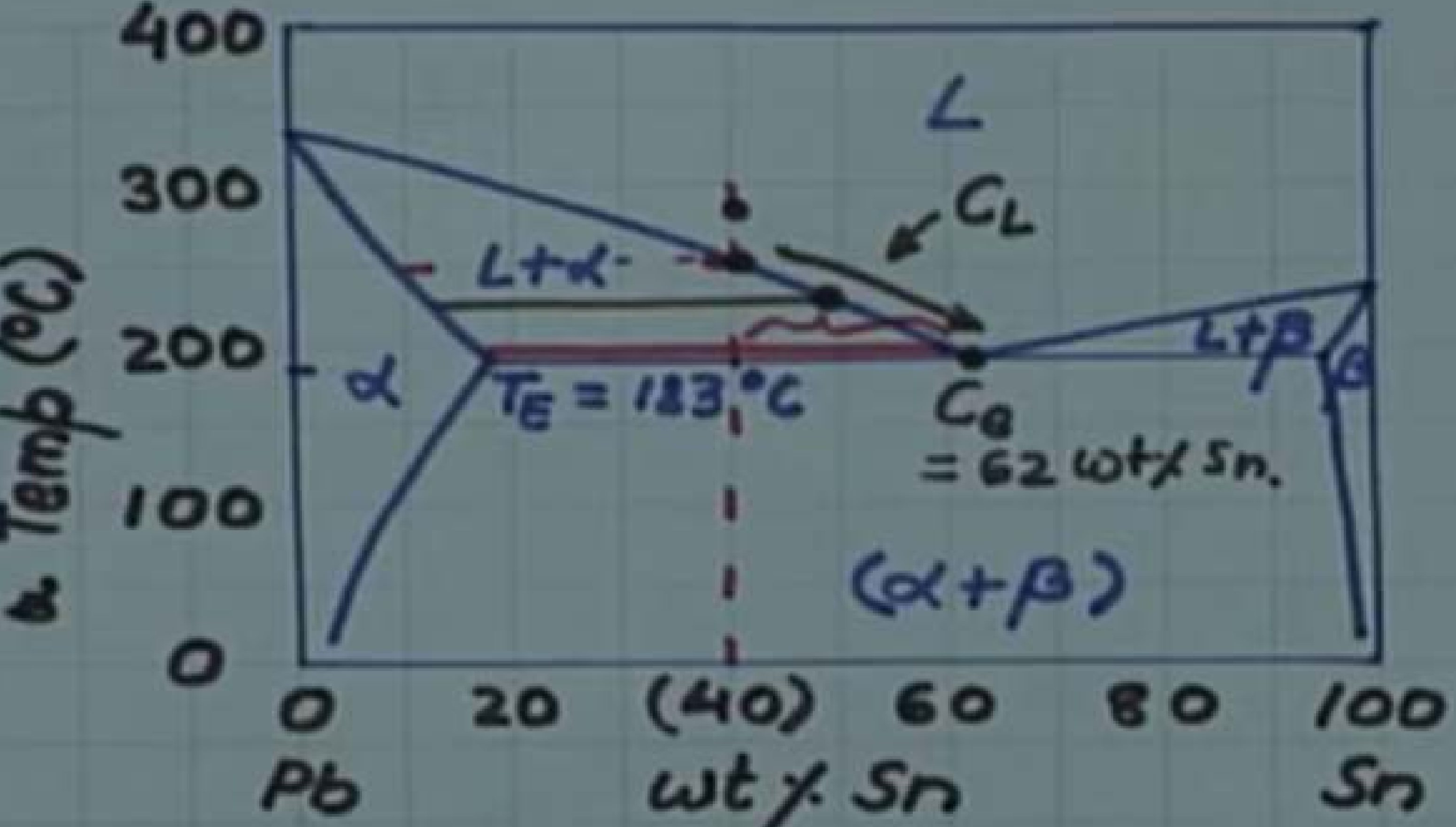
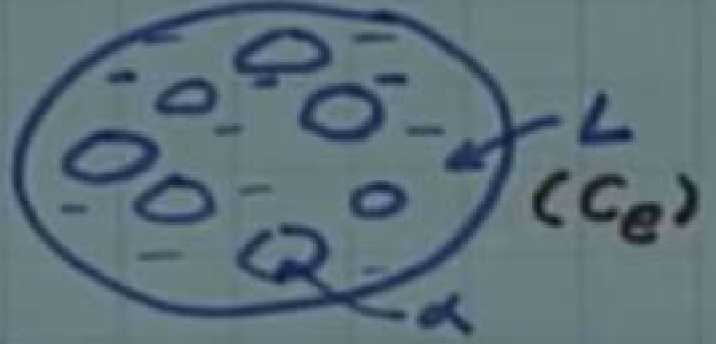


Figure 9.17 Photomicrograph showing the microstructure of a lead–tin alloy of composition 50 wt% Sn–50 wt% Pb. This microstructure is composed of a primary lead-rich α phase (large dark regions) within a lamellar eutectic structure consisting of a tin-rich β phase (light layers) and a lead-rich α phase (dark layers). 400×. (Reproduced with permission from *Metals Handbook*, 9th edition, Vol. 9, *Metallography and Microstructures*, American Society for Metals, Materials Park, OH, 1985.)



Phases in a hypoeutectic alloy



Just above T_E

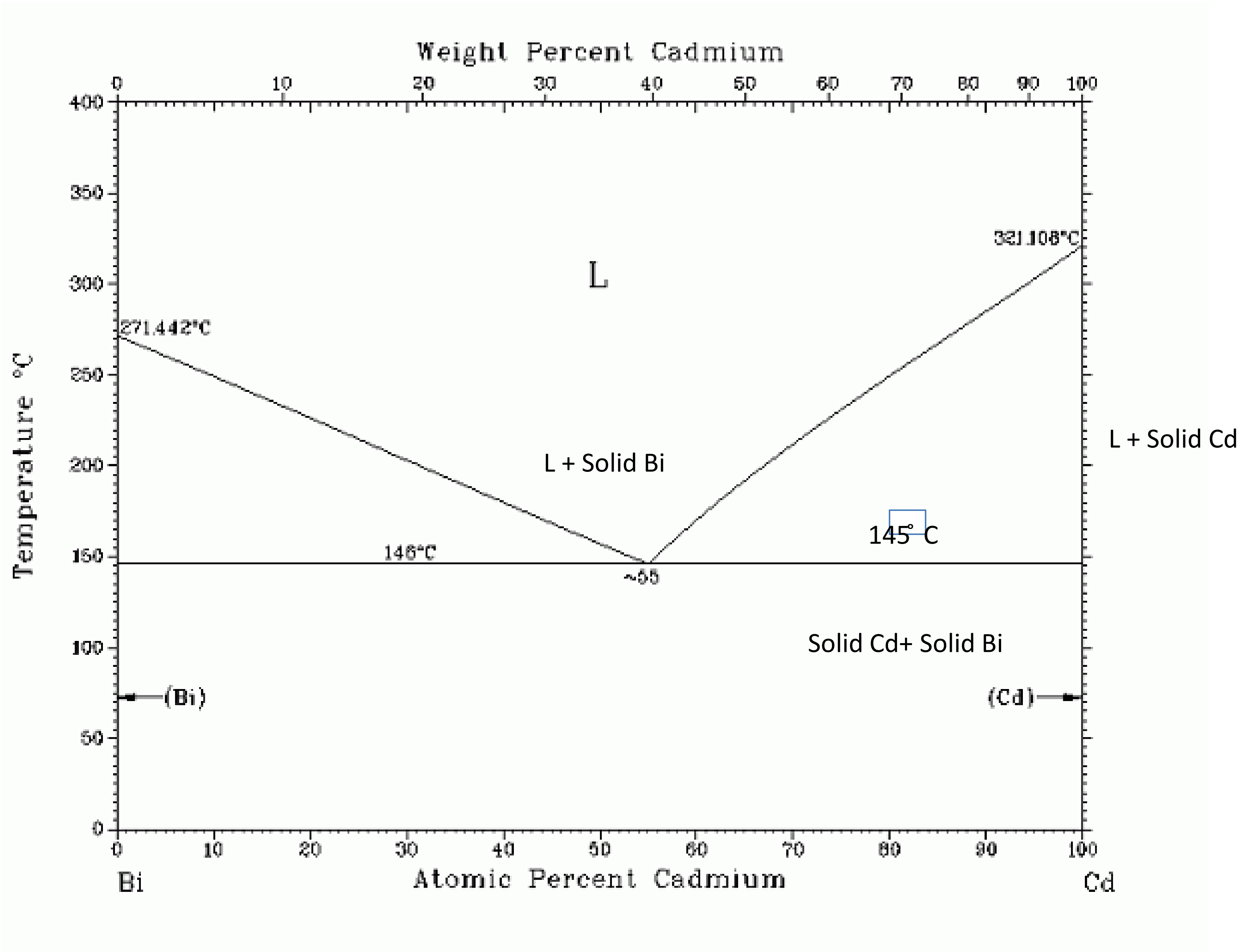
Microstructure evolution in a hypoeutectic alloy

- proeutectic α
- eutectic mixture (α+β)

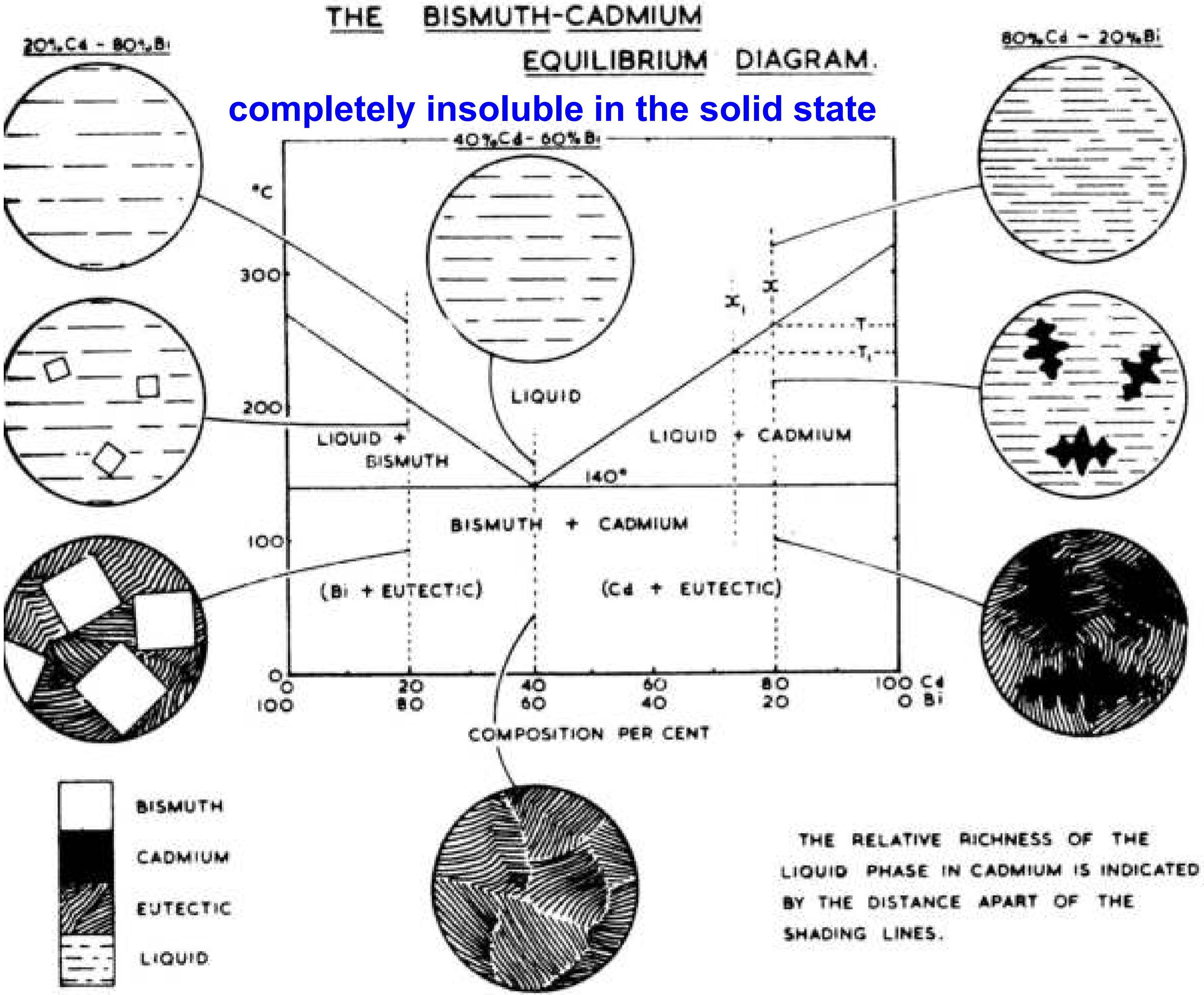
Just below T_E

Microconstituents of a hypoeutectic alloy.

(b) Components are completely soluble in liquid state and insoluble in solid state



Cadmium (Cd) –Bismuth(Bi) Phase diagram



completely insoluble in the solid state

Eutectic reaction = Liquid$\leftrightarrow$ Solid$_1$ + Solid$_2$

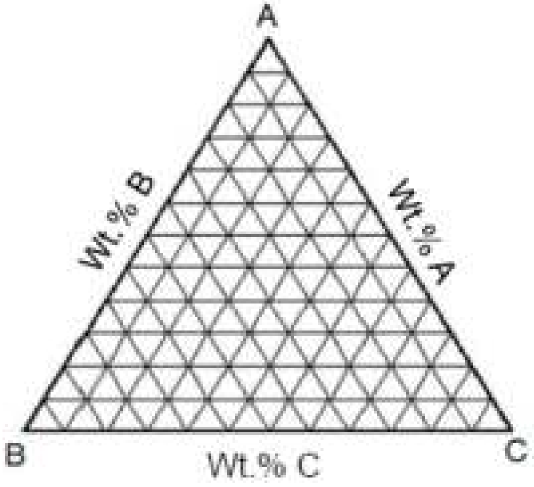
Fig. 9.8 The bismuth–cadmium equilibrium diagram.

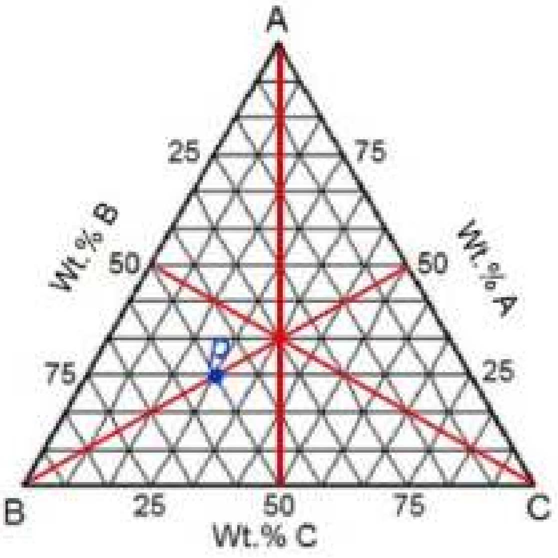
Courtesy:- Higgins

Ternary Phase diagram

- A ternary or *three component* phase diagram has the form of an *triangular prism* with an *equilateral triangle as a base.*

- Pure components are at each *vertex*, *sides* are binary compositions and ternary compositions are *within* the triangle.
- The composition lines on the triangle is constructed from projections of surfaces.





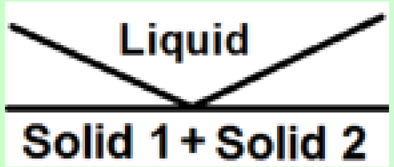
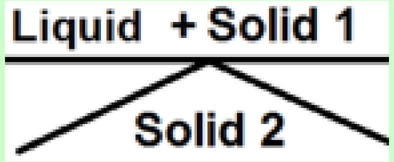
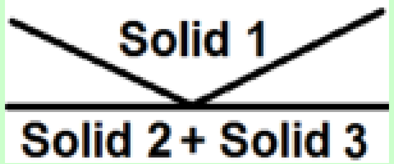
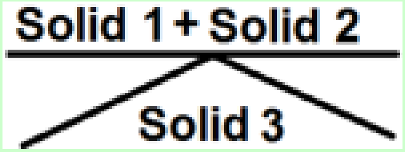
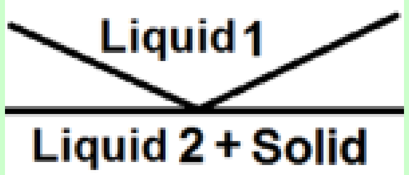
- The temperature varies along the *height* of the prism.

- The *composition triangle* is an isothermal section.

- The composition of any point in the triangle is determined by drawing perpendiculars from corners to the opposite sides and measuring the distance of the point along the perpendicular.

- Point *p, for example, lies on the isocomoposition line 25% A* along the perpendicular A-50. Hence, percentage of A in the alloy is 25%. Similarly B is 50% and C is 25%.

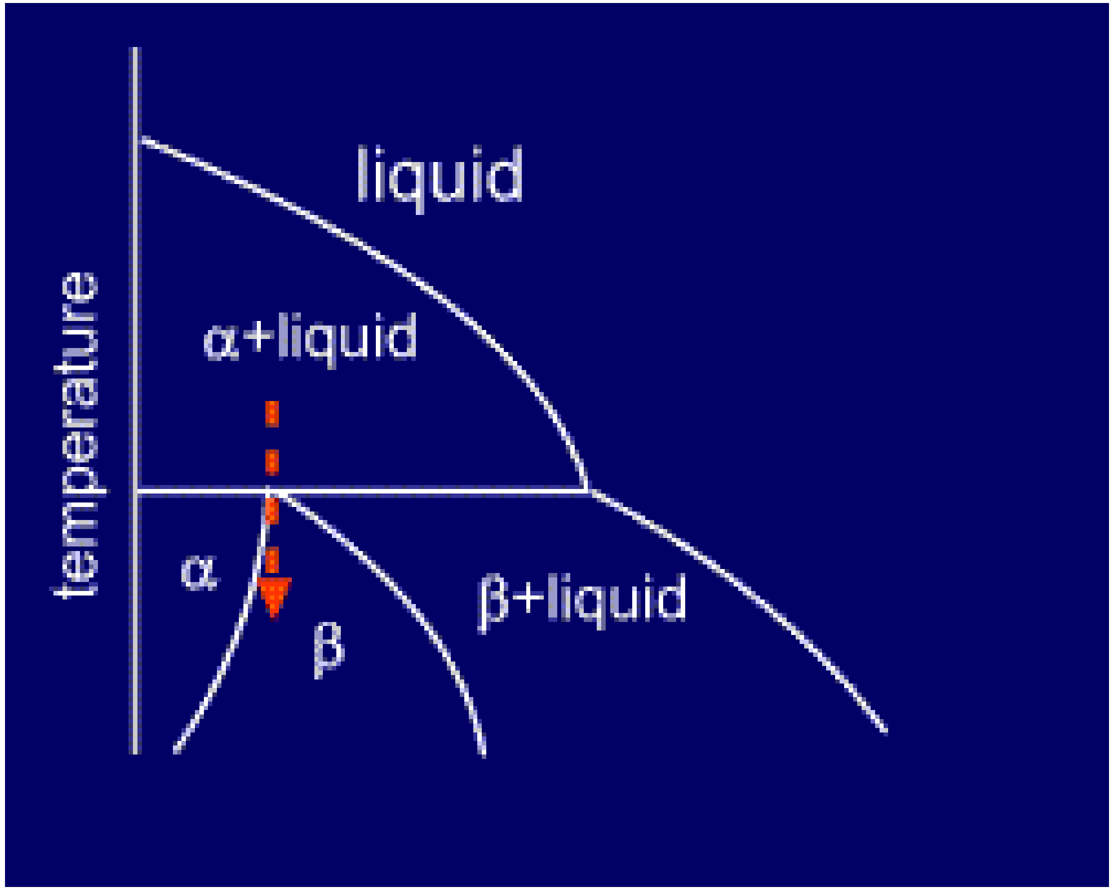
Invariant Reactions

Reaction	Characteristics	Schematic Representation	Examples
Eutectic	$\text{Liquid} \underset{\text{Heat}}{\overset{\text{Cool}}{\rightleftharpoons}} \text{Solid 1} + \text{Solid 2}$		Pb-Sn, Ag-Cu, Pb-Sb
Peritectic	$\text{Liquid} + \text{Solid 1} \underset{\text{Heat}}{\overset{\text{Cool}}{\rightleftharpoons}} \text{Solid 2}$		Ag-Pt, Fe-C, Fe-Ni, Cu-zn
Eutectoid	$\text{Solid 1} \underset{\text{Heat}}{\overset{\text{Cool}}{\rightleftharpoons}} \text{Solid 2} + \text{Solid 3}$		Fe-C, Cu-Zn Pd-Ti, Al-Cu
Peritectoid	$\text{Solid 1} + \text{Solid 2} \underset{\text{Heat}}{\overset{\text{Cool}}{\rightleftharpoons}} \text{Solid 3}$		Ag-Al, Al-Cu
Monotectic	$\text{Liquid 1} \underset{\text{Heat}}{\overset{\text{Cool}}{\rightleftharpoons}} \text{Solid} + \text{Liquid 2}$		Cu-Pb

Peritectic reaction

A peritectic reaction is a reaction where a solid phase and liquid phase will together form a second solid phase at a particular temperature and composition.

e.g. Liquid (L) + alpha (α) ➡ Beta (β)

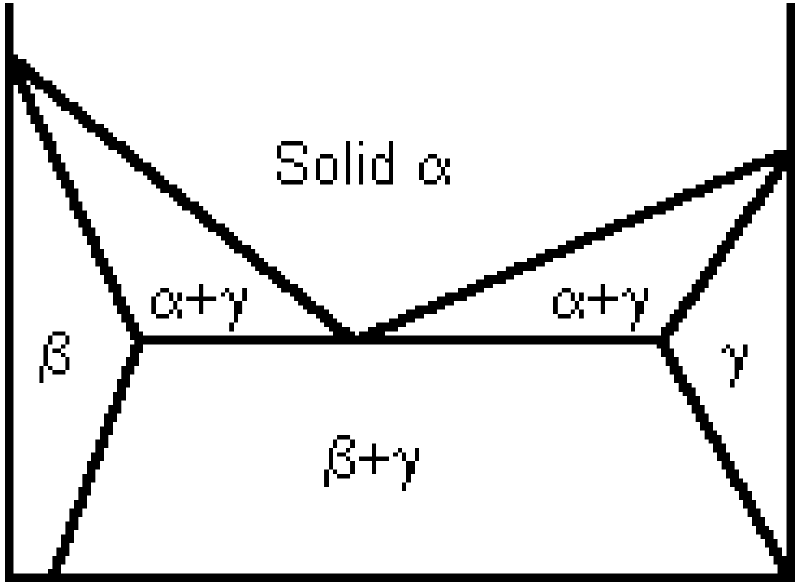


Peritectics are not as common as eutectics and eutectiods, but do occur in some alloy systems

Eutectoid reaction

This invariant reaction involves transformation of a solid phase on cooling to two other solid phases of different composition.

The eutectoid structure having alternate layers of the two solid phases resembles the eutectic structure



$$\text{Solid 1} \underset{\text{Heat}}{\overset{\text{Cool}}{\rightleftharpoons}} \text{Solid 2 + Solid 3}$$

Peritectoid reaction

Peritectoid reaction is simply the reverse of the eutectoid reaction. Two different solid phase on cooling form another solid phase

$$\text{Solid 1} + \text{Solid 2} \underset{\text{Heat}}{\overset{\text{Cool}}{\rightleftharpoons}} \text{Solid 3}$$

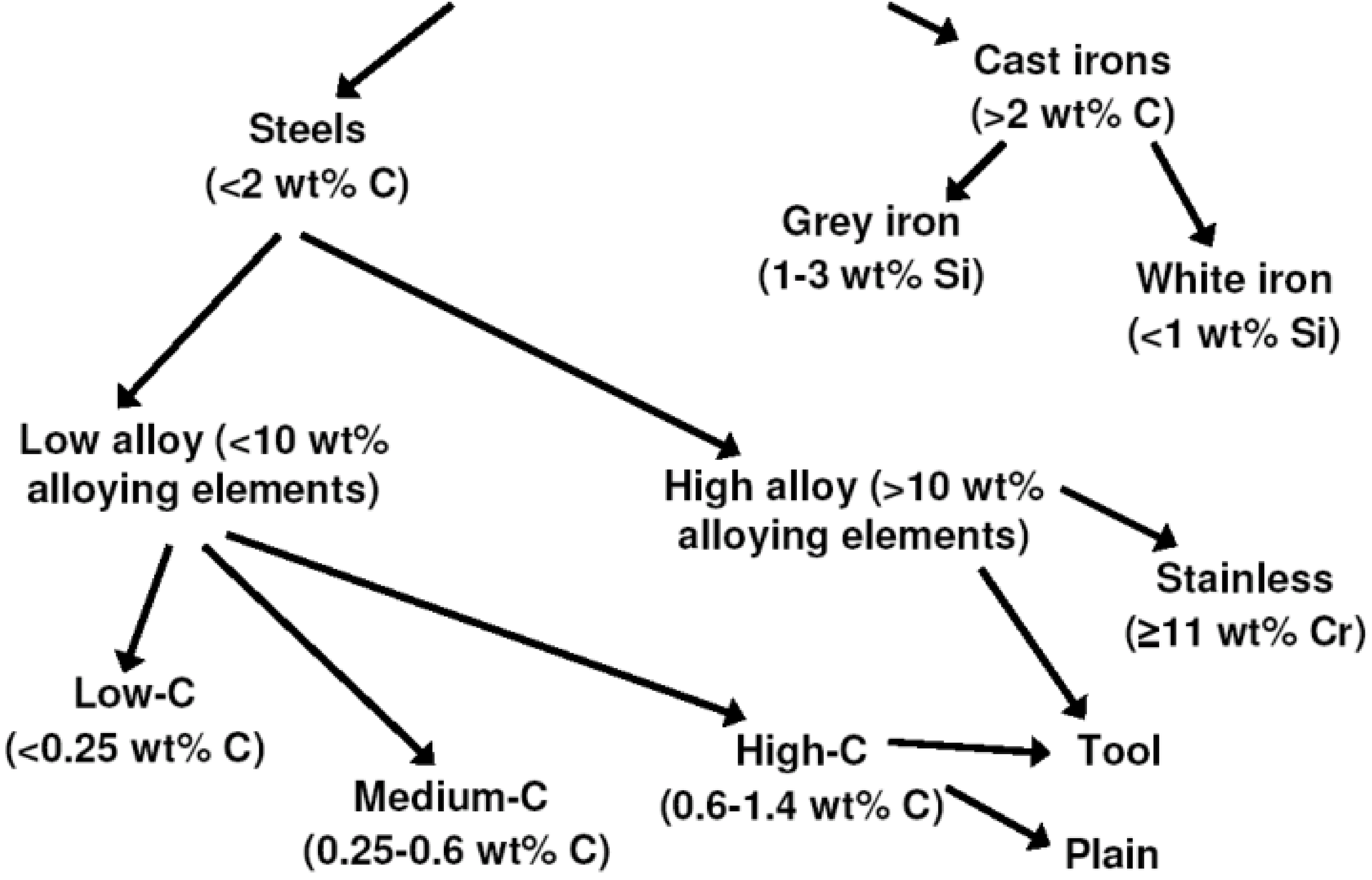
Monotectic reaction

Here, a liquid phase transforms into another liquid phase of a different composition and a new solid phase precipitates out.

$$\text{Liquid 1} \underset{\text{Heat}}{\overset{\text{Cool}}{\rightleftharpoons}} \text{Solid} + \text{Liquid 2}$$

The two liquid phases involved in the reaction are immiscible like water and oil.

Classification of ferrous alloys



Steels

(<2 wt% C)

Cast irons

(>2 wt% C)

Grey iron

(1-3 wt% Si)

White iron

(<1 wt% Si)

Low alloy (<10 wt% alloying elements)

High alloy (>10 wt% alloying elements)

Stainless

(≥11 wt% Cr)

Low-C

(<0.25 wt% C)

Medium-C

(0.25-0.6 wt% C)

High-C

(0.6-1.4 wt% C)

Tool

Plain

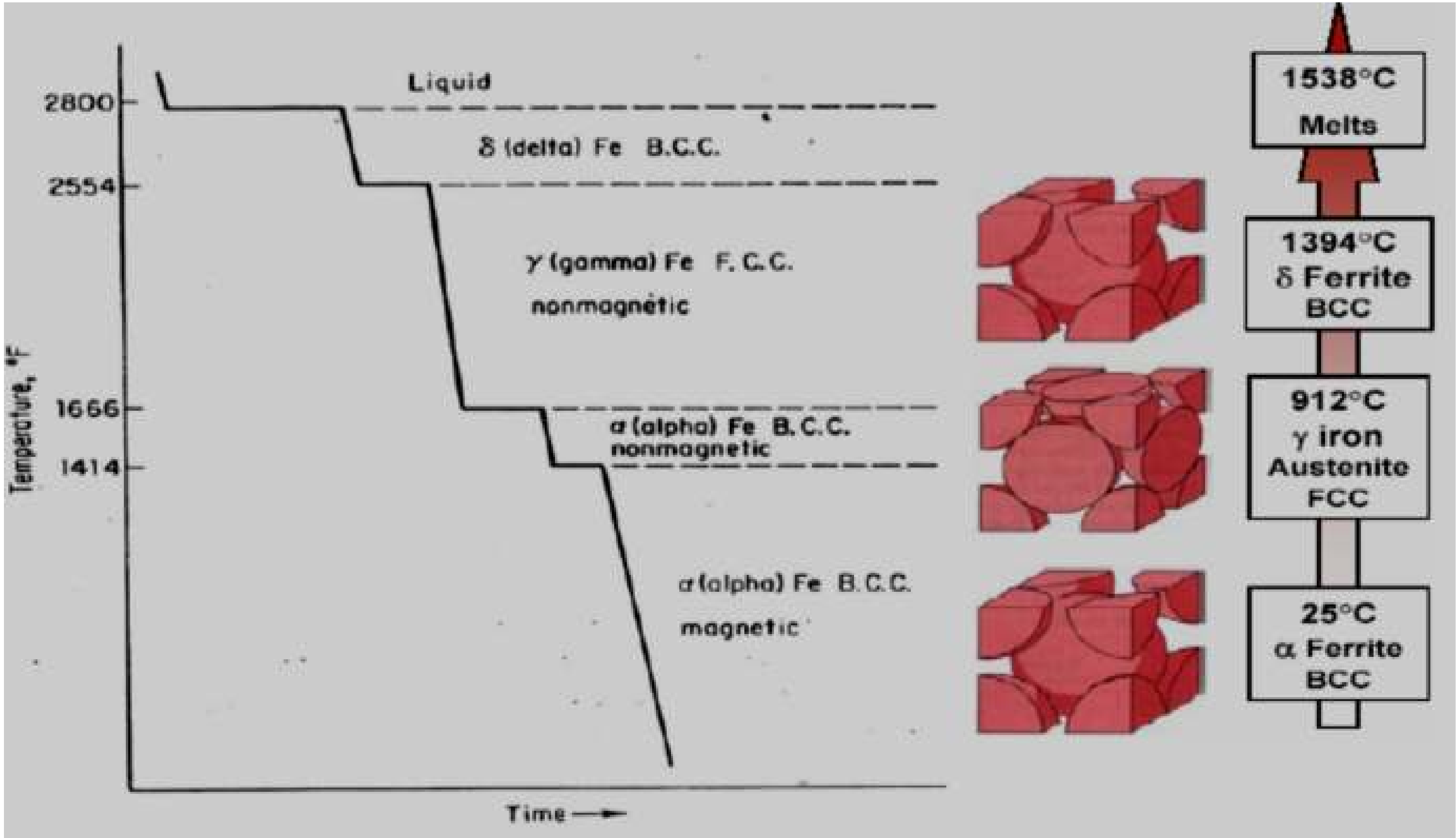
Steels

Steel is an interstitial solid solution of carbon in iron.

Theoretically steel has a maximum of 2.11% carbon.

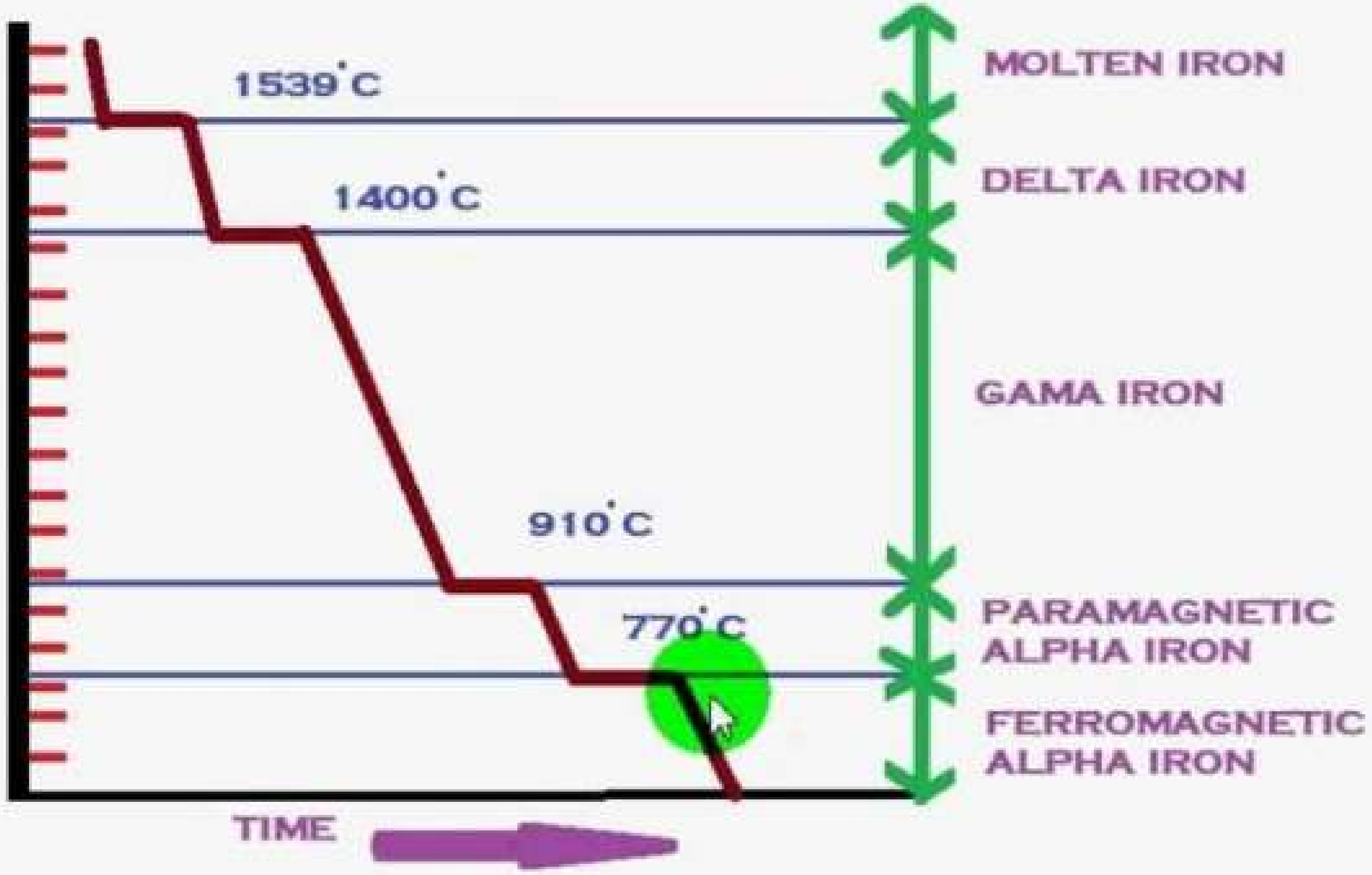
In practice, the amount of carbon rarely exceeds 0.8%

Polymorphic transformation in IRON

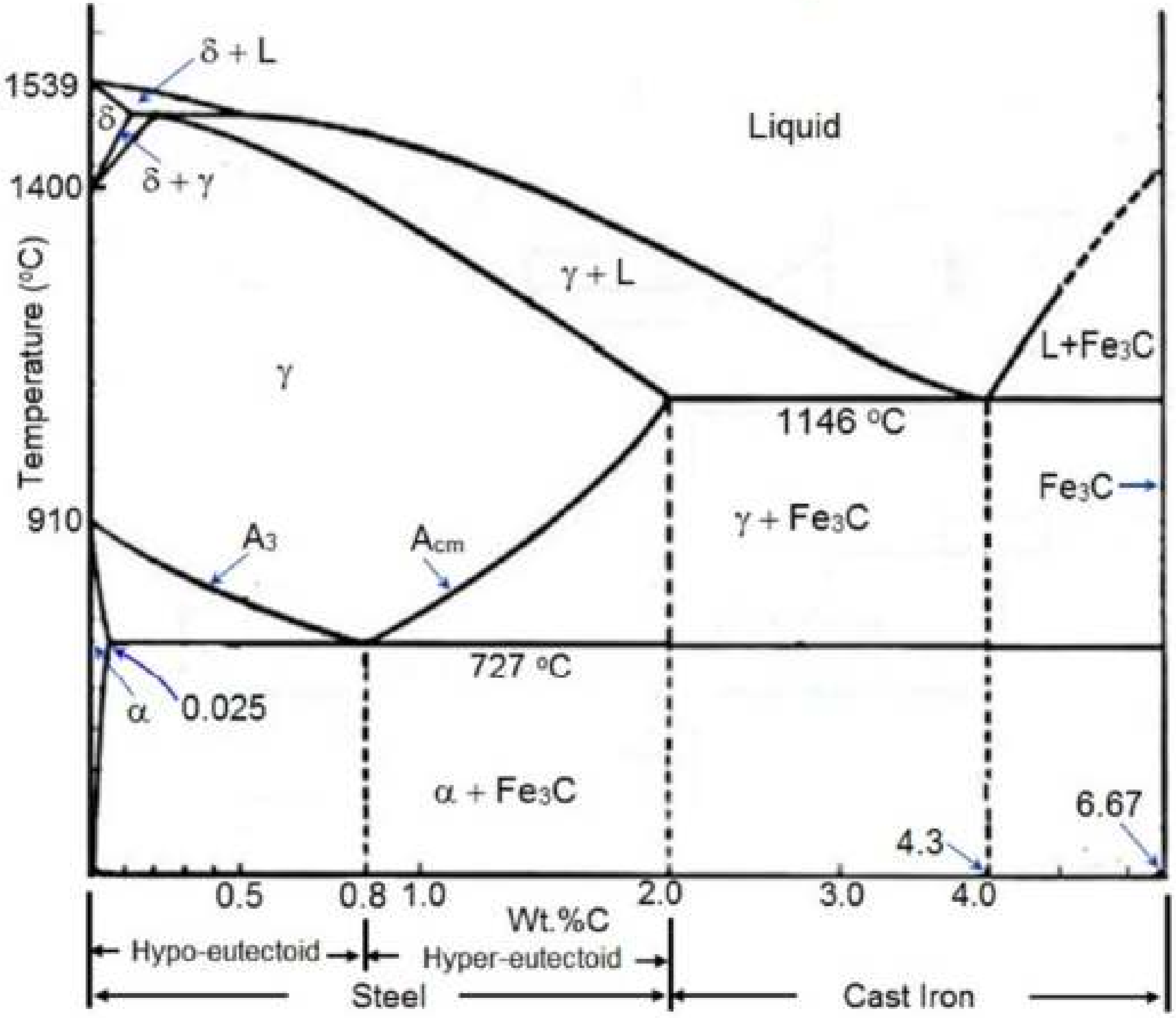


- Pure iron when heated experiences 2 changes in crystal structure before it melts.
- At room temperature the stable form, α ferrite has a BCC crystal structure.
- Ferrite experiences a polymorphic transformation to FCC γ austenite at 912 ˚C.
- At 1394˚C (2541˚F) austenite reverts back to BCC phase δ ferrite and melts at 1538 ˚C .

ALLOTROPIC FORMS OF IRON



Fe-C Phase diagram (Iron – Carbon Equilibrium Phase diagram



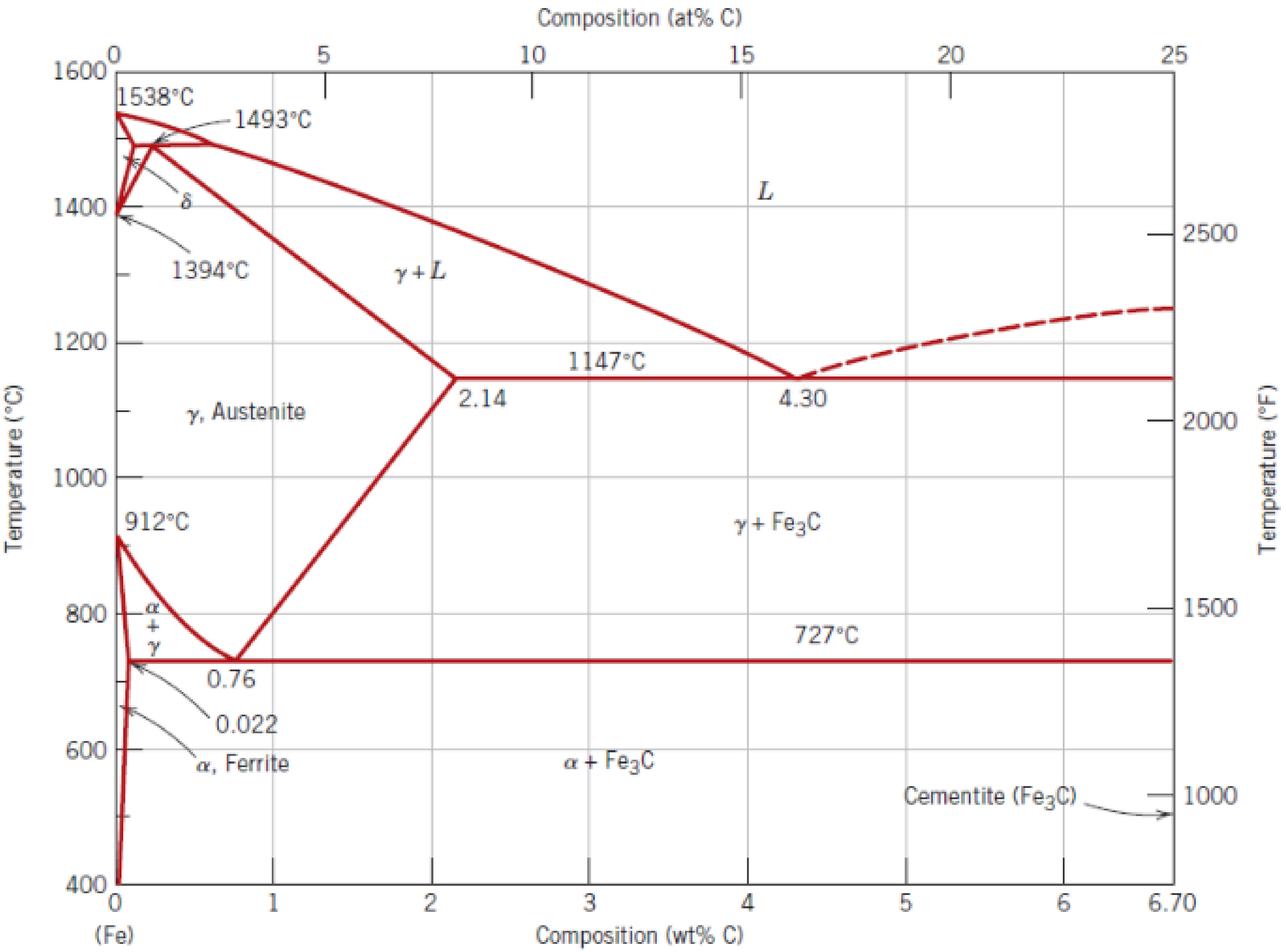
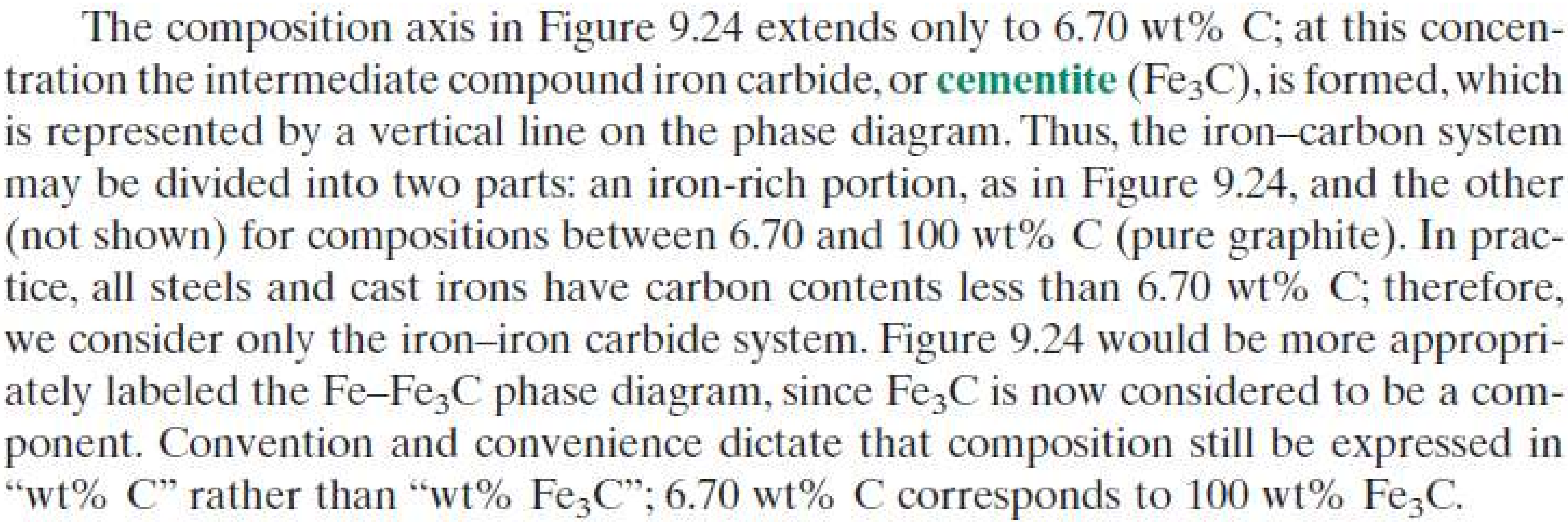


Figure 9.24 The iron–iron carbide phase diagram. [Adapted from *Binary Al*

Fe-C Phase diagram



The composition axis in Figure 9.24 extends only to 6.70 wt% C; at this concentration the intermediate compound iron carbide, or **cementite** (Fe_3C), is formed, which is represented by a vertical line on the phase diagram. Thus, the iron–carbon system may be divided into two parts: an iron-rich portion, as in Figure 9.24, and the other (not shown) for compositions between 6.70 and 100 wt% C (pure graphite). In practice, all steels and cast irons have carbon contents less than 6.70 wt% C; therefore, we consider only the iron–iron carbide system. Figure 9.24 would be more appropriately labeled the Fe–Fe_3C phase diagram, since Fe_3C is now considered to be a component. Convention and convenience dictate that composition still be expressed in "wt% C" rather than "wt% Fe_3C"; 6.70 wt% C corresponds to 100 wt% Fe_3C.

Carbon is an interstitial impurity in iron and forms a solid solution with each of α and δ ferrites, and also with austenite, as indicated by the α, δ, and γ single-phase fields in Figure 9.24. In the BCC α ferrite, only small concentrations of carbon are soluble; the maximum solubility is 0.022 wt% at 727°C (1341°F). The limited solubility is explained by the shape and size of the BCC interstitial positions, which make it difficult to accommodate the carbon atoms. Even though present in relatively low concentrations, carbon significantly influences the mechanical properties of ferrite. This particular iron–carbon phase is relatively soft, may be made magnetic at temperatures below 768°C (1414°F), and has a density of 7.88 g/cm^3. Figure 9.25*a* is a photomicrograph of α ferrite.

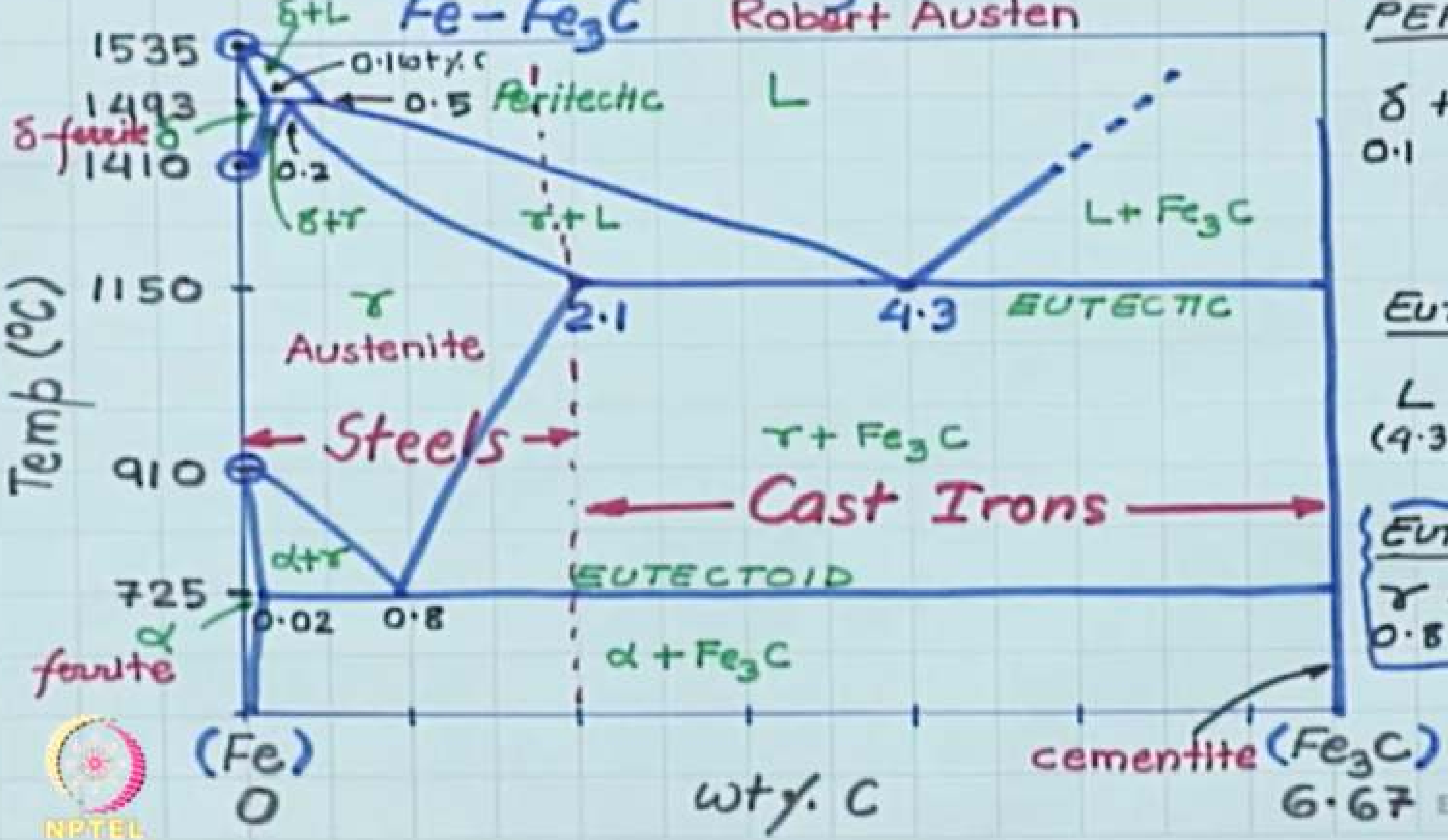
The austenite, or γ phase of iron, when alloyed with carbon alone, is not stable below 727°C (1341°F), as indicated in Figure 9.24. The maximum solubility of carbon in austenite, 2.14 wt%, occurs at 1147°C (2097°F). This solubility is approximately 100 times greater than the maximum for BCC ferrite, since the FCC interstitial positions are larger (see the results of Problem 4.5), and, therefore, the strains imposed on the surrounding iron atoms are much lower. As the discussions that follow demonstrate, phase transformations involving austenite are very important in the heat treating of steels. In passing, it should be mentioned that austenite is nonmagnetic. Figure 9.25*b* shows a photomicrograph of this austenite phase.

The δ ferrite is virtually the same as α ferrite, except for the range of temperatures over which each exists. Since the δ ferrite is stable only at relatively high temperatures, it is of no technological importance and is not discussed further.

Cementite (Fe_3C) forms when the solubility limit of carbon in α ferrite is exceeded below 727°C (1341°F) (for compositions within the $\alpha + Fe_3C$ phase region). As indicated in Figure 9.24, Fe_3C will also coexist with the γ phase between 727 and 1147°C (1341 and 2097°F). Mechanically, cementite is very hard and brittle; the strength of some steels is greatly enhanced by its presence.

Fe-C Phase Diagram

Fe - Fe_3C Robert Austen



Invariant Reax^n

PERITECTIC

$$\underset{0.1}{\delta} + \underset{0.5}{L} \xrightarrow[1493]{\text{Cool}} \underset{0.2}{\gamma}$$

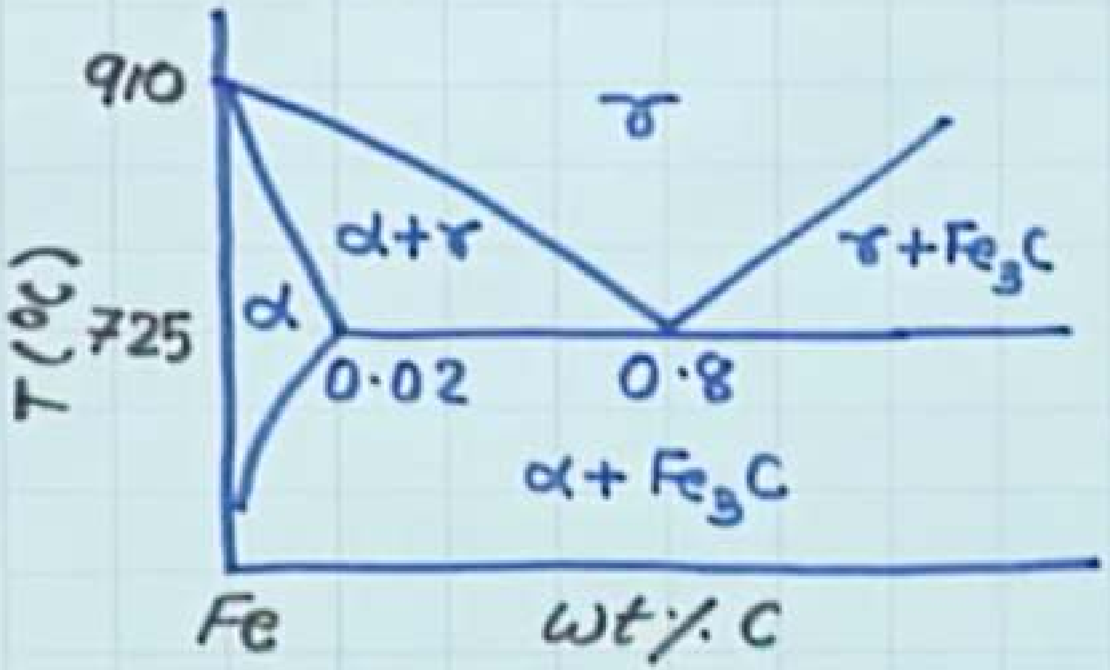
EUTECTIC

$$\underset{(4.3)}{L} \xrightarrow[1150^\circ C]{\text{Cool}} \underset{2.1}{\gamma} + \underset{6.67}{Fe_3C}$$

EUTECTOID

$$\underset{0.8}{\gamma} \xrightarrow[725]{\text{Cool}} \underset{0.02}{\alpha} + \underset{6.67}{Fe_3C}$$

Phases in Fe-C System



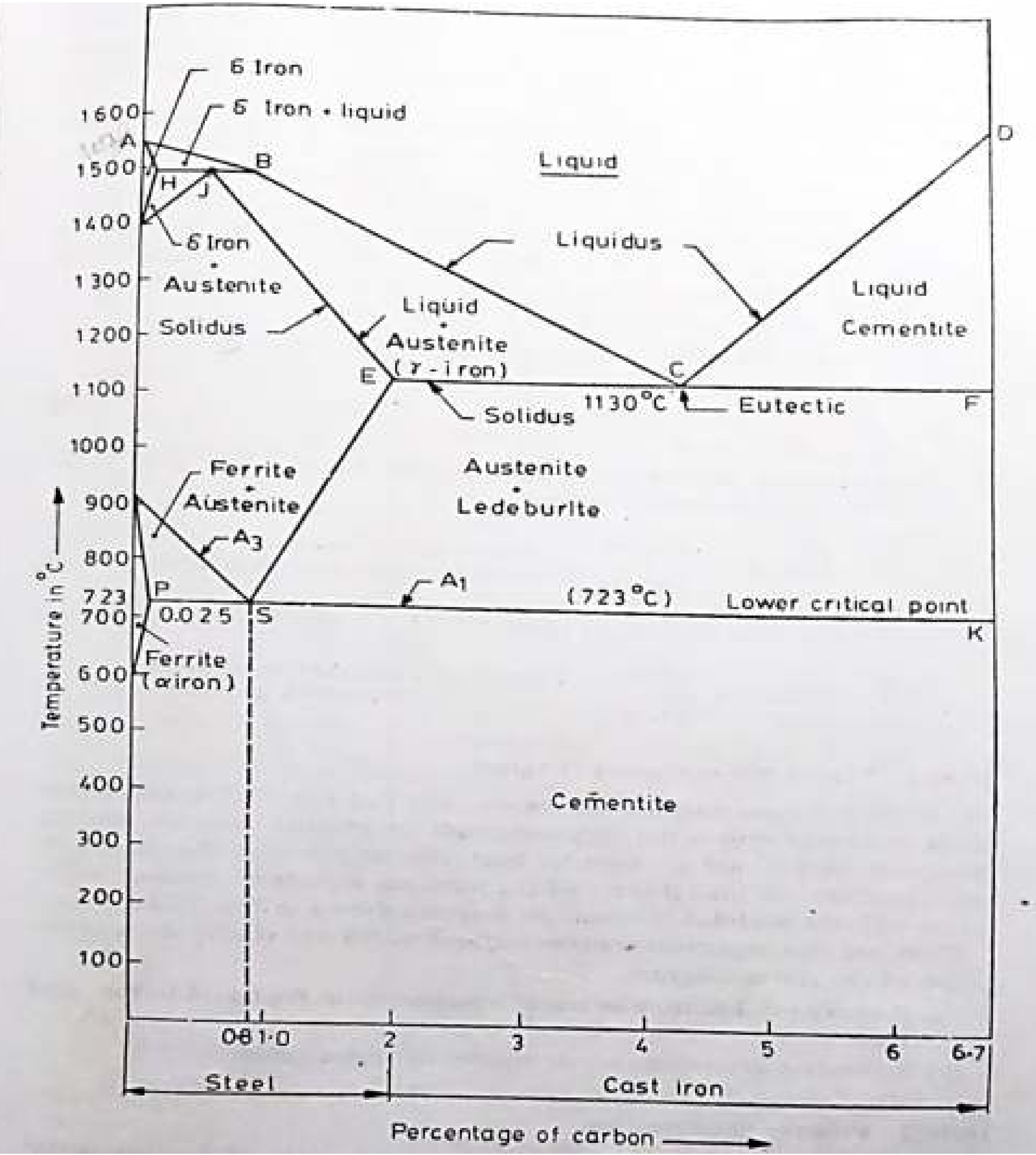
L: Liquid

δ-Ferrite (δ): Interstitial solid solution of C in δ-Fe (BCC) (High temp)

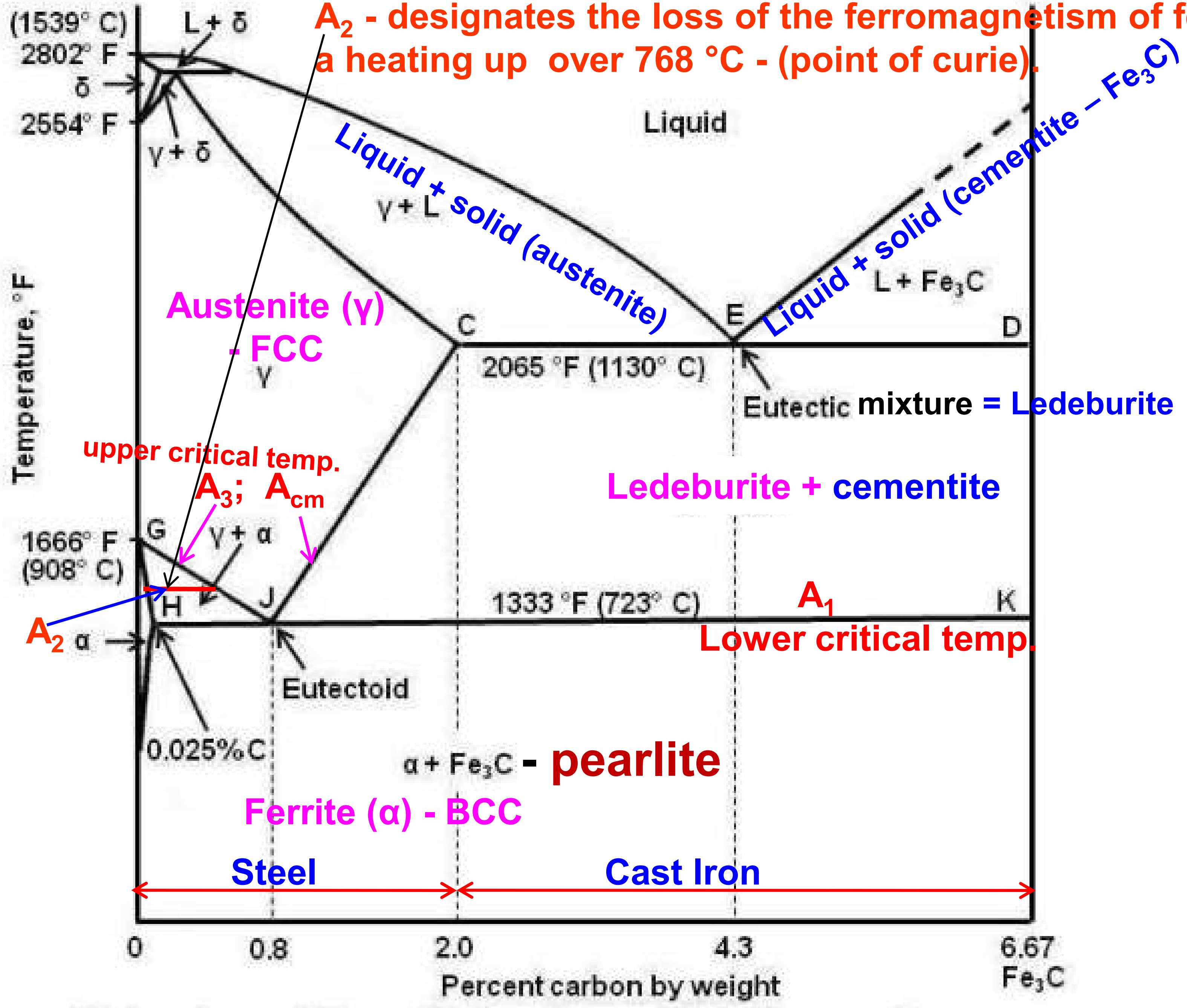
γ: Austentite: Interstitial solid solution of C in FCC Fe

α: Ferrite: Interstitial solid solution of C in BCC Fe (Low temp).

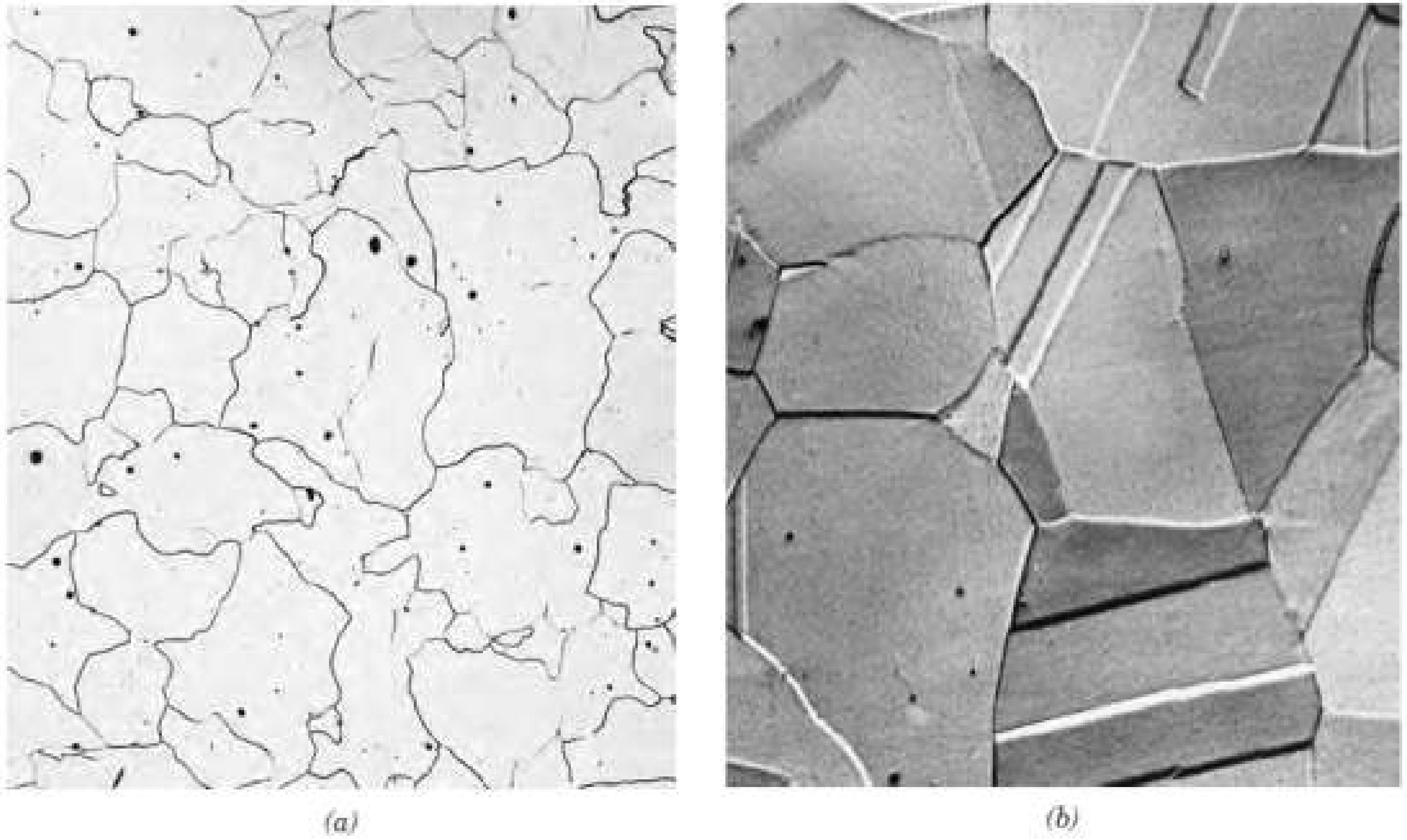
Fe_3C (Cementite): Intermetallic compound of Fe & C. Orthorhombic crystal system.


δ Iron
δ Iron + liquid
A
B
H
J
Liquid
D
Liquidus
δ Iron + Austenite
Solidus
Liquid + Austenite (γ - iron)
Liquid Cementite
E
C
1130°C
Eutectic
F
Solidus
Austenite + Ledeburite
Ferrite + Austenite
A3
A1
P
0.025
S
(723°C)
Lower critical point
K
Ferrite (α iron)
Cementite
1600
1500
1400
1300
1200
1100
1000
900
800
723
700
600
500
400
300
200
100
Temperature in °C
0.8 1·0
2
3
4
5
6
6·7
Steel
Cast Iron
Percentage of carbon

A_2 - designates the loss of the ferromagnetism of ferrite with a heating up over 768 °C - (point of curie).



The iron-iron carbide equilibrium diagram labeled in general terms



(a) (b)

Figure 9.25 Photomicrographs of (*a*) α ferrite (90×) and (*b*) austenite (325×). (Copyright 1971 by United States Steel Corporation.)

Phases in Fe-C system

- ***α-ferrite*** – *Interstitial solid solution of C in BCC iron.* *Max* solubility of C is 0.025%. Exists from 273˚C to 910˚C .
- ***γ-Austenite*** - *Interstitial solid solution of C in FCC iron.* *Max* solubility of C is 2.1%. Exists from 910 ˚C - 1394˚C .
- ***δ -ferrite (BCC)*** *exists over the temp range of 1394* ˚C *to* 1539 ˚C . Max solubility of C is 0.09%.
- ***Cementite(Fe_3C)*** *- is an intermetallic compound. C content in* Fe_3C *is 6.67%.*
- ***Graphite***- the free form of C, also exists in the Fe-C system

- **α-Ferrite (α)**
  - Solid solution of a carbon in α-Iron
  - BCC structure
  - Carbon only slightly soluble in matrix
    - Maximum solubility of 0.022 % wt C at 727°C to about 0.008 wt% C in room temperature
- **Austenite (γ)**
  - Solid solution of a carbon in δ-Iron
  - FCC structure → can accomodate more carbon than ferrite
    - Maximum solubility of 2.14 % wt C at 1147°C, then decreased to 0.8 wt% C at 727°C.
    - The difference in C solid solubility between γ and α is the basis of **hardening** in many steel.

- **δ-Ferrite (δ)**
  - Solid solution of a carbon in δ-Iron
  - BCC structure
  - **NO technological** importance cause only stable at high temperature.
    - Maximum solubility of ferrite being 0.09 % wt C at 1493°C

- **Cementite (Fe_3C)**
  - Intermetallic Fe-C compound
  - Fe_3C : 6.7 wt% C + 93.3 wt% Fe
  - Forms when solubility limit of carbon in α-ferrite is exceeded below 727°C
  - Orthorombic crystal structure : very hard and brittle.

Phases in Fe-C system

Phase	Symbol	Description
Liquid	L	Liquid solution of Fe and C
δ Ferrite	δ	Interstitial solid solution of C in δ-Fe (high temperature BCC phase)
Austenite	γ	Interstitial solid solution of C in γ-Fe (FCC phase of Fe)
α Ferrite	α	Interstitial solid solution of C in α-Fe (room temperature bcc phase) Soft and Ductile
Cementite	Fe_3C	Intermetallic compound of Fe and C (ortho rhombic system) Hard and Brittle

TYPE OF STEEL

- **Hypo-Eutectoid Steel:** % of Carbon < 0.76
- **Eutectoid Steel:** % of Carbon = 0.76
- **Hyper-Eutectoid Steel:** % of Carbon > 0.76

Critical temperatures in Fe-C system

- *Eutectoid temperature (727˚C)*
- *Currie temperature (768˚C) – temperature above which Fe turns paramagnetic while heating.*
- *Eutectic temperature (1147˚C)*
- *Peritectic temperature (1493˚C).*

The Iron-Iron Carbide Diagram

The diagram shows **three horizontal lines** which indicate isothermal reactions (on cooling / heating):

- **First horizontal** line is at 1493°C, where peritectic reaction takes place:

  Liquid + δ ↔ austenite γ

- **Second horizontal** line is at 1130°C, where eutectic reaction takes place- 4.3%C:

  Liquid ↔ austenite γ + cementite

- **Third horizontal line** is at 723°C, where eutectoid reaction takes place-0.8%C:

  Austenite γ ↔ pearlite (mixture of ferrite & cementite)

Phase transformation in Fe-C system

Peritectic reaction at 1493˚C

$$L\ (0.53\%\ C) + \delta\ (0.09\%\ C) \rightarrow \gamma\ (0.17\%\ C)$$

(almost **no engineering importance**)

Eutectic reaction at 1147˚C

$$L\ (4.3\%\ C) \rightarrow \gamma\ (2.1\ \%\ C) + Fe_3C\ (6.67\%\ C)$$

- The eutectic mixture of austenite (γ) and cementite (Fe_3C) is called ***Ledeburite***
- Compositions right and left of 4.3% are called hyper eutectic and hypoeutectic steels(cast Iron) respectively.

Eutectoid reaction at 727˚C

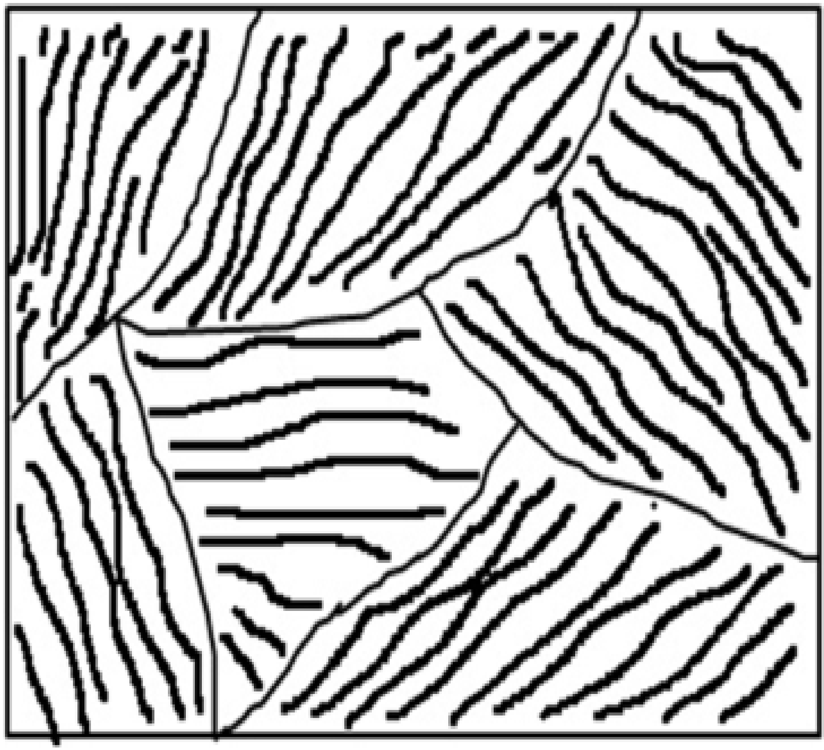
$$\gamma\ (0.8\ \%\ C) \rightarrow \alpha\ (0.025\%\ C) + Fe_3C\ (6.67\%\ C)$$

- The eutectoid mixture of ferrite (α) and cementite (Fe_3C) is called ***Pearlite***.
- Compositions right and left of 0.8% are called hyper eutectoid and hypoeutectoid steels respectively.
- Two-phase mixture (ferrite & cementite). They are steels

Microstructures

- A *eutectoid steel* (0.8% C) will have 100% pearlite (*p) at room* temperature
- The **pearlite** formed under equilibrium conditions consists of *alternate lamellas of ferrite and Fe_3C*
- *Hypoeutectoid* steels – α + *p; hypereutectoid – Fe3C + p.*
- *Hypoeutectic cast irons* consist of γ + *ledeburite (Le)*
- hyper eutectic cast irons will have a structure of Fe3C + *Le*

.



Microstructures Eutectoid composition

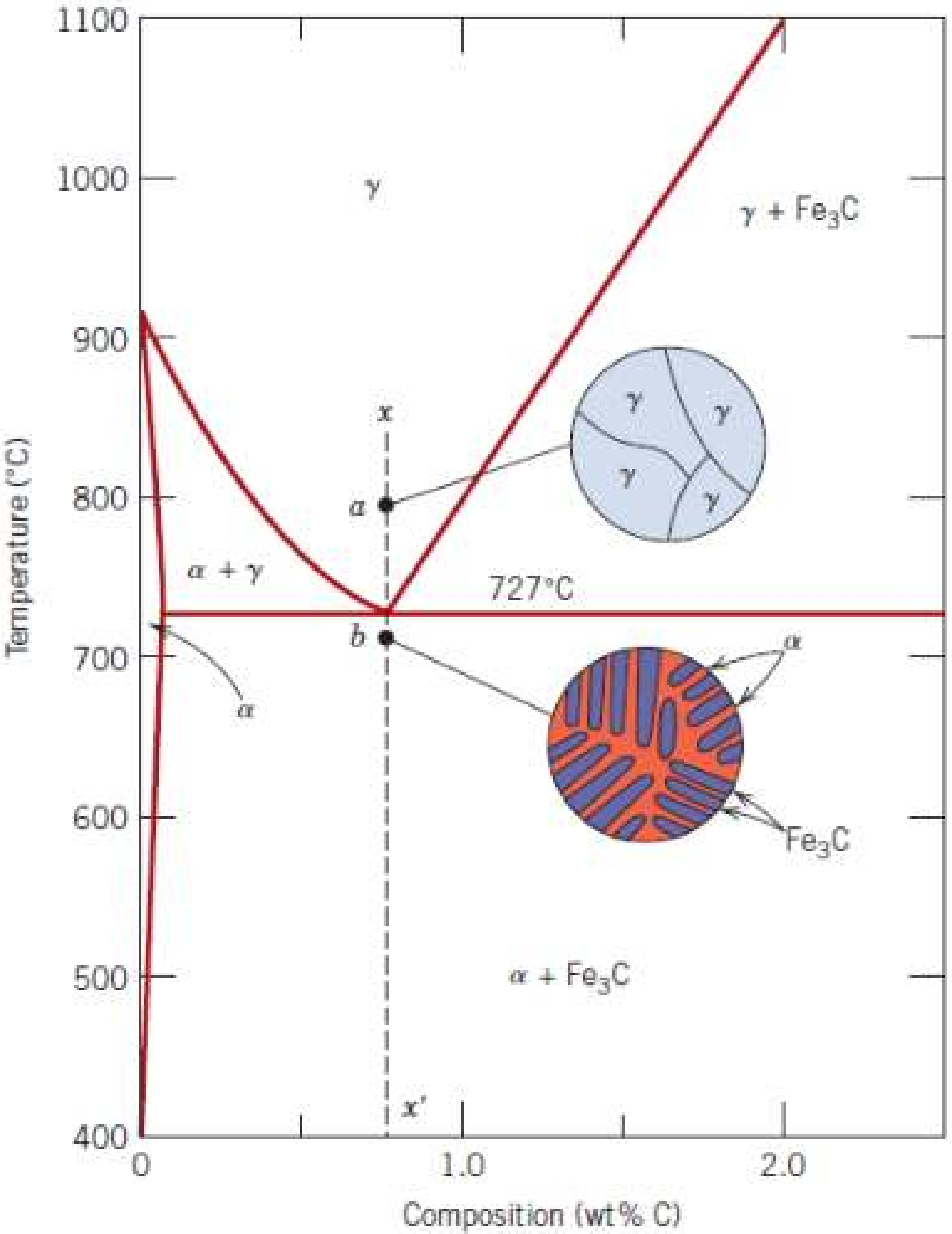


Figure 9.26 Schematic representations of the microstructures for an iron–carbon alloy of eutectoid composition (0.76 wt% C) above and below the eutectoid temperature.

Figure 9.27 Photomicrograph of a eutectoid steel showing the pearlite microstructure consisting of alternating layers of α ferrite (the light phase) and Fe_3C (thin layers most of which appear dark). 500×. (Reproduced with permission from *Metals Handbook,* 9th edition, Vol. 9, *Metallography and Microstructures,* American Society for Metals, Materials Park, OH, 1985.)

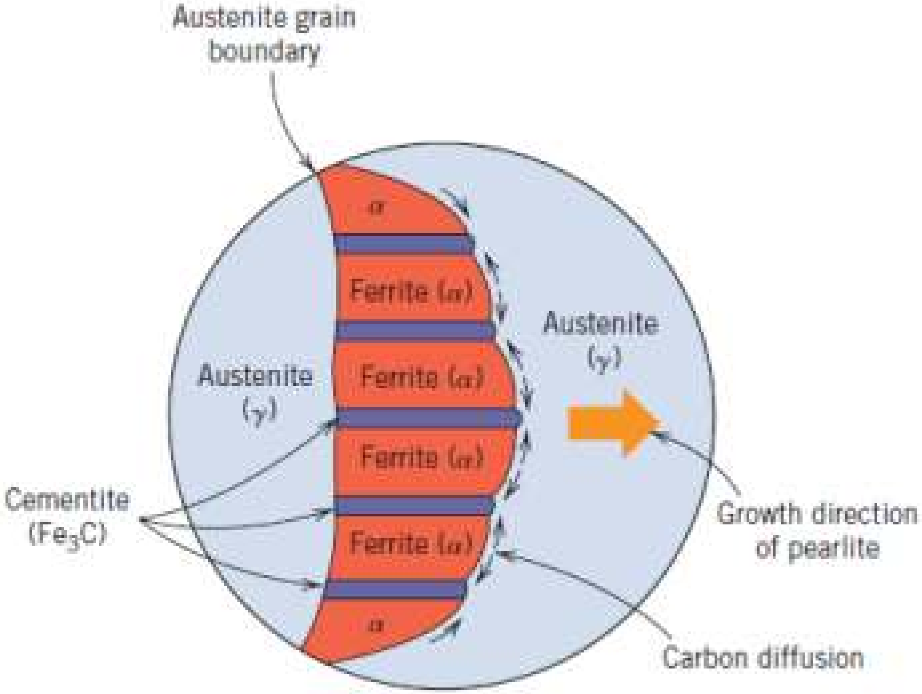


Figure 9.28 Schematic representation of the formation of pearlite fro austenite; direction of ca diffusion indicated by ar

Microstructures hypoeutectoid composition

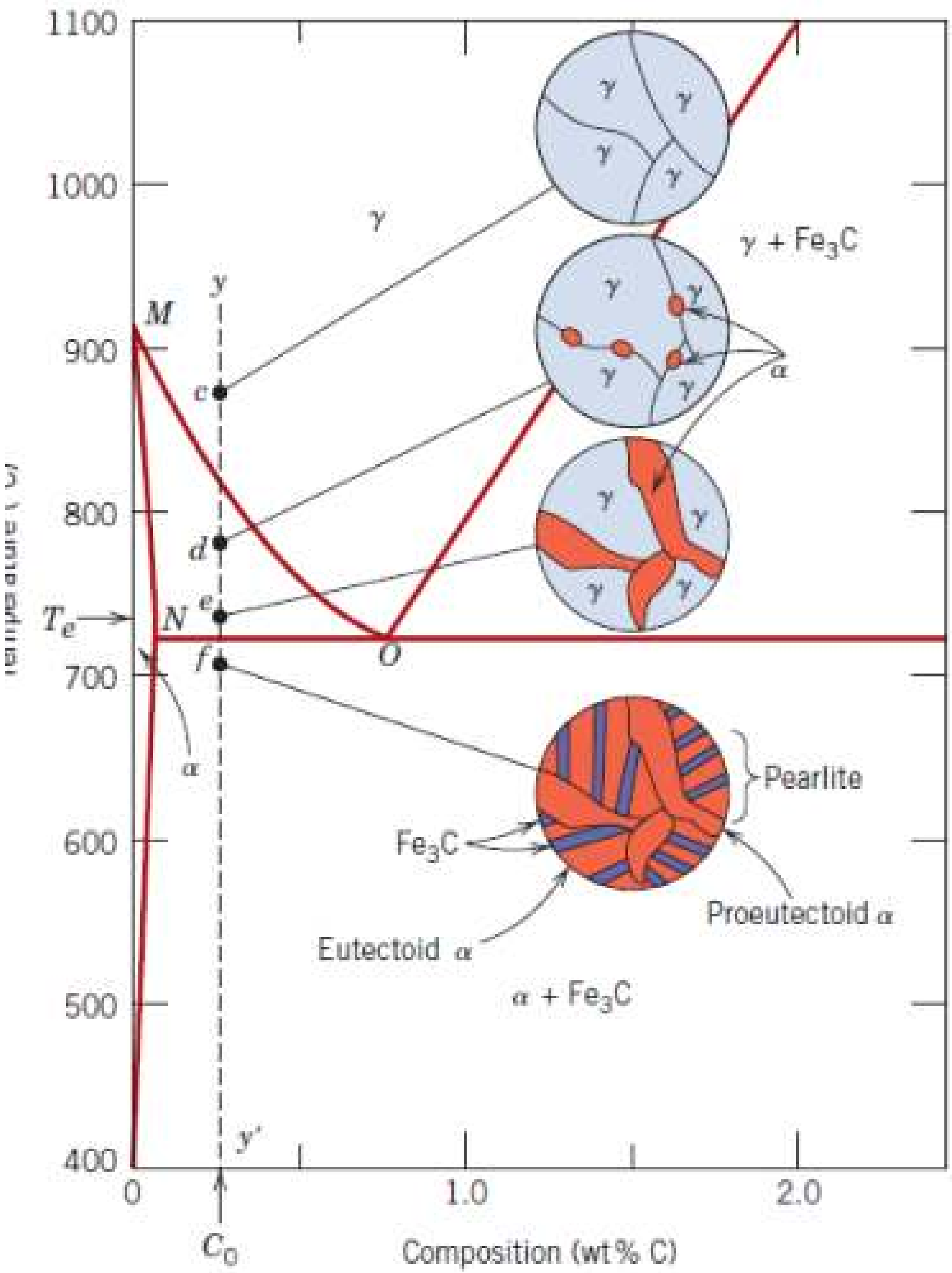


Figure 9.29 Schematic representations of the microstructures for an iron–carbon alloy of hypoeutectoid composition C_0 (containing less than 0.76 wt% C) as it is cooled from within the austenite phase region to below the eutectoid temperature.

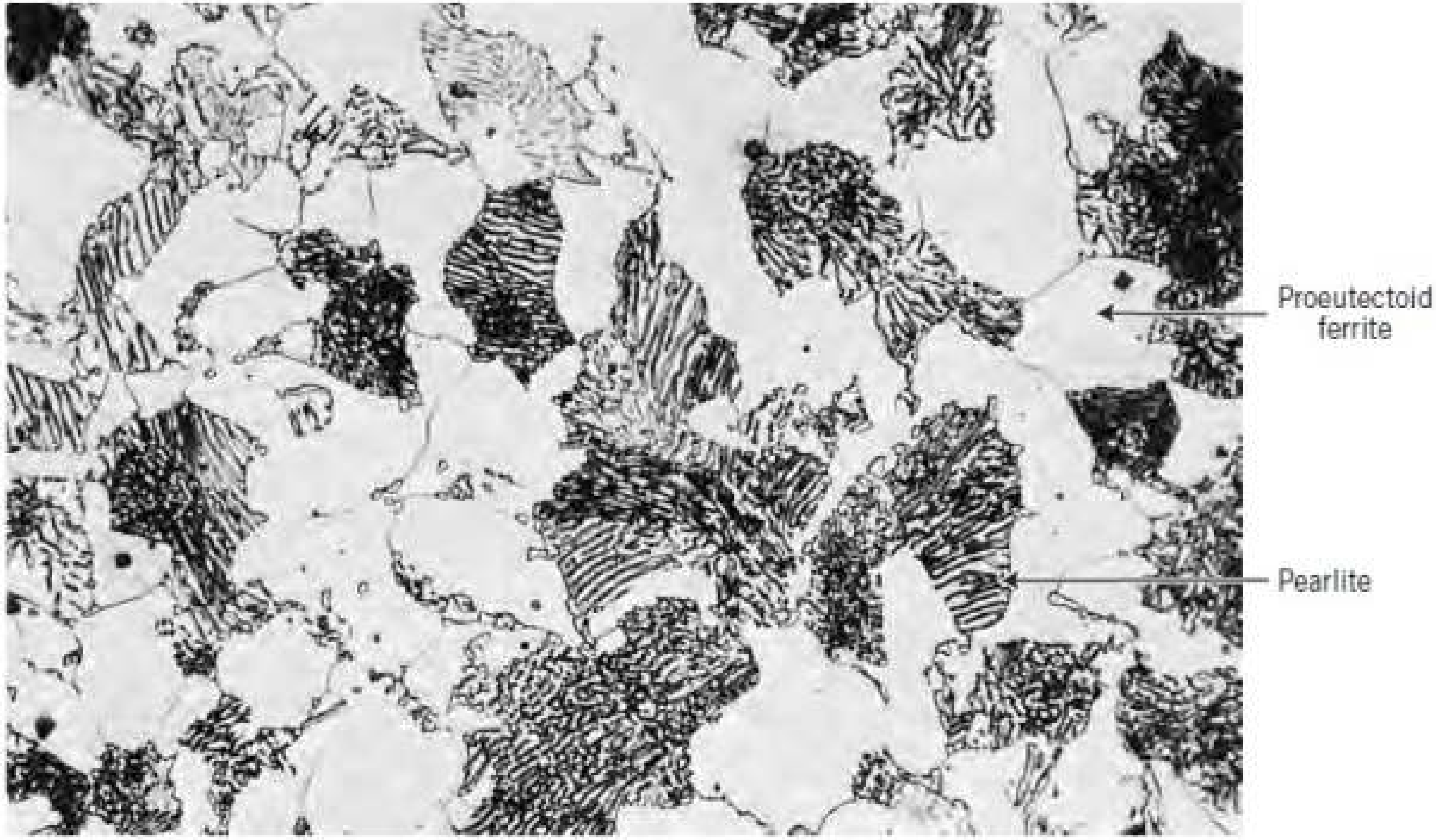


Figure 9.30 Photomicrograph of a 0.38 wt% C steel having a microstructure consisting of pearlite and proeutectoid ferrite. 635×. (Photomicrograph courtesy of Republic Steel Corporation.)

Microstructures hypereutectoid composition

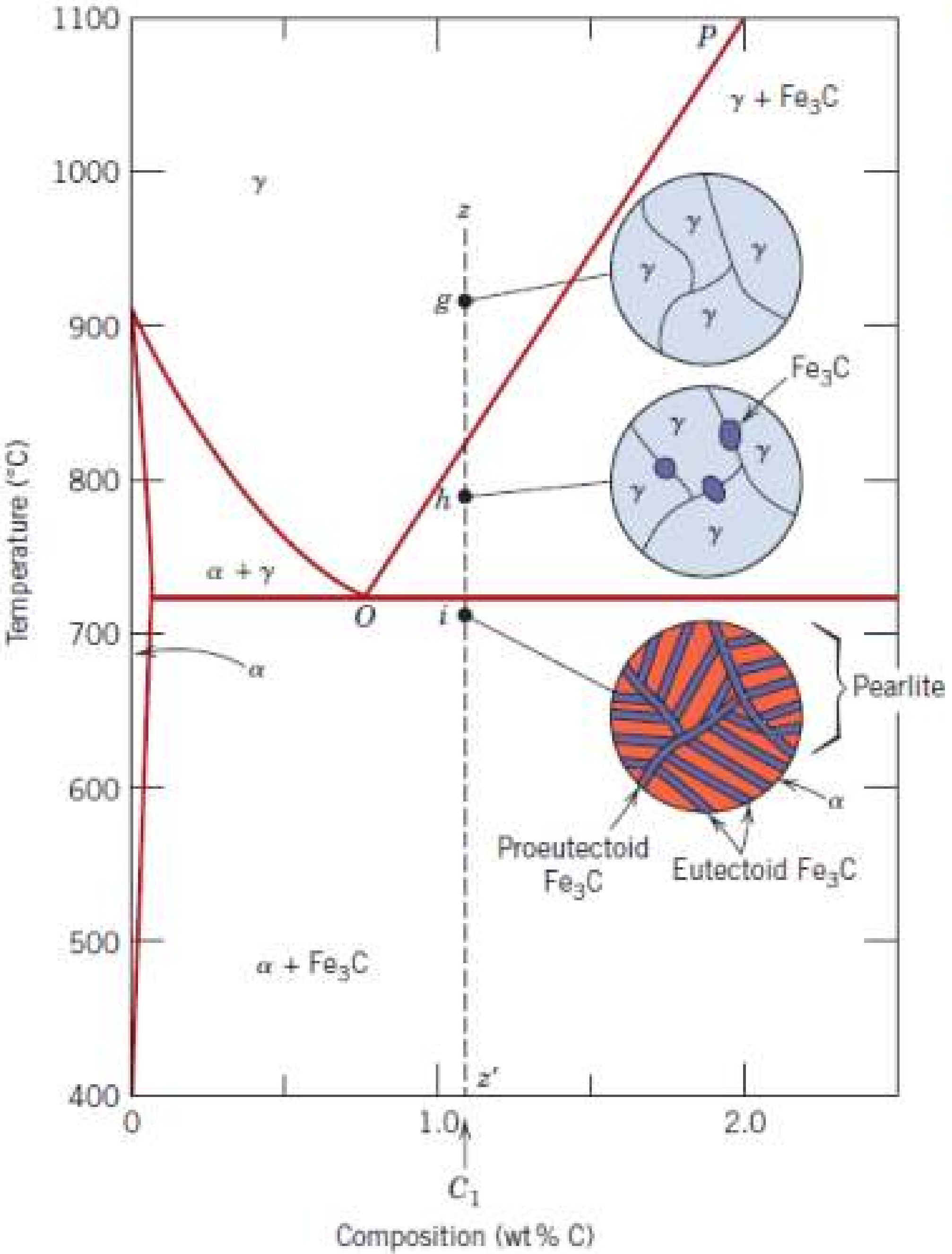
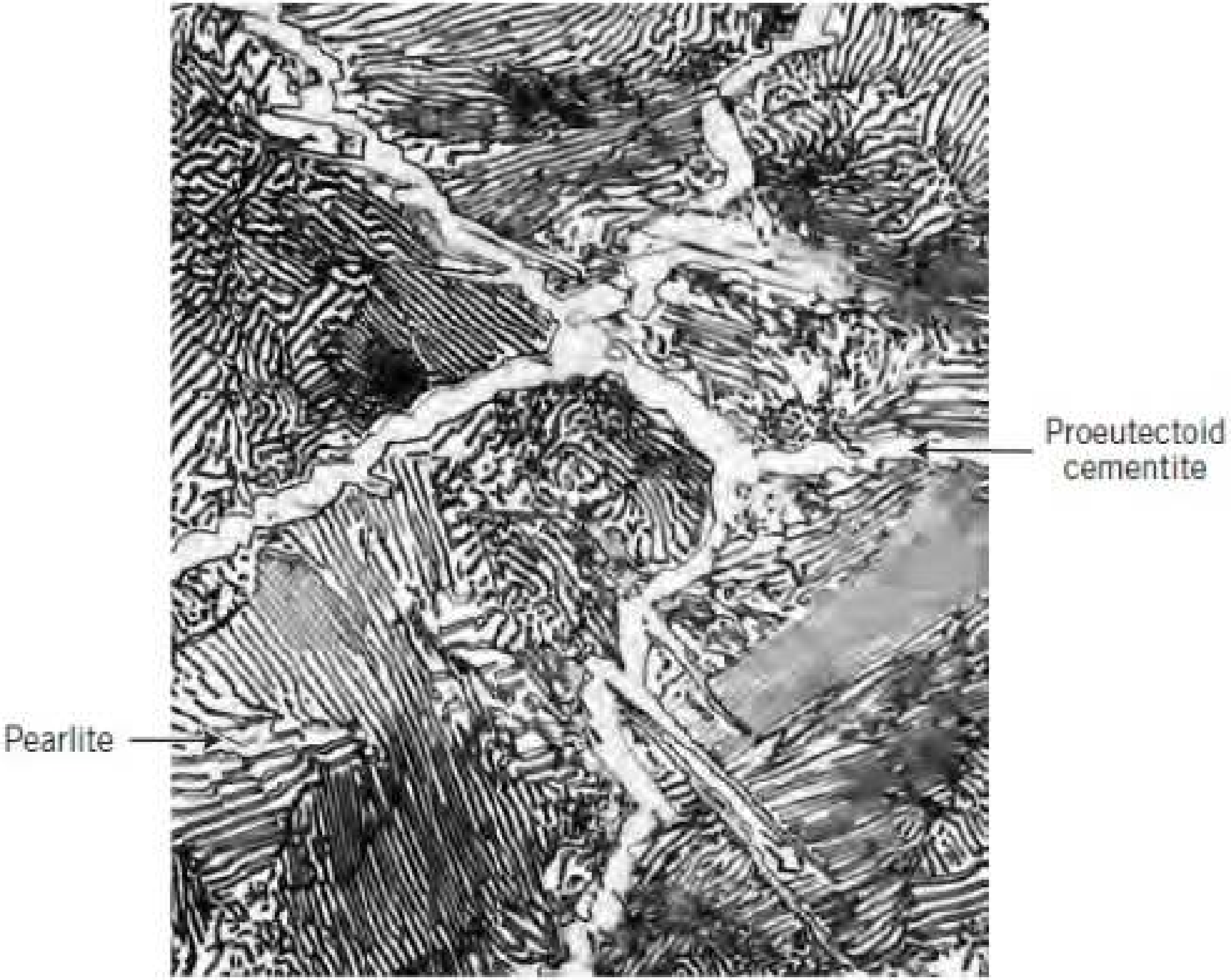
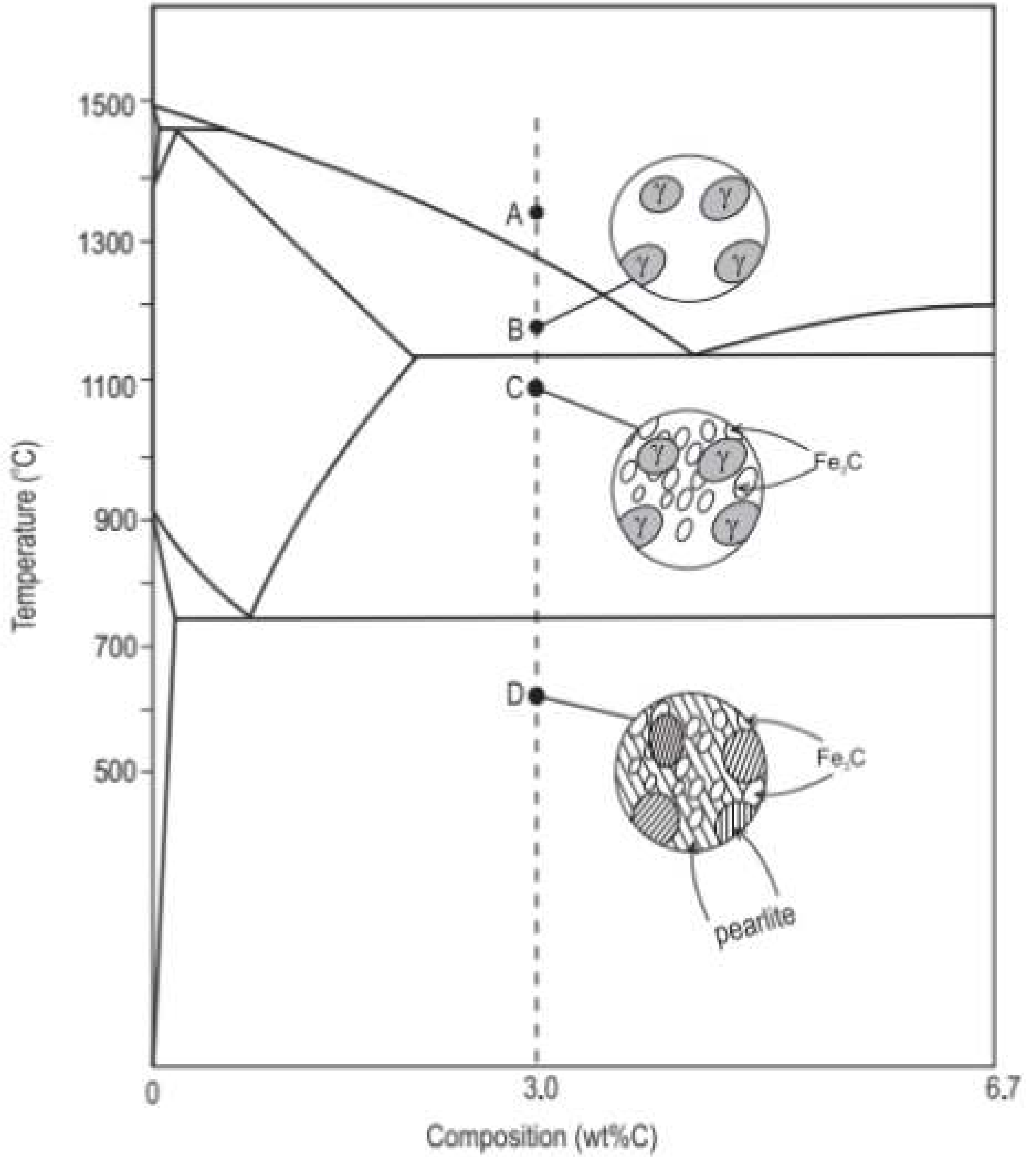


Figure 9.32 Schematic representations of the microstructures for an iron–carbon alloy of hypereutectoid composition C_1 (containing between 0.76 and 2.14 wt% C), as it is cooled from within the austenite phase region to below the eutectoid temperature.

Figure 9.33 Photomicrograph of a 1.4 wt% C steel having a microstructure consisting of a white proeutectoid cementite network surrounding the pearlite colonies. 1000×. (Copyright 1971 by United States Steel Corporation.)



Microstructure in Cast Irons



Microstructure - Property relationship

- An alloy of iron and carbon containing 0.77% carbon is held at a temperature above the eutectoid temperature (727^{O}C) the microstructure contains grains of a phase called **austenite**.
- When this alloy is slowly cooled to room temperature, the microstructure changes into a two phase lamellar structure called **pearlite**. In this condition, the alloy shows **poor ductility and hence it cannot be rolled or drawn into wires. But it is strong.**
-
- When this alloy is again heated to a temperature near to but less than the eutectoid temperature and held for a long period of time, the microstructure changes into grains of ferrite along with nearly spherical particles of cementite evenly distributed.

- At this condition, the ductility is very high and the alloy can be used for drawing wires. Though the alloy contains the same microconstituents, the properties are different.

- When the same alloy is rapidly cooled to room temperature from the austenitic range (above 727^{O}C), neither ferrite nor cementite is formed. The microstructure at room temperature is a single phase called **martensite**.

- The martensite has a body centered tetragonal structure and has **very poor ductility**. But it is having higher hardness and strength. Now the material can be used for making cutting tools.

- This example illustrates that the properties of a material are strongly governed by its microconstituents. Almost all properties like **mechanical, physical or electrical can be governed by properly controlling the formation of microconstituents.** Suitable modification in microstructure lead to the desired properties being imparted to the material.

T-T-T diagram

- Which information's are obtained from phase diagram or TTT diagram?

- **Phase diagram**
  - Describes equilibrium of the microstructural development that is obtained at extremely slow cooling or heating conditions.
  - Provides no information on **time to take** to form phase and on shapes, size and distribution of phase.
- **TTT diagram**
  - For a given alloy composition, the percentage completion of a given phase transformation on **temperature-time** axes is described.

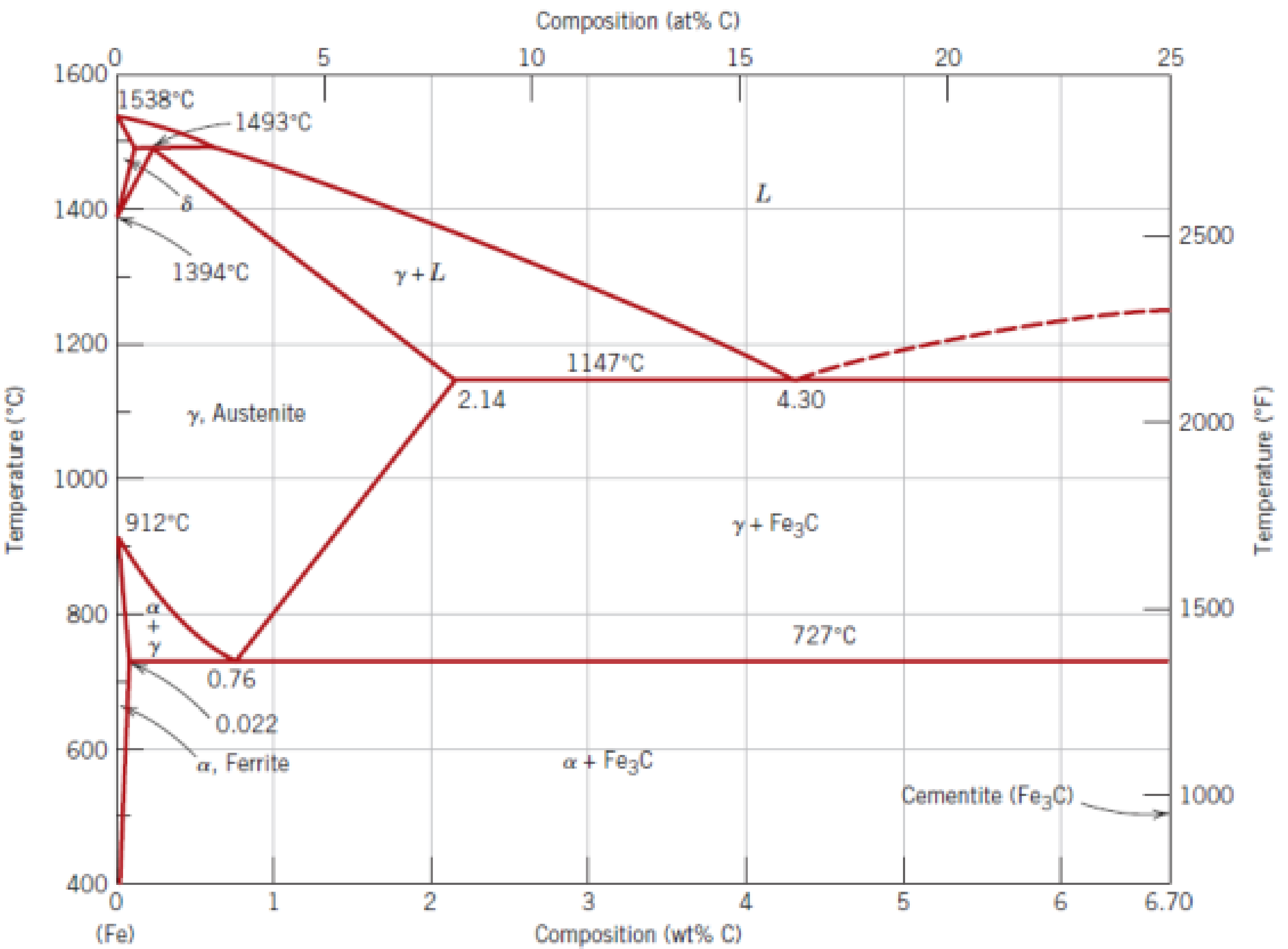


Figure 9.24 The iron–iron carbide phase diagram. [Adapted from *Binary Al*

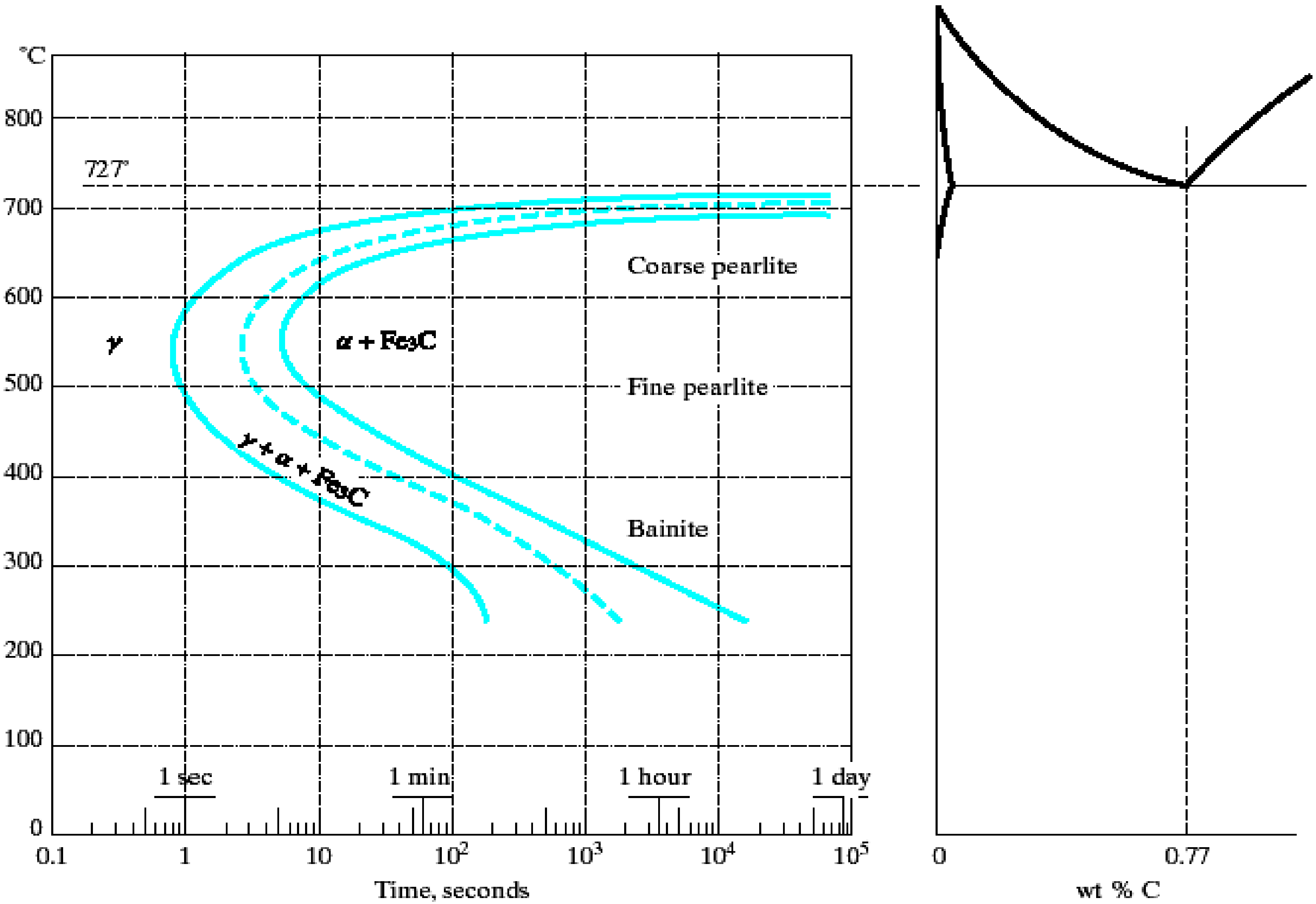
$$\gamma(0.76\text{ wt\% C}) \underset{\text{heating}}{\overset{\text{cooling}}{\rightleftharpoons}} \alpha(0.022\text{ wt\% C}) + \text{Fe}_3\text{C}(6.70\text{ wt\% C})$$

- This diagram indicates the phases existing in steel of a specific composition at various temperatures and times. The diagram is helpful in selecting a suitable cooling cycle to obtain desired microstructure and hence to design the properties of the alloy. Transformations under non-equilibrium cooling represented in this diagram are of much more practical use in heat treatment of alloys.

T-T-T diagram

- Measure the rate of transformation at a constant temperature. In other words a sample is austenitised and then **cooled rapidly** to a **lower temperature and** **held at that temperature** whilst the rate of transformation is measured. Obviously a large number of experiments is required to build up a complete TTT diagram.

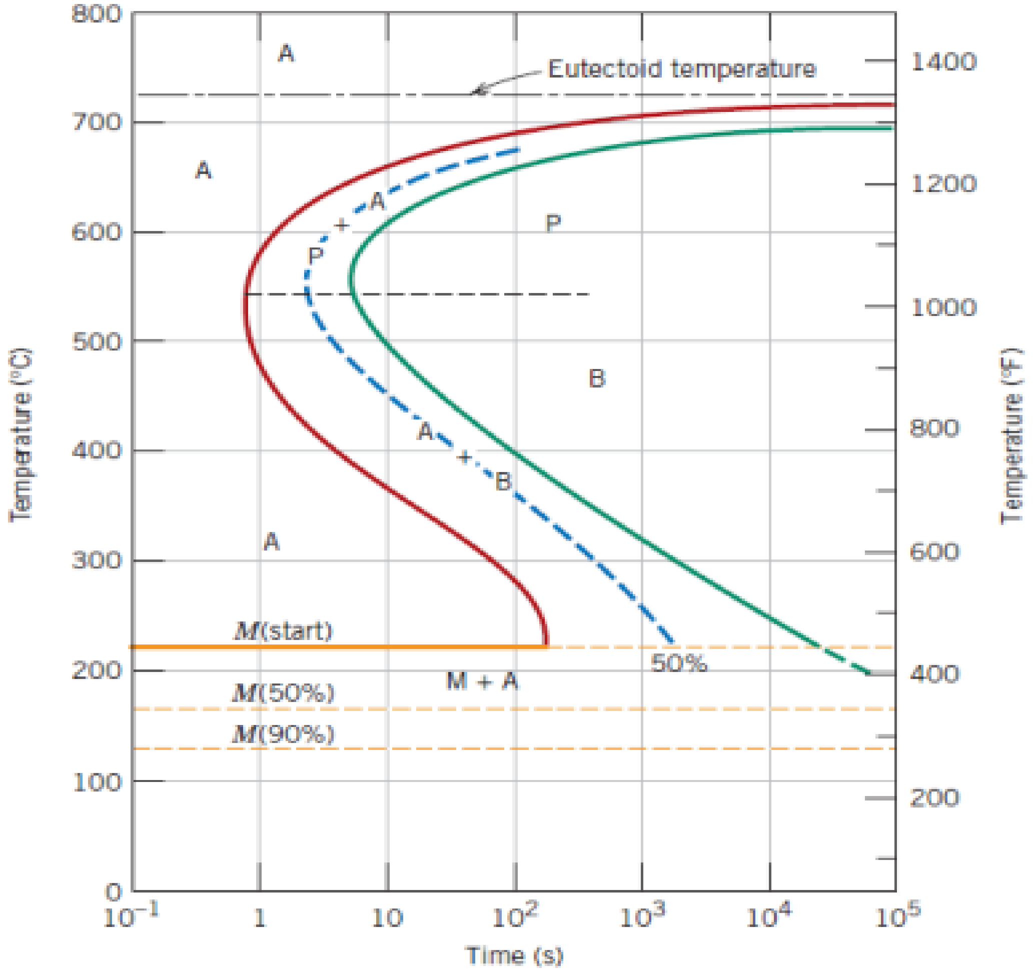
TTT Diagram for Eutectoid Steel



T-T-T diagram

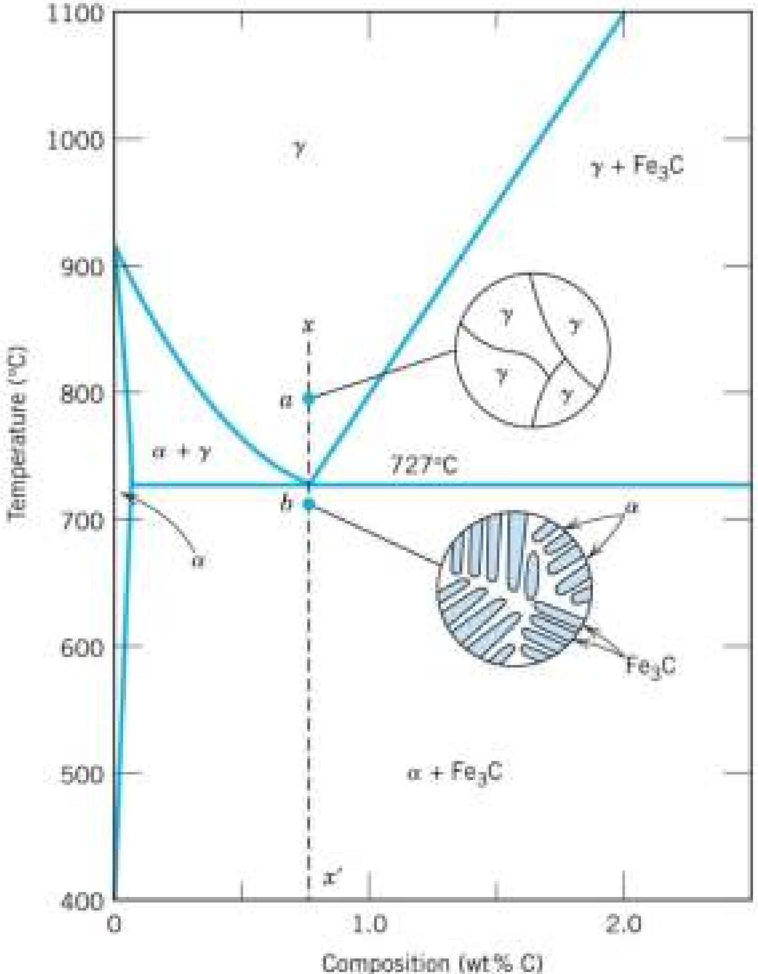
- The relation between *temperature and time for the formation of a phase* is given by T-T-T or temp – time – transformation diagrams also known as isothermal-transformation diagram

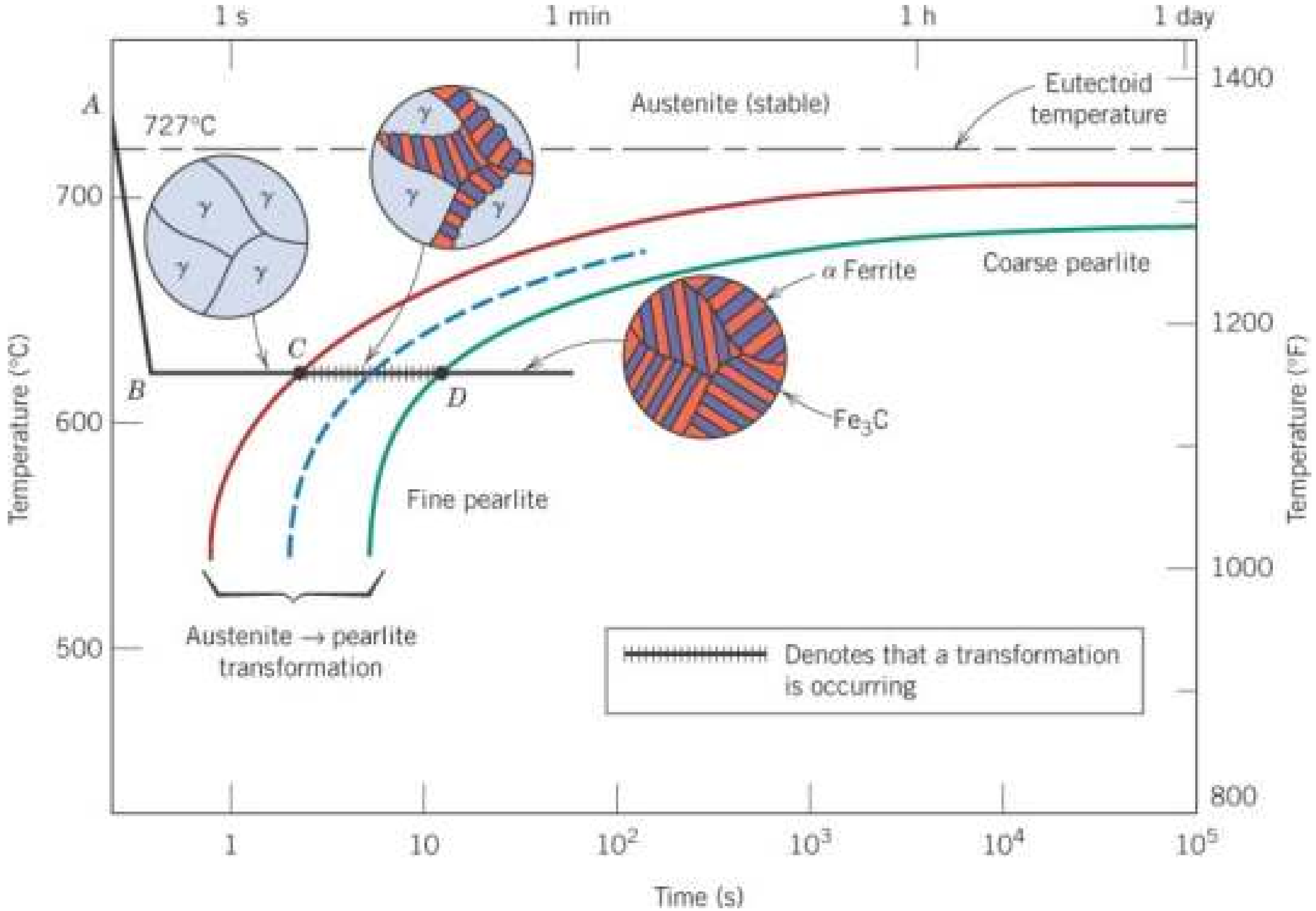
A -austenite
B- bainite
M-martensite
P- pearlite.



COOLING HISTORY Fe-C SYSTEM

- **Eutectoid composition, C_o = 0.76 wt %C**
- **Begin at T > 727 ^{0}C**
- **Rapidly cool to 625 ^{o}C and hold isothermally** (An isothermal process is a change of a system, in which the temperature remains constant: $\Delta T = 0$).





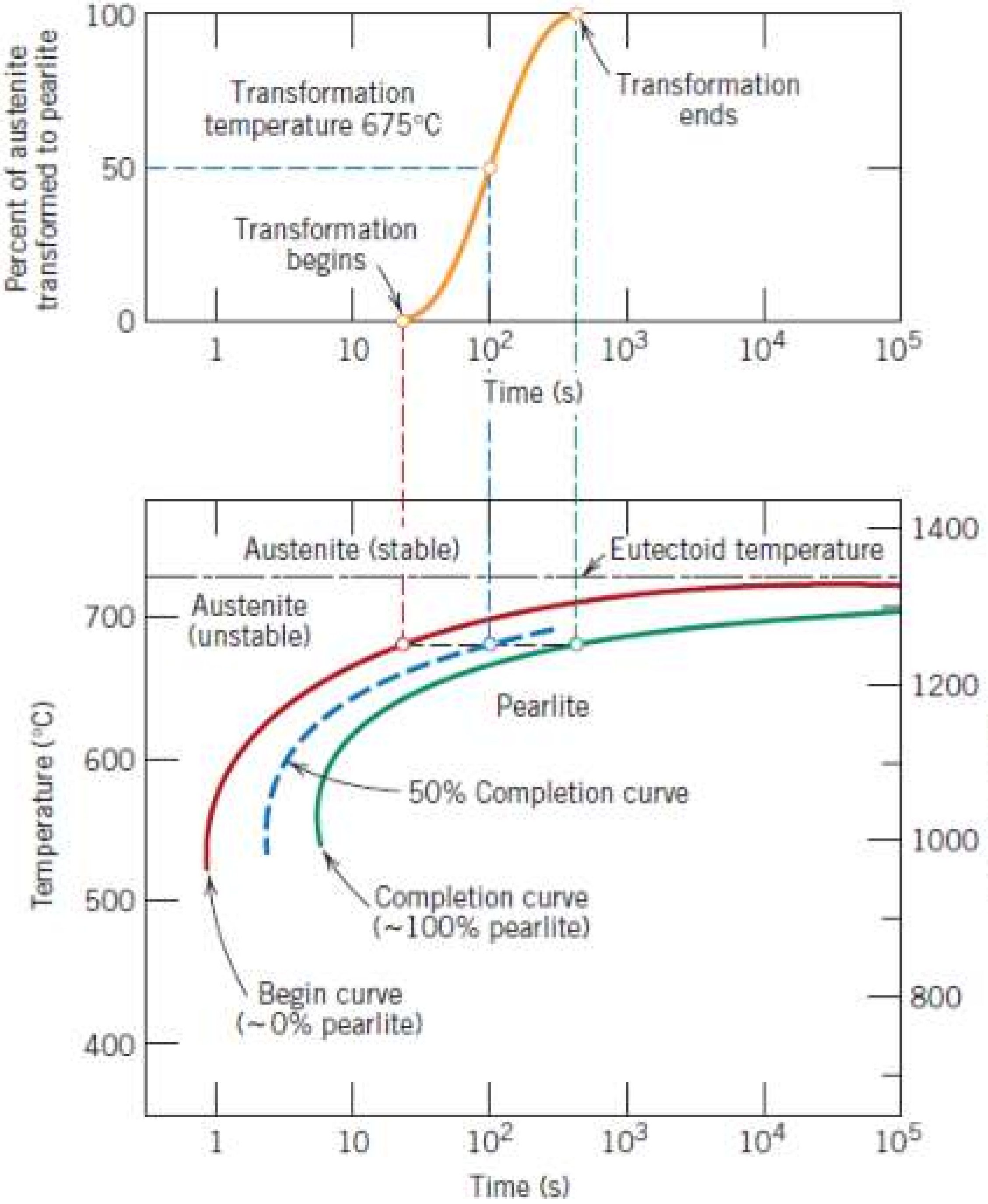


Figure 10.13 Demonstration of how an isothermal transformation diagram (bottom) is generated from percentage transformation-versus-logarithm of time measurements (top). [Adapted from H. Boyer, (Editor), *Atlas of Isothermal Transformation and Cooling Transformation Diagrams,* American Society for Metals, 1977, p. 369.]

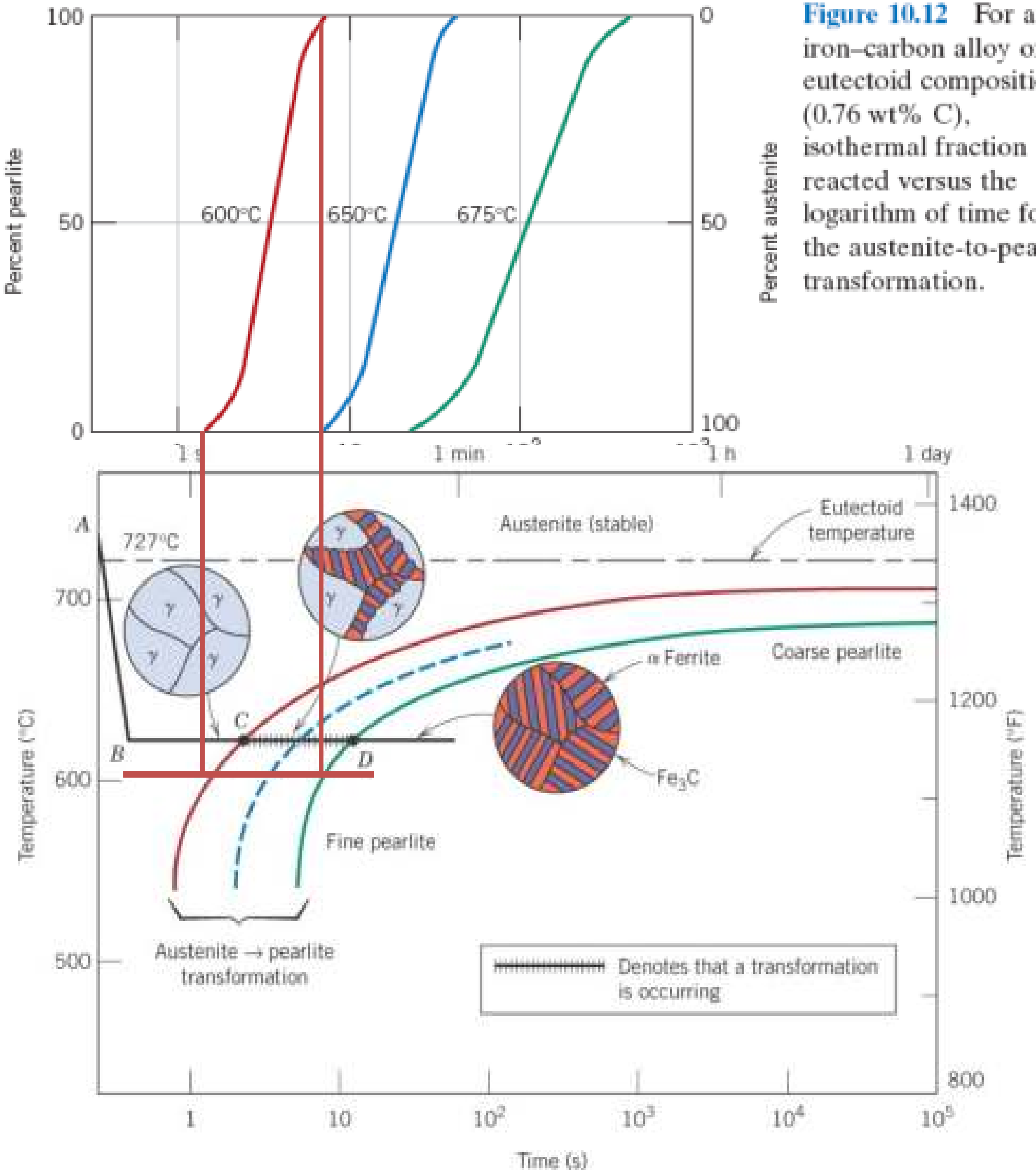
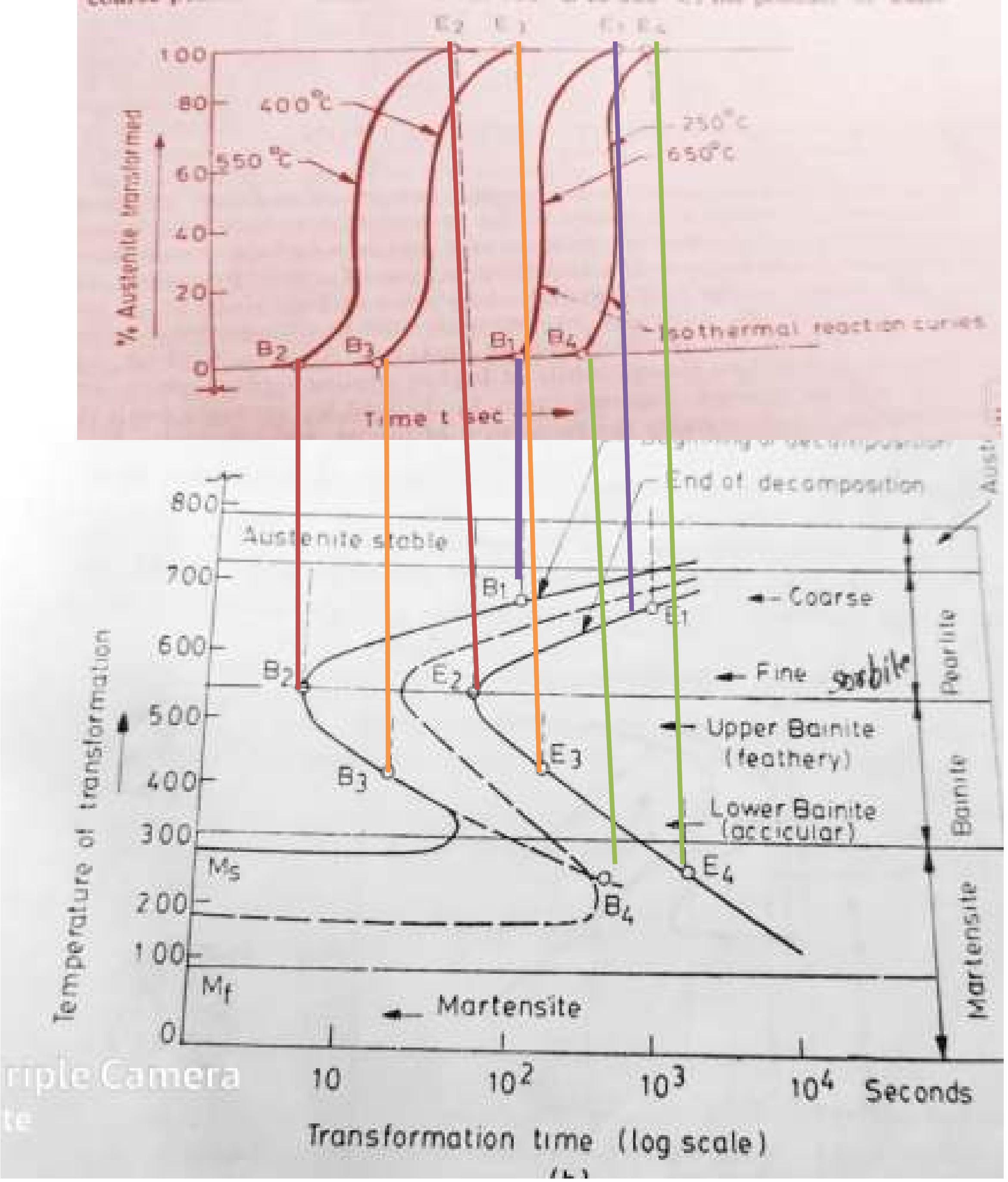
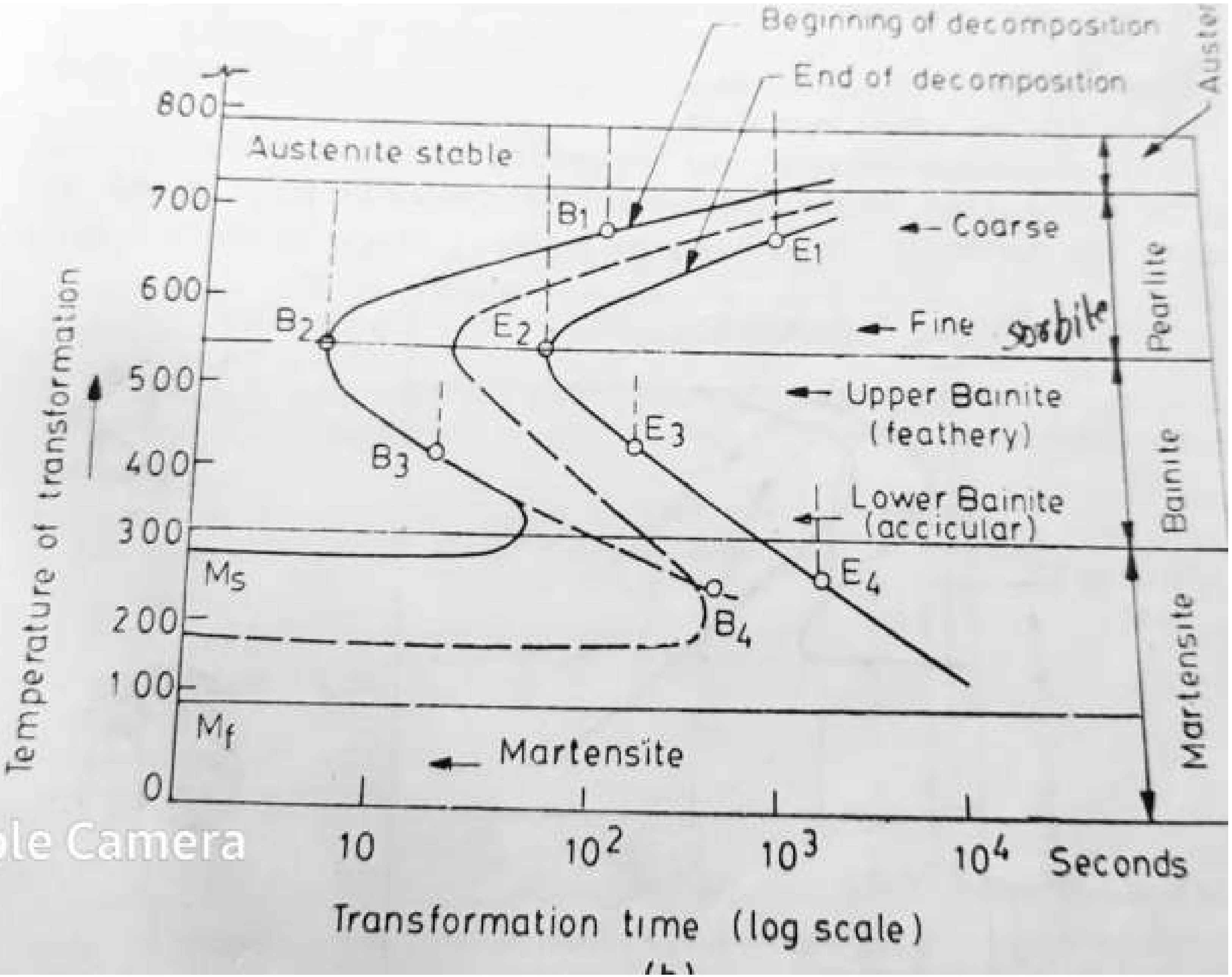


Figure 10.12 For an iron–carbon alloy of eutectoid composition (0.76 wt% C), isothermal fraction reacted versus the logarithm of time for the austenite-to-pearlite transformation.


E2
E3
E1
E4
100
80
60
40
20
0
% Austenite transformed
400°C
550°C
250°C
650°C
B2
B3
B1
B4
Isothermal reaction curves
Time t sec
Beginning of decomposition
End of decomposition
Austenite
800
700
600
500
400
300
200
100
0
Austenite stable
Temperature of transformation
B1
E1
B2
E2
B3
E3
B4
E4
Ms
Mf
Coarse
Fine
sorbite
Pearlite
Upper Bainite
(feathery)
Lower Bainite
(accicular)
Bainite
Martensite
Martensite
10
10^2
10^3
10^4
Seconds
Transformation time (log scale)


Beginning of decomposition
End of decomposition
Auste
800
700
600
500
400
300
200
100
0
Austenite stable
B1
E1
B2
E2
B3
E3
B4
E4
Coarse
Fine
sorbite
Pearlite
Upper Bainite (feathery)
Lower Bainite (accicular)
Bainite
Ms
Mf
Martensite
Martensite
Temperature of transformation
10
10^2
10^3
10^4
Seconds
Transformation time (log scale)

- At normal cooling rates pearlite *(P) forms, higher cooling* rates generates *bainite (B).*

- *The size of pearlite or bainite* depends on the transformation temperature.

- Martensite (*M) forms when the steel is cooled below the* martensite start (Ms) temperature at *much higher cooling rate* so that the nose of the T-T-T curve is avoided

- Diffusion rates below Ms is so low that *Austenite – Martensite transformation* is a diffusion less process (the C content remains same).

- However, the crystal structure changes from FCC (austenite) to *body centered tetragonal* (BCT).

TTT diagram gives

- Nature of transformation-isothermal or athermal (time independent) or mixed
- Type of transformation-reconstructive, or displacive
- Rate of transformation
- Stability of phases under isothermal transformation conditions
- Temperature or time required to start or finish transformation
- Qualitative information about size scale of diagram
- Composition of steel- (a) carbon wt%, (b) alloying element wt%
- Grain size of austenite
- Heterogeneity of austenite

Pearlite

- At temperatures just below the eutectoid, relatively thick layers of both the ***α-ferrite and Fe_3C phases*** are produced

- At higher temperatures, *high diffusion rates* allow for *larger grain growth* and formation of thick layered structure of pearlite this microstructure is called **coarse pearlite,** and the region at which it forms is indicated to the *right of the TTT curve*

- With decreasing temperature, the *carbon diffusion rate decreases*, and the layers become *progressively thinner*.

- The thin-layered structure produced in the vicinity of 540°C is termed **fine pearlite**

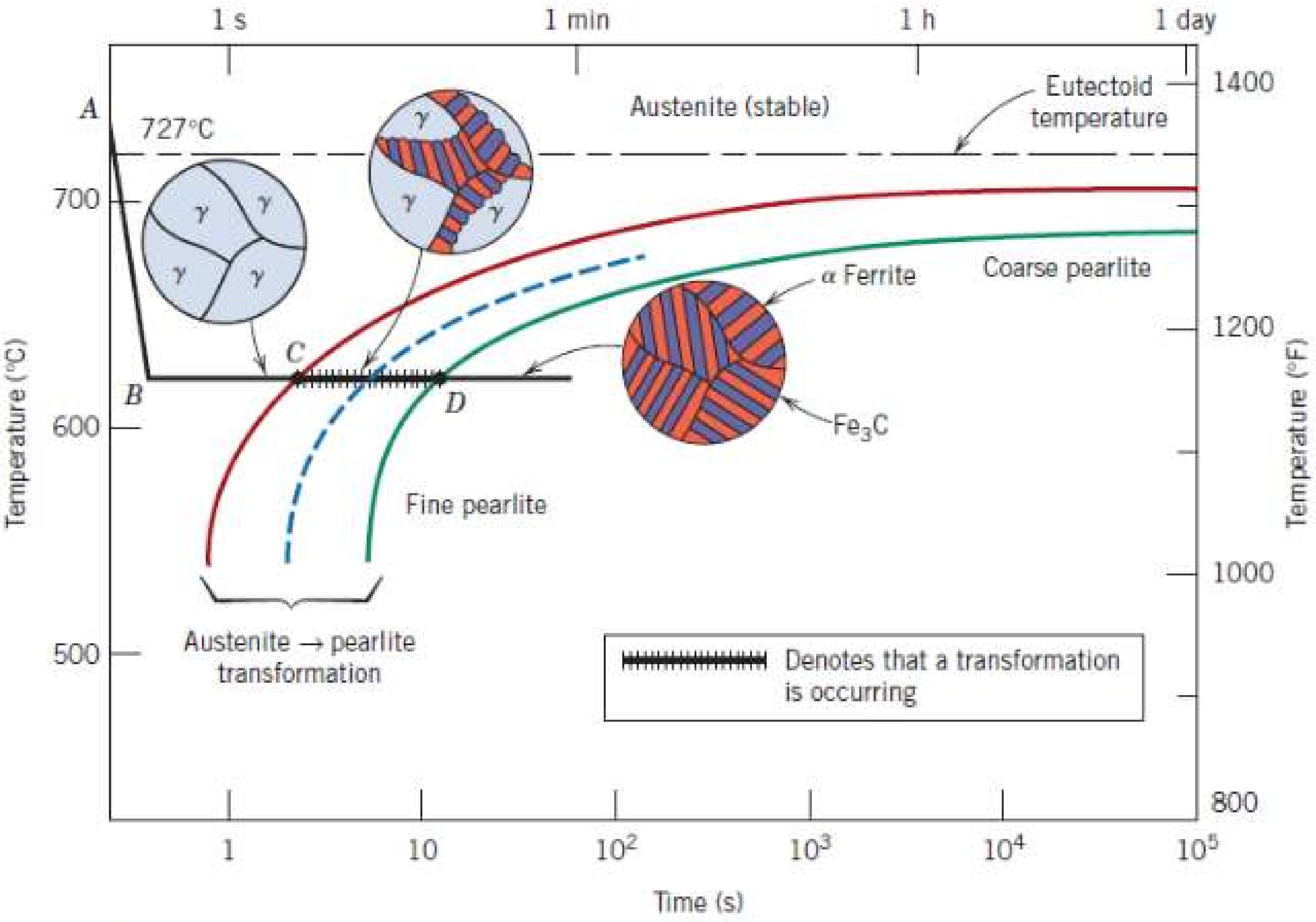


Figure 10.14 Isothermal transformation diagram for a eutectoid iron–carbon alloy, with superimposed isothermal heat treatment curve (*ABCD*). Microstructures before, during, and after the austenite-to-pearlite transformation are shown. [Adapted from H. Boyer

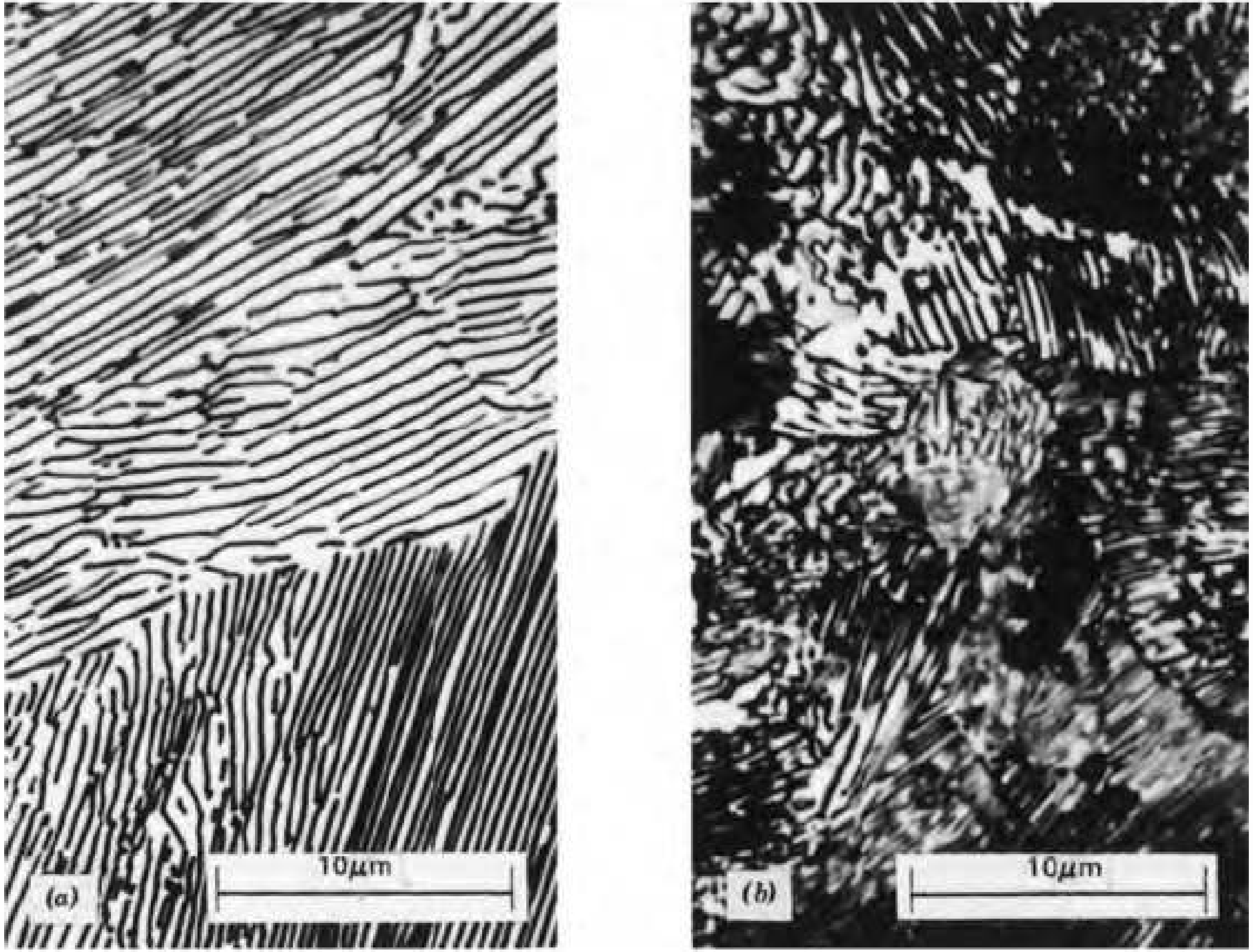


Figure 10.15 Photomicrographs of (*a*) coarse pearlite and (*b*) fine pearlite. 3000×. (From K. M. Ralls et al., *An Introduction to Materials Science and Engineering*, p. 361. Copyright © 1976 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)

Bainite

- In addition to pearlite, other micro constituents that are products of the austenitic transformation exist; one of these is called **bainite.**

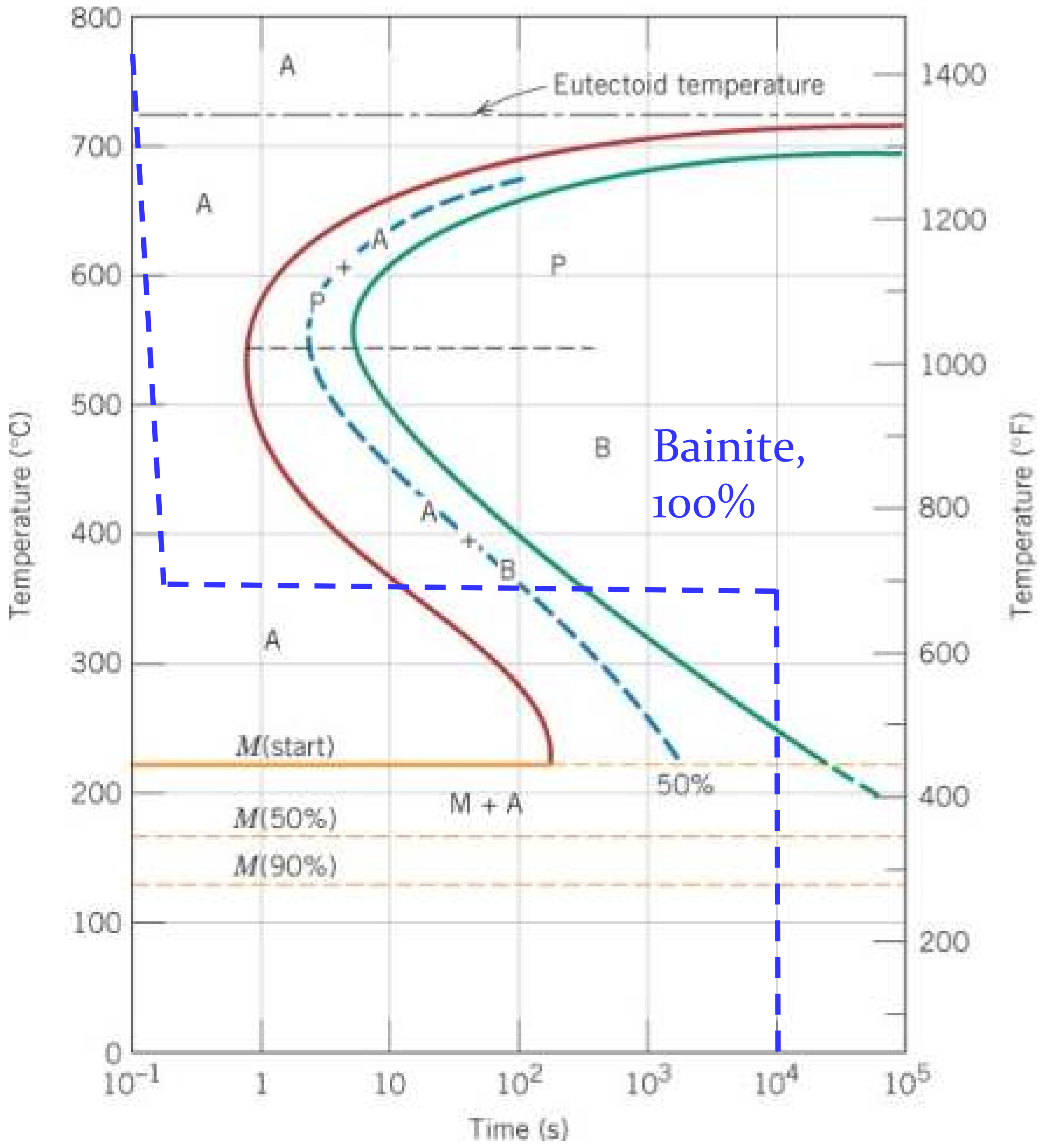
- The *microstructure of bainite* consists of ferrite and cementite phases, and thus diffusional processes are involved in its formation.

- Bainite forms as *needles or plates*, depending on the temperature of the transformation.

- It occurs at temperatures *below* those at which pearlite forms

Bainite Formation Example

- ❑Rapidly cool to 350 ˚C
- ❑Hold for 10^4 seconds
- ❑Quench to room temperature



TTT Diagram of Eutectoid steel

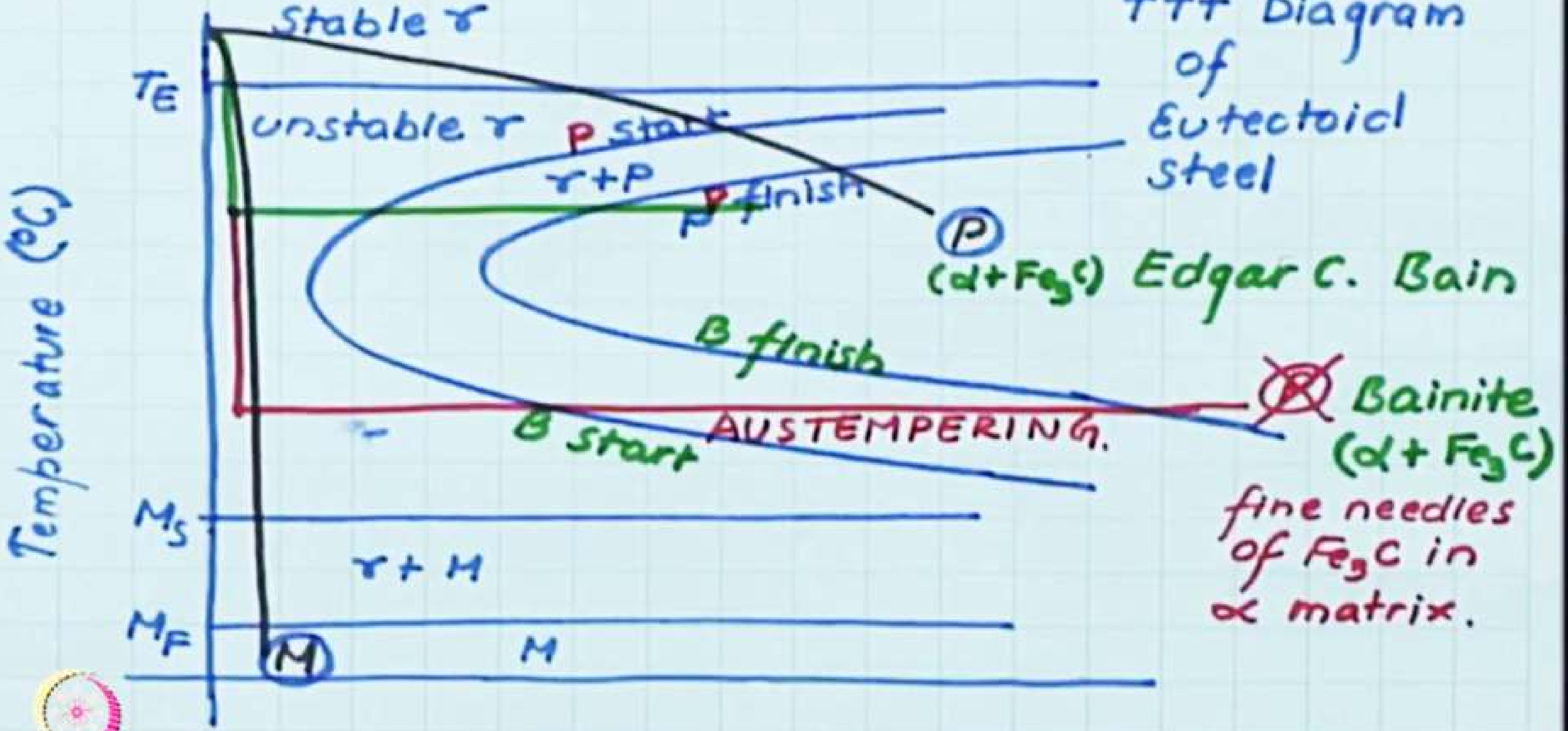
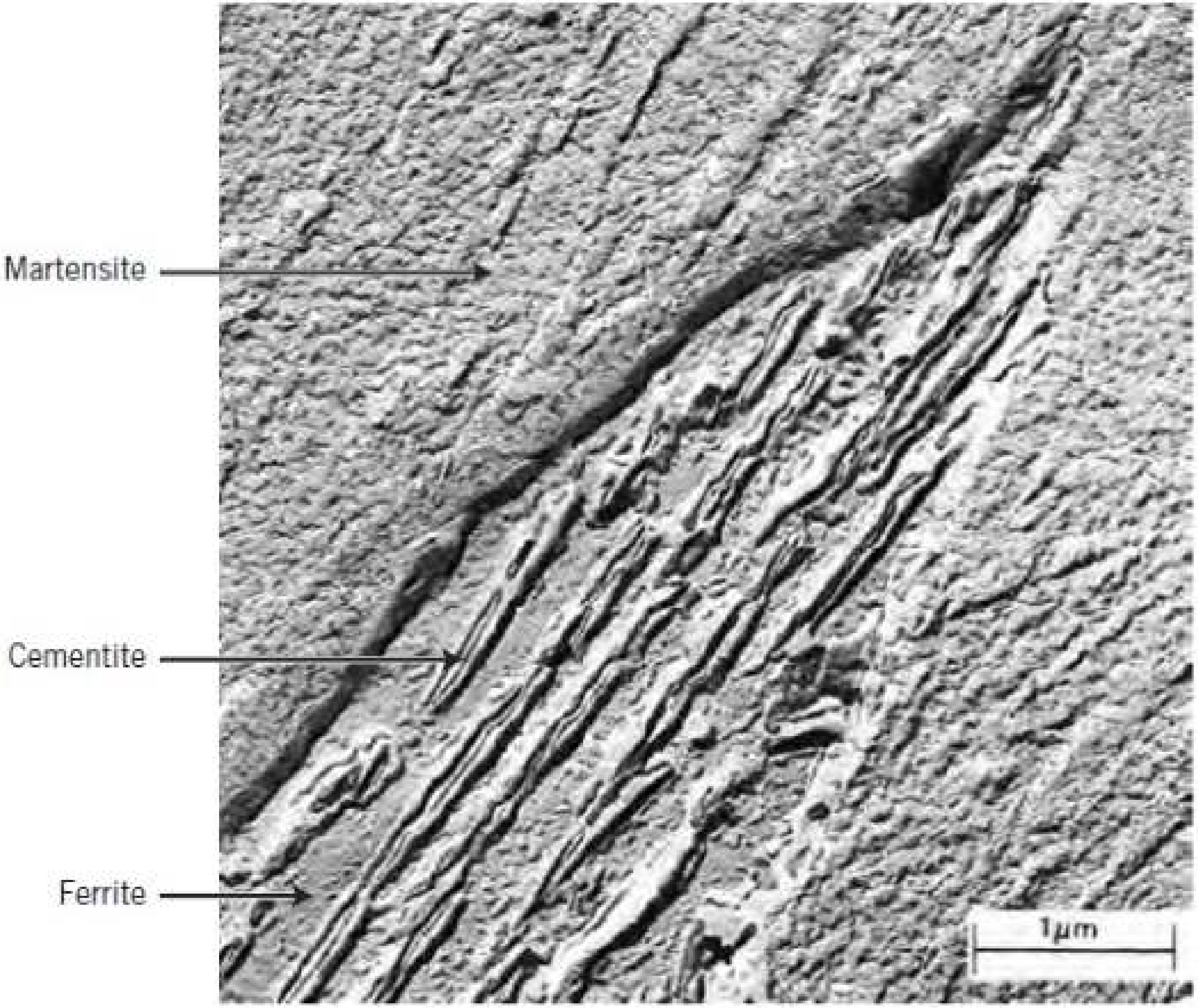


Figure 10.17 Transmission electron micrograph showing the structure of bainite. A grain of bainite passes from lower left to upper right-hand corners, which consists of elongated and needle-shaped particles of Fe_3C within a ferrite matrix. The phase surrounding the bainite is martensite. (Reproduced with permission from *Metals Handbook*, 8th edition, Vol. 8, *Metallography, Structures and Phase Diagrams,* American Society for Metals, Materials Park, OH, 1973.)



All three curves are C-shaped and have a "nose" at point *N*, where the rate of transformation is a maximum. As may be noted, whereas pearlite forms above the nose [i.e., over the temperature range of about 540 to 727°C (1000 to 1341°F)], at temperatures between about 215 and 540°C (420 and 1000°F), bainite is the transformation product.

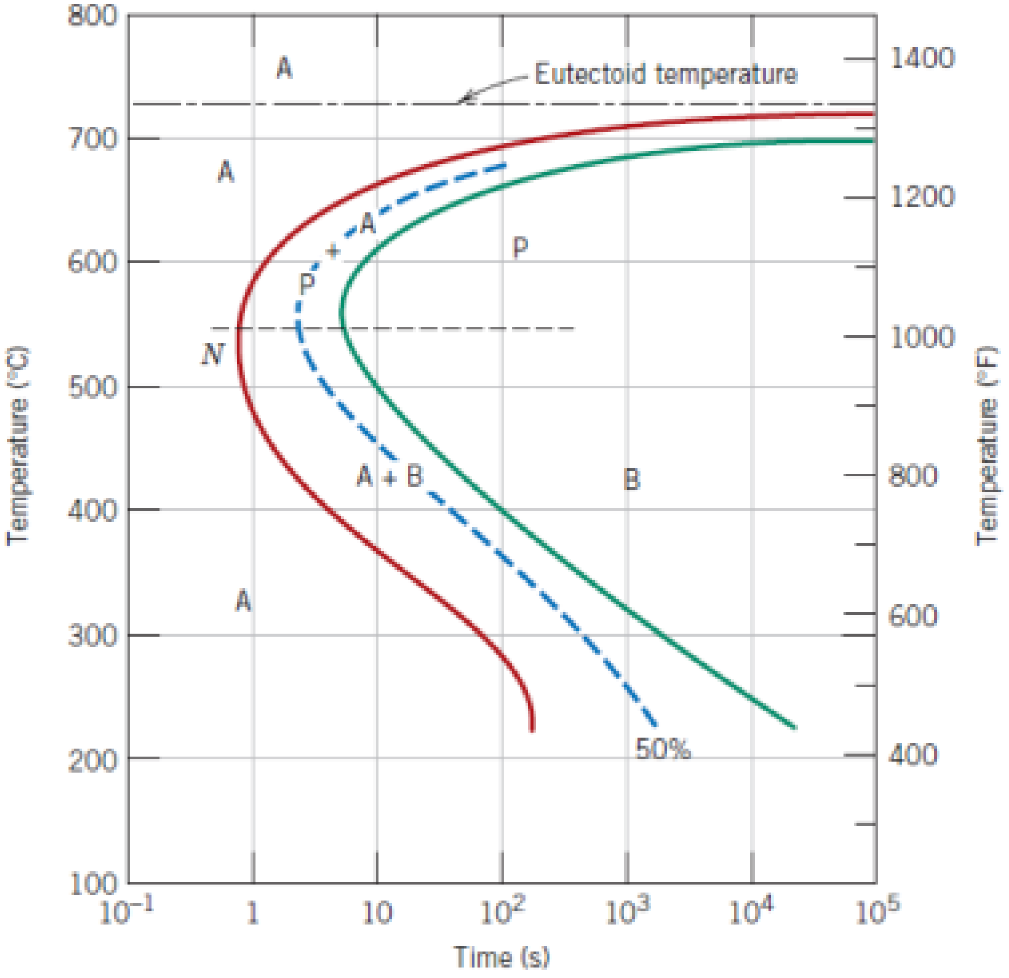


Figure 10.18 Isothermal transformation diagram for an iron–carbon alloy of eutectoid composition, including austenite-to-pearlite (A–P) and austenite-to-bainite (A–B) transformations. [Adapted from H. Boyer (Editor), *Atlas of Isothermal Transformation and Cooling Transformation Diagrams,* American Society for Metals, 1977, p. 28.]

Phases vs Microconstituent.

Pearlite and Bainite are mixtures of the same two phases ($\alpha + Fe_3C$) but are different microconstituents due to different shapes and distribution of these phases.

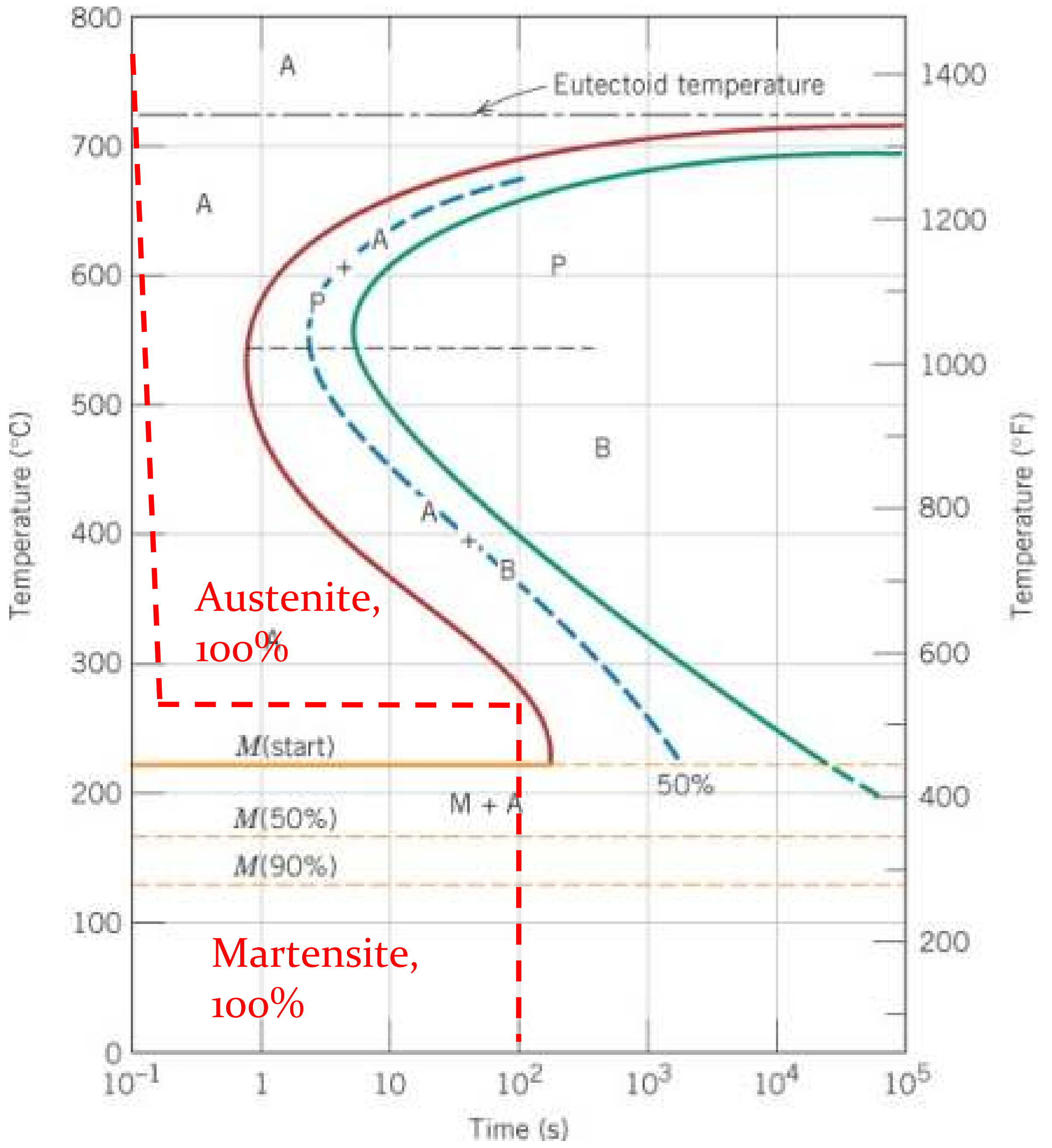
Martensite

- Another micro constituent or phase called **Martensite** is formed when austenitized iron–carbon alloys are *rapidly cooled (or quenched) to a relatively low temperature (220^{o}C).*
- Martensite is a non-equilibrium **single-phase structure** that results from a ***diffusionless transformation*** of austenite.
- The martensitic transformation occurs when the quenching rate is *rapid enough to prevent carbon diffusion.*
- *This occurs in such a way that the FCC austenite experiences a polymorphic transformation to a body-centered tetragonal (BCT) martensite.*
- All the carbon atoms remain as *interstitial impurities* in martensite; as such, they constitute a supersaturated solid solution that is having a *body-centred-tetragonal lattice*

- Instead of diffusion, a sudden reorientation of carbon and iron atoms from the FCC solid solution (austenite) into a body centred tetragonal (BCT) solid solution happens here. The carbon atoms occupy potential interstitial spaces in the BCT unit cell.

Martensite Formation example

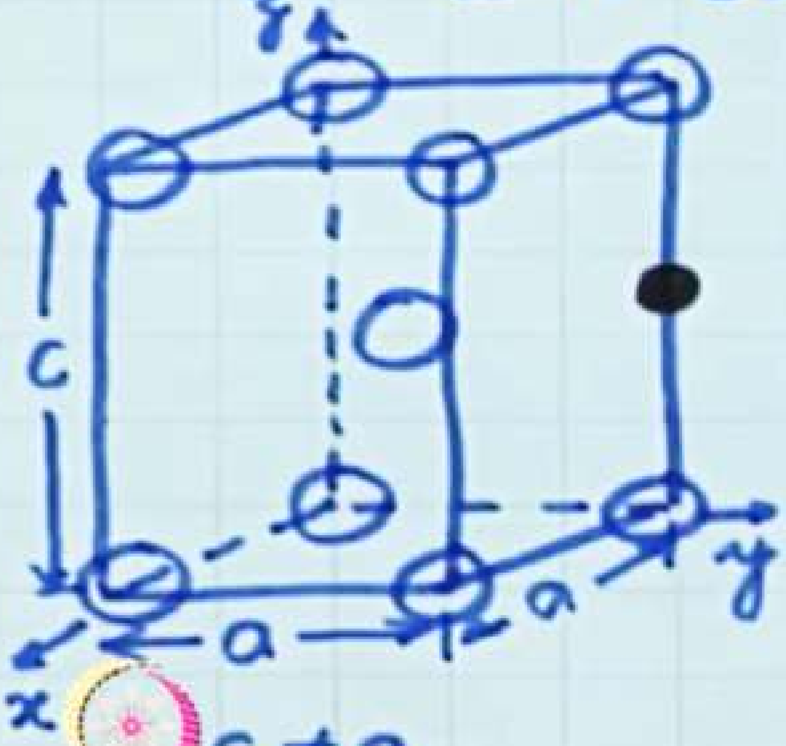
- ❑Rapidly cool to 250 ˚C
- ❑Hold for 100 seconds
- ❑Quench to room temperature



Martensite

Non equilibrium phase
forms on quenching of austenite

Interstitial solid solution of C in Fe
with Body-centred tetragonal structure.



$c \neq a$

○ Fe

● C

$c/a = 1 \Rightarrow$ BCC (Ferrite, α)

$\frac{c}{a} > 1 \Rightarrow$ BCT (Martensite, $M \equiv \alpha'$)

Very hard and brittle.

Martensitic Transformation

Austenite ⟶ Martensite

1. Transformation is ~~experi~~ extremely rapid.
2. Amount transformed depends only upon temperature and not on time.

   ATHERMAL : Rate of transformation does not depend on temp.
3. No change in composition.

   DIFFUSIONLESS : There is no long range atomic movement.

Martensitic microstructure.

The needle shaped grains are the martensite phase, and the white regions are austenite that failed to transform during the rapid quench.

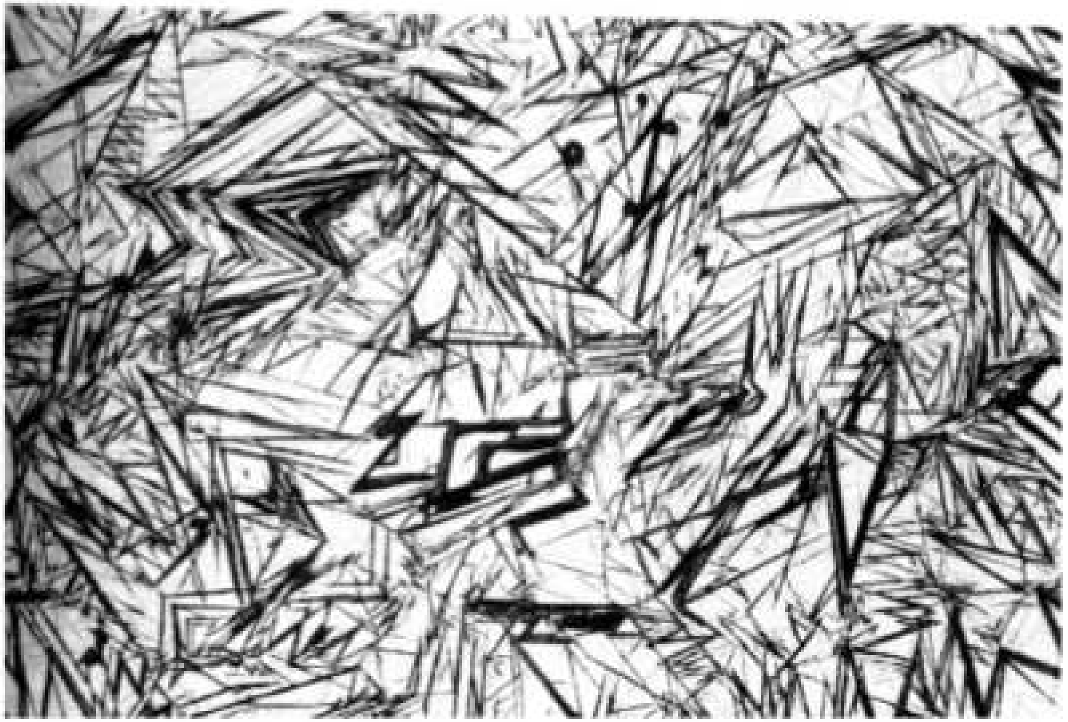


Figure 3.30 *Martensite*

- In C, rapid cooling is to 650^{O}C, held for 20 secs, again cooled to 420^{O}C, held till 103 secs and quenched to room temperature. Here at 650^{O}C, after about 7 secs pearlite transformation begins. At the end of 20 secs, about 50% pearlite transformation may be completed.
- During the second stage of cooling to 420^{O}C, no transformation may take place. When the specimen is held at 420^{O}C, the remaining austenite starts to transform into bainite. The time available here is enough to complete the bainite transformation.
- On further quenching, either pearlite or bainite does not transform. Microstructure at room temperature consists of 50% pearlite and 50% bainite.

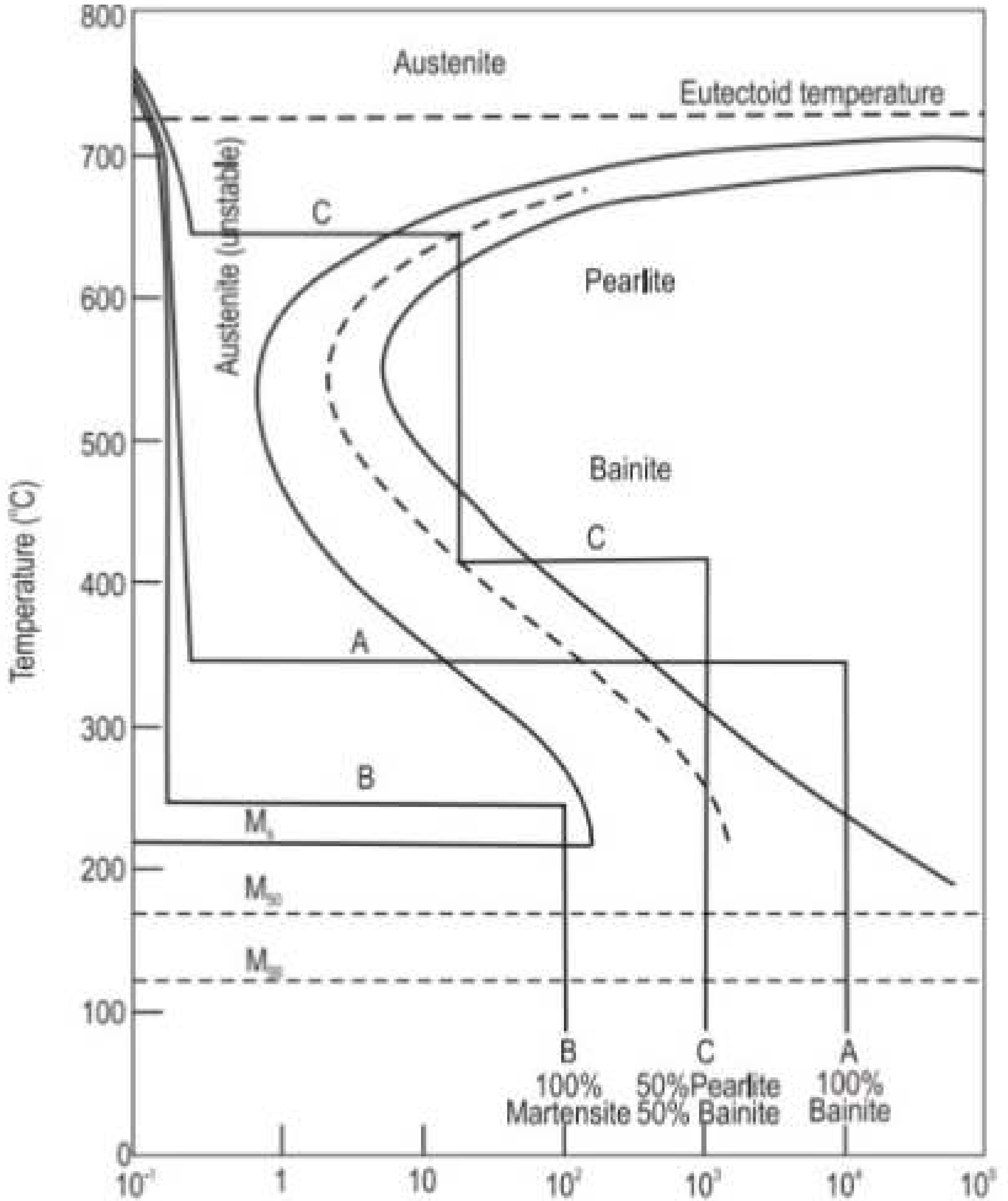


Figure 3.25 *TTT diagram for eutectoid steel*

Spheroidite

- If a steel alloy having either pearlitic or bainitic microstructures is heated to, and left at, a temperature below the eutectoid for a sufficiently long period of time—for example, at about (700 ^{0}C) for between 18 and 24 h—yet another microstructure will form. It is called **spheroidite** .

- Instead of the alternating ferrite and cementite lamellae (pearlite), or the microstructure observed for bainite, the Fe3C phase appears as sphere-like particles embedded in a continuous phase matrix. This transformation has occurred by additional carbon diffusion with no change in the compositions or relative amounts of ferrite and cementite phase.

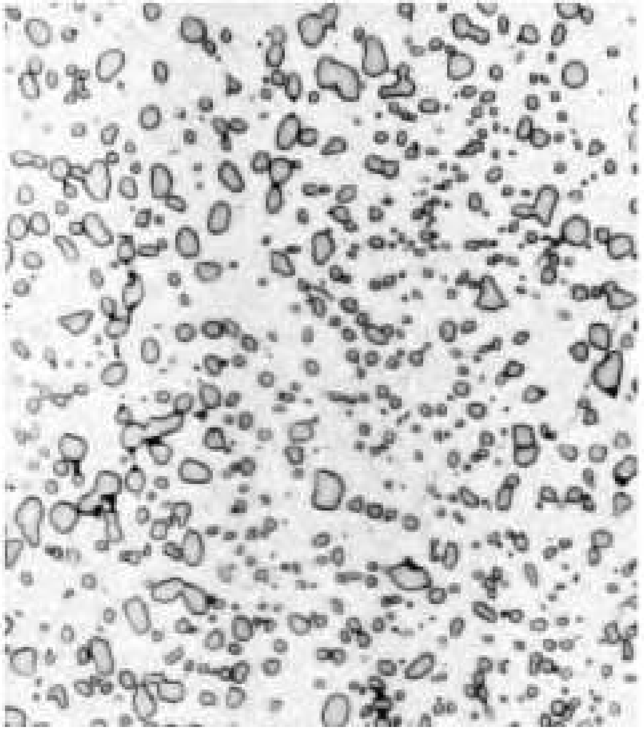


Figure 10.19 Photomicrograph of a steel having a spheroidite microstructure. The small particles are cementite; the continuous phase is α ferrite. 1000×. (Copyright 1971 by United States Steel Corporation.)

TEMPERED MARTENSITE

- In the as-quenched state, martensite, in addition to being very hard, is so brittle that it cannot be used for most applications; also, any internal stresses that may have been introduced during quenching have a weakening effect.
- The ductility and toughness of martensite may be enhanced and these internal stresses relieved by a heat treatment known as tempering.
- Tempering is accomplished by heating a martensitic steel to a temperature below the eutectoid for a specified time period. Normally, tempering is carried out at temperatures between 250 and 650^{0}C.
- This tempering heat treatment allows, by diffusional processes, the formation of tempered martensite, according to the reaction

Martensite to tempered martensite transformation reaction

$$\text{martensite (BCT, single phase)} \rightarrow \text{tempered martensite } (\alpha + Fe_3C \text{ phases}) \tag{10.20}$$

- The microstructure of tempered martensite consists of extremely small and uniformly dispersed cementite particles embedded within a continuous ferrite matrix.
- This is similar to the microstructure of spheroidite except that the cementite particles are much, much smaller.

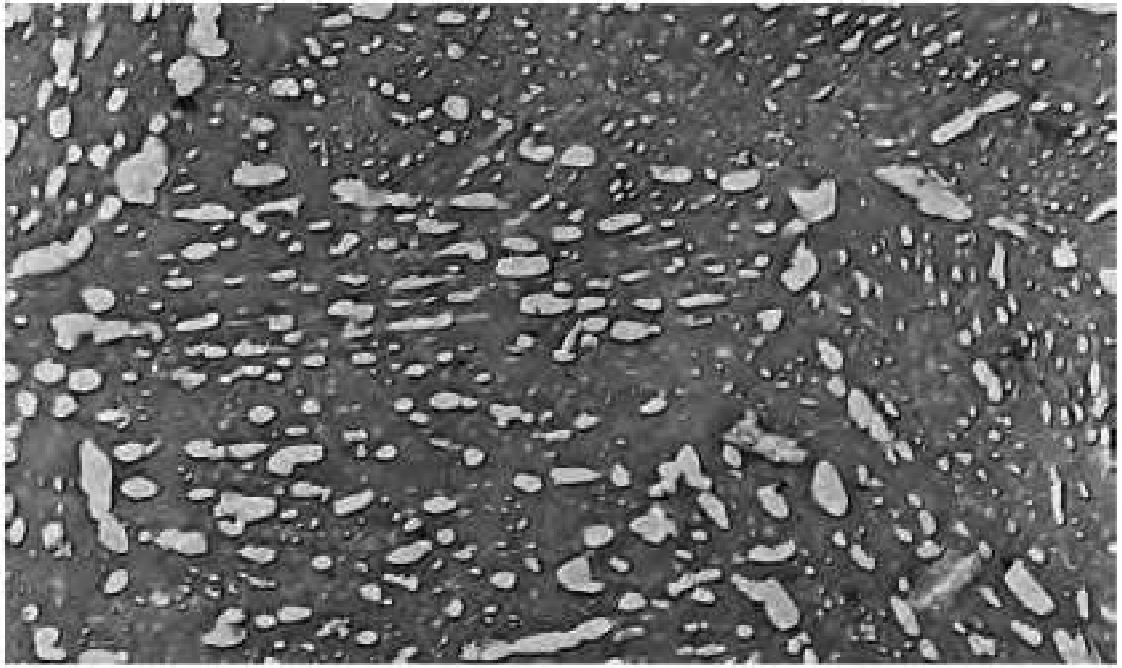
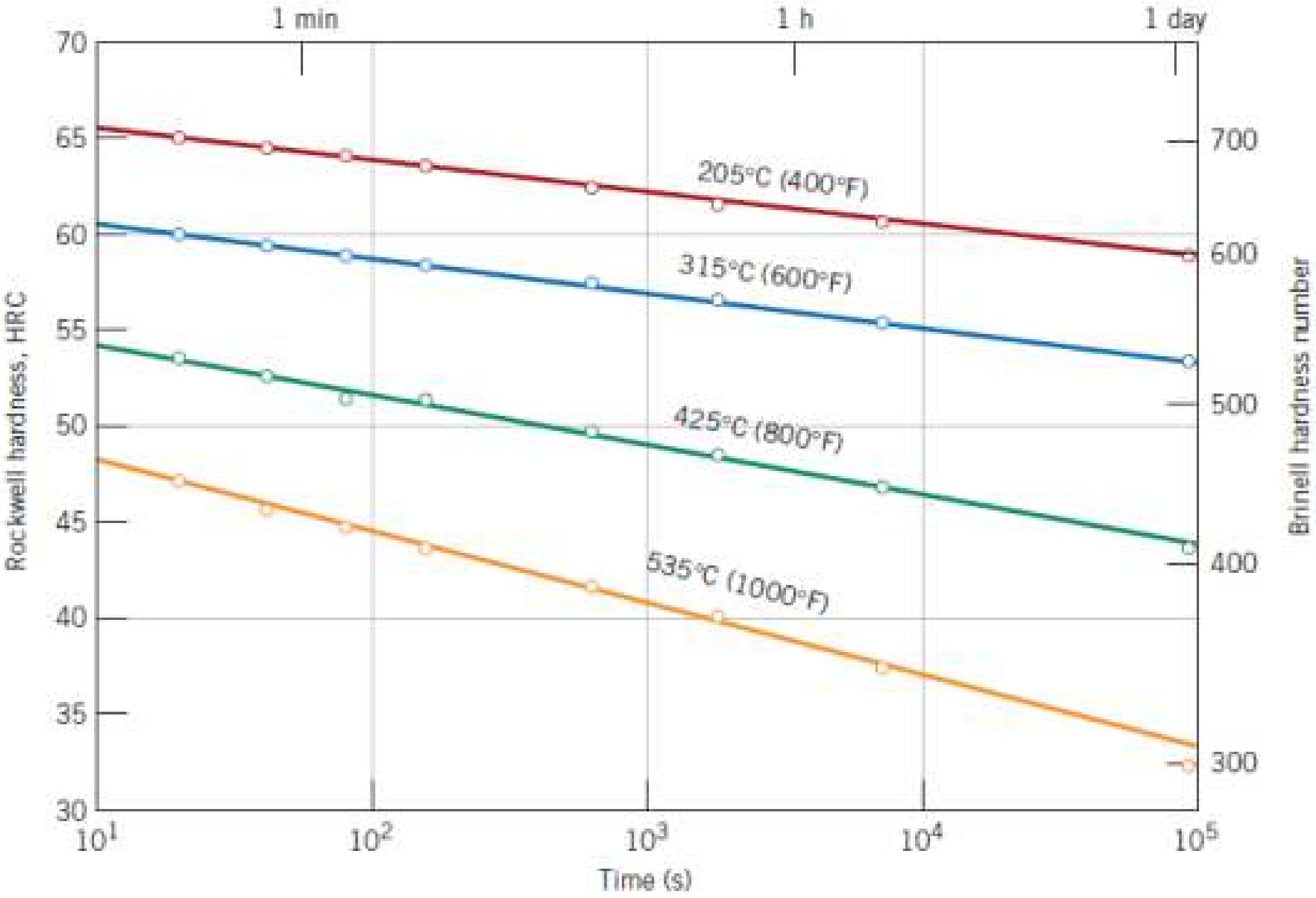
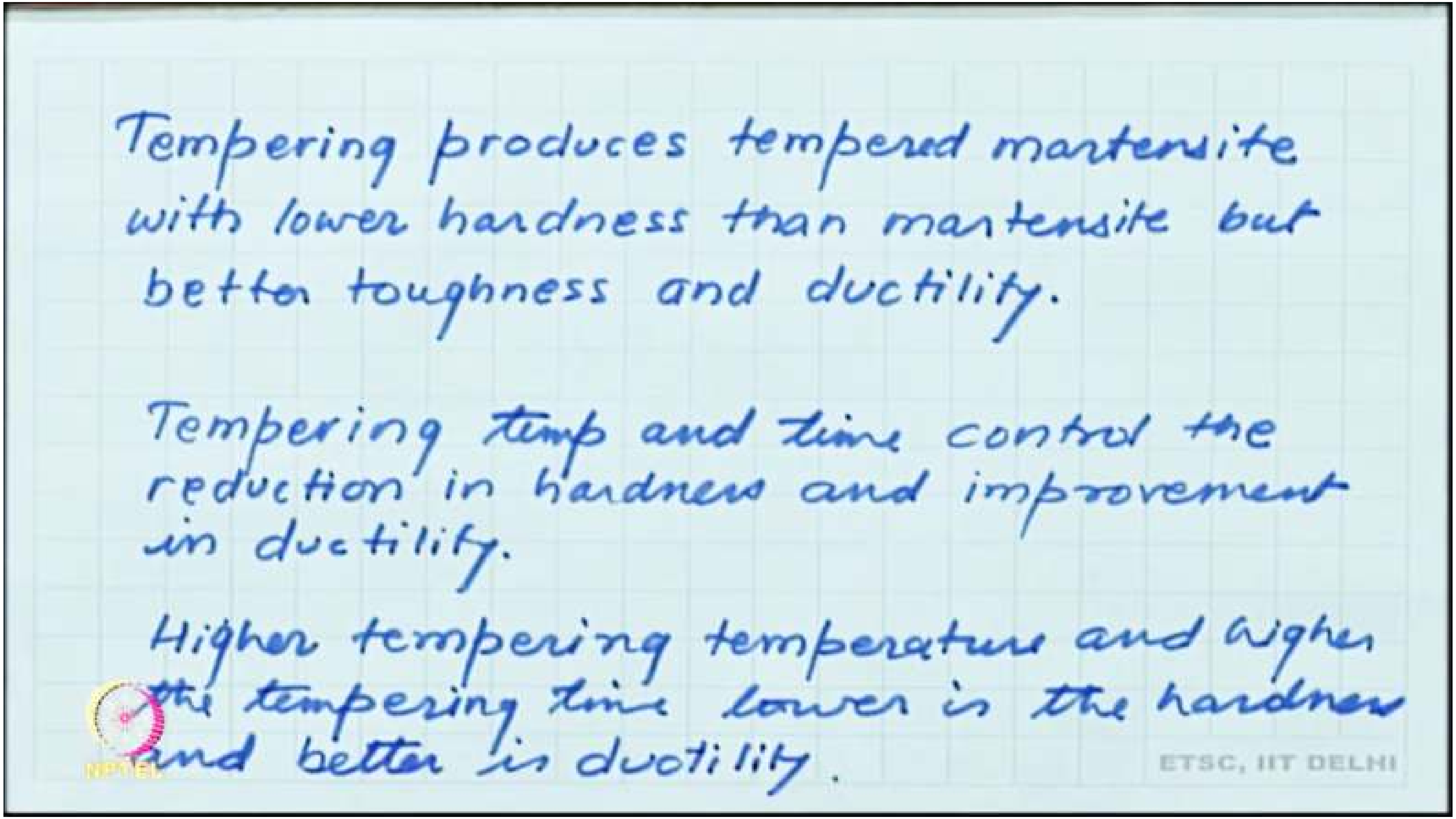


Figure 10.33 Electron micrograph of tempered martensite. Tempering was carried out at 594°C (1100°F). The small particles are the cementite phase; the matrix phase is α-ferrite. 9300×. (Copyright 1971 by United States Steel Corporation.)

Figure 10.35 Hardness (at room temperature) versus tempering time for a water-quenched eutectoid plain carbon (1080) steel. (Adapted from Edgar C. Bain, *Functions of the Alloying Elements in Steel,* American Society for Metals, 1939, p. 233.)



Tempered Martensite

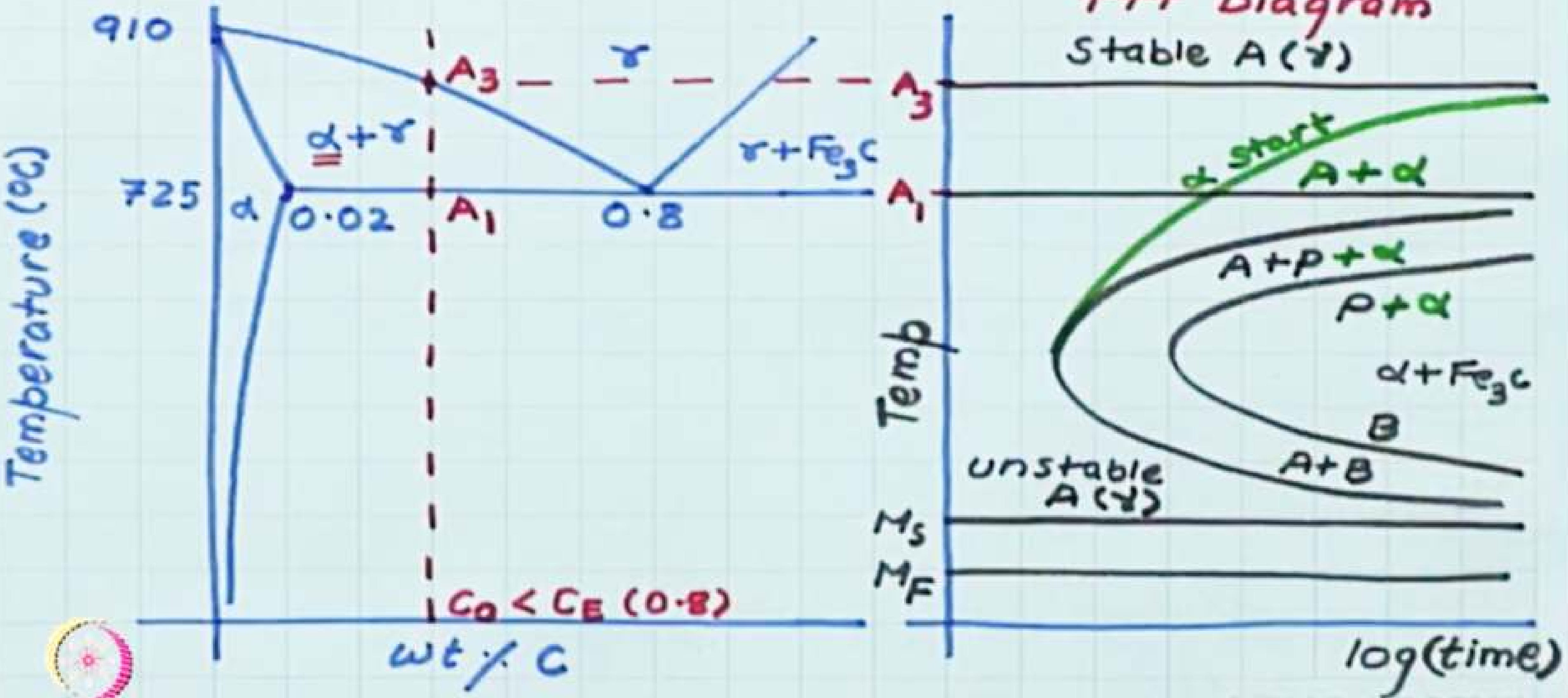


Tempering produces tempered martensite with lower hardness than martensite but better toughness and ductility.

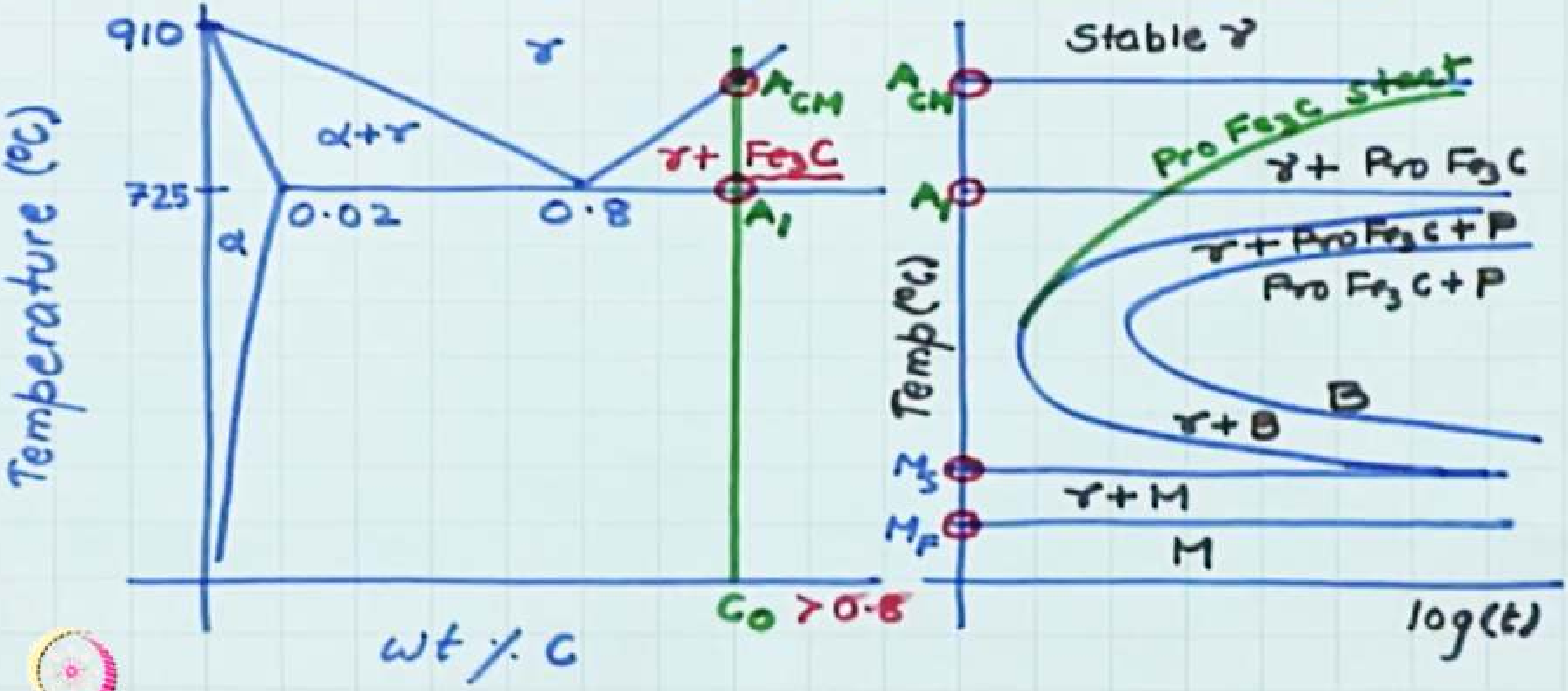
Tempering temp and time control the reduction in hardness and improvement in ductility.

Higher tempering temperature and higher the tempering time lower is the hardness and better is ductility.

TTT Diagram of Hypoeutectoid Steel



TTT Diagram of Hypereutectoid Steel



C-C-T Diagram

- Isothermal heat treatments are not the most practical to conduct because an alloy must be rapidly cooled to and maintained at an elevated temperature from a higher temperature above the eutectoid.

- Most heat treatments for steels involve the continuous cooling of a specimen to room temperature. An isothermal transformation diagram(TTT) is valid only for conditions of constant temperature.

- TTT diagram modified to CCT diagram for transformations that occur as the temperature is constantly changing.

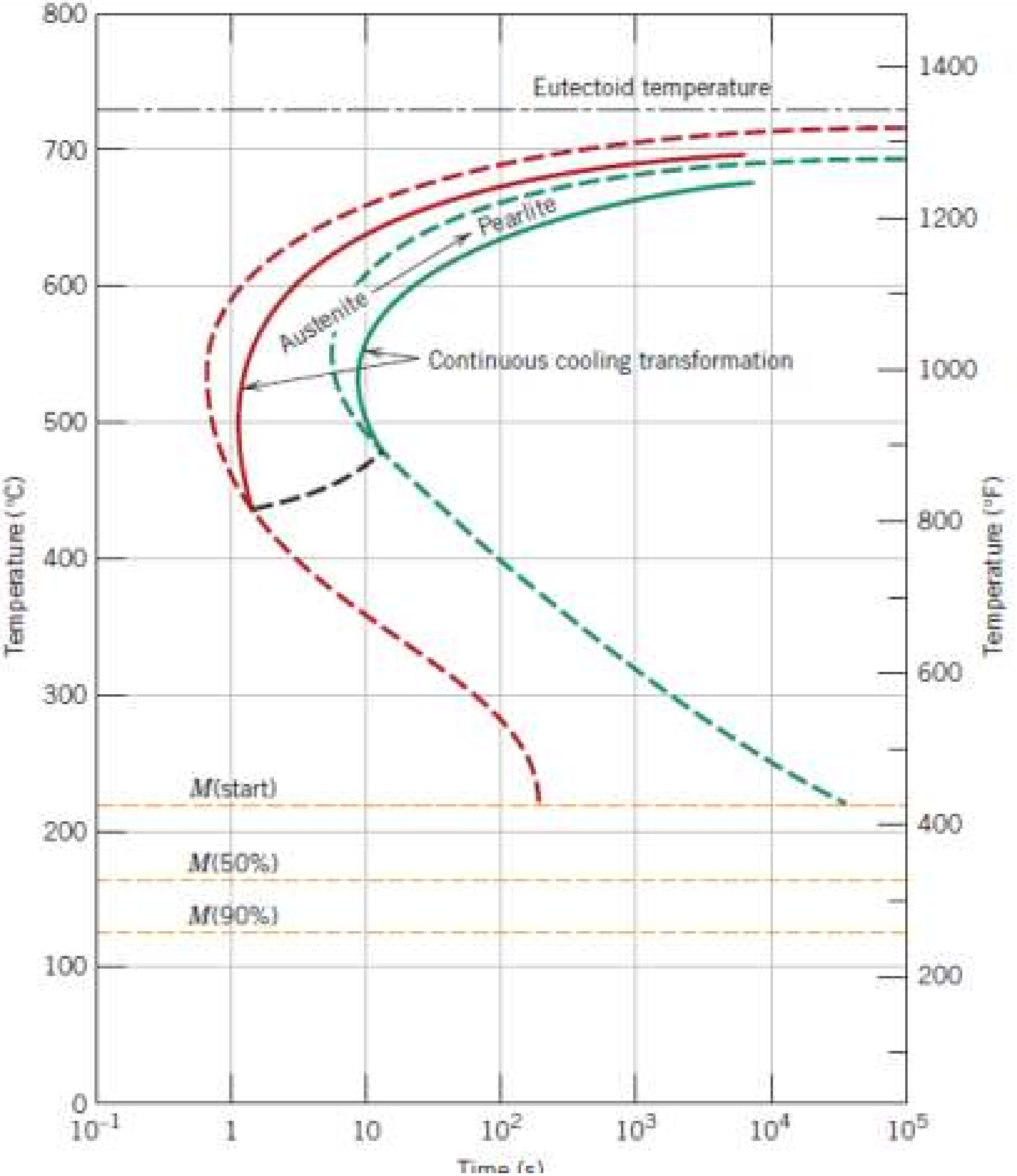
- In actual practice, steel is rarely quenched to a constant temperature and isothermally transformed. But it is continuously cooled from the austenitic range to room temperature following different cooling rates.

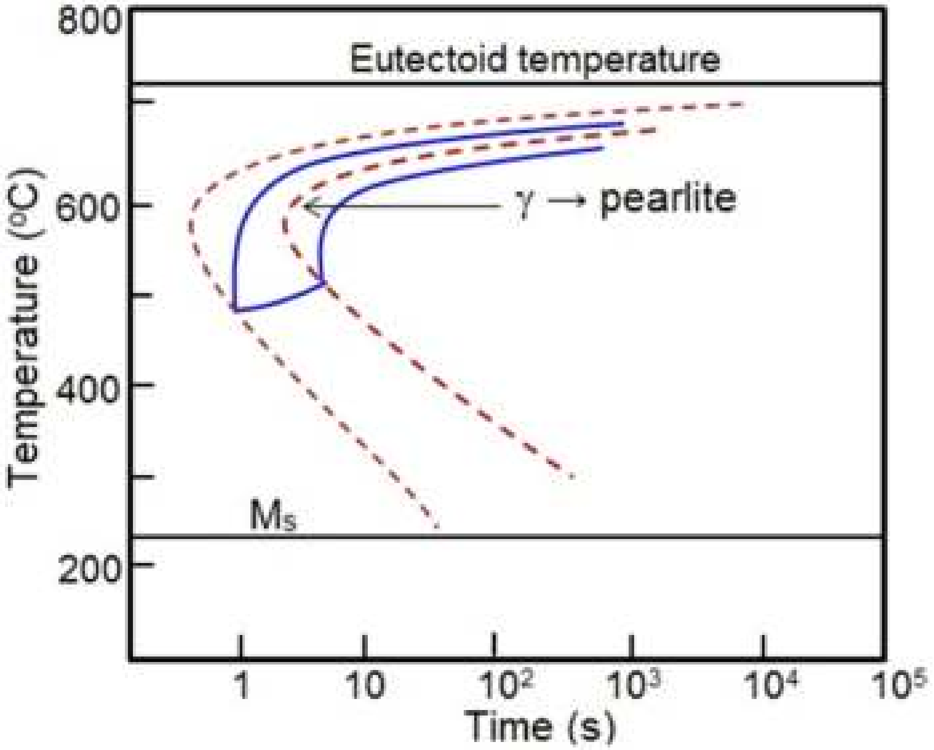
- Continuous Cooling Transformation (CCT) diagram shows the relationship between transformation temperature and time during continuous cooling.

- For continuous cooling, the time required for a reaction to begin and end is delayed. The CCT diagram for eutectoid steel is shown in figure along with the TTT diagram.

- The two curves represent start and finish of pearlite transformation. It can be seen that the transformation on continuous cooling starts at lower temperatures and after longer times as compared to isothermal transformation.

Figure 10.25 Superimposition of isothermal and continuous cooling transformation diagrams for a eutectoid iron–carbon alloy. [Adapted from H. Boyer (Editor), *Atlas of Isothermal Transformation and Cooling Transformation Diagrams*, American Society for Metals, 1977, p. 376.]





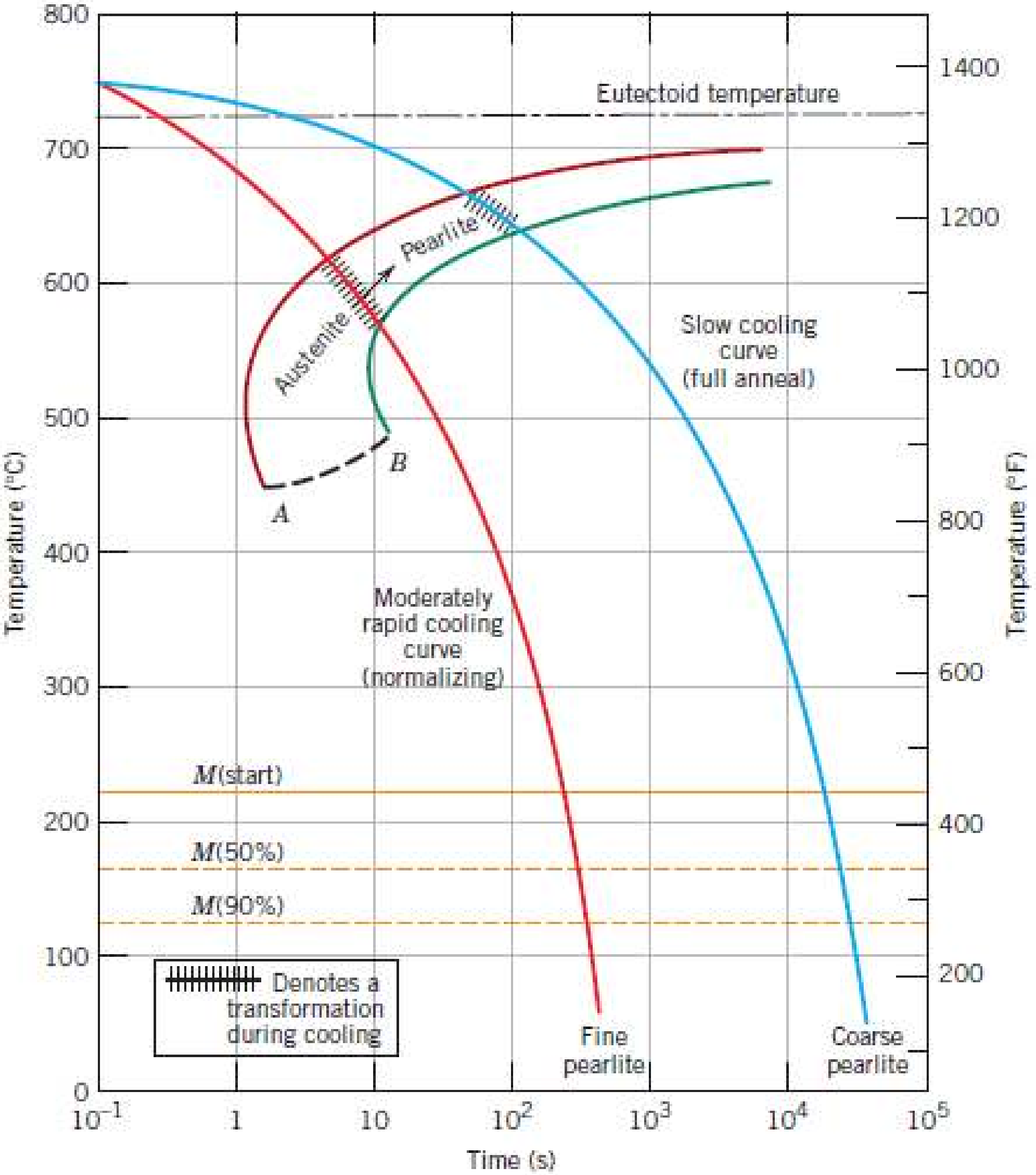
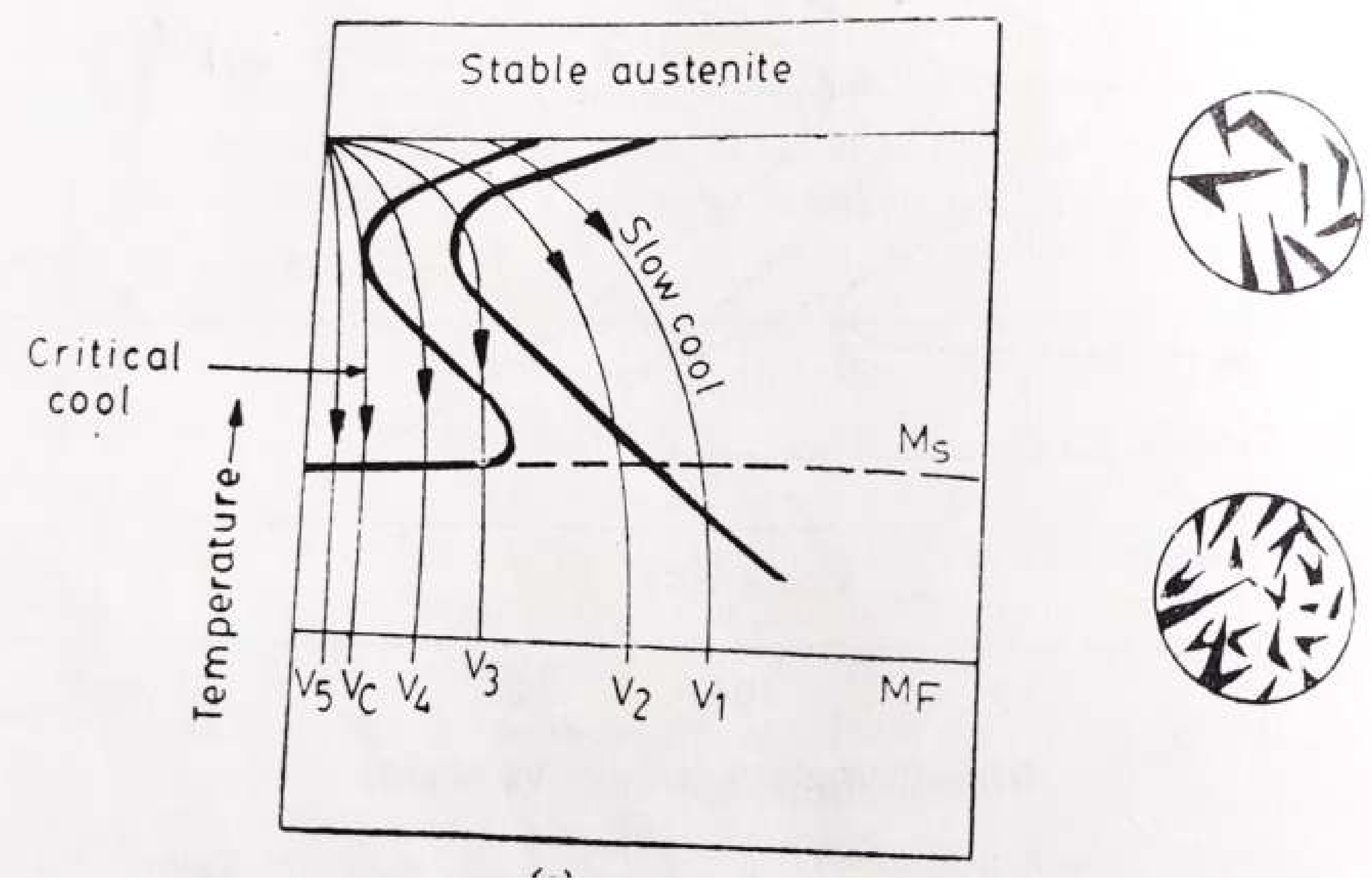


Figure 10.26 Moderately rapid and slow cooling urves superimposed on a continuous cooling transformation diagram for a eutectoid iron–carbon alloy.

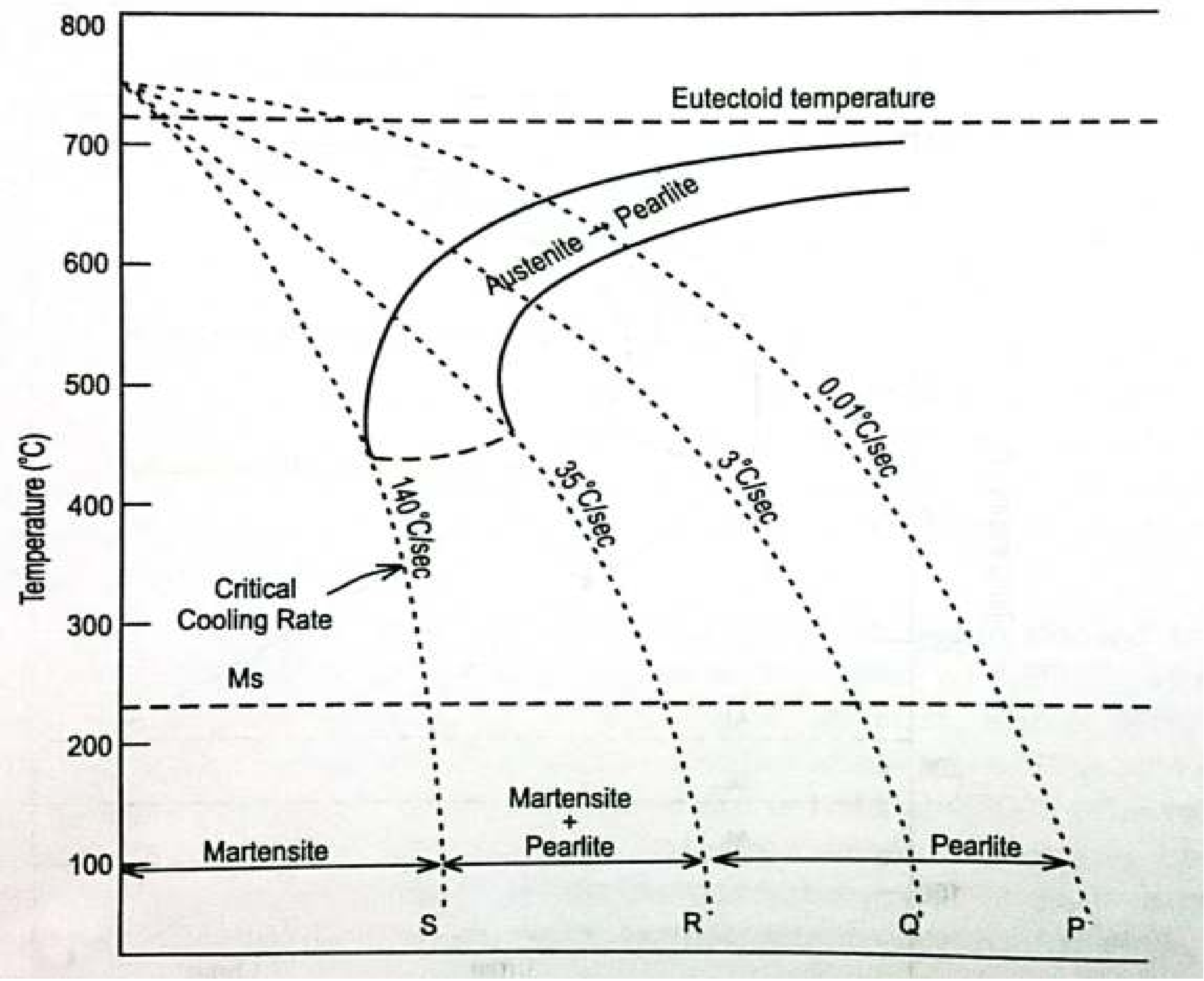
C-C-T Diagram

- Measure the extent of transformation as a function of time for a continuously decreasing temperature. In other words a sample is austenitised and then **cooled at a predetermined rate** and the degree of transformation is measured. Obviously a large number of experiments is required to build up a complete CCT diagram.

- CCT diagrams are generally more appropriate for **engineering applications** as components are cooled (air cooled, furnace cooled, quenched etc.) from a processing temperature as this is more economic than transferring to a separate furnace for an isothermal treatment.


Stable austenite
Slow cool
Critical cool
Temperature
M_S
M_F
V_5
V_C
V_4
V_3
V_2
V_1

C-C-T Diagram



800
700
600
500
400
300
200
100
Temperature (°C)
Eutectoid temperature
Austenite → Pearlite
0.01°C/sec
3°C/sec
35°C/sec
140°C/sec
Critical Cooling Rate
Ms
Martensite
Martensite + Pearlite
Pearlite
S
R
Q
P

- Cooling rate is slow in curve P (0.01˚/s) and leads to 100 % coarse pearlite at room temperature
- A cooling rate of 3˚C/s leads to 100% fine pearlite at room temperature
- A cooling rate of 35˚C/s leads to 100% fine pearlite which is the limiting value for 100% pearlite
- A cooling rate of 140˚C/s misses pearlite start curve and doesn’t enter in to pearlite or bainite region
- Austenite transforms completely to martensite when crosses Ms line
- This cooling rate is called **critical cooling rate.**
- For cooling rates between 35^{O}C/sec and 140^{O}C/sec, the cooling curve crosses the pearlite start curve, but not the pearlite finish curve. Only a part of austenite is transformed to pearlite. A small portion of the austenite is transformed to bainite and the remaining transforms to martensite on crossing the Ms line.

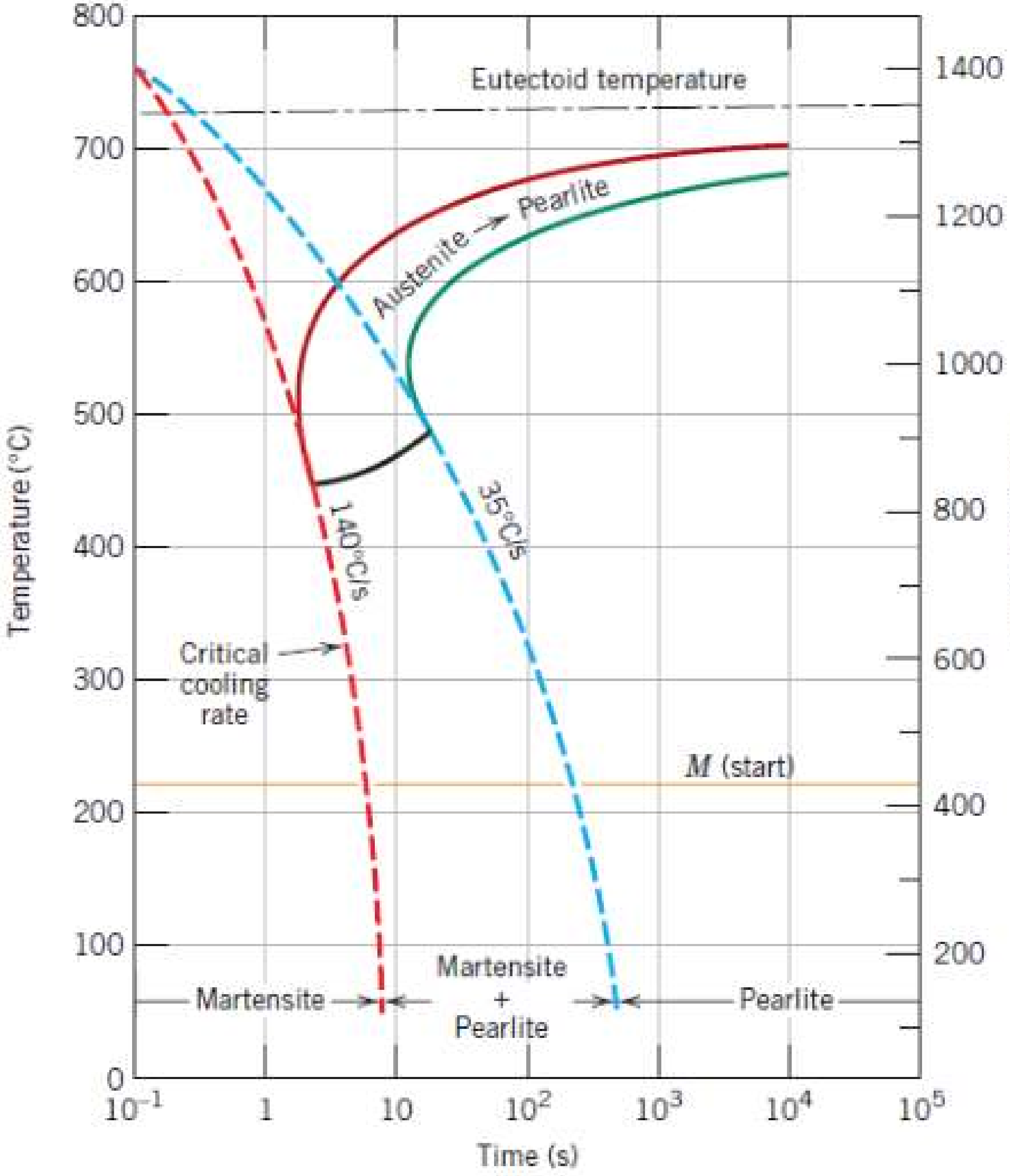


Figure 10.27 Continuous cooling transformation diagram for a eutectoid iron–carbon alloy and superimposed cooling curves, demonstrating the dependence of the final microstructure on the transformations that occur during cooling.

Table 10.2 Summary of Microstructures and Mechanical Properties for Iron–Carbon Alloys

Microconstituent	*Phases Present*	*Arrangement of Phases*	*Mechanical Properties (Relative)*
Spheroidite	α Ferrite + Fe_3C	Relatively small Fe_3C sphere-like particles in an α-ferrite matrix	Soft and ductile
Coarse pearlite	α Ferrite + Fe_3C	Alternating layers of α ferrite and Fe_3C that are relatively thick	Harder and stronger than spheroidite, but not as ductile as spheroidite
Fine pearlite	α Ferrite + Fe_3C	Alternating layers of α ferrite and Fe_3C that are relatively thin	Harder and stronger than coarse pearlite, but not as ductile as coarse pearlite
Bainite	α Ferrite + Fe_3C	Very fine and elongated particles of Fe_3C in an α-ferrite matrix	Hardness and strength greater than fine pearlite; hardness less than martensite; ductility greater than martensite
Tempered martensite	α Ferrite + Fe_3C	Very small Fe_3C sphere-like particles in an α-ferrite matrix	Strong; not as hard as martensite, but much more ductile than martensite
Martensite	Body-centered tetragonal, single phase	Needle-shaped grains	Very hard and very brittle

Heat Treatment of Steel

Heat Treatment

Heating a material to a temperature ,holding it at that temperature for a period of time followed by **cooling at a specified rate** is called heat treatment.

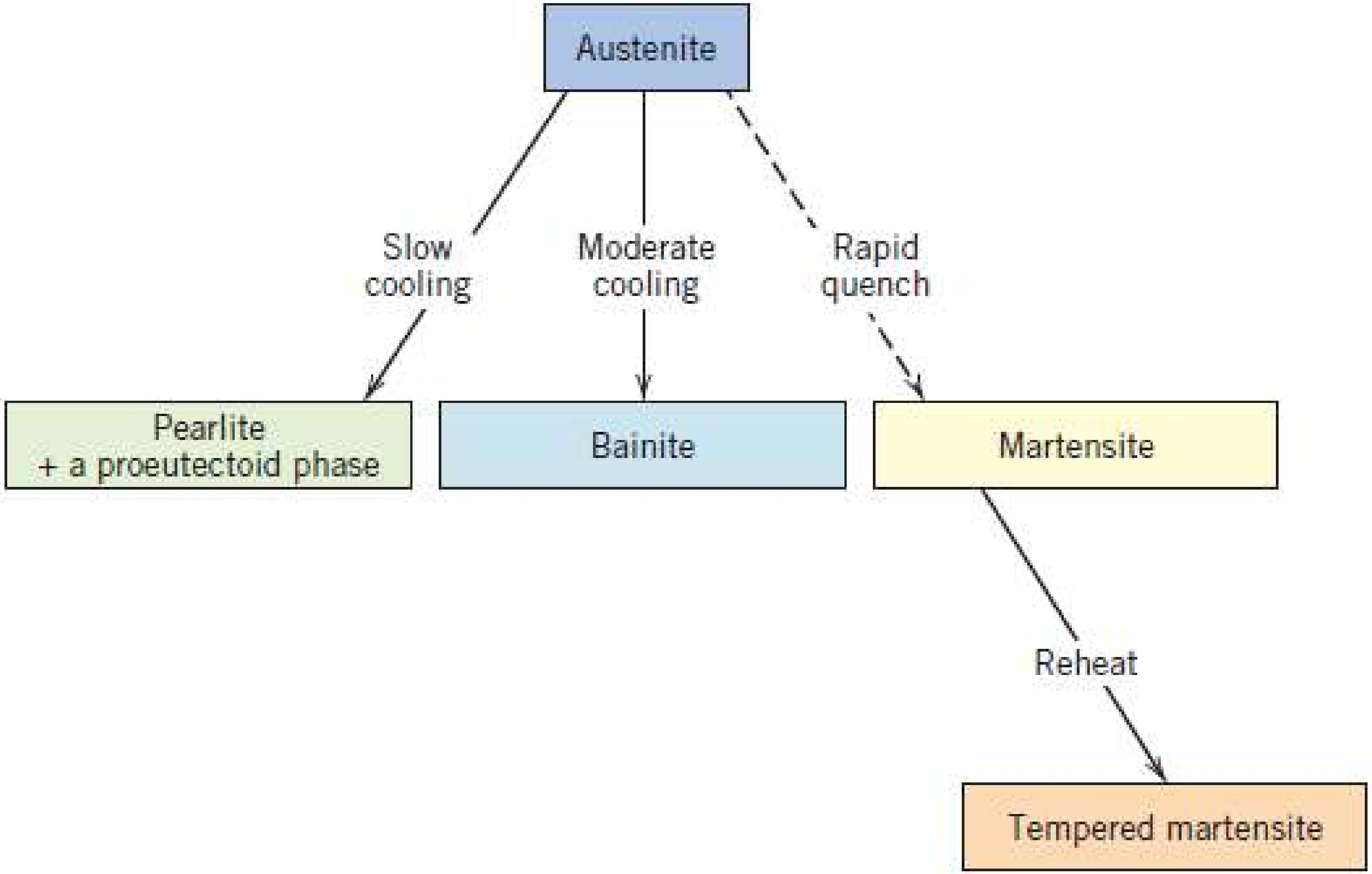
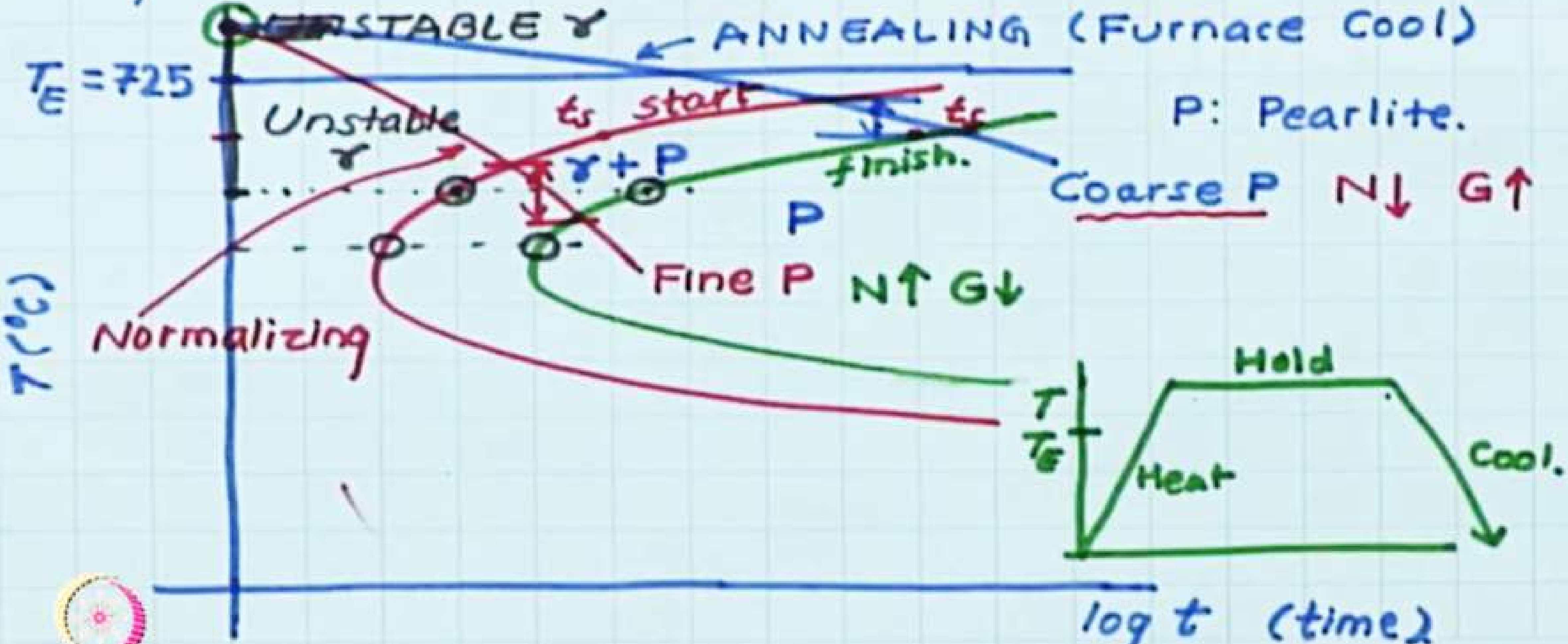
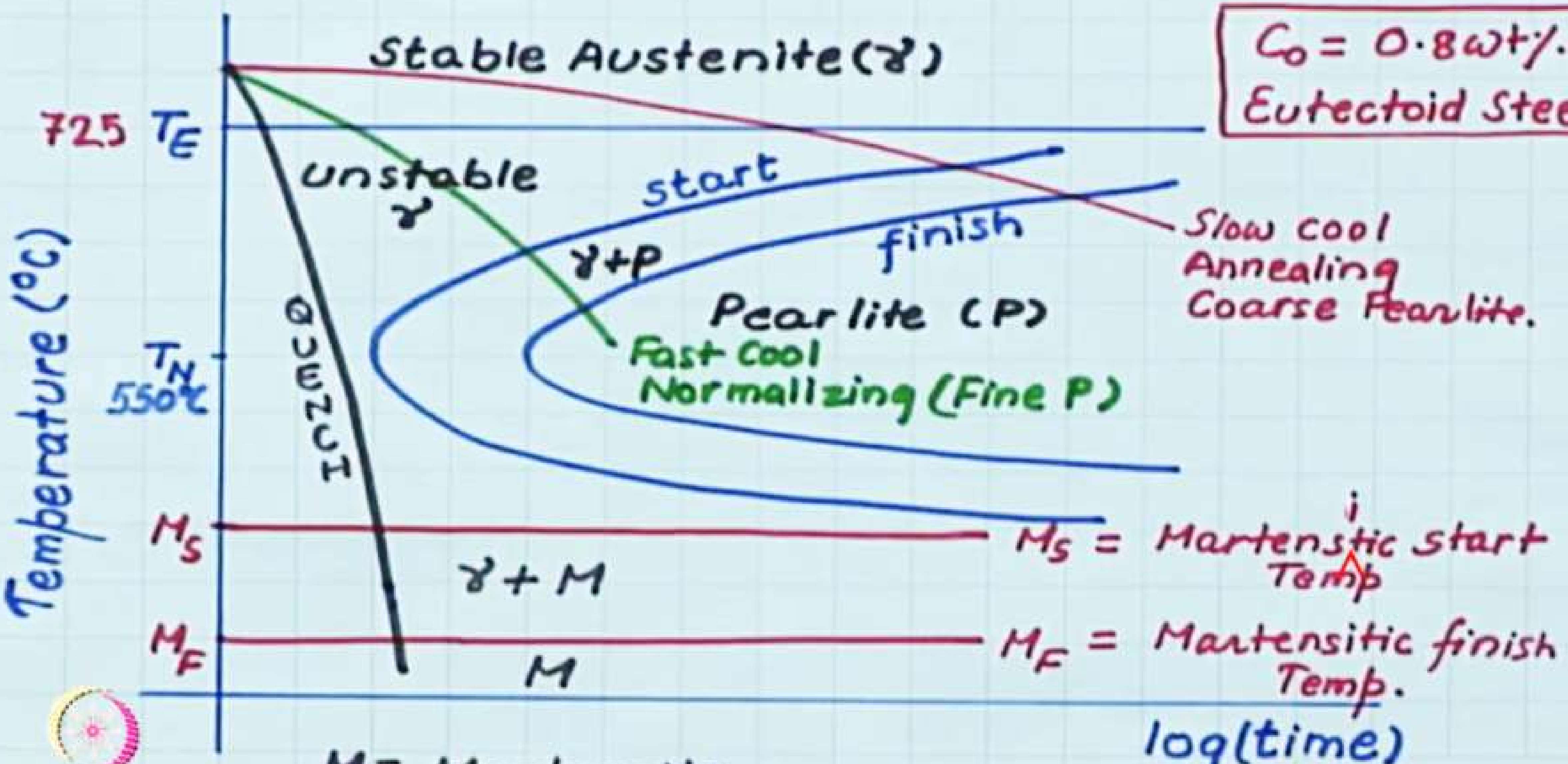


Figure 10.36 Possible transformations involving the decomposition of austenite. Solid arrows, transformations nvolving diffusion; dashed arrow, diffusionless transformation.

Time-Temperature-Transformation Diagram for Eutectoid Steel (C_0 = 0.8 wt% C)



$C_0 = 0.8\text{wt\%}\cdot C$
Eutectoid Steel



M_S = Martensitic start Temp

M_F = Martensitic finish Temp.

M ≡ Martensite

Heat Treatment of Steel

- Most heat treating operations begin with *heating the alloy into the austenitic phase* field to dissolve the carbide in the iron and then cooling.
- Steel heat treating practice rarely involves the use of temperatures above 1040°C
- Classification
  - Heating and rapid cooling (quenching)
  - Heating and slow cooling

Purpose of heat treatment:

- Improvement in ductility
- Relieving internal stresses
- Grain size refinement
- Increase of strength and hardness
- Improvement in machinability and toughness
- Improve surface hardness

Factors involved

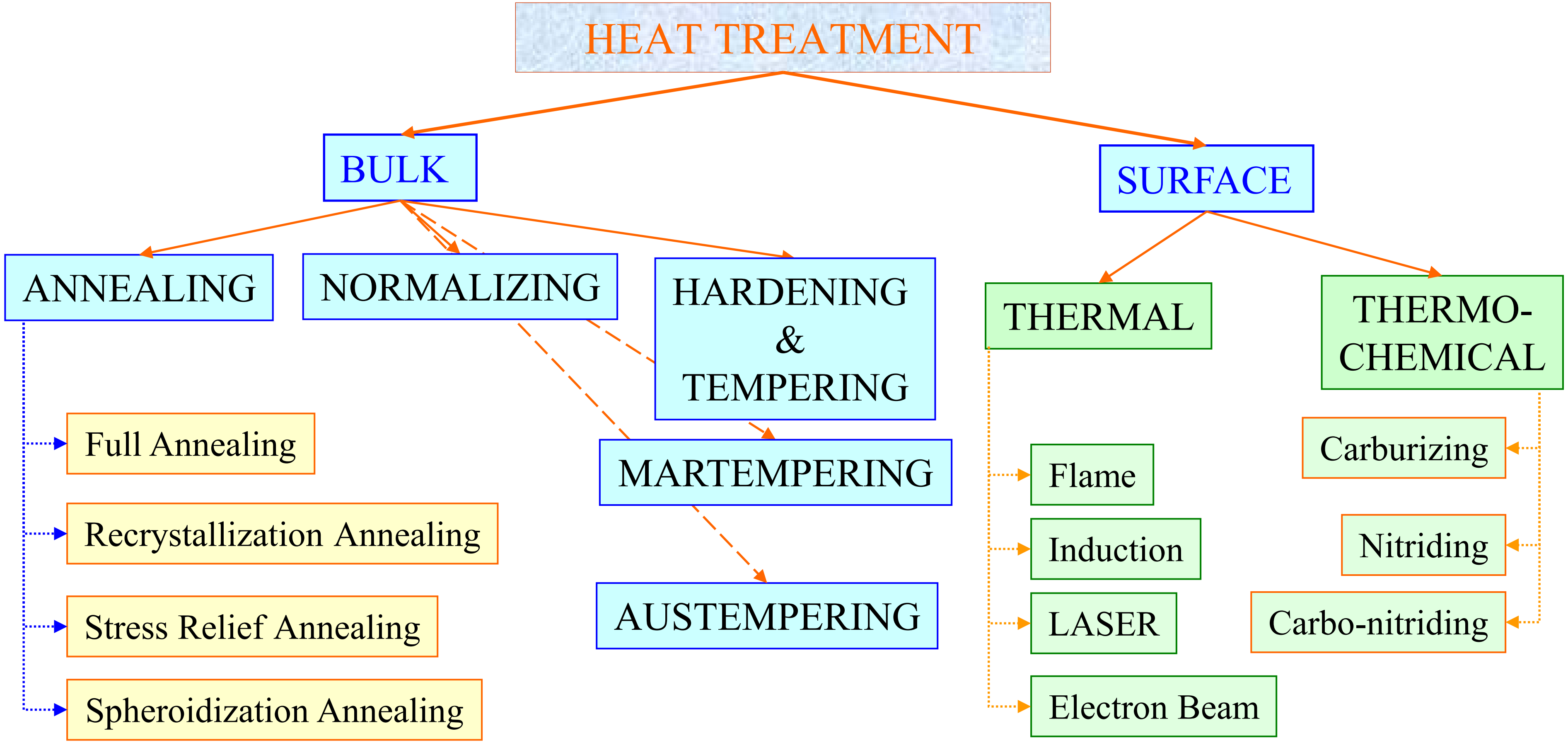
- *Temperature* up to which material is heated
- Length of time that the material is held at the elevated temperature – *Soaking time*
- *Rate of cooling*
- The *surrounding atmosphere* under the thermal treatment.

Types of Heat Treatment

1	Annealing	Slow cooling (Furnace ")	Coarse Pearlite
2.	Normalizing	Faster cooling (Air cooling)	Fine Pearlite
3.	Austempering	Interpupted Quench	Bainite.
4.	Tempering	Heating afte Quench	Tempered Martensite.
5.	Quenching	V. Fast Cooling (Water)	Martensite.

Types of Heat Treatment

- A broad classification of heat treatments possible are given below. Many more specialized treatments or combinations of these are possible.



HEAT TREATMENT

BULK

SURFACE

ANNEALING

NORMALIZING

HARDENING & TEMPERING

MARTEMPERING

AUSTEMPERING

Full Annealing

Recrystallization Annealing

Stress Relief Annealing

Spheroidization Annealing

THERMAL

THERMO-CHEMICAL

Flame

Induction

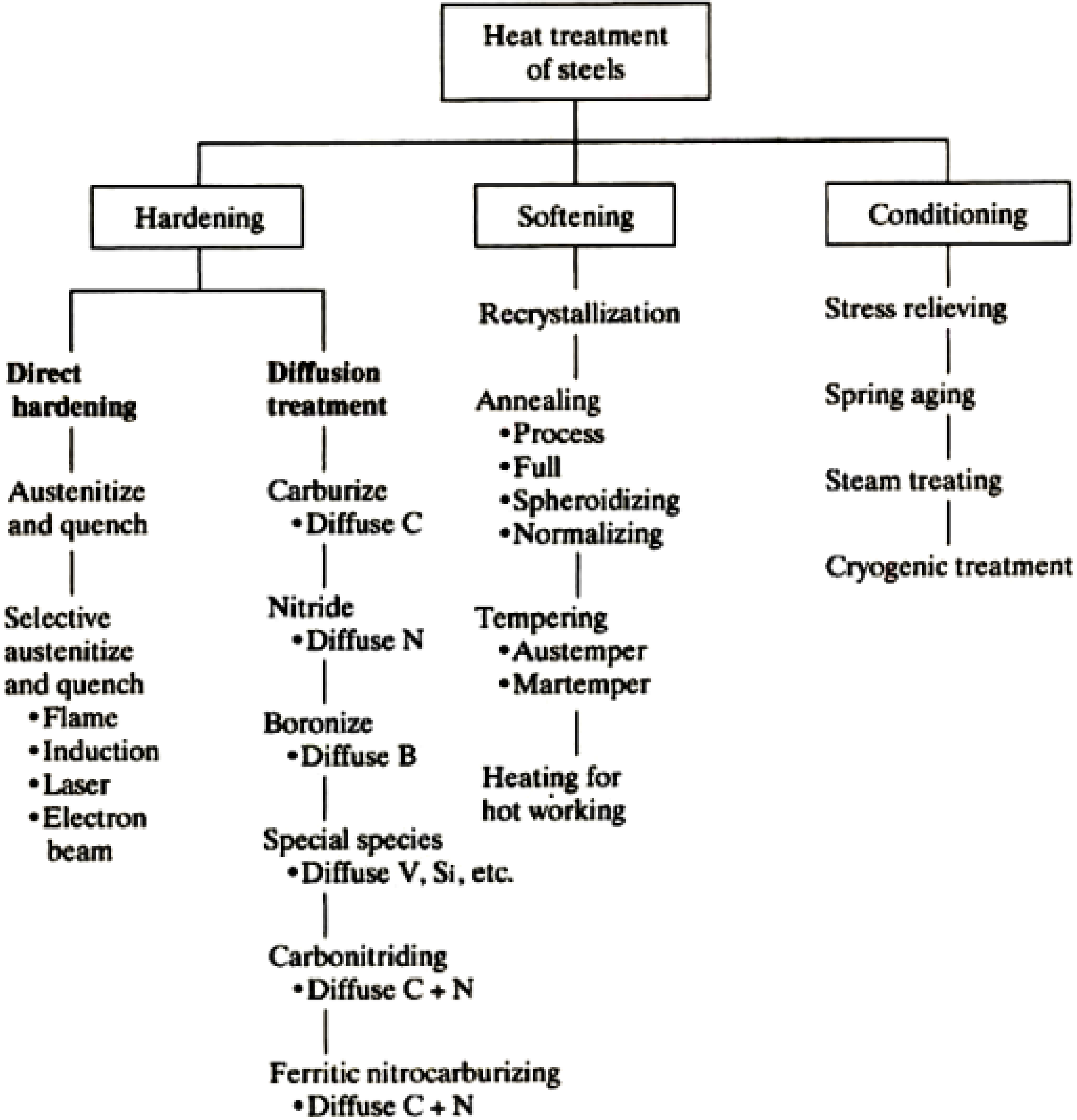
LASER

Electron Beam

Carburizing

Nitriding

Carbo-nitriding


Heat treatment of steels
Hardening
Softening
Conditioning
Direct hardening
Diffusion treatment
Austenitize and quench
Selective austenitize and quench
•Flame
•Induction
•Laser
•Electron beam
Carburize
•Diffuse C
Nitride
•Diffuse N
Boronize
•Diffuse B
Special species
•Diffuse V, Si, etc.
Carbonitriding
•Diffuse C + N
Ferritic nitrocarburizing
•Diffuse C + N
Recrystallization
Annealing
•Process
•Full
•Spheroidizing
•Normalizing
Tempering
•Austemper
•Martemper
Heating for hot working
Stress relieving
Spring aging
Steam treating
Cryogenic treatment

Types of Heat Treatment

1. Simple Heat Treatment
    - Process **Annealing**
        - Full Annealing
        - Spheroidsing
    - **Normalizing**

2. Quench & Temper Heat Treatments
    - **Quenching or Hardening**
    - **Tempering**

3.Iso Thermal Heat Treatments

- **Austempering**
- Martempering
- Marquenching

4.Precipitation Hardening

5.Surface Heat Treatments

A. Diffusion Methods

- Carburising
- Cyaniding
- Nitriding
- Carbonitriding

B. Selective Hardening

- Flame Hardening
- Induction Hardening
- Laser Hardening
- Selective Carburising

Effect of Quenching Medium

Medium	Severity of Quench	Hardness
air	small	low
oil	moderate	moderate
water	large	High

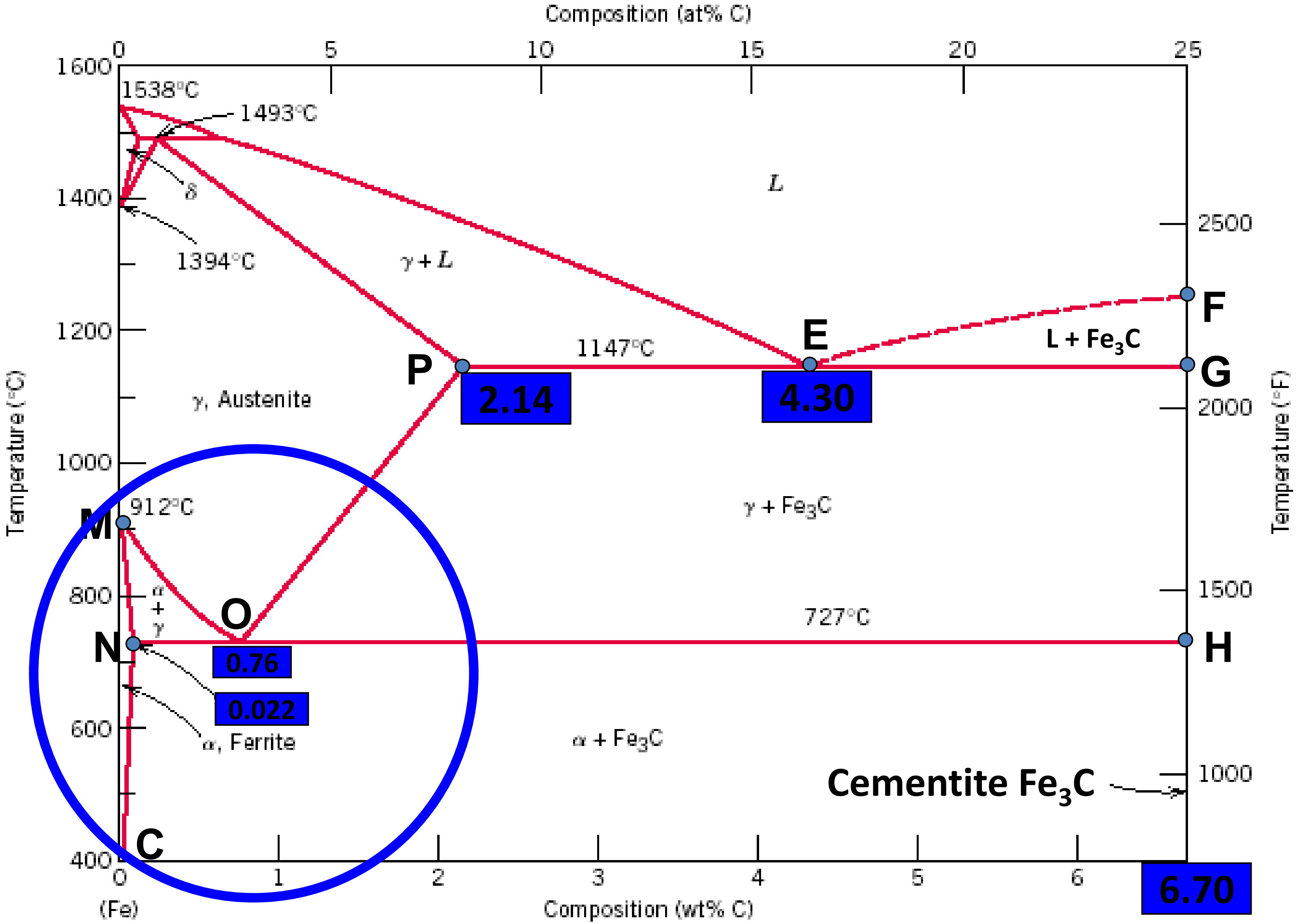
The severity of quench: water > oil > air

- During annealing or normalizing material is cooled in air and/or heating furnace itself.
- For hardening, material is immersed in water / oil quench bath.

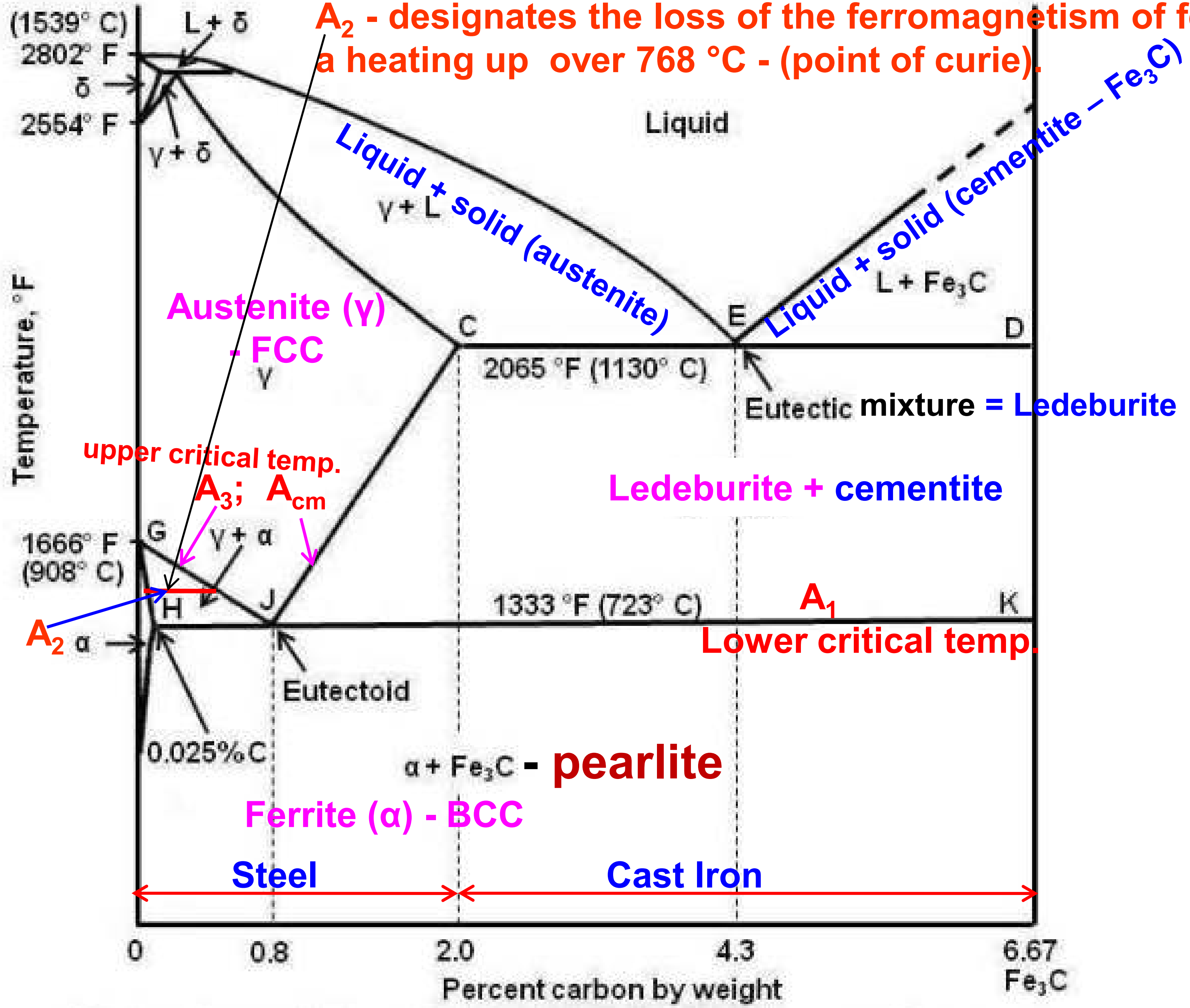
Effects of Heat treatment

Annealing & Normalizing	Hardening or Quenching		
Furnace Cooling	**Air Cooling**	**Oil Quenching**	**Water Quenching**
← Softer, less strong	Harder and stronger →		
← More ductile	More brittle →		
← Less internal stress	More internal stress →		
← Less distortion, cracking	More distortion, cracking →		

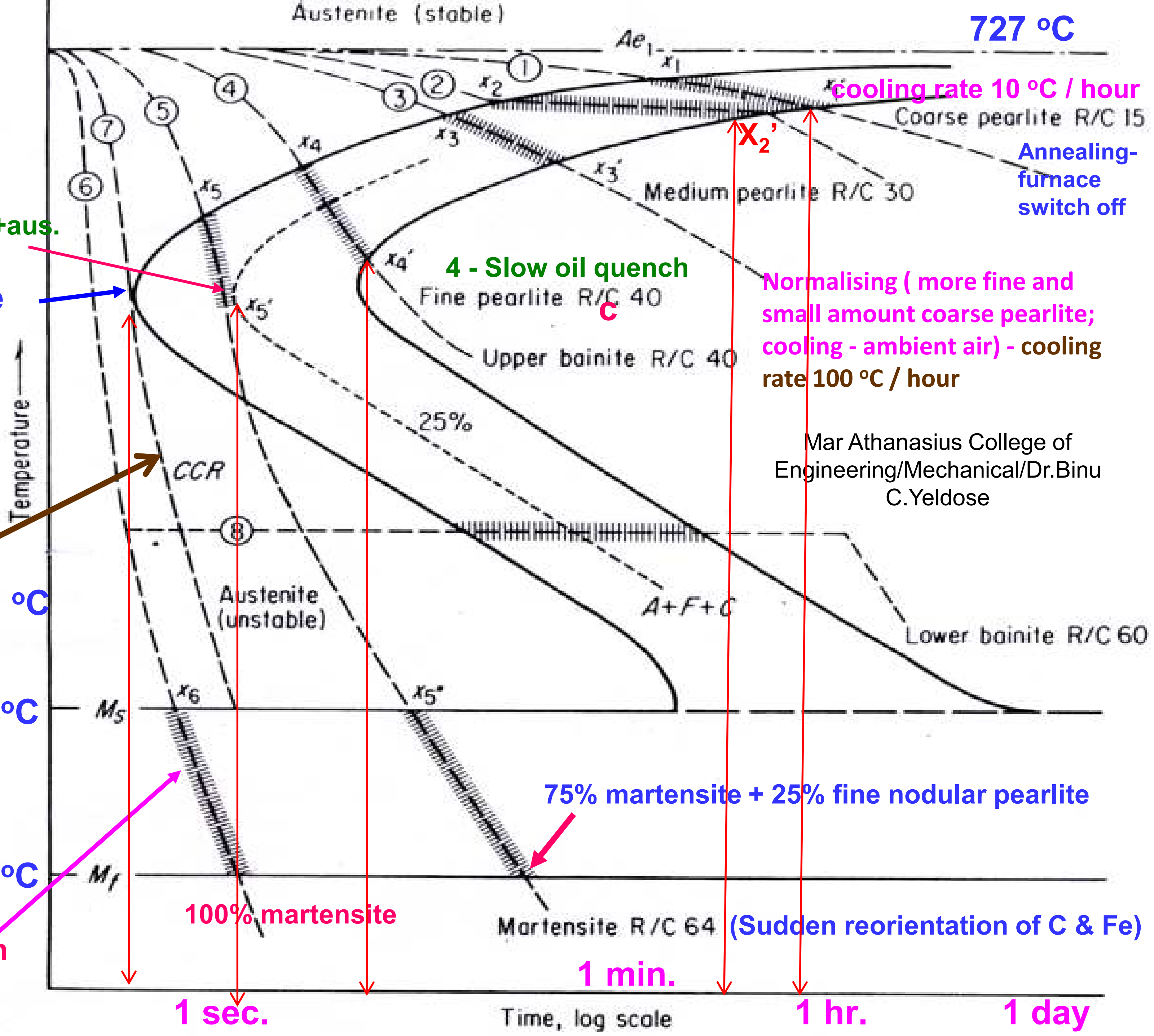
The Iron– Carbon Phase Diagram



A_2 - designates the loss of the ferromagnetism of ferrite with a heating up over 768 °C - (point of curie).



The iron-iron carbide equilibrium diagram labeled in general terms



727 °C

cooling rate 10 °C / hour

Annealing-furnace switch off

X_2'

At X_5'-25% fine Nodular pearlite+aus.

550 °C - nose

4 - Slow oil quench

C

Normalising (more fine and small amount coarse pearlite; cooling - ambient air) - cooling rate 100 °C / hour

Mar Athanasius College of Engineering/Mechanical/Dr.Binu C.Yeldose

Critical cooling Rate – CCR 140°C/sec

250 °C

215 °C

100 °C

75% martensite + 25% fine nodular pearlite

100% martensite

(Sudden reorientation of C & Fe)

Drastic quench - Water

1 sec.

1 min.

1 hr.

1 day

CRITICAL TEMPERATURE

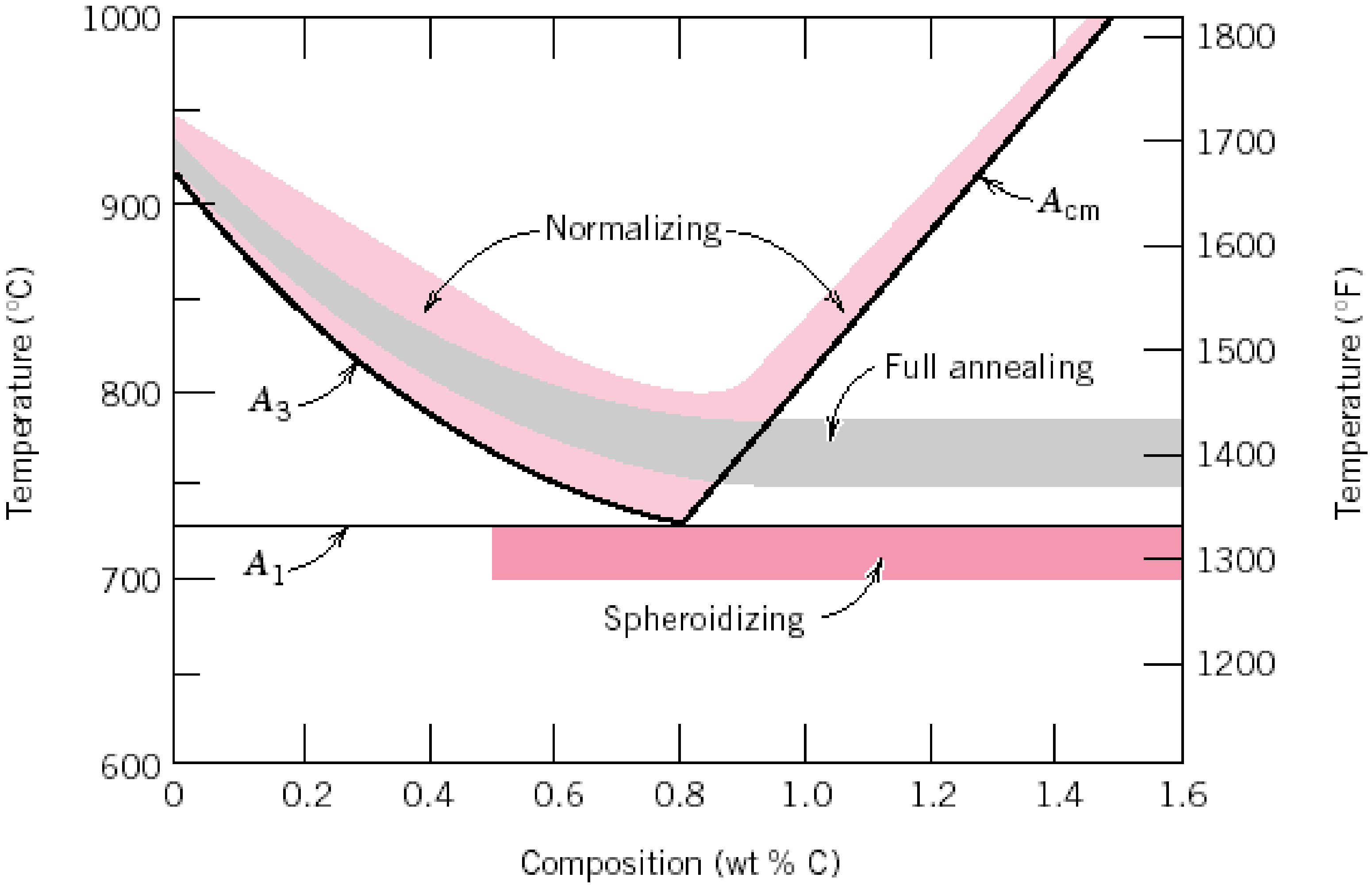
- ***Upper critical temperature (point)*** A_3 *is the temperature, below which ferrite starts to form as a result of ejection from austenite in the hypoeutectoid alloys.*

- ***Upper critical temperature (point)*** A_{CM} *is the temperature, below which cementite starts to form as a result of ejection from austenite in the hypereutectoid alloys.*

- ***Lower critical temperature (point)*** A_1 *is the temperature of the austenite-to-pearlite eutectoid transformation. Below this temperature austenite does not exist.*

- ***Magnetic transformation temperature*** A_2 *is the temperature below which α-ferrite is ferromagnetic.*

Heat Treatment of Steel



Annealing Process

- Material is exposed to an elevated temperature for an extended time period and then slowly cooled, allowing phase changes.
- Utilized for low- and medium-carbon steels.
- Different types
  - Full Annealing
  - Process Annealing

    or Stress Relief Annealing
  - Spheroidising

Three stages of annealing

- **Heating to the desired temperature** : The material is austenitized by heating to 15 to 40°C above the A_3 or A_1 lines until equilibrium is achieved (i.e., the alloy changes to austenite),
- **Soaking or holding time**: The material is held for 1h at the annealing temperature for every inch of thickness (a rule of thumb)
- **Cooling to room temperature**: cooling rate of 100°F/hr is typical for full annealing. Done in furnace itself.

Purposes of Annealing

1. Relieve Internal Stresses
    - Internal stresses can build up in metal as a result of processing.
        - such as welding, cold working, casting, forging, or machining.
    - If internal stresses are allowed to remain in a metal, the part may eventually distort or crack.
    - Annealing helps relieve internal stresses and *reduce the chances for distortion and cracking.*

2. Increasing Softness, Machinability, and Formability
    - A softer and more ductile material is easier to machine in the machine shop.
    - An annealed part will respond better to forming operations.

3. Refinement of Grain Structures
    - After some types of metalworking (particularly cold working), the crystal structures are elongated.
    - Annealing can *change the shape of the grains back to the desired form.*

Full Annealing (Annealing)

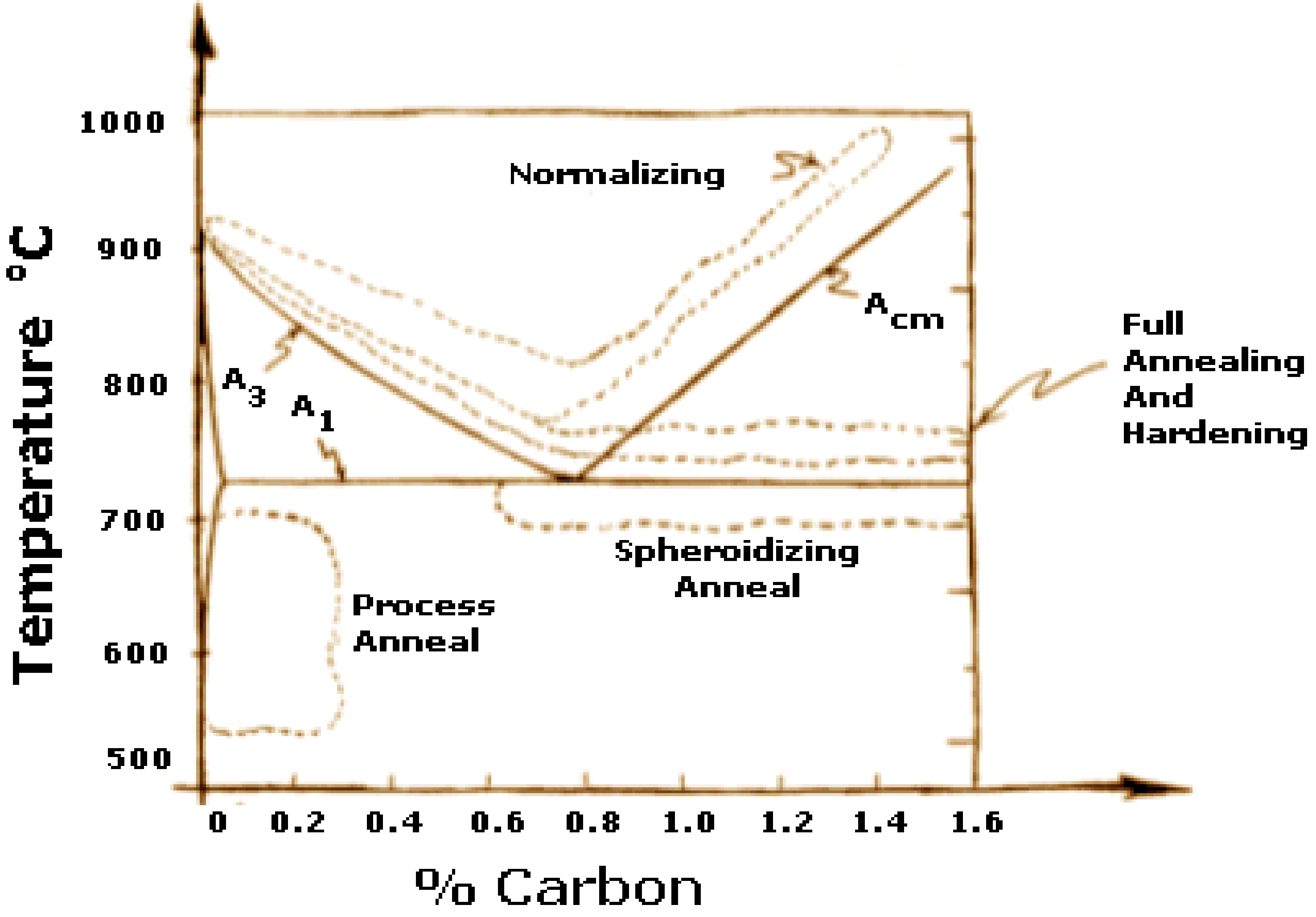
- **Hypoeutectoid steels** are heated about *50-90^{0}C above the upper critical temperature line(A3 line)*
- *Upon very slow cooling in the furnace* the austenite decomposes into ferrite and cementite
- The material gets softened and mechanical properties are improved
- **Purpose:** Remove structural imperfections by complete recrystallisation. Relieve internal stresses due to cold working and hence improve ductility.

Process Annealing (Intermediate Annealing)

- A heat treatment used to negate the effects of cold work, i.e., to soften and increase the ductility of a previously strain-hardened metal
- In process annealing, parts are not as completely softened as they are in full annealing, but the time required is considerably lessened.
- Process annealing or stress-relief annealing is frequently used as an intermediate heat-treating step during the manufacture of a part.
- Recovery and recrystallization processes occur during the process.
- Used for steels having less than 0.25%Carbon
- Heating the material to *550-650^{0}C ,just below the lower critical tem(A1 line in Fe-C Diagram)*
- It is kept at this temp for certain duration and then slowly cooled in air
- It relieves the effects of cold working, reduces hardness and increase ductility
- This process is also called ***Sub-critical annealing***

https://www.youtube.com/watch?v=GFVeYXJJndw

Annealing – 1.20 -1.30 and 3.35 Minutes



HEAT TREATMENT PROCESS

Spheroidising

- This is similar to process annealing but results in a structure consists of globules or spheroids of cementite in a matrix of ferrite.

- The material is heated to 30^0C below the eutectoid temp. Or lower critical temperature line.

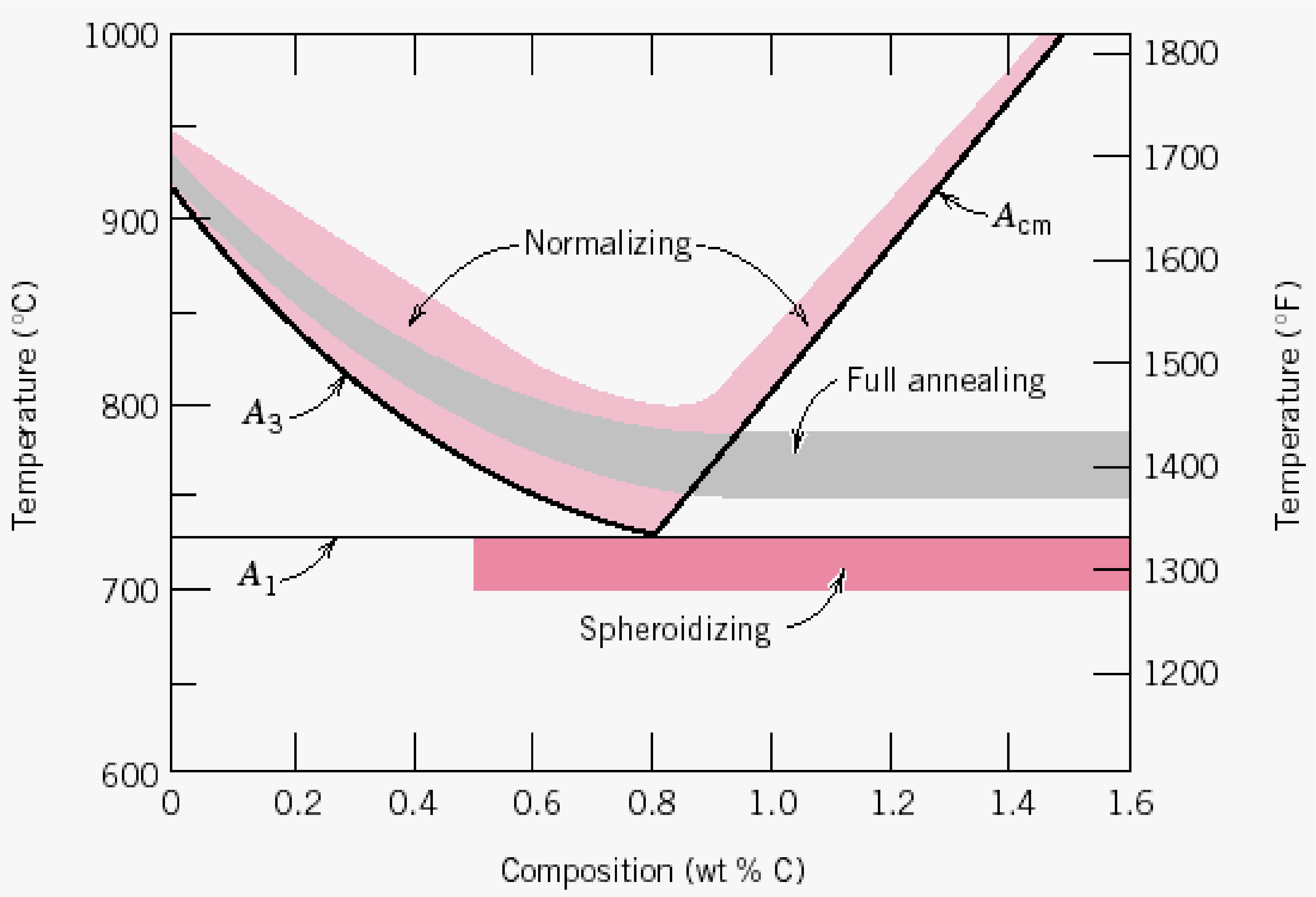
- It is held at this temp. For several hours and then allowed to *cool very slowly in the furnace*

- It is used for **high carbon steels(>0.6%C)**

- The microstructure obtained as a result of this process is known as spheroidite, which has a continuous matrix of soft machinable ferrite

- **Purpose:**

- To improve machinability and facilitate further cold working operations for hypereutectoid steels
- To reduce hardness and to increase ductility



Temperature (°C)
Temperature (°F)
1000
900
800
700
600
1800
1700
1600
1500
1400
1300
1200
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
Composition (wt % C)
Normalizing
Full annealing
Spheroidizing
A_{cm}
A_3
A_1

Normalising

- The name “normalising” comes from the original intended purpose of the process — to return steel to the “normal” condition it was in before it was altered by cold working or other processing.
- Heating the alloy to *55 to 85 ℃ above the A_3 or A_{cm}* and holding for sufficient time so that the alloy completely transforms to austenite, followed by air cooling.
- To refine the grains and produce a more uniform and desirable size distribution for steels that have been plastically deformed
- Normalising does not soften the material as much as full annealing does.
- The cooling process does not leave the material as ductile or as internally stress-free.
- A normalised part will usually be a *little stronger, harder, and more brittle than a full-annealed part*.

Normalising

1. Heat to Upper Critical Temperature, at which point the structure is all Austenite.
2. Cool slowly in air.
3. Structure will now be fine pearlite.
4. Used to restore the ductility of cold or hot worked materials whilst retaining other properties.

2.Quench & Temper Heat Treatments

Quenching or Hardening

- Hardening of steels done to increase the strength and wear resistance

- Heated to *30-50 °C above the upper critical temperature and then quenched*

- The quicker the steel is cooled, the *harder* it would be

Hardening Temperatures

- The temperatures for hardening depend on the carbon content.
- Plain carbon steels below 0.4% will not harden by heat treatment.
- The temperature decreases from approx 820 °C to 780 °C as carbon content increases from 0.4% up to 0.8%.
- Above 0.8% the temperature remains constant at 780 °C.
- Hardening temperature same as that for normalising

Purpose:

- To increase hardness, strength and wear resistance
- Suitable microstructure which will have desired mechanical properties

Quenching Media

Four commonly used quenching media:

- Brine – the fastest cooling rate
- Water – moderate cooling rate
- Oil – slowest cooling rate
- Gas – used in automatic furnaces, usually liquid nitrogen, can be very fast cooling.

  Too rapid cooling can cause cracking in complex and heavy sections.

Hardenability

- Steel become hard after hardening
- Hardness usually determined on the surface of the hardened component
- The hardness decreases along the cross section and this hardness is called hardenability.
- Hardenability is a qualitative measure of the rate at which hardness decreases with the distances from the surface of hardened specimen due to decreased martensitic content.

Hardenability

- The hardenability of a steel is broadly defined as the property which determines the depth and distribution of hardness induced by quenching.
- This is dependent upon the chemical composition of the steel alloy.
- The addition of Nickel, Chromium and Molybdenum will slow the transformation to other phases and allow more martensite to form.
- Most heat treatable steels are alloys rather than plain carbon steels.

- Various elements like Cr, Mn, Ni, W, Mo etc are added to plain carbon steels to create alloy steels
- The alloys elements move the nose of the TTT diagram to the right
  → this implies that a slower cooling rate can be employed to obtain martensite → increased HARDENABILITY
- The *'C' curves* for pearlite and bainite transformations overlap in the case of plain carbon steels
  → in alloy steels pearlite and bainite transformations can be represented by separate *'C' curves*

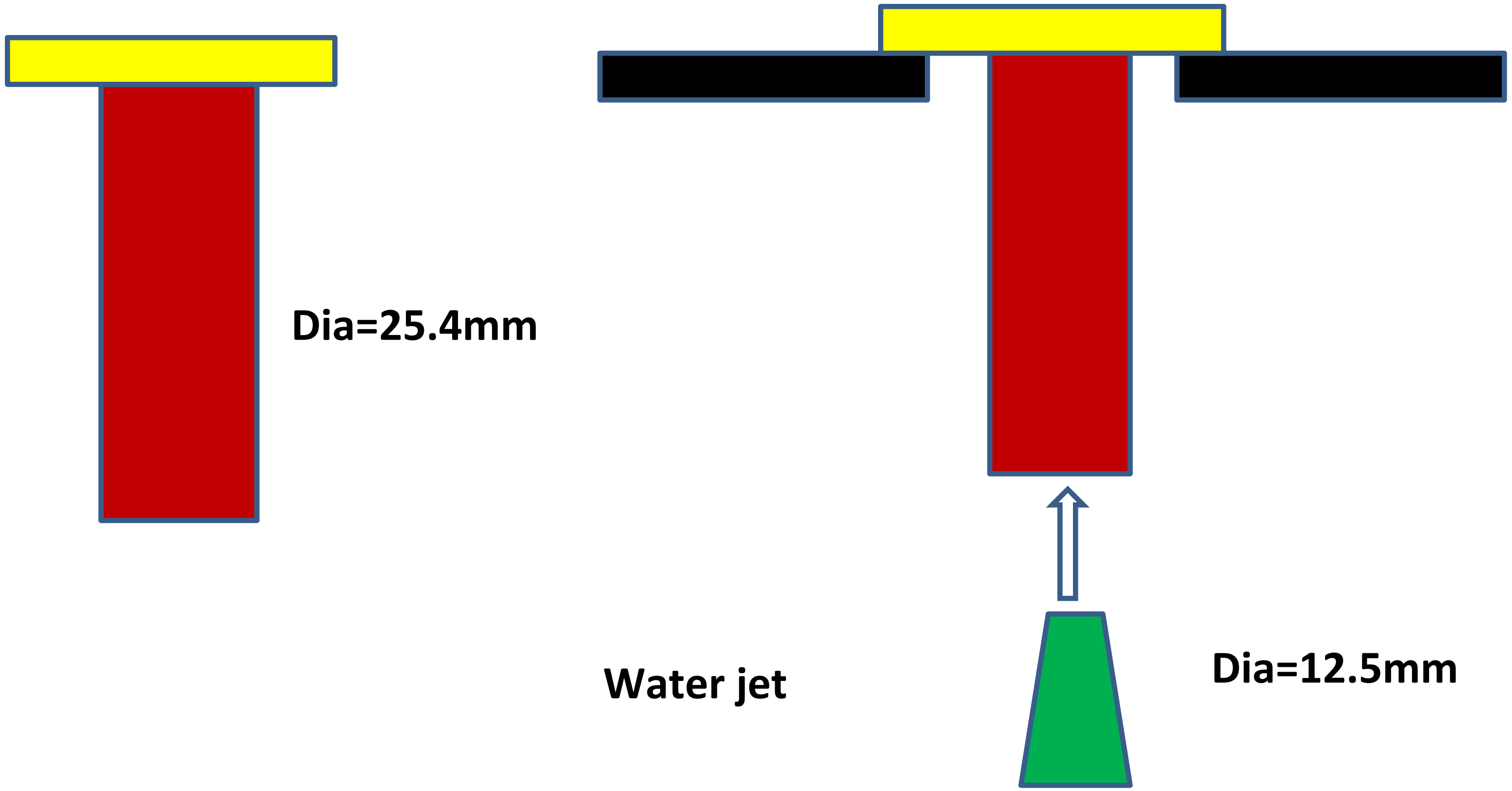
Test for Hardenability

- Jominy End Quench test - An austenitized steel bar is quenched at one end only, thus producing a range of cooling rates along the bar.
- Hardenability curves - Graphs showing the effect of the cooling rate on the hardness of as-quenched steel.
- Jominy distance - The distance from the quenched end of a Jominy bar. The Jominy distance is related to the cooling rate.

Jominy End Quench Test

- A standard specimen of 25.4mm dia and 100mm length is heated above the austenising temp. for a specified period of time
- The specimen is removed from the furnace and quickly transferred to a fixture.
- The lower end of specimen is quenched by a jet of water at a specific flow rate.
- This results in different rates of cooling along the length of specimen.
- Surface hardness is measured along the length of the specimen and curve is plotted between hardness and distance from quenched end
- The resulting curve is called Jominy curve.

Jominy End Quench Test



- Hardenability is dependent mainly upon
  1. The amount of alloying elements present
  2. Composition
  3. Homogeneity and grain size of austenite

Tempering

- The brittleness of martensite makes hardened steels unsuitable for most applications.
- Different cooling rates between edge and core of components result in internal stresses.
- This requires the steel to be tempered by re-heating to a lower temperature to reduce the hardness and improve the toughness.
- This treatment converts some of the martensite to bainite.

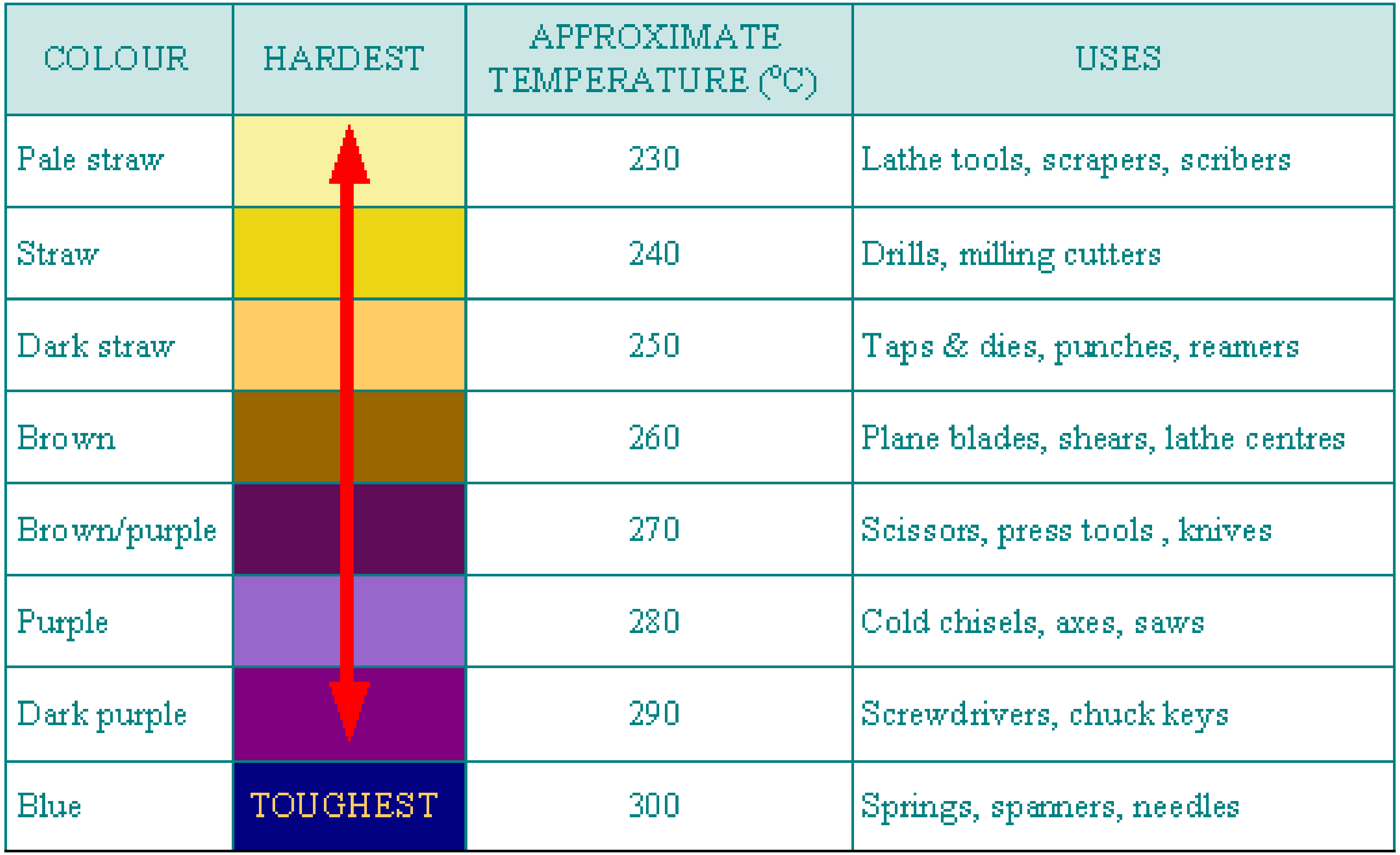
Tempering

- The tempering temp varies from 150-680^{0}C depending on the purpose for which it is used.
- When steel heated to low temp.150-250^{0}C the internal stresses are removed. Toughness and ductility increases.
- **Low temp tempering** is applied to cutting tools made of tool steels and low alloy steels
- When tempering is carried out in the range of 300-450^{0}C ,the microstructure consists of martensite and fine pearlite called troosite.
- This leads to decrease in hardness and strength with increase ductility
- This medium temperature tempering is used for springs, axles, hammers, chisels etc

Tempering

- High temp.tempering is done above450^{0}C
- At this temp. martensite transforms into sorbite
- It increases ductility with hardness and strength
- It is applied to components like connecting rods, shafts, gears etc

Tempering Temperatures

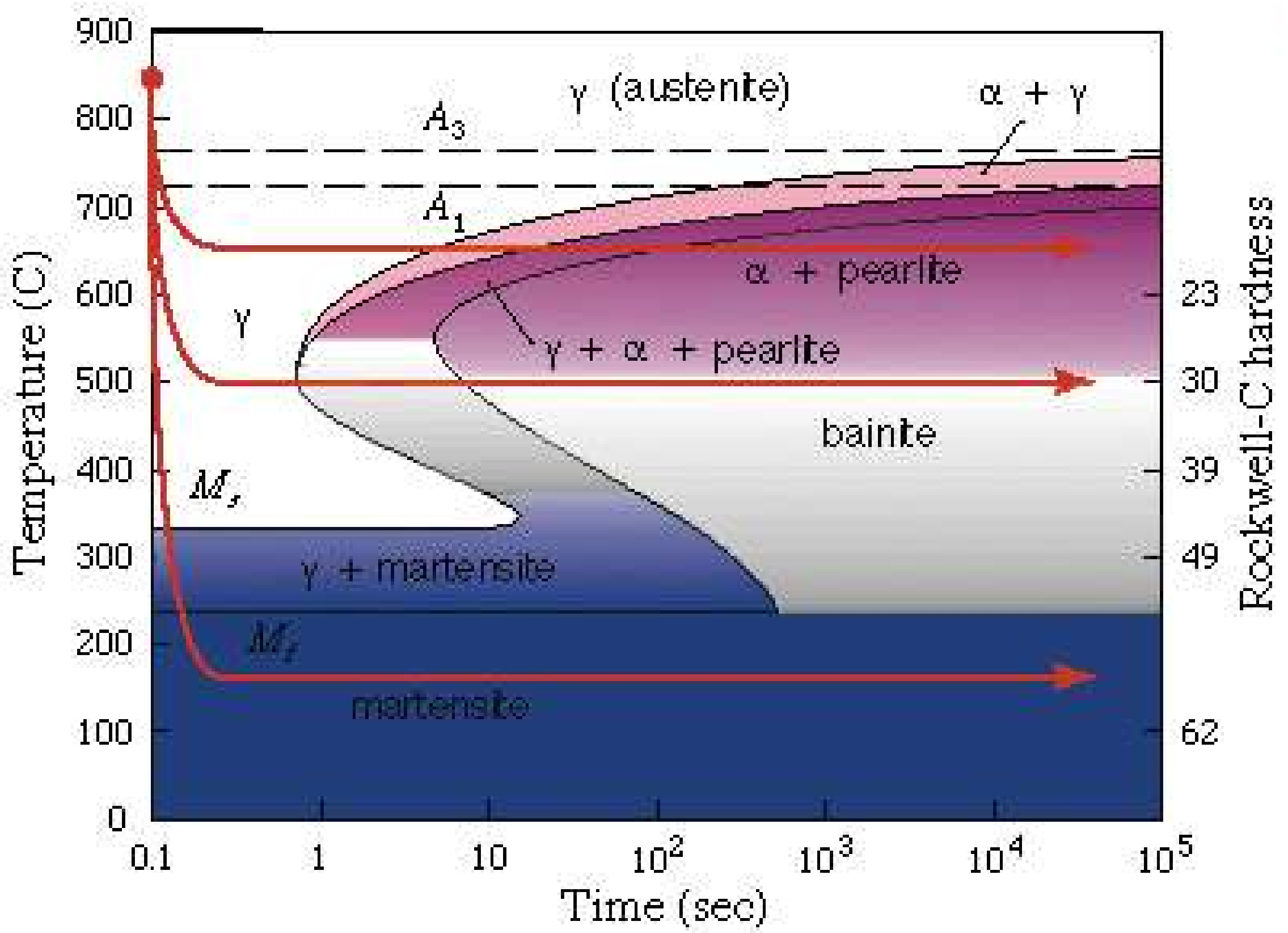


COLOUR	HARDEST	APPROXIMATE TEMPERATURE (°C)	USES
Pale straw	🟨	230	Lathe tools, scrapers, scribers
Straw	🟨	240	Drills, milling cutters
Dark straw	🟧	250	Taps & dies, punches, reamers
Brown	🟫	260	Plane blades, shears, lathe centres
Brown/purple	🟪	270	Scissors, press tools , knives
Purple	🟪	280	Cold chisels, axes, saws
Dark purple	🟪	290	Screwdrivers, chuck keys
Blue	TOUGHEST	300	Springs, spanners, needles

Isothermal Heat Treatments

- Austempering - The isothermal heat treatment by which austenite transforms to bainite.
- Isothermal annealing - Heat treatment of a steel by austenitizing, cooling rapidly to a temperature between the A_1 and the nose of the TTT curve, and holding until the austenite transforms to pearlite.

TTT Diagram


γ (austenite)
α + γ
A3
A1
α + pearlite
γ + α + pearlite
γ
bainite
Ms
γ + martensite
Mf
martensite
900
800
700
600
500
400
300
200
100
0
Temperature (C)
23
30
39
49
62
Rockwell-C hardness
0.1
1
10
10^2
10^3
10^4
10^5
Time (sec)

Microstructure Produced by Heat Treatment Process

Table 10.2 **Summary of Microstructures and Mechanical Properties for Iron–Carbon Alloys**

Microconstituent	*Phases Present*	*Arrangement of Phases*	*Mechanical Properties (Relative)*
Spheroidite	α Ferrite + Fe_3C	Relatively small Fe_3C sphere-like particles in an α-ferrite matrix	Soft and ductile
Coarse pearlite	α Ferrite + Fe_3C	Alternating layers of α ferrite and Fe_3C that are relatively thick	Harder and stronger than spheroidite, but not as ductile as spheroidite
Fine pearlite	α Ferrite + Fe_3C	Alternating layers of α ferrite and Fe_3C that are relatively thin	Harder and stronger than coarse pearlite, but not as ductile as coarse pearlite
Bainite	α Ferrite + Fe_3C	Very fine and elongated particles of Fe_3C in an α-ferrite matrix	Hardness and strength greater than fine pearlite; hardness less than martensite; ductility greater than martensite
Tempered martensite	α Ferrite + Fe_3C	Very small Fe_3C sphere-like particles in an α-ferrite matrix	Strong; not as hard as martensite, but much more ductile than martensite
Martensite	Body-centered tetragonal, single phase	Needle-shaped grains	Very hard and very brittle

Pearlite

- At temperatures just below the eutectoid, relatively thick layers of both the ***α-ferrite and Fe_3C phases*** are produced

- At higher temperatures, *high diffusion rates* allow for *larger grain growth* and formation of thick layered structure of pearlite this microstructure is called **coarse pearlite,** and the region at which it forms is indicated to the *right of the TTT curve*

- With decreasing temperature, the *carbon diffusion rate decreases*, and the layers become *progressively thinner*.

- The thin-layered structure produced in the vicinity of 540°C is termed **fine pearlite**

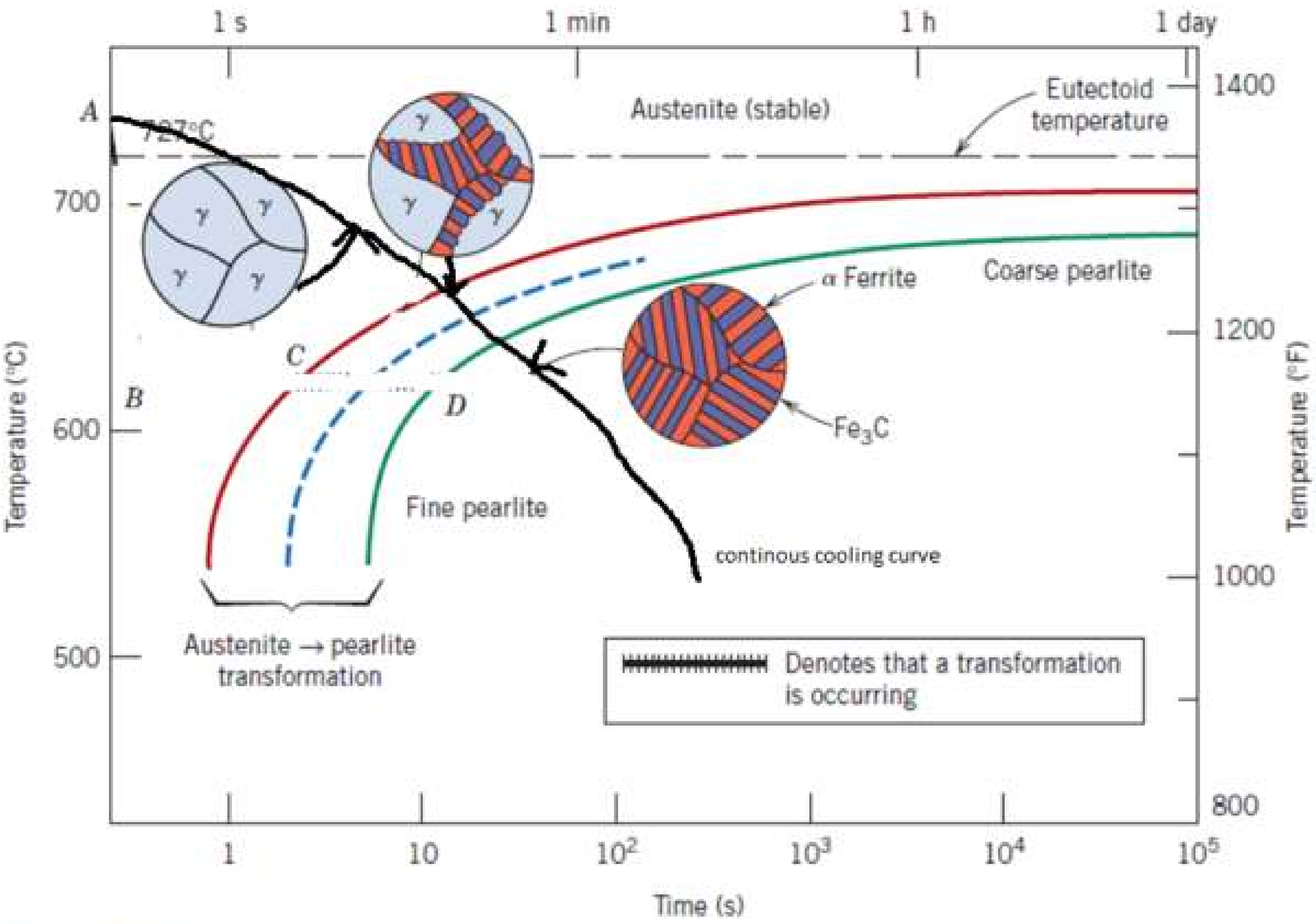
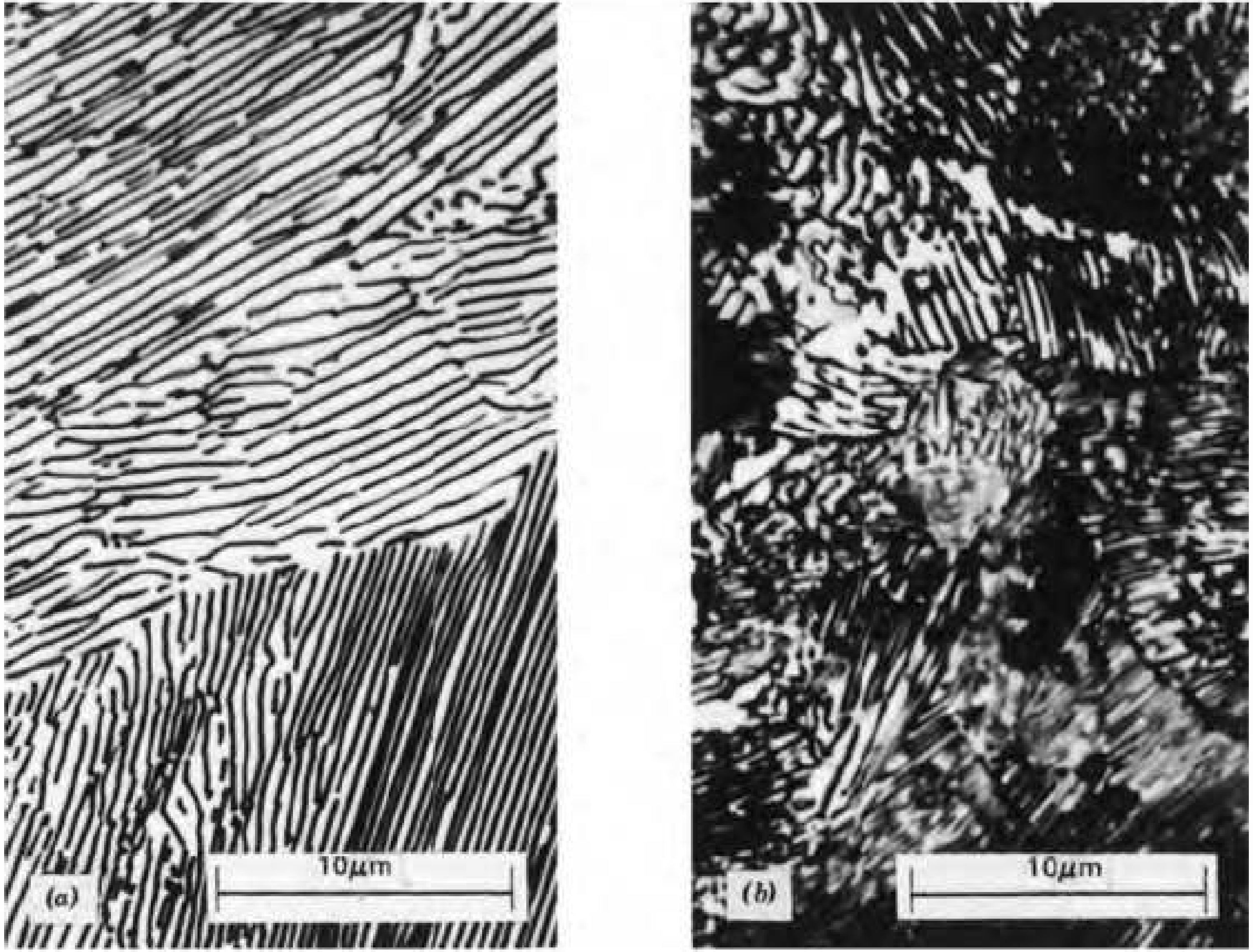


Figure 10.14 • Continuous Cooling Transformation diagram for a eutectoid iron–carbon alloy, with superimposed isothermal heat treatment curve (*ABCD*). Microstructures before, during, and after the austenite-to-pearlite transformation are shown. [Adapted from H. Boyer

Figure 10.15 Photomicrographs of (*a*) coarse pearlite and (*b*) fine pearlite. 3000×. (From K. M. Ralls et al., *An Introduction to Materials Science and Engineering*, p. 361. Copyright © 1976 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)



Bainite

- In addition to pearlite, other micro constituents that are products of the austenitic transformation exist; one of these is called **bainite.**

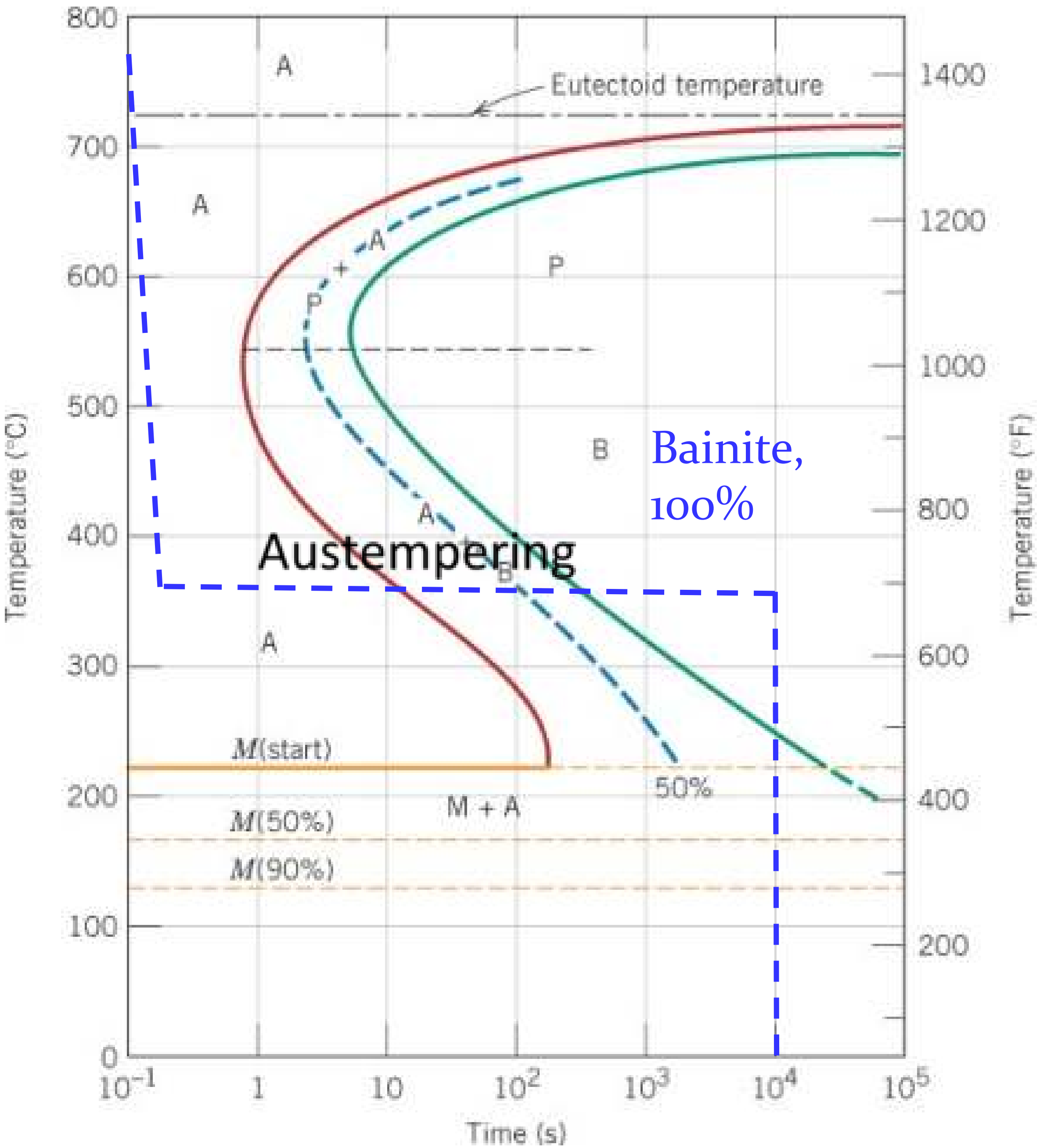
- The *microstructure of bainite* consists of ferrite and cementite phases, and thus diffusional processes are involved in its formation.

- Bainite forms as *needles or plates*, depending on the temperature of the transformation.

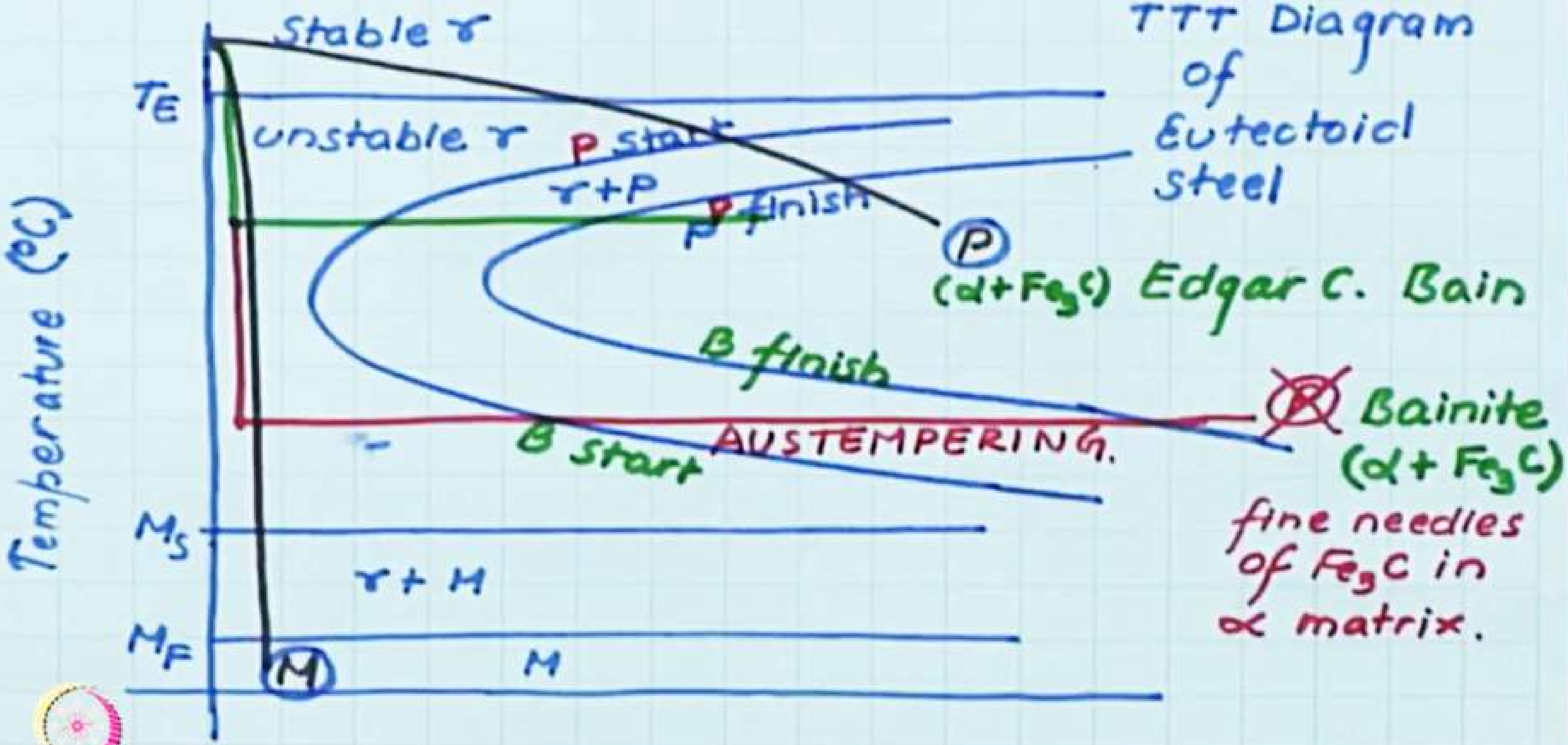
- It occurs at temperatures *below* those at which pearlite forms

Bainite Formation Example

- Rapidly cool to 350 ̊C
- Hold for 10^4 seconds
- Quench to room temperature
- Formed by Austempering



TTT Diagram of Eutectoid steel



Edgar C. Bain

~~Ⓑ~~ Bainite (α+Fe₃C)

fine needles of Fe₃C in α matrix.

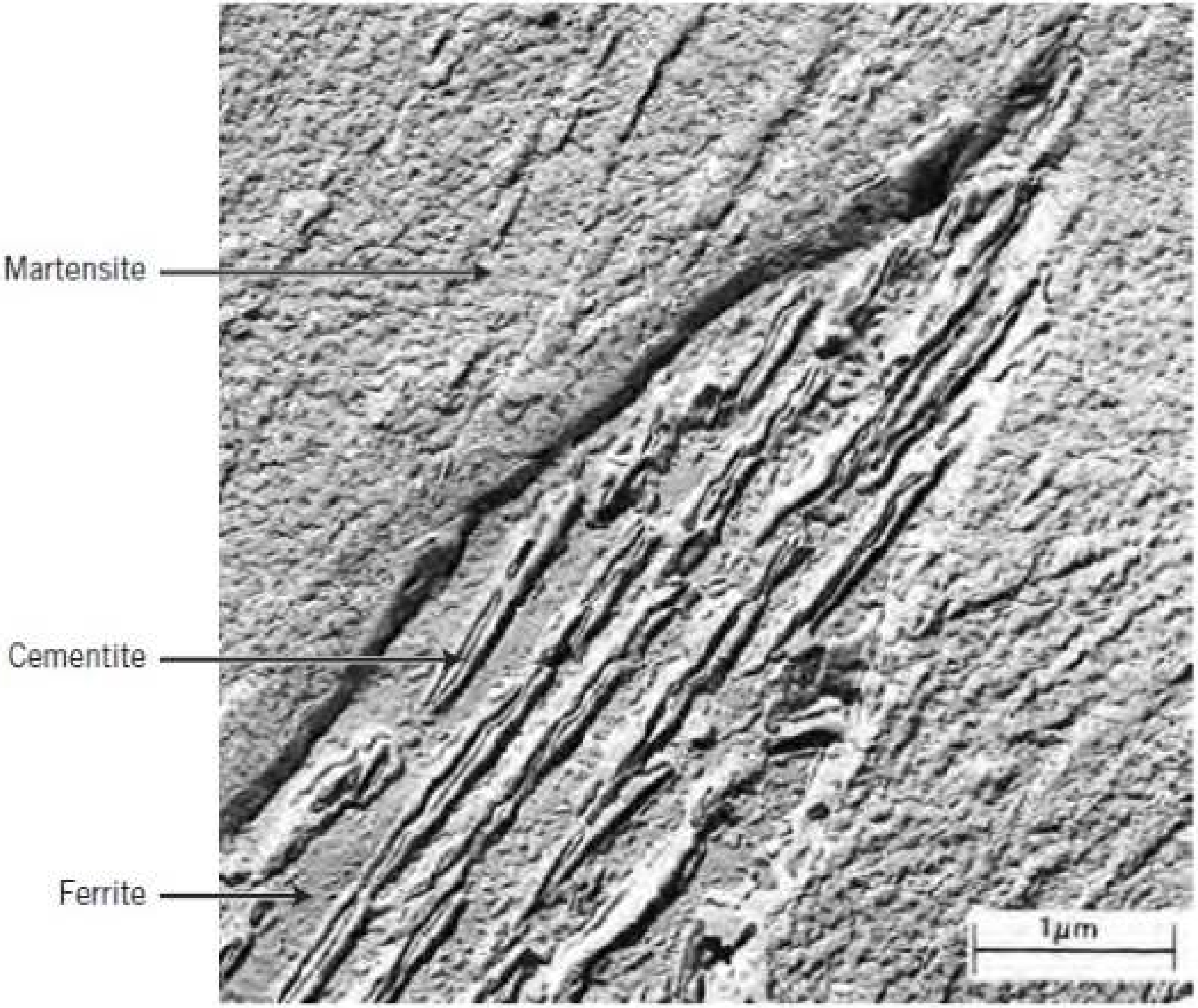


Figure 10.17 Transmission electron micrograph showing the structure of bainite. A grain of bainite passes from lower left to upper right-hand corners, which consists of elongated and needle-shaped particles of Fe_3C within a ferrite matrix. The phase surrounding the bainite is martensite. (Reproduced with permission from *Metals Handbook*, 8th edition, Vol. 8, *Metallography, Structures and Phase Diagrams,* American Society for Metals, Materials Park, OH, 1973.)

Martensite

- Another micro constituent or phase called **Martensite** is formed when austenitized iron–carbon alloys are *rapidly cooled (or quenched) to a relatively low temperature (220^{o}C).*

- Martensite is a non-equilibrium **single-phase structure** that results from a ***diffusionless transformation*** of austenite.

- The martensitic transformation occurs when the quenching rate is *rapid enough to prevent carbon diffusion.*

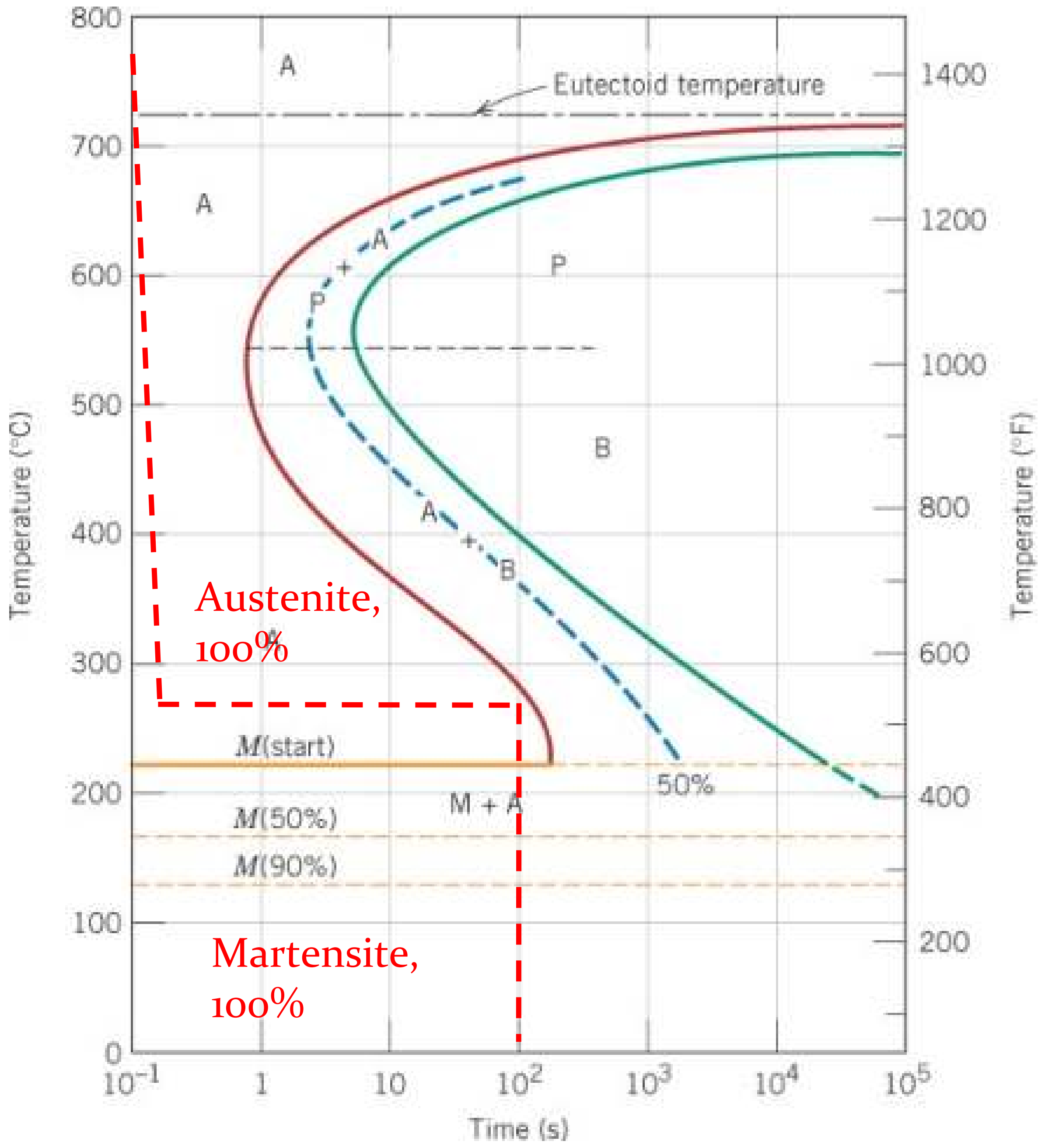
- *This occurs in such a way that the FCC austenite experiences a polymorphic transformation to a body-centered tetragonal (BCT) martensite.*

- All the carbon atoms remain as *interstitial impurities* in martensite; as such, they constitute a supersaturated solid solution that is having a *body-centred-tetragonal lattice*

- Instead of diffusion, a sudden reorientation of carbon and iron atoms from the FCC solid solution (austenite) into a body centred tetragonal (BCT) solid solution happens here. The carbon atoms occupy potential interstitial spaces in the BCT unit cell.

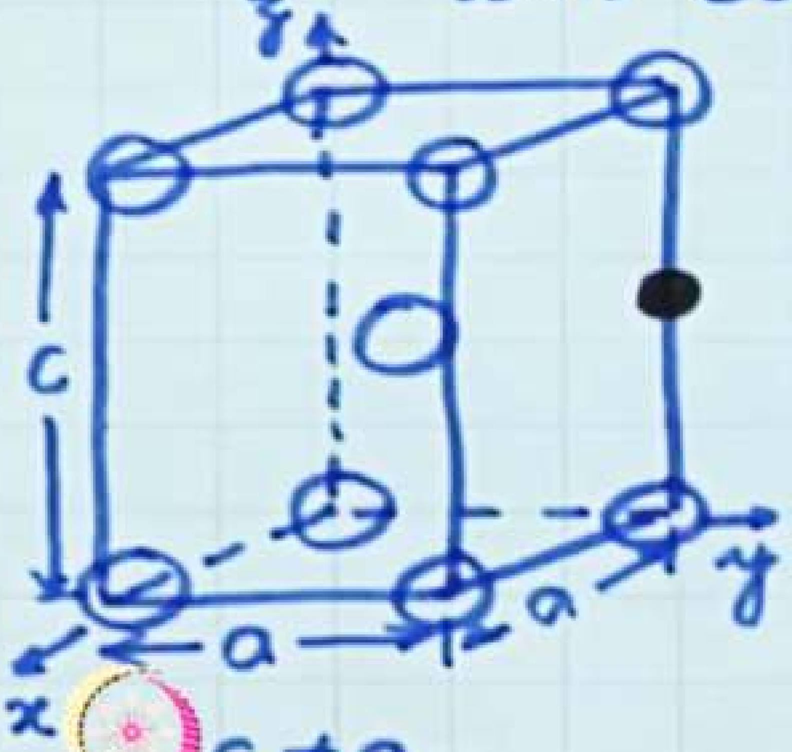
Martensite Formation example

- ☐Rapidly cool to 250 ˚C
- ☐Hold for 100 seconds
- ☐Quench to room temperature



Martensite Non equilibrium phase
forms on quenching of austenite

Interstitial solid solution of C in Fe
with Body-centred tetragonal structure.



○ Fe

● C

$\frac{c}{a} = 1 \Rightarrow$ BCC (Ferrite, α)

$\frac{c}{a} > 1 \Rightarrow$ BCT (Martensite, $M \equiv \alpha'$)

Very hard and brittle.

$c \neq a$

Martensitic Transformation

Austenite ⟶ Martensite

1. Transformation is ~~experi~~ extremely rapid.
2. Amount transformed depends only upon temperature and not on time.

   ATHERMAL : Rate of transformation does not depend on temp.

3. No change in composition.

   DIFFUSIONLESS : There is no long range atomic movement.

Martensitic microstructure.

The needle shaped grains are the martensite phase, and the white regions are austenite that failed to transform during the rapid quench.

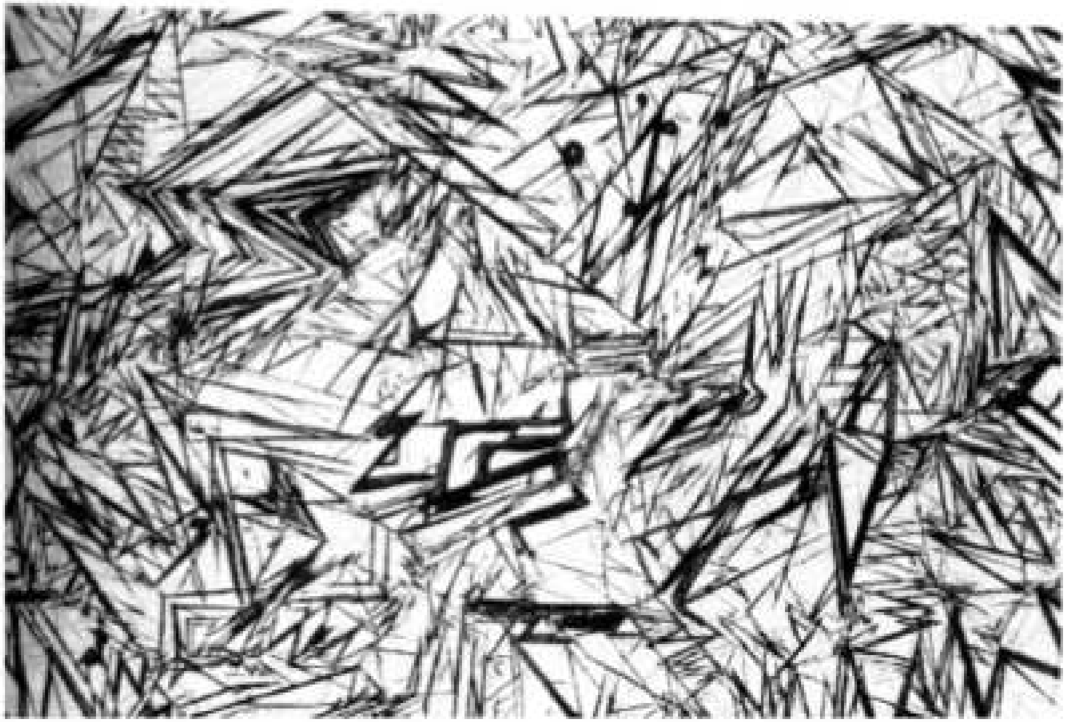


Figure 3.30 *Martensite*

Spheroidite

- If a steel alloy having either pearlitic or bainitic microstructures is heated to, and left at, a temperature below the eutectoid for a sufficiently long period of time—for example, at about (700 ^{0}C) for between 18 and 24 h—yet another microstructure will form. It is called **spheroidite** .
- Instead of the alternating ferrite and cementite lamellae (pearlite), or the microstructure observed for bainite, the Fe3C phase appears as sphere-like particles embedded in a continuous phase matrix. This transformation has occurred by additional carbon diffusion with no change in the compositions or relative amounts of ferrite and cementite phase.

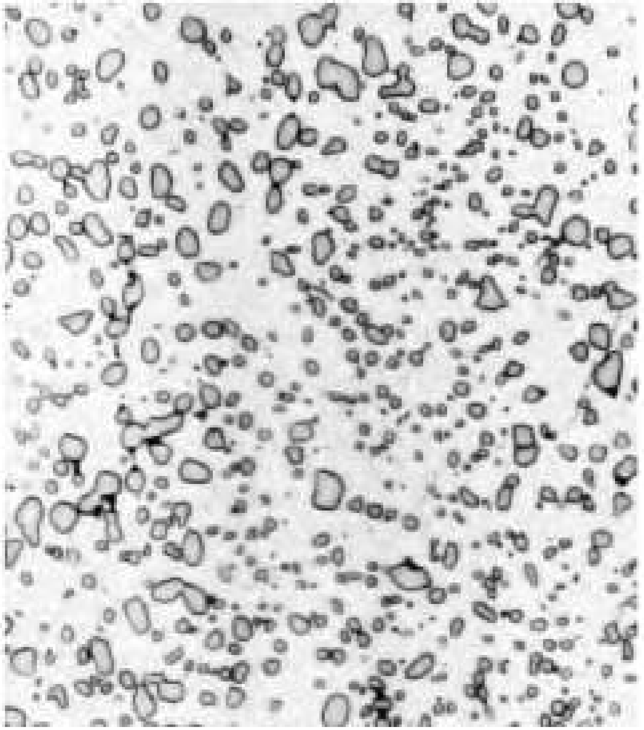


Figure 10.19 Photomicrograph of a steel having a spheroidite microstructure. The small particles are cementite; the continuous phase is α ferrite. 1000×. (Copyright 1971 by United States Steel Corporation.)

TEMPERED MARTENSITE

- In the as-quenched state, martensite, in addition to being very hard, is so brittle that it cannot be used for most applications; also, any internal stresses that may have been introduced during quenching have a weakening effect.
- The ductility and toughness of martensite may be enhanced and these internal stresses relieved by a heat treatment known as tempering.
- Tempering is accomplished by heating a martensitic steel to a temperature below the eutectoid for a specified time period. Normally, tempering is carried out at temperatures between 250 and 650^{0}C.
- This tempering heat treatment allows, by diffusional processes, the formation of tempered martensite, according to the reaction

Martensite to tempered martensite transformation reaction

martensite (BCT, single phase) → tempered martensite (α + Fe_3C phases) (10.20)

- The microstructure of tempered martensite consists of extremely small and uniformly dispersed cementite particles embedded within a continuous ferrite matrix.
- This is similar to the microstructure of spheroidite except that the cementite particles are much, much smaller.

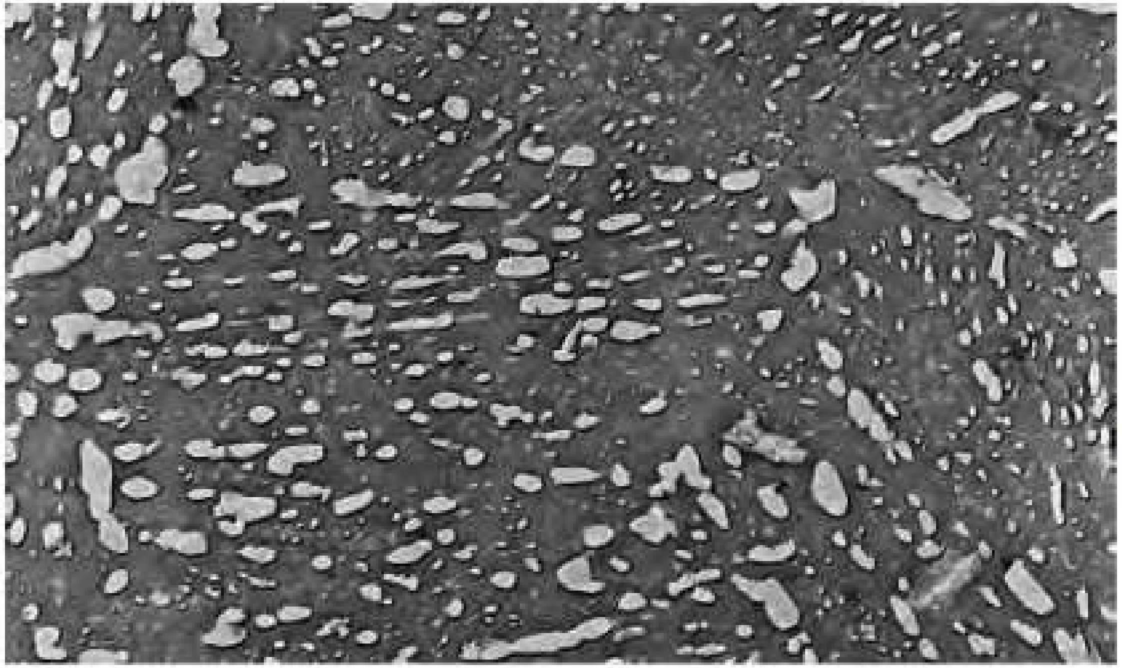
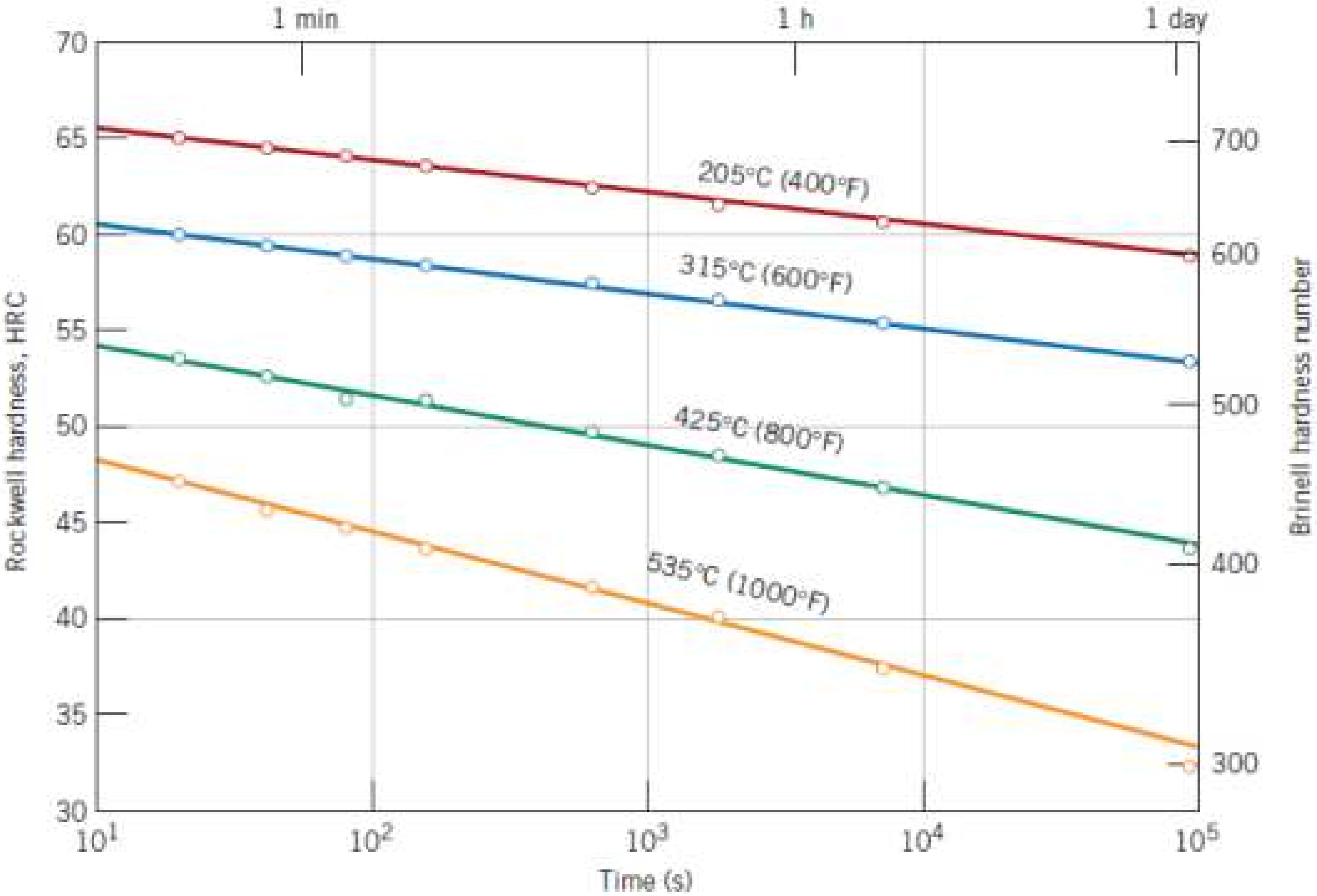
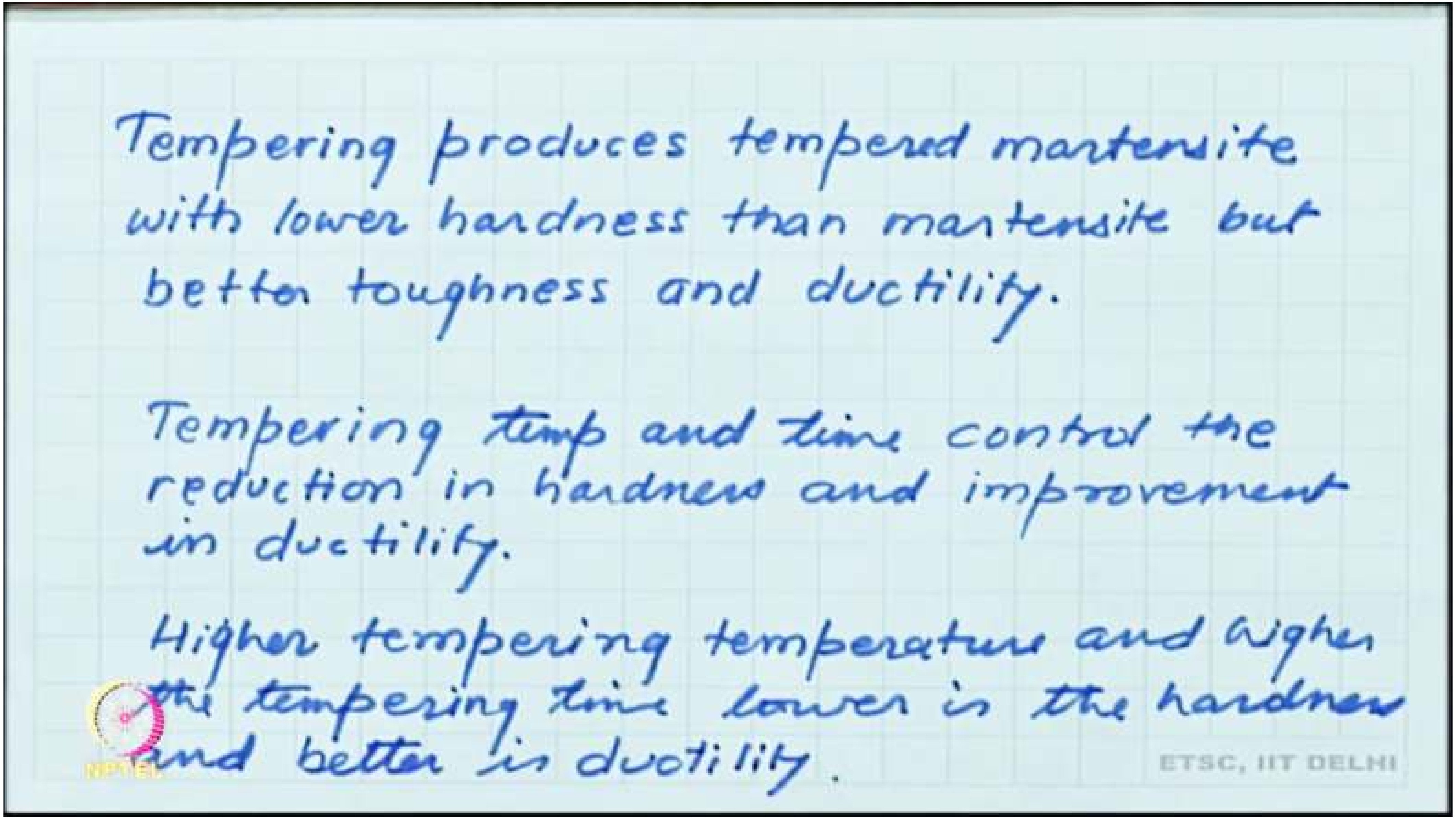


Figure 10.33 Electron micrograph of tempered martensite. Tempering was carried out at 594°C (1100°F). The small particles are the cementite phase; the matrix phase is α-ferrite. 9300×. (Copyright 1971 by United States Steel Corporation.)

Figure 10.35 Hardness (at room temperature) versus tempering time for a water-quenched eutectoid plain carbon (1080) steel. (Adapted from Edgar C. Bain, *Functions of the Alloying Elements in Steel,* American Society for Metals, 1939, p. 233.)



Tempered Martensite



Tempering produces tempered martensite with lower hardness than martensite but better toughness and ductility.

Tempering temp and time control the reduction in hardness and improvement in ductility.

Higher tempering temperature and higher the tempering time lower is the hardness and better is ductility.

MECHANICAL BEHAVIOR OF IRON–CARBON ALLOYS:

Pearlite

- Cementite is much harder but more brittle than ferrite.
  - increasing the fraction of Fe_3C while holding other microstructural elements constant will result in a harder and stronger material.
  - the tensile, yield strengths, and the Brinell hardness number increase with increasing the weight percent carbon (or the percentage of Fe_3C for steels that are composed of fine pearlite).

- Cementite is more brittle, increasing its content will result in a decrease in both ductility and toughness (or impact energy).

MECHANICAL BEHAVIOR OF IRON–CARBON ALLOYS:
Pearlite

- The layer thickness of each of the ferrite and cementite phases in the microstructure influences the mechanical behavior of the material.
  - Fine pearlite is harder and stronger than coarse pearlite.
    - This behavior relate to phenomena that occur at the α–Fe_3C phase boundaries.

- First, there is a large degree of adherence between the two phases across a boundary.
  - the strong and rigid cementite phase severely restricts deformation of the softer ferrite phase in the regions adjacent to the boundary;
  - the cementite reinforces the ferrite.
- The degree of this reinforcement is substantially higher in fine pearlite
  - because of the greater phase boundary area per unit volume of material.

MECHANICAL BEHAVIOR OF IRON–CARBON ALLOYS:
Pearlite

- Second, phase boundaries serve as barriers to dislocation motion in much the same way as grain boundaries.
  - For fine pearlite there are more boundaries through which a dislocation must pass during plastic deformation.
- **The greater reinforcement and restriction of dislocation motion in fine pearlite account for its greater hardness and strength.**

MECHANICAL BEHAVIOR OF IRON–CARBON ALLOYS:

Spheroidite

- In spheroidite microstructures, the cementite phase has distinctly different shapes and arrangements to the pearlite microstructures.
- Alloys containing **pearlitic** microstructures have greater strength and hardness than do those with **spheroidite**.
- There is less boundary area per unit volume in spheroidite,
  - plastic deformation is not nearly as constrained,
  - gives rise to a relatively soft and weak material.

MECHANICAL BEHAVIOR OF IRON–CARBON ALLOYS:
Spheroidite

- In fact, of all steel alloys:
  - spheroidite microstructure are softest and weakest.
  - spheroidized steels are extremely ductile, much more than either fine or coarse pearlite.
  - spheroidite microstructure are notably tough because any crack can encounter only a very small fraction of the brittle cementite particles as it propagates through the ductile ferrite matrix.

MECHANICAL BEHAVIOR OF IRON–CARBON ALLOYS:

Bainite

- Bainitic steels have a finer structure (i.e., smaller α-ferrite and Fe_3C particles),
  - generally stronger and harder than pearlitic ones; yet they exhibit a desirable combination of strength and ductility.

MECHANICAL BEHAVIOR OF IRON–CARBON ALLOYS:

Martensite

- Martensite is
  - the hardest and strongest
  - the most brittle; it has negligible ductility.
- Its hardness is dependent on the carbon content, up to about 0.6 wt%.

MECHANICAL BEHAVIOR OF IRON–CARBON ALLOYS:

Martensite

- In contrast to pearlitic steels, strength and hardness of **martensite** are not thought to be related to microstructure. Rather,
  - attributed to the effectiveness of the interstitial carbon atoms in hindering dislocation motion (as a solid-solution effect),
  - and to the relatively few slip systems (along which dislocations move) for the BCT structure.

Table 10.2 Summary of Microstructures and Mechanical Properties for Iron–Carbon Alloys

Microconstituent	*Phases Present*	*Arrangement of Phases*	*Mechanical Properties (Relative)*
Spheroidite	α Ferrite + Fe_3C	Relatively small Fe_3C sphere-like particles in an α-ferrite matrix	Soft and ductile
Coarse pearlite	α Ferrite + Fe_3C	Alternating layers of α ferrite and Fe_3C that are relatively thick	Harder and stronger than spheroidite, but not as ductile as spheroidite
Fine pearlite	α Ferrite + Fe_3C	Alternating layers of α ferrite and Fe_3C that are relatively thin	Harder and stronger than coarse pearlite, but not as ductile as coarse pearlite
Bainite	α Ferrite + Fe_3C	Very fine and elongated particles of Fe_3C in an α-ferrite matrix	Hardness and strength greater than fine pearlite; hardness less than martensite; ductility greater than martensite
Tempered martensite	α Ferrite + Fe_3C	Very small Fe_3C sphere-like particles in an α-ferrite matrix	Strong; not as hard as martensite, but much more ductile than martensite
Martensite	Body-centered tetragonal, single phase	Needle-shaped grains	Very hard and very brittle

Module 4

SYLLABUS

Strengthening mechanisms - cold and hot working - alloy steels: how alloying elements affecting properties of steel - nickel steels - chromium steels - high speed steels -cast irons - principal non ferrous alloys.

Course Outcomes

At the end of the Module students will be able to,

CO 3: Apply the basic principles of ferrous and non-ferrous metallurgy for selecting materials for specific applications.

CO 5 : Define and differentiate engineering materials on the basis of structure and properties for engineering applications

Course Outcome 4 (CO4): Apply the basic principles of ferrous and non-ferrous metallurgy for selecting materials for specific applications.

1. What are the classification, compositions and applications of high speed steel? identify 18:4:1
2. Describe the composition, properties, and use of Bronze and Gun metal.
3. Explain the importance of all the non-ferrous alloys in automotive applications. Elaborate on the composition, properties and typical applications of any five non-ferrous alloys.

Course Outcome 5 (CO5): Define and differentiate engineering materials on the basis of structure and properties for engineering applications.

1. Carbon is allowed to diffuse through a steel plate 15 mm thick. The concentrations of carbon at the two faces are 0.65 and $0.30 kgC/m^3Fe$, which are maintained constant. If the pre-exponential and activation energy are $6.2x10^{-7} m^2/s$ and 80,000 J/mol, respectively, compute the temperature at which the diffusion flux is $1.43 \text{ x } 10^{-9} kg/m^2$-s.
2. Explain the fundamental effects of alloying elements in steel on polymorphic transformation temperatures, grain growth, eutectoid point, retardation of the transformation rates, formation and stability of carbides.
3. Describe the kind of fracture which may occur as a result of a loose fitting key on a shaft.

Strengthening Mechanisms

- Strengthening mechanisms involves different processes to restrict/prevent dislocation motion of a material, there by improving its mechanical properties.
- Strengthening mechanisms is the relation between dislocation motion and mechanical behavior of metals.
- Because macroscopic plastic deformation corresponds to the motion of large numbers of dislocations, the ability of a metal to plastically deform depends on the ability of dislocations to move.
- Since hardness and strength (both yield and tensile) are related to the ease with which plastic deformation can be made to occur, by reducing the mobility of dislocations, the mechanical strength may be enhanced; that is, greater mechanical forces will be required to initiate plastic deformation.
- The more unconstrained the dislocation motion, the greater is the facility with which a metal may deform, and the softer and weaker it becomes.

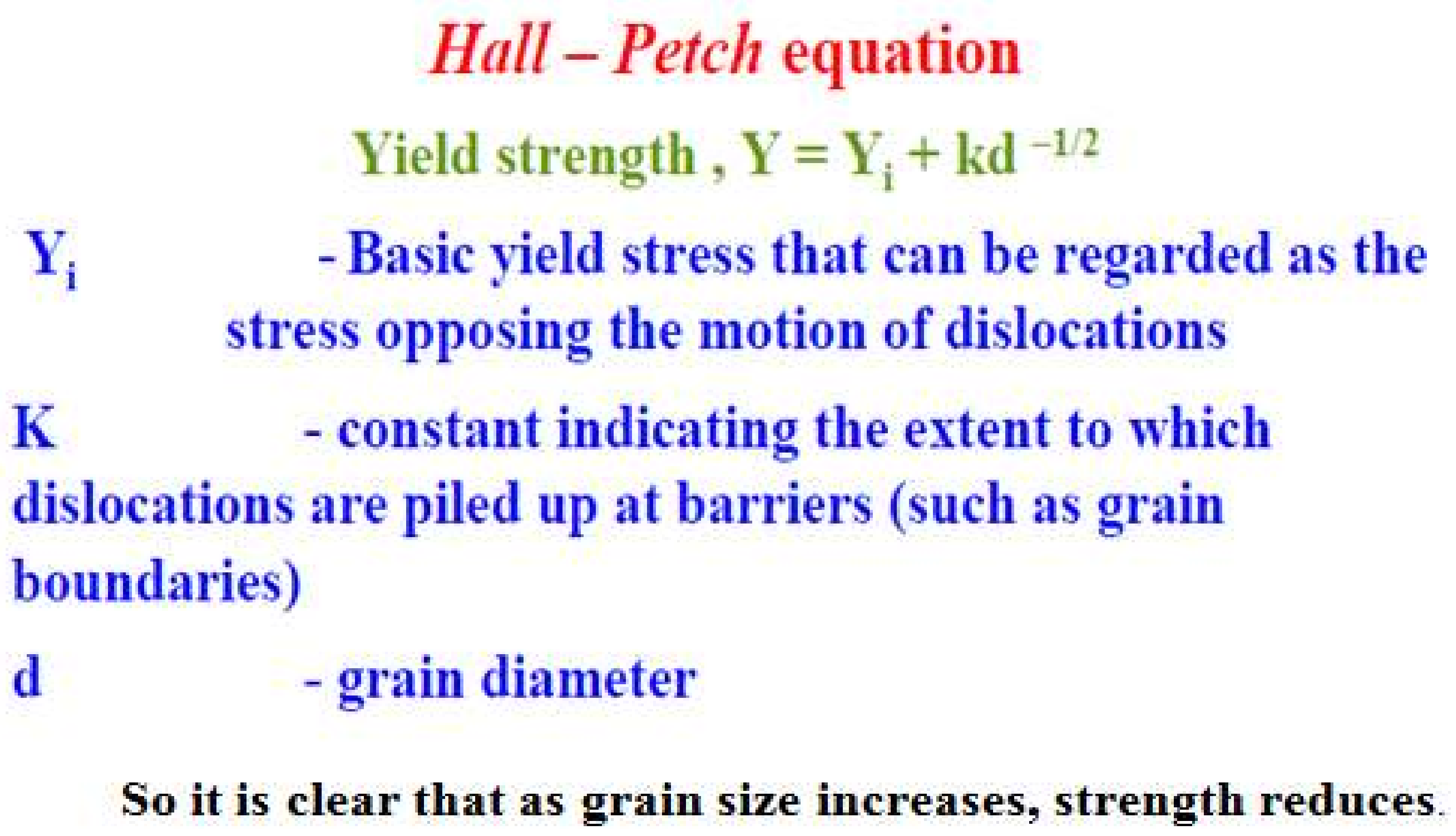
Virtually all strengthening techniques rely on this simple principle: restricting or hindering dislocation motion renders a material harder and stronger.

Strengthening Mechanisms

1. Grain size reduction
2. Solid solution hardening
3. Work or Strain hardening
4. Age or Precipitation hardening
5. Dispersion hardening

1. Grain Size Reduction

- The size of the grains, or average grain diameter, in a polycrystalline metal influences the mechanical properties.



Hall – Petch equation

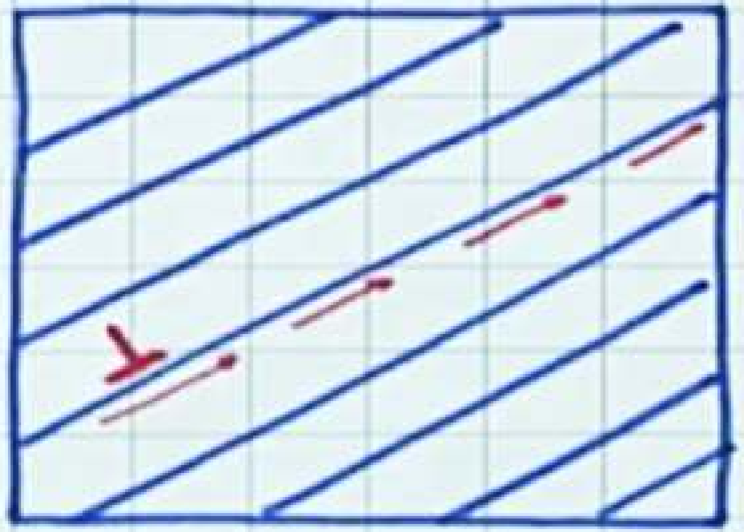
Yield strength , $Y = Y_i + kd^{-1/2}$

Y_i - Basic yield stress that can be regarded as the stress opposing the motion of dislocations

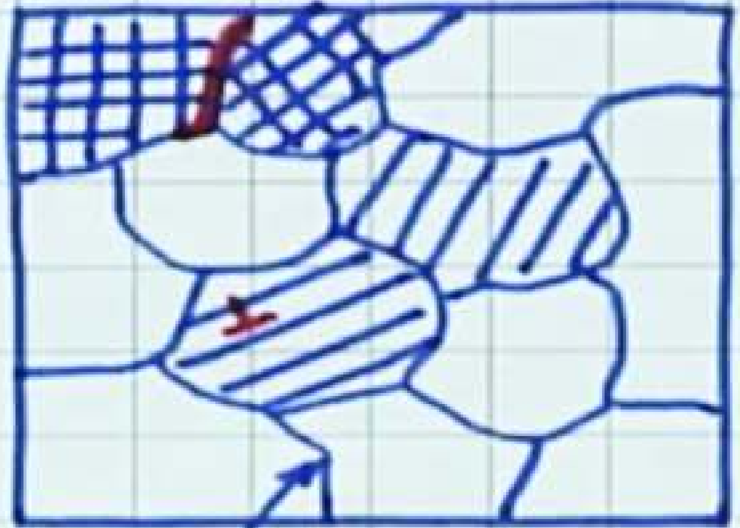
K - constant indicating the extent to which dislocations are piled up at barriers (such as grain boundaries)

d - grain diameter

So it is clear that as grain size increases, strength reduces.



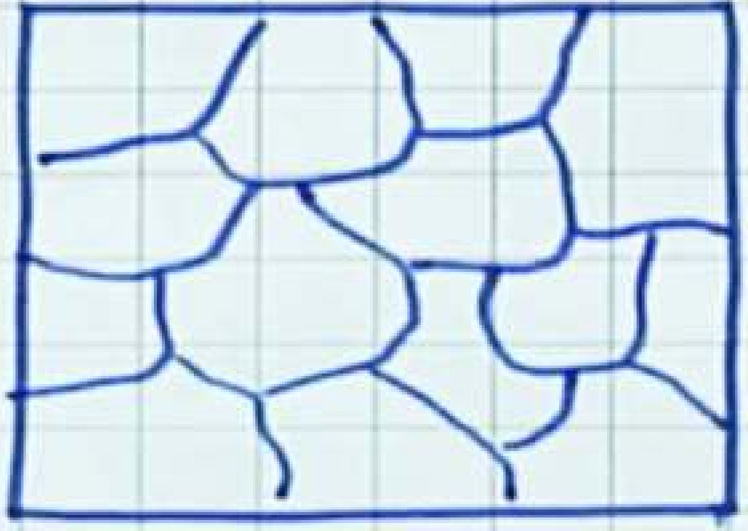
Single crystal



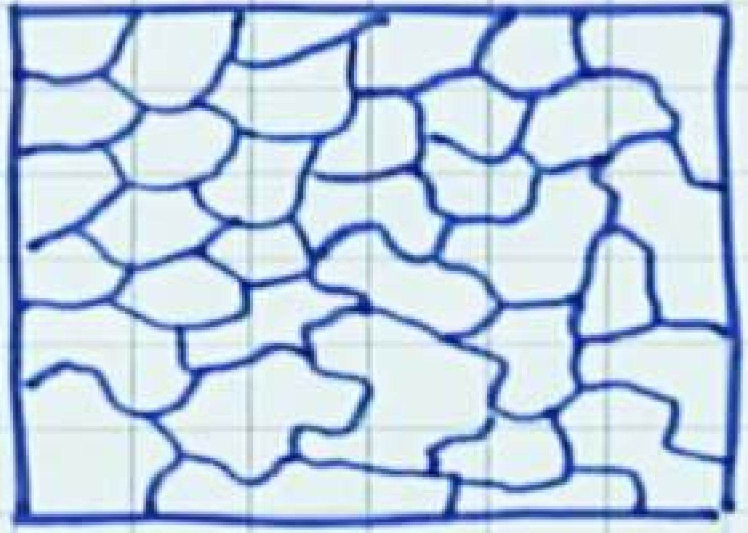
Polycrystal

Grain Boundaries act as obstacles to dislocation motion.

Coarse grains



fine grains



Finer grains ⇒ More grain boundaries

⇒ More obstacle to dislocation motion

→ Higher strength

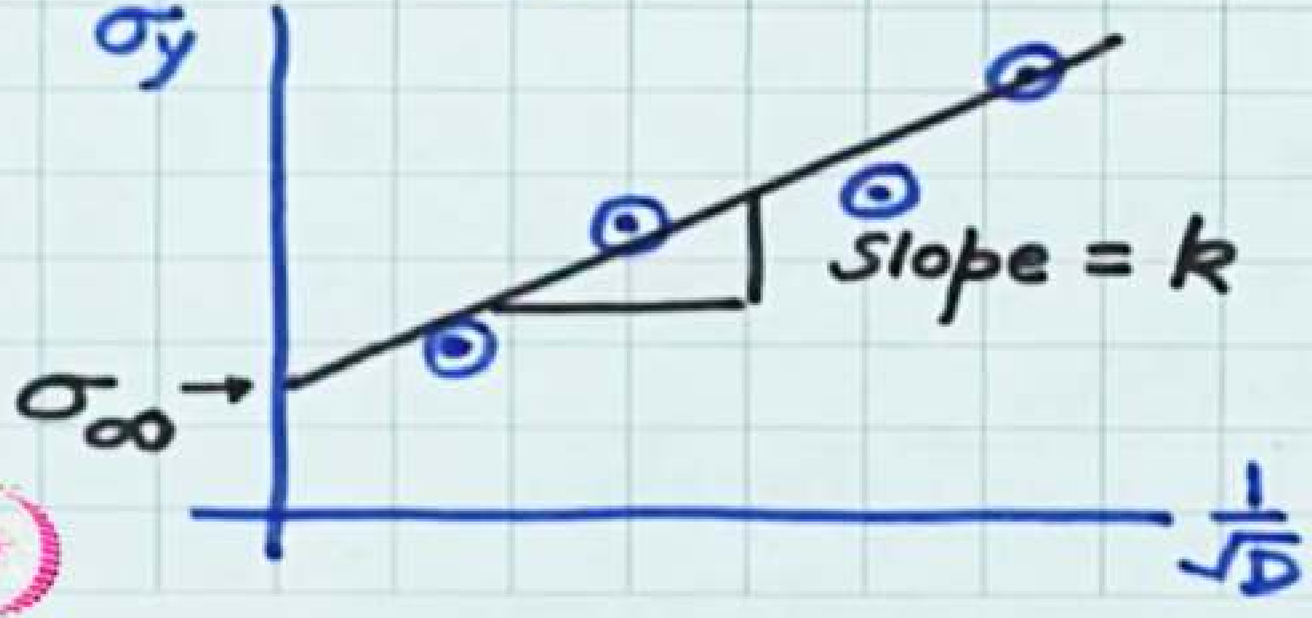
Hall-Petch Relation

constants.

$$\sigma_y = \sigma_\infty + \frac{k}{\sqrt{D}}$$

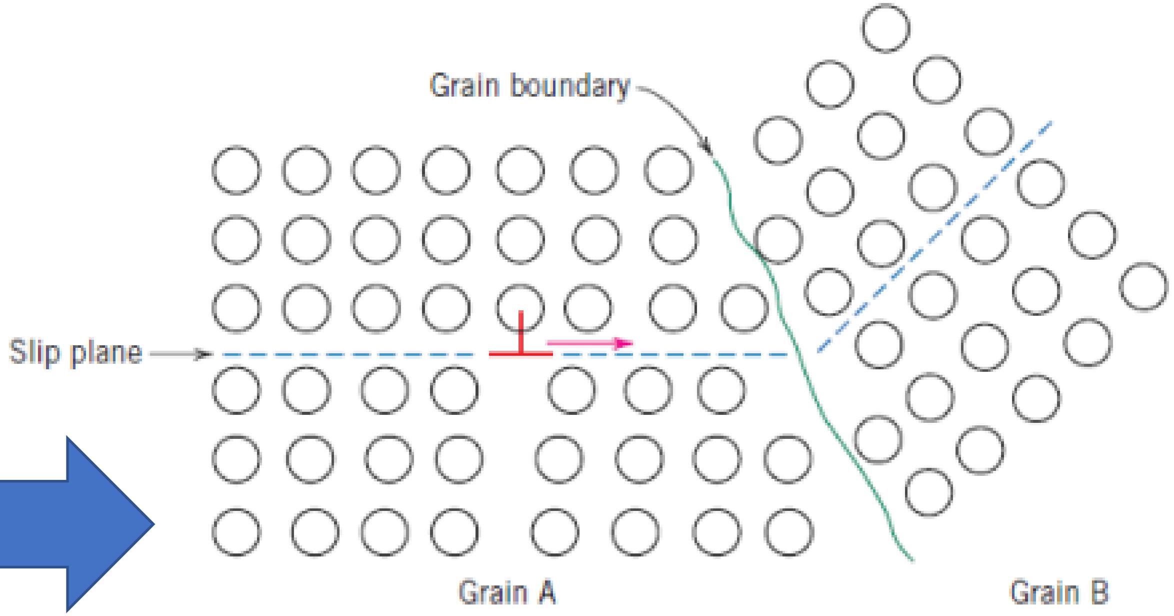
Yield strength

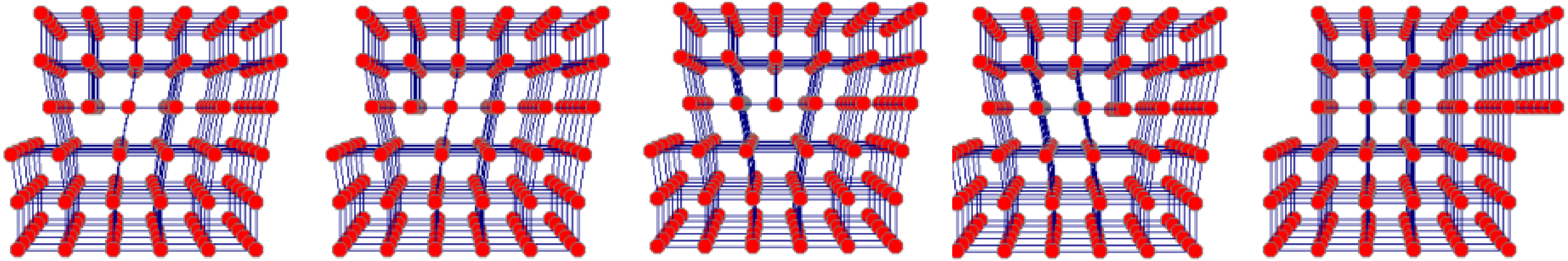
Grain diameter.



σ_∞ is the yield stress for infinitely large grain size (single crystal)

Figure 7.14 The motion of a dislocation as it encounters a grain boundary, illustrating how the boundary acts as a barrier to continued slip. Slip planes are discontinuous and change directions across the boundary. (From Van Vlack, *A Textbook of Materials Technology*, 1st edition, © 1973, p. 53. Adapted by permission of Pearson Education, Inc., Upper Saddle River, NJ.)





- During plastic deformation, slip or dislocation motion must take place across this common boundary—say, from grain A to grain B in Figure

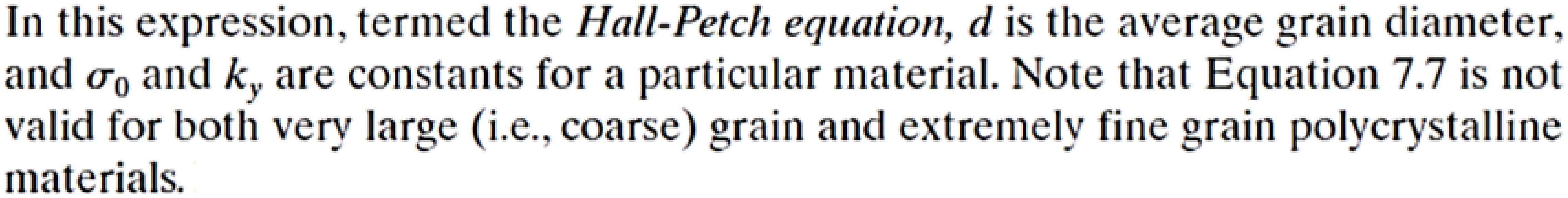
- The grain boundary acts as a barrier to dislocation motion for two reasons:

  1. Since the two grains are of different orientations, a dislocation passing into grain B will have to change its direction of motion; this becomes more difficult as the crystallographic misorientation increases.
  2. The atomic disorder within a grain boundary region will result in a discontinuity of slip planes from one grain into the other.

- For high-angle grain boundaries, dislocations tend to “pile up” (or back up) at grain boundaries. These pile-ups introduce stress concentrations ahead of their slip planes, which generate new dislocations in adjacent grains.

- A fine-grained material (one that has small grains) is harder and stronger than one that is coarse grained, since the former has a greater total grain boundary area to impede dislocation motion. For many materials, the yield strength varies with grain size according to,

$$\sigma_y = \sigma_0 + k_y d^{-1/2}$$



In this expression, termed the *Hall-Petch equation, d* is the average grain diameter, and σ_0 and k_y are constants for a particular material. Note that Equation 7.7 is not valid for both very large (i.e., coarse) grain and extremely fine grain polycrystalline materials.

- Small-angle grain boundaries are not effective in interfering with the slip process because of the slight crystallographic misalignment across the boundary.
- Twin boundaries will effectively block slip and increase the strength of the material.
- Boundaries between two different phases are also impediments to movements of dislocations; this is important in the strengthening of more complex alloys.
- The sizes and shapes of the constituent phases significantly affect the mechanical properties of multiphase alloys

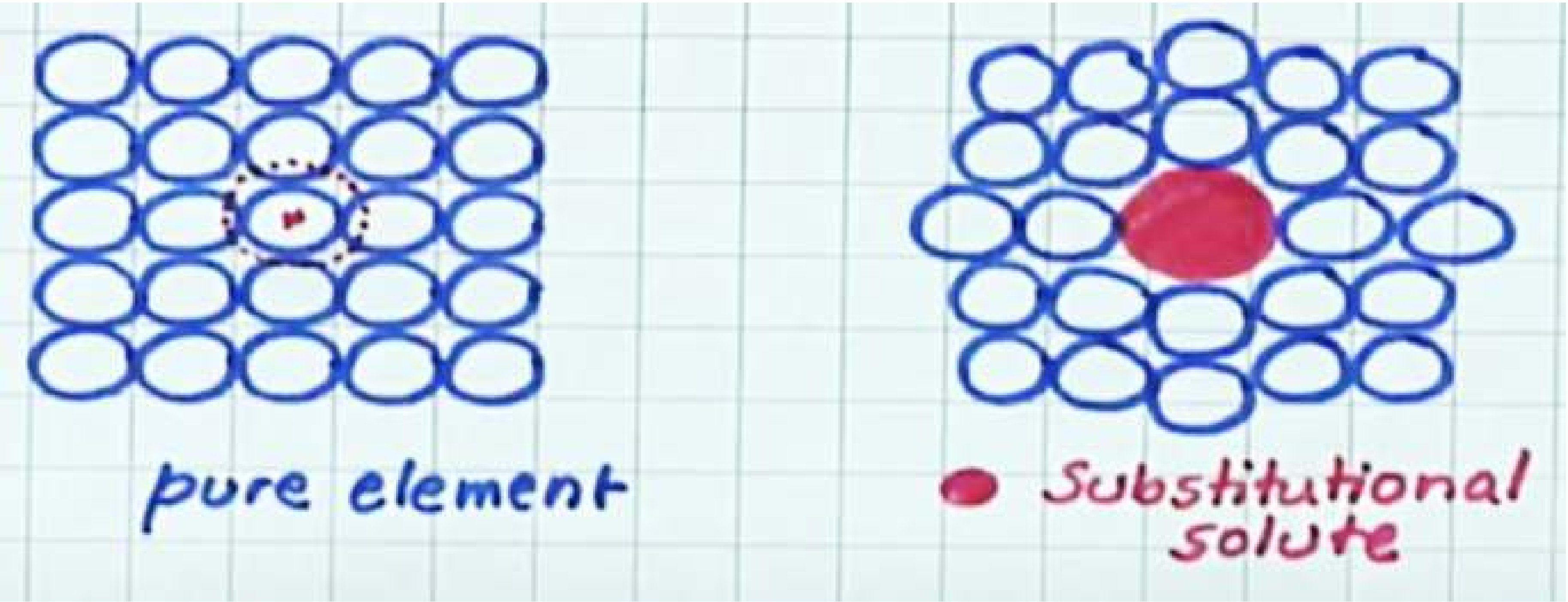
Advantages

1. As grain size reduces yield strength increases. (Hall – Petch equation)
2. As grain size reduces, grain boundary increases which will prevent dislocation motion. This will increase strength of the material.

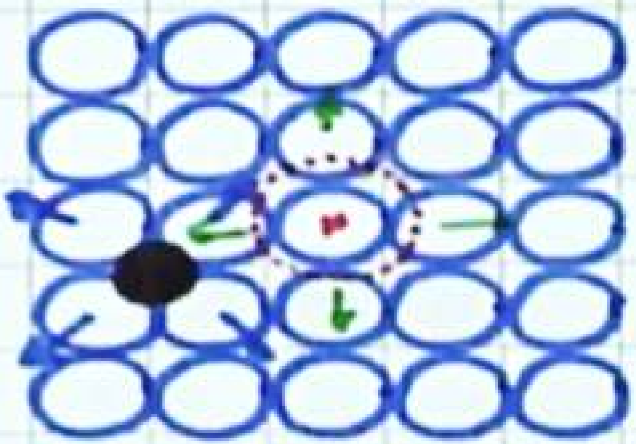
2. Solid Solution Strengthening

Solute + Solvent = Solid solution

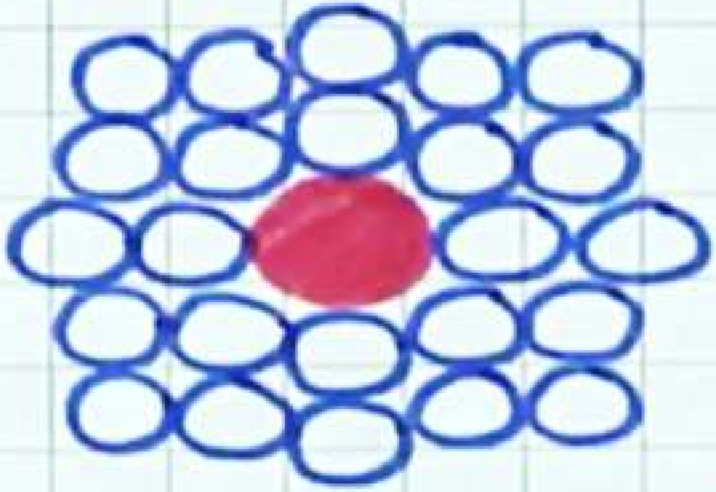
- Solis solution is stronger than pure element.
- Solute atoms added will act as a barrier for dislocation motion.
- So adding solute atoms will increase the material strength.
- Alloying with impurity atoms that go into either substitutional or interstitial solid solution.
- High-purity metals are almost always softer and weaker than alloys composed of the same base metal. Increasing the concentration of the impurity results in an attendant increase in tensile and yield strengths,


pure element
Substitutional solute

Higher size difference ⇒ higher strain



pure element

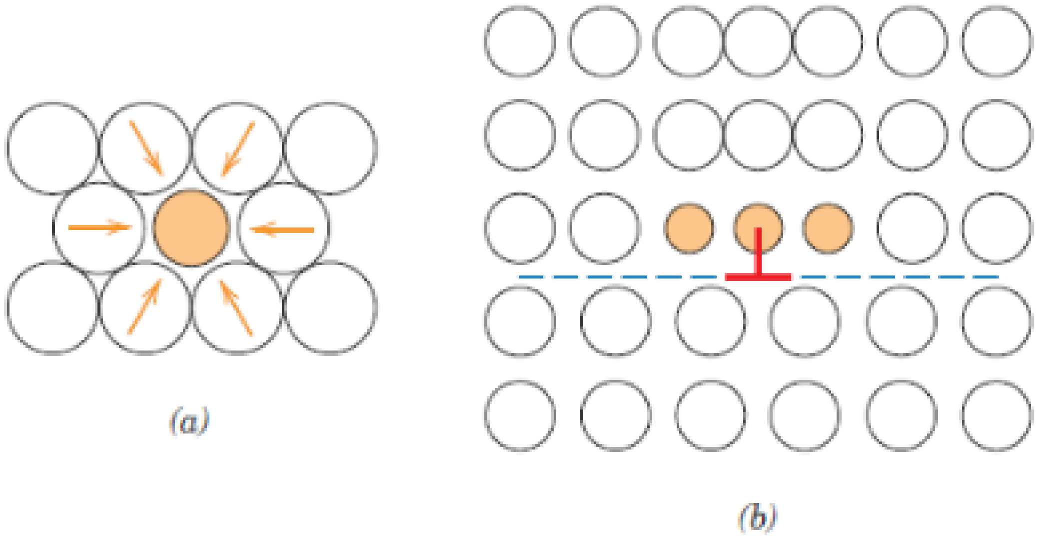


● Substitutional solute

Strain field around the solute atom.

This strain field interacts with strain field of a dislocation.

⇒ Impediment in dislocation motion.


(a)

(b)

Figure 7.17 (*a*) Representation of tensile lattice strains imposed on host atoms by a smaller substitutional impurity atom. (*b*) Possible locations of smaller impurity atoms relative to an edge dislocation such that there is partial cancellation of impurity–dislocation lattice strains.

- Alloys are stronger than pure metals because impurity atoms that go into solid solution ordinarily impose lattice strains on the surrounding host atoms.
- Lattice strain field interactions between dislocations and these impurity atoms result, and, consequently, dislocation movement is restricted.

- An impurity atom that is smaller than a host atom for which it substitutes exerts tensile strains on the surrounding crystal lattice
- Conversely, a larger substitutional atom imposes compressive strains in its vicinity.
- The resistance to slip is greater when impurity atoms are present because the overall lattice strain must increase if a dislocation is torn away from them. Furthermore, the same lattice strain interactions will exist between impurity atoms and dislocations that are in motion during plastic deformation.
- Thus, a greater applied stress is necessary to first initiate and then continue plastic deformation for solid-solution alloys, as opposed to pure metals; this is evidenced by the enhancement of strength and hardness.

3. Work or Strain hardening or Cold working

- Strain hardening is the phenomenon whereby a ductile metal becomes harder and stronger as it is plastically deformed. Sometimes it is also called work hardening, or, because the temperature at which deformation takes place is “cold” relative to the absolute melting temperature of the metal, cold working. Most metals strain harden at room temperature.
- During strain hardening the work piece is loaded/deformed.
- During deformation the dislocation density increases.
- As dislocation density increases, the dislocations will act as barrier to each other.
- On the average, dislocation–dislocation strain interactions are repulsive. The net result is that the motion of a dislocation is hindered by the presence of other dislocations.
- As the mobility of dislocations is hindered, the strength of material will increase.

Dislocation - Dislocation Interactions.

⇒ Interference by other dislocations for motion of a given dislocation

→ Difficulty in motion

⇒ Strengthening

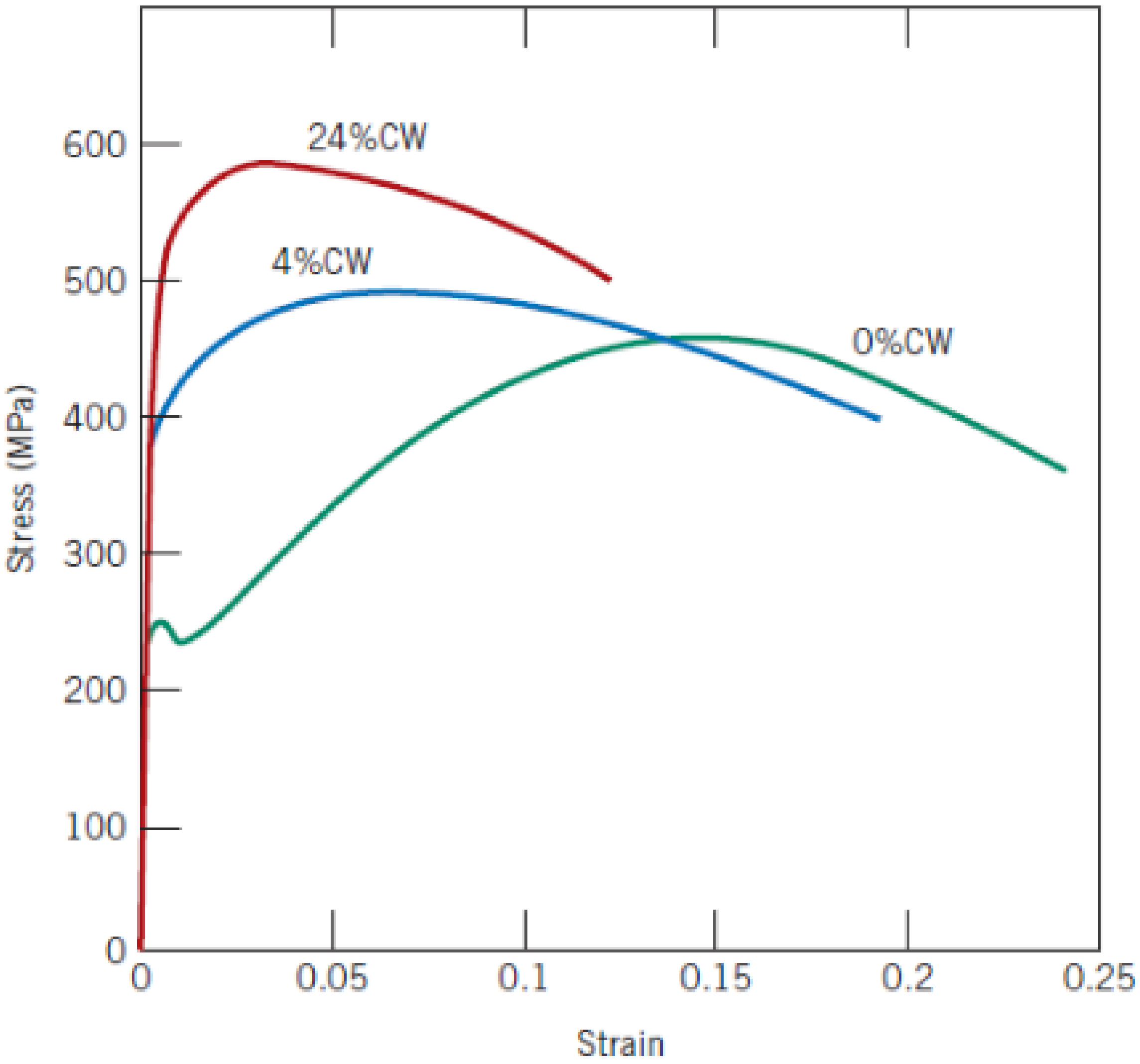
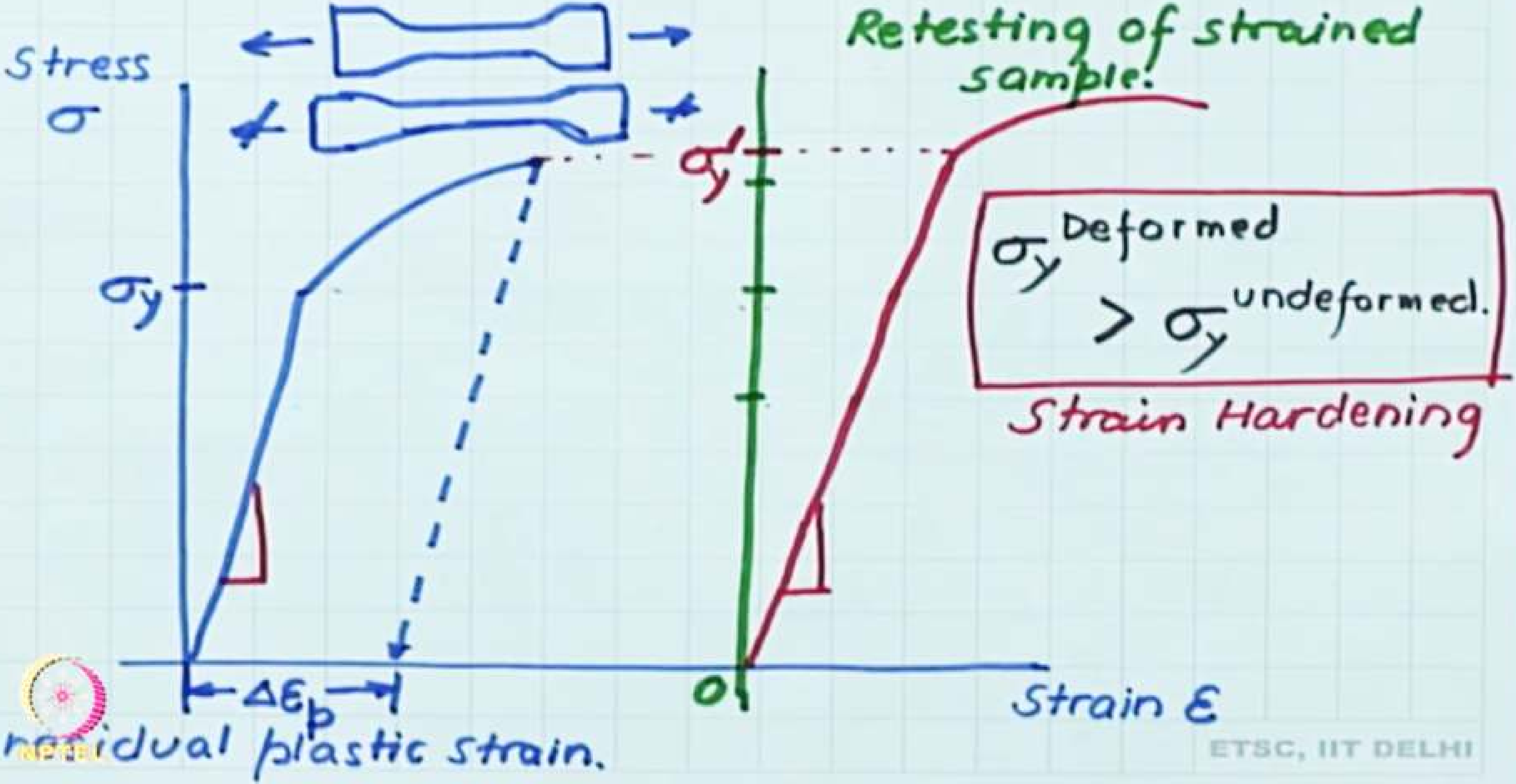


Figure 7.20 The influence of cold work on the stress–strain behavior of a low-carbon steel; curves are shown for 0%CW, 4%CW, and 24%CW.

Retesting of strained sample!



$$\boxed{\sigma_y^{\text{Deformed}} > \sigma_y^{\text{undeformed}}.}$$

Strain Hardening

residual plastic strain.

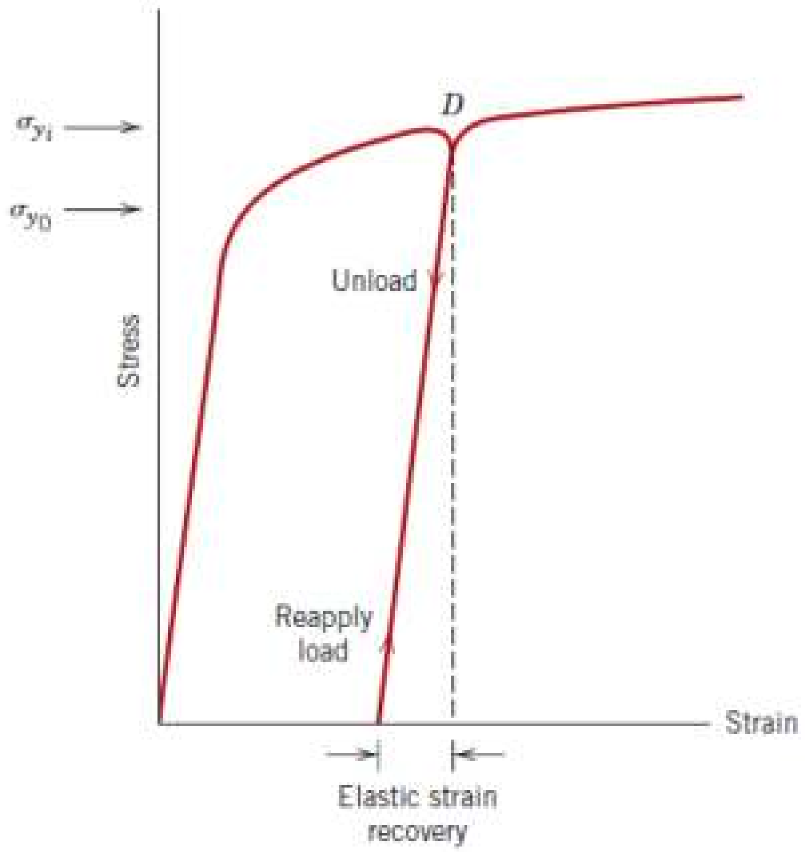
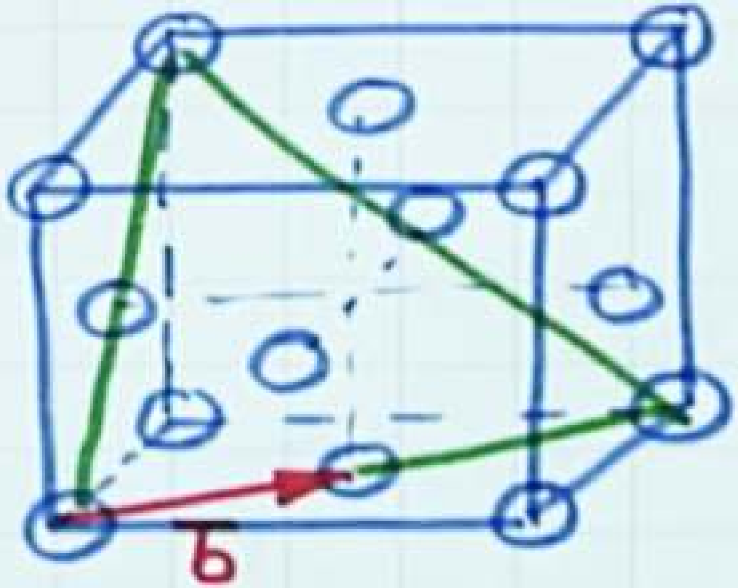
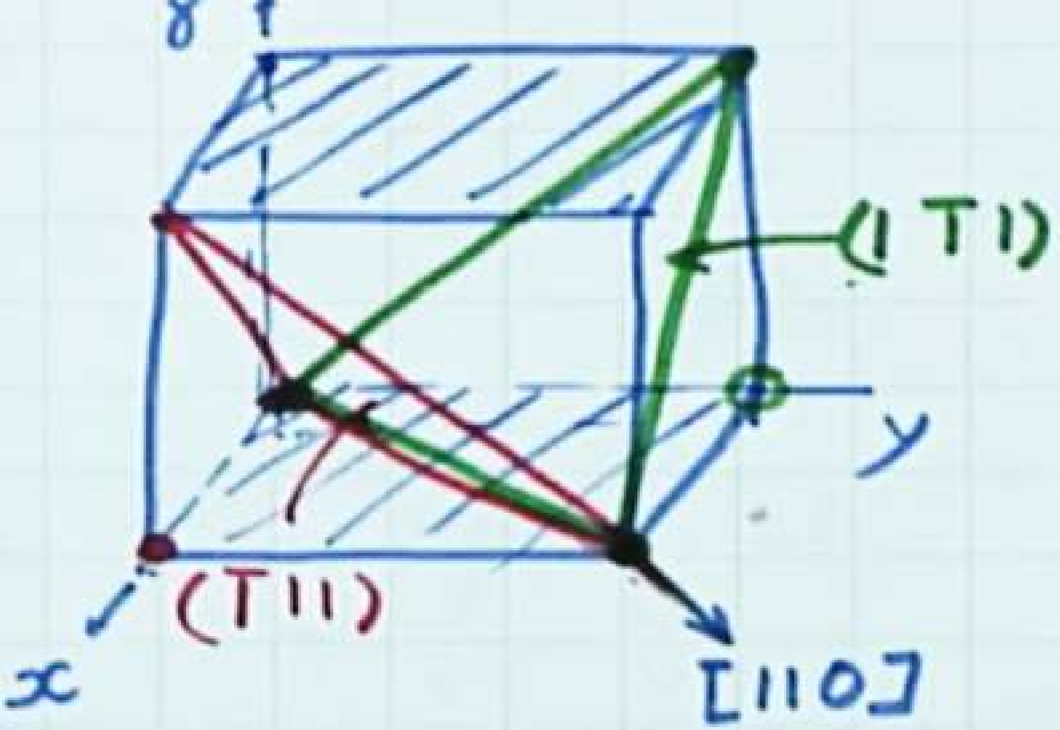


Figure 6.17 Schematic tensile stress–strain diagram showing the phenomena of elastic strain recovery and strain hardening. The initial yield strength is designated as σ_{y_0}; σ_{y_i} is the yield strength after releasing the load at point *D*, and then upon reloading.

Strain hardening is demonstrated in a stress–strain diagram presented earlier (Figure 6.17). Initially, the metal with yield strength σ_{y_0} is plastically deformed to point *D*. The stress is released, then reapplied with a resultant new yield strength, σ_{y_i}. The metal has thus become stronger during the process because σ_{y_i} is greater than σ_{y_0}.

- The effects of strain hardening may be removed by an annealing heat treatment.
- The strengthening effects due to grain size reduction and strain hardening can be eliminated or at least reduced by an elevated temperature heat treatment. Conversely, solid-solution strengthening is unaffected by heat treatment.





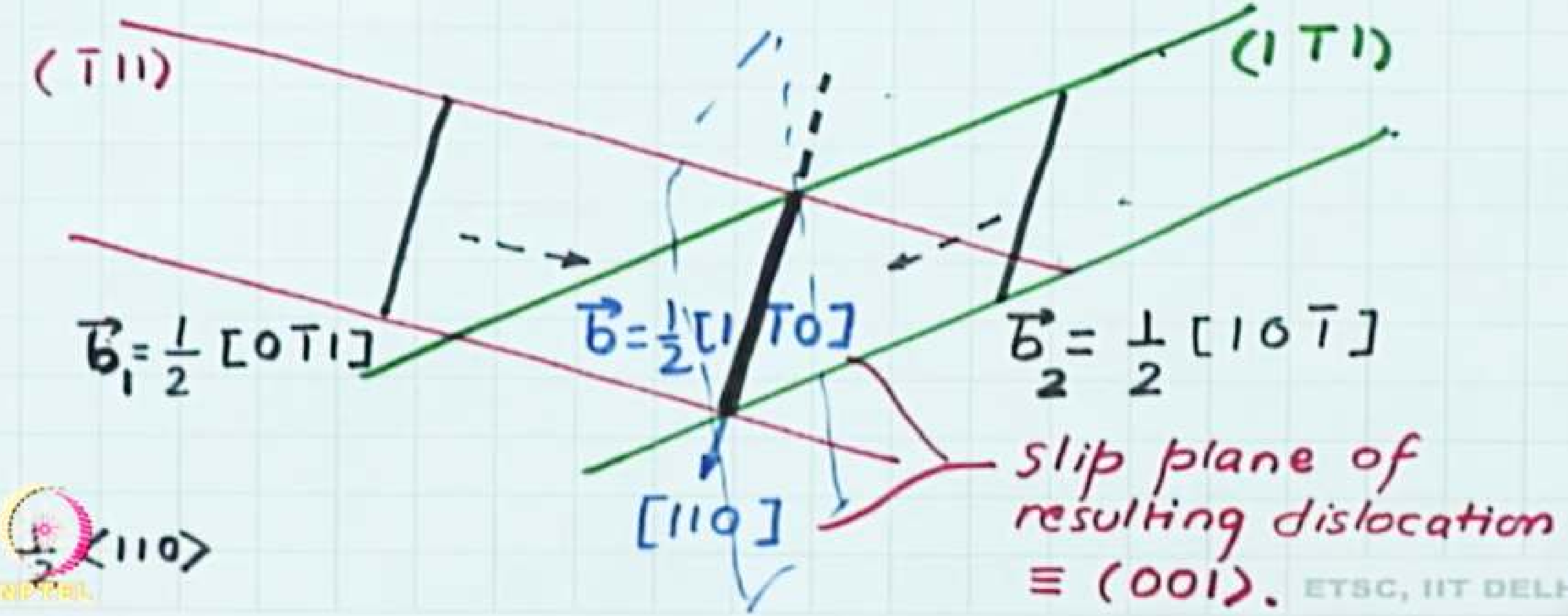
$\vec{b} = \frac{1}{2}\langle 110 \rangle$

Slip planes $\{111\} \equiv (111), \underbrace{(\bar{1}11)}, \underbrace{(1\bar{1}1)}, (11\bar{1})$

(001)

$$\vec{b} = \vec{b}_1 + \vec{b}_2 = \frac{1}{2}[0\bar{1}1] + \frac{1}{2}[10\bar{1}] = \frac{1}{2}[1\bar{1}0]$$

Energies: $$\left(\frac{a}{\sqrt{2}}\right)^2 + \left(\frac{a}{\sqrt{2}}\right)^2 > \left(\frac{a}{\sqrt{2}}\right)^2$$



Slip plane of resulting dislocation ≡ (001).

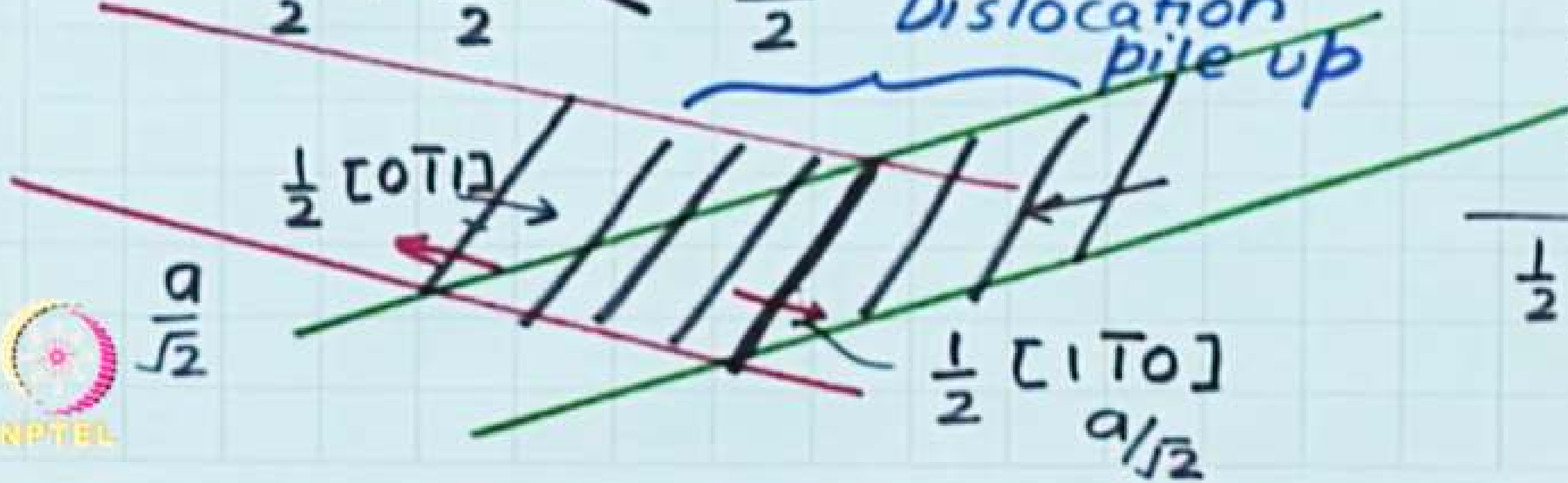
The resulting dislocation has a slip plane (001)

⇒ Not a favourable slip plane for CCP

⇒ The dislocation is unable to move

(SESSILE ≡ unable to move).

$$\frac{a^2}{2} + \frac{a^2}{2} < \frac{3a^2}{2}$$



$$\begin{array}{l} \frac{1}{2}[0\bar{1}1] \\ \frac{1}{2}[1\bar{1}0] \\ \hline \frac{1}{2}[1\bar{2}1] \end{array}$$

$$\frac{a\sqrt{6}}{2} = \frac{\sqrt{3}a}{\sqrt{2}}$$

4. Age or Precipitation Hardening

- During precipitation hardening, small particles are made to precipitate into the material by heat treatment.
- The strength and hardness of some metal alloys may be enhanced by the formation of extremely small uniformly dispersed particles of a second phase within the original phase matrix; this must be accomplished by phase transformations that are induced by appropriate heat treatments.
- The process is called **precipitation hardening** because the small particles of the new phase are termed "precipitates." "Age hardening" is also used to designate this procedure because the strength develops with time, or as the alloy ages.
- Precipitation hardening is accomplished by two different heat treatments.
- The first is a solution heat treatment in which all solute atoms are dissolved to form a single phase solid solution.

For the second or **precipitation heat treatment,** the supersaturated α solid solution is ordinarily heated to an intermediate temperature T_2 (Figure 11.21) within the $\alpha + \beta$ two-phase region, at which temperature diffusion rates become appreciable. The β precipitate phase begins to form as finely dispersed particles of composition C_β, which process is sometimes termed "aging."

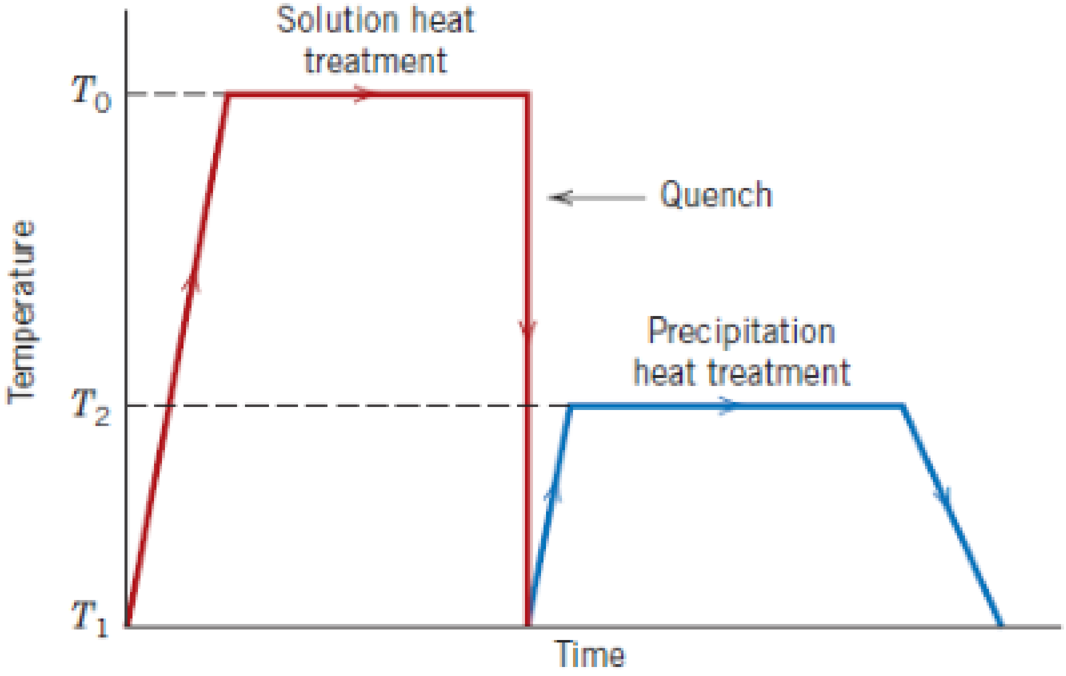


Figure 11.22 Schematic temperature-versus-time plot showing both solution and precipitation heat treatments for precipitation hardening.

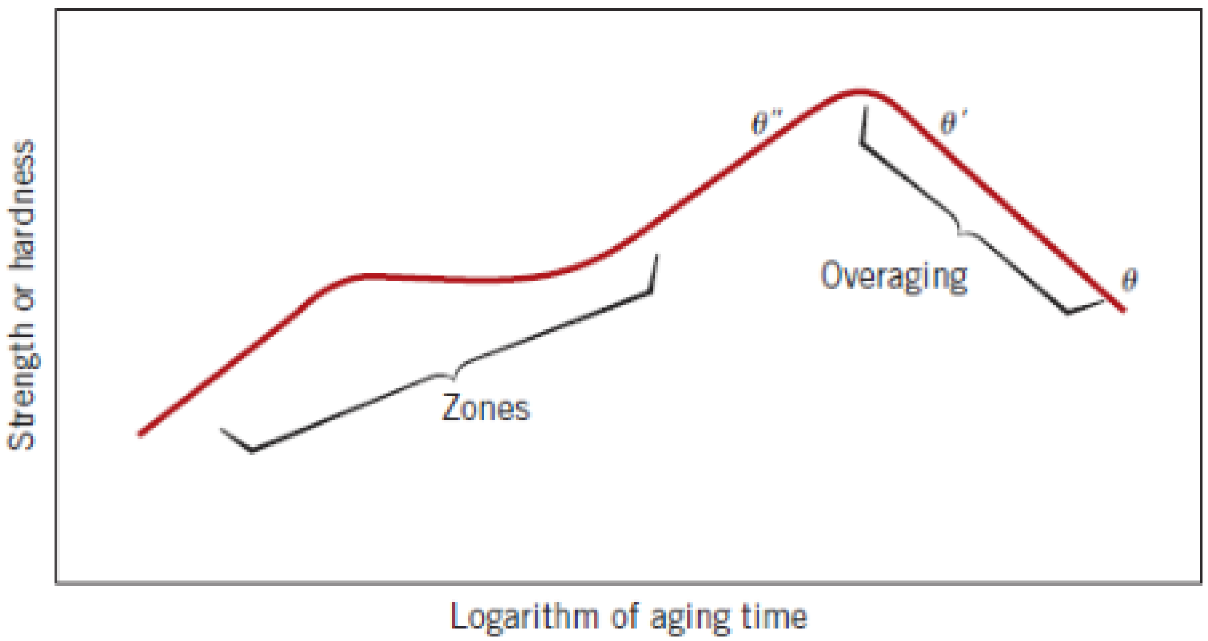
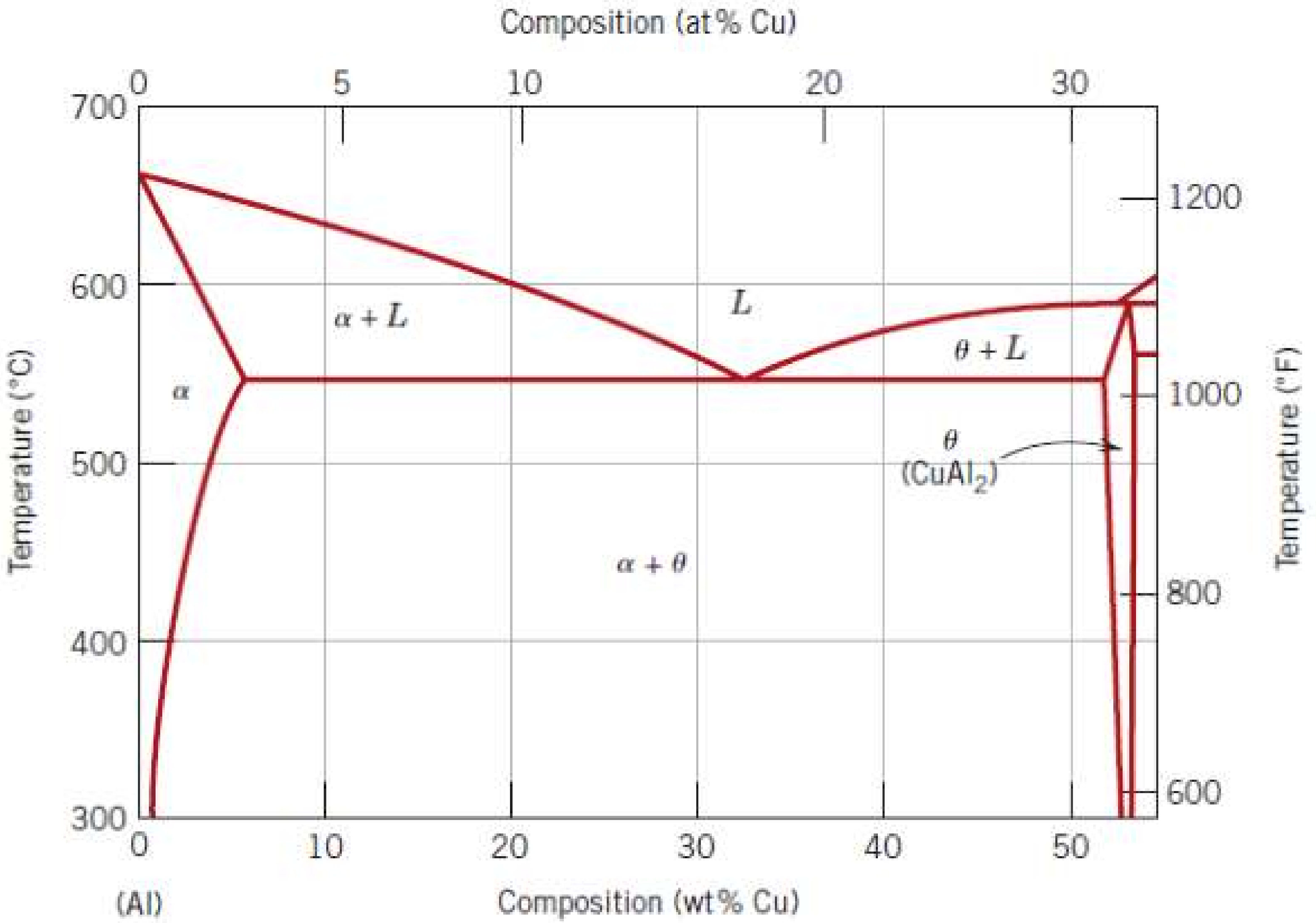


Figure 11.23 Schematic diagram showing strength and hardness as a function of the logarithm of aging time at constant temperature during the precipitation heat treatment.

Figure 11.24 The aluminum-rich side of the aluminum–copper phase diagram. (Adapted from J. L. Murray, *International Metals Review*, **30**, 5, 1985. Reprinted by permission of ASM International.)



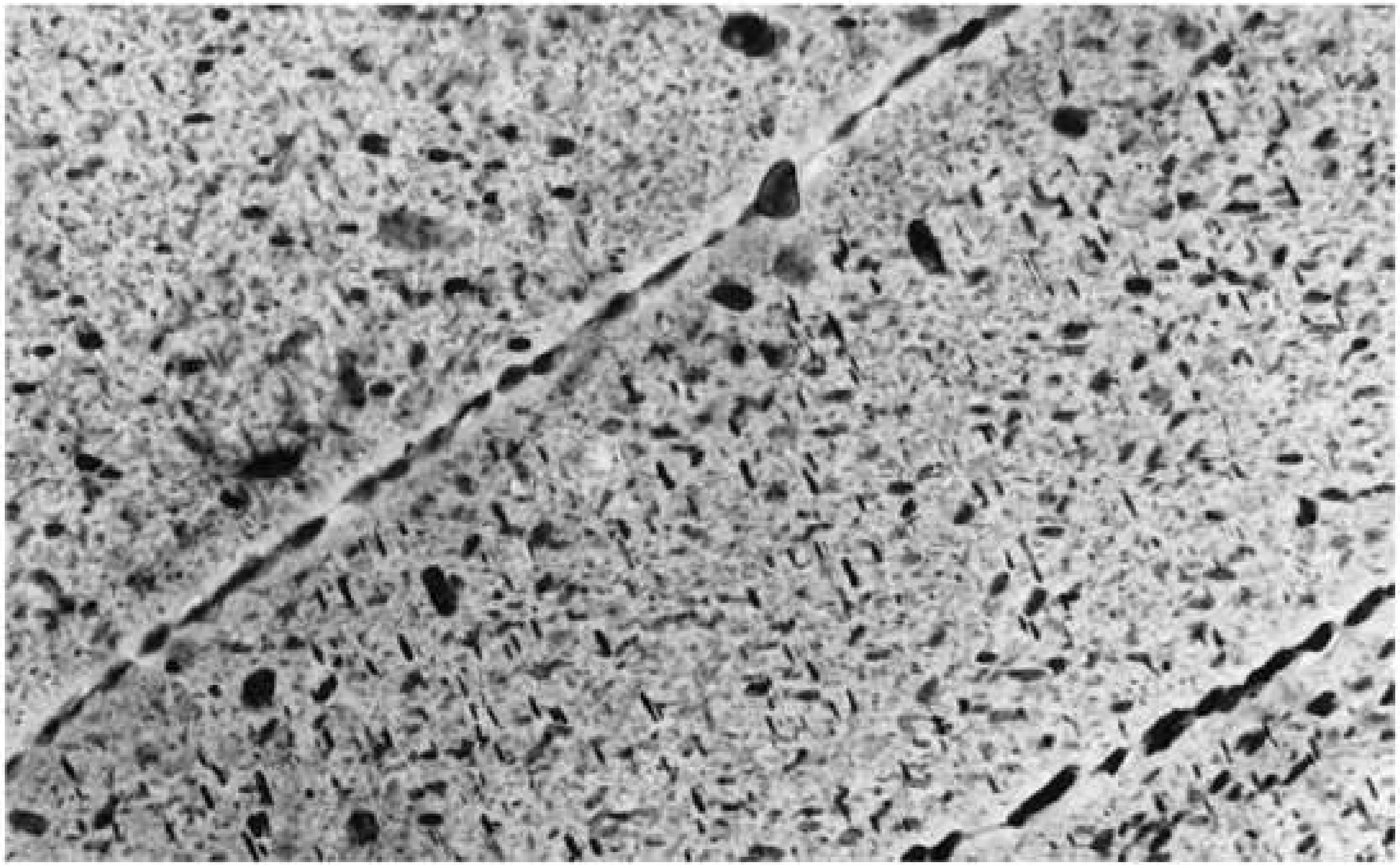


Figure 11.26 A transmission electron micrograph showing the microstructure of a 7150-T651 aluminum alloy (6.2Zn, 2.3Cu, 2.3Mg, 0.12Zr, the balance Al) that has been precipitation hardened. The light matrix phase in the micrograph is an aluminum solid solution. The majority of the small plate-shaped dark precipitate particles are a transition η' phase, the remainder being the equilibrium η ($MgZn_2$) phase. Note that grain boundaries are "decorated" by some of these particles. 90,000×. (Courtesy of G. H. Narayanan and A. G. Miller, Boeing Commercial Airplane Company.)

5. Dispersion Hardening

- In dispersion hardened alloys, fine particles of one phases are added to another phase which is weak.
- Fine particles are added in minor quantity.
- Fine particles act as obstacle for dislocation motion.
- This will increase the material strength.

Cold working Vs Hot working

Cold working

Mechanical working is done with out raising the temperature.

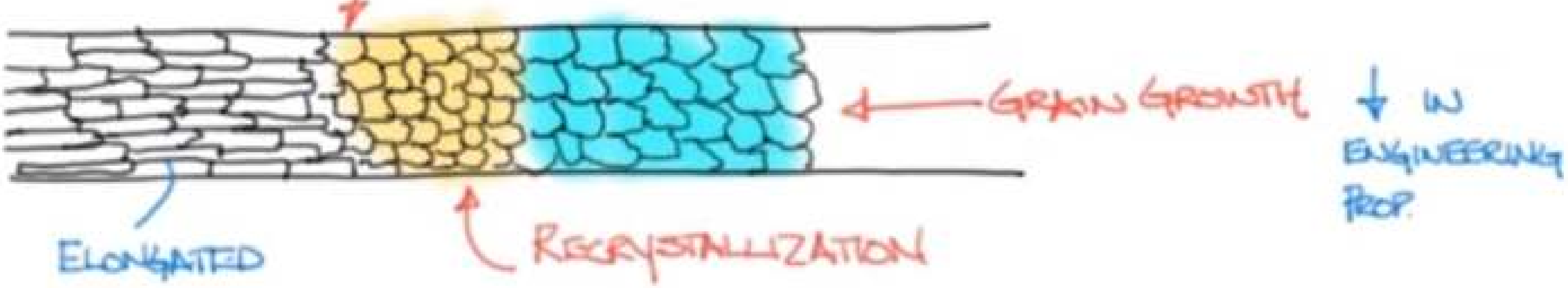
- After cold working, the grains will be in distorted condition.
- Cold working will affect tensile strength, yield strength, hardness & electrical conductivity.

Hot working

Mechanical working is done above the recrystallisation temperature.

- Specimen will become soft & ductile after hot working.

COLD WORKING



↑ STRENGTH
↓ DUCTILITY
} DUE TO COLD WORKING

↓ STRENGTH
↑ DUCTILITY
} RECRYSTALLIZATION → MORE COLD WORKING = MORE INTERNAL ENERGY

⇓

LESS HEAT NEEDED FOR RECRYSTALLIZATION

COLD WORKING = BELOW RECRYSTALLIZATION

HOT WORKING = ABOVE RECRYSTALLIZATION

Annealing of cold-worked metals

Annealing

Steel

Cooling from Austenite at a very slow rate to form coarse pearlite

Any Deformed metal

Heating a deformed metal to restore properties to values prior to deformation

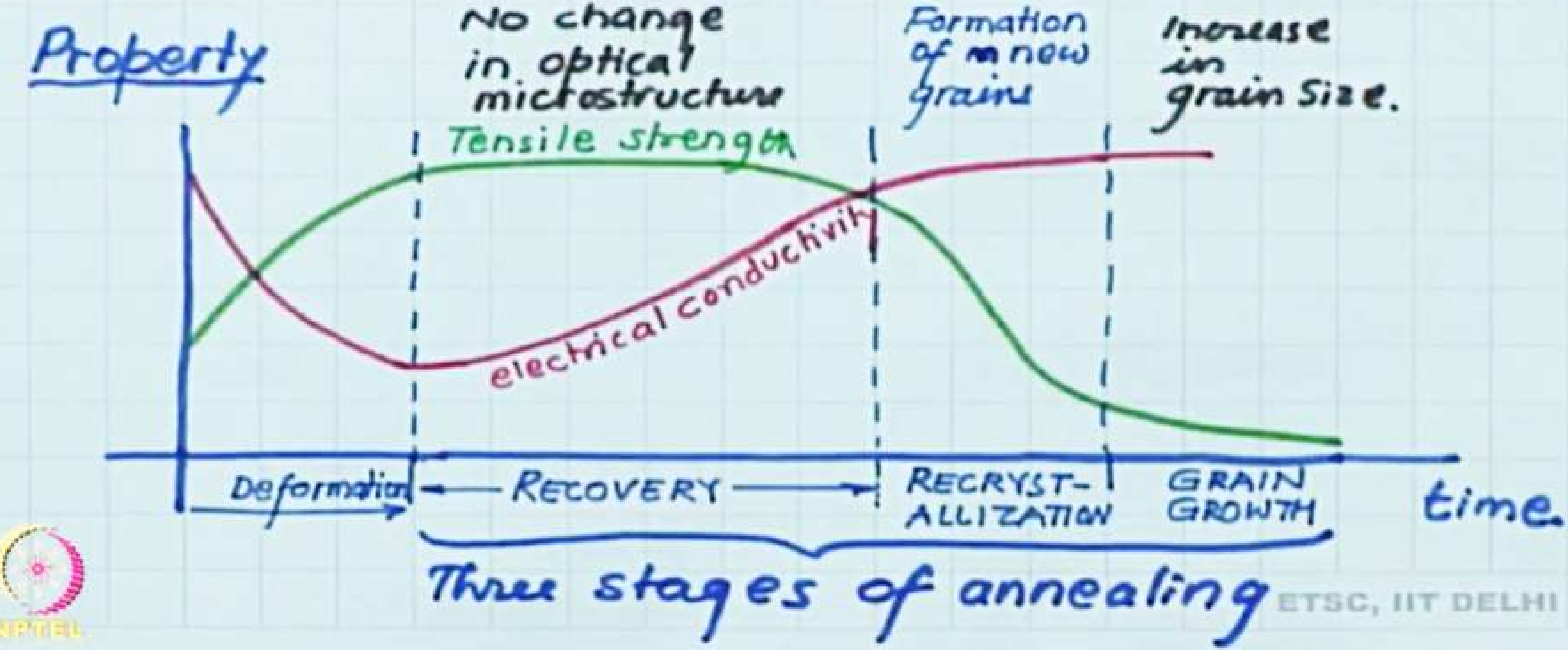
COLD-WORKING:

1. Defect density increases
   - increase in point defects
   - increase in dislocation density

2. Change in grain shape.

3. Increase in strain energy (due to #1)

ANNEALING:


Property
No change in optical microstructure
Formation of new grains
Increase in grain size.
Tensile strength
electrical conductivity
Deformation
RECOVERY
RECRYSTALLIZATION
GRAIN GROWTH
time
Three stages of annealing

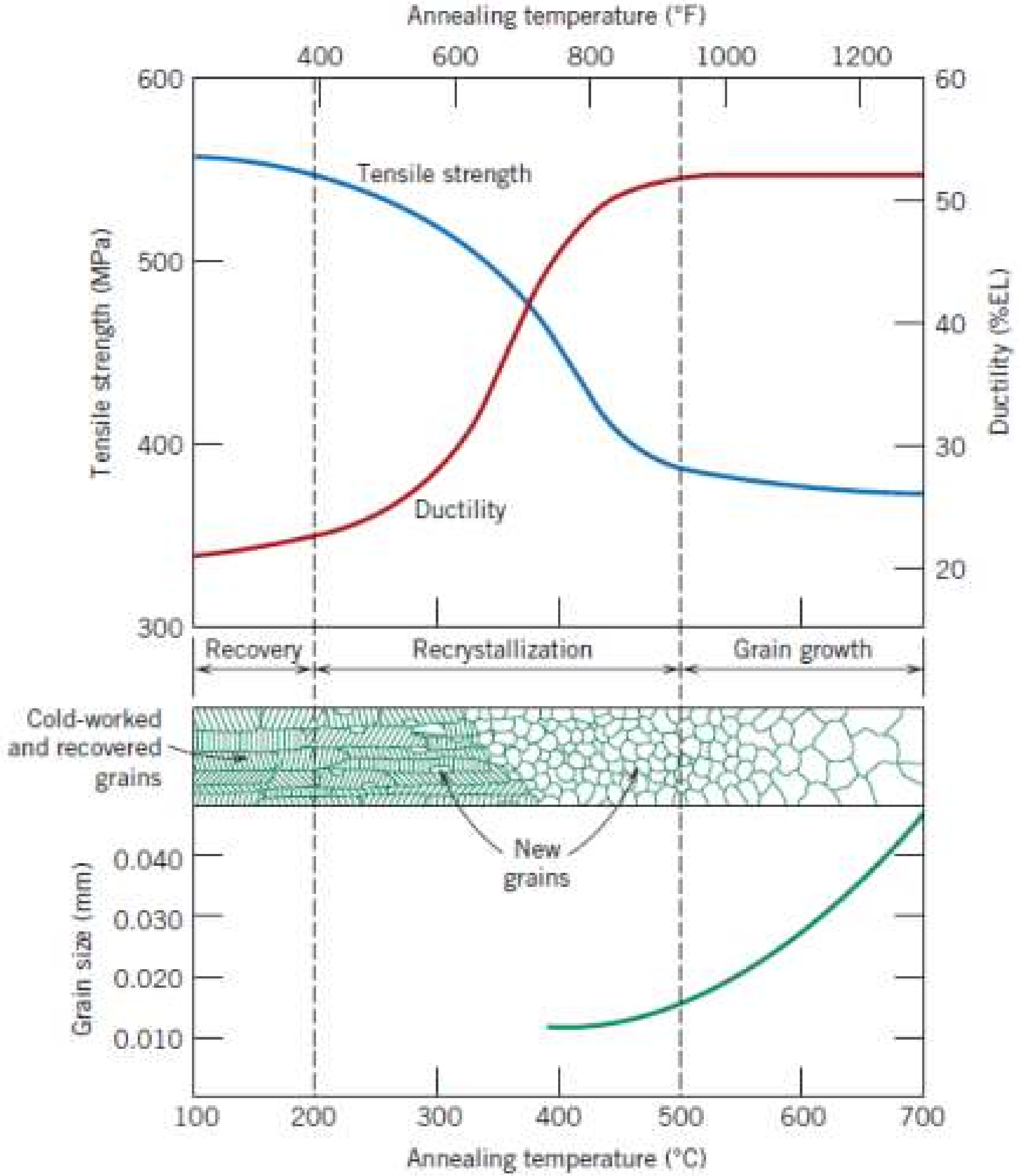


Figure 7.22 The influence of annealing temperature (for an annealing time of 1 h) on the tensile strength and ductility of a brass alloy. Grain size as a function of annealing temperature is indicated. Grain structures during recovery, recrystallization, and grain growth stages are shown schematically. (Adapted from G. Sachs and K. R. Van Horn, *Practical Metallurgy, Applied Metallurgy and the Industrial Processing of Ferrous and Nonferrous Metals and Alloys,* American Society for Metals, 1940, p. 139.)

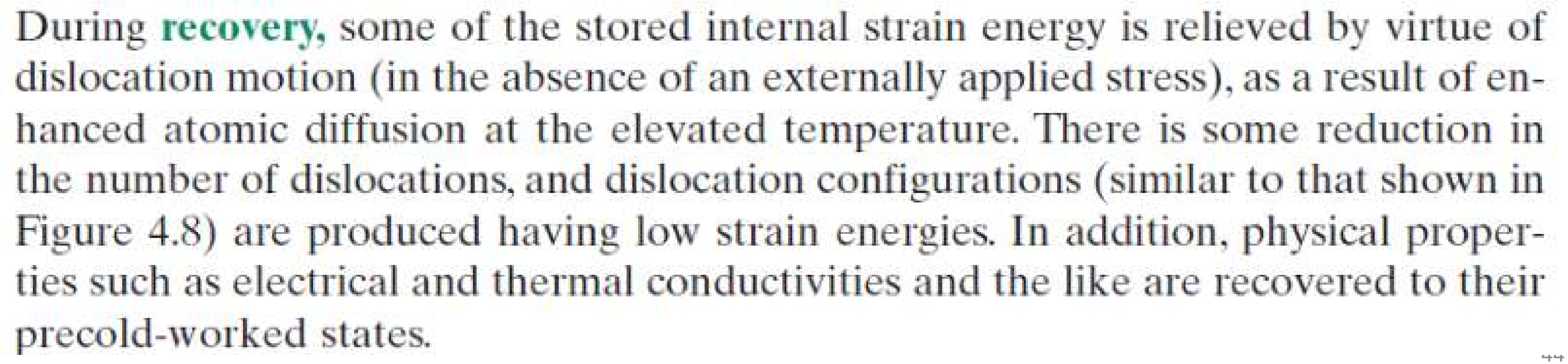
Recovery, Recrystallisation & Grain Growth

The phase transformation taking place during *annealing* can be divided into 3 stages:

1. Recovery,
2. Recrystallisation,
3. Grain growth.

Recovery

- Happens during initial stage of annealing,
- Low temperature process,
- Microstructure is not affected,
- Internal stresses are released,
- Mechanical properties remains unchanged.



During **recovery,** some of the stored internal strain energy is relieved by virtue of dislocation motion (in the absence of an externally applied stress), as a result of enhanced atomic diffusion at the elevated temperature. There is some reduction in the number of dislocations, and dislocation configurations (similar to that shown in Figure 4.8) are produced having low strain energies. In addition, physical properties such as electrical and thermal conductivities and the like are recovered to their precold-worked states.

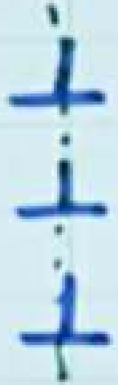
Effects of Recovery

1. **Point Defects:**
   Density decreases : to surfaces or gb.
   Dislocation climb up : decrease in vac.
2. **Dislocations of opposite sign**

Come together and annihilate.

3. **Dislocation of same sign**

form low angle tilt (edge) or twist (screw) boundaries.



Low angle tilt boundary.

Recrystallisation

- As annealing temperature & internal energy rises, the atoms break free to form new crystals.
- New grains are formed from a group of atoms called nucleus.
- The nucleus will grow in size until the elongated grains of the deformed material is completely transformed into strain free equiaxed grains.
- Internal energy is released completely during recrystallisation process.

Recrystallisation:

Replacement of deformed crystals of high dislocation density by strain free crystals of low dislocation density.

Driving force: Strain energy associated with dislocations.

Recrystallisation Temperature:

A temperature at which 50% recrystallisation happens in 1 hr.

Effect on recrystallisation of different process variables:

1. **Degree of prior deformation**

   Higher the prior deformation, higher is the stored energy ⇒ Higher driving force ⇒ Lower recrystallisation temp. + finer recrystallised grains

2. **Initial Grain Size**

   Finer Initial grain ⇒ Lower recrystallisation temp + finer recrystallised grain size.

Effect of processing variables on recrystallization (contd.)

3. Temperature of Cold Working:

Lower temp. of CW → Higher strain energy

→ Higher driving force

→ Lower recrystallization temperature

4. Temperature of recrystallisation:

Recrystallization rate depends exponentially on temperature

$$\text{rate} = A \exp\left(-\frac{Q}{RT}\right)$$

← Activation energy for recrystallization

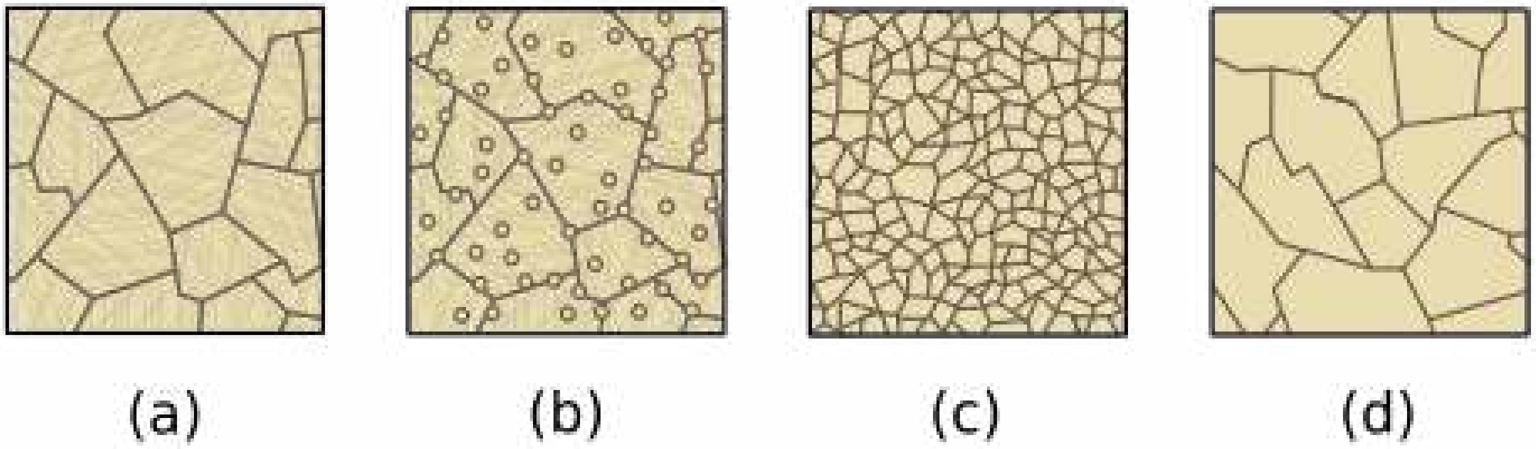
Effect of Solute Atoms and Second Phase

Solute atoms and second phase particles hinder the motion of grain boundaries during recrystallisation.

→ Lower recrystallisation rate

or Higher " temperature.

Stages of Recrystallisation



(a) Elongated & Deformed grains,
(b) Nuclei formation, **(c)** New grains growing from nuclei,
(d) Equiaxial grains after recrystallisation

Grain Growth

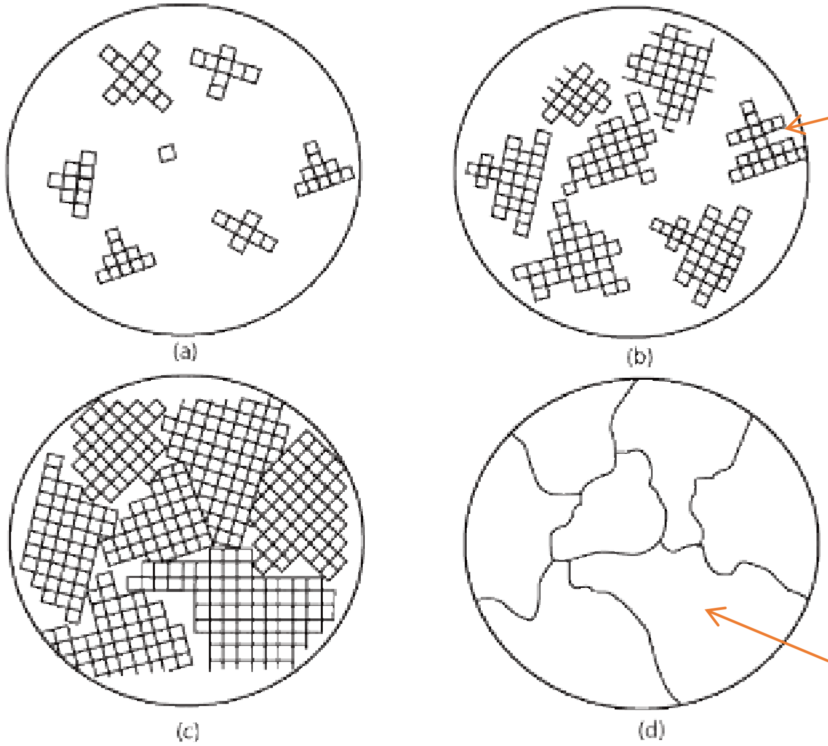
- Grain growth happens when the specimen is kept at elevated temperature after recrystallisation.
- After recrystallisation the grains will continue to grow and will become coarse.
- This phenomenon is termed as grain growth.

Grain Growth:

Increase in the average grain size and decrease in the number of grains

Driving force: Reduction in surface energy associated with grain boundaries.

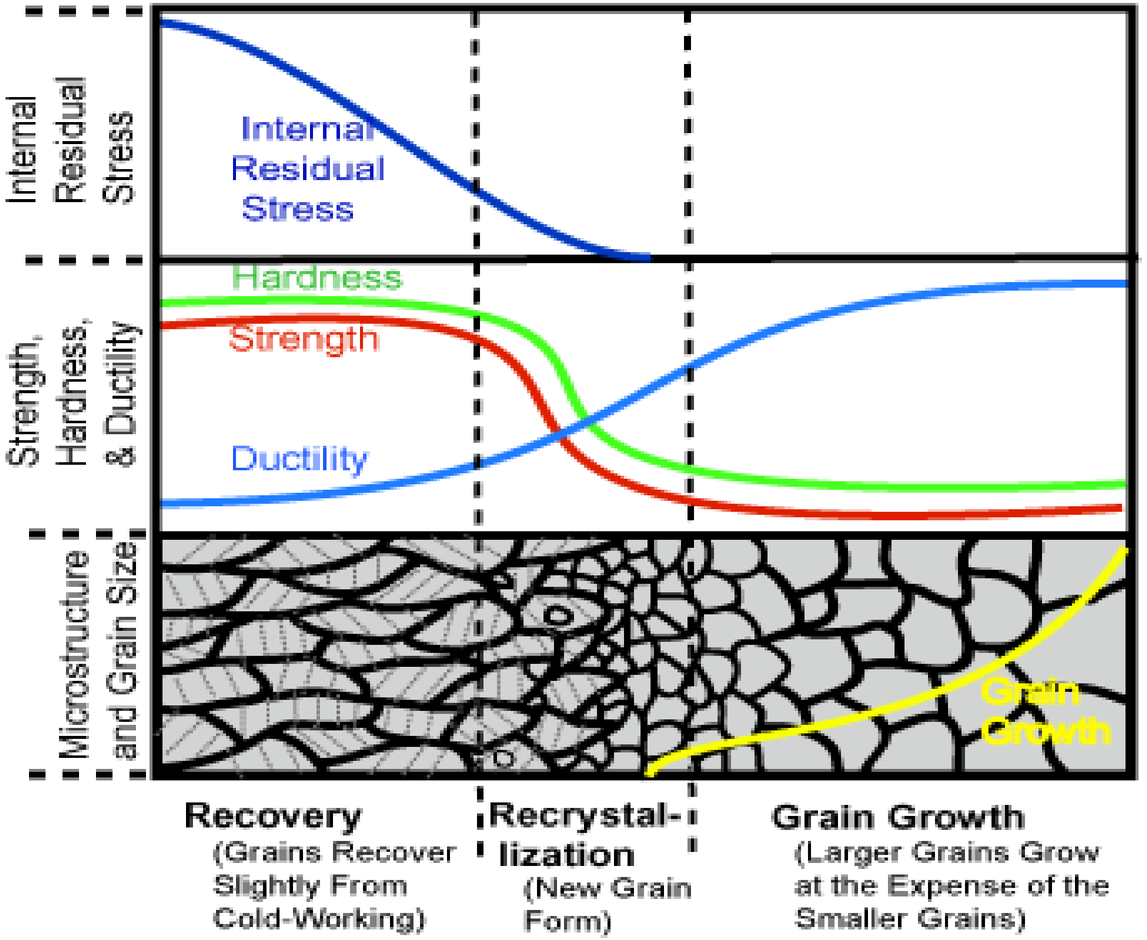
Grain Growth



Fine grains during recrystallisation

Coarse grains after grain growth

Hardness, Strength & Ductility during recovery, recrystallisation & grain growth



Cold working Vs Hot working

Cold working: Mechanical working is done with out raising the temperature.

- After cold working, the grains will be in distorted condition.
- Cold working will affect tensile strength, yield strength, hardness & electrical conductivity.

Hot working: Mechanical working is done above the recrystallisation temperature.

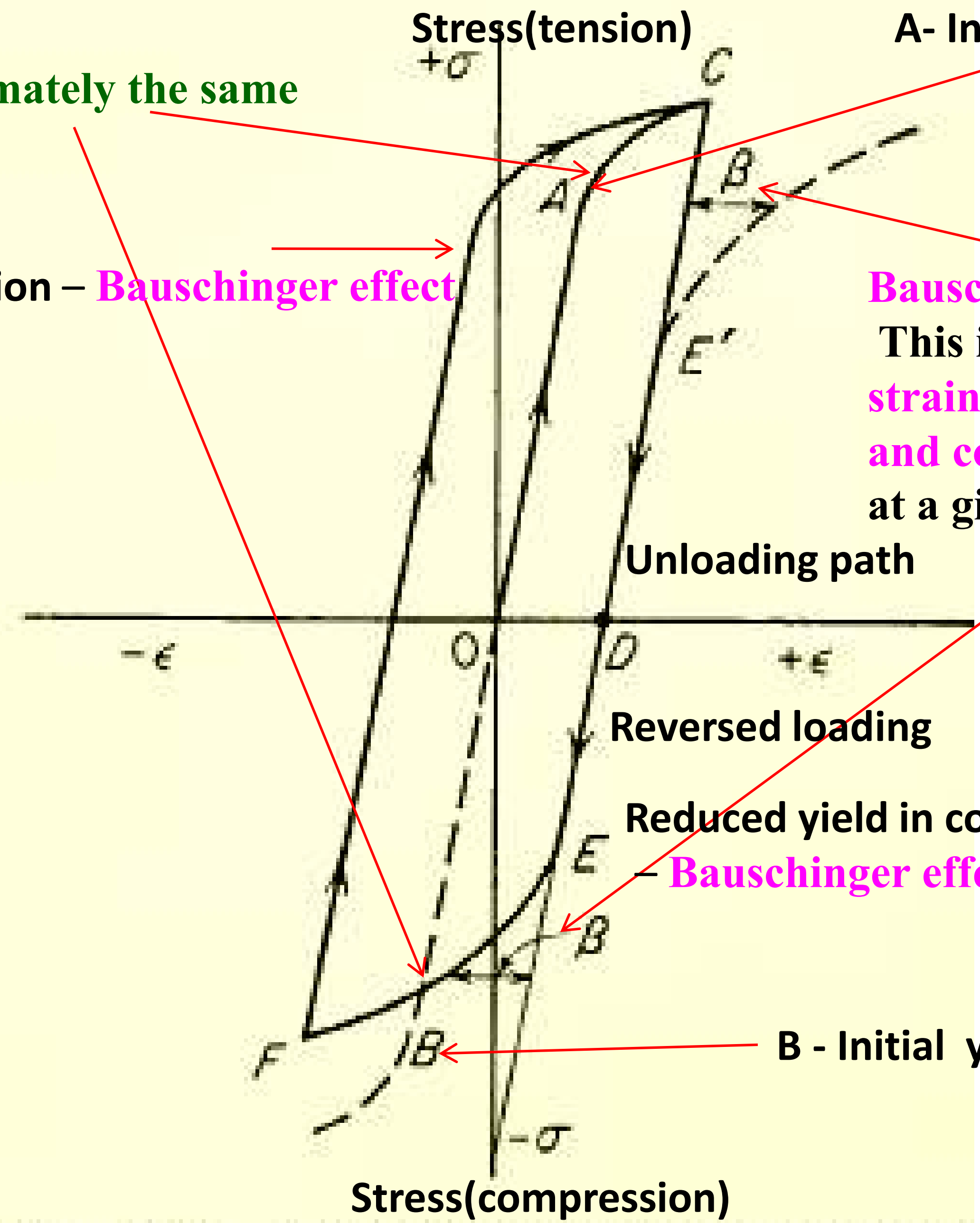
- Specimen will become soft & ductile after hot working.

Bauschiner Effect

- During plastic deformation, dislocations will move along slip planes and gets piled up at various barriers.
- These dislocation pile ups **develops a back stress**, which will be directed opposite to the applied stress.
- If the direction of applied stress is reversed, deformation will occur in the reverse direction.
- Now the back stress developed will support the dislocation movement.
- Due to this, the deformation will be initiated at a lower applied stress.
- This lowering of yield stress when deformation in one direction is followed by deformation in opposite direction is called ***Bauschiner Effect.***

The initial yield stress of the material in tension is A. If the same ductile material were tested in compression, the yield strength would be approximately the same, point B on the dashed curve.

Now, consider that a new specimen is loaded in tension past the tensile yield stress to C along the path OAC. If the specimen is then unloaded, it will follow the path CD, small elastic-hysteresis effects being neglected. If now a compressive stress is applied, plastic flow will begin at the stress corresponding to point E, which is appreciably lower than the original compressive yield stress (point B) of the material. While the yield stress in tension was increased by strain hardening from A to C, the yield stress in compression was decreased. This is the Bauschinger effect.



Stress(tension)

A- Initial yield in tension

A and B are approximately the same

Reduced yield in tension – Bauschinger effect

Bauschinger strain β
This is the difference in strain between the tension and compression curves at a given stress.

Unloading path

Reversed loading

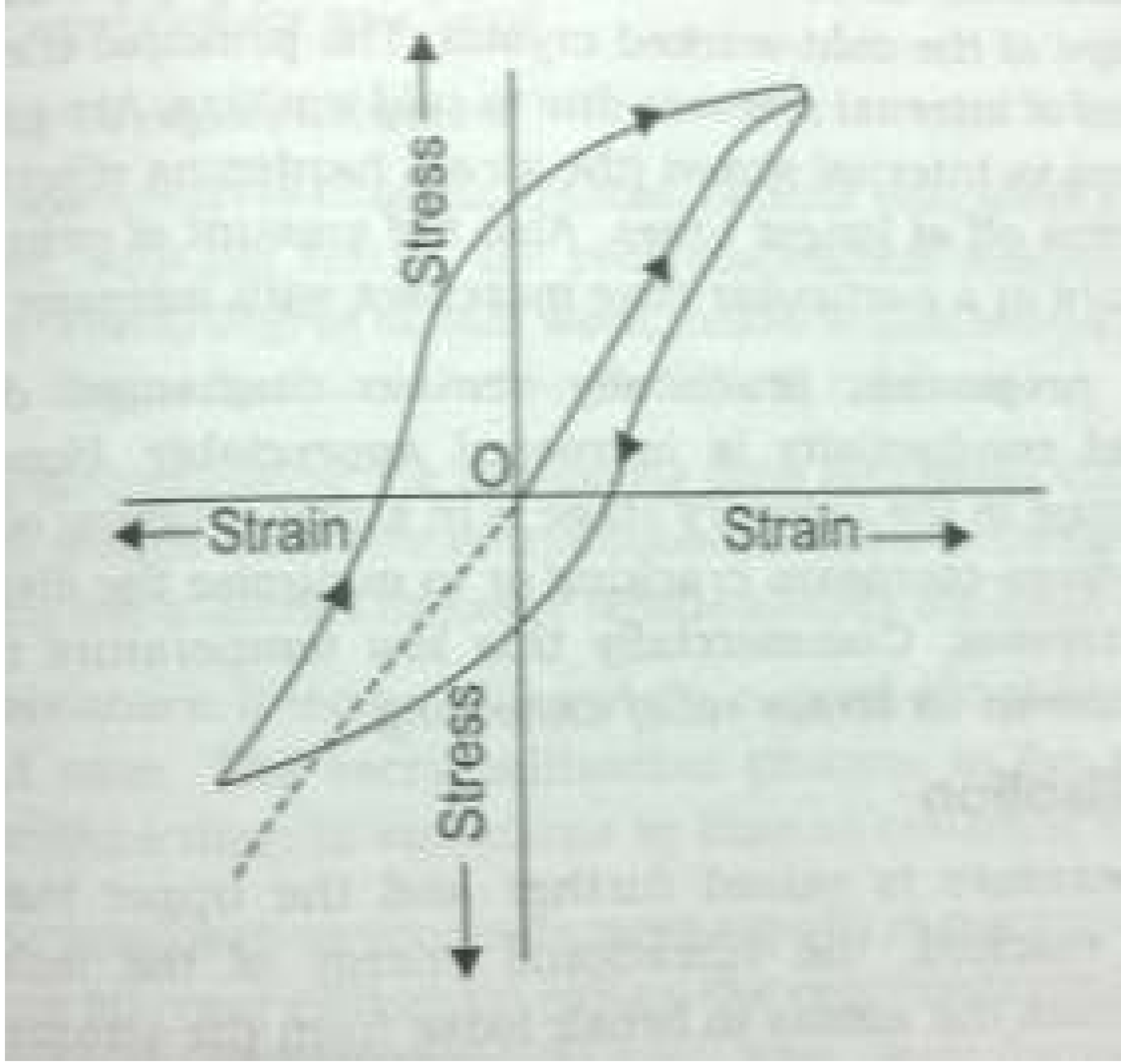
Reduced yield in compression
– Bauschinger effect

B - Initial yield in compression

Stress(compression)

Fig. 5-19. Bauschinger effect and hysteresis loop.

Bauschiner Effect



- The phenomenon is reversible, for had the specimen originally been stressed plastically in compression, the yield stress in tension would have been decreased. One way of describing the amount of Bauschinger effect is by the Bauschinger strain β . This is the difference in strain between the tension and compression curves at a given stress. If the loading cycle is completed by loading further in compression to point F, then unloading, and reloading in tension, a mechanical-hysteresis loop is obtained. The area under the loop will depend upon the initial overstrain beyond the yield stress and the number of times the cycle is repeated. If the cycle is repeated many times, failure by fatigue is likely to occur. The Bauschinger effect plays an important role in mechanical processing of steels and other alloys.

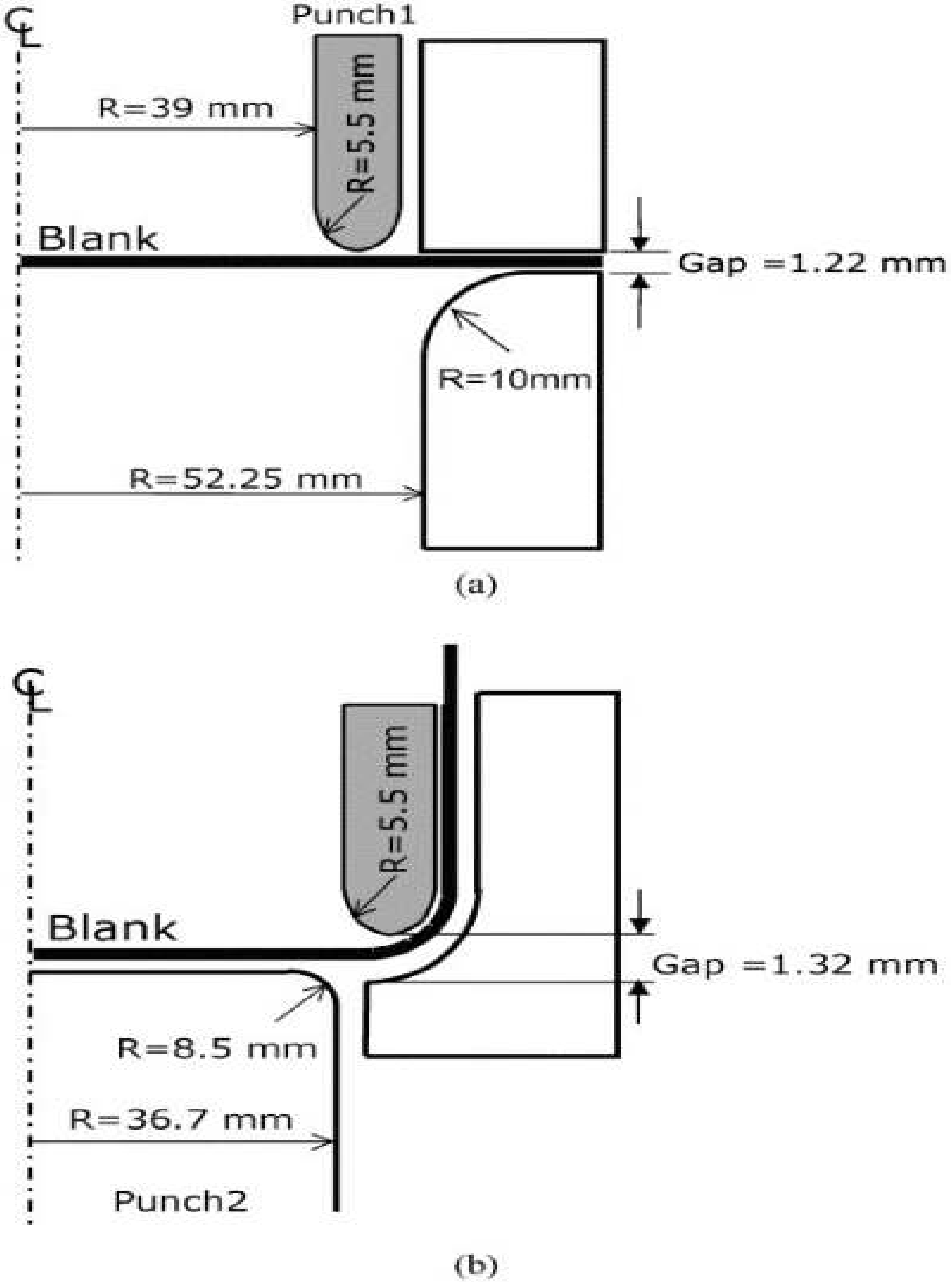
Courtesy - Dieter

- **Bauschinger effect** may be reduced by thermal treatment. Complete removal is possible only by recrystallization of strained material. However, it may be reduced by stress aging which is a process

  of heating the material to a certain temperature while it is subjected to suitable value of stress. By this process **Bauschinger effect** may be reduced at a low temperatures (less than 200°C).

- The Bauschinger effect contributes to work softening of the workpiece, for example in straightening of drawn bars or rolled sheets, where rollers subject the workpiece to alternate bending stresses, thereby reducing the yield strength and enabling greater cold drawability of the workpiece.

The cylindrical cup reverse drawing test is composed of two stages; forward draw and reverse draw.

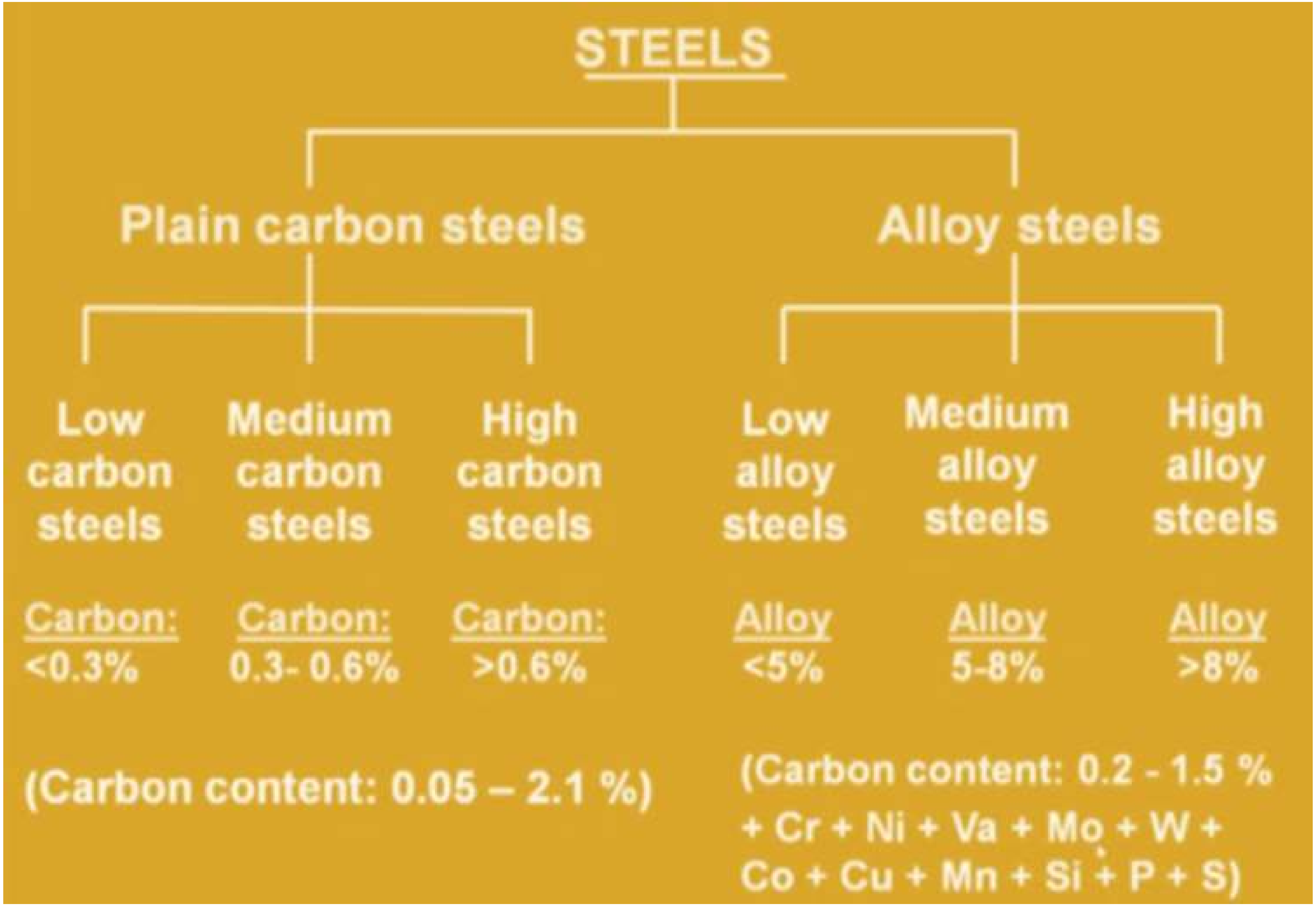


Alloying

- An alloy is a substance that has metallic properties and is composed of two or more chemical elements, of which at least one is metal.
- During alloying impurity atoms are intentionally added to impart specific properties to material such as improved strength, corrosion resistance etc.

Steels - classification

- Steels – Alloys containing up to 2.14 % C
- Cast Iron – 2.1 to 4.3% C
- Plain Carbon Steels: C is the main alloying element
- Alloy steels: in addition to C, one or more other metallic elements also present
- Low C steels: 0.1 to 0.25%
- Medium C steels: 0.25 to 0.6%
- High C steels: 0.6 to 1.4%



STEELS

Plain carbon steels

- Low carbon steels
  - Carbon: <0.3%
- Medium carbon steels
  - Carbon: 0.3- 0.6%
- High carbon steels
  - Carbon: >0.6%

(Carbon content: 0.05 – 2.1 %)

Alloy steels

- Low alloy steels
  - Alloy <5%
- Medium alloy steels
  - Alloy 5-8%
- High alloy steels
  - Alloy >8%

(Carbon content: 0.2 - 1.5 % + Cr + Ni + Va + Mo + W + Co + Cu + Mn + Si + P + S)

Effect of alloying elements on Steel

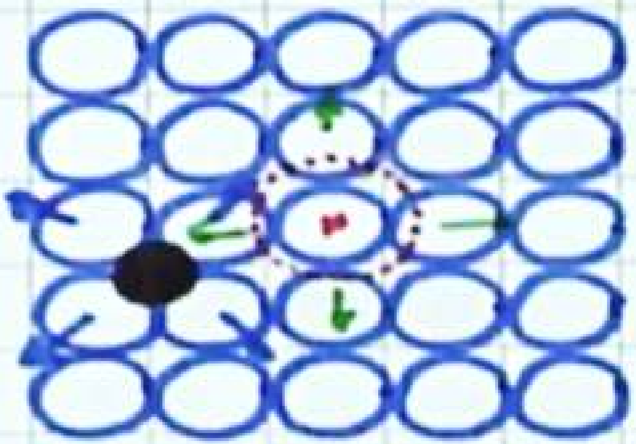
1. Dislocation movement
2. Polymorphic transformation temperature
3. Formation & Stability of carbides
4. Grain growth
5. Displacement of eutectoid point
6. Retardation of the transformation rates
7. Improvement in corrosion resistance
8. Mechanical properties

1. Effect of alloying elements on dislocation movement

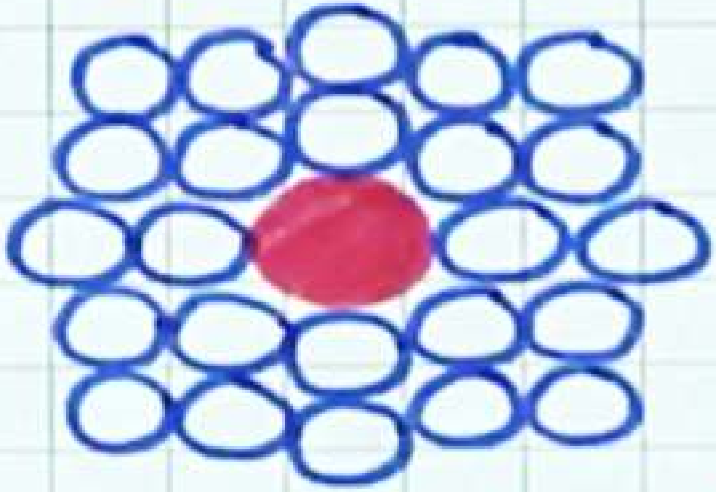
- During alloying new atoms are introduced to the crystal structure.
- These added atoms will act as a barrier to dislocation motion to propagate
- Since dislocation is prevented the strength of material is increased.
- So simply, alloying prevents dislocation movements.

- Introduction of impurity atoms creates a pinning point for dislocations
- An alloying element is by nature a point defect
- It creates a stress field (due to size) when placed in to another crystallographic position
- The alloying atom may have a different elastic modulus
- Reduce dislocation mobility; increase strength and hardness

Higher size difference ⇒ higher strain



pure element



● Substitutional solute

Strain field around the solute atom.

This strain field interacts with strain field of a dislocation.

⇒ Impediment in dislocation motion.

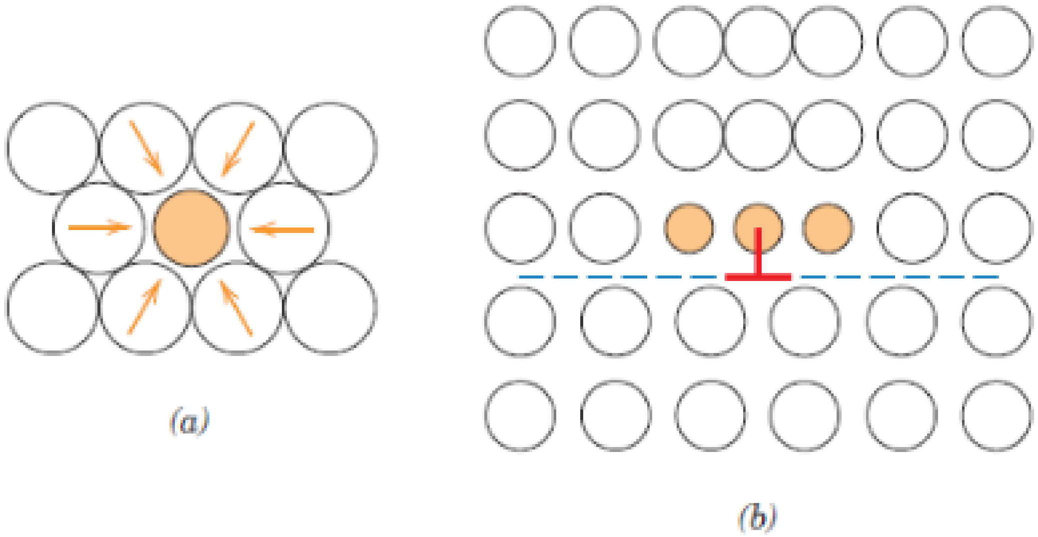

(a)
(b)

Figure 7.17 (*a*) Representation of tensile lattice strains imposed on host atoms by a smaller substitutional impurity atom. (*b*) Possible locations of smaller impurity atoms relative to an edge dislocation such that there is partial cancellation of impurity–dislocation lattice strains.

- Alloys are stronger than pure metals because impurity atoms that go into solid solution ordinarily impose lattice strains on the surrounding host atoms.
- Lattice strain field interactions between dislocations and these impurity atoms result, and, consequently, dislocation movement is restricted.

2. Effect of alloying elements on Polymorphic transformation temperature

- α-γ transformation at A3 (912˚C) and γ-δ transformation at A4 (1394˚C)
- δ –ferrite, γ-austenite, α-ferrite exist in distinct regions of phase diagram.
- Mo, Cr, W, Si, V, Ti raise the A3 temp and lower the A4 temp…….
- Contract γ region and enlarge ferrite region.
- Ni, Mn, Cu, Co has the opposite effect.
- Cr, Mo, and W form very stable carbides and favour precipitation of carbides.
- In second case carbon tends to remain in solid solution in the austenite.

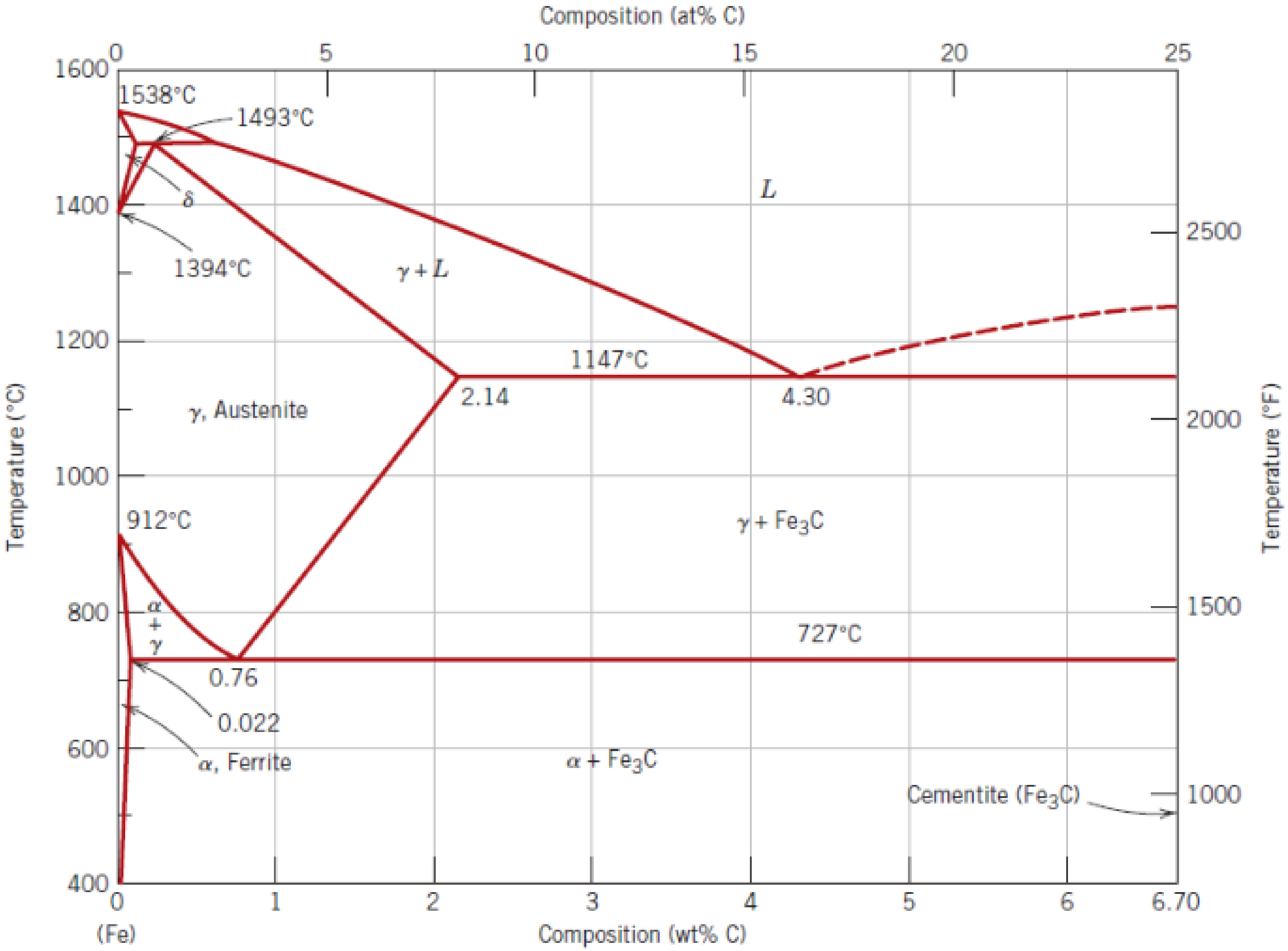


Figure 9.24 The iron–iron carbide phase diagram. [Adapted from *Binary Al*

3. Effect of alloying elements on formation of carbides

- Alloying elements combines with carbon in steel and form carbides.
- The hard carbides formed will increase the hardness, brittleness & wear resistance.
- Carbides of Cr and V have very high hardness and wear resistance.
- Also act to reduce grain growth.
- Ni, Al, Si don’t form carbides in the presence of iron and causes instability of iron carbide.
- Ti and Niobium have very strong carbide forming tendencies.
- Cr, Mo, W, V, Mn also form carbides.
- When more than one is added Complex carbides formed.
- Eg: TiC

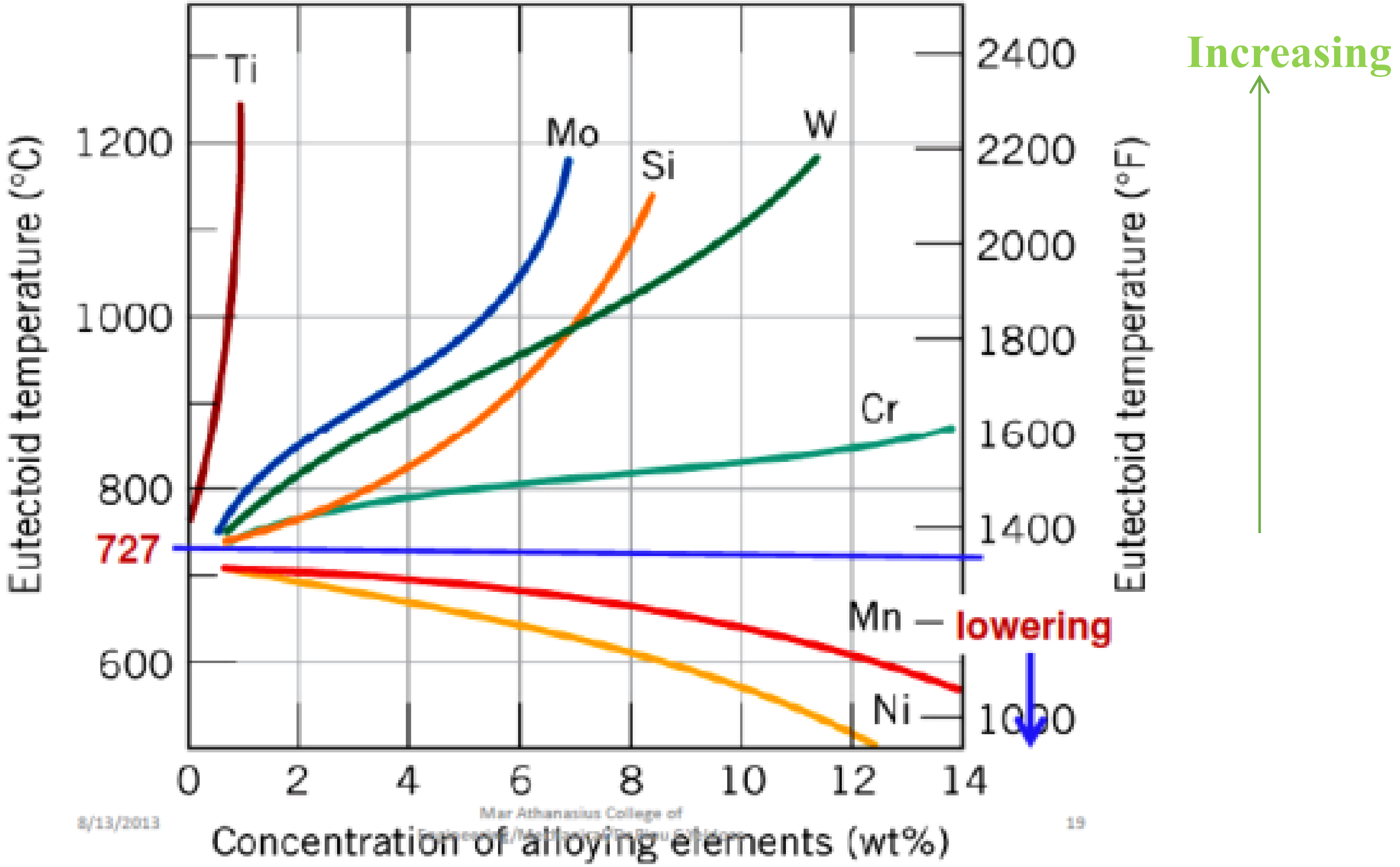
4. Effect of alloying elements on Grain growth

- Accelerate grain growth and increase brittleness
- Cr is the most important
- Ni, V retard grain growth
- Grain refiners

5. Effect of alloying elements on displacement of Eutectoid point.

- Affects equilibrium conditions.
- The addition of any alloying element to carbon steel diminishes the solubility of carbon in austenite and so results in a displacement of the eutectoid point towards the left of the equilibrium diagram.
- Change position of eutectoid point and the positions of α and δ phase fields
- Eg: Addition of 2.5% Manganese to steel containing 0.65% carbon will give it a completely pearlitic structure in the normalised condition, along with a reduction in the eutectoid temperature to about 650°C
- Presence of Ni and Mn lowers the Eutectoid temperature

Effect of 7 different alloying elements on displacement of eutectoid point.



6. Effect of alloying elements on retardation of transformation rates

- Alloying has got high influence in phase transformation rates.
- Austenite transformation temp is shifted up or down by alloying elements
- Ni and Mn content lower Austenite transformation temp – postpone transformation of Austenite on slow cooling
- Austenite stabilizers.

7. Effect of alloying elements on corrosion resistance

- Alloying of elements has got good influence in corrosion resistance.
- Eg: Alloying **Al/ Si/ Cr** with steel will form thin oxide layers on the surface. This layer will improve corrosion resistance of the material.

8. Effect of alloying elements on mechanical properties

- Mechanical properties of a material is greatly influenced by the presence of alloying elements.
- Eg: Alloying Iron with Carbon.

Enhancement of steel properties by adding…

1. Molybdenum
2. Nickel
3. Chromium
4. Vanadium
5. Tungsten
6. Cobalt
7. Silicon
8. Copper
9. Lead
10. Sulphur
11. Titanium
12. Aluminium
13. Boron
14. Phosphorus

Effect on properties of steel by adding Molybdenum (0.1-0.4%)

1. Promotes hardenability of steel
2. Makes steel fine grained
3. Makes steel unusually tough at various hardness levels
4. Counteracts tendency towards temper brittleness
5. Raises tensile and creep strength at high temperatures
6. Enhances corrosion resistance in stainless steels
7. Forms abrasion resisting particles.

Effect on properties of steel by adding
Nickel (1.0-5.0%)

1. Increases toughness and resistance to impact
2. Reduces distortion in quenching
3. Lowers the critical temperatures of steel and widens the range of successful heat treatment
4. Strengthens steels
5. Renders high-chromium iron alloys austenitic
6. Does not unite with carbon.

Effect on properties of steel by adding Chromium (0.5-4.0%)

❖ Combines with carbon to form chromium carbide, thus increases hardenability & improves…

1. Resistance to abrasion and wear
2. Corrosion resistance
3. Resistance to oxidation
4. Strength

Effect on properties of steel by adding Vanadium (0.1-0.3%)

1. Promotes fine grains in steel
2. Increases hardenability (when dissolved)
3. Imparts strength and toughness to heat-treated steel
4. Causes secondary hardening.

Effect on properties of steel by adding Tungsten (2.0-3.0%)

1. Increases hardness (and also red-hardness)
2. Promotes fine grains
3. Resists heat
4. Promotes strength at elevated temperatures.

Effect on properties of steel by adding
Cobalt (5.0-10.0%)

1. Contributes to red-hardness by hardening ferrite
2. Improves mechanical properties such as tensile strengths, fatigue strength and hardness
3. Refines pearlite
4. Is a mild stabilizer of carbides
5. Improves heat resistance
6. Retards the transformation of austenite and thus increases hardness and protection from cracking and distortion.

Effect on properties of steel by adding Silicon (1.5-2.5%)

- Removes oxygen from molten metal
- Improves,

1. Strength
2. Toughness
3. Magnetic properties

Effect on properties of steel by adding Copper (0.15-0.25%)

❖ Improves

1. Corrosion resistance
2. Strength
3. Hardness

Effect on properties of steel by adding
Lead (0.10-0.30%)

- Improves machinability.

High Speed Steel (HSS)

- Composition: 18% Tungsten, 4% Chromium, 1% Vanadium, Carbon 0.6%, Iron – Remaining.

- Advantages:

1. Maintains hardness at high temperature (600° C)
2. Presence of carbides improves wear resistance
3. Increased shock resistance
4. Good machinability.

Types of High Speed Steel

1. Tungsten HSS,
2. Molybdenum HSS

Tungsten HSS

- Tungsten HSS contains tungsten as dominant alloying element along with Cromium, Vanadium & Cobalt.
- Eg: 18W4Cr1V HSS or 18:4:1 HSS

Molybdenum HSS

- Molybdenum HSS consists of tungsten, chromium, vanadium, cobalt & molybdenum.
- Eg: 6W6Mo4Cr1V or 6:6:4:1 HSS

Effect of different alloying elements on HSS

1. Cobalt- Improves hardness
2. Vanadium- Improves hardness & abrasion resistance
3. Chromium- Improves hardness
4. Silicon- Improves toughness
5. Tungsten & Molybdenum- Prevents softening at high temperatures
6. Manganese- Improves hardness of HSS

Cast Iron

Iron – Carbon alloys containing more than 2% carbon are called cast iron.

❖ Properties

1. Low melting temperature (About 1200° C)
2. Cast iron is brittle & has low tensile strength
3. High compressive strength
4. Ability to absorb vibrations (Damping capacity)
5. High heat & corrosion resistance.
6. Have high wear resistance
7. Have high hardness
8. Process good machinability
9. Can be cast in to intricate shapes

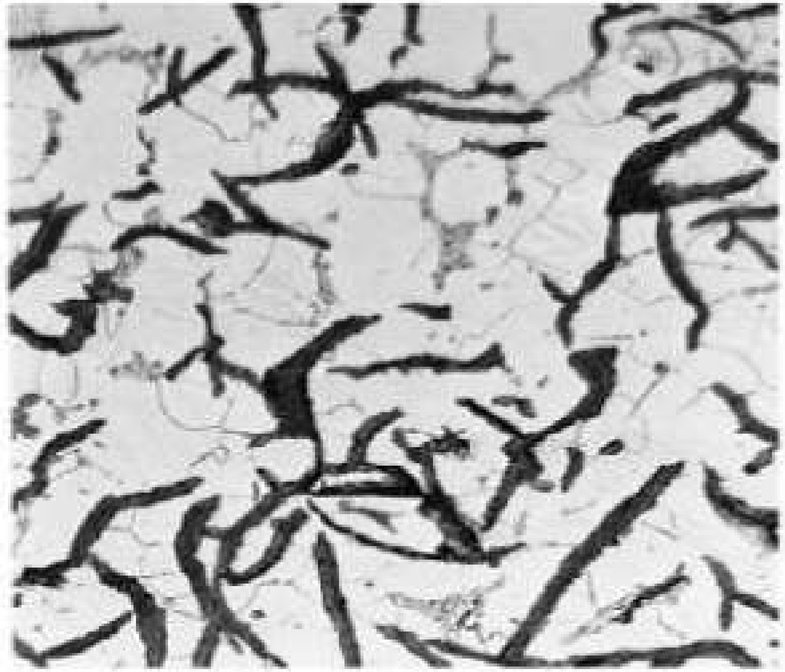
- Cast iron is made by re-melting pig iron, often along with substantial quantities of scrap iron and scrap steel.
- During melting various steps are taken to remove undesirable contaminants such as phosphorus and sulfur.
- Depending on the application , carbon and silicon contents are reduced to the desired levels

Types of cast iron

1) Grey cast iron
2) White cast iron
3) Malleable cast iron
4) Ductile/ Nodular/ Spheroidal Graphite cast iron.

1. Grey cast iron

- If cast iron is **cooled slowly**, graphitization takes place and graphite flakes will get a chance to form.
- Carbon 2.5 - 4% + Silicon 1.0 - 3% + Manganese (Max 1.0 %) + Sulpher (max 0.25%) + Phosphorous (max 1%) + Iron (Remaining)
- Carbon is present in a free form (graphite) in a matrix of ferrite and pearlite.



Gray Cast Iron

❖Properties

- Shows poor strength during tensile loading
- Performs well during compressive loading.
- Low melting point, good castability, good wear resistance.

❖Advantages

- Graphite act as a chip braker
- Graphite act as a lubricant during machining
- Good dry bearing qualities due to graphite
- High castability

❖Disadvantages

- Highly brittle
- Graphite act as a void and reduces strength
- Change in section size will cause variations in machining characteristics due to variation in microstructure
- High strength gray cast irons are more expensive to produce

Applications

Applications of Gray Cast Iron

Pump housings

Engine head

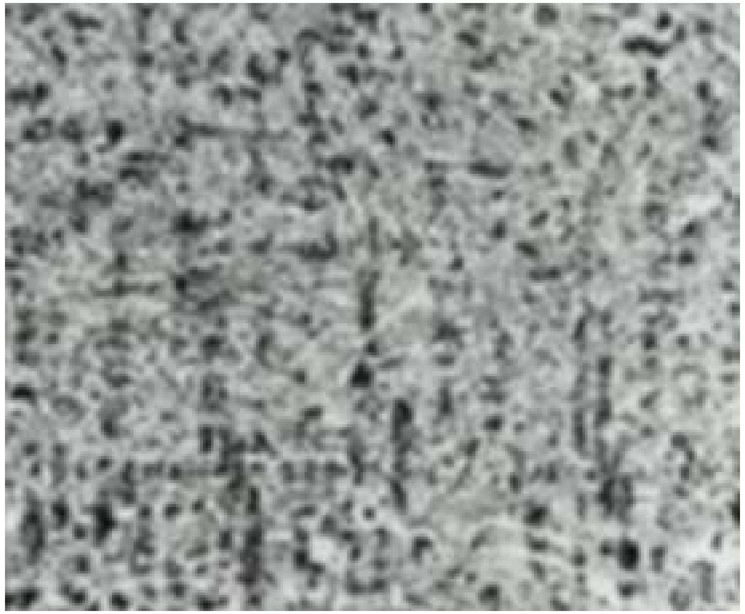
Sanitary pipes

Machine-tool bases

Flywheels

2. White Cast Iron

- If cast iron is **cooled rapidly** , the graphite flakes do not get a chance to form
- Instead , white cast iron forms with cementite
- Carbon 1.8-3.6% + Silicon 0.5-1.9% + Manganese (0.25-0.8%) + Sulpher (0.2%) + Phosphorous (0.18%) + Iron (Remaining)
- Carbon is present in a combined form (Fe_3C) which is known as Cementite.



❖Properties

- Hard & brittle,
- Machinability is poor
- Good wear resistance & compressive strength

❖ Applications

- Brake shoes, Mining Shovels, Rolls for rolling mills, Rail car brake shoes, liners in machinery for processing abbressive materials.

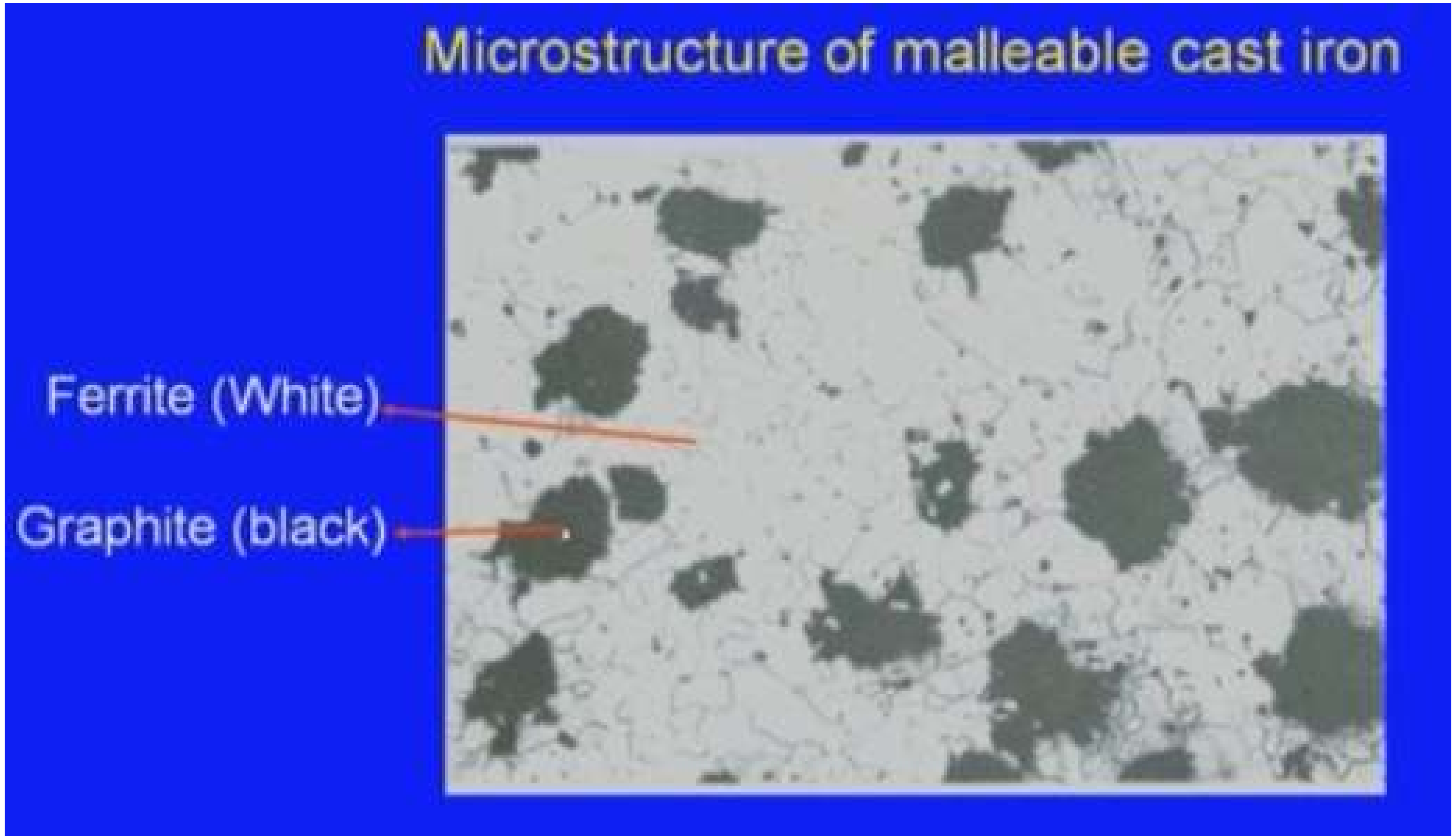
3. Malleable Cast Iron

- Malleable cast iron is obtained from white cast iron, but with improved malleability
- Prepared by Reheating white cast iron to 927^{o} C for a long periods of time in the presence of materials containing oxygen, such as iron oxide.
- At elevated temperature cementite (Fe_3C) decomposes into ferrite and free carbon
- Upon cooling, the combined carbon further decomposes to small compact particles of (instead of flake like graphite in Gray cast iron)
- This free carbon is referred to as temper carbon, and the process is called Malleabilising.

- Carbon 1.8-3.6% + Silicon 0.5-1.9% + Manganese (0.25-0.8%) + Sulpher (0.2%) + Phosphorous (0.18%) + Iron (Remaining)
- Carbon is present in the form of **'Tempered Carbon Packets'**

❖ Properties:

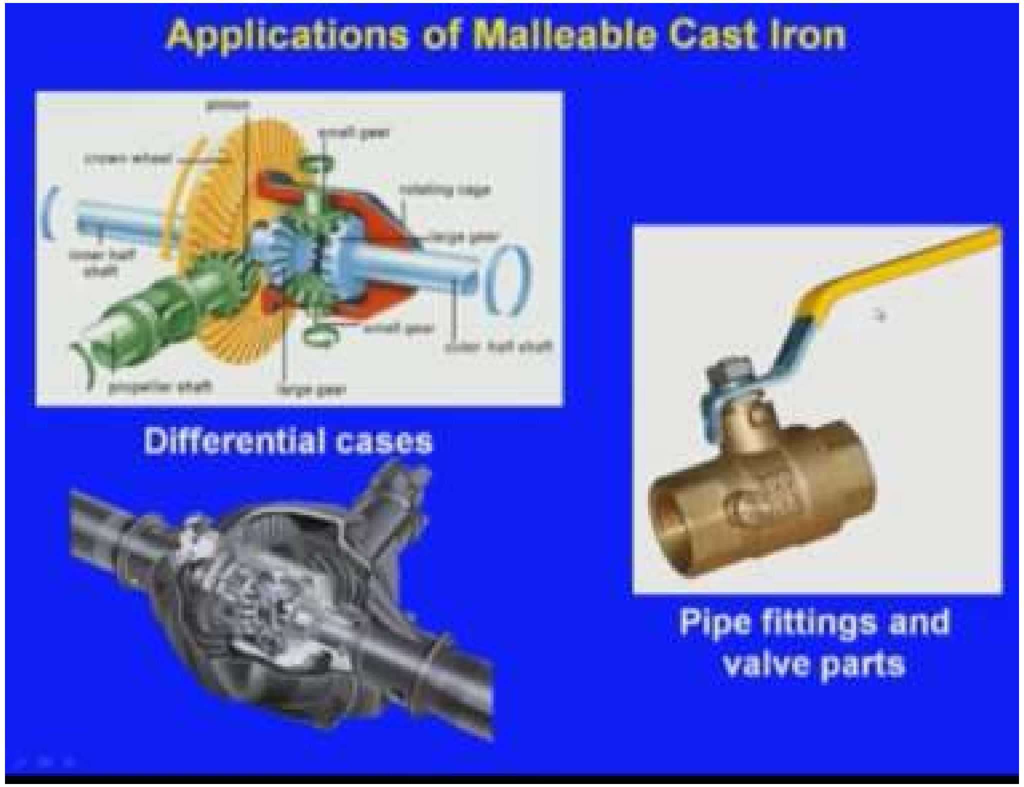
- Possess good mechanical & physical properties
- Good vibration & wear resistance
- Used for making brake drums, cam shafts & crank shafts



- Advantages:
    - Excellent Machinability
    - Significant Ductility
    - Good Shock resistance properties
- Disadvantages:
    - Malleable cast iron undergoes excessive shrinkage during solidification
    - As a result, large feeders are required.

Applications of Malleable Cast Iron

1. Universal joint yokes
2. Transmission gears
3. Difierential cases
4. Crankshafts and hubs
5. Flanges
6. Pipe fittings and valve parts
7. Marine and other heavy-duty applications



Applications of Malleable Cast Iron

Differential cases

Pipe fittings and valve parts

4. Ductile/ Nodular/ Spheroidal Graphite Cast Iron

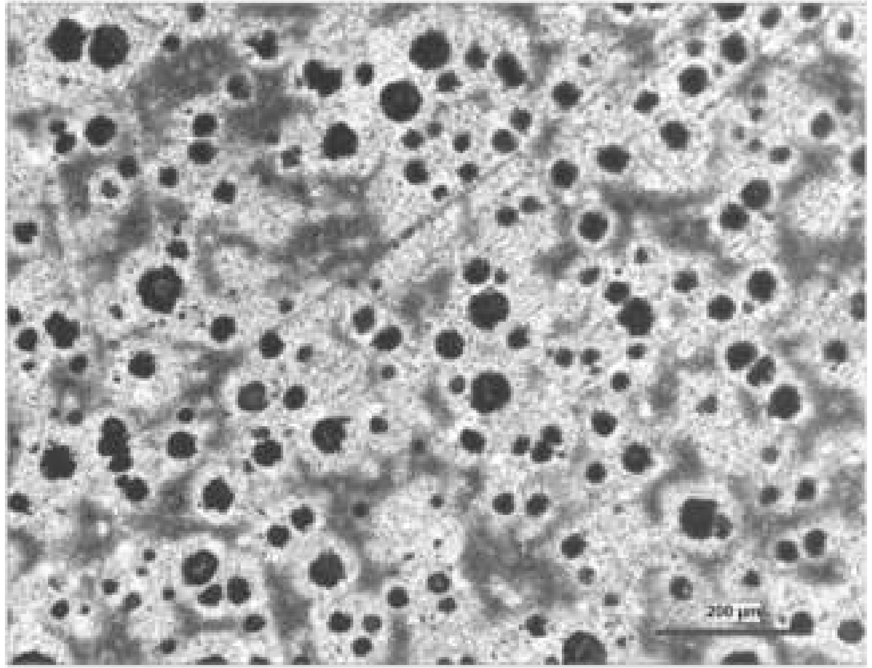
- In spheroidal graphite cast iron, graphite is present in form of **spherical nodules** rather than flakes, thus inhibiting the creation of cracks and providing the enhanced ductility that gives the alloy its name.
- Mg, Ce, Ca or other spheroidizing elements are added in very small quantity.
- The elements added to promote spheroidization react with the solute in the liquid, to form heterogeneous **nucleation sites**.
- The alloying elements are injected into mould before pouring.
- Carbon is present in the form of ‘Speroids’ or Nodules.

❖Composition:

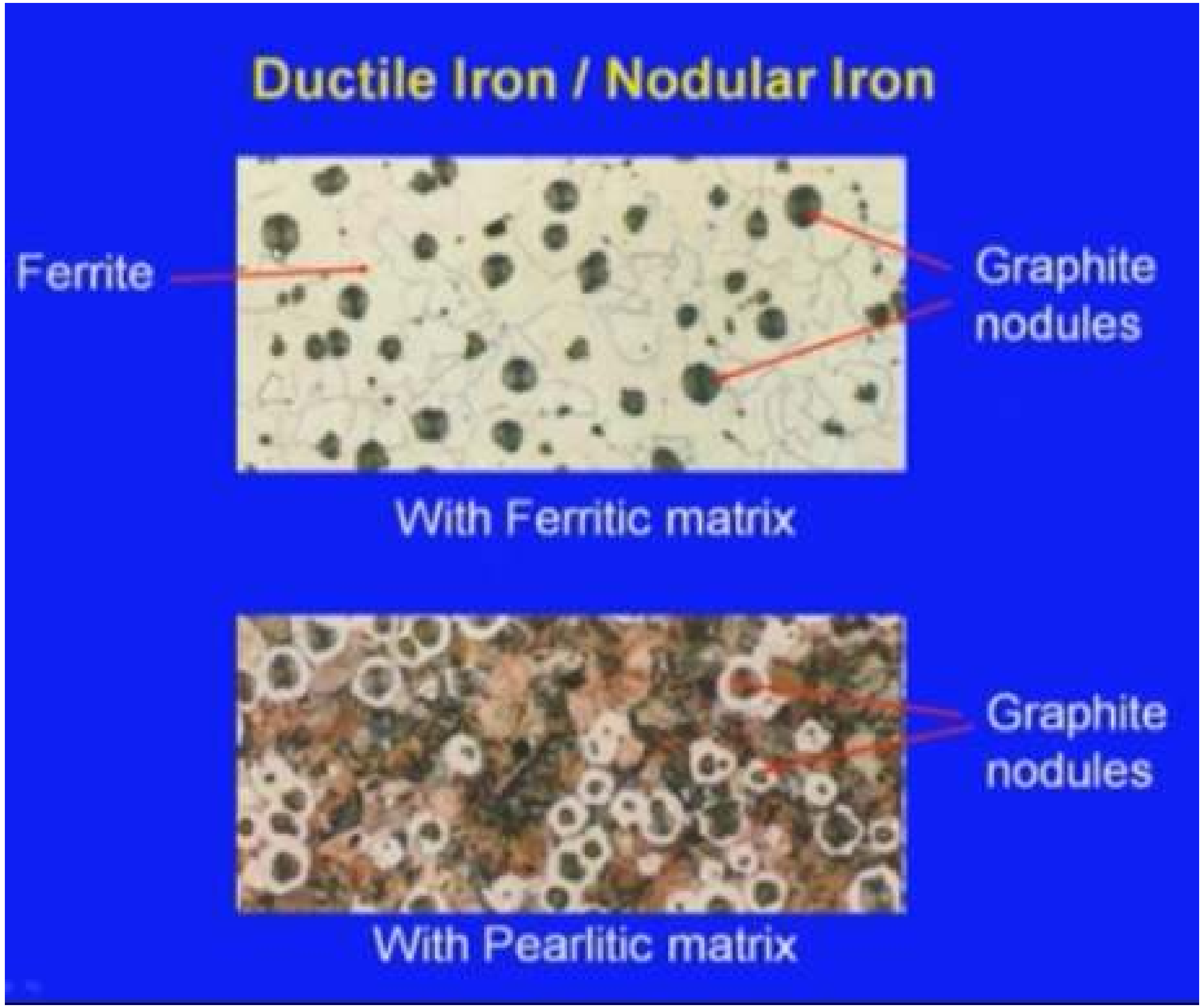
- Iron , Carbon 3 to 4%, Silicon 1.8 to 2.8%, Manganese 0.1 to 0.5%, Magnesium 0.03 to 0.05%, Phosphorus 0.1%, Sulphur 0.03%

❖Application:

- Oil well pumps, automobile industry, aerospace applications…



Micro-Structure



Ductile Iron / Nodular Iron

Ferrite

Graphite nodules

With Ferritic matrix

Graphite nodules

With Pearlitic matrix

- Advantages:
  - High ductility
  - High machinability
  - High wear resistance
  - Can be forged

Applications of Ductile Cast Iron

1. Engine connecting rods
2. Truck axles
3. Front wheel spindle supports
4. Disk brake calipers
5. Suspension system parts
6. Power transmission yokes
7. The cast iron pipes

Disk brake calipers

Non ferrous alloys

What is the material composition of a Beverage Can?

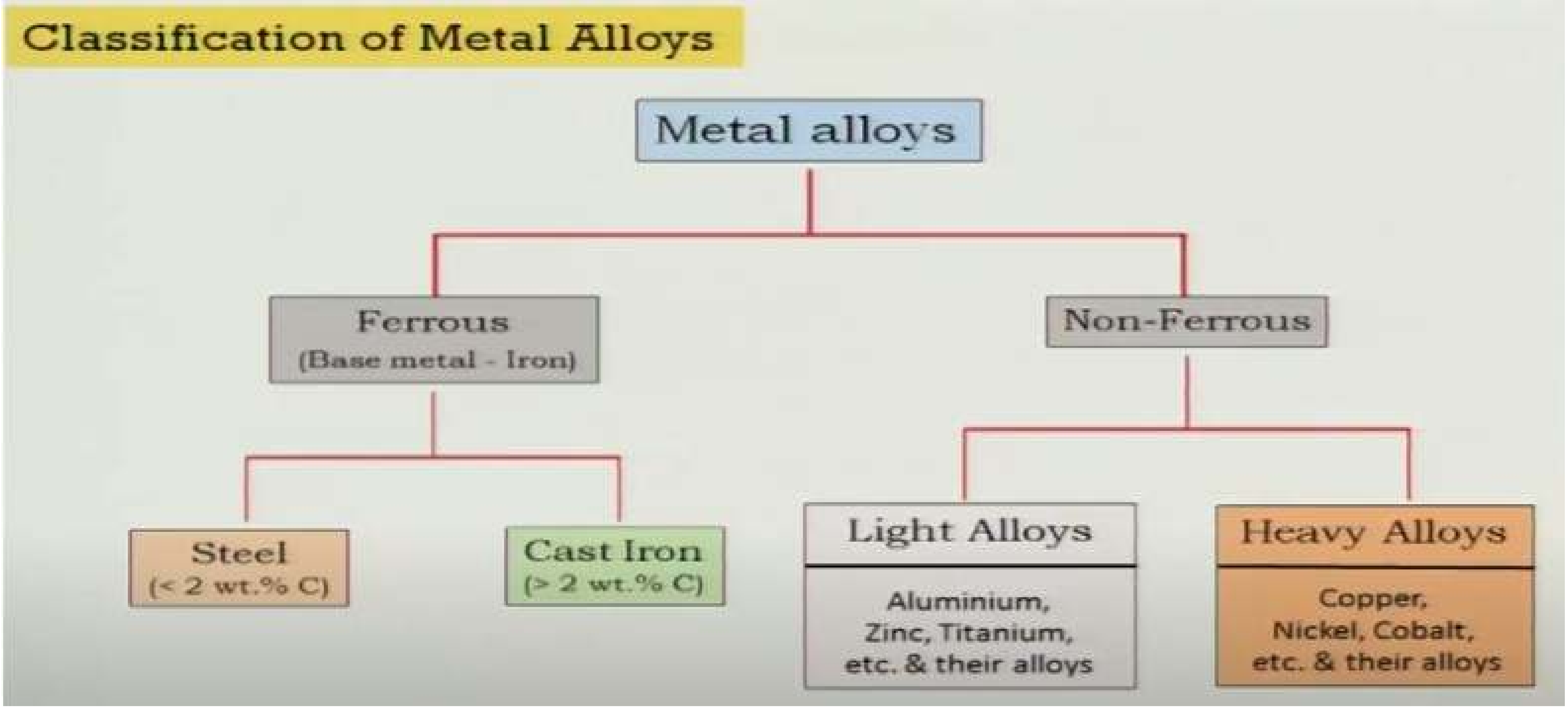
Non ferrous alloys

The constituents of a Coke-Can

- The aluminum base, for beverage cans consists mostly of aluminum, but it contains small amounts of other metals as well. These are typically 1% magnesium, 1% manganese, 0.4% iron, 0.2% silicon, and 0.15% copper. A large portion of the aluminum used in the beverage can industry is derived from recycled material.
- http://www.madehow.com/Volume-2/Aluminum-Beverage-Can.html

Limitations of Ferrous alloys

- Relatively high density.
- Comparatively low electrical conductivity.
- An inherent susceptibility to corrosion in certain environments



Classification of Metal Alloys

Metal alloys

- Ferrous (Base metal - Iron)
  - Steel (< 2 wt.% C)
  - Cast Iron (> 2 wt.% C)
- Non-Ferrous
  - Light Alloys: Aluminium, Zinc, Titanium, etc. & their alloys
  - Heavy Alloys: Copper, Nickel, Cobalt, etc. & their alloys

Non ferrous alloys

1. Aluminium alloys
2. Copper
3. Magnesium alloys
4. Copper – Nickel alloys
5. Titanium alloys
6. Babbitt metal

Aluminium & its alloys

❖ Aluminium:

- Aluminium very abundant in the earth crust
- FCC Crystal structure
- **2700kg/m3 Density**
- High thermal and electrical conductivity
- Pure aluminium has good Machinability, formability, workability and castability. It is non-magnetic, non-toxic, easily available & less expensive.
- Main draw back is its low strength & hardness.

Wing ribs of an A340 Airbus wing box are made from Aluminium alloy plate

Aerospace industry demands include:

- ✓ Improved toughness,
- ✓ Lower weight,
- ✓ Increased resistance to fatigue and corrosion.

Manufacturer: British Aluminium Plate (BAP), The Luxfer Group

Reference: http://www.azom.com/article.aspx?ArticleID=502

Smart Materials Structures and Systems Laboratory IIT Kanpur

- Aluminium alloys: Poor strength of aluminium can be improved by alloying it with Copper, Silicon, Magnesium, Chromium & Zinc.

Types of Aluminium alloys

1. Duralumin: Consists of 94% Aluminium + 4% Copper + 0.5% each of Mg, Mn, Si & Fe.
   - Good tensile strength & electrical conductivity.
   - Used in aerospace applications, for making sheets, tubes, forgings, rivets, surgical equipments…

2. Y- alloy: Consists of 92.5% Al + 4% Cu + 2% Ni + 1.5% Mg

- Good strength & hardness at elevated temperatures.
- Suitable for cold working & casting.
- Used for making cylinder heads & crank cases of engines.

3. Magnelium: The major alloying elements are Magnesium & Copper. In addition to this traces of Ni, Sn, Fe, Mn & Si are also added.

- High tensile strength & machinability, but possess brittleness.
- Used in air craft & automobile industries.

4. Silumin alloys: Alloys based on Al-Si system are known as silumin alloys.

- Consists of 88% Al + 12% Si.
- Possess good castability, corrosion resistance, high ductility & low density.

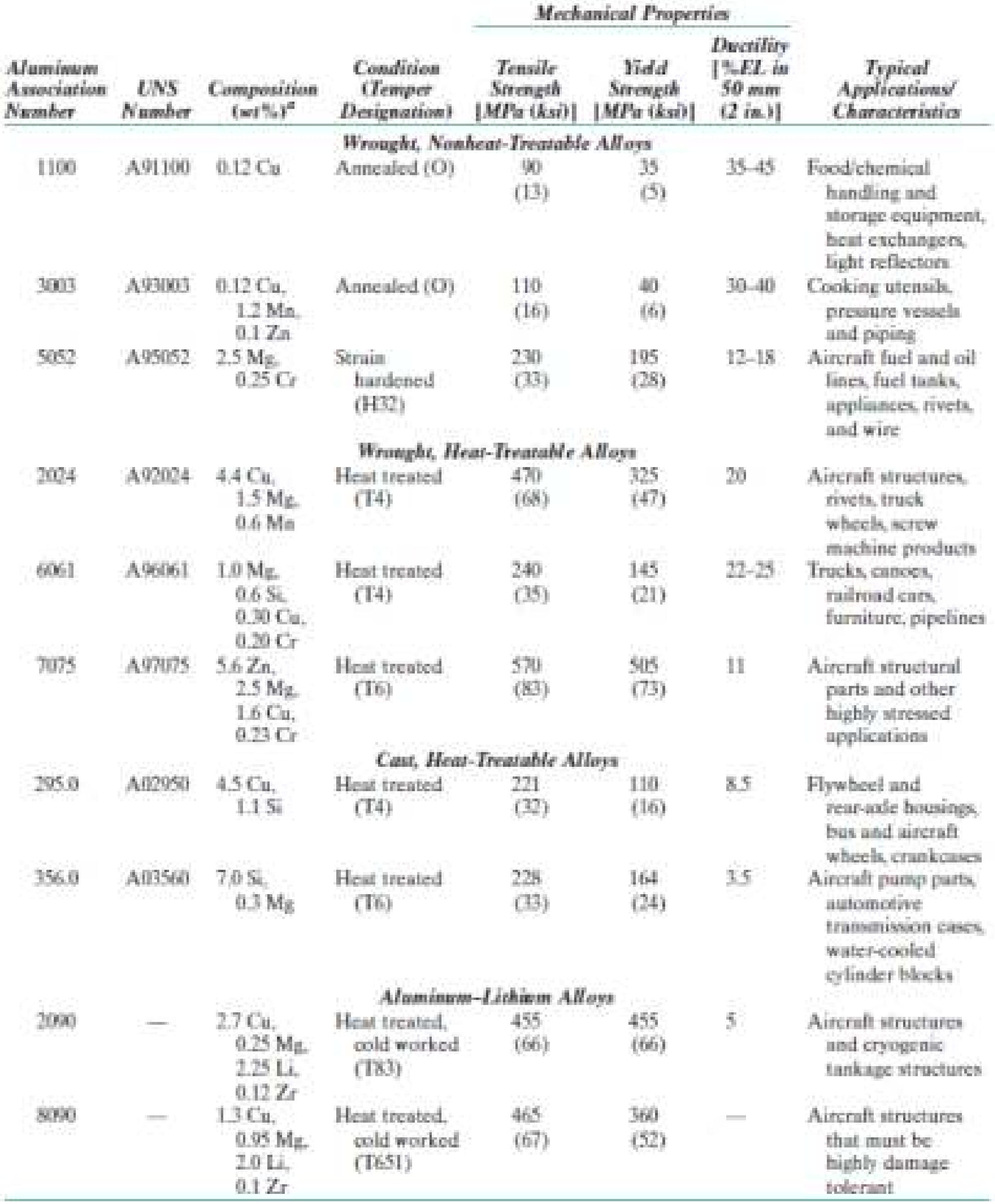
5. Wrought alloys: Al-Mg & Al-Mn alloys are generally termed as wrought alloys.

- Possess low hardness & high ductility.

6. Casting alloys:

- Prepared by adding traces of Mg, Mn & Cu to Silumin alloy (Al + Si).

Compositions, Mechanical Properties, and Typical Applications for Several Common Aluminum Alloys



Aluminum Association Number	UNS Number	Composition (wt%)^a	Condition (Temper Designation)	Mechanical Properties: Tensile Strength [MPa (ksi)]	Mechanical Properties: Yield Strength [MPa (ksi)]	Mechanical Properties: Ductility [%EL in 50 mm (2 in.)]	Typical Applications/ Characteristics
Wrought, Nonheat-Treatable Alloys							
1100	A91100	0.12 Cu	Annealed (O)	90 (13)	35 (5)	35–45	Food/chemical handling and storage equipment, heat exchangers, light reflectors
3003	A93003	0.12 Cu, 1.2 Mn, 0.1 Zn	Annealed (O)	110 (16)	40 (6)	30–40	Cooking utensils, pressure vessels and piping
5052	A95052	2.5 Mg, 0.25 Cr	Strain hardened (H32)	230 (33)	195 (28)	12–18	Aircraft fuel and oil lines, fuel tanks, appliances, rivets, and wire
Wrought, Heat-Treatable Alloys							
2024	A92024	4.4 Cu, 1.5 Mg, 0.6 Mn	Heat treated (T4)	470 (68)	325 (47)	20	Aircraft structures, rivets, truck wheels, screw machine products
6061	A96061	1.0 Mg, 0.6 Si, 0.30 Cu, 0.20 Cr	Heat treated (T4)	240 (35)	145 (21)	22–25	Trucks, canoes, railroad cars, furniture, pipelines
7075	A97075	5.6 Zn, 2.5 Mg, 1.6 Cu, 0.23 Cr	Heat treated (T6)	570 (83)	505 (73)	11	Aircraft structural parts and other highly stressed applications
Cast, Heat-Treatable Alloys							
295.0	A02950	4.5 Cu, 1.1 Si	Heat treated (T4)	221 (32)	110 (16)	8.5	Flywheel and rear-axle housings, bus and aircraft wheels, crankcases
356.0	A03560	7.0 Si, 0.3 Mg	Heat treated (T6)	228 (33)	164 (24)	3.5	Aircraft pump parts, automotive transmission cases, water-cooled cylinder blocks
Aluminum–Lithium Alloys							
2090	—	2.7 Cu, 0.25 Mg, 2.25 Li, 0.12 Zr	Heat treated, cold worked (T83)	455 (66)	455 (66)	5	Aircraft structures and cryogenic tankage structures
8090	—	1.3 Cu, 0.95 Mg, 2.0 Li, 0.1 Zr	Heat treated, cold worked (T651)	465 (67)	360 (52)	—	Aircraft structures that must be highly damage tolerant

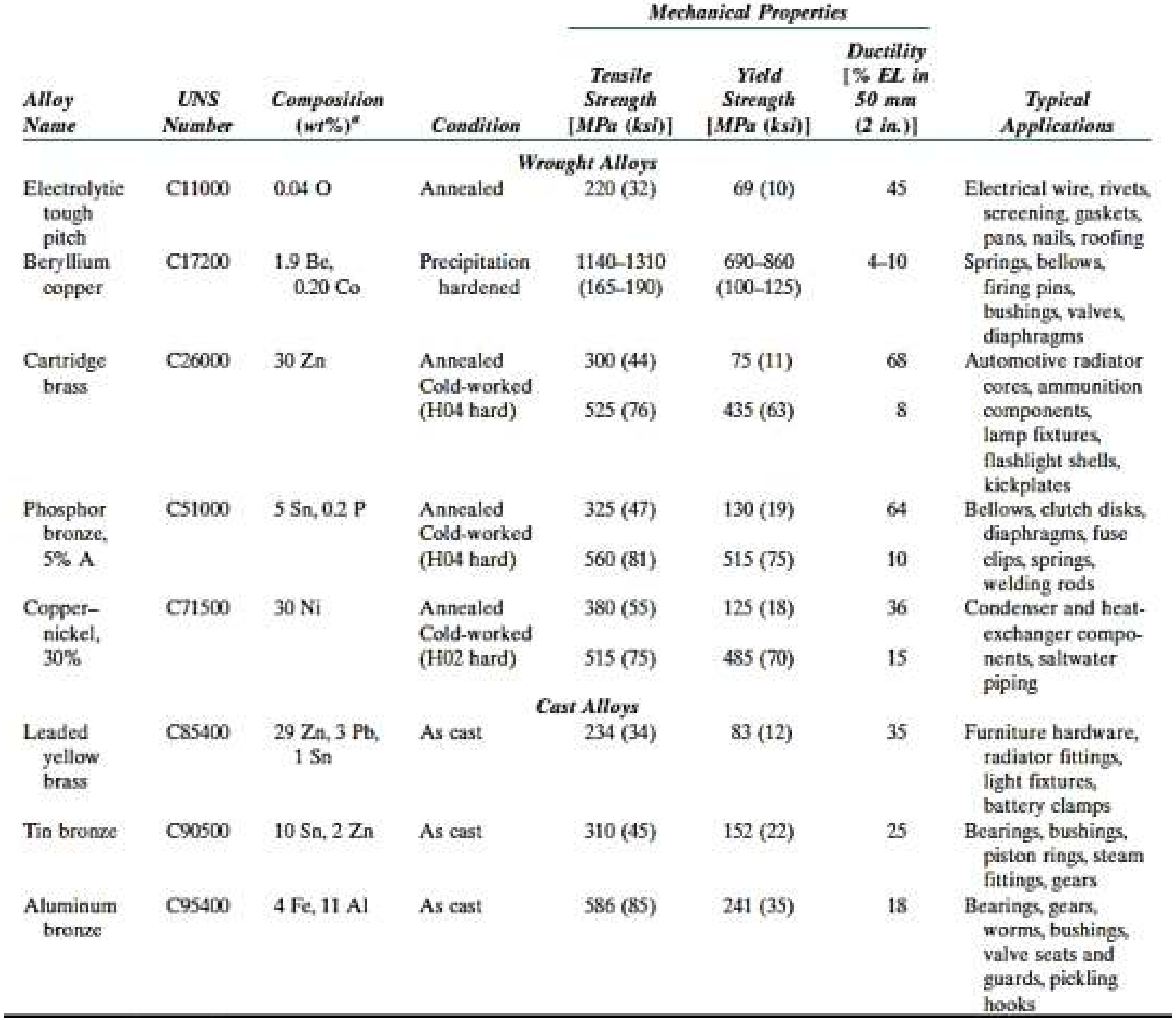
Copper & its alloys

- Crystal structure: Face Centered Cubic (FCC)
- Melting paint: 1085^{0}C
- Density: 8920 kg/m^3
- Distinctive reddish orange color
- Good corrosion resistance.
- Soft, malleable, ductile and very tough.
- High electrical and thermal conductivity.
- Thermal conductivity Order: Ag >Cu> Al
- 99.99% pure copper is used for wiring application.
- Possess around 97% conductivity of silver at 1/8 cost

- Copper & its alloys

1. Brass
2. Bronze

Compositions, Mechanical Properties, and Typical Applications for Eight Copper Alloys



Alloy Name	UNS Number	Composition (wt%)^a	Condition	*Mechanical Properties* Tensile Strength [MPa (ksi)]	Yield Strength [MPa (ksi)]	Ductility [% EL in 50 mm (2 in.)]	Typical Applications
			Wrought Alloys				
Electrolytic tough pitch	C11000	0.04 O	Annealed	220 (32)	69 (10)	45	Electrical wire, rivets, screening, gaskets, pans, nails, roofing
Beryllium copper	C17200	1.9 Be, 0.20 Co	Precipitation hardened	1140–1310 (165–190)	690–860 (100–125)	4–10	Springs, bellows, firing pins, bushings, valves, diaphragms
Cartridge brass	C26000	30 Zn	Annealed	300 (44)	75 (11)	68	Automotive radiator cores, ammunition components, lamp fixtures, flashlight shells, kickplates
			Cold-worked (H04 hard)	525 (76)	435 (63)	8	
Phosphor bronze, 5% A	C51000	5 Sn, 0.2 P	Annealed	325 (47)	130 (19)	64	Bellows, clutch disks, diaphragms, fuse clips, springs, welding rods
			Cold-worked (H04 hard)	560 (81)	515 (75)	10	
Copper–nickel, 30%	C71500	30 Ni	Annealed	380 (55)	125 (18)	36	Condenser and heat-exchanger components, saltwater piping
			Cold-worked (H02 hard)	515 (75)	485 (70)	15	
			Cast Alloys				
Leaded yellow brass	C85400	29 Zn, 3 Pb, 1 Sn	As cast	234 (34)	83 (12)	35	Furniture hardware, radiator fittings, light fixtures, battery clamps
Tin bronze	C90500	10 Sn, 2 Zn	As cast	310 (45)	152 (22)	25	Bearings, bushings, piston rings, steam fittings, gears
Aluminum bronze	C95400	4 Fe, 11 Al	As cast	586 (85)	241 (35)	18	Bearings, gears, worms, bushings, valve seats and guards, pickling hooks

1.Brass

- Brass: Alloy of Copper + Zinc (5-54 %)
- Zinc, as a substitutional impurity,
- As zinc content increases , the strength, ductility and hardness increases but conductivity decreases

Traces of Lead, Tin & Aluminium are also added to impart specific properties to make it suitable for specific applications.

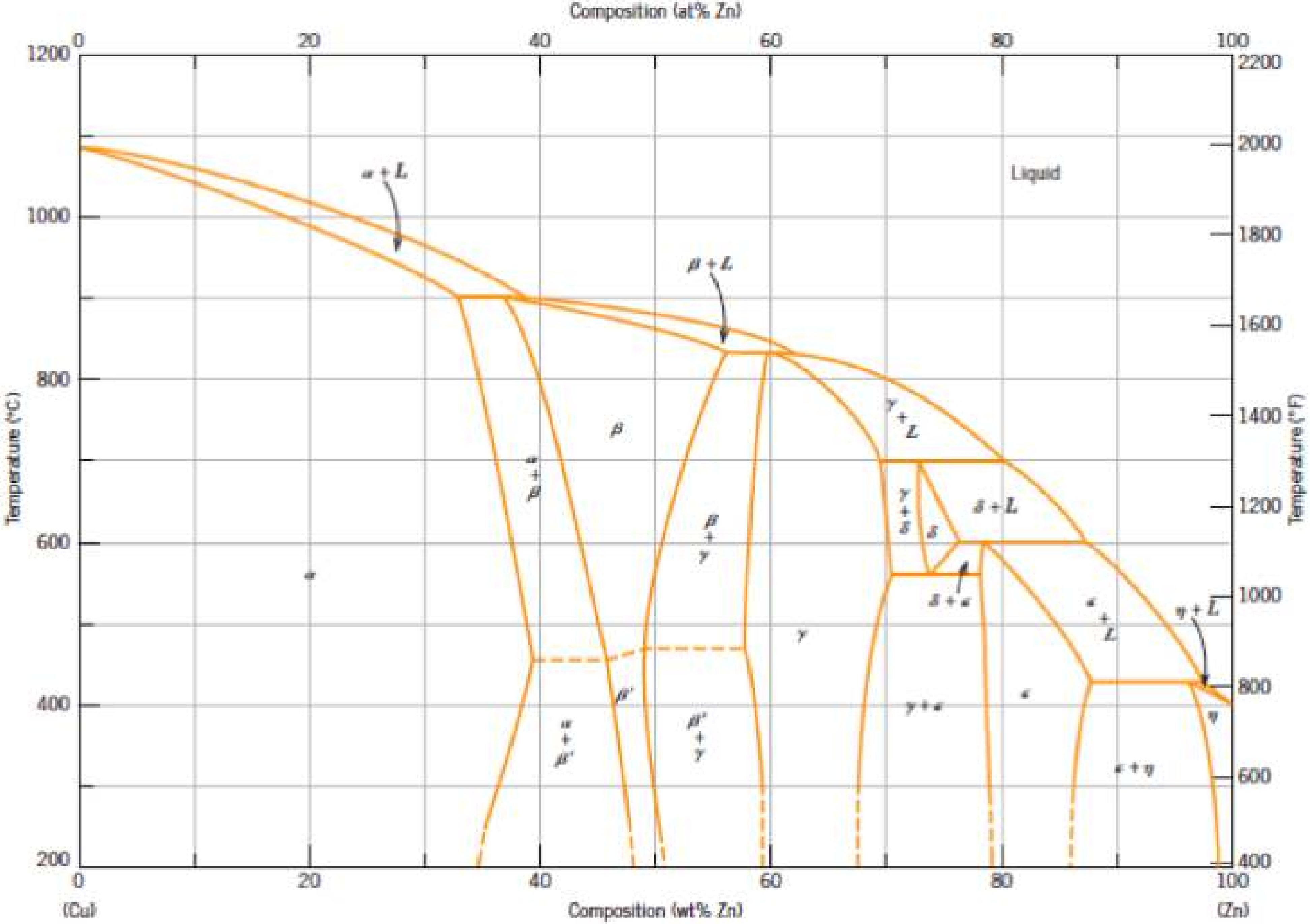
- Properties:

1. Good strength, ductility & formability
2. Good Machinability
3. Good electrical & thermal conductivity
4. Excellent wear & corrosion resistance
5. Non – magnetic
6. Shining appearance

Types of brass

1. α – brass
2. Yellow α – brass
3. Cartridge brass
4. Admiralty brass
5. Aluminium brass
6. Red α – brass
7. Gilding metal
8. Leaded red brass
9. Duplex / (α + β) brass

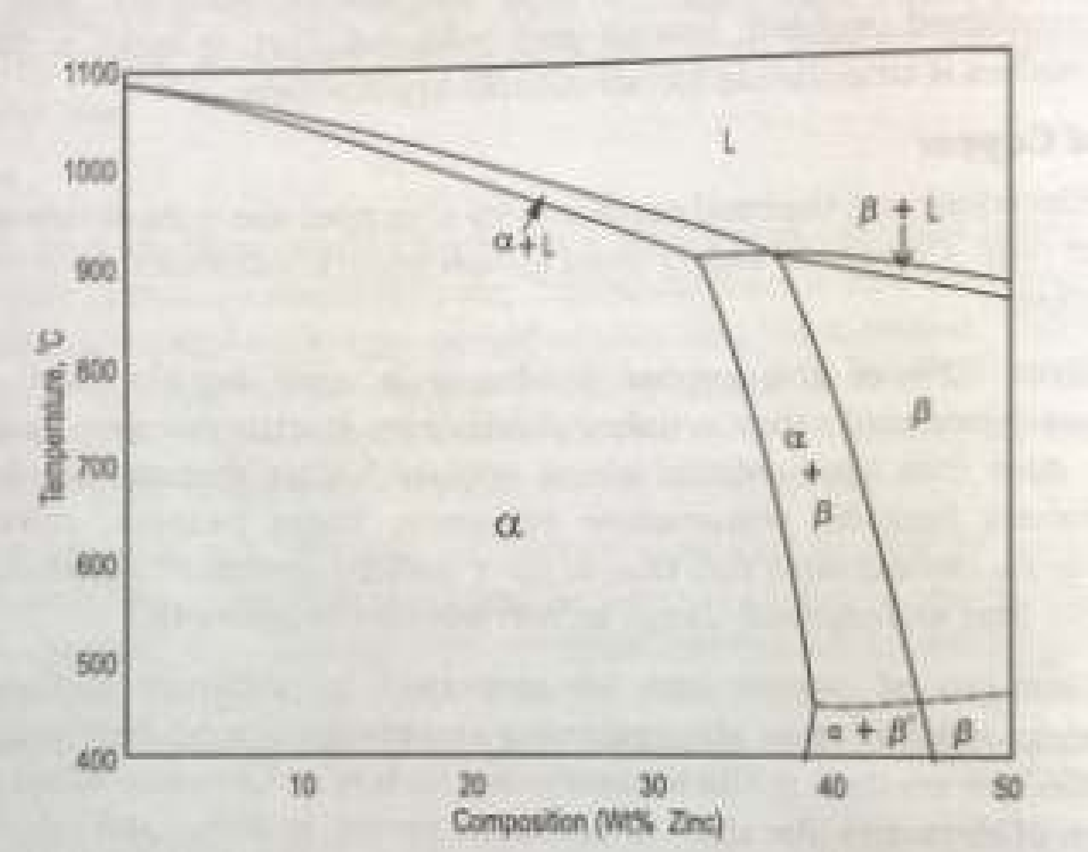
Some of the common uses for brass alloys include costume jewelry, cartridge casings, automotive radiators, musical instruments, electronic packaging, and coins.


Composition (at% Zn)
0
20
40
60
80
100
1200
1000
800
600
400
200
2200
2000
1800
1600
1400
1200
1000
800
600
400
Temperature (°C)
Temperature (°F)
Liquid
α + L
β + L
β
α + β
β + γ
γ + L
γ + δ
δ
δ + L
δ + ε
ε + L
η + L
α
γ
β'
α + β'
β' + γ
γ + ε
ε
η
ε + η
0
20
40
60
80
100
(Cu)
Composition (wt% Zn)
(Zn)

Types of brass

1. α – brass: Copper + Zinc (Max. 38%)

- Brasses containing only α phase are called α – brass
- Highly ductile & Corrosion resistant
- FCC crystal structure, and
- Relatively soft, ductile,
- and easily cold worked



Types of brass

2. Yellow α – brass: Copper + Zinc (20-38%)
   - Appears in yellow colour & possess good corrosion resistance.

3. Cartridge brass: 70% Cu + 30% Zn
   - Suitable for deep drawing process
   - Used for making cartridges, shell cases & barrels of rifles.

4. Admiralty brass: 71% Cu + 28% Zn + 1% Sn
   - Traces of tin is added to improve corrosion resistance.
   - Widely used in marine applications.

Types of brass

5. Aluminium brass: 76% Cu + 22% Zn + 2% Al
   - Aluminium is added to improve the corrosion resistance.

6. Red α – brass: Copper + Zinc (5-20% Max.)
   - Due to high copper content, the alloy is having a red appearance.
   - Good corrosion resistance & workability.

7. Gilding metal: 95% Cu + 5% Zn.
   - Resembles gold in colour & is very soft.
   - High ductility & corrosion resistance
   - Used for making coins, medals, imitation jewellery…

Types of brass

8. Leaded red brass/ Three fives: Cu 85% + Lead + Tin + Zinc (5% each)
    - Improved strength & Machinability.
    - Used for making valves, pipe fittings, pump castings…

Duplex or (α+β) brass

Upon crossing 38% Zinc level, a new solid solution called β is also formed along with existing α phase. This mixture is termed as duplex or (α+β) brass.

Possess high hardness but poor ductility.

Types of Duplex

1. Muntz / Yellow metal: 60% Cu + 40% Zn.
    - High strength & excellent hot working properties.
    - Used for making chains, springs…

2. Naval brass: 60% Cu + 39% Zn + 1% Sn.
    - Addition of Tin improves corrosion resistance.
    - Used in marine applications, propeller shafts, valves, impellers for pumps…

3. Forging brass: 60% Cu + 38% Zn + 2% Pb
    - Good hot working properties
    - Used for making hardware & plumbing parts.

Bronze

- The bronzes are alloys of copper and several other elements, including tin, aluminum, silicon, and nickel.
- Contain Tin(Sn) as a main substitutional impurity
- E.g. – 88% Copper + 12% Tin.
- Bronzes in general are softer & weaker than steel.
- These alloys are somewhat stronger than the brasses, yet they still have a high degree of corrosion resistance.
- Possess good corrosion resistance, castability, anti-friction or bearing properties, heat & electrical conductivity.
- Used for making bearings, springs, castings, bells, coins, statues…

Types of bronze

1. Tin bronze
2. Gun metal
3. Aluminium bronze
4. Silicon bronze
5. Beryllium bronze

Types of bronze

1. Tin bronze: 88-98% Copper + 1-11% Tin + 0.1-0.5% Phosphorus.
    - Tin improves the wear & corrosion resistance of the alloy.
    - Phosphorus improves hardness & wear resistance.
    - Used for making springs, electrical contacts, clutch discs, taps…

2. Gun metal: Consists of 88% Copper + 10% Tin + 2% Zinc.
    - Possess good corrosion resistance.
    - Widely used in marine applications.

3. Aluminium bronze: Alloys of Copper & Aluminium are called aluminium bronze, which usually contains 4-11% aluminium.

- Traces of Nickel, Manganese & Silicon are also added to impart specific properties.
- Also known as imitation gold as it resembles gold in appearance.
- Good strength & corrosion resistance, but shows poor castability.

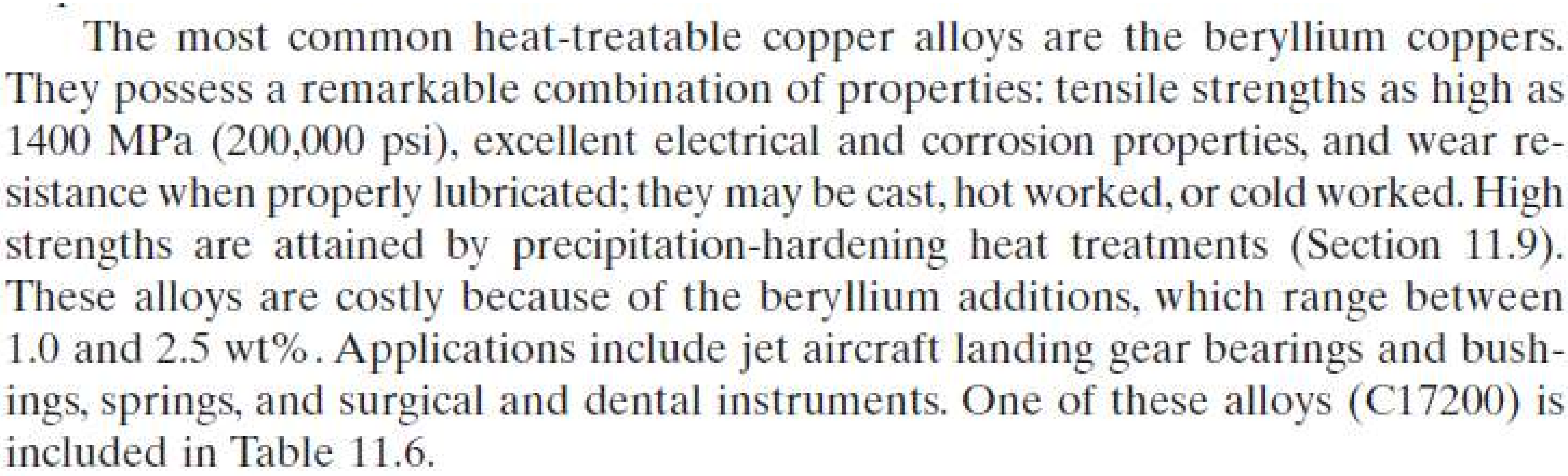
4. Silicon bronze: Copper + Silicon (1-4%)

- Silicon improves strength of the alloy.
- Suitable for both hot & cold working.
- Possess good corrosion resistance & weldability.
- Traces of Manganese & Zinc are added to impart specific properties.
- Used for making rivets, bolts, nuts, screws & fasteners.

Types of bronze

5. Beryllium bronze: Copper + Beryllium (0.6-3%)

- Possess high strength, conductivity, elasticity & fatigue resistance.
- Also called beryllium copper.
- Used for making springs.



The most common heat-treatable copper alloys are the beryllium coppers. They possess a remarkable combination of properties: tensile strengths as high as 1400 MPa (200,000 psi), excellent electrical and corrosion properties, and wear resistance when properly lubricated; they may be cast, hot worked, or cold worked. High strengths are attained by precipitation-hardening heat treatments (Section 11.9). These alloys are costly because of the beryllium additions, which range between 1.0 and 2.5 wt%. Applications include jet aircraft landing gear bearings and bushings, springs, and surgical and dental instruments. One of these alloys (C17200) is included in Table 11.6.

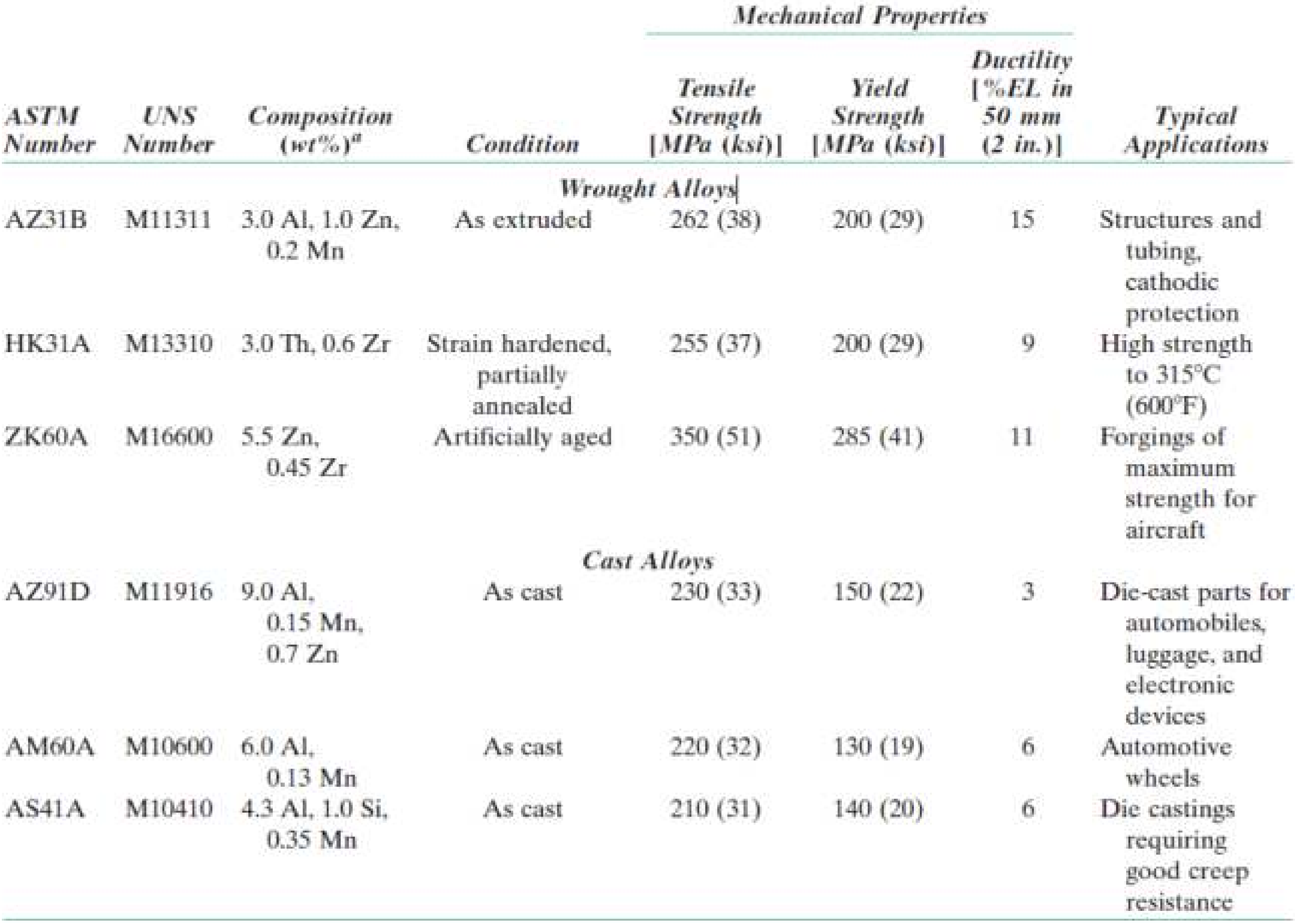
Magnesium and Its Alloys

- The most outstanding characteristic of magnesium is its density, 1.7 g/cm^3, which is the lowest of all the structural metals; therefore, its alloys are used where light weight is an important consideration (e.g., in aircraft components).
- Magnesium has HCP crystal structure.
- Possess brittle nature, poor modulus of elasticity, low resistance to wear, fatigue & creep.
- Has a moderately low melting temperature 651^{0}C
- Chemically, magnesium alloys are relatively unstable and especially susceptible to corrosion in marine environments.
- On the other hand, corrosion or oxidation resistance is reasonably good in the normal atmosphere;

Magnesium alloys

- Aluminum, zinc, manganese, and some of the rare earths are the major alloying elements.
- Addition of Al to Mg increases strength, hardness & castability.
- Zinc & Manganese are added to Magnesium to improve its mechanical properties & corrosion resistance.
- Adding traces of Zr refines grains of Mg & improves its strength.
- Mg alloys are used in aerospace applications, for making high speed machinery, transportation & material handling equipments.
- Furthermore, in the last several years the demand for magnesium alloys has increased dramatically in a host of different industries.
- For many applications, magnesium alloys have replaced engineering plastics that have comparable densities inasmuch as the magnesium materials are stiffer, more recyclable, and less costly to produce. For example, magnesium is now employed in a variety of hand-held devices (e.g., chain saws, power tools, hedge clippers), in automobiles (e.g., steering wheels and columns, seat frames, transmission cases), and in audio-video-computer-communications equipment (e.g., laptop computers, camcorders, TV sets, cellular telephones).

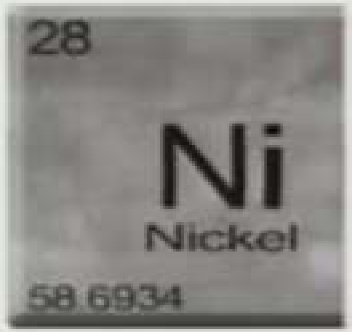
Compositions, Mechanical Properties, and Typical Applications for Six Common Magnesium Alloys



				Mechanical Properties			
ASTM Number	*UNS Number*	*Composition (wt%)[a]*	*Condition*	*Tensile Strength [MPa (ksi)]*	*Yield Strength [MPa (ksi)]*	*Ductility [%EL in 50 mm (2 in.)]*	*Typical Applications*
			Wrought Alloys				
AZ31B	M11311	3.0 Al, 1.0 Zn, 0.2 Mn	As extruded	262 (38)	200 (29)	15	Structures and tubing, cathodic protection
HK31A	M13310	3.0 Th, 0.6 Zr	Strain hardened, partially annealed	255 (37)	200 (29)	9	High strength to 315°C (600°F)
ZK60A	M16600	5.5 Zn, 0.45 Zr	Artificially aged	350 (51)	285 (41)	11	Forgings of maximum strength for aircraft
			Cast Alloys				
AZ91D	M11916	9.0 Al, 0.15 Mn, 0.7 Zn	As cast	230 (33)	150 (22)	3	Die-cast parts for automobiles, luggage, and electronic devices
AM60A	M10600	6.0 Al, 0.13 Mn	As cast	220 (32)	130 (19)	6	Automotive wheels
AS41A	M10410	4.3 Al, 1.0 Si, 0.35 Mn	As cast	210 (31)	140 (20)	6	Die castings requiring good creep resistance

Nickel (Ni)

- Crystal structure: Face centered cubic (FCC)
- Melting point: 1455°C
- Density: 8900 kg/m^3
- Silvery - white lustrous metal with a slight golden colour.



Nickel
Image: Wikipedia

Applications

- **Nickel** metal hydride rechargeable **batteries**
- **Monel metal**
  - ✓ Primarily composed of Ni & Cu - with traces of Fe, Mn, Si, C.
  - ✓ Strong corrosion resistant.
  - ✓ Heat exchanger tubes, food processing plant, marine applications
- **Super alloys (Ni-Cr) -** high creep and oxidation resistance at elevated temperatures (approx. 1100°C) - turbine blades

Nickel metal hydride battery
Image: Wikipedia

Ni superalloy jet engine blade
Image: Wikipedia

Copper – Nickel alloys

- When Ni & Cu are alloyed in the ratio 2:1, the alloy *Monel* is obtained.
- Monel possess excellent mechanical properties, corrosion resistance, toughness & fatigue strength.
- R- Monel: Monel + Sulphur
- Adding Sulphur improves machinability
- K- Monel: Monel + 3% Aluminium
- H- Monel: Monel + 3% Silicon
- S- Monel: Monel + 4% Silicon

Copper – Nickel alloys

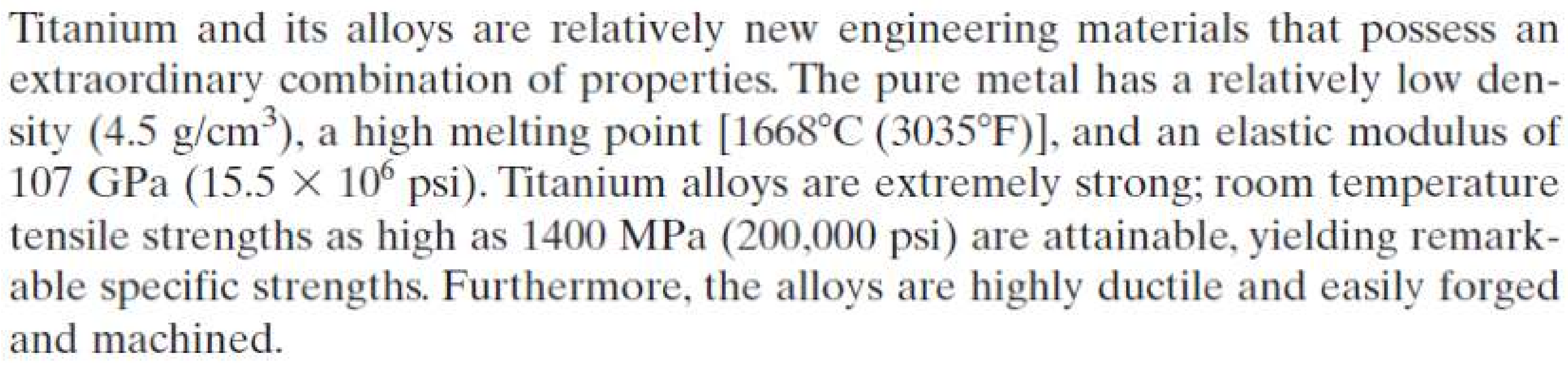
❖Constantan: Consists of 58.5% Cu + 40% Ni + 1.5% Mn

- Possess high electrical resistivity.
- Used for making rheostats, thermocouples…

❖Nickel silver/ German silver: Contains Cu + 5-45% Zn + 5-30% Ni.

- Possess good strength, plasticity & low thermal conductivity.
- Used for making plumbing accessories.

Titanium and its alloys



Titanium and its alloys are relatively new engineering materials that possess an extraordinary combination of properties. The pure metal has a relatively low density (4.5 g/cm^3), a high melting point [1668°C (3035°F)], and an elastic modulus of 107 GPa (15.5 × 10^6 psi). Titanium alloys are extremely strong; room temperature tensile strengths as high as 1400 MPa (200,000 psi) are attainable, yielding remarkable specific strengths. Furthermore, the alloys are highly ductile and easily forged and machined.

- The major limitation of titanium is its chemical reactivity with other materials at elevated temperatures. This property has necessitated the development of nonconventional refining, melting, and casting techniques; consequently, titanium alloys are quite expensive.
- In spite of this high temperature reactivity, the corrosion resistance of titanium alloys at normal temperatures is unusually high; they are virtually immune to air, marine, and a variety of industrial environments.
- They are commonly utilized in airplane structures, space vehicles, surgical implants, and in the petroleum and chemical industries.

Titanium

Titanium
Image: Wikipedia

- Pure Titanium – low density (4500 kg/m^3)
- High Melting point (1660 °C)
- Elastic modulus = 107 GPa
- Tensile Strength = 150-500Mpa
- **Appearance** : Silvery grey-white metallic lustre
- Alloying required to reduce cost, increase strength & control phase.
- **Applications** – High strength & temperature components, biomedical, jewelry, etc.
- Two crystal forms – below 883°C alpha structure (HCP) and beyond 883°C beta (BCC)
- **Four alloys**: Alpha, Near Alpha, Alpha-Beta, Beta
- Alpha phase stabilizers: Al, Ga, Ge, C, N
- Beta phase stabilizers: Mo, V, Ta, Nb, Mn, Fe, Cr, Co, Ni, Cu, Si

Titanium Ring

$Al < Ti < Fe$

Titanium alloys

a) Alpha Titanium Alloys

- Contains alpha-phase stabilizers only.
- Low to medium strength.
- Good notch toughness.
- Reasonably good ductility.
- Excellent mechanical properties at cryogenic temperatures.
- Non-heat treatable and are generally very weldable.
- Example: **Ti-8AL-1MO-1V (Tensile strength = 950MPa)** - jet engine components.

Jet Engine

b) Near alpha Titanium alloy

- Besides alpha-phase stabilizers, near-alpha alloys are alloyed with 1–2% of beta phase stabilizers
- Offer high temperature creep strength and oxidation resistance.
- **Ti-6Al-2Sn-4Zr-2Mo (Tensile strength = 1100MPa)** used for creating high temperature jet engines components and high performance automotive valves

Titanium alloys (contd.)

c) Alpha Beta Titanium Alloys

- Metastable and generally include some combination of both alpha and beta stabilizer's.
- Weldable with the risk of some loss of ductility in the weld area.
- Strength levels are medium to high.
- Hot forming qualities are good but cold forming often presents difficulties.
- Creep strength is not usually as good as in most alpha alloys.
- **Example: Ti-6Al-4V (Tensile strength = 940MPa)** used where low density and good corrosion resistance is necessary such as aerospace industry and bio-implants and prostheses applications.

d) Beta Titanium Alloys

- Metastable and which contain sufficient beta stabilizers.
- Fully heat treatable.
- Generally weldable.
- Capable of high strength.
- Possess good creep resistance up to intermediate temperatures.
- Cold formability is generally excellent.
- **Ti-10V-2Fe-3Al (Tensile strength = 1200MPa)** used for critical aircraft structures, such as landing gear.

Landing gear

Titanium and its alloys

- Important alloying elements of Titanium are Al, Cr, Mn, V, Fe, Mo & Sn.
- Alloying Titanium improves its mechanical properties, creep resistance, fatigue strength & corrosion resistance.
- Ti-6Al-4V is the most widely used titanium alloy.
- Used for making air craft turbines, air craft structures, chemical processing equipments, valves, tanks…

Table 11.9 Compositions, Mechanical Properties, and Typical Applications for Several Common Titanium Alloys

				Average Mechanical Properties			
Alloy Type	*Common Name (UNS Number)*	*Composition (wt%)*	*Condition*	*Tensile Strength [MPa (ksi)]*	*Yield Strength [MPa (ksi)]*	*Ductility [%EL in 50 mm (2 in.)]*	*Typical Applications*
Commercially pure	Unalloyed (R50500)	99.1 Ti	Annealed	484 (70)	414 (60)	25	Jet engine shrouds, cases and airframe skins, corrosion-resistant equipment for marine and chemical processing industries
α	Ti-5Al-2.5Sn (R54520)	5 Al, 2.5 Sn, balance Ti	Annealed	826 (120)	784 (114)	16	Gas turbine engine casings and rings; chemical processing equipment requiring strength to temperatures of 480°C (900°F)
Near α	Ti-8Al-1Mo-1V (R54810)	8 Al, 1 Mo, 1 V, balance Ti	Annealed (duplex)	950 (138)	890 (129)	15	Forgings for jet engine components (compressor disks, plates, and hubs)
α-β	Ti-6Al-4V (R56400)	6 Al, 4 V, balance Ti	Annealed	947 (137)	877 (127)	14	High-strength prosthetic implants, chemical-processing equipment, airframe structural components
α-β	Ti-6Al-6V-2Sn (R56620)	6 Al, 2 Sn, 6 V, 0.75 Cu, balance Ti	Annealed	1050 (153)	985 (143)	14	Rocket engine case airframe applications and high-strength airframe structures
β	Ti-10V-2Fe-3Al	10 V, 2 Fe, 3 Al, balance Ti	Solution + aging	1223 (178)	1150 (167)	10	Best combination of high strength and toughness of any commercial titanium alloy; used for applications requiring uniformity of tensile properties at surface and center locations; high-strength airframe components

Babbitt metal

❖ Babbitt metal/ White metal represents Tin or Lead based alloys.

- Some of the common compositions of babbitt alloys are:

1. 90% Tin + 10% Copper
2. 89% Tin + 7% Antimony + 4% Copper
3. 80% Lead + 15% Antimony + 5% Tin

- Used for making bearing shells.

MODULE 5

SYLLABUS

Fatigue: - creep -DBTT - super plasticity - need, properties and applications of composites, super alloy, intermetallics, maraging steel, Titanium - Ceramics:- structures, applications.

5.1	Fracture: – Brittle and ductile fracture – Griffith theory of brittle fracture – Stress concentration, stress raiser – Effect of plastic deformation on crack propagation - transgranular, intergranular fracture - Effect of impact loading on ductile material and its application in forging, applications - Mechanism of fatigue failure.	2	CO3
5.2	Structural features of fatigue: - crack initiation, growth, propagation - Fracture toughness (definition only), applications - Ductile to brittle transition temperature (DBTT) in steels and structural changes during DBTT, applications.	1	
5.3	Creep: - Creep curves – creep tests - Structural change:- deformation by slip, sub-grain formation, grain boundary sliding - Mechanism of creep deformation - threshold for creep, prevention against creep - Super plasticity: need and applications	2	CO3
5.4	Composites: - Need of development of composites; fiber phase; matrix phase; only need and characteristics of PMC, MMC, and CMC.	2	CO3 CO5
5.5	Modern engineering materials: - only fundamentals, need, properties and applications of, intermetallics, maraging steel, super alloys, Titanium-Ceramics:-coordination number and radius ratios- AX, A_mX_p, $A_mB_mX_p$ type structures – applications.	3	

Course Outcomes

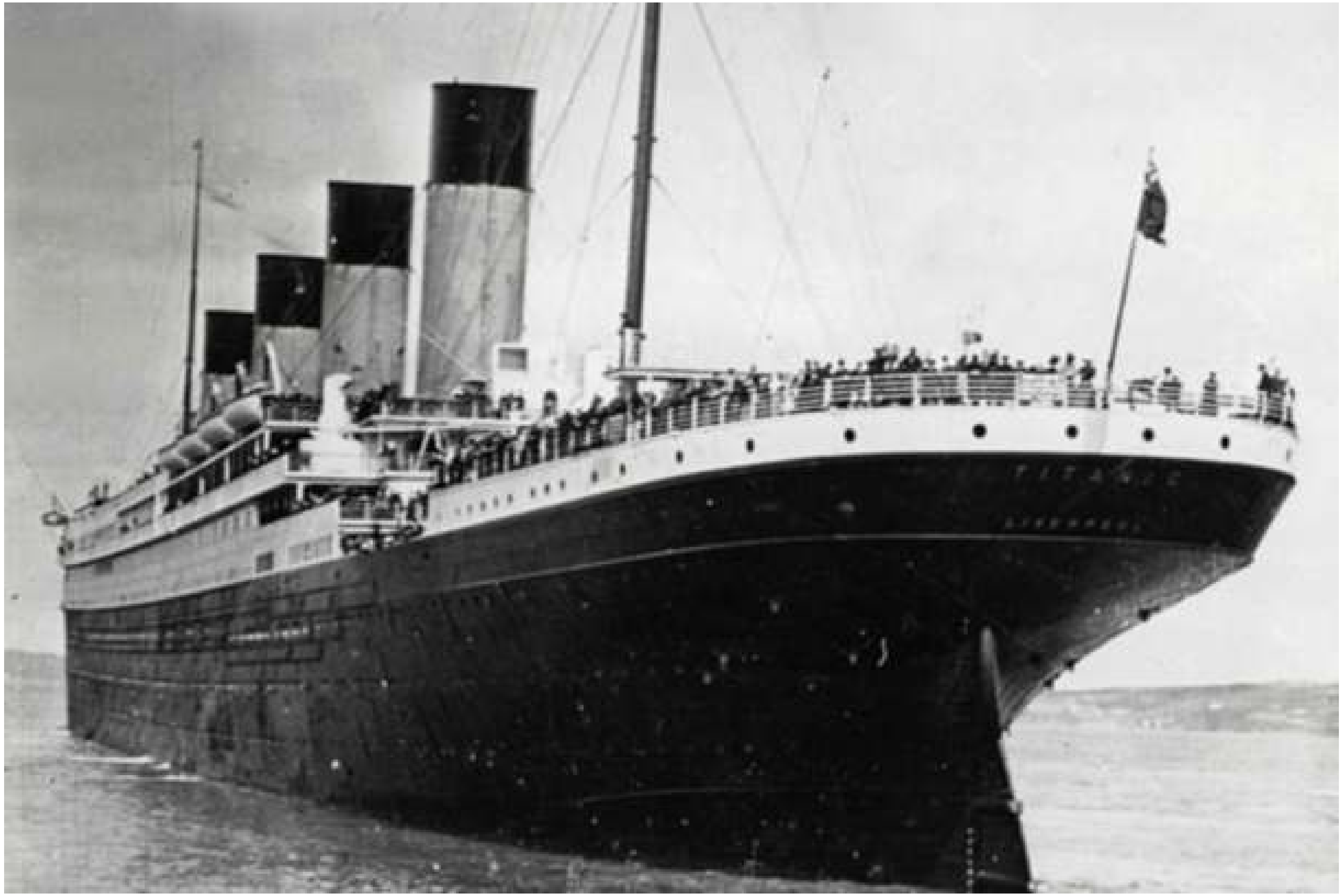
At the end of the course students will be able to,

CO 3 : How to quantify mechanical integrity and failure in materials.

CO 5 : Define and differentiate engineering materials on the basis of structure and properties for engineering applications.

Fracture

- The ultimate failure or rupture of a material under the influence of an external load is called fracture.
- Simple fracture is the separation of a body into two or more pieces in response to an imposed static stress at temperatures that are lower than material’s melting point.
- Any fracture process involves two steps
  - Crack formation and
  - Crack Propagation in response to an imposed stress.
- The mode of fracture is highly dependent on the mechanism of crack propagation.


TITANIC
LIVERPOOL

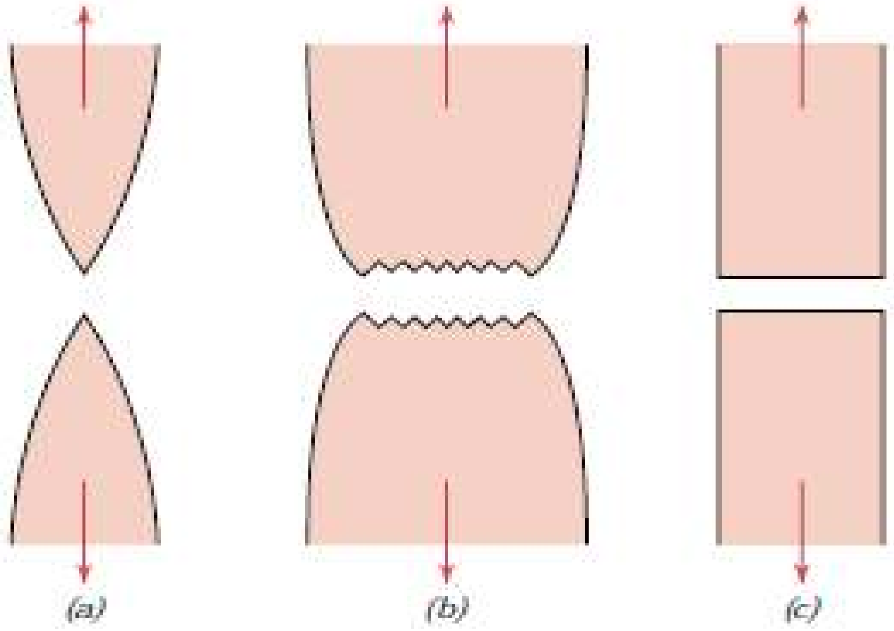
Types of Fractures

- Ductile fracture
- Brittle fracture

- Ductile fracture
  - Ductile materials typically exhibit substantial plastic deformation with high energy absorption before fracture.

- Brittle fracture
  - There is normally little or no plastic deformation with low energy absorption accompanying a brittle fracture.

Brittle and Ductile fracture

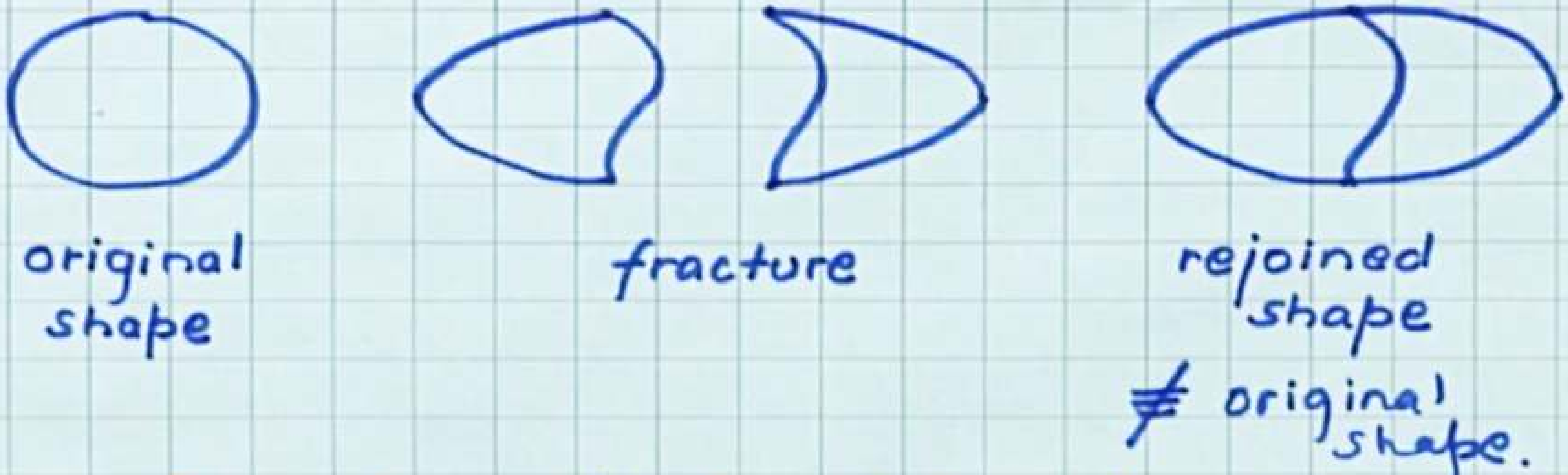


- (a) Highly ductile fracture in which the specimen necks down to a point. (b) Moderately ductile fracture after some necking. (c) Brittle fracture without any plastic deformation.

Ductile fracture

- Ductile fracture is characterized by extensive plastic deformation in the vicinity of an advancing crack.
- The process proceeds relatively slowly as the crack length is extended. Such a crack is often said to be stable.
- That is, it resists any further extension unless there is an increase in the applied stress.
- In addition, there will ordinarily be evidence of appreciable gross deformation at the fracture surfaces (e.g., twisting and tearing).

Ductile Fracture



Significant plastic deformation before fracture.

5 Stages of Moderately ductile fracture

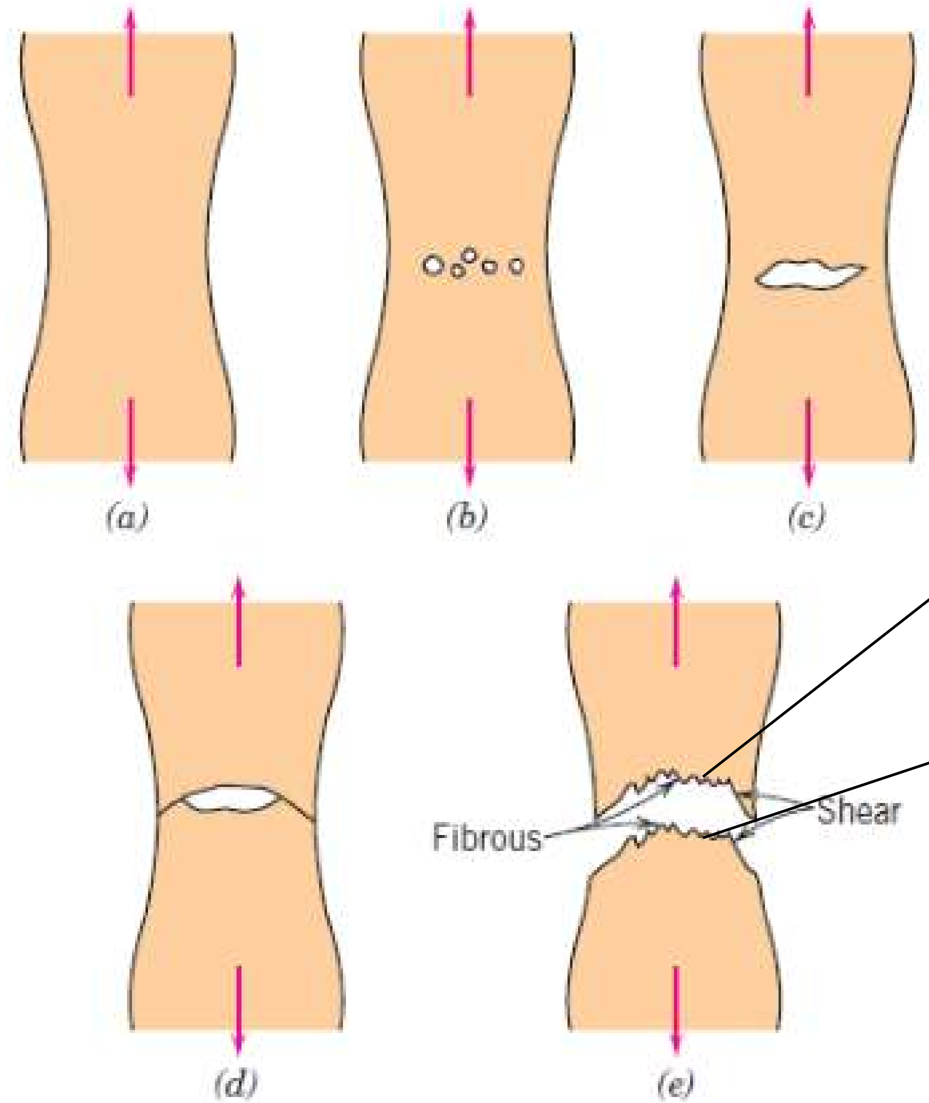
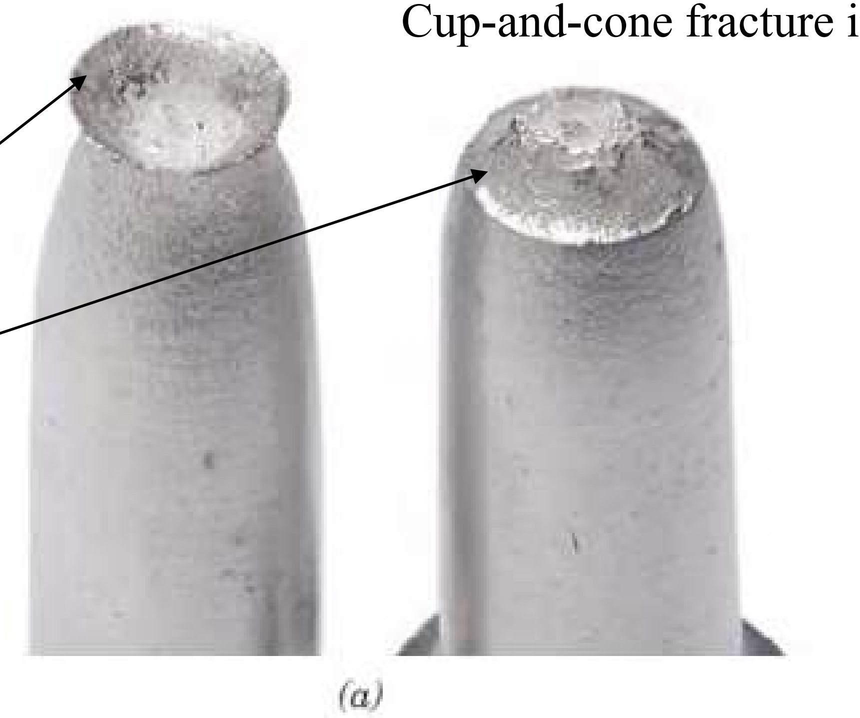


Figure 8.2 Stages in the cup-and-cone fracture. (*a*) Initial necking. (*b*) Small cavity formation. (*c*) Coalescence of cavities to form a crack. (*d*) Crack propagation. (*e*) Final shear fracture at a 45° angle relative to the tensile direction.

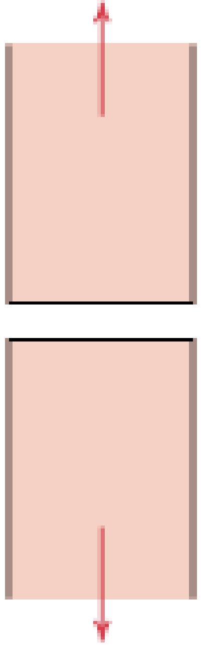
Cup-and-cone fracture in aluminum



(a) Initial necking (b) Small cavity or microvoids formation (c) Coalescence/combination of cavities to form a crack (d) Crack propagation (e) Final shear fracture

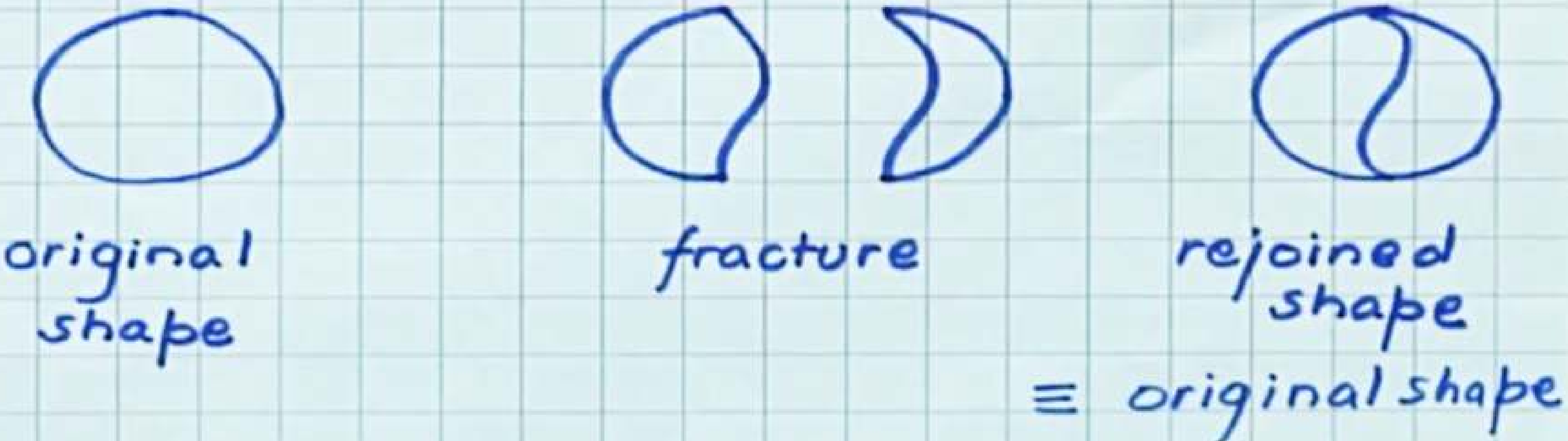
Brittle fracture

- Brittle fracture takes place with out any appreciable plastic deformation, and is caused by rapid crack propagation.
- In brittle fracture, cracks may spread extremely rapidly, with very little accompanying plastic deformation.
- Such cracks may be said to be unstable, and crack propagation, once started, will continue spontaneously without an increase in magnitude of the applied stress.



Brittle fracture in a mild steel.

Brittle Fracture



A Little or No plastic deformation before fracture.

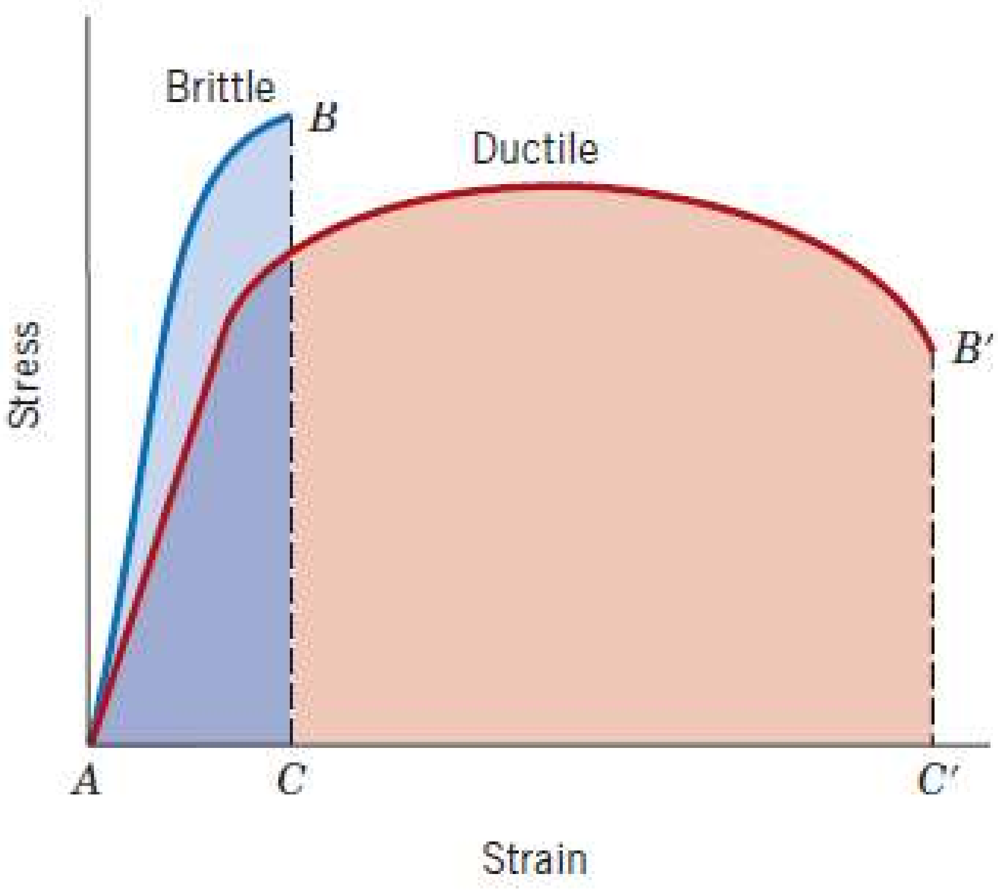
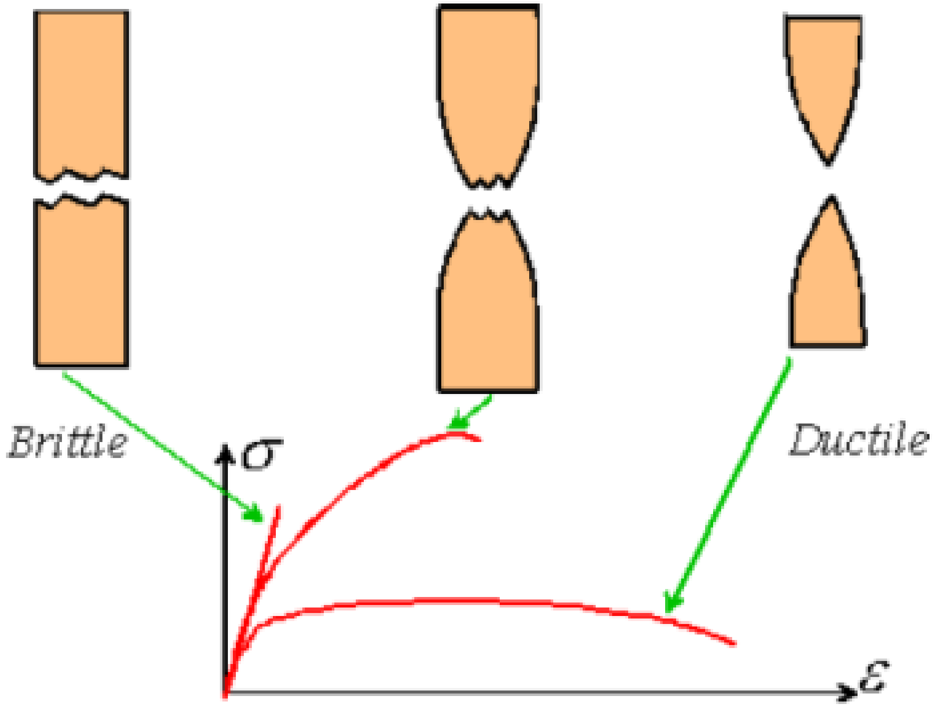


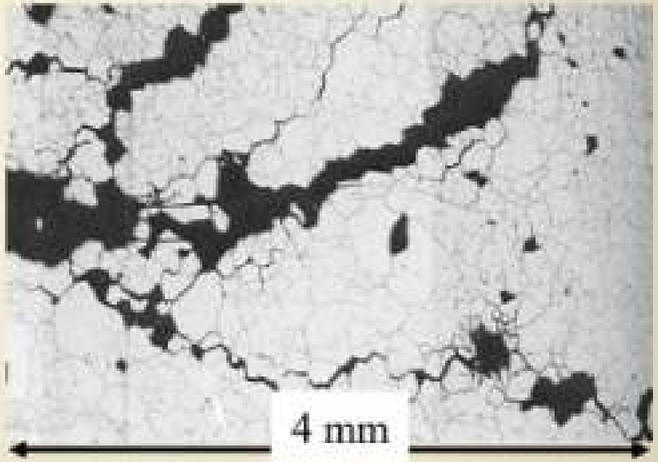
Figure 6.13 Schematic representations of tensile stress–strain behavior for brittle and ductile materials loaded to fracture.



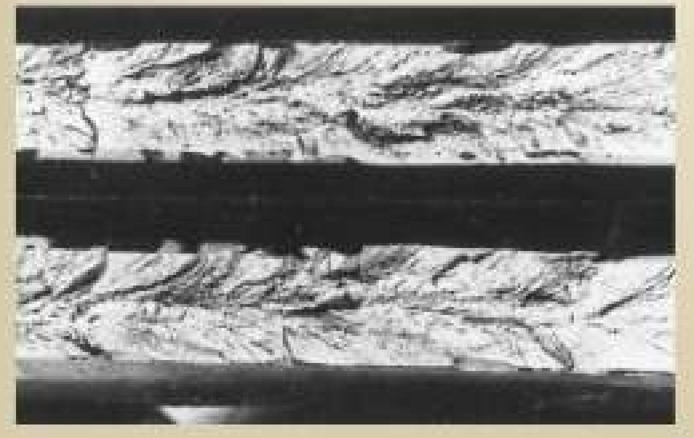
- Brittle fracture is a low energy fracture
- Ductile fracture is a High energy fracture

BRITTLE FAILURE

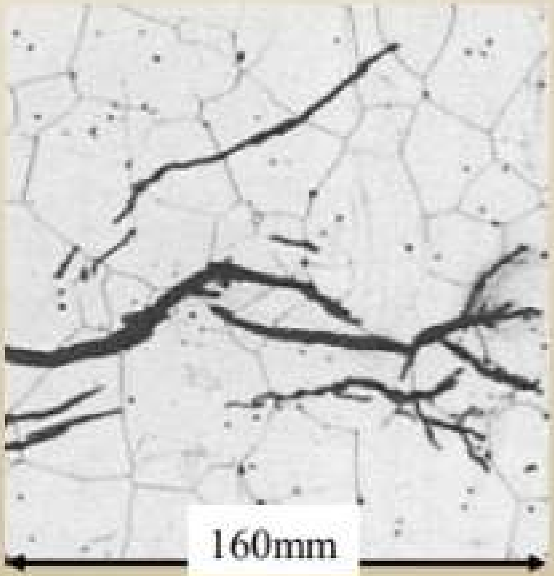
Brittle fracture in a mild steel



Intergranular fracture (between **grains**)



V-shaped "chevron" markings
Characteristic of brittle fracture



Intragranular fracture (within **grains**)

- Ductile fracture is almost always preferred for two reasons.

1. First, brittle fracture occurs suddenly and catastrophically without any warning; this is a consequence of the spontaneous and rapid crack propagation.

   On the other hand, for ductile fracture, the presence of plastic deformation gives warning that fracture is imminent, allowing preventive measures to be taken.

2. Second, more strain energy is required to induce ductile fracture inasmuch as ductile materials are generally tougher.

- Under the action of an applied tensile stress, most metal alloys are ductile, whereas ceramics are notably brittle, and polymers may exhibit both types of fracture.

Ductile fracture	**Brittle fracture**
• Material fractures after plastic deformation and slow propagation of crack	• Material fractures with very little or no plastic deformation.
• Surface obtained at the fracture is dull or fibrous in appearance	• Surface obtained at the fracture is shining and crystalling appearance
• It occurs when the material is in plastic condition.	• It occurs when the material is in elastic condition.
• It is characterized by the formation of cup and cone	• It is characterized by separation of normal to tensile stress.
• The tendency of ductile fracture is increased by dislocations and other defects in metals.	• The tendency brittle fracture is increased by decreasing temperature, and increasing strain rate.
• There is reduction in cross – sectional area of the specimen	• There is no change in the cross – sectional area.

Ductile vs. Brittle Failure

cup-and-cone fracture

brittle fracture

Adapted from Fig. 8.3, *Callister 7e.*

Intergranular fracture

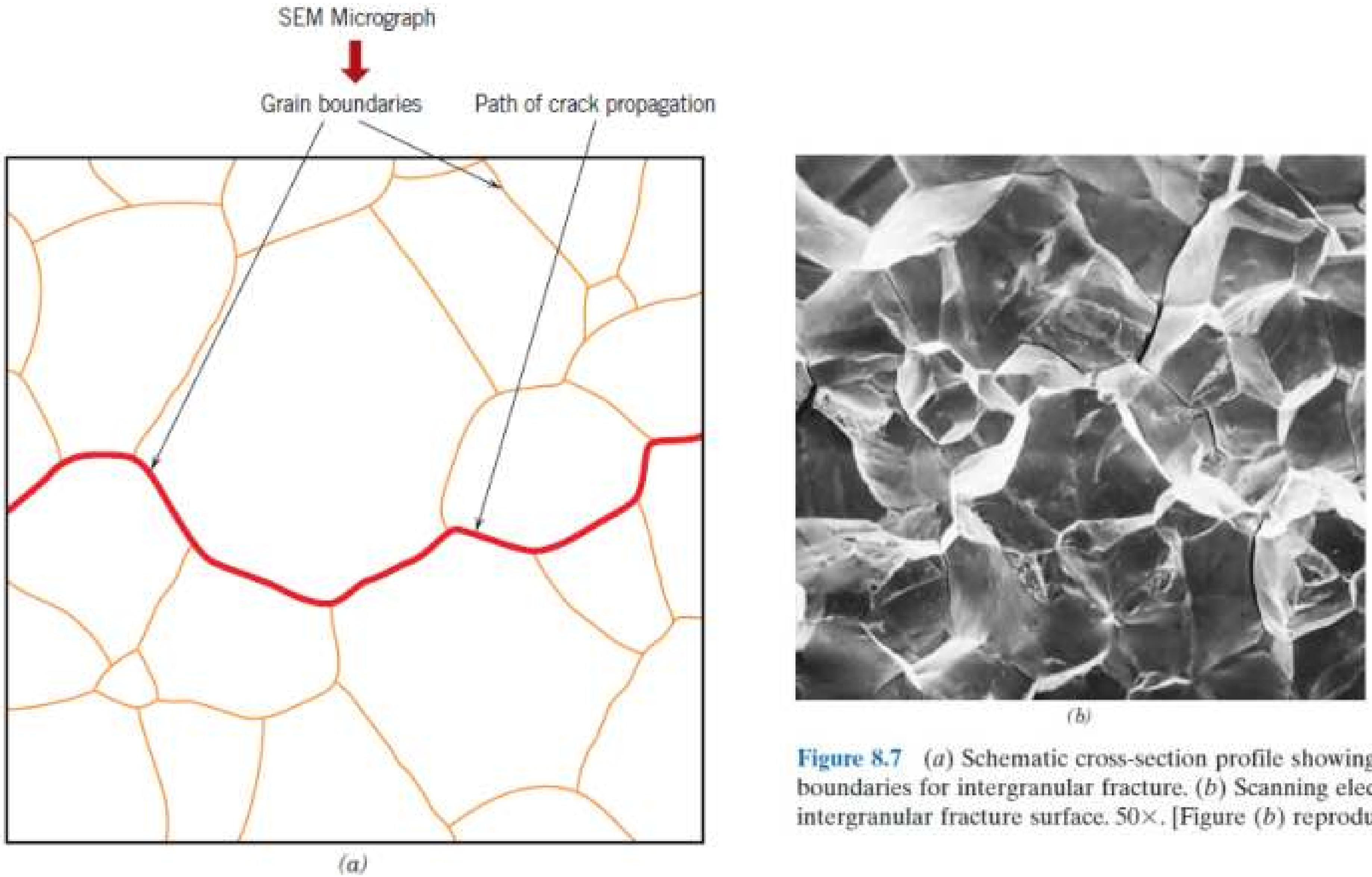


Figure 8.7 (*a*) Schematic cross-section profile showing crack propagation along grain boundaries for intergranular fracture. (*b*) Scanning electron fractograph showing an intergranular fracture surface. 50×. [Figure (*b*) reproduced with permission from *ASM*

- In intergranular fracture, cracks pass through grain boundaries.

- Intergranular failure is typically due to elemental depletion (chromium) at the grain boundaries or some type of weakening of the grain boundary due to chemical attack, oxidation, embrittlement or due to the precipitation of brittle phase along grain boundaries
- Some FCC metals otherwise FCC metals are ductile in nature.

Transgranular (or transcrystalline) Fracture

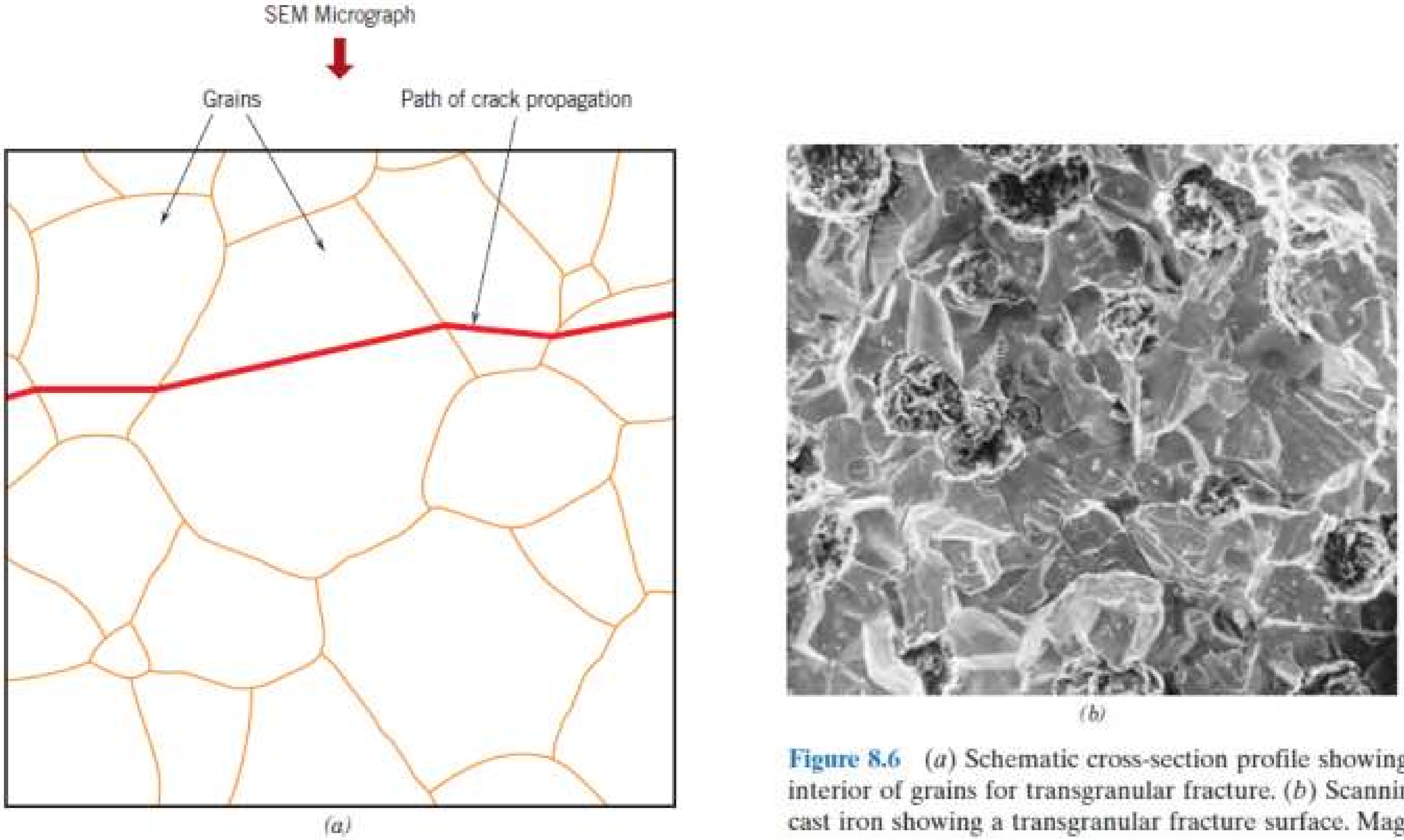


Figure 8.6 (*a*) Schematic cross-section profile showing crack propagation through the interior of grains for transgranular fracture. (*b*) Scanning electron fractograph of ductile cast iron showing a transgranular fracture surface. Magnification unknown. [Figure (*b*)

- In transgranular fracture, cracks pass through the grains

- Cleavage - in most brittle crystalline materials, crack propagation that results from the successive & repeated breaking of atomic bonds along specific planes – particularly along those planes with fewer inter atomic bonds.
- Such a process is termed as cleavage and known as cleavage fracture Flat surface look grainy or granular BCC and HCP metals

Role of crack size on fracture

- Fracture stress on a body is not a material property
- Its depends on the cracks present in the body

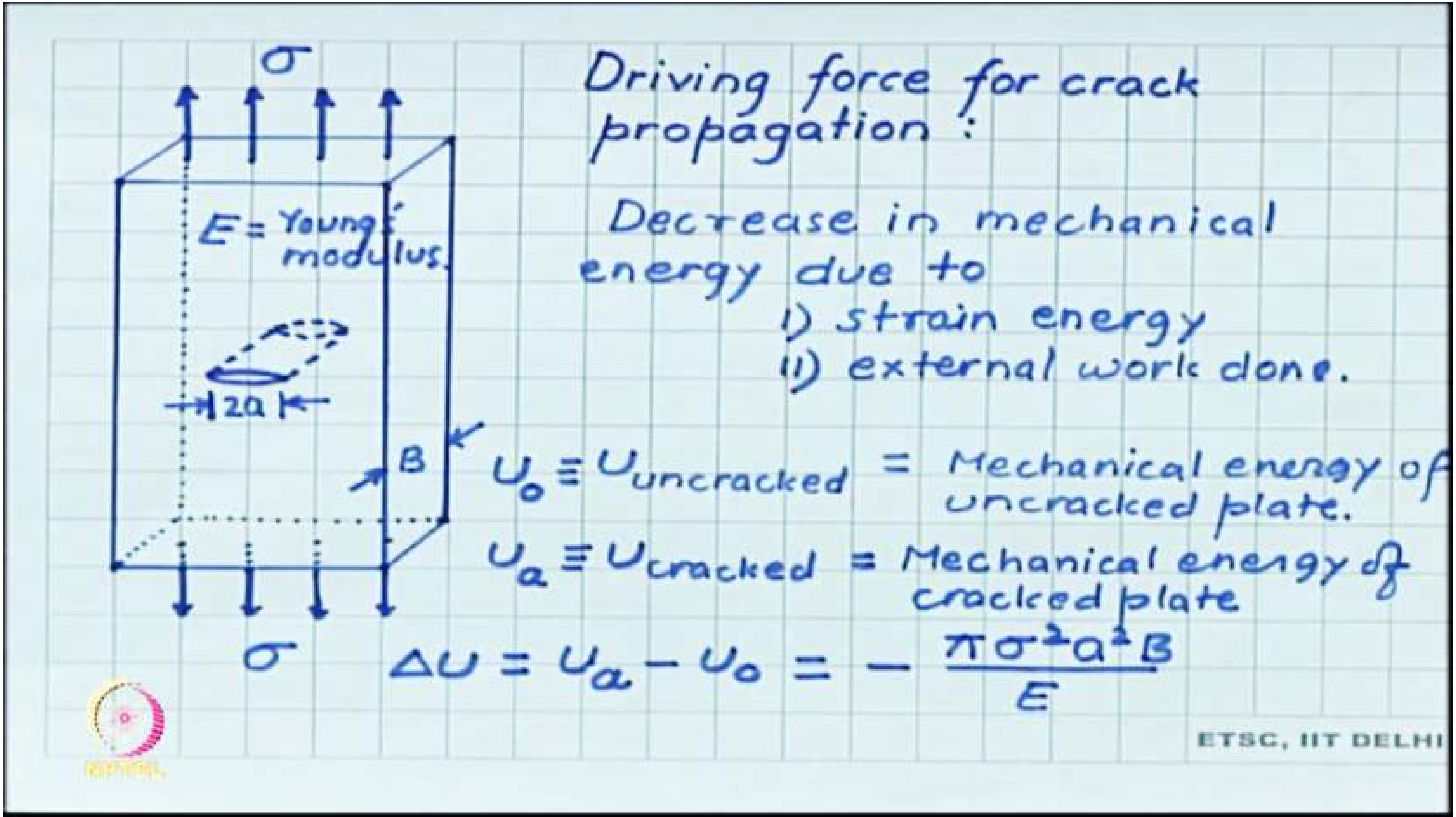
- Paper experiment
- Larger the crack size smaller the fracture stress
- Fracture stress also depends the material property
    - Higher stiffness the higher fracture stress

Griffith theory of brittle fracture

- It was observed that the measured fracture strengths of most brittle materials are much lower than predicted by theoretical calculations based on atomic bonding energy.
- As an explanation Griffith proposed that brittle materials contains large number of fine cracks, which causes stress concentration.
- This leads to reach the theoretical cohesive strength near the cracks, Hence crack propagates and cause the material to fracture
- As the applied stress increases, the crack enlarges and causes material failure.
- Due to the ability to amplify an applied stress, the cracks or flaws are also called ***stress raisers.***

- All brittle materials contain a population of small cracks and flaws that have a variety of sizes, geometries, and orientations.
- When the magnitude of a tensile stress at the tip of one of these flaws exceeds the value of this critical stress, a crack forms and then propagates, which results in fracture.
- Very small and virtually defect-free metallic and ceramic whiskers have been grown with fracture strengths that approach their theoretical values.

Griffith theory of brittle fracture



Driving force for crack propagation:

Decrease in mechanical energy due to
i) strain energy
ii) external work done.

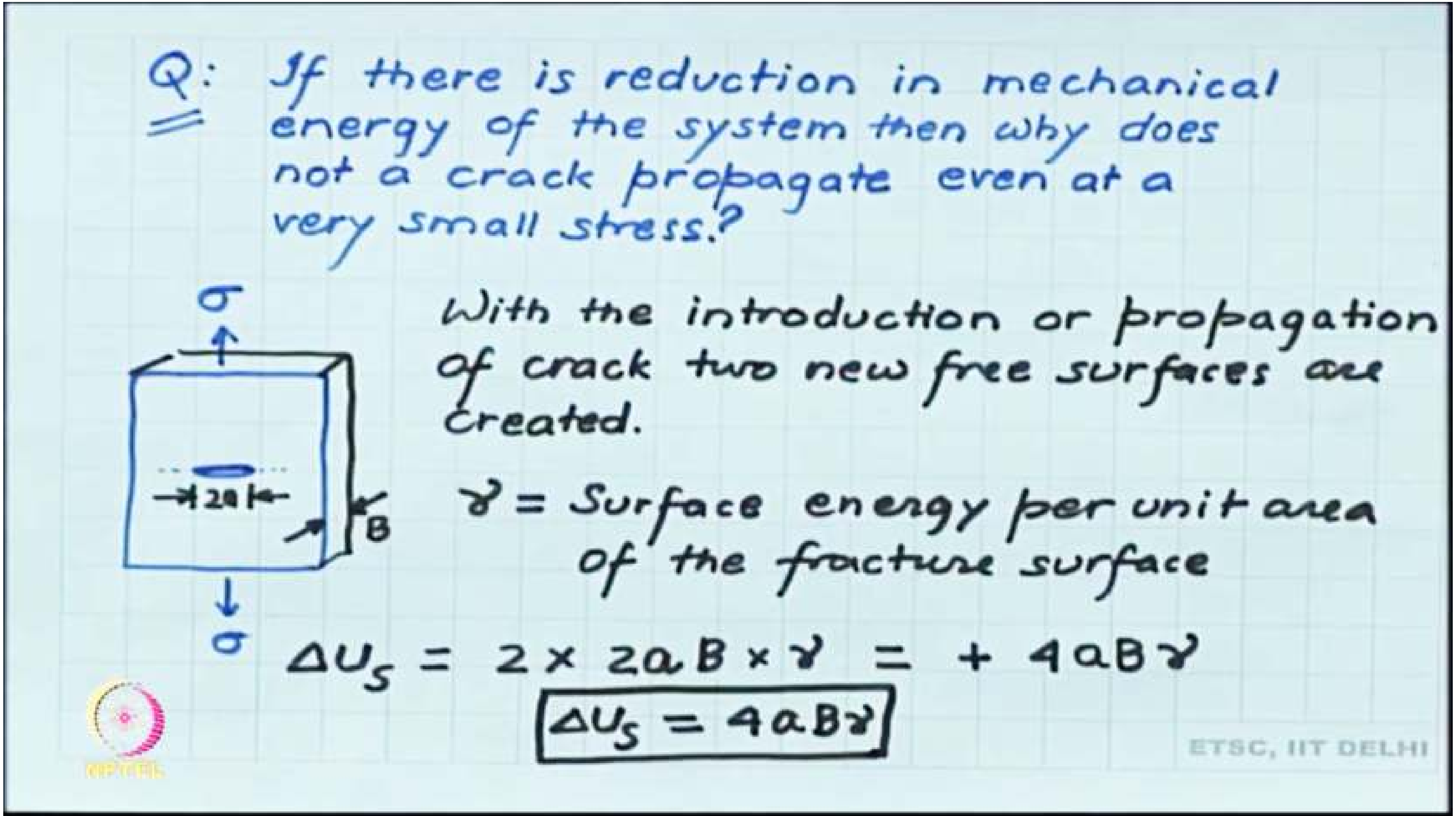
$U_0 \equiv U_{uncracked}$ = Mechanical energy of uncracked plate.

$U_a \equiv U_{cracked}$ = Mechanical energy of cracked plate

$$\Delta U = U_a - U_0 = -\frac{\pi \sigma^2 a^2 B}{E}$$

ETSC, IIT DELHI

Griffith theory of brittle fracture



Q: If there is reduction in mechanical energy of the system then why does not a crack propagate even at a very small stress?

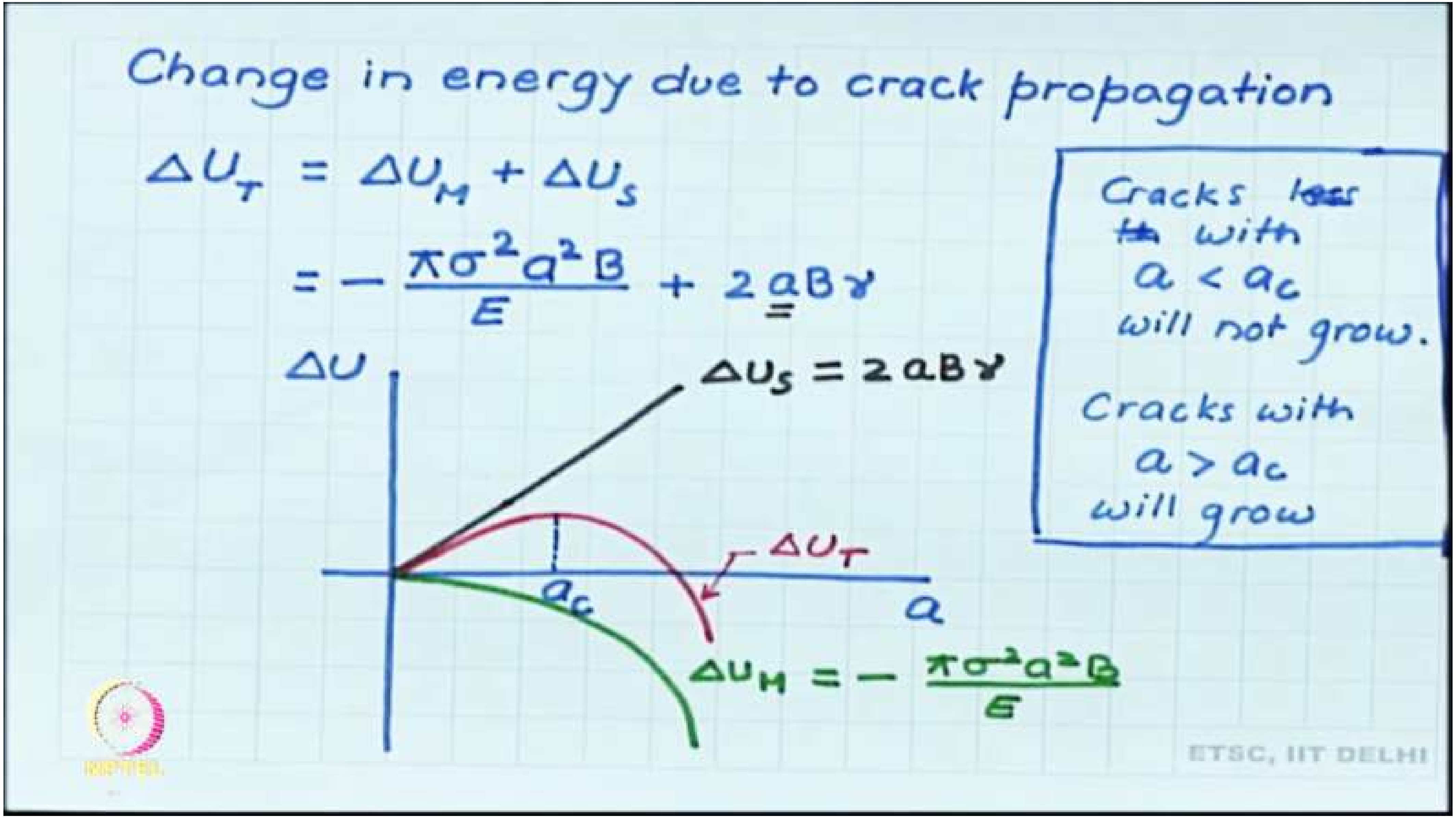
With the introduction or propagation of crack two new free surfaces are created.

γ = Surface energy per unit area of the fracture surface

$$\Delta U_s = 2 \times 2aB \times \gamma = +4aB\gamma$$

$$\boxed{\Delta U_s = 4aB\gamma}$$

Griffith theory of brittle fracture



Change in energy due to crack propagation

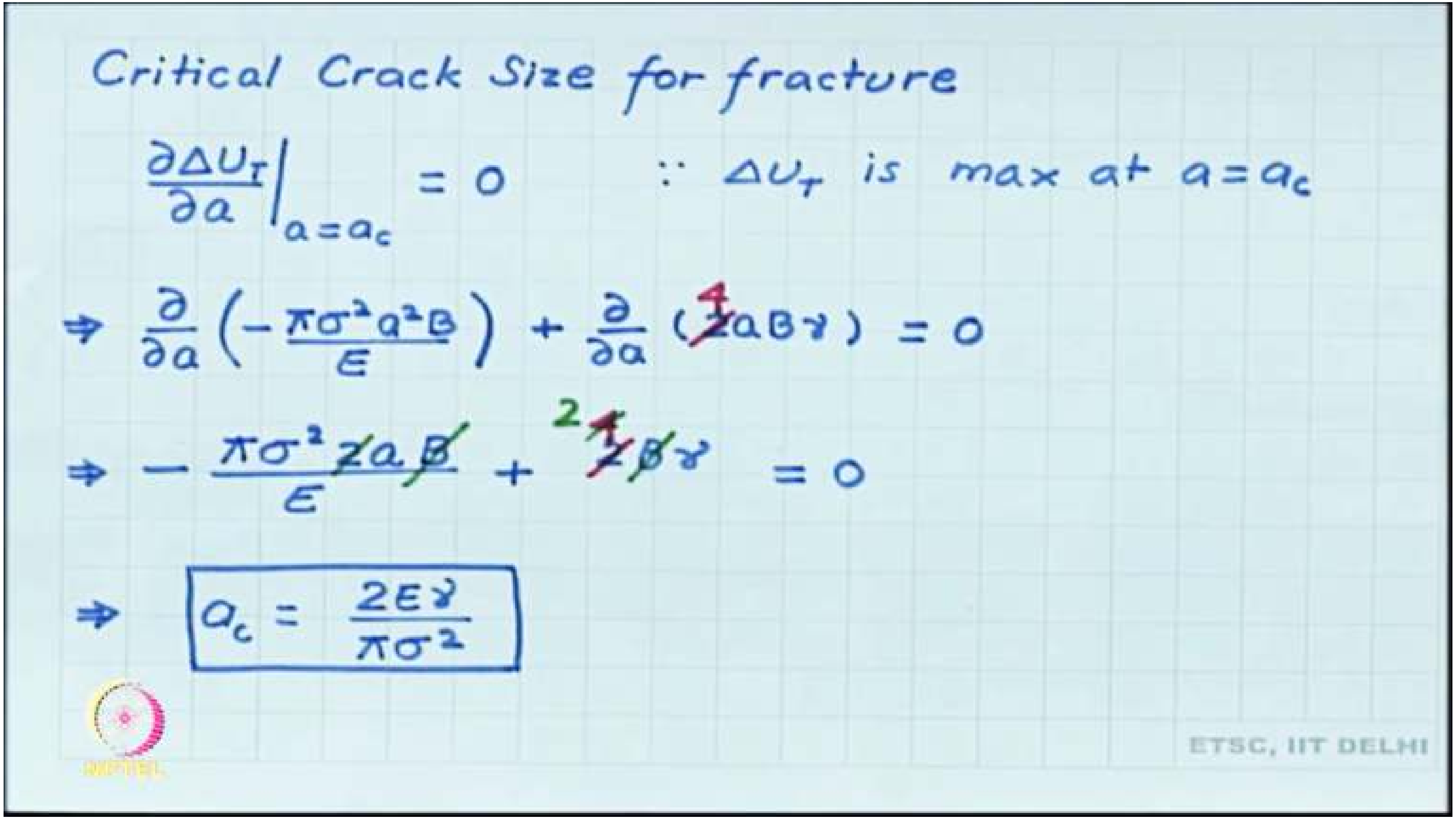
$$\Delta U_T = \Delta U_M + \Delta U_S$$

$$= -\frac{\pi \sigma^2 a^2 B}{E} + 2\underline{\underline{a}}B\gamma$$

Cracks ~~less~~ ~~th~~ with $a < a_c$ will not grow.

Cracks with $a > a_c$ will grow

Griffith theory of brittle fracture



Critical Crack Size for fracture

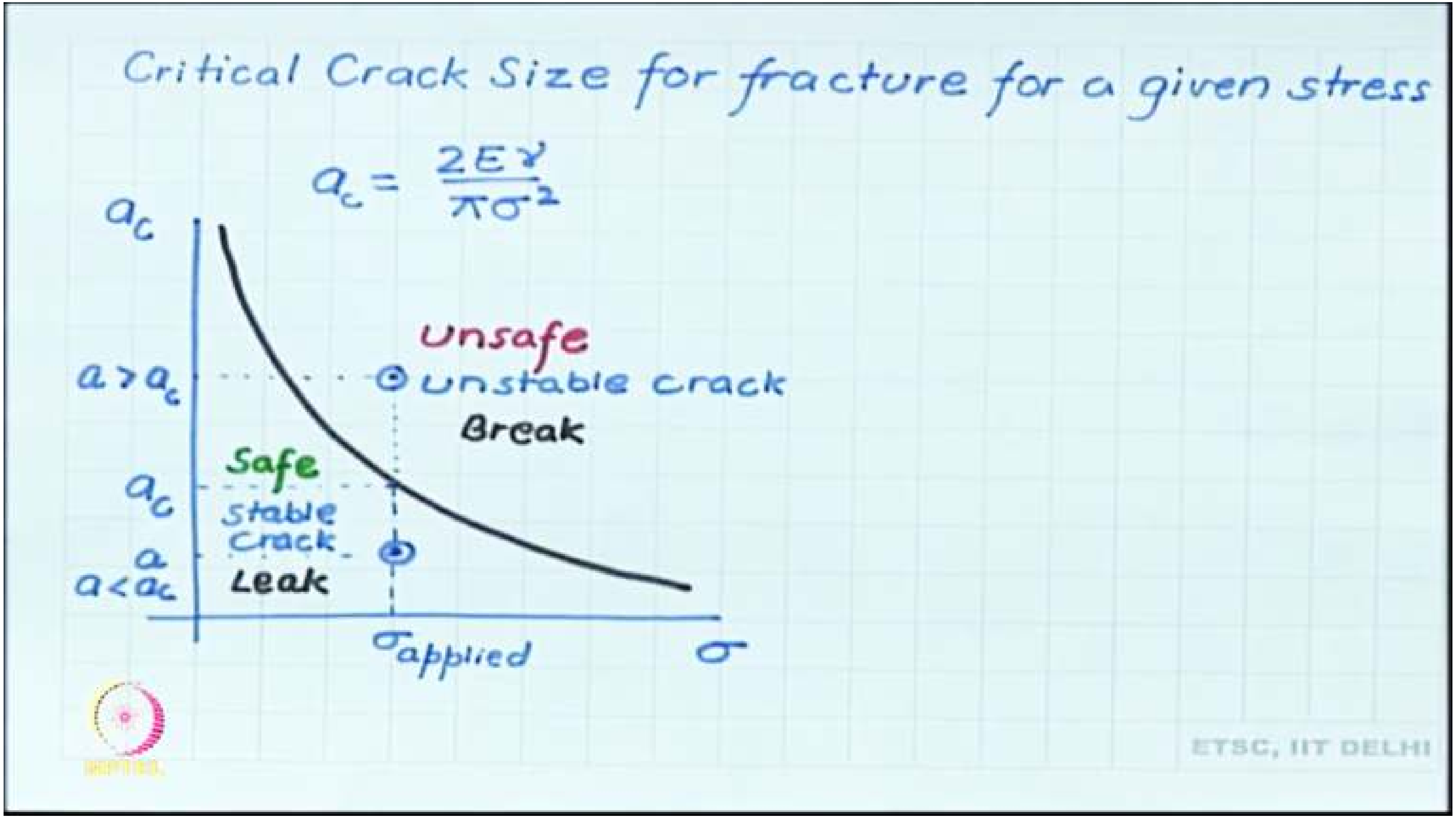
$$\left.\frac{\partial \Delta U_T}{\partial a}\right|_{a=a_c} = 0 \qquad \because \Delta U_T \text{ is max at } a = a_c$$

$$\Rightarrow \frac{\partial}{\partial a}\left(-\frac{\pi\sigma^2 a^2 B}{E}\right) + \frac{\partial}{\partial a}\left(\overset{4}{\cancel{2}}aB\gamma\right) = 0$$

$$\Rightarrow -\frac{\pi\sigma^2\cancel{2}a\cancel{B}}{E} + \overset{2\,\cancel{4}}{\cancel{2}}\cancel{B}\gamma = 0$$

$$\Rightarrow \boxed{a_c = \frac{2E\gamma}{\pi\sigma^2}}$$

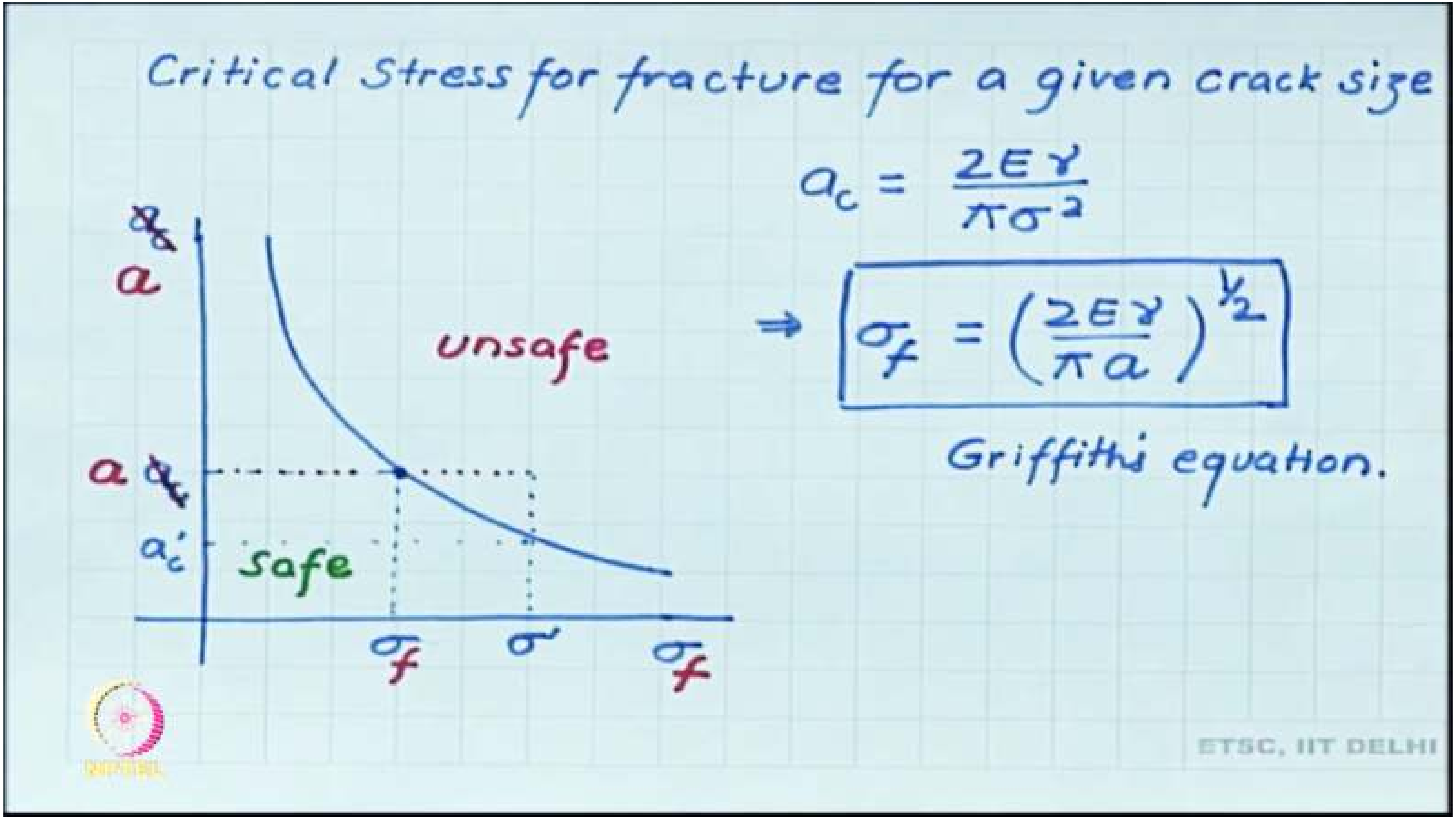
Griffith theory of brittle fracture



Critical Crack Size for fracture for a given stress

$$a_c = \frac{2E\gamma}{\pi\sigma^2}$$

Griffith theory of brittle fracture



Critical Stress for fracture for a given crack size

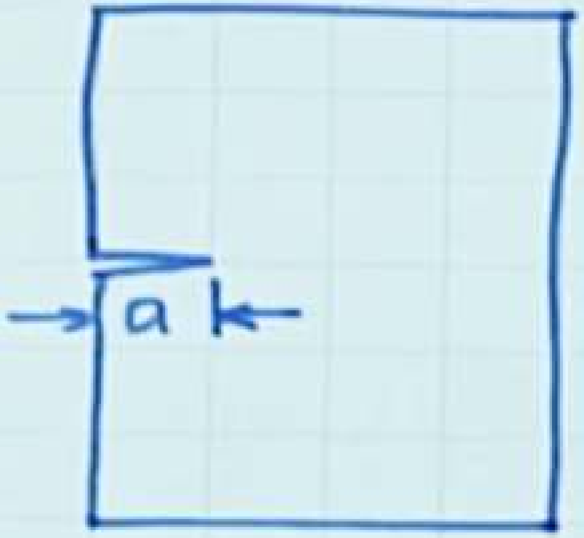
$$a_c = \frac{2E\gamma}{\pi\sigma^2}$$

$$\Rightarrow \boxed{\sigma_f = \left(\frac{2E\gamma}{\pi a}\right)^{1/2}}$$

Griffith's equation.

Central Crack

Edge Crack



Edge crack of length 'a' has the same fracture stress as central crack of length 2a

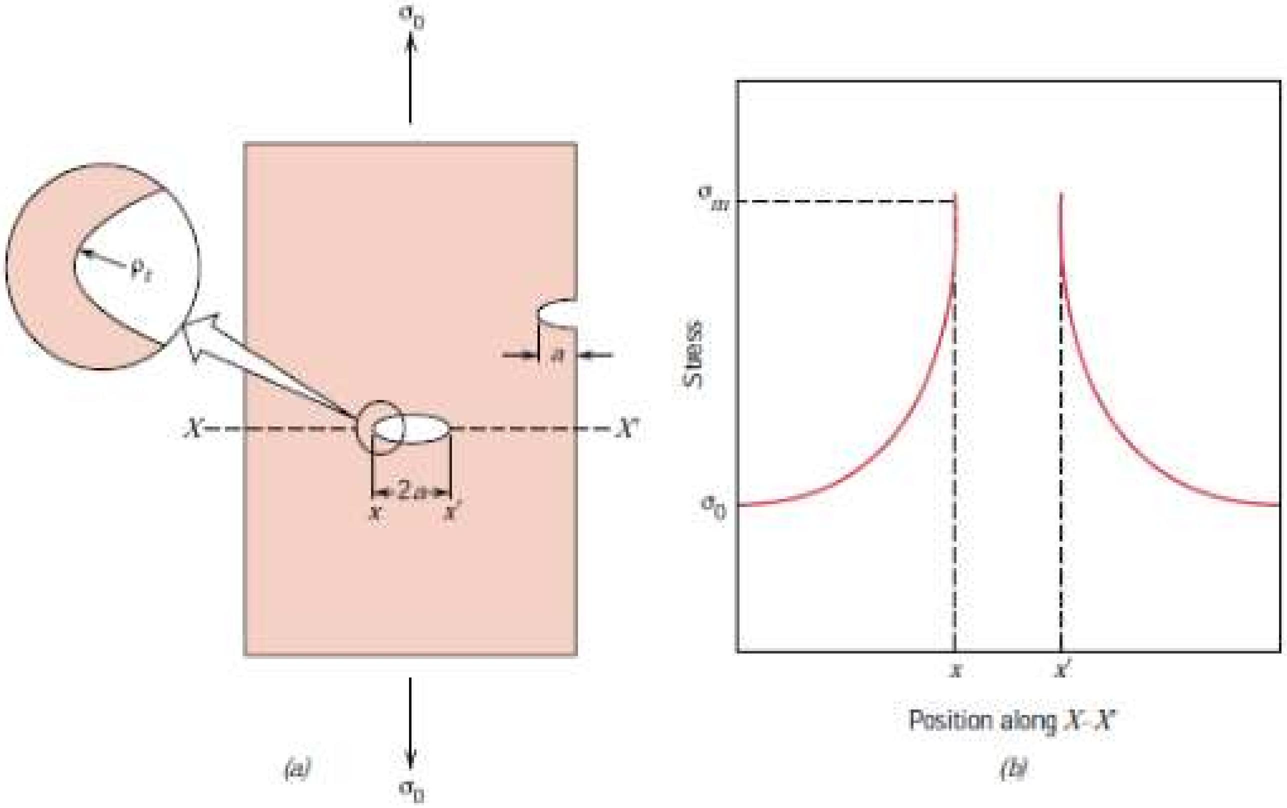
$$\sigma_f = \left(\frac{2E\gamma}{\pi a}\right)^{1/2}$$

$a = \frac{1}{2}$ crack length for a central crack

a = Full crack length for edge crack.

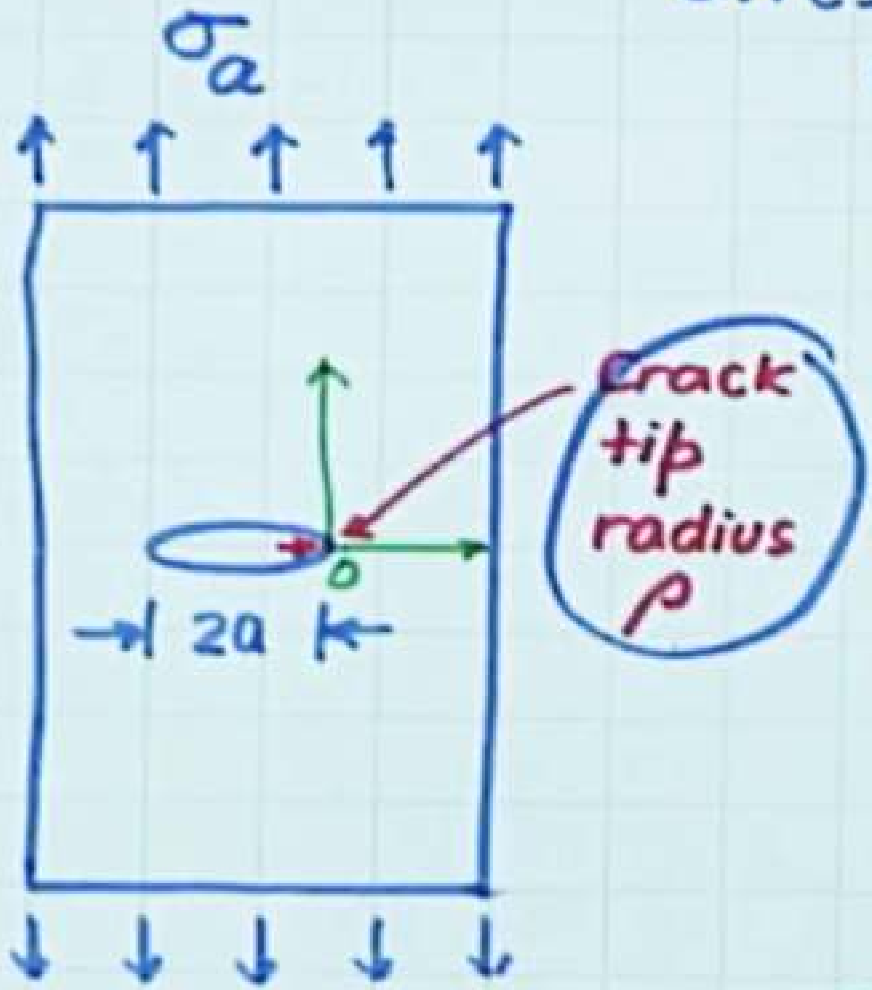
Stress concentration

- Stress concentration/amplification will take place at the tip of the crack, which will force the crack to propagate and thus causing the material to fail.

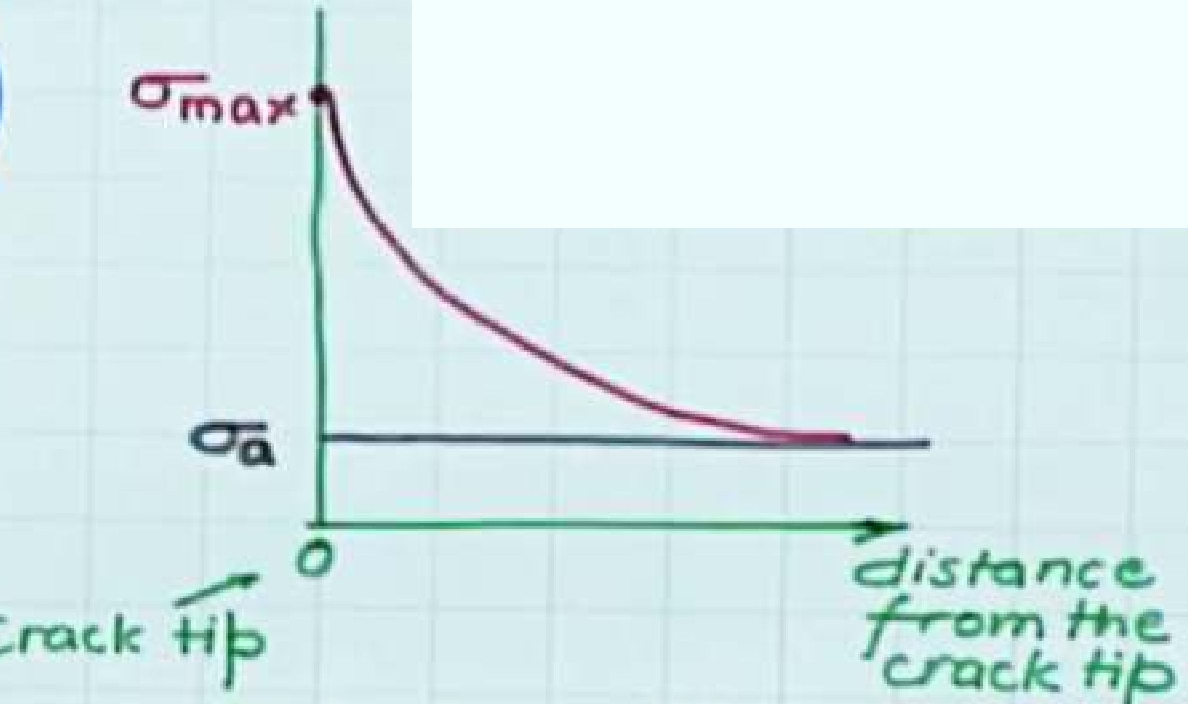


(a) The geometry of surface and internal cracks. (b) Schematic stress profile along the line X–X' demonstrating stress amplification at crack tip positions.

Stress concentration ahead of a crack tip



σ_a = applied stress



σ_a square window

circular windows.

$$\sigma_m = 2\sigma_0 \left(\frac{a}{\rho_t}\right)^{1/2}$$

Where σ_m = Maximum stress at crack tip
σ_o = Magnitude of applied stress
a = length of surface crack or half length of internal crack
ρ_t = radius of curvature at crack tip

$a >> \rho_t$, i.e $\sigma_m >> \sigma_o$
So it is clear that magnitude of stress at crack tip is much higher compared to magnitude of applied stress and this is due to stress concentration

Stress Concentration Factor (Kt)

$$K_t = \frac{\sigma_m}{\sigma_0} = 2\left(\frac{a}{\rho_t}\right)^{1/2}$$

Primary & Secondary stress raisers

- Change in geometry of the part, key ways, holes, threads, steps or change in diameter, bolt head etc. are *Primary Stress Raisers.*

- Surface discontinuities such as nicks, notches, machining marks, pitting, corrosion, defects inherent in the material – non metallic inclusion, minute cracks, voids etc. are *Secondary Stress Raisers.*

- Furthermore, the effect of a stress raiser is more significant in brittle than in ductile materials.
- For a ductile material, plastic deformation ensues when the maximum stress exceeds the yield strength. This leads to a more uniform distribution of stress in the vicinity of the stress raiser and to the development of a maximum stress concentration factor less than the theoretical value.
- Such yielding and stress redistribution do not occur to any appreciable extent around flaws and discontinuities in brittle materials; therefore, essentially the theoretical stress concentration will result.

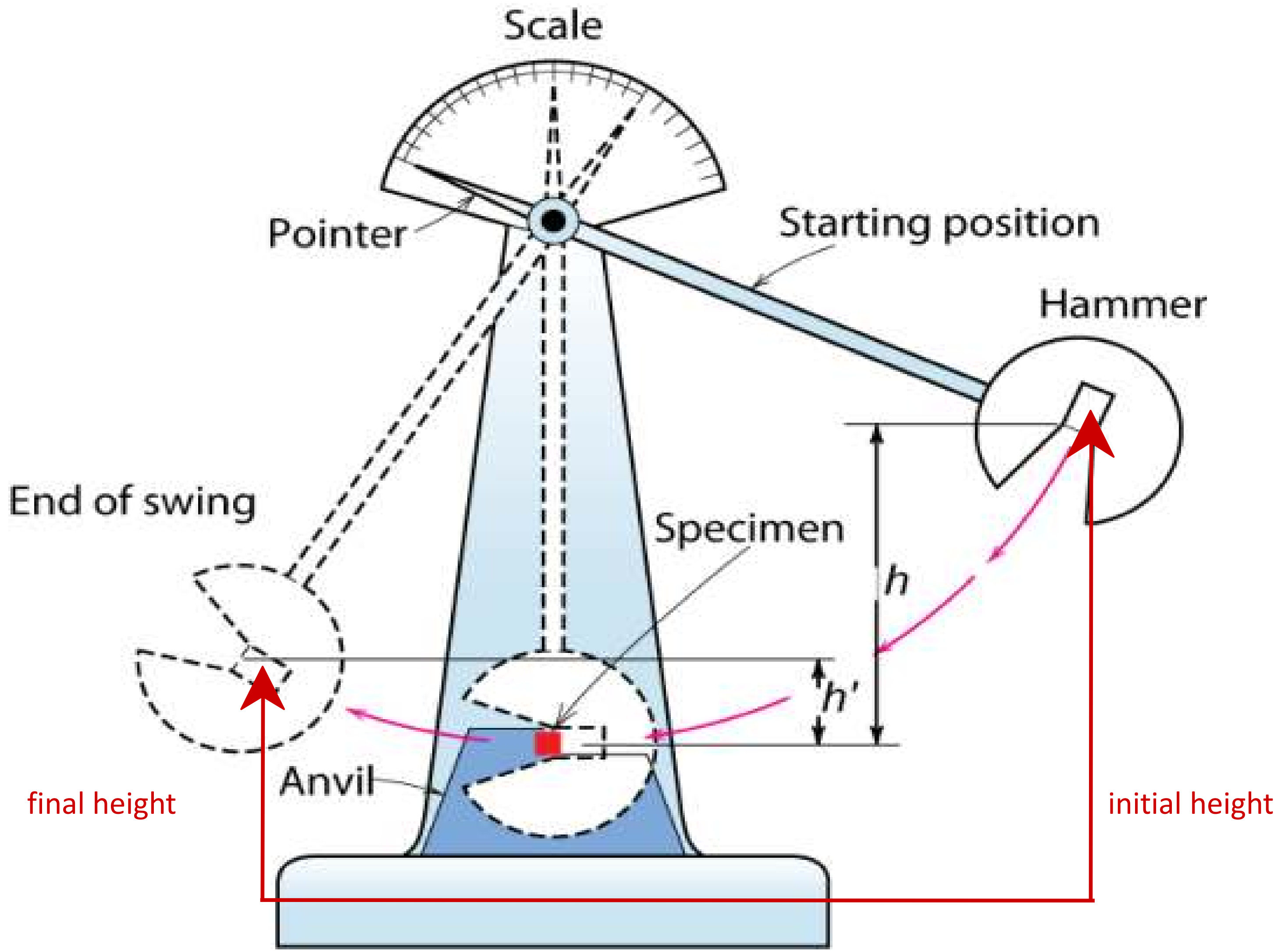
Effect of impact loading on ductile material and its application in forging

- An impact load is a dynamic load; where load is suddenly applied.
- When a material is subjected to a sudden, intense blow, in which the strain rate is extremely rapid, it may behave in much more brittle a manner than is observed in the tensile test.
- Its effect is much grater than a steady load of same magnitude.
- Impact test is used to measure the **toughness of the material**, a measure on the capacity of a material to store strain energy before it fails.
- High toughness is exhibited by materials with high strength and ductility.
- During impact loads, the ductile materials with voids and cracks will behave like brittle materials, and it is not indicated in tensile tests.

- A brittle material requires less energy to break and hence lacks toughness than pure ductile materials.
- Impact test are particularly useful for finding the ductile to brittle transition characteristics of materials.
- The main objective of impact tests is to select materials with high fracture toughness.

- **In forging process** the forces are applied on the raw material such that the stresses induced are greater than yield and less than ultimate strength so that material is experiencing plastic or permanent deformation to get required shape.
- But in forging operation force applied can be either continuous or intermittent impact loads.
- There are two kinds of forging process, impact forging and press forging. In the former, the load is applied by impact, and deformation takes place over a very short time.
- Press forging, on the other hand, involves the gradual build up of pressure to cause the metal to yield. The time of application is relatively long.

Impact Testing Apparatus



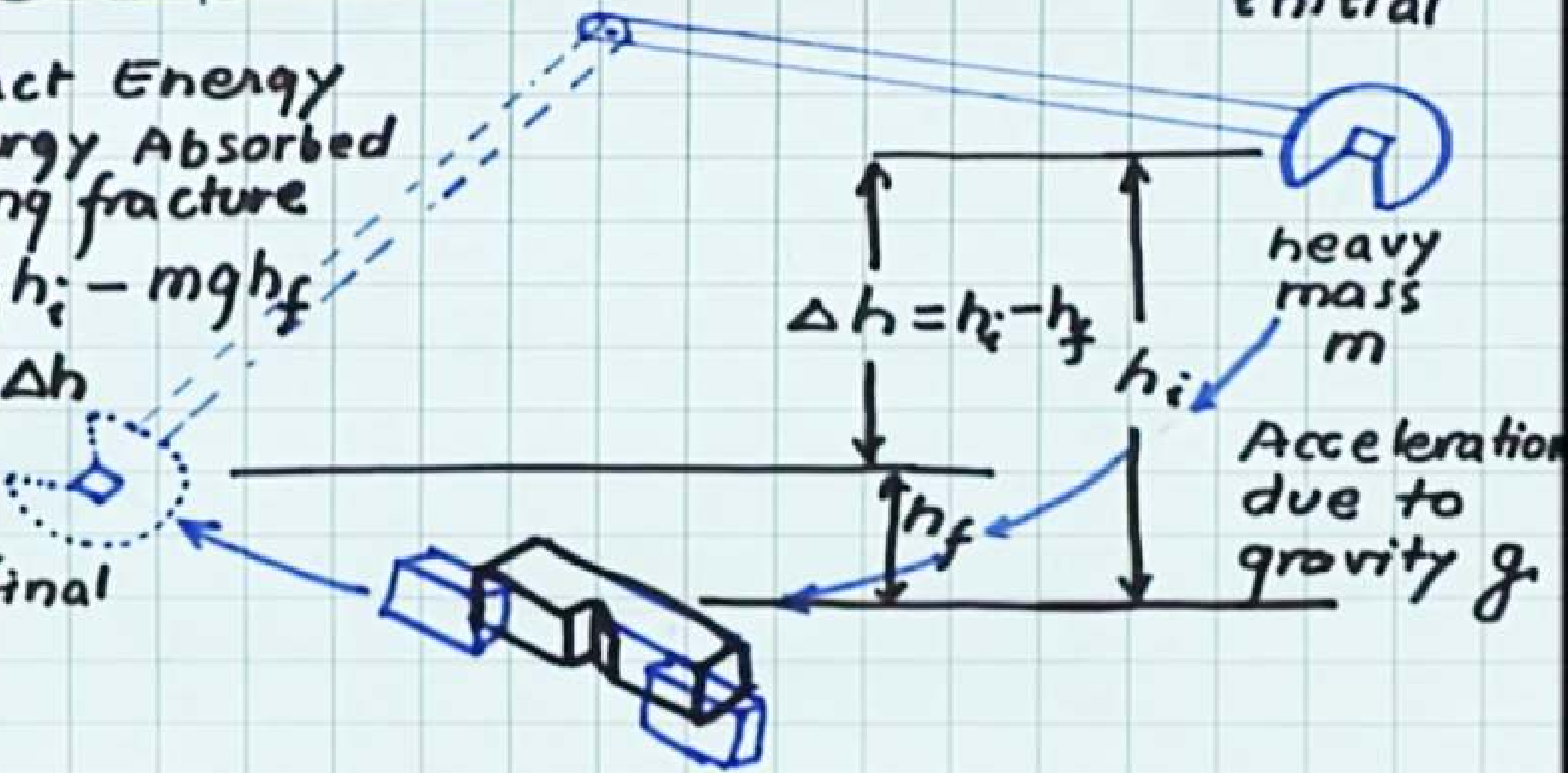
Charpy Impact test

Impact Energy

= Energy Absorbed during fracture

$= mgh_i - mgh_f$

$= mg\Delta h$



Impact tests – Izod & Charpy

V notch

Test specimen

Izod test

Charpy test

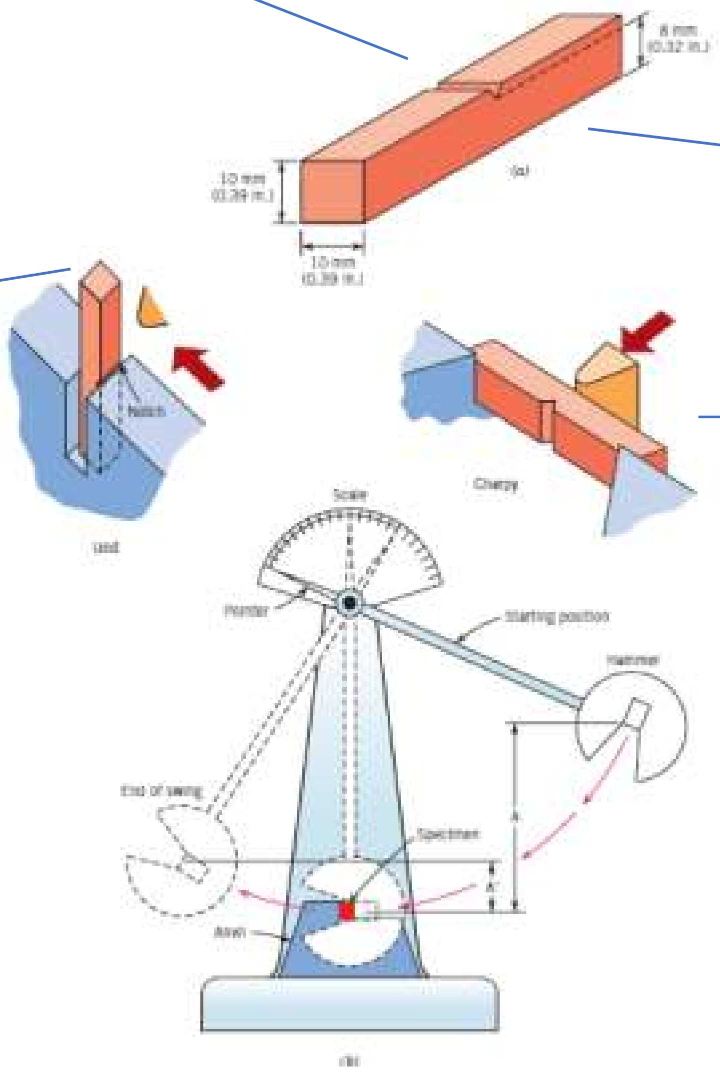


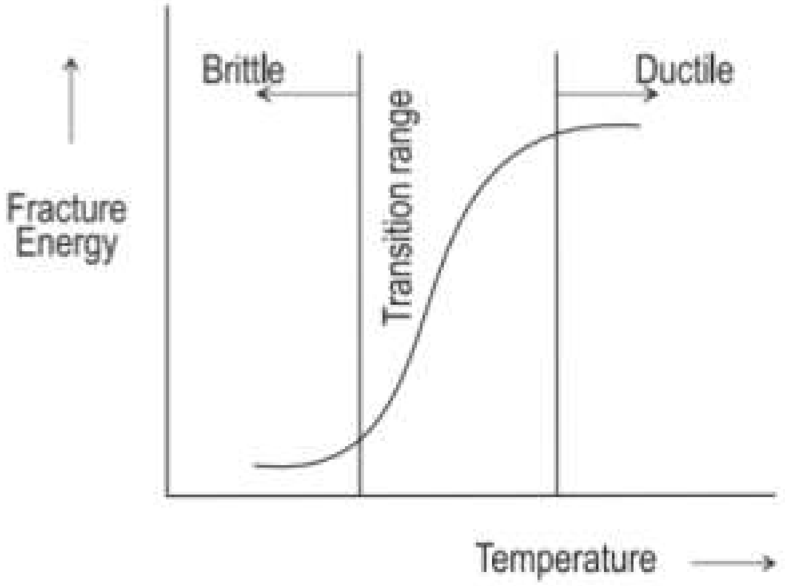
Figure 8.12 (*a*) Specimen used for Charpy and Izod impact tests. (*b*) A schematic drawing of an impact testing apparatus. The hammer is released from fixed height *h* and strikes the specimen; the energy expended in fracture is reflected in the difference between *h* and the swing height *h*'. Specimen placements for both Charpy and Izod tests are also shown. [Figure (*b*) adapted from H. W. Hayden, W. G. Moffatt, and J. Wulff, *The Structure and Properties of Materials*, Vol. III, *Mechanical Behavior*, p. 13. Copyright © 1965 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.]

Izod & Charpy Tests

- For both Charpy and Izod tests, the specimen is in the shape of a bar of square cross section.
- A V-notch is machined to the cross section.
- The load is applied as an impact blow from a weighted pendulum hammer that is released from a cocked position at a fixed height h.
- The specimen is positioned at the base.
- Upon release, a knife edge mounted on the pendulum strikes and fractures the specimen at the notch, which acts as a point of stress concentration for this high velocity impact blow.
- The pendulum continues its swing, rising to a maximum height h' which is lower than h. The energy absorption, computed from the difference between h and h' is a measure of the impact energy.

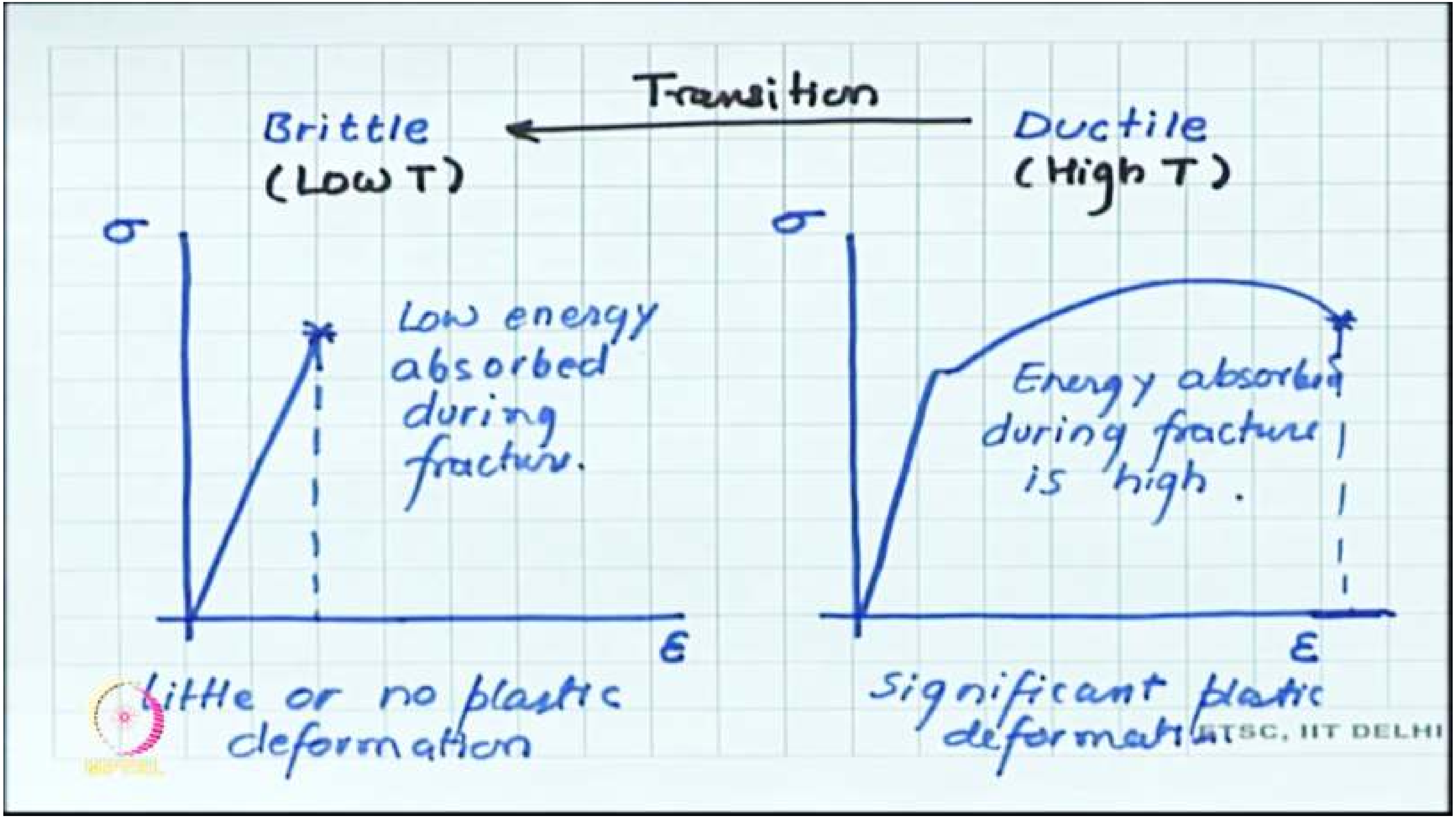
Ductile to Brittle Transition

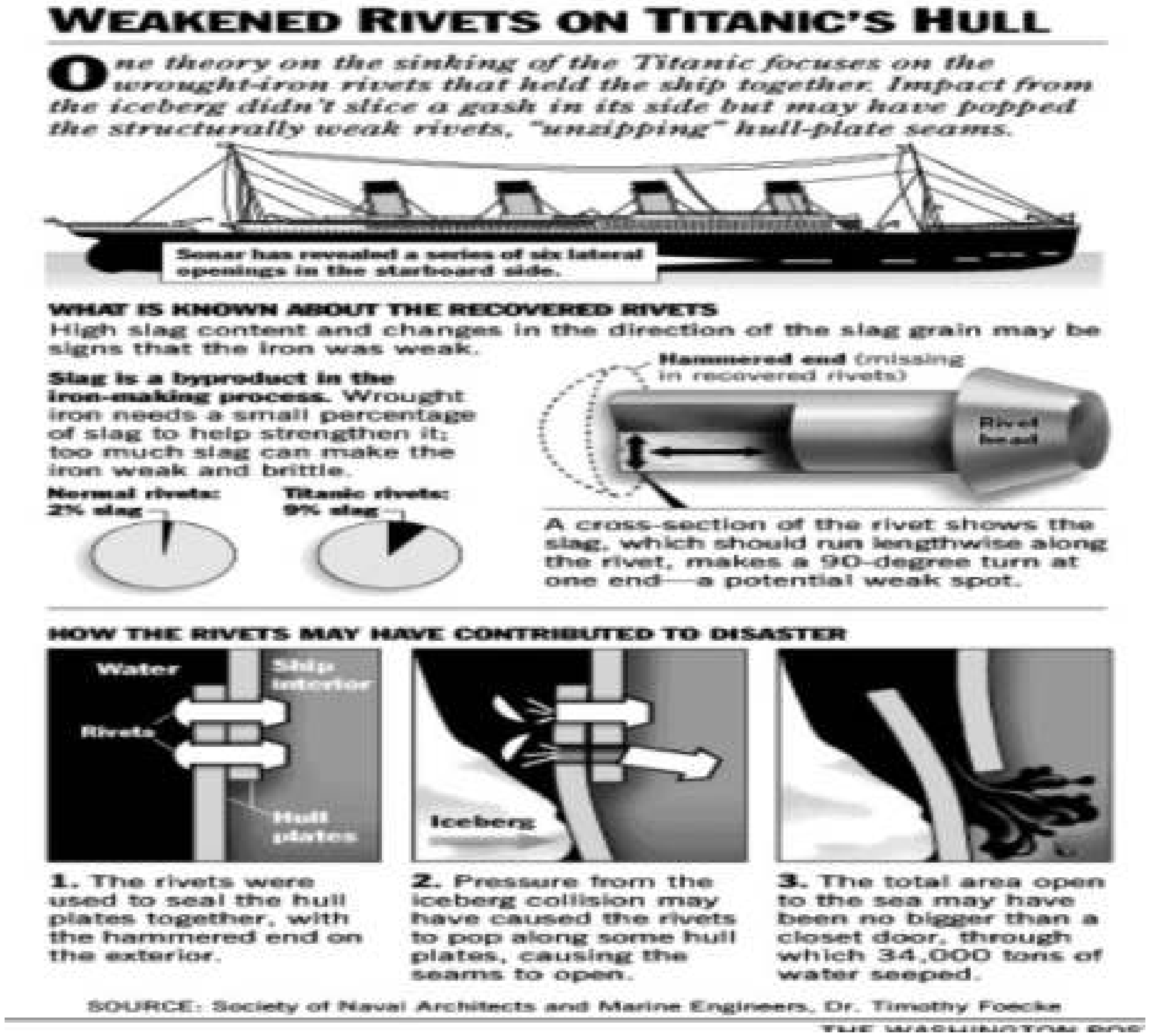
- Under some circumstances, ductile materials fracture abruptly and with very little plastic deformation. Thus there is a transition from ductile to brittle fracture, as crack propagation takes precedence over plastic deformation.
- This ductile to brittle fracture transition occurs in some metals when
  - a) the temperature is lowered
  - (b) the rate of straining increased and/ or
  - (c) a notch or stress raiser is introduced in the material.



- In steel and other BCC materials the ductile behavior changes to brittle with decreasing temperature. This transition from ductile to brittle fracture behavior is an important engineering phenomenon.

Ductile to brittle transition temperature (DBTT) in steels





WEAKENED RIVETS ON TITANIC'S HULL

One theory on the sinking of the Titanic focuses on the wrought-iron rivets that held the ship together. Impact from the iceberg didn't slice a gash in its side but may have popped the structurally weak rivets, "unzipping" hull-plate seams.

Sonar has revealed a series of six lateral openings in the starboard side.

WHAT IS KNOWN ABOUT THE RECOVERED RIVETS

High slag content and changes in the direction of the slag grain may be signs that the iron was weak.

Slag is a byproduct in the iron-making process. Wrought iron needs a small percentage of slag to help strengthen it; too much slag can make the iron weak and brittle.

A cross-section of the rivet shows the slag, which should run lengthwise along the rivet, makes a 90-degree turn at one end—a potential weak spot.

HOW THE RIVETS MAY HAVE CONTRIBUTED TO DISASTER

1. The rivets were used to seal the hull plates together, with the hammered end on the exterior.

2. Pressure from the iceberg collision may have caused the rivets to pop along some hull plates, causing the seams to open.

3. The total area open to the sea may have been no bigger than a closet door, through which 34,000 tons of water seeped.

SOURCE: Society of Naval Architects and Marine Engineers, Dr. Timothy Foecke

THE WASHINGTON POS

- Titanic's hull was triple riveted with using mild steel rivets, and double riveted using wrought iron, in the central length of the ship where maximum stress was assumed to be located .
- Where as the use of wrought iron and mild steel rivets instead of steel rivets caused the titanic disaster to take place .
- The steel rivets have good strength as compared to wrought iron.
- Titanic had experienced a great forcefull impact which caused the six compartments of it to be opened to sea where the used wrought iron rivets failed.

Sinking of Titanic -14th April 1912

"All the News That's Fit to Print."

The New York Times.

TITANIC SINKS FOUR HOURS AFTER HITTING ICEBERG;
866 RESCUED BY CARPATHIA, PROBABLY 1250 PERISH;
ISMAY SAFE, MRS. ASTOR MAYBE, NOTED NAMES MISSING

Col. Astor and Bride, Isidor Straus and Wife, and Maj. Butt Aboard.

"RULE OF SEA" FOLLOWED

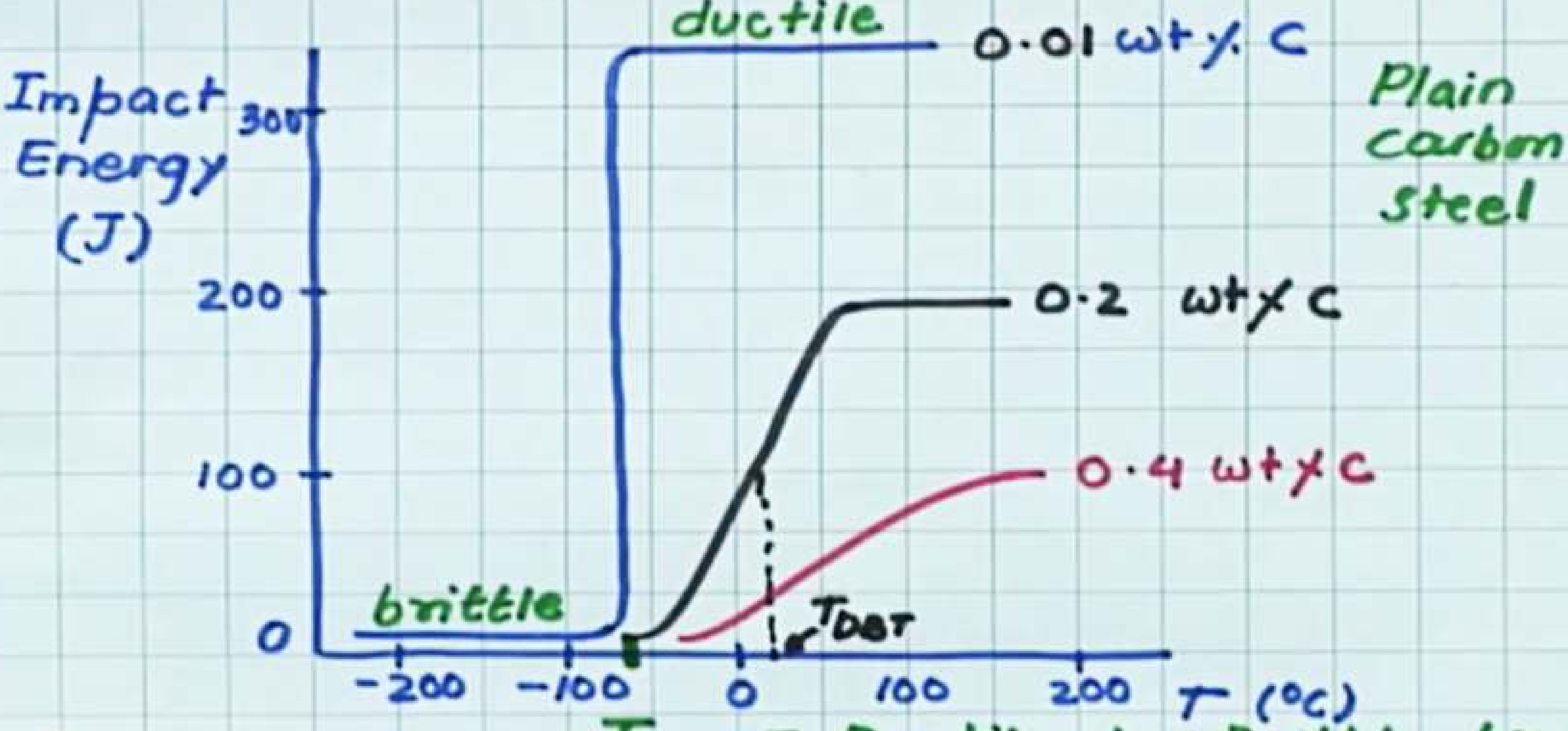
PICKED UP AFTER 8 HOURS

Biggest Liner Plunges to the Bottom at 2:20 A. M.

RESCUERS THERE TOO LATE

WOMEN AND CHILDREN FIRST

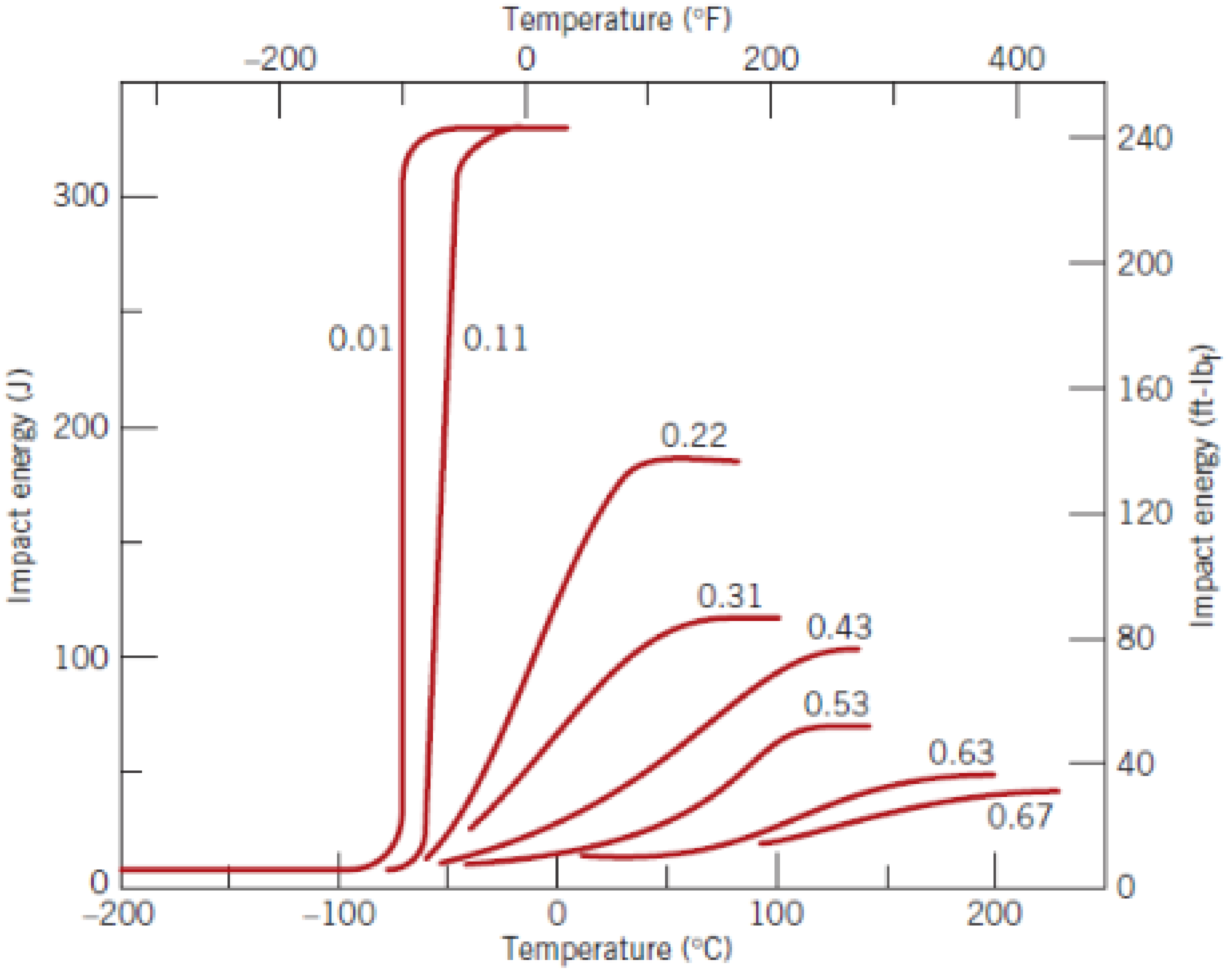
Titanic was made up of steel which has moderately high DBT temperature. On the day of sinking, the temperature was –2 ^{0}C which made the structure highly brittle which caused the damage.



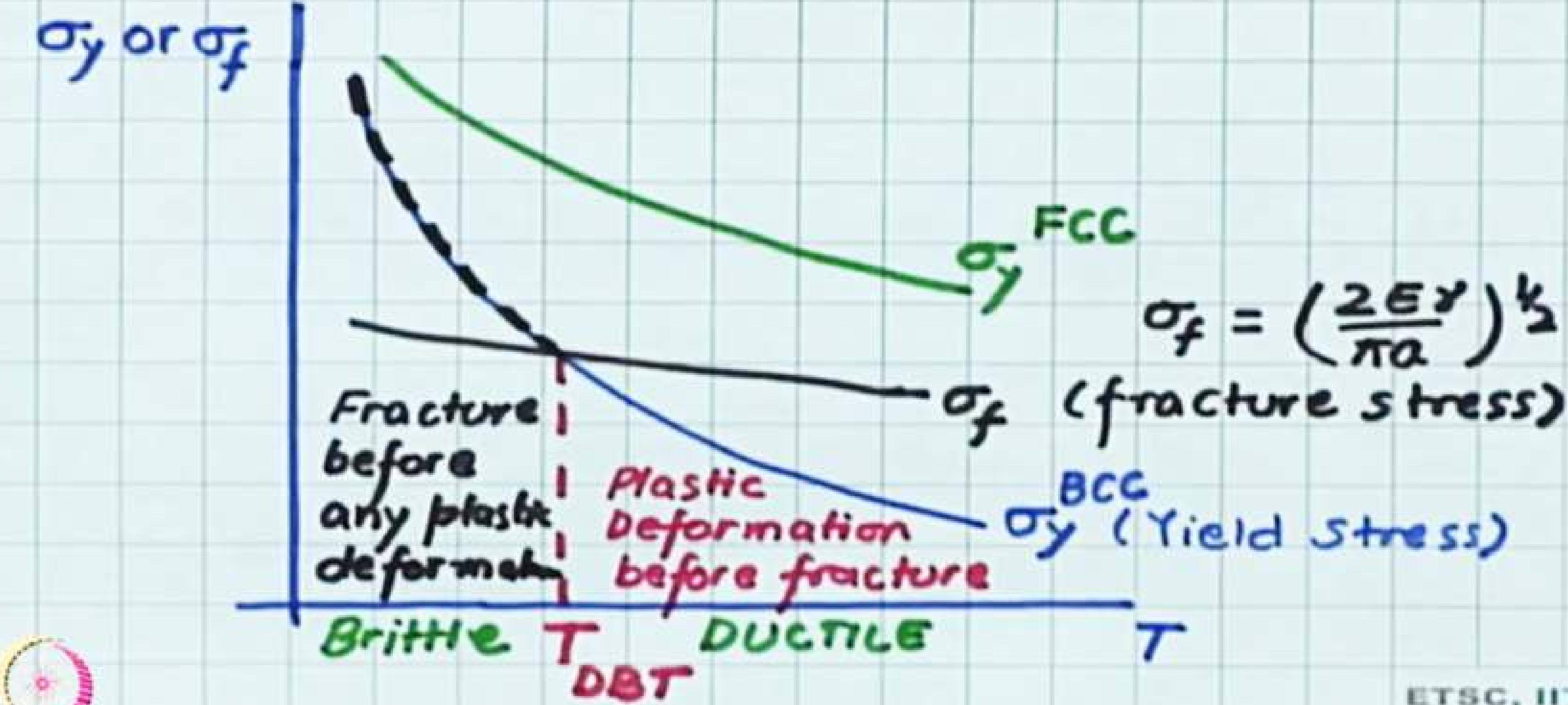
T_{DBT} = Ductile-to-Brittle transition temperature

- For these low-strength steels, the transition temperature is sensitive to both alloy composition and microstructure. For example, decreasing the average grain size results in a lowering of the transition temperature. Hence, refining the grain size both strengthens and toughens steels. In contrast, increasing the carbon content, while increasing the strength of steels, also raises the CVN transition of steels,

Figure 8.16 Influence of carbon content on the Charpy V-notch energy-versus-temperature behavior for steel. (Reprinted with permission from ASM International, Metals Park, OH 44073-9989, USA; J. A. Reinbolt and W. J. Harris, Jr., "Effect of Alloying Elements on Notch Toughness of Pearlitic Steels," *Transactions of ASM*, Vol. 43, 1951.)



BCC : Yield Stress a strong function of temp.



$$\sigma_f = \left(\frac{2E\gamma}{\pi a}\right)^{1/2}$$

(fracture stress)

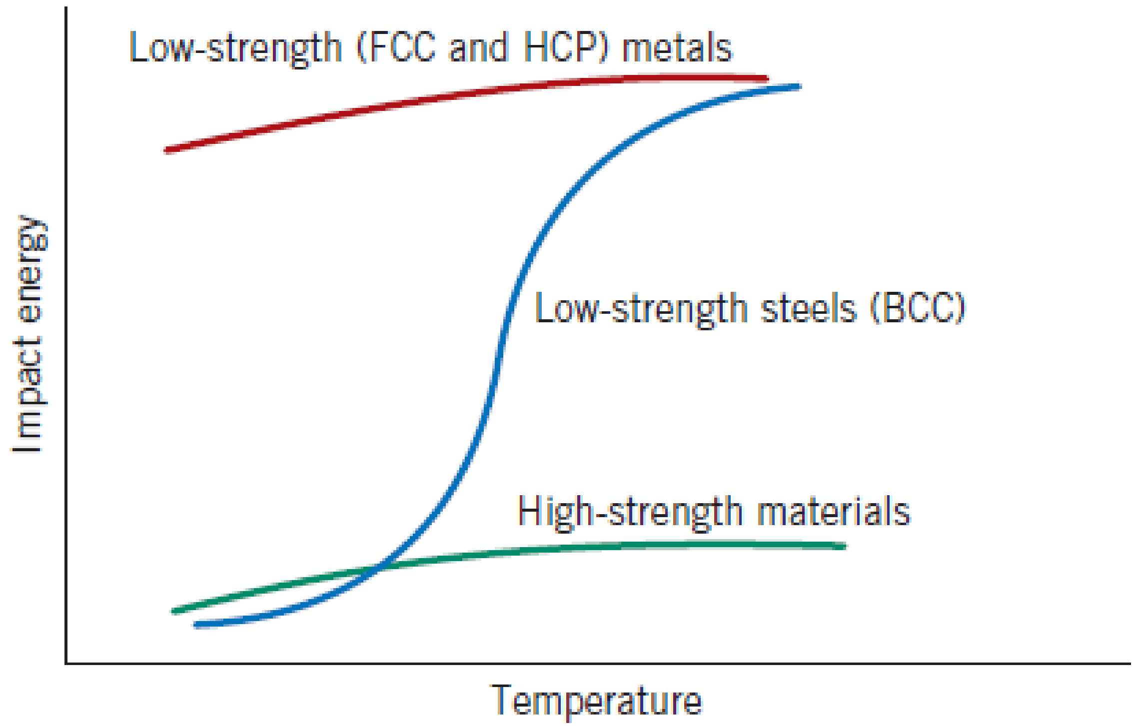


Figure 8.15 Schematic curves for the three general types of impact energy-versus-temperature behavior.

- low-strength FCC metals (some aluminum and copper alloys) and most HCP metals do not experience a ductile-to-brittle transition and retain high impact energies (i.e., remain ductile) with decreasing temperature.
- For high-strength materials (e.g., high-strengthsteels and titanium alloys), the impact energy is also relatively insensitive to temperature however, these materials are also very brittle, as reflected by their low impact energy values.

Ductile to brittle transition (DBT)

1. FCC materials do not show DBT
   - Good for cryogenic application
   - Austenic stainless steel is good for low temp use (Astenite : FCC)
   - Mild steel is not good for low temp use (Ferrite BCC)
2. Finer grain size lower the transition temp.
   - Enhances the ductile behavior
3. High strain rate increases the transition temp.
   - Enhances the brittle behavior
4. Notches increases the transition temp.
   - Enhances the brittle behavior

Structural changes during DBTT

- The reason for this transition is that, at higher temperatures, the atoms in the materials vibrate with greater frequency and amplitude. This increase allows the atoms under stress to slip to new positions within the material (to break bonds and form new ones with other atoms in the material).
- This slippage of atoms is observed outside of the material as plastic deformation, a feature of ductile fracture.
- However, when the temperature is lowered, the atoms may not be able to slip to new positions in the material. As the applied stress becomes high enough the atoms just break their bonds, but do not form new ones.
- The decrease in slippage does not cause plastic deformation. Thus, the material behaves in a brittle manner at lower temperatures.

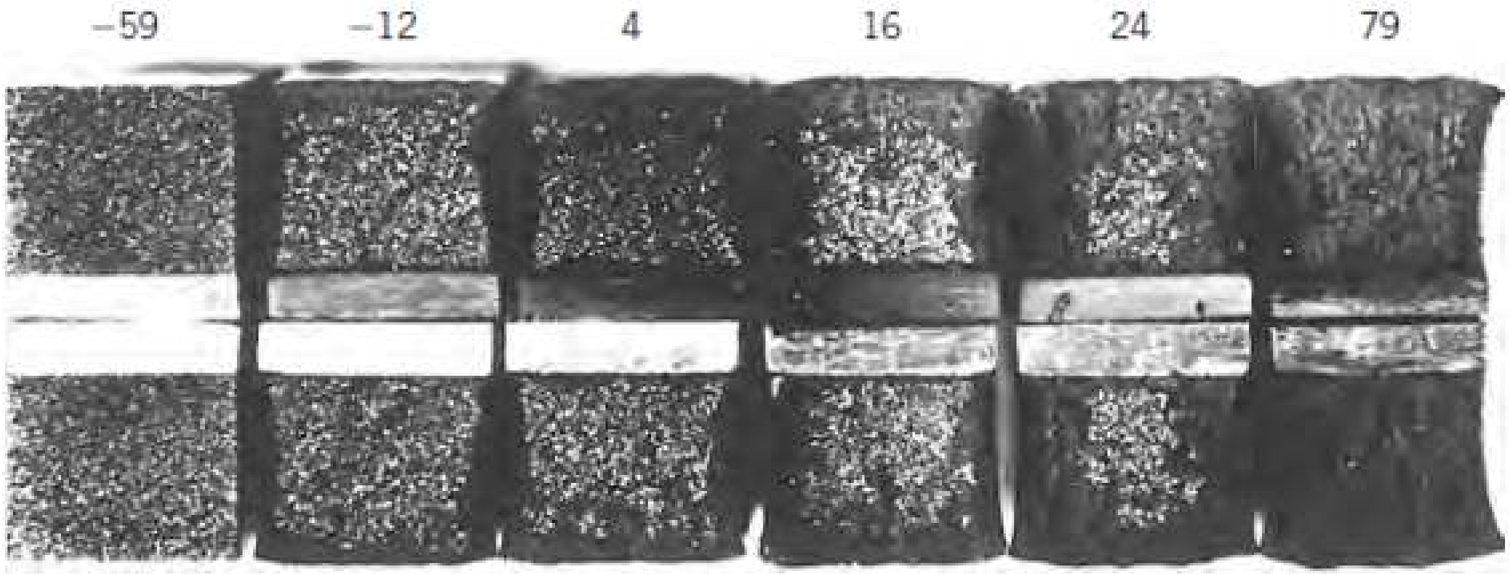


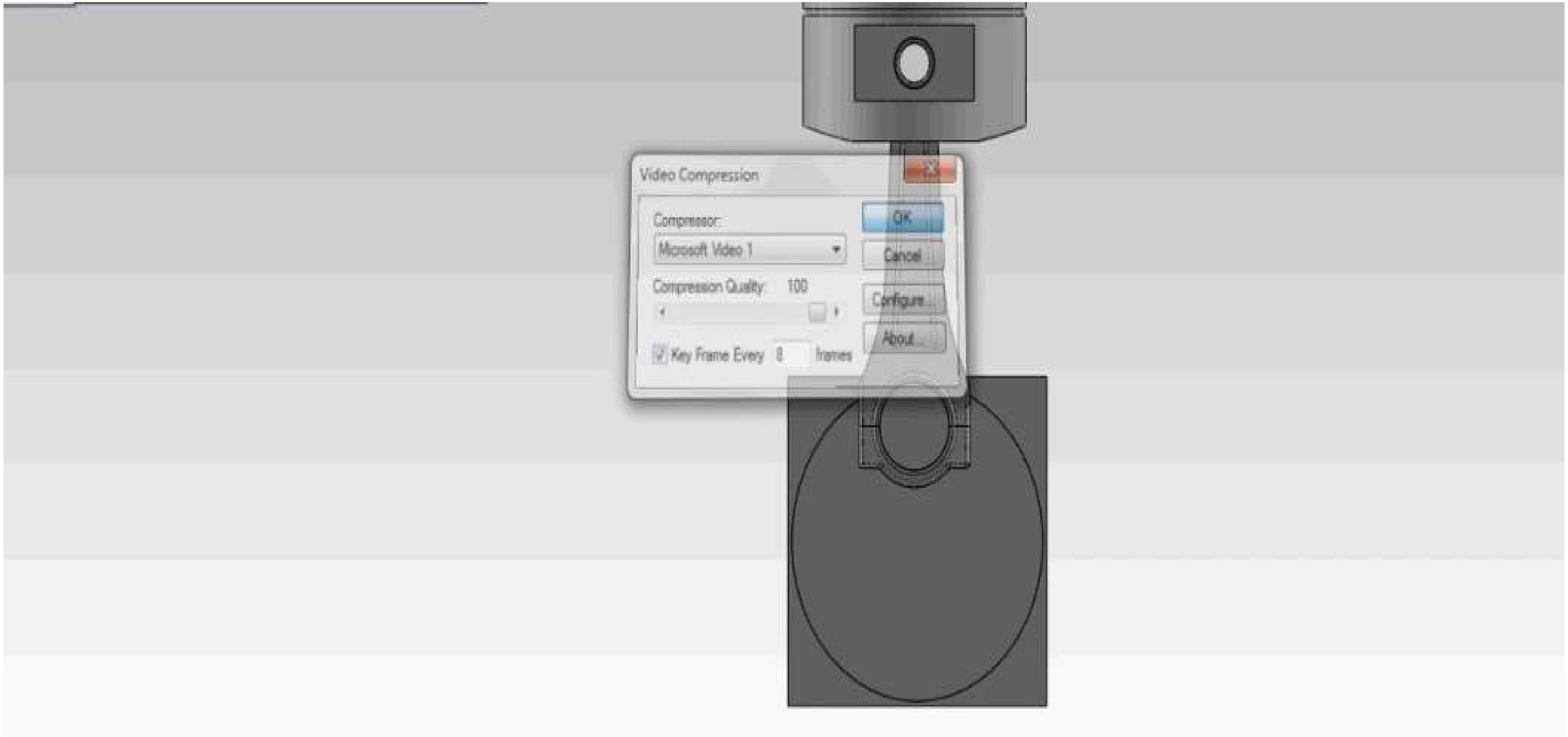
Figure 8.14 Photograph of fracture surfaces of A36 steel Charpy V-notch specimens tested at indicated temperatures (in °C). (From R. W. Hertzberg, *Deformation and Fracture Mechanics of Engineering Materials*, 3rd edition, Fig. 9.6, p. 329. Copyright © 1989 by John Wiley & Sons, Inc., New York. Reprinted by permission of John Wiley & Sons, Inc.)

- The appearance of the failure surface is indicative of the nature of fracture and may be used in transition temperature determinations. For ductile fracture this surface appears fibrous or dull (or of shear character), as in the steel specimen
- A brittle surfaces have a granular (shiny) texture (or cleavage character)
- Over the ductile-to-brittle transition, features of both types will exist

Fatigue

- Materials subjected to repetitive or fluctuating stress will fail at a stress much lower than that required to cause failure under steady loads. This behavior is called fatigue.
- Failure of a component subjected to cyclic loading at a stress considerably lower than the yield stress of a static loading.
- Fatigue is an important form of behavior in all materials including metals, polymers and ceramics. Fatigue is important, because it is the single largest cause of failure in metals (almost 80 to 90% of all metallic failure is due to fatigue).
- This type of failure is very dangerous, because it occurs without any warning or signs of failure.
- Fatigue failure is brittle like in nature even in normally ductile metals, in that there is very little, if any, gross plastic deformation associated with failure. The process occurs by the initiation and propagation of cracks, and ordinarily the fracture surface is perpendicular to the direction of an applied tensile stress.

Fatigue occurs in structures that are subjected to dynamic, rapidly fluctuating and cyclic stresses (e.g, rotating shafts, bridges, air craft wings, machine components, automobile parts etc.).



Video Compression

Compressor: Microsoft Video 1

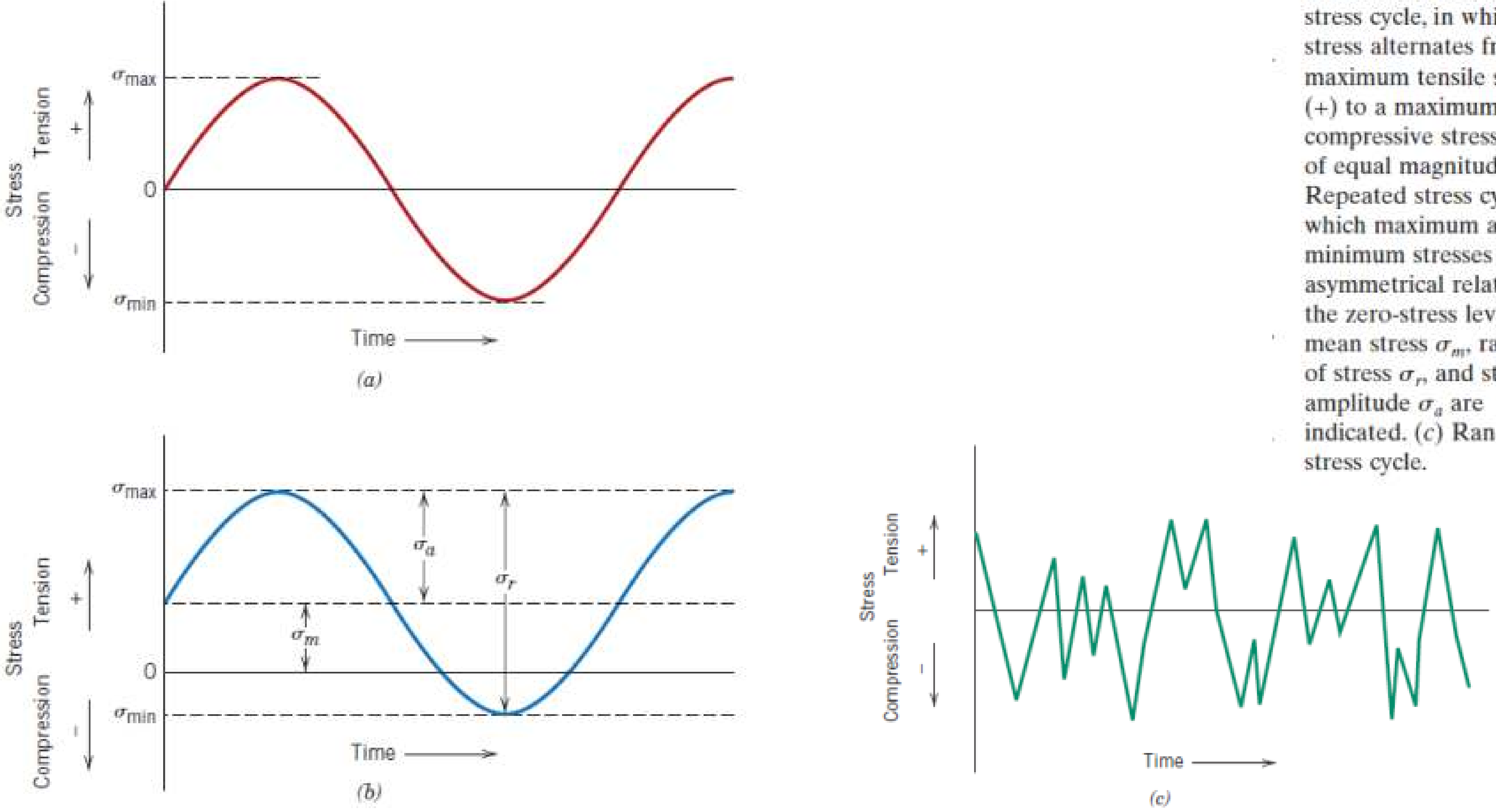
Compression Quality: 100

☑ Key Frame Every 0 frames

Types of Loading

1. Axial loading (Tensile or Compressive)
2. Shear loading (Torsional OR Twisting)
3. Flexural loading (Bending)

Stress cycles



(a) (b) (c)

Figure 8.17 Variation of stress with time that accounts for fatigue failures. (*a*) Reversed stress cycle, in which the stress alternates from a maximum tensile stress (+) to a maximum compressive stress (−) of equal magnitude. (*b*) Repeated stress cycle, in which maximum and minimum stresses are asymmetrical relative to the zero-stress level; mean stress σ_m, range of stress σ_r, and stress amplitude σ_a are indicated. (*c*) Random stress cycle.

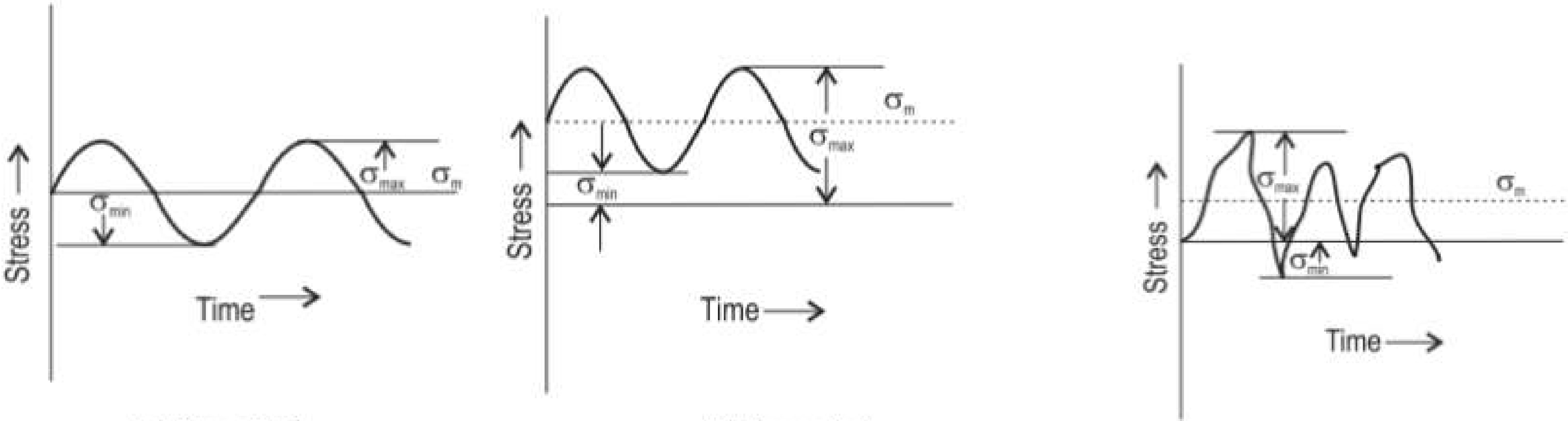
(a)Reversed (sinusoidal) stress cycle,

- In which the stress alternates from a maximum tensile stress to a maximum compressive stress of equal magnitude.
- The amplitude is symmetrical about a mean zero stress level.

(b) Repeated stress cycle

- In which maximum and minimum stresses are asymmetrical relative to the zero stress level

(c) Random stress cycle.



(a) Sinusoidal (b) Repeated (c) Random

Mean stress for cyclic loading—dependence on maximum and minimum stress levels

$$\sigma_m = \frac{\sigma_{\max} + \sigma_{\min}}{2} \tag{8.14}$$

Furthermore, the *range of stress* σ_r is just the difference between $\sigma_{\max}$ and $\sigma_{\min}$—namely,

Computation of range of stress for cyclic loading

$$\sigma_r = \sigma_{\max} - \sigma_{\min} \tag{8.15}$$

Stress amplitude σ_a is just one half of this range of stress, or

Computation of stress amplitude for cyclic loading

$$\sigma_a = \frac{\sigma_r}{2} = \frac{\sigma_{\max} - \sigma_{\min}}{2} \tag{8.16}$$

Finally, the *stress ratio* R is just the ratio of minimum and maximum stress amplitudes:

Computation of stress ratio

$$R = \frac{\sigma_{\min}}{\sigma_{\max}} \tag{8.17}$$

By convention, tensile stresses are positive and compressive stresses are negative. For example, for the reversed stress cycle, the value of R is -1.

Fatigue test

- Rotating-bending test apparatus, commonly used for fatigue testing
- The compression and tensile stresses are imposed on the specimen as it is simultaneously bent and rotated.
- Tests are also frequently conducted using an alternating uniaxial tension-compression stress cycle

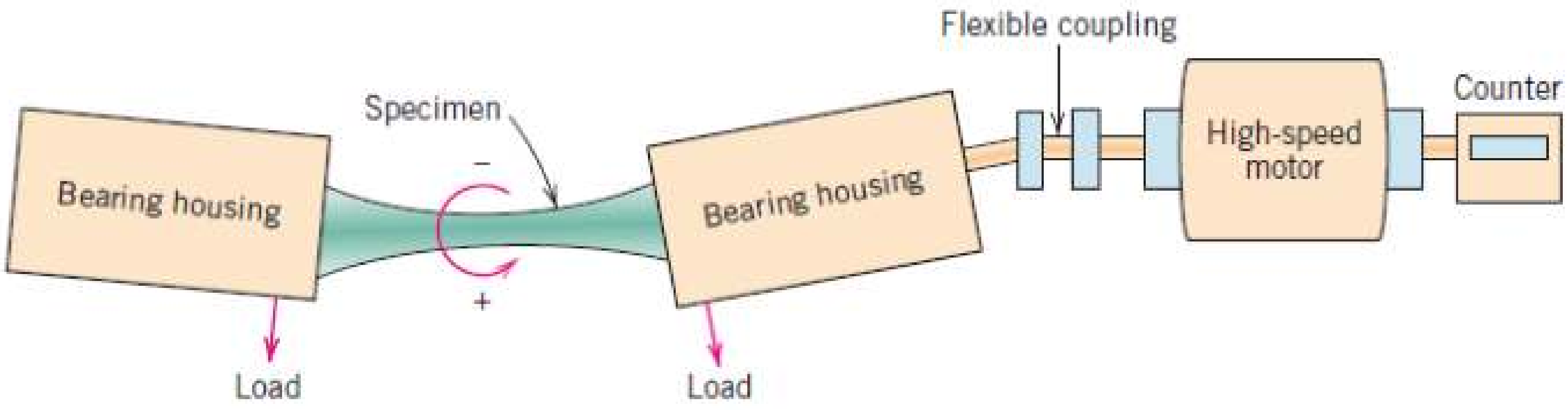
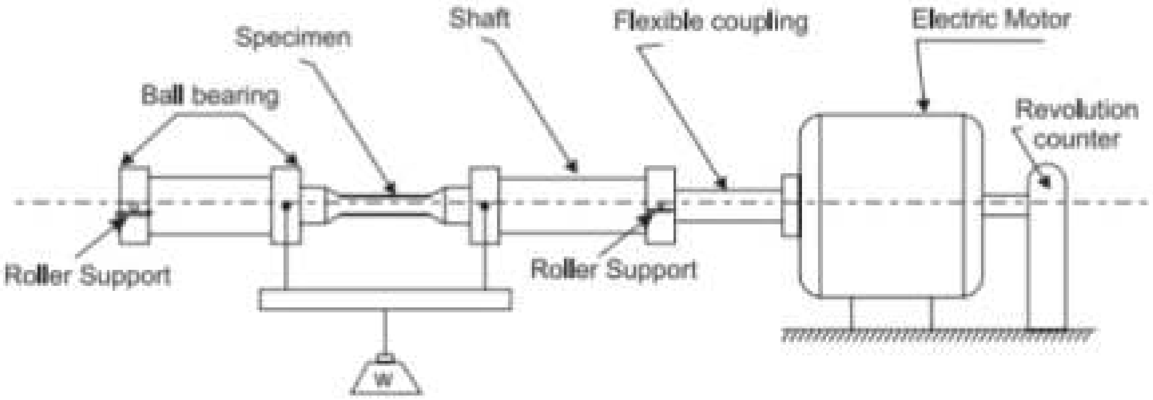


Figure 8.18 Schematic diagram of fatigue-testing apparatus for making rotating-bending tests. (From Keyser, *Materials Science in Engineering*, 4th Edition, © 1986, p. 88. Adapted by permission of Pearson Education, Inc., Upper Saddle River, NJ.)

- The machine consists of an electric motor, bearings and collets to support the specimen and a revolution counter. The test specimen, which forms the extension of a shaft, is placed in the machine.
- A dead weight is attached at the center of the specimen. When the specimen is rotated by a motor, the center of the specimen will be under tension on the lower surface and compression on the upper surface due to the attached weight.
- Hence, the specimen is subjected to alternate tensile and compressive stresses while it is rotating. This sinusoidal variation of stress leads to the condition that the stress is greatest at the surface and zero at the centre.
- The number of cycles for failure to occur depends on the value of applied stress. When the applied stress is high, the number of cycles to failure will be small. As the stress is reduced, failure can be expected after a larger number of cycles. When the applied stress is lowered again, an ultimate value will be reached, below which failure will not take place within the limits of the test. This value of stress is the endurance limit or fatigue limit.

Fatigue test

- The test is carried out by subjecting a specimen to the stress cycling at a maximum stress amplitude σ_{max}, usually on the order of two-thirds of the static tensile strength.
- The number of cycles to failure is counted.
- This procedure is repeated on other specimens at progressively decreasing maximum stress amplitudes.
- The resulting data is presented as a plot of stress (S) versus the logarithm of the number of cycles (N) to failure for each of the specimen.

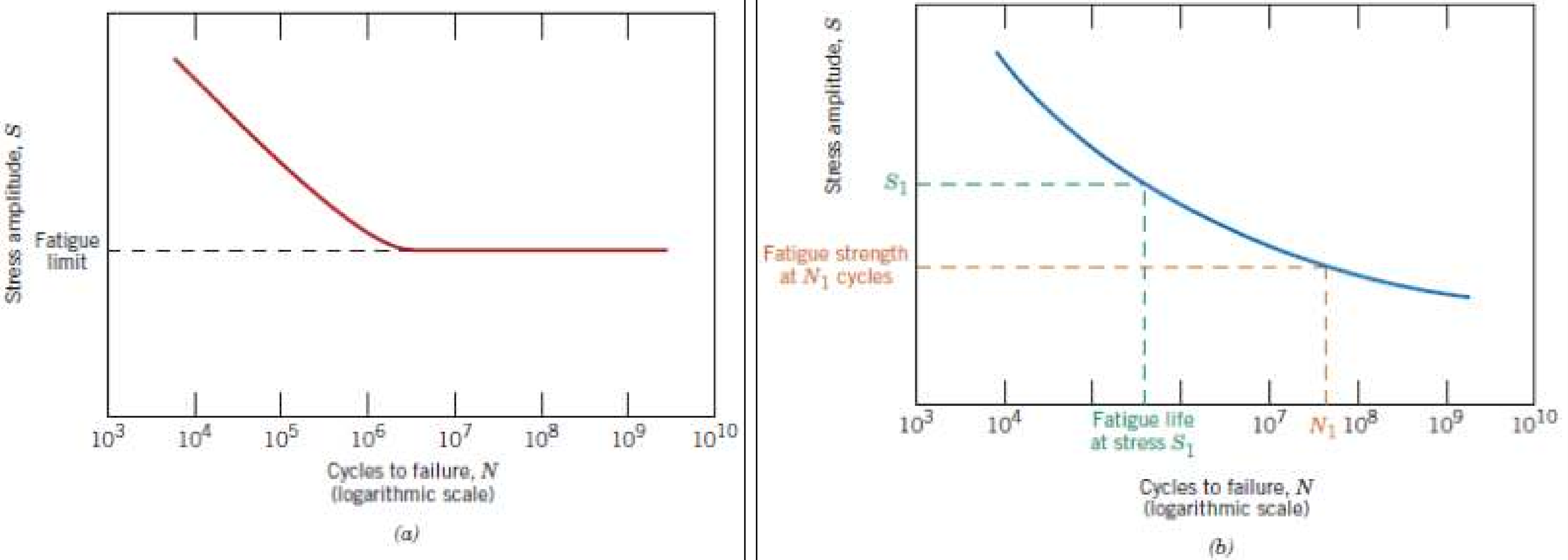


Fatigue testing machine

S-N curve

- Two distinct types of S–N behavior are observed.
- As these plots indicate, the higher the magnitude of the stress, the smaller the number of cycles the material is capable of sustaining before failure.

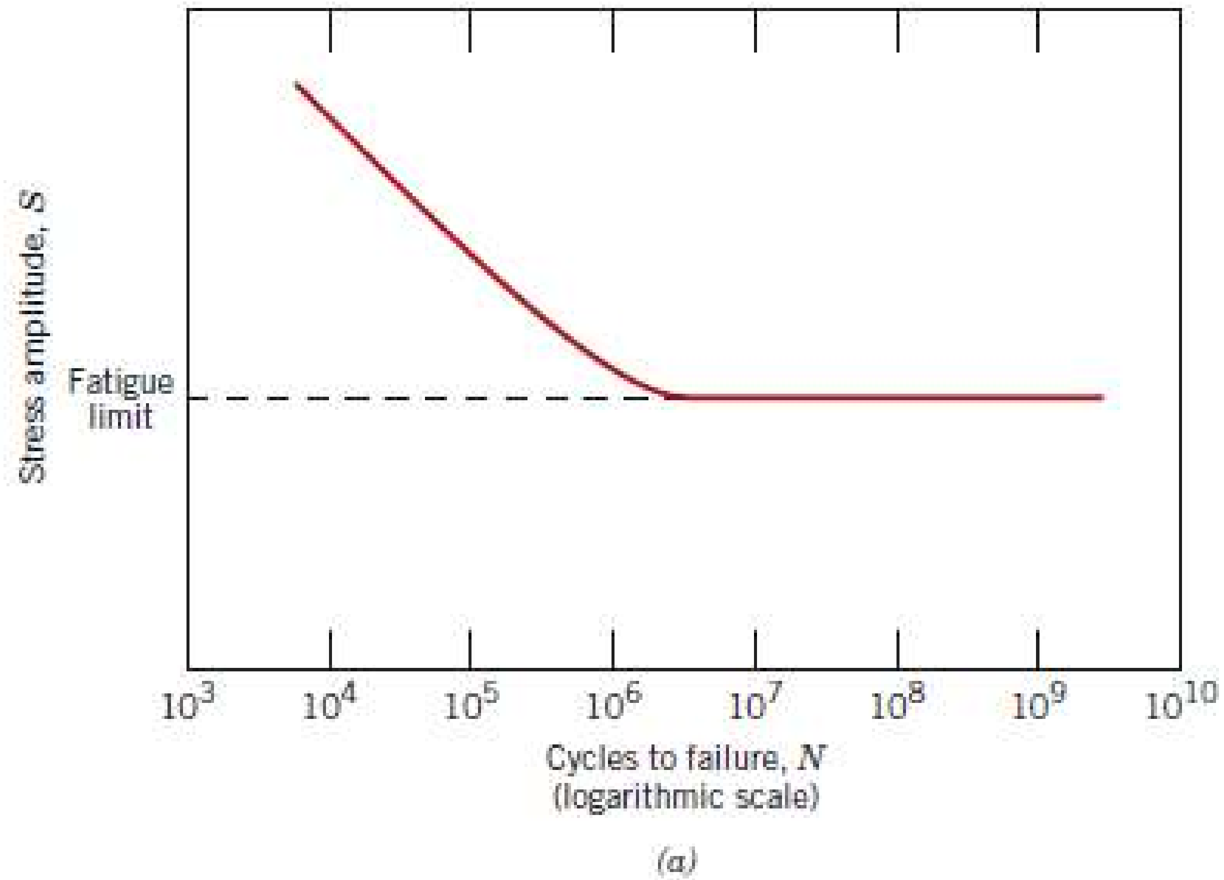
Figure 8.19 Stress amplitude (S) versus logarithm of the number of cycles to fatigue failure (N) for (a) a material that displays a fatigue limit, and (b) a material that does not display a fatigue limit.



S-N curve

- For some ferrous (iron base) and titanium alloys, the S–N curve becomes (figure a) horizontal at higher N values; or there is a limiting stress level, called the fatigue limit (also sometimes the **endurance limit**), below which fatigue failure will not occur.

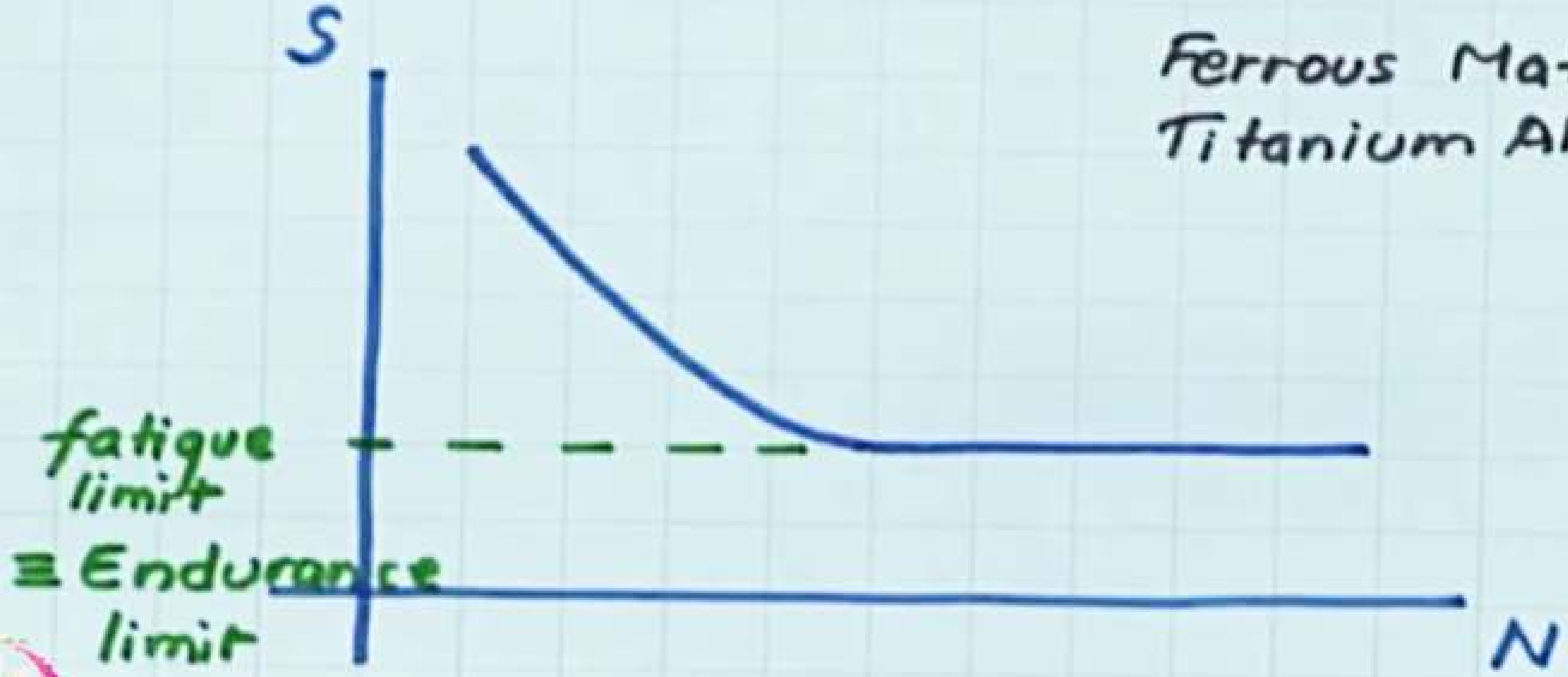
- This fatigue limit represents the largest value of fluctuating stress that will not cause failure for essentially an infinite number of cycles.
- For many steels, fatigue limits range between 35% and 60% of the tensile strength.



S-N Curve

S = stress amplitude = $\sigma_a = (\sigma_{max} - \sigma_{min})/2$

N = No. of cycles to failure



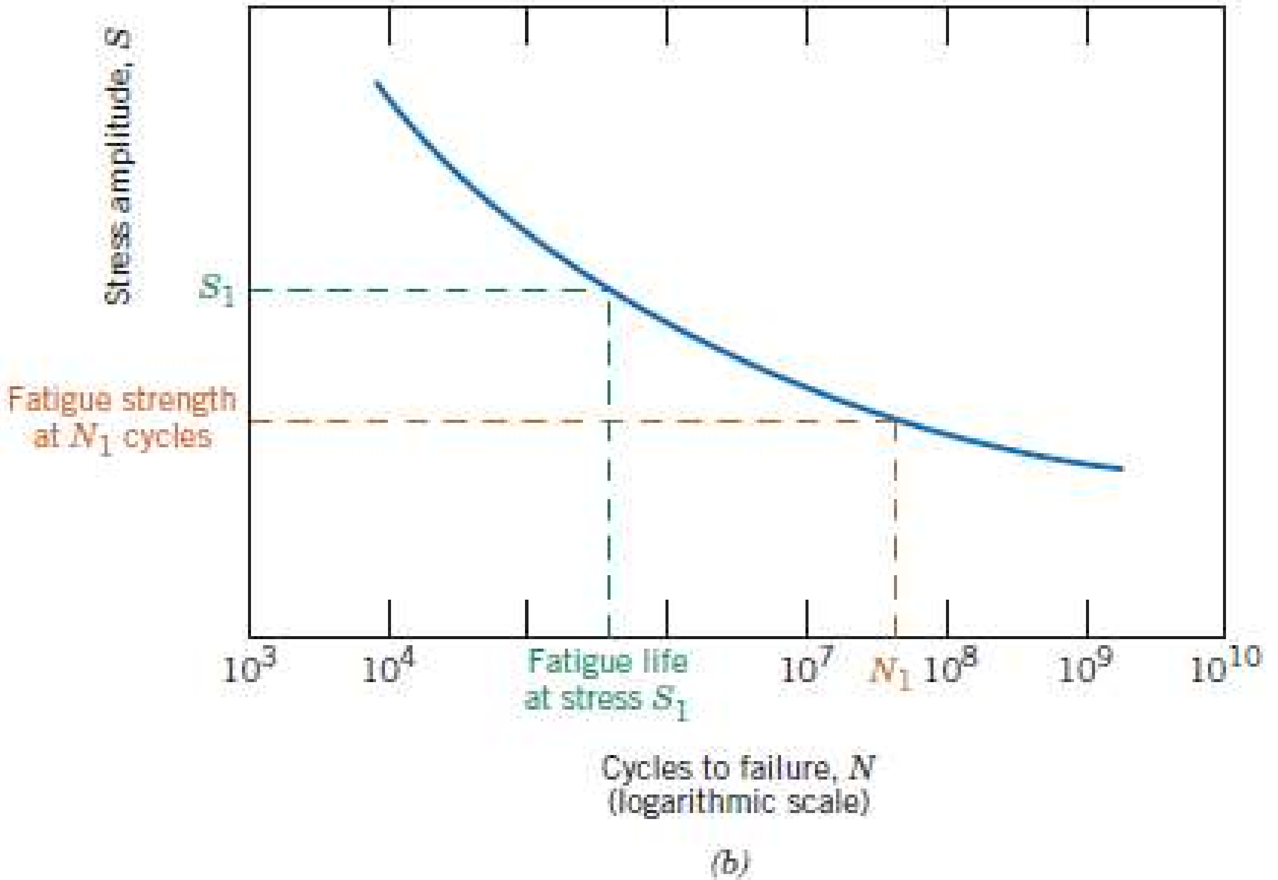
Ferrous Materials

Titanium Alloys

S-N curve

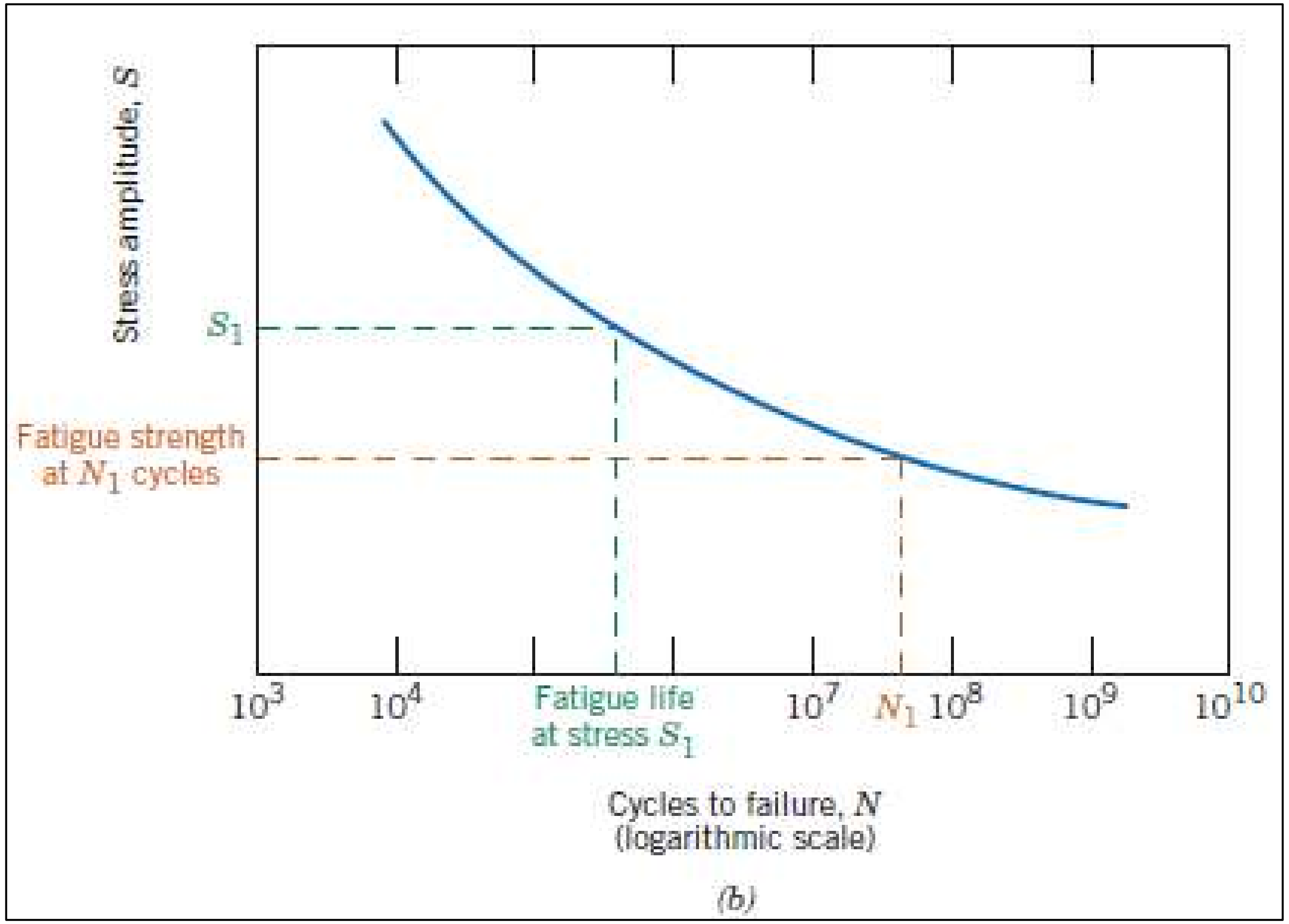
- Most nonferrous alloys (e.g., aluminum, copper, magnesium) do not have a fatigue limit, in that the S–N curve continues its downward trend at increasingly greater N values (Figure b).Thus, fatigue will ultimately occur regardless of the magnitude of the stress.

- For these materials, the fatigue response is specified as fatigue strength, which is defined as the stress level at which failure will occur for some specified number of cycles (e.g., 10^7cycles).



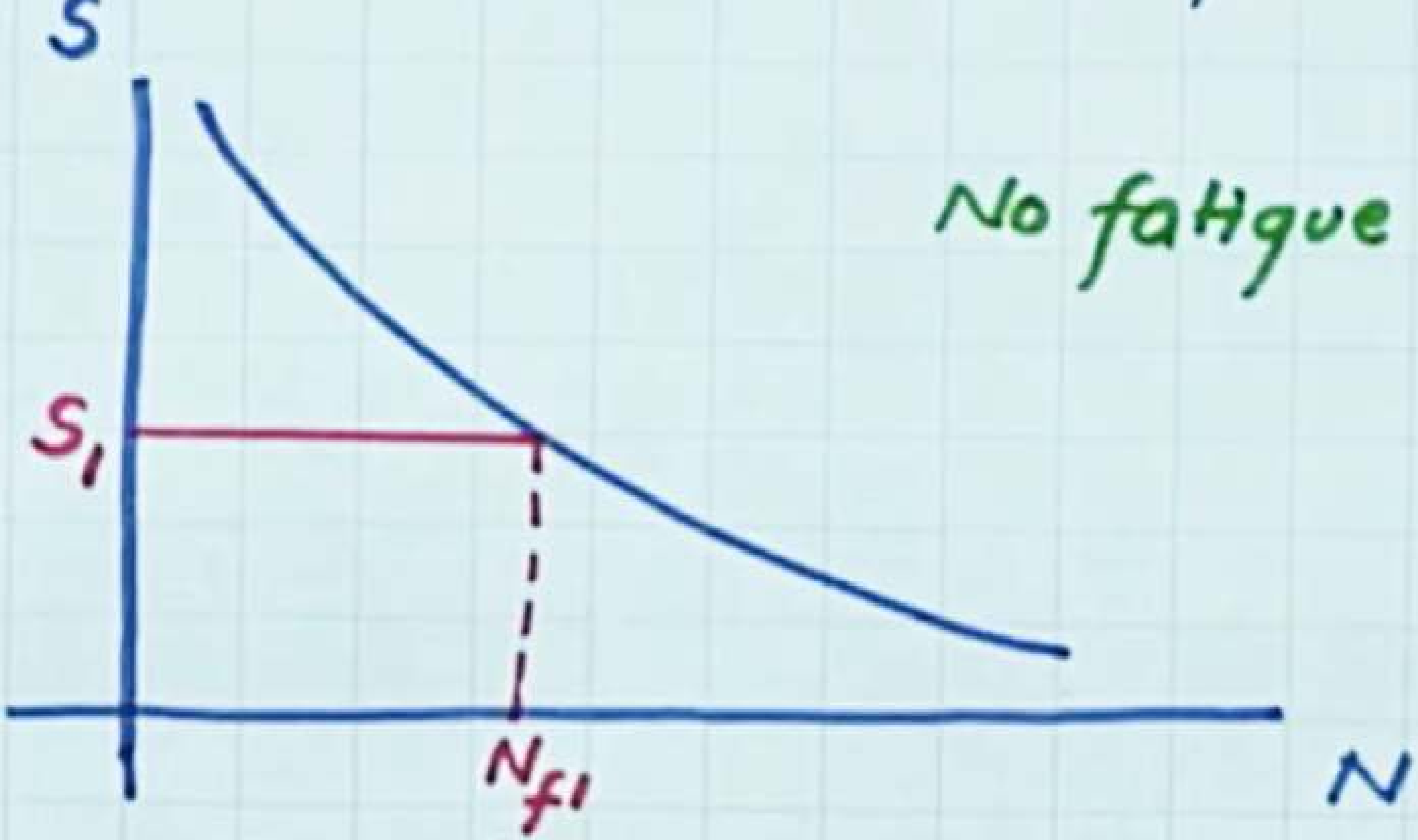
S-N curve

- Another important parameter that characterizes a material’s fatigue behavior is fatigue life (N_f).
- It is the number of cycles to cause failure at a specified stress level, as taken from the S–N plot.



Non ferrous alloy

No fatigue limit.



fatigue life at stress amplitude S_1

Fatigue

Fatigue life (N_f)

It is the number of cycles to cause failure at a specified stress level, as taken from the S–N plot.

Fatigue strength

The stress level at which failure will occur for some specified number of cycles (e.g., 10^7 cycles).

Mechanism of fatigue failure.

- The process of fatigue failure is characterized by three distinct steps:
  - (1) Crack initiation, wherein a small crack forms at some point of high stress concentration;
  - (2) Crack propagation, during which this crack advances incrementally with each stress cycle
  - (3) Final failure, which occurs very rapidly once the advancing crack has reached a critical size.

- Thus the fatigue life of a structure consists of the time required for initiation and growth of a crack to the point of failure.
- Cracks associated with fatigue failure almost always initiate (or nucleate) on the surface of a component at some point of stress concentration.
- Crack nucleation sites include surface scratches, sharp fillets, keyways, threads, dents, and the like.
- In addition, cyclic loading can produce microscopic surface discontinuities resulting from dislocation slip steps that may also act as stress raisers, and therefore as crack initiation sites.

Mechanism of fatigue failure.

- The fracture surface is relatively smooth, and on close examination, concentric curves can be seen. The portion of the surface that experienced rapid crack growth ordinarily has a rougher texture.

- Fracture surface with crack initiation at top edge. The smooth region also near the top corresponds to the area over which the crack propagated slowly.
- Surface shows predominantly dull fibrous texture where rapid failure occurred after crack achieved critical size.

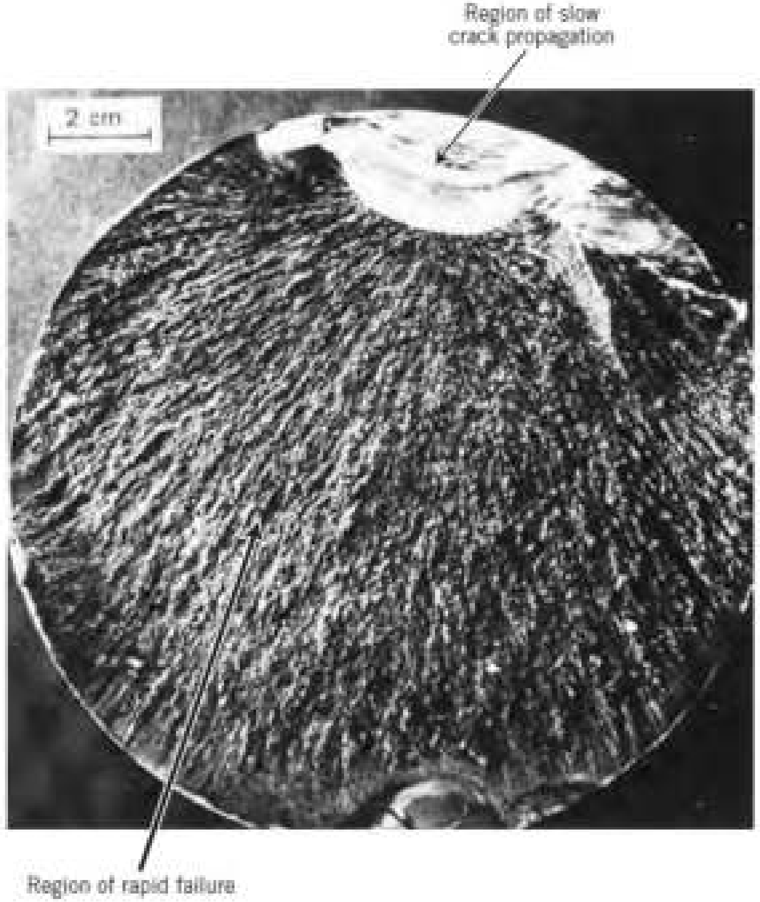


Figure 8.23 Fatigue failure surface. A crack formed at the top edge. The smooth region also near the top corresponds to the area over which the crack propagated slowly. Rapid failure occurred over the area having a dull and fibrous texture (the largest area). Approximately 0.5×. [Reproduced by permission from *Metals Handbook: Fractography and Atlas of Fractographs,* Vol. 9, 8th edition, H. E. Boyer (Editor), American Society for Metals, 1974.]

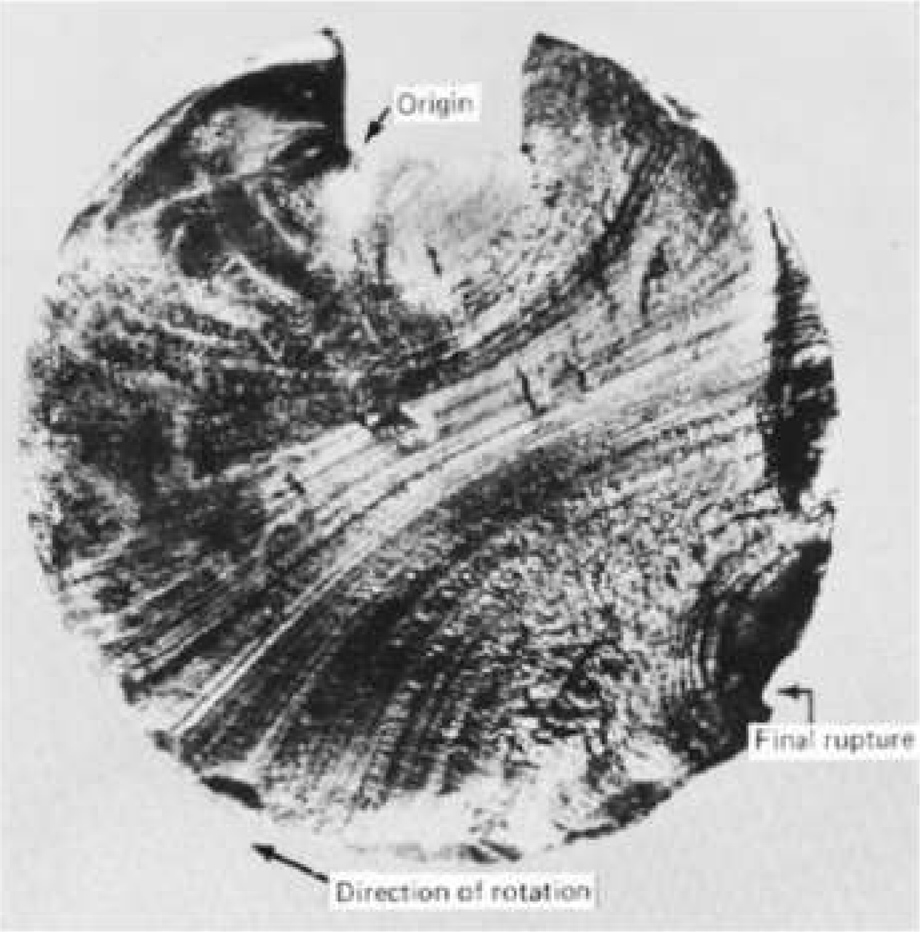


Figure 8.21 Fracture surface of a rotating steel shaft that experienced fatigue failure. Beachmark ridges are visible in the photograph. (Reproduced with permission from D. J. Wulpi, *Understanding How Components Fail,* American Society for Metals, Materials Park, OH, 1985.)

Mechanism of fatigue failure.

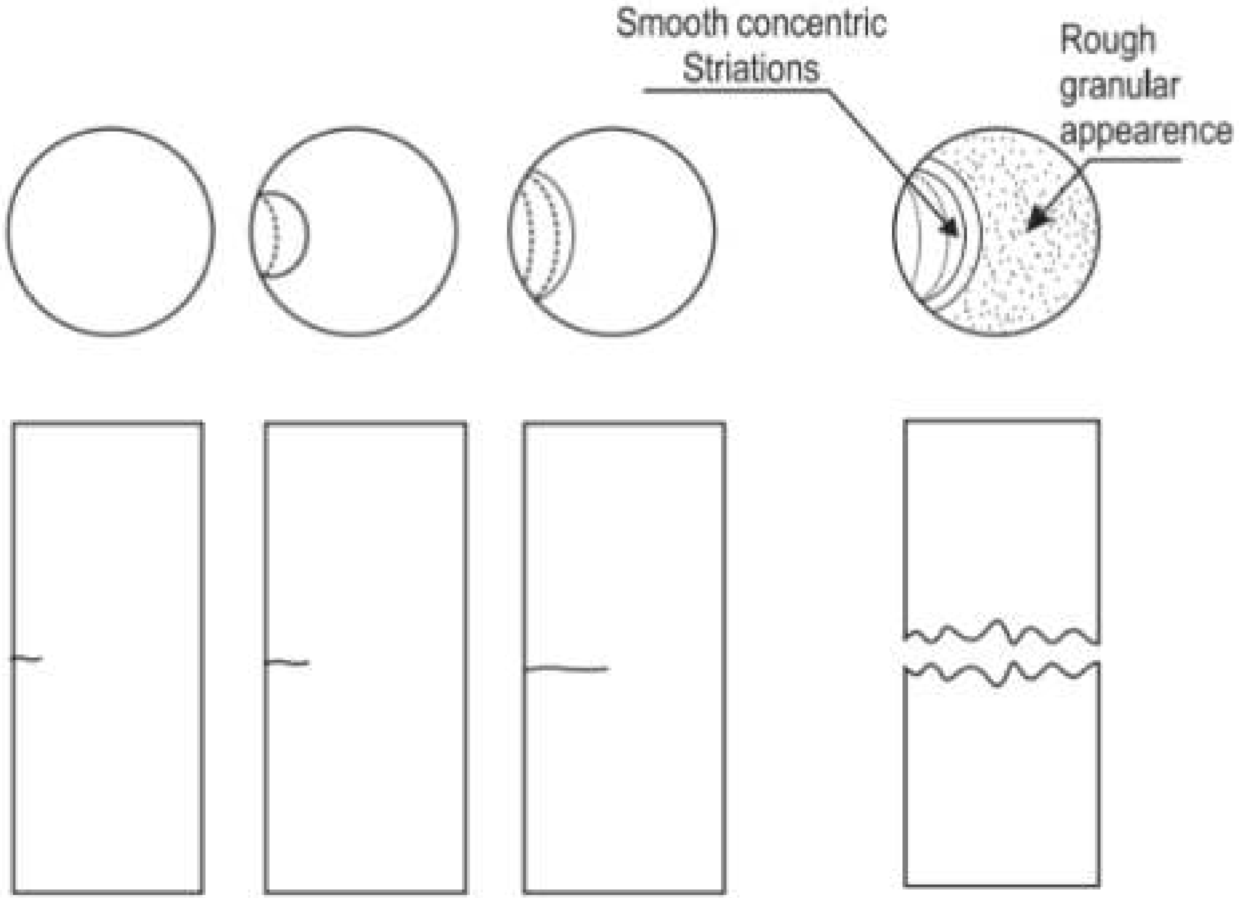
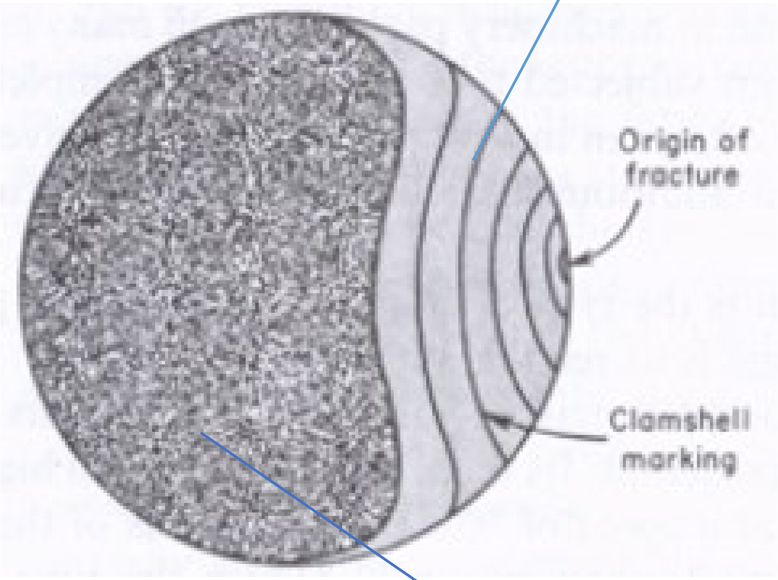
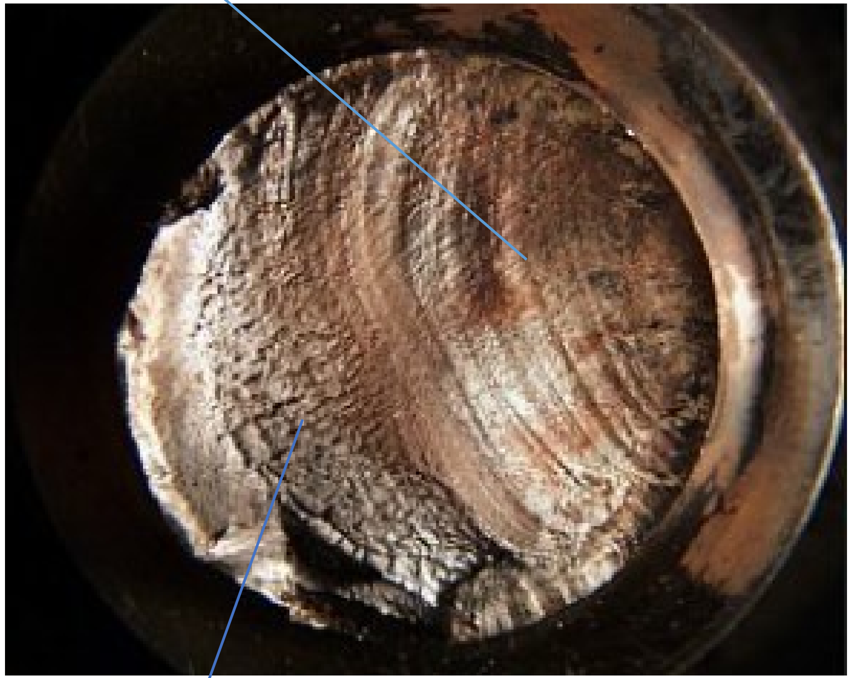


Figure 4.12 *Stages of fatigue failure*

Fatigue failure

Smooth concentric striations





Rough granular appearance

Factors affecting fatigue strength

- Fatigue behavior of engineering materials is highly sensitive to a number of variables. Some of these factors include mean stress level, geometrical design, surface effects, and metallurgical variables, as well as the environment.

- Different factors are,
  - Mean Stress
  - Design Factors(Stress concentration)
  - Size effect(Size of the component)
  - Surface Effects(Surface roughness)
  - Surface Treatments(Change in surface properties)
  - Surface residual stress.
  - Environment in which component is functioning
    - The environment in which the component is functioning has a marked influence on fatigue. It has been observed that the fatigue life in vacuum is about 10 times more than that in a moist atmosphere. Hence a corrosive atmosphere reduces fatigue life. Fatigue resulting out of corrosion is known as corrosion fatigue.

1. Stress concentration

- The design of a component can have a significant influence on its fatigue characteristics. Any notch or geometrical discontinuity can act as a stress raiser and fatigue crack initiation site; these design features include grooves, holes, keyways, threads, and so on.
- The sharper the discontinuity (i.e., the smaller the radius of curvature), the more severe the stress concentration. The probability of fatigue failure may be reduced by avoiding (when possible) these structural irregularities, or by making design modifications whereby sudden contour changes leading to sharp corners are eliminated—for example, calling for rounded fillets with large radii of curvature at the point where there is a change in diameter for a rotating shaft

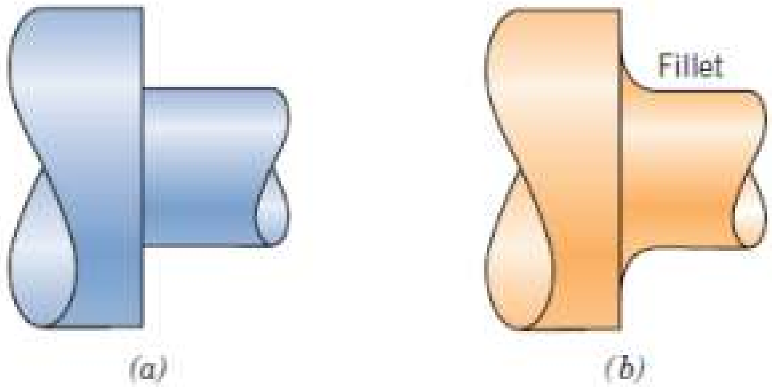


Figure 8.25 Demonstration of how design can reduce stress amplification. (*a*) Poor design: sharp corner. (*b*) Good design: fatigue lifetime improved by incorporating rounded fillet into a rotating shaft at the point where there is a change in diameter.

2. Size effect

- Tests show that larger specimens have lower fatigue strength than smaller ones.
- This is called the size/thickness effect. It is comprised by different sub-effects; the so-called geometric, statistical size effects.
- The **geometric size effect** relates to the stress gradient due to stress concentrations and direct or superimposed bending, which becomes steeper when the joint become thinner. The combined stress field at the crack tip of a given crack size a_i will thus be less intense for a thin joint compared to a thick joint, i.e. for $t_1 < t_2$, we get $\sigma_1 < \sigma_2$, when the nominal surface stress is the same.

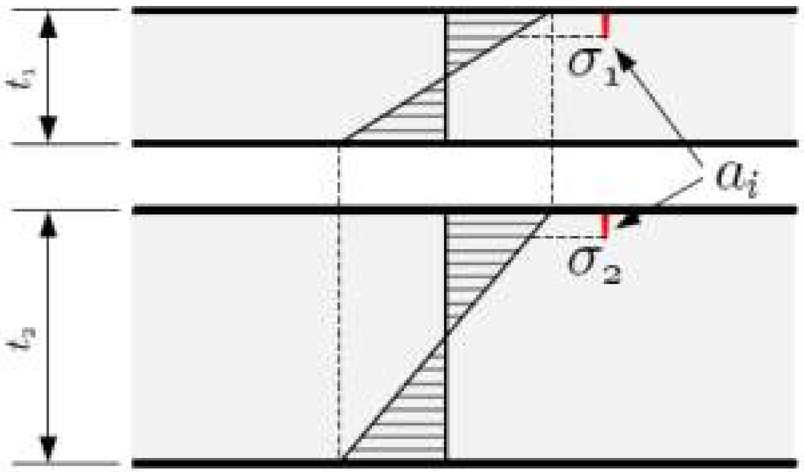
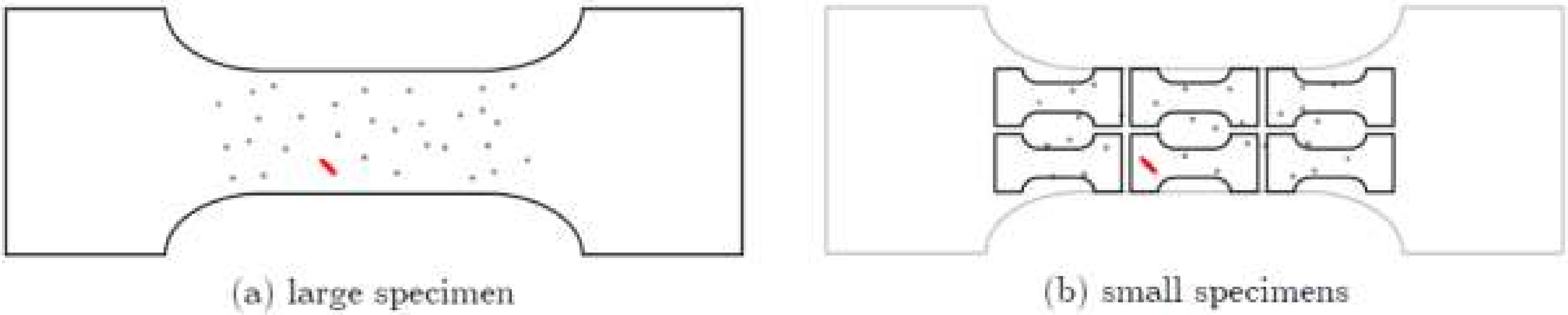


Figure 14: Geometric size effect.

Statistical size effect

- The statistical size effect considers that the probability of a severe defect occurring is higher in a large volume (thick joints) than in a small volume (thin joints).
- On a large specimen from all the material, it will necessarily contain the severe defect and, when tested, it will show low fatigue strength.
- If instead we made 6 small specimens from the same material, only one of them will contain the severe defect. So when testing, one of the resulting data points will show low fatigue strength, while the other 5 will show much higher fatigue strength.


(a) large specimen

(b) small specimens

Figure 15: Statistical size effect.

3. Surface roughness

- During machining operations, small scratches, machining marks and grooves are invariably introduced into the workpiece surface by cutting tool action. These surface markings can limit the fatigue life.
- It has been observed that improving the surface finish by polishing will enhance fatigue life significantly.

4. Change in surface properties(Case hardening)

- By this technique both surface hardness and fatigue life are enhanced for steel alloys. This is accomplished by a carburizing or nitriding process whereby a component is exposed to a carbonaceous or nitrogenous atmosphere at an elevated temperature.
- A carbon- or nitrogen-rich outer surface layer (or "case") is introduced by atomic diffusion from the gaseous phase. The case is normally on the order of 1 mm deep and is harder than the inner core of material.
- The improvement of fatigue properties results from increased hardness within the case, as well as the desired residual compressive stresses the formation of which attends the carburizing or nitriding process.

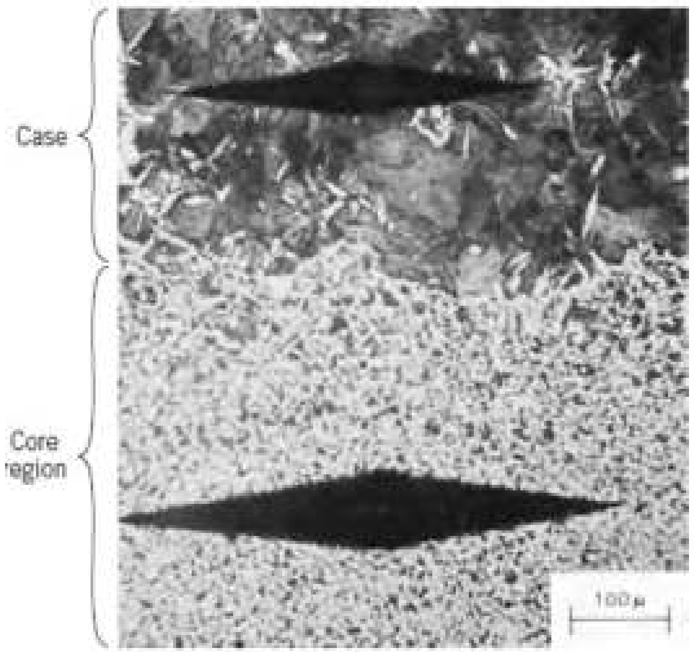
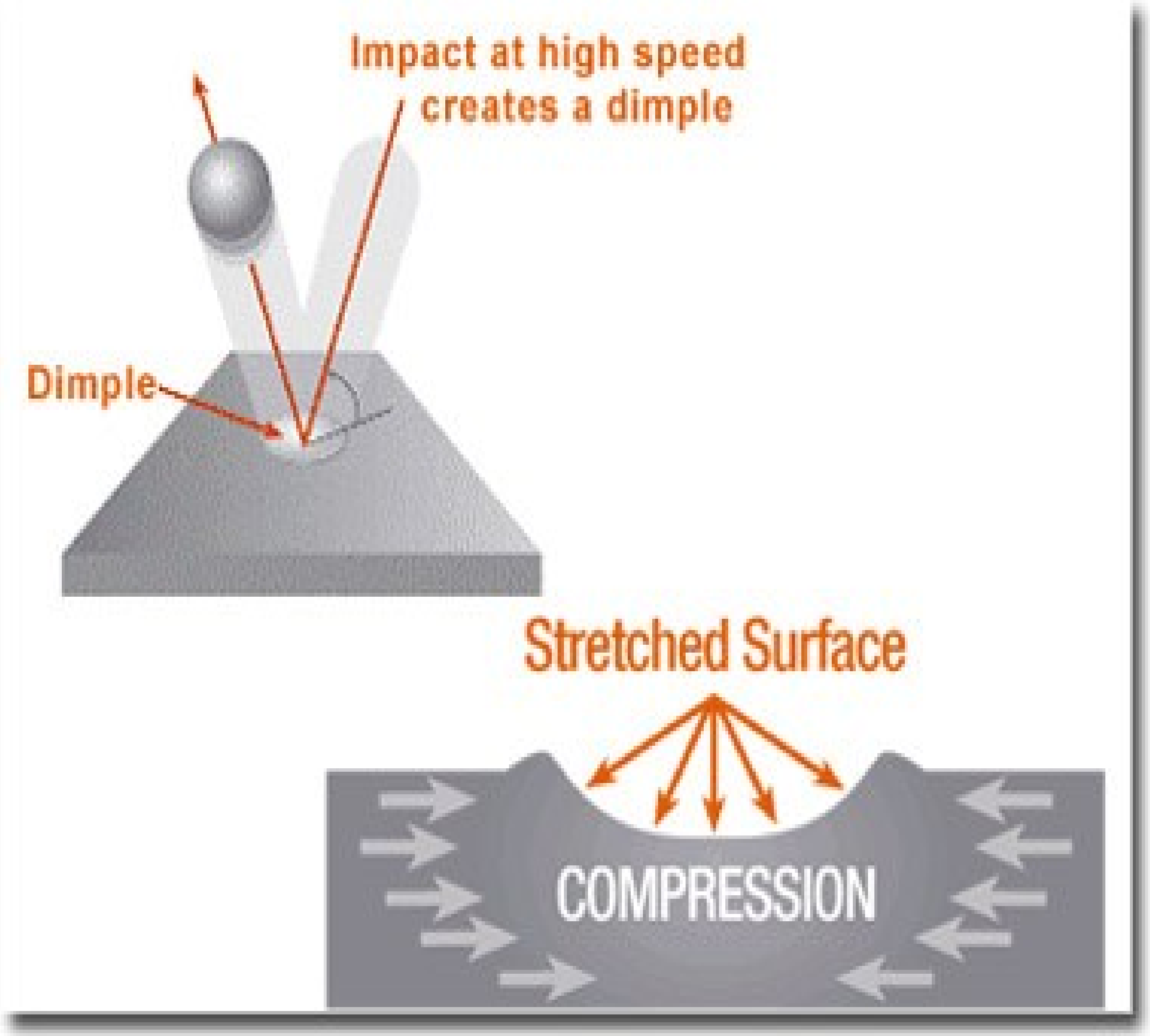


Figure 8.27 Photomicrograph showing both core (bottom) and carburized outer case (top) regions of a case-hardened steel. The case is harder as attested by the smaller microhardness indentation. 100×. (From R. W. Hertzberg, *Deformation and Fracture Mechanics of Engineering Materials*, 3rd edition. Copyright © 1989 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)

5. Surface residual stress

- One of the most effective methods of increasing fatigue performance is by imposing residual compressive stresses within a thin outer surface layer.
- Thus, a surface tensile stress of external origin will be partially nullified and reduced in magnitude by the residual compressive stress. The net effect is that the likelihood of crack formation and therefore of fatigue failure is reduced.
- Residual compressive stresses are commonly introduced into ductile metals mechanically by localized plastic deformation within the outer surface region. Commercially, this is often accomplished by a process termed shot peening.
- Small, hard particles (shot) having diameters within the range of 0.1 to 1.0 mm are projected at high velocities onto the surface to be treated.
- The resulting deformation induces compressive stresses to a depth of between one-quarter and one-half of the shot diameter.

Shot Peening



Ways to improve fatigue life

- By preventing or delaying the initiation of cracks at the surface

Methods

1. Surface treatments

Fatigue failure is observed to be caused by tensile stresses on areas of stress concentration. If compressive stresses are introduced at the surface of a component, the applied tensile stresses get cancelled, thereby considerably increasing the fatigue life of components.

a) Shot peening

b) Surface rolling

2. Carburising followed by hardening and nitriding
   - Carburising and nitriding introduce strong and hard surface layers which also increase the resistance to crack initiation at the surface. This method is particularly useful in alloy steels.

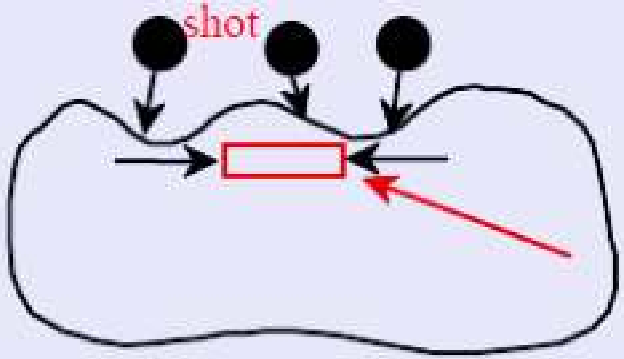
Ways to improve fatigue life

3. Polishing the surface
   - Improving the surface finish is another effective method in enhancing the fatigue life. Rough surfaces invariably have potential sites of stress concentration. Therefore, polishing the surfaces of component to a good surface finish removes surface irregularities which may act as stress raisers.

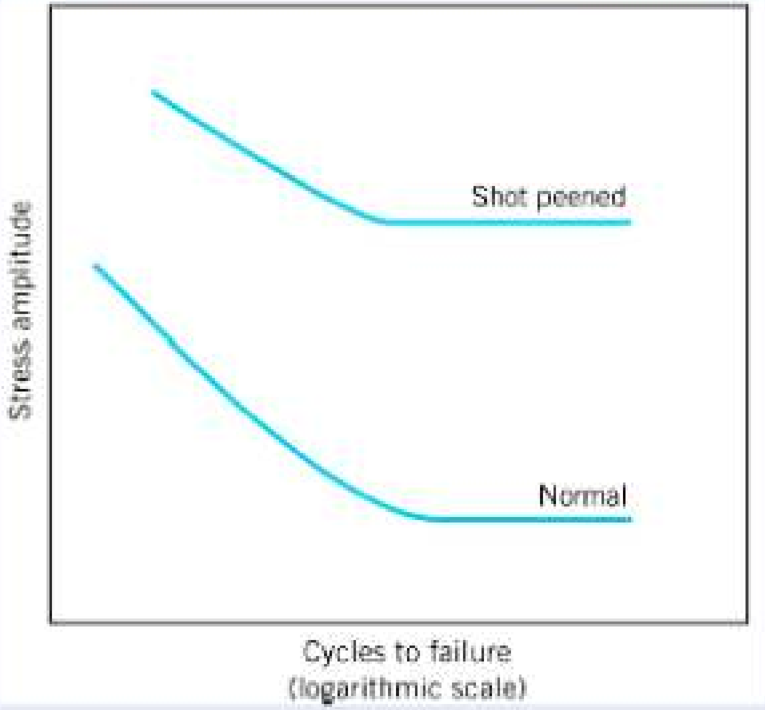
4. Preventing decarburisation while heat treatment
5. Grain refinement
   - A fine grain structure is found to improve fatigue resistance.
6. Proper design
   - Regions of stress concentration like notches, sharp corners, sudden contour changes etc. should be avoided. Processing methods, which reduce the number of internal/ external defects must also be adopted. Prevention from corrosive, chemical or abrasive atmosphere will also enhance fatigue life.

1. Impose a **compressive surface stress**: to suppress surface cracks from growing.

-Approach 1: **shot peening**

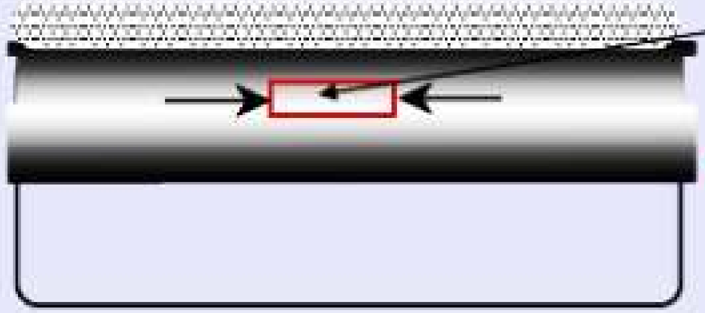


put surface under compression



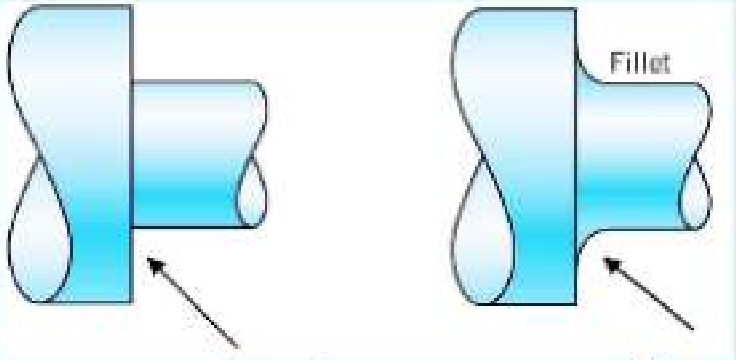
-Approach 2: **carburizing or nitriding**

C-rich or N_2-rich gas



put surface into compression

2. Remove stress concentrators.



bad

better

Thermal fatigue and its applications in metal cutting.

- Thermal stresses result when the change in dimensions of a member as result of temperature change is prevented by some kind of a constraint. If a bar with fixed supports is heated thermal stresses will develop by a temperature change.
- The value of thermal stress so developed is given by $\sigma = E\alpha\Delta T$, where α – linear thermal co-efficient of expansion, E- elastic modulus and ΔT- change in temperature.
- If the failure occurs by a single application of stress, then it is called thermal shock.
- If failure occurs after repeated application of thermal stress, it is called thermal fatigue.

❖ **Thermal Fatigue:** Thermal cycling causes expansion and contraction, which will act as tensile and compressive loads.

- *Solutions:*
  - Eliminate restraint by design
  - Use materials with low thermal expansion coefficients

Thermal fatigue and its applications in metal cutting.

- Principle of thermal fatigue is made use of in thermo mechanical machining. This method is used for the removal of burrs and fins by exposing the material to hot corrosive gases for a short period of time.
- Hot gases are formed by detonating an explosive mixture of oxygen, hydrogen and natural gas in a chamber with the material. A thermal shock wave vaporizes the burrs found on gears, die castings, valves and so on.

Thermal fatigue and its applications in metal cutting.

- Another area where thermal fatigue becomes significant is in metal cutting tool life. In machining operations in which there is interrupted cutting, such as milling, heat is generated at each cut. Thus the tool is subjected to a heating and cooling cycle.
- If the thermal conductivity of the tool material is low and the coefficient of thermal expansion is high, tool failure can take place soon. Similar situation may exist in hot forging dies. Careful considerations in selection of tool material is required to avoid tool failure due to thermal fatigue.

Effect of temperature on fatigue life

- As temperature increases, the crack growth rate will also increases.
- So an increase in temperature decreases fatigue strength.

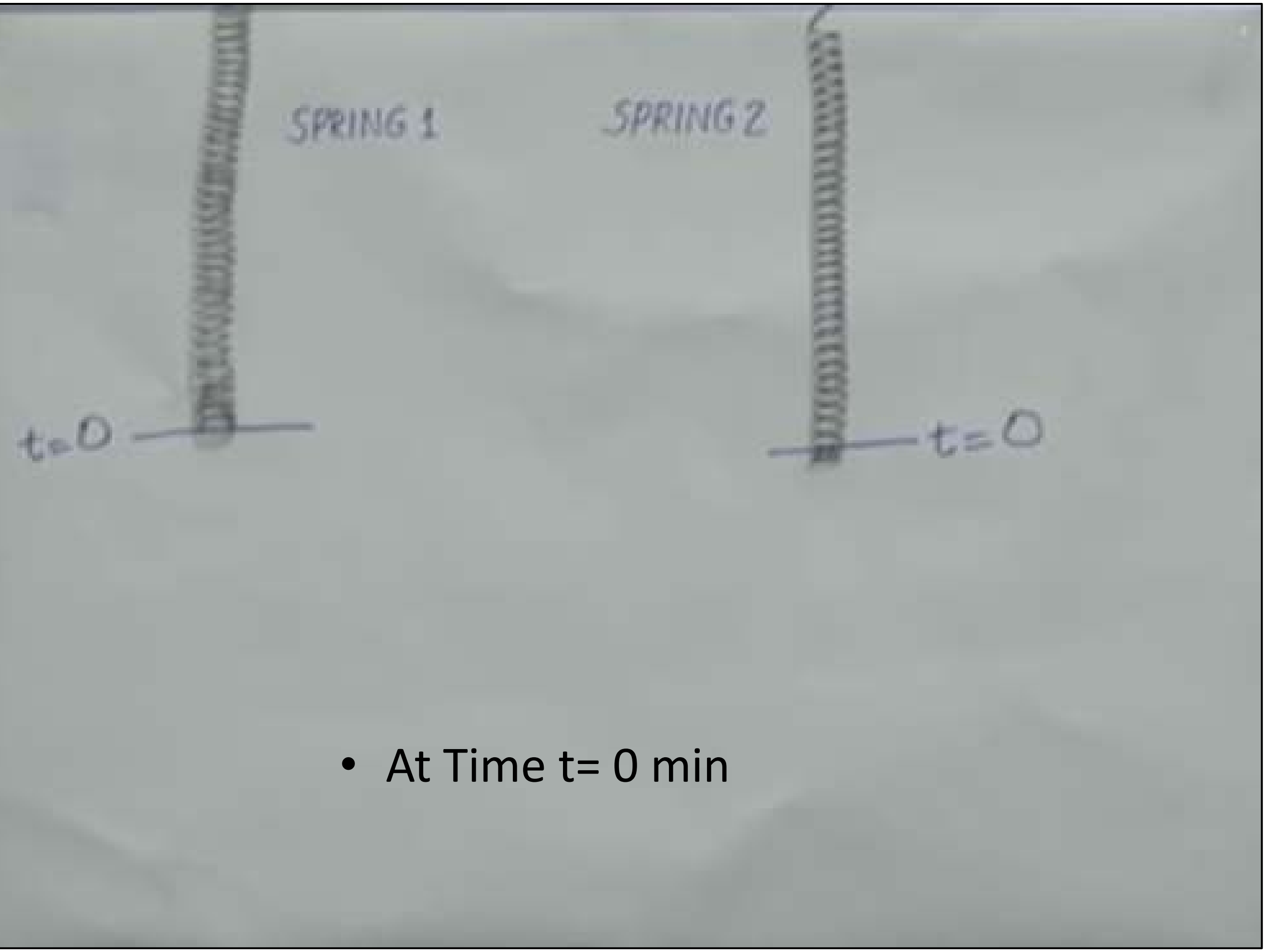
Fracture toughness, applications

- Fracture toughness is the ability of a material to resist fracture or Fracture toughness is a quantitative way of expressing a material's resistance to brittle fracture.
- Fracture Toughness is the ability of material with indigenous cracks to resist fracture by absorbing energy. Also defined as the resistance to cracks propagation.
- If a material has high fracture toughness it will probably undergo ductile fracture and brittle fracture usually happens to materials with less fracture toughness.
- Fracture toughness is one of the most important property of a material for many design applications.
- Fracture toughness values are applied practically in fracture mechanics studies for material selection to avoid catastrophic failure, for example, in nuclear power stations, aeronautics, off-shore applications, ships, bridges, pipelines, and pressure vessels. Also they can be used advantageously in the rehabilitation of old bridges or pressure vessels.

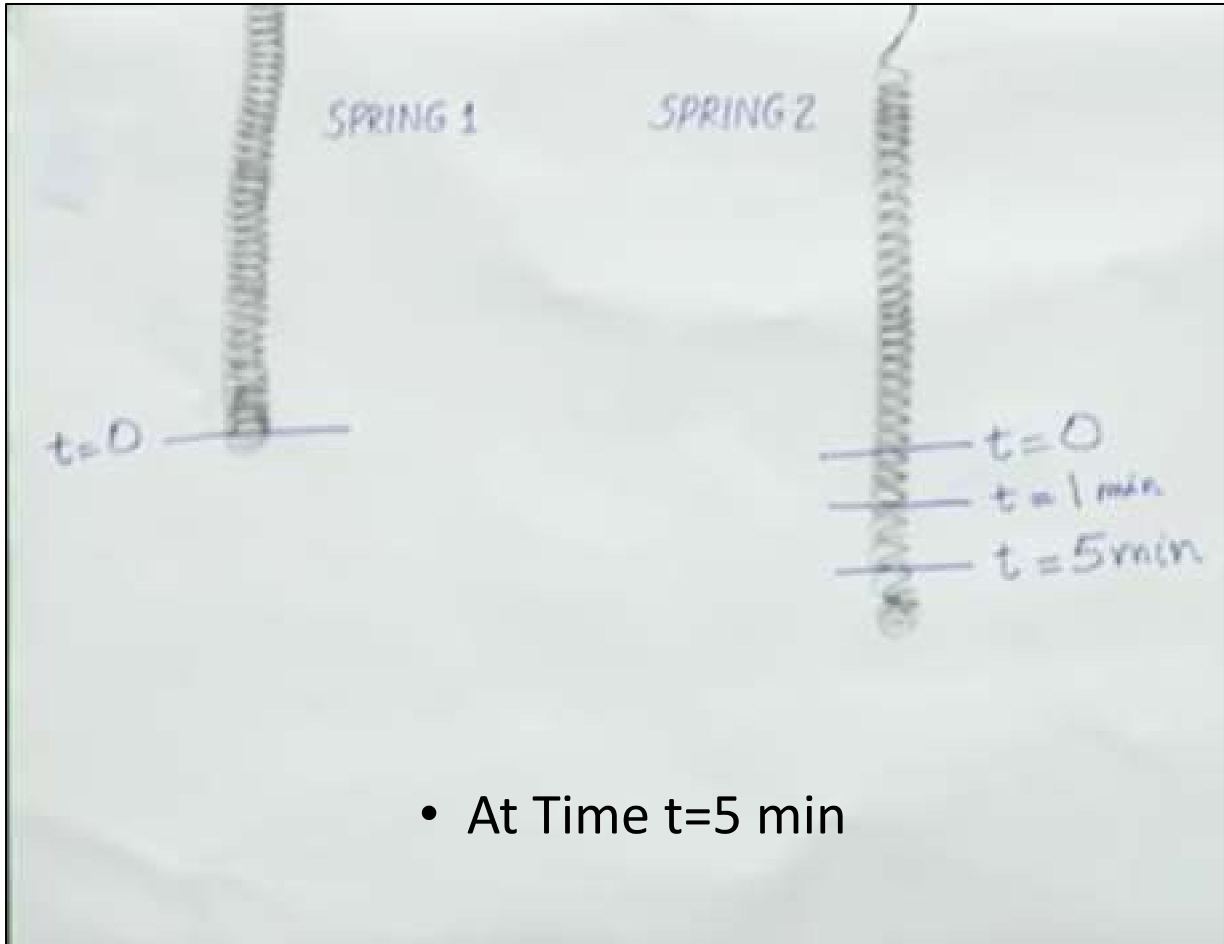
Creep

- Q1. Why do tungsten filament bulbs fuse?
- Q2. How do glaciers move?
- Q3. What limits the life of a jet engine turbine blades?

Creep



- At Time t= 0 min

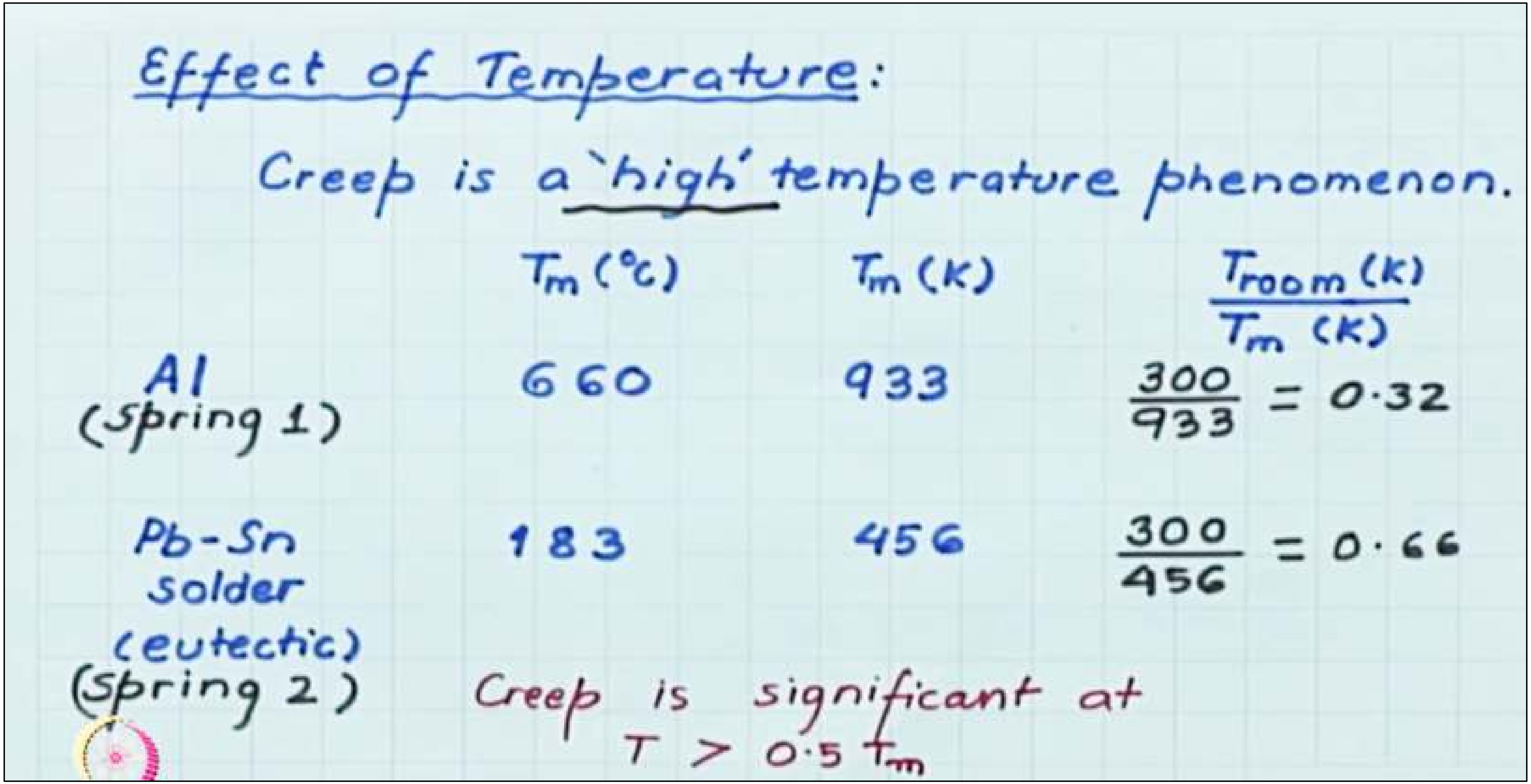


- At Time t=5 min

Creep

- Creep is time dependent continued plastic deformation at constant load or stress at high temperature (> 0.5 Tm).

Effect of Temperature



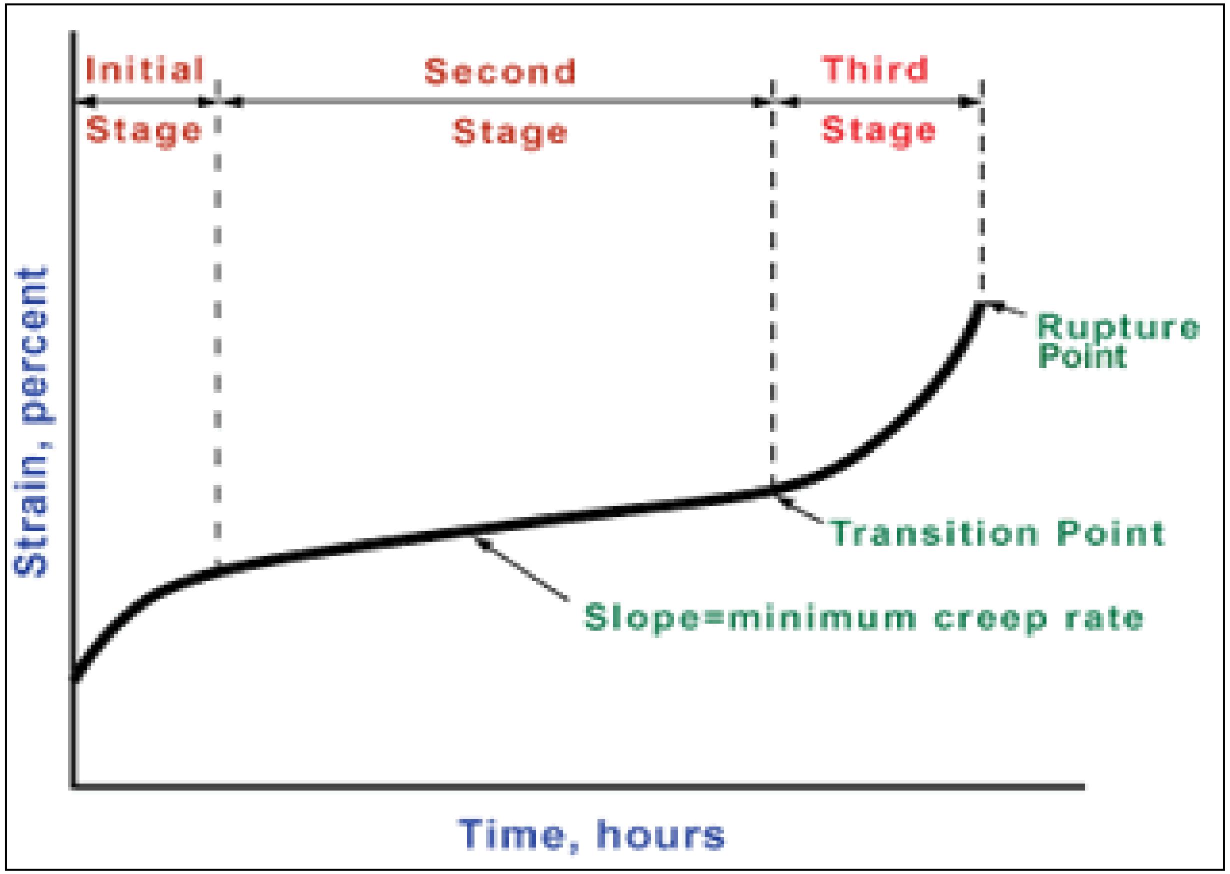
Effect of Temperature:

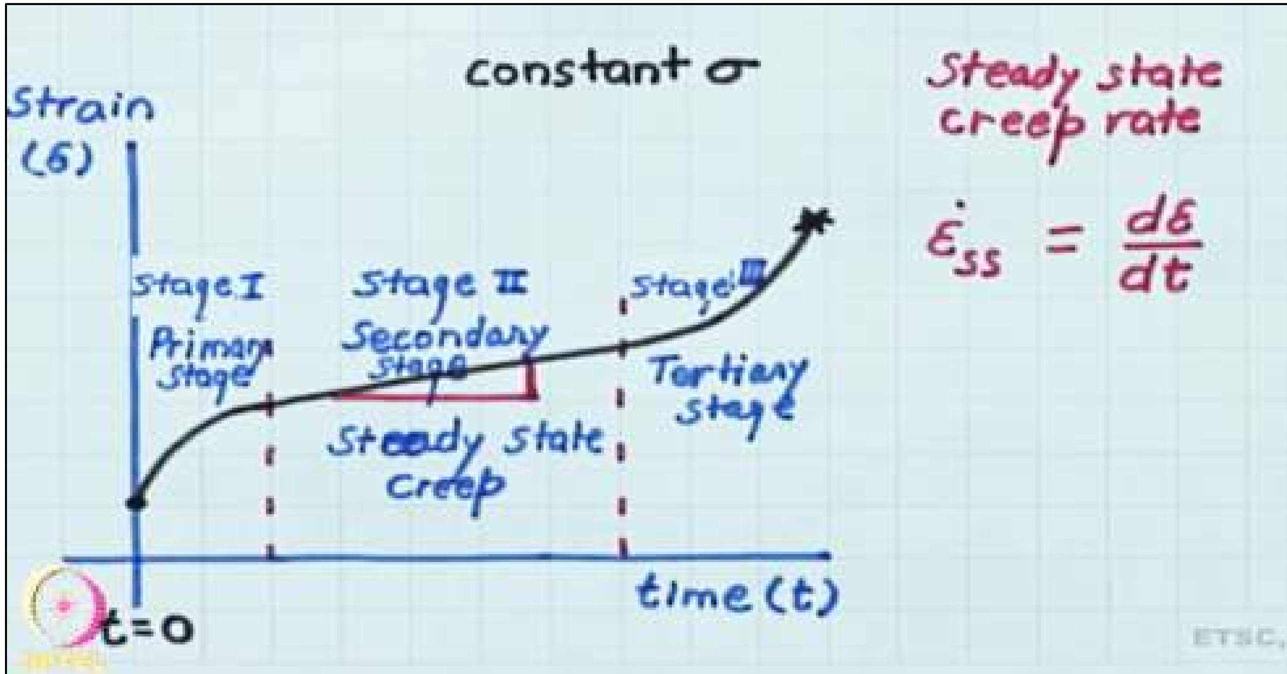
Creep is a 'high' temperature phenomenon.

	T_m (°C)	T_m (K)	$\frac{T_{room}\,(K)}{T_m\,(K)}$
Al (Spring 1)	660	933	$\frac{300}{933} = 0.32$
Pb-Sn solder (eutectic) (Spring 2)	183	456	$\frac{300}{456} = 0.66$

Creep is significant at $T > 0.5\, T_m$

Creep curves





MODULE 5

SYLLABUS

Fatigue: - creep -DBTT - super plasticity - need, properties and applications of composites, super alloy, intermetallics, maraging steel, Titanium - Ceramics:- structures, applications.

5.1	Fracture: – Brittle and ductile fracture – Griffith theory of brittle fracture – Stress concentration, stress raiser – Effect of plastic deformation on crack propagation - transgranular, intergranular fracture - Effect of impact loading on ductile material and its application in forging, applications - Mechanism of fatigue failure.	2	CO3
5.2	Structural features of fatigue: - crack initiation, growth, propagation - Fracture toughness (definition only), applications - Ductile to brittle transition temperature (DBTT) in steels and structural changes during DBTT, applications.	1	
5.3	Creep: - Creep curves – creep tests - Structural change:- deformation by slip, sub-grain formation, grain boundary sliding - Mechanism of creep deformation - threshold for creep, prevention against creep - Super plasticity: need and applications	2	CO3
5.4	Composites: - Need of development of composites; fiber phase; matrix phase; only need and characteristics of PMC, MMC, and CMC.	2	CO3 CO5
5.5	Modern engineering materials: - only fundamentals, need, properties and applications of, intermetallics, maraging steel, super alloys, Titanium-Ceramics:-coordination number and radius ratios- AX, A_mX_p, $A_mB_mX_p$ type structures – applications.	3	

Course Outcomes

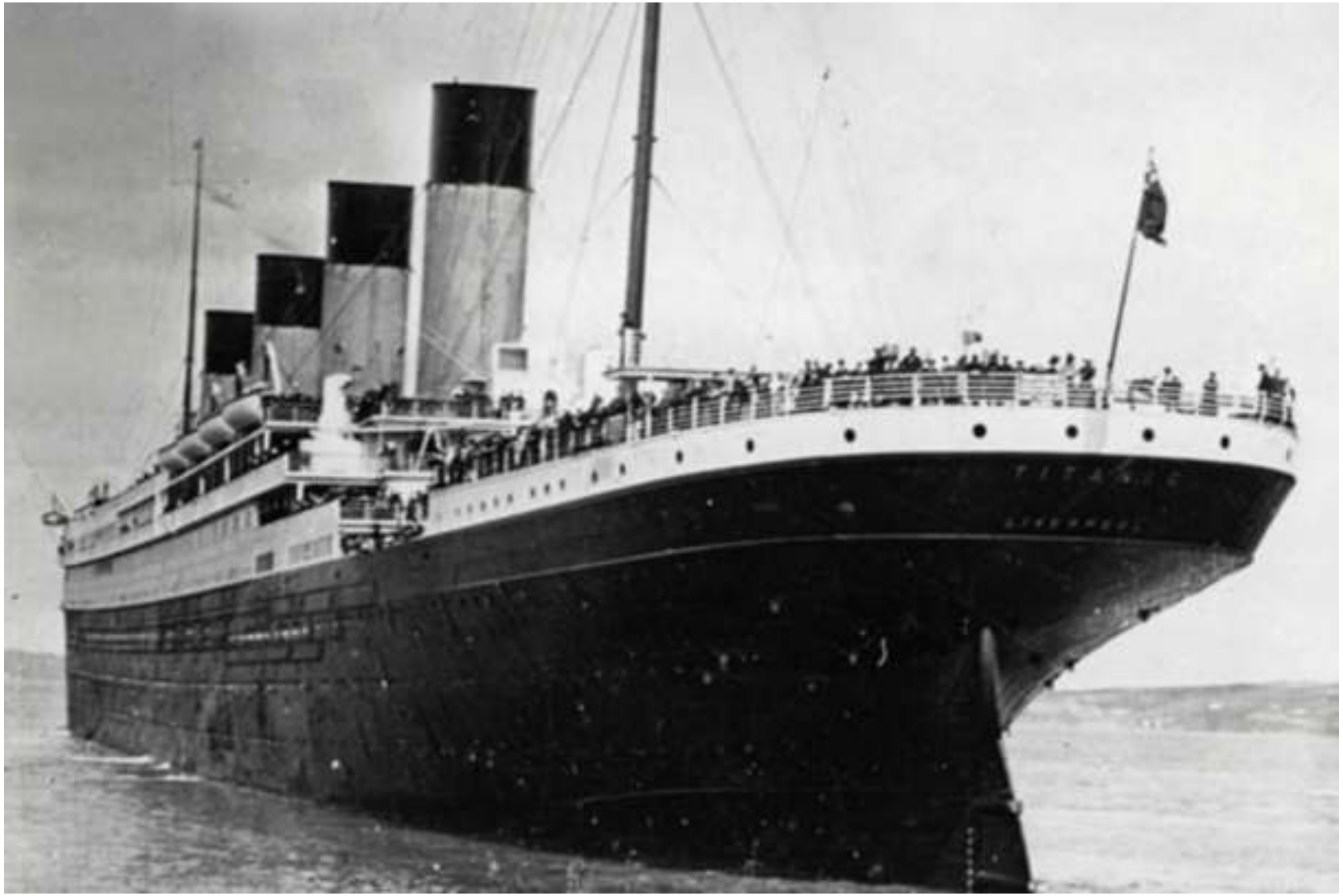
At the end of the course students will be able to,

CO 3 : How to quantify mechanical integrity and failure in materials.

CO 5 : Define and differentiate engineering materials on the basis of structure and properties for engineering applications.

Fracture

- The ultimate failure or rupture of a material under the influence of an external load is called fracture.
- Simple fracture is the separation of a body into two or more pieces in response to an imposed static stress at temperatures that are lower than material's melting point.
- Any fracture process involves two steps
  - Crack formation and
  - Crack Propagation in response to an imposed stress.
- The mode of fracture is highly dependent on the mechanism of crack propagation.



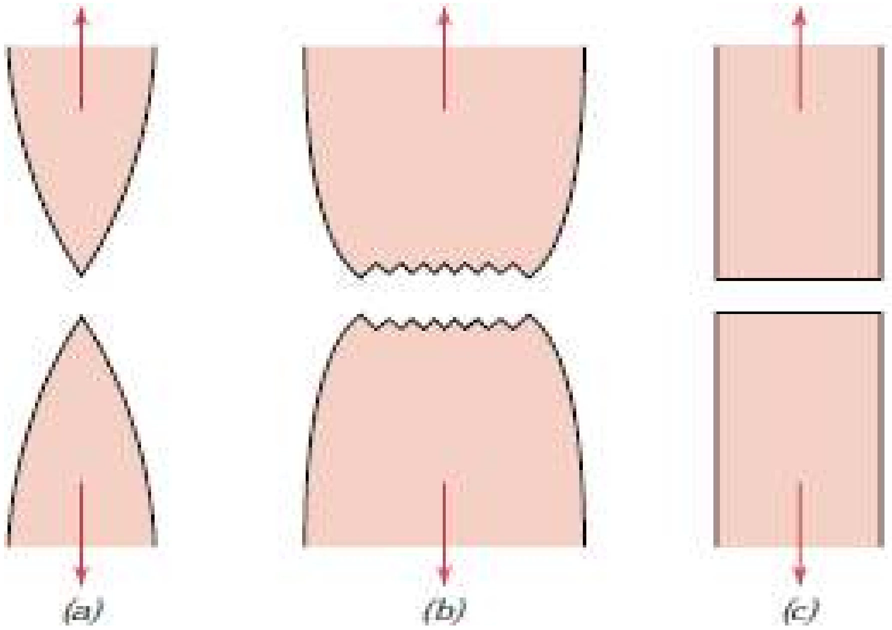
Types of Fractures

- Ductile fracture
- Brittle fracture

- Ductile fracture
  - Ductile materials typically exhibit substantial plastic deformation with high energy absorption before fracture.

- Brittle fracture
  - There is normally little or no plastic deformation with low energy absorption accompanying a brittle fracture.

Brittle and Ductile fracture

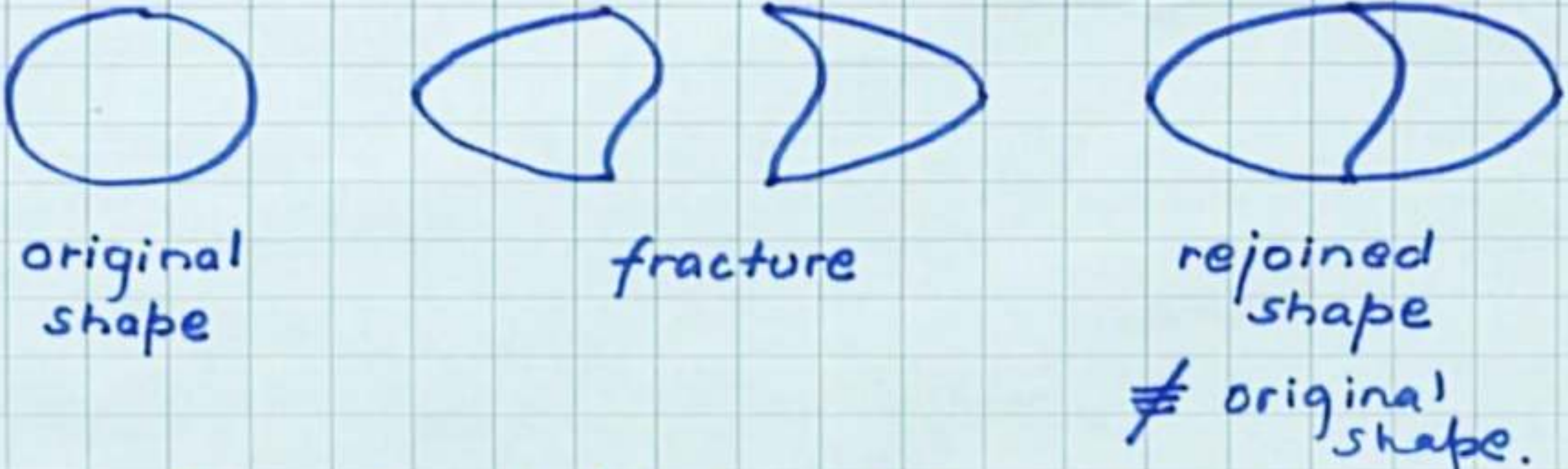


- (a) Highly ductile fracture in which the specimen necks down to a point. (b) Moderately ductile fracture after some necking. (c) Brittle fracture without any plastic deformation.

Ductile fracture

- Ductile fracture is characterized by extensive plastic deformation in the vicinity of an advancing crack.
- The process proceeds relatively slowly as the crack length is extended. Such a crack is often said to be stable.
- That is, it resists any further extension unless there is an increase in the applied stress.
- In addition, there will ordinarily be evidence of appreciable gross deformation at the fracture surfaces (e.g., twisting and tearing).

Ductile Fracture



Significant plastic deformation before fracture.

5 Stages of Moderately ductile fracture

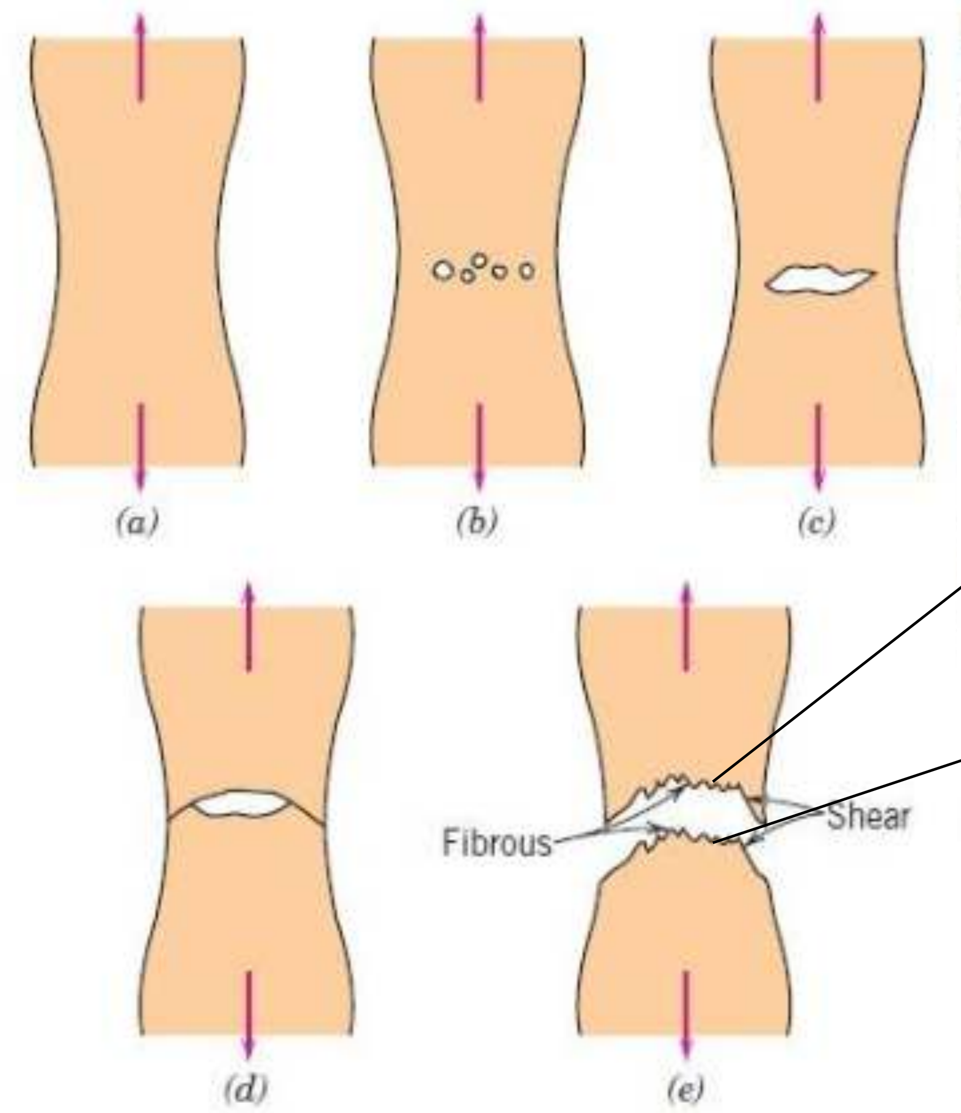
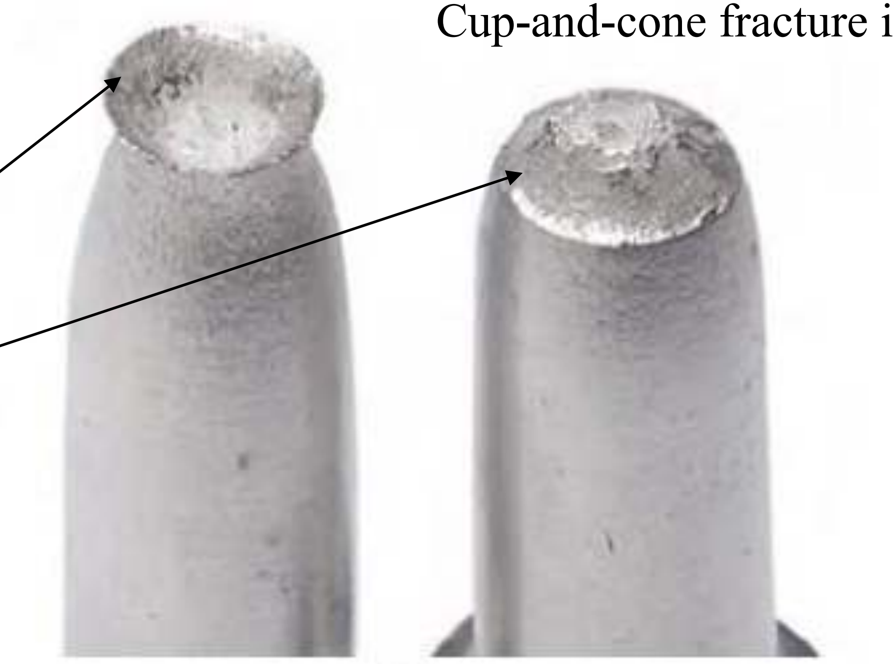


Figure 8.2 Stages in the cup-and-cone fracture. (*a*) Initial necking. (*b*) Small cavity formation. (*c*) Coalescence of cavities to form a crack. (*d*) Crack propagation. (*e*) Final shear fracture at a 45° angle relative to the tensile direction.

Cup-and-cone fracture in aluminum

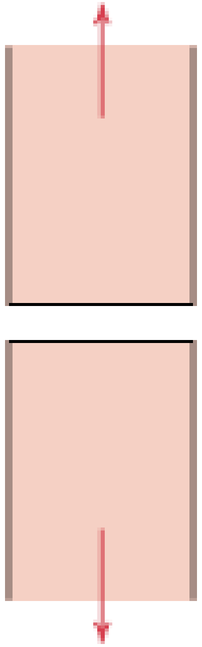


(a)

(a) Initial necking (b) Small cavity or microvoids formation (c) Coalescence/combination of cavities to form a crack (d) Crack propagation (e) Final shear fracture

Brittle fracture

- Brittle fracture takes place with out any appreciable plastic deformation, and is caused by rapid crack propagation.
- In brittle fracture, cracks may spread extremely rapidly, with very little accompanying plastic deformation.
- Such cracks may be said to be unstable, and crack propagation, once started, will continue spontaneously without an increase in magnitude of the applied stress.



Brittle fracture in a mild steel.

Brittle Fracture

A Little or No plastic deformation before fracture.

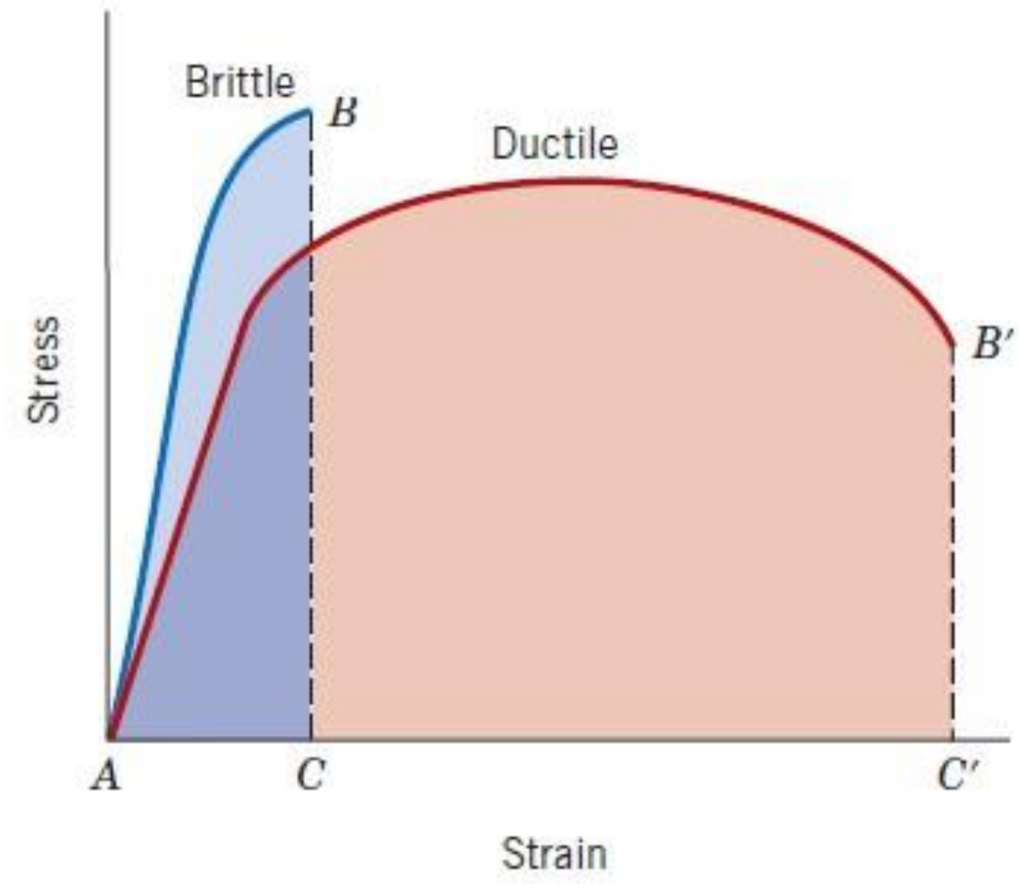
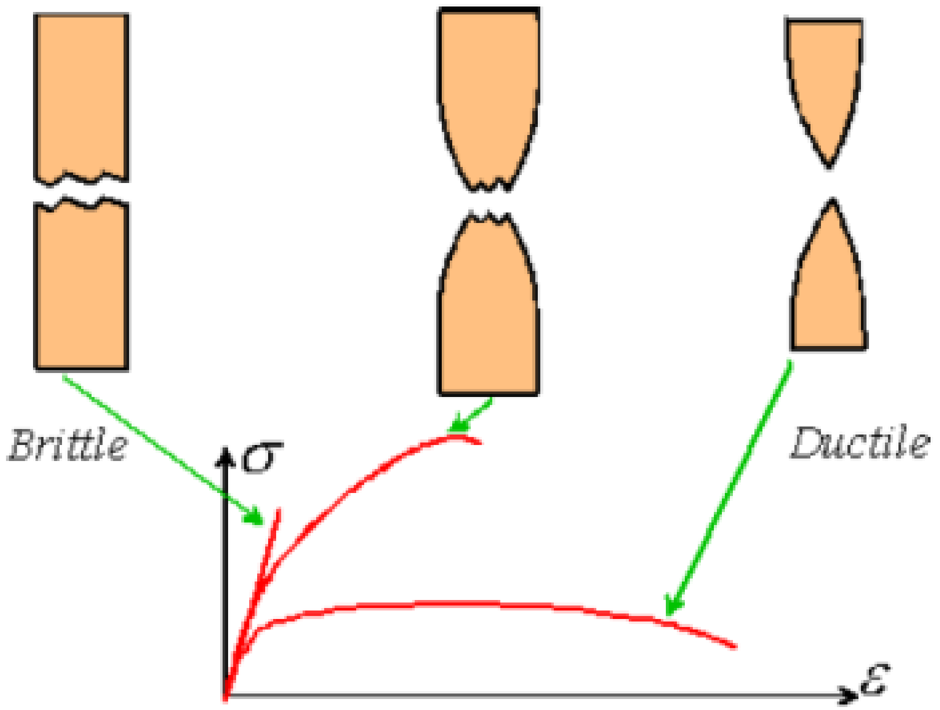


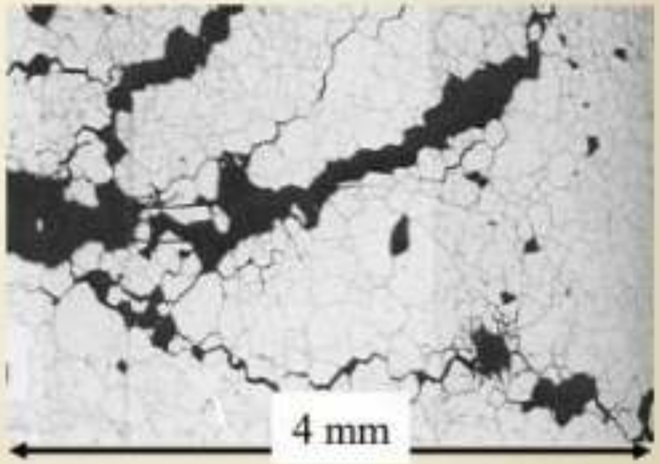
Figure 6.13 Schematic representations of tensile stress–strain behavior for brittle and ductile materials loaded to fracture.



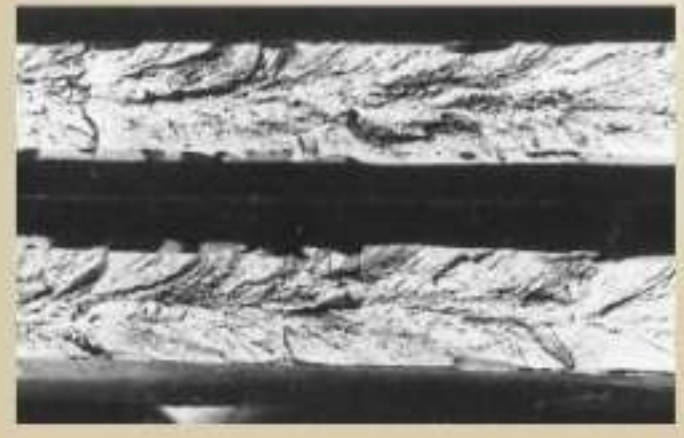
- Brittle fracture is a low energy fracture
- Ductile fracture is a High energy fracture

BRITTLE FAILURE

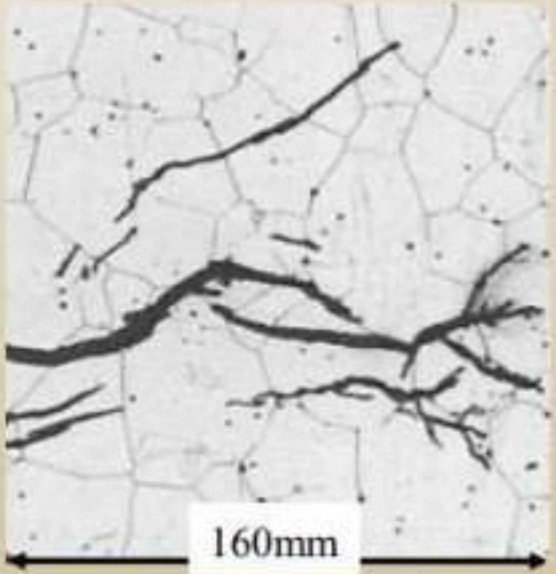
Brittle fracture in a mild steel



Intergranular fracture (between **grains**)



V-shaped "chevron" markings
Characteristic of brittle fracture



Intragranular fracture (within **grains**)

- Ductile fracture is almost always preferred for two reasons.

1. First, brittle fracture occurs suddenly and catastrophically without any warning; this is a consequence of the spontaneous and rapid crack propagation.

   On the other hand, for ductile fracture, the presence of plastic deformation gives warning that fracture is imminent, allowing preventive measures to be taken.
2. Second, more strain energy is required to induce ductile fracture inasmuch as ductile materials are generally tougher.

- Under the action of an applied tensile stress, most metal alloys are ductile, whereas ceramics are notably brittle, and polymers may exhibit both types of fracture.

Ductile fracture	**Brittle fracture**
• Material fractures after plastic deformation and slow propagation of crack	• Material fractures with very little or no plastic deformation.
• Surface obtained at the fracture is dull or fibrous in appearance	• Surface obtained at the fracture is shining and crystalling appearance
• It occurs when the material is in plastic condition.	• It occurs when the material is in elastic condition.
• It is characterized by the formation of cup and cone	• It is characterized by separation of normal to tensile stress.
• The tendency of ductile fracture is increased by dislocations and other defects in metals.	• The tendency brittle fracture is increased by decreasing temperature, and increasing strain rate.
• There is reduction in cross – sectional area of the specimen	• There is no change in the cross – sectional area.

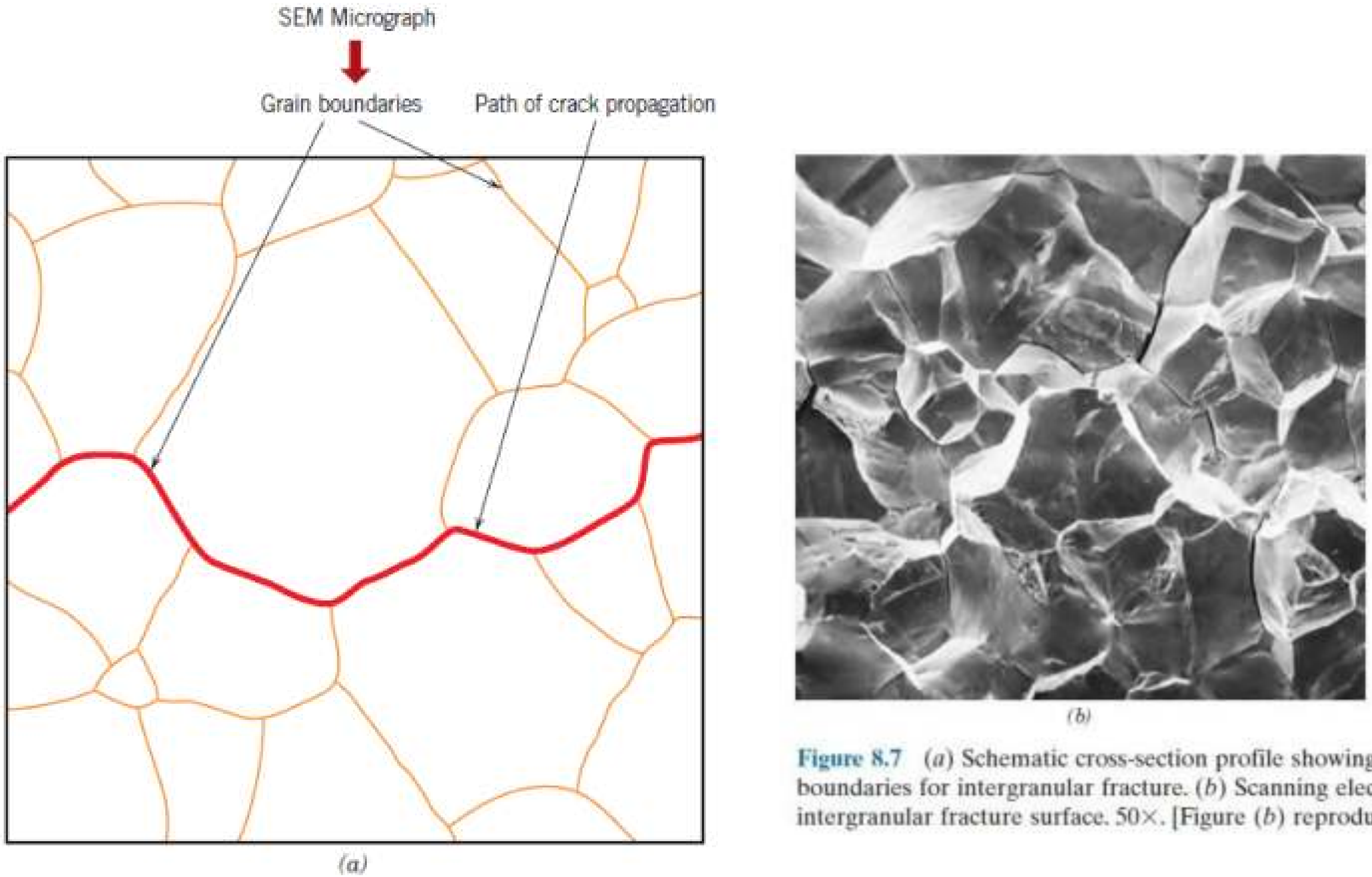
Ductile vs. Brittle Failure

cup-and-cone fracture

brittle fracture

Adapted from Fig. 8.3, *Callister 7e.*

Intergranular fracture



(a)

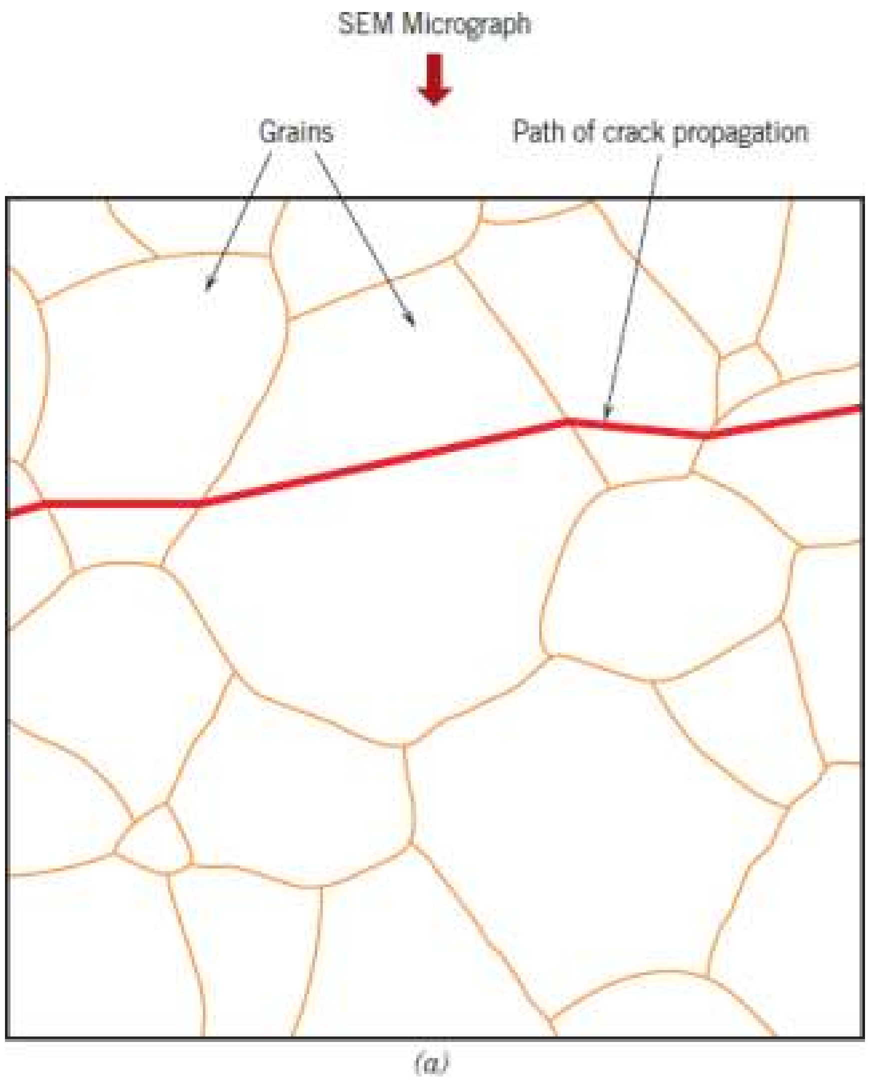
(b)

Figure 8.7 (*a*) Schematic cross-section profile showing crack propagation along grain boundaries for intergranular fracture. (*b*) Scanning electron fractograph showing an intergranular fracture surface. 50×. [Figure (*b*) reproduced with permission from *ASM*

- In intergranular fracture, cracks pass through grain boundaries.

- Intergranular failure is typically due to elemental depletion (chromium) at the grain boundaries or some type of weakening of the grain boundary due to chemical attack, oxidation, embrittlement or due to the precipitation of brittle phase along grain boundaries
- Some FCC metals otherwise FCC metals are ductile in nature.

Transgranular (or transcrystalline) Fracture



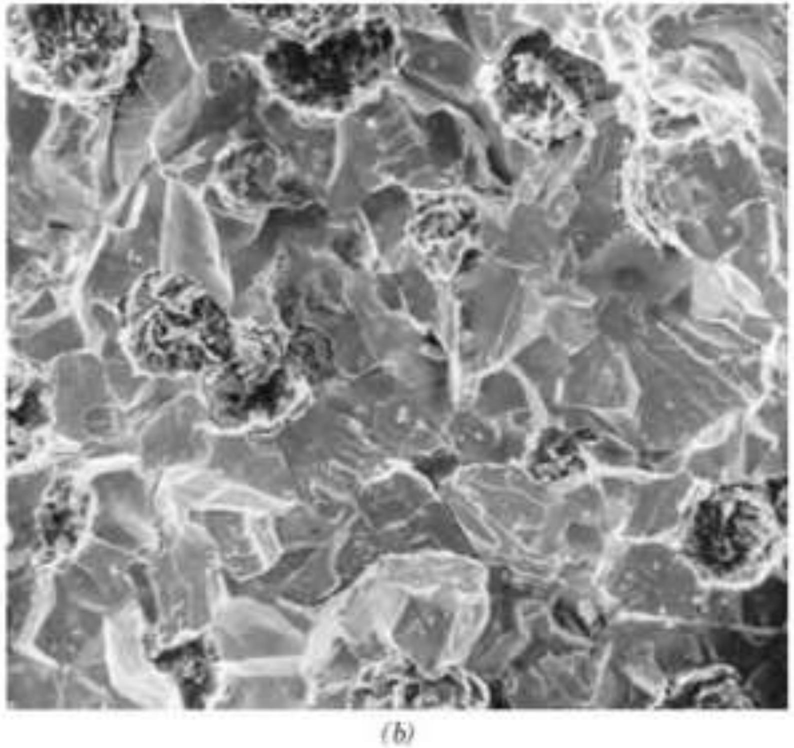


Figure 8.6 (*a*) Schematic cross-section profile showing crack propagation through the interior of grains for transgranular fracture. (*b*) Scanning electron fractograph of ductile cast iron showing a transgranular fracture surface. Magnification unknown. [Figure (*b*)

- In transgranular fracture, cracks pass through the grains

- Cleavage - in most brittle crystalline materials, crack propagation that results from the successive & repeated breaking of atomic bonds along specific planes – particularly along those planes with fewer inter atomic bonds.
- Such a process is termed as cleavage and known as cleavage fracture Flat surface look grainy or granular BCC and HCP metals

Role of crack size on fracture

- Fracture stress on a body is not a material property
- Its depends on the cracks present in the body

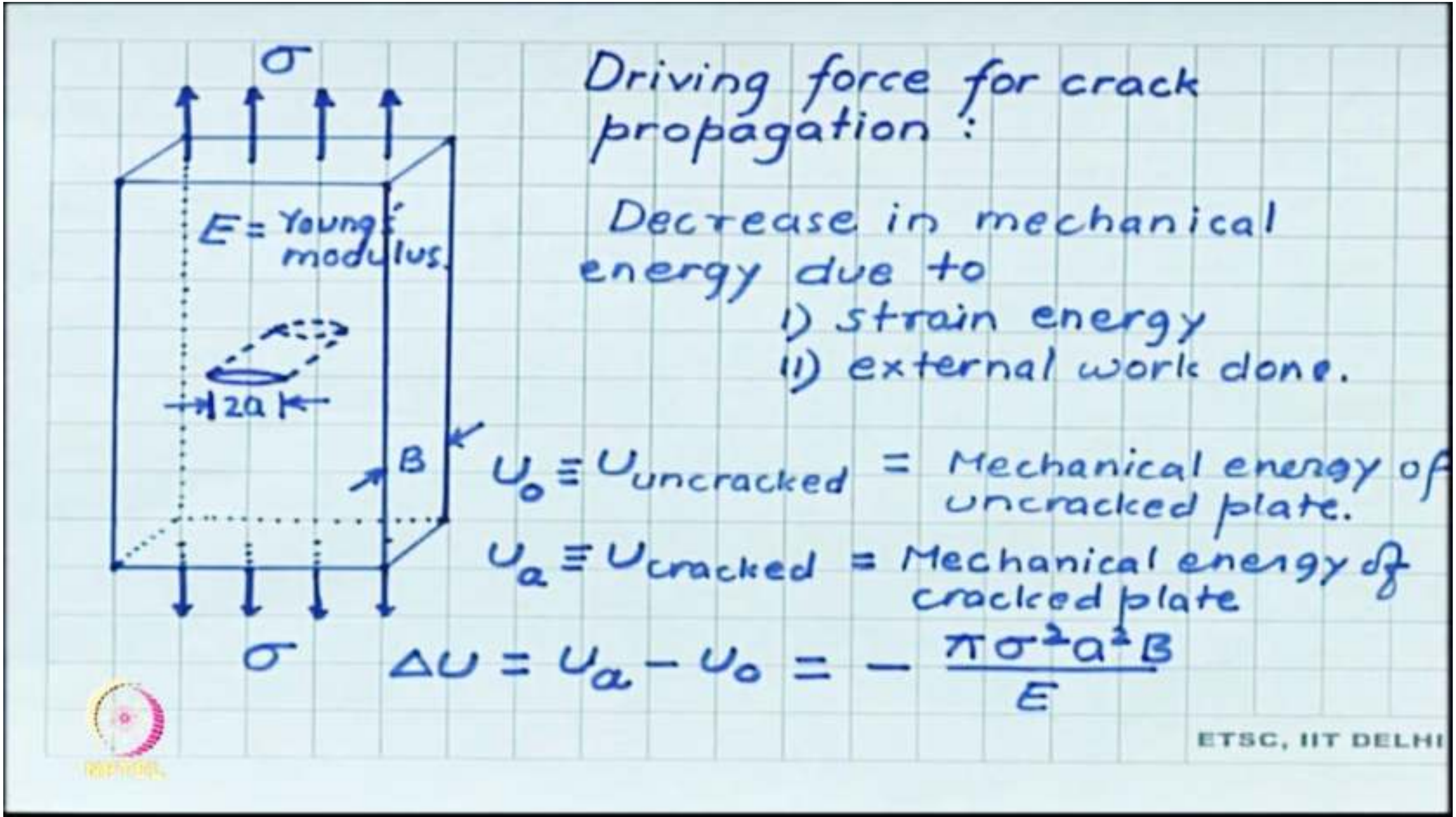
- <u>Paper experiment</u>
- Larger the crack size smaller the fracture stress
- Fracture stress also depends the material property
    - Higher stiffness the higher fracture stress

Griffith theory of brittle fracture

- It was observed that the measured fracture strengths of most brittle materials are much lower than predicted by theoretical calculations based on atomic bonding energy.
- As an explanation Griffith proposed that brittle materials contains large number of fine cracks, which causes stress concentration.
- This leads to reach the theoretical cohesive strength near the cracks, Hence crack propagates and cause the material to fracture
- As the applied stress increases, the crack enlarges and causes material failure.
- Due to the ability to amplify an applied stress, the cracks or flaws are also called ***stress raisers.***

- All brittle materials contain a population of small cracks and flaws that have a variety of sizes, geometries, and orientations.
- When the magnitude of a tensile stress at the tip of one of these flaws exceeds the value of this critical stress, a crack forms and then propagates, which results in fracture.
- Very small and virtually defect-free metallic and ceramic whiskers have been grown with fracture strengths that approach their theoretical values.

Griffith theory of brittle fracture



Driving force for crack propagation :

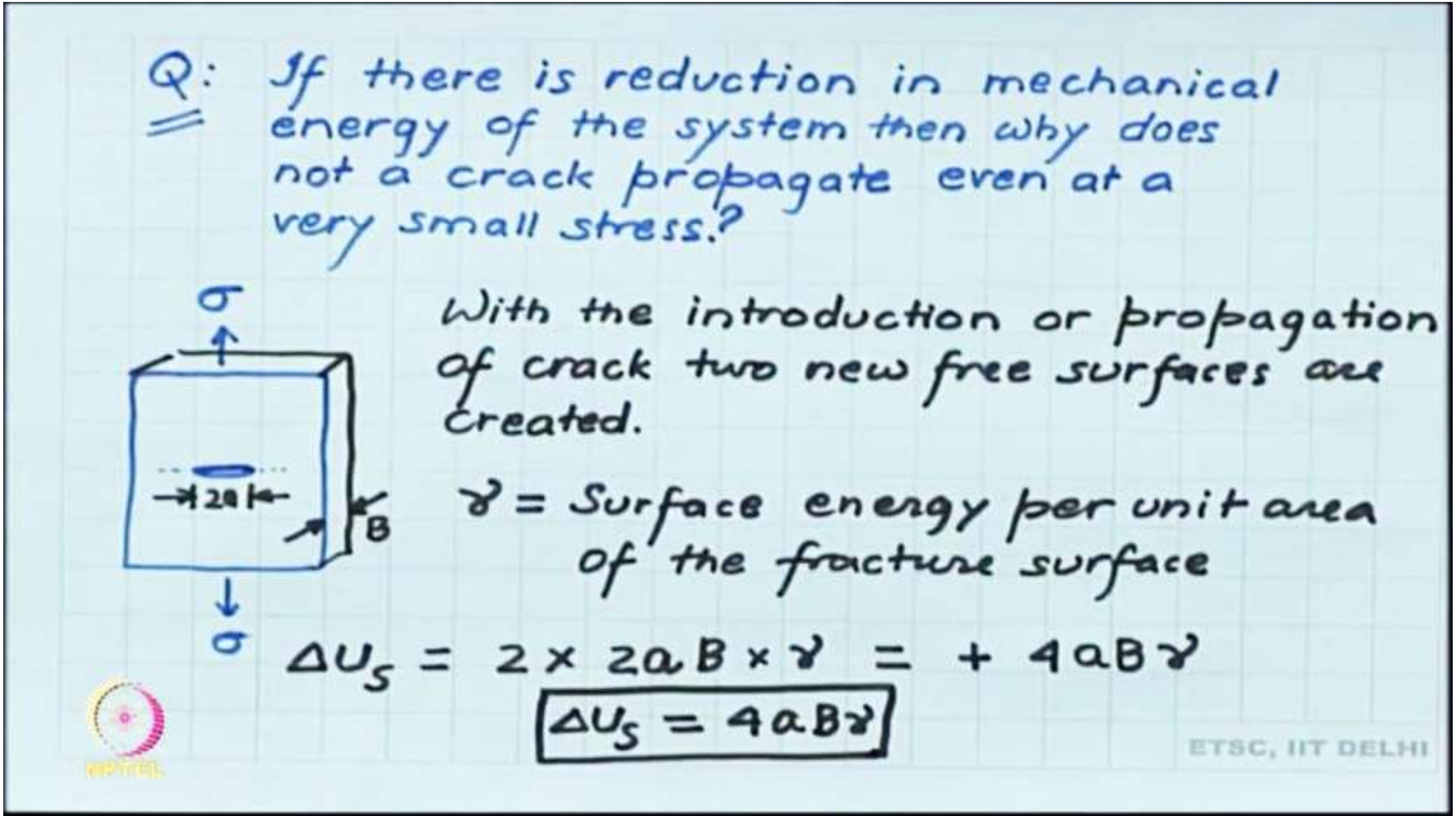
Decrease in mechanical energy due to
1) strain energy
ii) external work done.

$U_o \equiv U_{uncracked}$ = Mechanical energy of uncracked plate.

$U_a \equiv U_{cracked}$ = Mechanical energy of cracked plate

$$\Delta U = U_a - U_o = -\frac{\pi \sigma^2 a^2 B}{E}$$

Griffith theory of brittle fracture



Q: If there is reduction in mechanical energy of the system then why does not a crack propagate even at a very small stress?

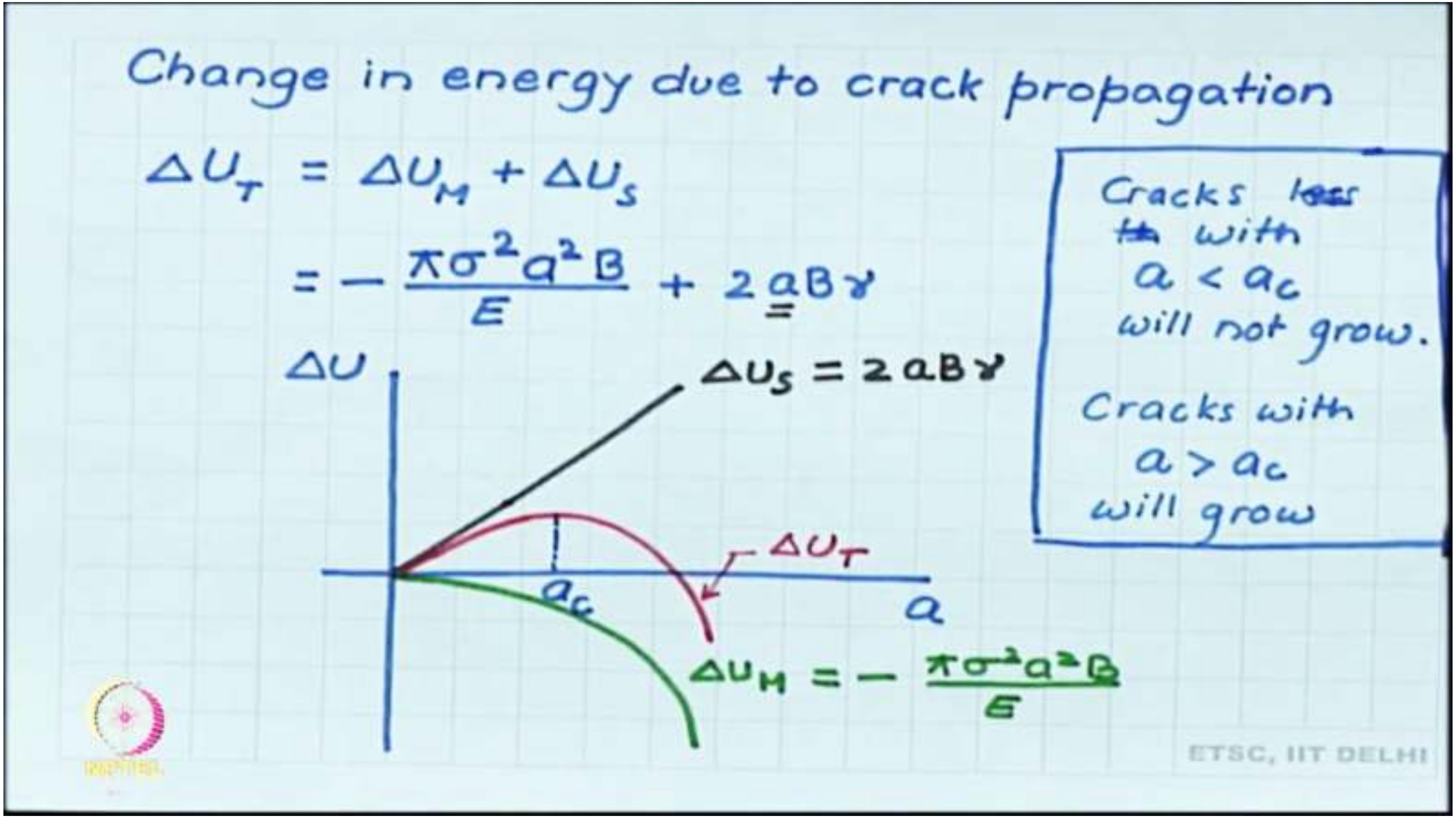
With the introduction or propagation of crack two new free surfaces are created.

γ = Surface energy per unit area of the fracture surface

$$\Delta U_s = 2 \times 2aB \times \gamma = +4aB\gamma$$

$$\boxed{\Delta U_s = 4aB\gamma}$$

Griffith theory of brittle fracture



Change in energy due to crack propagation

$$\Delta U_T = \Delta U_M + \Delta U_S$$

$$= -\frac{\pi\sigma^2 a^2 B}{E} + 2\underline{\underline{a}}B\gamma$$

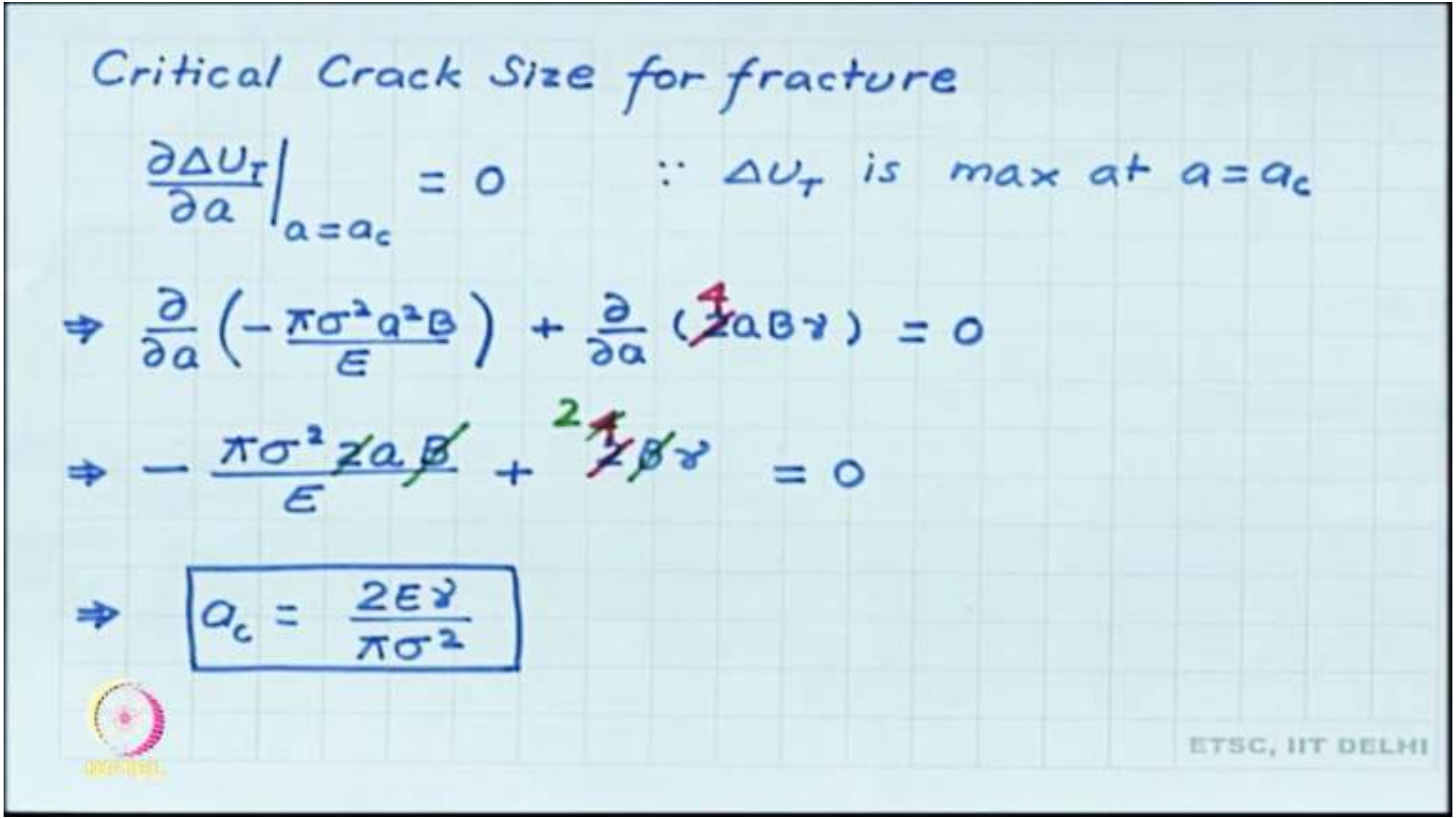
$$\Delta U_S = 2aB\gamma$$

$$\Delta U_M = -\frac{\pi\sigma^2 a^2 B}{E}$$

Cracks ~~less~~ ~~th~~ with $a < a_c$ will not grow.

Cracks with $a > a_c$ will grow

Griffith theory of brittle fracture



Critical Crack Size for fracture

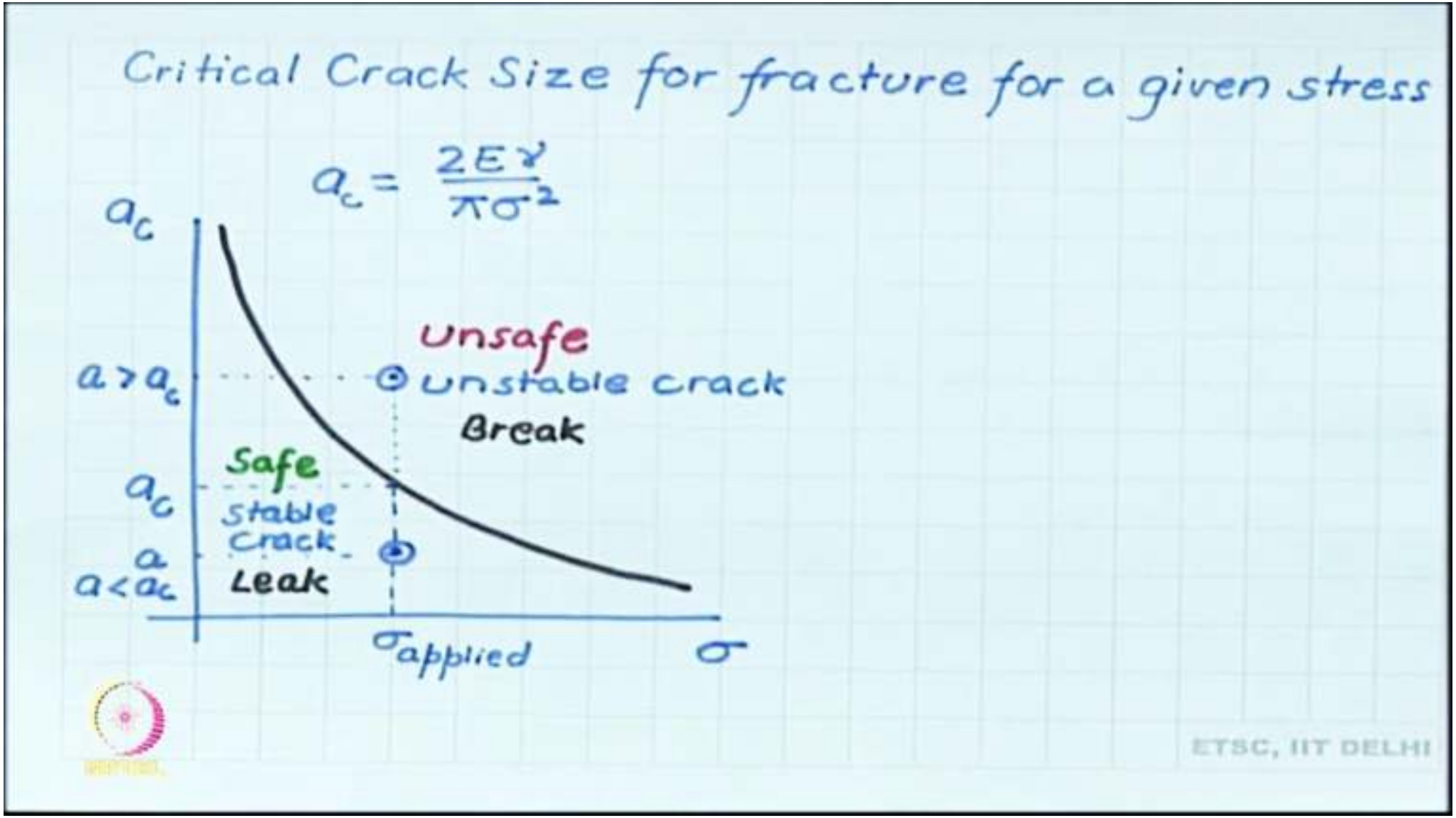
$$\left.\frac{\partial \Delta U_T}{\partial a}\right|_{a=a_c} = 0 \qquad \because \Delta U_T \text{ is max at } a=a_c$$

$$\Rightarrow \frac{\partial}{\partial a}\left(-\frac{\pi\sigma^2 a^2 B}{E}\right) + \frac{\partial}{\partial a}\left(\overset{4}{\cancel{2}}aB\gamma\right) = 0$$

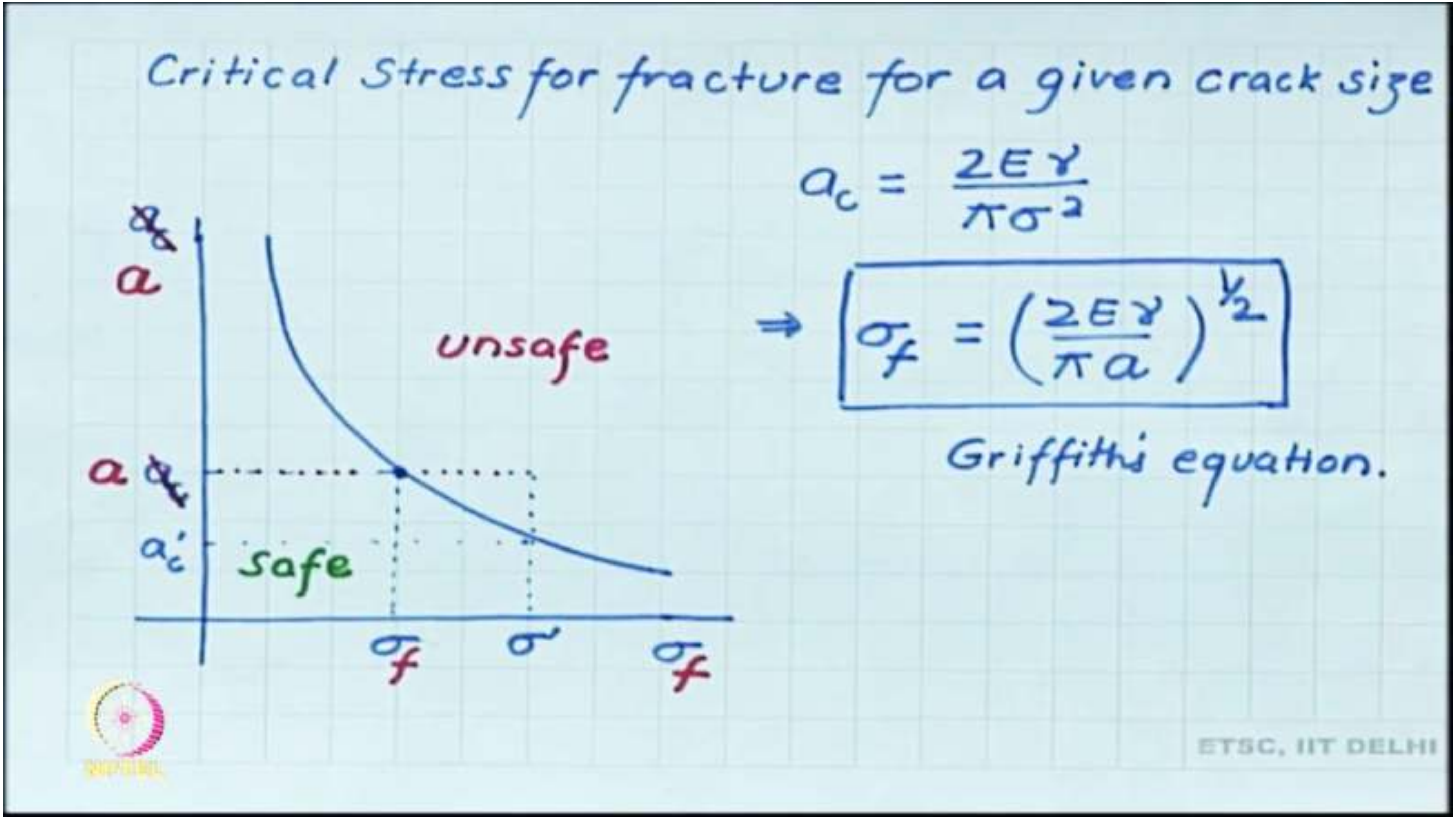
$$\Rightarrow -\frac{\pi\sigma^2 \cancel{2}a\cancel{B}}{E} + \overset{2\,\cancel{4}}{\cancel{2}}\cancel{B}\gamma = 0$$

$$\Rightarrow \boxed{a_c = \frac{2E\gamma}{\pi\sigma^2}}$$

Griffith theory of brittle fracture



Griffith theory of brittle fracture



Critical Stress for fracture for a given crack size

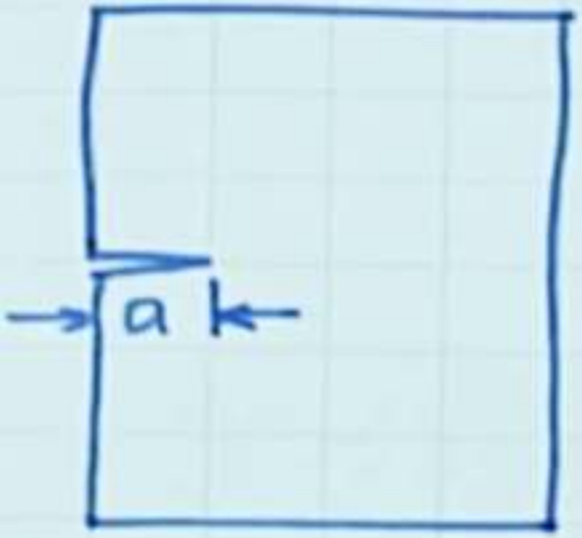
$$a_c = \frac{2E\gamma}{\pi\sigma^2}$$

$$\Rightarrow \boxed{\sigma_f = \left(\frac{2E\gamma}{\pi a}\right)^{1/2}}$$

Griffith's equation.

Central Crack

Edge Crack



Edge crack of length 'a' has the same fracture stress as central crack of length 2a

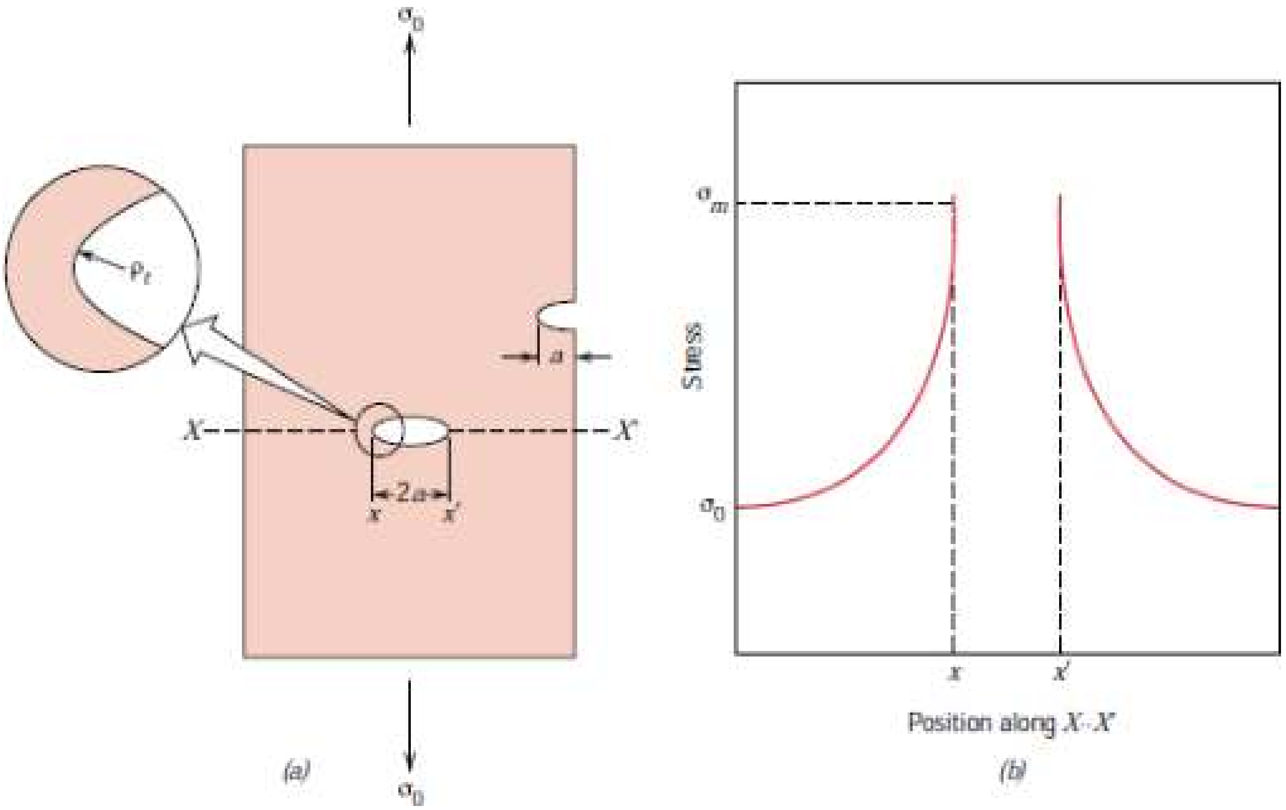
$$\sigma_f = \left(\frac{2E\gamma}{\pi a}\right)^{1/2}$$

$a = \frac{1}{2}$ crack length for a central crack

$a =$ Full crack length for edge crack.

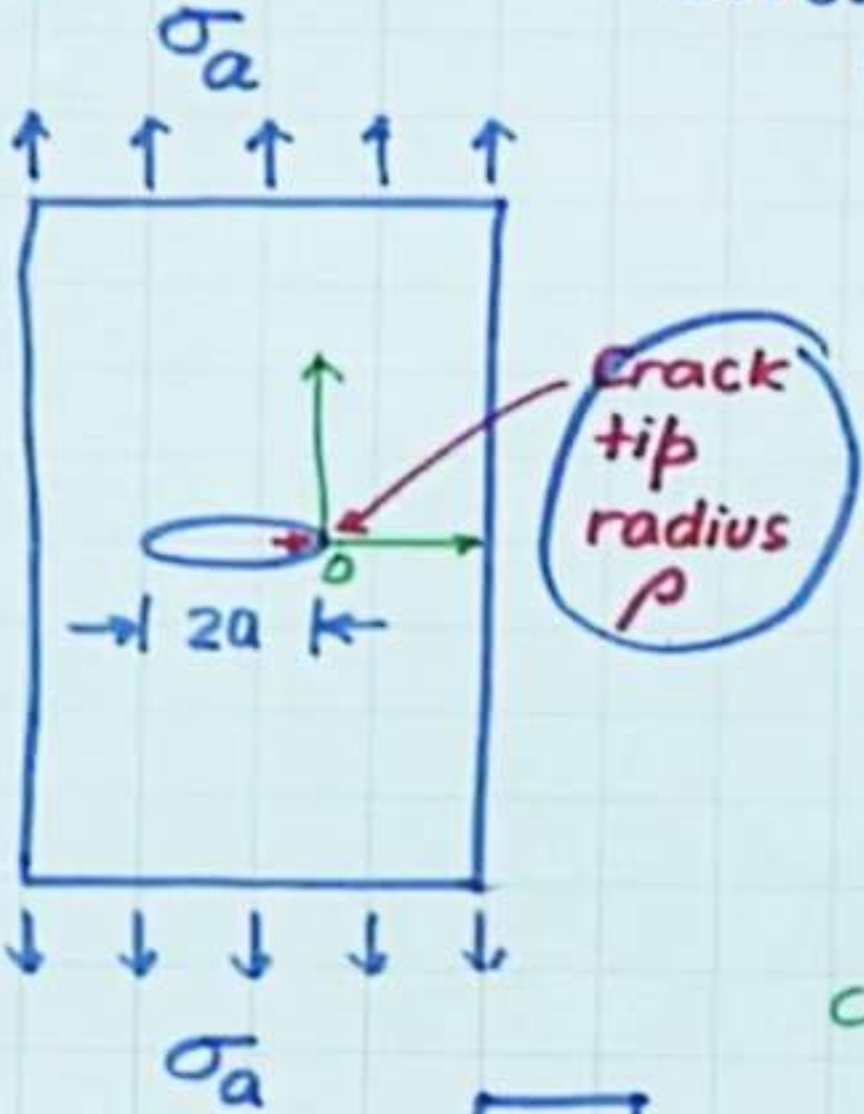
Stress concentration

- Stress concentration/amplification will take place at the tip of the crack, which will force the crack to propagate and thus causing the material to fail.

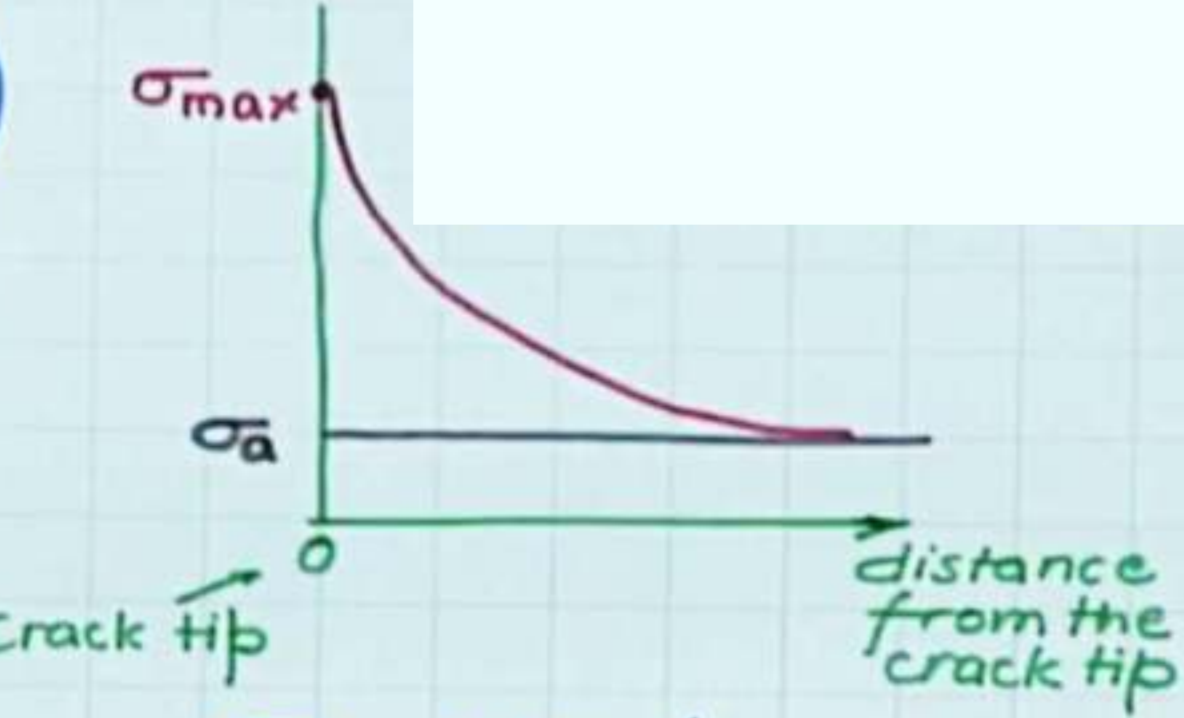


(a) The geometry of surface and internal cracks. (b) Schematic stress profile along the line X–X' demonstrating stress amplification at crack tip positions.

Stress concentration ahead of a crack tip



σ_a = applied stress



square window

circular windows.

$$\sigma_m = 2\sigma_0\left(\frac{a}{\rho_t}\right)^{1/2}$$

Where σ_m = Maximum stress at crack tip
σ_o = Magnitude of applied stress
a = length of surface crack or half length of internal crack
ρ_t = radius of curvature at crack tip

a >> ρ_t, i.e σ_m >> σ_o
So it is clear that magnitude of stress at crack tip is much higher compared to magnitude of applied stress and this is due to stress concentration

Stress Concentration Factor (Kt)

$$K_t = \frac{\sigma_m}{\sigma_0} = 2\left(\frac{a}{\rho_t}\right)^{1/2}$$

Primary & Secondary stress raisers

- Change in geometry of the part, key ways, holes, threads, steps or change in diameter, bolt head etc. are *Primary Stress Raisers.*

- Surface discontinuities such as nicks, notches, machining marks, pitting, corrosion, defects inherent in the material – non metallic inclusion, minute cracks, voids etc. are *Secondary Stress Raisers.*

- Furthermore, the effect of a stress raiser is more significant in brittle than in ductile materials.
- For a ductile material, plastic deformation ensues when the maximum stress exceeds the yield strength. This leads to a more uniform distribution of stress in the vicinity of the stress raiser and to the development of a maximum stress concentration factor less than the theoretical value.
- Such yielding and stress redistribution do not occur to any appreciable extent around flaws and discontinuities in brittle materials; therefore, essentially the theoretical stress concentration will result.

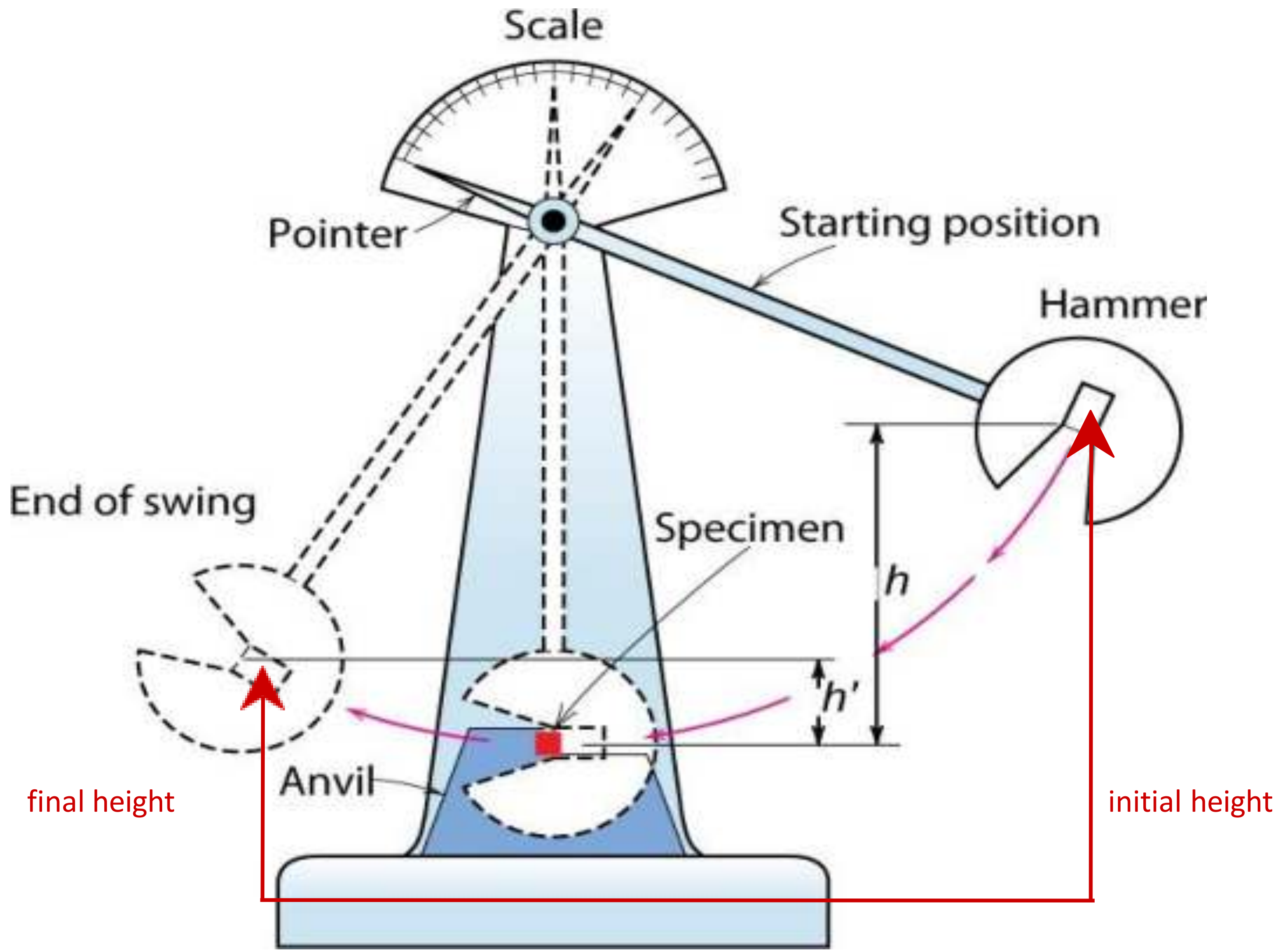
Effect of impact loading on ductile material and its application in forging

- An impact load is a dynamic load; where load is suddenly applied.
- When a material is subjected to a sudden, intense blow, in which the strain rate is extremely rapid, it may behave in much more brittle a manner than is observed in the tensile test.
- Its effect is much grater than a steady load of same magnitude.
- Impact test is used to measure the **toughness of the material**, a measure on the capacity of a material to store strain energy before it fails.
- High toughness is exhibited by materials with high strength and ductility.
- During impact loads, the ductile materials with voids and cracks will behave like brittle materials, and it is not indicated in tensile tests.

- A brittle material requires less energy to break and hence lacks toughness than pure ductile materials.
- Impact test are particularly useful for finding the ductile to brittle transition characteristics of materials.
- The main objective of impact tests is to select materials with high fracture toughness.

- **In forging process** the forces are applied on the raw material such that the stresses induced are greater than yield and less than ultimate strength so that material is experiencing plastic or permanent deformation to get required shape.
- But in forging operation force applied can be either continuous or intermittent impact loads.
- There are two kinds of forging process, impact forging and press forging. In the former, the load is applied by impact, and deformation takes place over a very short time.
- Press forging, on the other hand, involves the gradual build up of pressure to cause the metal to yield. The time of application is relatively long.

Impact Testing Apparatus



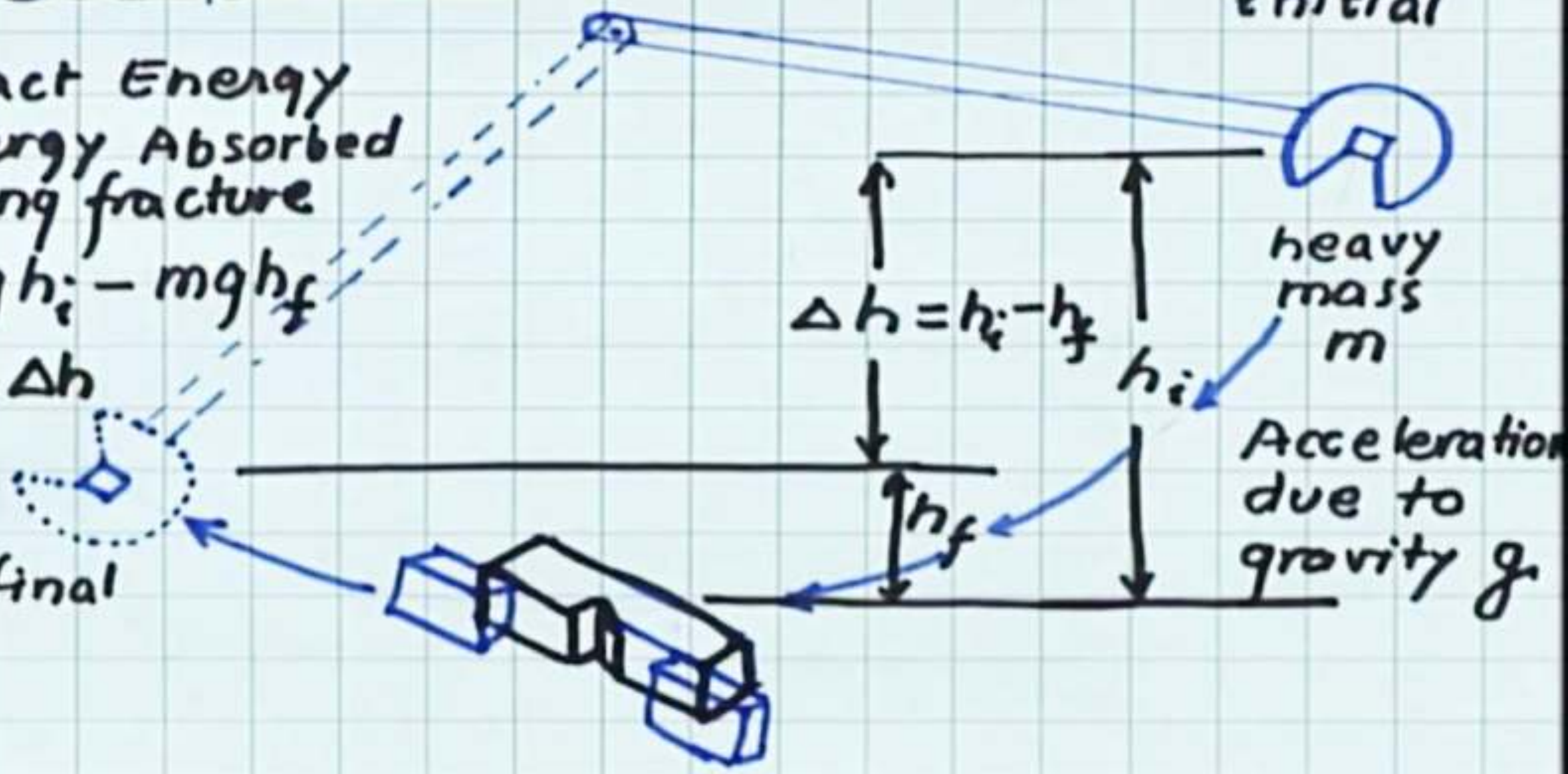
Charpy Impact test

Impact Energy

= Energy Absorbed during fracture

$= mgh_i - mgh_f$

$= mg\Delta h$



Impact tests – Izod & Charpy

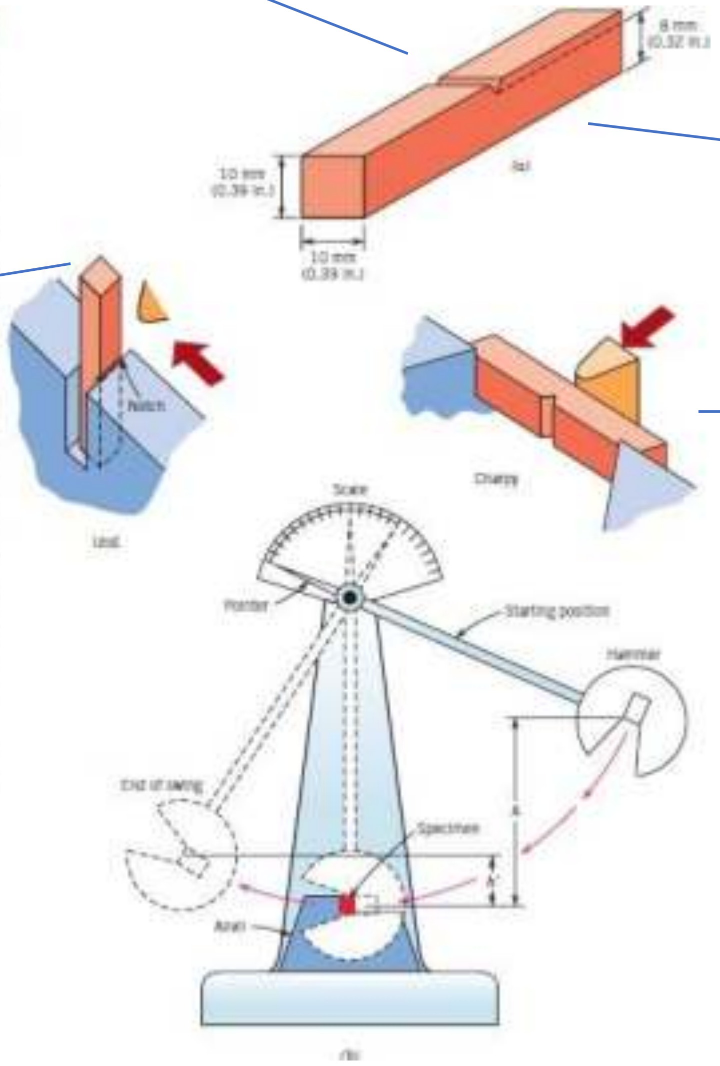


Figure 8.12 (*a*) Specimen used for Charpy and Izod impact tests. (*b*) A schematic drawing of an impact testing apparatus. The hammer is released from fixed height *h* and strikes the specimen; the energy expended in fracture is reflected in the difference between *h* and the swing height *h'*. Specimen placements for both Charpy and Izod tests are also shown. [Figure (*b*) adapted from H. W. Hayden, W. G. Moffatt, and J. Wulff, *The Structure and Properties of Materials*, Vol. III, *Mechanical Behavior*, p. 13. Copyright © 1965 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.]

V notch

Test specimen

Izod test

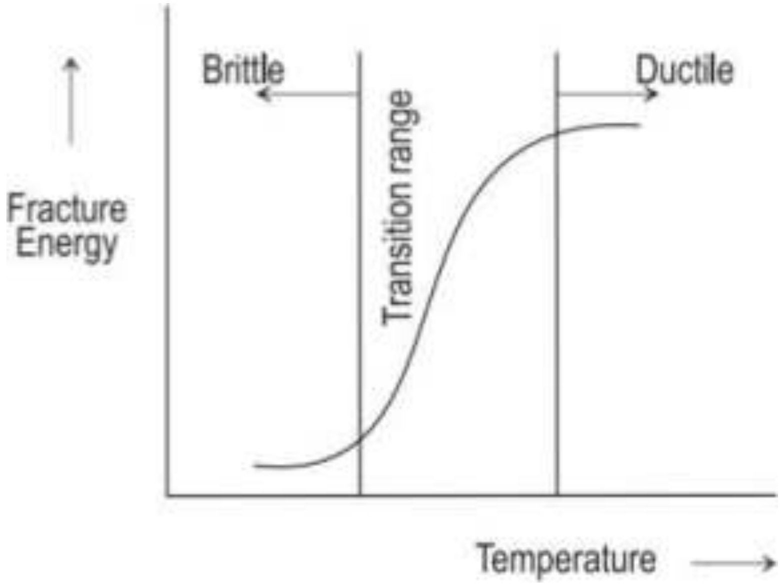
Charpy test

Izod & Charpy Tests

- For both Charpy and Izod tests, the specimen is in the shape of a bar of square cross section.
- A V-notch is machined to the cross section.
- The load is applied as an impact blow from a weighted pendulum hammer that is released from a cocked position at a fixed height h.
- The specimen is positioned at the base.
- Upon release, a knife edge mounted on the pendulum strikes and fractures the specimen at the notch, which acts as a point of stress concentration for this high velocity impact blow.
- The pendulum continues its swing, rising to a maximum height h’ which is lower than h. The energy absorption, computed from the difference between h and h’ is a measure of the impact energy.

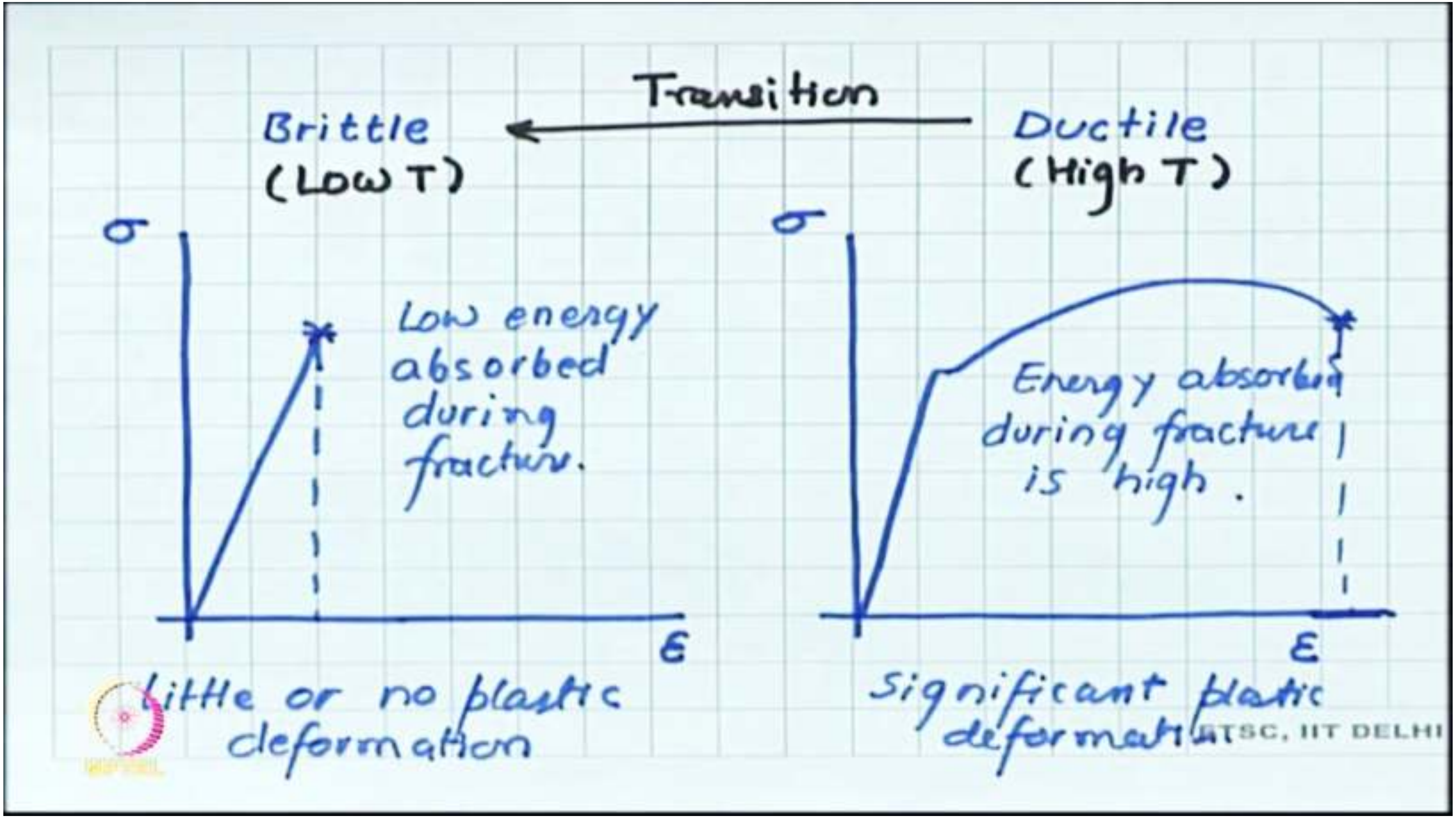
Ductile to Brittle Transition

- Under some circumstances, ductile materials fracture abruptly and with very little plastic deformation. Thus there is a transition from ductile to brittle fracture, as crack propagation takes precedence over plastic deformation.
- This ductile to brittle fracture transition occurs in some metals when
  - a) the temperature is lowered
  - (b) the rate of straining increased and/ or
  - (c) a notch or stress raiser is introduced in the material.



- In steel and other BCC materials the ductile behavior changes to brittle with decreasing temperature. This transition from ductile to brittle fracture behavior is an important engineering phenomenon.

Ductile to brittle transition temperature (DBTT) in steels

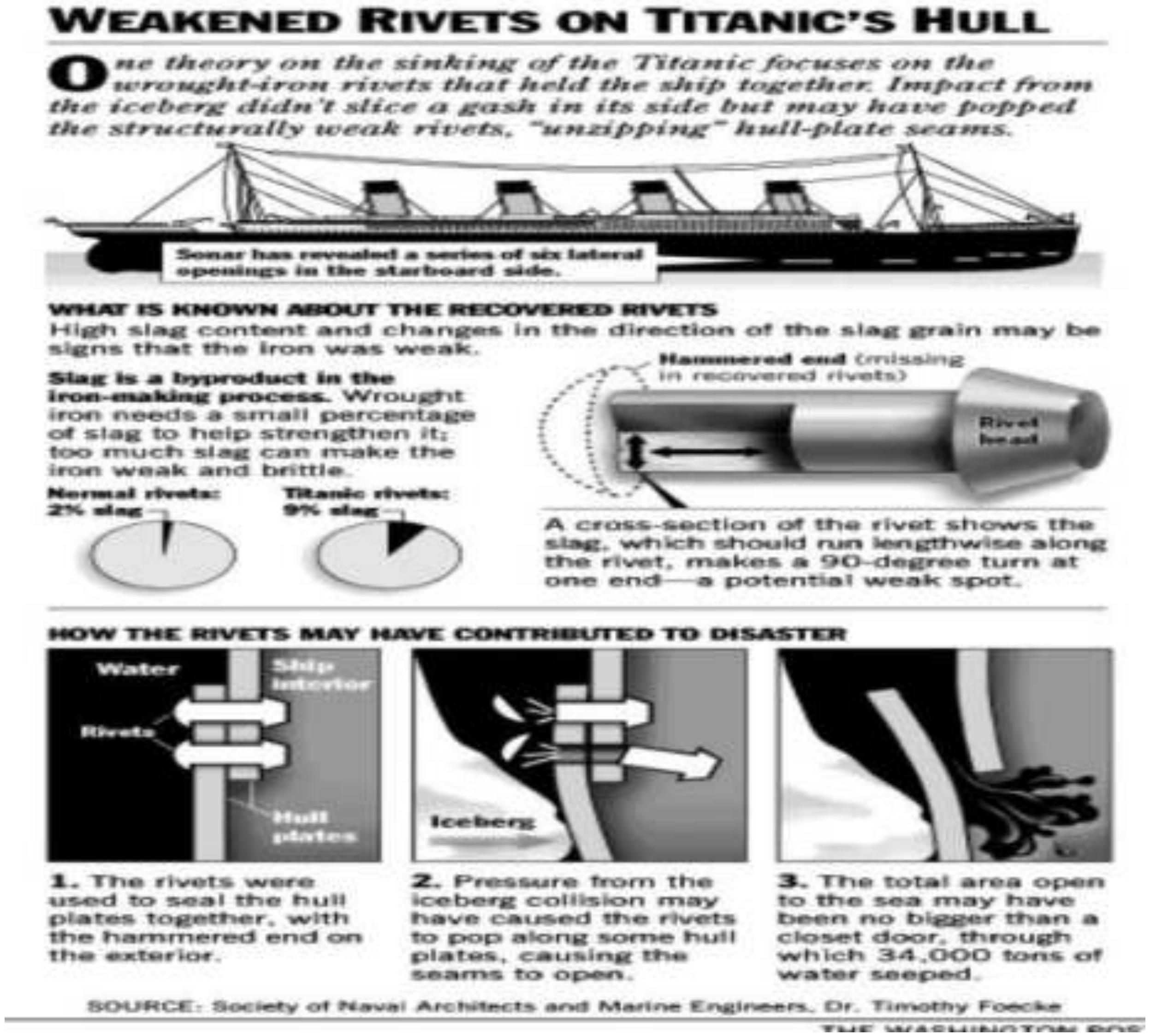


Low energy absorbed during fracture.

Little or no plastic deformation

Energy absorbed during fracture is high.

Significant plastic deformation



WEAKENED RIVETS ON TITANIC'S HULL

One theory on the sinking of the Titanic focuses on the wrought-iron rivets that held the ship together. Impact from the iceberg didn't slice a gash in its side but may have popped the structurally weak rivets, "unzipping" hull-plate seams.

Sonar has revealed a series of six lateral openings in the starboard side.

WHAT IS KNOWN ABOUT THE RECOVERED RIVETS

High slag content and changes in the direction of the slag grain may be signs that the iron was weak.

Slag is a byproduct in the iron-making process. Wrought iron needs a small percentage of slag to help strengthen it; too much slag can make the iron weak and brittle.

Normal rivets: 2% slag

Titanic rivets: 9% slag

Hammered end (missing in recovered rivets)

A cross-section of the rivet shows the slag, which should run lengthwise along the rivet, makes a 90-degree turn at one end—a potential weak spot.

HOW THE RIVETS MAY HAVE CONTRIBUTED TO DISASTER

1. The rivets were used to seal the hull plates together, with the hammered end on the exterior.

2. Pressure from the iceberg collision may have caused the rivets to pop along some hull plates, causing the seams to open.

3. The total area open to the sea may have been no bigger than a closet door, through which 34,000 tons of water seeped.

SOURCE: Society of Naval Architects and Marine Engineers, Dr. Timothy Foecke

THE WASHINGTON POS

- Titanic's hull was triple riveted with using mild steel rivets, and double riveted using wrought iron, in the central length of the ship where maximum stress was assumed to be located .
- Where as the use of wrought iron and mild steel rivets instead of steel rivets caused the titanic disaster to take place .
- The steel rivets have good strength as compared to wrought iron.
- Titanic had experienced a great forcefull impact which caused the six compartments of it to be opened to sea where the used wrought iron rivets failed.

Sinking of Titanic -14th April 1912

"All the News That's Fit to Print."

The New York Times.

TITANIC SINKS FOUR HOURS AFTER HITTING ICEBERG;
866 RESCUED BY CARPATHIA, PROBABLY 1250 PERISH;
ISMAY SAFE, MRS. ASTOR MAYBE, NOTED NAMES MISSING

Col. Astor and Bride, Isidor Straus and Wife, and Maj. Butt Aboard.

"RULE OF SEA" FOLLOWED

PICKED UP AFTER 8 HOURS

FRANKLIN HOPEFUL ALL DAY

HEAD OF THE LINE ABOARD

Biggest Liner Plunges to the Bottom at 2:20 A. M.

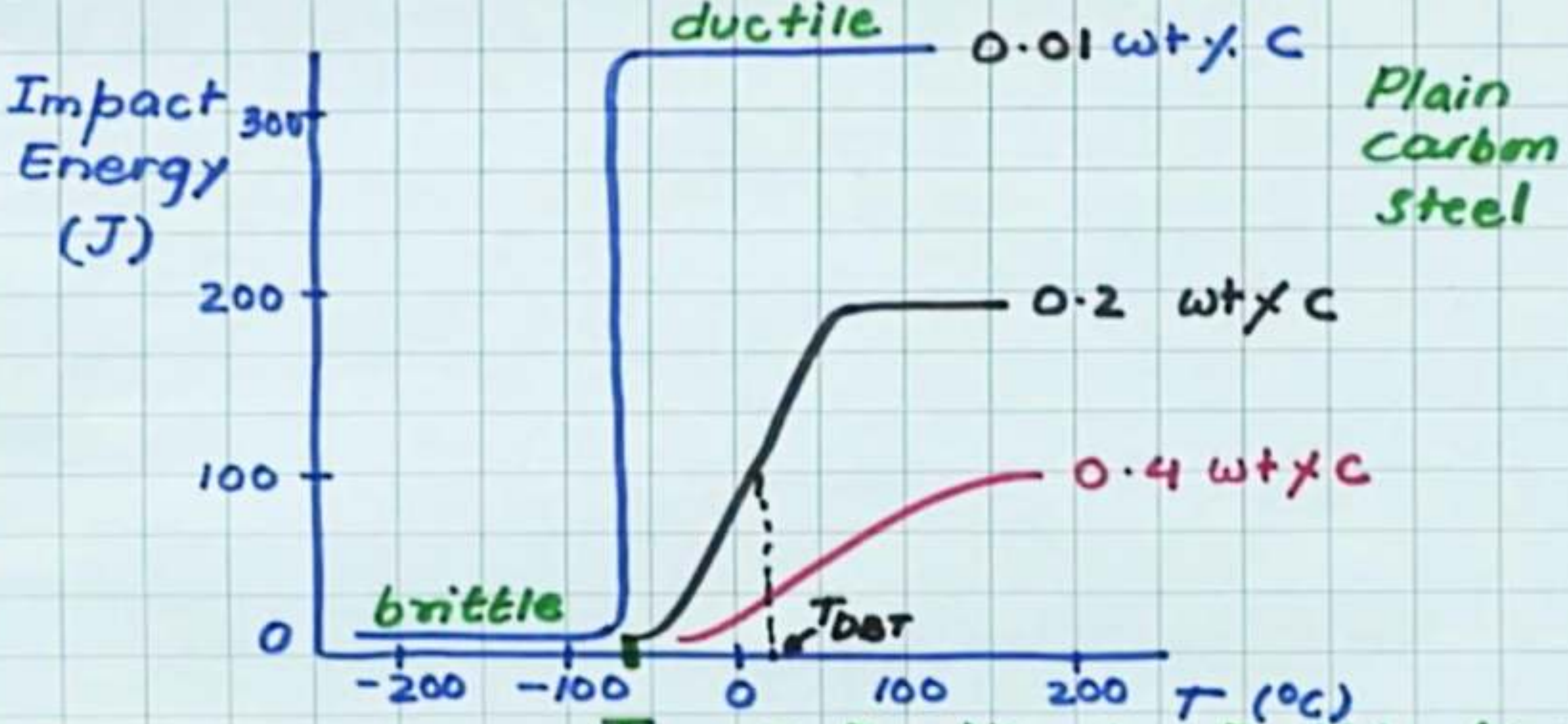
RESCUERS THERE TOO LATE

WOMEN AND CHILDREN FIRST

SEA SEARCH FOR OTHERS

OLYMPIC SENDS THE NEWS

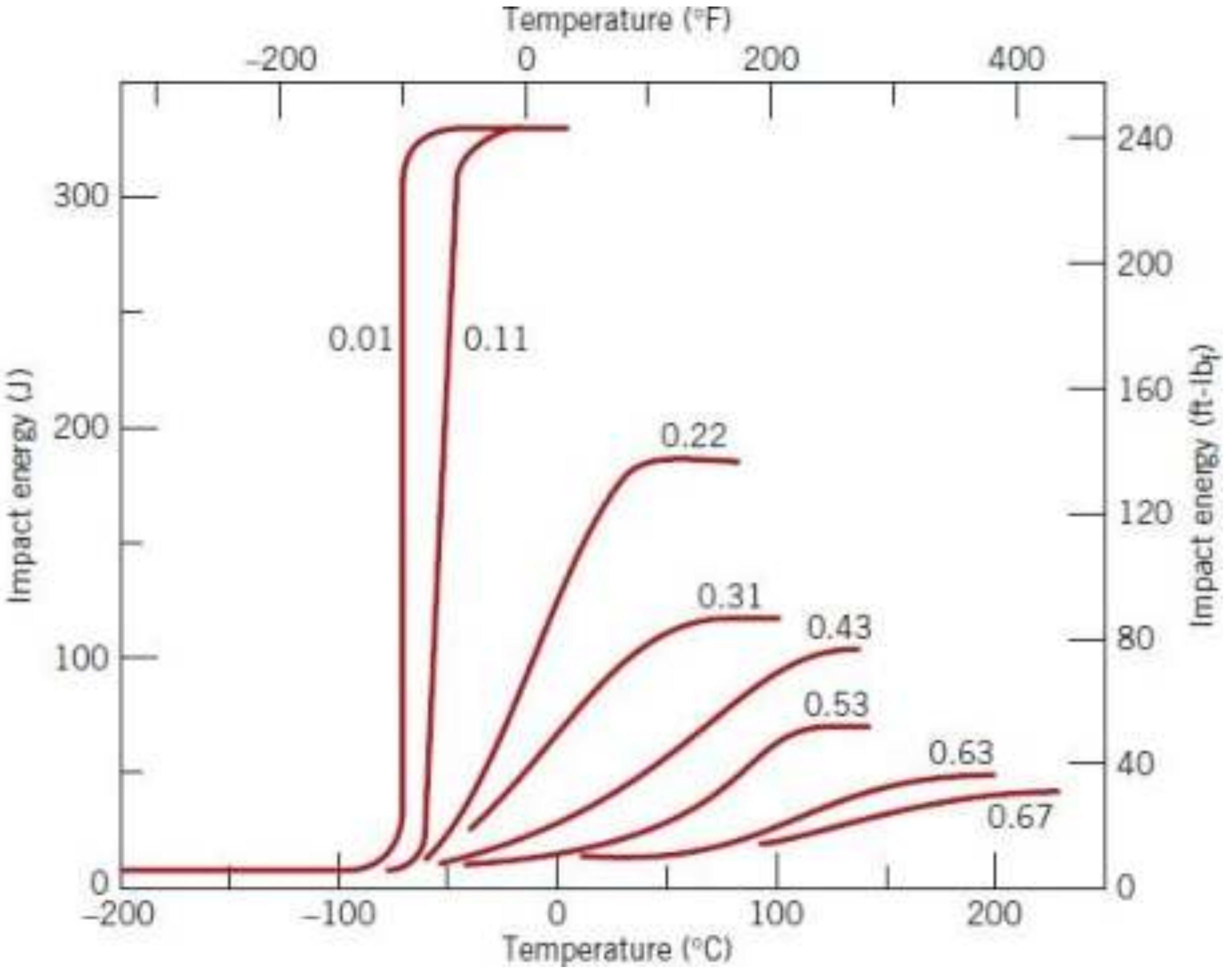
Titanic was made up of steel which has moderately high DBT temperature. On the day of sinking, the temperature was –2 ^{0}C which made the structure highly brittle which caused the damage.



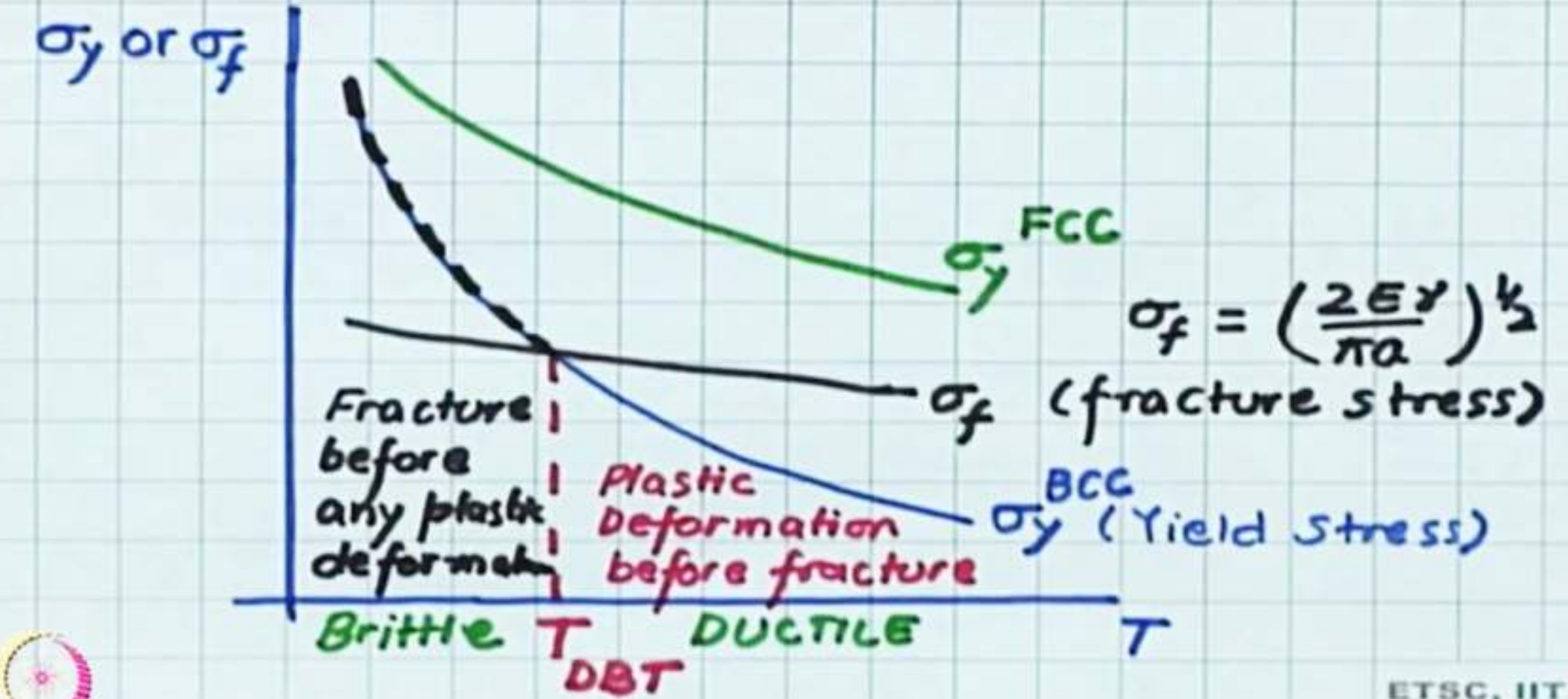
T_{DBT} = Ductile-to-Brittle transitio
temperature

- For these low-strength steels, the transition temperature is sensitive to both alloy composition and microstructure. For example, decreasing the average grain size results in a lowering of the transition temperature. Hence, refining the grain size both strengthens and toughens steels. In contrast, increasing the carbon content, while increasing the strength of steels, also raises the CVN transition of steels,

Figure 8.16
Influence of carbon content on the Charpy V-notch energy-versus-temperature behavior for steel. (Reprinted with permission from ASM International, Metals Park, OH 44073-9989, USA; J. A. Reinbolt and W. J. Harris, Jr., "Effect of Alloying Elements on Notch Toughness of Pearlitic Steels," *Transactions of ASM*, Vol. 43, 1951.)



BCC : Yield Stress a strong function of temp.



$$\sigma_f = \left(\frac{2E\gamma}{\pi a}\right)^{1/2}$$

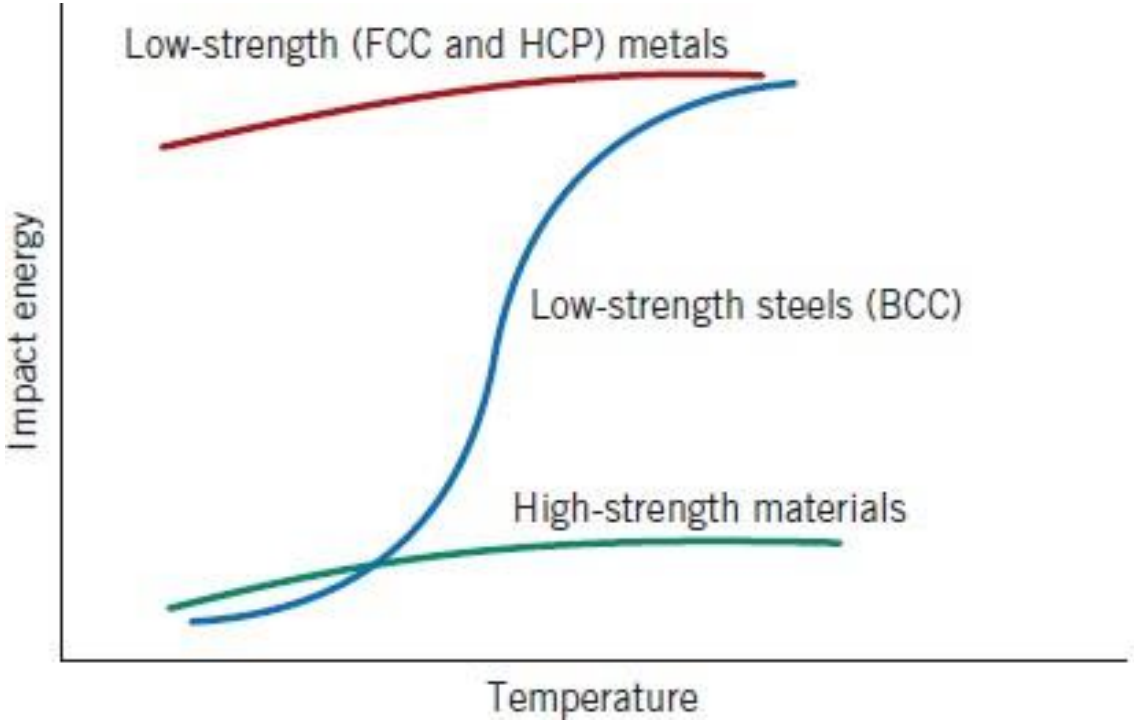


Figure 8.15 Schematic curves for the three general types of impact energy-versus-temperature behavior.

- low-strength FCC metals (some aluminum and copper alloys) and most HCP metals do not experience a ductile-to-brittle transition and retain high impact energies (i.e., remain ductile) with decreasing temperature.
- For high-strength materials (e.g., high-strengthsteels and titanium alloys), the impact energy is also relatively insensitive to temperature however, these materials are also very brittle, as reflected by their low impact energy values.

Ductile to brittle transition (DBT)

1. FCC materials do not show DBT
   - Good for cryogenic application
   - Austenic stainless steel is good for low temp use (Astenite : FCC)
   - Mild steel is not good for low temp use (Ferrite BCC)
2. Finer grain size lower the transition temp.
   - Enhances the ductile behavior
3. High strain rate increases the transition temp.
   - Enhances the brittle behavior
4. Notches increases the transition temp.
   - Enhances the brittle behavior

Structural changes during DBTT

- The reason for this transition is that, at higher temperatures, the atoms in the materials vibrate with greater frequency and amplitude. This increase allows the atoms under stress to slip to new positions within the material (to break bonds and form new ones with other atoms in the material).
- This slippage of atoms is observed outside of the material as plastic deformation, a feature of ductile fracture.
- However, when the temperature is lowered, the atoms may not be able to slip to new positions in the material. As the applied stress becomes high enough the atoms just break their bonds, but do not form new ones.
- The decrease in slippage does not cause plastic deformation. Thus, the material behaves in a brittle manner at lower temperatures.

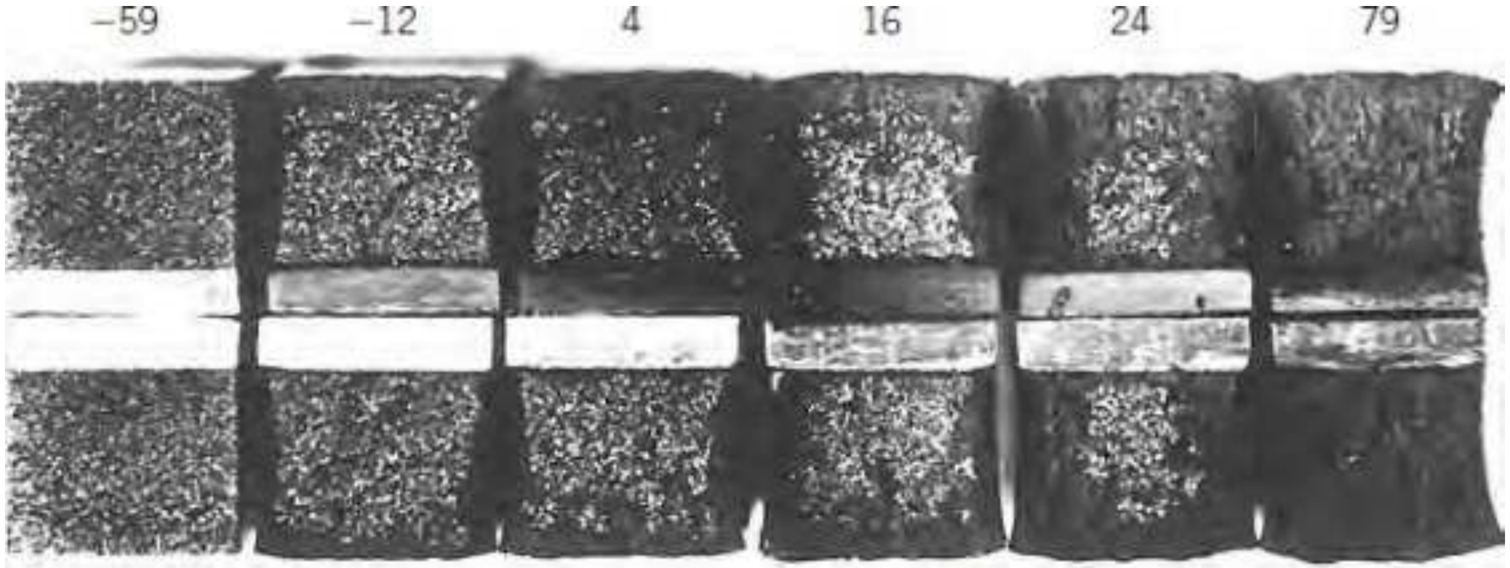


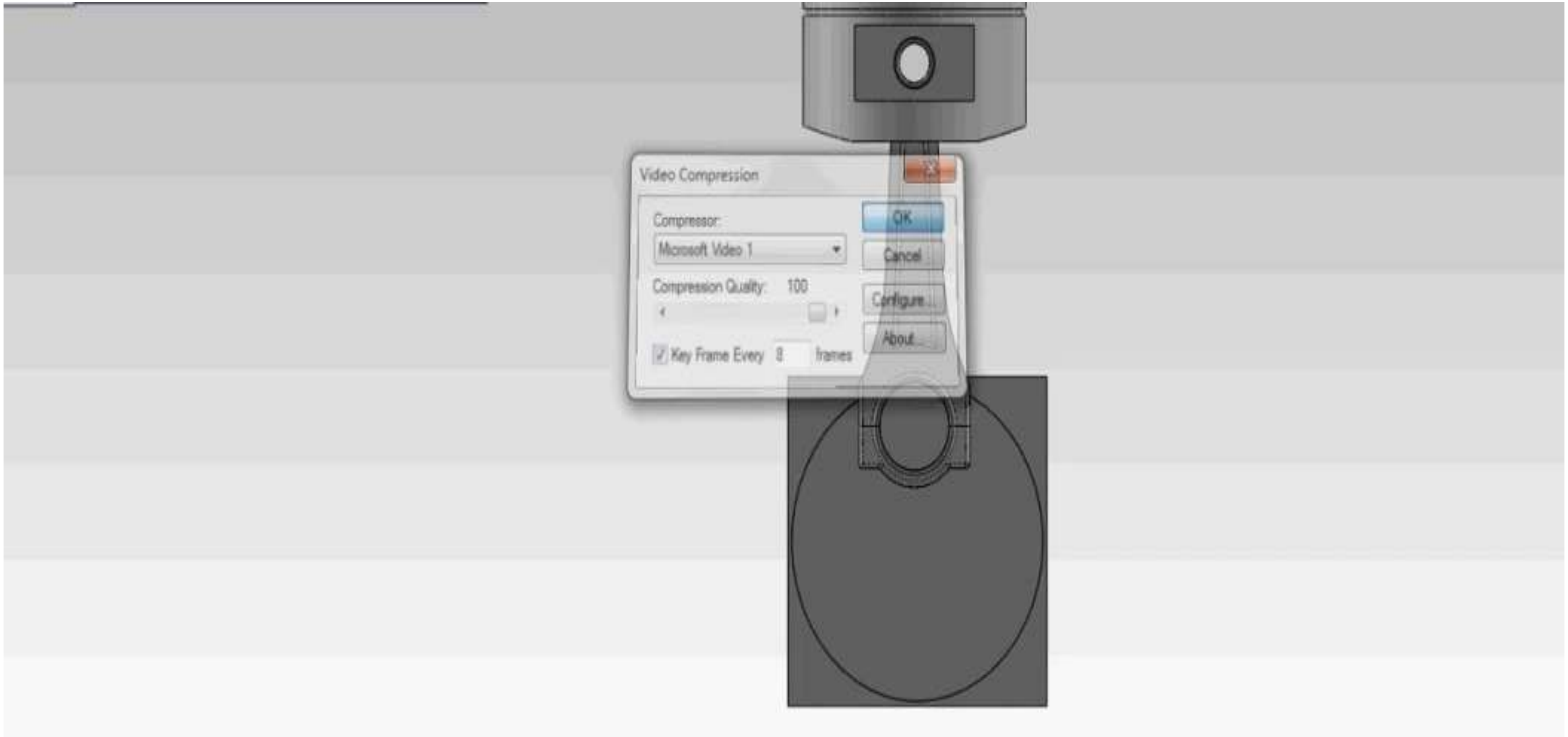
Figure 8.14 Photograph of fracture surfaces of A36 steel Charpy V-notch specimens tested at indicated temperatures (in °C). (From R. W. Hertzberg, *Deformation and Fracture Mechanics of Engineering Materials,* 3rd edition, Fig. 9.6, p. 329. Copyright © 1989 by John Wiley & Sons, Inc., New York. Reprinted by permission of John Wiley & Sons, Inc.)

- The appearance of the failure surface is indicative of the nature of fracture and may be used in transition temperature determinations. For ductile fracture this surface appears fibrous or dull (or of shear character), as in the steel specimen
- A brittle surfaces have a granular (shiny) texture (or cleavage character)
- Over the ductile-to-brittle transition, features of both types will exist

Fatigue

- Materials subjected to repetitive or fluctuating stress will fail at a stress much lower than that required to cause failure under steady loads. This behavior is called fatigue.
- Failure of a component subjected to cyclic loading at a stress considerably lower than the yield stress of a static loading.
- Fatigue is an important form of behavior in all materials including metals, polymers and ceramics. Fatigue is important, because it is the single largest cause of failure in metals (almost 80 to 90% of all metallic failure is due to fatigue).
- This type of failure is very dangerous, because it occurs without any warning or signs of failure.
- Fatigue failure is brittle like in nature even in normally ductile metals, in that there is very little, if any, gross plastic deformation associated with failure. The process occurs by the initiation and propagation of cracks, and ordinarily the fracture surface is perpendicular to the direction of an applied tensile stress.

Fatigue occurs in structures that are subjected to dynamic, rapidly fluctuating and cyclic stresses (e.g, rotating shafts, bridges, air craft wings, machine components, automobile parts etc.).



Compressor: Microsoft Video 1

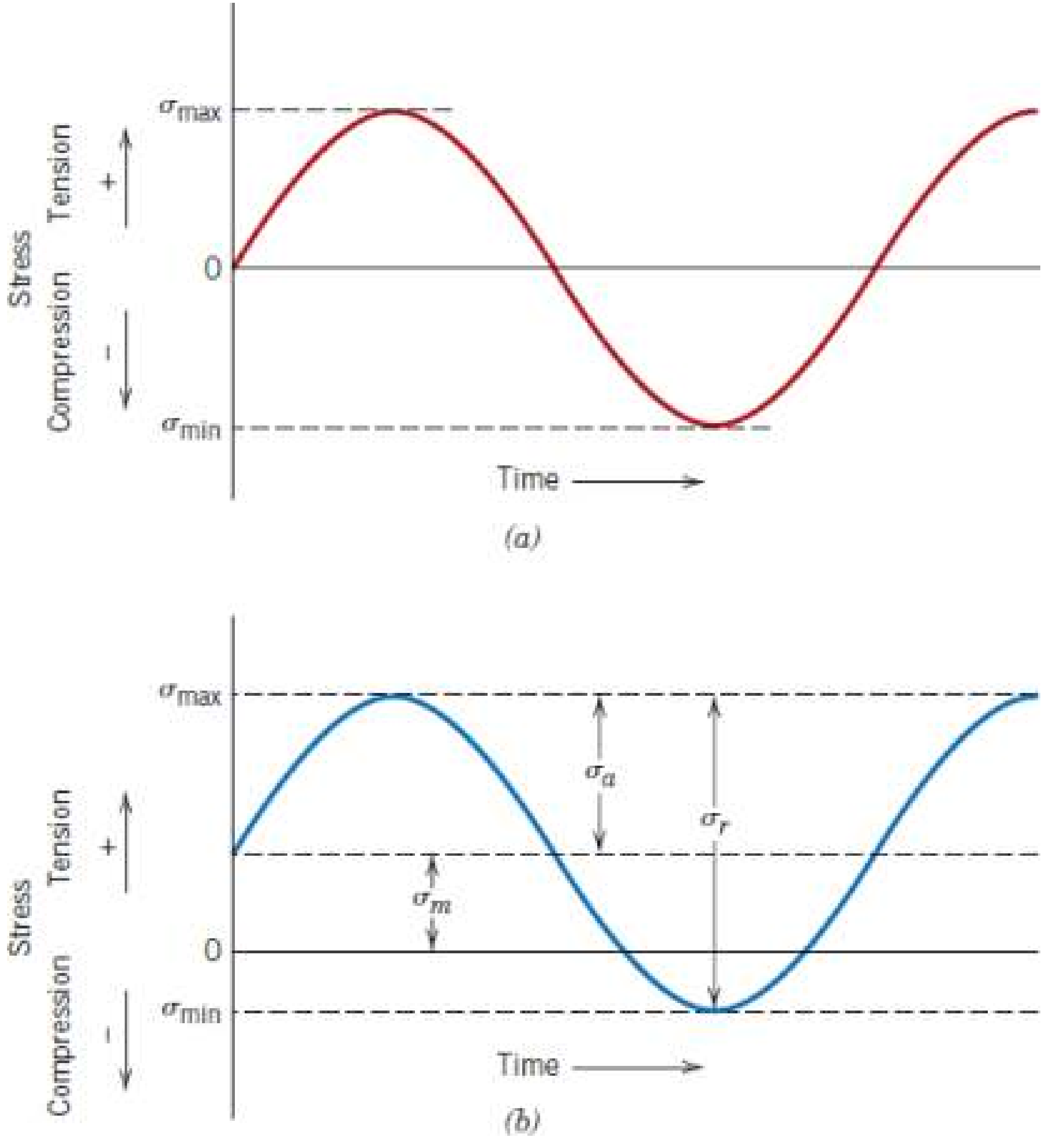
Compression Quality: 100

☑ Key Frame Every 8 frames

Types of Loading

1. Axial loading (Tensile or Compressive)
2. Shear loading (Torsional OR Twisting)
3. Flexural loading (Bending)

Stress cycles



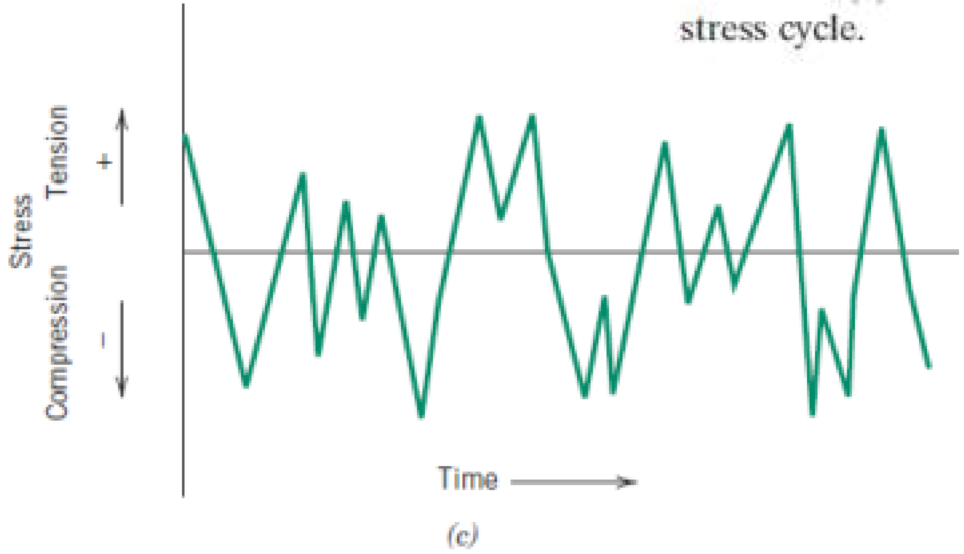


Figure 8.17 Variation of stress with time that accounts for fatigue failures. (*a*) Reversed stress cycle, in which the stress alternates from a maximum tensile stress (+) to a maximum compressive stress (−) of equal magnitude. (*b*) Repeated stress cycle, in which maximum and minimum stresses are asymmetrical relative to the zero-stress level; mean stress σ_m, range of stress σ_r, and stress amplitude σ_a are indicated. (*c*) Random stress cycle.

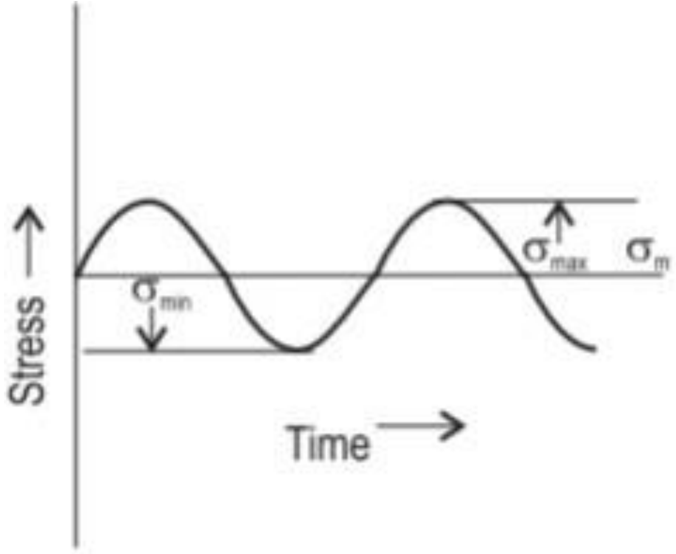
(a)Reversed (sinusoidal) stress cycle,

- In which the stress alternates from a maximum tensile stress to a maximum compressive stress of equal magnitude.
- The amplitude is symmetrical about a mean zero stress level.

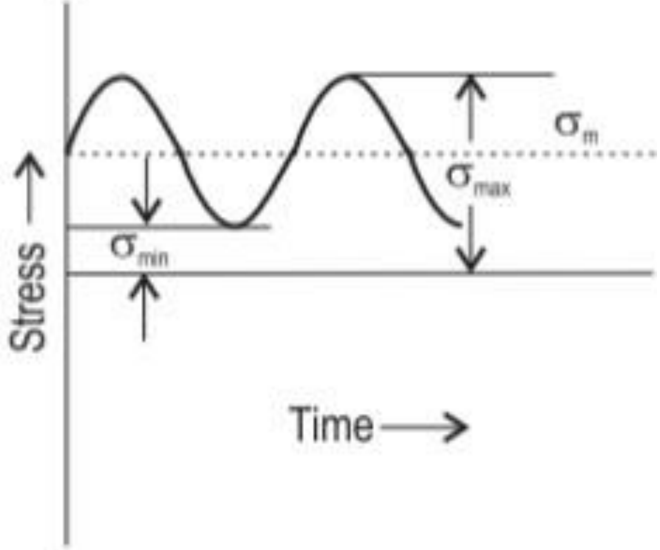
(b) Repeated stress cycle

- In which maximum and minimum stresses are asymmetrical relative to the zero stress level

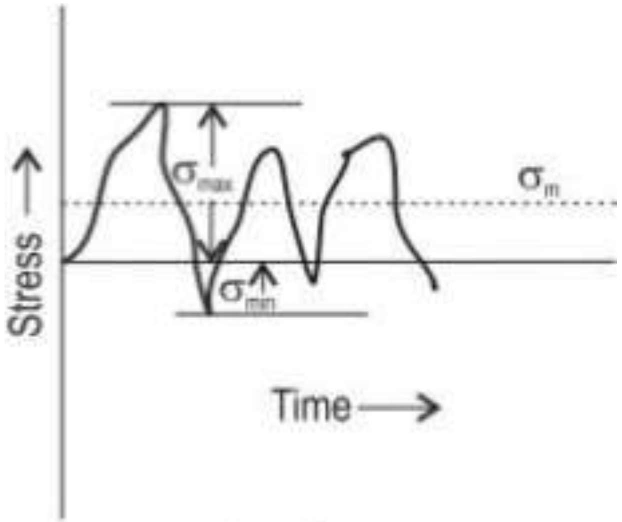
(c) Random stress cycle.



(a) Sinusoidal



(b) Repeated



(c) Random

Mean stress for cyclic loading—dependence on maximum and minimum stress levels

$$\sigma_m = \frac{\sigma_{\max} + \sigma_{\min}}{2} \tag{8.14}$$

Furthermore, the *range of stress* σ_r is just the difference between $\sigma_{\max}$ and $\sigma_{\min}$—namely,

Computation of range of stress for cyclic loading

$$\sigma_r = \sigma_{\max} - \sigma_{\min} \tag{8.15}$$

Stress amplitude σ_a is just one half of this range of stress, or

Computation of stress amplitude for cyclic loading

$$\sigma_a = \frac{\sigma_r}{2} = \frac{\sigma_{\max} - \sigma_{\min}}{2} \tag{8.16}$$

Finally, the *stress ratio* R is just the ratio of minimum and maximum stress amplitudes:

Computation of stress ratio

$$R = \frac{\sigma_{\min}}{\sigma_{\max}} \tag{8.17}$$

By convention, tensile stresses are positive and compressive stresses are negative. For example, for the reversed stress cycle, the value of R is -1.

Fatigue test

- Rotating-bending test apparatus, commonly used for fatigue testing
- The compression and tensile stresses are imposed on the specimen as it is simultaneously bent and rotated.
- Tests are also frequently conducted using an alternating uniaxial tension-compression stress cycle

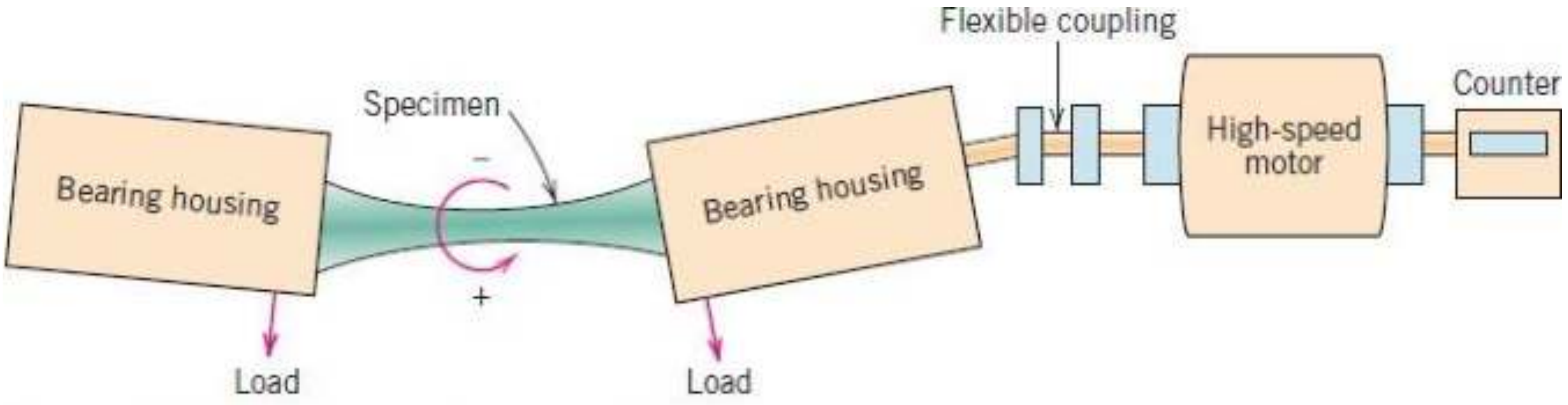
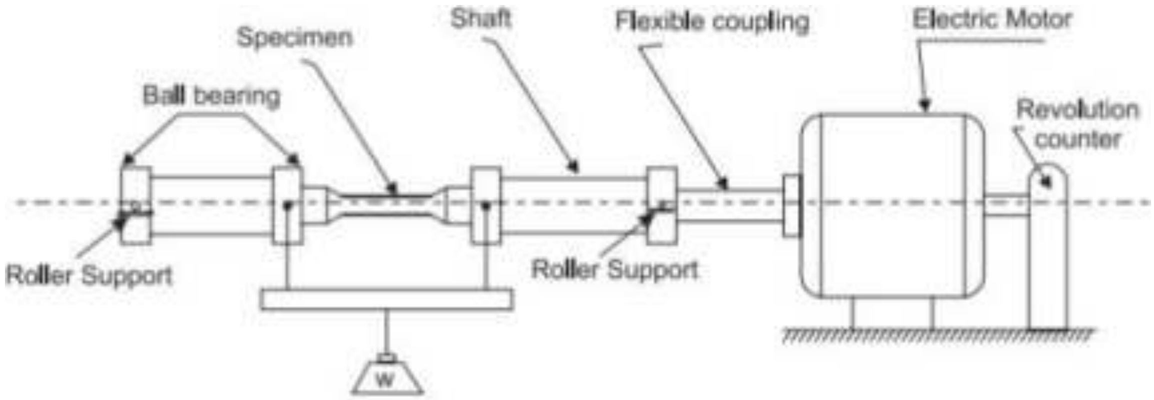


Figure 8.18 Schematic diagram of fatigue-testing apparatus for making rotating-bending tests. (From Keyser, *Materials Science in Engineering*, 4th Edition, © 1986, p. 88. Adapted by permission of Pearson Education, Inc., Upper Saddle River, NJ.)

- The machine consists of an electric motor, bearings and collets to support the specimen and a revolution counter. The test specimen, which forms the extension of a shaft, is placed in the machine.
- A dead weight is attached at the center of the specimen. When the specimen is rotated by a motor, the center of the specimen will be under tension on the lower surface and compression on the upper surface due to the attached weight.
- Hence, the specimen is subjected to alternate tensile and compressive stresses while it is rotating. This sinusoidal variation of stress leads to the condition that the stress is greatest at the surface and zero at the centre.
- The number of cycles for failure to occur depends on the value of applied stress. When the applied stress is high, the number of cycles to failure will be small. As the stress is reduced, failure can be expected after a larger number of cycles. When the applied stress is lowered again, an ultimate value will be reached, below which failure will not take place within the limits of the test. This value of stress is the endurance limit or fatigue limit.

Fatigue test

- The test is carried out by subjecting a specimen to the stress cycling at a maximum stress amplitude σ_{max}, usually on the order of two-thirds of the static tensile strength.
- The number of cycles to failure is counted.
- This procedure is repeated on other specimens at progressively decreasing maximum stress amplitudes.
- The resulting data is presented as a plot of stress (S) versus the logarithm of the number of cycles (N) to failure for each of the specimen.



Fatigue testing machine

S-N curve

- Two distinct types of S–N behavior are observed.
- As these plots indicate, the higher the magnitude of the stress, the smaller the number of cycles the material is capable of sustaining before failure.

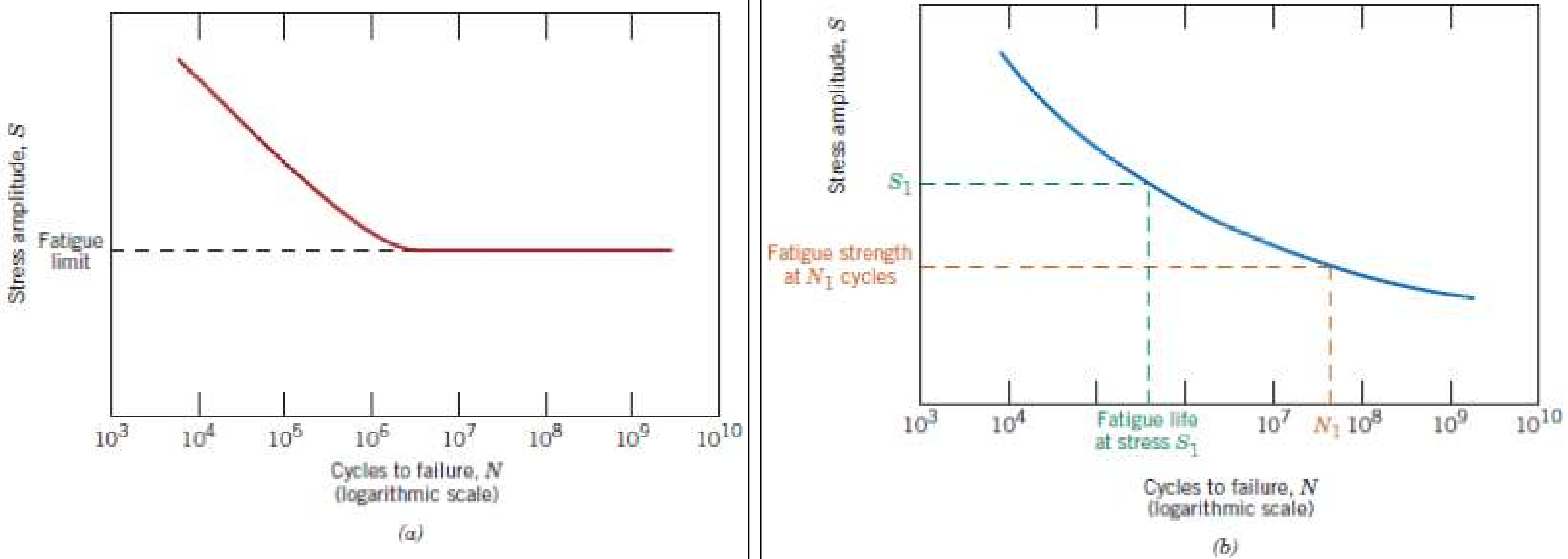
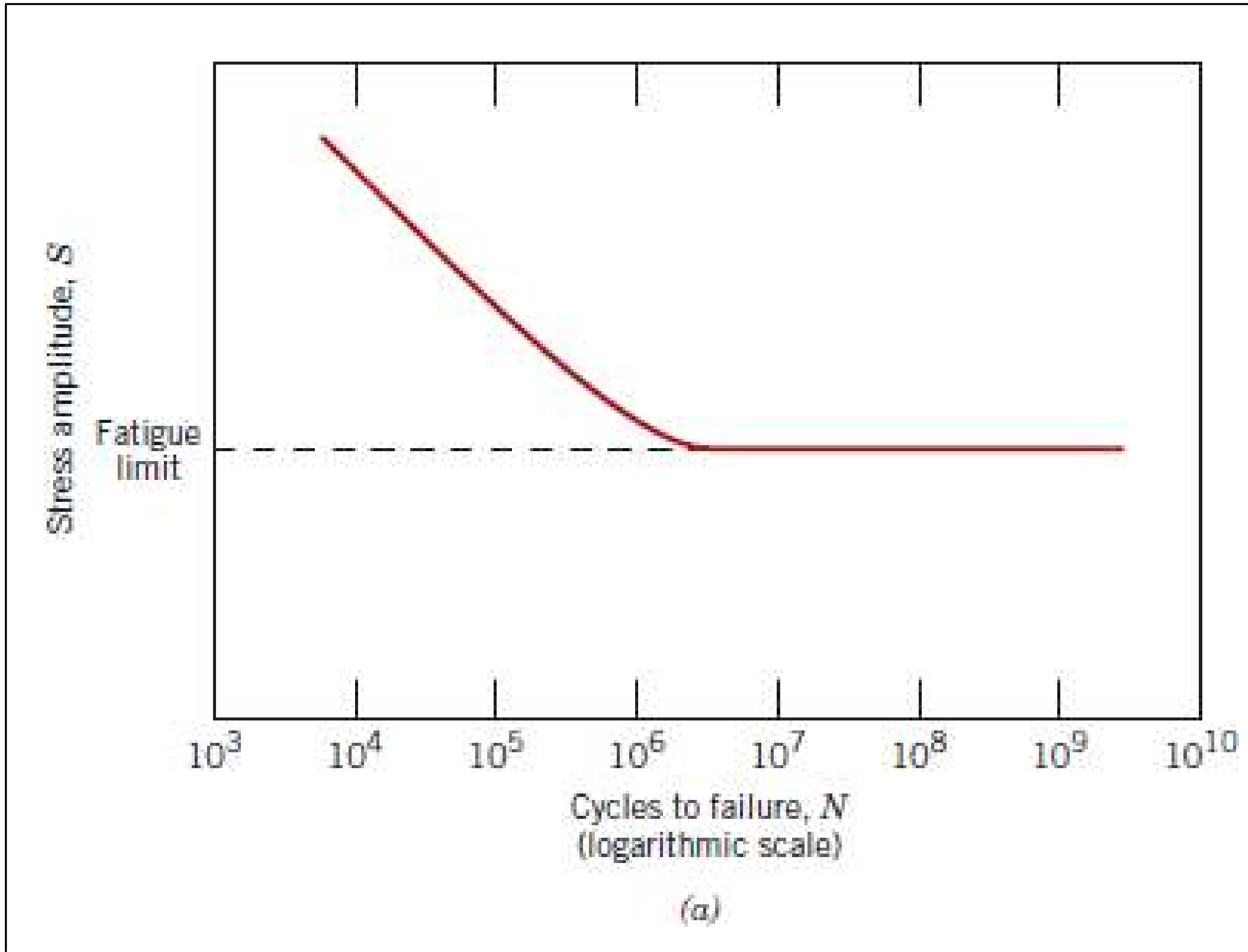


Figure 8.19 Stress amplitude (S) versus logarithm of the number of cycles to fatigue failure (N) for (a) a material that displays a fatigue limit, and (b) a material that does not display a fatigue limit.

S-N curve

- For some ferrous (iron base) and titanium alloys, the S–N curve becomes (figure a) horizontal at higher N values; or there is a limiting stress level, called the fatigue limit (also sometimes the **endurance limit**), below which fatigue failure will not occur.

- This fatigue limit represents the largest value of fluctuating stress that will not cause failure for essentially an infinite number of cycles.
- For many steels, fatigue limits range between 35% and 60% of the tensile strength.



S-N Curve

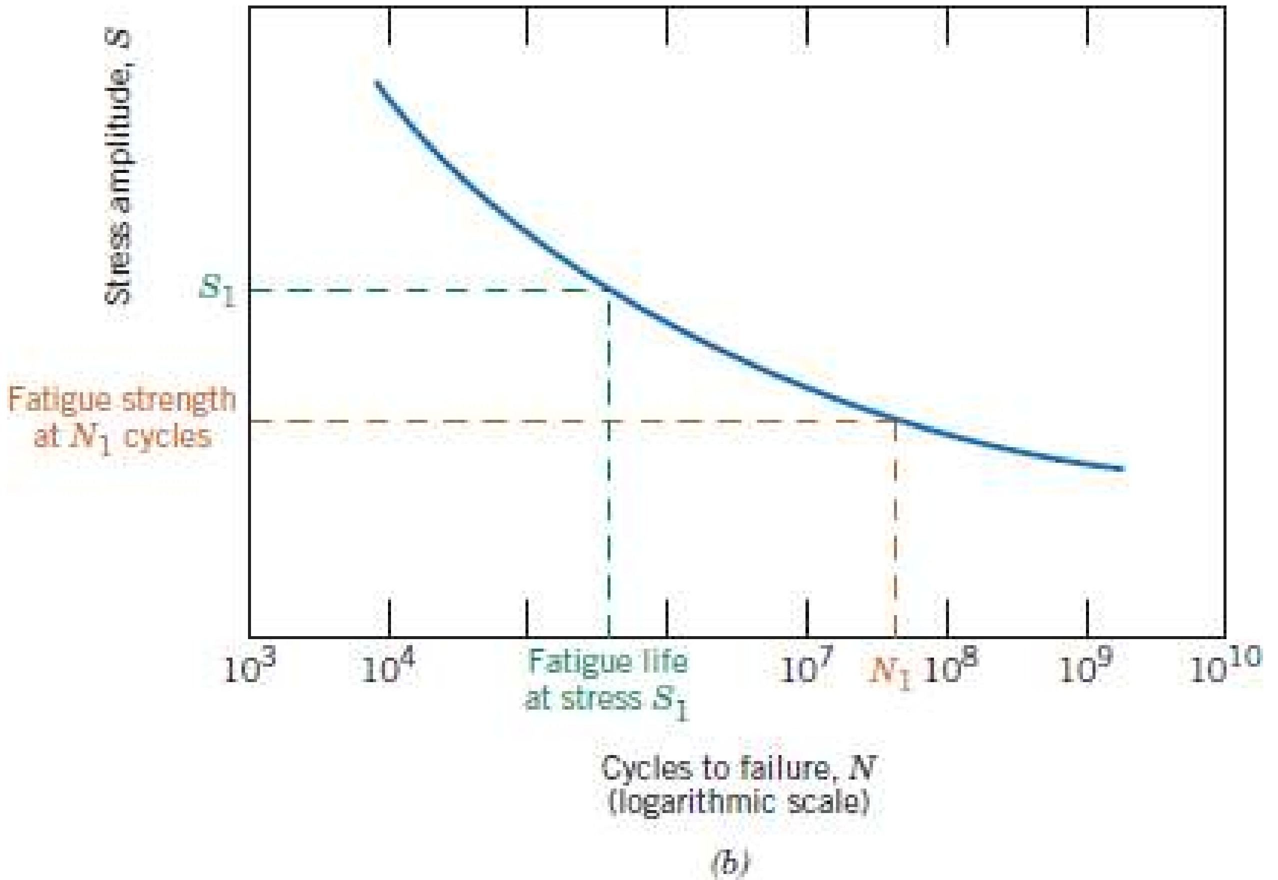
S = stress amplitude = $\sigma_a = (\sigma_{max} - \sigma_{min})/2$
N = No. of cycles to failure

Ferrous Materials
Titanium Alloys

S-N curve

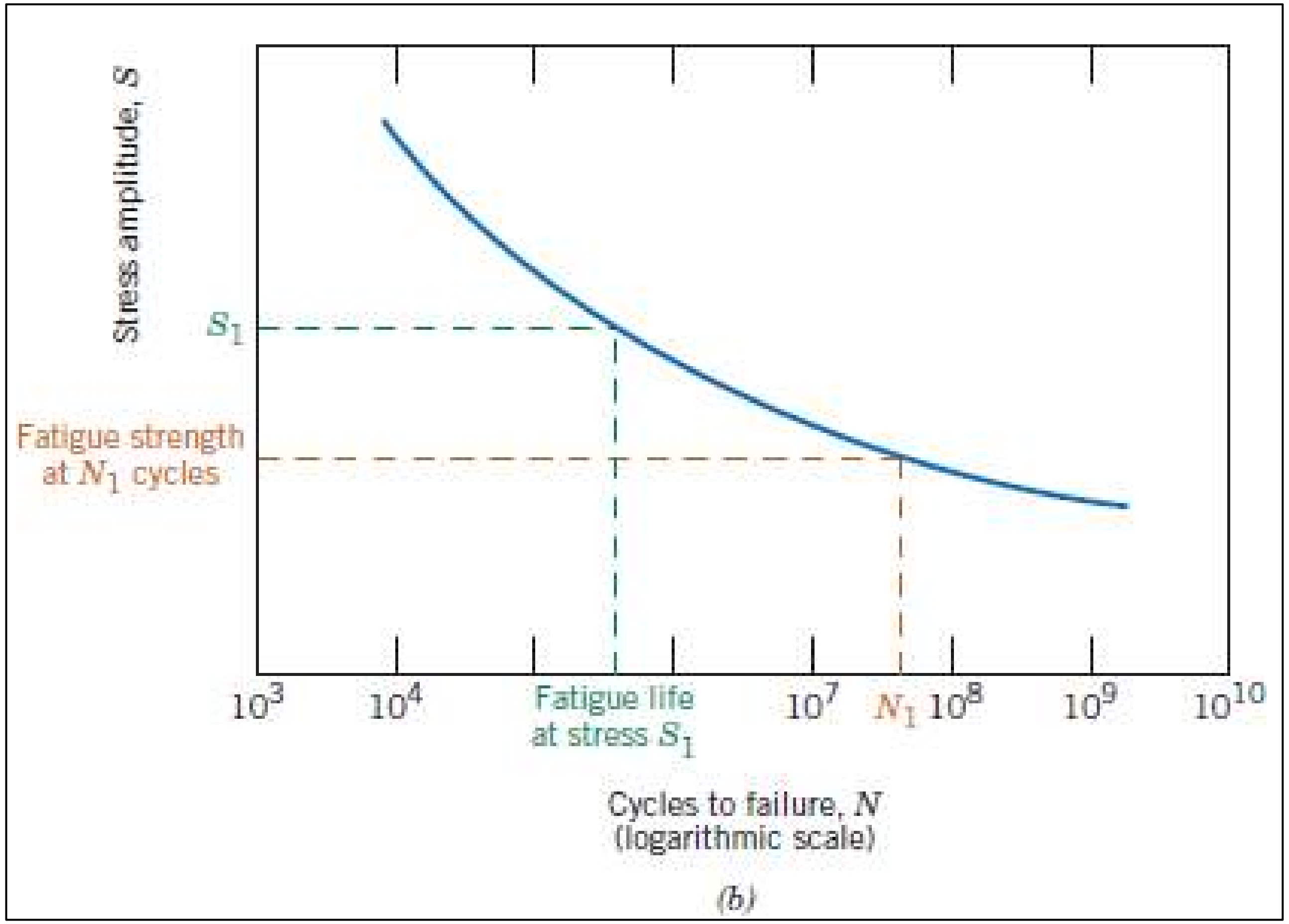
- Most nonferrous alloys (e.g., aluminum, copper, magnesium) do not have a fatigue limit, in that the S–N curve continues its downward trend at increasingly greater N values (Figure b).Thus, fatigue will ultimately occur regardless of the magnitude of the stress.

- For these materials, the fatigue response is specified as fatigue strength, which is defined as the stress level at which failure will occur for some specified number of cycles (e.g., 10^7cycles).



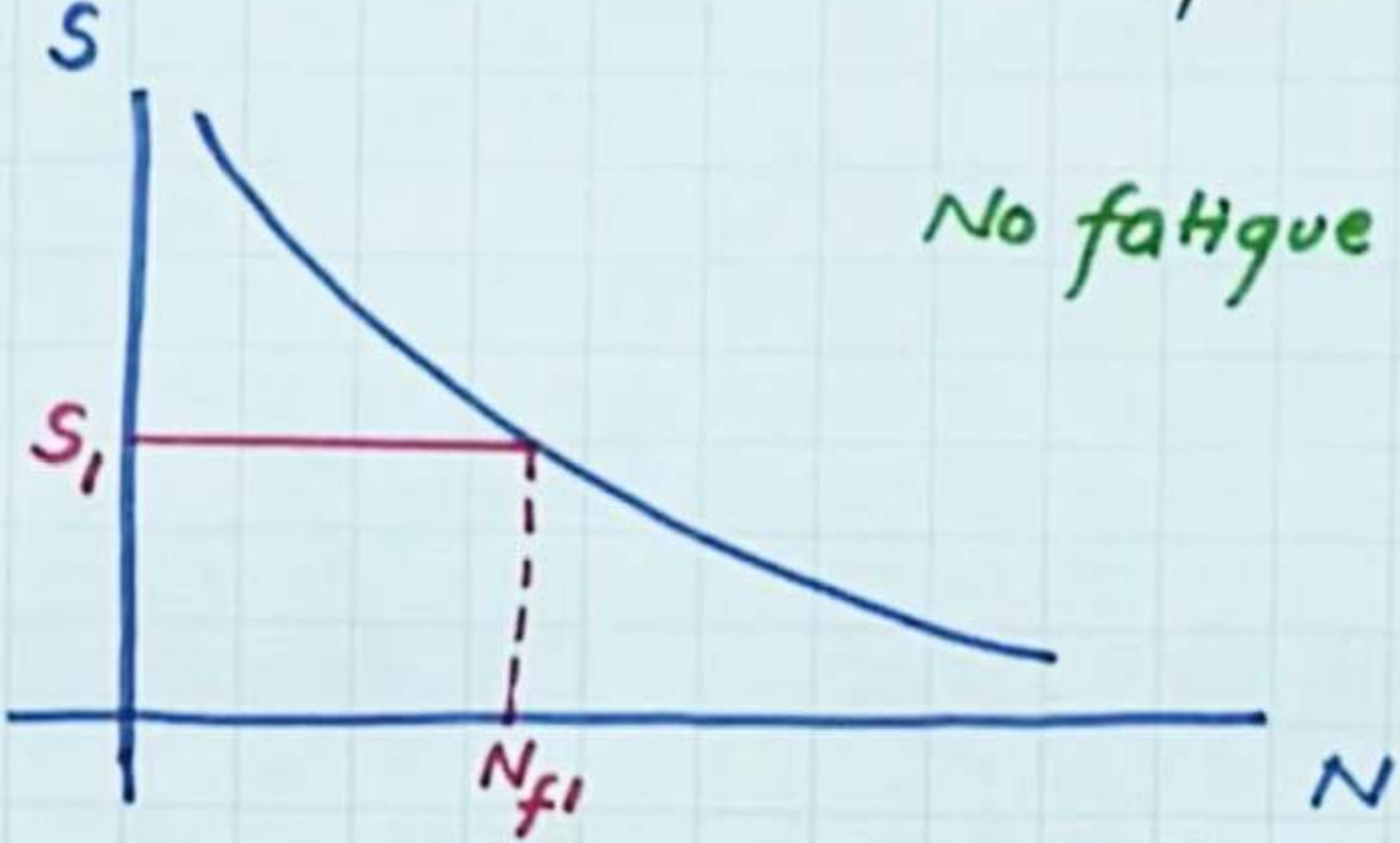
S-N curve

- Another important parameter that characterizes a material’s fatigue behavior is fatigue life (N_f).
- It is the number of cycles to cause failure at a specified stress level, as taken from the S–N plot.



Non ferrous alloy

No fatigue limit.



fatigue life at stress amplitude S_1

Fatigue

Fatigue life (N_f)

It is the number of cycles to cause failure at a specified stress level, as taken from the S–N plot.

Fatigue strength

The stress level at which failure will occur for some specified number of cycles (e.g., 10^7 cycles).

Mechanism of fatigue failure.

- The process of fatigue failure is characterized by three distinct steps:
  (1) Crack initiation, wherein a small crack forms at some point of high stress concentration;
  (2) Crack propagation, during which this crack advances incrementally with each stress cycle
  (3) Final failure, which occurs very rapidly once the advancing crack has reached a critical size.

- Thus the fatigue life of a structure consists of the time required for initiation and growth of a crack to the point of failure.
- Cracks associated with fatigue failure almost always initiate (or nucleate) on the surface of a component at some point of stress concentration.
- Crack nucleation sites include surface scratches, sharp fillets, keyways, threads, dents, and the like.
- In addition, cyclic loading can produce microscopic surface discontinuities resulting from dislocation slip steps that may also act as stress raisers, and therefore as crack initiation sites.

Mechanism of fatigue failure.

- The fracture surface is relatively smooth, and on close examination, concentric curves can be seen. The portion of the surface that experienced rapid crack growth ordinarily has a rougher texture.

- Fracture surface with crack initiation at top edge. The smooth region also near the top corresponds to the area over which the crack propagated slowly.
- Surface shows predominantly dull fibrous texture where rapid failure occurred after crack achieved critical size.

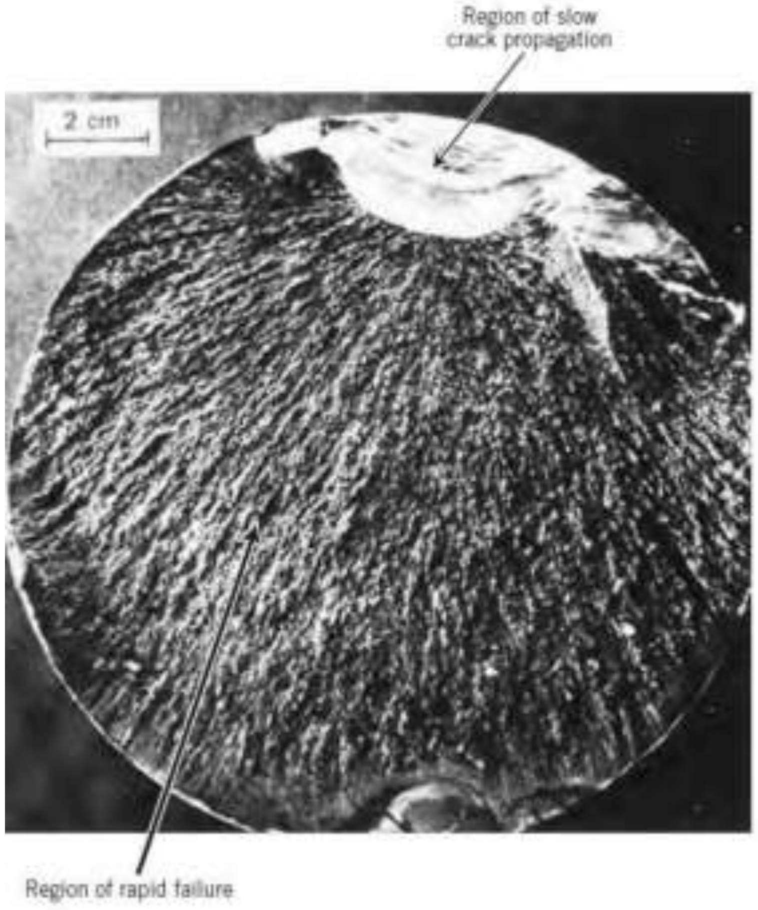


Figure 8.23 Fatigue failure surface. A crack formed at the top edge. The smooth region also near the top corresponds to the area over which the crack propagated slowly. Rapid failure occurred over the area having a dull and fibrous texture (the largest area). Approximately 0.5×. [Reproduced by permission from *Metals Handbook: Fractography and Atlas of Fractographs*, Vol. 9, 8th edition, H. E. Boyer (Editor), American Society for Metals, 1974.]

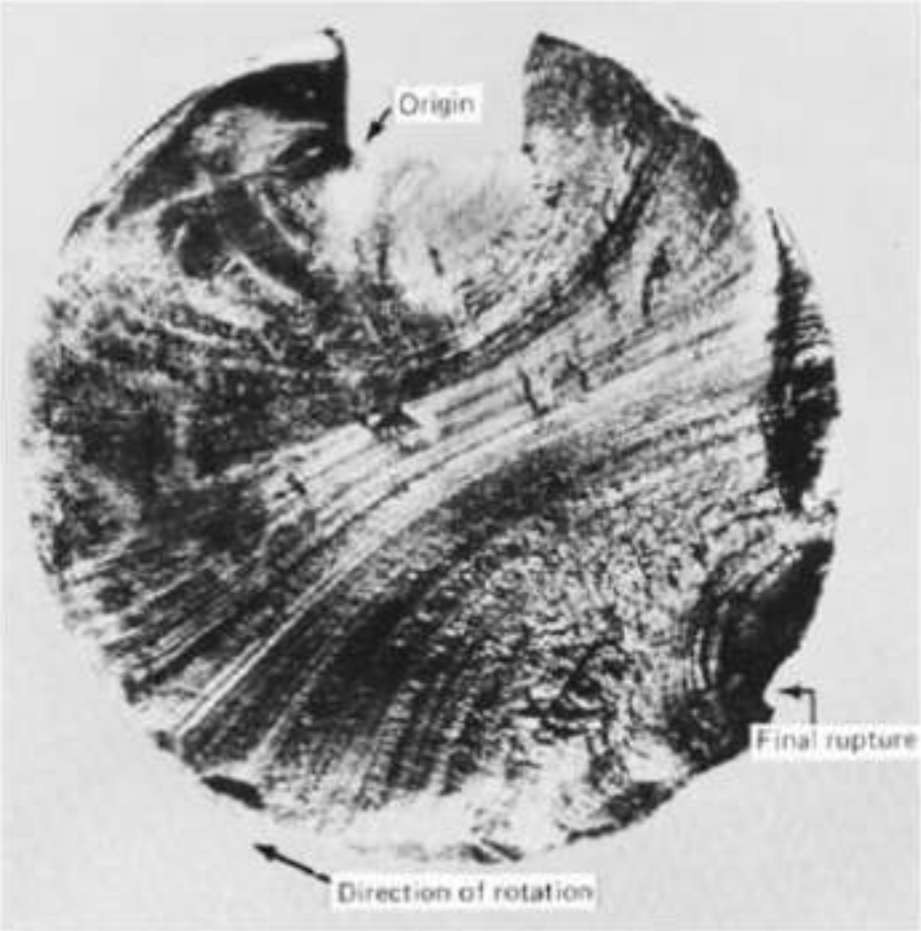


Figure 8.21 Fracture surface of a rotating steel shaft that experienced fatigue failure. Beachmark ridges are visible in the photograph. (Reproduced with permission from D. J. Wulpi, *Understanding How Components Fail,* American Society for Metals, Materials Park, OH, 1985.)

Mechanism of fatigue failure.

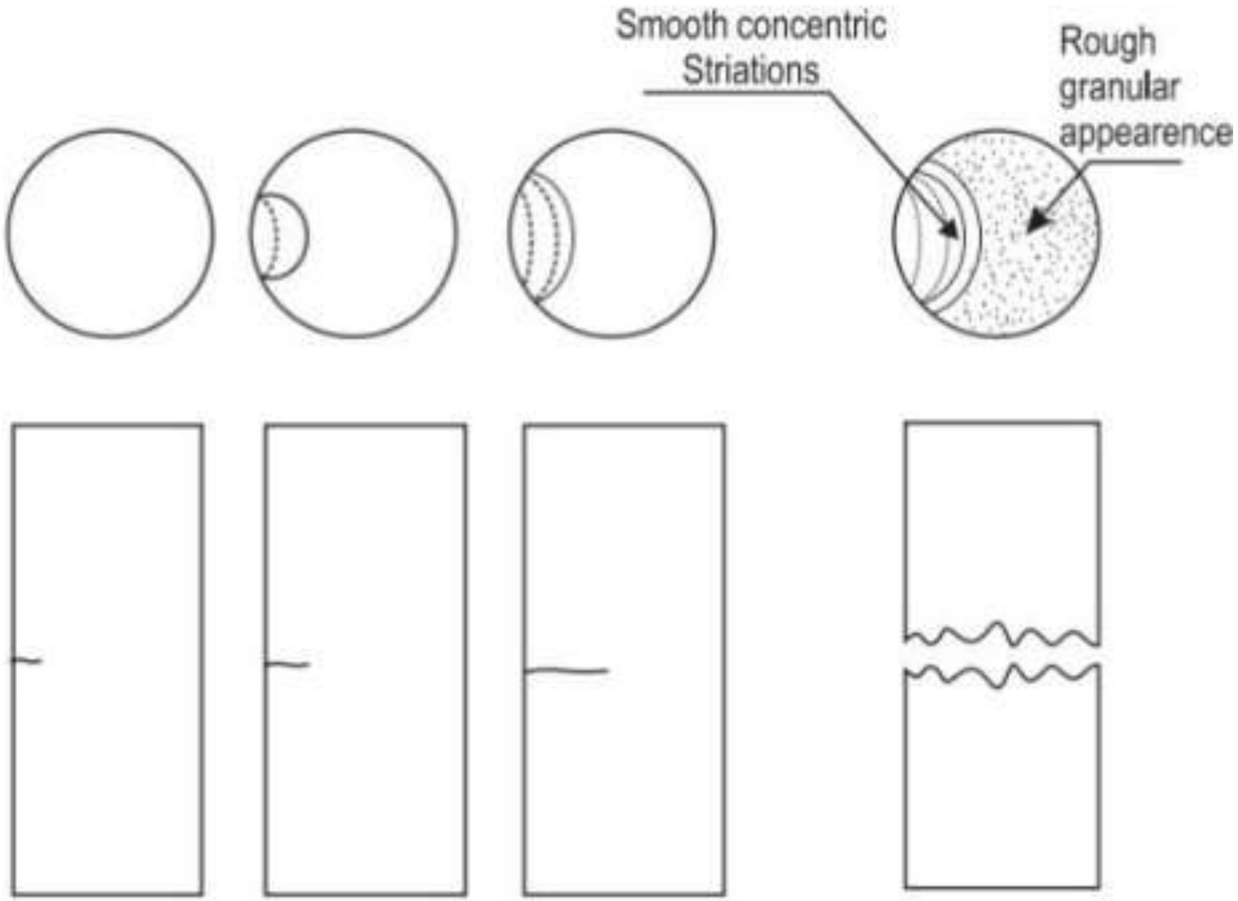
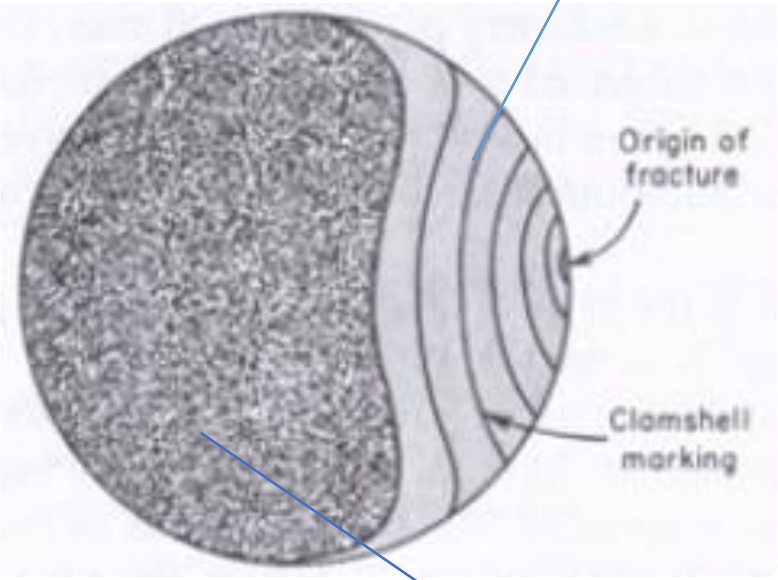
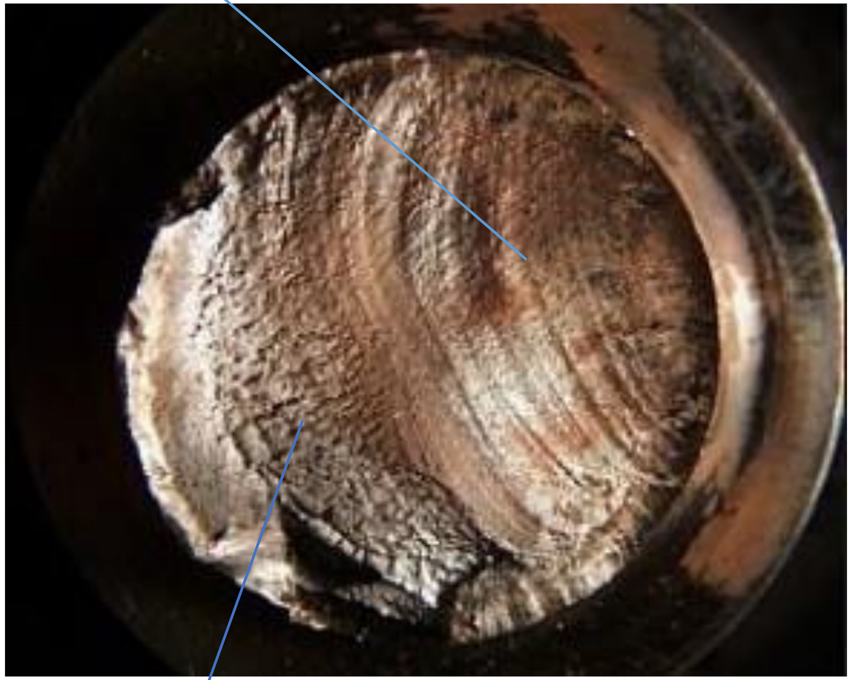


Figure 4.12 *Stages of fatigue failure*

Fatigue failure

Smooth concentric striations





Rough granular appearance

Factors affecting fatigue strength

- Fatigue behavior of engineering materials is highly sensitive to a number of variables. Some of these factors include mean stress level, geometrical design, surface effects, and metallurgical variables, as well as the environment.

- Different factors are,
  - Mean Stress
  - Design Factors(Stress concentration)
  - Size effect(Size of the component)
  - Surface Effects(Surface roughness)
  - Surface Treatments(Change in surface properties)
  - Surface residual stress.
  - Environment in which component is functioning
    - The environment in which the component is functioning has a marked influence on fatigue. It has been observed that the fatigue life in vacuum is about 10 times more than that in a moist atmosphere. Hence a corrosive atmosphere reduces fatigue life. Fatigue resulting out of corrosion is known as corrosion fatigue.

1. Stress concentration

- The design of a component can have a significant influence on its fatigue characteristics. Any notch or geometrical discontinuity can act as a stress raiser and fatigue crack initiation site; these design features include grooves, holes, keyways, threads, and so on.
- The sharper the discontinuity (i.e., the smaller the radius of curvature), the more severe the stress concentration. The probability of fatigue failure may be reduced by avoiding (when possible) these structural irregularities, or by making design modifications whereby sudden contour changes leading to sharp corners are eliminated—for example, calling for rounded fillets with large radii of curvature at the point where there is a change in diameter for a rotating shaft

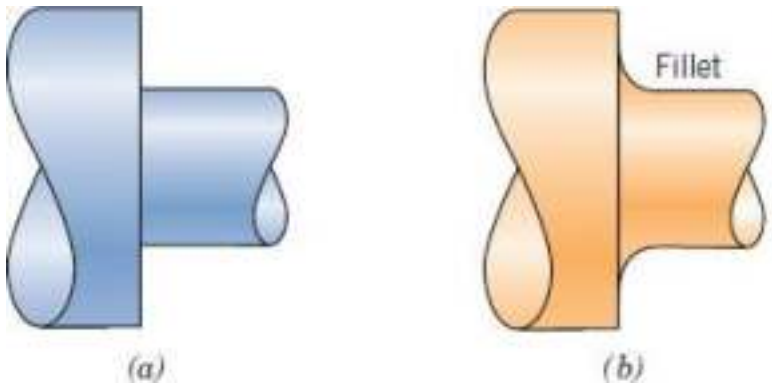


Figure 8.25 Demonstration of how design can reduce stress amplification. (*a*) Poor design: sharp corner. (*b*) Good design: fatigue lifetime improved by incorporating rounded fillet into a rotating shaft at the point where there is a change in diameter.

2. Size effect

- Tests show that larger specimens have lower fatigue strength than smaller ones.
- This is called the size/thickness effect. It is comprised by different sub-effects; the so-called geometric, statistical size effects.
- The **geometric size effect** relates to the stress gradient due to stress concentrations and direct or superimposed bending, which becomes steeper when the joint become thinner. The combined stress field at the crack tip of a given crack size a_i will thus be less intense for a thin joint compared to a thick joint, i.e. for $t_1 < t_2$, we get $\sigma_1 < \sigma_2$, when the nominal surface stress is the same.

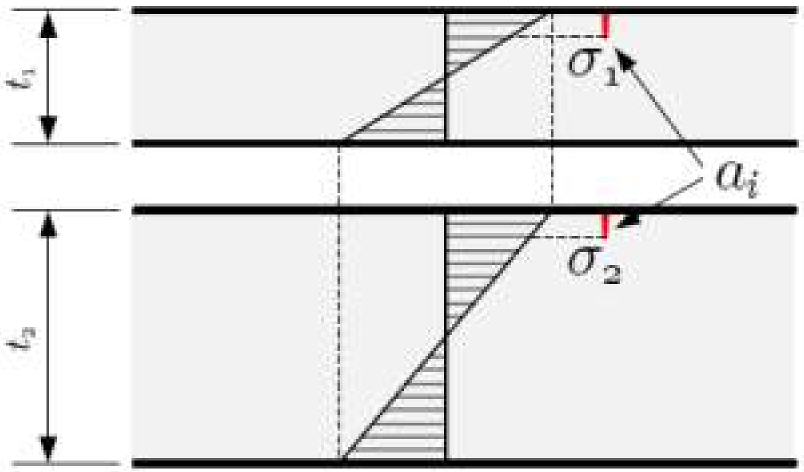


Figure 14: Geometric size effect.

Statistical size effect

- The statistical size effect considers that the probability of a severe defect occurring is higher in a large volume (thick joints) than in a small volume (thin joints).
- On a large specimen from all the material, it will necessarily contain the severe defect and, when tested, it will show low fatigue strength.
- If instead we made 6 small specimens from the same material, only one of them will contain the severe defect. So when testing, one of the resulting data points will show low fatigue strength, while the other 5 will show much higher fatigue strength.

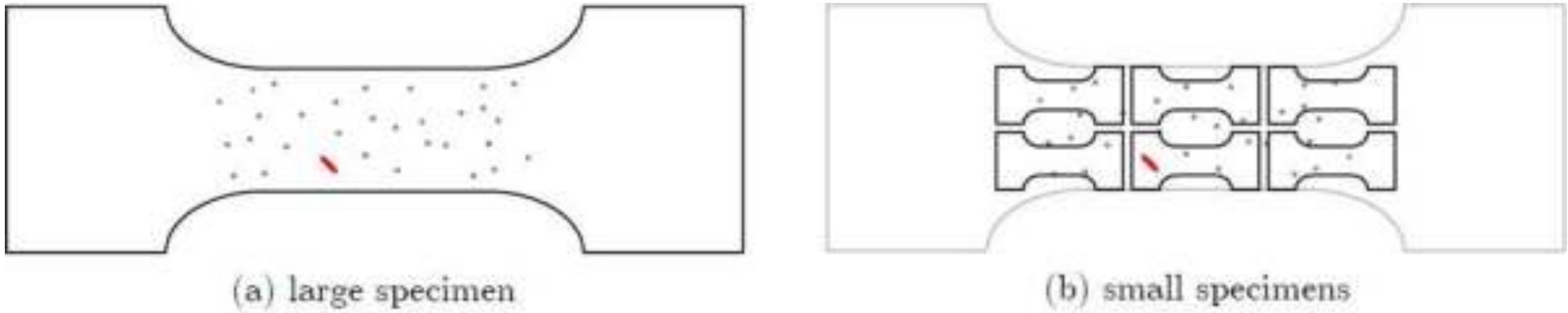

(a) large specimen (b) small specimens

Figure 15: Statistical size effect.

3. Surface roughness

- During machining operations, small scratches, machining marks and grooves are invariably introduced into the workpiece surface by cutting tool action. These surface markings can limit the fatigue life.
- It has been observed that improving the surface finish by polishing will enhance fatigue life significantly.

4. Change in surface properties(Case hardening)

- By this technique both surface hardness and fatigue life are enhanced for steel alloys. This is accomplished by a carburizing or nitriding process whereby a component is exposed to a carbonaceous or nitrogenous atmosphere at an elevated temperature.
- A carbon- or nitrogen-rich outer surface layer (or "case") is introduced by atomic diffusion from the gaseous phase. The case is normally on the order of 1 mm deep and is harder than the inner core of material.
- The improvement of fatigue properties results from increased hardness within the case, as well as the desired residual compressive stresses the formation of which attends the carburizing or nitriding process.

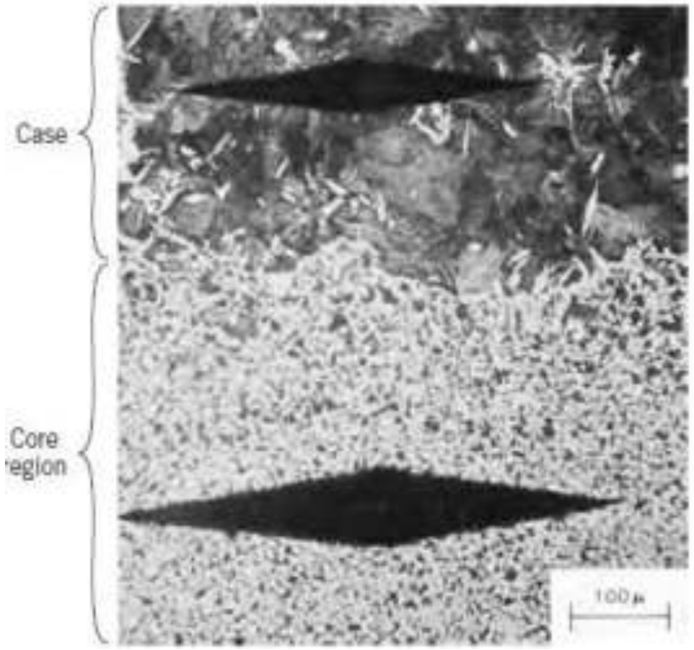
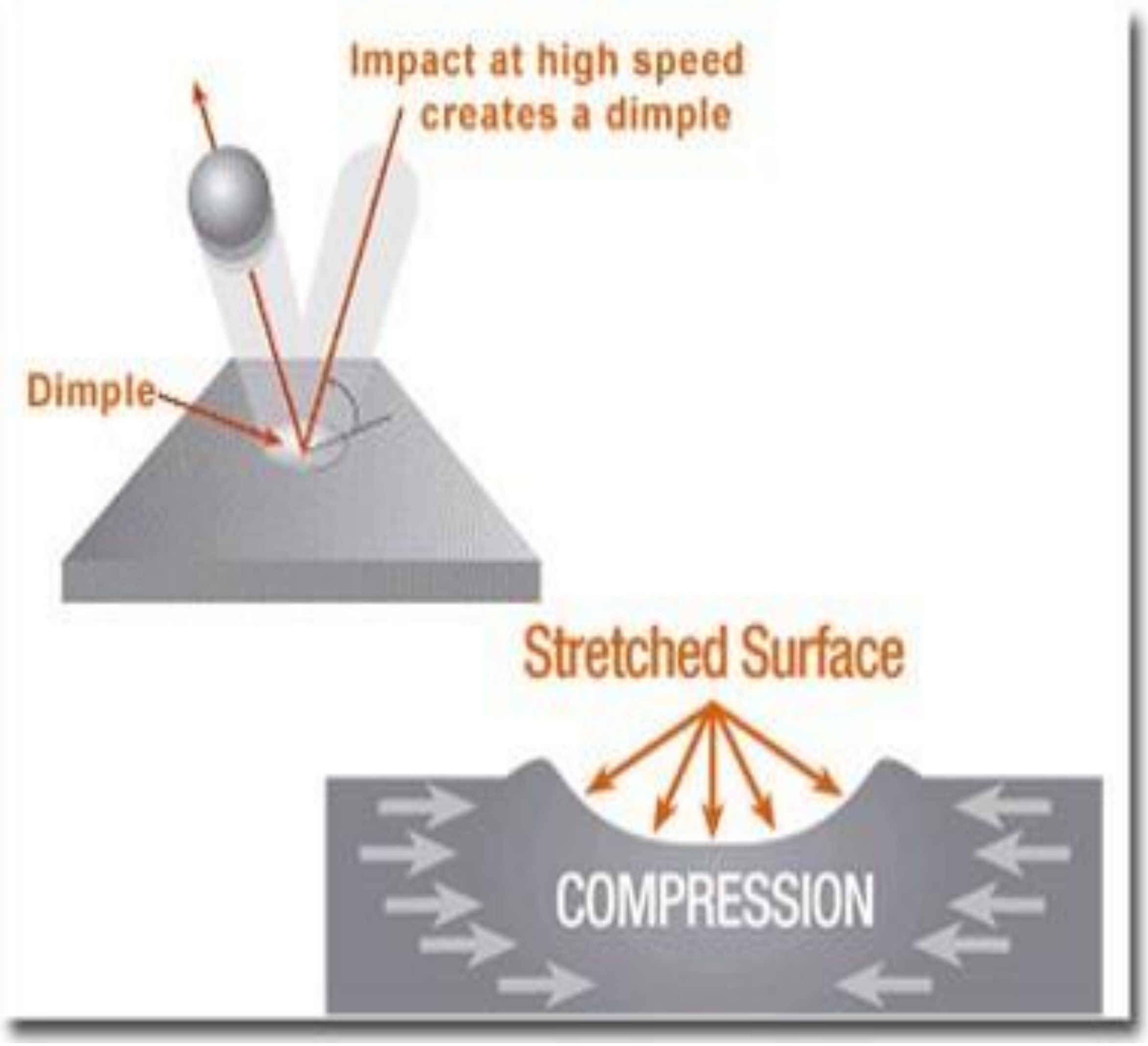


Figure 8.27 Photomicrograph showing both core (bottom) and carburized outer case (top) regions of a case-hardened steel. The case is harder as attested by the smaller microhardness indentation. 100×. (From R. W. Hertzberg, *Deformation and Fracture Mechanics of Engineering Materials*, 3rd edition. Copyright © 1989 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)

5. Surface residual stress

- One of the most effective methods of increasing fatigue performance is by imposing residual compressive stresses within a thin outer surface layer.
- Thus, a surface tensile stress of external origin will be partially nullified and reduced in magnitude by the residual compressive stress. The net effect is that the likelihood of crack formation and therefore of fatigue failure is reduced.
- Residual compressive stresses are commonly introduced into ductile metals mechanically by localized plastic deformation within the outer surface region. Commercially, this is often accomplished by a process termed shot peening.
- Small, hard particles (shot) having diameters within the range of 0.1 to 1.0 mm are projected at high velocities onto the surface to be treated.
- The resulting deformation induces compressive stresses to a depth of between one-quarter and one-half of the shot diameter.

Shot Peening



Ways to improve fatigue life

- By preventing or delaying the initiation of cracks at the surface

Methods

1. Surface treatments

Fatigue failure is observed to be caused by tensile stresses on areas of stress concentration. If compressive stresses are introduced at the surface of a component, the applied tensile stresses get cancelled, thereby considerably increasing the fatigue life of components.

a) Shot peening

b) Surface rolling

2. Carburising followed by hardening and nitriding
   - Carburising and nitriding introduce strong and hard surface layers which also increase the resistance to crack initiation at the surface. This method is particularly useful in alloy steels.

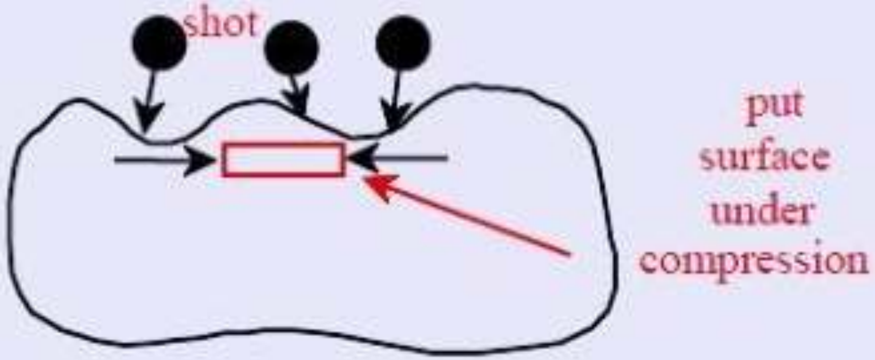
Ways to improve fatigue life

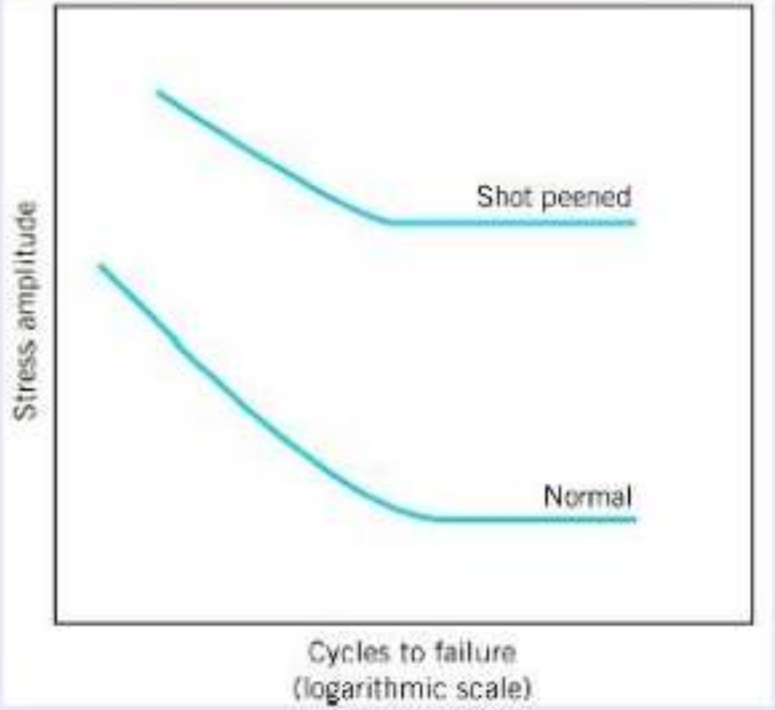
3. Polishing the surface
   - Improving the surface finish is another effective method in enhancing the fatigue life. Rough surfaces invariably have potential sites of stress concentration. Therefore, polishing the surfaces of component to a good surface finish removes surface irregularities which may act as stress raisers.

4. Preventing decarburisation while heat treatment
5. Grain refinement
   - A fine grain structure is found to improve fatigue resistance.
6. Proper design
   - Regions of stress concentration like notches, sharp corners, sudden contour changes etc. should be avoided. Processing methods, which reduce the number of internal/ external defects must also be adopted. Prevention from corrosive, chemical or abrasive atmosphere will also enhance fatigue life.

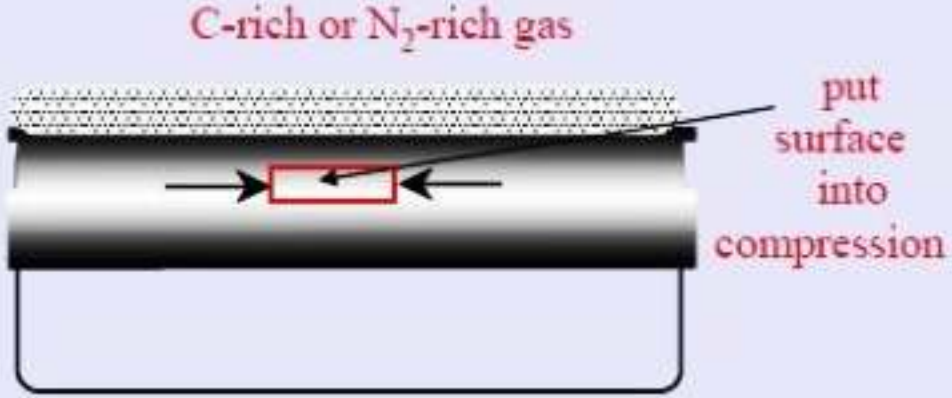
1. Impose a **compressive surface stress**: to suppress surface cracks from growing.

-Approach 1: **shot peening**

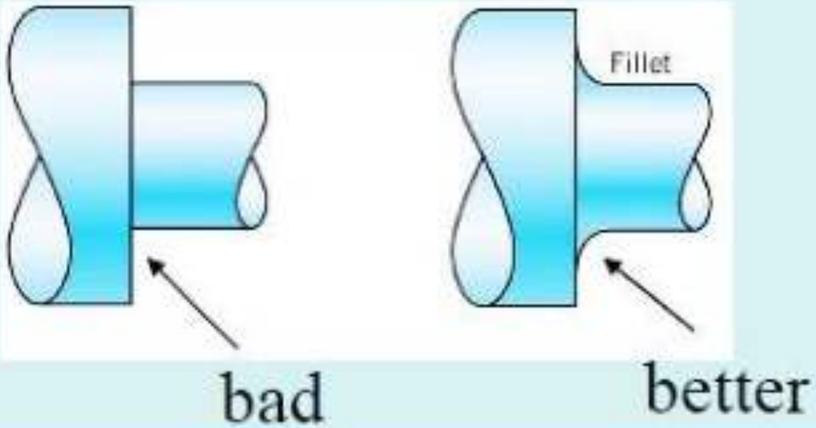




-Approach 2: **carburizing or nitriding**



2. Remove stress concentrators.



Thermal fatigue and its applications in metal cutting.

- Thermal stresses result when the change in dimensions of a member as result of temperature change is prevented by some kind of a constraint. If a bar with fixed supports is heated thermal stresses will develop by a temperature change.
- The value of thermal stress so developed is given by $\sigma = E\alpha\Delta T$, where α – linear thermal co-efficient of expansion, E- elastic modulus and ΔT- change in temperature.
- If the failure occurs by a single application of stress, then it is called thermal shock.
- If failure occurs after repeated application of thermal stress, it is called thermal fatigue.

❖ Thermal Fatigue: Thermal cycling causes expansion and contraction, which will act as tensile and compressive loads.

- *Solutions:*
  - Eliminate restraint by design
  - Use materials with low thermal expansion coefficients

Thermal fatigue and its applications in metal cutting.

- Principle of thermal fatigue is made use of in thermo mechanical machining. This method is used for the removal of burrs and fins by exposing the material to hot corrosive gases for a short period of time.
- Hot gases are formed by detonating an explosive mixture of oxygen, hydrogen and natural gas in a chamber with the material. A thermal shock wave vaporizes the burrs found on gears, die castings, valves and so on.

Thermal fatigue and its applications in metal cutting.

- Another area where thermal fatigue becomes significant is in metal cutting tool life. In machining operations in which there is interrupted cutting, such as milling, heat is generated at each cut. Thus the tool is subjected to a heating and cooling cycle.
- If the thermal conductivity of the tool material is low and the coefficient of thermal expansion is high, tool failure can take place soon. Similar situation may exist in hot forging dies. Careful considerations in selection of tool material is required to avoid tool failure due to thermal fatigue.

Effect of temperature on fatigue life

- As temperature increases, the crack growth rate will also increases.
- So an increase in temperature decreases fatigue strength.

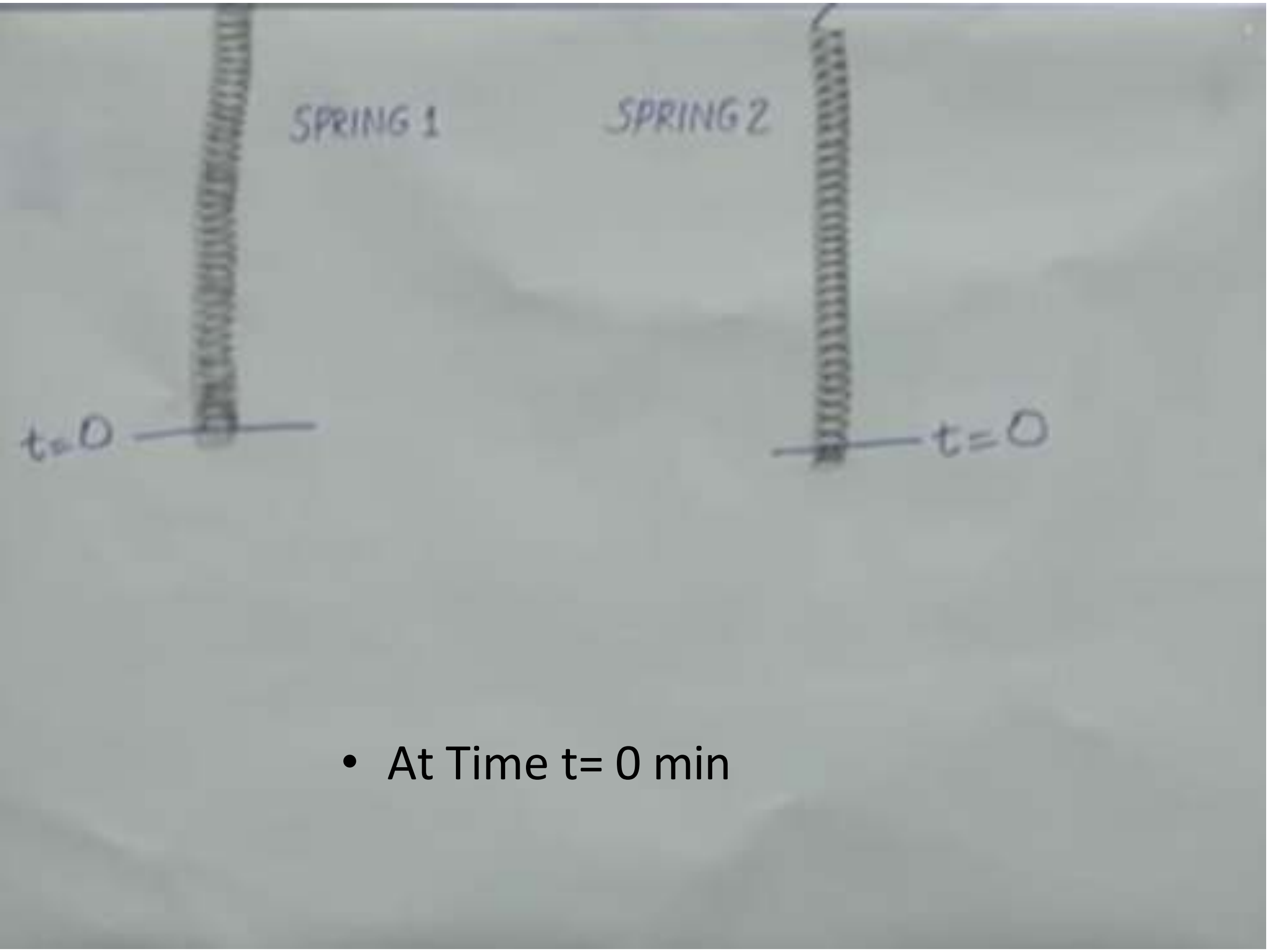
Fracture toughness, applications

- Fracture toughness is the ability of a material to resist fracture or Fracture toughness is a quantitative way of expressing a material's resistance to brittle fracture.
- Fracture Toughness is the ability of material with indigenous cracks to resist fracture by absorbing energy. Also defined as the resistance to cracks propagation.
- If a material has high fracture toughness it will probably undergo ductile fracture and brittle fracture usually happens to materials with less fracture toughness.
- Fracture toughness is one of the most important property of a material for many design applications.
- Fracture toughness values are applied practically in fracture mechanics studies for material selection to avoid catastrophic failure, for example, in nuclear power stations, aeronautics, off-shore applications, ships, bridges, pipelines, and pressure vessels. Also they can be used advantageously in the rehabilitation of old bridges or pressure vessels.

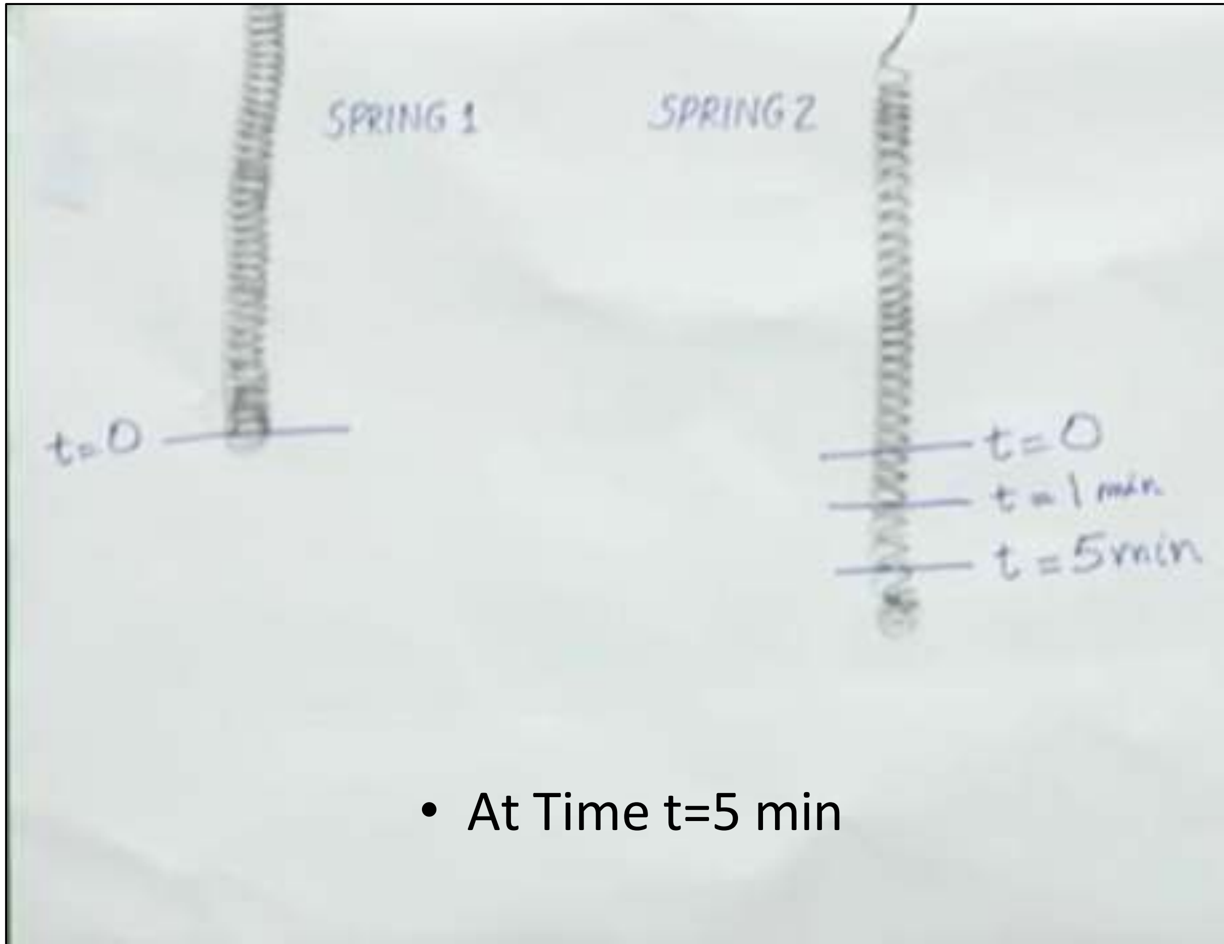
Creep

- Q1. Why do tungsten filament bulbs fuse?
- Q2. How do glaciers move?
- Q3. What limits the life of a jet engine turbine blades?

Creep



- At Time t= 0 min

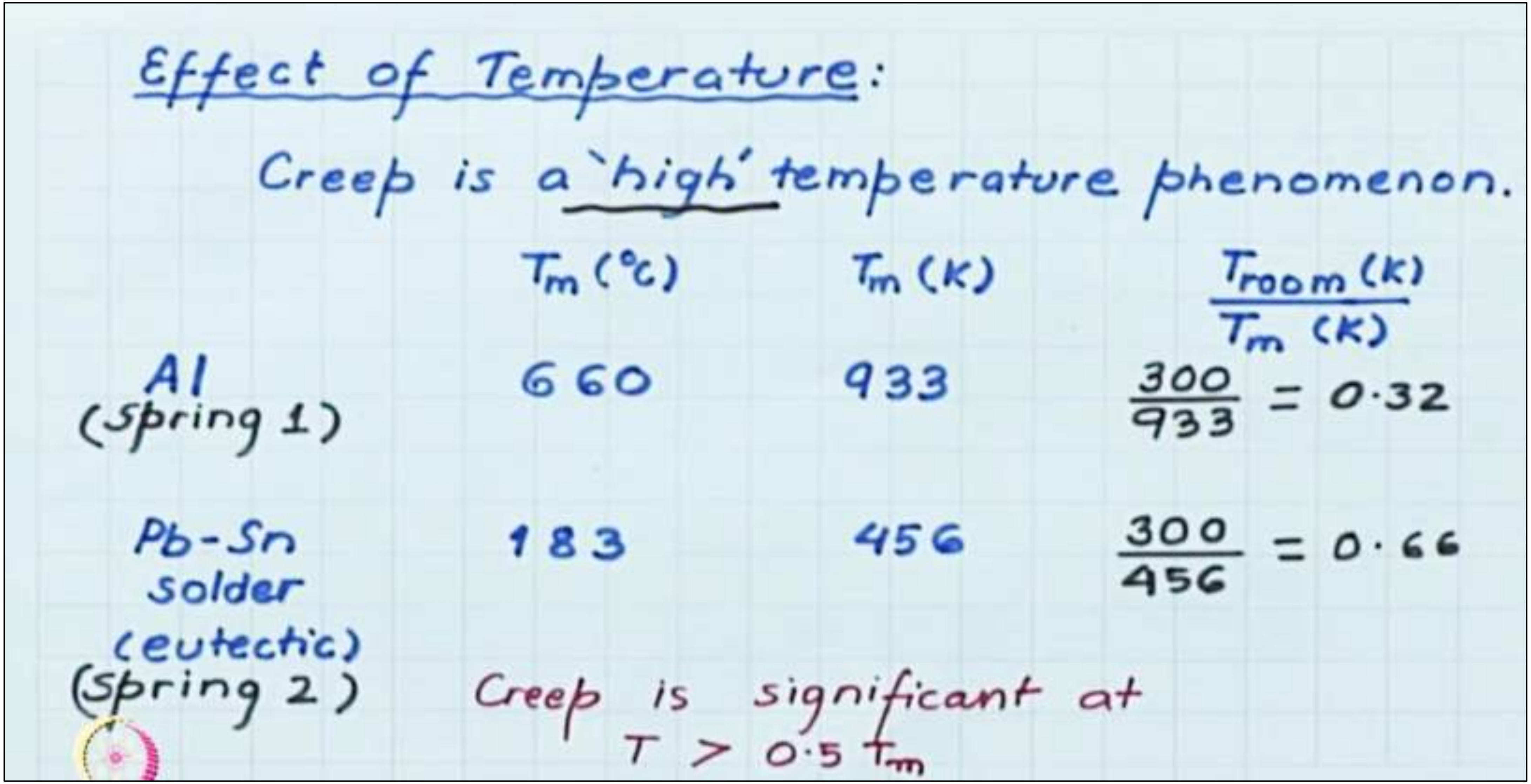


- At Time t=5 min

Creep

- Creep is time dependent continued plastic deformation at constant load or stress at high temperature (> 0.5 Tm).

Effect of Temperature



Effect of Temperature:

Creep is a 'high' temperature phenomenon.

	T_m (°C)	T_m (K)	$\frac{T_{room} (K)}{T_m (K)}$
Al (Spring 1)	660	933	$\frac{300}{933} = 0.32$
Pb-Sn solder (eutectic) (Spring 2)	183	456	$\frac{300}{456} = 0.66$

Creep is significant at $T > 0.5\, T_m$

- Both temperature and the level of the applied stress influence the creep characteristics.
- At a temperature substantially below 0.5 Tm , and after the initial deformation, the strain is virtually independent of time. With either increasing stress or temperature, the following will be noted: (1) the instantaneous strain at the time of stress application increases, (2) the steady-state creep rate is increased, and (3) the rupture lifetime is diminished.

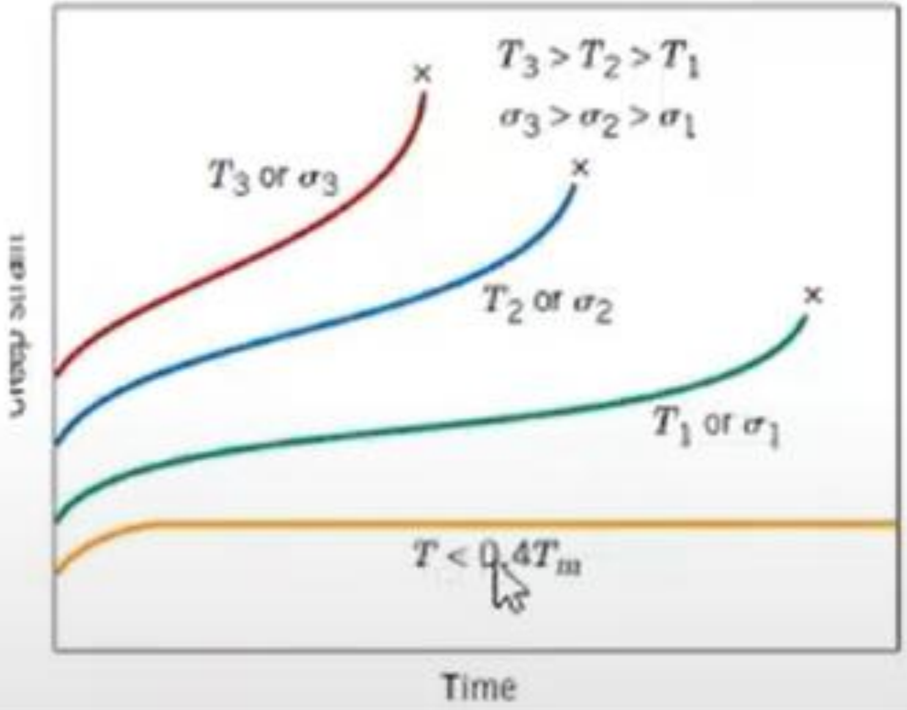
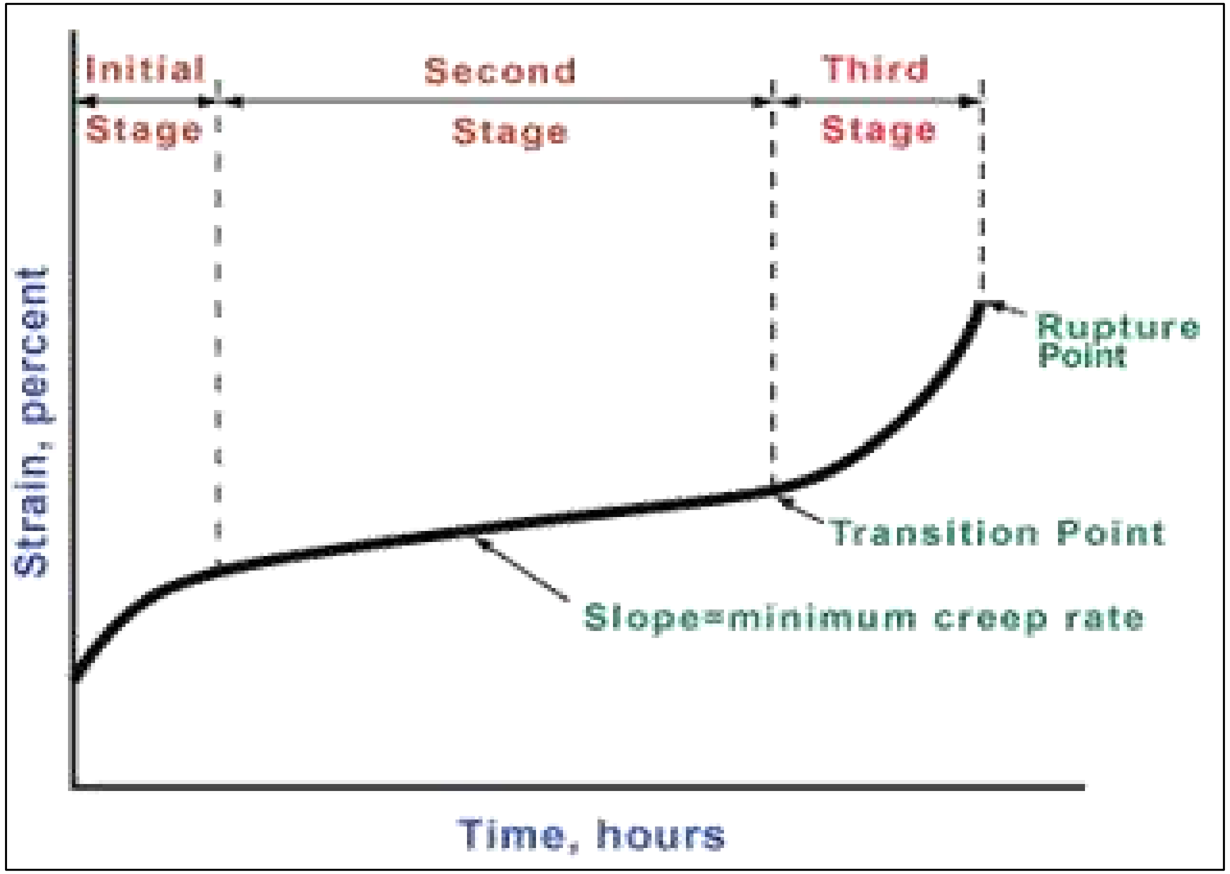
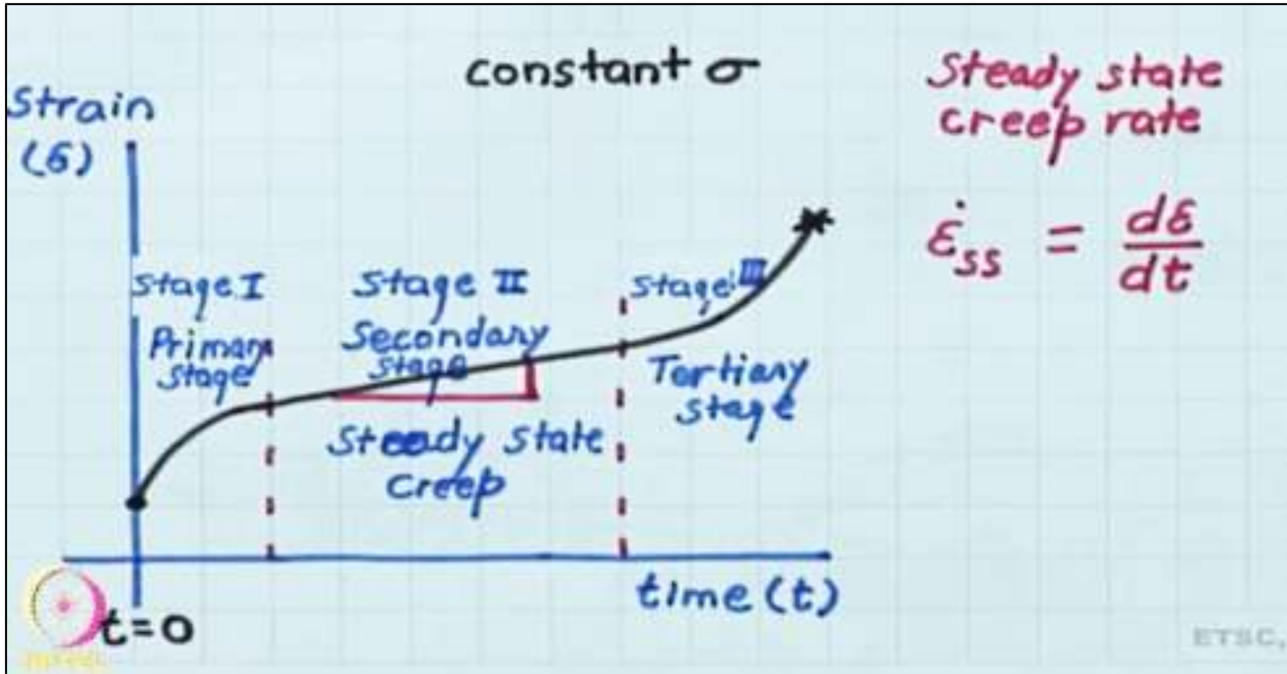


Figure 8.29 Influence of stress σ and temperature T on creep behavior.

Creep curves





Creep curves

- Upon application of the load there is an instantaneous deformation, which is mostly elastic. The resulting creep curve consists of three regions, each of which has its own distinctive strain–time feature.
- Primary or transient creep occurs first, typified by a continuously decreasing creep rate; that is, the slope of the curve diminishes with time. This suggests that the material is experiencing an increase in creep resistance or strain hardening deformation becomes more difficult as the material is strained.
- For secondary creep, sometimes termed steady-state creep, the rate is constant; that is, the plot becomes linear. This is often the stage of creep that is of the longest duration. The constancy of creep rate is explained on the basis of a balance between the competing processes of strain hardening and recovery, recovery being the process whereby a material becomes softer and retains its ability to experience deformation.

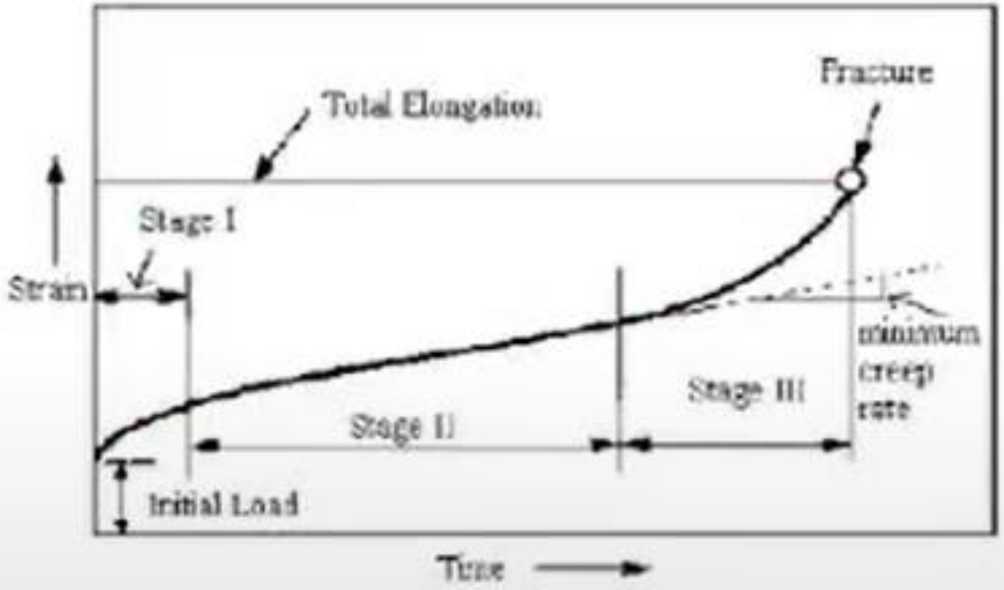
Creep curves

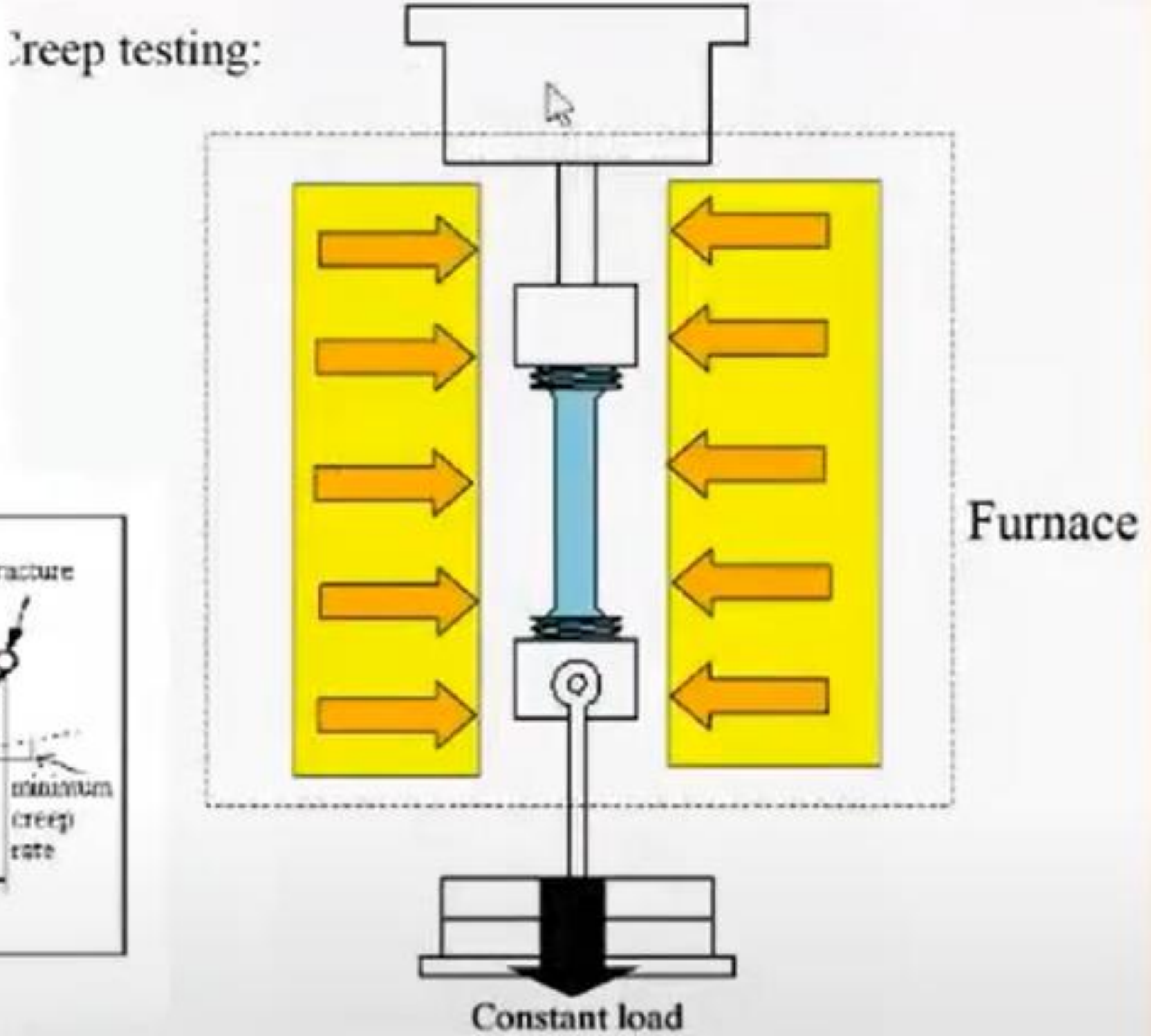
- Finally, for tertiary creep, there is an acceleration of the rate and ultimate failure. This failure is frequently termed rupture and results from microstructural and/or metallurgical changes; for example, grain boundary separation, and the formation of internal cracks, cavities, and voids. Also, for tensile loads, a neck may form at some point within the deformation region. These all lead to a decrease in the effective cross-sectional area and an increase in strain rate.

- *Initial/ first stage - Primary Creep*: starts at a rapid rate and slows with time.
- *Second stage - Secondary Creep*: has a relatively uniform rate.
- *Third stage - Tertiary Creep*: has an accelerated creep rate and terminates when the material breaks or ruptures. It is associated with both necking and formation of grain boundary voids.

Creep tests

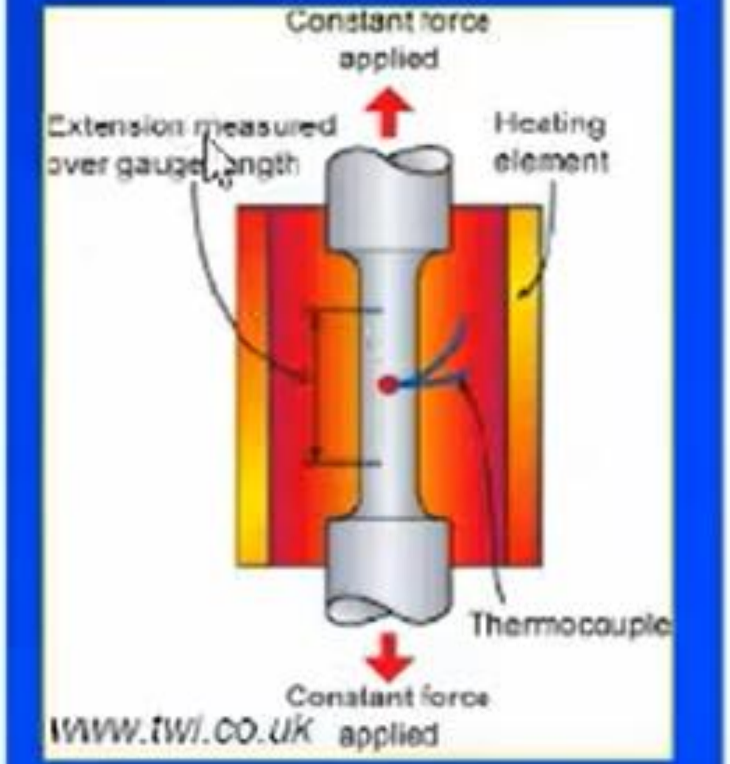
- The creep test is carried out by applying a constant load to a tensile specimen maintained at a constant temperature.





Creep tests

Creep test setting



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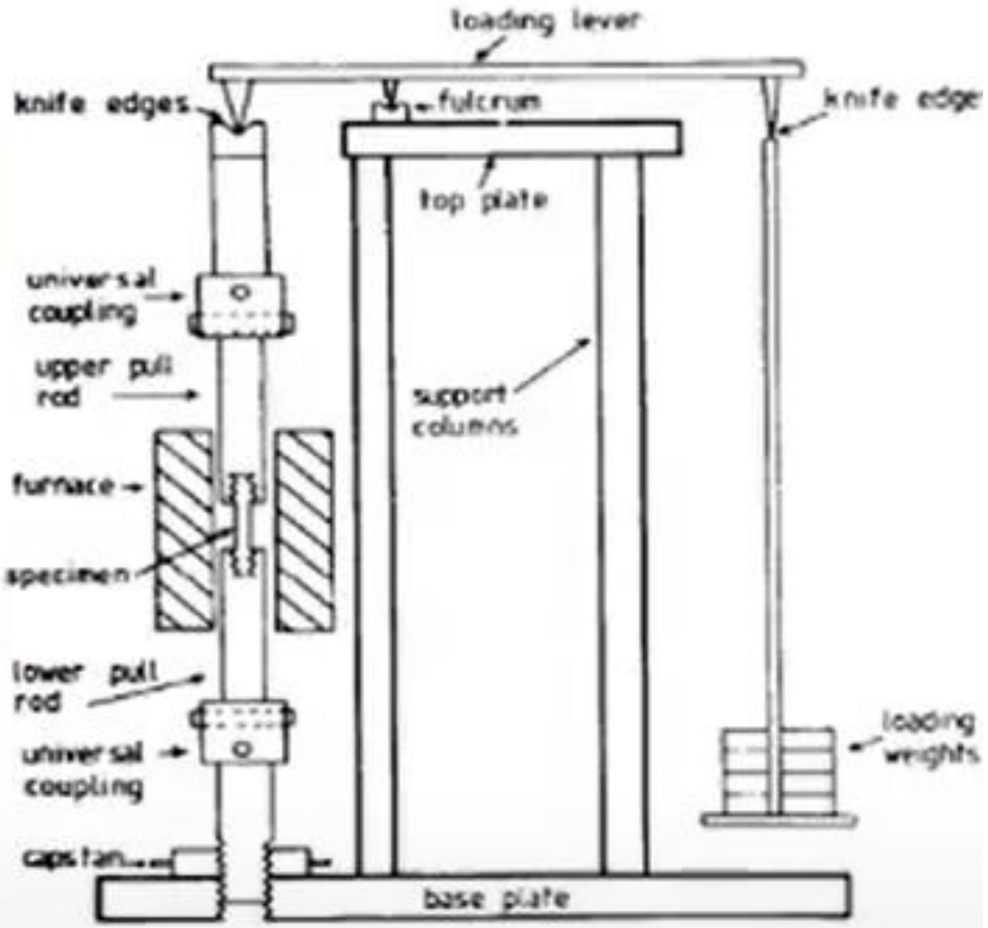
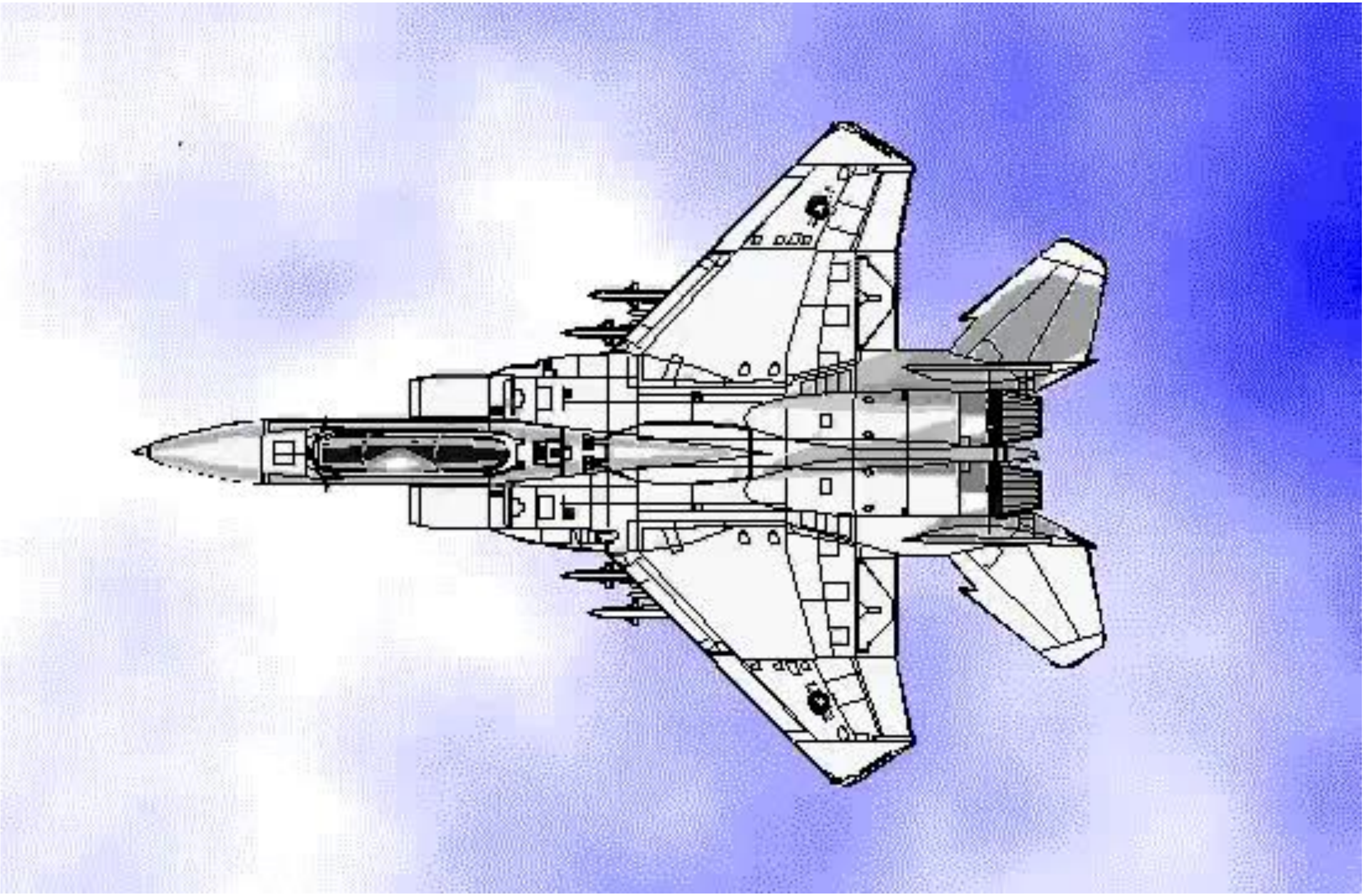
Schematic creep test



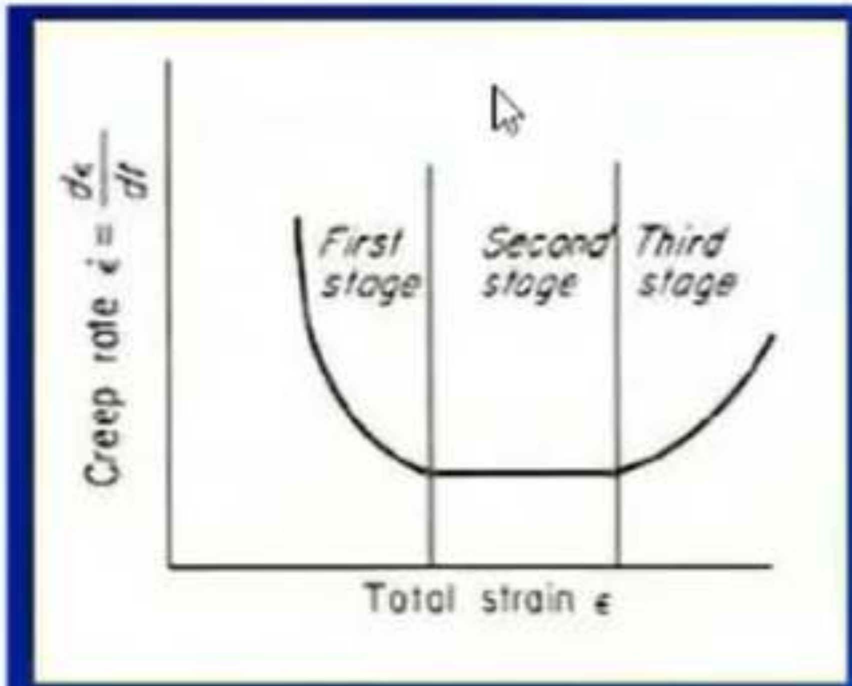


Creep tests

- A typical creep test consists of subjecting a specimen to a constant load or stress while maintaining the temperature constant; deformation or strain is measured and plotted as a function of elapsed time.
- Most tests are the constant load type, which yield information of an engineering nature; constant stress tests are employed to provide a better understanding of the mechanisms of creep.

- Procedure,
  - The unloaded specimen is first heated to the required temperature and the gauge length is measured.
  - A predetermined load is applied quickly without shock.
  - Measurement of the extension are observed at frequent interval.
  - An average of about 50 readings are taken.

Structural change during Creep



Creep rate and total strain relationship

Different creep rates result from ***changes in internal structure*** of the materials with creep rate and time.

There are ***three principal deformation processes*** at elevated temperature.

1) *Deformation by slip*

- More slip systems operate at high temperature
- Slip bands are coarser and widely spaced.

2) *Subgrain formation*

- Creep deformation produces imhomoginiety especially around grain boundaries, allowing dislocations to arrange themselves into a low-angle grain boundary. Easy for metals with high stacking false energy.

3) *Grain boundary sliding*

- Produced by shear process and promoted by increasing temperature/or decreasing strain rate.
- Results in grain boundary folding or grain boundary migration.

Structural change during Creep

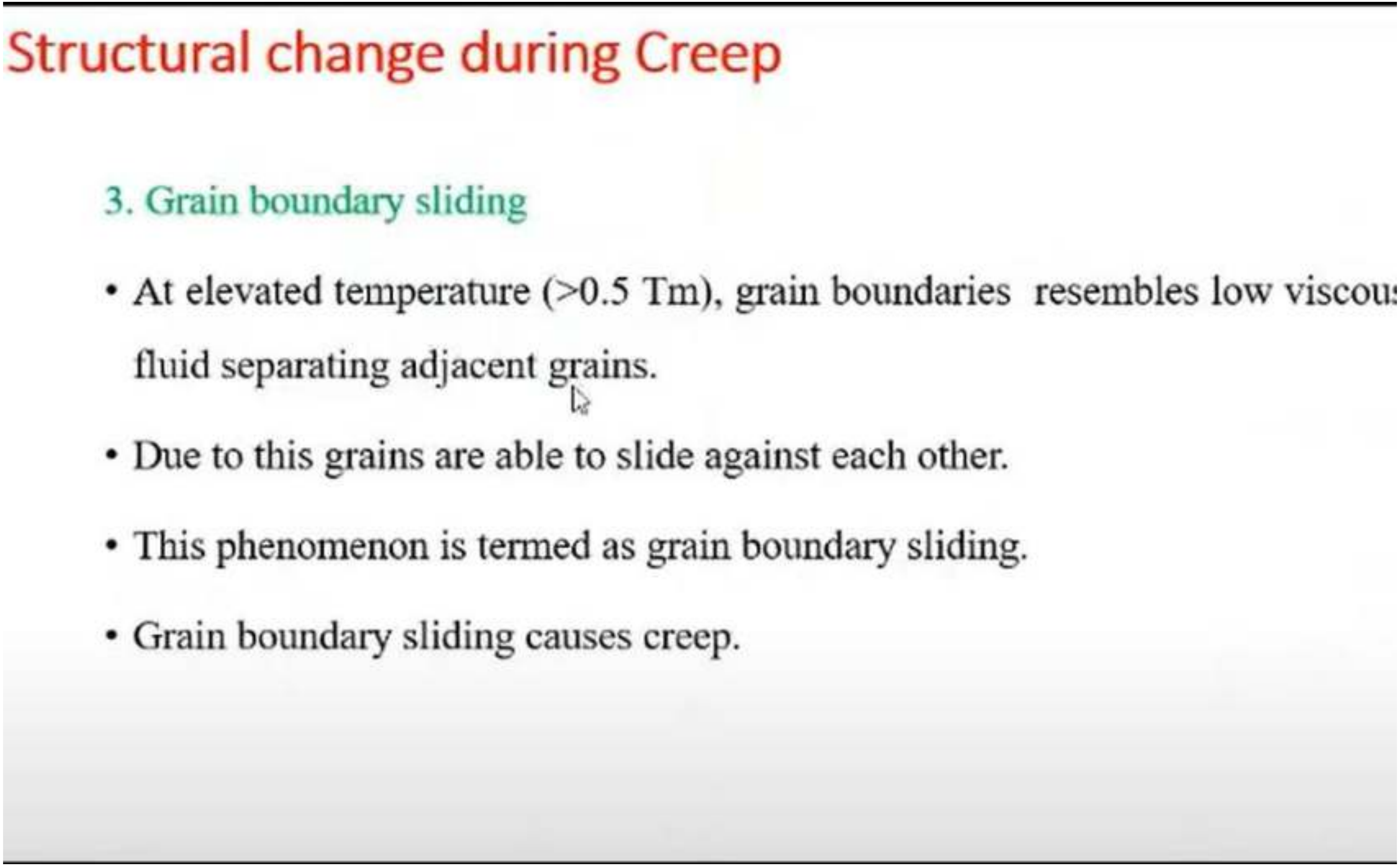
1. Deformation by Slip

- At high temperatures new slip systems become operative.
- The Critical Resolved Shear Stress (CRSS) required for slip of these new planes at elevated temperature is much lower than that at low temperature.
- So slip occurs easily at elevated temperature, which is a major cause of creep.

Structural change during Creep

2. Sub-grain formation

- During high temperature applications dislocation climb can occur readily.
- These dislocations rearrange them selves into low angle boundaries.
- The crystal regions formed by these sub-boundaries are called sub-grains and this process is called sub-grain formation.
- The sub-grains are less capable of preventing dislocation motion, as grain boundaries resembles less viscous fluids at elevated temperature.
- So sub-grain formation at elevated temperature causes creep.

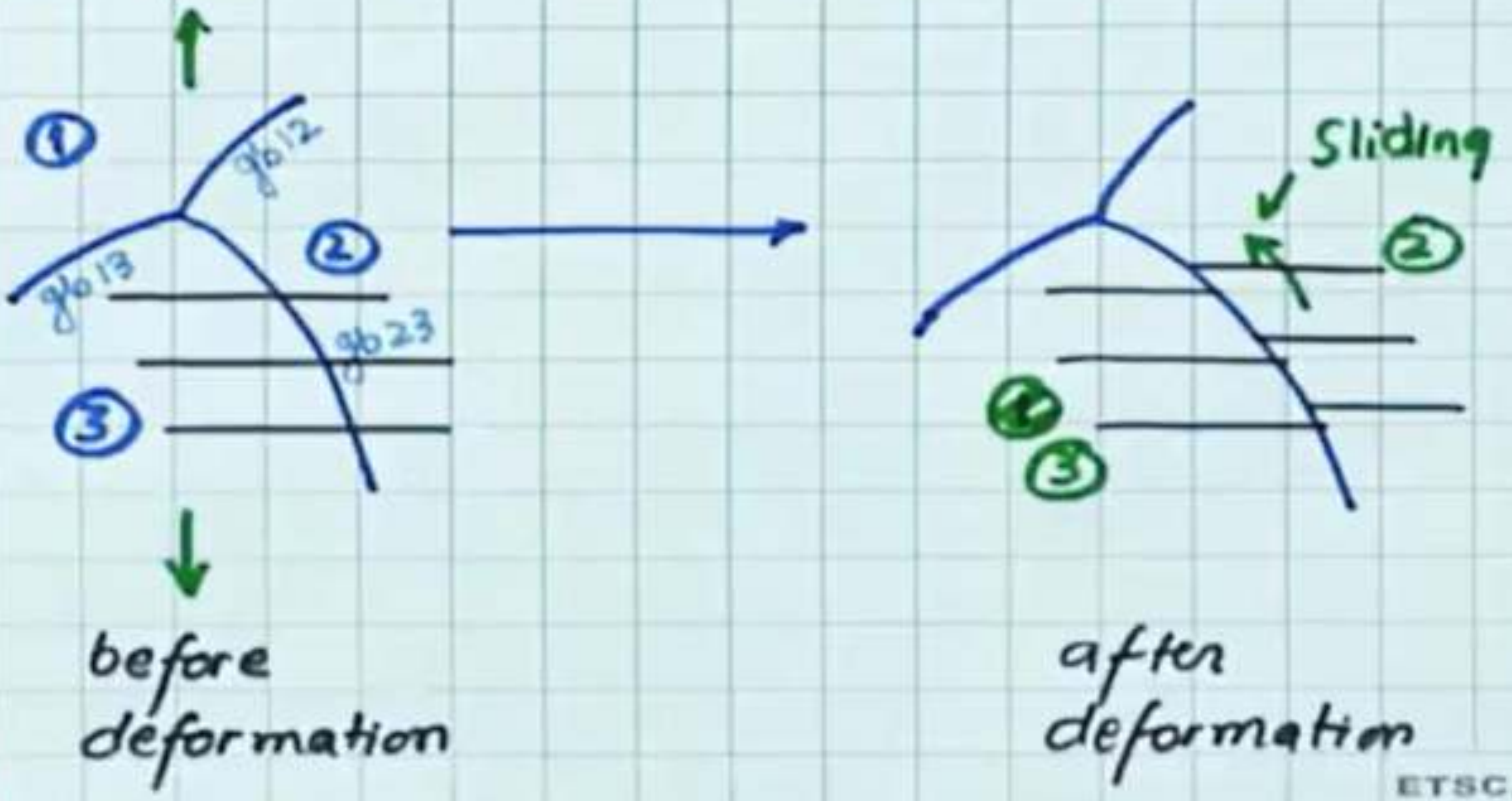


Structural change during Creep

3. Grain boundary sliding

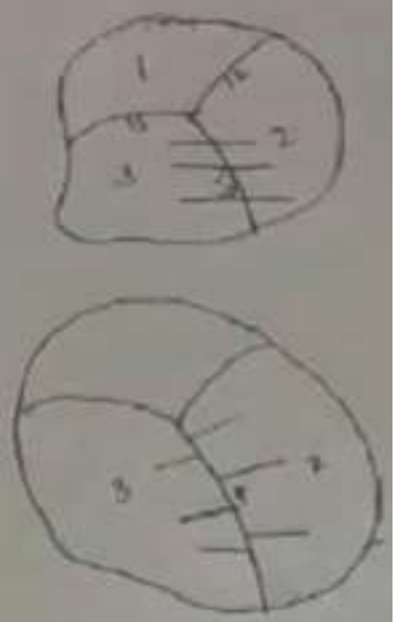
- At elevated temperature (>0.5 Tm), grain boundaries resembles low viscou fluid separating adjacent grains.
- Due to this grains are able to slide against each other.
- This phenomenon is termed as grain boundary sliding.
- Grain boundary sliding causes creep.

GRAIN BOUNDARY SLIDING

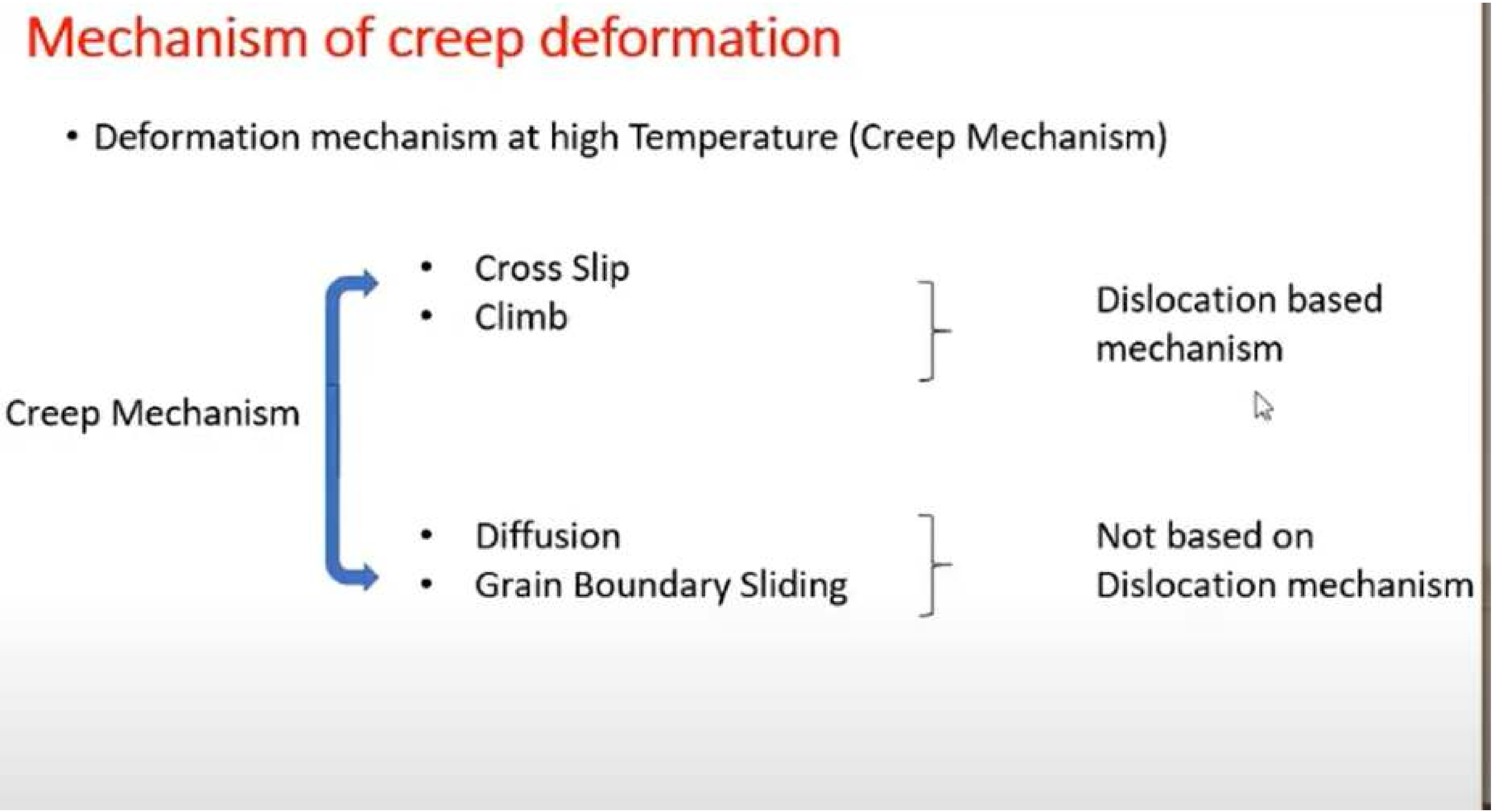


before deformation

after deformation



ETSC, IIT DELHI



Mechanism of creep deformation

- Deformation mechanism at high Temperature (Creep Mechanism)

Creep Mechanism

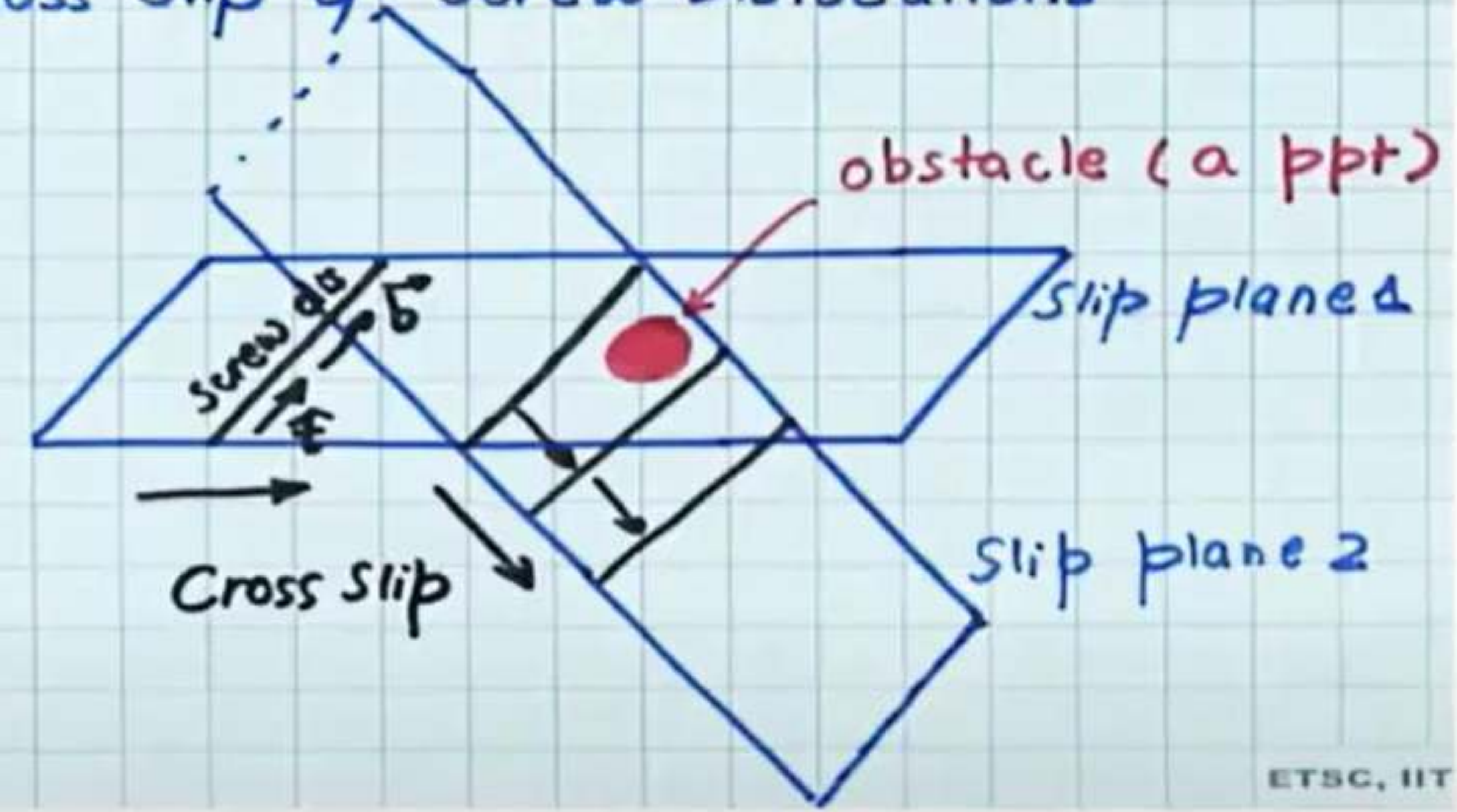
- Cross Slip
- Climb

Dislocation based mechanism

- Diffusion
- Grain Boundary Sliding

Not based on Dislocation mechanism

Cross Slip of Screw Dislocations



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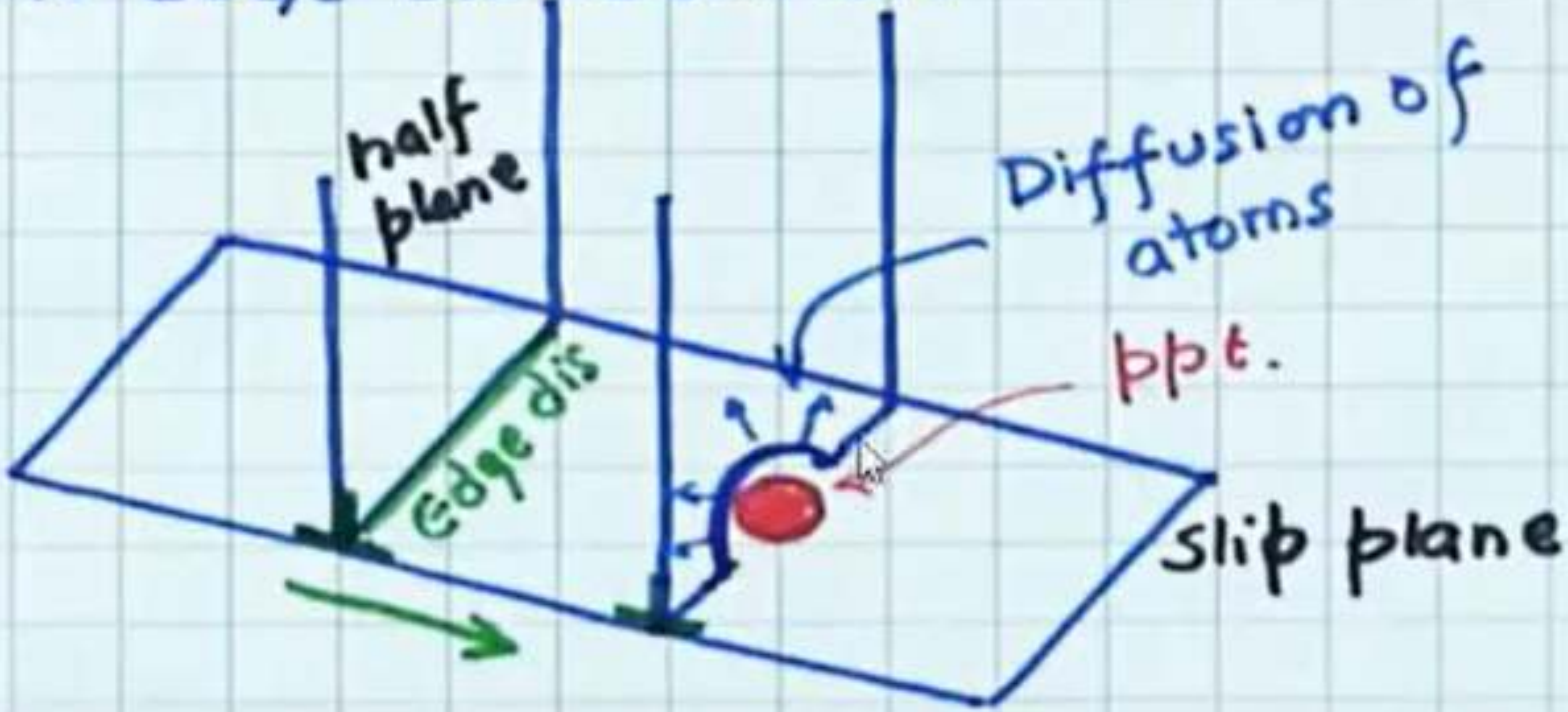
CLIMB OF AN EDGE DISLOCATION

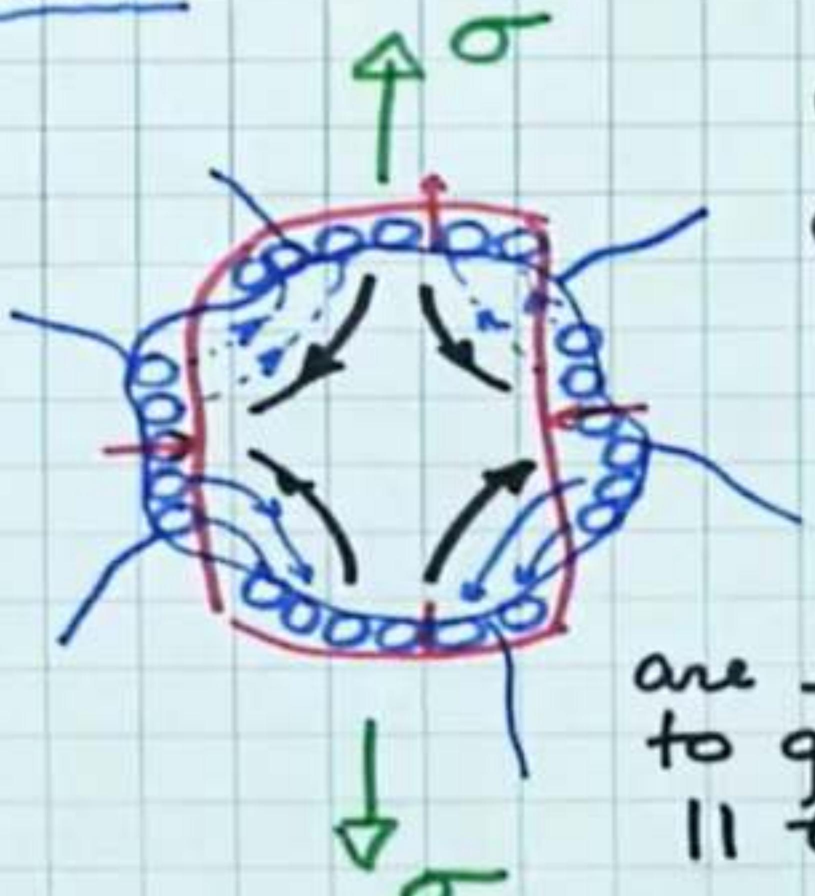


DIFFUSION CREEP

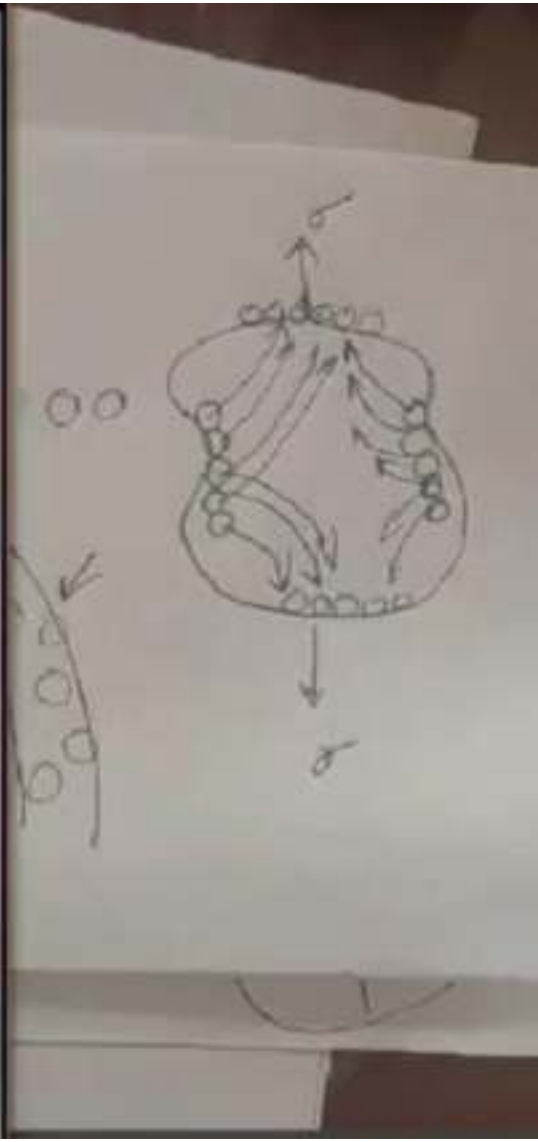
Stress assisted diffusion

substitutional diffusion

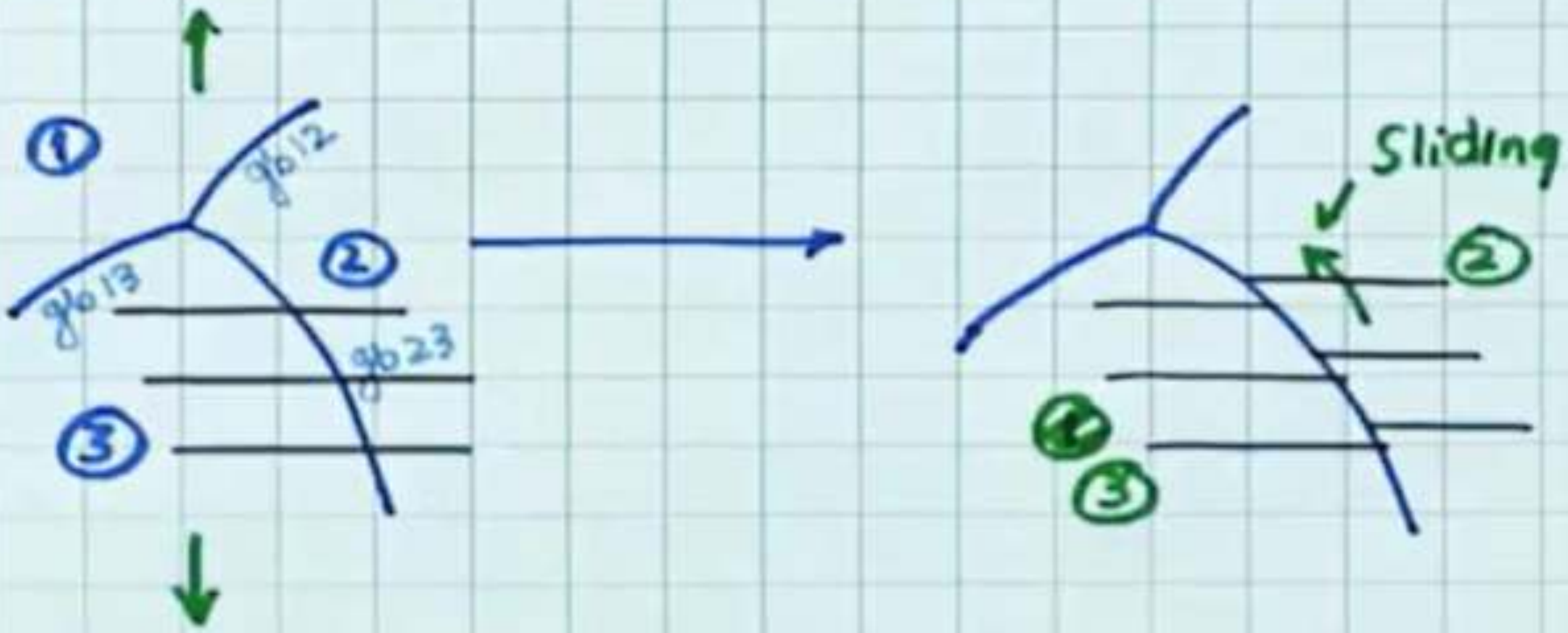
Vacancy assisted



vacancy migrates from gb which are are $\perp$ to stress to gb which are $\parallel$ to stress axis.

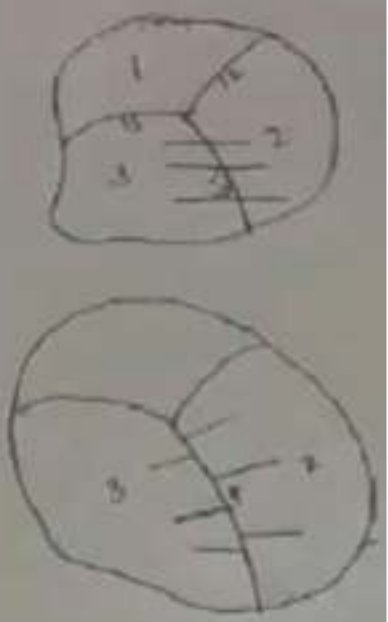


GRAIN BOUNDARY SLIDING

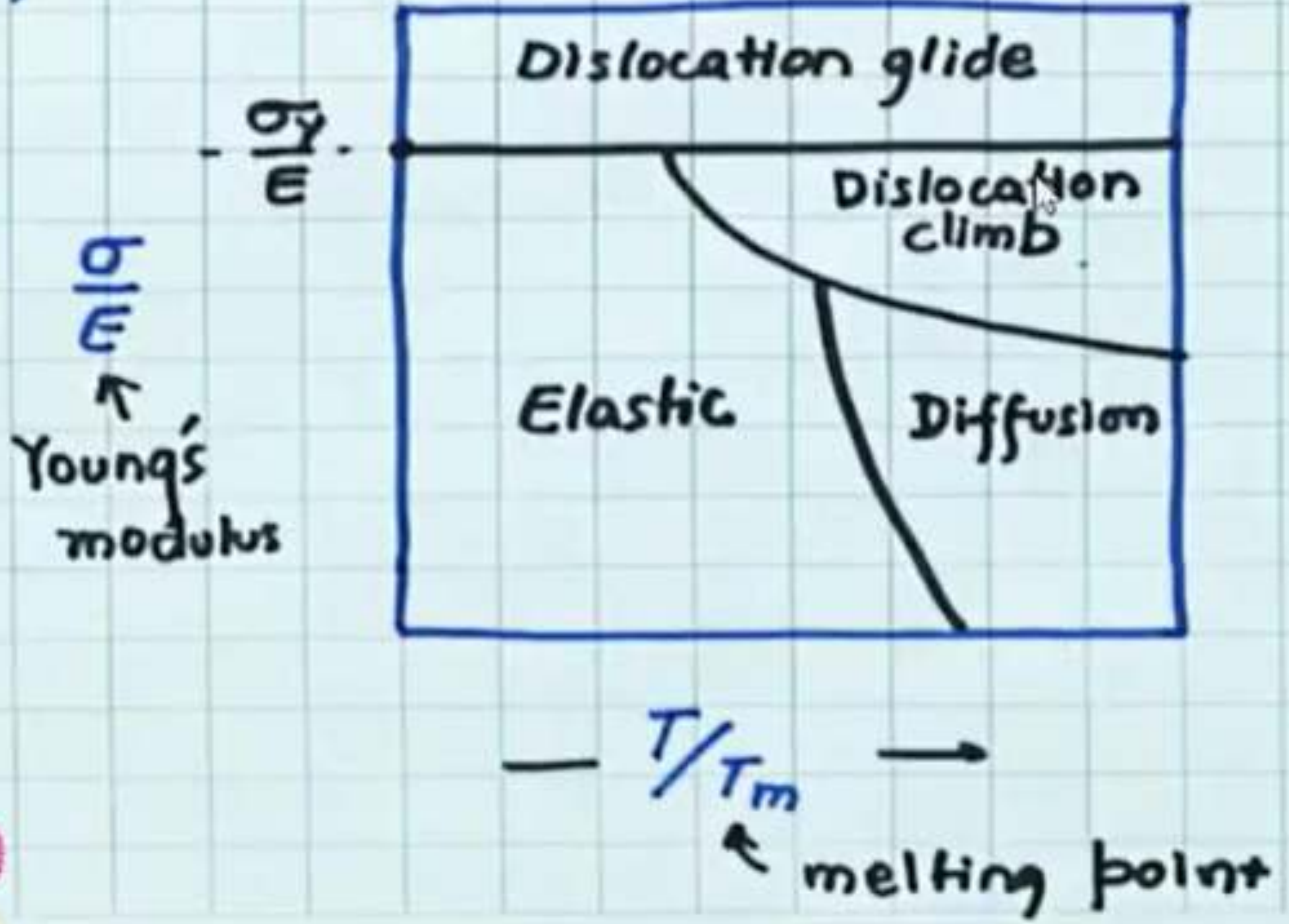


before deformation

after deformation



Deformation Mechanism Map



Threshold for creep

- Temperature & applied stress are the key influencers of creep.
- The Critical Temperature for Creep is 40% of the Melting Temperature.
- With increase in temperature & stress the following will happen,
  1. The instantaneous strain at the time of application of stress increases,
  2. The strain rate increases,
  3. Time required for rupture reduces.

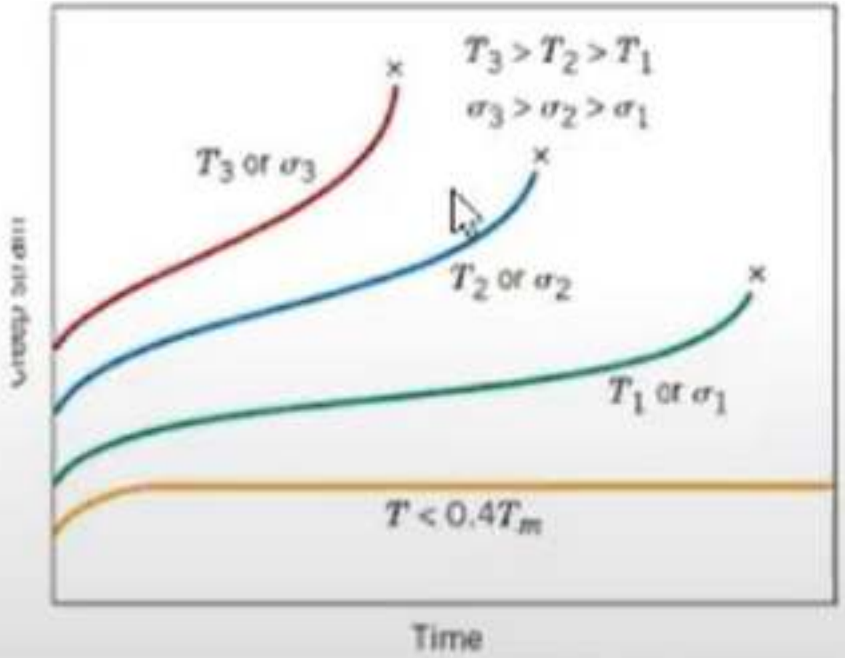
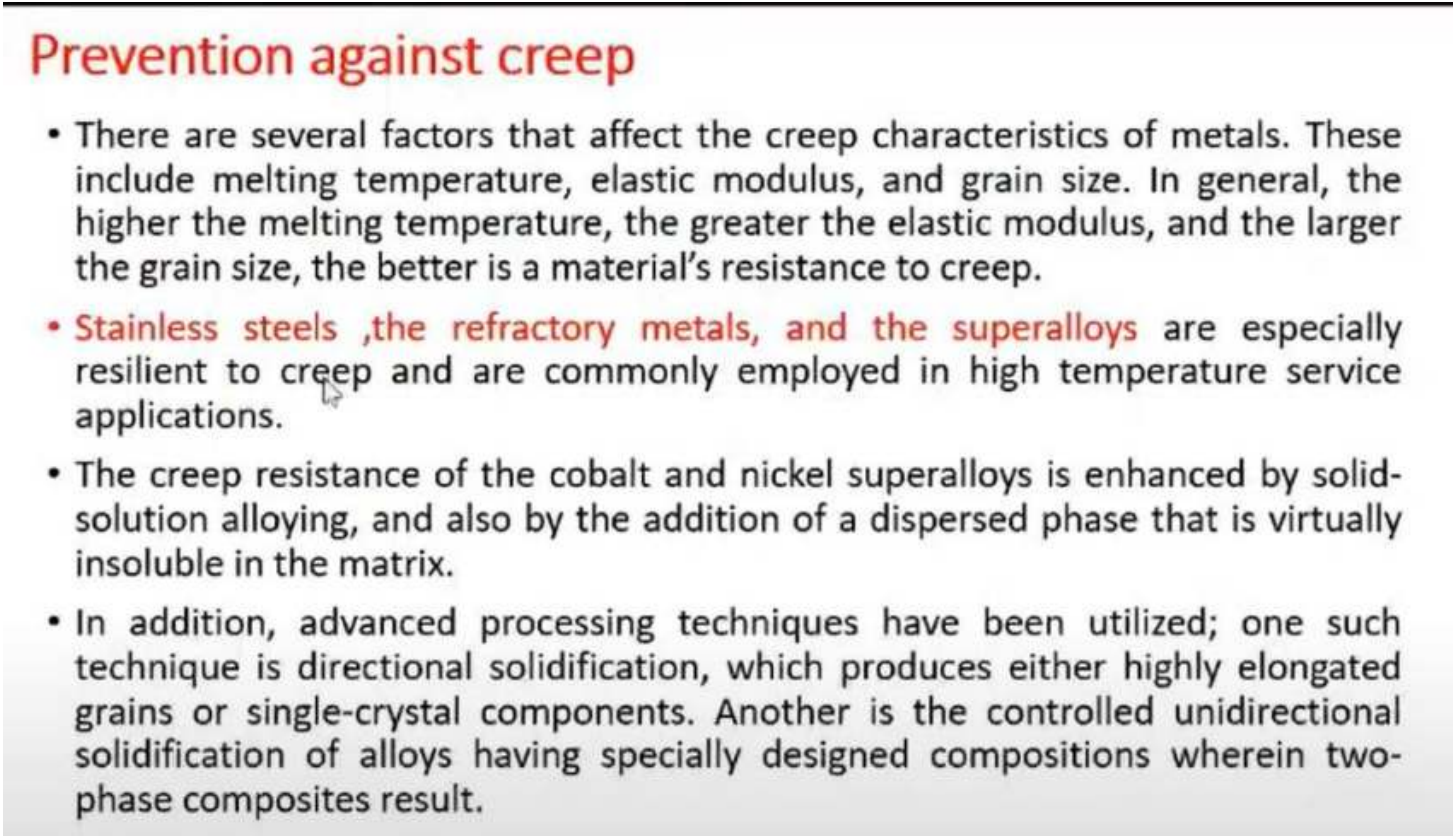


Figure 8.29 Influence of stress σ and temperature T on creep behavior.

Prevention against creep

1. Materials with high thermal stability & higher melting point will resist creep more effectively.
2. Precipitation hardening of alloys will offer more resistance to dislocation motion & improves creep resistance.
3. Dispersion hardening prevents grain boundary sliding. So it improves creep resistance.
4. Cold working/work hardening improves yield strength of a material thereby increasing creep resistance.
5. Formation of substitutional solid solution improves creep resistance as dislocation motion is reduced.



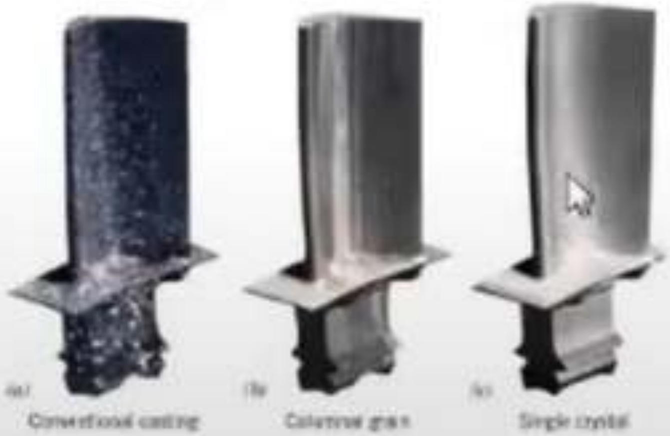
Prevention against creep

- There are several factors that affect the creep characteristics of metals. These include melting temperature, elastic modulus, and grain size. In general, the higher the melting temperature, the greater the elastic modulus, and the larger the grain size, the better is a material's resistance to creep.
- Stainless steels ,the refractory metals, and the superalloys are especially resilient to creep and are commonly employed in high temperature service applications.
- The creep resistance of the cobalt and nickel superalloys is enhanced by solid-solution alloying, and also by the addition of a dispersed phase that is virtually insoluble in the matrix.
- In addition, advanced processing techniques have been utilized; one such technique is directional solidification, which produces either highly elongated grains or single-crystal components. Another is the controlled unidirectional solidification of alloys having specially designed compositions wherein two-phase composites result.

Prevention against creep

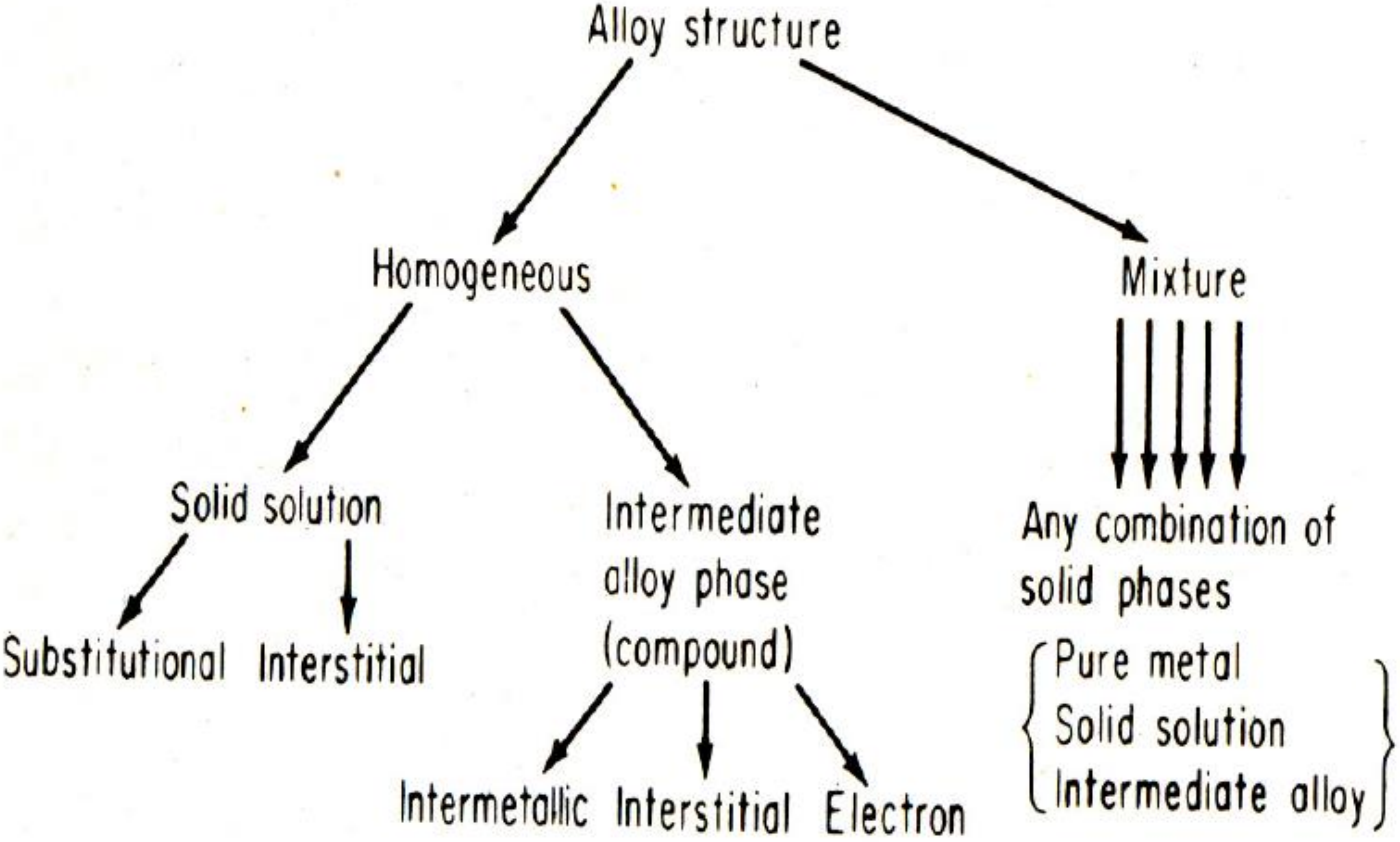
1. Effect of grain boundaries
    - Use single crystal material with refined grains.
    - Addition of solid solutions to eliminate vacancies.
2. Employ materials with high melting temperatures
3. Consult creep test data during materials selection
    - Type of service application
    - Set adequate inspection intervals according to life expectancy.

Figure 8.33 (*a*) Polycrystalline turbine blade that was produced by a conventional casting technique. High-temperature creep resistance is improved as a result of an oriented columnar grain structure (*b*) produced by a sophisticated directional solidification technique. Creep resistance is further enhanced when single-crystal blades (*c*) are used. (Courtesy of Pratt & Whitney.)



Module 5

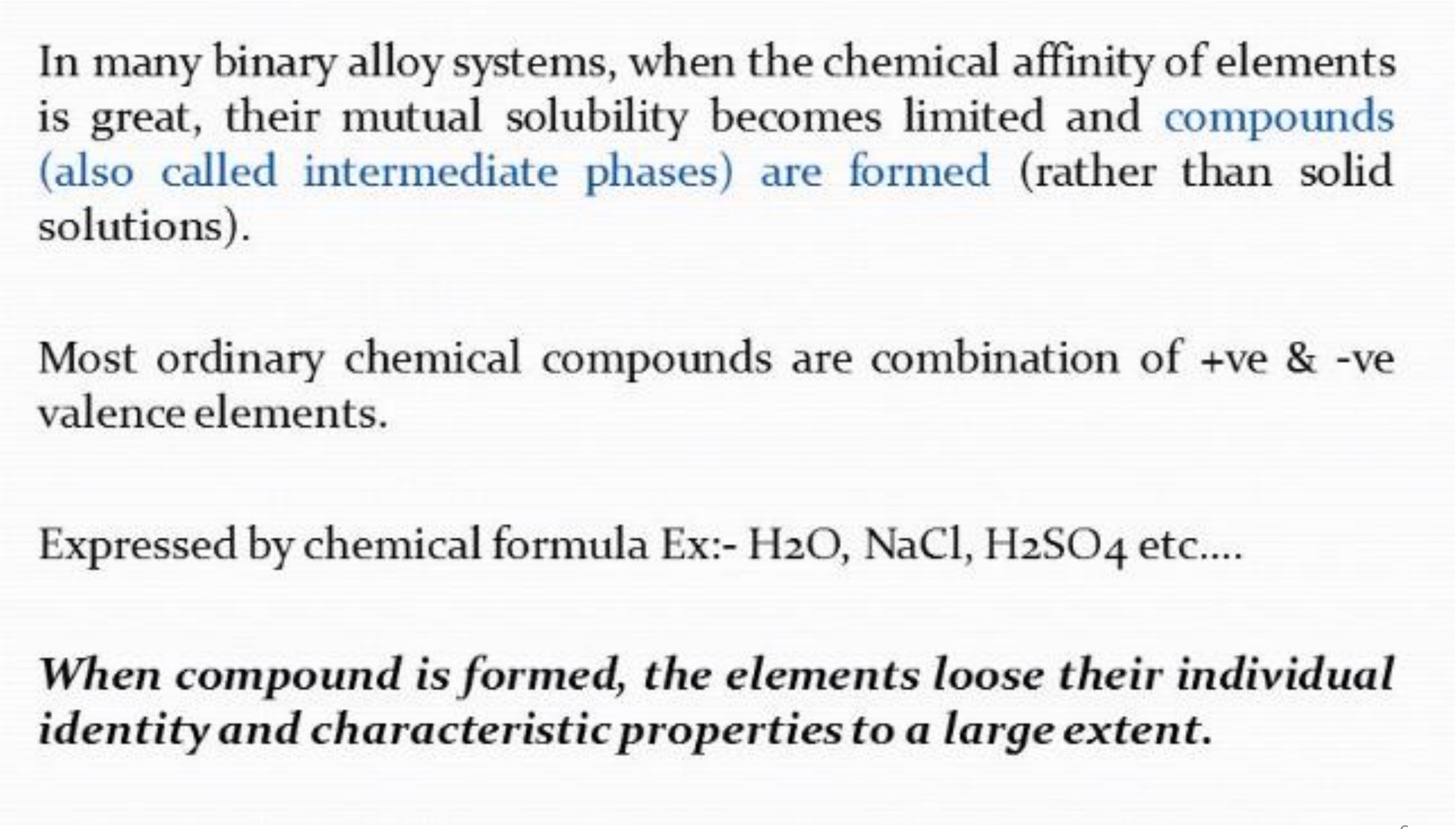
INTERMETALLIC COMPOUNDS


Alloy structure
Homogeneous
Mixture
Solid solution
Intermediate alloy phase (compound)
Any combination of solid phases
Substitutional
Interstitial
Pure metal
Solid solution
Intermediate alloy
Intermetallic
Interstitial
Electron

Intermetallics

- A compound of two metals that has a distinct chemical formula. On a phase diagram it appears as an intermediate phase that exists over a very narrow range of compositions.
- Most of the alloy system do not show complete solid solubility. When the amount of solute element is more than the limit of solid solubility, a second phase also appears apart from the primary solid solution. The second phase which forms is an intermediate phase.
- It is a phase formed at intermediate composition between the two primary components (pure metals).
- The crystal structure of the intermediate phase is different from the both primary components.
- Some of these intermediate phases have a fixed composition and are called **Intermetallic compounds.**

- **Intermetallic compound,** any of a class of substances composed of definite proportions of two or more elemental metals, rather than continuously variable proportions (as in solid solutions).
- The crystal structures and the properties of intermetallic compounds often differ markedly from those of their constituents.
- In addition to the normal valences of their components, the relative sizes of the atoms and the ratio of the total number of valence electrons to the total number of atoms have important effects on the composition of intermetallic compounds.

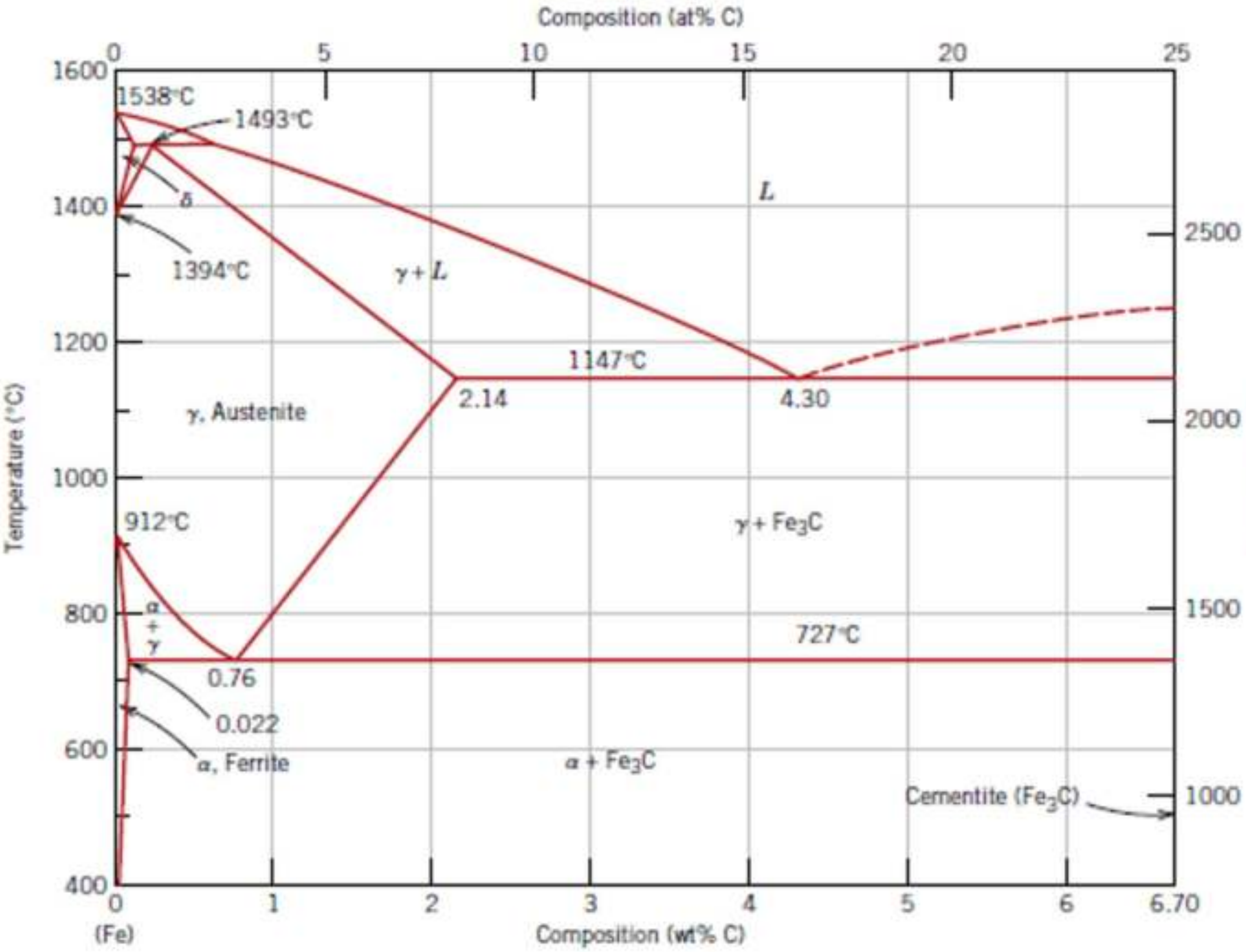


In many binary alloy systems, when the chemical affinity of elements is great, their mutual solubility becomes limited and compounds (also called intermediate phases) are formed (rather than solid solutions).

Most ordinary chemical compounds are combination of +ve & -ve valence elements.

Expressed by chemical formula Ex:- H_2O, NaCl, H_2SO_4 etc....

When compound is formed, the elements loose their individual identity and characteristic properties to a large extent.


Composition (at% C)
0
5
10
15
20
25
1600
1538°C
1493°C
L
1400
δ
1394°C
γ + L
2500
1200
1147°C
2.14
4.30
γ, Austenite
2000
Temperature (°C)
Temperature (°F)
1000
912°C
γ + Fe₃C
800
α
+
γ
727°C
1500
0.76
0.022
600
α, Ferrite
α + Fe₃C
Cementite (Fe₃C)
1000
400
0
(Fe)
1
2
3
4
5
6
6.70
Composition (wt% C)

Intermetallics are similar to alloys, but the bonding between the different types of atoms is partly ionic, leading to different properties than traditional alloys.

In general, the larger the electro negativity difference between the host atom and the impurity, the greater the tendency to form compounds and the less solubility there is.

So, elements with similar electro negativities tend to form alloy, whereas elements with large electro negativity difference tend to have more ionic bonds.

An **intermetallic compound** contains two or more metallic elements, producing a new phase with its own composition, crystal structure, and properties.

Intermetallic compounds are almost always very hard and brittle.

Intermetallics or intermetallic compounds are similar to ceramic materials in terms of their mechanical properties.

Often dispersion-strengthened alloys contain an intermetallic compound as the dispersed phase

Intermetallics:

Classification:

Stoichiometric intermetallic compounds have a fixed composition. They are represented in the phase diagram by a vertical line.

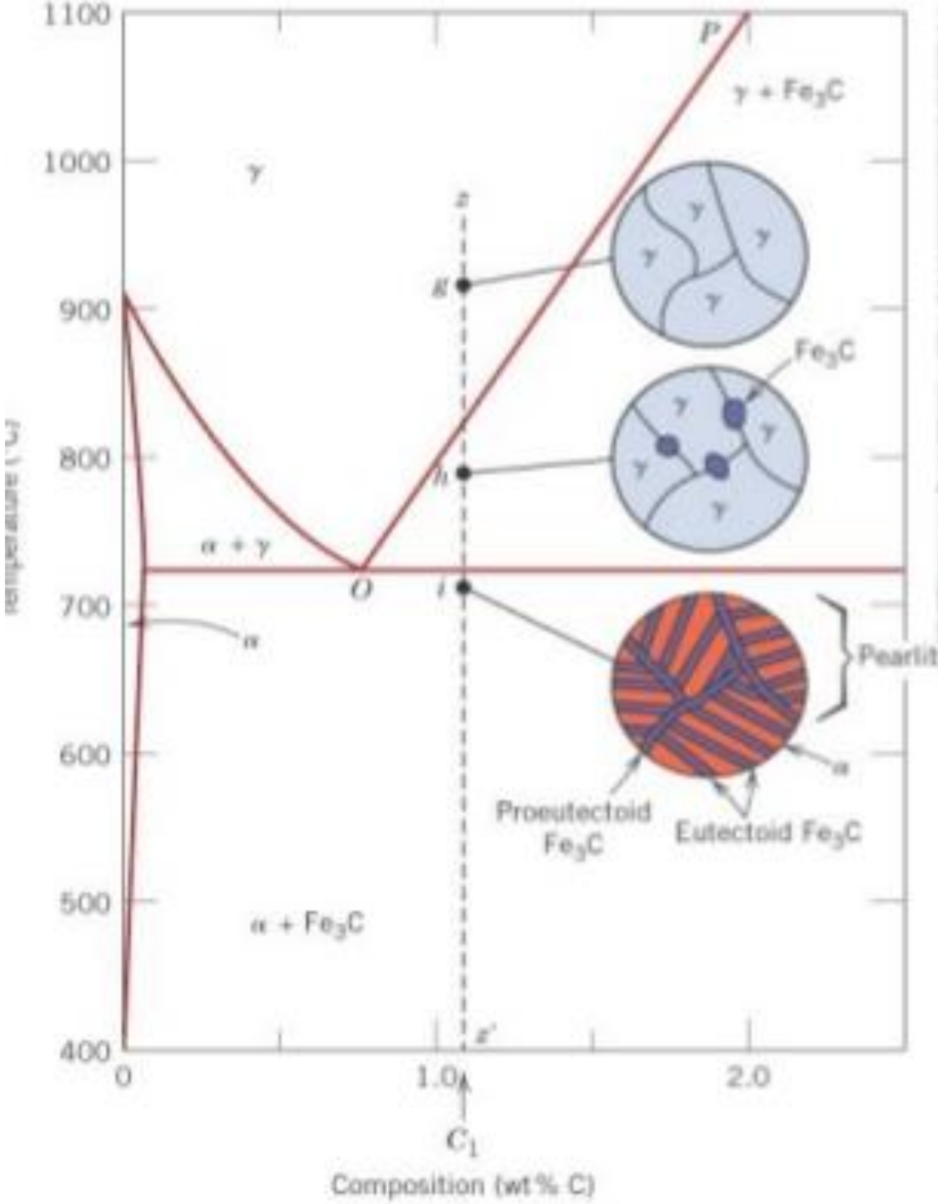
Examples:

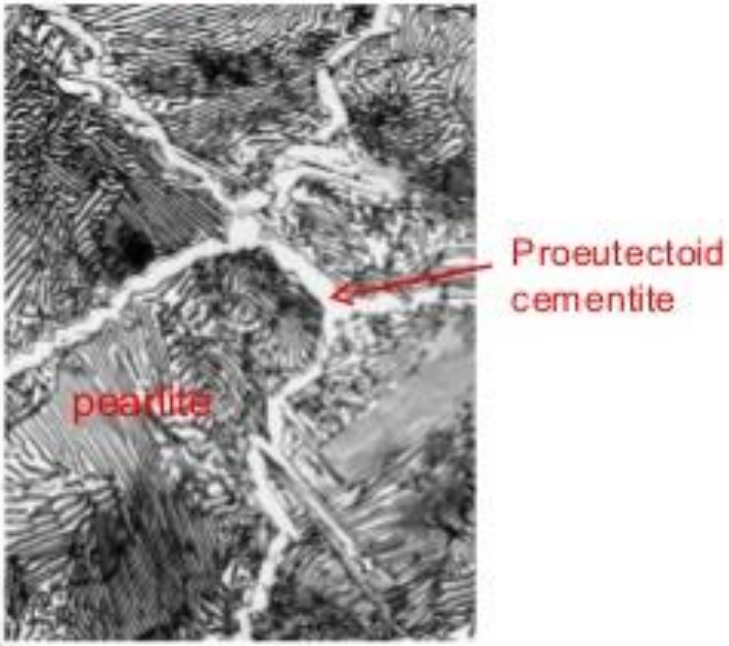
- Au_2Pb in Au-Pb system,
- AlSb in Al-Sb system,
- $MoSi_2$ in Mo-Si system,
- Fe_3C in Steels,
- Mg_2Pb in Mg-Pb system,
- $MgNi_2$, Mg_2Ni in Mg-Ni system

- **Nonstoichiometric intermetallic compounds** have a range of compositions and are sometimes called intermediate solid solutions.

- Examples:
  - γ phase in Mo-Rh system,
  - β'phase in brass,
  - $CuAl_2$ in Al-Cu system,
  - Mg_2Al_3 in Al-Mg system,
  - $TiAl_3$ in Al-Ti system.

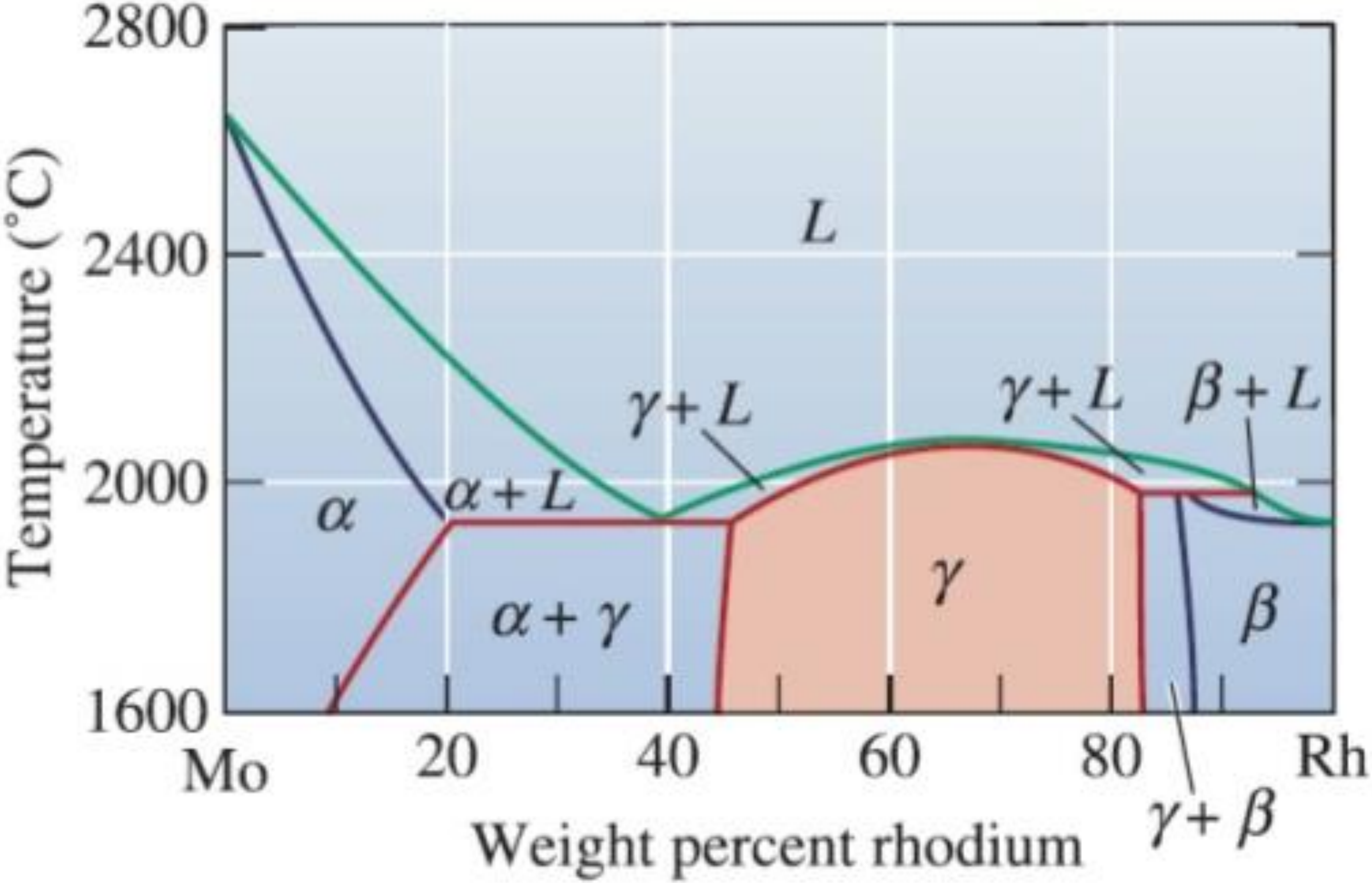
• Stoichiometric intermetallic compounds:





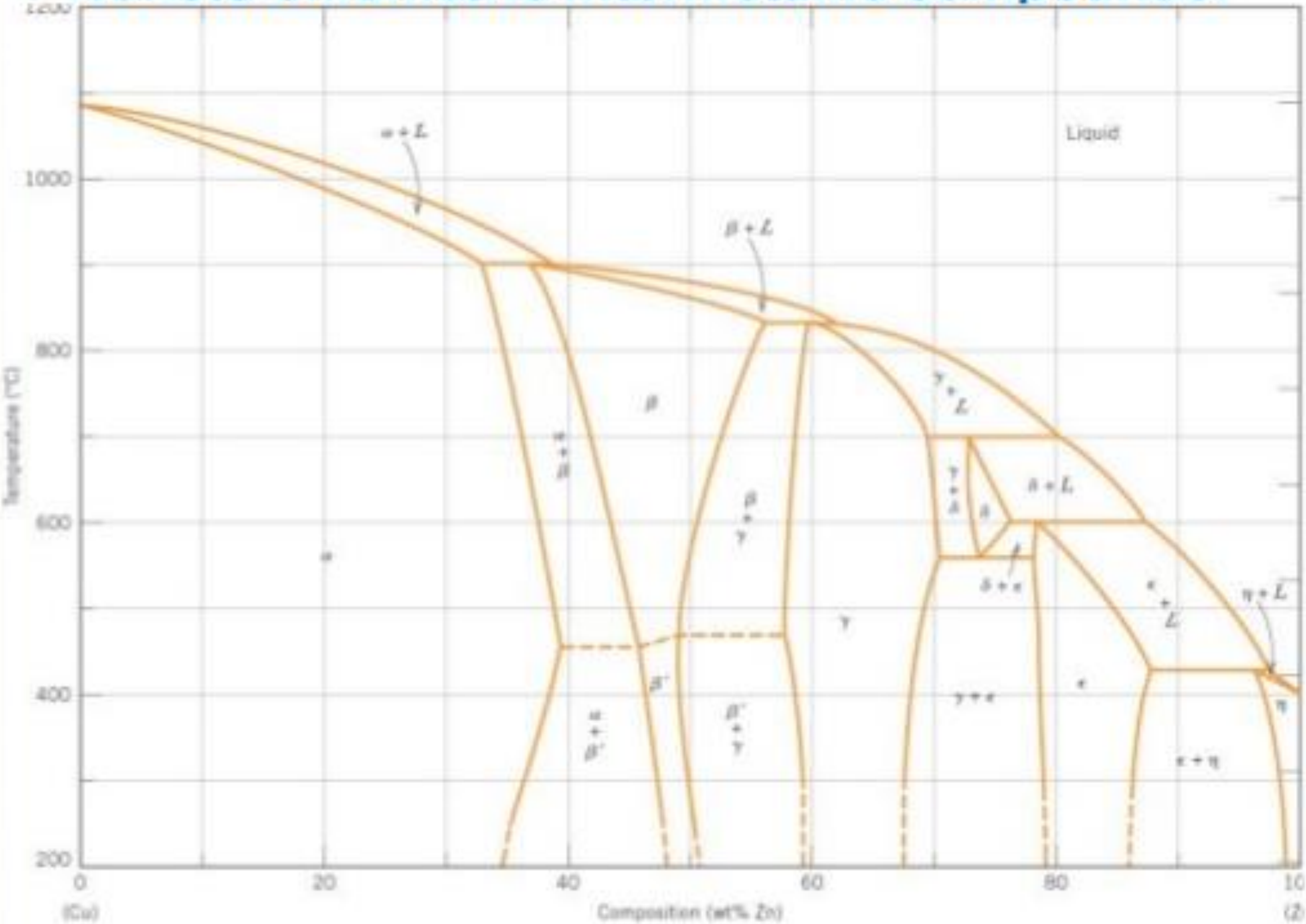
Hypereuctoid steel (1.2%C) contains metastable proeutectoid and eutectoid Fe_3C, which has a fixed ratio of three iron atoms to one carbon atom (Interstitial compound).

- **Nonstoichiometric intermetallic compounds:**



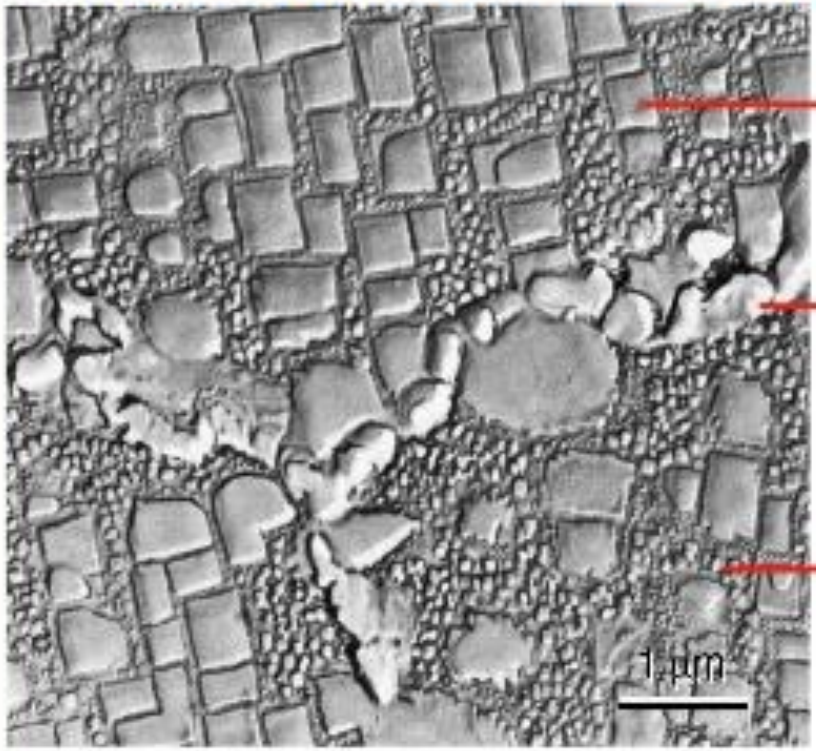
he molybdenum-rhodium phase diagram includes a onstoichiometric intermetallic compound γ.

Nonstoichiometric intermetallic compounds:



The Copper - Zinc Phase diagram, containing more than 30% Zn, a second phase β' forms because of the limited solubility of zinc in copper.

- **Nonstoichiometric intermetallic compounds:**



$Ni_3(Al,Ti)$ (γ' prime) priciptate (FCC)

Carbids ($M_{23}C_6$, M_6C or MC)

γ Matrix (FCC austenite)

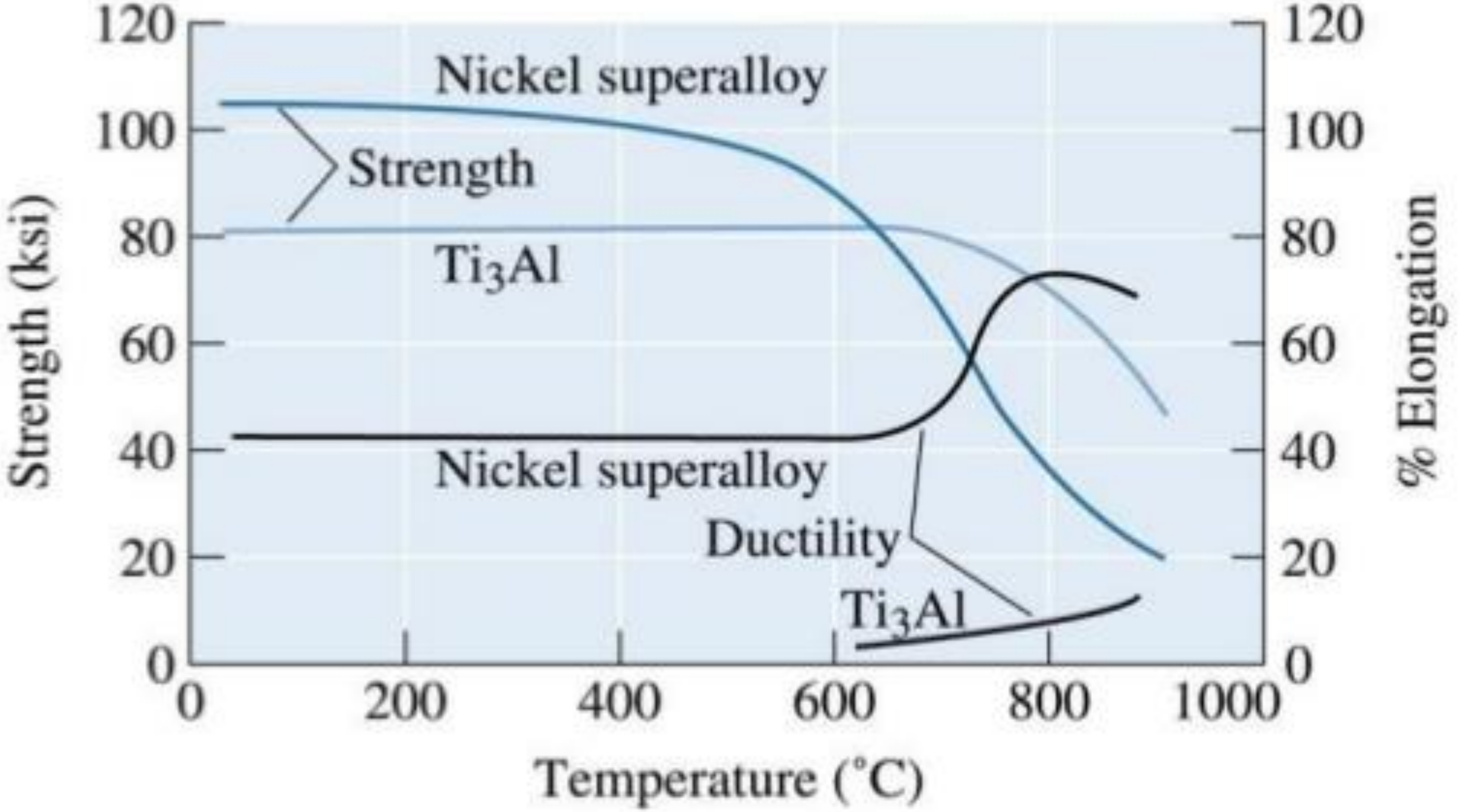
Nickel base superalloys, addition of small amount of Al, Ti, Nb forms precipitates with Cuboid shape.
The elements C, Cr, Ta, Hf, Ti, Nb,W forms Carbides.
The elements Co, Fe, Cr, Nb, Ta, Mo, W, V, Ti, B, Zr and Al strengthen the Matrix.

- **Properties of some Intermetallic compounds**

Intermetallic Compound	Crystal Structure	Melting Temperature (°C)	Density $\left(\frac{g}{cm^3}\right)$	Young's Modulus (GPa)
FeAl	Ordered BCC	1250–1400	5.6	263
NiAl	Ordered FCC (B2)*	1640	5.9	206
Ni_3Al	Ordered FCC ($L1_2$)*	1390	7.5	337
TiAl	Ordered tetragonal ($L1_0$)*	1460	3.8	94
Ti_3Al	Ordered HCP	1600	4.2	210
$MoSi_2$	Tetragonal	2020	6.31	430

* B2 – Binary compound structure having 1:1 stoichiometry,
* L1 – Alloys.

- **Properties of intermetallic compounds:**

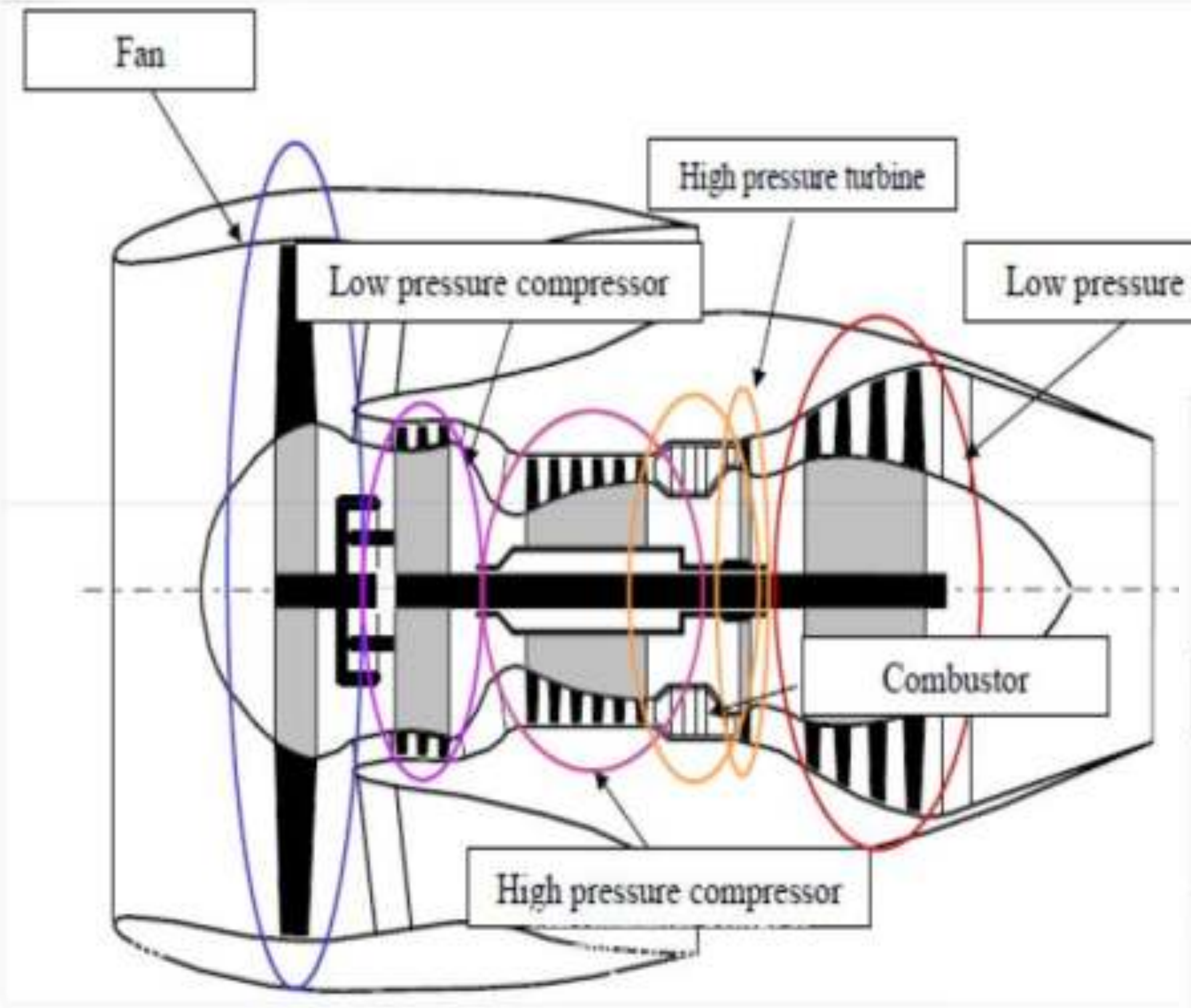


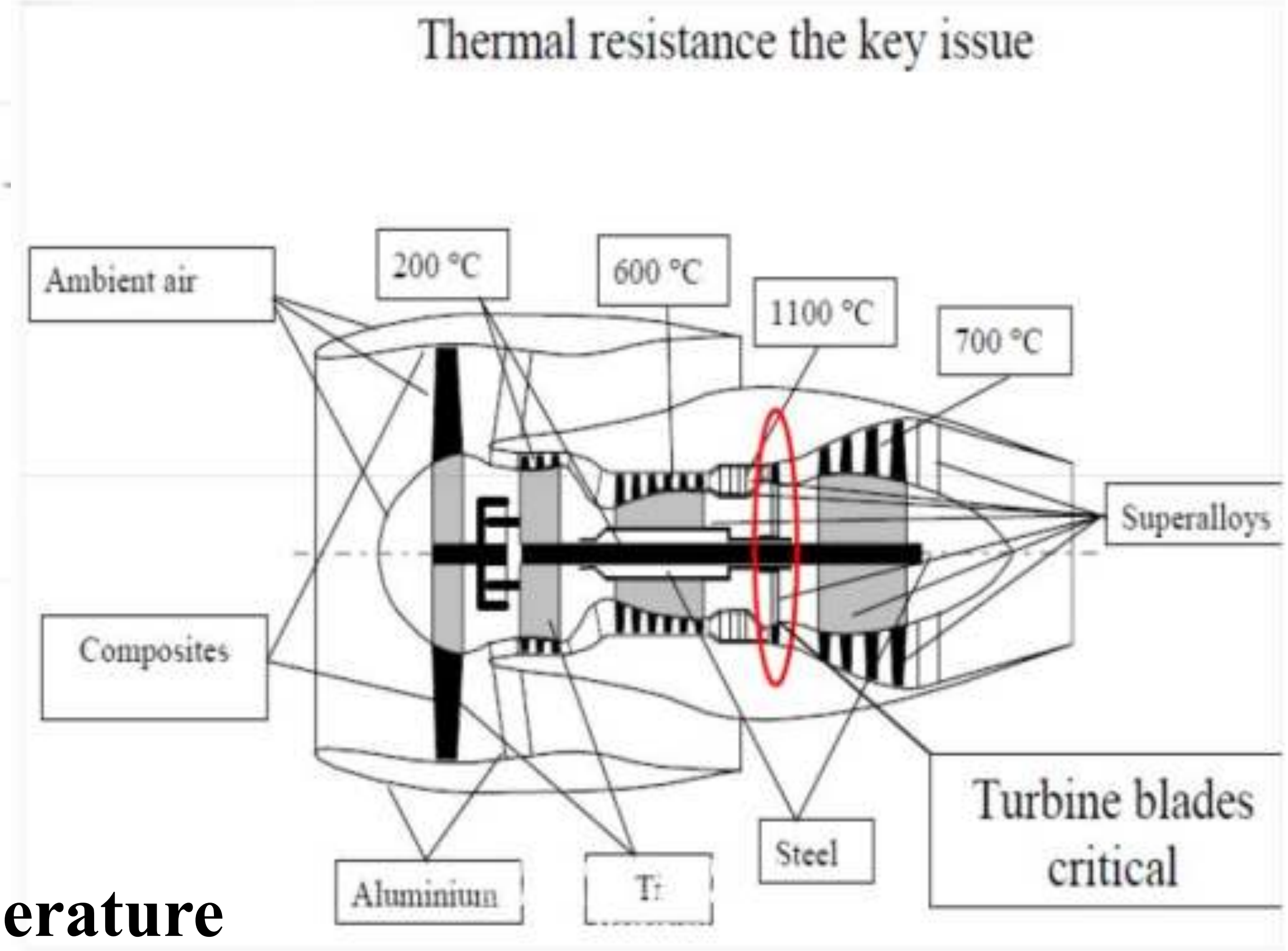
The strength and ductility of the intermetallic compound Ti_3Al compared with that of a conventional nickel superalloy. The Ti_3Al maintains strength to higher temperatures longer than does the nickel superalloy.

- **Properties and Applications:**
- **TiAl and Ni3Al (Nickel base superalloys)**

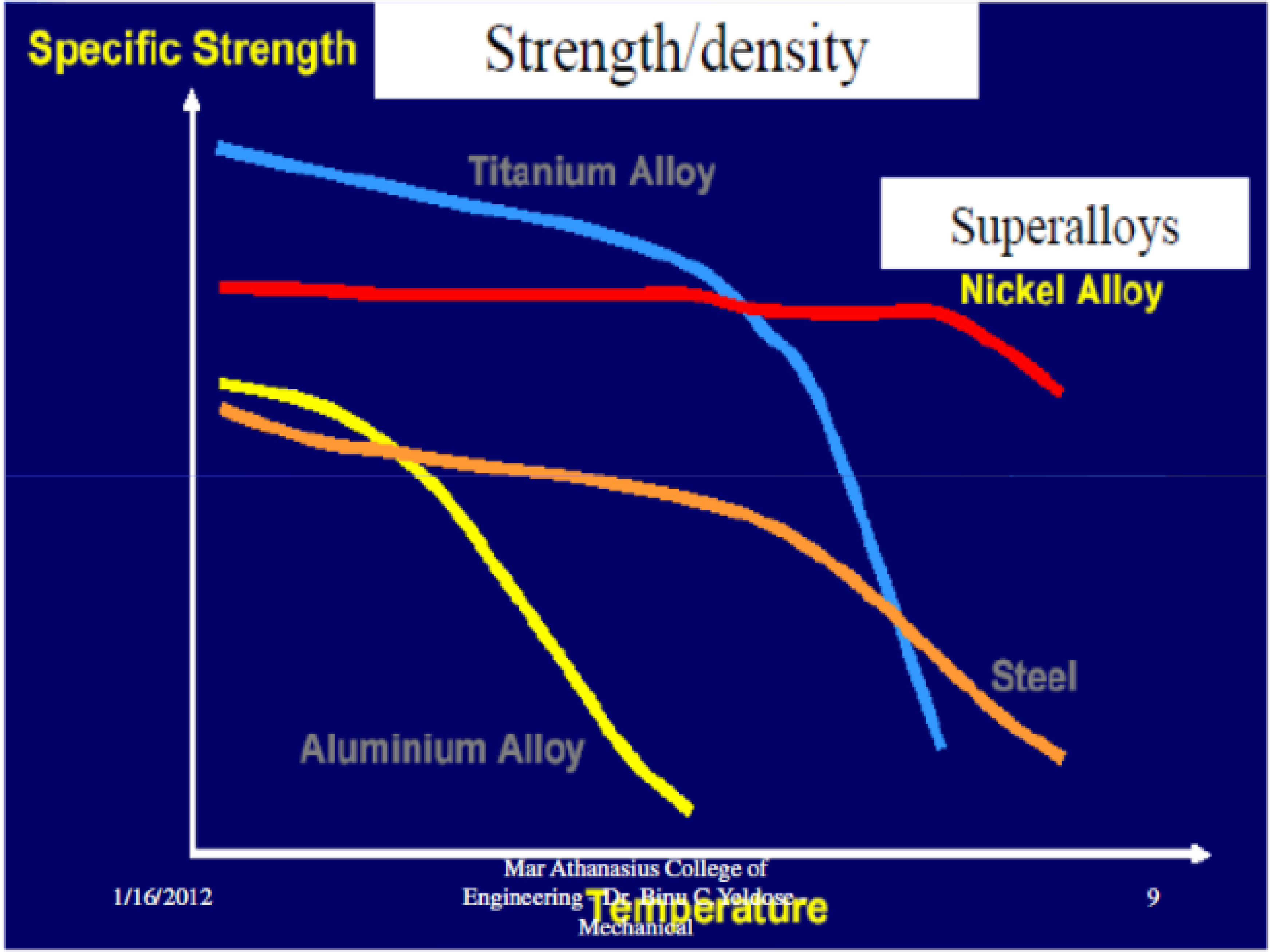
- **Properties:**
- TiAl and Ni_3Al possess good combinations of high-temperature mechanical properties and oxidation resistance up to approximately 650 - 960°C.
- Good Toughness and Corrosion resistance.
- **Applications:**
  - Aircrafts, space vehicles, rocket engines
  - Industrial gas turbines (IN 738LC).
  - Nuclear reactors, submarines.
  - Steam power plants, petrochemical equipment.
  - Combustion Engine Exhaust Valves
  - Submarines

Superalloys





Amazing property of superalloys:
they become stronger at higher temperature


Specific Strength
Strength/density
Titanium Alloy
Superalloys
Nickel Alloy
Steel
Aluminium Alloy
Temperature
1/16/2012
Mar Athanasius College of Engineering Dr. Binu C Yeldose Mechanical
9

- Superalloys are high-temperature alloys use in jet engines, gas turbines and reciprocating engines.

- Able to maintain high strengths at high temperatures
- Good corrosion and oxidation resistance at high temperatures (Cr, Al)
- Good resistance to creep and rupture at high temperatures

- Developed in 1930s during the second world war.

- Three classes
  - Ni based------most commonly used
  - Co based
  - Fe based

- Ni through out the temperature it has FCC crystal structure

- Co at room temp HCP, above 400ºC FCC

- Fe based b/w (910ºC 1400ºC) FCC

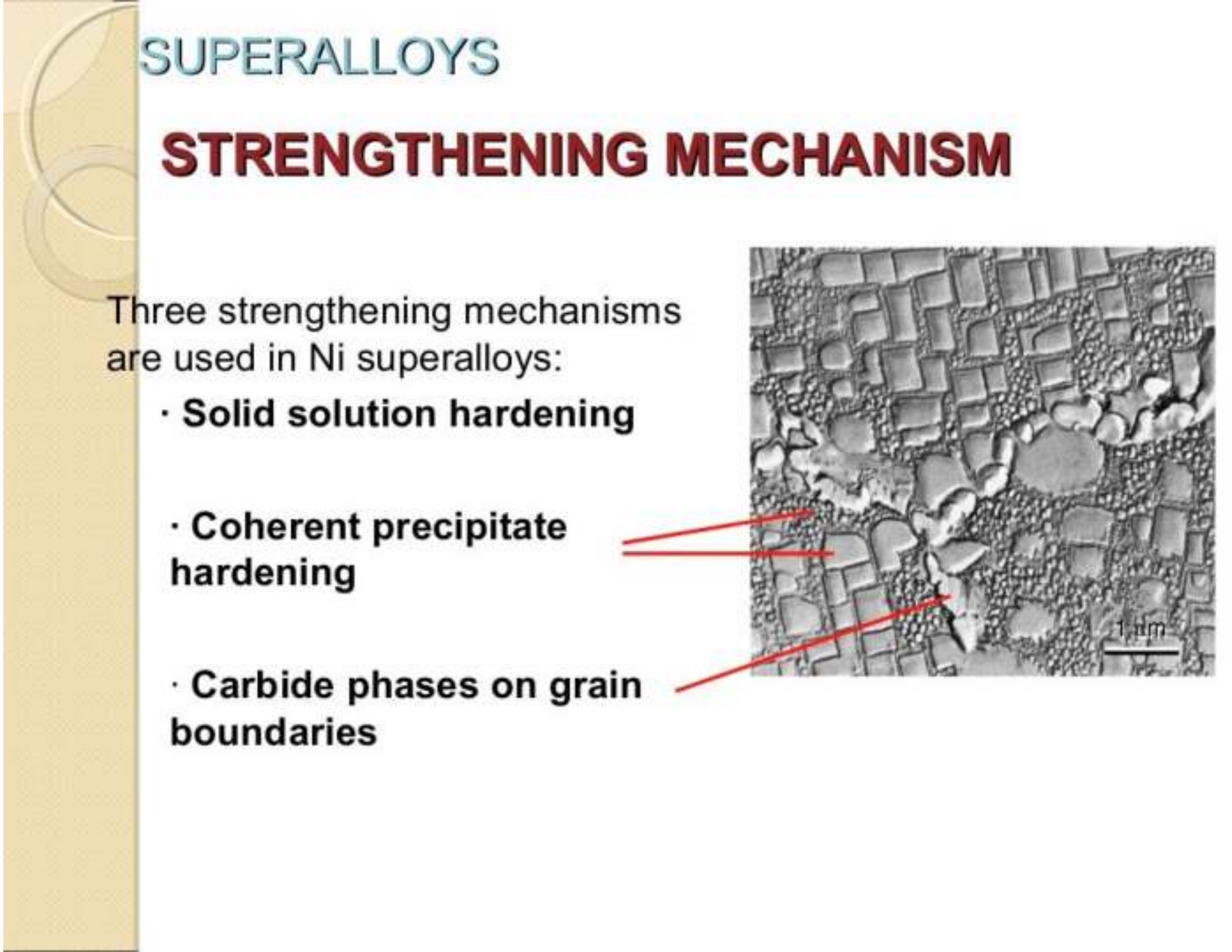
- Why do we want FCC?
  - FCC structure is more close packed
  - Hence diffusibility are very low, so the creep resistance are very high

- We use stabilizers to **stabilize close packed structures** for high temperature applications.

- **Tungsten** has BCC structure at high temp, hence creep resistance is very low

- Examples of super alloys
  - Nimonic 75----(75% Ni, 19.5%Cr)
  - Nimonic 80----(80% Ni, 19.5%Cr)

Also add Al &Ti for
Ni3 (Al &Ti)
Precipitate
strengthening

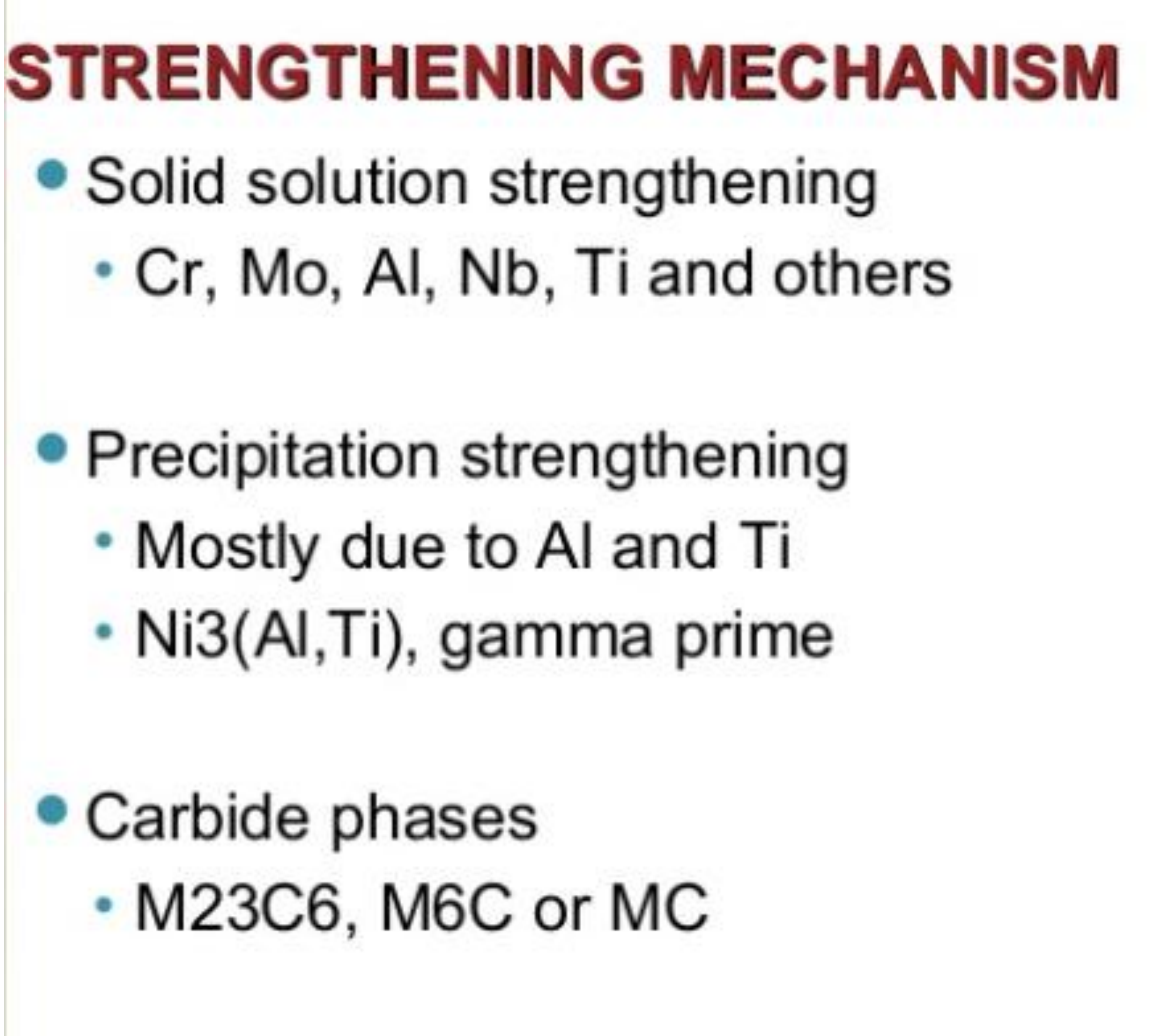


SUPERALLOYS

STRENGTHENING MECHANISM

Three strengthening mechanisms are used in Ni superalloys:

- **Solid solution hardening**
- **Coherent precipitate hardening**
- **Carbide phases on grain boundaries**



STRENGTHENING MECHANISM

- Solid solution strengthening
  - Cr, Mo, Al, Nb, Ti and others

- Precipitation strengthening
  - Mostly due to Al and Ti
  - Ni3(Al,Ti), gamma prime

- Carbide phases
  - M23C6, M6C or MC

Ni based super alloys

- Basilcally they get their strength at high temperature because of
  - The matrix (γ phase) Nickel (solid solution strengthening)
  - γ ‘ prime phase (precipitate (precipitation strengthening))
  - γ ‘‘ double prime phase Strengthener at low Temperature, issues at high Temperature
  - Some carbides and borides

Strengthening mechanisms in Nickel based super alloy

The microstructure of a typical superalloy consists therefore of different phases, drawn from the following list [2].

(i) The gamma phase, denoted γ. This exhibits the FCC structure, and in nearly all cases it forms a continuous, matrix phase in which the other phases reside. It contains significant concentrations of elements such as cobalt, chromium, molybdenum, ruthenium and rhenium, where these are present, since these prefer to reside in this phase.

(ii) The gamma prime precipitate, denoted γ'. This forms as a precipitate phase, which is often coherent with the γ-matrix, and rich in elements such as aluminium, titanium and tantalum. In nickel–iron superalloys and those rich in niobium, a related ordered phase, γ'', is preferred instead of γ'.

(iii) Carbides and borides. Carbon, often present at concentrations up to 0.2 wt%, combines with reactive elements such as titanium, tantalum and hafnium to form MC carbides. During processing or service, these can decompose to other species, such as $M_{23}C_6$ and M_6C, which prefer to reside on the γ–grain boundaries, and which are rich in chromium, molybdenum and tungsten. Boron can combine with elements such as chromium or molybdenum to form borides which reside on the γ–grain boundaries.

Other phases can be found in certain superalloys, particularly in the service-aged condition, for example, the topologically close-packed (TCP) phases μ, σ, Laves, etc. However, the compositions of the superalloys are chosen to avoid, rather than to promote, the formation of these compounds.

1.The matrix (γ phase) Nickel

- **Solid solution strengthening** (strength the matrix)
- By adding different alloy elements to the Ni base metal
- Considering the solubility of impurities
- Strength achieved proportional to the size difference b/w base metal & impurities or size factor(ρ)
- But solubility indirectly proportional to size factor
- So a trade off b/w size factor(ρ) and solubility required

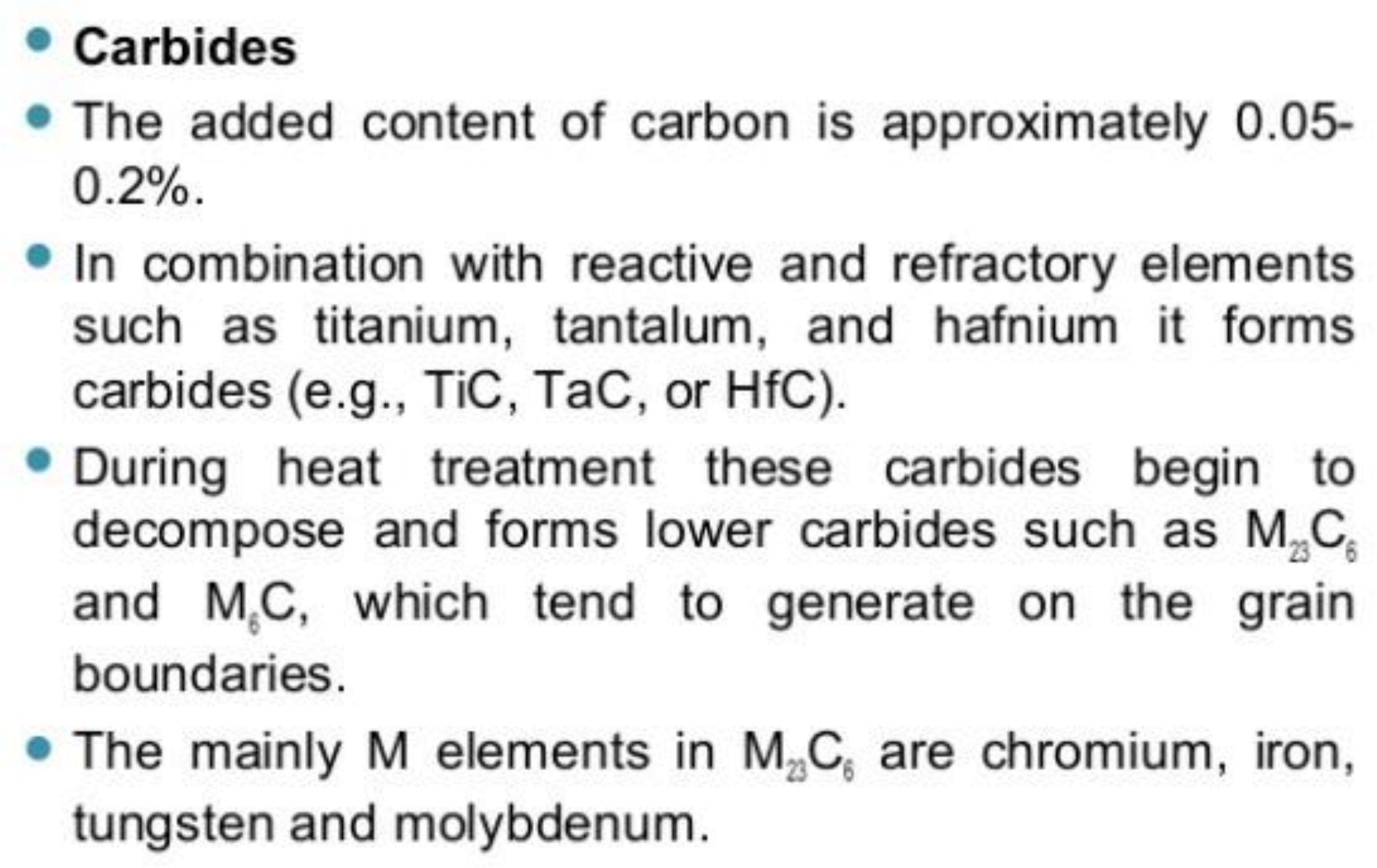
2.Precipitation strengthening γ’ $Ni_3(Al, Ti)$

- These intermetallic compounds give additional strength
- A_3B Structure
- γ’ FCC structure in all direction it is close packed
- A element go to face Center
- B go to body corner

3. Dispersion strengthening

   Y_2O_3 , ThO_2, Al_2O_3

4. Formation of carbides at the grain boundary



- **Carbides**
- The added content of carbon is approximately 0.05-0.2%.
- In combination with reactive and refractory elements such as titanium, tantalum, and hafnium it forms carbides (e.g., TiC, TaC, or HfC).
- During heat treatment these carbides begin to decompose and forms lower carbides such as $M_{23}C_6$ and M_6C, which tend to generate on the grain boundaries.
- The mainly M elements in $M_{23}C_6$ are chromium, iron, tungsten and molybdenum.

– Ni Base Superalloys.

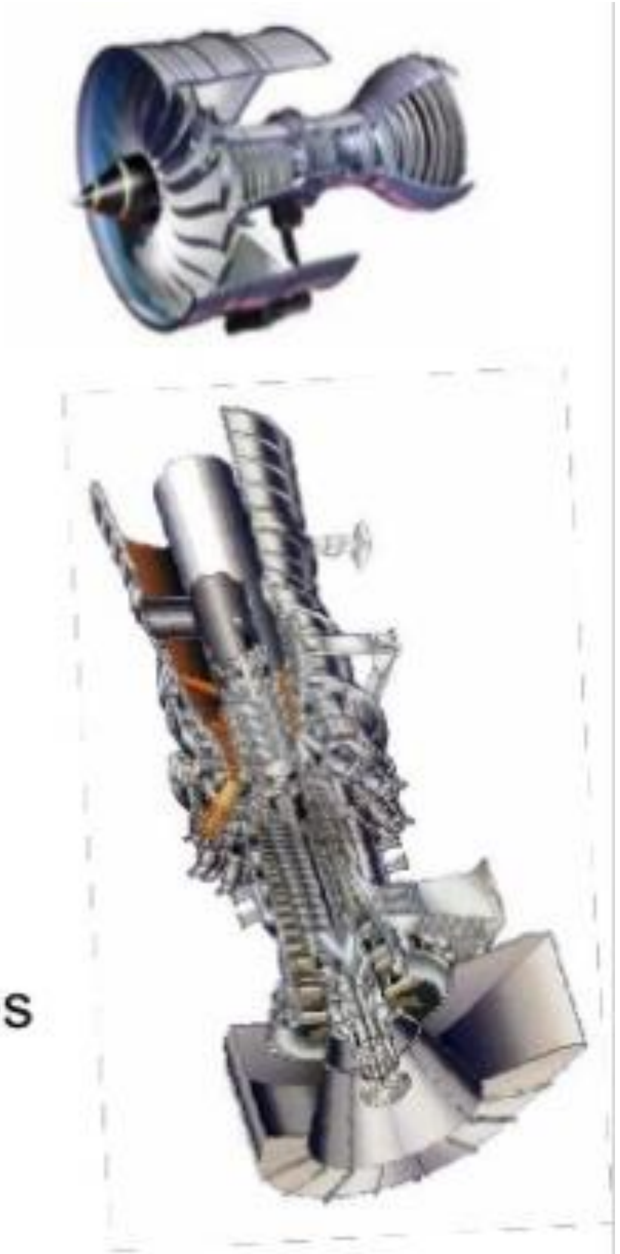
– γ, γ' and carbides, dispersoids.

- solid solution strengthening – γ
- Precipitation $Ni_3(Al,Ti)$
- Dispersion Y_2O_3, ThO_2, Al_2O_3
- increase of APB energy.
- solid solution strengthening of γ'
- increase in coherency strains below 0.6 Tm.
- Decrease in ripening rate above 0.6Tm
- minimise formation of TCPs $\left(\overset{Ni_3Ti(HCP)}{\eta}, \sigma, \underset{\gamma''(Ord.BCT)}{Ni_3Nb}, etc\right)$
- control on carbide formation at gbs.
- control thickness to grain size ratio.

SUPERALLOYS

Applications:

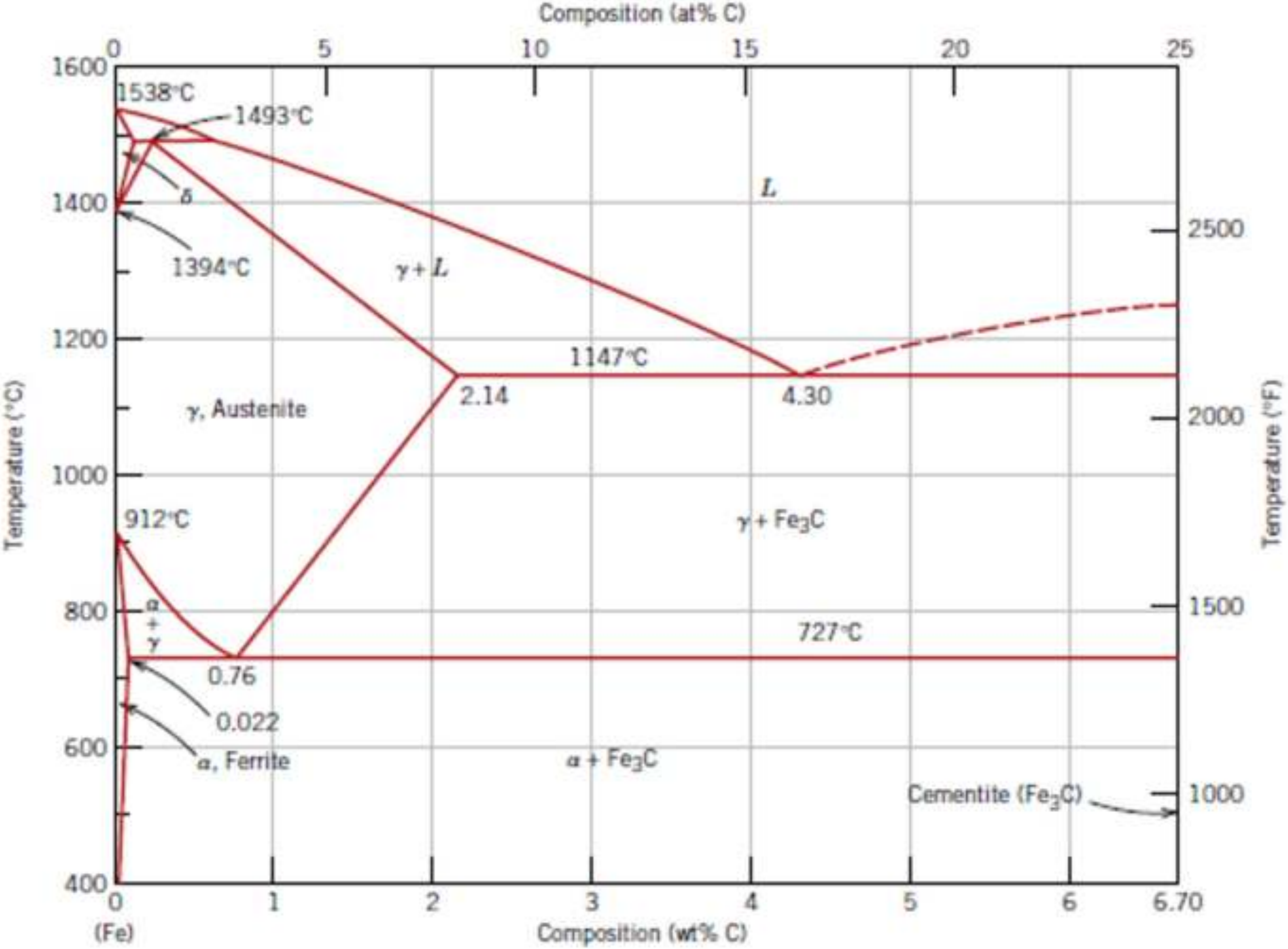
- Aerospace Gas Turbine Engines
- Space vehicles - Rocket engines,
- Nuclear reactors
- Power Generation Turbines
- Submarines.
- Petrochemical equipment.
- High-Temperature Fasteners
- Combustion Engine Exhaust Valves
- Hot Working Tooling and Dies,

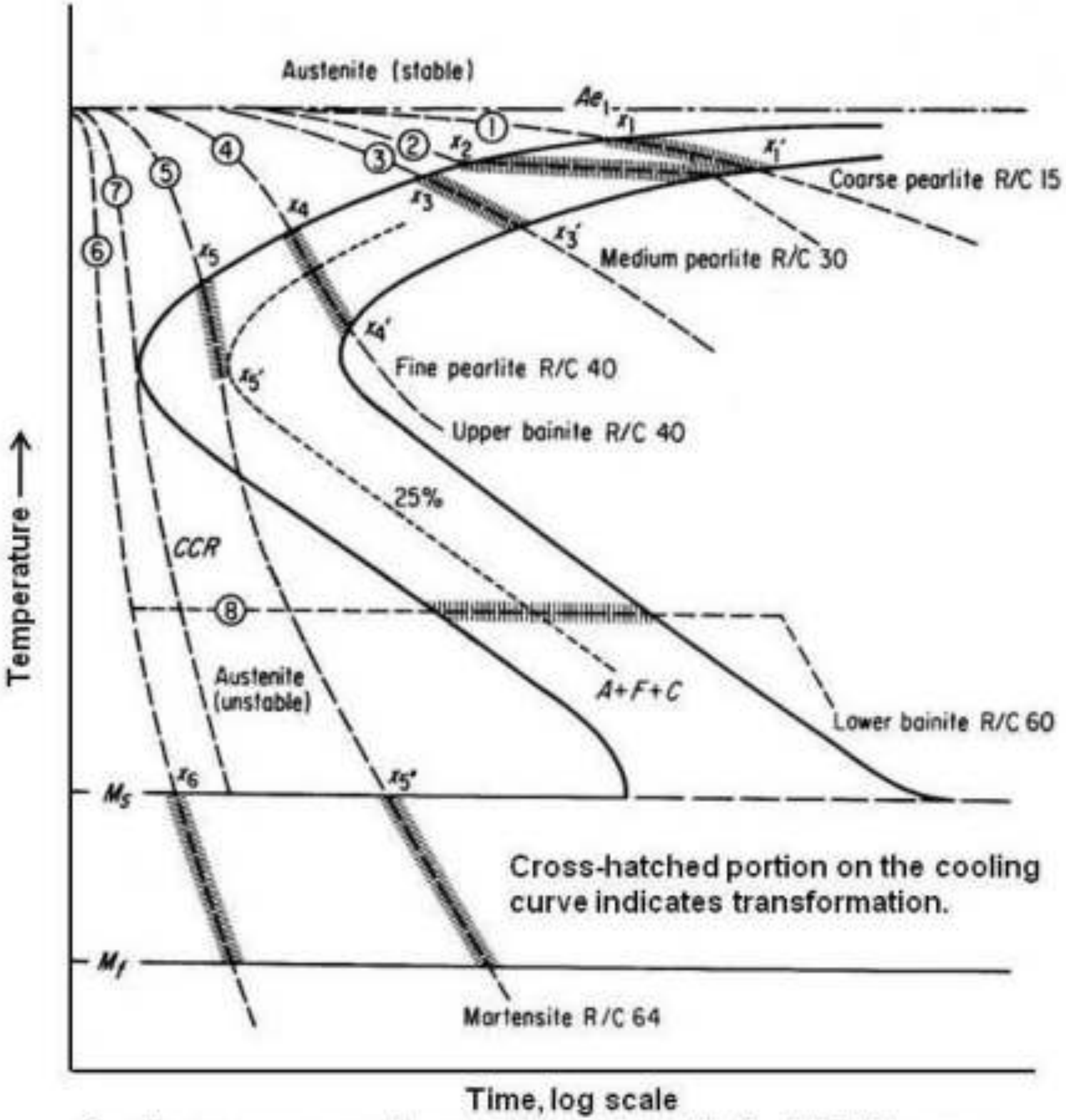


Maraging steels

Introduction

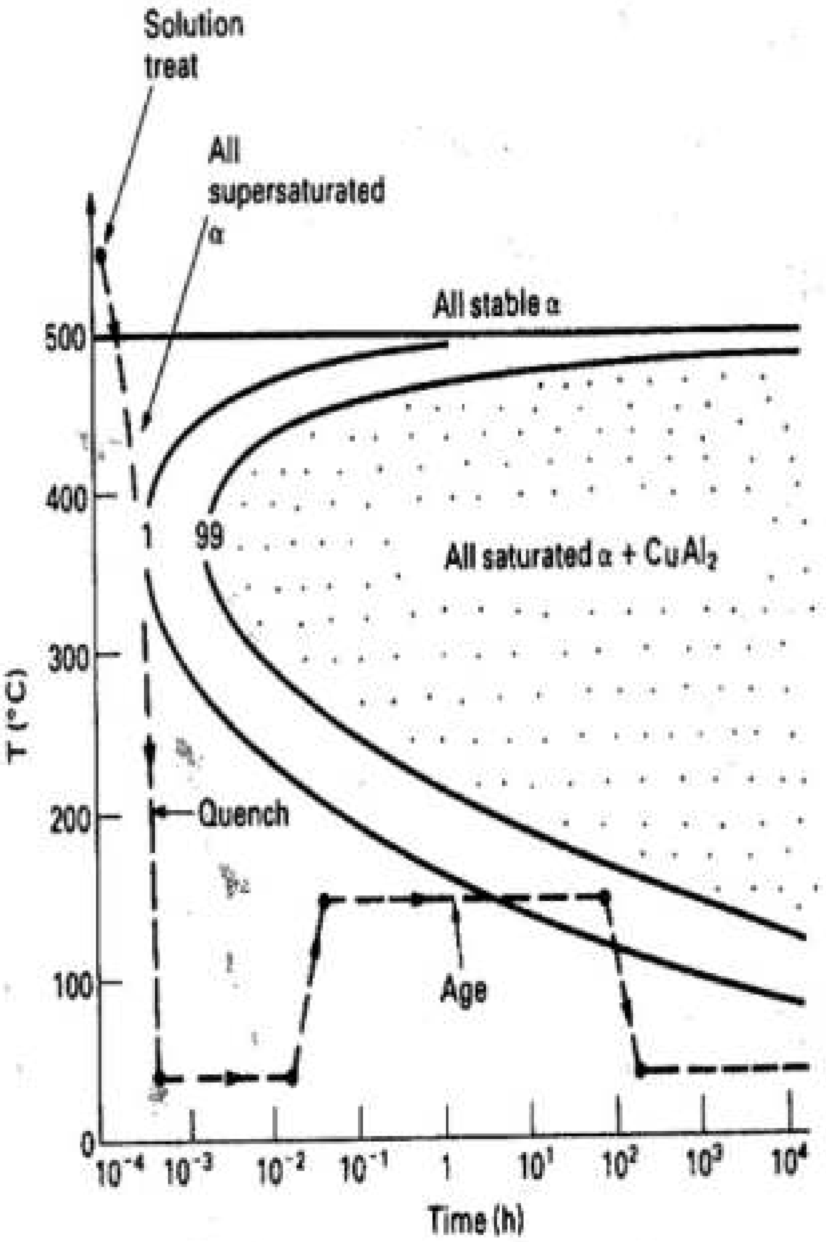
- MARAGING STEELS are *low-carbon < 0.02%,* iron-nickel steels that possess an excellent combination of strength and toughness superior to carbon-hardened steels
- Very high nickel, cobalt, and molybdenum contents and very low carbon contents.
- Strength due to the formation of iron-nickel martensite and then formation of **iron nickel intermetallic** compounds as precipitate phase during aging.
- Hence the name maraging steel – **Martensite + Aging**
- Carbon content in these **alloys is kept very low** in order to prevent the formation of TiC.


Composition (at% C)
0
5
10
15
20
25
1600
1400
1200
1000
800
600
400
Temperature (°C)
2500
2000
1500
1000
Temperature (°F)
1538°C
1493°C
δ
1394°C
L
γ + L
1147°C
2.14
4.30
γ, Austenite
912°C
γ + Fe3C
α
+
γ
727°C
0.76
0.022
α, Ferrite
α + Fe3C
Cementite (Fe3C)
0
1
2
3
4
5
6
6.70
(Fe)
Composition (wt% C)



Cross-hatched portion on the cooling curve indicates transformation.

Cooling curves superimposed on a hypothetical I-T diagram



- The martensite obtained is soft due to very low Carbon content

- This allow cold working of alloys to desired shape

- After cold working, this martensite is subjected to artificial ageing at 500 ^{0} C

- Due to ageing, strain induced precipitation hardening occur due to precipitation of intermetallic compounds.

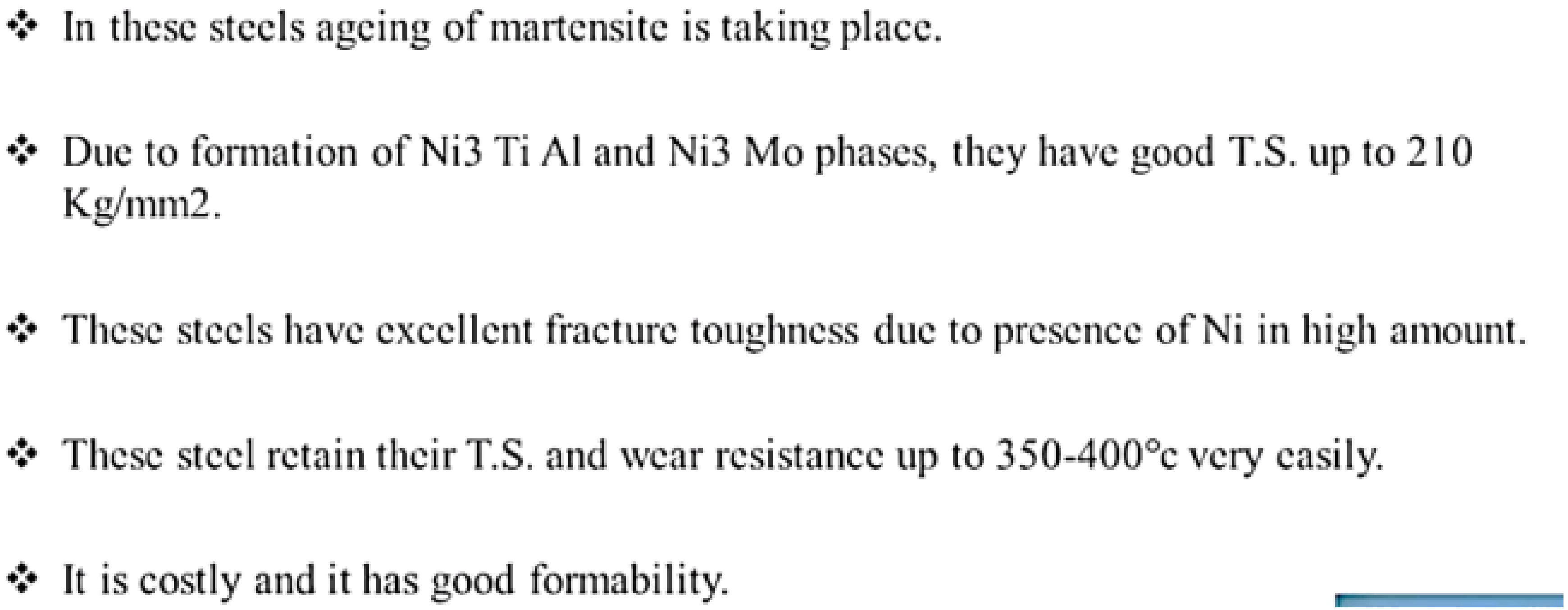
- Maraging steels are special class of high strength steels that differ from conventional steels in that they are hardened by a metallurgical reaction that does not involve carbon.
- Maraging steels are highly alloyed with **Ni, Co, and Mo** and possess yield strengths up to 2400 MPa.
- They derive such a high strength from age hardening of low carbon, Fe-Ni martensitic matrix.

- ***Maraging = Martensite + Aging***

Properties	Structural Steels	HSLA Steels	Maraging Steels
σ_Y (MPa)	250	350	1700
UTS (MPa)	400	490	1800
Ductility(%e)	40	18	13-15

Advantages of maraging steels

- High yield strength(2000-3000MPa)
- High weldability
- High fracture toughness
- Intricate shapes can be easily machined



- In these steels ageing of martensite is taking place.
- Due to formation of Ni3 Ti Al and Ni3 Mo phases, they have good T.S. up to 210 Kg/mm2.
- These steels have excellent fracture toughness due to presence of Ni in high amount.
- These steel retain their T.S. and wear resistance up to 350-400°c very easily.
- It is costly and it has good formability.

- Maraging steels are a specific class of carbon-free (or small amounts) ultrahigh-strength steels that derive their strength not from carbon but from precipitation of intermetallic compounds and martensitic transformation

- The commonly available maraging steels contain 10–19% Ni, 0–18% Co, 3–14% Mo, 0.2–1.6% Ti, 0.1–0.2% Al, and some intermetallic compounds are Ni_3Ti, Ni_3Mo, Fe_2Mo, etc. Since these steels develop very high strength by martensitic transformation and subsequent age-hardening, they are termed maraging steels.

- There are four types of maraging steels, namely 200,250,300,and 350 grades;

- The number refers to the ultimate tensile strength in ksi (kpsi). The tensile strength is based on the Ti content, which varies between 0.2 and 1.85%.

- In these grades, C content is maintained at a very low level (<0.02%); the sum of Si and Mn is lower (0.2%); and P and S contents are also very small (<0.005 and <0.008%, respectively)

- Carbon content restricted to less than 0.02%

Applications

- Maraging steels have found applications where lightweight structures with ultrahigh strength and high toughness are essential and cost is not a major concern.

- Aerospace and aircraft industry for critical components such as missile cases, load cells, helicopter flexible drive shafts, jet engine drive shafts, and landing gear.

- Tool manufacturing industries for stub shafts, flexible drive shafts, splined shafts, springs, plastic molds, hot-forging dies, aluminum and zinc die casting dies, cold- heading dies and cases, diesel fuel pump pins, router bits, clutch disks, gears in the machine tools, carbide die holders, auto frettage equipment, etc.

Typical Grades:

Grade	Ni	Mo	Co	Ti	Al
18Ni 200 grade	18	3.3	8.5	0.2	0.1
18Ni 250 grade	18	5.0	8.5	0.4	0.1
18Ni 300 grade	18	5.0	9.0	0.7	0.1
18Ni 350 grade	18	4.2	12.5	1.6	0.1

Advantages of maraging steels:

- Good combination of strength and toughness
- No quench crack problems.
- Good dimensional stability during heat treatment.
- Excellent workability and machiniability.
- They can be hot- worked as well as cold- worked.
- No danger of decarburization during any stage of thermal processing.
- Good weldability

Strength of maraging steels

1. Formation of lath martensite
2. Precipitation/age hardening of lath martensite

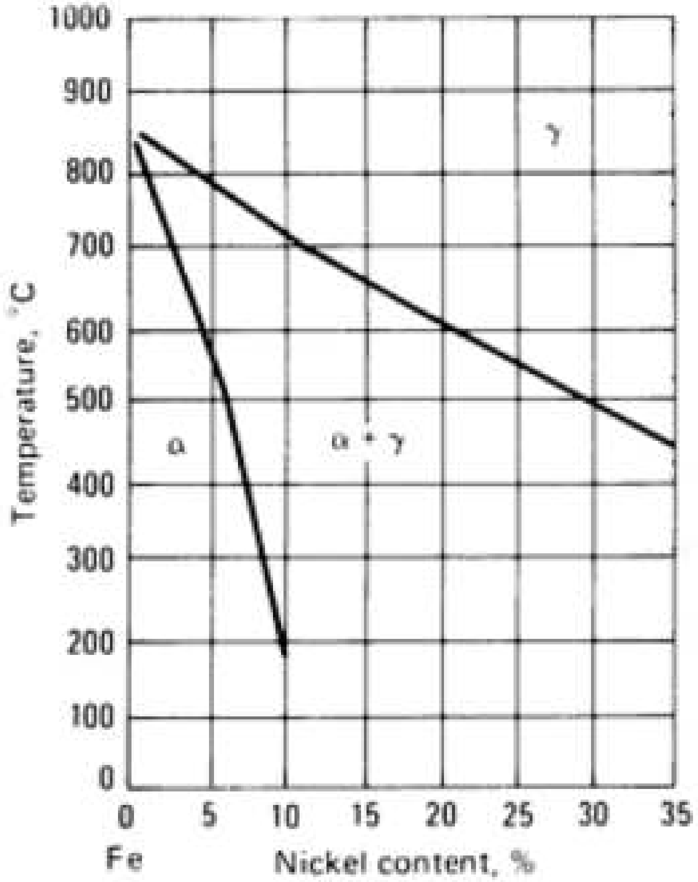
1. Formation of iron nickel lath Martensite

- Iron nickel martensite – martensitic structure formed when iron nickel alloy is heated above 800 °C (austenite formation temperature) and then cooled to temp below 300 °C

- Iron nickel martensite is called lath martensite with **BCC** structure formed by **diffusionless** transformation of FCC austenite (no diffusion to α phase during cooling, but crystal structure changes from FCC to BCC)

- **LATH martensite is not as hard as ordinary martensite but more tough and ductile.**

Phase diagram of iron nickel alloys



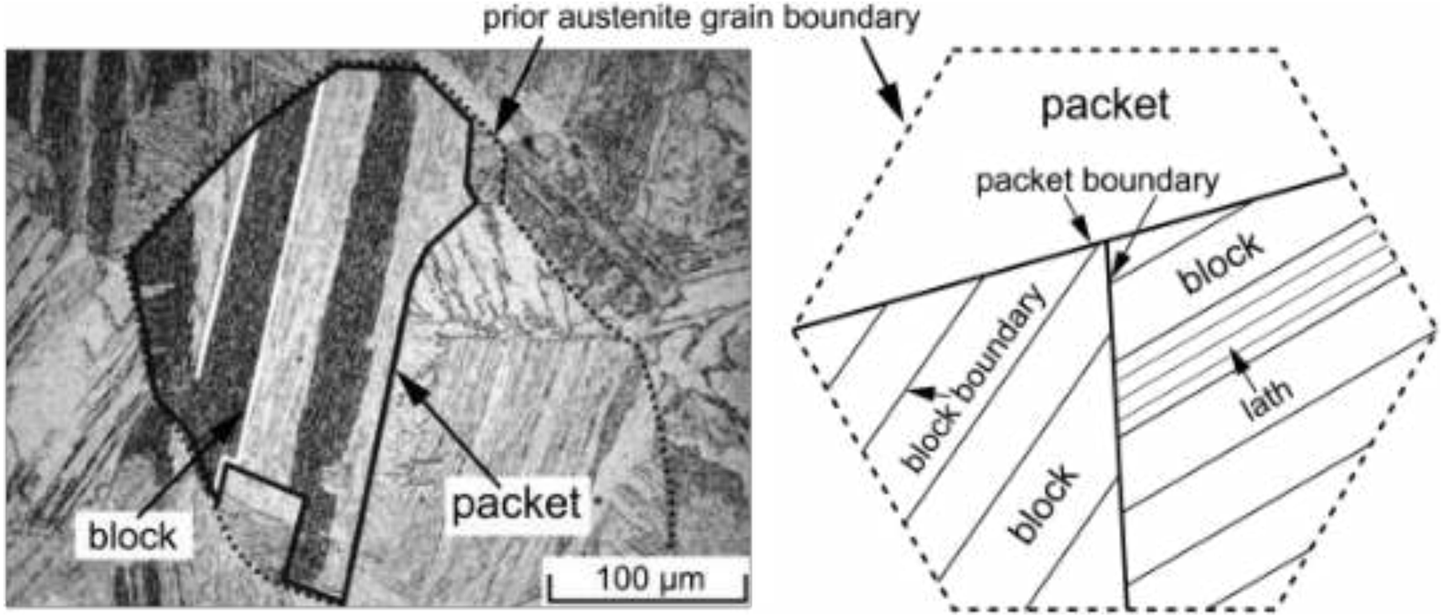
- Nickel levels > 18% results in the retention of austenite and thus prevent complete transformation into martensite
- **18 Ni chosen** as the standard maraging steel composition as it prevent complete transformation into martensite during quenching

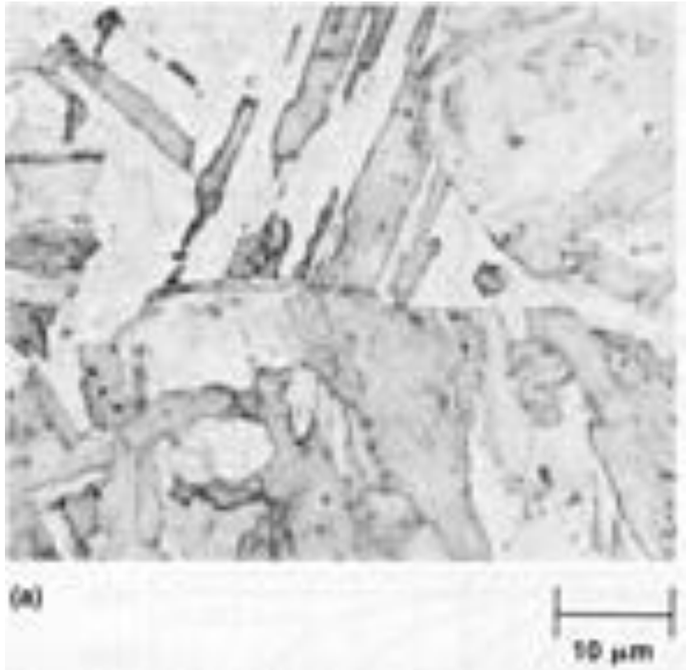
Martensite formation & morphology

- For iron containing 5 to 10% Ni, martensite is formed with **rapid cooling**
- Excess of 10% Ni lowers the cooling rate required for martensite formation
- lath martensite is formed in iron containing up to 23% Ni
- If the nickel content is increased above 23%, the lath martensitic structure is replaced by a **twinned martensite**
- **Lath martensitic structure is preferred in maraging steels because**, following aging, this structure is ***tougher*** than a twinned martensitic structure

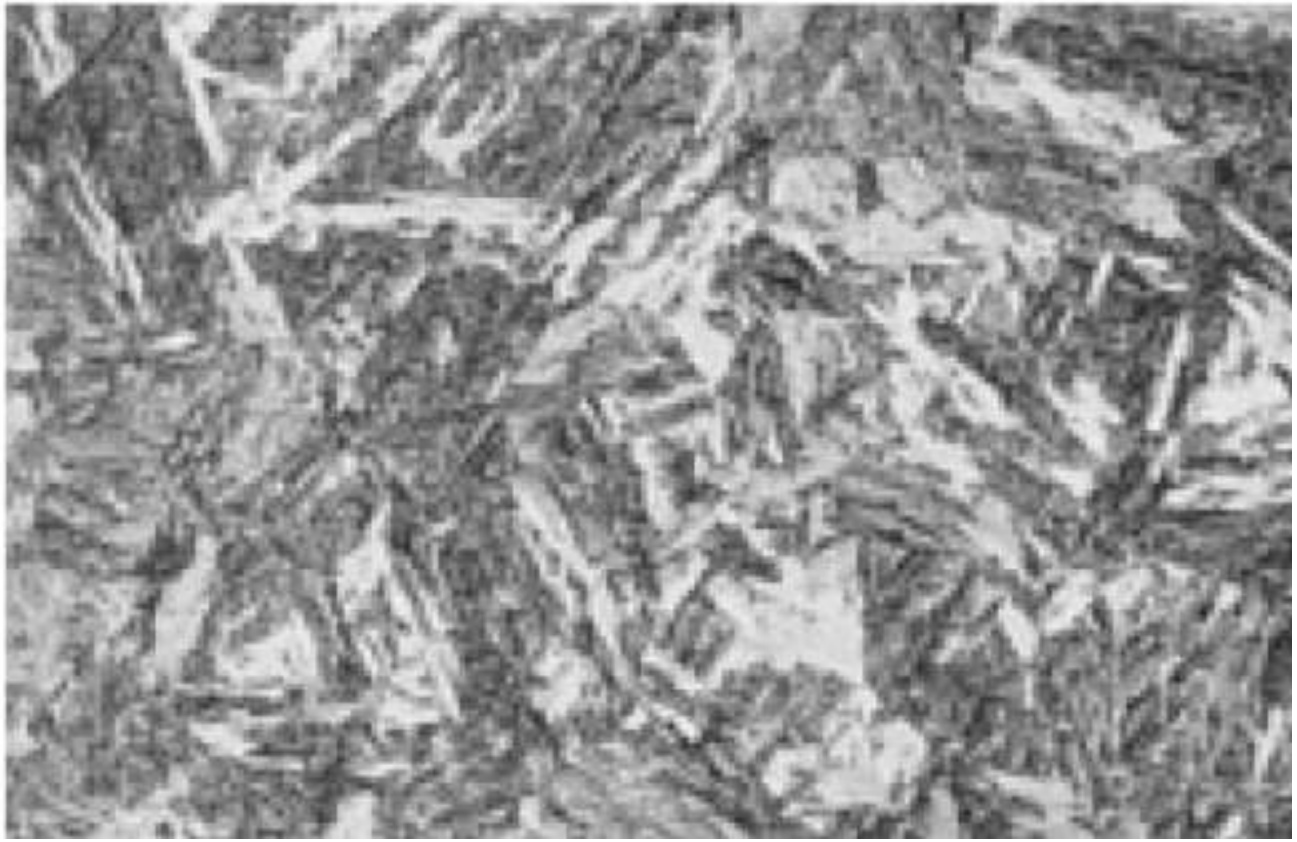
Lath martensite

- The lath martensitic structure of maraging steels consists of several martensitic packets and numerous blocks within each packet
- Packets and blocks are planar, lie along one direction, and are parallel to each other
- Packets are the predominant structure of lath martensite followed by the block structures that appear as discrete areas within each packet





- The martensite is normally a low-carbon, body-centered cubic (bcc) lath martensite containing a high dislocation density but no twinning. This martensite is relatively soft (30 HRC), ductile, and machinable

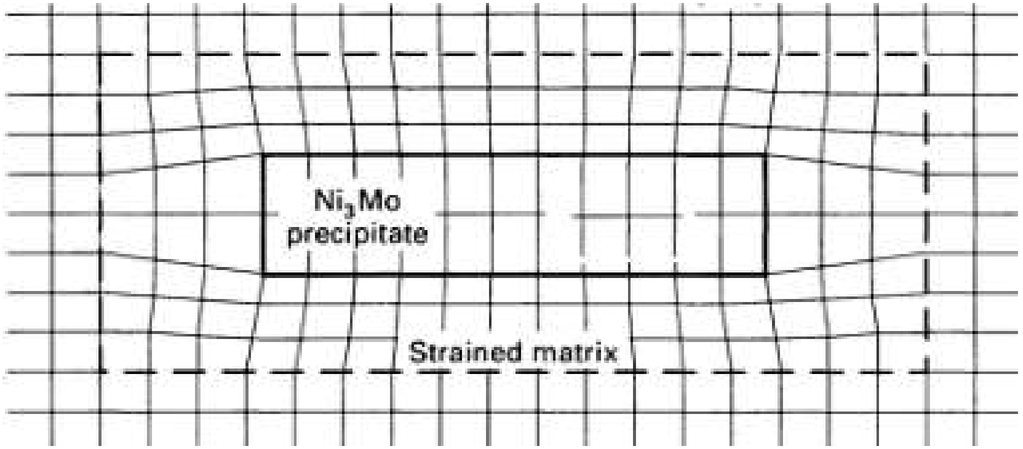


- The low carbon martensite formed after annealing has hardness value very low (30-35 HRC). Intricate shapes can be machined in soft conditions and then it can be hardened as there is only a slight change in dimensions during age hardening.

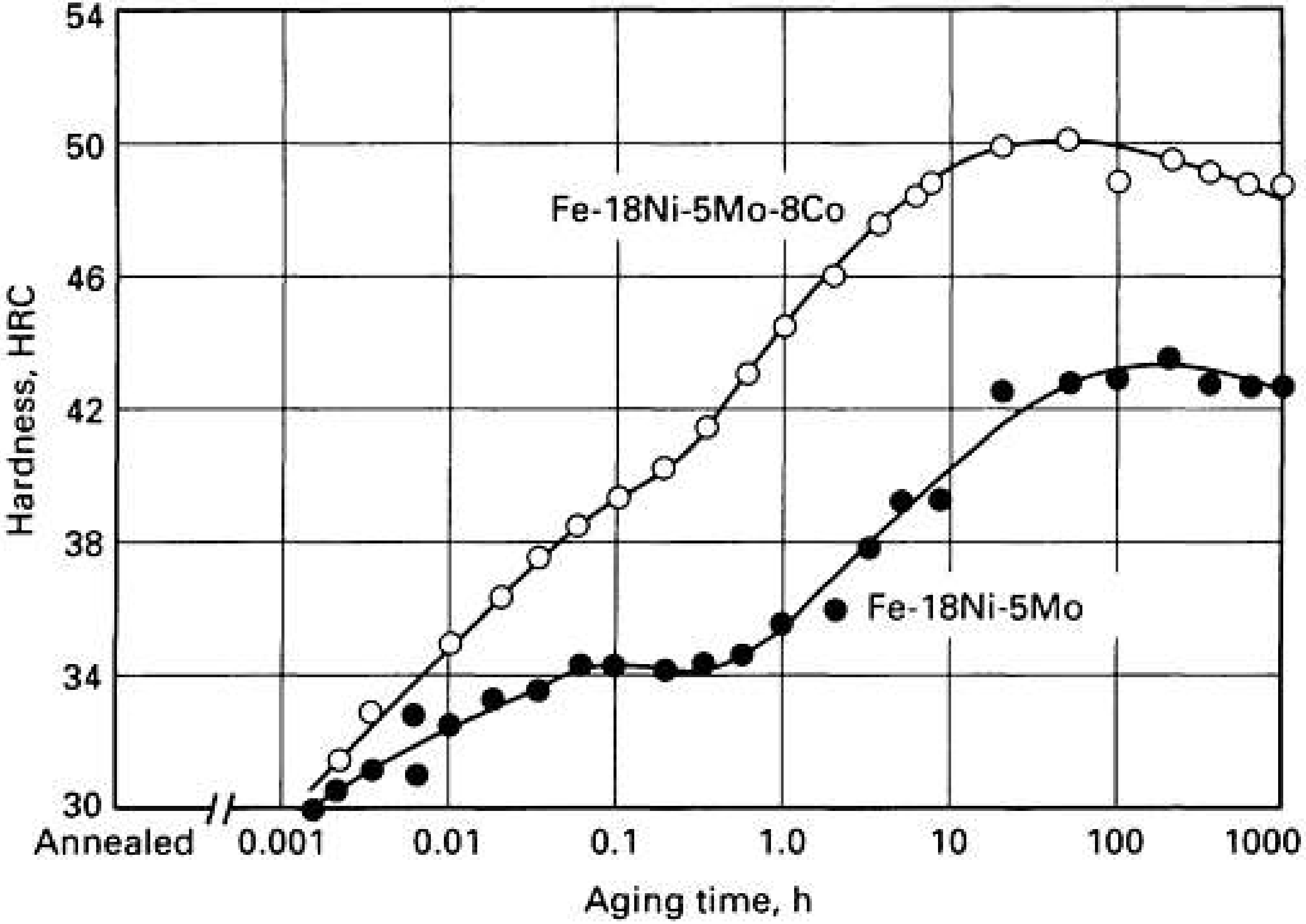
- The precipitate particles are of a lattice size comparable to that of the martensite matrix and cause little distortion of the matrix. This characteristic, together with the absence of carbon, allows the steel to be age hardened to very high strength levels while minimizing changes in the shape of the part being hardened.

2. Precipitation Aging of lath martensite

- Lath martensite is again reheated in the temperature range 450-500 °C and aging is done for a certain time period(1 – 6 hr)
- Aging is done to minimize or eliminate the reversion of martensite into austenite(γ) and ferrite(α)
- During aging, ***ordered precipitate phase*** of **nickel-rich intermetallic compounds** is formed in the lath martensitic structure
- Precipitation of the Ni_3Mo and Ni_3Ti intermetallic compounds

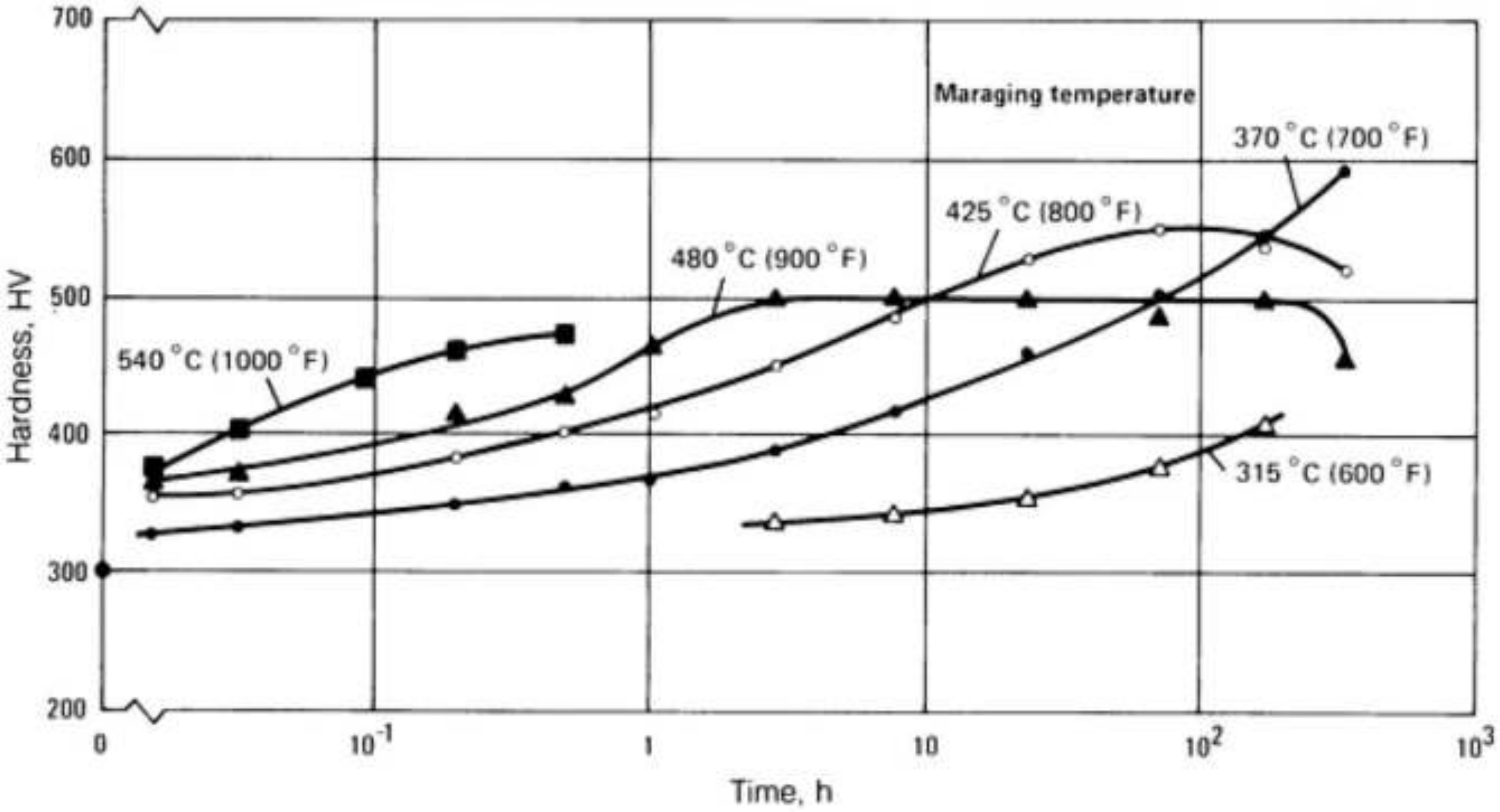


Effect of aging time on hardness



Plots of aged hardness versus aging time at 455 °C (850 °F) for Fe-18Ni-5Mo and Fe-18Ni-5Mo-8Co maraging steels

Effect of aging time on hardness



Hardness of 18Ni(250) maraging steel versus aging time for various aging temperatures

- The above graph clearly shows that the hardness first increases and then decreases with the increase in the time of aging because of the fact that its structure has a tendency to revert to equilibrium phases-mainly ferrite and pearlite on prolonged aging but enough hardness is achieved up to 1035 MPa before this reaction starts.

- This softening occurs due to 2 reasons

  a) over aging i.e. coarsening of precipitate particles.

  b) austenitic reversion

These two processes are interlinked i.e. the dissolution of metastable nickel-rich precipitate particle in favor of equilibrium iron rich precipitate locally enriches the matrix in nickel, which favors austenite formation.

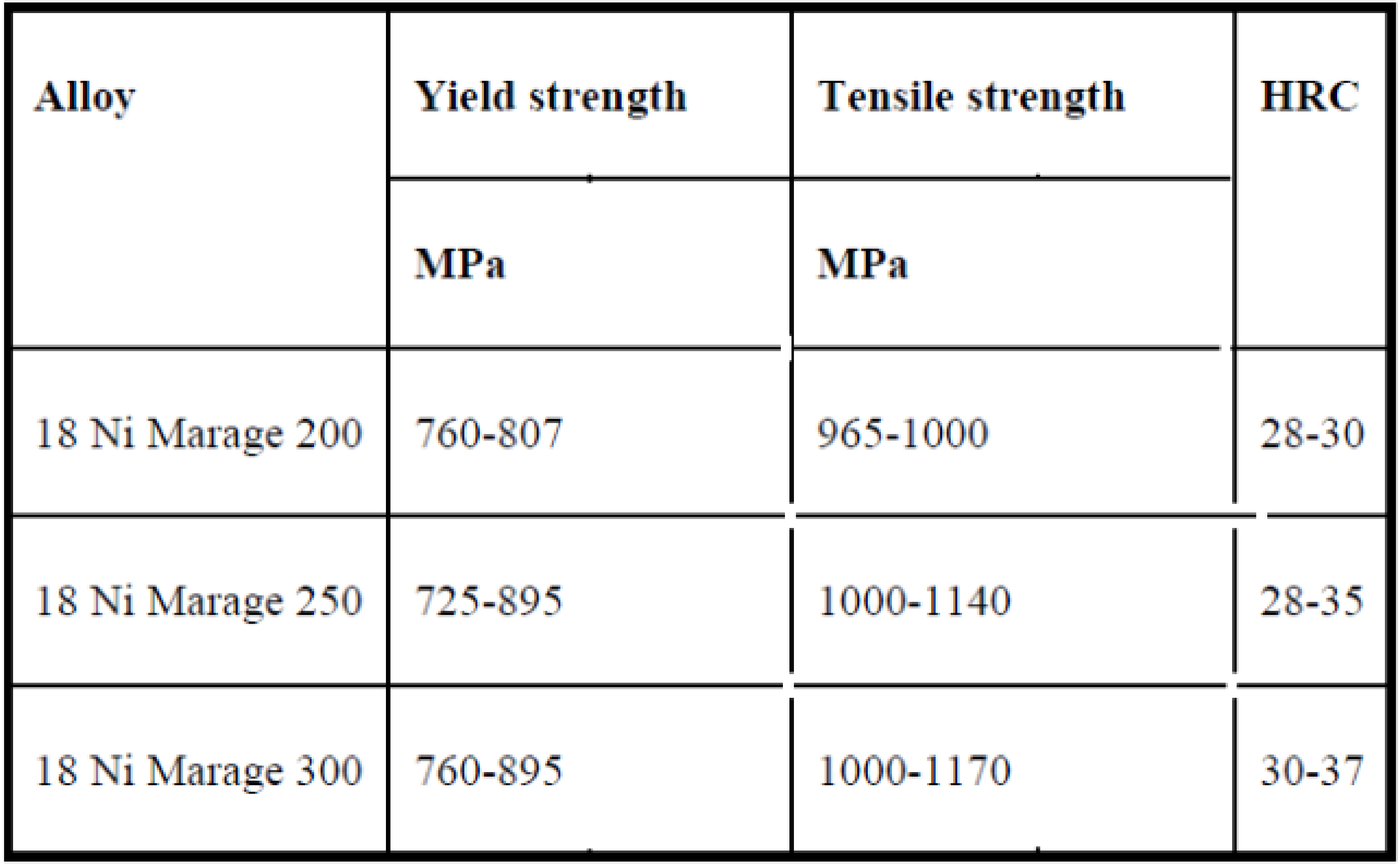
Effect of Ti, Mo and Cobalt

- Ti – strong hardener and Mo - Moderate hardener
- Co helps the precipitation of Ni_3Mo and a finer, more uniform distribution of Ni_3Mo precipitates is formed
- The good structural fit between (Ni_3Mo and Ni_3Ti) precipitates and the BCC martensitic matrix gives coherence and ordered precipitate phase necessary for required hardness and toughness

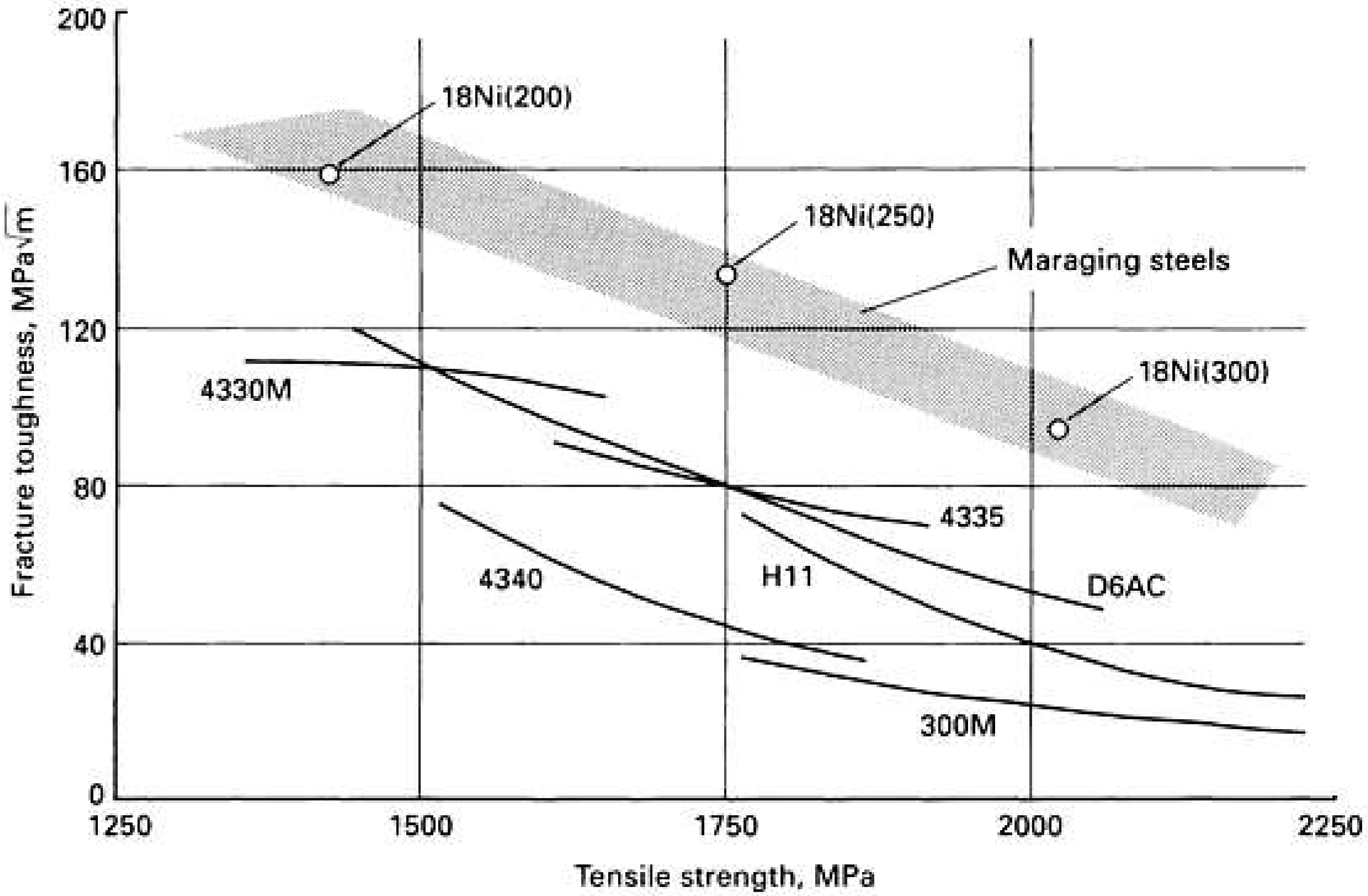
Effect of alloying elements – Ni, Mo, Ti, Co, Al

- Ni, Mo, Ti – lowers M_s (martensite formation start – 200-300 ^{0}C) temperature, low M_s favors formation of twinned martensite which is not desirable
- Ni, Mo, Ti – helps in precipitation hardening(desirable)
- Co – increases M_s temp and favors formation of lath martensite (upto 6-8% composition)
- Hence Co added to compensate for excess use of Ni, Mo, Ti and maintains Ms temperature required for lath martensite formation
- In the absence of cobalt, other elements such as nickel, molybdenum, and titanium must be maintained or reduced to levels to ensure an adequately high Ms temperature
- Nickel lowers Ms temperature heavily if in excess of 18%, hence Ni level kept at 18%
- Upto 0.1% Al slightly increases Ms temperature

Variation of strength and hardness in maraging steels



Alloy	Yield strength	Tensile strength	HRC
	MPa	MPa	
18 Ni Marage 200	760-807	965-1000	28-30
18 Ni Marage 250	725-895	1000-1140	28-35
18 Ni Marage 300	760-895	1000-1170	30-37



Strength/toughness combination of 18 Ni maraging steels compared to conventional high-strength carbon steels

Super Plasticity

- Super plasticity is the ability of some metals and alloys to deform as much as 20 times at elevated temperature and slow loading rates.
- These metals or alloys will not show super plasticity when loaded at normal temperature.

Conditions for super plasticity

The following conditions are to be met by the material & loading process to attain super plasticity

1. The material should have very fine grain size. (5-10µm)
2. Loading temperature should be high. ($> 0.5\ T_m$)
3. A low loading rate should be adopted and it should be strain rate sensitive.

Advantages of super plastic forming

1. Reduced number of assembly operations,
2. Reduced number of fastening holes to be drilled, which will prevent initiation of fatigue cracks due to stress concentration.
3. Reduced weight of the component with increased durability,
4. Reduced tooling & manufacturing cost.

Applications of super plasticity

The property of super plasticity is widely used in metal forming process like,

1. Thermo forming
2. Blow forming
3. Vacuum forming
4. Deep drawing

- ❖ Deep or complex shapes can be made as one piece by single operation pressing, thus avoiding multistep conventional pressing or multi piece assemblies.

- The four variables measured during a creep test are stress, strain, temperature and time. The test is carried out at constant temperature by applying a fixed load or stress and the induced strain in the specimen is noted at regular intervals of time.
- The specimen of the same dimensions used for the tensile test is usually employed for creep testing. For applying a constant load, the test setup requires a dead weight and a system of levers to multiply it to the targeted load.

- In order to conduct a creep test at elevated temperature, the specimen needs to be placed in an electric furnace.
- Now the specimen can be heated to a specified temperature and at the same time a constant load can be applied using the setup as shown in figure.

- The resulting strain in the specimen is measured using a strain gauge or an extensometer. The test is repeated with four or five specimens tested under different loads at each temperature.
- The change in length (strain) of the specimen over a period of time is plotted against time to obtain a creep curve. The characteristics of creep are studied based on the creep curve obtained.

Super plasticity

- Super plasticity refers to the ability of some metals and alloys, such as aluminium and titanium alloys, to deform as much as 2000 percent at elevated temperatures and slow loading rates. These alloys do not behave super plastically when loaded under normal temperatures

To achieve superplastic behavior, the material and the loading process must meet the following conditions.

- The material must possess very fine grain size (5-10mm)
- It must be highly strain rate sensitive
- A high loading temperature, greater than 50 percent of the melting temperature of the metal (>0.5T_m)
- A low and controlled strain rate. (0.01-0.001 s-1)

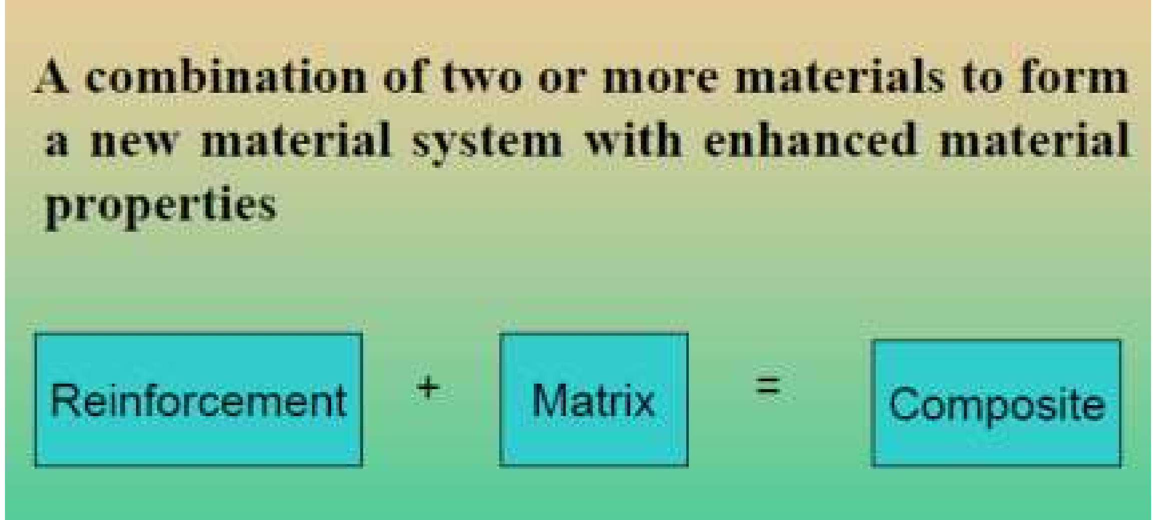
- The deformation mechanisms like grain boundary sliding, grain boundary diffusion (or grain boundary migration) which are operative at elevated temperatures are responsible for superplastic behavior.
- At elevated temperatures a large amount of strain is believed to be accumulated by the sliding and rotation of individual grains or clusters of grains.

Application

- The property of superplasticity has been widely made use of in metal forming processes like thermoforming, blow forming, vacuum forming, deep drawing etc. for the production of large complex shaped products.
- Deep or complex shapes can be made as one piece, single operation pressings, rather than multistep conventional pressings or multipiece assemblies.
- The elevated temperatures required to promote superplasticity also reduce the flow stress of the material and thereby the force requirements.

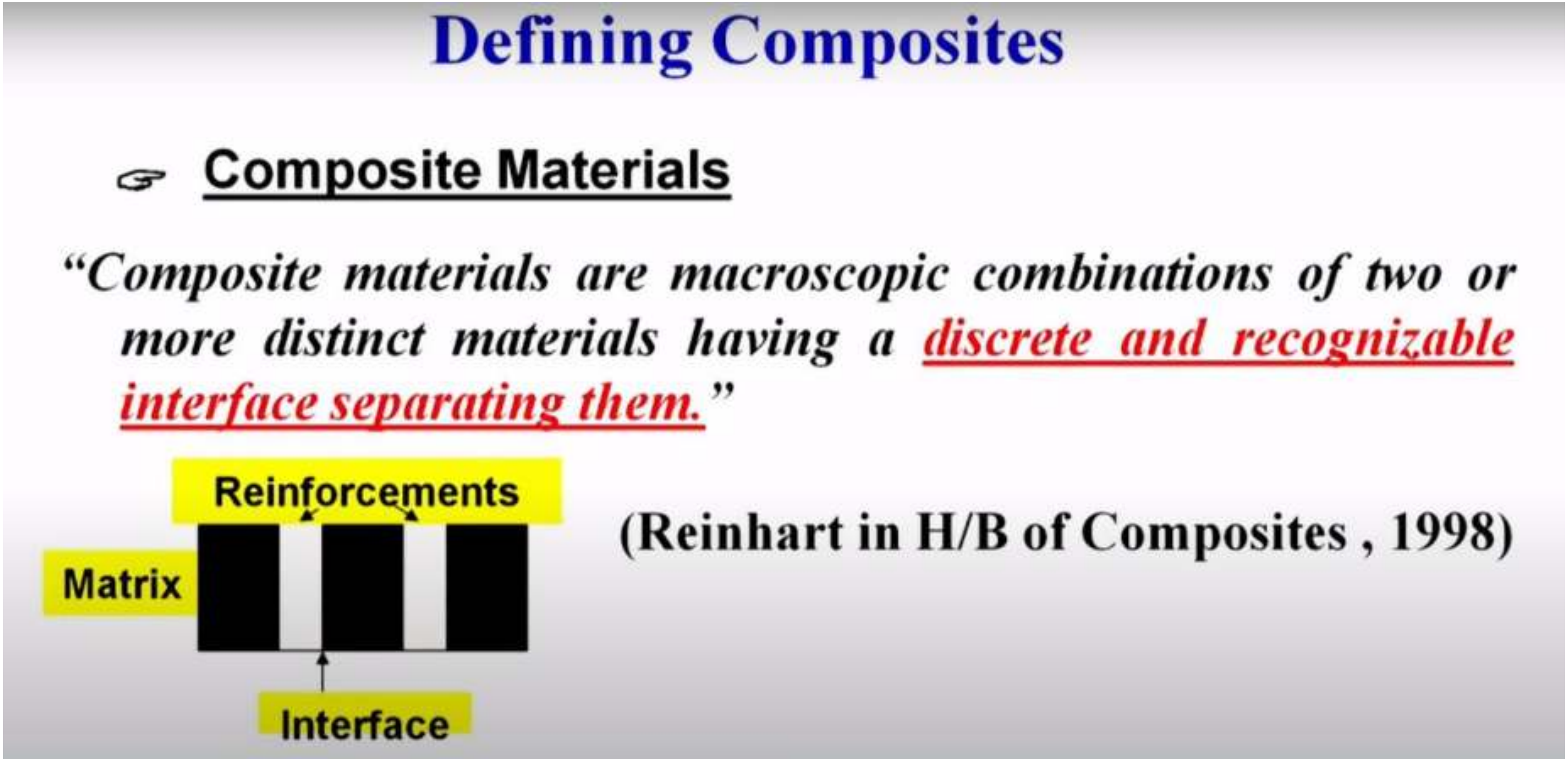
Composites / Composite Materials

- Composites are combinations of two materials in which one of the materials, called the **reinforcing phase** (in the form of fibers, sheets, or particles) is embedded in other material called **matrix phase**.
- It can be defined as a combination of two or more dissimilar materials having a distinct interface between them such that the properties of the resulting materials are superior to the individual constituting components.
- The reinforcing material and the matrix material can be metal, ceramic, or polymer.



A combination of two or more materials to form a new material system with enhanced material properties

Reinforcement + Matrix = Composite

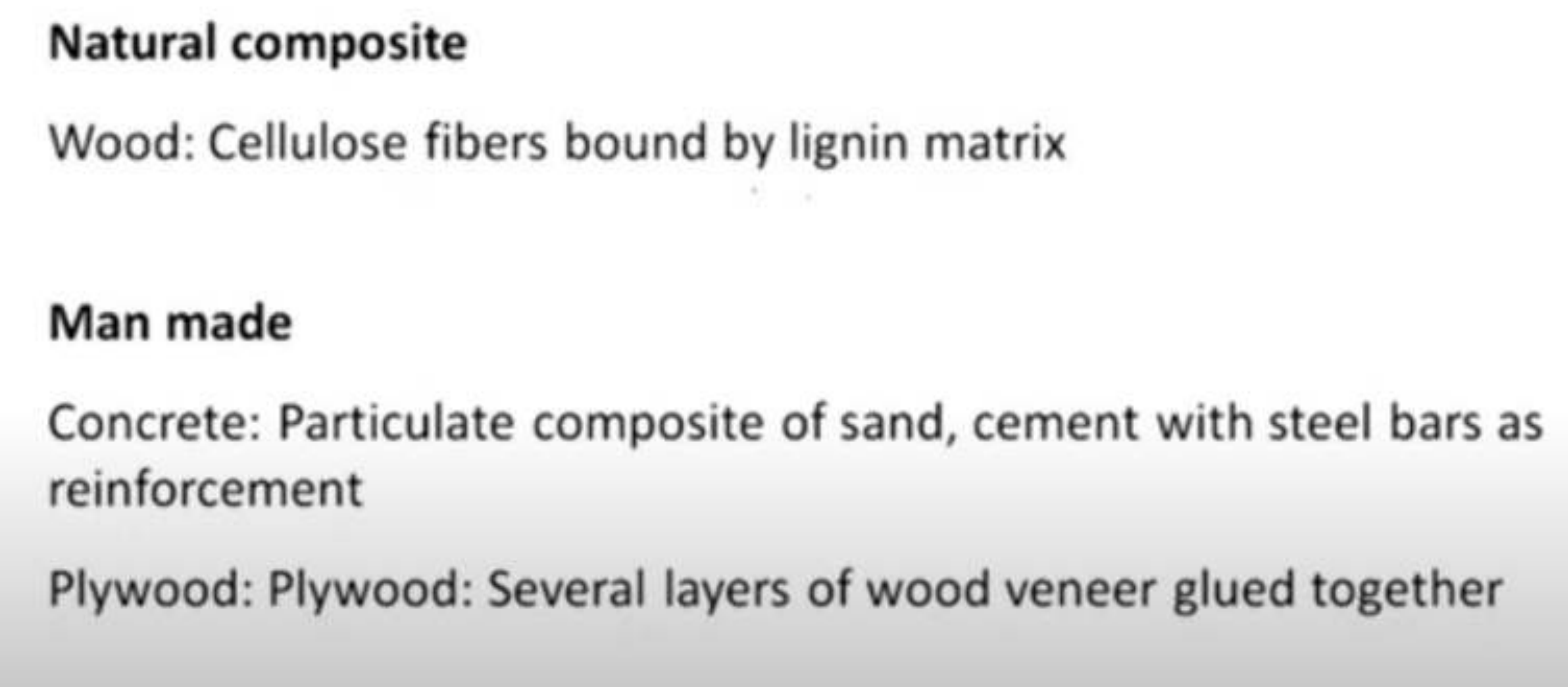


Defining Composites

- **Composite Materials**

"Composite materials are macroscopic combinations of two or more distinct materials having a discrete and recognizable interface separating them."

(Reinhart in H/B of Composites , 1998)



Natural composite

Wood: Cellulose fibers bound by lignin matrix

Man made

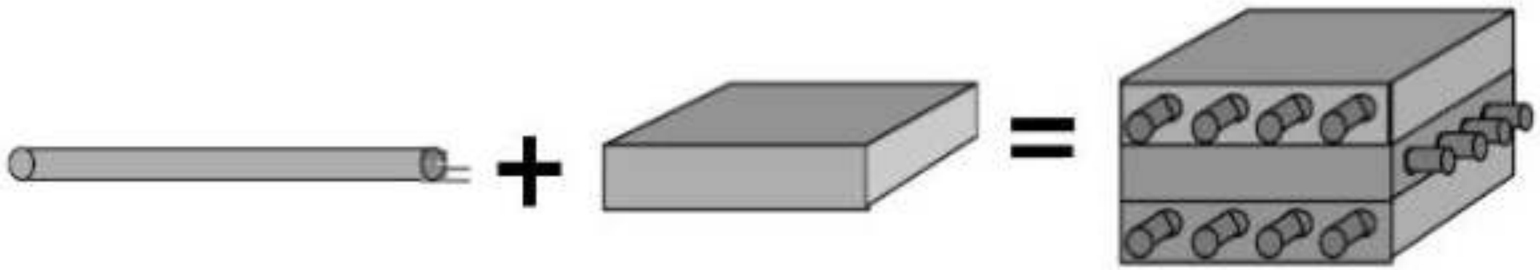
Concrete: Particulate composite of sand, cement with steel bars as reinforcement

Plywood: Plywood: Several layers of wood veneer glued together

E.g. Reinforced concrete
Concrete (Matrix) + Steel (Reinforcement)

Wood --- Lignin (Matrix) + Cellulose fibre (Reinforcement)

Composition of Composites



Fiber/Filament Reinforcement

- High strength
- High stiffness
- Low density

Matrix

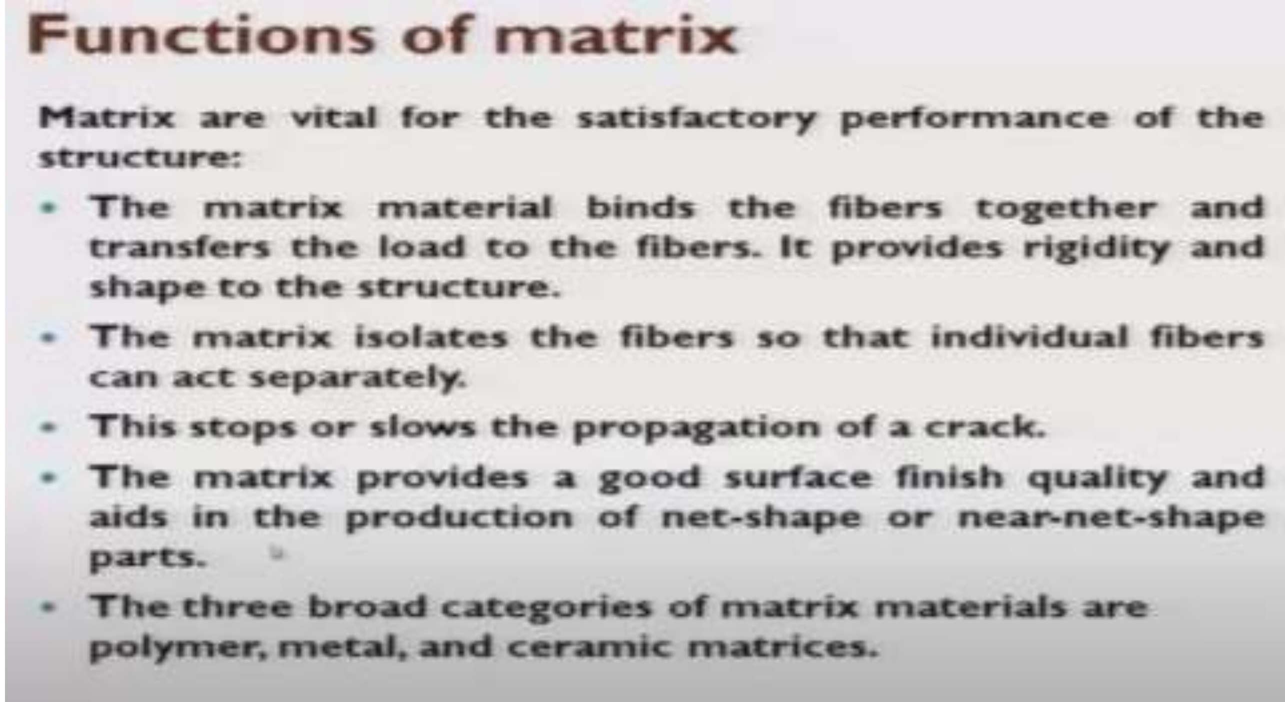
- Good shear properties
- Low density

Composite

- High strength
- High stiffness
- Good shear properties
- Low density

Components in a Composite Material

- **Matrix**
  - Material that holds the reinforcements in place.
  - Provides the bulk form of the part or product made of the composite material.
  - When a load is applied, the matrix shares the load with the reinforcing element.



Functions of matrix

Matrix are vital for the satisfactory performance of the structure:

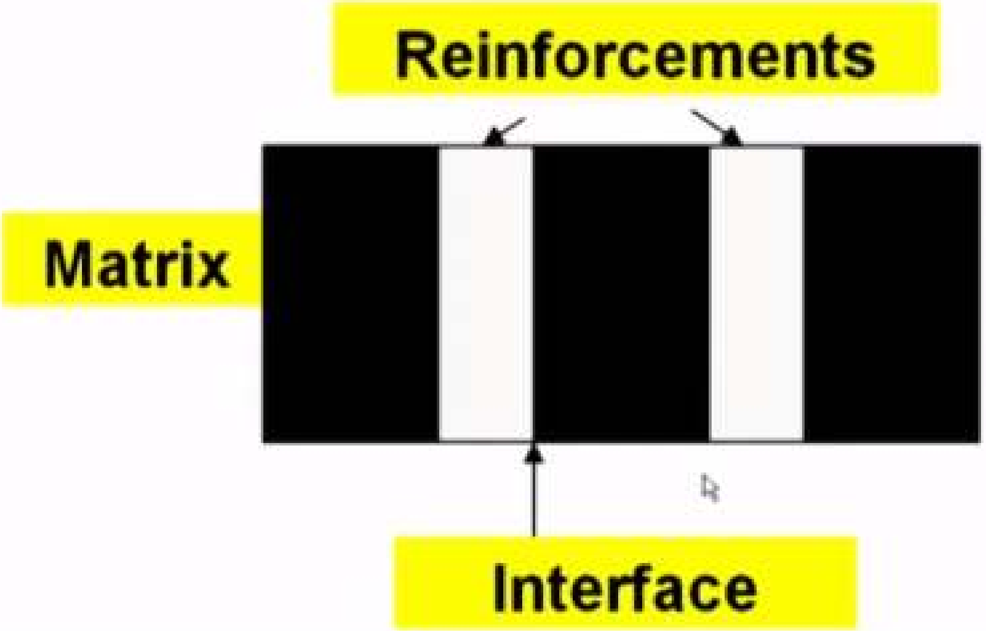
- **The matrix material binds the fibers together and transfers the load to the fibers. It provides rigidity and shape to the structure.**
- **The matrix isolates the fibers so that individual fibers can act separately.**
- **This stops or slows the propagation of a crack.**
- **The matrix provides a good surface finish quality and aids in the production of net-shape or near-net-shape parts.**
- **The three broad categories of matrix materials are polymer, metal, and ceramic matrices.**

Role of constituent phase (matrix)

- The matrix material holds the fibres together.
- The matrix plays an important role to keep the fibres at desired positions. The desired distribution of the fibres is very important from micromechanical point of view.
- The matrix keeps the fibres separate from each other so that the mechanical abrasion between them does not occur.
- It transfers the load uniformly between fibers. Further, in case a fibre is broken or fibre is discontinuous, then it helps to redistribute the load in the vicinity of the break site.
- It provides protection to fibers from environmental effects.
- It provides better finish to the final product.
- The matrix material enhances some of the properties of the resulting material and structural component (that fibre alone is not able to impart). For example, such properties are: transverse strength of a lamina, impact resistance

Components in a Composite Material

- **Reinforcing element**
  - Material that provides strength (Reinforcement) to the matrix



Reinforcements

Matrix

Interface

Role of reinforcement phase

- In most of the composites the load on the material is mainly born by the reinforcing phase.
- The reinforcing phase, embedded in the matrix, may be present in the form of either particles or fibers.
- The reinforcing phase is usually of low density, strong, stiff and thermally stable in nature.
- These are the main load carrying constituents.
- The reinforcing materials, in general, have significantly higher desired properties. Hence, they contribute the desired properties to the composite.
- It transfers the strength and stiffness to the matrix material.

Classification

A material is classified as composite If…

- Both constituents are present in reasonable proportion (>5%).
- Composite properties are noticeably different from the properties of the constituents.
- A man-made composite is usually produced by intimately mixing and combining the constituents.

Types of composites

Composites primarily consist of

Matrix – ductile but with low strength

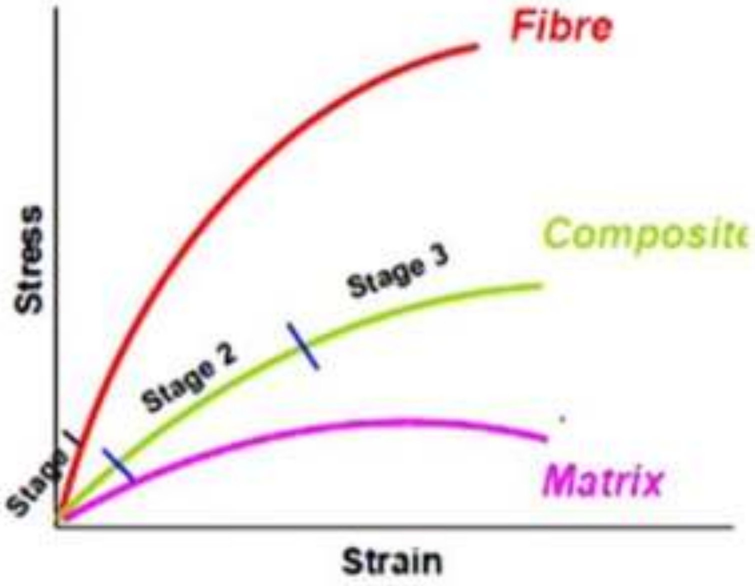
Reinforcement – strong but may be brittle

- ➢ The matrix transfer the load to the fibres
- ➢ Protect fibers from surface damage

Carbon fibre reinforced epoxy crossply laminate

Silicon carbide particulate reinforced aluminium

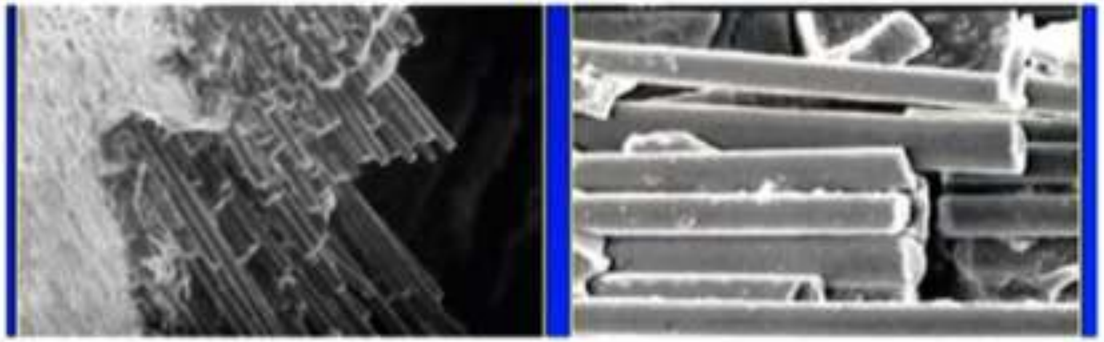
Silicon carbide monofilament reinforced glass ceramic



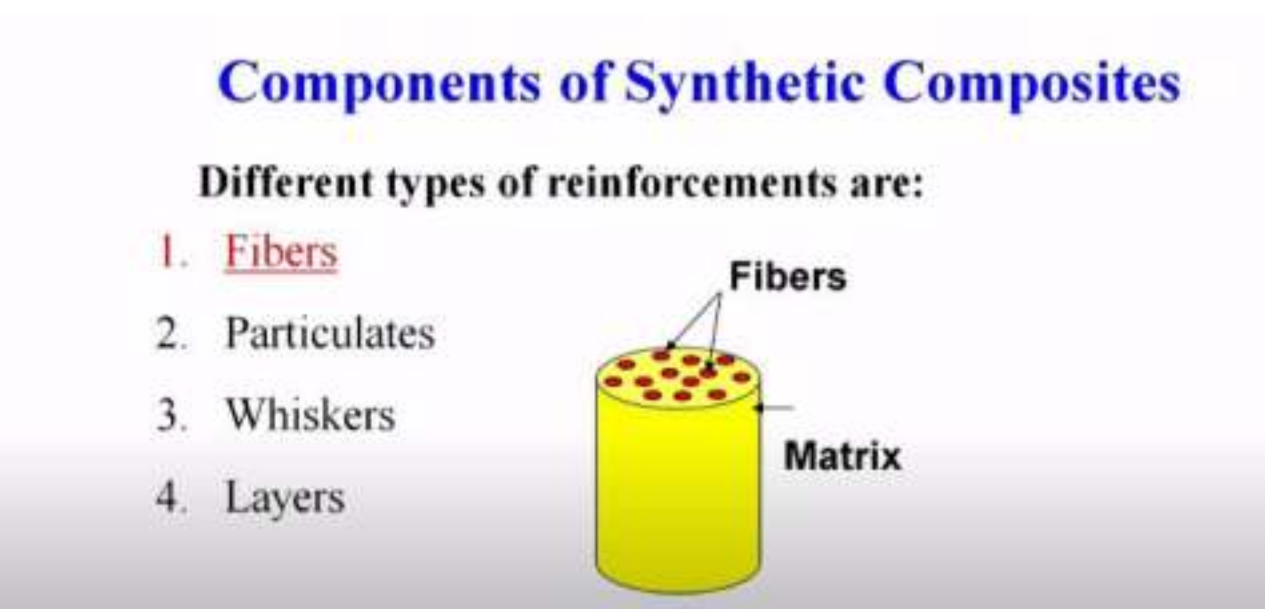
Stage 1 – Both fibres and matrix undergo elastic deformation

Stage 2 – Matrix deform plastically but fibres defrom elastically

Stage 3 – Both matrix and fibres undergo plastic deformation



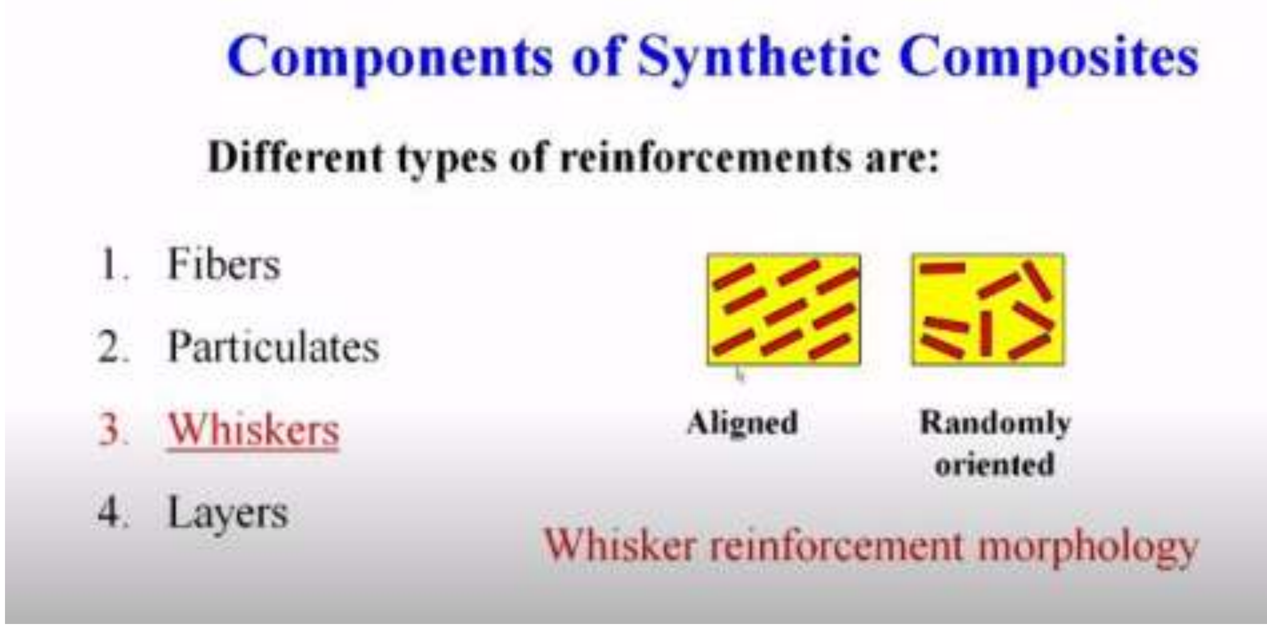
Pull out and breakage of fibres



Components of Synthetic Composites

Different types of reinforcements are:

1. Fibers
2. Particulates
3. Whiskers
4. Layers

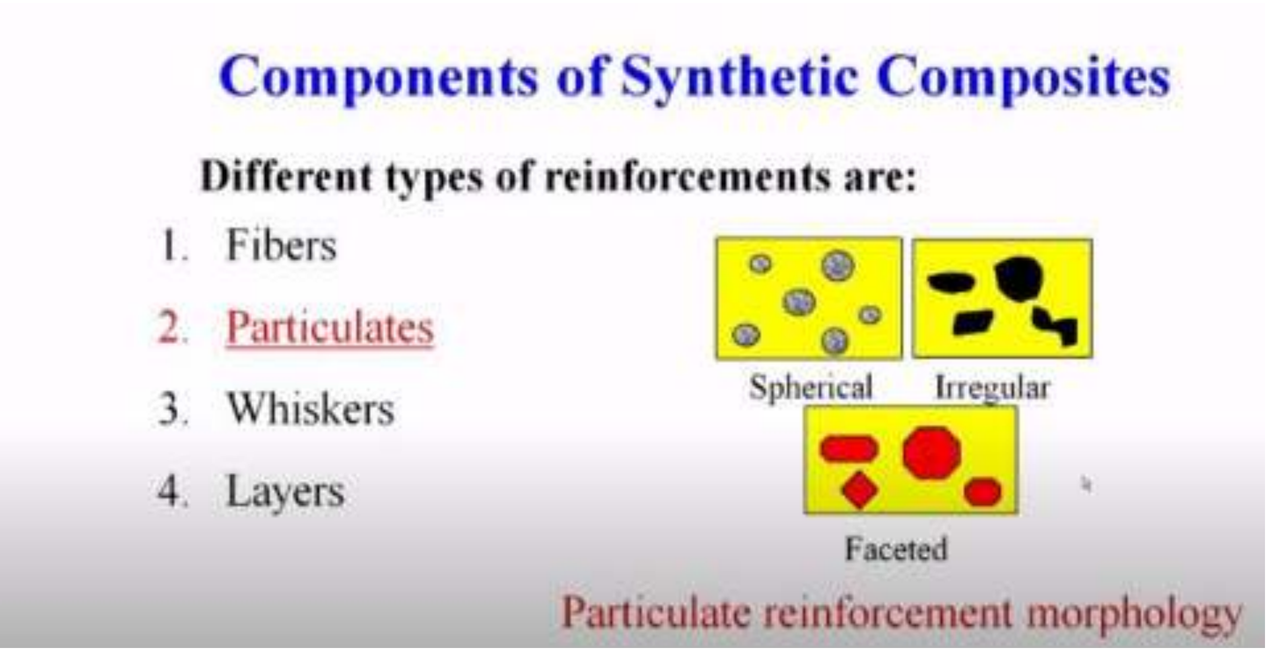


Components of Synthetic Composites

Different types of reinforcements are:

1. Fibers
2. Particulates
3. Whiskers
4. Layers

Whisker reinforcement morphology

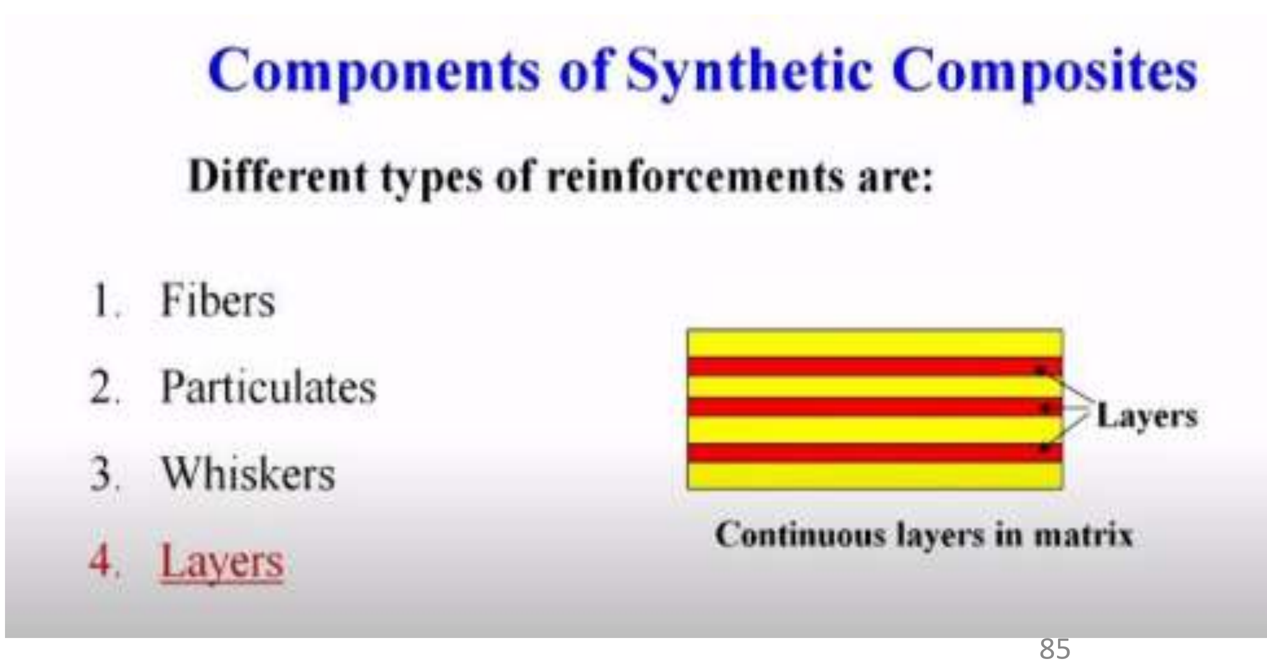


Components of Synthetic Composites

Different types of reinforcements are:

1. Fibers
2. Particulates
3. Whiskers
4. Layers

Particulate reinforcement morphology

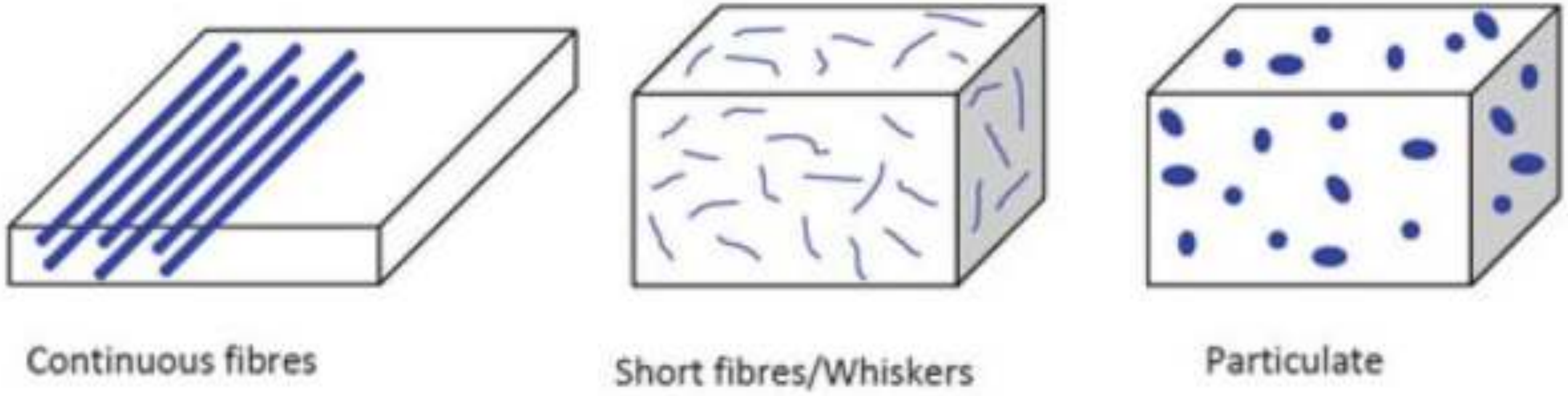


Components of Synthetic Composites

Different types of reinforcements are:

1. Fibers
2. Particulates
3. Whiskers
4. Layers

Continuous layers in matrix



Continuous fibres

Short fibres/Whiskers

Particulate

Figure 1.1 Types of reinforcement in a composite

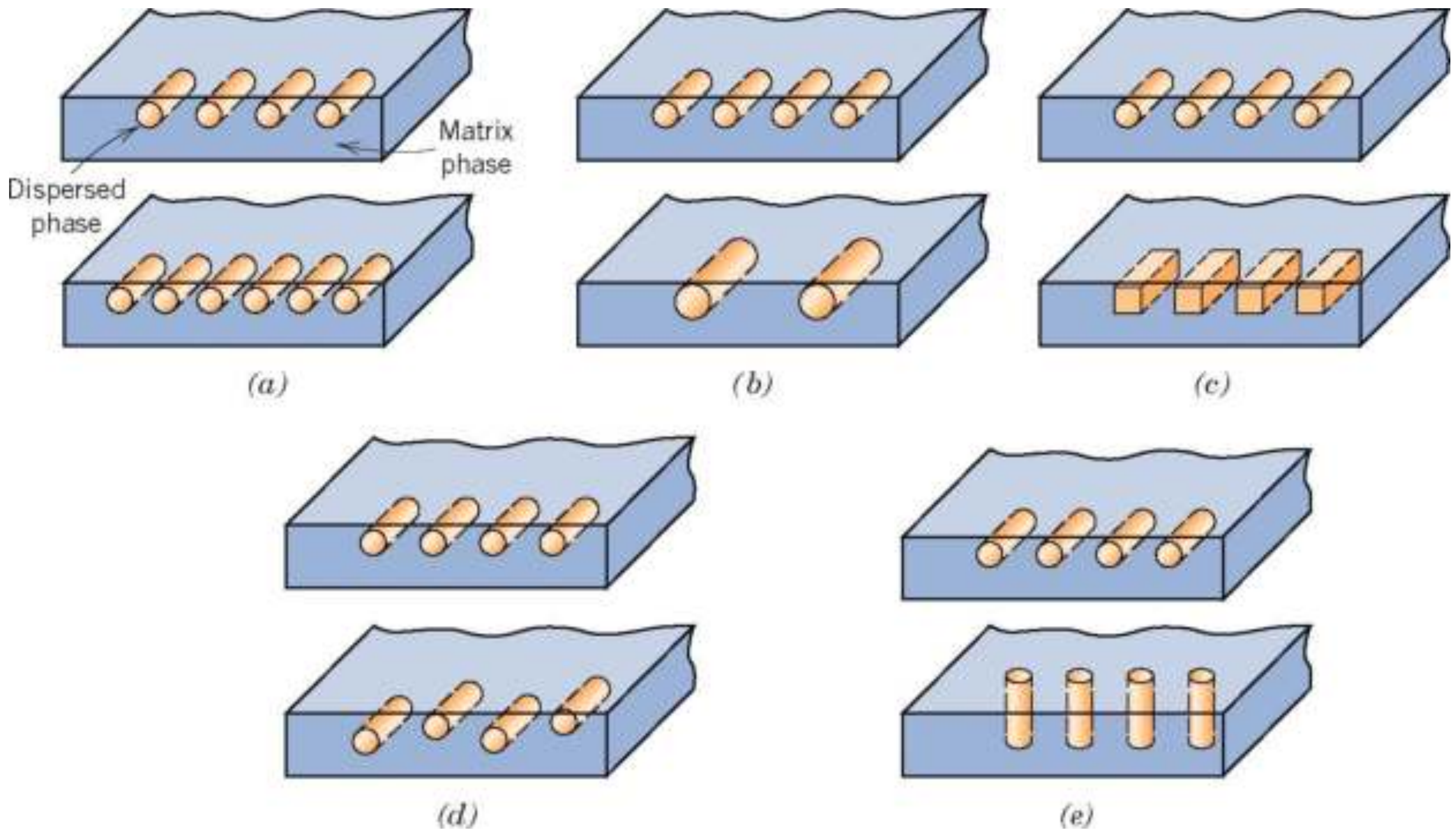
Need of development of composites

- The need for new materials with properties different from that of the existing materials.
- The need for developing totally new materials with precise combination of properties needed for meeting the design requirements for specific tasks of the future.

- The list of the desired properties, depending upon the requirement of the application, is given below.

1. Strength
2. Stiffness
3. Toughness
4. High corrosion resistance
5. High wear resistance
6. High chemical resistance
7. High environmental degradation resistance
8. Reduced weight
9. High fatigue life
10. Thermal insulation or conductivity
11. Electrical insulation or conductivity
12. Acoustic insulation
13. Radar transparency
14. Energy dissipation
15. Reduced cost
16. Attractiveness

Geometrical & spatial characteristics of particles



(a) Concentration (b) Size (c) Shape (d) Distribution (e) Orientation

CLASSIFICATION OF COMPOSITES

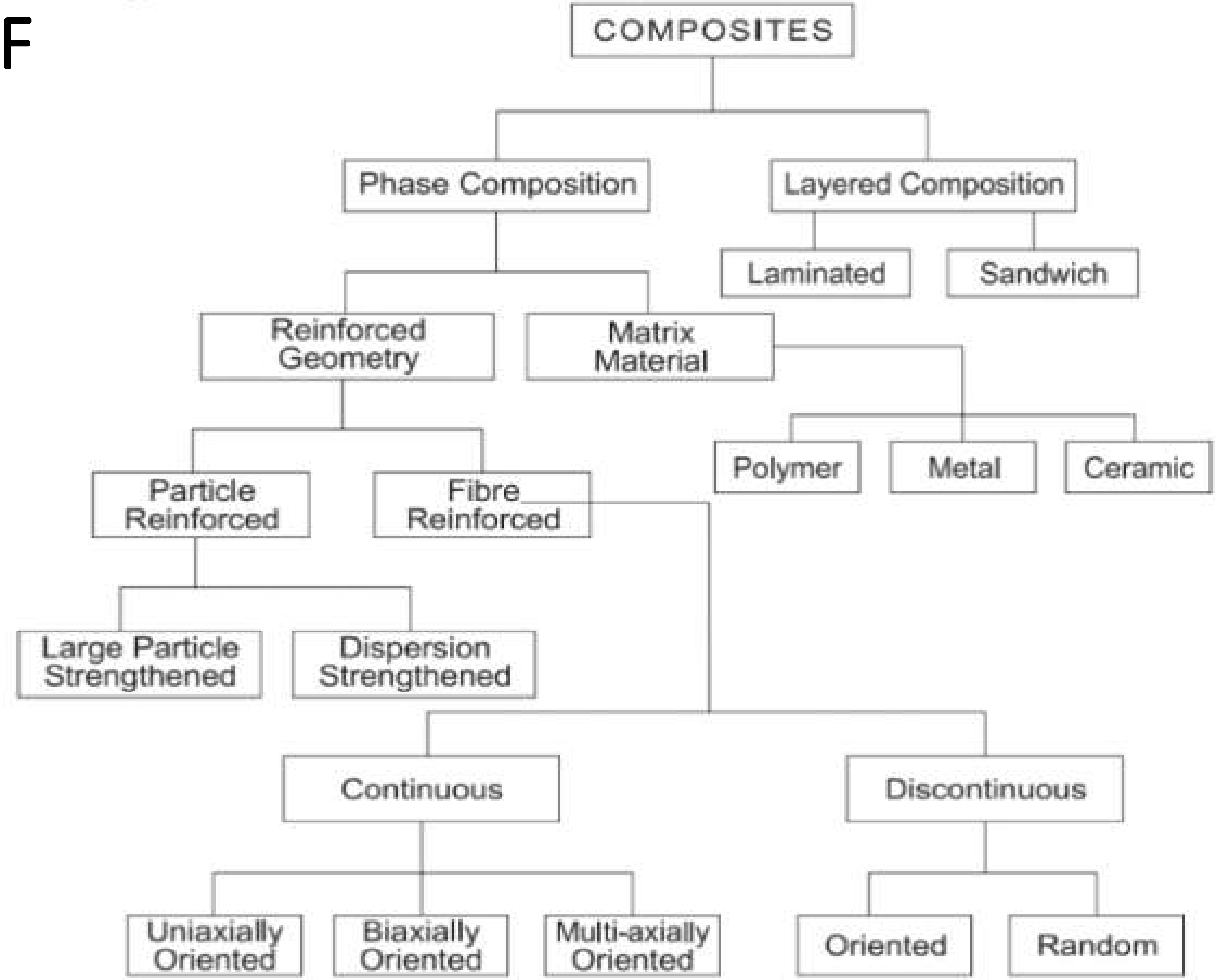


Figure 5.12 *Classification of Composites*

PARTICLE REINFORCED COMPOSITE

These are the cheapest and used.

They fall in two categories (size)

1. **Large-Particle Composites**

   -Consist of a high volume fraction of large sized hard particles embedded in a relatively soft matrix.

2. **Dispersion-Strengthened Composites**

   -Contains extremely small sized particles dispersed

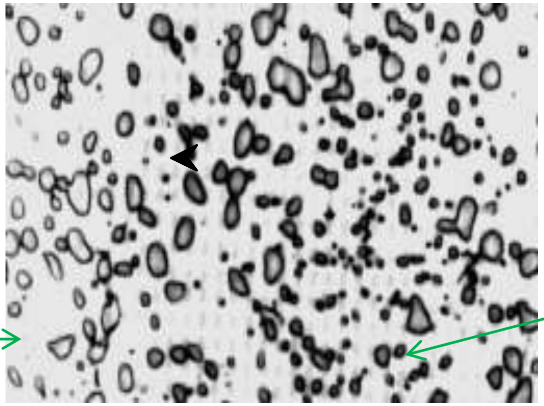
   -At low concentration which increases the matrix attractions

   -At the atomic level there by enhancing the strength

Particle reinforced composites

1. Dispersion Strengthened Composite. E.g.: Spheroidite Steel

Matrix: ferrite (α)
Ductile nature



Particles: Cementite (Fe3C)
Brittle nature

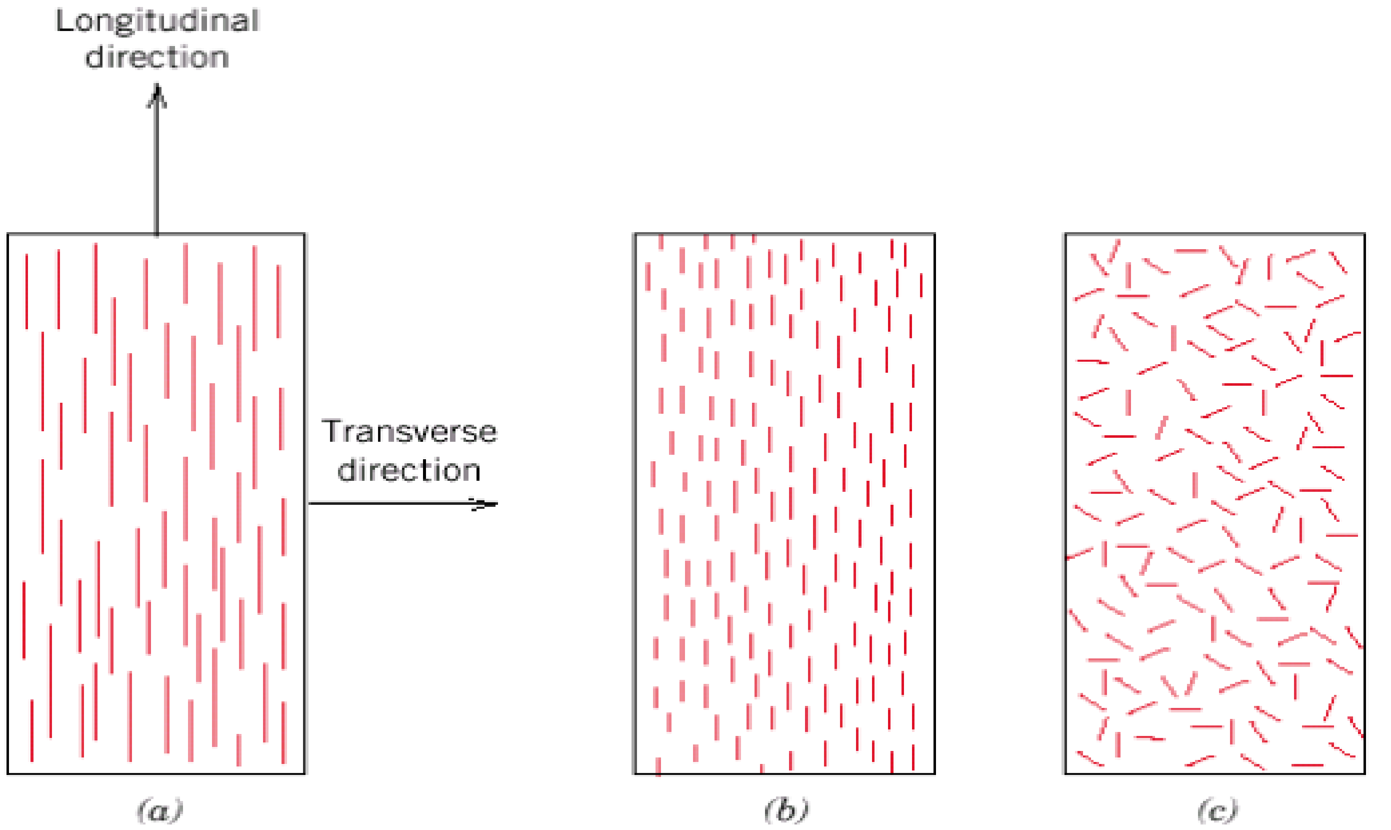
2. Large Particle Composite

Concrete : gravel + sand + cement

- Why sand and gravel?

: Sand packs into gravel voids

Fiber reinforced composites



Aligned
Continuous

Aligned Random
Discontinuous

Structural composites

1. Laminates

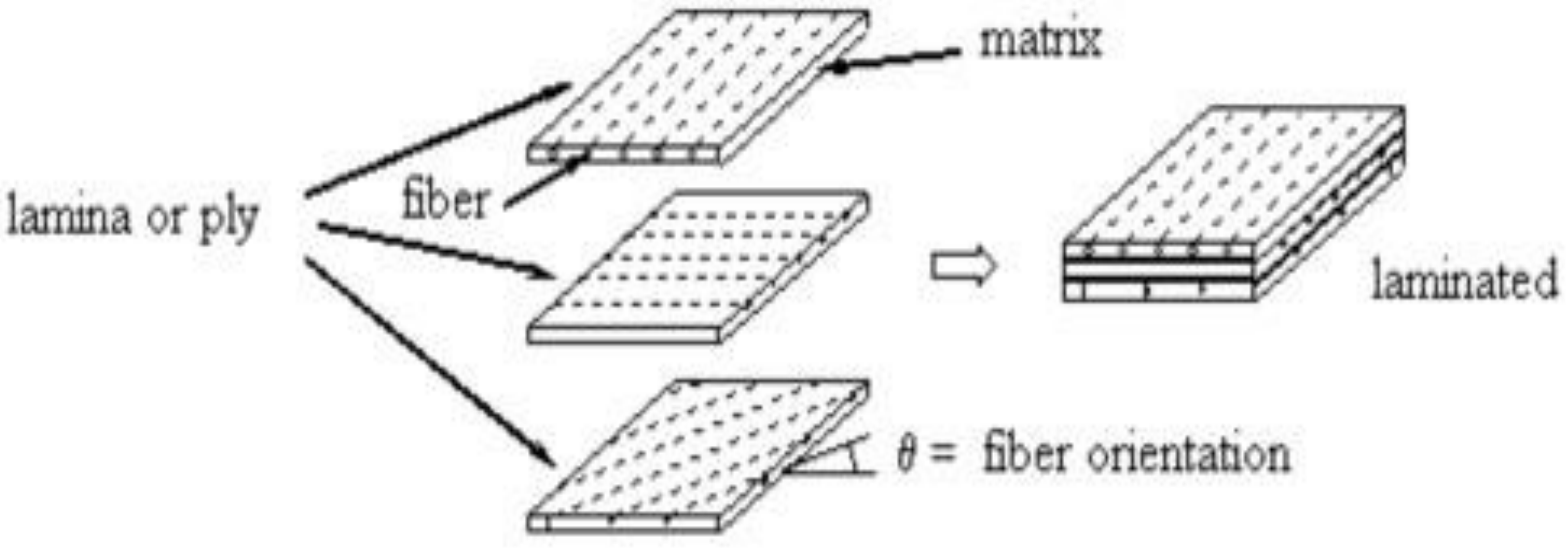
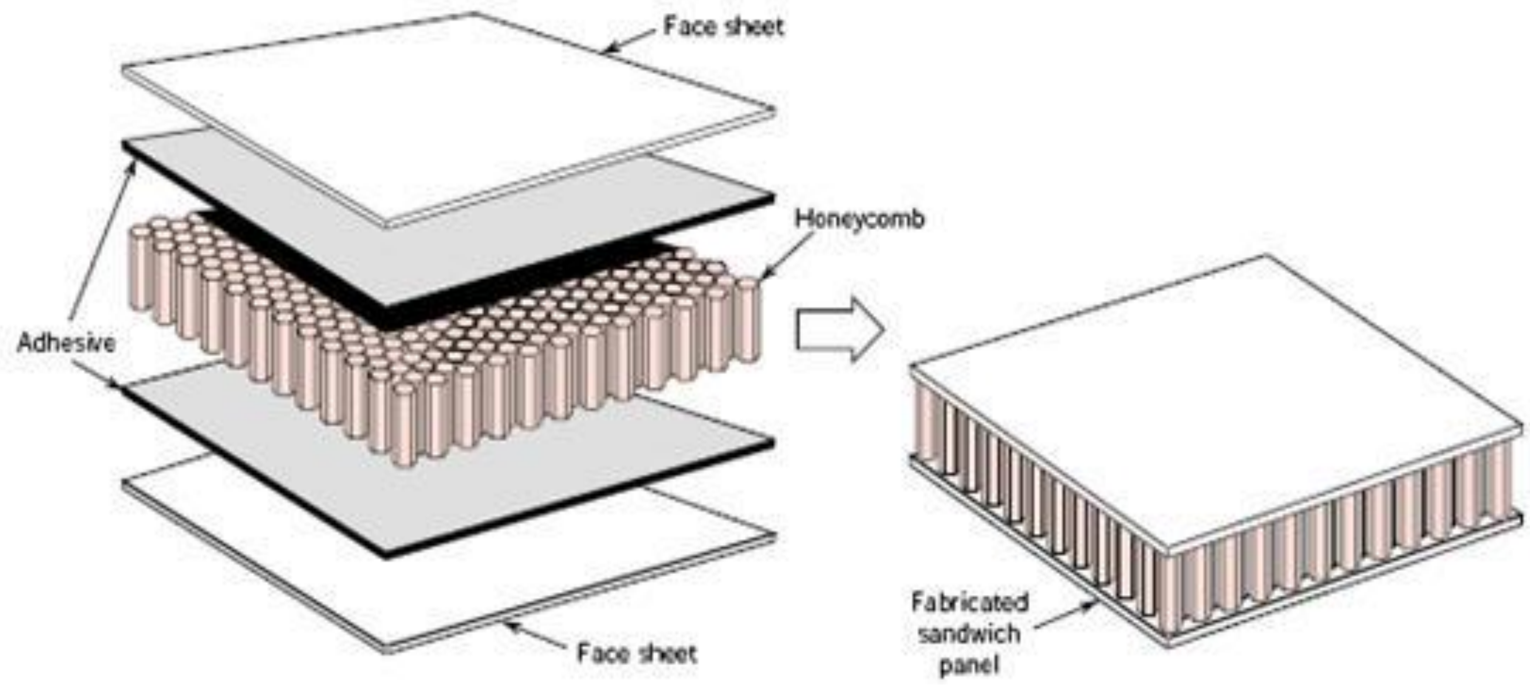


Figure 1 Laminated composite materials

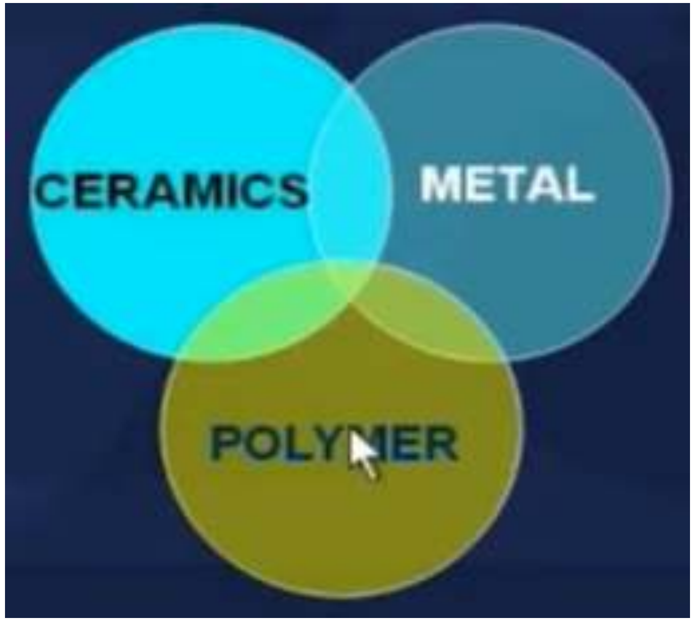
Structural composites

2. Sandwich panels



Classification of composites – based on type of matrix used

1. Polymer Matrix Composite (PMC)
2. Metal Matrix Composite (MMC)
3. Ceramic Matrix Composite (CMC)



PMC

- The polymeric matrix materials are further divided into:

  Thermoplastic – which soften upon heating and can be reshaped with heat and pressure.

  Thermoset – which become cross linked during fabrication and does not soften upon reheating.

- These composites are composed of a polymer resin (a high molecular weight plastic) in which are embedded the high strength, high stiffness fibres. Reinforcements other than fibres are very uncommon.

- PMCs have some advantages over metal or ceramic matrix composites because of their low density, high specific strength, high specific stiffness, ease of fabrication, ability to be made into intricate shapes and low fabrication cost. In addition they also posses reasonably good mechanical and electrical properties, and good corrosion resistance.

Polymer Matrix Composites

On the basis of type of polymer resin used, composite materials can be classified into two categories.

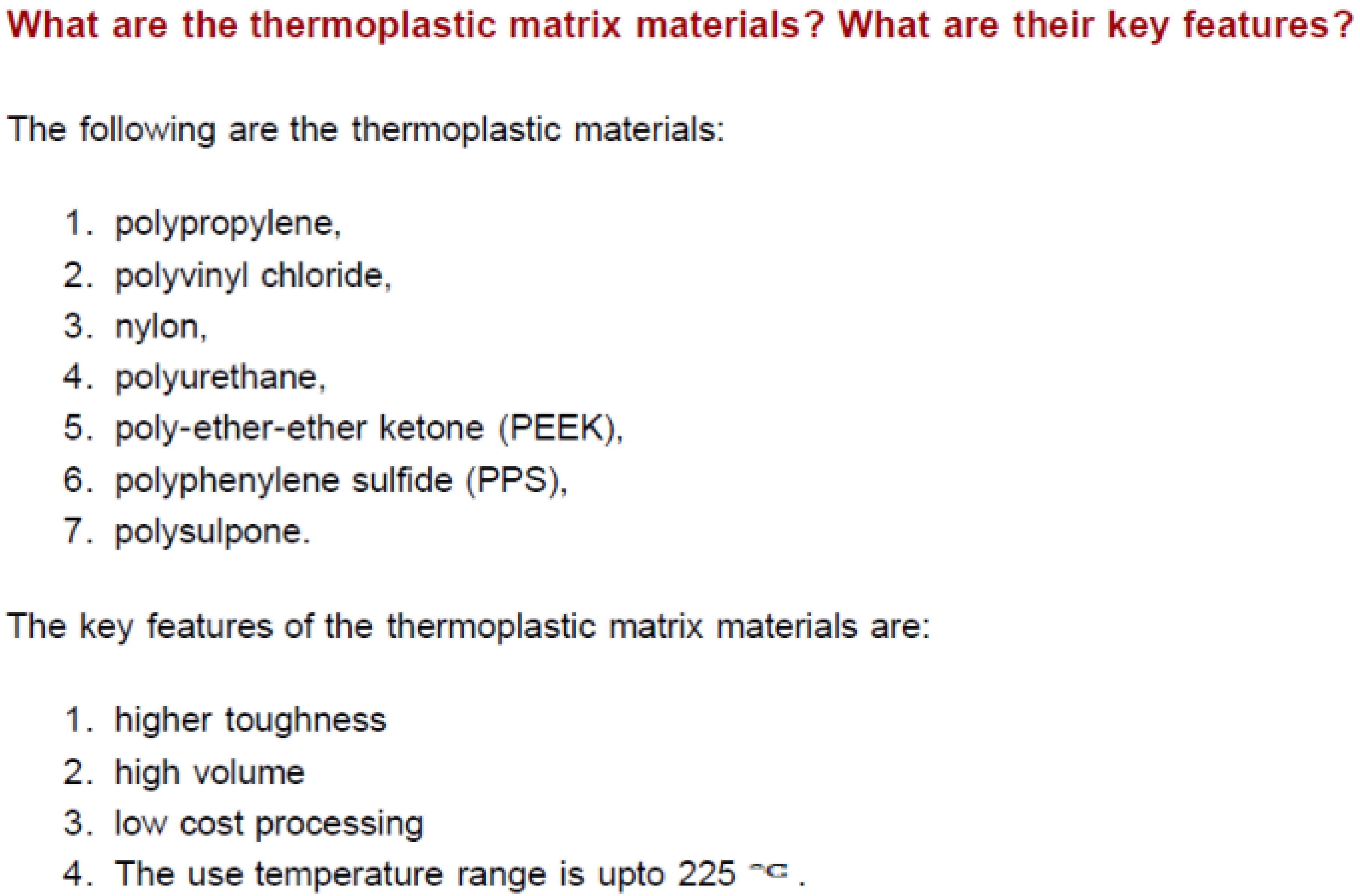
- Thermoplastic Composites
- Thermo-set Composites

Thermoplastic Composites:

This is type of composite material with thermoplastic resin like polyester, HDPE etc. They are lesser used as high-tech materials due to their higher viscosity which cause problem during their penetration into the reinforcement.

Thermo-set Composites:

In these composites thermo-set polymers like epoxy, unsaturated polyester and vinyl-ester are used as resin. They are most used type of composites materials in automotive, naval, aeronautical and aerospace applications.



What are the thermoplastic matrix materials? What are their key features?

The following are the thermoplastic materials:

1. polypropylene,
2. polyvinyl chloride,
3. nylon,
4. polyurethane,
5. poly-ether-ether ketone (PEEK),
6. polyphenylene sulfide (PPS),
7. polysulpone.

The key features of the thermoplastic matrix materials are:

1. higher toughness
2. high volume
3. low cost processing
4. The use temperature range is upto 225 °C .

What are the thermoset matrix materials? What are their key features?

The thermoset matrix materials are:

1. polyesters,
2. epoxies,
3. polyimides

The key features of these materials are given for individual material in the following.

Polyesters

1. Used extensively with glass fibers
2. Inexpensive
3. Light weight
4. Temperature range upto 100 °C.
5. Resistant to environmental exposures

Epoxy

1. Expensive
2. Better moisture resistance
3. Lower shrinkage on curing
4. Use temperature is about 175 °C

Polyimide

1. Higher use temperature about 300 °C
2. Difficult to fabricate

- Thermosetting plastics like epoxies and phenolics which can withstand high temperatures are common polymer matrix materials with continuous fibres as the reinforcing phase.

- Epoxies have better mechanical and electrical properties, but costlier. Phenolics, though cheaper than the epoxies, can withstand higher service temperatures, but have relatively lower mechanical properties.

- Thermoplastics are also used as matrix materials because they can be reworked, have low processing time and at normal temperature they have an optimum combination of toughness, rigidity and creep resistance.

- Glass, graphite, carbon and aramid are the most common fibre materials used with PMCs.

What are the problems with the use of polymer matrix materials?

1. Limited temperature range.
2. Susceptibility to environmental degradation due to moisture, radiation, atomic oxygen (in space)
3. Low transverse strength.
4. High residual stress due to large mismatch in coefficients of thermal expansion between fiber and matrix.
5. Polymer matrix cannot be used near or above the glass transition temperature.

Glass Fibre – reinforced polymer (GFRP) composites.

- Popularly known as fibre glass, these composites contains glass fibre as reinforcing phase in a polymer matrix.
- Glass fibres can easily be drawn into high strength fibres, and when embedded in a plastic matrix, produces a composite having very high specific strength.
- Applications of fibre glass are:Automotive and marine bodies, storage containers, industrial floorings, plastic pipes etc.

Carbon Fibre - Reinforced Polymer (CFRP) Composites

- Mostly used fibers
- The reasons are: of all the reinforcing fibre materials carbon fibres have the highest specific strength.
- They retain their higher strength even at elevated temperatures.
- At room temperatures carbon fibres are not affected by moisture or a wide variety of solvents and acids.
- Relatively inexpensive manufacturing process have also been developed.

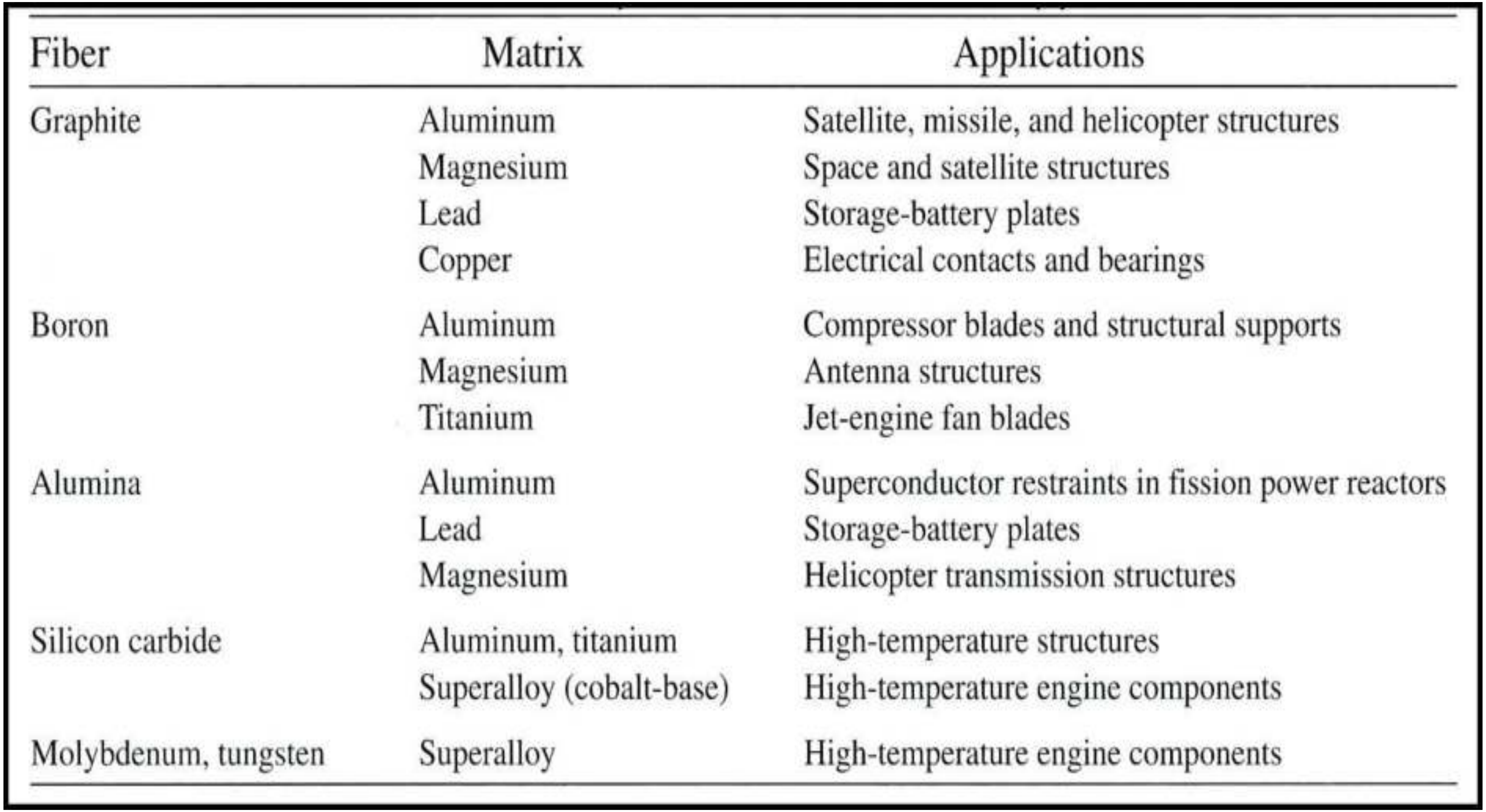
Applications

- CFRP applications include:
- aerospace structural components,
- filament wound rocket motor cases,
- sports and recreational equipments,
- pressure vessels etc

Metal Matrix Composites (MMC)

- Metal matrix composites (MMCs), as the name implies, have a metal matrix. Examples of matrices in such composites include aluminum, magnesium, and titanium.
- Typical fibers include carbon and silicon carbide.
- Metals are mainly reinforced to increase or decrease their properties to suit the needs of design. For example, the elastic stiffness and strength of metals can be increased, and large coefficients of thermal expansion and thermal and electric conductivities of metals can be reduced, by the addition of fibers such as silicon carbide.

Examples of Metal Matrix Composites (MMC)



Fiber	Matrix	Applications
Graphite	Aluminum	Satellite, missile, and helicopter structures
	Magnesium	Space and satellite structures
	Lead	Storage-battery plates
	Copper	Electrical contacts and bearings
Boron	Aluminum	Compressor blades and structural supports
	Magnesium	Antenna structures
	Titanium	Jet-engine fan blades
Alumina	Aluminum	Superconductor restraints in fission power reactors
	Lead	Storage-battery plates
	Magnesium	Helicopter transmission structures
Silicon carbide	Aluminum, titanium	High-temperature structures
	Superalloy (cobalt-base)	High-temperature engine components
Molybdenum, tungsten	Superalloy	High-temperature engine components

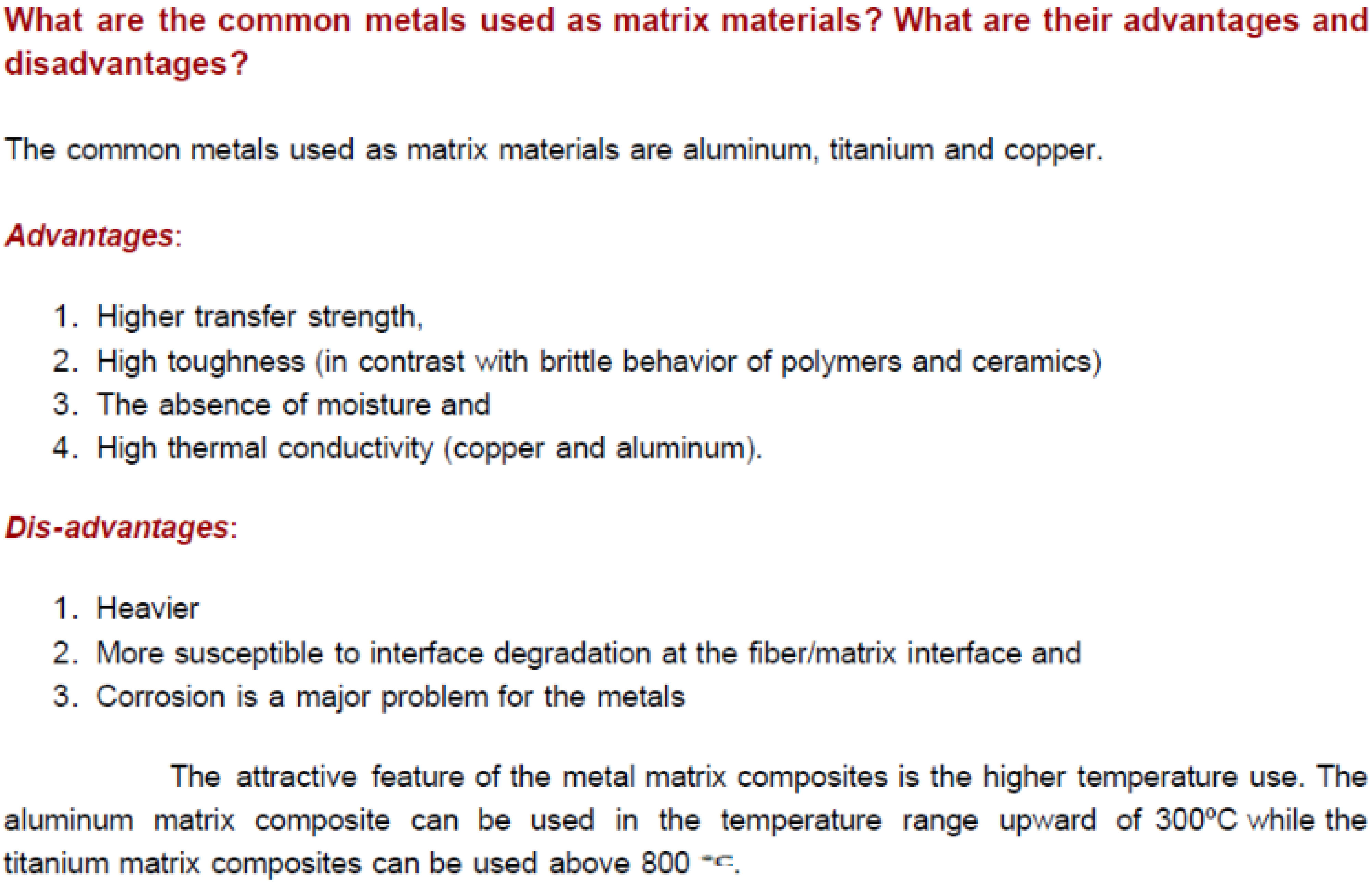
MMC

- In practice metal matrices are used for those applications where polymer matrices are unable to meet the service and engineering requirements.
- MMCs are capable of developing better characteristics than their base metals. Hence reinforcing metal matrices are observed to have improved specific strength, specific stiffness, abrasion resistance, creep resistance, thermal conductivity and dimensional stability.
- Some of the advantages of MMCs over PMCs are their higher operating temperatures, non flammability and greater resistance to degradation by organic fluids.
- MMCs are much more expensive than PMCs. Hence their use is somewhat restricted.

- Generally, metals with low density, together with their low temperature toughness are preferred as the matrix metal
- The most commonly used metal matrices are aluminium, magnesium, titanium and their alloys.
- The other metal matrices which are used for special purpose include super alloys, copper, nickel and silver.
- The reinforcement may be in the form of particulates, both continuous and discontinuous fibres and whiskers in selected applications.

Applications of MMCs

- MMCs with Al, Mg and Ti matrices are used in automobile and aerospace applications.
- MMCs with super alloys as matrices are used for high temperature applications like, gas turbine blades because of their high temperature creep and rupture properties, together with high temperature oxidation resistance and impact resistance.
- Copper and Silver based MMCs are used for electrical contacts and such other applications. Cemented carbides, and dispersion strengthened composites discussed earlier belong to MMCs.



What are the common metals used as matrix materials? What are their advantages and disadvantages?

The common metals used as matrix materials are aluminum, titanium and copper.

Advantages:

1. Higher transfer strength,
2. High toughness (in contrast with brittle behavior of polymers and ceramics)
3. The absence of moisture and
4. High thermal conductivity (copper and aluminum).

Dis-advantages:

1. Heavier
2. More susceptible to interface degradation at the fiber/matrix interface and
3. Corrosion is a major problem for the metals

The attractive feature of the metal matrix composites is the higher temperature use. The aluminum matrix composite can be used in the temperature range upward of 300ºC while the titanium matrix composites can be used above 800 °C.

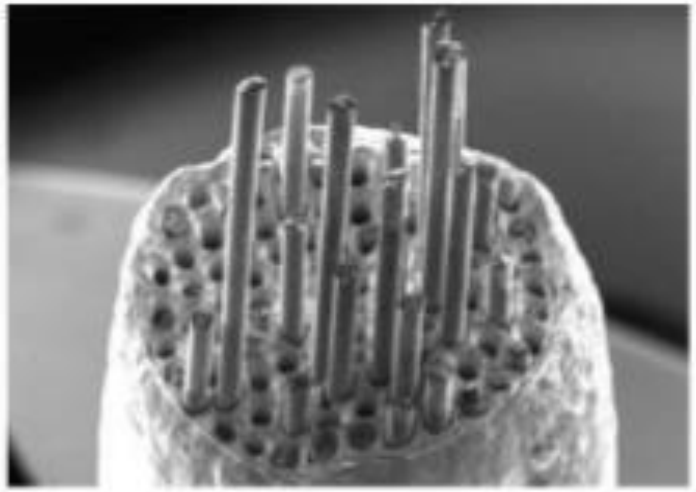
Ceramic Matrix Composites

Ceramic matrix composites (CMC) are used in applications where resistance to high temperature and corrosive environment is desired. CMCs are strong and stiff but they lack toughness (ductility).

Matrix materials are usually silicon carbide, silicon nitride and aluminum oxide, and mullite (compound of aluminum, silicon and oxygen). They retain their strength up to 3000 °F.

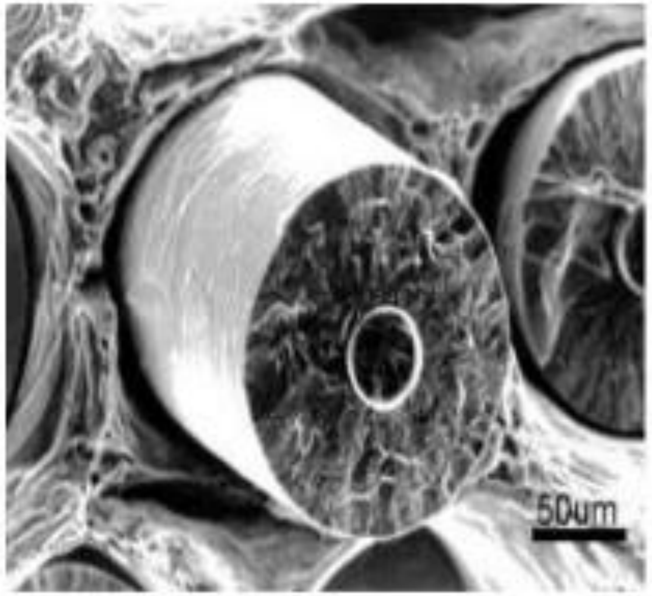
Fiber materials used commonly are carbon and aluminum oxide.

Applications are in jet and automobile engines, deep-see mining, cutting tools, dies and pressure vessels.



Ceramic composites

REINFORCEMENT- SiC (Silicon carbide)

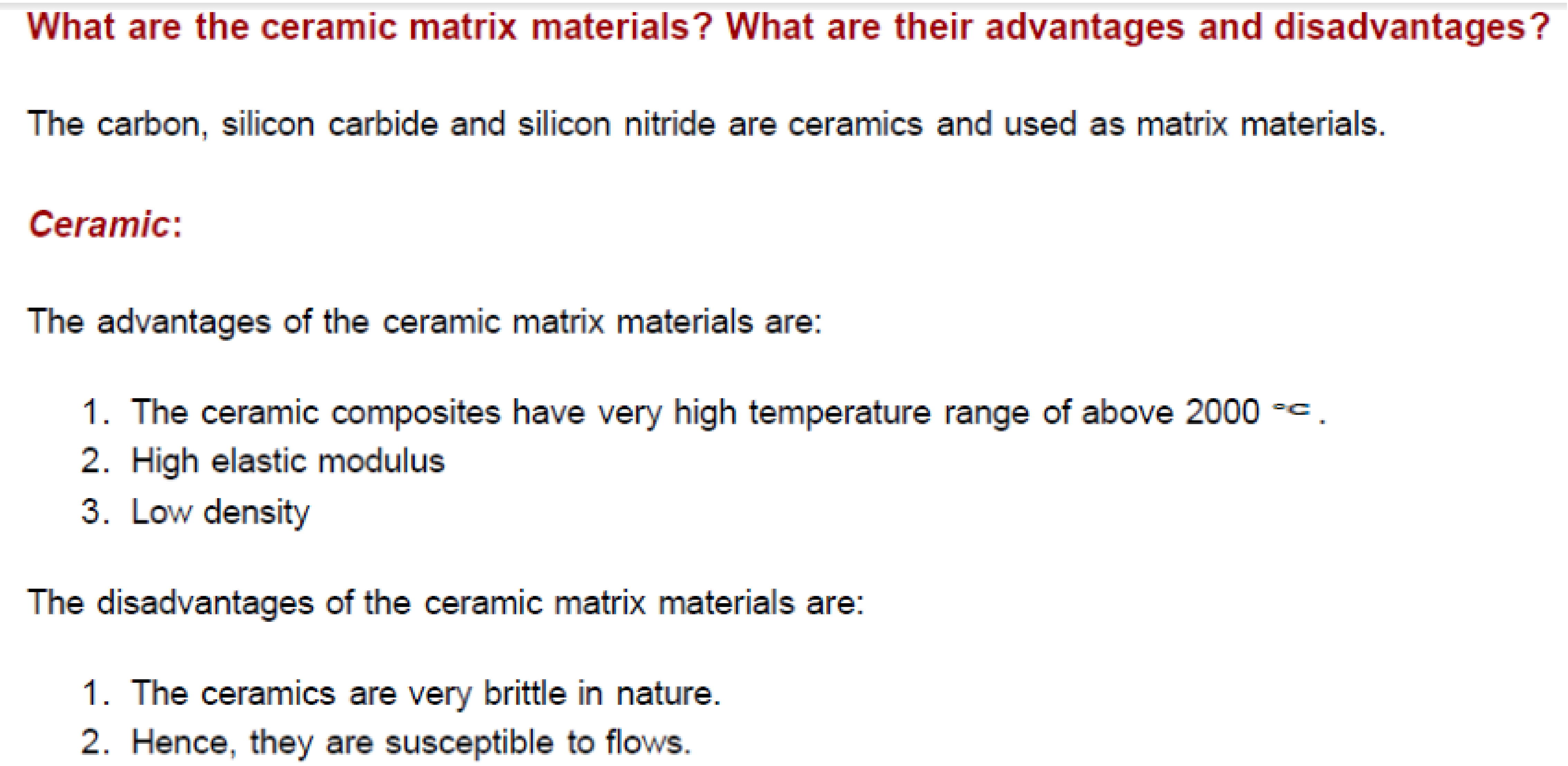


CMC

- Ceramic materials have high melting points and good resistance to oxidation and deterioration at elevated temperature.
- But they are brittle with very low tensile strength, impact resistance and thermal shock resistance.
- So the primary objective for developing CMCs was to enhance the toughness while retaining the high temperature properties.
- The fracture toughness of ceramic materials have been improved significantly by embedding particles, fibres or whiskers of another suitable material.
- Crack initiation normally occurs with the matrix phase, while the crack propagation is impeded or hindered by the embedded second phase particles.

- Increasing the content of second phase improves strength and fracture toughness.
- In addition, these CMCs exhibit improved high temperature creep behaviour and resistance to thermal shock.

- CMCs are used for components in automobile and aircraft gas turbine engines, as cutting tool inserts for machining hard metal alloys.
- Carbon-carbon composites are developed by reinforcing the carbon matrix with carbon fibres.
- High elastic strength and elastic modulus are achieved in these composites which are retained even at high temperatures of the order of 2000°C.
- Carbon-carbon composites are used in rocket motors, as frictional material in aircrafts and in high performance automobiles.



What are the ceramic matrix materials? What are their advantages and disadvantages?

The carbon, silicon carbide and silicon nitride are ceramics and used as matrix materials.

Ceramic:

The advantages of the ceramic matrix materials are:

1. The ceramic composites have very high temperature range of above 2000 °C.
2. High elastic modulus
3. Low density

The disadvantages of the ceramic matrix materials are:

1. The ceramics are very brittle in nature.
2. Hence, they are susceptible to flows.

Carbon

The advantages of the carbon matrix materials are:

1. High temperature at 2200 °C.
2. Carbon/carbon bond is stronger at elevated temperature than room temperature.

The disadvantages of the carbon matrix materials are:

1. The fabrication is expensive.

2. The multistage processing results in complexity and higher additional cost.

It should be noted that a composite with carbon fibres as reinforcement as well as matrix material is known as ***carbon-carbon composite***. The application of carbon-carbon composite is seen in leading edge of the space shuttle where the high temperature resistance is required. The carbon-carbon composites can resist the temperatures upto 3000°C .

The advantages of these composites are:

1. Very strong and light as compared to graphite fibre alone.
2. Low density.
3. Excellent tensile and compressive strength.
4. Low thermal conductivity.
5. High fatigue resistance.
6. High coefficient of friction.

The disadvantages include:

1. Susceptible to oxidation at elevated temperatures.
2. High material and production cost.
3. Low shear strength.

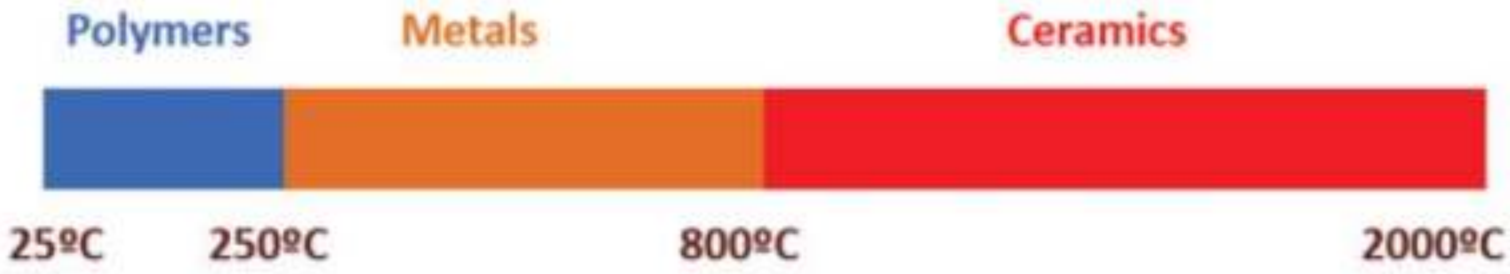
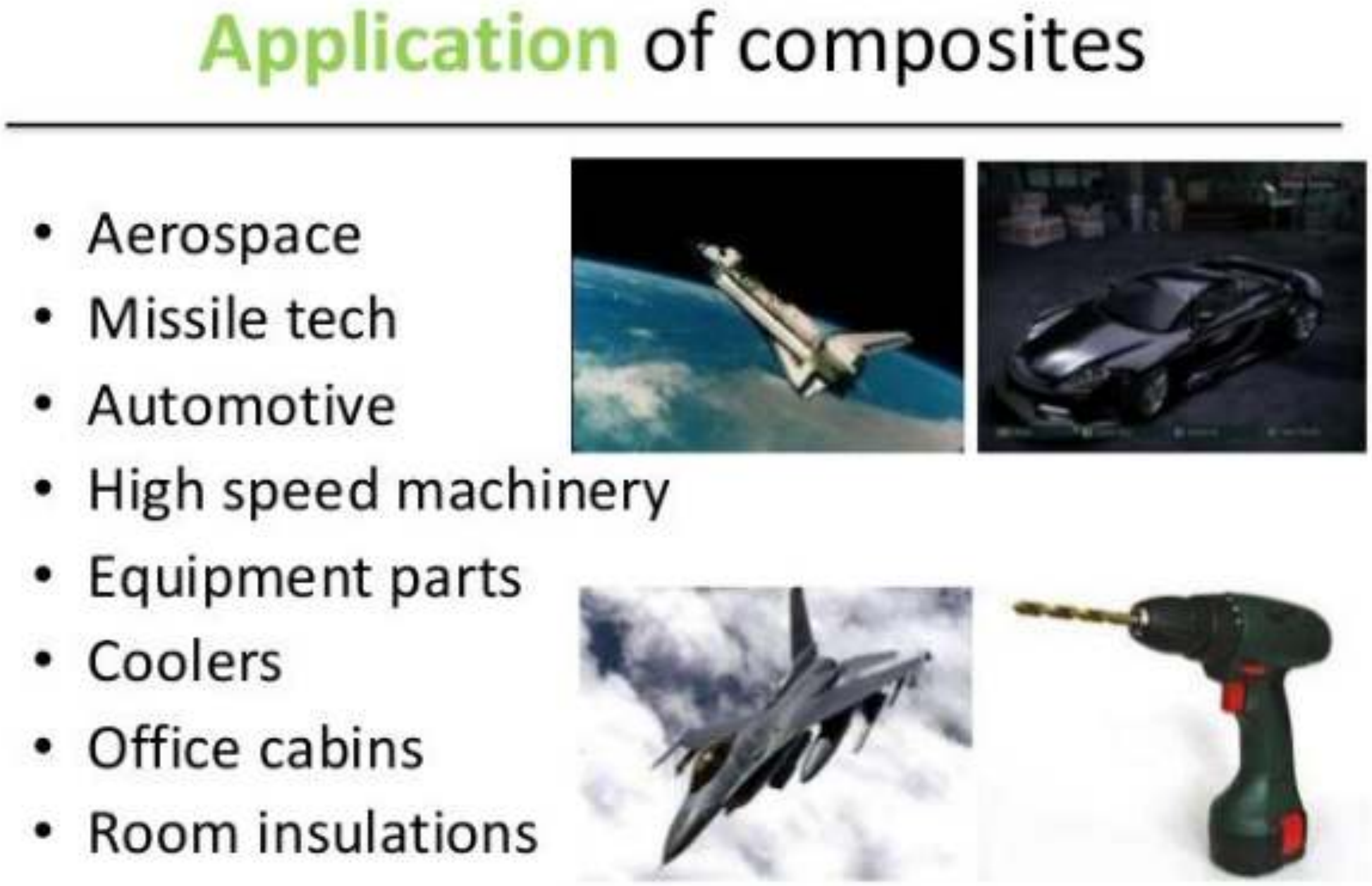


Figure 1.12: Range of use temperature for matrix materials in composites



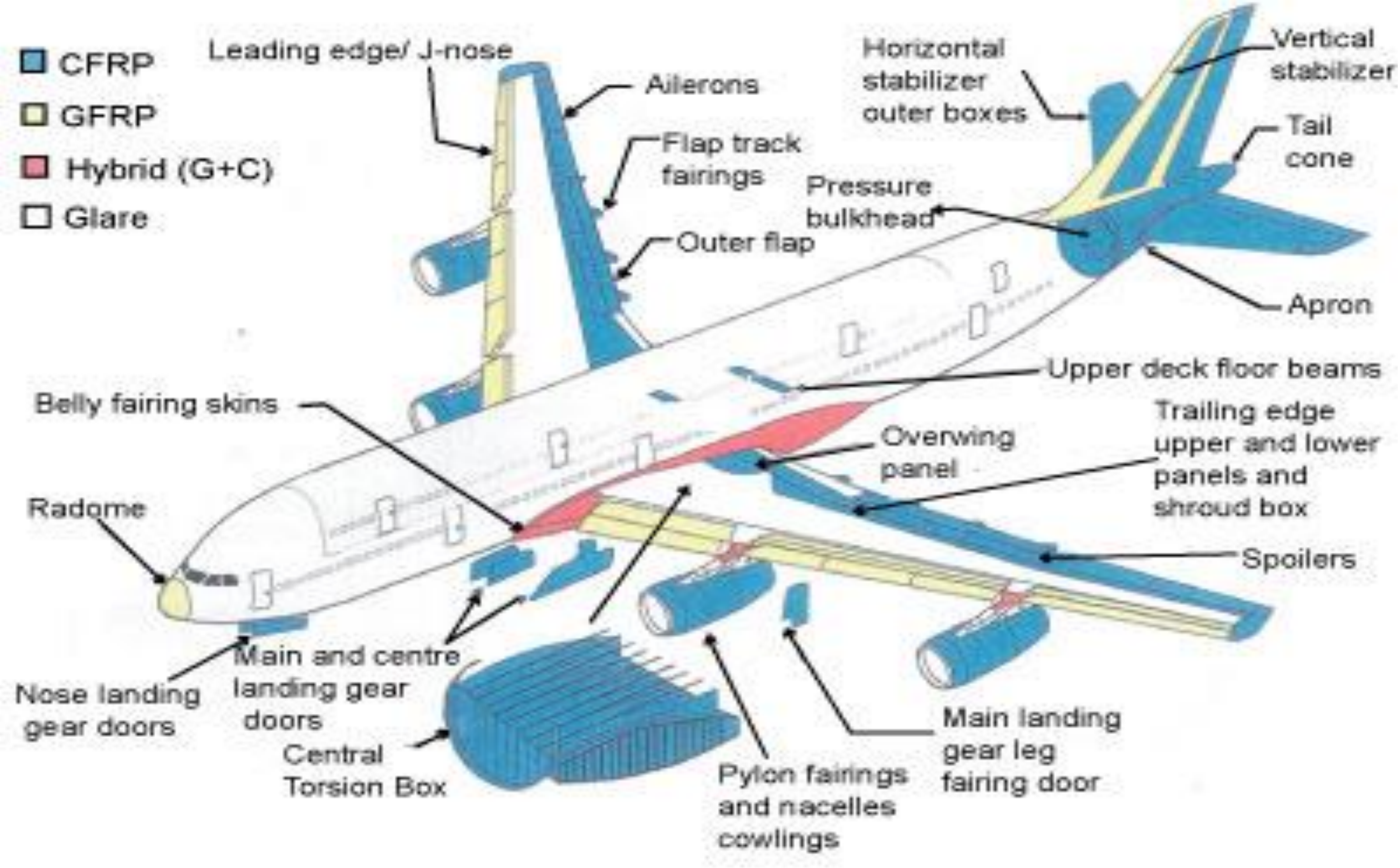
Application of composites

- Aerospace
- Missile tech
- Automotive
- High speed machinery
- Equipment parts
- Coolers
- Office cabins
- Room insulations

Applications Of Composite Material

1. In automobile industries (e.g. Steel &Aluminium body)
2. Marine applications like shafts, hulls, spars (for racing boats)
3. Aeronautical application like components of rockets, aircrafts (business and military), missiles etc.
4. Communication antennae, electronic circuit boards (e.g. PCB, breadboard)
5. Safety equipment like ballistic protection and Air bags of cars.

Composites used in aircraft structures



CFRP: Carbon Fibre Reinforced Polymer
GFRP: Glass Fibre Reinforced Plastic
GLARE: Glass Laminate Aluminium Reinforced Epoxy

Why composites in maritime industry?

- Form
  - Form freedom at relatively low cost with glass fiber composites
- Performance
  - Energy saving with lighter structures and superstructures
  - Increased impact and shock absorption using aramid
  - High stiffness using carbon fibers
  - Use of non-magnetic materials, radar absorbing coatings, etc.
- Maintenance
  - Composites are non-corrosive and require less maintenance
  - Repairable

SPORTS EQUIPMENTS

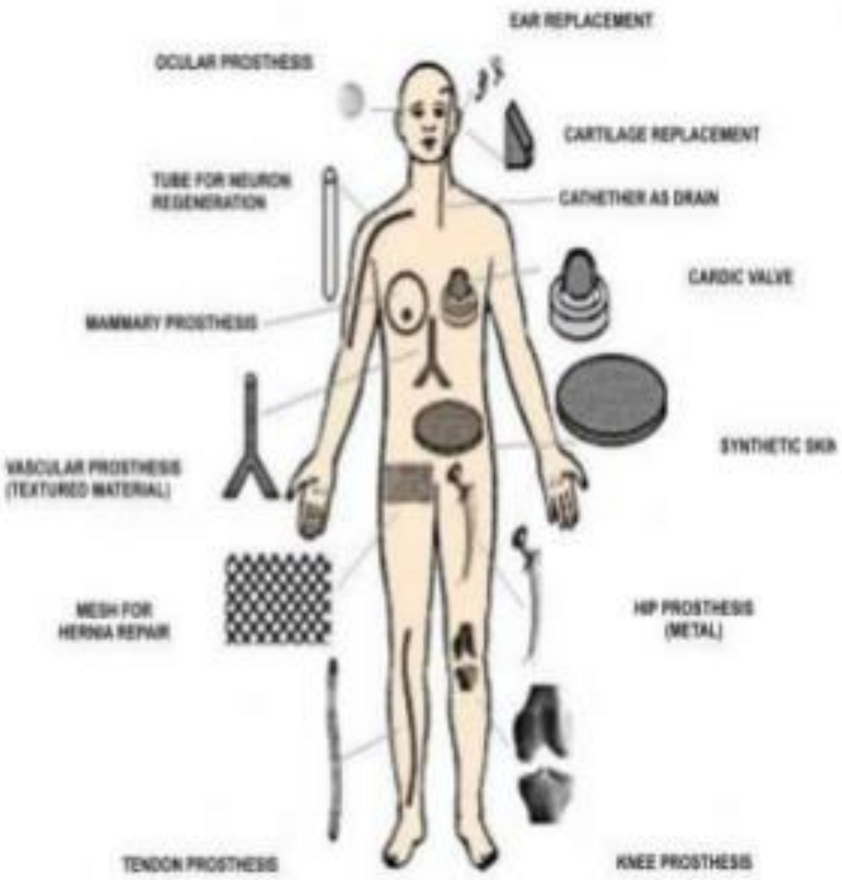
- Tennis rackets, golf clubs, softball bats, hockey sticks, and products commonly manufactured with carbon fiber reinforced composites
- Anywhere where high performance is required carbon fiber's superior strength to weight ratio offers significant advantages, and sporting goods are no exception. It is used to replace or reduce metal, wood and steel content in a wide variety of sports applications.

SOME OF THE SPORTS APPLICATIONS IN WHICH CARBON FIBER IS USED

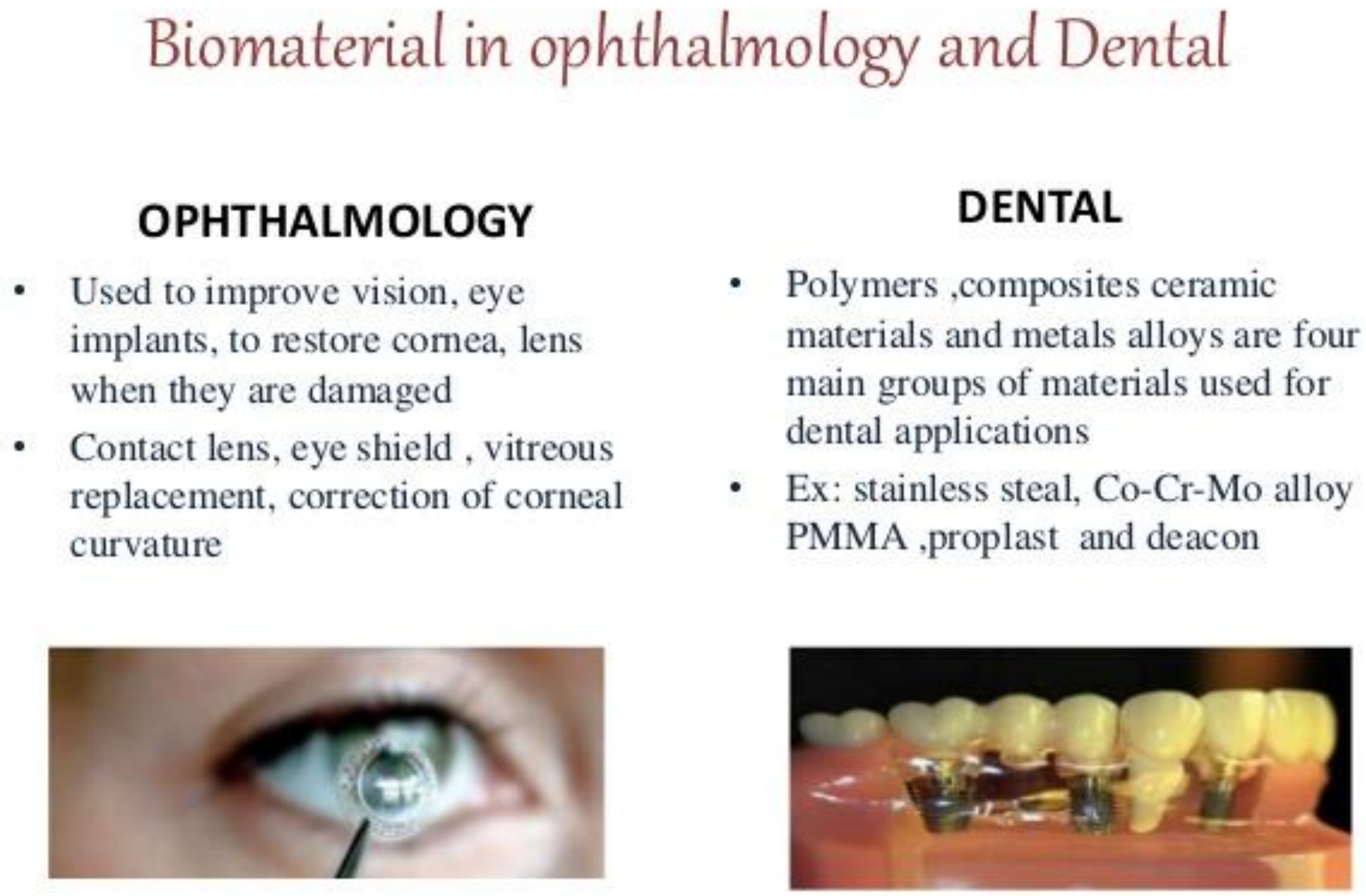
- Sailboats
- Gliders
- Fishing rods
- Running shoes
- Bicycles
- Rowing shells
- archery arrows

BIOMATERIAL

- The Materials Which are used for structural applications in the fields of medicine are know as biomaterials
- These materials are used to make devices to replace damaged or diseased body parts in human and animal bodies
- A variety of devices and materials are used in the treatment of disease or injury. Commonplace examples include suture needles, plates, teeth fillings, etc



Applications of composites in biomaterials



Biomaterial in ophthalmology and Dental

OPHTHALMOLOGY

- Used to improve vision, eye implants, to restore cornea, lens when they are damaged
- Contact lens, eye shield , vitreous replacement, correction of corneal curvature

DENTAL

- Polymers ,composites ceramic materials and metals alloys are four main groups of materials used for dental applications
- Ex: stainless steal, Co-Cr-Mo alloy PMMA ,proplast and deacon

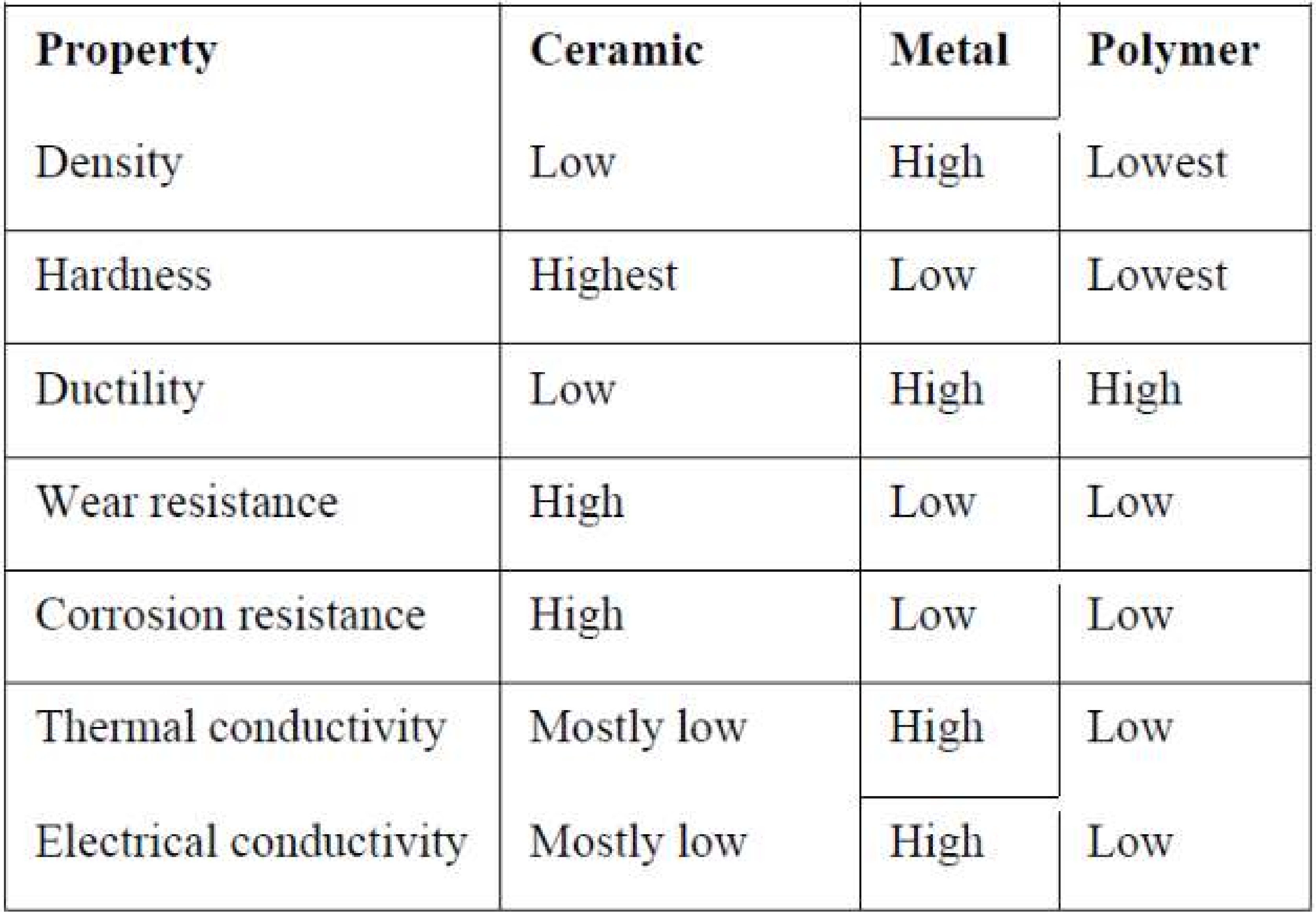
Ceramics

- The term “ceramic” comes from the Greek word keramikos, which means “burnt stuff,” indicating that desirable properties of these materials are normally achieved through a high-temperature heat treatment process called firing.
- Most ceramics are compounds between metallic and nonmetallic elements for which the interatomic bonds are either totally ionic, or predominantly ionic but having some covalent character.

PROPERTIES OF CERAMICS

- ☐ Extreme hardness:
  - ➢High wear resistance
  - ➢Extreme hardness can ***reduce wear caused by friction***
- ☐ Corrosion resistance
- ☐ Heat resistance:
  - ➢Low electrical conductivity
  - ➢Low thermal conductivity
  - ➢Low thermal expansion
  - ➢Poor thermal shock resistance
- ☐Low ductility:
  - ➢Very brittle
  - ➢High elastic modulus
- ☐ Low toughness:
  - ➢Low fracture toughness
  - ➢Indicates the ability of a crack or flaw to produce a catastrophic failure
- ☐ Low density:
  - ➢Porosity affects properties
- ☐ High strength at elevated temperatures

Ceramic Vs Metal Vs Polymer



Property	**Ceramic**	**Metal**	**Polymer**
Density	Low	High	Lowest
Hardness	Highest	Low	Lowest
Ductility	Low	High	High
Wear resistance	High	Low	Low
Corrosion resistance	High	Low	Low
Thermal conductivity	Mostly low	High	Low
Electrical conductivity	Mostly low	High	Low

What are ceramics?

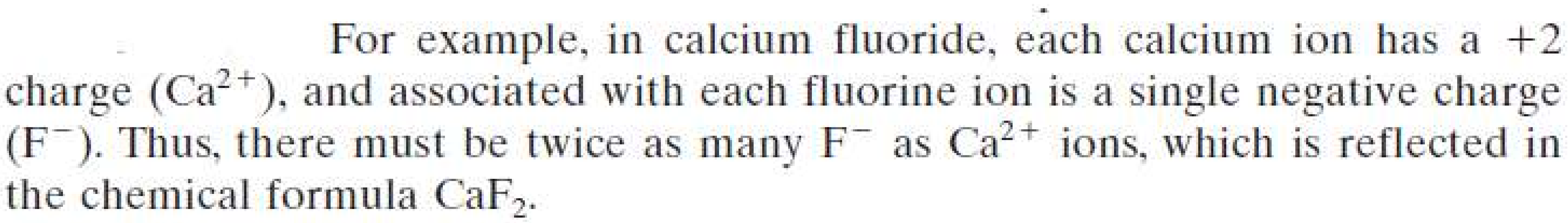
1. Compounds between metallic and nonmetallic elements (C, N, O, P, S)
2. To be most frequently silicates, oxides, nitrides and carbides
3. Typically insulative to the passage of electricity and heat
4. More resistant to high temperatures and harsh environments than metals and polymers
5. Hard but very brittle

Eg: Al_2O_3, NaCl, SiC, SiO_2

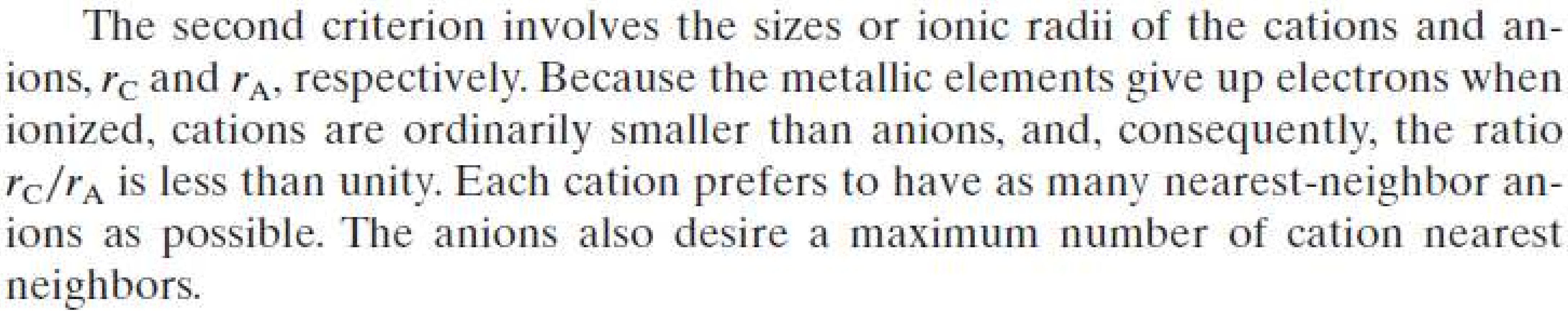
Ceramic Structures

- For those ceramic materials for which the atomic bonding is predominantly ionic, the crystal structures may be thought of as being composed of electrically charged ions instead of atoms.
- The metallic ions, or cations, are positively charged, because they have given up their valence electrons to the nonmetallic ions, or anions, which are negatively charged.
- Two characteristics of the component ions in crystalline ceramic materials influence the crystal structure: the magnitude of the electrical charge on each of the component ions, and the relative sizes of the cations and anions.
- With regard to the first characteristic, the crystal must be electrically neutral; that is, all the cation positive charges must be balanced by an equal number of anion negative charges.
- The chemical formula of a compound indicates the ratio of cations to anions, or the composition that achieves this charge balance.

Ceramic Structures



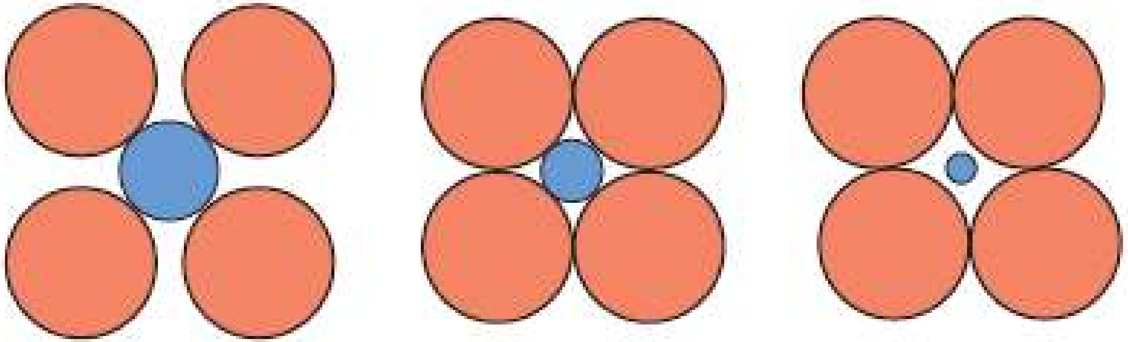
For example, in calcium fluoride, each calcium ion has a +2 charge (Ca^{2+}), and associated with each fluorine ion is a single negative charge (F^-). Thus, there must be twice as many F^- as Ca^{2+} ions, which is reflected in the chemical formula CaF_2.



The second criterion involves the sizes or ionic radii of the cations and anions, r_C and r_A, respectively. Because the metallic elements give up electrons when ionized, cations are ordinarily smaller than anions, and, consequently, the ratio r_C/r_A is less than unity. Each cation prefers to have as many nearest-neighbor anions as possible. The anions also desire a maximum number of cation nearest neighbors.

Ceramic Structures

Stable ceramic crystal structures form when those anions surrounding a cation are all in contact with that cation, as illustrated in Figure 12.1. The coordination number (i.e., number of anion nearest neighbors for a cation) is related to the cation–anion radius ratio. For a specific coordination number, there is a critical or minimum r_C/r_A ratio for which this cation–anion contact is established (Figure 12.1); this ratio may be determined from pure geometrical considerations (see Example Problem 12.1).



Stable Stable Unstable

Figure 12.1 Stable and unstable anion–cation coordination configurations. Red circles represent anions; blue circles denote cations.

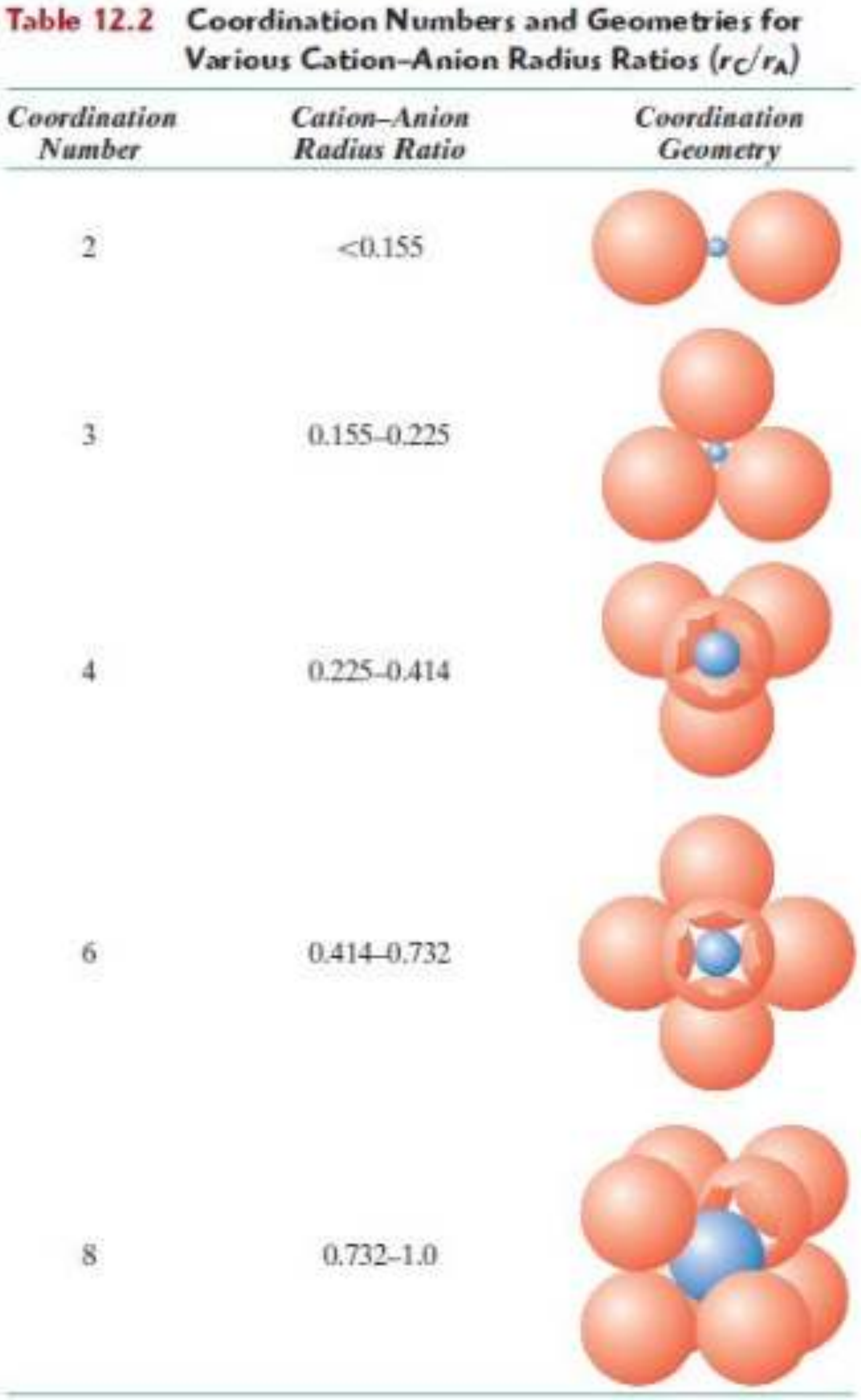


Table 12.2 Coordination Numbers and Geometries for Various Cation–Anion Radius Ratios (r_C/r_A)

Coordination Number	*Cation–Anion Radius Ratio*	*Coordination Geometry*
2	<0.155	
3	0.155–0.225	
4	0.225–0.414	
6	0.414–0.732	
8	0.732–1.0	

The coordination numbers and nearest-neighbor geometries for various r_C/r_A ratios are presented in Table 12.2. For r_C/r_A ratios less than 0.155, the very small cation is bonded to two anions in a linear manner. If r_C/r_A has a value between 0.155 and 0.225, the coordination number for the cation is 3. This means each cation is surrounded by three anions in the form of a planar equilateral triangle, with the cation located in the center. The coordination number is 4 for r_C/r_A between 0.225 and 0.414; the cation is located at the center of a tetrahedron, with anions at each of the four corners. For r_C/r_A between 0.414 and 0.732, the cation may be thought of as being situated at the center of an octahedron surrounded by six anions, one at each corner, as also shown in the table. The coordination number is 8 for r_C/r_A between 0.732 and 1.0, with anions at all corners of a cube and a cation positioned at the center. For a radius ratio greater than unity, the coordination number is 12. The most common coordination numbers for ceramic materials are 4, 6, and 8.

Crystal structure of ceramics are influenced by

1. **Magnitude of the electrical charge of each ions**

- Charge balance dictates chemical formula (Ca^{2+} and F^- form CaF_2).

2. **Relative sizes of cation (r_C) and anions (r_A)**

Cations are generally smaller than anions

$$\frac{r_C}{r_A} < 1$$

AX - Type crystal structures

- Some of the common ceramic materials are those in which there are equal numbers of cations and anions. These are often referred to as AX compounds, where A denotes the cation and X the anion. There are several different crystal structures for AX compounds; each is normally named after a common material that assumes the particular structure.
- ***Rock Salt Structure***
  - Perhaps the most common AX crystal structure is the sodium chloride (NaCl), or rock salt, type. The coordination number for both cations and anions is 6, and therefore the cation–anion radius ratio is between approximately 0.414 and 0.732.
  - A unit cell for this crystal structure is generated from an FCC arrangement of anions with one cation situated at the cube center and one at the center of each of the 12 cube edges. An equivalent crystal structure results from a face-centered arrangement of cations. Thus, the rock salt crystal structure may be thought of as two interpenetrating FCC lattices, one composed of the cations, the other of anions. Some of the common ceramic materials that form with this crystal structure are NaCl, MgO, MnS, LiF, and FeO.

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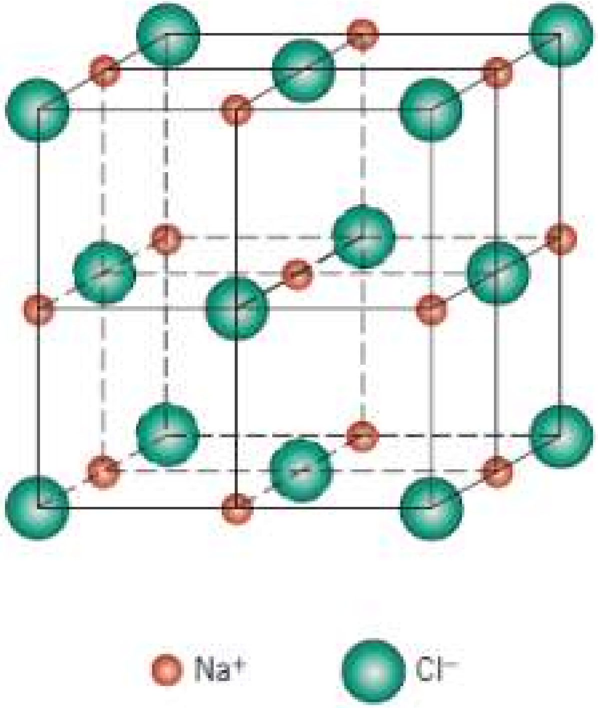


Figure 12.2 A unit cell for the rock salt, or sodium chloride (NaCl), crystal structure.

- Cesium Chloride Structure
  - a unit cell for the cesium chloride (CsCl) crystal structure; the coordination number is 8 for both ion types. The anions are located at each of the corners of a cube, whereas the cube center is a single cation. Interchange of anions with cations, and vice versa, produces the same crystal structure. This is not a BCC crystal structure because ions of two different kinds are involved.

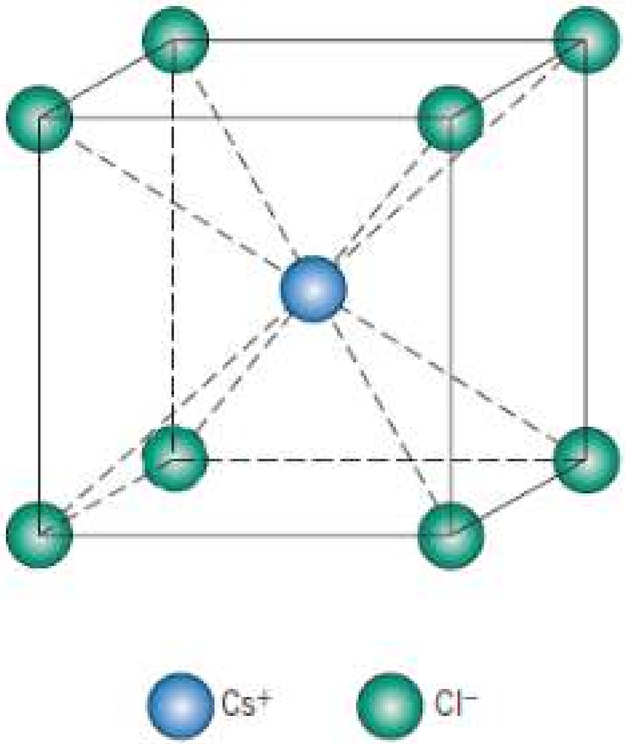
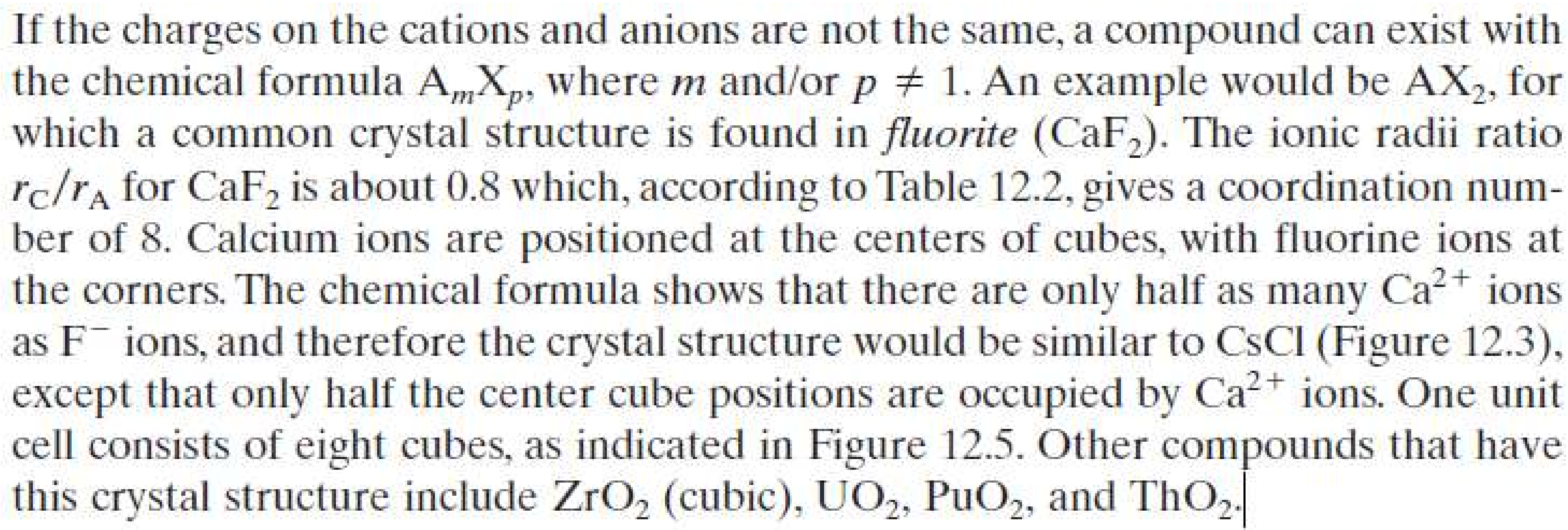


Figure 12.3 A unit cell for the cesium chloride (CsCl) crystal structure.

A_mX_p - Type crystal structures



If the charges on the cations and anions are not the same, a compound can exist with the chemical formula A_mX_p, where m and/or $p \neq 1$. An example would be AX_2, for which a common crystal structure is found in *fluorite* (CaF_2). The ionic radii ratio r_C/r_A for CaF_2 is about 0.8 which, according to Table 12.2, gives a coordination number of 8. Calcium ions are positioned at the centers of cubes, with fluorine ions at the corners. The chemical formula shows that there are only half as many Ca^{2+} ions as F^- ions, and therefore the crystal structure would be similar to CsCl (Figure 12.3), except that only half the center cube positions are occupied by Ca^{2+} ions. One unit cell consists of eight cubes, as indicated in Figure 12.5. Other compounds that have this crystal structure include ZrO_2 (cubic), UO_2, PuO_2, and ThO_2.

A_mX_p - Type crystal structures

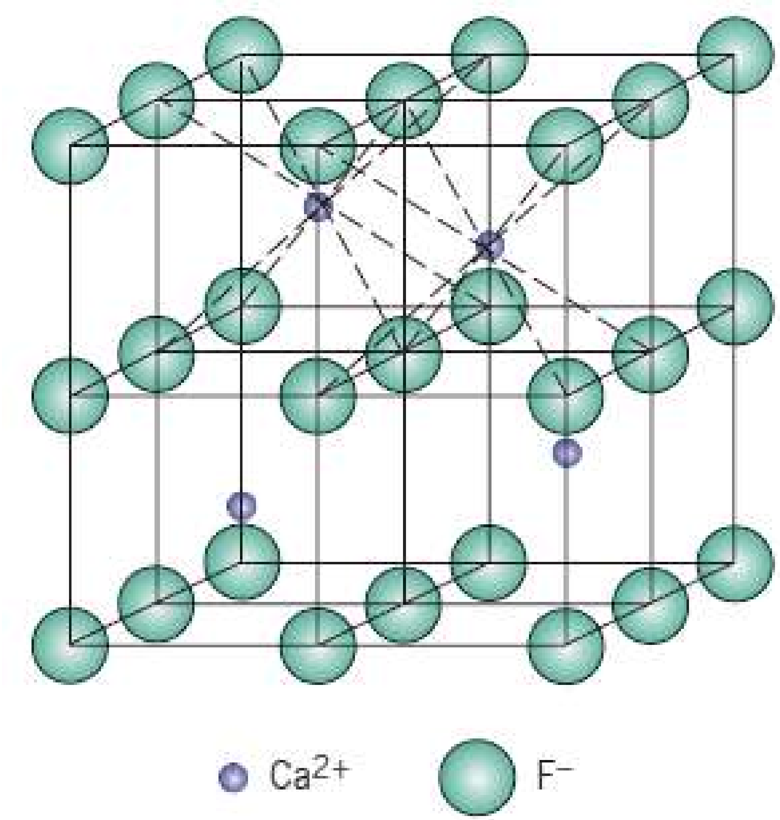
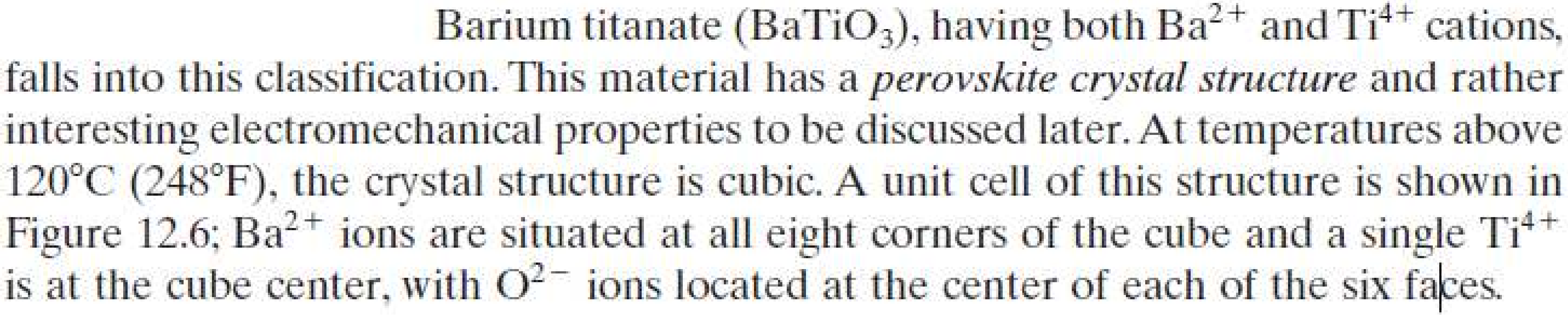


Figure 12.5 A unit cell for the fluorite (CaF_2) crystal structure.

$A_m\,B_mX_p$ - Type crystal structures

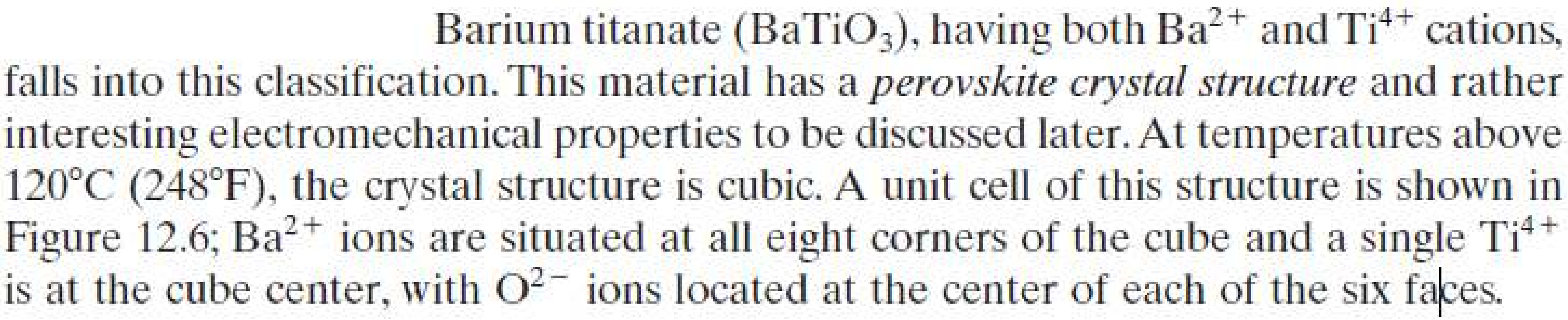
- It is also possible for ceramic compounds to have more than one type of cation; for two types of cations (represented by A and B), their chemical formula may be designated as $A_m\,B_mX_p$.

Eg: $BaTiO_3$, $SiZrO_2$ and $SiSeO_3$



Barium titanate ($BaTiO_3$), having both Ba^{2+} and Ti^{4+} cations, falls into this classification. This material has a *perovskite crystal structure* and rather interesting electromechanical properties to be discussed later. At temperatures above 120°C (248°F), the crystal structure is cubic. A unit cell of this structure is shown in Figure 12.6; Ba^{2+} ions are situated at all eight corners of the cube and a single Ti^{4+} is at the cube center, with O^{2-} ions located at the center of each of the six faces.

$A_m B_m X_p$ - Type crystal structures



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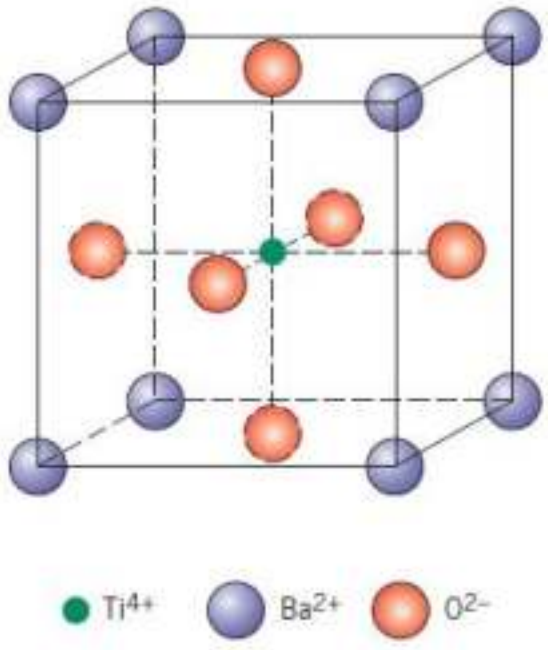


Figure 12.6 A unit cell for the perovskite crystal structure.

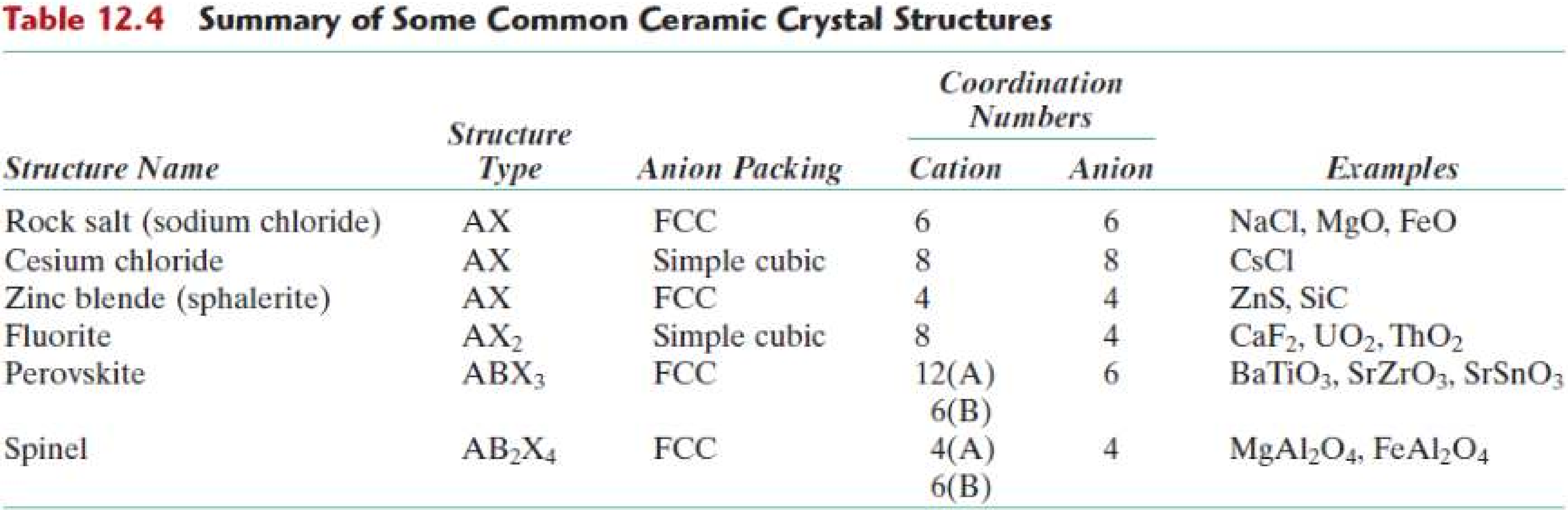


Table 12.4 Summary of Some Common Ceramic Crystal Structures

			Coordination Numbers		
Structure Name	*Structure Type*	*Anion Packing*	*Cation*	*Anion*	*Examples*
Rock salt (sodium chloride)	AX	FCC	6	6	NaCl, MgO, FeO
Cesium chloride	AX	Simple cubic	8	8	CsCl
Zinc blende (sphalerite)	AX	FCC	4	4	ZnS, SiC
Fluorite	AX_2	Simple cubic	8	4	CaF_2, UO_2, ThO_2
Perovskite	ABX_3	FCC	12(A) 6(B)	6	$BaTiO_3$, $SrZrO_3$, $SrSnO_3$
Spinel	AB_2X_4	FCC	4(A) 6(B)	4	$MgAl_2O_4$, $FeAl_2O_4$

Types and Applications of Ceramics

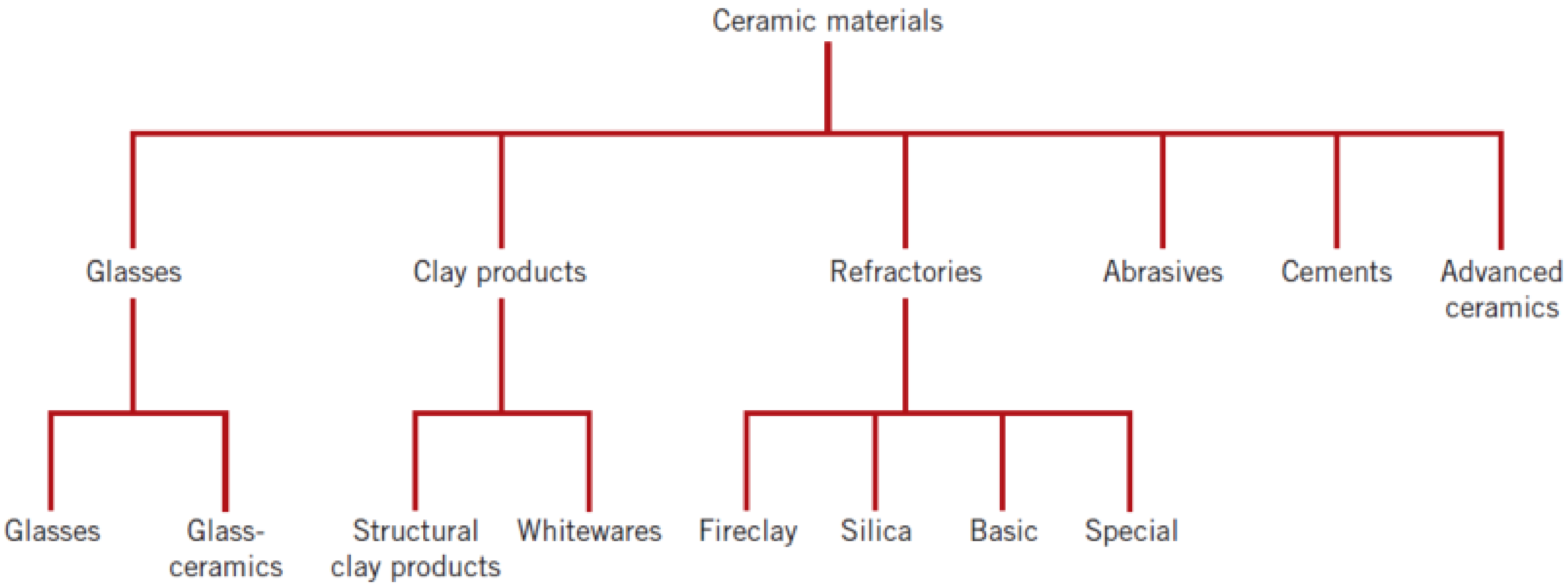
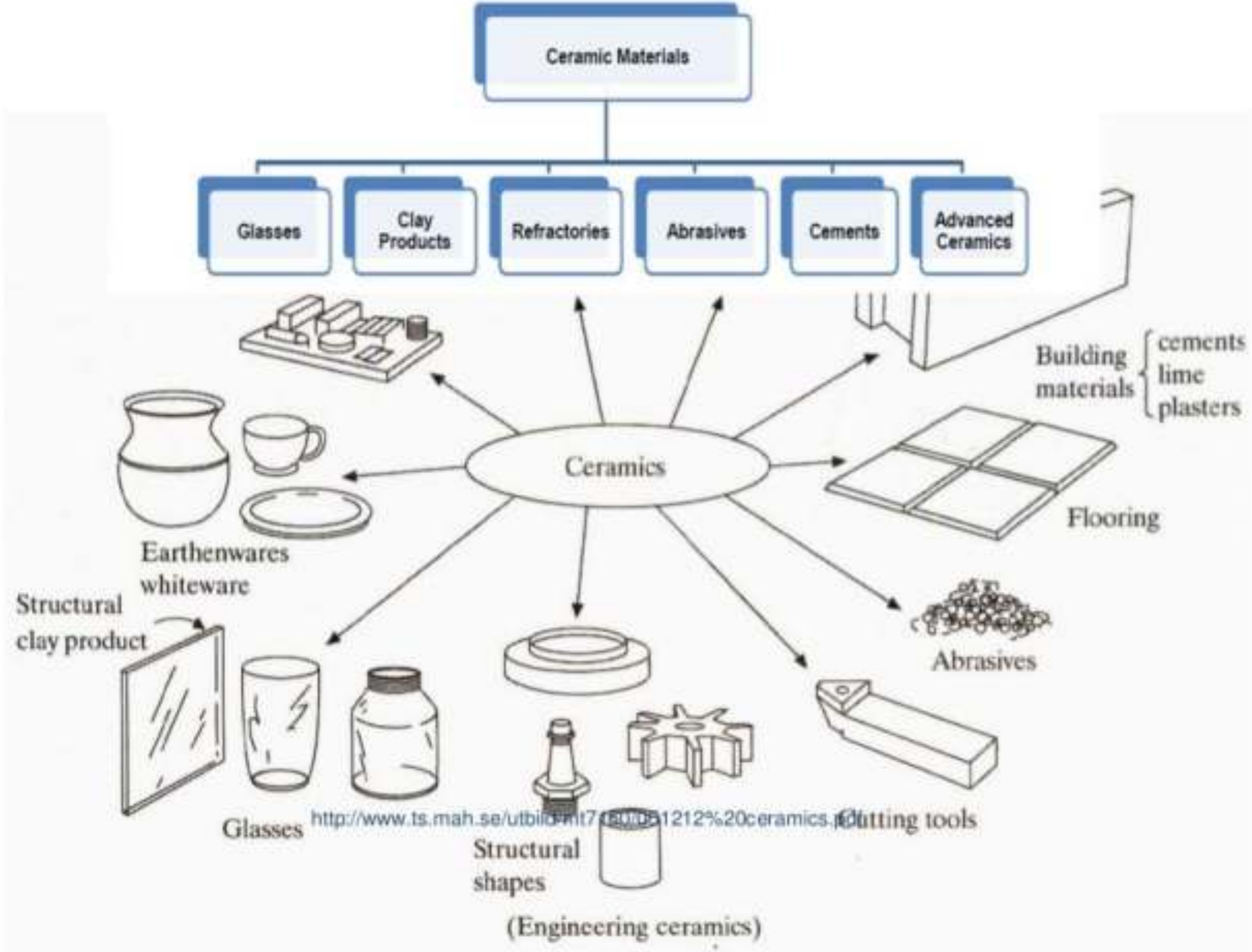


Figure 13.1 Classification of ceramic materials on the basis of application.

SPECTRUM OF CERAMICS USES



- Ceramic Materials
  - Glasses
  - Clay Products
  - Refractories
  - Abrasives
  - Cements
  - Advanced Ceramics

http://www.ts.mah.se/utbild/mt7080/051212%20ceramics.pdf

Types and Applications of Ceramics

- Glasses
  - They are noncrystalline silicates containing other oxides, notably CaO, Na_2O, K_2O, and Al_2O_3, which influence the glass properties
  - The glasses are a familiar group of ceramics; containers, lenses, and fiberglass represent typical applications.
- Glass–ceramic.
  - Most inorganic glasses can be made to transform from a noncrystalline state to one that is crystalline by the proper high-temperature heat treatment. This process is called crystallization, and the product is a fine-grained polycrystalline material which is often called a glass–ceramic.
  - The most common uses for these materials are as ovenware, tableware, oven windows, and range tops—primarily because of their strength and excellent resistance to thermal shock. They also serve as electrical insulators and as substrates for printed circuit boards, and are used for architectural cladding, and for heat exchangers and regenerators

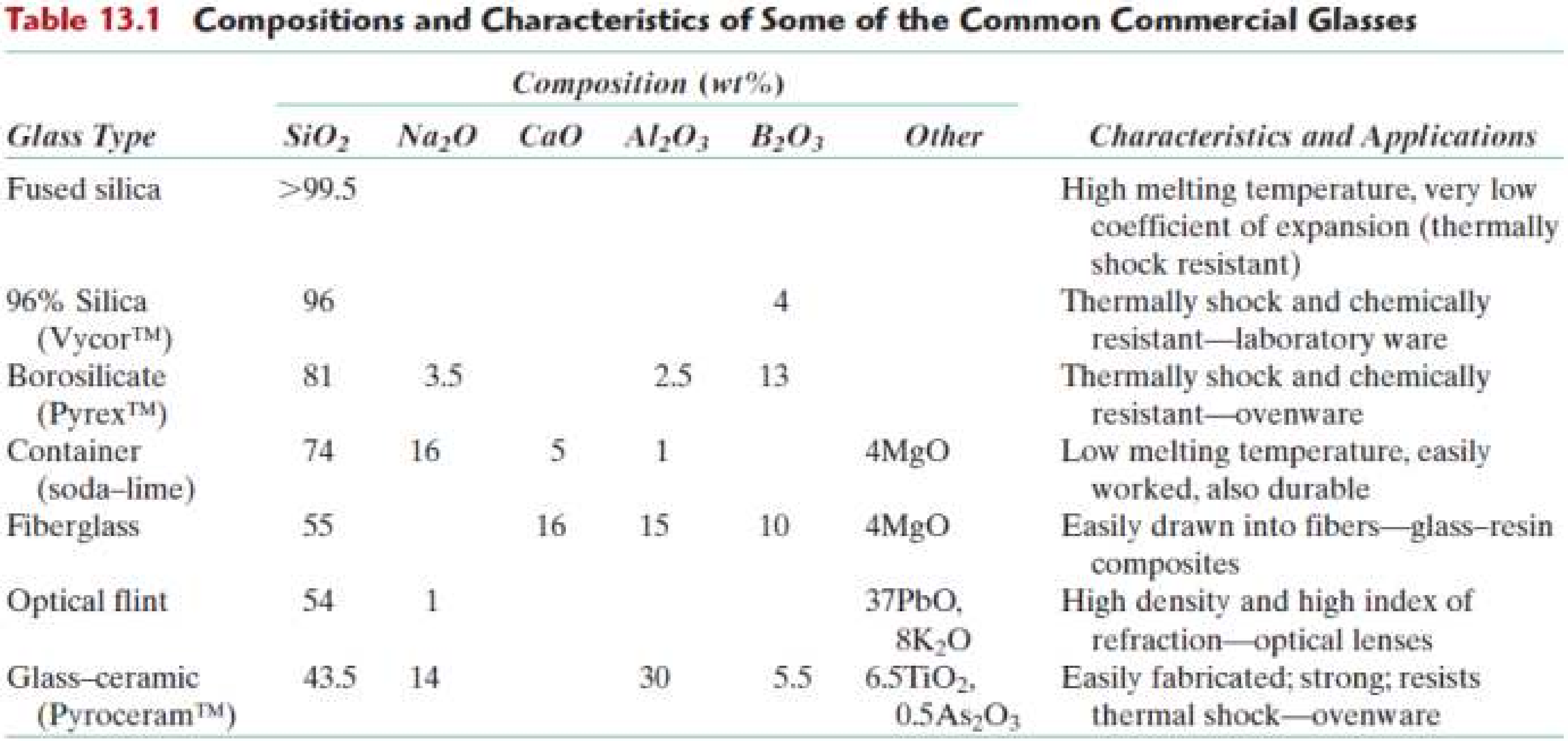


Table 13.1 **Compositions and Characteristics of Some of the Common Commercial Glasses**

	Composition (wt%)						
Glass Type	*SiO_2*	*Na_2O*	*CaO*	*Al_2O_3*	*B_2O_3*	*Other*	*Characteristics and Applications*
Fused silica	>99.5						High melting temperature, very low coefficient of expansion (thermally shock resistant)
96% Silica (Vycor™)	96				4		Thermally shock and chemically resistant—laboratory ware
Borosilicate (Pyrex™)	81	3.5		2.5	13		Thermally shock and chemically resistant—ovenware
Container (soda–lime)	74	16	5	1		4MgO	Low melting temperature, easily worked, also durable
Fiberglass	55		16	15	10	4MgO	Easily drawn into fibers—glass–resin composites
Optical flint	54	1				37PbO, $8K_2O$	High density and high index of refraction—optical lenses
Glass–ceramic (Pyroceram™)	43.5	14		30	5.5	$6.5TiO_2$, $0.5As_2O_3$	Easily fabricated; strong; resists thermal shock—ovenware

Types and Applications of Ceramics

- CLAY PRODUCTS
  - One of the most widely used ceramic raw materials is clay. This inexpensive ingredient, found naturally in great abundance, often is used as mined without any upgrading of quality. Another reason for its popularity lies in the ease with which clay products may be formed; when mixed in the proper proportions, clay and water form a plastic mass that is very amenable to shaping. The formed piece is dried to remove some of the moisture, after which it is fired at an elevated temperature to improve its mechanical strength.
  - Most of the clay-based products fall within two broad classifications: the structural clay products and the whitewares. Structural clay products include building bricks, tiles, and sewer pipes—applications in which structural integrity is important. The whiteware ceramics become white after the high-temperature firing. Included in this group are porcelain, pottery, tableware, china, and plumbing fixtures (sanitary ware).

Types and Applications of Ceramics

- REFRACTORIES
  - The salient properties of these materials include the capacity withstand high temperatures without melting or decomposing, and the capacity to remain unreactive and inert when exposed to severe environments. In addition, the ability to provide thermal insulation is often an important consideration. Refractory materials are marketed in a variety of forms, but bricks are the most common. Typical applications include furnace linings for metal refining, glass manufacturing, metallurgical heat treatment, and power generation.

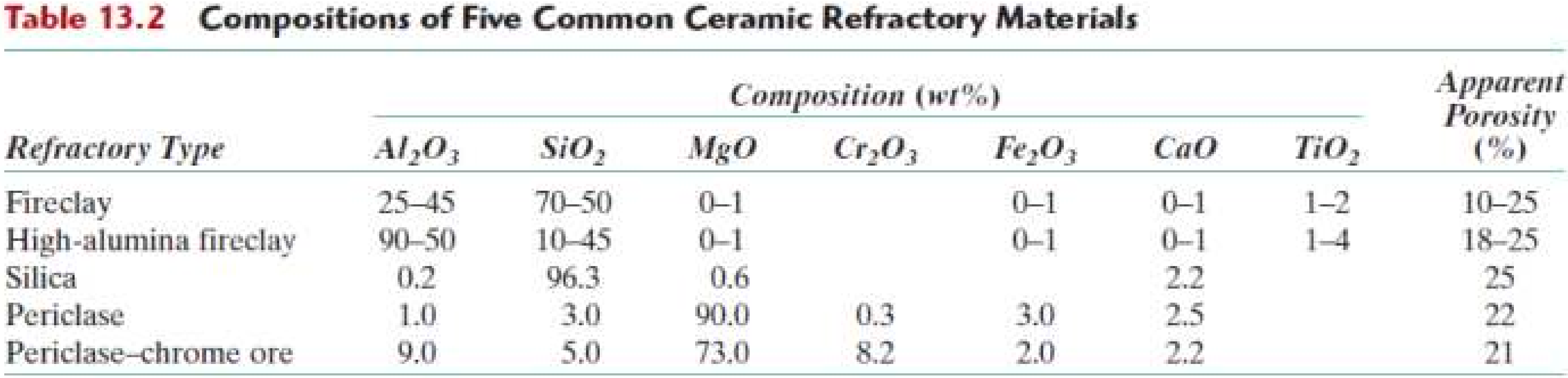


Table 13.2 **Compositions of Five Common Ceramic Refractory Materials**

	Composition (wt%)							
Refractory Type	*Al_2O_3*	*SiO_2*	*MgO*	*Cr_2O_3*	*Fe_2O_3*	*CaO*	*TiO_2*	*Apparent Porosity (%)*
Fireclay	25–45	70–50	0–1		0–1	0–1	1–2	10–25
High-alumina fireclay	90–50	10–45	0–1		0–1	0–1	1–4	18–25
Silica	0.2	96.3	0.6			2.2		25
Periclase	1.0	3.0	90.0	0.3	3.0	2.5		22
Periclase–chrome ore	9.0	5.0	73.0	8.2	2.0	2.2		21

Types and Applications of Ceramics

- Abrasive ceramics
  - Abrasive ceramics are used to wear, grind, or cut away other material, which necessarily is softer. Therefore, the prime requisite for this group of materials is hardness or wear resistance; in addition, a high degree of toughness is essential to ensure that the abrasive particles do not easily fracture. Furthermore, high temperatures may be produced from abrasive frictional forces, so some refractoriness is also desirable.
  - Abrasives are used in several forms—bonded to grinding wheels, as coated abrasives, and as loose grains.

The abrasive ceramics, being hard and tough, are utilized to cut, grind, and polish other softer materials. Diamond, silicon carbide, tungsten carbide, corundum, and silica sand are the most common examples. The abrasives may be employed in the form of loose grains, bonded to an abrasive wheel, or coated on paper or a fabric.

Types and Applications of Ceramics

- CEMENTS
  - Several familiar ceramic materials are classified as inorganic cements: cement, plaster of paris, and lime, which, as a group, are produced in extremely large quantities. The characteristic feature of these materials is that when mixed with water, they form a paste that subsequently sets and hardens.
  - When mixed with water, inorganic cements form a paste that is capable of assuming just about any desired shape. Subsequent setting or hardening is a result of chemical reactions involving the cement particles and occurs at the ambient temperature. For hydraulic cements, of which portland cement is the most common, the chemical reaction is one of hydration.

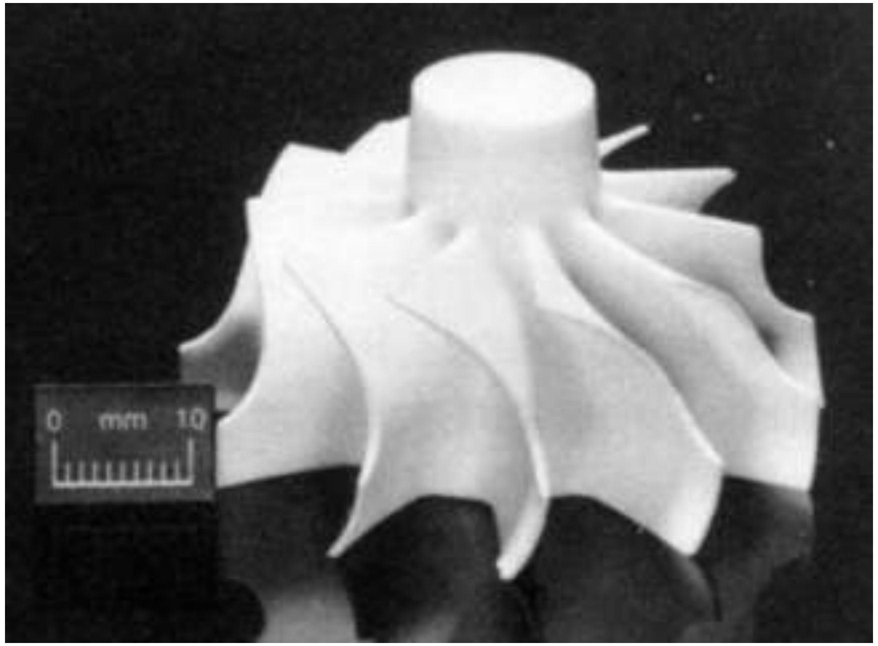
- ADVANCED CERAMICS
  - Many of our modern technologies utilize and will continue to utilize advanced ceramics because of their unique mechanical, chemical, electrical, magnetic, and optical properties and property combinations.

1. Microelectromechanical Systems (MEMS)
   - Microelectromechanical systems (abbreviated MEMS) are miniature "smart" systems consisting of a multitude of mechanical devices that are integrated with large numbers of electrical elements on a substrate of silicon. The mechanical components are microsensors and microactuators. Microsensors collect environmental information by measuring mechanical, thermal, chemical, optical, and/or magnetic phenomena. The microelectronic components then process this sensory input, and subsequently render decisions that direct responses from the microactuator devices—devices that perform such responses as positioning, moving, pumping, regulating, and filtering. These actuating devices include beams, pits, gears, motors, and membranes, which are of microscopic dimensions, on the order of microns in size.
2. Optical Fibers
   - The optical fiber is made of extremely high-purity silica, which must be free of even minute levels of contaminants and other defects that absorb, scatter, and attenuate a light beam.

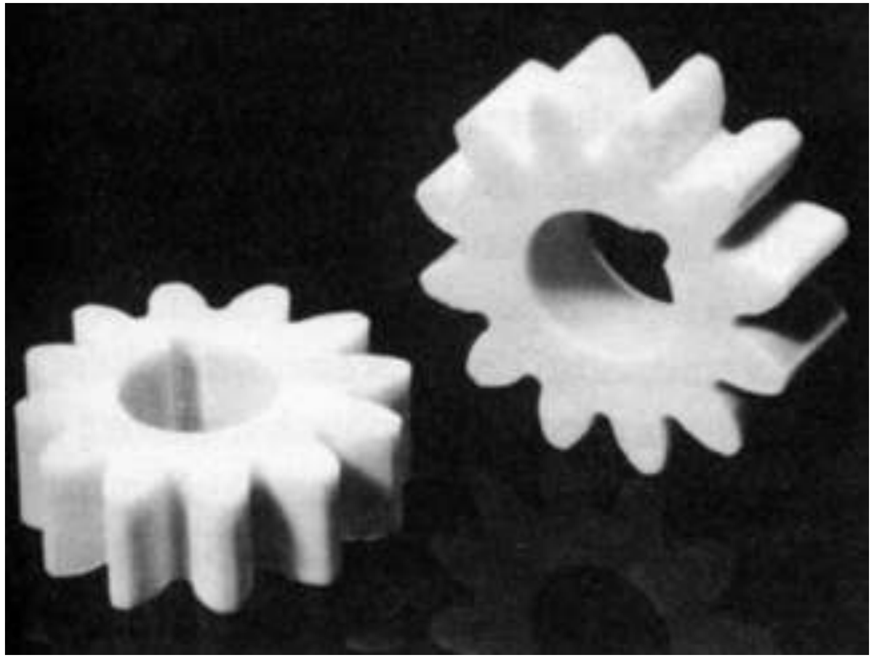
Types and Applications of Ceramics

4. Ceramic Ball Bearings
   - silicon nitride (Si3N4) balls have begun replacing steel balls in a number of applications, since several properties of Si3N4 make it a more desirable material.
5. Piezoelectric Ceramics
   - A few ceramic materials (as well as some polymers) exhibit the unusual phenomenon of piezoelectricity—electric polarization (i.e., an electric field or voltage) is induced in the ceramic crystal when a mechanical strain (dimensional change) is imposed on it.
   - Commonly used piezoelectric ceramics include barium titanate ($BaTiO_3$), lead titanate ($PbTiO_3$), lead zirconate–titanate (PZT) [$Pb(Zr,Ti)O_3$], and potassium niobate ($KNbO_3$)

Engine Components



Rotor (Alumina)



Gears (Alumina)

Ceramic disc brakes

TITANIUM

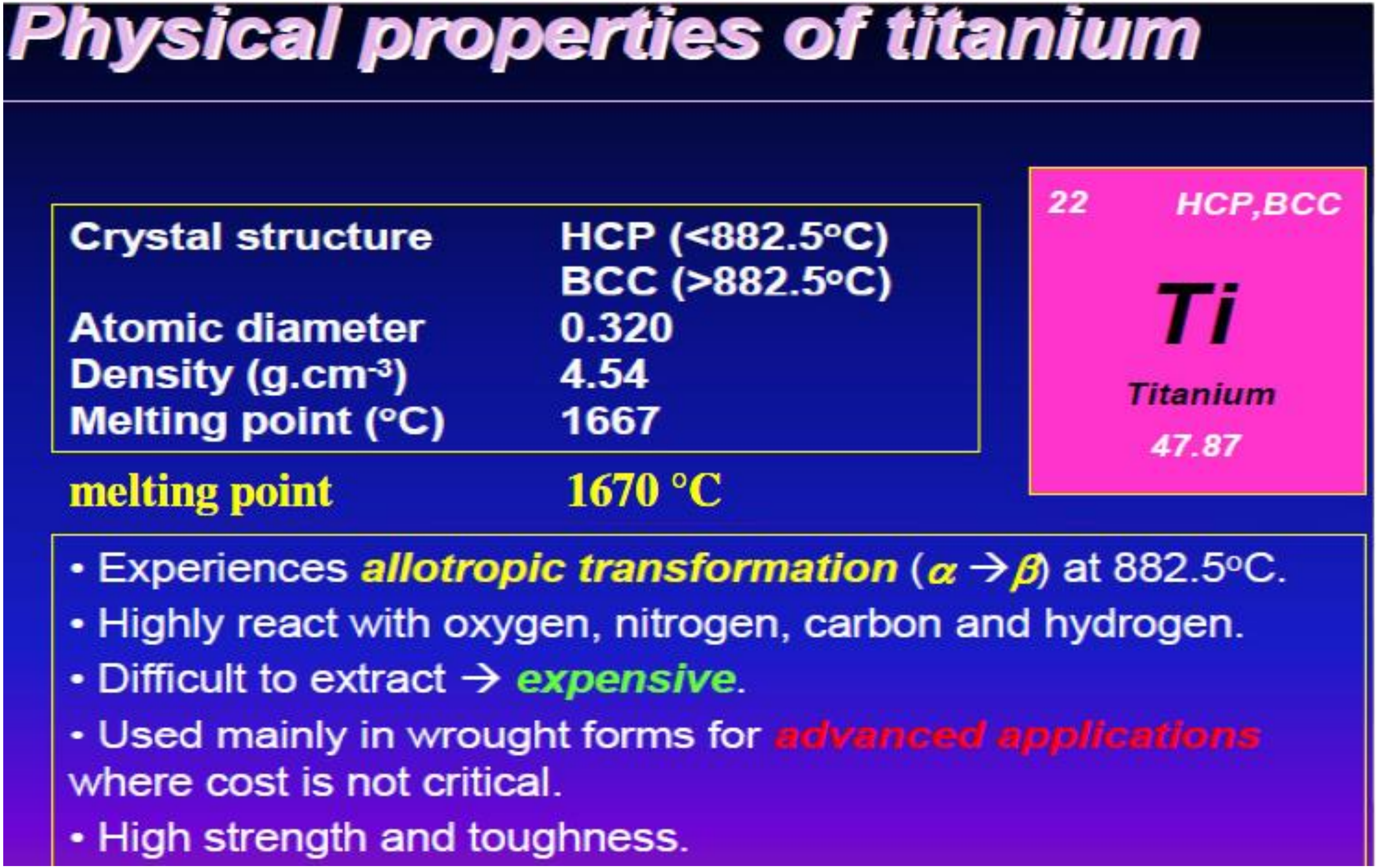
Introduction- Titanium and its alloys

- ***Titanium*** is named after the ***Titans***, the powerful sons of the earth in Greek mythology.
- Titanium is the ***forth abundant metal*** on earth crust (~ 0.86%) after aluminium, iron and magnesium.
- Not found in its free, pure metal form in nature but as ***oxides***, i.e., ilmenite (***$FeTiO_3$***) and rutile (***TiO_2***).
- Found only in small amount in Thailand.
- Have similar ***strength as steel*** but with a ***weight nearly half of steel.***

Titans

Ilmenite ($FeTiO_3$)

Rutile (TiO_2)



Physical properties of titanium

Crystal structure	HCP (<882.5°C) BCC (>882.5°C)
Atomic diameter	0.320
Density (g.cm^{-3})	4.54
Melting point (°C)	1667

melting point **1670 °C**

22 HCP,BCC

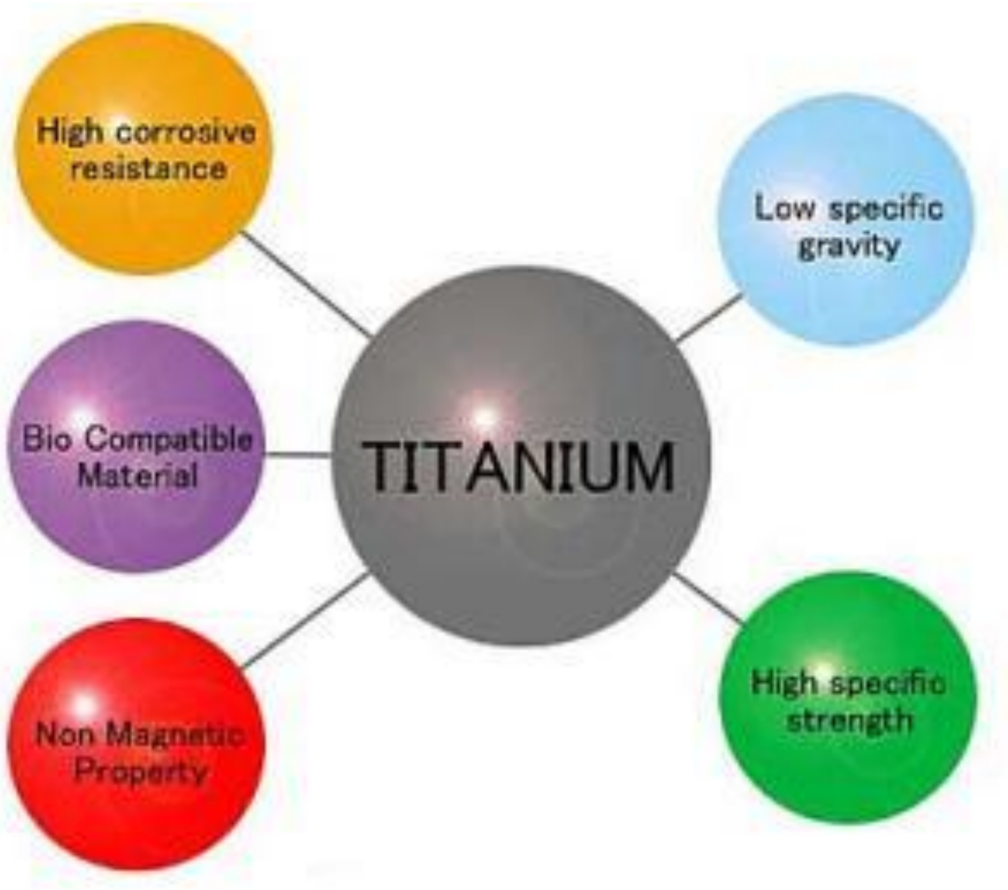
Ti

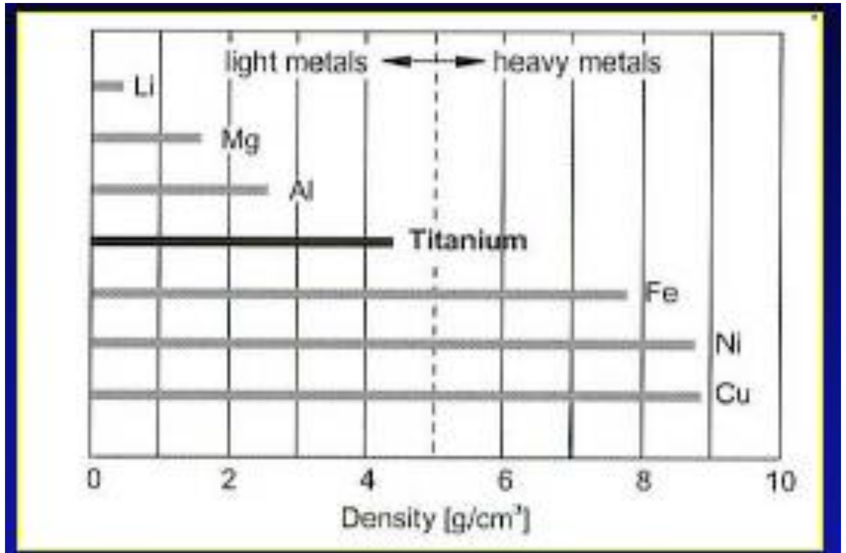
Titanium

47.87

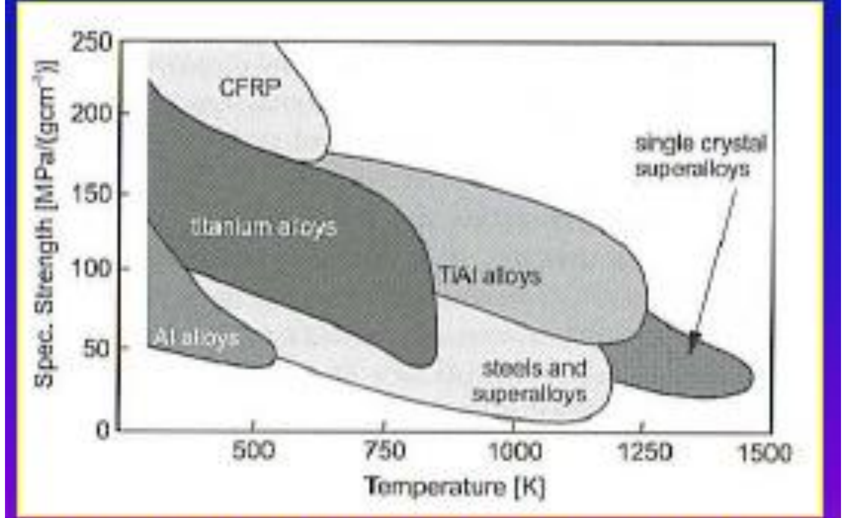
- Experiences ***allotropic transformation*** ($\alpha \rightarrow \beta$) at 882.5°C.
- Highly react with oxygen, nitrogen, carbon and hydrogen.
- Difficult to extract → ***expensive***.
- Used mainly in wrought forms for ***advanced applications*** where cost is not critical.
- High strength and toughness.

Advantages of titanium alloys





Density of selected metals



Specific strength vs temperature

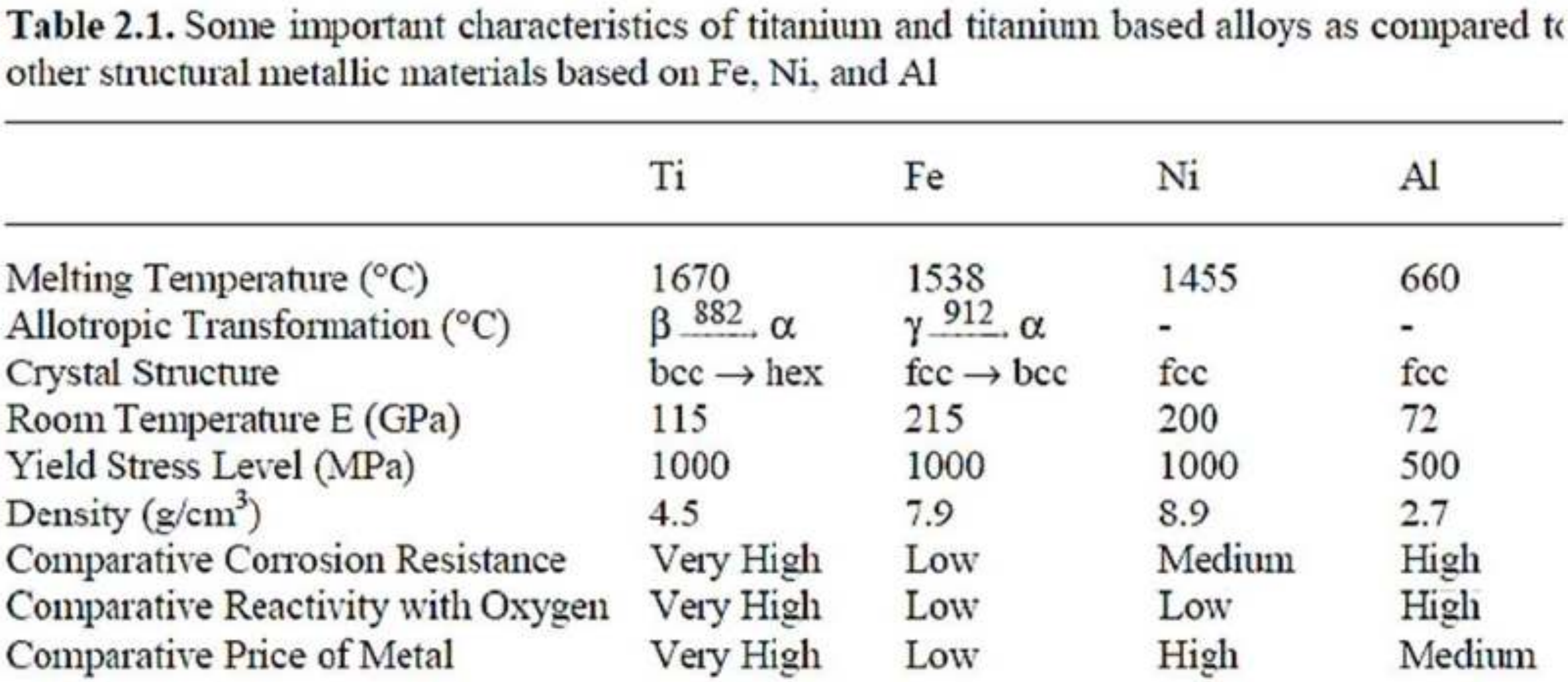
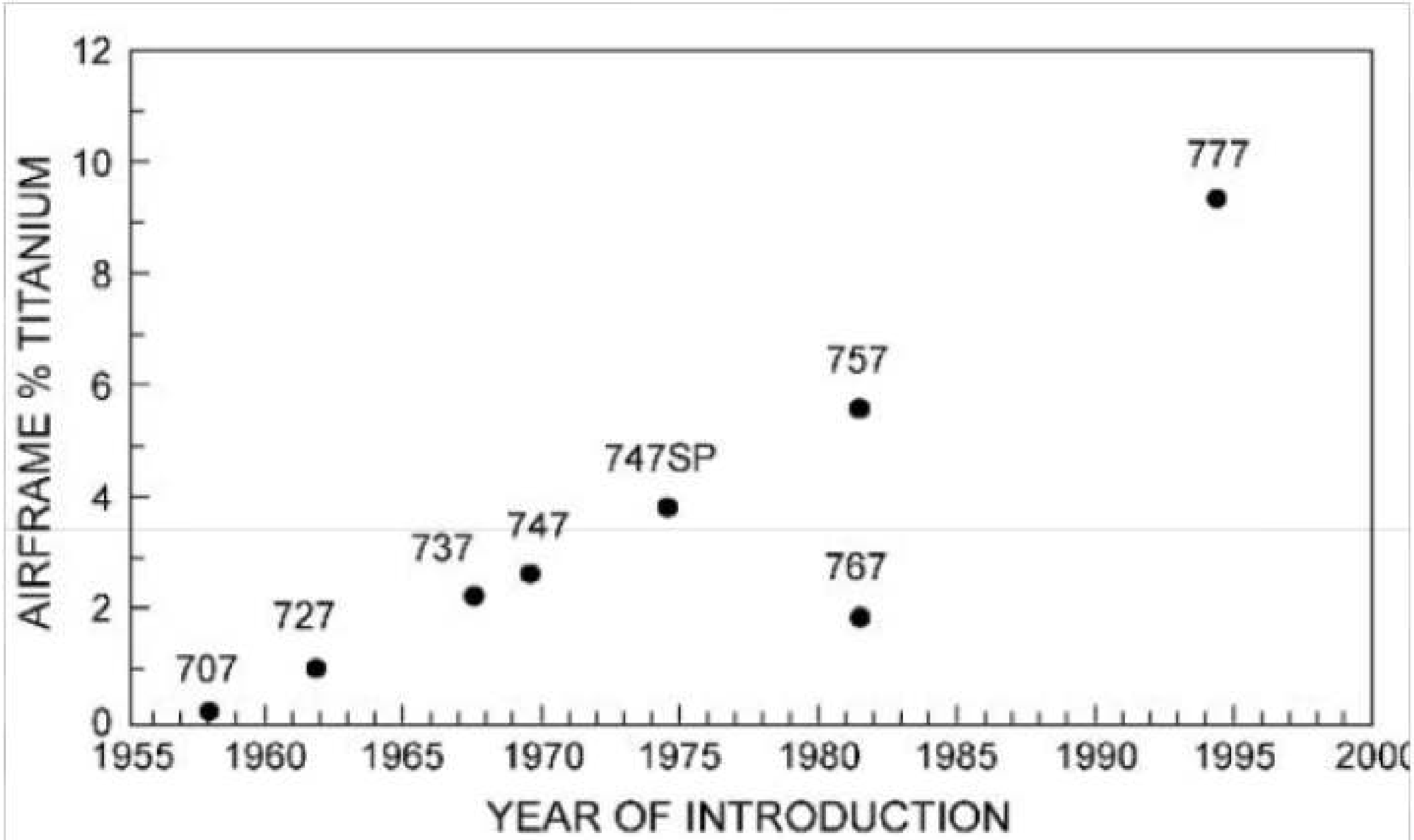


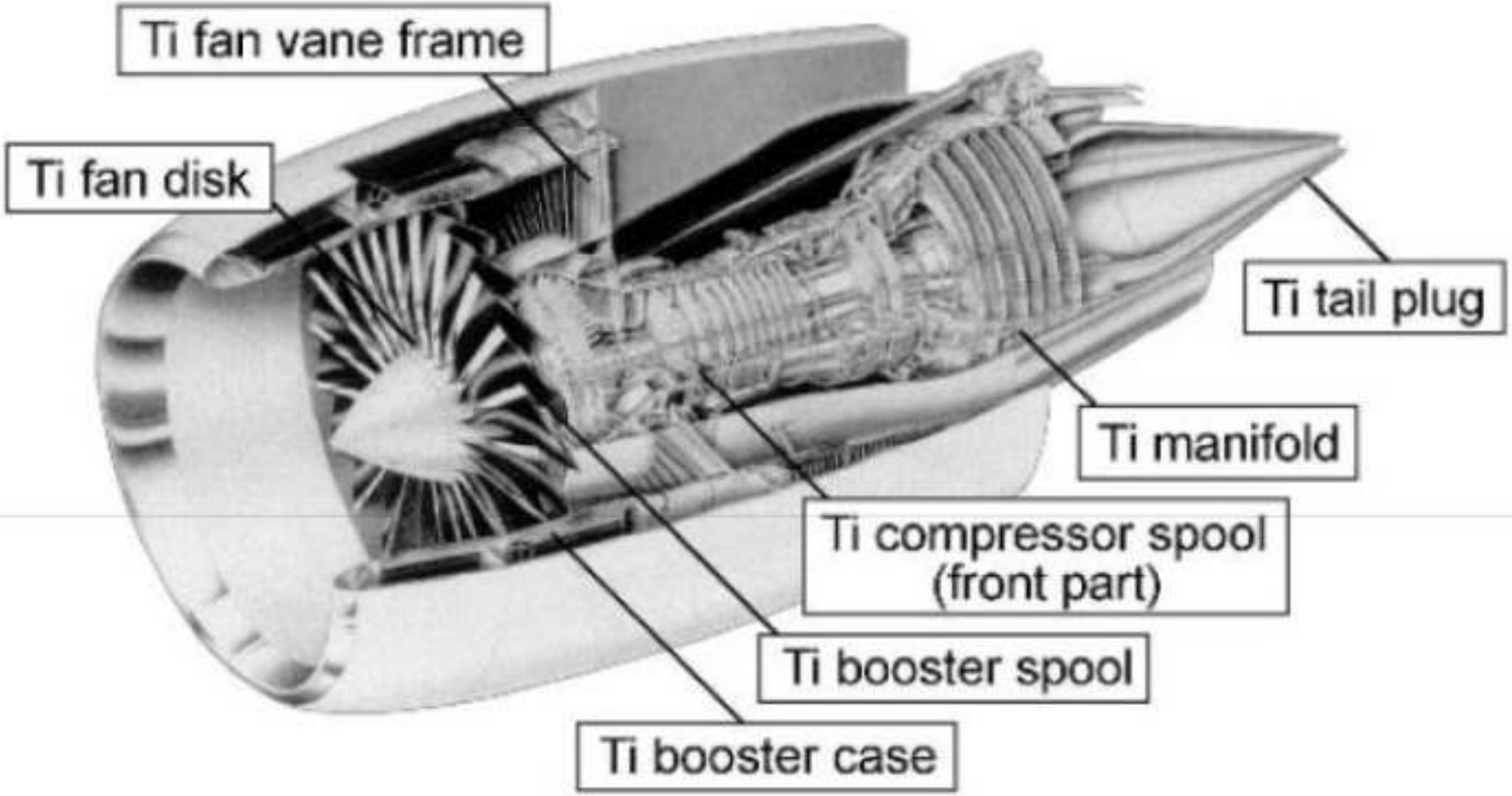
Table 2.1. Some important characteristics of titanium and titanium based alloys as compared t
other structural metallic materials based on Fe, Ni, and Al

	Ti	Fe	Ni	Al
Melting Temperature (°C)	1670	1538	1455	660
Allotropic Transformation (°C)	$\beta \xrightarrow{882} \alpha$	$\gamma \xrightarrow{912} \alpha$	-	-
Crystal Structure	bcc → hex	fcc → bcc	fcc	fcc
Room Temperature E (GPa)	115	215	200	72
Yield Stress Level (MPa)	1000	1000	1000	500
Density (g/cm^3)	4.5	7.9	8.9	2.7
Comparative Corrosion Resistance	Very High	Low	Medium	High
Comparative Reactivity with Oxygen	Very High	Low	Low	High
Comparative Price of Metal	Very High	Low	High	Medium

- Pure titanium exhibits an allotropic phase transformation at 882°C, changing from a body-centered cubic crystal structure (β phase) at higher temperatures to a hexagonal close-packed crystal structure (α phase) at lower temperatures.



Titanium usage in Boeing airframes



Titanium usage in the GE-90 aero-engine

Titanium ore – rutile (TiO_2) is converted into titanium sponge

- This high price is mainly a result of the high reactivity of titanium with oxygen. The use of inert atmosphere or vacuum is required during the production process of titanium sponge from titanium tetrachloride as well as during the melting process.

- The high reactivity with oxygen leads to the immediate formation of a stable and adherent oxide surface layer when exposed to air, resulting in the superior corrosion resistance of titanium in various kinds of aggressive environments, especially in aqueous acid environments.

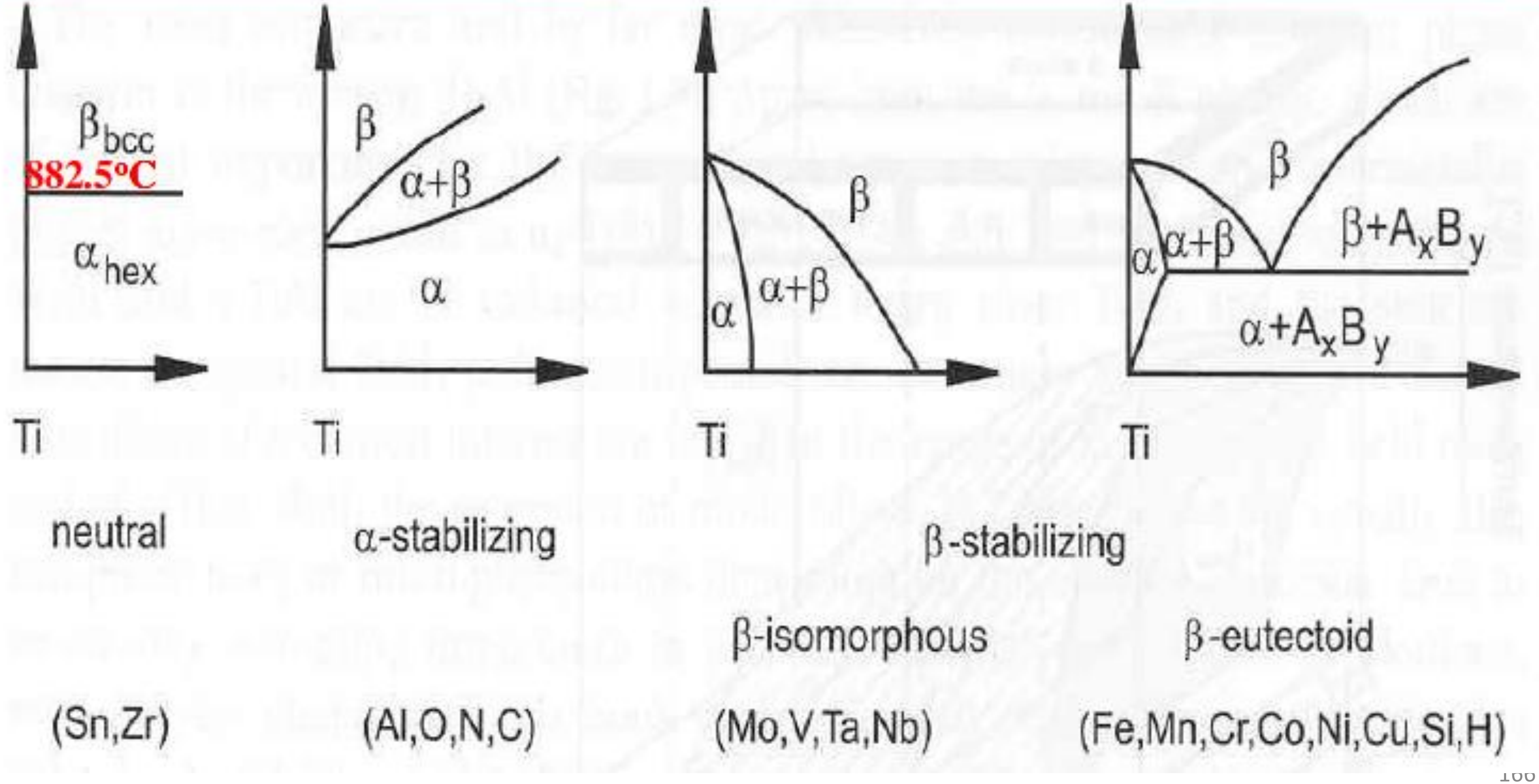
Classification of titanium alloys

- Commercially pure (CP) titanium alpha and near alpha titanium alloys
  - Generally non-heat treatable and weldable
  - Medium strength, good creep strength, good corrosion resistance

- Alpha-beta titanium alloys
  - Heat treatable, good forming properties
  - Medium to high strength, good creep strength

- Beta titanium alloys
  - Heat treatable and readily formable
  - Very high strength, low ductility

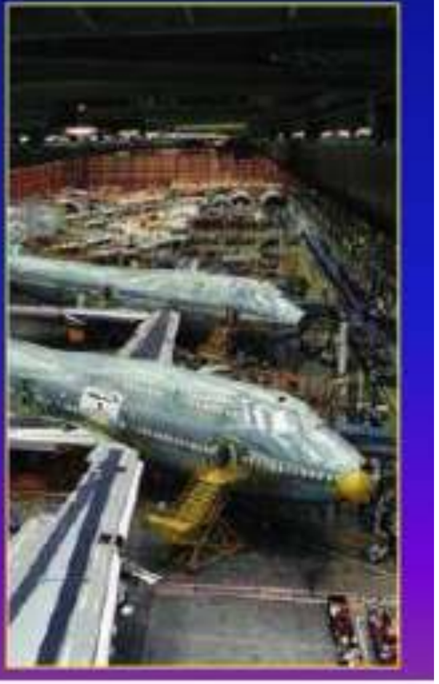
The substitutional element Al and the interstitial elements O, N, and C are all strong α stabilizers and increase the transus temperature with increasing solute content seen from the schematic phase diagram



Applications of titanium alloys in summary

- Aeroengines
- Automotive and road transport
- Dental alloys
- Electrochemical anodes
- Geothermal plant
- Marine
- Military hardware
- Offshore production tubulars
- Airframes
- Condensers
- Desalination plant
- Flue gas desulpherisation
- Nuclear and environmental safety
- Petrochemical refineries
- Architectural
- Cryogenic logging tools
- Food, brewing and pharmaceutical
- Jewellery manufacture
- Metal extraction equipment
- Offshore piping systems
- Pulp and paper
- Heat exchangers
- Medical implants

Titanium implants



Problems in machining titanium

Compared to high strength steels, titanium, due to its unique physical and chemical properties, poses the following problems:

- Lower thermal conductivity of Ti hinders quick dissipation of the heat caused by machining, leading to increased wear of cutting tools.
- Lower modulus of elasticity leads to high spring back, causing Ti parts to move away from the cutting tool
- Lower hardness and high chemical reactivity of Ti lead to galling with the cutting tool.

WELDING OF TITANIUM

- For fabrication of chemical engg. plant & Eqpt., commercially pure titanium is used. TIG & MIG welding methods are used.
- Welding of alloy titanium is difficult compared to welding pure titanium:

  α alloys are weldable

  Among α+β alloys Ti-6Al-4V has good weldability

  β alloys are not weldable
- Titanium being a reactive metal, entry of air to the weldzone is to be strictly prevented through protection with an inert gas cover to prevent access to air