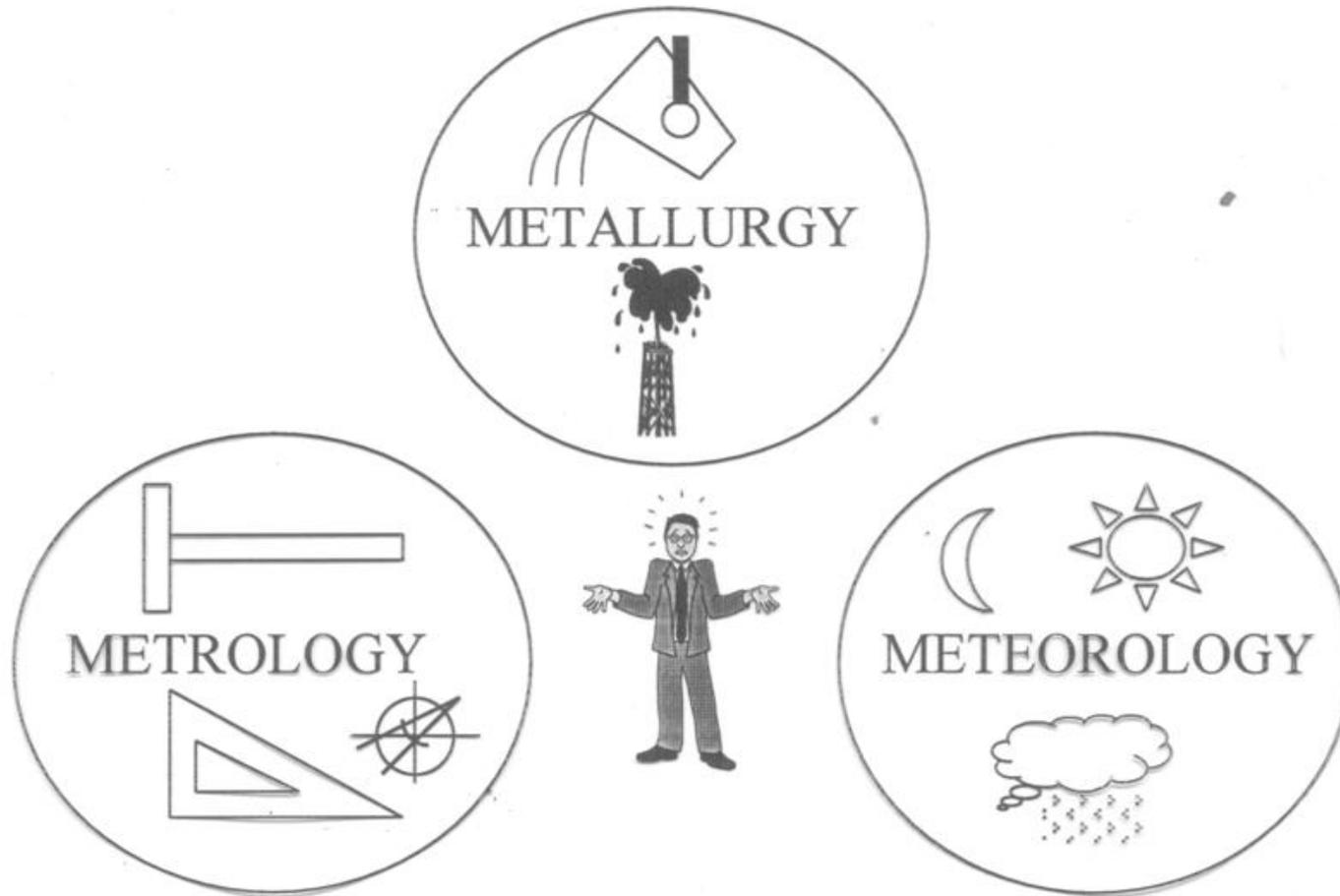


## CHAPTER 1

# INTRODUCTION TO ENGINEERING METALLURGY AND MATERIALS



## 1.1 MATERIALS and ENGINEERING

**Metallurgy** is the art and science of making metals and alloys in forms and with properties suitable for practical use. It had a place in ancient history, having brought us out of the Stone Age into the Iron Age. Now, however, metals are not sufficient to fulfill the requirements of innumerable engineering applications.

Thus, currently a broader term, **material science** has been introduced which deals with all sorts of material-structure-property-process relationships.

The rise of materials from a relatively dormant role to one of foremost importance is recent. For several centuries the **few metals and alloys** (such as iron, copper, brass, tin and zinc), the **few ceramics** (such as pottery), and **natural polymers** (such as wool, cotton, asbestos, and cellulose) were sufficient to meet most human needs. The birth of the new age of materials took place in the late nineteenth and early twentieth centuries. **Steel** became a major engineering material, aluminum became a commercial metal, and Bakeland developed Bakelite.

This modest start spawned a virtual revolution in materials. Only routine progress had been made for centuries, but now new materials were being developed at a greatly increased rate. Technical ceramics and polymers, almost unknown about 1900, have increased several hundred fold in quantity and variety. Even metals, with a slower rate of development, have expanded greatly with many new alloys becoming available each year.

Not only the number of materials increased but the combinations have also increased. Clad metals, reinforced polymers, laminates, honeycombs, organometallic, and composites of many types have introduced the systems concept to material usage.

Engineers in all disciplines should have some basic and applied knowledge of engineering materials, so that they will be able to do their work more effectively when using materials. The purpose of this course is to serve as an introduction to the internal **structure**, **properties**, **processing**, and applications of engineering materials. Because of the enormous amount of information available about engineering materials and due to the limitations of the course, the material presented has had to be selective. However, when possible, up to date references are listed to enable the student engineer to further study the **fascinating world of engineering materials.**

# Early History

## Stone Age (Paleolithic, ~2.5 Million BC)

Flint: cutting edge easily formed by chipping

## Copper Age (~8000 – 5000 BC)

Pottery kilns hot enough to melt Cu from ore (Cu  $T_m = 1085^\circ\text{C}$ )  
strength  $\sigma_y = 70 \text{ MPa}$  (10,000 lb/in<sup>2</sup>)

## Bronze Age (~3500 BC)

“Alloying”: add tin to copper (Sn  $T_m = 232^\circ\text{C}$ )  
strength  $\sigma_y = 125 \text{ MPa}$  (18,000 lb/in<sup>2</sup>)

## Iron Age (~1500 BC)

Reduce Fe ore at high T with charcoal to capture O<sub>2</sub>, release Fe metal  
(Fe  $T_m = 1538^\circ\text{C}$ )

strength  $\sigma_y = 275 \text{ MPa}$  (40,000 lb/in<sup>2</sup>)

Add carbon to Fe → Steel!  $\sigma_y \rightarrow > 1500 \text{ MPa}$  (200,000 lb/in<sup>2</sup>)

Improve material properties,  
Increase design flexibility!





Power Generation

- Fuel cells, batteries
- Renewable energy collector/converter



Automotive & Aerospace

- Engines
- Frames



Food Processing

- Chocolate
- Ice cream

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What do Materials Scientists and Engineers make?



Environmental

- Recycled/recyclable materials
- Pollutant/chemical/biohazard sensors

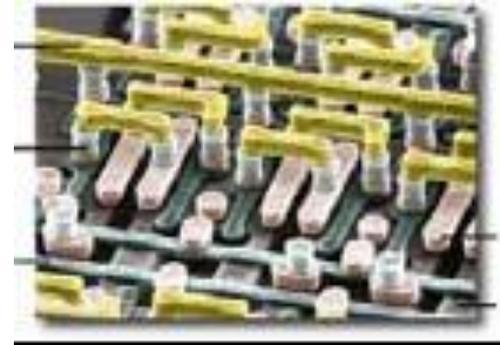
Biomedical

- Implants, tissue scaffolding
- Drug delivery devices



Computers/Electronics

- Microchips
- Data storage



Recreation

- Athletic equipment
- Sportswear

Materials enable all products from candy bars to rockets

## 1.2 TYPES OF MATERIALS

For convenience most engineering materials are divided into three main classes: metallic, polymeric (plastic), and ceramic materials. In addition to the three main classes of materials, composite materials and electronic materials will be considered as two more types.

**Metals** are inorganic substances, which are composed of one or more metallic elements and may contain some non-metallic elements. They have a crystalline structure in which the atoms are arranged in an orderly manner. Metals in general are good thermal and electrical conductors. Most metals are relatively strong, ductile, and are heavier than other substances.

**Polymers (Plastics)** consist of organic (carbon containing) long molecular chains or networks. Structurally, most polymeric materials are non-crystalline but some consist of mixtures of crystalline and non-crystalline regions. The strength and ductility of polymeric materials vary greatly. They are poor conductors of heat and electricity. In general, polymeric materials have low densities and relatively low softening or decomposition temperatures.

**Ceramics** are any inorganic, non-metallic solids (or supercooled liquids) processed or used at high temperatures. They can be crystalline, non-crystalline, or mixtures of both. Most ceramic materials have mechanical brittleness, high hardness, and high temperature strength. They have low thermal and electrical conductivity, which makes them useful as insulators.

**Composites** are regarded as a combination of two or more materials, which are used together to support a weakness in one material by strength in another. Usually, the components do not dissolve in each other and can be physically identified by an interface between the components. Composites can be of many types: fibrous (fibers in a matrix) or particulate (particles in a matrix). Two outstanding types are fiberglass reinforcing in polyester and carbon fibers in epoxy.

**Electronic materials** are not a major type of material by volume but are an extremely important type of material for advanced engineering technology. The most important electronic material is pure silicon, which is modified in various ways to change its electrical characteristics. A multitude of complex electronic circuits can be miniaturised on a silicon chip, which is about 0.5 cm square.

## 1.3 MATERIAL SELECTION

One of the most important areas of design thinking is the selection of the material from which a part will be produced. The enormity of this decision process can be appreciated when it is realised that there are over 40,000 currently useful metallic alloys and probably close to that number of non-metallic engineering materials. An improperly chosen material can lead not only to failure of the part or component but also to unnecessary cost. It is not possible to select a material for one property alone. It is in the balance of one factor against another that engineers find their challenge and satisfaction.

Much materials selection is based on past experience. What worked before obviously is a solution, but it is not necessarily the optimum solution. Materials were selected from handbooks with limited choice and on the basis of limited property data. Today, however, that is an unacceptable approach for all but the routine and simple design. In many advanced aerospace and energy applications, materials are subjected to the limits of their properties. In the more consumer-oriented applications, the pressures to decrease cost are stronger than ever. In the automotive industry, the drive to increase energy efficiency through weight reduction is revolutionising material selection.

### 1.3.1 Performance Characteristics of Materials

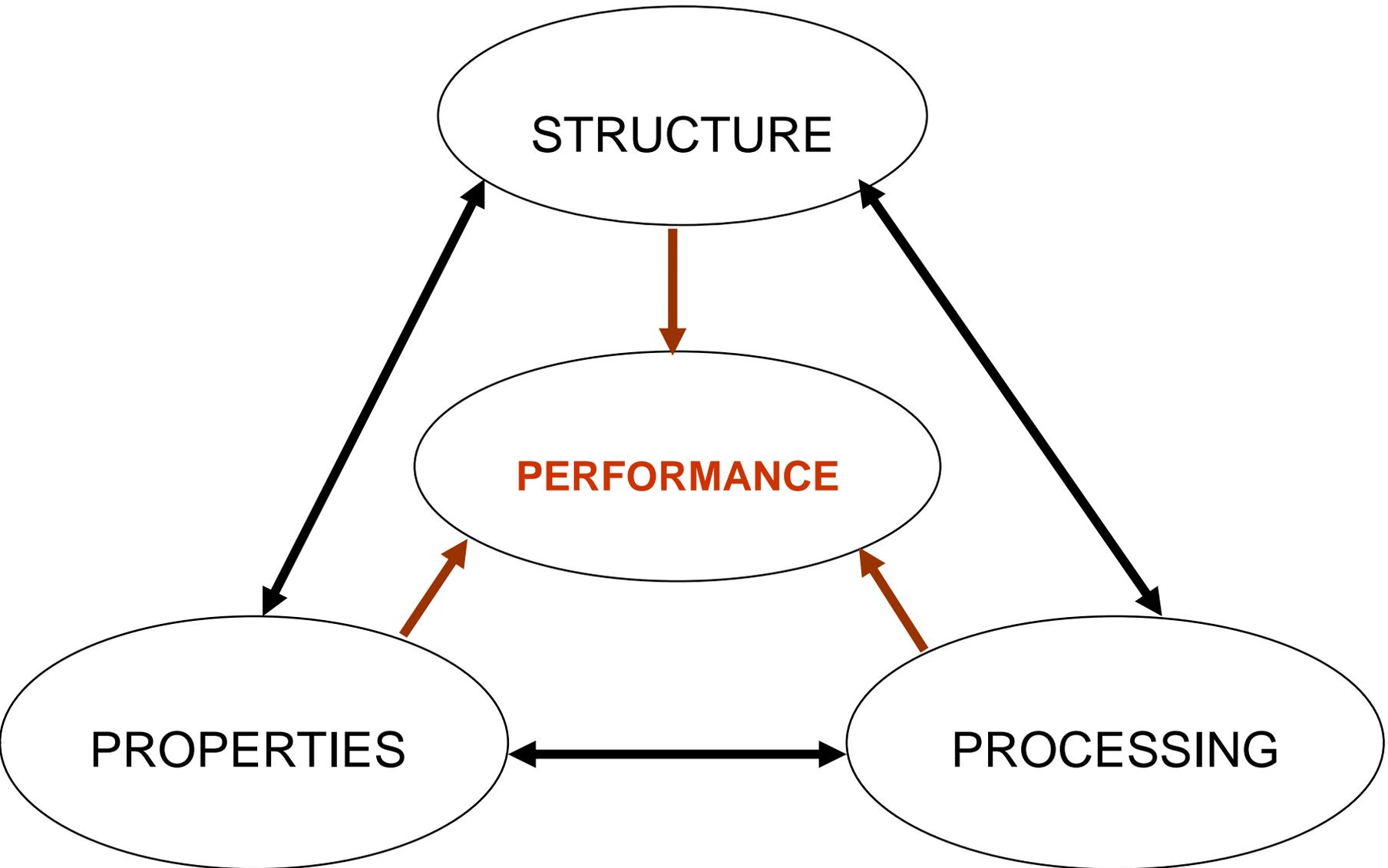
The **performance** or **functional requirements** of a material usually are expressed in terms of physical, mechanical, thermal, electrical, or chemical properties. Material properties are the link between the basic structure and composition of the material and the service performance of the part.

Table 1.1 provides a fairly complete listing of material performance characteristics. It can serve as a checklist in selecting materials to assure that no important properties are overlooked. The subject of material properties can quickly become rather complex. A consideration of any one of the properties listed in Table 1.1 can be expanded to include the type of test environment, stress state, or even specimen configuration.

**TABLE 1.1 Material performance characteristics**

<p><b><i>Physical properties</i></b> Crystal structure Density Melting point Vapor pressure Viscosity Porosity Reflectivity Transparency Dimensional stability</p> <p><b><i>Electrical properties</i></b> Conductivity Dielectric constant Hysteresis</p> <p><b><i>Nuclear properties</i></b> Half life Cross section Stability</p> <p><b><i>Mechanical properties</i></b> Hardness Modulus of elasticity Poisson's ratio Stress-strain curve Yield strength Ultimate strength in Tension in Shear in Bearing Fatigue properties Corrosion fatigue</p>	<p><b><i>Fracture toughness</i></b> High temperature creep Wear properties Abrasion wear Erosion wear Cavitation Ballistic impact</p> <p><b><i>Thermal properties</i></b> Conductivity Specific heat Coef. of expansion Emissivity Fire resistance</p> <p><b><i>Chemical properties</i></b> Position in elect. series Corrosion and degrad. in Atmosphere in Salt water in Acids Oxidation Thermal stability Stress corrosion</p> <p><b><i>Fabrication properties</i></b> Castability Heat treatability Hardenability Formability Machinability Weldability</p>
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# The essence of MATERIALS SCIENCE & ENGINEERING

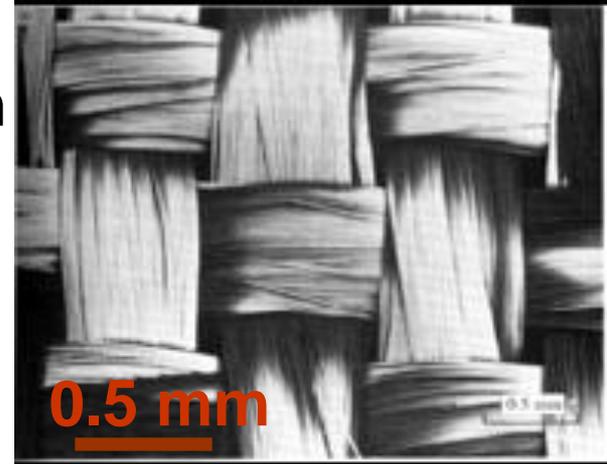




Crystal<sup>b</sup>  
 $10^{-9} - 10^{-1}$  m

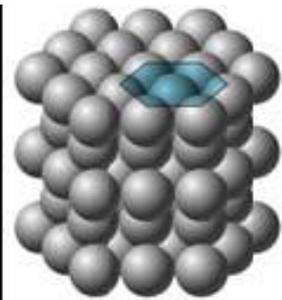


Grain<sup>c</sup>  
 $10^{-9} - 10^{-2}$  m

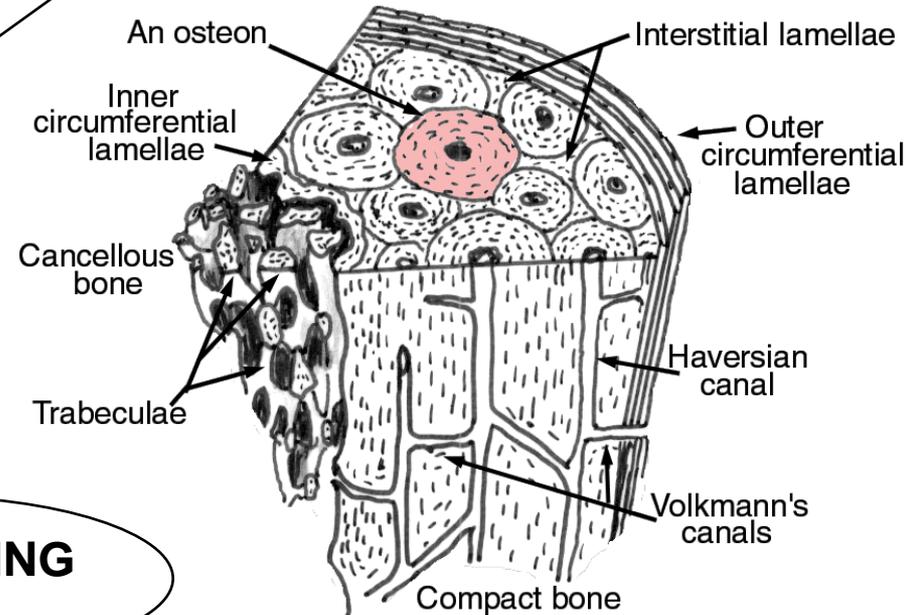


woven  
fibers

Engineered Composite<sup>d</sup>  
 $10^{-4} - 10^{-1}$  m



Atomic<sup>a</sup>  
Up to  $10^{-10}$  m



Natural Composite<sup>e</sup> 12

PROPERTY

PROCESSING

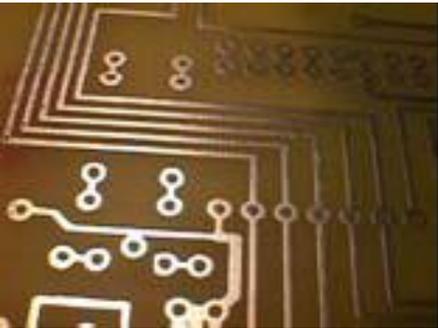
**STRUCTURE**

**PROPERTIES**

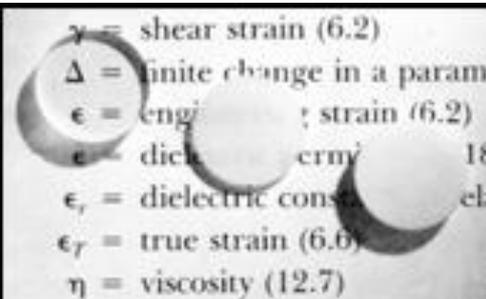
**PROCESSING**



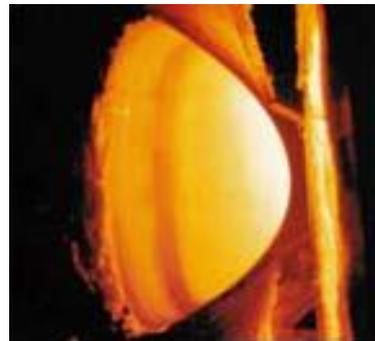
Mechanical<sup>a</sup>  
(Strength, etc.)



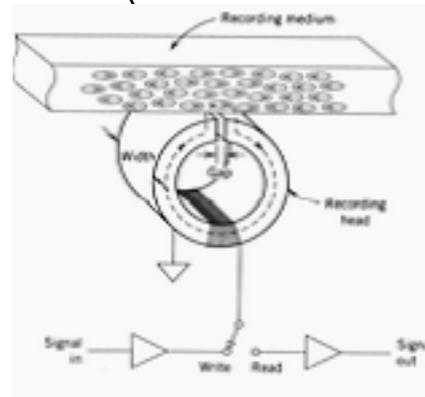
Electrical<sup>b</sup>  
(Resistivity, etc.)



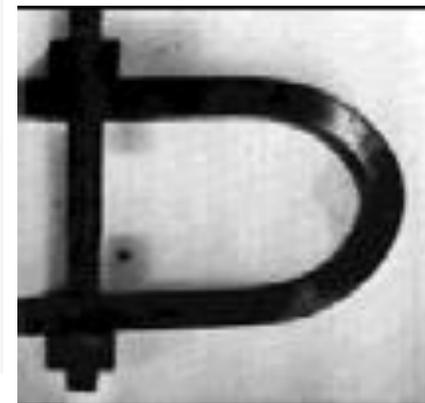
Optical<sup>c</sup>  
(Transmittance, etc.)



Thermal<sup>d</sup>  
(Conductivity, etc.)

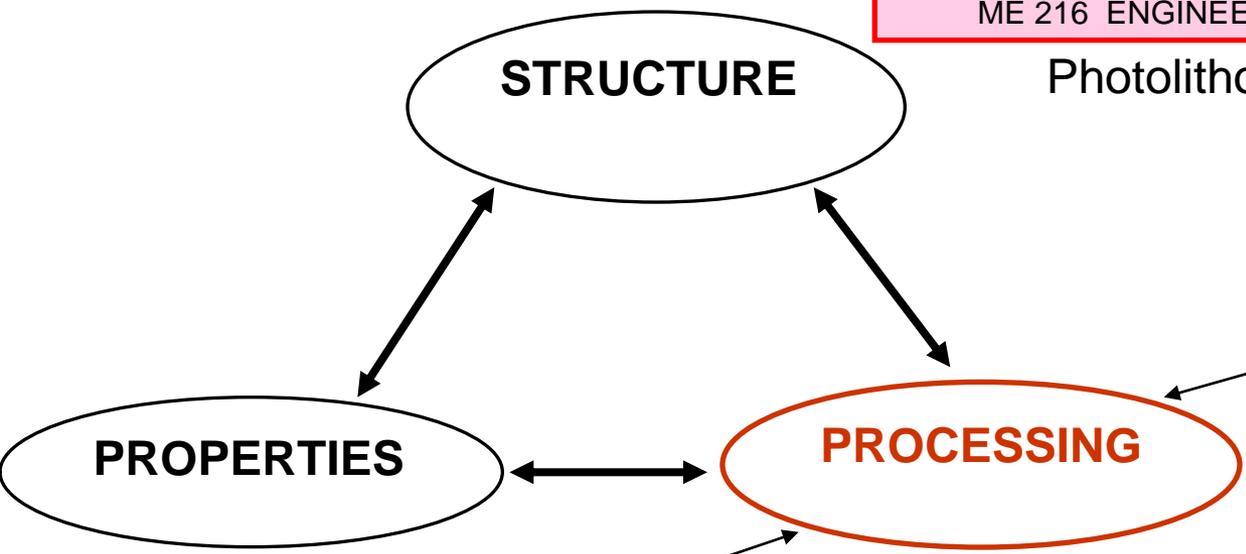


Magnetic<sup>e</sup>  
(Permeability, etc.)

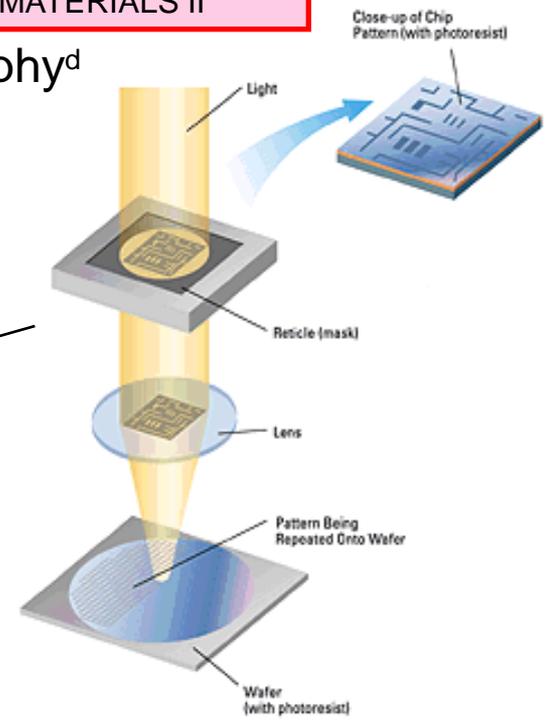


Deteriorative<sup>f</sup>  
(Galvanic Potential, etc.)

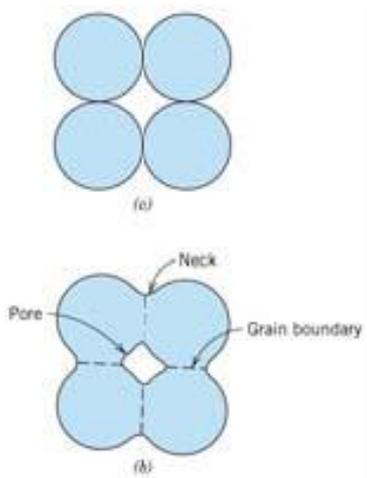




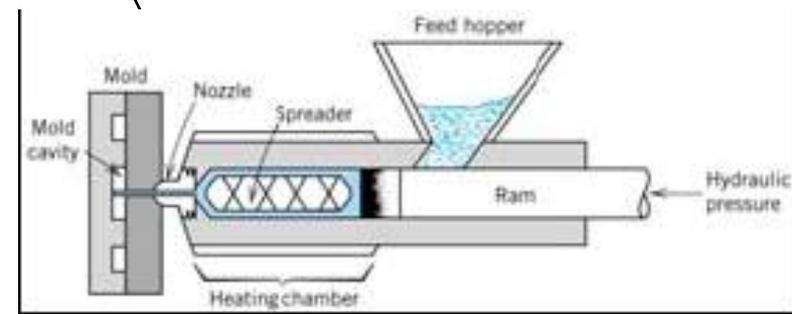
### Photolithography<sup>d</sup>



Drawing<sup>a</sup>



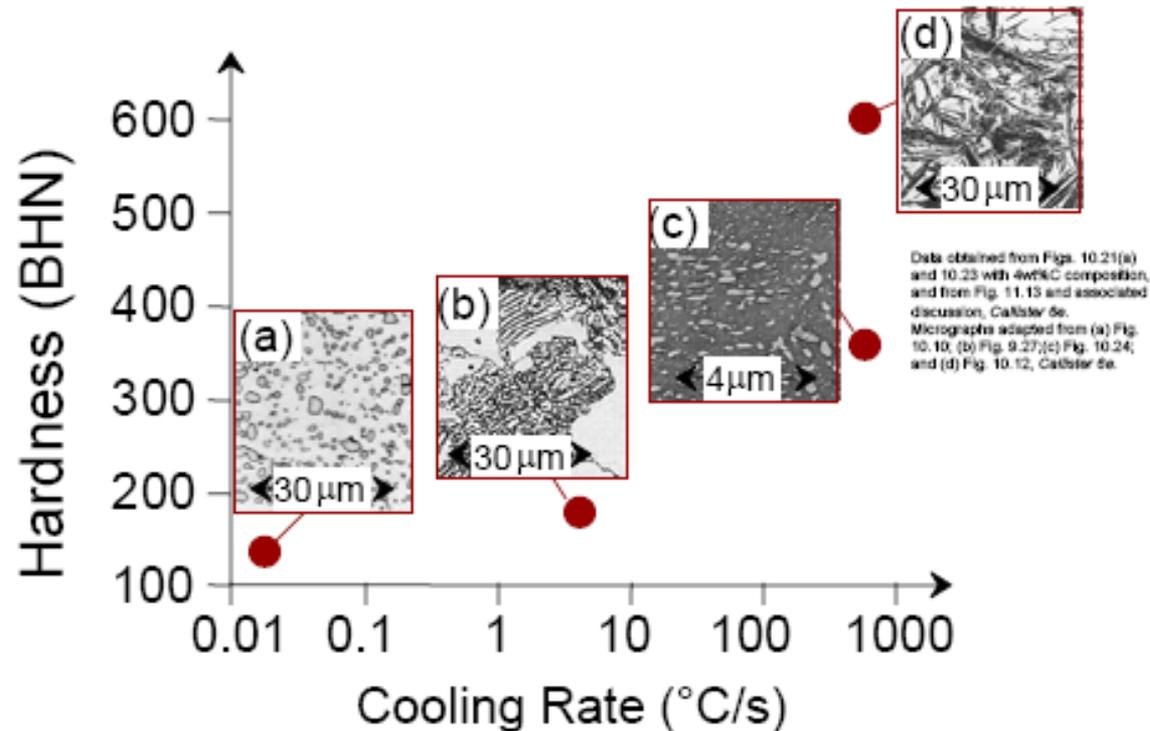
Sintering<sup>b</sup>



Injection moulding<sup>c</sup>

# STRUCTURE, PROCESSING, & PROPERTIES

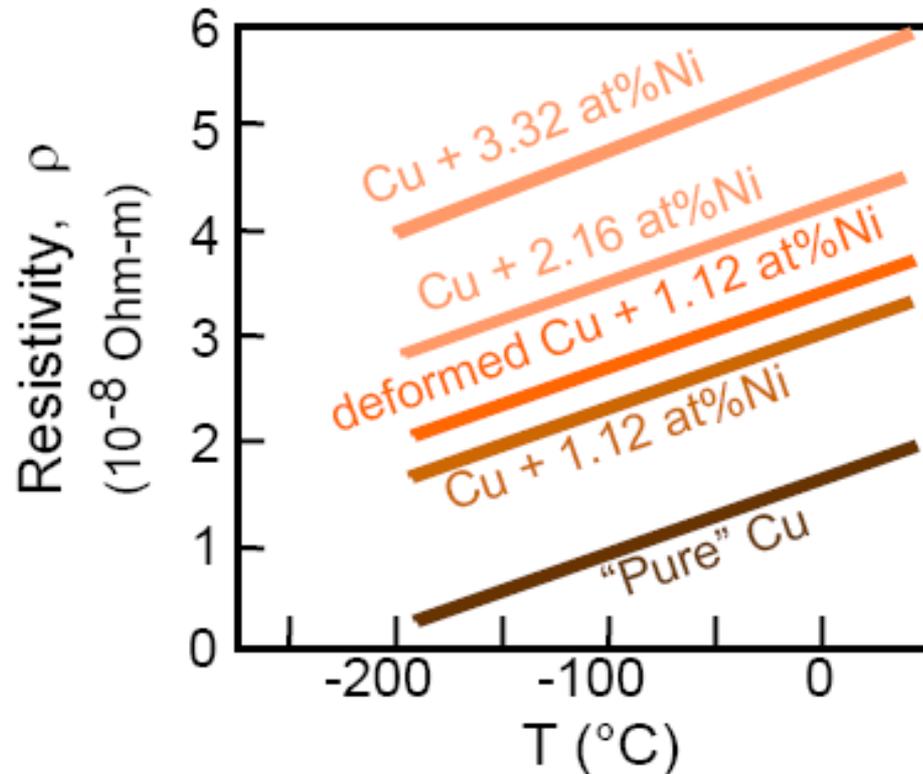
- **Processing** can change **structure**  
ex: structure vs cooling rate of steel



- **Properties** depend on **structure**  
ex: hardness vs structure of steel

# STRUCTURE, PROCESSING, & PROPERTIES

- Electrical Resistivity of Copper:



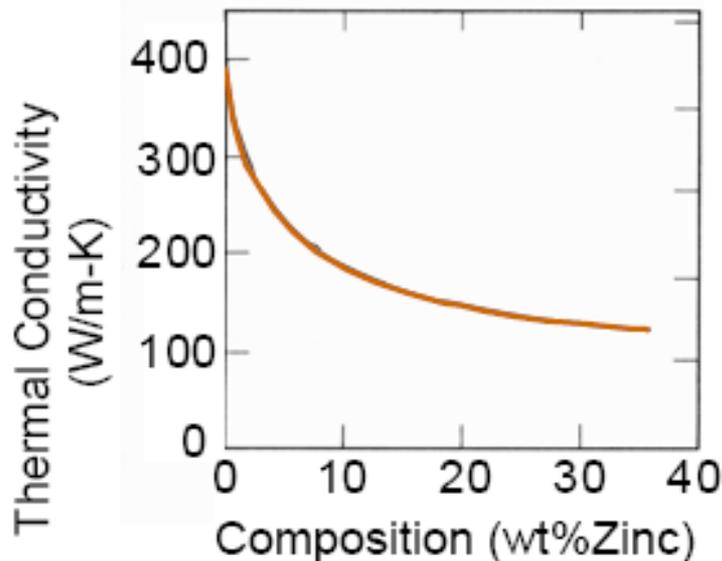
Adapted from Fig. 18.8, Callister 6e. (Fig. 18.8 adapted from J.O. Linde, *Ann Phys* 6, 219 (1932); and C.A. Wert and R.M. Thomson, *Physics of Solids*, 2nd edition, McGraw-Hill Company, New York, 1970.)

- Adding “impurity” atoms to Cu increases resistivity.
- Deforming Cu increases resistivity.

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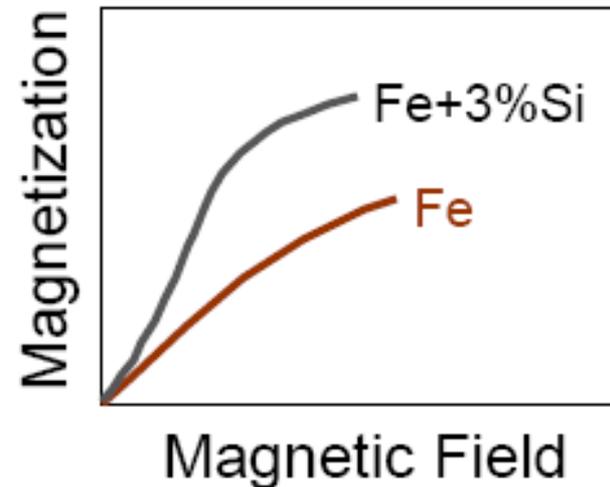
# STRUCTURE, PROCESSING, & PROPERTIES

- **Thermal Conductivity** of Copper,  $\kappa$ :  
--It decreases when you add zinc!



Adapted from Fig. 19.4, Callister 5e.  
(Fig. 19.4 is adapted from Metals Handbook: Properties and Selection: Nonferrous alloys and Pure Metals, Vol. 2, 9th ed., H. Baker, (Managing Editor), American Society for Metals, 1979, p. 315.)

- **Magnetic Permeability** vs. Composition:  
--Adding 3 atomic % Si makes Fe a better recording medium!



Adapted from C.R. Barrett, W.D. Nix, and A.S. Teitelman, The Principles of Engineering Materials, Fig. 1-7(a), p. 9, 1973. Electronically reproduced by permission of Pearson Education, Inc., Upper Saddle River, New Jersey.

# THE MATERIALS SELECTION PROCESS

1. **Application** → Determine required **Properties**

Properties: mechanical, electrical, thermal, magnetic, optical, deteriorative.

2. **Properties** → Identify candidate **Material(s)**

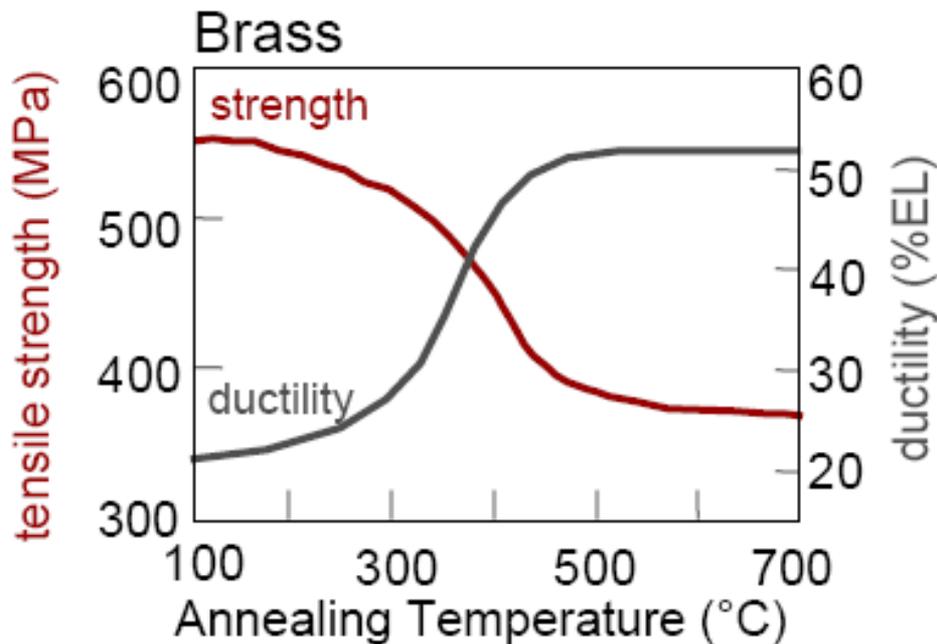
Material: composition, structure.

3. **Material** → Identify required **Processing**

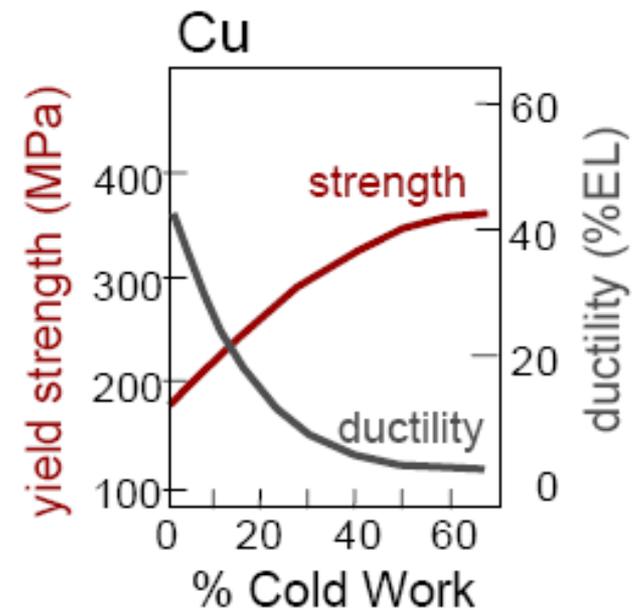
Processing: changes *structure* and overall *shape*  
ex: casting, sintering, vapor deposition, doping, forming, joining, annealing.

# STRUCTURE, PROCESSING, & PROPERTIES

Processing → Property trade-offs!  
(e.g. strength tends to be inverse to ductility)



Adapted from Fig. 7.20, Callister *et al.* (Fig. 7.20 is 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.)



Adapted from Fig. 7.17, Callister *et al.* (Fig. 7.17 is adapted from *Metals Handbook: Properties and Selection: Iron and Steels*, Vol. 1, 9th ed., B. Bardet (Ed.), American Society for Metals, 1978, p. 226; and *Metals Handbook: Properties and Selection: Nonferrous Alloys and Pure Metals*, Vol. 2, 9th ed., H. Baker (Managing Ed.), American Society for Metals, 1978, p. 276 and 327.)

### 1.3.2 The Selection Process

Material selection, like any other aspects of engineering design, is a problem solving process. The steps in the process can be defined as follows:

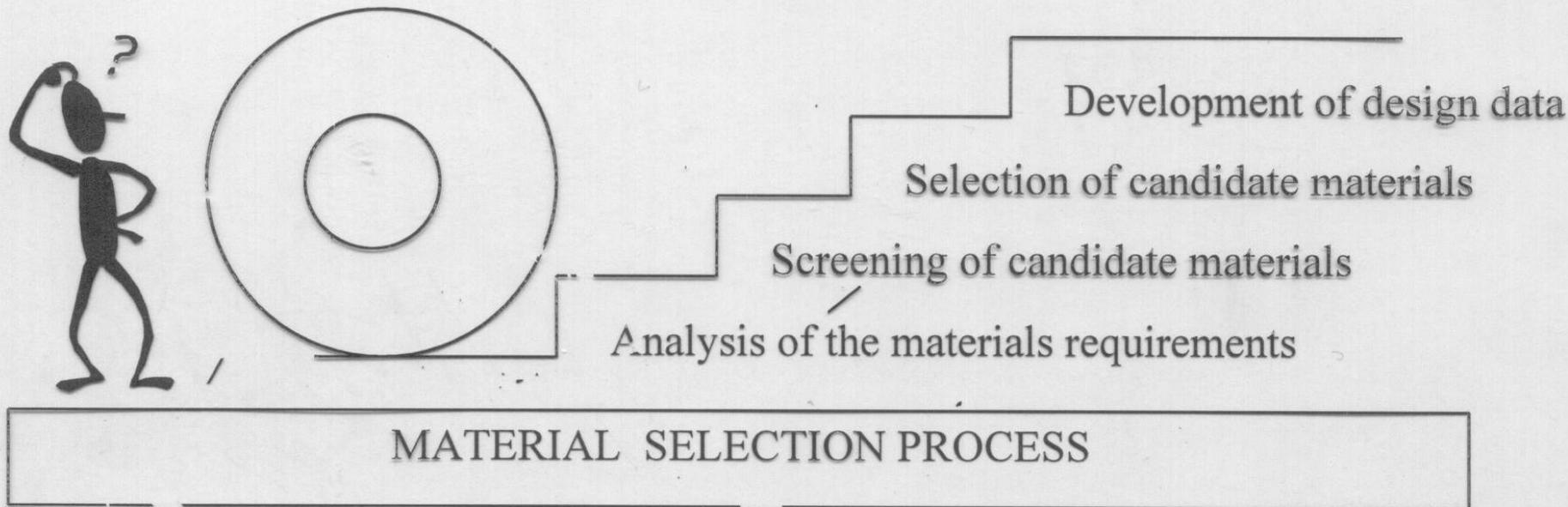
**Analysis of the materials requirements.** Determine the conditions of service and environment that the product must withstand. Translate them into critical material properties.

**Screening of candidate materials.** Compare the needed properties with a large material property database to select a few materials that look promising for the application.

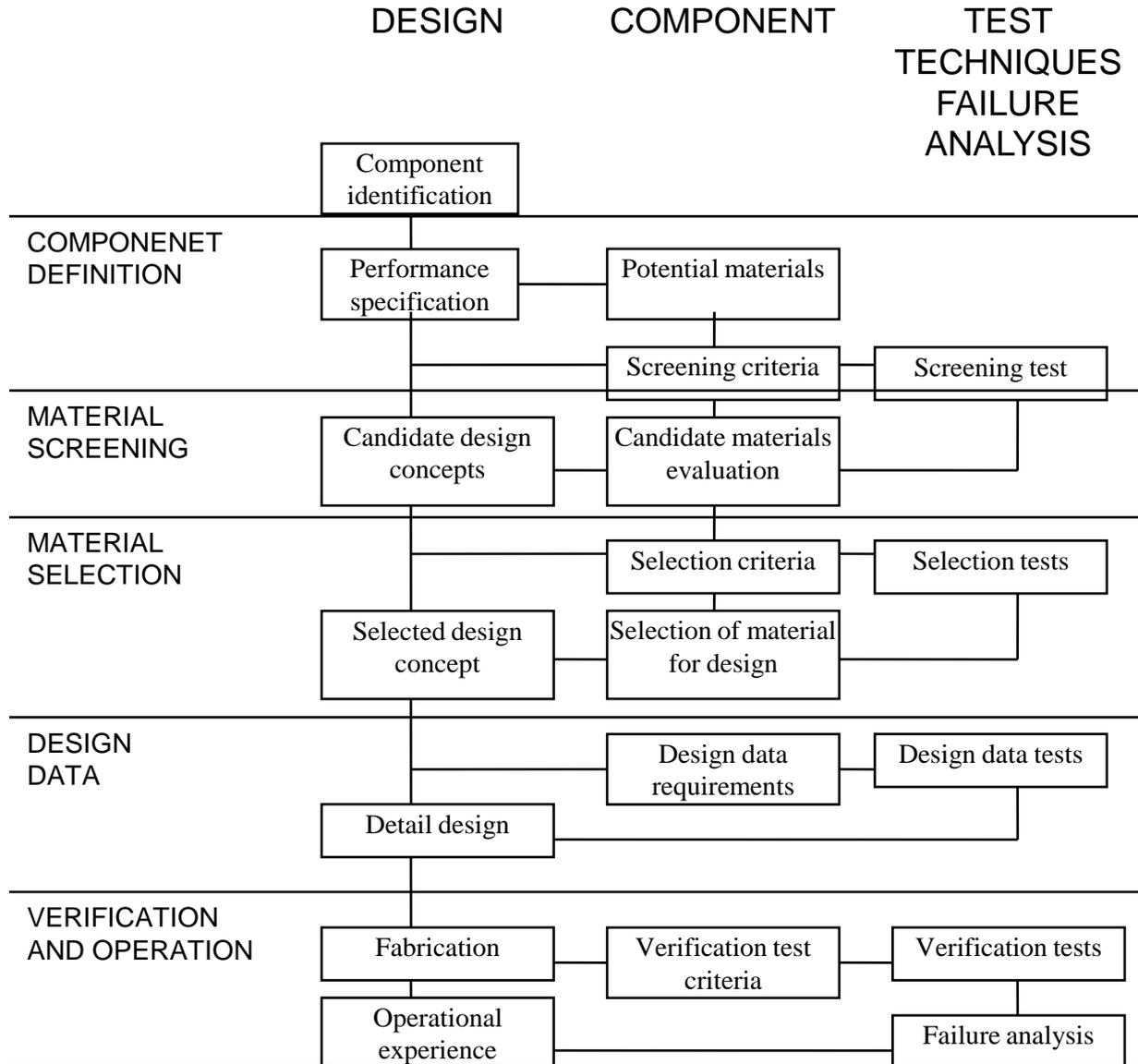
**Selection of candidate materials.** Analyze candidate materials in terms of trade-offs of product performance, cost, fabricability, and availability to select the best material for the application.

**Development of design data.** Determine experimentally the key material properties for the selected material to obtain statistically reliable measures of the material performance under the specific conditions expected to be encountered in service.

## 1.3.2 The Selection Process



The materials selection and evaluation process for a complex or advanced design is illustrated in Fig. 1.1 The design process is broken down in the vertical direction into overall design, analysis of components, and testing. Starting with the overall design concept for the system, the individual system components are identified and specifications for their performance are developed. Potential materials that could meet the performance specifications are identified, and they are evaluated on the basis of screening properties. Frequently, actual screening tests are performed to eliminate the unsatisfactory materials. The successful materials in the screening tests now become the candidate materials for evaluation in the candidate design concept. In the material selection phase these materials are further evaluated and tested against a broader and more discriminating set of properties. Trade-offs are made with respect to performance, cost, and availability to arrive at a single or small number of materials for the selected design concept. These detailed property data are fed into the final detailed design. When the design is fabricated into a working concept, additional property testing is required to establish the influence of manufacturing processes on critical design properties. As designs are put into service, operational experience begins to accumulate. Hopefully, the design will work to perfection, but it is not uncommon in a complex system to experience service failures that are not anticipated by the design analysis. Component failures are a sure indication that the material selection and/or design was faulty.



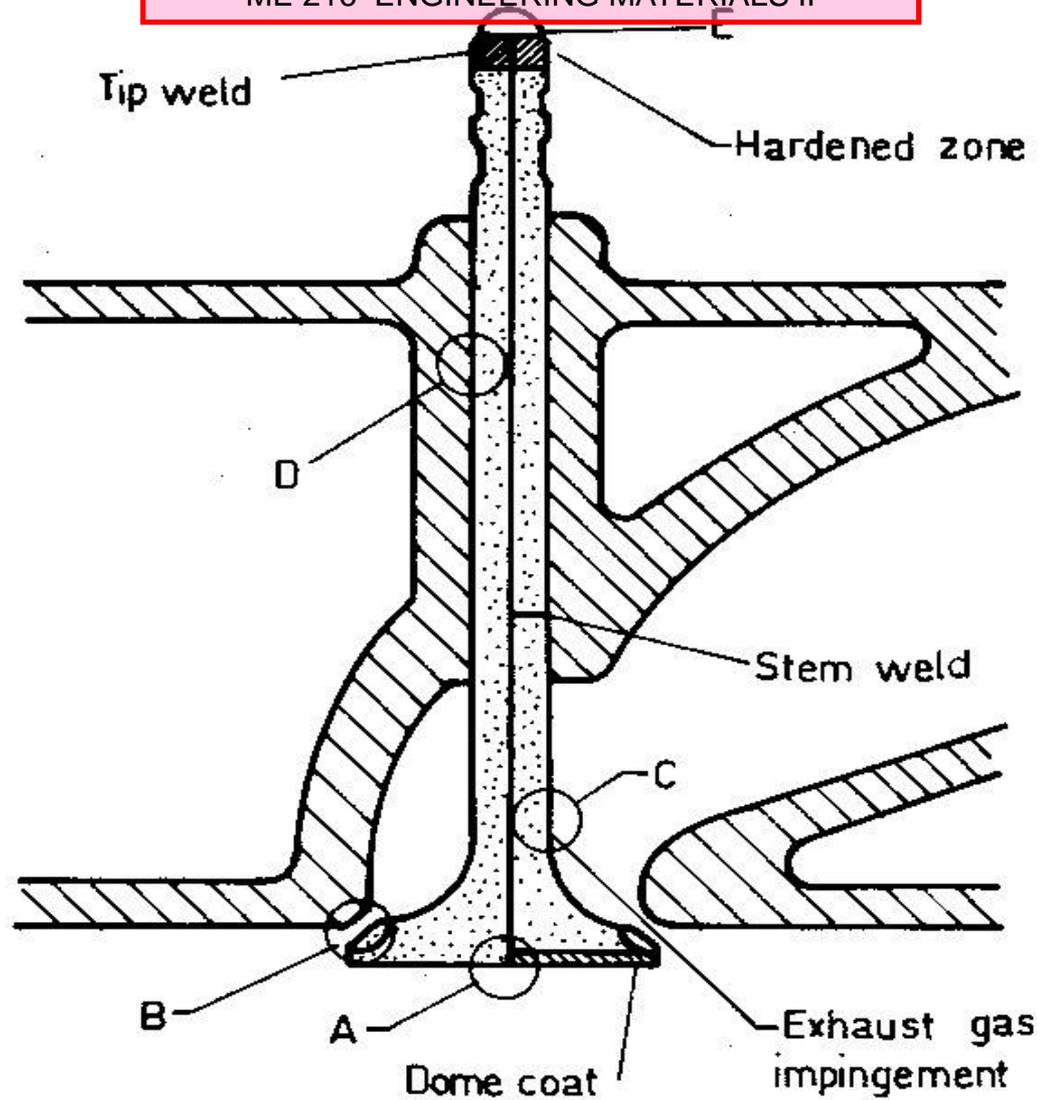
### 1.3.3 Selection Example

Engineered systems contain many components, and for each a material must be selected. The automobile is our most familiar engineering system and one that is undergoing a major change in the materials used for its construction. These trends in materials selection reflect the great effort that is being made to decrease the fuel consumption of cars by down sizing the designs and adopting weight saving materials.

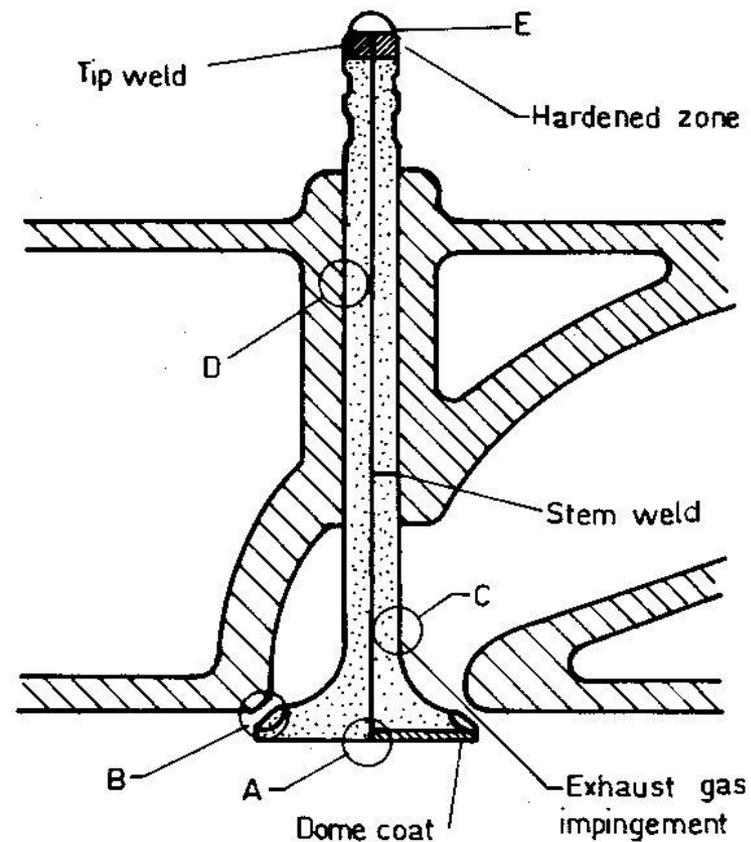
An excellent example of a complex materials system used in a difficult environment is the exhaust valve in an internal combustion engine. Valve materials must have excellent corrosion and oxidation resistance properties to resist "burning" in the temperature range 700 to 900 °C.

They must have:

- 1) sufficient high temperature fatigue strength and creep resistance to resist failure, and
- 2) suitable hot hardness to resist wear and abrasion.



*Fig.1.2 Typical exhaust valve showing critical regions of failure*



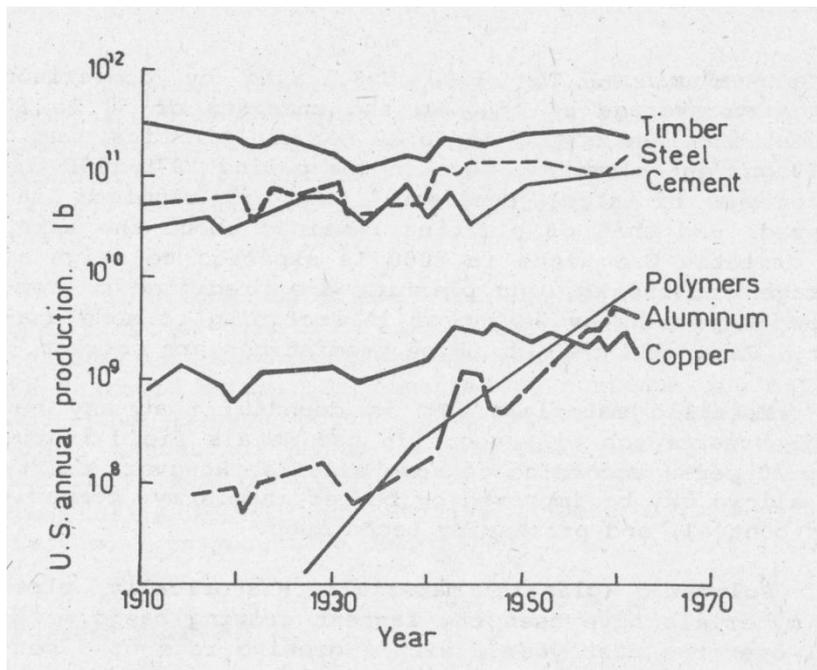
The critical failure regions in an exhaust valve are shown in Fig.1.2. Maximum operating temperature occurs in areas A and C. Corrosion and oxidation resistance are especially critical there. The under head area of the valve, area C, experiences cyclic loading, and because of the mild stress concentrations, fatigue failure may occur at that point. The valve face, area B, operates at a somewhat lower temperature because of heat conduction into the valve seat. However, if an insulating deposit builds up on the valve face, it can lead to burning. Also, the valve seat can be damaged by indentation of abrasive fuel ash deposits. The valve stem is cooler than the valve head. However, wear resistance is needed. Surface wear of the valve stem, area D, can lead to scuffing, which will cause the valve to stick open and burn. Wear at the valve tip, area E, where the valve contacts the rocker arm, will cause valve lash and cause the valve to seat with higher than the normal forces. Eventually, that will cause failure.

The basic valve material for passenger car application, where maximum temperature is 700°C, is an austenitic stainless steel that obtains its good high temperature properties from a dispersion of precipitates. This alloy, 21-2N, contains 20 percent chromium for oxidation and corrosion resistance. It has good lead oxide corrosion resistance, and its high temperature fatigue strength is exceeded only by that of the more expensive nickel base super alloys.

The entire body of one-piece valves is 21-2N, except for a hard steel tip at E and a hard chromium plate in area D. However, it is generally more economical to use a two piece valve in which 21-2N is replaced in the cooler stem portions by a cheaper alloy steel such as SAE 3140 or 4140. Either steel will have sufficient wear resistance, and the lower stem does not need the high oxidation and corrosion resistance of the high chromium, high nickel steel. The two materials are joined by friction welding, as shown in Fig.1.3. Burning of the valve face, area B, is generally avoided by coating the valve surface with aluminum to produce an Fe-Al alloy or, in severe cases, by hard facing the valve seat with one of the Co-C-Cr-W Stellite alloys.

## 1.4 FUTURE TRENDS IN MATERIAL USAGE

Materials compete with each other for existing and new markets. Over a period of time many factors arise which make it possible for one material to replace another for certain applications. Certainly cost is a factor. If a breakthrough is made in the processing of a certain type of material so that its cost is decreased substantially, this material may replace another for some applications. Another factor, which causes material replacement changes, is the development of a new material with special properties for some applications. As a result, over a period of time, the usage of different materials changes.



Left hand side figure shows graphically how the production of six materials in the United States on a weight basis varied over the past years. Aluminum and polymers show an outstanding increase in production since 1930. On a volume basis the production increases for aluminum and polymers are even more accentuated since these are light materials.

**Metallic materials:** It is doubtful that any new major breakthrough will occur in the metals field in the next 20 years according to some experts. However, existing alloys may be improved by better chemistry, composition control, and processing techniques.

**Polymeric (plastic) materials:** Historically, plastic materials have been the fastest growing basic material over the past years, with a growing rate of 9 percent/year on a weight basis. However, the growth rate for plastics through 1995 is expected to average below 5 percent, a significant decrease. This drop is expected because plastics have substituted for metals, glass, and paper in most of the main volume markets such as packaging and construction for which plastics are suitable.

**Ceramic materials:** The historical growth of traditional ceramic materials such as clay, glass, and stone has been 3 percent. The expected growth rate of these materials till 1995 is expected to be about 2 percent.

In the past decade an entire new family of engineering ceramics of nitrides, carbides, and oxides has been produced. New applications for these materials are being found constantly, particularly for high temperature uses and for electronic ceramics.

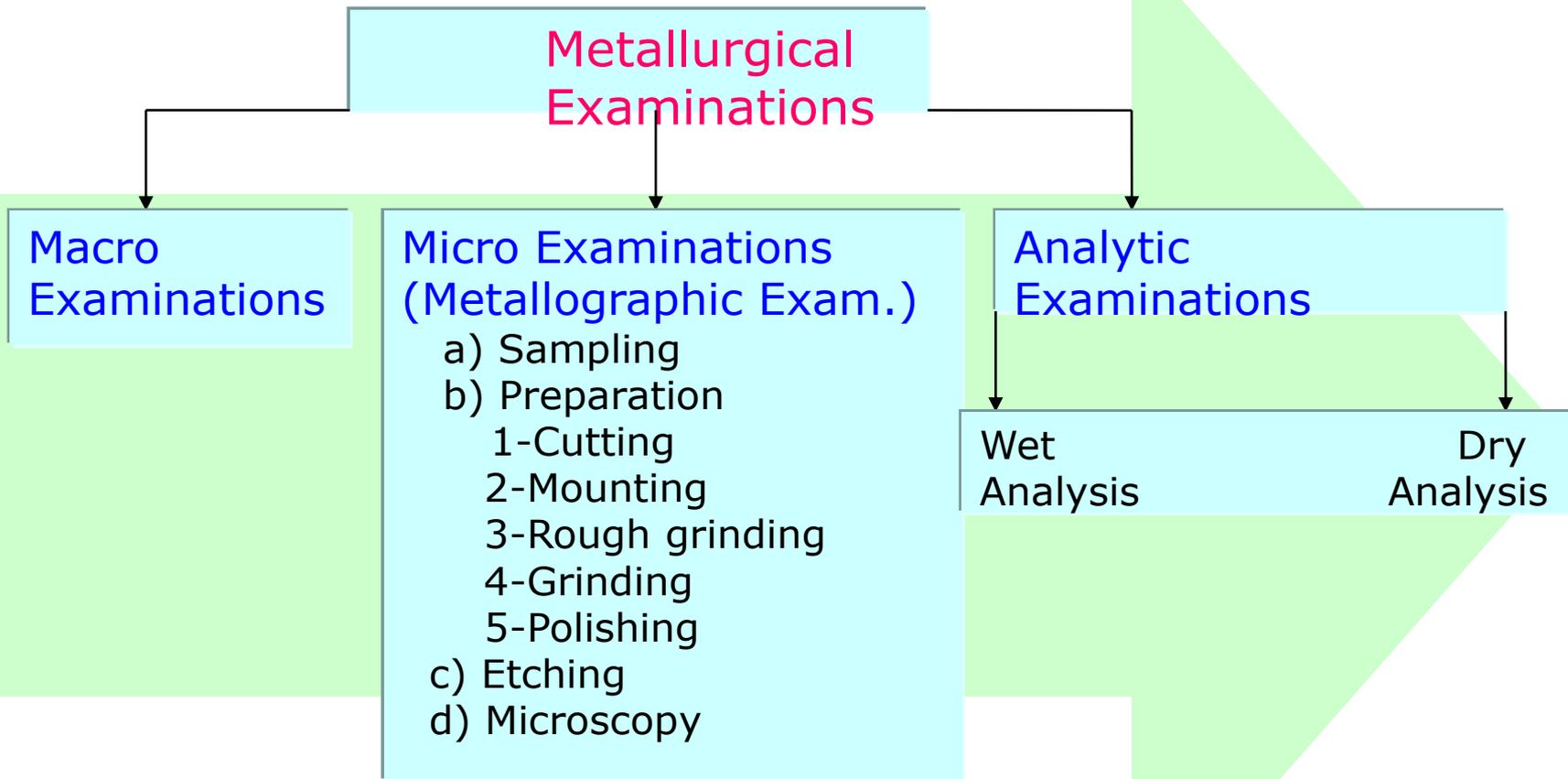
**Composite materials:** Fiber reinforced plastics are the main type of composite material used by industry, with glass being the dominant fiber. Advanced composite materials such as fiberglass-epoxy and graphite-epoxy combinations are becoming more important all the time for high performance and critical structural applications. An annual growth of about 18 percent is predicted for the future usage of these materials.

**Electronic materials:** The use of silicon and other semiconductor materials in solid state and microelectronics has shown a tremendous growth since 1970, and this growth pattern is expected to continue at least to 2000 and perhaps beyond. The impact of computers and other industrial types of equipment using integrated circuits made from silicon chips has been spectacular. The full effect of computerized robots in modern manufacturing is yet to be determined.

**CHAPTER 2****METALLURGICAL  
EXAMINATIONS****2.1 INTRODUCTION**

A prerequisite for study of metals is tools and techniques to examine various aspects of metal science just as surgical equipment are required by a medical examiner to successfully complete his diagnosis. Such equipment are essential for both the examination of materials and for altering and treatment of metals. An engineer involved with the design development and maintenance of service components would inevitably require a working knowledge of such techniques to be able to assess the situation and attend to it satisfactorily. These techniques can be classified into three broad categories viz:

1. Macro,
2. Micro or Metallographic and
3. Analytical examinations.



## 2.2 MACRO EXAMINATIONS

Macro examinations are, as the title suggests, observations made on a relatively large scale such that the examination can usually be carried out by the **naked eye**. Such observations do not involve any detailed study of the microstructure and therefore are undertaken to analyse larger features such as

fractures,  
casting defects, and  
weld failures.

In general micro examinations follow macro examination rather than precede it. Macro examinations are used:

either to test the suitability of a metal before putting it in service or to identify the causes of any undesirable features in a metal.

These are comparatively simple tests as sophisticated equipment are not required and they can be performed on site if need be. These tests are very useful for engineers and are very versatile as they save a great deal of expense, time and trouble by either identifying an improper material or process beforehand or by identifying a small area for micro-examination.

These tests generally yield the following information:

1. Source of fracture or crack initiation site,
2. Inhomogeneity, inclusions, second phase particle segregation,
3. Casting defects such as blow holes and shrinkage cavities,
4. Weld defects,
5. Plastic deformation.

There are various means of macro examination which depend upon the type of information sought and the type of material. For each case however it is very important to select an appropriate sample and prepare the surface accordingly (see section 2.2).

## 2.2.1 Macro Etching

Etching is chemical process whereby a clean polished metallic surface is subjected to a chemical attack by a suitable reagent. The reagent attacks parts of the metal surface selectively depending on the energy levels. **Grain boundaries, cavities, strained fields** etc. are high energy areas and are therefore preferentially attacked. Such attacks dissolve the material from these areas making the polished surface uneven. Such areas, therefore, become highlighted and are observable. It, however, follows that if the metal is kept in the reagent for too long a time (over-etching) then, eventually all of the surface will be chemically attacked and the distinction between the desirable features and the rest of the surface will be lost. On the other hand under-etching would not allow enough attack and the features will not be distinguished. Proper etching times are a matter of trial and error and experience dictates how etching time is obtained and in general a few initial disasters are common place. Etching is performed either by dipping the sample in solution for a specified time or the solution is spread over the sample. The specimen is washed with water and dried before examination.

The choice of reagents (etchant) is very wide and may vary from one metal to another and from feature to feature. Following list is a generalized range of etchants but more details may be obtained for a particular case.

**Etchants:**Deep etch for steel;

Hydrochloric acid	140 ml
Sulphuric acid	3 ml
Water	50 ml

Etching temperature of 90°C for 15-30 minutes.

To reveal structural variations in steels;

Ammonium persulphate	10 g
or nitric acid	10 g
Water	90 ml

To reveal segregation in steels;

Iodine	10 g
Potassium Iodide	20 g
Water	100 ml

To reveal plastic deformation in steel (Fry's solution);

Cupric chloride	90 g
Hydrochloric acid	120 ml
Water	100 ml

Heat the specimen to 200-250°C prior to etching and etch for 2-24 hours.

The above list is just a guideline and a specific reagent for a particular case may be obtained from Metals Handbook. The details obtained from macro etching can be recorded by photography if needed.

Sulphide prints may be used to identify sulphides which are a class of detrimental inclusions and second phase particles. The principle involved in the printing is that when sulphides are attacked by dilute acids they evolve hydrogen sulphide gas according to the reaction



Hydrogen sulphide gas stains the bromide paper. If, therefore, a sulphide containing metal is dipped in a dilute acid and then put in contact with bromide paper, an imprint of areas of sulphides will be obtained on the bromide paper due to the evolution of hydrogen sulphide gas. The procedure is as follows:

A clean polished surface is prepared using abrasive paper. A bromide paper is soaked in 3% sulphuric acid in water for two minutes (excess time causes gelatine on paper to swell). Take the paper out and remove excess solution using blotting paper. Stick the paper on polished metal surface and stroke it so that air bubbles are removed. Leave it for 1-2 minutes until brown stains can be seen on peeling the paper on one end. Remove the paper and wash it in water for 3 minutes before putting it in 20% hypo solution for 5 minutes. Wash in water for 20 minutes and dry. Dark room is not required and a print is obtained which gives the distribution of sulphides. Sulphide prints can not, however, be made from **high alloy steels or non-ferrous metals**.

### 2.2.3 Failure Analysis

An engineer is invariably involved with service failures of components and in order to avoid a recurrence of disasters he/she must be capable of analyzing failures and understanding its causes. An expedient diagnosis of causes of failure can be carried out by using macro examination. Information obtained from etching or sulphide print may be used for the purpose. An initial idea of the type of failure can be obtained by the appearance of the fracture surface which is characteristic for ductile, brittle, fatigue and cleavage failures (see chapter 11). The actual cause can then be determined by examining the crack initiation site. These are areas where the cracking starts and propagates up-to the final fracture. Cracks could initiate from inclusions or second phase particles, from corrosion pits, from pores or cavities produced during casting, from internally strained areas due to bad design or faulty fabrication and so on. Macro examination would give a reasonably accurate picture which can then be confirmed by undertaking a micro or metallographic examination.

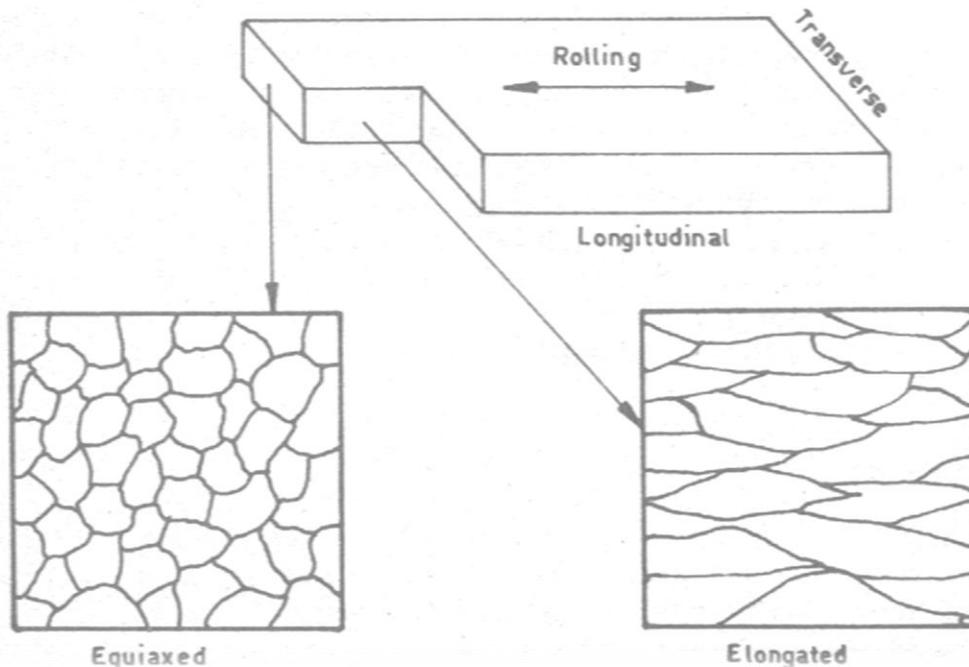
## 2.3 METALLOGRAPHY

Metallography is the most important technique and an absolute must for a metallurgist, material scientist or engineer dealing with metals. In broad sense of the word **it is a method of observing the structure of metal through its surface**. In later years, however, it has developed to include internal examinations as well especially after the advent of electron microscopy. Metallographic observations could be carried out on plain surfaces to study the micro structural details or on fractured surfaces to study the mode of cracking and failure of metals.

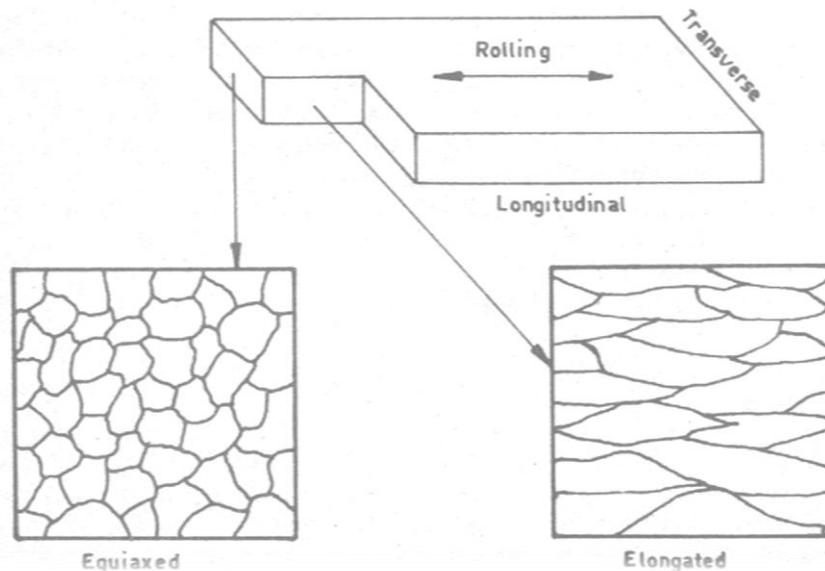
The purpose of metallographic examinations is to obtain information for determining characteristics of that particular material. It, therefore, follows that the examination should be complete in every respect for it to be reliable. Factors which affect the accuracy of these examinations are sampling, preparation and microscopy and each of these is important in its own right.

The importance of sampling stems from the fact that metals are **heterogeneous** structures. Heterogeneity denotes non-uniformity of properties and structure along various directions. Consider, for example, a piece of metal as shown in Fig.2.1. Two structures taken from transverse and longitudinal directions show different grain shapes. Such variations in different directions may, for example, result from mechanical working (rolling etc.) or from an inherent population of inclusions in metal which may not be uniformly distributed in the matrix. There are many sources of heterogeneity in metallic structures which must be borne in mind when selecting a sample.

The sample must represent the bulk material as closely as possible.



*Fig.2.1 Difference in structures of transverse and longitudinal sections of a rolled sheet.*

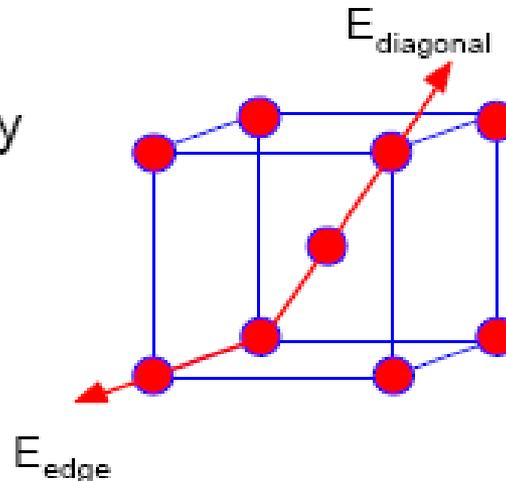


*Fig.2.1 Difference in structures of transverse and longitudinal sections of a rolled sheet.*

Being mindful of source of heterogeneity would make sampling realistic. The point can be illustrated by considering a metal containing inclusions which has been rolled. The two major sources of heterogeneity are inclusions and the effect of rolling. To minimize the effect of inclusion distribution a large enough sample must be selected which would even out any non-uniformity. Furthermore the cross-section of the sample must be recorded which would account for the effect of rolling.

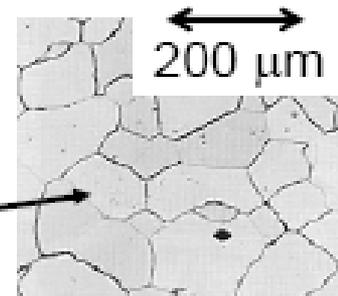
# ISOTROPY vs. ANISOTROPY

- Single Crystals
  - **Anisotropy**: properties vary with direction
  - Example: the modulus of elasticity ( $E$ ) in BCC iron:



Data from Table 3.3, Callister 6e.  
(Source of data is R.W. Hertzberg, Deformation and Fracture Mechanics of Engineering Materials, 2nd ed., John Wiley and Sons, 1989.)

- Polycrystals
    - **Isotropy**: properties same in any direction
    - Polycrystals are *isotropic* if grains are **randomly oriented**
- $E_{\text{poly Fe}} =$



Adapted from Fig. 4-12(b), Callister 6e.  
(Fig. 4-12(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].)

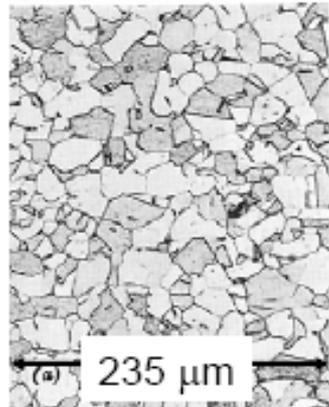
- Polycrystals are *anisotropic* if grains are **textured**



## ANISOTROPY in $\sigma_y$

- Definition: different values in different directions.
- Can be induced by rolling a polycrystalline metal.

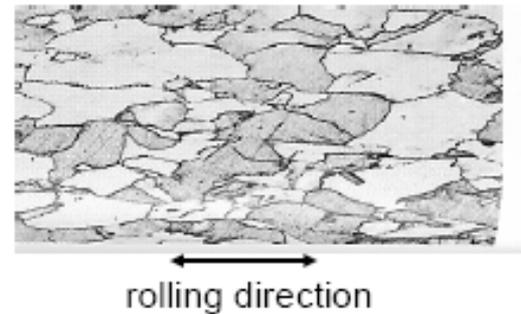
before rolling



Adapted from Fig. 7.11, Callister 6e. (Fig. 7.11 is from W.G. Moffat, G.W. Pezzoni, and J. Vokit, The Structure and Properties of Metals, Vol. 1, Structure, p. 140, John Wiley and Sons, New York, 1964.)

Isotropic:

after rolling



Anisotropic:

# ANISOTROPY IN DEFORMATION

1. Cylinder of tantalum machined from a rolled plate:

2. Fire cylinder at a target.

3. Deformed cylinder

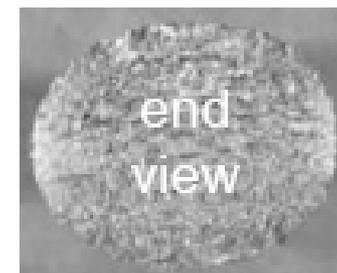
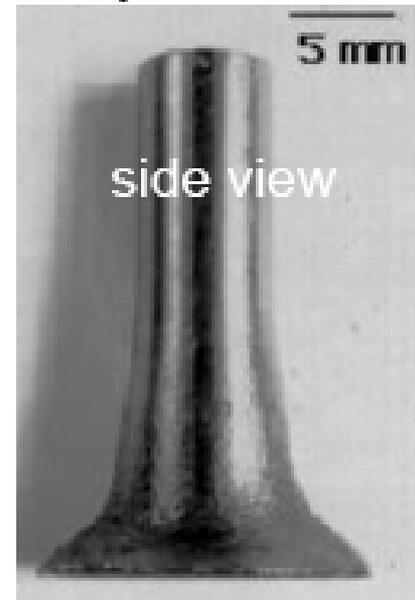
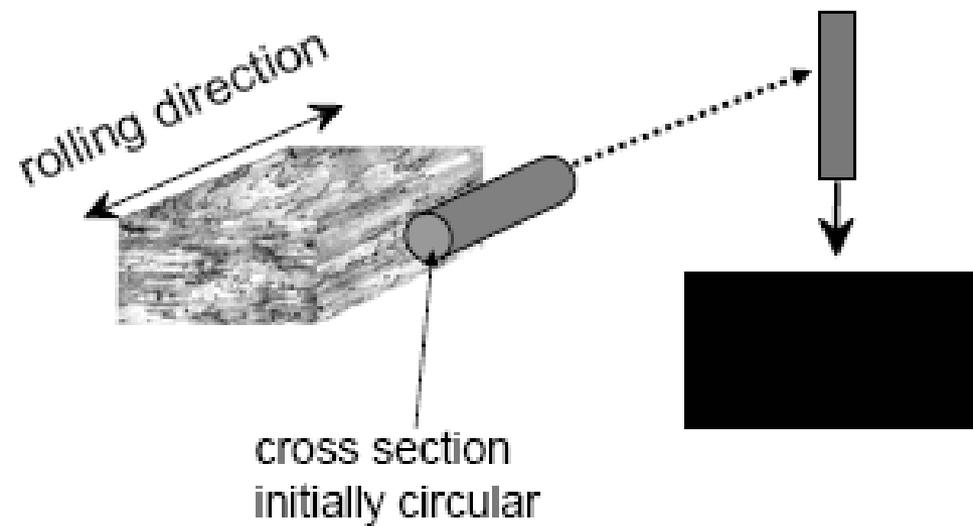


plate thickness direction

Photos courtesy of G.T. Gray III, Los Alamos National Labs. Used with permission.

Once a sample has been selected, it then has to be prepared for the examination. Basically it needs to be cut into a reasonable size, ground and polished to a satisfactory finish before etching. Due care has to be taken, however, at each of these stages as any errors would reflect on the final analysis.

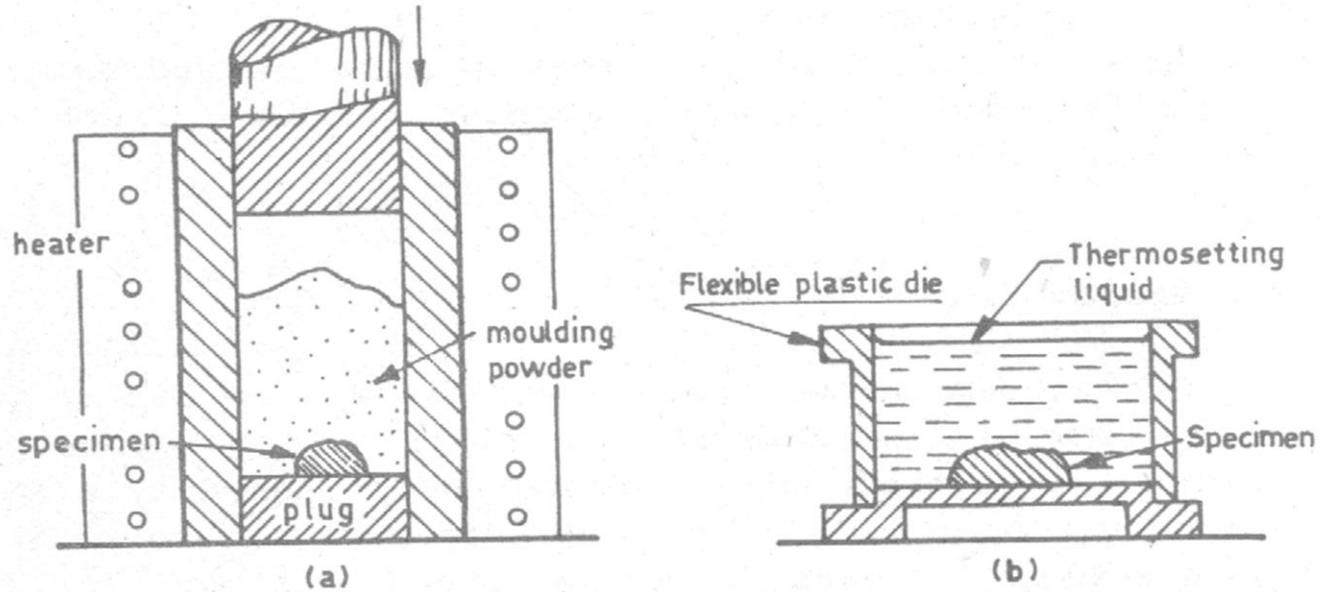
### **CUTTING**

There are many ways of cutting a sample from a bulk piece. The method to be used is dictated by the type of metal and the analysis. An ordinary sample for routine metallography may be obtained using a hacksaw or other types of saws but the same could not be done for a metal containing small inclusions or second phase particles whose analysis is to be carried out. As a consequence of a saw cut in the later case, some of the inclusions may be lost rendering the analysis unreliable. A laser or spark cut which has a minimal loss of material is, therefore, more appropriate for such metals. Laser machines use laser beams for cutting whereas electrical sparks are used in spark cutting machines.

The foregoing example illustrates the importance of the correct of medium for obtaining a sample from a large piece. In summary, therefore, the choice of cutting method should be made in view of metal characteristics and the objective of final examination. In all cases the specimen must not be overheated during cutting as it may lead to a change in microstructure.

## MOUNTING

Preparation of specimens for metallography is carried out by manual polishing of the metal surface. The sample is, therefore, mounted for easy handling during polishing. Mounting is carried out either using heat with thermoplastic resins such as polystyrene or methyl-methacrylate, or by cold thermosetting epoxy resins. In the hot process the resin is heated and pressed simultaneously. The specimen is placed on a platform with the surface to be observed facing down. The platform is enclosed in a cylinder as shown in the schematic diagram of Fig.2.2. The cylinder is filled with resin and heated to about 230°C and compressed at the same time. The resin is sintered around the specimen and a mount is obtained. Sophisticated machines are available which perform the whole sequence automatically to produce a good mount. An alternative method is to place the specimen face down in a mold and pour a mixture of thermosetting epoxy and hardener and leave it for a specified period during which the epoxy hardens to yield a cold mounting. Mounted sample is ground and polished for microscopic observations.



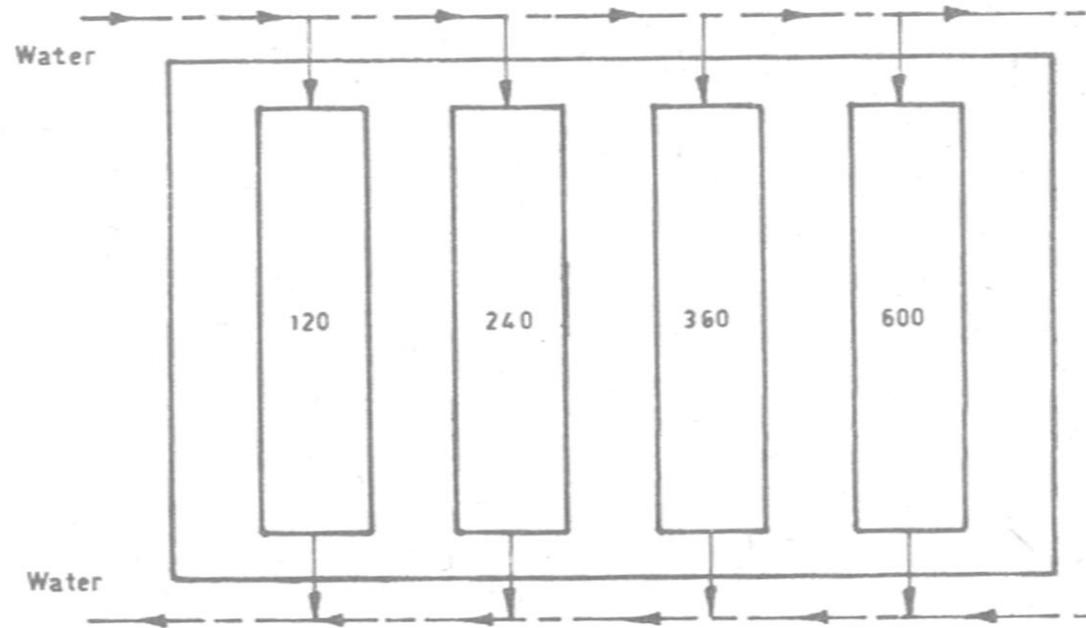
*Fig.2.2 Specimen mounting: (a) Hot mounting, (b) Cold mounting.*

## **ROUGH GRINDING**

Surface of metal has to be polished to an excellent finish for microscopy. Initially the surface is rough due to cutting. It needs smoothening to reduce grinding time. Rough grinding is usually carried out on a belt sprinkled with abrasives. The specimen is held stationary and the movement of the belt causes the abrasive to grind the surface to a smoothness which depends upon the mean distance between the abrasive particles.

## GRINDING

Grinding has the same principle as rough grinding except that the abrasive medium has progressively finer finish. Generally silicon carbide coated paper (emery paper) is used to grind the specimen. A series of paper in the order 120, 240, 400 and 600 grades are used which represent increasing fineness of scratches. Strips of paper are mounted on a glass holder as depicted in Fig.2.3 and are ground in running water. The objective is to grind the surface by removing previous scratches. The procedure is to grind the surface at right angles to the previous scratches so that the old and the new scratches could be distinguished. Grinding is carried out until all previous scratches are replaced by new scratches which are finer due to fineness of grinding paper. The specimen is washed in water and dried before transferring to next paper so that any abrasive particles attached to the surface are removed and do not impair further grinding. Grinding is continued up to 600 grade paper which gives a reasonably fine ground surface.



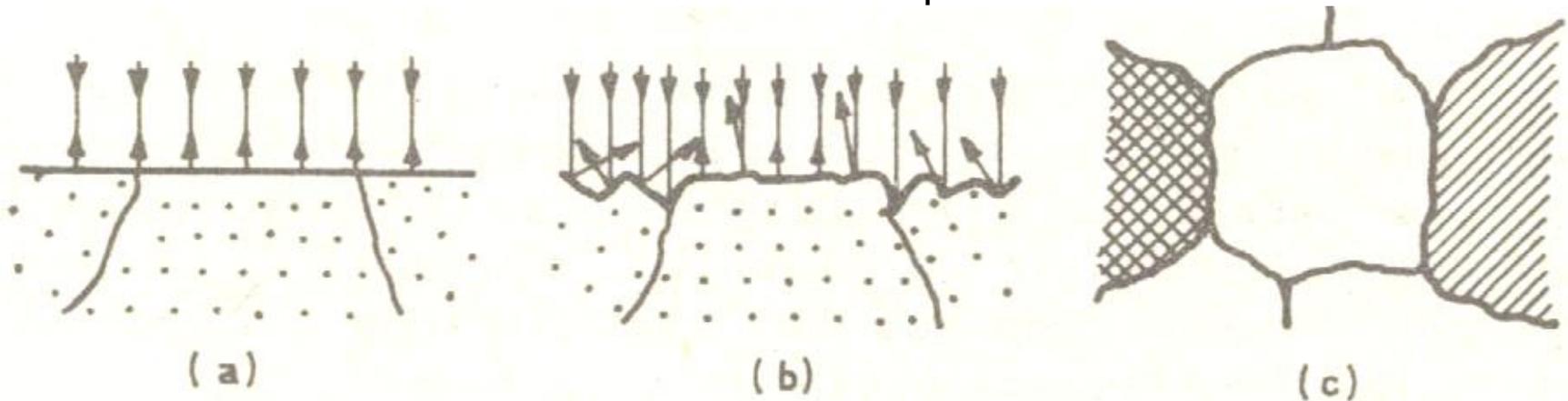
*Fig.2.3 Grinding set up of emery papers.*

## POLISHING

The final polishing is accomplished by using fine flaky diamond powders on broad cloth, chamois leather or selvyt which is stretched on a motor operated disc. The specimen is held down and moved slowly against the direction of rotating disc. Diamond dust paste is applied on the disc at the beginning of polishing and it is kept moist with a mixture of powder and water. The finishing is in the order  $6\ \mu\text{m}$ ,  $1\ \mu\text{m}$  and  $1/4\ \mu\text{m}$  which gives a mirror bright surface for observation. The specimen is cleaned with soap and dried between successive wheels. Diamond dust is used for hard metals such as steels but other powders namely alumina, green chromic oxide and magnesia may be used as well.

Another method of final polishing is electrolytic polishing in which the protruding rough surface is dissolved away chemically to yield fine polished surface. The specimen is made into anode while an aluminum or Stainless steel cathode is used and by proper adjustment of solution, temperature, current density, voltage and time the roughness can be removed to obtain a polished surface. Each material requires a specific combination of above variables and ASTM standard E3-4.4T describes these combinations. Proper polishing produces a mirror finish and the specimen is generally observed under the microscope to if any scratches still remain. The only observable features under a microscope at this stage are inclusions and other impurities such as pores or cavities but the microstructure only becomes visible after etching.

Microetching is similar to macroetching in principle except that the etchant is different. Furthermore the features revealed by microetching are very small and only observable under a microscope. As a result of preferential attack of chemicals on grain boundaries and other high energy features, these are dissolved away leaving grooves on the polished surface as depicted in the Fig.2.4. Under the microscope the light rays are reflected by smooth surface of the metal back into the microscope giving shining appearance. The dissolved areas, however, disperse the light rays which are not focused back into the microscope and consequently they appear dark. This contrast makes such features visible in a microscope.

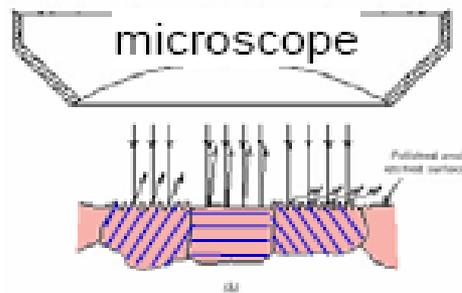


*Fig.2.4 Effect of etching. Reflection of light in (a) unetched, (b) etched, and (c) appearance in microscope.*

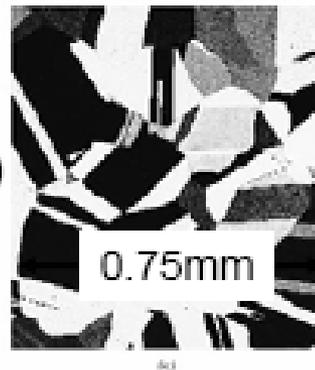
# OBSERVATION OF GRAINS

- Optical microscopy (up to 2000x) can be used to see grains
- Sample surface first polished to mirror finish
- Acid etch attacks grain boundaries and gives surface reflectance that varies with crystal orientation.

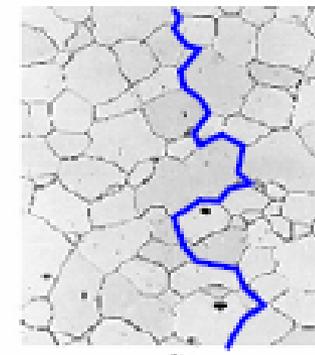
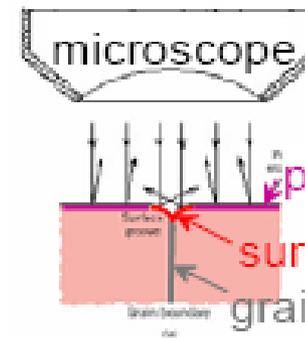
close-packed  
planes



micrograph of  
Brass (Cu and Zn)



Adapted from Fig. 4.11(b) and (c),  
Callister 6e. (Fig. 4.11(c) is courtesy  
of J.E. Burke, General Electric Co.)



Fe-Cr alloy

Adapted from Fig. 4.12(a) and (b), Callister 6e.  
(Fig. 4.12(b) is courtesy  
of L.C. Smith and C. Srody, the National Bureau of  
Standards, Washington, DC (now the National Institute of  
Standards and Technology, Gaithersburg, MD).)

The difficulties that one may come across in etching are usually due to an uneven attack, over or under etching or stains. An uneven attack by the chemical would make only certain features visible. Over and under etching has been explained earlier and stains result from chemicals left on the surface which decompose the light to give various colors. These pitfalls can easily be overcome by practice. Etchants are chemicals and may be hazardous if mishandled. It is therefore recommended that protective clothing (face masks, gloves etc.) must be worn and fume cupboards must be employed for etching. A general list of etchants is given in the Table 2.1.

The listing in Table 2.1 is only elementary and a complete repertoire of etchants can be obtained from the Metals Handbook. On successful completion of etching the specimen is ready for examination under the microscope. The specimen is fixed to a glass plate with plasticine and punched into a perfectly horizontal position before putting it under the microscope.

**TABLE 2.1 Etching reagents for metals and alloys**

<b>Metal</b>	<b>Etchant</b>	<b>Composition</b>	<b>Remarks</b>
Iron and carbon steels	Nital	2-5% nitric acid in methyl alcohol	Time: 5-60 seconds For pearlite, ferrite and martensite
	Picral	4g picric acid 100ml methyl alcohol	Time: 5-120 seconds For annealed and hardened steels
	HCl and picric acid	5g HCl, 1g picric acid, 100ml methyl alcohol	Time: 5-90 seconds Reveals austenite in quenched steels
Alloy and stainless steels	Ferric chloride and HCl distilled water	5g ferric chloride 20ml HCl, 100ml,	Time: 15-120 seconds For stainless and austenitic steels
High speed steels	HCl and nitric acid	9ml HCl, 9ml nitric acid, 100ml alcohol	Time: 15 secs-15 mins For hardened HSS steels
Aluminum and alloys	Sodium hydroxide	10g NaOH, 90ml distilled water	Time: 5 seconds Macro and micro etching
Magnesium and alloys	Glycol	75ml ethylene glycol, 24ml water, 1ml nitric acid	Time: 5-15 seconds
Nickel and alloys	Acetic acid	50 ml galacial acetic acid, 50 ml nitric acid	Time: 5-20 seconds
Copper and alloys	Nitric acid	12-30% nitric acid in distilled water	Time: 5-20 minutes
	Keller's conc. etch	10ml HF, 15ml HCl, 25ml nitric acid 50ml distilled water	Time: 5-20 seconds
Zinc and alloys	Nitric acid	2% nitric acid in alcohol	Time: 15-90 seconds
Lead	Glycerol	40ml glycerol, 10ml acetic acid, 10ml nitric acid	Time: 30-120 seconds
Titanium and Zirconium	HF and nitric acid	1-5% aqueous solution of HF, little nitric acid or phos. Acid	Time: 1-5 minutes

## 2.3.4 The Metallurgical Microscope

Metals are opaque bodies and therefore metallography of their surfaces is carried out with light reflecting microscopes. A metallurgical microscope serves this purpose. Basically it consists of an objective lens, an eyepiece lens, a source of illumination, a mirror and various adjustments as schematically shown in Fig.2.5. Light rays from the illuminator are reflected to the specimen surface by the mirror through the objective. Reflected rays from the metal surface are magnified and channeled to the eyepiece by the objective which can then be observed by the examiner. The mirror is especially made so that it allows the light to pass through.

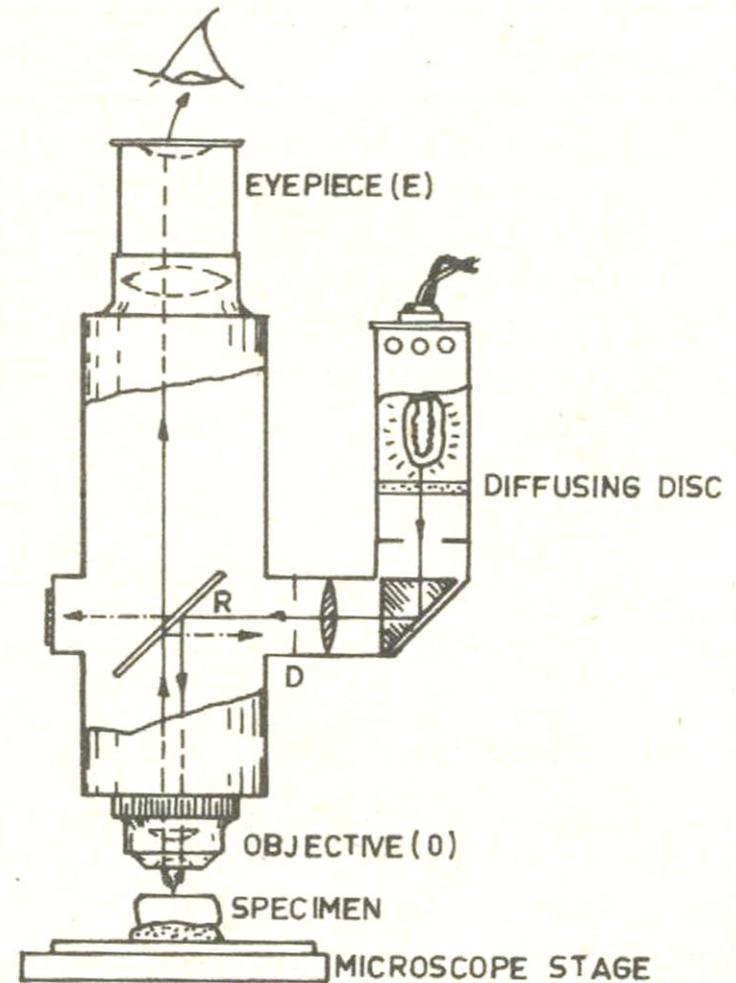


Fig.2.5 Metallurgical microscope.

The quality of objectives govern the quality of final image. The smaller the focal length of the objective the better the magnification. Magnification of a microscope depends in addition to the objective, upon the power of the eyepiece and the distance between objective and eyepiece as given by

$$\text{Magnification} = D/F \times \text{Power of the eyepiece} \quad (2.1)$$

where

D is the distance from back of objective to the eyepiece and F is the focal length of objective.

Magnification in itself is, however, not enough. It only enlarges the features and makes them visible. Resolving power of a microscope is also a very important property. It is the ability of a microscope to distinguish between two small separated bands in a specimen. Resolution reveals the features and magnification enlarges them so that a combination of the two determines the quality of a microscope. Resolution depends upon the numerical aperture of the objective and is given by

$$\text{Resolving power} = 2n \sin \alpha / \lambda. \quad (2.2)$$

where  $\alpha$  is the half angle subtended by the maximum cone of rays entering the objective,  $n$  is the refractive index of the medium between specimen and objective (air = 1, cedar oil - 1.5) and  $\lambda$ , is the wave length of the light rays.

Present day microscopes have more than one objectives on a revolving nose piece as well as a choice of eyepieces which give progressively higher magnifications. These lenses are marked with their powers and the attainable magnification can be estimated using equation 2.1. For example a  $\times 40$  objective and a  $\times 12.5$  eyepiece will enlarge 500 times. An oil immersion lens is also available in modern microscopes which uses a drop of cedar oil between objective and specimen surface to produce better resolution as can be deduced from equation 2.2.

**Inverted stage microscopes** are a more modern design in which the specimen is placed face down on the stage. Observation is made on a screen or closed circuit television which enlarges the image even further. Some resolution is however lost but they are very useful for group viewing.

All the microscopes are capable of taking pictures of microstructures. Cameras are fitted to microscopes with automated shutter systems which adjust the exposure time according to the brightness of the metal surface and produce good micrographs.

Several techniques have been developed in recent years to make metallurgical microscopes more useful.

**Hot stage microscopy** is used for elevated temperatures enabling observations of such phenomena as recrystallization and grain growth. In such cases metallography is carried out in vacuum or inert atmospheres to avoid oxidation of specimen surface due to high temperatures. Specimen is viewed through a silica window and therefore the objective should have a reasonable clearing from the specimen. For low magnifications an ordinary objective with a working distance of 5mm may be used but for high magnifications the working distance is improved with a reflecting objective.

## 2.4 ANALYTICAL EXAMINATIONS

Information obtained from macro and micro examinations is not complete as it only reveals structural features and does not provide any information on the chemistry of materials. Chemical analysis is, however, very important because the chemistry of constituents plays an important role in structural and mechanistic phenomena. Analytical methods have consequently been devised to analyze a metal chemically. These methods fall into two broad categories of:

1. **Wet analysis and**
2. **Dry analysis.**

## 2.4 ANALYTICAL EXAMINATIONS

Wet analysis uses chemical reagents which react with various constituents and the resulting products are used to identify the constituents. Tests are carried out in chemical laboratories and the metal being analyzed is consumed in the process. These tests are therefore used for specific purposes.

Wet analysis proves to be restrictive, however, as the chemistry can not be related to structural details because the metal is consumed in testing and its structural observation can not be made.

Dry analysis, on the other hand, uses the metal non-destructively so that a simultaneous observation of structure and chemistry is possible. Consequently dry analyses have acquired a great deal of importance and very sophisticated techniques have been developed recently. These techniques are based on the principle that when a beam of electrons strikes a metal surface, a variety of radiation is produced by the metal as shown in Fig.2.8. These radiations are characteristic of the metal and their analysis would reveal the identity of the metal in question.

## 2.5 TEMPERATURE MASUREMENTS

An important aspect of studying metals is the measurement of temperature which is important not only in thermal treatments but also in high temperature processes. Temperature measurement above about 500°C is called **pyrometry** whereas below this temperature it is known as **thermometry**.

**Thermometers** record temperature either mechanically by measuring the expansion of solid, liquid, gas or vapors, or electrically by measuring resistance. A common example of metal expansion thermometer is a bimetallic strip used in thermostats whereby a metal of larger coefficient of thermal expansion is attached to a metal with smaller coefficient. When the temperature changes, the strip curves due to different expansions of the two metals, and the degree of curvature determines the temperature on a dial. Liquid expansion thermometer is the commonly used mercury thermometer in which temperature change expands or contracts mercury which then rises or falls in the capillary tube. Gas or vapor thermometers use a volatile liquid which vaporizes with increase in temperature and the pressure of vapors, which depends on temperature, is used to measure temperature.

**Resistance thermometers** work on the principle that the resistance of a conductor increases with increasing temperature. Resistance is measured by a Wheatstone bridge arrangement and by using a calibration of resistance vs. temperature for that particular conductor the temperature is determined.

**Pyrometers** are either electrically based whereby the emf is measured and converted into temperature or radiation type whereby the radiation emitted by a hot body is converted into temperature. Thermocouple and thermoelectric pyrometers are of first type whereas radiation and optical pyrometers, constitute the other type.

**Thermocouple** is a junction of two dissimilar metals which will produce an emf if heated. The emf from a hot junction is measured or recorded on a graph and is converted into temperature. Only a limited number of metal combinations are suitable for this purpose.

**Thermoelectric pyrometers** use a thermocouple with a hot as well as a cold junction. In addition to emf generated by hot and cold junctions, emf is also created by the lengths of two metal wires constituting the thermocouple and a combination of all four emfs is measured by a potentiostate and displayed as a measure of temperature.

**Radiation and optical pyrometers** work on the principle of Stefan-Boltzmann law whereby the radiation emitted by a black body is proportional to the fourth power of its absolute temperature. Hence an analysis of the emitted radiation is convertible to the temperature of that body. Radiation pyrometers respond to all wavelengths whereas optical pyrometers are limited to a single wavelength or a narrow band in visible part of the spectrum.

Preceding discussion enables an engineer to understand the mechanisms and principles of various tools and techniques so that they can be used efficiently. Data from these examinations can be interpreted by the engineer in the light of a knowledge of metallurgy so that appropriate measures may be taken for a particular situation. In the following chapters engineering aspects of metallurgy will be dealt with.

## **CHAPTER 3.0**

### **METALS AND ALLOYS**

#### **3.01 INTRODUCTION**

Properties and other technical issues related to metals are considered in this chapter. The technological and commercial importance of metals is due to the following general properties possessed by virtually all the common metals.

*High stiffness and strength.* Metals can be alloyed for high rigidity, strength, and hardness; thus they are used to provide the structural framework for most engineered products.

*Toughness.* Metals have the capacity to absorb energy better than other classes of materials.

*Good electrical conductivity.* Metals are conductors because of their metallic bonding, which permits the free movement of electrons as charge carriers.

*Good thermal conductivity.* Metallic bonding also explains why metals generally conduct heat better than ceramics or polymers.

In addition, certain metals have specific properties that make them attractive for specialised applications. Many common metals are available at relatively low cost per unit weight and are often the material of choice simply because of this.

Metals are converted into parts and products using a variety of manufacturing processes. The starting form of the metal differs depending on the process. The major categories are (1) *cast metal*, in which the initial form is a casting; (2) *wrought metal*, in which the metal has been worked or can be worked (for example, rolled or otherwise formed) after casting; better mechanical properties are generally associated with wrought metals compared to cast metals; and (3) *powdered metal*, in which the metal is purchased in the form of very small powders for conversion into parts using powder metallurgy techniques. Most metals are available in all three forms. In this chapter, our discussion will focus on categories 1 and 2, which are of greatest commercial and engineering interest. Powder metallurgy techniques are examined in Chapter 6.

Metals are classified into two major groups: (1) *ferrous*, those based on iron, and (2) *nonferrous*, all other metals. The ferrous group can be further subdivided into steels and cast irons. Most of our discussion in the present chapter will be organised around this classification, but let us first examine the general topic of alloys and phase diagrams.

## 3.02 ALLOYS AND PHASE DIAGRAMS

Although some metals are important as pure elements (for example, gold, silver, and copper), most engineering applications require the enhanced properties obtained by alloying. Through alloying, it is possible to enhance strength, hardness, and other properties compared to pure metals. In this section, we define and classify alloys; we then discuss phase diagrams, which indicate the phases of an alloy system as a function of composition and temperature.

### 3.02.1 Alloys

An *alloy* is a metal comprised of two or more elements, at least one of which is metallic. The two main categories of alloys are (1) **solid solutions** and (2) **intermediate phases**.

**Solid Solutions:** A *solid solution* is an alloy in which one element is dissolved in another to form a single-phase structure. The term *phase* describes any homogeneous mass of material, such as a metal in which the grains all have the same crystal lattice structure. In a solid solution, the solvent or base element is metallic, and the dissolved element can be either metallic or nonmetallic. Solid solutions come in two forms, as shown in Figure 3. 01. The first is a *substitutional solid solution*, in which atoms of the solvent element are replaced in its unit cell by the dissolved element. Brass is an example, in which zinc is dissolved in copper. To make the substitution, several rules must be satisfied: (1) the atomic radii of the two elements must be similar, usually within 15%; (2) their lattice types must be the same; (3) if the elements have different valencies, the lower valency metal is more likely to be the solvent; and (4) if the elements have high chemical affinity for each other, they are less likely to form a solid solution and more likely to form a compound.

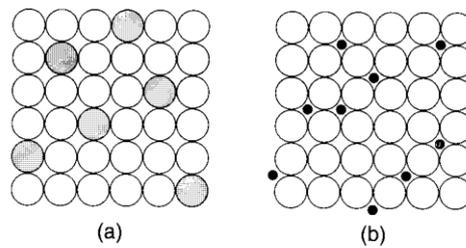


FIGURE 7.1 Two forms of solid solutions: (a) substitutional solid solution and (b) interstitial solid solution.

Fig. 3.01.

The second type of solid solution is an *interstitial solid solution*, in which atoms of the dissolving element fit into the vacant spaces between base metal atoms in the lattice structure. It follows that the atoms fitting into these interstices must be small compared to those of the solvent metal, for example, hydrogen, carbon, nitrogen, and boron. The most important example of this second type is carbon dissolved in iron to form steel.

In both forms of solid solution, the alloy structure is generally stronger and harder than either of the component elements.

**Intermediate Phases** There are usually limits to the solubility of one element in another. When the amount of the dissolving element in the alloy exceeds the solid solubility limit of the base metal, a second phase forms in the alloy. The term *intermediate phase* is used to describe it because its chemical composition is intermediate between the two pure elements. Its crystalline structure is also different from those of the pure metals. Depending on composition, and recognising that many alloys consist of more than two elements, these intermediate phases can be of several types, including (1) metallic compounds consisting of a metal and nonmetal, such as  $\text{Fe}_3\text{C}$ , and (2) intermetallic compounds, consisting of two metals that form a compound, such as  $\text{Mg}_2\text{Pb}$ . The composition of the alloy is often such that the intermediate phase is mixed with the primary solid solution to form a two-phase structure, one phase dispersed throughout the second. These two-phase alloys are important because they can be formulated and heat treated for significantly higher strength than solid solutions.

### 3.02.2 Phase Diagrams

As we shall use the term in this text, a *phase diagram* is a graphical means of representing the phases of a metal alloy system as a function of composition and temperature. Our discussion of the diagram will be limited to alloy systems consisting of two elements at atmospheric pressures. This type of diagram is called a *binary phase diagram*

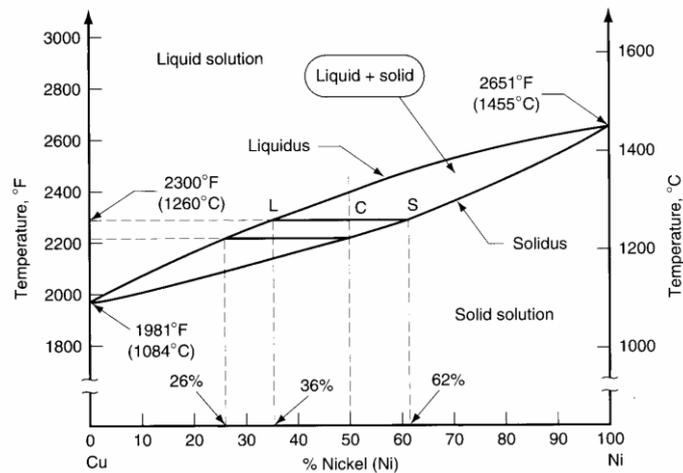


FIGURE 7.2 Phase diagram for the copper-nickel alloy system.

Fig. 3.02.

**Copper-Nickel Alloy System:** The best way to describe the phase diagram and its use is by example. Figure 3.02 presents one of the simplest cases, the Cu-Ni alloy system. Composition is plotted on the horizontal axis and temperature on the vertical axis. Thus, any point in the diagram indicates the overall composition and the phase or phases present at the given temperature. Pure copper melts at  $1083^{\circ}\text{C}$ , and pure nickel at  $1455^{\circ}\text{C}$ . Alloy compositions between these extremes exhibit gradual melting, which commences at the solidus and concludes at the liquidus as temperature is increased.

The copper-nickel system is a solid solution alloy throughout its entire range of compositions. Anywhere in the region below the solidus line, the alloy is a solid solution; there are no intermediate solid phases in this system. However, there is a mixture of phases in the region bounded by the solidus and liquidus. Recall from Chapter 4 that the solidus is the temperature at which the solid metal begins to melt as temperature is increased, and the liquidus is the temperature at which melting is completed. We now see from the phase diagram that these temperatures vary with composition. Between the solidus and liquidus, the metal is a solid-liquid mix.

**Determining Chemical Compositions of Phases** Although the overall composition of the alloy is given by its position along the horizontal axis, the compositions of the liquid and solid phases are not the same. It is possible to determine these compositions from the phase diagram by drawing a horizontal line at the temperature of interest. The points of intersection between the horizontal line and the solidus and liquidus indicate the compositions of the solid and liquid phases present, respectively. We simply construct the vertical projections from the intersection points to the x-axis and read the corresponding compositions.

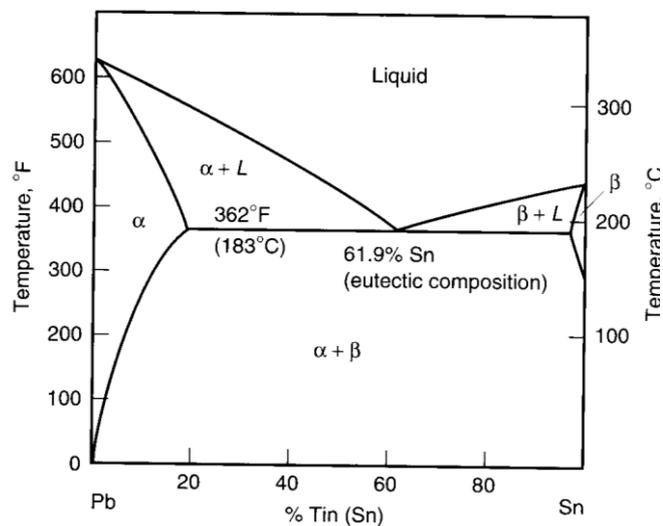


Fig. 3.03.

**Tin-Lead Alloy System** A more complicated phase diagram is the Sn-Pb system shown in Figure 3.03. Tin-lead alloys are widely used in soldering for making electrical connections. The phase diagram exhibits several features not included in the previous Cu-Ni system. One feature is the presence of two solid phases, alpha (α) and beta (β). The α phase is a solid solution of tin in lead at the left side of the diagram, and the β phase is a solid solution of lead in tin that occurs only at elevated temperatures around 200°C at the right side of the diagram. Between these solid solutions lies a mixture of the two solid phases, α + β.

Another feature of interest in the tin-lead system is how melting differs for different compositions. Pure tin melts at 232°C, and pure lead melts at 327°C. Alloys of these elements melt at lower temperatures. The diagram shows two liquidus lines, which begin at the melting points of the pure metals and meet at a composition of 61.9% Sn. This is the eutectic composition for the tin-lead system. In general, a *eutectic alloy* is a particular composition in an alloy system for which the solidus and liquidus are at the same temperature. The corresponding *eutectic temperature*, the melting point of the eutectic composition, is 183°C in the present case. The eutectic temperature is always the lowest melting point for an alloy system (eutectic is derived from the Greek word *eutektos*, meaning easily melted).

Methods for determining the chemical analysis of the phases and the proportions of phases present can be readily applied to the Sn-Pb system just as it was used in the Cu-Ni system. In fact, these methods are applicable in any region containing two phases, including two solid phases. Most alloy systems are characterised by the existence of multiple solid phases and eutectic compositions, and so the phase diagrams of these systems are often similar to the tin-lead diagram. Of course, many alloy systems are considerably more complex. We examine one of these as we consider next the alloys of iron and carbon.

### 3.03 FERROUS METALS

The ferrous metals are based on iron, one of the oldest metals known to humans (see Historical Note 7.1). The properties and other data relating to iron are itemized in Table 7.1 (a). The ferrous metals of engineering importance are alloys of iron and carbon. These alloys divide into two major groups: steel and cast iron. Together, they constitute approximately 85% of metal tonnage in the United States.

# **CHAPTER 3**

## **METALS AND ALLOYS**

### **PART I**

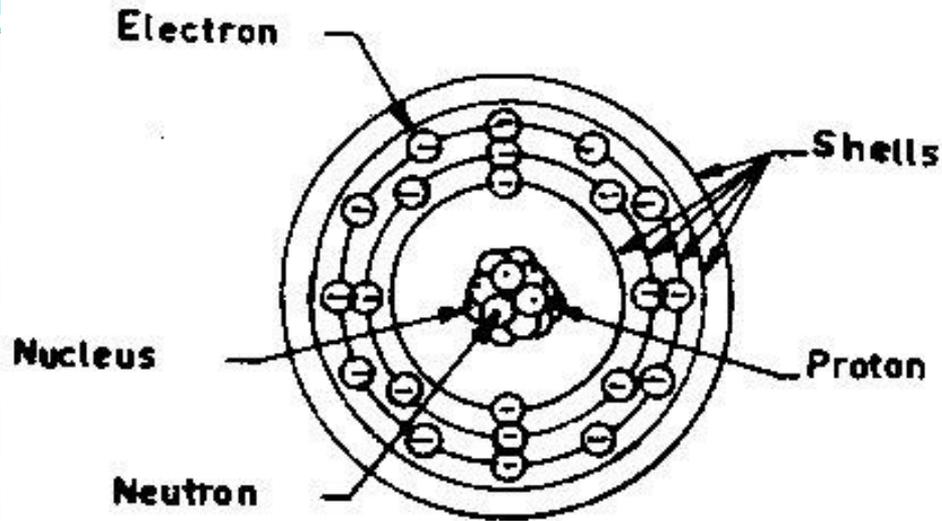
#### **3.1 INTRODUCTION**

Two most important constituents of our world are **matter and energy** which have been shown by Einstein to be interrelated. The relationship is based on the atomic structure of matter which forms the basis of energy. Neither matter nor energy can be created or developed but can only change forms. These physical laws play a very important role in metallurgical energy as it deals with changes of structure and forms with heat and mechanical energy. In order to understand the implication of above mentioned laws and consequently to understand the changes in metal structures and behavior, an engineer should, therefore, have a working knowledge of the **atomic arrangements and structure of metals**. An understanding of atomic structures also makes it easier to comprehend the changes that take place in atomic scale to **produce compounds and alloys** as well as their behavior under the influence of heat or mechanical energy.

Matter is composed of atoms that are too small to be seen with the aid of ordinary microscopes, but the outline of molecules has been detected by field ion and electron microscopes. **The molecule** is defined as the smallest particle of any substance that can exist free and still exhibit all the chemical properties of that substance. **A molecule may consist of one or more atoms.** Matter compound of a single kind of atom is called an **element**. There are more than 100 elements and new ones are being discovered all the time. Those having atomic number greater than 92 are not found in nature but are produced by atomic reactions such as in nuclear reactions.

*There are two types of elements: Metals and non-metals.*

A compound is composed of two or more elements combined chemically when as a physical mixture of two or more elements is called a mixture. Hydrogen and oxygen combine chemically to form water which is a compound where as sugar and salt can only mix physically to give a mixture.



*Fig.3.1 Atomic structure*

An atom resembles a solar system on a mini scale having orbits in many planes. It consists of neutrons, protons and electrons as shown in Fig.3.1 although recent research in particle physics has discovered even smaller constituents of atoms. The nucleus of an atom consists of protons and neutrons while much smaller electrons revolve around the nucleus at very high speeds.

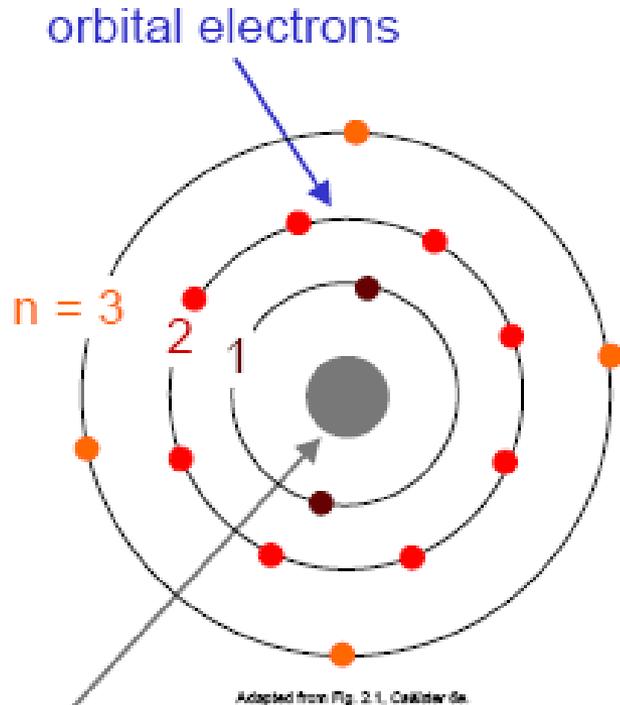
Protons have a positive electrical charge. Neutrons weigh essentially the same as protons but do not carry any charge. Electrons are negatively charged and consequently they are strongly attracted to the positively charged nucleus.

Each atom has preferred electron paths or orbits called **shells**. The **number, arrangement and spin of the electrons** in these shells in combination with the constituents of the nucleus determine the kind of atom and its characteristics.

Quick Chemistry Review:

# ELECTRON ENERGY STATES

## The Bohr Atom



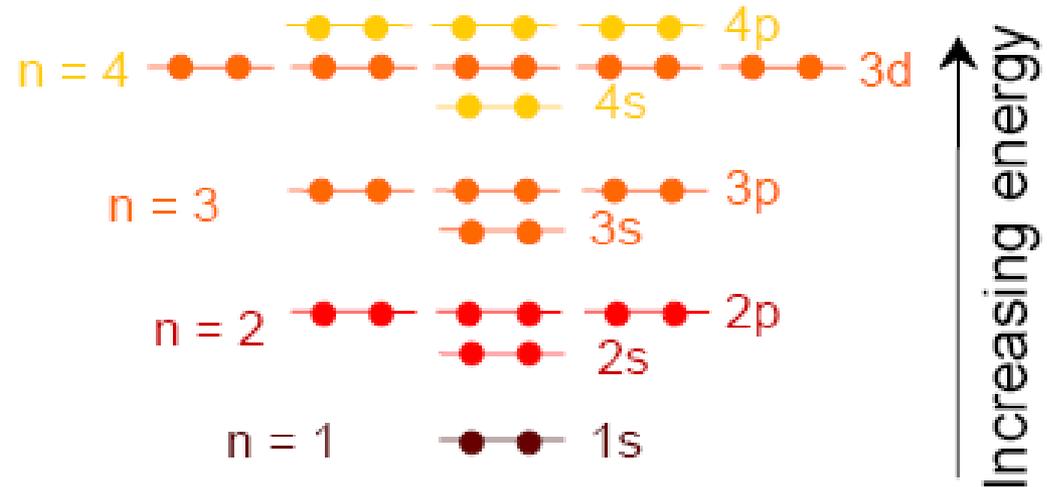
Nucleus:  $Z = \#$  protons  
 $= 1$  for H to  $94$  for Pu

$N = \#$  neutrons

Atomic mass  $A \approx Z + N$

## Electrons...

- have discrete **energy states**
- tend to occupy lowest available energy state.



# SURVEY OF ELEMENTS

<u>Element</u>	<u>Atomic #</u>	<u>Electron configuration</u>
Hydrogen	1	$1s^1$
Helium	2	$1s^2$ (stable)
Lithium	3	$1s^2 2s^1$
Beryllium	4	$1s^2 2s^2$
Boron	5	$1s^2 2s^2 2p^1$
Carbon	6	$1s^2 2s^2 2p^2$
...	...	...
Neon	10	$1s^2 2s^2 2p^6$ (stable)
Sodium	11	$1s^2 2s^2 2p^6 3s^1$
Magnesium	12	$1s^2 2s^2 2p^6 3s^2$
Aluminum	13	$1s^2 2s^2 2p^6 3s^2 3p^1$
...	...	...
Argon	18	$1s^2 2s^2 2p^6 3s^2 3p^6$ (stable)
...	...	...
Krypton	36	$1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^6$ (stable)

Adapted from Table 2.2, Callister 6e.

- Most elements: Electron configuration **not stable**.  
Why? **Valence** (outer) shell not completely filled.  
**Origin of atomic bonding:**

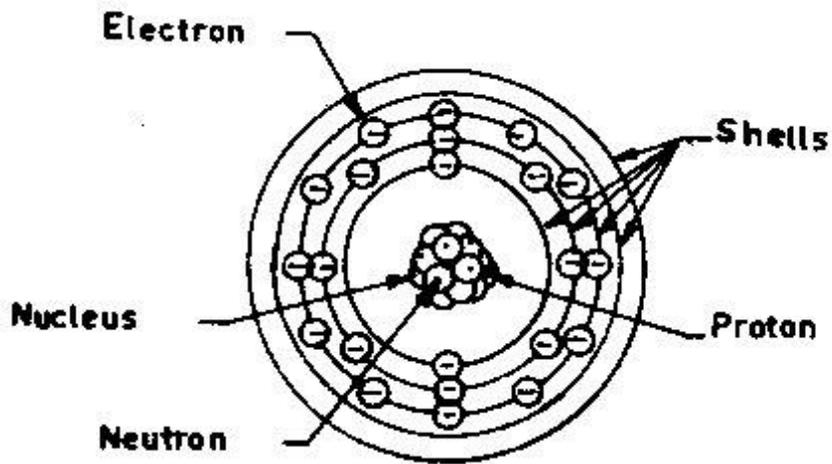


Fig.3.1 Atomic structure

Each shell contains a given number of electrons for each atom. The total number of electrons in an atom is called **atomic number** of atom. The total number of protons and neutrons in the nucleus is called **the atomic weight** of an atom. The number of protons also equals the atomic number in a stable atom because they balance the electrical charge of an electron. If the number of electrons and protons were not the same then an atom would display an electronic charge and would become unstable.

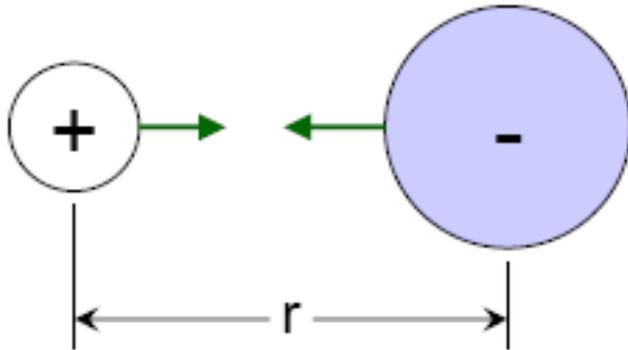
The electrons in the outermost shells are the most important electrons. They are called **valence electrons** and they determine the physical and chemical properties of an atom. The importance of valence electrons stems from the fact that the most stable (lowest energy) condition for an atom is obtained when the outermost shell is complete and has a full complement of electrons. If, however, an atom has less than complete quota of electrons in its shell, then it tries to either acquire or release some electrons to complete its valence shell. Number of valence electrons determine the way in which an atom completes its valence shell and hence they play a vital role in determining the characteristics of that atom.

## Why review bonding?

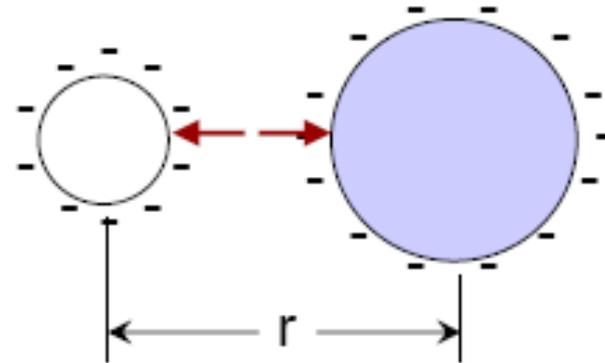
- The type, strength, and directionality of atomic bonding controls what structures may form and many material properties.
  - Melting temperature
  - Thermal expansion
  - Elastic stiffness
  - Electrical properties
  - Ductility and toughness

# BOND ENERGY

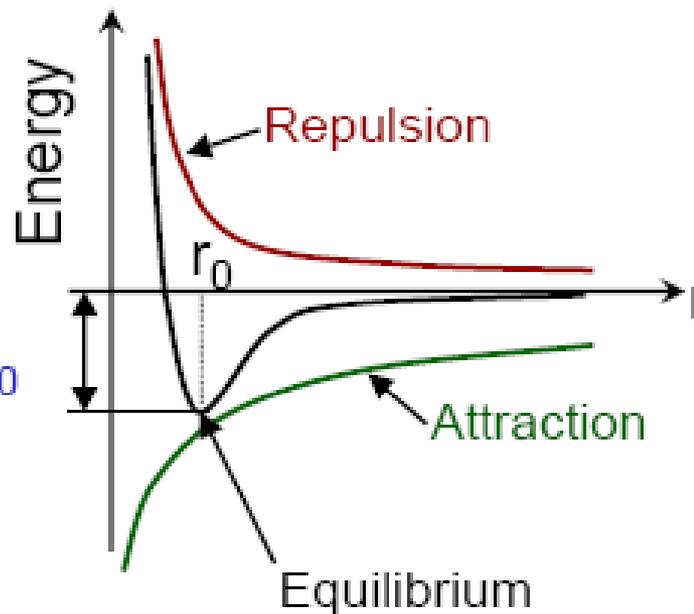
Attraction (ionic)



Repulsion

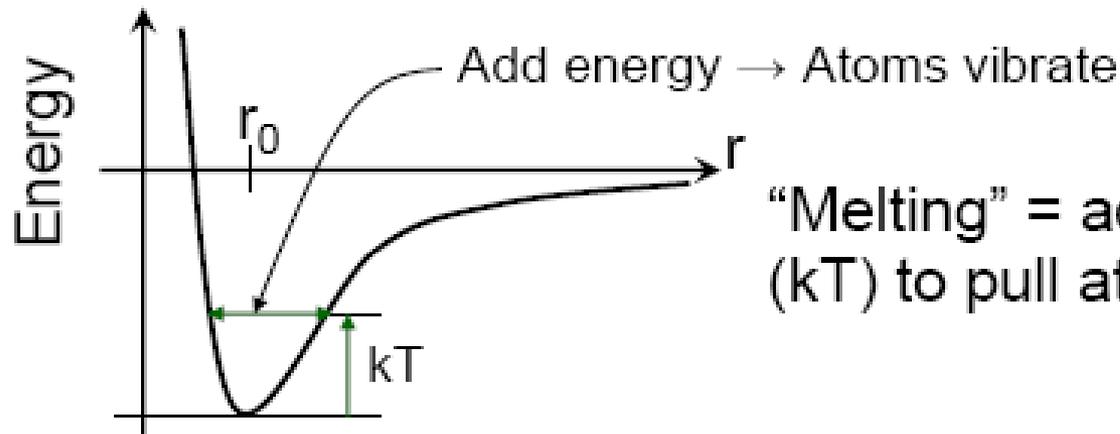


Bond Energy,  $E_0$



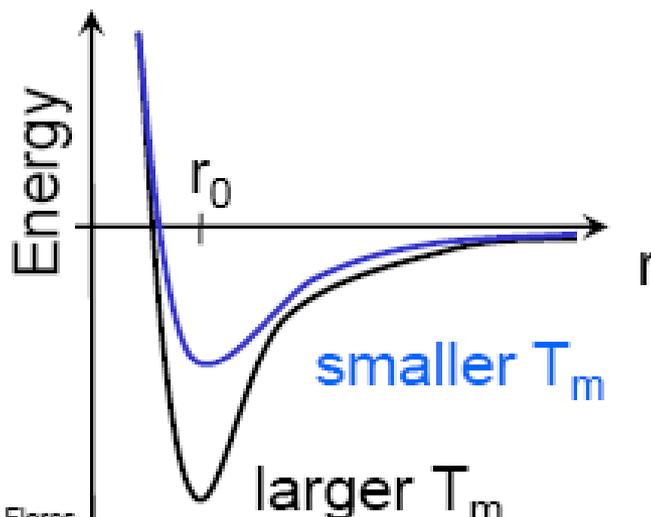
# PROPERTIES FROM BONDING: $T_M$

- Melting Temperature,  $T_m$



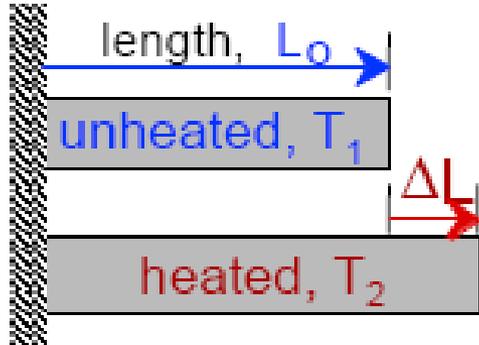
“Melting” = add thermal energy ( $kT$ ) to pull atoms apart,  $r \rightarrow \infty$

- $T_m \sim$  depth at  $r_0$



# PROPERTIES FROM BONDING: $\alpha$

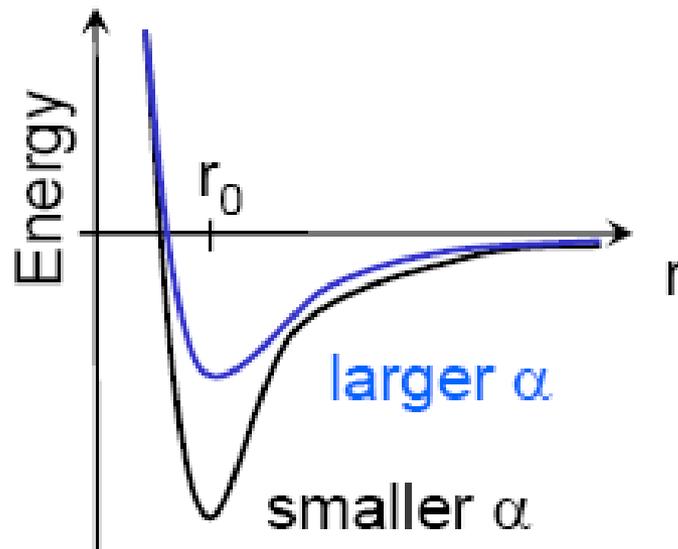
- Coefficient of thermal expansion,  $\alpha$



coeff. thermal expansion

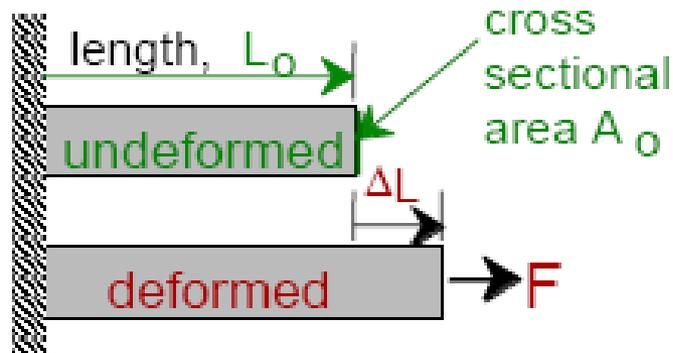
$$\frac{\Delta L}{L_0} = \alpha (T_2 - T_1)$$

- $\alpha \sim$  asymmetry at  $r_0$



# PROPERTIES FROM BONDING: E

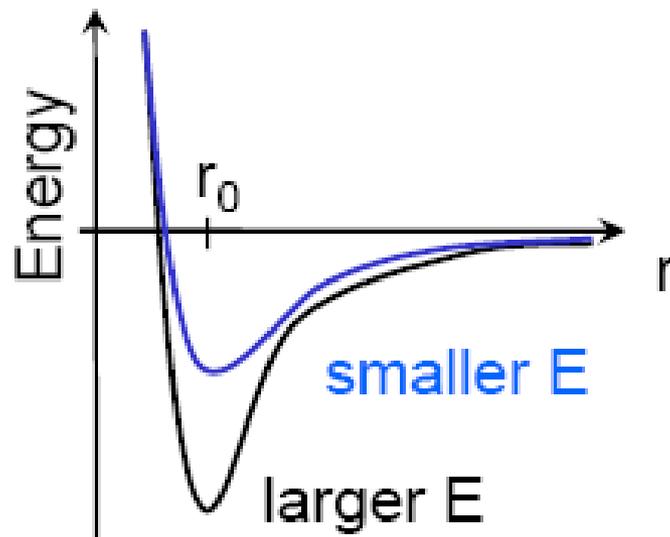
- Elastic modulus (stiffness), E



Elastic modulus

$$\frac{F}{A_0} = E \frac{\Delta L}{L_0}$$

- $E \sim$  curvature at  $r_0$



## 3.2.1 Bonding of Atoms

There are various ways in which atoms can join together to form molecules depending upon the character of atoms involved.

Four basic types of bonding arrangements are,

- ionic,
- covalent,
- metallic and
- Van-der-Wall's forces.

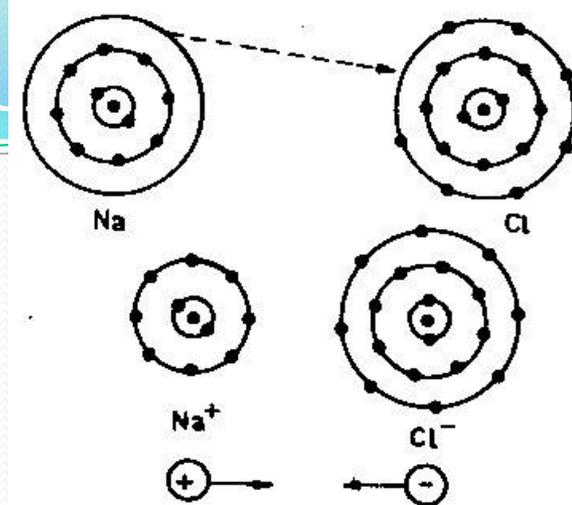
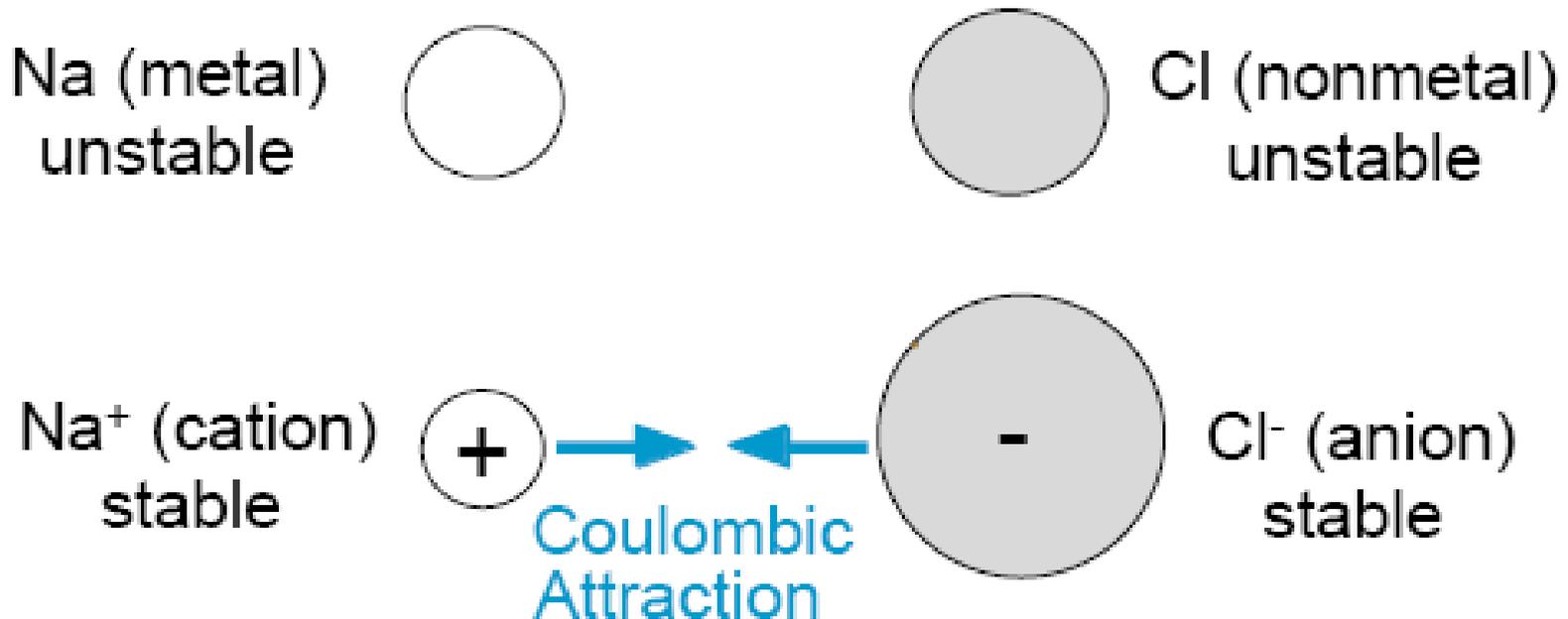


Fig.3.2 Ionic bonding in salt.

A molecule may be held together by either of these or a combination of them. In an ionic bond an element which has one valence electron releases it to complete its outer shell. On the other hand an element which has one less electron in its valence shell finds it easier to acquire it from a donor to complete the valence shell. For example sodium has one valence electron and it is easier for it to release it and complete its valence shell rather than acquire seven more electrons. Chlorine, on the other hand has seven electrons and it is easier for it to acquire one electron to complete its valence shell rather than release seven electrons. In doing so, therefore sodium acquires a positive charge (because it has one less electron) and chlorine becomes negative due to extra electron. As a result an electronic attraction is developed between Na and Cl ions and an ionic bond is formed. The structure resulting from such a bond (Fig.3.2) is, however, **weak** and **brittle** as the electrostatic forces are very **selective** and **directional**.

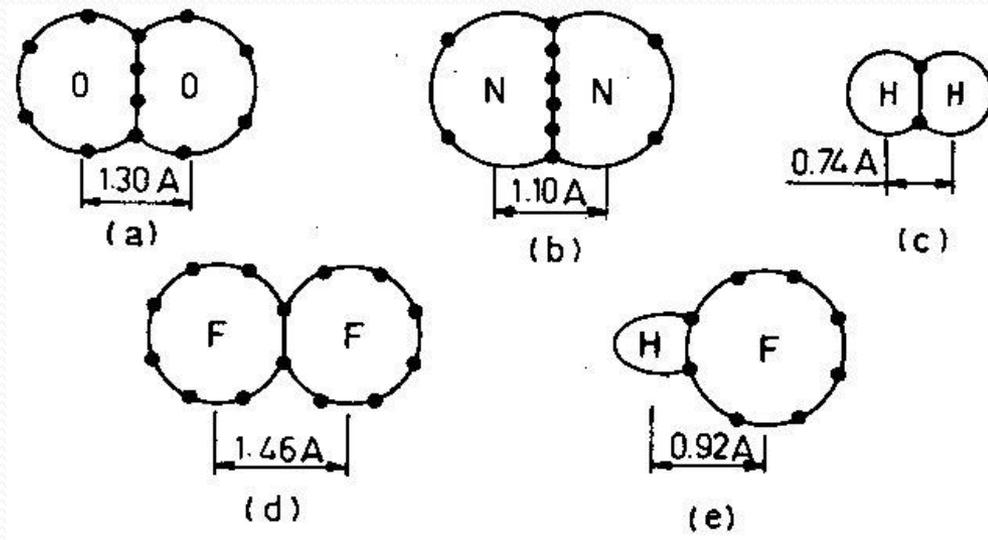
# IONIC BONDING

- Predominant bonding in **ceramics**
- Electrons **transferred** from one atom to another → ions
- Bonding between + and - ions.
- Compounds have a **balanced** (neutral) charge.
- Example: NaCl





A **covalent bond** is based on sharing electrons by atoms involved. For example oxygen has six valence electrons and it can complete its valence shell by acquiring two electrons. It is considerably difficult for oxygen to acquire two electrons out right so it shares two electrons with another oxygen atom as shown in Fig.3.3. This arrangement completes the outer shells of both oxygen atoms to produce an oxygen molecule. This type of bonding is very strong and the strength depends upon number of shared electrons. It generally takes place in **non-metals** such as carbon (diamond bond) and like ionic bond it gives **rigid and directional structure**.



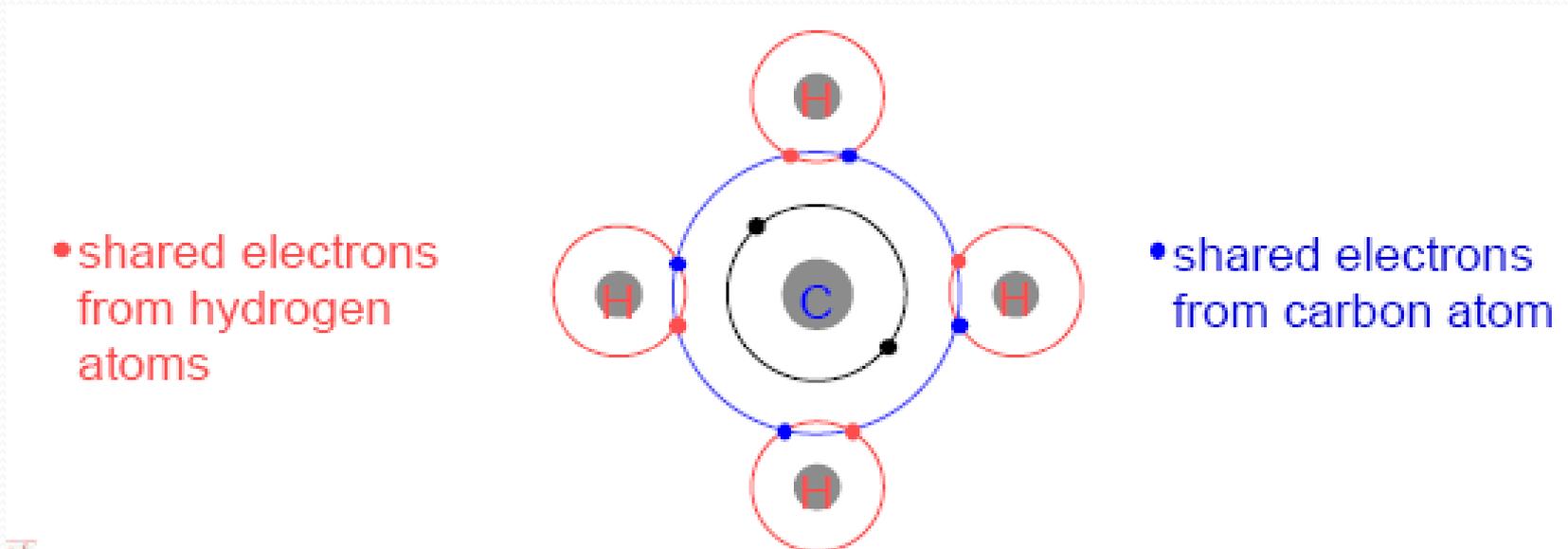
*Fig.3.3 Covalent bonding of some molecules*



# COVALENT BONDING

- Electrons **shared** between atoms
- Example: CH<sub>4</sub> **Methane**

	<u>e<sup>-</sup> config</u>	<u># valence e<sup>-</sup></u>	<u>needs?</u>	<u>Electronegativity</u>
H	1s <sup>1</sup>	1	1	2.1
C	1s <sup>2</sup> 2s <sup>2</sup> 2p <sup>2</sup>	4	4	2.5



# IONIC vs COVALENT BONDING

- Bonds are typically not purely ionic or covalent

H 2.1																	He -
Li 1.0	Be 1.5											B 2.0	C 2.5	N 3.0	O 3.5	F 4.0	Ne -
Na 0.9	Mg 1.2											Al 1.5	Si 1.8	P 2.1	S 2.5	Cl 3.0	Ar -
K 0.8	Ca 1.0	Sc 1.3	Ti 1.5	V 1.6	Cr 1.6	Mn 1.5	Fe 1.8	Co 1.8	Ni 1.8	Cu 1.9	Zn 1.6	Ga 1.6	Ge 1.8	As 2.0	Se 2.4	Br 2.8	Kr -
Rb 0.8	Sr 1.0	Y 1.2	Zr 1.4	Nb 1.6	Mo 1.8	Tc 1.9	Ru 2.2	Rh 2.2	Pd 2.2	Ag 1.9	Cd 1.7	In 1.7	Sn 1.8	Sb 1.9	Te 2.1	I 2.5	Xe -
Cs 0.7	Ba 0.9	Rare earth series	Hf 1.3	Ta 1.5	W 1.7	Re 1.9	Os 2.2	Ir 2.2	Pt 2.2	Au 2.4	Hg 1.9	Tl 1.8	Pb 1.8	Bi 1.9	Po 2.0	At 2.2	Rn -
Fr 0.7	Ra 0.9	Actinide series															

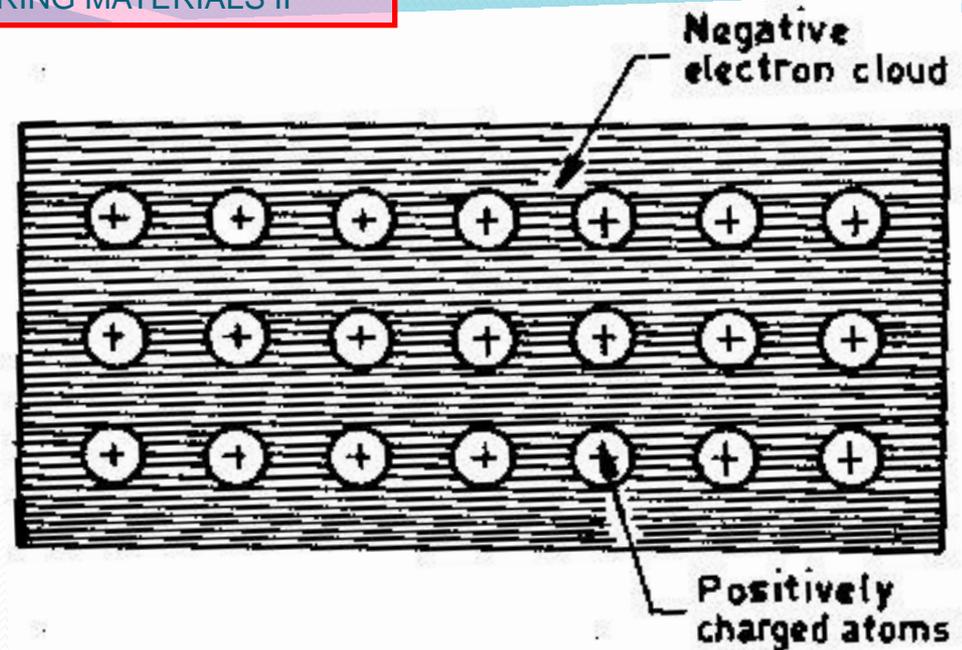
Adapted from Fig. 2-7, Callister 6e. (Fig. 2-7 is adapted from Linus Pauling, *The Nature of the Chemical Bond*, 3rd edition, Copyright 1939 and 1940, 3rd edition, Copyright 1960 by Cornell University.)

For elements A and B with electronegativities  $X_A$  and  $X_B$ :

$$\% \text{ ionic character} = \{1 - \exp[-(0.25)(X_A - X_B)^2]\} \times 100$$

As difference in electronegativity increases, ionic character of bond increases.

Metallic bonding is peculiar to metals only. It is formed among similar metal atoms such that some of the valence electrons leave their respective atoms to form a cloud surrounding the positively charged ions. When valence electrons leave an atom it becomes positively charged ion.



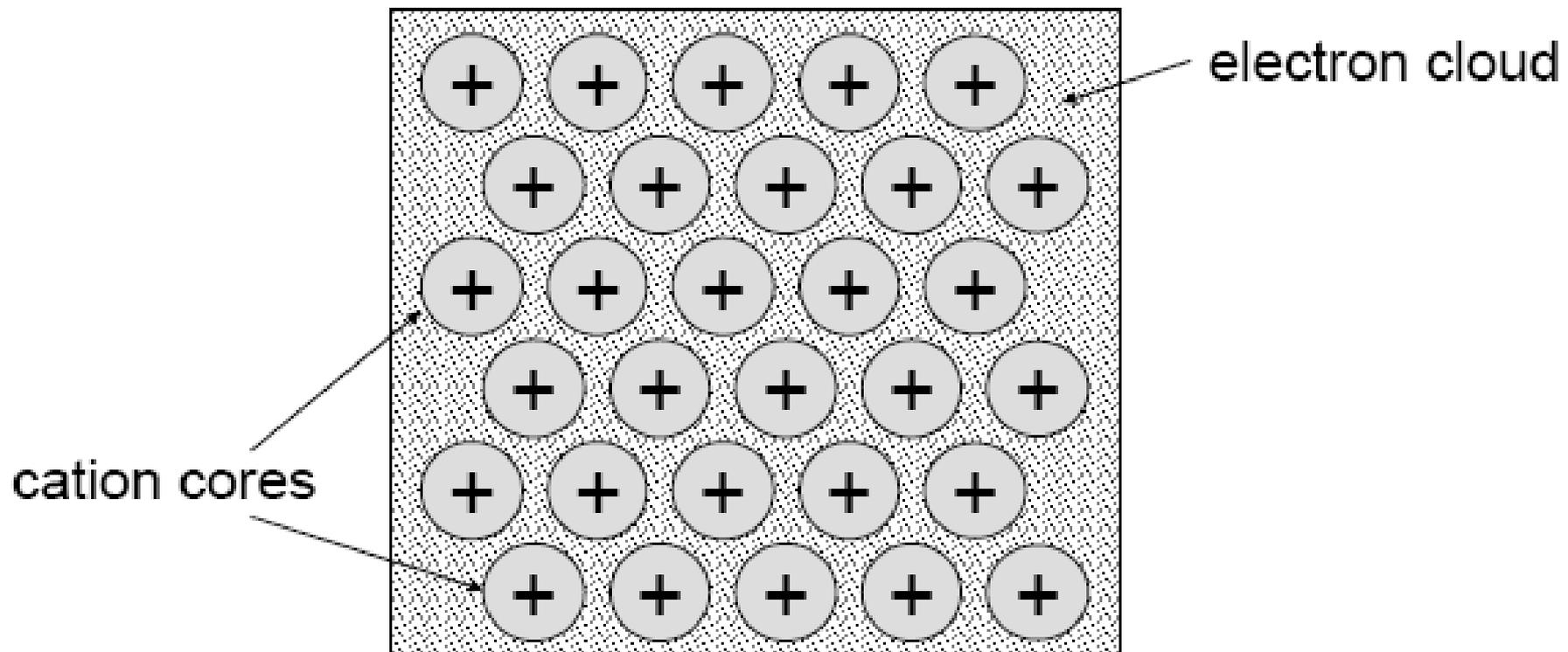
*Fig.3.4 Metallic bond*

The cloud surrounds all such positively charged ions and as a result these ions arrange themselves in a very orderly manner and are held in their place due their attraction for the negatively charged electron cloud surrounding them as shown in Fig.3.4. The electrons in cloud are **free to move all over** the metal and hence, metals **exhibit good electrical and thermal conductivity** as well as elasticity and plasticity. **The metallic bond is very strong.**

**Van der Wall's forces** are very weak and are formed in neutral atoms such as inert gases. They only become important for metals at low temperatures.

# METALLIC BONDING

- Primary bond for **metals** and their **alloys**
- Cores surrounded by sea of **donated valence electrons** (1, 2, or 3 from each atom).



Adapted from Fig. 2-11, Callister 6e.

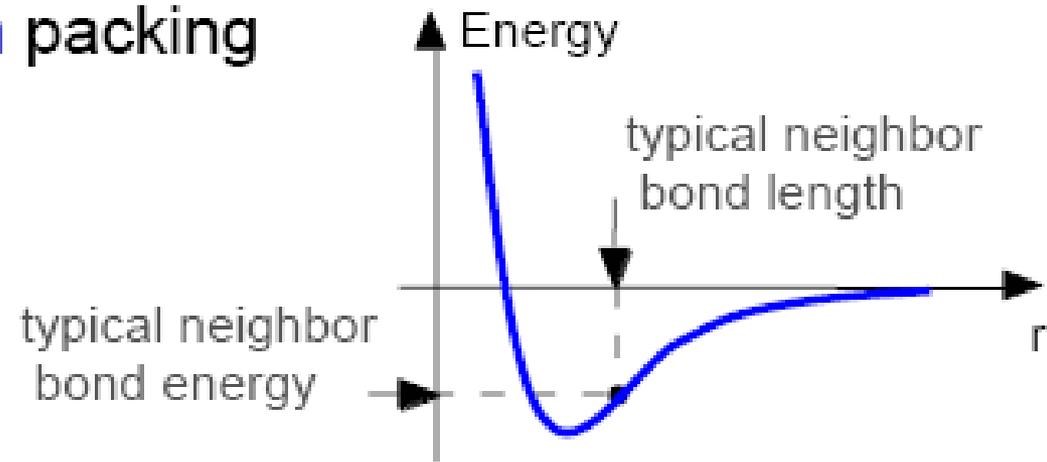
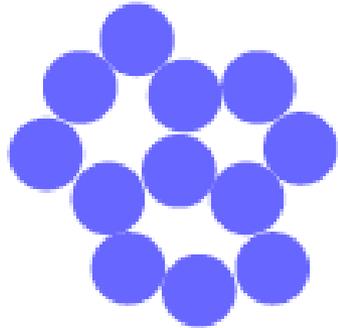
# METALLIC CRYSTALS...

- Have the simplest crystal structures
- Tend to be densely packed:
  - Metallic bonding is not directional.
  - Typically, only one element is present: all atomic radii are the same.
  - “Nearest neighbor” distances typically small to lower bond energy.

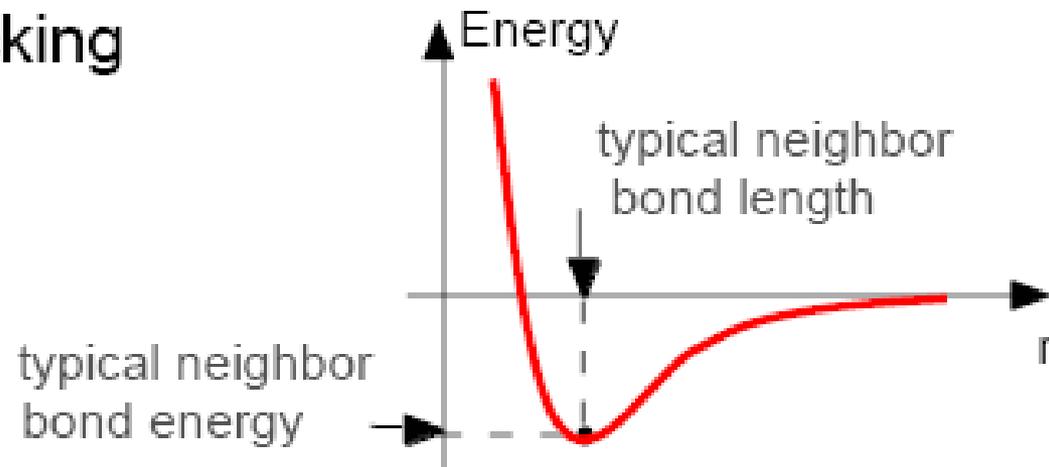
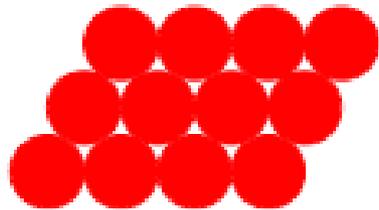
We will look at **four** such structures...

# ENERGY AND PACKING

- Non dense, **random** packing



- Dense, **regular** packing



# MATERIALS AND PACKING

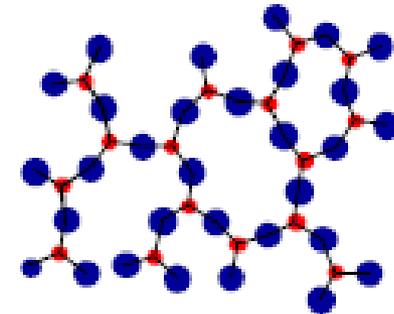
## Noncrystalline materials...

- atoms have no periodic packing
- occurs for: complex structures  
rapid cooling

"Amorphous" = Noncrystalline

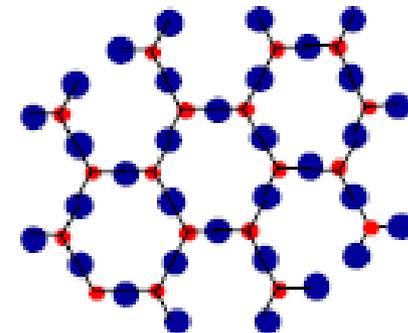
## Crystalline materials...

- atoms pack in periodic, 3D arrays
- typical of: - metals  
- many ceramics  
- some polymers



noncrystalline SiO<sub>2</sub>

Adapted from Fig. 3.18(b),  
Callister 6e.



crystalline SiO<sub>2</sub>

Adapted from Fig. 3.18(a),  
Callister 6e.

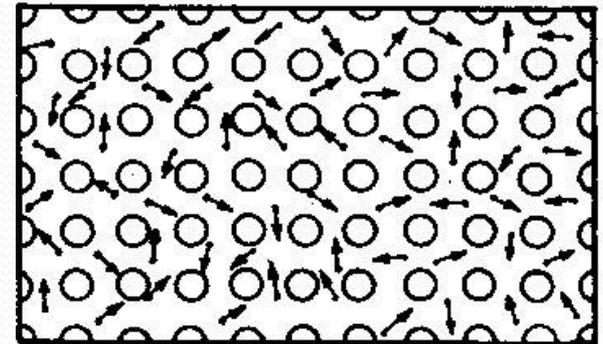


Metals have a very definite arrangement of atoms and specific structures. Metallic bond imparts certain characteristics to metals which distinguish them from non-metals. A metal has the following properties:

1. Ability to donate electron and become positively charged ion.
2. Crystalline structure.
3. High thermal and electrical conductivity.
4. Ability to be deformed plastically.
5. Metallic lustre.

Some elements such as silicon and germanium possess one or more of these properties and are termed metalloids.

Metals in solid state possess a definite arrangement of atoms which is called **crystalline structure**. When metal is in liquid form above its melting temperature, the atomic forces are reduced and the atoms can move freely within the limits of the molten mass as shown in Fig.3.5

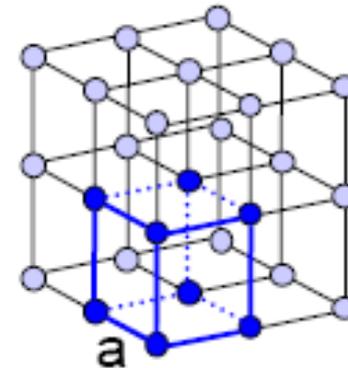


*Fig.3.5 Atoms in a molten metal.*

# UNIT CELL

Small grouping of atoms that generate complete crystal structure by repetitive displacement.

Edge of length “a”.



## ATOMIC PACKING FACTOR

Relative density of atomic packing in unit cell, assuming atoms are hard spheres.

$$APF = \frac{\frac{\text{atoms}}{\text{unit cell}} \frac{\text{volume}}{\text{atom}}}{\frac{\text{volume}}{\text{unit cell}}}$$

When the temperature is reduced, the thermal energy available to the atoms is also reduced and consequently their motion is limited until a temperature is reached when the atoms are no longer able to move from their definite arrangement resulting from metallic bond. This temperature is the **solidification temperature** and at this temperature the force between atoms is greater than the thermal activity of the atoms and hence the atoms are unable to leave the arrangement. This arrangement of atoms into a definite pattern is called **a space lattice**. **Space lattice** is a series of points in space which are arranged in a pattern. Space lattice has a single pattern which is repeated again and again as shown in Fig.3.6. This recurring single pattern is called **the unit cell**. **A unit cell** is specific to a space lattice and space lattices are generally described in terms of unit cells. Space lattice consists of millions of unit cells joint together.

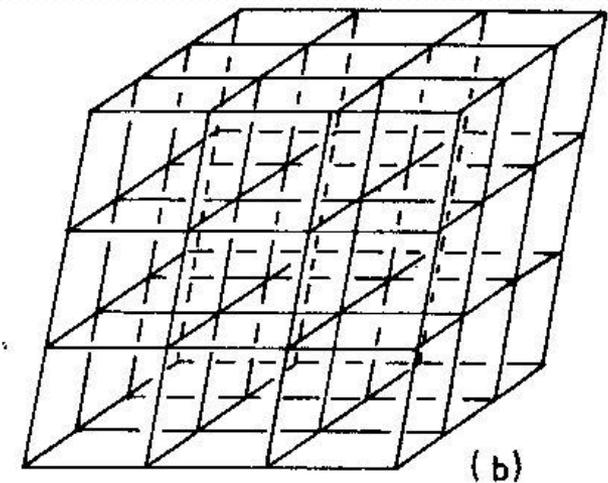
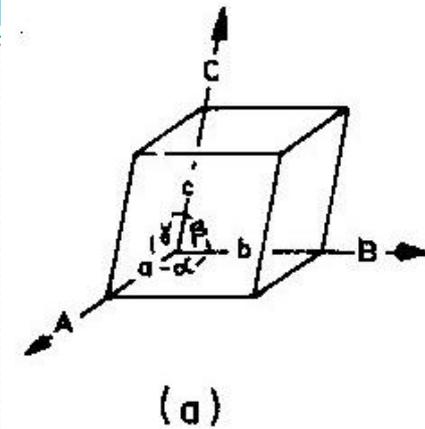
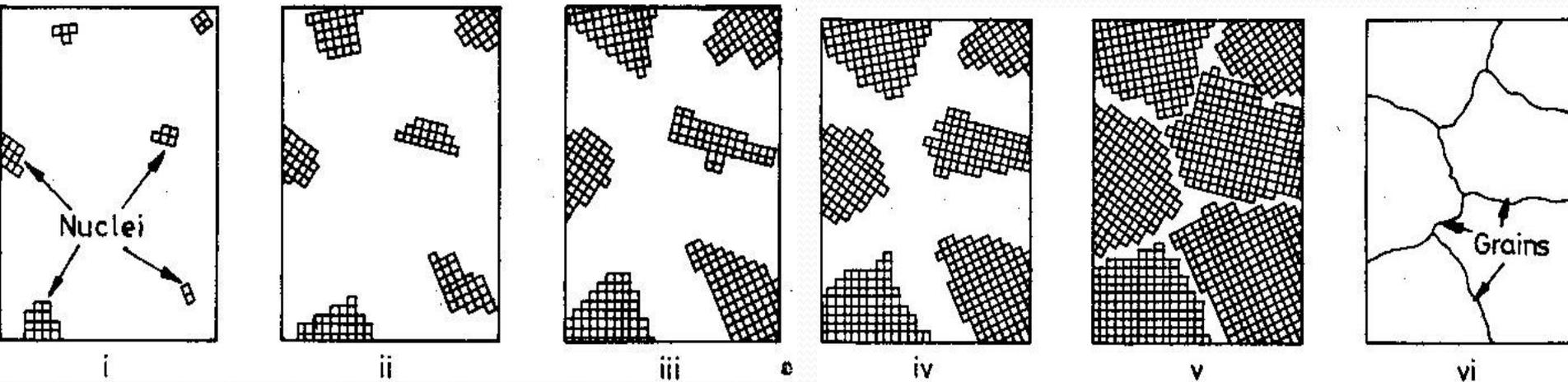


Fig.3.6 Unit cell and space lattice.

When a metal begins to solidify, the free atoms start to condense not just at one site but at many sites and each of these sites grows by the addition of unit cells to create space lattices which continue to grow as the temperature is lowered. A situation is therefore reached, just before the completion of solidification, when these adjoining space lattices having different orientations meet each other. Due to differences in orientations they do not join each other coherently and therefore a boundary interface is created between them which represents an area of mis-match as shown in Fig.3.7.



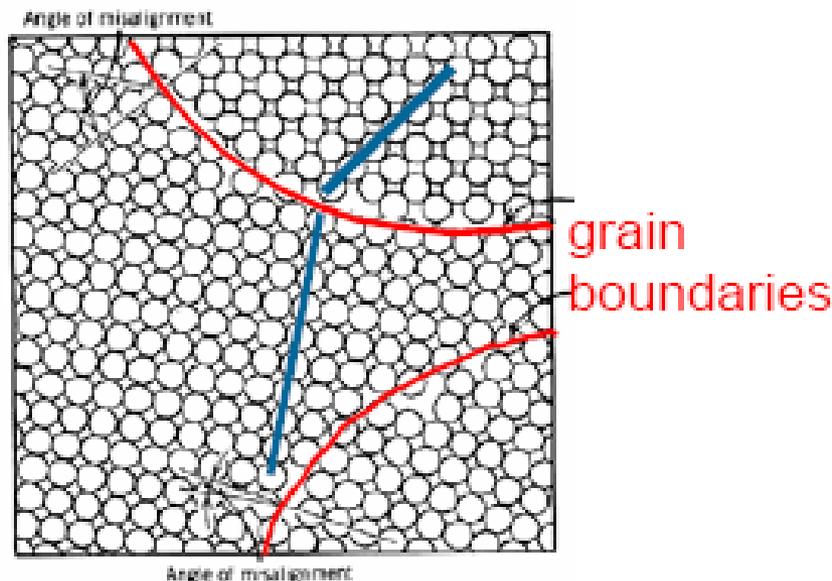
*Fig.3.7 Development of grains and boundaries*

# AREA DEFECTS: GRAIN BOUNDARIES

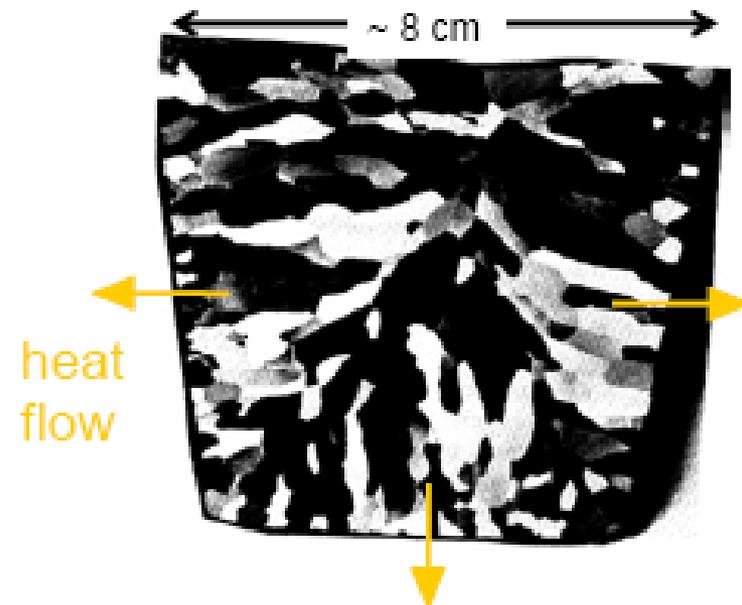
## Grain boundaries:

- are boundaries between crystals with different orientation (planes go in different directions).
- are produced by the solidification process, for example.
- have a change in crystal orientation across them.
- impede dislocation motion.

### Schematic

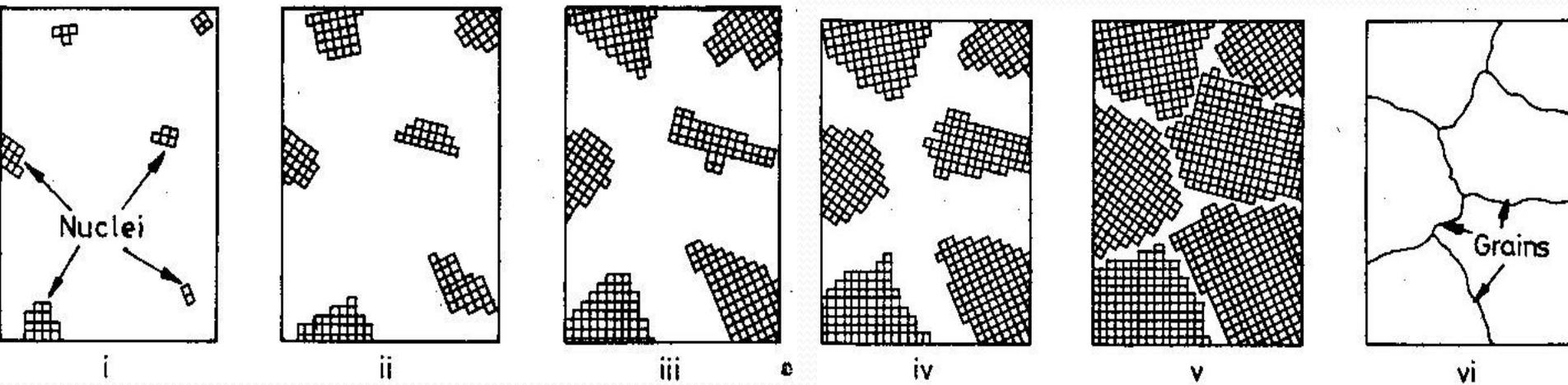


### Metal Ingot

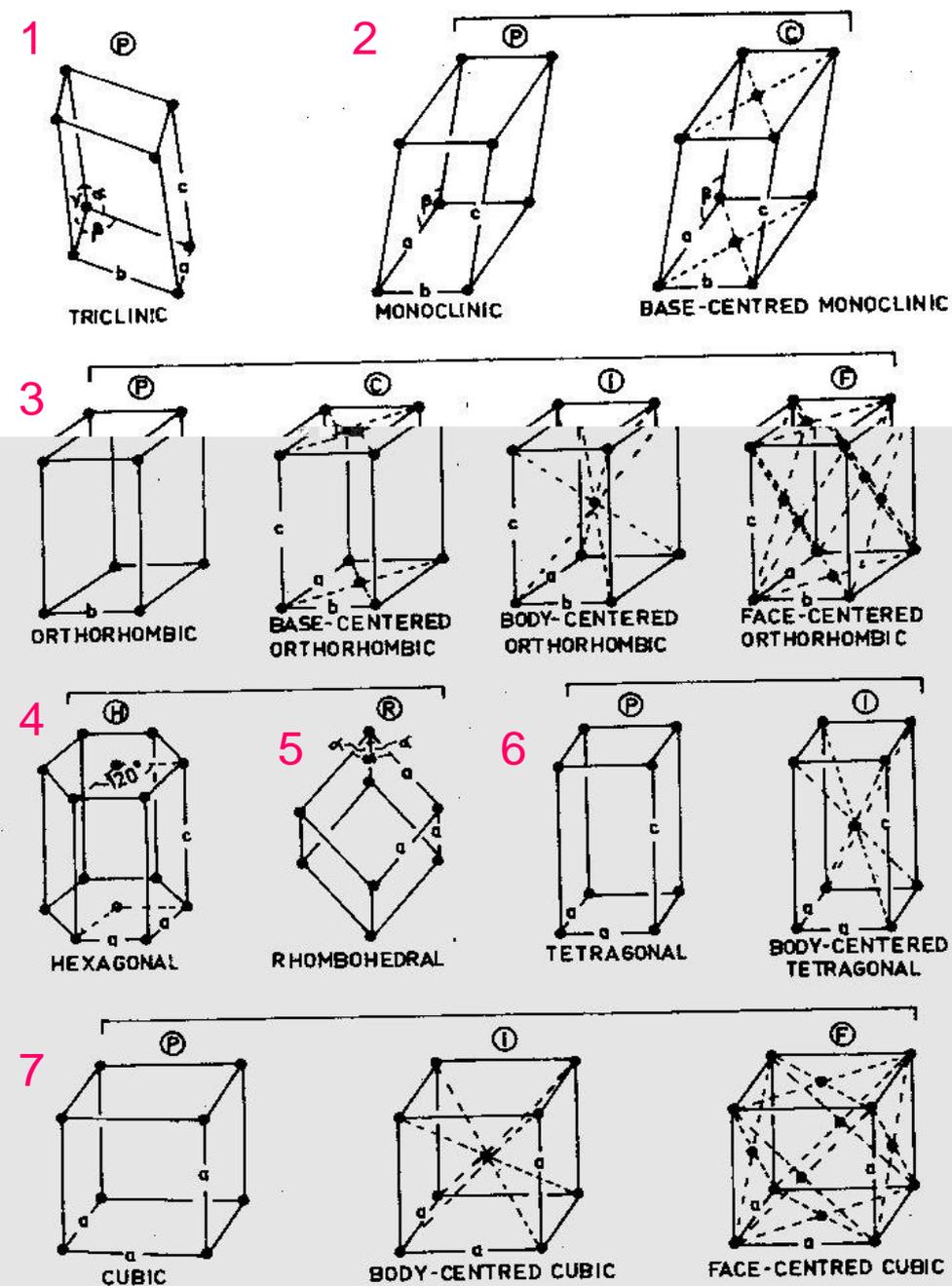


The situation is similar to the confluence of two rivers coming from different directions. At their junction the water is very turbulent due to the differences in the directions of two water flows. Each grain in metal is, therefore, a space lattice and the interface between the space lattices is a **grain boundary**. The nature of these boundaries is not very well understood as yet but it is believed that they are only one or two atoms wide and they are an interlocking border in a very highly strained condition.

Arrangements of unit cells in metals (space lattices) can be observed by using X-ray diffraction.



*Fig.3.7 Development of grains and boundaries*

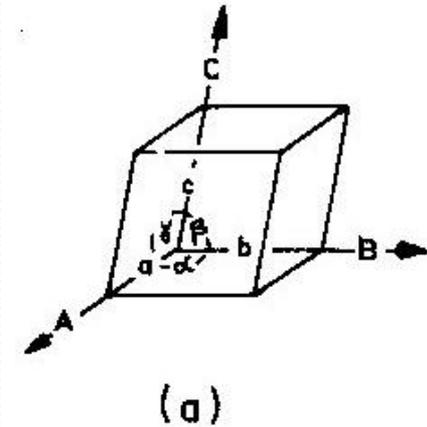


These studies have revealed that there are fourteen different types of lattice arrangements (unit cells) possible in a metal. They are called **Bravais lattices** and are shown in Fig.3.8, P means primitive where atoms occupy only the corners of the lattice; I means body centered where atoms occupy the corners of the lattice and an additional atom at the gravitational center of the lattice; F means face centered where atoms occupy the corners of the lattice and centers of the each face of the lattice; C means base centered where atoms occupy the corners of the lattice and basal face centers of the lattice.

It can be seen from the figure that these lattices are based on seven basic geometries which are described in Table 3.1.

System	Axes	Axial angles
Cubic	$A = b = c$	All angles $90^\circ$
Tetragonal	$A = b \neq c$	All angles $90^\circ$
Orthorhombic	$A \neq b \neq c$	All angles $90^\circ$
Monoclinic	$a \neq b \neq c$	$\alpha = \beta = 90^\circ, \gamma \neq 90^\circ$
Triclinic	$a \neq b \neq c$	$\alpha \neq \beta \neq \gamma \neq 90^\circ$
Hexagonal	$a = b \neq c$	$\alpha = \beta = 120^\circ, \gamma = 90^\circ$
Rhombohedral	$a = b = c$	$\alpha = \beta = \gamma \neq 90^\circ$

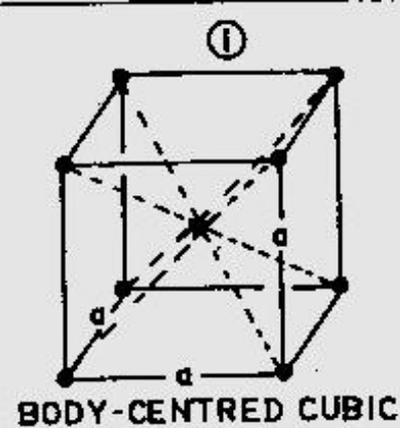
The fundamental geometry of the space lattice can be described by lattice vectors A, B and C (Fig.3.6). The vectors define the unit cell and the geometry of the space lattice is specified satisfactorily by the lattice constants: vector lengths a, b and c and the inter-axial angles  $\alpha$ ,  $\beta$ , and  $\gamma$ .



The most common and important of these lattices are **Body Centred Cubic (BCC)**, **Face Centred Cubic (FCC)** and **Hexagonal Close Packed (HCP)**

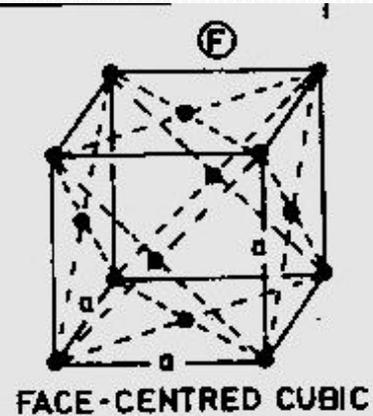
## BODY CENTRED CUBIC

This unit cell consists of atoms at each corner of a cube and one in the very center. Steel under  $723\text{ }^{\circ}\text{C}$  ( $\alpha$ ) has this structure. Other metals such as chromium and tungsten also possess BCC structure. *Molibdenum, Tantalum, Vanadium.*



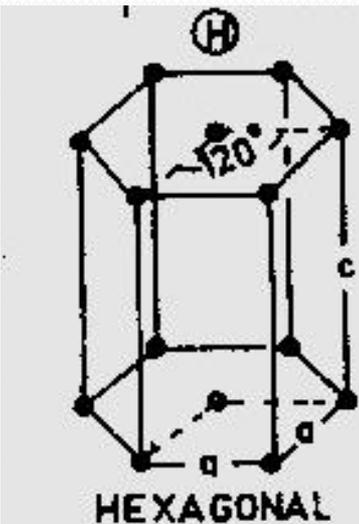
## FACE CENTRED CUBIC

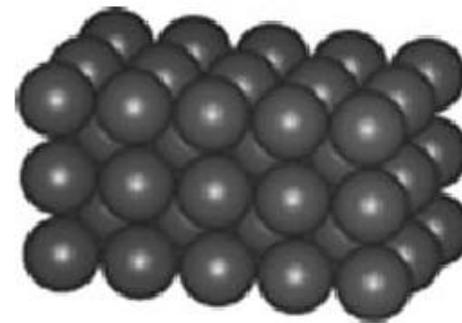
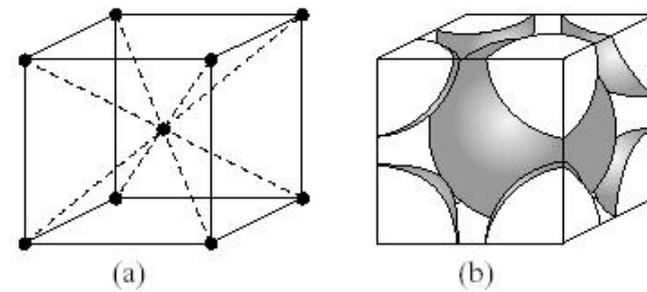
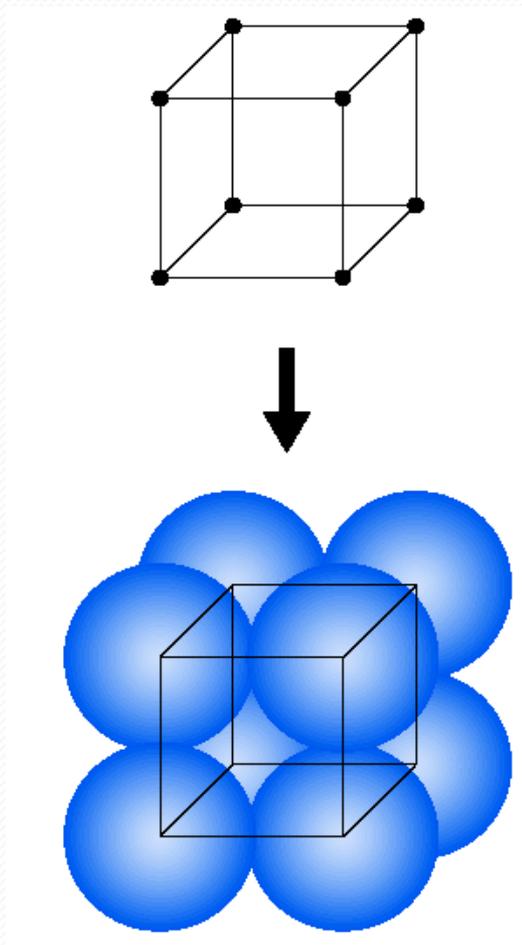
In this lattice atoms occupy each corner of a cube and centers of each face of the cube. Steel above  $723\text{ }^{\circ}\text{C}$  ( $\gamma$ ) possesses this structure as well as copper and aluminum etc. FCC metals in general have lower yield strength and higher ductility compared to BCC metals. *Nickel, Lead, Silver, Gold*



## HEXAGONAL CLOSE PACKED

This structure is found in many rarer metals such as beryllium, titanium etc. Because of the spacing of the lattice structure, rows of atoms cannot slide over each other easily making these metals very brittle. The arrangement consists of atoms in the center and each corner of upper and lower hexagonals, and three atoms in a triangle in the center of the unit cell. *Titanium, Magnesium, Cobalt, Zinc.*



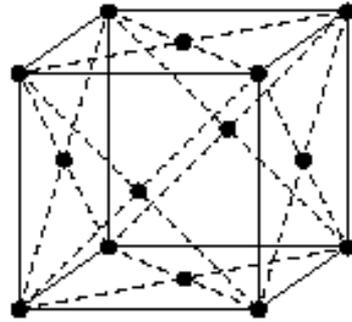


(c)

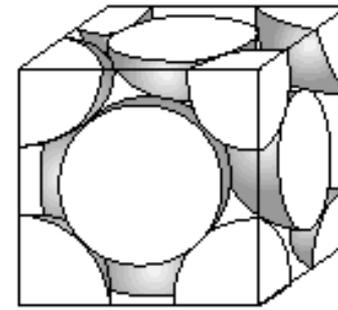
Structure: body-centered cubic (bcc)

Bravais lattice: bcc

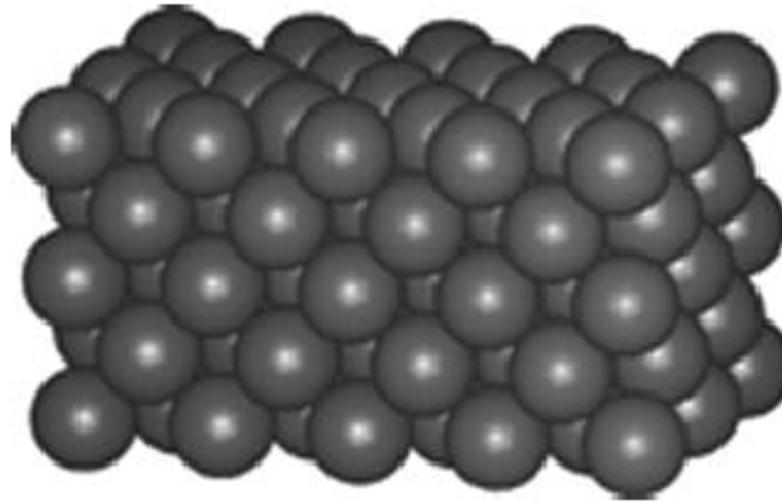
Atoms/unit cell:  $1 + 8 \times \frac{1}{8} = 2$ Typical metals:  $\alpha$ -Fe, V, Cr, Mo, and W



(a)



(b)



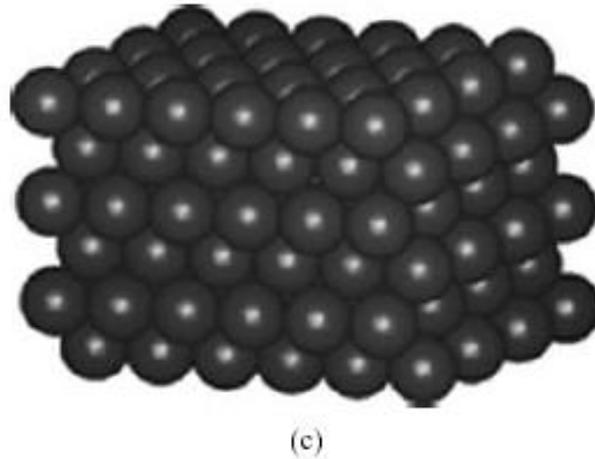
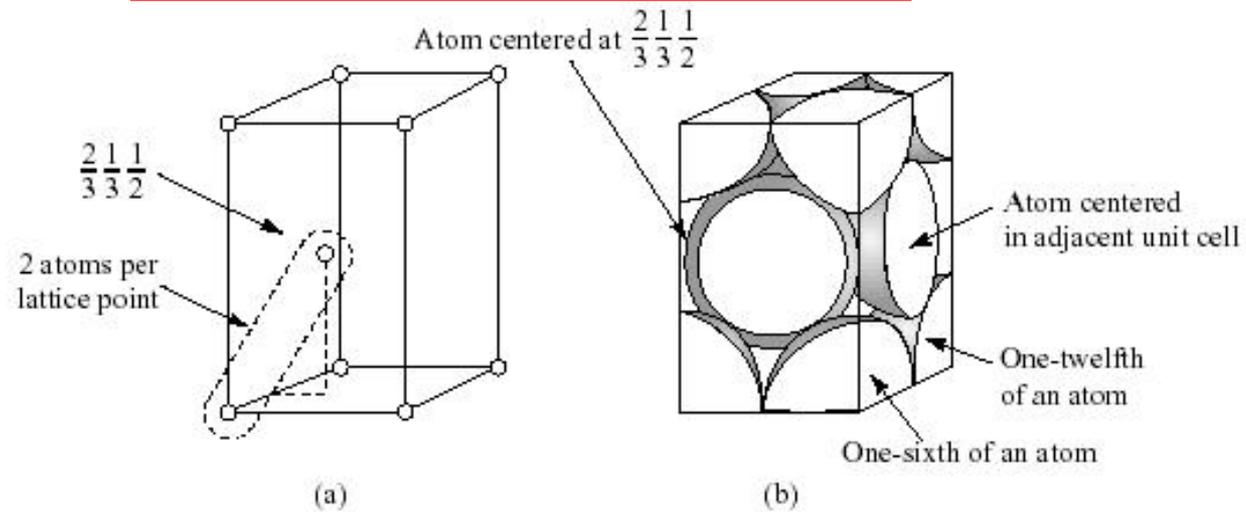
(c)

Structure: face-centered cubic (fcc)

Bravais lattice: fcc

$$\text{Atoms/unit cell: } 6 \times \frac{1}{2} + 8 \times \frac{1}{8} = 4$$

Typical metals:  $\gamma$ -Fe, Al, Ni, Cu, Ag, Pt, and Au



Structure: hexagonal close-packed (hcp)

Bravais lattice: hexagonal

$$\text{Atoms/unit cell: } 1 + 4 \times \frac{1}{6} + 4 \times \frac{1}{12} = 2$$

Typical metals: Be, Mg,  $\alpha$ -Ti, Zn, and Zr

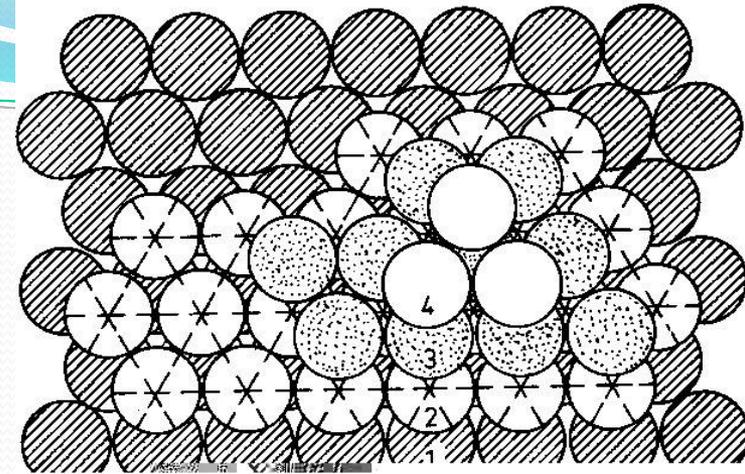
## OTHER STRUCTURES

Manganese has a simple cubic structure and antimony has a rhombohedral structure and they are used as alloying elements for steel. Martensite is a supersaturated solution of carbon in BCC iron. Because carbon cannot occupy any of the lattice positions (corner or center of the cube) it sits in the spaces in between iron atoms and hence elongates the cubic lattice to make it body centered tetragonal. This distortion by carbon imparts to martensite a very high hardness.

### 3.3.1. STACKING

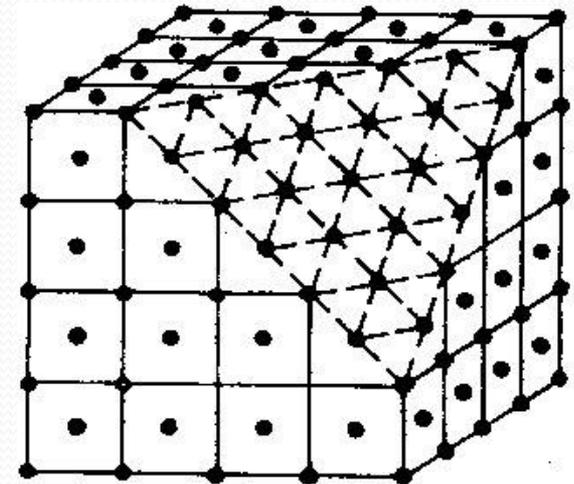
FCC and HCP structures mentioned above (but not BCC) are obtained when layers of atoms are stacked on top of each other in a specific manner. When solidification of a molten metal occurs, the metal atoms join together to form layers and these layers sit on top of each other in a manner analogous to a packet of sliced bread in which bread slices are stacked on top of each other. Fig.3.9 shows closely packed layers and stacking sequence in which atoms of layer 2 sit in the pockets produced by three adjoining atoms of layer 1.

This 1, 2 arrangement leads to very close packing of atoms. It can be seen that the same close packing can also be obtained if the atoms of layer 3 were to occupy the pockets produced by three atoms of layer 2 instead of three atoms of layer 1.



*Fig.3.9 Stacking of atomic layers*

A close packing can, therefore, be obtained by stacking atoms on top of each other in 1, 2 or 1, 3 or 2, 3 fashion, but not on top of atoms such as 1, 1 or 2, 2. FCC lattice is obtained by a sequence 123123 whereas HCP is obtained by a sequence 121212. As shown in Fig.3.10, stacking of atomic layers in FCC takes place on a plane which is at  $45^\circ$  to the sides of the cube. The density of packing in various structures is described in examples, at the end of the chapter.



*Fig.3.10 Arrangements of atoms on (111) plane to produce FCC structure*

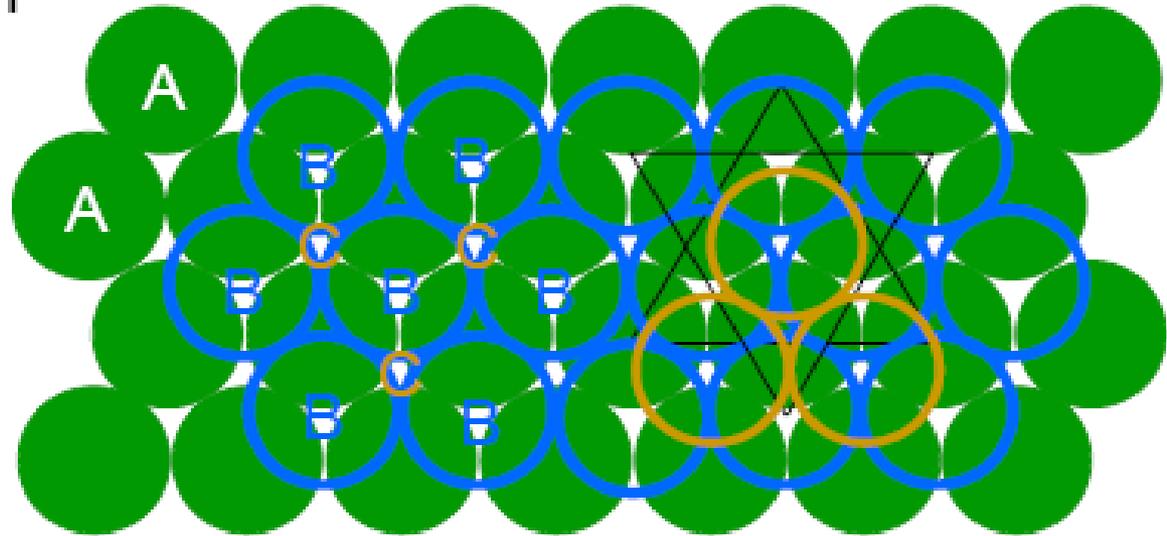
# FCC STACKING SEQUENCE

- ABCABC... Stacking Sequence
- 2D Projection

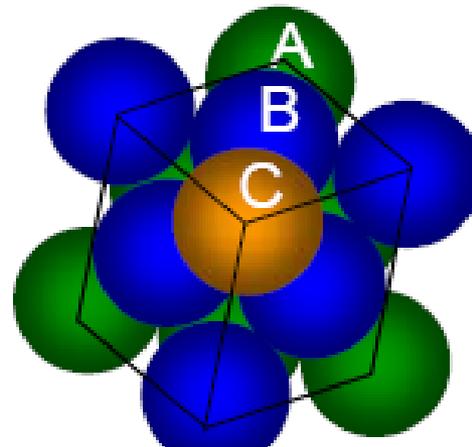
A sites

B sites

C sites

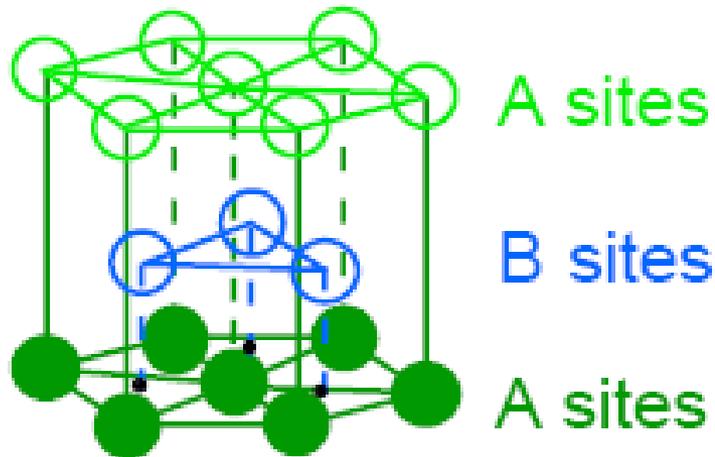


- FCC Unit Cell



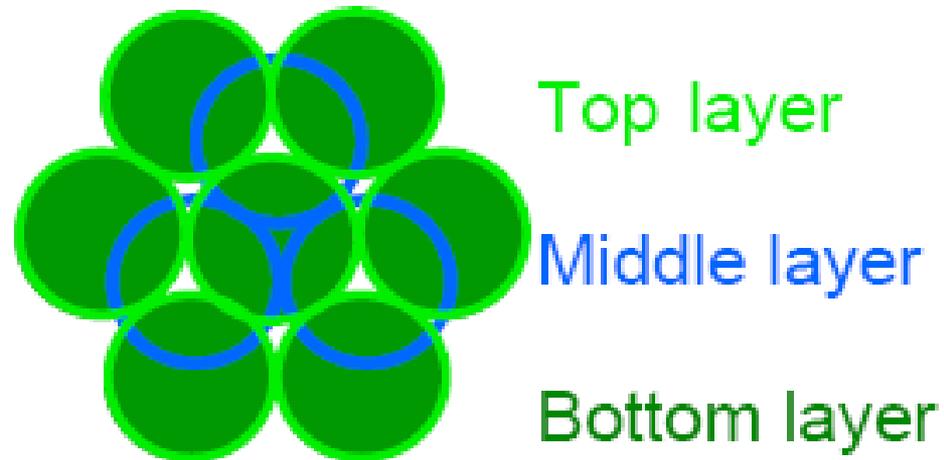
# HEXAGONAL CLOSE-PACKED STRUCTURE (HCP)

- ABAB... Stacking Sequence
- Unit cell:



Adapted from Fig. 3.3,  
Callister 6e.

- 2D Projection



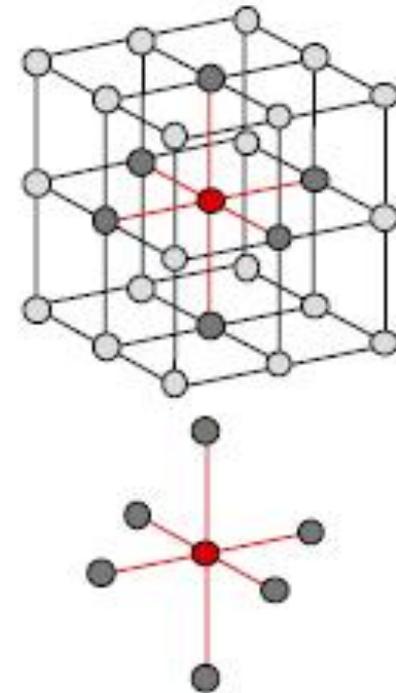
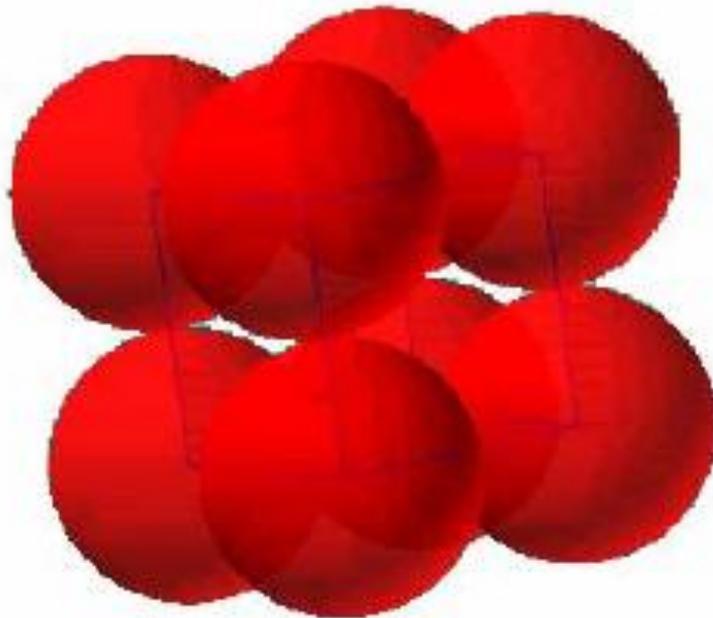
**EXAMPLE**

Determine the density of packing of:

Simple cubic, SC,  
Body Centered Cubic, BCC,  
Face Centered Cubic, FCC and  
Hexagonal Close Packed, HCP  
structures.

# SIMPLE CUBIC STRUCTURE (SC)

- Rare due to poor packing (only Po has this structure)



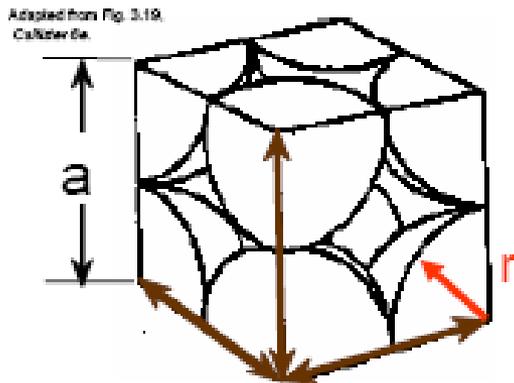
# ATOMIC PACKING FACTOR for SC

$$APF = \frac{\text{Volume of atoms in unit cell}}{\text{Volume of unit cell}} = \frac{\frac{\text{atoms}}{\text{unit cell}} \frac{\text{volume}}{\text{atom}}}{\frac{\text{volume}}{\text{unit cell}}}$$

$\leftarrow (4/3)\pi r^3$   
 $\leftarrow a^3$

Need: **atoms/cell** and **r(a)**, relation between atom radius and cube edge length:

Unit cell contains 1/8<sup>th</sup> of 8 atoms (corners)



SC: close-packed directions are cube edges

$$APF = \frac{\frac{\text{atoms}}{\text{unit cell}} \frac{\text{volume}}{\text{atom}}}{\frac{\text{volume}}{\text{unit cell}}}$$

$1 \quad \frac{4}{3} \pi (a/2)^3$   
 $a^3$

$\leftarrow \frac{\text{volume}}{\text{unit cell}}$

## EXAMPLE

### Simple Cubic

It can be seen from the diagram that  $a = 2r$

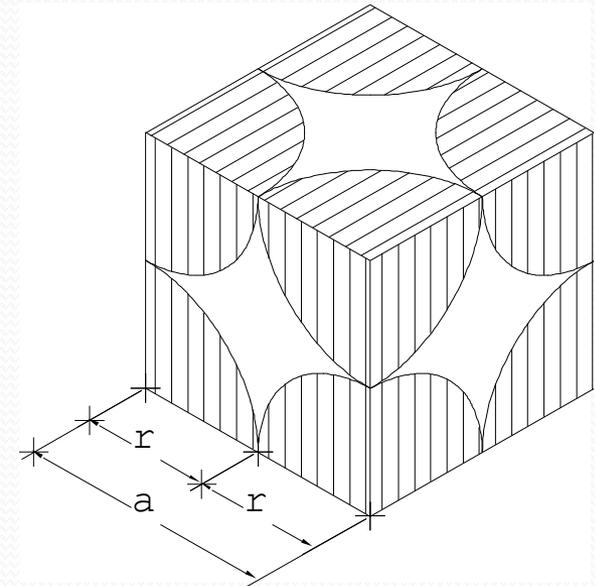
Total number of atoms in the cell =  $1/8 \times 8 = 1$

Total volume of atoms =  $(4/3)\pi r^3 \times 1 = 4.19 r^3$

Total volume of unit cell =  $a^3 = (2r)^3 = 8r^3$

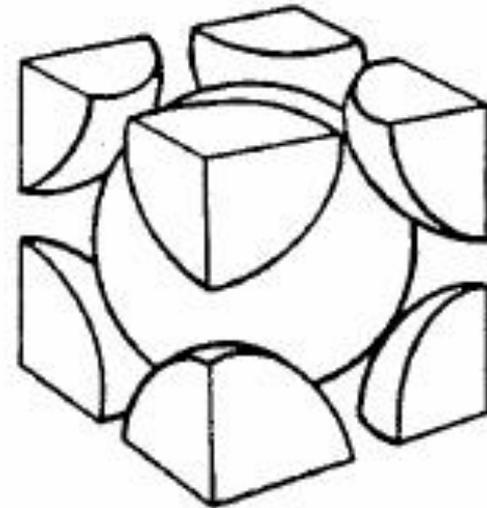
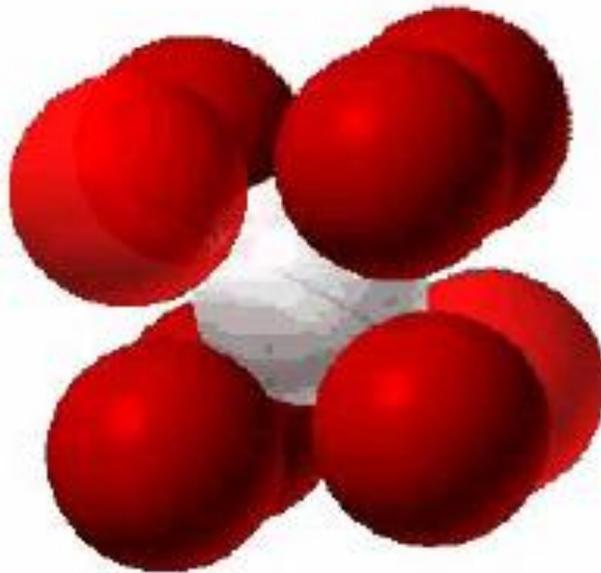
$$\text{Atomic packing factor} = \frac{\text{Volume of atoms}}{\text{Volume of unit cell}} = \frac{4.19r^3}{8r^3} = 0.52$$

hence only 52% of the space in this cell is occupied by the atoms.



# BODY CENTERED CUBIC STRUCTURE (BCC)

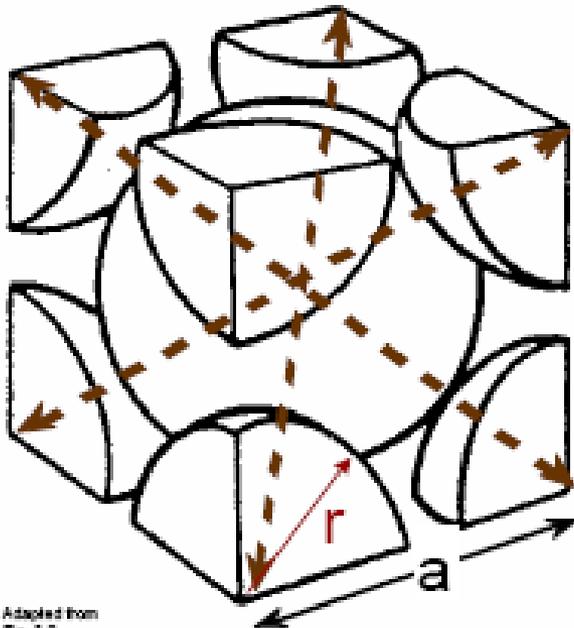
- Close packed directions are cube diagonals.  
--Note: All atoms are identical; the center atom is shaded differently only for ease of viewing.



Adapted from Fig. 3.2,  
Callister 9e.

# ATOMIC PACKING FACTOR for BCC

Close-packed direction are cube diagonals:



Unit cell contains:

1 (center) + 8 x 1/8 (corners)

Adapted from  
Fig. 3.2,  
Callister 6e.

$$\text{APF} = \frac{\text{atoms/unit cell} \times \text{volume/atom}}{\text{volume/unit cell}}$$

The diagram shows the calculation of the Atomic Packing Factor (APF) for a BCC unit cell. The numerator is the product of the number of atoms per unit cell (2) and the volume of one atom ( $\frac{4}{3}\pi(a\sqrt{3}/4)^3$ ). The denominator is the volume of the unit cell ( $a^3$ ). Arrows indicate the contribution of each term to the overall calculation.

## EXAMPLE

### BCC

It can be seen from the diagram that;

$$3a^2 = (4r)^2 \text{ or } a = 2.31 r$$

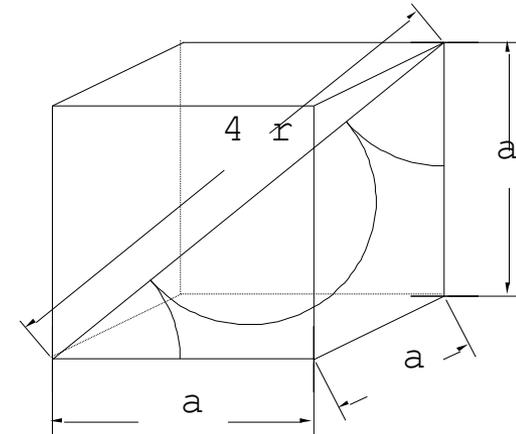
$$\text{Total number of atoms in the unit cell} = 1/8 \times 8 + 1 = 2$$

$$\text{Total volume of atoms} = (4/3)\pi r^3 \times 2 = 8.38 r^3$$

$$\text{Volume of unit cell} = a^3 = 12.32 r^3$$

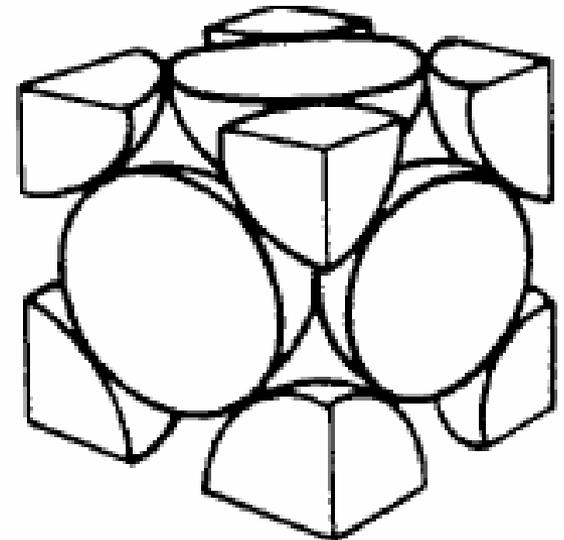
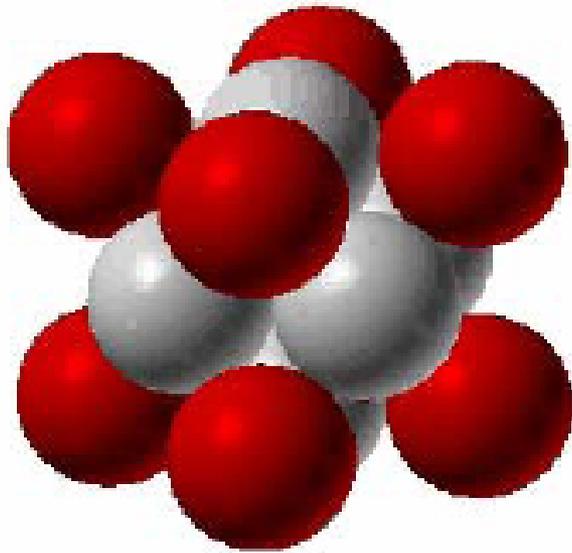
$$\text{Atomic packing factor} = \frac{\text{Volume of atoms}}{\text{Volume of unit cell}} = \frac{8.38r^3}{12.32r^3} = 0.68$$

hence 68% of the space in this unit cell is occupied by the atoms.



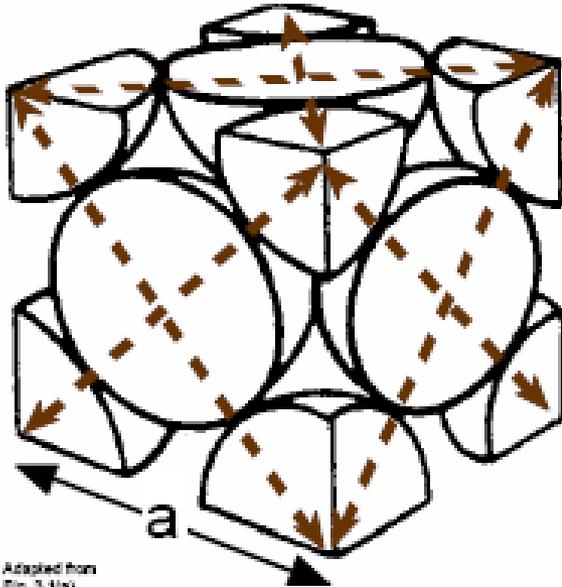
# FACE CENTERED CUBIC STRUCTURE (FCC)

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



# ATOMIC PACKING FACTOR for FCC

Close-packed directions are face diagonals:



Adapted from  
Fig. 3.10a,  
Callister 6e.

Unit cell contains  $\frac{1}{2}$  of 6 atoms on face and  $\frac{1}{8}$ th of 8 atoms on corners:

$$\text{APF} = \frac{\text{atoms unit cell} \times \text{volume atom}}{\text{volume unit cell}}$$

The diagram shows the calculation of the Atomic Packing Factor (APF) for an FCC unit cell. The numerator is the product of the number of atoms per unit cell (4) and the volume of one atom ( $\frac{4}{3} \pi (a\sqrt{2}/4)^3$ ). The denominator is the volume of the unit cell ( $a^3$ ). Arrows indicate the contribution of each term to the overall equation.

## EXAMPLE

## FCC

It can be seen from the diagram that  $2a^2 = (4r)^2$  or  $a = 2.83r$

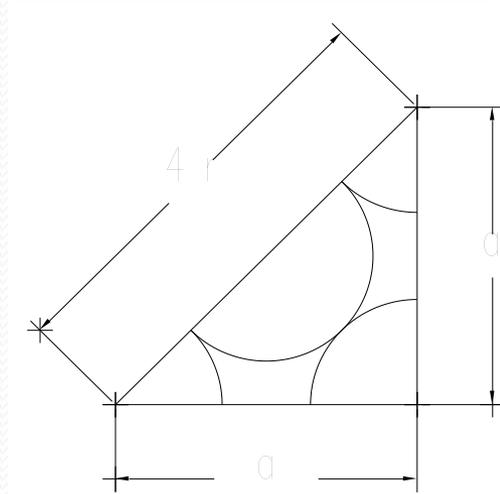
Total number of atoms in the unit cell =  $1/8 \times 8 + 1/2 \times 6 = 4$

Total volume of atoms =  $(4/3)\pi r^3 \times 4 = 16.76 r^3$

Volume of unit cell =  $a^3 = 22.72 r^3$

$$\text{Atomic packing factor} = \frac{\text{Volume of atoms}}{\text{Volume of unit cell}} = \frac{16.76r^3}{22.72r^3} = 0.74$$

hence 74 % of the space is occupied by the atoms in the unit cell.



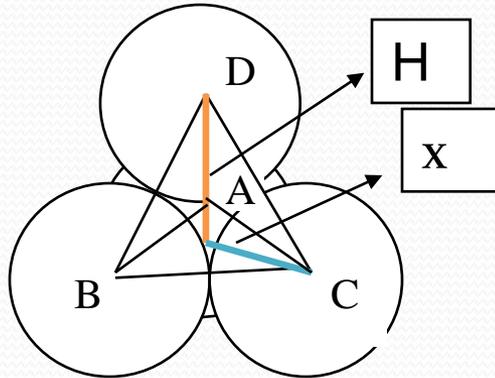
# EXAMPLE

## HCP

From the diagram,

Total number of atoms in the unit cell is =  $1/6 \times 12$  (corner atoms)  
 +  $1/2 \times 2$  (basal atoms) +  $3 \times 1$  (internal atoms) = 6

Total volume of atoms =  $(4/3)\pi r^3 \times 6 = 25.14 r^3$



$$h/3 = (a\sqrt{3}/2)/3,$$

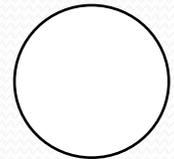
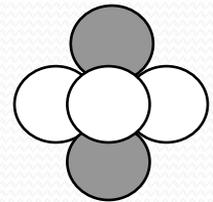
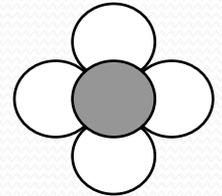
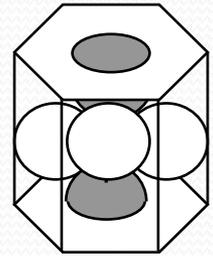
$$x = \sqrt{(2r\sqrt{3}/6)^2 + (r)^2}$$

$$= 4r^2 \cdot 3/36 + r^2 = r^2 (1/3 + 1)$$

$$= 4r^2/3 \qquad = 2r/\sqrt{3}$$

$$H = \sqrt{(2r)^2 - (x)^2} = \sqrt{4r^2 - 4r^2/3}$$

$$= \sqrt{(8/3)r^2} = \sqrt{8/3} r = (8/3)^{1/2} r$$



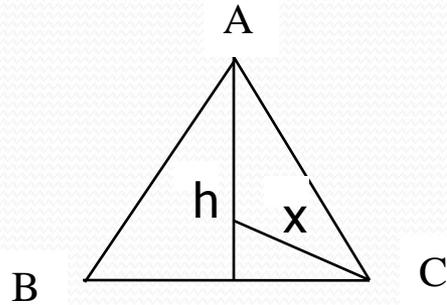
The height,  $c$ , of a HCP unit cell containing atoms of equal size is twice of the height of the pyramid ABCD. It can easily be calculated that height of pyramid is

$$= (8/3)^{1/2} r, \text{ thus, height of unit cell is}$$

$$c = 2 (8/3)^{1/2} r = (8/3)^{1/2} a = 1.633 a$$

# EXAMPLE

## HCP



$$h = a \frac{\sqrt{3}}{2}, \quad \frac{\sqrt{3}}{2} = \sin 60 = 0.866$$

$$\text{area of equilateral triangle} = \frac{a^2 \sqrt{3}}{4}$$

$$\text{area of equilateral triangle} = \frac{h^2 \sqrt{3}}{3}$$

The area of basal hexagon would be 6 times of the area of triangle ABC;  
 $= 6 \times \left(\frac{1}{2} \times a \times a \sin 60\right) = 2.6 a^2$

Volume of unit cell is

$$v = c \times \text{area of basal hexagon} = 1.633 a \times 2.6 a^2 = 4.24 a^3$$

$$\text{but } a = 2r, \text{ hence; } v = 33.94r^3$$

$$\text{Atomic packing factor} = \frac{25.14r^3}{33.94r^3} = 0.74$$

hence 74% of the space is occupied by atoms in this unit cell.

# EXAMPLE

## HCP

From the diagram,

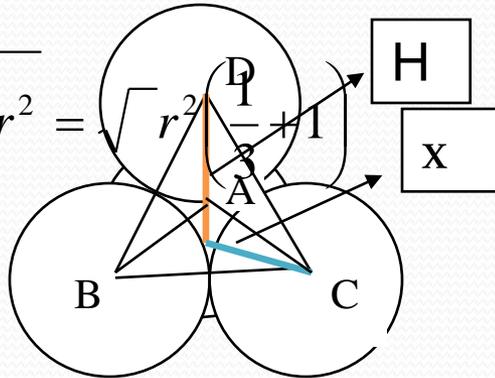
Total number of atoms in the unit cell is =  $1/6 \times 12$  (corner atoms)

+  $1/2 \times 2$  (basal atoms) +  $3 \times 1$  (internal atoms) = 6

Total volume of atoms =  $(4/3)\pi r^3 \times 6 = 25.14 r^3$

$$\sqrt{\left(2r \frac{\sqrt{3}}{6}\right)^2 + (r)^2}$$

$$\sqrt{\left(4r^2 \frac{3}{36}\right) + r^2} =$$



$$h/3 = (a\sqrt{3}/2)/3,$$

$$x = \sqrt{(2r\sqrt{3}/6)^2 + (r)^2}$$

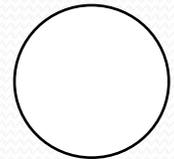
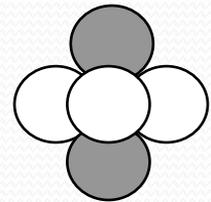
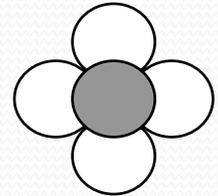
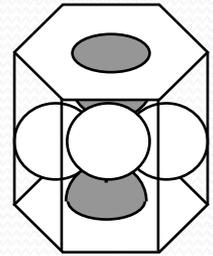
$$\frac{h}{3} = \frac{\left(a \frac{\sqrt{3}}{2}\right)}{3}$$

$$= 4r^2 \frac{3}{36} + r^2 = r^2 (1/3 + 1)$$

$$= 4r^2/3 \qquad = 2r/\sqrt{3}$$

$$H = \sqrt{(2r)^2 - (x)^2} = \sqrt{4r^2 - 4r^2/3}$$

$$= \sqrt{(8/3)r^2} = \sqrt{(8/3)} r = (8/3)^{1/2} r$$



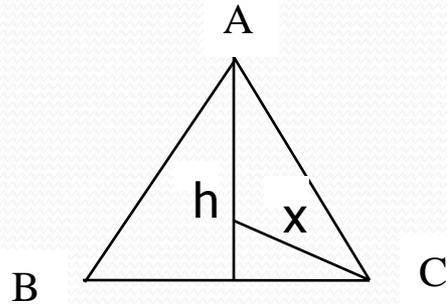
The height, c, of a HCP unit cell containing atoms of equal size is twice of the height of the pyramid ABCD. It can easily be calculated that height of pyramid is

=  $(8/3)^{1/2} r$ , thus, height of unit cell is

$c = 2 (8/3)^{1/2} r = (8/3)^{1/2} a = 1.633 a$

## EXAMPLE

### HCP



$$h = a \frac{\sqrt{3}}{2}, \quad \frac{\sqrt{3}}{2} = \sin 60 = 0.866$$

$$\text{area of equilateral triangle} = \frac{a^2 \sqrt{3}}{4}$$

$$\text{area of equilateral triangle} = \frac{h^2 \sqrt{3}}{3}$$

The area of basal hexagon would be 6 times of the area of triangle ABC;  
 $= 6 \times \left(\frac{1}{2} \times a \times a \sin 60\right) = 2.6 a^2$

Volume of unit cell is

$$v = c \times \text{area of basal hexagon} = 1.633 a \times 2.6 a^2 = 4.24 a^3$$

$$\text{but } a = 2r, \text{ hence; } v = 33.94r^3$$

$$\text{Atomic packing factor} = \frac{25.14r^3}{33.94r^3} = 0.74$$

hence 74% of the space is occupied by atoms in this unit cell.

## CHAPTER 3 METALS AND ALLOYS PART II

### 3.3.2. CRYSTAL PLANES and DIRECTIONS

Structure of a unit cell plays a very important role in determining the characteristics of a metal, because mechanical properties of a metal are related to the way atoms are packed (or arranged) in a lattice. This point will be discussed in details in chapter 10, but suffice it to say now that atomic arrangements in unit cells give rise to certain planes and directions in the lattices which are more closely packed than others and therefore are easy to slip or deform. It, therefore, follows that in order to understand the mechanical characteristics of a particular structure and hence metal, it is essential to be able to identify such planes and directions. They are best described by a set of numbers known as **Miller indices**.

To explain these indices let us consider a plane shown in Fig.3.11. It is assigned three axes X, Y and Z with unit dimensions in these directions a, b and c. To determine the Miller indices, first the intercepts of the plane on all three axes are determined which, in present case is  $X=3$ ,  $Y=1$  and  $Z=2$ . Next, the reciprocals of these values are taken ( $1/3$ ,  $1/1$ ,  $1/2$ ) and it is converted to whole numbers (2,6,3) if in fractions. Thus, Miller indices of the **plane** ABC is (263). Parenthesis are used to describe one plane and large brackets are used to describe a family of planes. For example, the indices for the cross hatched plane in Fig.3.12(vi) would be ( $1/1, 1/1, 1/1$ ) and hence (111).

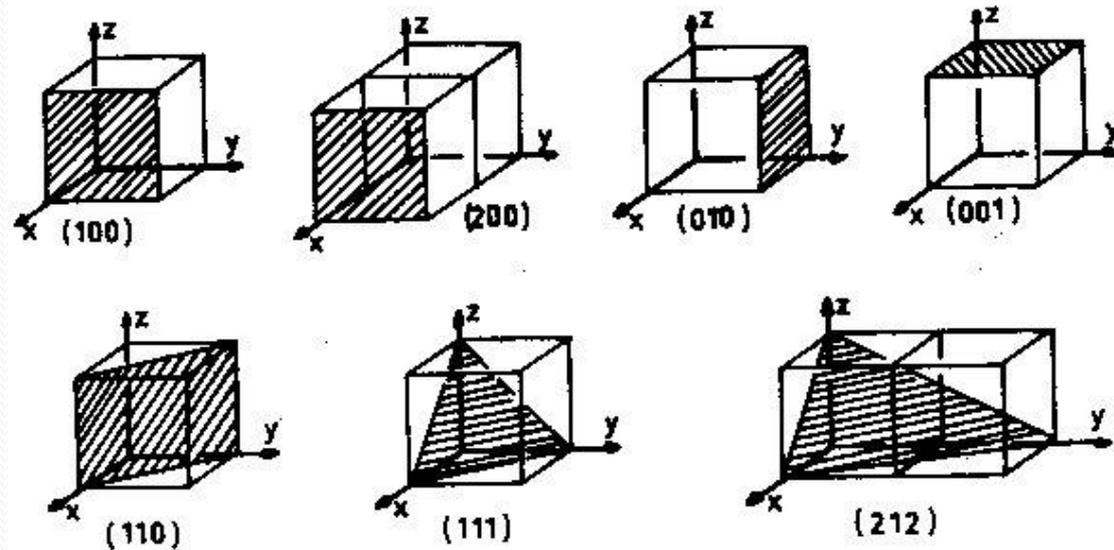
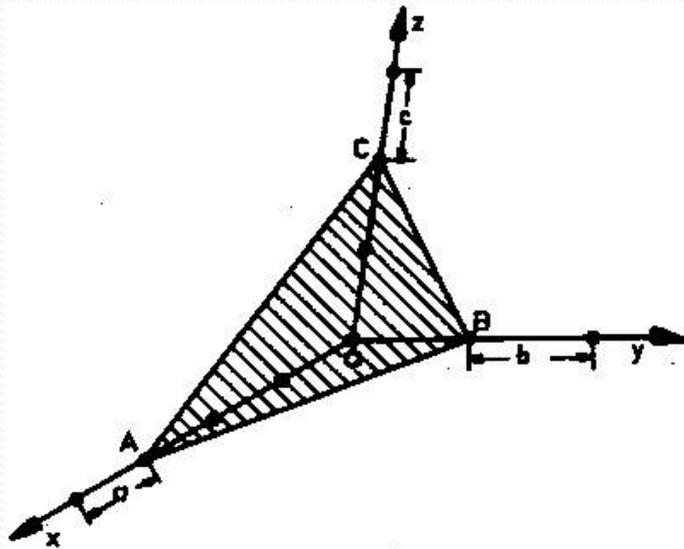


Fig.3.11 Derivation of Miller indices for a plane

Fig.3.12 Miller indices for planes in a cubic cell

On the other hand, **Directions** are given according to the distance travelled along the three axes to reach from the start of the direction to its end. For example, the direction OA in Fig.3.13(a) would be  $[111]$  because to reach from the start of the direction at O to its end at A, unit distances have to be travelled along the three axes. The reader can appreciate that the direction OB would be  $[101]$ . Again, a family of directions is represented by an angular bracket such as  $\langle 101 \rangle$ . A relationship exists between planes and directions in the cubic system such that, e.g., the direction  $[111]$  is normal to the plane  $(111)$ . Negative numbers are denoted by a bar such as  $(\bar{1}01)$ . For hexagonal close packed cells a four axes arrangement is used such as shown in Fig.3.13(b). and consequently the planes and directions have four numbers such as  $(0001)$ .

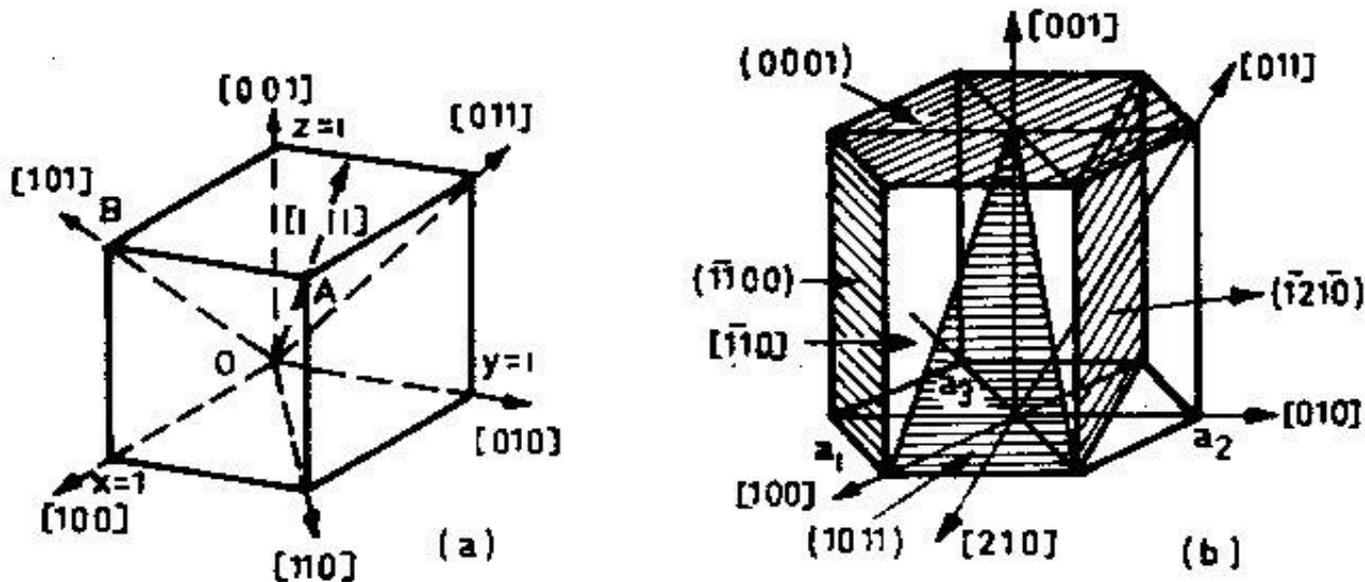
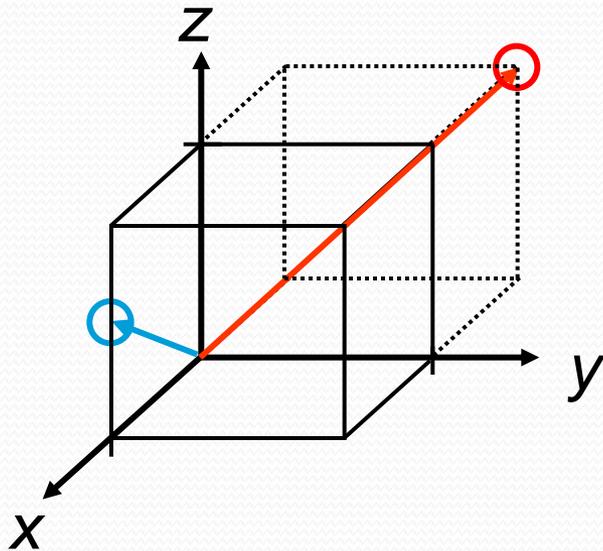


Fig.3.13 (a) Crystal directions in a cubic cell,  
(b) directions and some planes in a hexagonal unit cell.

# Crystallographic Points, Directions, and Planes

- Crystallographic direction is a vector  $[uvw]$ 
  - Always passes thru origin  $000$
  - Measured in terms of unit cell dimensions  $a$ ,  $b$ , and  $c$
  - Smallest integer values
- Planes with Miller Indices  $(hkl)$ 
  - If plane passes thru origin, translate
  - Length of each planar intercept in terms of the lattice parameters  $a$ ,  $b$ , and  $c$ .
  - Reciprocals are taken
  - If needed multiply by a common factor for integer representation

# Crystallographic Directions



## Algorithm

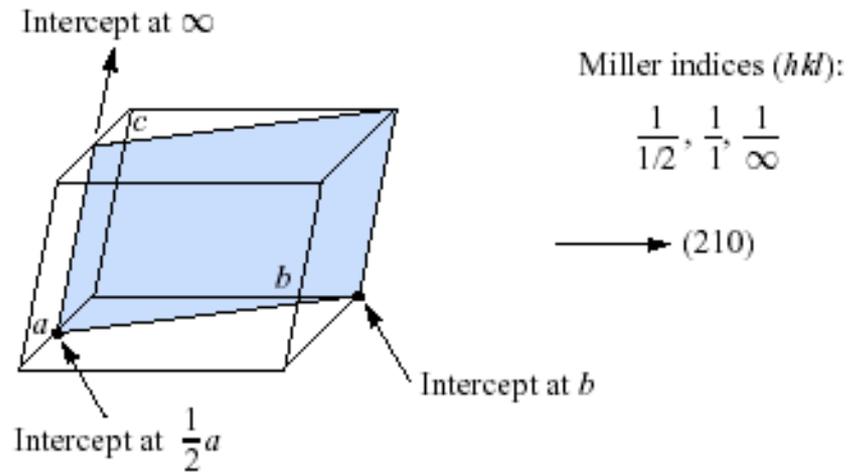
1. Vector repositioned (if necessary) to pass through origin.
2. Read off projections in terms of unit cell dimensions  $a$ ,  $b$ , and  $c$
3. Adjust to smallest integer values
4. Enclose in square brackets, no commas

$[uvw]$

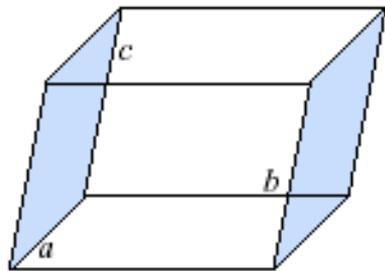
ex:  $1, 0, \frac{1}{2} \Rightarrow 2, 0, 1 \Rightarrow [201]$

$-1, 1, 1 \Rightarrow [\bar{1}11]$  where overbar represents a negative index

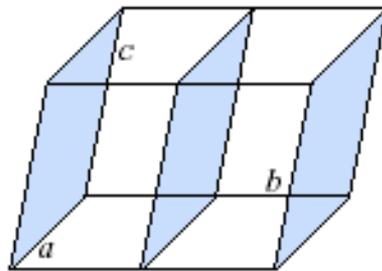
families of directions  $\langle uvw \rangle$



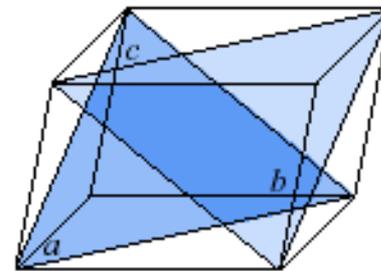
(a)



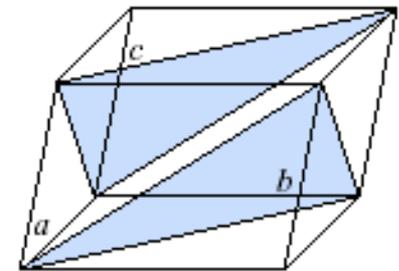
(010)



(020)

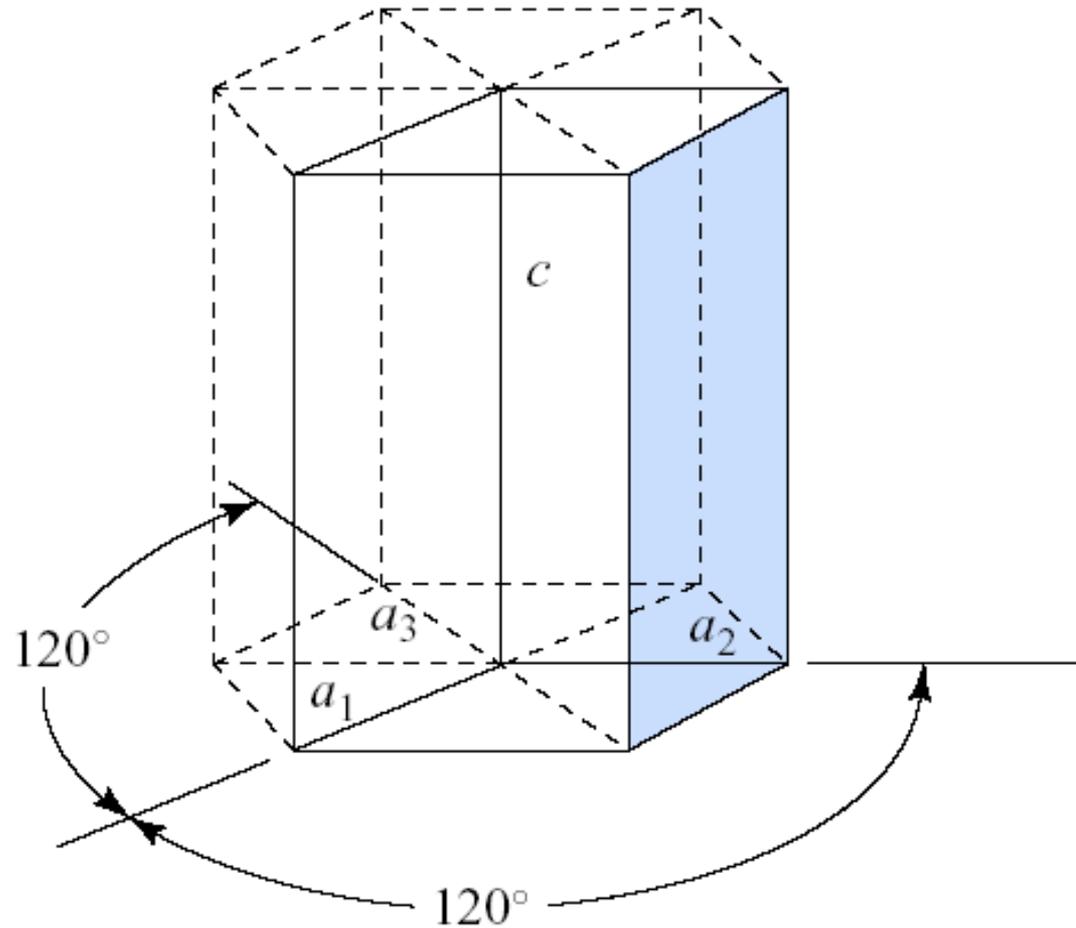


(111)



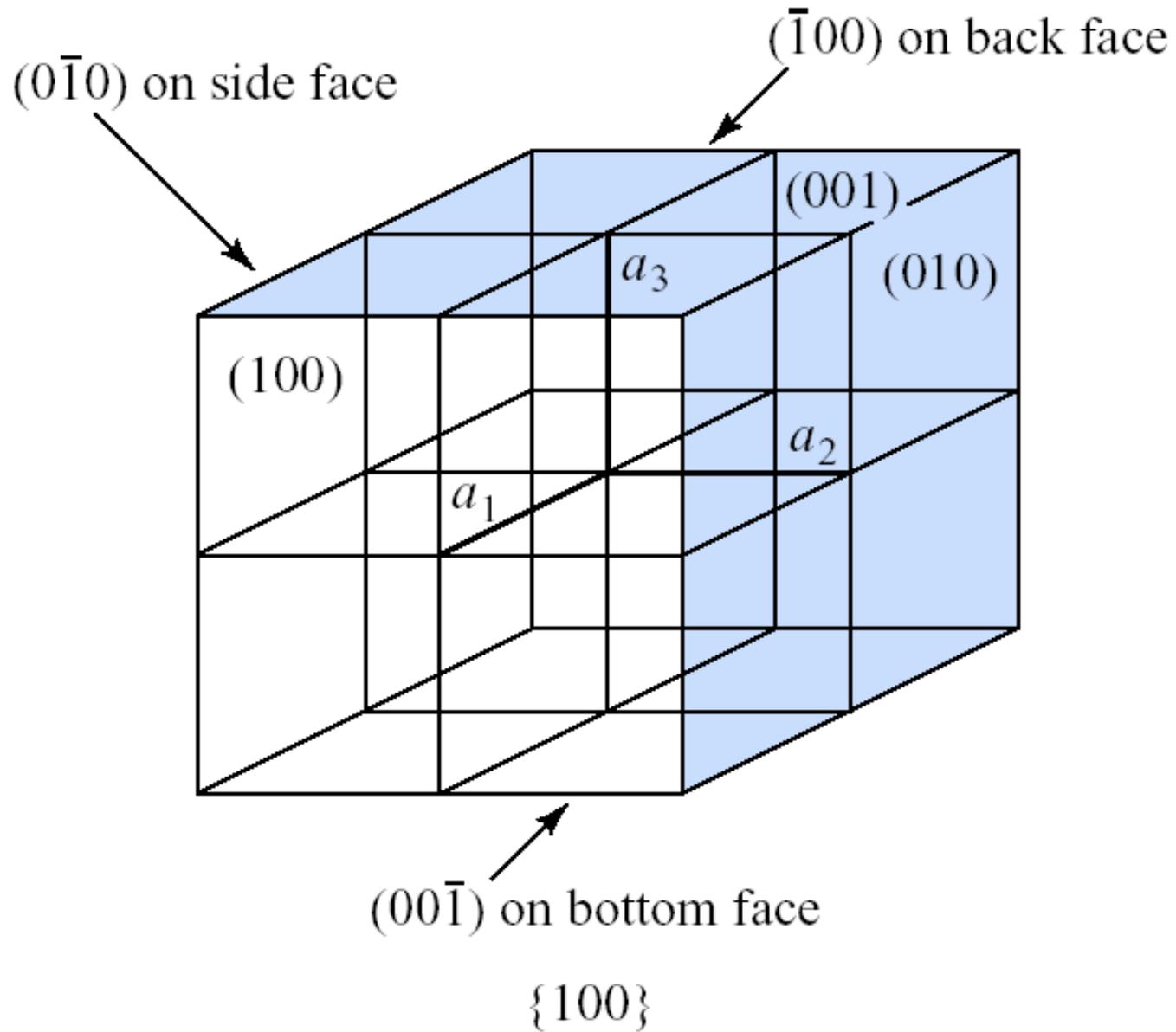
(11 $\bar{1}$ )

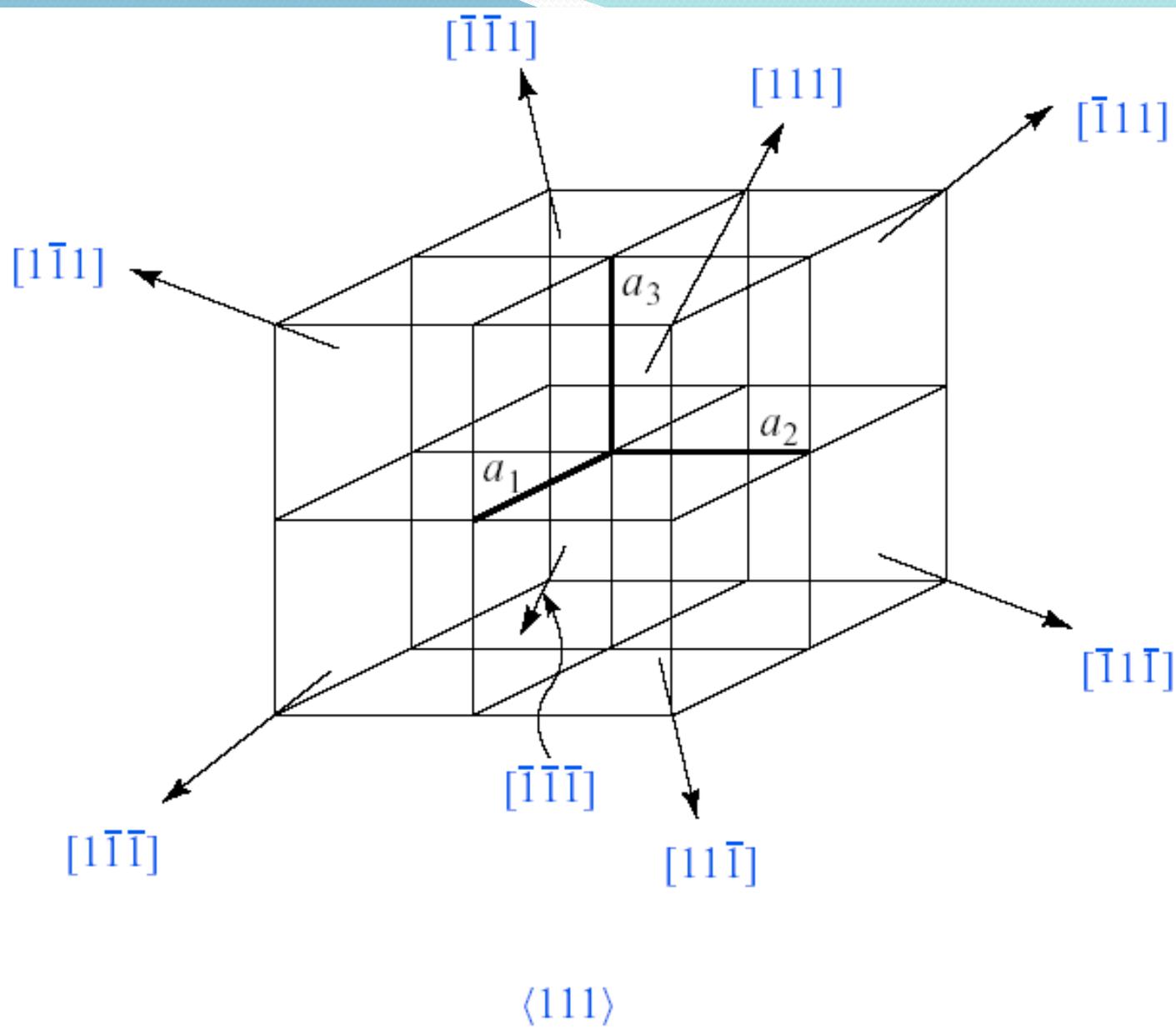
(b)



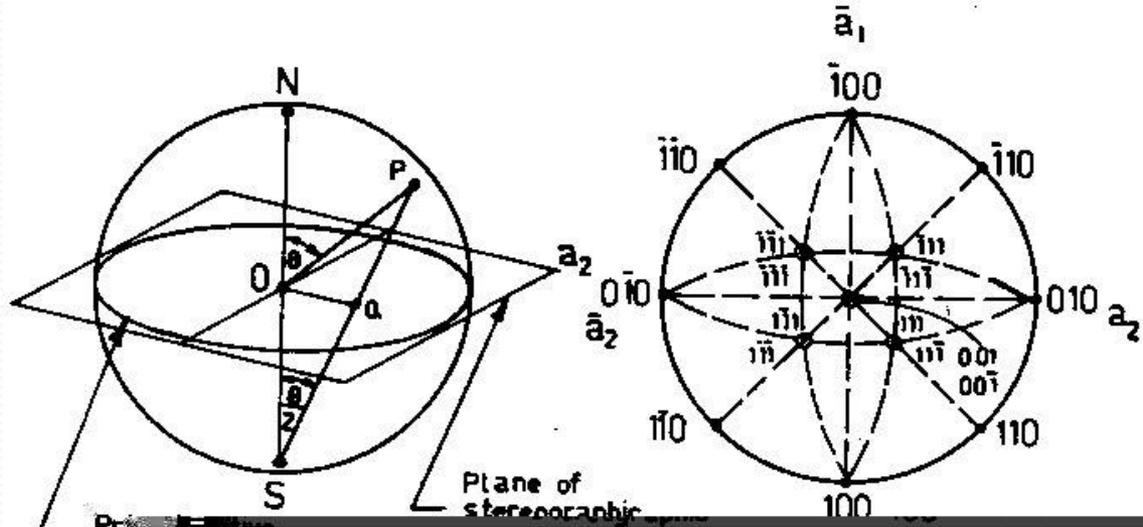
Miller-Bravais indices ( $hkil$ ):  $\frac{1}{\infty}, \frac{1}{1}, \frac{1}{-1}, \frac{1}{\infty} \rightarrow (01\bar{1}0)$

Note:  $h + k = -i$





**Stereographic projections** are used to describe all the possible planes for a particular structure by using an imaginary sphere whose center is occupied by the structure in question. Normals from each plane intersect the imaginary sphere at some point (P in Fig.3.14), and the projection of that point on the equatorial plane describes that plane in, the stereograph, as shown in Fig 3.14.



*Fig.3.14 Stereographic projections.*

It can be seen from the foregoing that a metal is a combination of atoms which are arranged in a very specific manner which gives the metal its character. Any change in the structure would give rise to a change in the characteristics of that metal. Having acquired this basic knowledge, it would become easier for an engineer to understand **how and why different metals and alloys, with differing structures, behave differently.**

### 3.4. ALLOYS

The way in which an alloying element may change the structure of the parent metal (and hence the structure of the alloy as a whole) and the degree of solubility of the two elements depends upon the **atomic structure of the two, their relative sizes and valencies**. Depending upon the nature of alloying element and the parent metal as well as the temperature, **the alloy** may exhibit a solid solution, in which case the two elements are completely dissolved in each other just like sugar and water are dissolved in each other in liquid state (liquid solution). Alternatively, the two elements may not be dissolved and may exist as two separate phases.

Steel is the most common example of an alloy of iron and carbon which exhibits complete solubility in **ferrite** solid solution (below 723 °C) and **austenite** region (between 1401 °C and 723 °C) and a two phase region of ferrite and cementite which is called **pearlite**.

A solid solution resembles a liquid solution in so much as it preserves the inter-atomic state of the liquid form and the atoms of the two elements are intermingled with each other. However, being in a solid crystalline state, this mixing is based on a definite arrangement which is usually a distorted structure of one of the two constituent elements.

A **complete solution** is obtained if the two elements have the same lattice structures, nearly equal atomic diameters and equal number of valence electrons. If the difference in atomic diameters **exceeds 14-15%** then the range of solubility is restricted because of distortion caused by the misfit due to diameter difference. Lead and antimony have a large difference in their diameters, as lead has an atomic number of 82 compared to 51 for antimony; consequently they do not dissolve in each other at all. A large difference between the electronegativity of the two elements also reduces solubility as the two tend to form intermetallic compounds rather than solid solution.

**Aluminum** has an electrode potential of -1.67 and copper of +0.34 and due to this large difference in electronegativity the two elements tend to form an intermetallic compound  $\text{CuAl}_2$ . Furthermore an element of lower valency dissolves a metal of higher valency more readily than vice versa- known as **relative valency effect**. Silicon (valence 4) dissolves little copper (valence 2) whereas copper dissolves an appreciable amount of silicon.

The intermingling of solute and solvent atoms in a solid solution structure can be one of many types. **Substitutional solid solutions** are those in which the solute atom (alloying element atom) occupies one of the lattice positions of the solvent (parent) metal matrix as shown in Fig.3.15.

In most alloy systems this substitution is disordered whereby substitutional atoms occupy lattice positions indiscriminately in the proportion required by the chemical composition of the alloy. However, in some cases, such as gold-copper alloy system at low temperatures, the substitution is not random but orderly, such that the solute atoms form a pattern superimposed on the structure of the solvent matrix. The superimposed pattern is called a **superlattice**. In some alloy systems such ordering increases the strength of the metal.

If the solute atoms are very small compared to the solvent atoms then they have a tendency to sit in the spaces between the solvent atoms, called interstices (Fig.3.15). Such a solid solution is called **interstitial solid solution** and small atoms of boron, nitrogen, hydrogen and carbon have a tendency to form interstitial solid solutions. In general, the size of solute atom is half that of solvent atom. In some alloys both substitutional and interstitial solid solutions occur simultaneously.

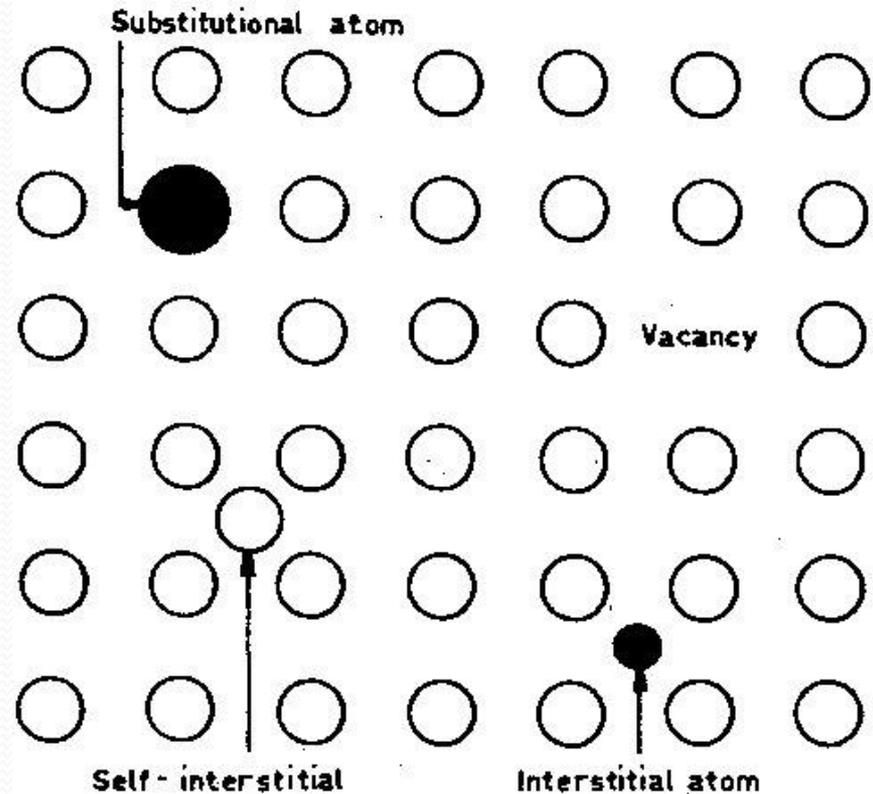


Fig.3.15 Schematic diagram of point defects

# METALS AND ALLOYS

## 3.01 INTRODUCTION

Properties and other technical issues related to metals are considered in this chapter. The technological and commercial importance of metals is due to the following general properties possessed by virtually all the common metals.

*High stiffness and strength.* Metals can be alloyed for high rigidity, strength, and hardness; thus they are used to provide the structural framework for most engineered products.

*Toughness.* Metals have the capacity to absorb energy better than other classes of materials.

*Good electrical conductivity.* Metals are conductors because of their metallic bonding, which permits the free movement of electrons as charge carriers.

*Good thermal conductivity.* Metallic bonding also explains why metals generally conduct heat better than ceramics or polymers.

In addition, certain metals have specific properties that make them attractive for specialised applications. Many common metals are available at relatively low cost per unit weight and are often the material of choice simply because of this.

Metals are converted into parts and products using a variety of manufacturing processes. The starting form of the metal differs depending on the process. The major categories are (1) *cast metal*, in which the initial form is a casting; (2) *wrought metal*, in which the metal has been worked or can be worked (for example, rolled or otherwise formed) after casting; better mechanical properties are generally associated with wrought metals compared to cast metals; and (3) *powdered metal*, in which the metal is purchased in the form of very small powders for conversion into parts using powder metallurgy techniques. Most metals are available in all three forms. In this chapter, our discussion will focus on categories 1 and 2, which are of greatest commercial and engineering interest. Powder metallurgy techniques are examined in Chapter 6.

Metals are classified into two major groups: (1) *ferrous*, those based on iron, and (2) *nonferrous*, all other metals. The ferrous group can be further subdivided into steels and cast irons. Most of our discussion in the present chapter will be organised around this classification, but let us first examine the general topic of alloys and phase diagrams.

## 3.02 ALLOYS

Although some metals are important as pure elements (for example, gold, silver, and copper), most engineering applications require the enhanced properties obtained by alloying. Through alloying, it is possible to enhance strength, hardness, and other properties compared to pure metals. In this section, we define and classify alloys; we then discuss phase diagrams, which indicate the phases of an alloy system as a function of composition and temperature.

### 3.02.1 Alloys

An *alloy* is a metal comprised of two or more elements, at least one of which is metallic.

The two main categories of alloys are

- (1) solid solutions** and
- (2) intermediate phases.**

**Solid Solutions:** A *solid solution* is an alloy in which one element is dissolved in another to form a **single-phase structure**. The term *phase* describes any homogeneous mass of material, such as a metal in which the grains all have the same crystal lattice structure. In a solid solution, the solvent or base element is metallic, and the dissolved element can be either metallic or nonmetallic. Solid solutions come in two forms, as shown in Figure 3. 01.(3.15).

The first is a *substitutional solid solution*, in which atoms of the solvent element are replaced in its unit cell by the dissolved element. Brass is an example, in which zinc is dissolved in copper. To make the substitution, several rules must be satisfied:

- (1) the atomic radii of the two elements must be similar, usually within 15%;
- (2) their lattice types must be the same;
- (3) if the elements have different valencies, the lower valency metal is more likely to be the solvent; and
- (4) if the elements have high chemical affinity for each other, they are less likely to form a solid solution and more likely to form a compound.

- The second type of solid solution is an *interstitial solid solution*, in which atoms of the dissolving element fit into the vacant spaces between base metal atoms in the lattice structure. It follows that the atoms fitting into these interstices must be small compared to those of the solvent metal, for example, hydrogen, carbon, nitrogen, and boron. The most important example of this second type is carbon dissolved in iron to form steel.
- In both forms of solid solution, the alloy structure is generally stronger and harder than either of the component elements.

- **Intermediate Phases** There are usually limits to the solubility of one element in another. When the amount of the dissolving element in the alloy exceeds the solid solubility limit of the base metal, a second phase forms in the alloy. The term *intermediate phase* is used to describe it because its chemical composition is intermediate between the two pure elements. Its crystalline structure is also different from those of the pure metals. Depending on composition, and recognising that many alloys consist of more than two elements, these intermediate phases can be of several types, including:
  - (1) metallic compounds consisting of a metal and nonmetal, such as  $\text{Fe}_3\text{C}$ , and
  - (2) intermetallic compounds, consisting of two metals that form a compound, such as  $\text{Mg}_2\text{Pb}$ .
- The composition of the alloy is often such that the intermediate phase is mixed with the primary solid solution to form a two-phase structure, one phase dispersed throughout the second. These two-phase alloys are important because they can be formulated and heat treated for significantly higher strength than solid solutions.

## Why study imperfections?

- Crystalline defects drive most material behaviors, both good and bad.
- Diffusion/alloying
- Deformation/strengthening
- Corrosion
- Semiconductors
- Optical properties
- Control defects  control properties!

Metals and alloys do not possess perfect crystal structures. Imperfections are inherently present in their matrices. These matrix defects play a very important role in deformation of metals and alloys and consequently their presence alters the mechanical properties of engineering materials and alloys.

# TYPES OF DEFECTS (IMPERFECTIONS)

**Defect** is a general term covering all types of **lattice imperfections**. Defects can be classified as:

- (1) Point defects; vacancies, interstitials and substitutionals,
- (2) Line defects or dislocations, and
- (3) Surface defects or plane defects

### 3.5.1. POINT DEFECTS

Point defects are atomic defects schematically depicted in Fig.3.15.

**Vacancies** are empty atomic positions from which atoms have been removed by the application of some form of energy. Interstitial and substitutional atoms have already been described. Sometimes due to high temperature vibrations, an atom of parent matrix is displaced from its site creating a vacancy, and the atom may occupy an interstitial site. Such a defect is called **self-interstitial**.

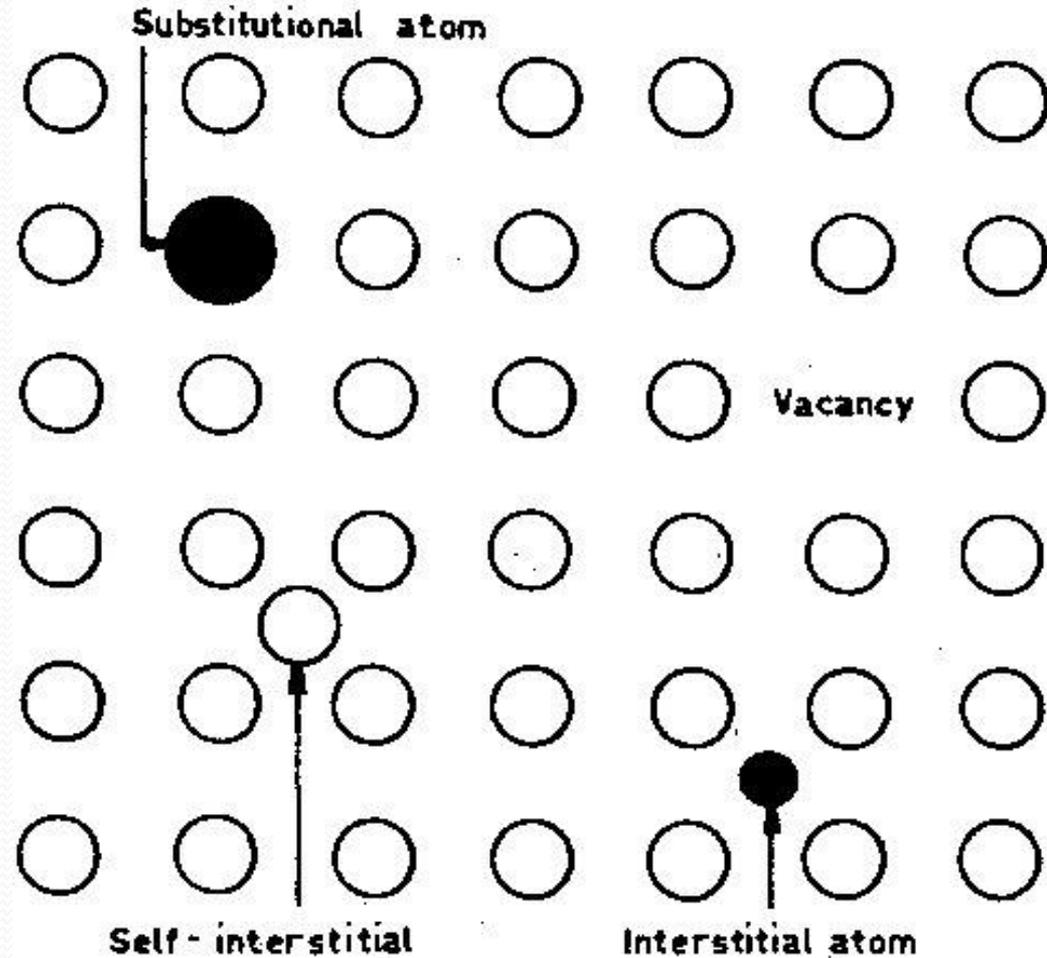
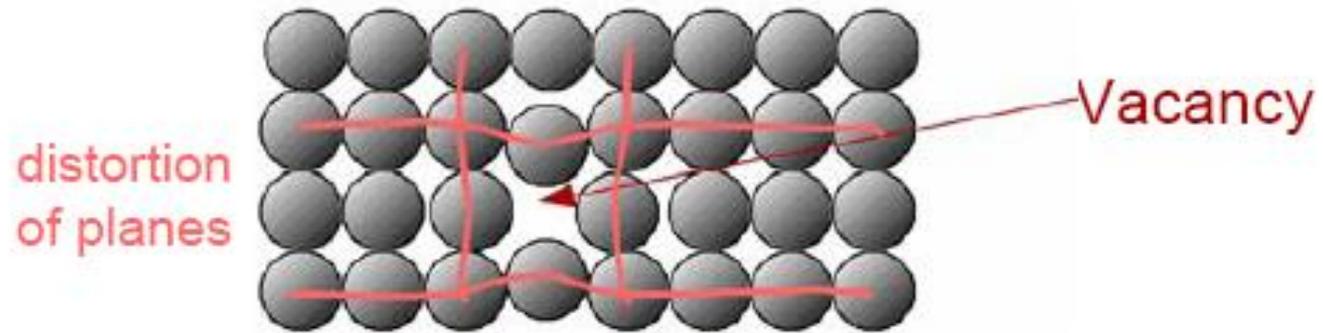


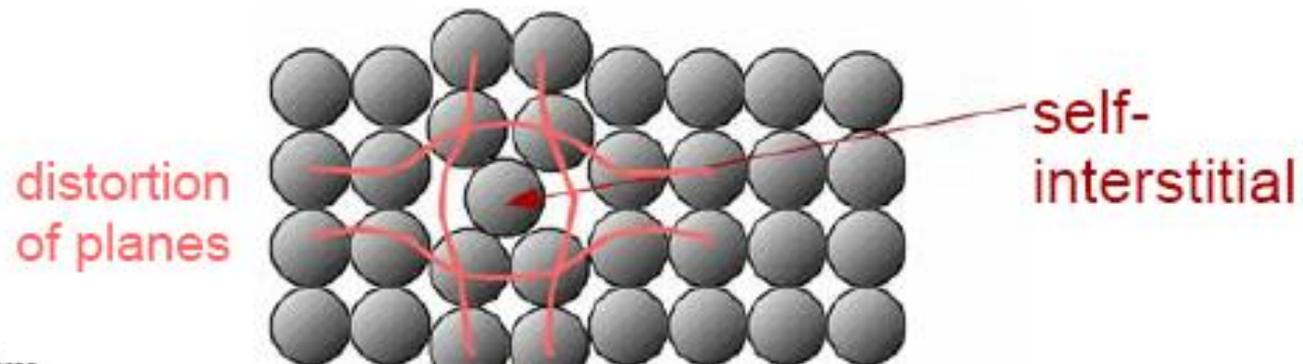
Fig.3.15 Schematic diagram of point defects

# POINT DEFECTS

- Vacancies:



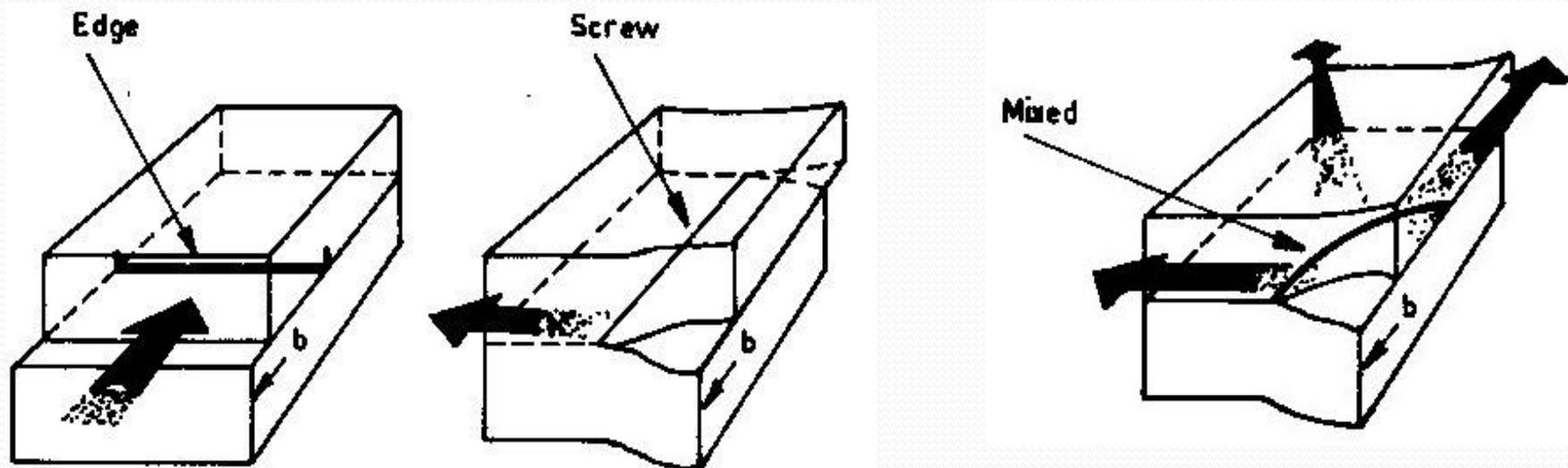
- Self-Interstitials:



Line defects are long in one direction, while only a few atomic diameters wide. **Dislocation** is a line defect which is an extra half plane of atoms inserted between atomic planes in a crystal. Fig.3.16 shows two types of line defects:

**Edge dislocation** has an extra half plane running perpendicularly into the page.

**Screw dislocation** has also an extra half plane of atoms but it differs from edge dislocation in the way it moves under a shear stress. Dislocations play a vital role in the deformation of metal and they will be discussed in greater details in chap 10.



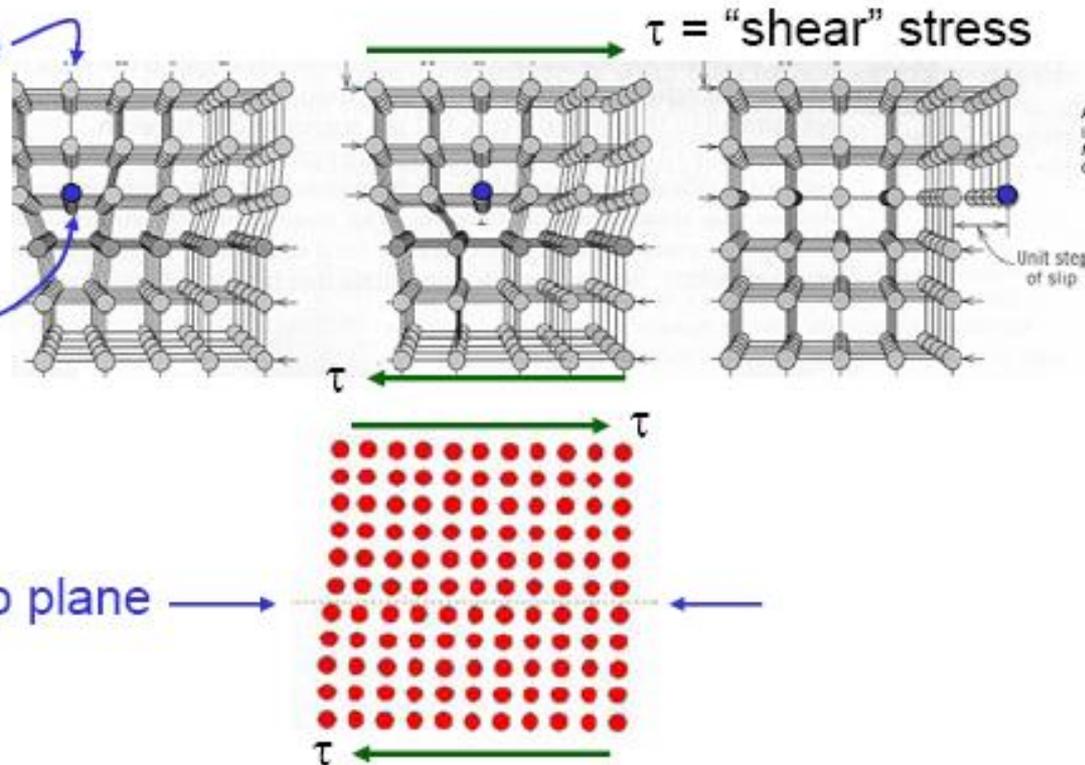
*Fig.3.16 Edge and screw dislocations*

# LINE DEFECTS: DISLOCATIONS

“Edge” dislocation: line of imperfect bonds at the bottom of an extra half plane:

“extra” half plane

Dislocation line

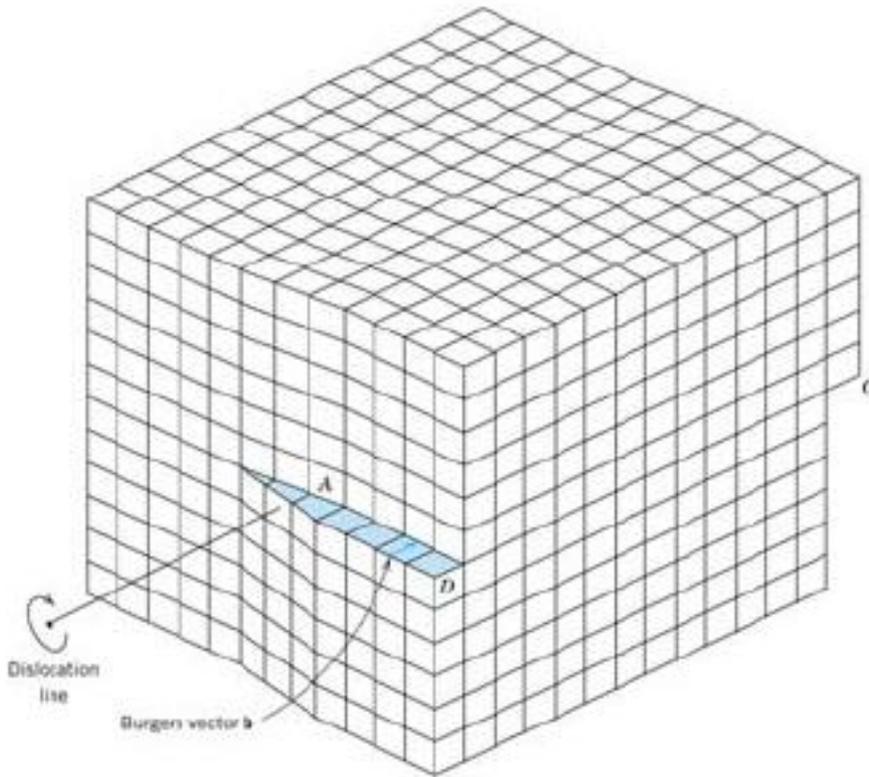


Adapted from Fig. 7.1, Callister 6e. (Fig. 7.1 is adapted from A.G. Guy, *Essentials of Materials Science*, McGraw-Hill Book Company, New York, 1976. p. 153.)

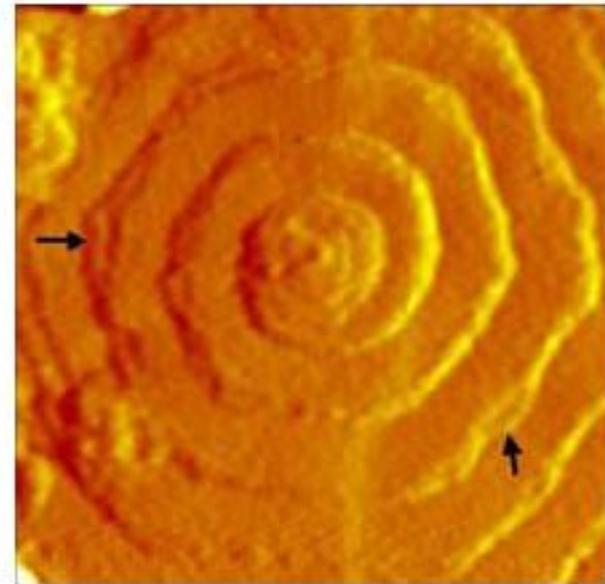
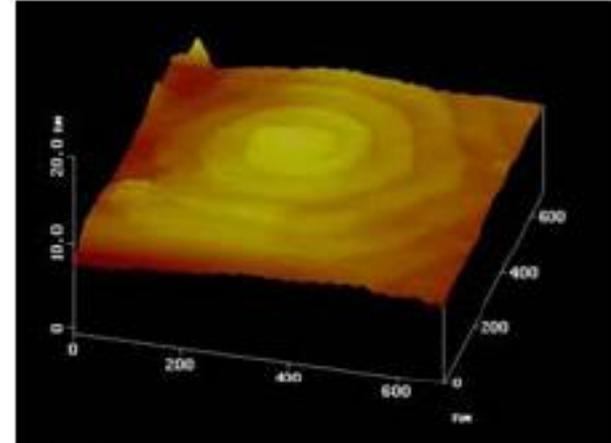
- Material **permanently deforms** as dislocation moves through the crystal.
- **Bonds break and reform**, but only along the dislocation line at any point in time, not along the whole plane at once.
- Dislocation line **separates slipped and unslipped** material.

# LINE DEFECTS: DISLOCATIONS

“Screw” dislocation: line of imperfect bonds along axis of a corkscrew in crystal



Adapted from Fig. 4.4, Callister 8e.



**Internal planar defects** are those defects which occur inside the crystal structure of metals and are large defects of few atomic diameter thickness. They are classified as **grain boundaries**, **twin interfaces** or **stacking faults**.

**Grain boundaries** are areas of mismatch produced due to a difference in orientation of neighboring space lattices. They are associated with high energy.

**Twin interfaces** are planes across which atoms are arranged so as to form a mirror image of each other. They are produced as a result of either deformation known as deformation twins found in many HCP metals, or produced during growth of a crystal- known as annealing twins found in many FCC metals. During stacking of planes of atoms ABCABC, a plane B may be stacked inadvertently on top of C layer and it is followed by a reverse stacking sequence to give an arrangement ABCAB [C] BACBA in which case the atomic arrangement on either side of [C] is a mirror image of each other.

**Stacking faults** are similar to twin interfaces, except that after a fault the sequence is not reversed but continues in the same way to produce a configuration such as ABCAB[C]BCABC.

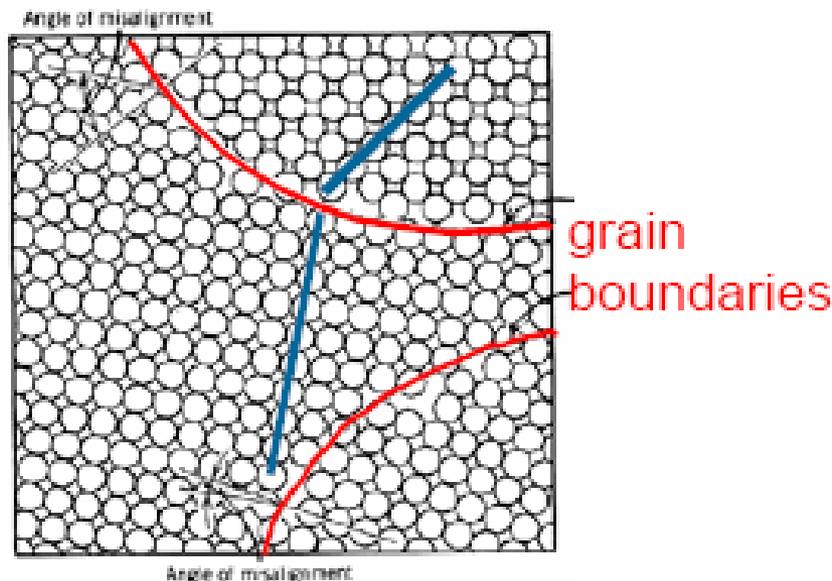
This chapter has described the constitution, structure and structural defects in metals and alloys. Properties and behavior of metals and alloys are governed by their structures and inherent defects and this chapter provides a sound platform which will help understanding of later chapters.

# AREA DEFECTS: GRAIN BOUNDARIES

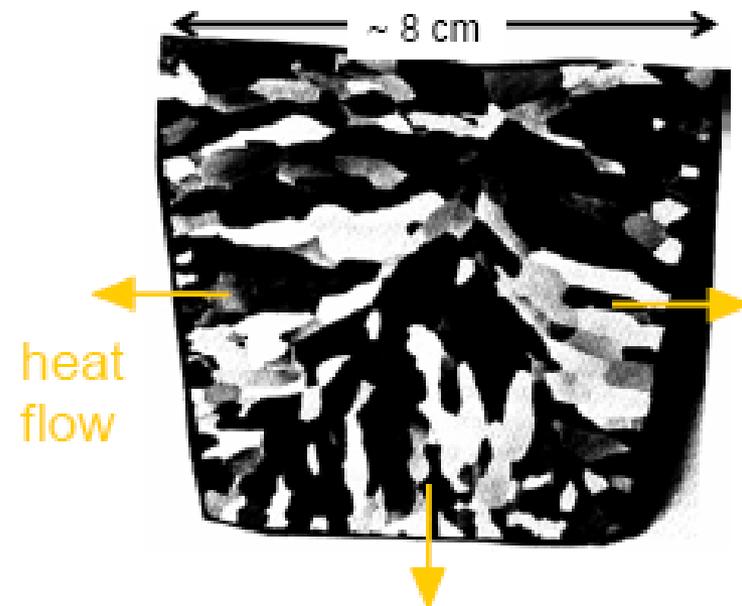
## Grain boundaries:

- are boundaries between crystals with different orientation (planes go in different directions).
- are produced by the solidification process, for example.
- have a change in crystal orientation across them.
- impede dislocation motion.

### Schematic



### Metal Ingot



# THEORETICAL DENSITY, $\rho$

$$\rho = \frac{nA}{V_c N_A}$$

# atoms/unit cell  $\rightarrow$   $n$   
 Atomic weight (g/mol)  $\rightarrow$   $A$   
 Volume/unit cell (cm<sup>3</sup>/unit cell)  $\rightarrow$   $V_c$   
 Avogadro's number (6.023 x 10<sup>23</sup> atoms/mol)  $\rightarrow$   $N_A$   
 gr/atom

## Example: COPPER

- FCC Crystal Structure:  $n = 4$  atoms/unit cell
- atomic weight:  $A = 63.55$  gr/mol
- atomic radius:  $r = 0.128$  nm =  $0.128 \times 10^{-7}$  cm

$$V_c = a^3; \text{ For FCC, } a = 4r/2 \quad V_c = 4.75 \times 10^{-23} \text{ cm}^3$$

Result: theoretical  $\rho_{\text{Cu}} = 8.89$  gr/cm<sup>3</sup>

actual  $\rho_{\text{Cu}} = 8.94$  gr/cm<sup>3</sup>

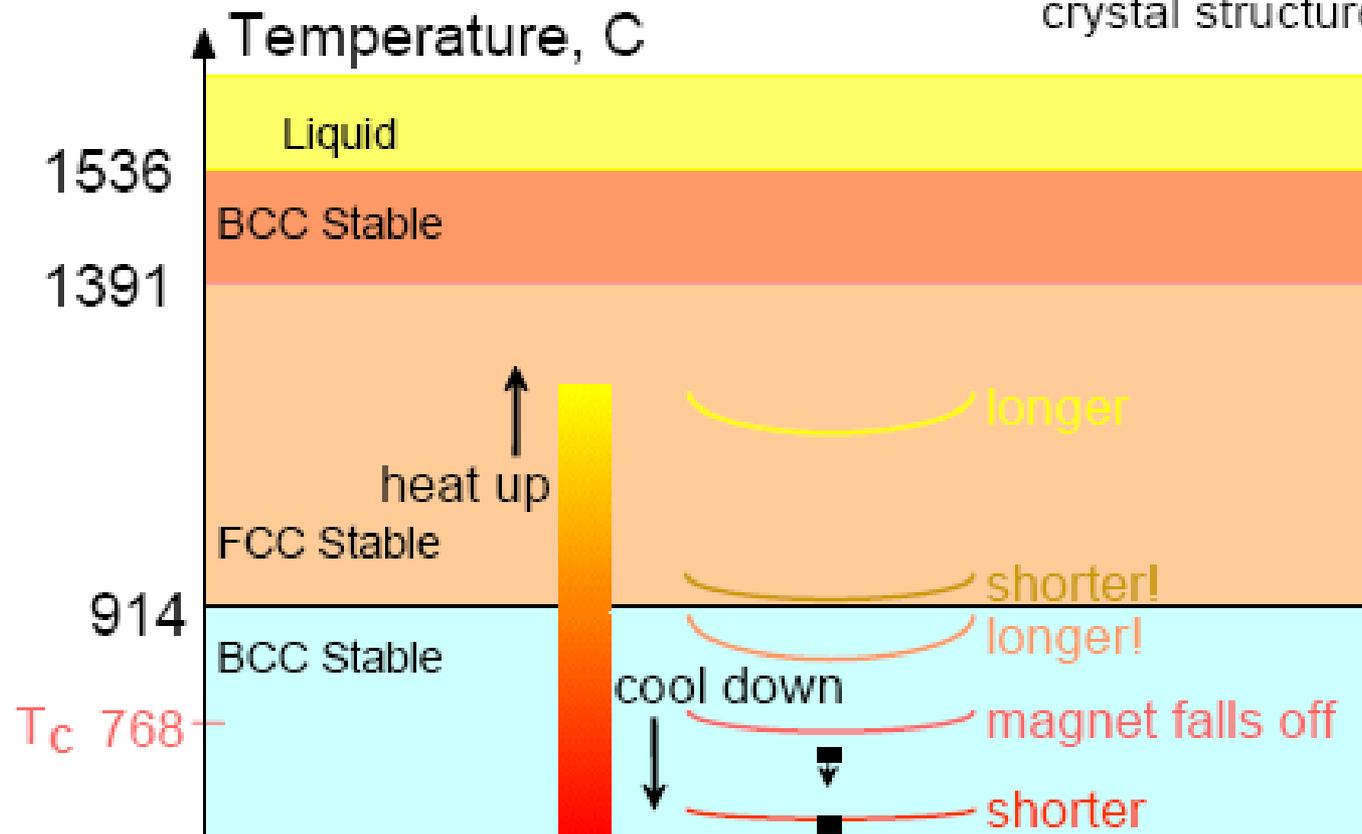
impurities

# DEMO: BCC → FCC

## TRANSFORMATION OF IRON

- Demonstrates "polymorphism"

← The same atoms can have more than one crystal structure.



# BCC → FCC TRANSFORMATION OF IRON AT 914°C

Density will change because of change in crystal structure:

$$\rho = \frac{nA_{\text{Fe}}}{V_c N_A}$$

$$\frac{\rho_{\text{FCC}}}{\rho_{\text{BCC}}} = \left( \frac{n_{\text{FCC}} A_{\text{Fe}}}{V_{c,\text{FCC}} N_A} \right) \left( \frac{V_{c,\text{BCC}} N_A}{n_{\text{BCC}} A_{\text{Fe}}} \right) = \frac{n_{\text{FCC}} V_{c,\text{BCC}}}{n_{\text{BCC}} V_{c,\text{FCC}}}$$

$V_{c,\text{BCC}} = a_{\text{BCC}}^3$   
 $V_{c,\text{FCC}} = a_{\text{FCC}}^3$

$$\left( \frac{4}{3} r \right)^3$$

$$\left( \frac{4}{2} r \right)^3$$

$$\frac{\rho_{\text{FCC}}}{\rho_{\text{BCC}}} = 1.09$$

*: FCC 9 % more dense*

# DENSITIES OF MATERIAL CLASSES

$$\rho_{\text{metals}} > \rho_{\text{ceramics}} > \rho_{\text{polymers}}$$

Why?

**Metals** have:

- dense packing
- heavy elements

**Ceramics** have:

- light elements
- more open packing
- covalent
- ion-ion required

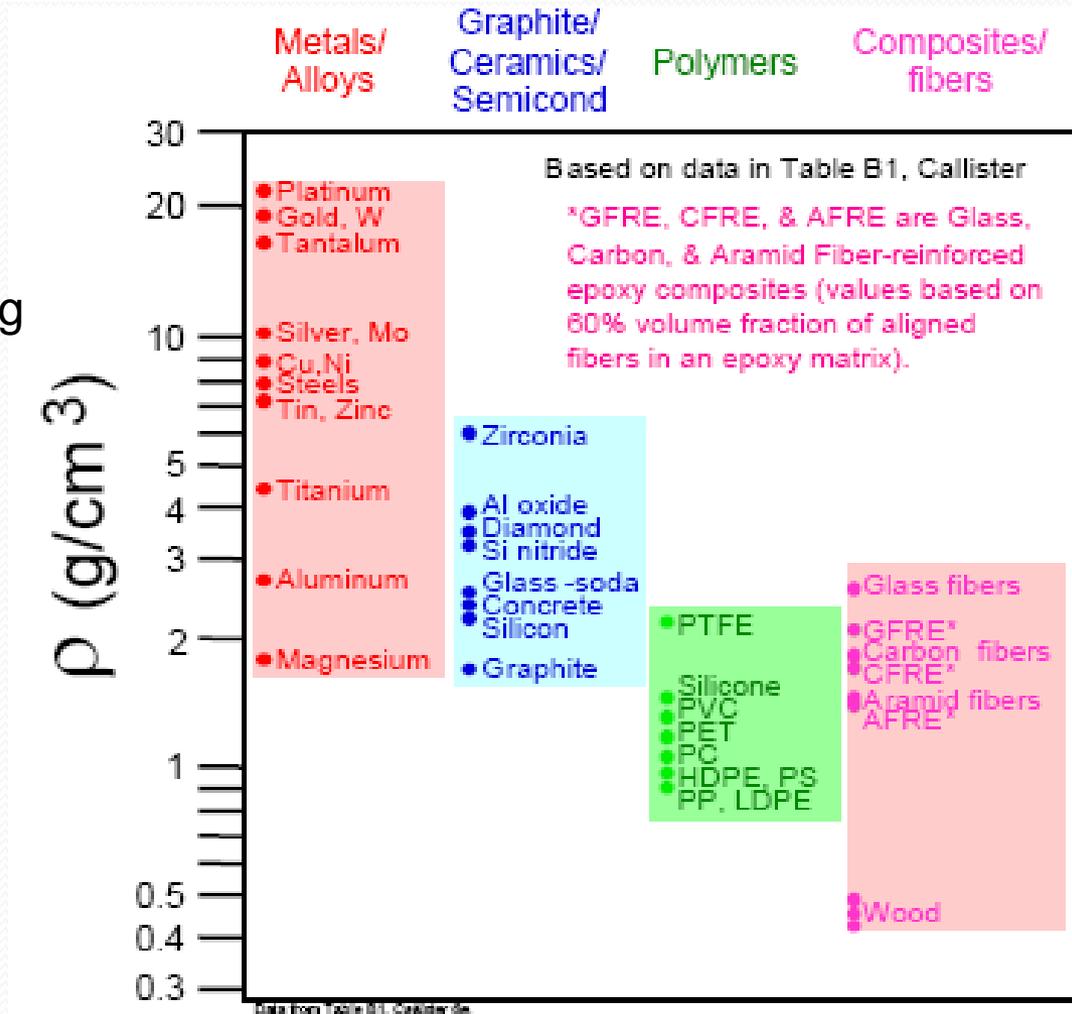
**Metals** have:

- light elements

random packing

**Composites**

- intermediate



# CHAPTER 4

## PHASE DIAGRAMS-I

### 4.1 INTRODUCTION

When two or more metals combine to form alloys, a range of **products** may be obtained depending upon the temperature and composition of the constituent elements. Each of these products may display a different structure and hence different mechanical properties. It is, therefore, imperative to know the relationship between these variables and resulting products to be able to develop alloys with desirable properties. A pictorial representation of such relationship and products description has, therefore, been developed which is called **a phase diagram**. Phase diagram is to an engineer what map is to a geologist. A map describes the areas where there is a sea, or a mountain or a valley or a forest etc., and similarly a phase diagram describes where there is liquid, a solid solution, an intermetallic compound etc. An understanding and interpretation of phase diagrams is therefore very essential for an engineer dealing with alloys.

Phase diagrams or constitutional diagrams which show the equilibrium phases which exist in an alloy at various temperatures. **These diagrams** are based on slow cooling of an alloy from molten state to obtain phases which are stable at room temperature. Phase diagrams vary according to the number of constituent elements. **Binary diagrams** represent two element systems whereas **ternary diagram** are for three alloy systems and so on. In order to understand and subsequently interpret phase diagrams it is helpful to learn how these are obtained. The construction of phase diagrams will therefore be considered followed by their interpretation. Finally, phase diagrams of the most important alloy system of steels will be discussed in detail.

Constitutional: yapısal

# Nomenclature / Definitions / Basic Concepts

(I)

- Component: Unique chemical species that an alloy is composed, i.e. elements (Fe, C, Cu, B, N...) and compounds ( $\text{Al}_2\text{O}_3$ ,  $\text{H}_2\text{O}$ ,  $\text{NaCl}$ ...).
- Phase: a homogeneous portion of a system that has uniform physical and chemical characteristics.
  - Two distinct phases in a system have distinct physical **or** chemical characteristics (e.g. water and ice). A phase may contain one or more components.
  - One phase system is a homogeneous system, if there are more than one phase, then the system is said to be a mixture or heterogeneous.
- Solvent - host or major component in solution, solute - minor component (Chapter 4).

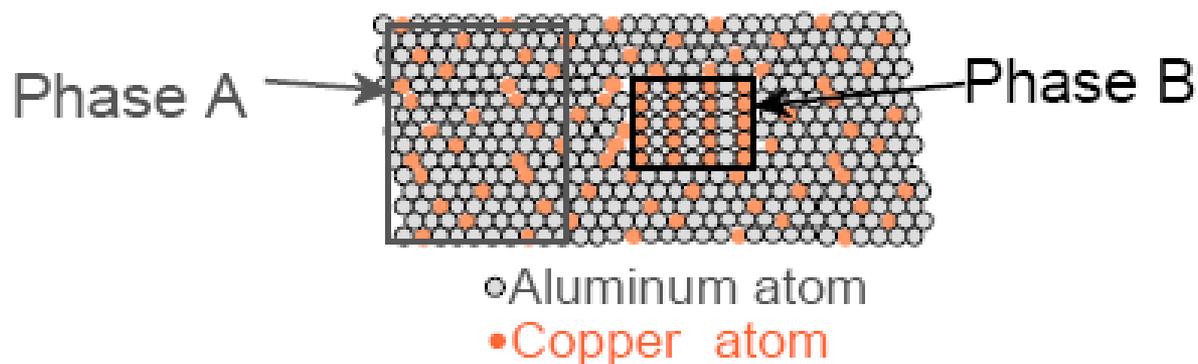
**Solubility Limit** of a *component* in a *phase* is the maximum amount of the component that can be dissolved in it (e.g. alcohol has unlimited solubility in water, sugar has a limited solubility, oil is insoluble). The same concepts apply to solid phases: Cu and Ni are mutually soluble in any amount (unlimited solid solubility), while C has a limited solubility in Fe.

# PHASE DIAGRAMS

When we combine elements, what is the equilibrium structure?

For a given composition and temperature:

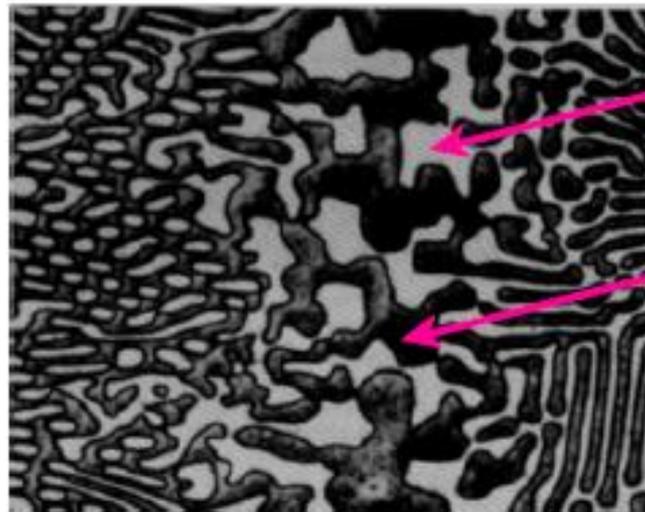
- How many phases do we get?
- What is the composition of each phase?
- How much of each phase do we get?



# COMPONENTS AND PHASES

- **Components:** Elements or compounds that are mixed
- **Phases:** Physically and chemically distinct regions that result from mixture
- **Composition:** Amount of a component in a phase

Aluminum-  
Copper  
Alloy



$\beta$  (lighter  
phase)

$\alpha$  (darker  
phase)

Adapted from Fig. 9.0,  
Callister Jr.

# THE SOLUBILITY LIMIT

- **Solubility Limit:**  
Max concentration for which only a solution occurs.
- **Ex: Phase Diagram: Water-Sugar System**

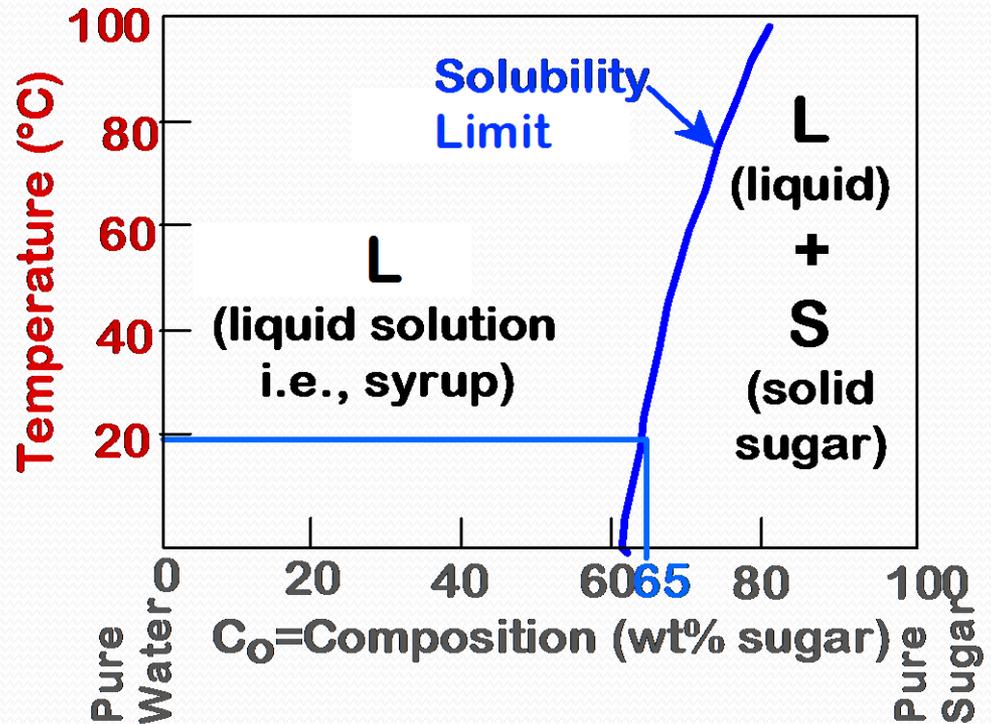
Question: What is the solubility limit at **20C**?

Answer: **65wt% sugar.**

If  $C_0 < 65\text{wt\%}$  sugar: sugar

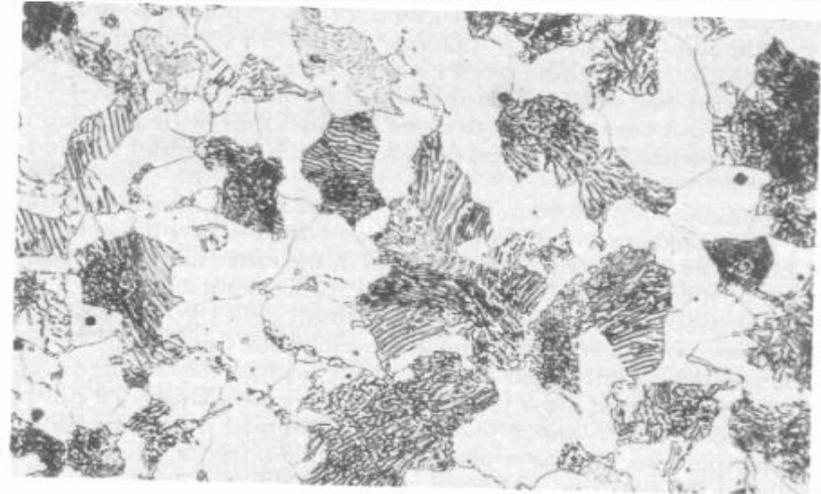
If  $C_0 > 65\text{wt\%}$  sugar: syrup + sugar.

- **Solubility limit increases with T:**  
e.g., if  $T = 100\text{C}$ , solubility limit = **80wt% sugar.**



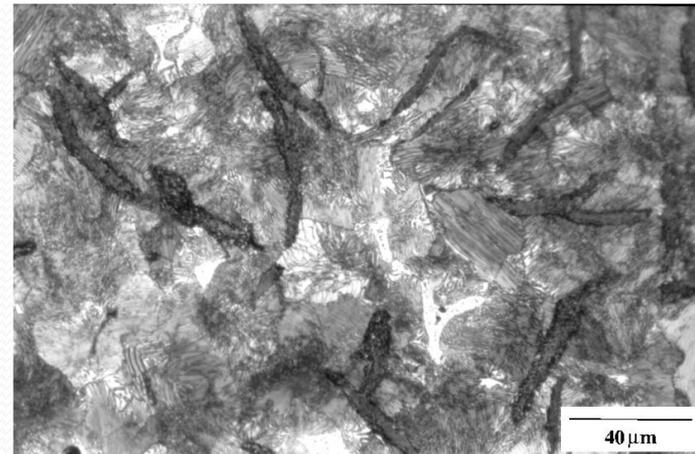
# Nomenclature / Definitions / Basic Concepts (II)

- In general, many materials properties of materials (mechanical properties) of the material depend on the microstructure, i.e texture...
- The properties of an alloy depend not only on proportions of the phases but also on how they are arranged structurally at the microscopic level. Thus, the microstructure is specified by the number of phases, their proportions, and their arrangement in space.
- Microstructure also depends on processing, heat treatment....
- Phase diagrams are a guide for us to help understand, explain and predict microstructures of materials as shown on the right:



**Figure 8.15.** Photomicrograph of a 0.38 wt% C steel having a microstructure consisting of pearlite and proeutectoid ferrite, 635 $\times$ . (Photomicrograph courtesy of Republic Steel Corporation.)

William D. Callister, Jr. *Materials Science and Engineering, An Introduction*. John Wiley & Sons, Inc. 1985



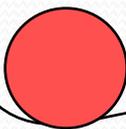
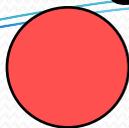
Grey cast iron, Fe-3.2C-2.5Si wt%, containing graphite flakes in a matrix which is pearlitic. The lamellar structure of the pearlite can be resolved, appearing to consist of alternating layers of cementite ( $\text{Fe}_3\text{C}$ ) and ferrite (BCC-Fe). Courtesy of [http://www.msm.cam.ac.uk/phasetrans/2001/adi/cast\\_iron](http://www.msm.cam.ac.uk/phasetrans/2001/adi/cast_iron)

# Nomenclature / Definitions / Basic Concepts (III)

- A system is at **equilibrium** if at constant temperature, pressure and composition the system is chemically and structurally stable, not changing with time.
- Equilibrium is the state that is achieved given sufficient time. But sometimes it will take too much time to achieve equilibrium due the kinetics, hence a state along the path to the equilibrium may *appear* to be stable. This is called a **meta-stable state**.
- In thermodynamics the equilibrium is described as the state of system that corresponds to the minimum of thermodynamic function called the **free energy**.
  - Thermodynamics tells us that
    - under conditions of a constant temperature and pressure and composition, the direction of any spontaneous change is toward a lower free energy.
    - the state of stable thermodynamic equilibrium is the one with minimum free energy.
    - a system at a metastable state is trapped in a local minimum of free energy that is not the global one.

Free Energy

Unstable



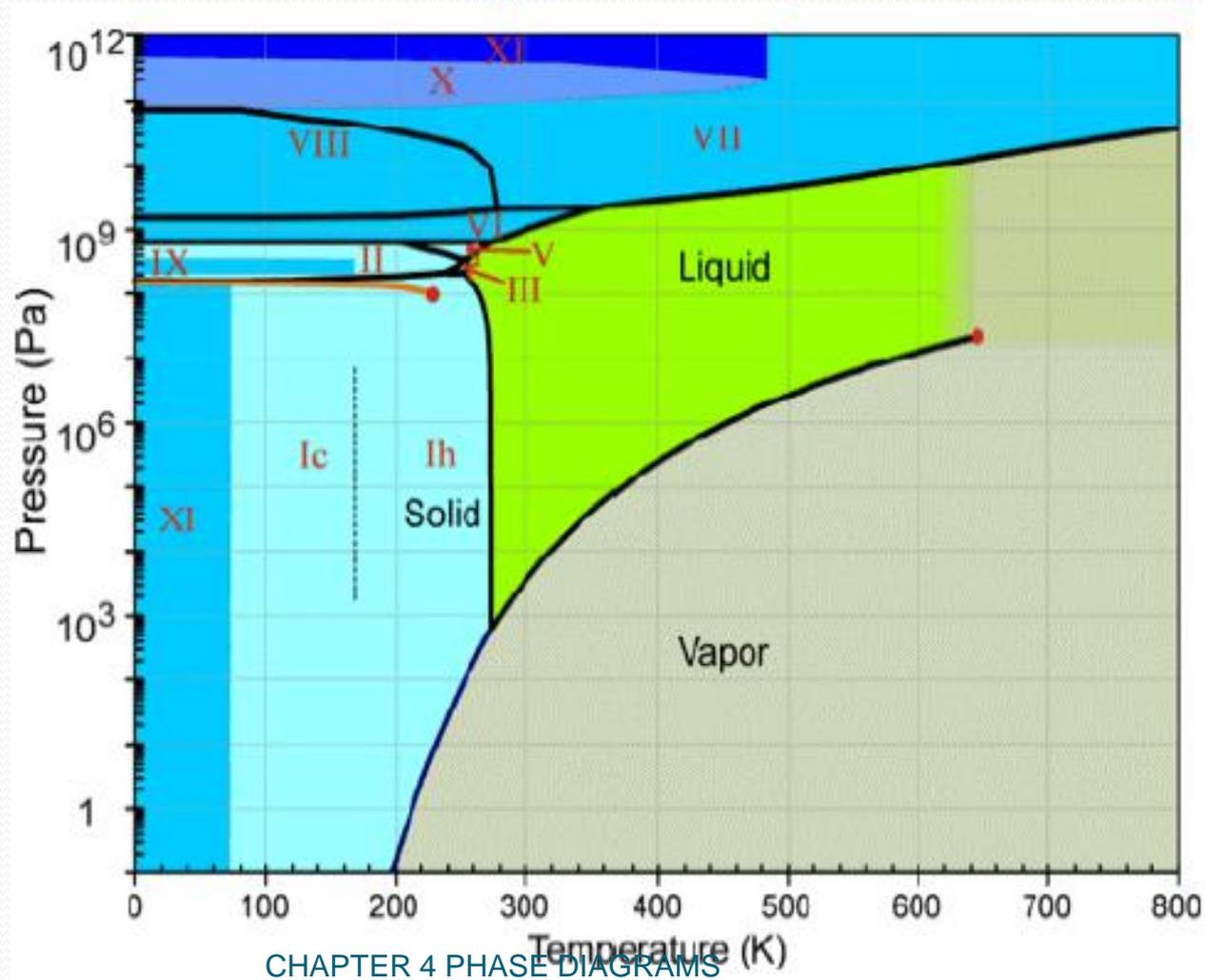
Metastable

Stable



# Phase Diagrams

- A **phase diagram** - graphical representation of the combinations of temperature, pressure, composition, etc. for which specific phases exist at equilibrium.

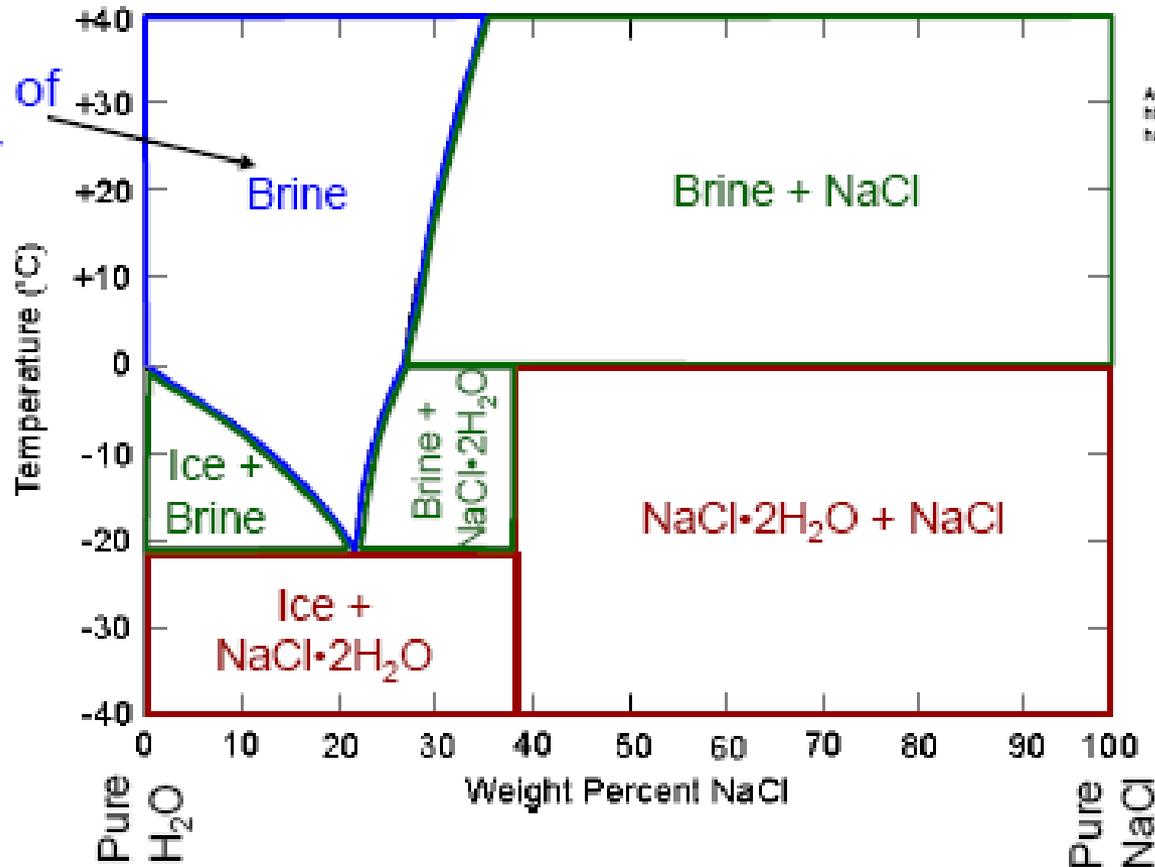


# Ice-Salt Phase Diagram

Phase Diagram: Map of material phases

- **Borders = Solubility Limits**: Max concentration for which only a solution is present

Brine: solution of salt in water

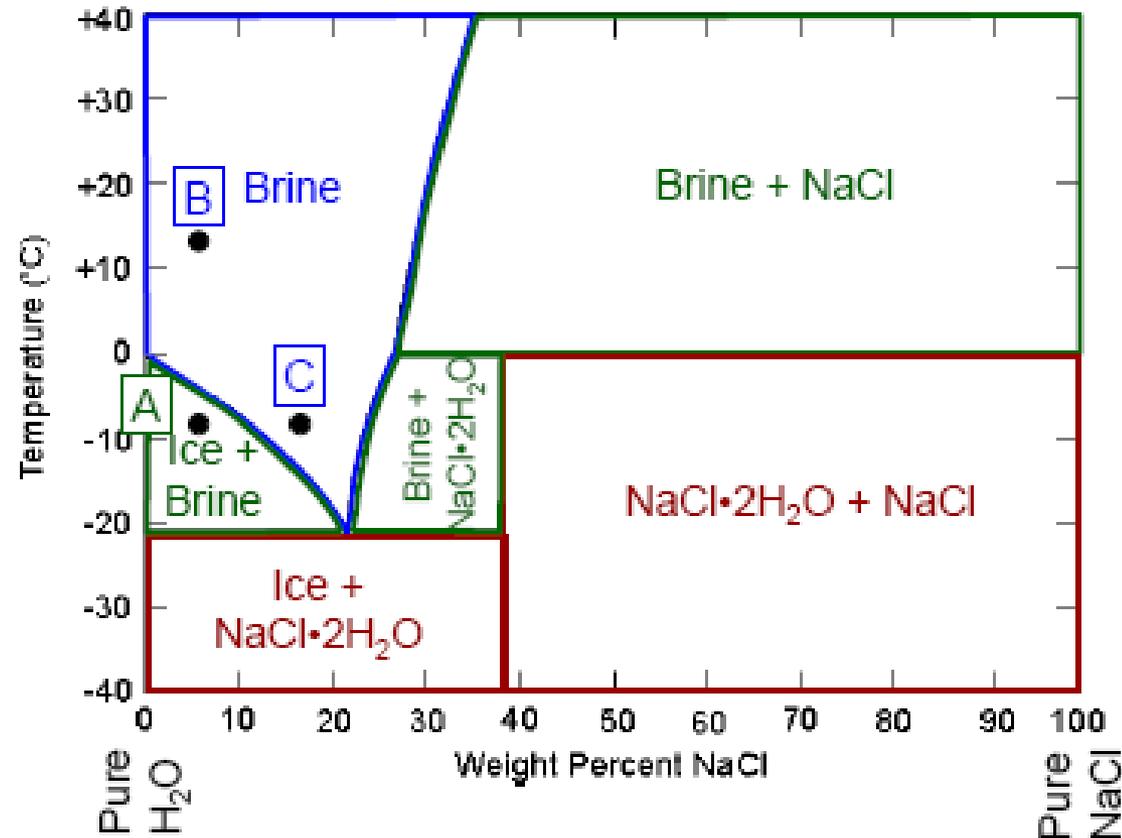


Solubility limit of ice in brine at -10°C:

Solubility limit of salt in brine at 20°C:

# EFFECT OF T & C<sub>0</sub> ON PHASES

- Changing T can change # of phases: path A to B.
- Changing C<sub>0</sub> can change # of phases: path A to C.



## 4.2 TYPES of PHASE DIAGRAMS

Phase diagrams may be classified according to the miscibility of constituents in liquid and solid states as follows:

1. **Components completely soluble in liquid state**
  - A. complete solubility in solid state
  - B. partial solubility in solid state
  - C. complete insolubility in solid state.
2. **Components partially soluble in liquid state**
  - A. partial solubility in solid state
  - B. complete insolubility in solid state.
3. **Components completely insoluble in liquid state**
  - A. complete insolubility in solid state.

Most common and important engineering alloy systems are **binary systems** exhibiting **complete solubility in liquid state**. They may show complete or partial solubility or complete insolubility upon cooling to room temperature. Such systems only would therefore be tackled in detail in this chapter.

## 4.3 RULES of PHASE DIAGRAMS

A few general rules which govern the construction and interpretation of phase diagrams are as follows:

1. Phase diagrams are based on slow cooling of alloys to obtain structures which are thermodynamically stable at room temperature. The Gibb's free energy for transformation reaction is minimum and is given by the expression

$$G = U + PV - TS \quad (4.1)$$

where

**G** is Gibb's free energy,

**U** is total energy,

**P** is pressure,

**V** is volume,

**T** is temperature and

**S** is entropy of the system.

2. The condition of equilibrium for an alloy system is determined by a relation between the number of coexisting phases, the number of components and the number of variables given by the Gibb's phase rule:

$$P + F = V + C \quad (P - C = V - F) \quad (4.2)$$

Where

**P** is number of phases,

**C** is number of components,

**V** is number of variables and

**F** is degree of freedom.

For the most common case where pressure is constant (atmospheric pressure) and only temperature is variable, V becomes 1 and the phase rule becomes

$$P + F = 1 + C \quad (4.3)$$

3. The weight proportion of various phases in equilibrium at any temperature can be determined by the difference between the composition of a phase at that temperature and the overall composition of the alloy using **lever arm principle** of mechanics.

4. Three phases cannot coexist at one time except at a constant temperature such as **eutectic** or **peritectic**.

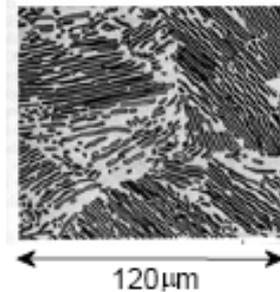
5. Two phases are always separated by a two-phase region.

# IRON-CARBON (Fe-C) PHASE DIAGRAM

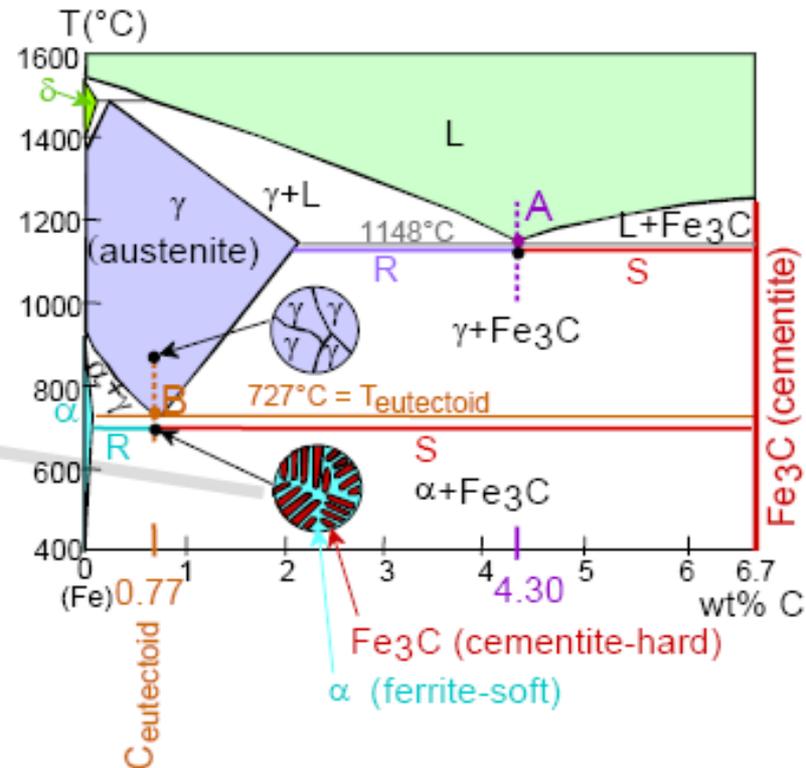
• 2 important points:

-Eutectic (A):

-Eutectoid (B):



Result: Pearlite = alternating layers of  $\alpha$  and  $\text{Fe}_3\text{C}$



## 4.4 CONSTRUCTION of PHASE DIAGRAMS

When a pure metal is cooled from liquid state, at a particular temperature liquid begins to transform to solid and nuclei of solid phase begin to appear. This temperature is called the **solidification temperature**. Upon further cooling, however, the temperature of the metal does not change but more solidification takes place, **because the heat energy released by the melt by cooling is used up in forming increasing amount of liquid-solid interface and hence more solid is formed.** After the solidification is complete further cooling reduces the temperature of the solid metal. In case of an alloy however, unlike pure metal the solidification does not take place at a constant temperature because more than one element is involved whose solidification temperatures would be different. Solidification begins when one of the elements begins to solidify and the temperature also continues to drop until the solidification is complete.

### System Completely Soluble in Liquid and Solid States

Phase diagram of **copper-nickel**, a binary system completely soluble in liquid and solid states, will be constructed as an example. A series of alloys containing different amounts of copper and nickel will be made. Each sample is heated until molten and uniform in composition, and then it is allowed to cool very slowly. Change in temperature by time is recorded.

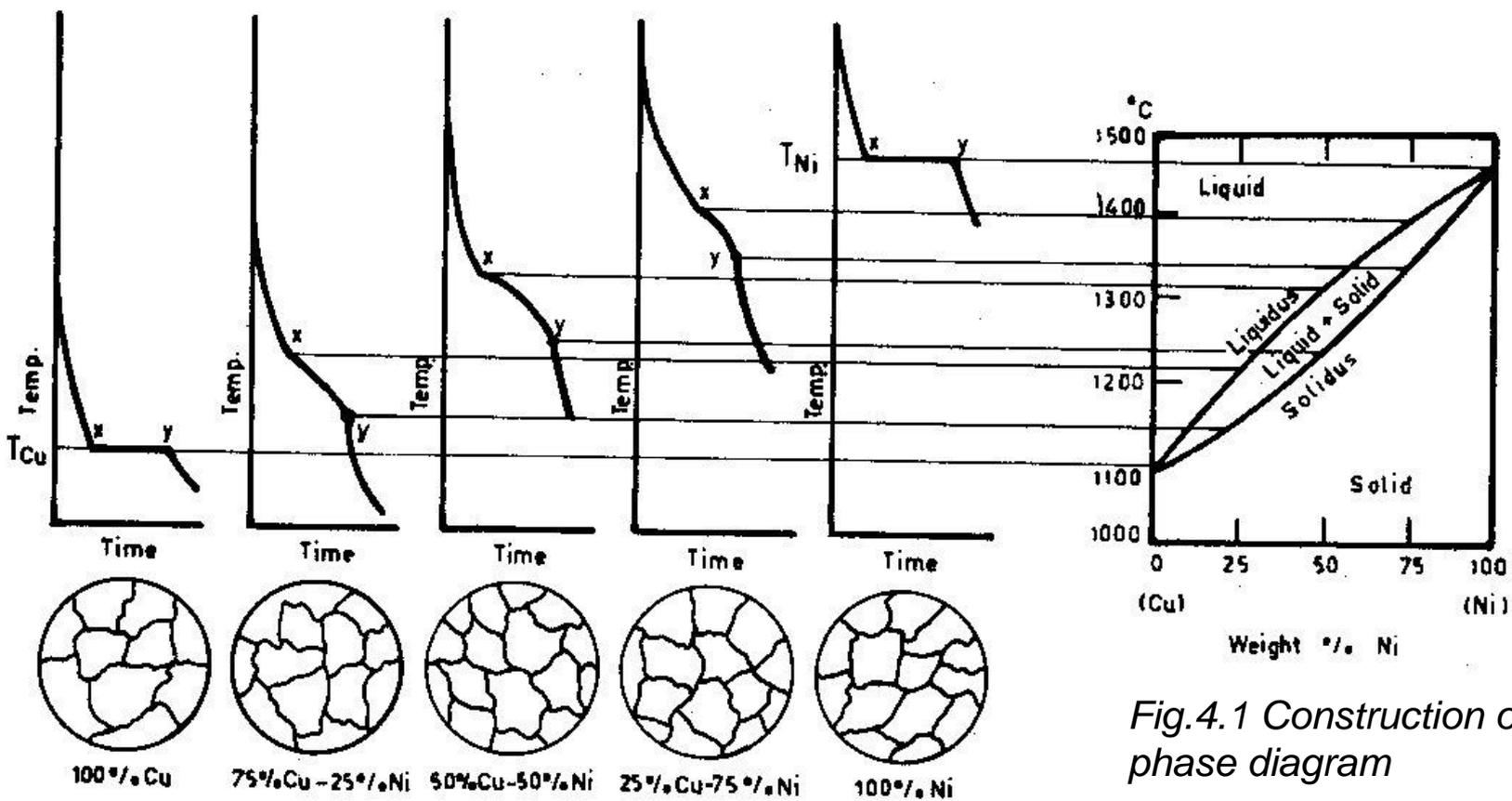


Fig.4.1 Construction of Cu-Ni phase diagram

First pure copper is cooled. Solidification starts at temperature x and finishes at temperature y. For pure metals these temperatures are equal as explained above, which is 1084 °C for copper. Subsequently an alloy (75 % Cu / 25 % Ni) is cooled from the liquid state to obtain the solidification start temperature x and finish temperature y for this alloy. The exercise is repeated for a (50 % Cu / 50 % Ni) and a (25 % Cu / 75 % Ni) alloy to obtain solidification start temperature x and finish temperature y for these alloys. The cooling curve for pure nickel is similar to pure copper where temperatures x and y are equal, which is 1455 °C for nickel. These x and y temperatures are then plotted on a diagram with coordinates of temperature and composition as shown in Fig 4.1.

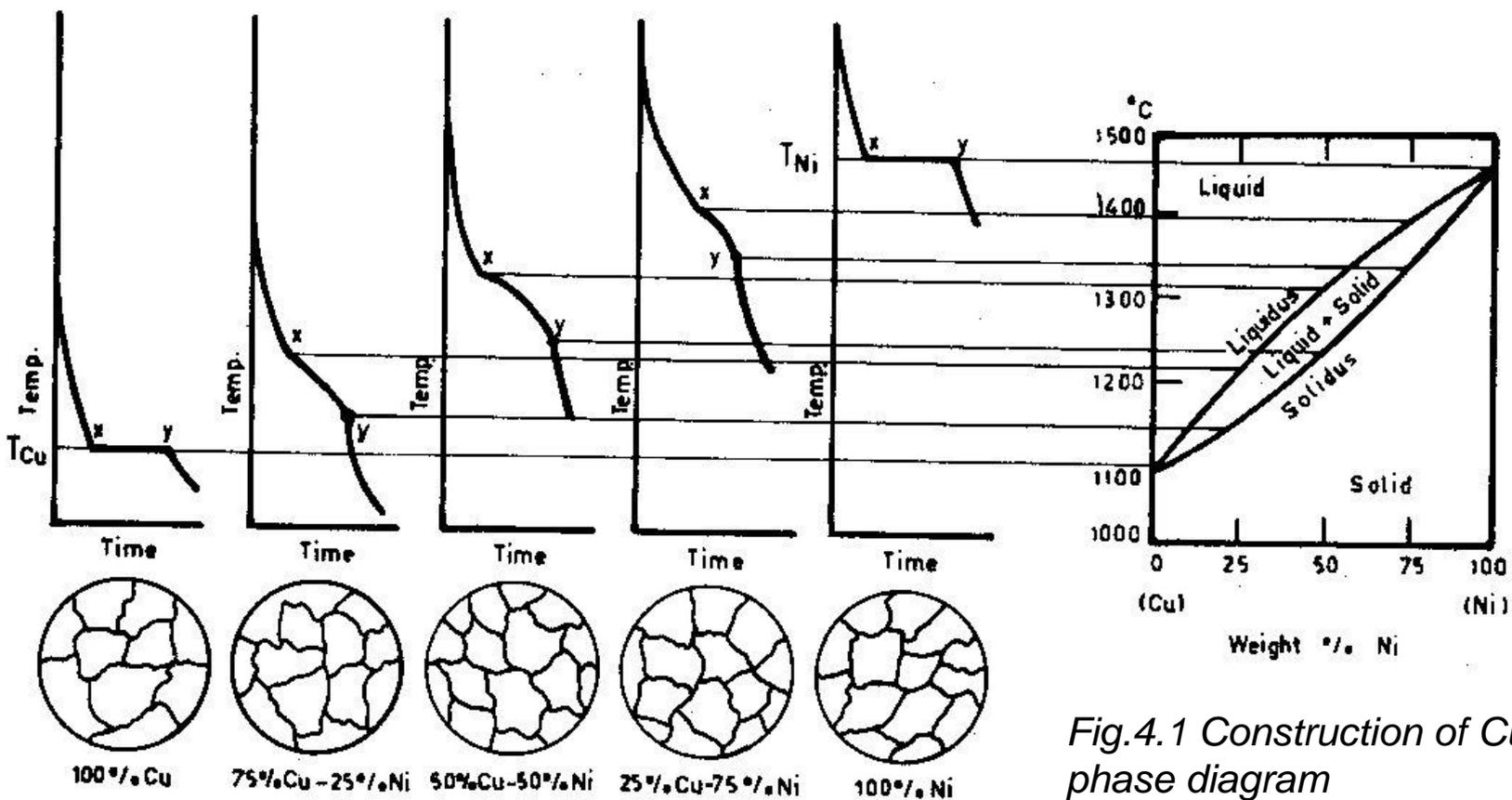


Fig.4.1 Construction of Cu-Ni phase diagram

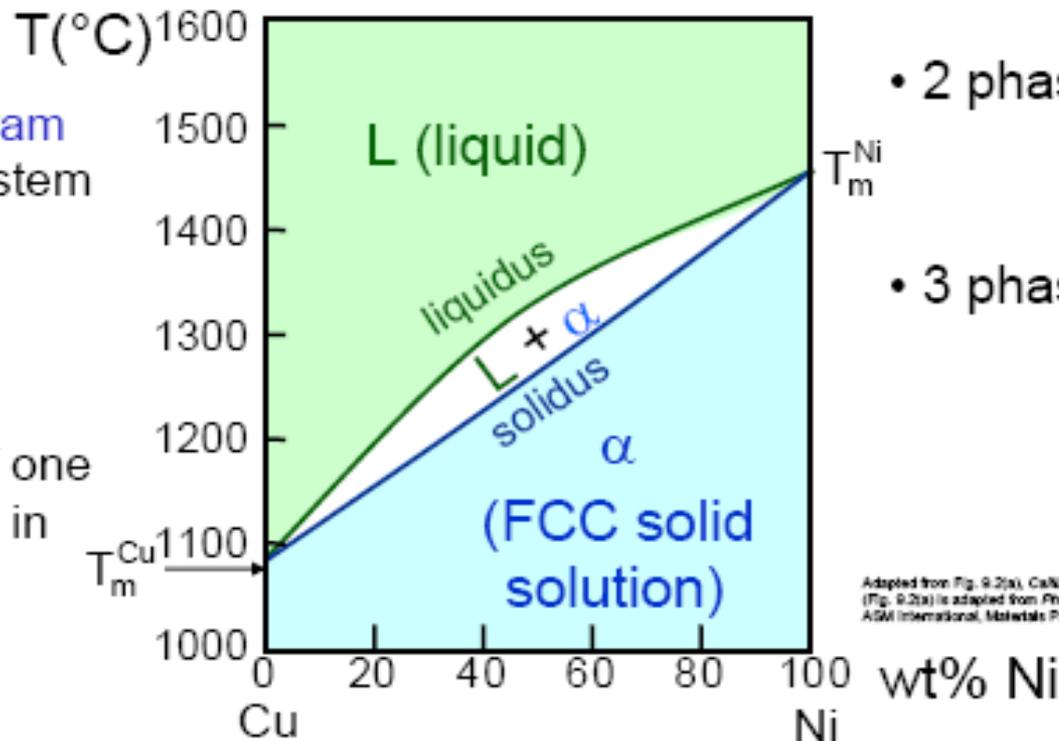
A line through the solidification start temperatures is drawn and another through the solidification finish temperatures is drawn to complete the phase diagram. It can be seen that the line joining x points represents points where solidification begins from liquid and it is called **liquidus**, whereas the line joining y points, where solidification is complete is called **solidus**. The region between liquidus and solidus lines is in a mixed state where **both solid and liquid phases** are present. The two phases (solid and liquid) are, therefore, separated by a two-phase region.

# PHASE DIAGRAMS

- Predict phases present as function of  $T$ ,  $C_0$ ,  $P$ .
- For this course:
  - binary systems: just 2 components.
  - independent variables:  $T$  and  $C_0$  ( $P = 1\text{atm}$  is always used).

Phase Diagram  
for Cu-Ni system

- complete solubility of one component in another



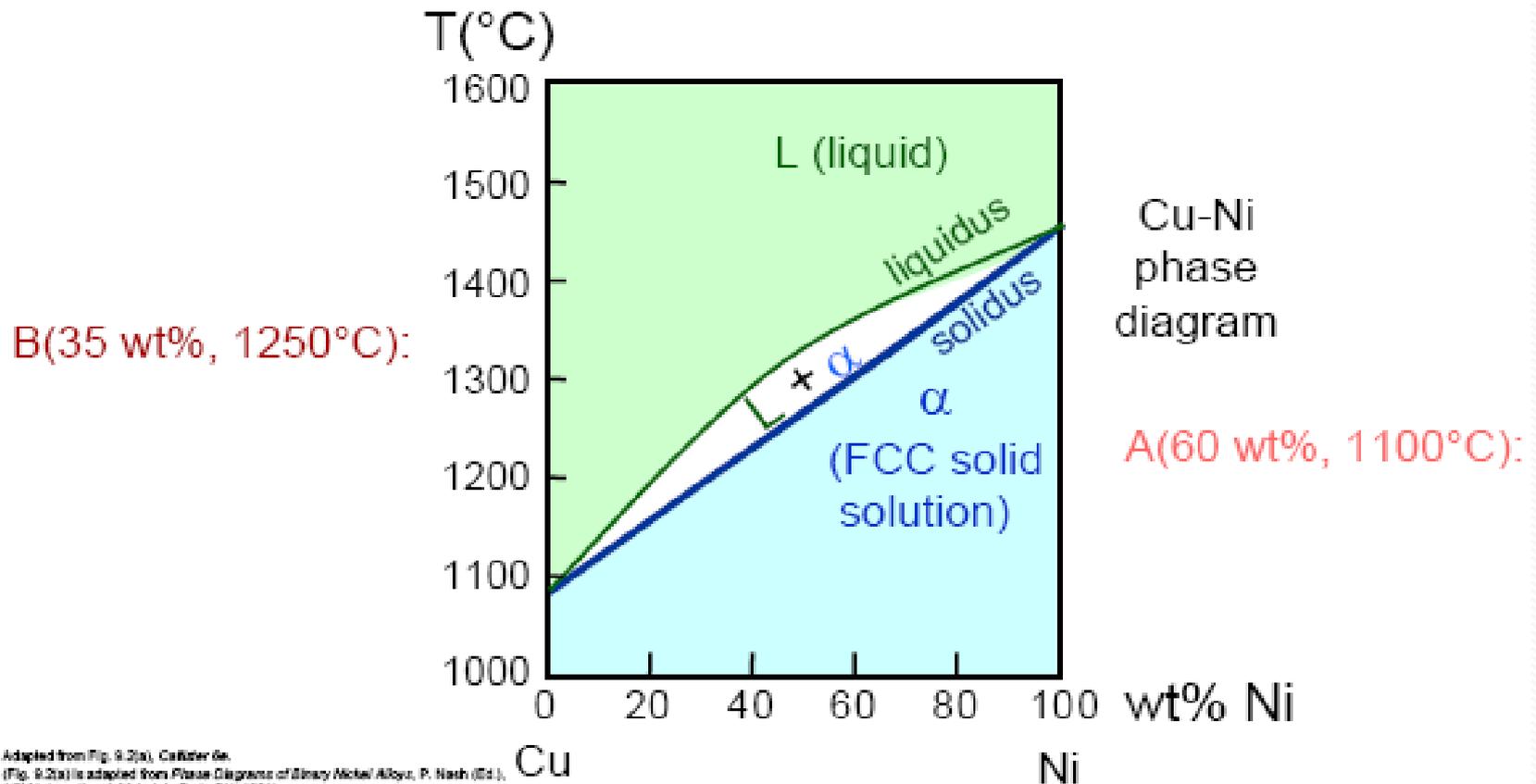
- 2 phases:

- 3 phase fields:

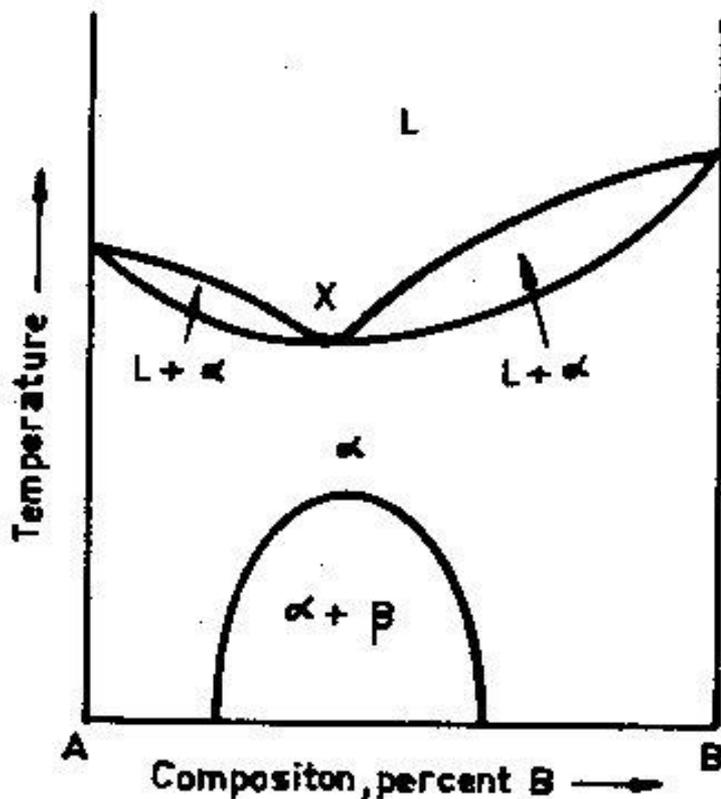
Adapted from Fig. 9.2(a), Callister 6e.  
(Fig. 9.2(a) is adapted from Phase Diagrams of Binary Metal Alloys, P. Nash (Ed.), ASM International, Materials Park, OH (1997).)

# PHASE DIAGRAMS: # and types of phases

If we know  $T$  and  $C_0$ , then we know the # and types of phases present.



Copper-Nickel system also shows complete solubility in vapor state and such systems with complete solubility in vapor, liquid and solid states are called **isomorphous systems**.



Some binary systems with complete liquid and solid solubility, however, do not have a continuous region of solid + liquid as shown by the Cu-Ni system. The solidus and liquidus lines meet tangentially at a minimum temperature which is below the melting point of both components as illustrated in the upper portion of Fig 4.2. Examples of such behavior are found in Au-Cu, Au-Ni and Cr-Fe systems etc. The alloy X corresponding to this temperature is called an **azeotropic alloy** and it behaves like pure metal during solidification.

Fig.4.2 Phase diagram with an azeotrope

# Interpretation of Phase Diagrams

- For a given temperature,  $T$ , and composition,  $C_0$ , we can use the phase diagram to determine:
  1. The # of phases that are present
  2. Compositions of these phases
  3. The relative fractions of the phases
- Finding the composition in a two phase region:
  1. Locate composition and temperature in the diagram
  2. In a two phase region draw the **tie line** or an isotherm
  3. Note the intersection with phase boundaries. Read compositions at the intersections.

The liquid and/or solid phases have these compositions.

LETS TRY



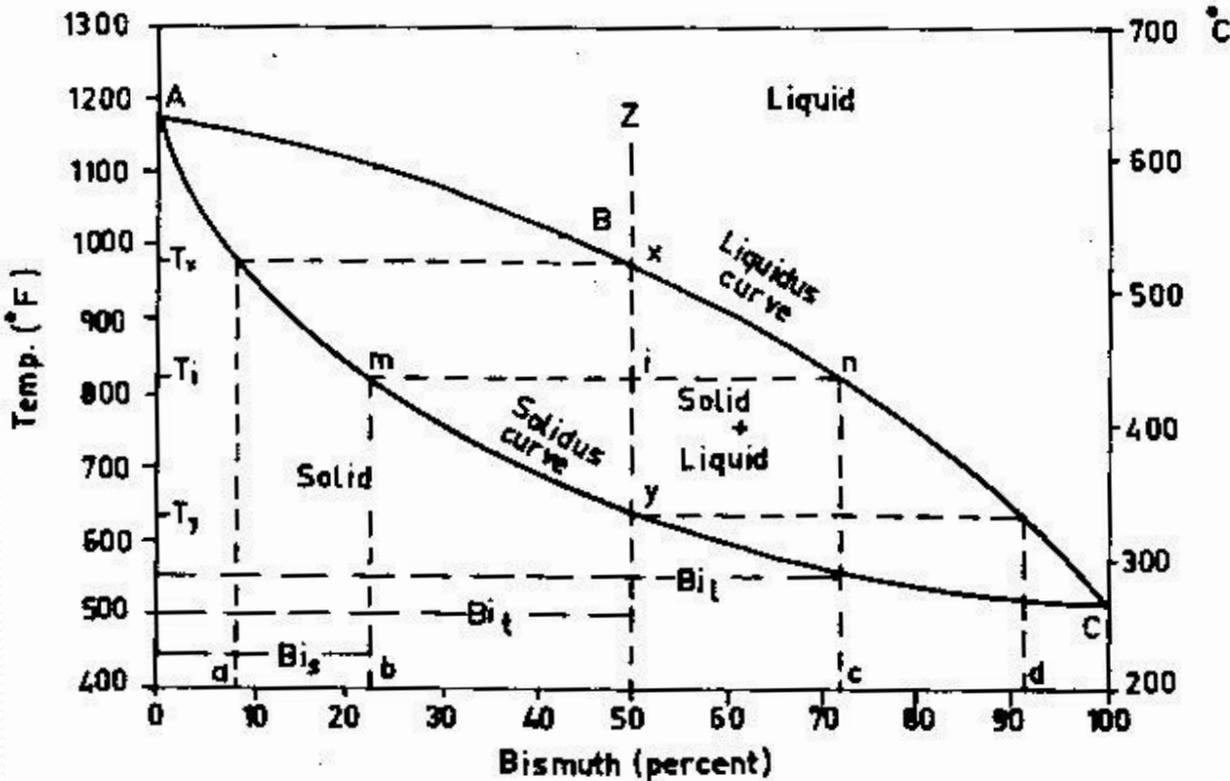
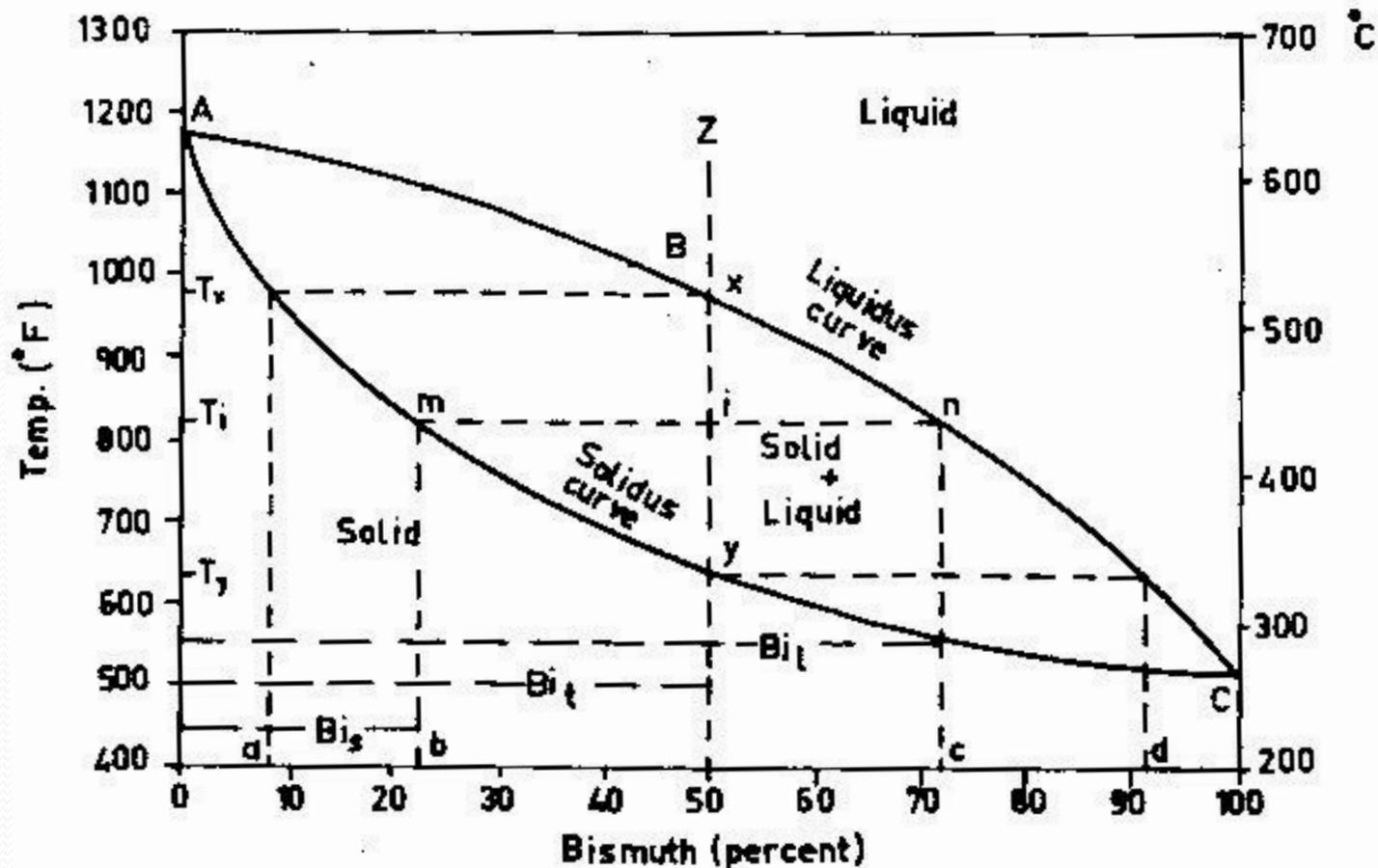


Fig.4.3 Phase diagram of antimony and bismuth

Further cooling to  $T_i$  results information of more solid of composition 23% Bi (not 50% or 8%) and the remaining liquid has a composition of 73% Bi as shown in the figure. The reason for a change in the composition of remaining liquid is that when first solids begin to solidify their compositions have less Bi in it ( $50 - 8 = 42\%$  less) and since the overall composition of the alloy Z is not changing, the liquid becomes enriched in Bi and hence contains more Bi than original composition.

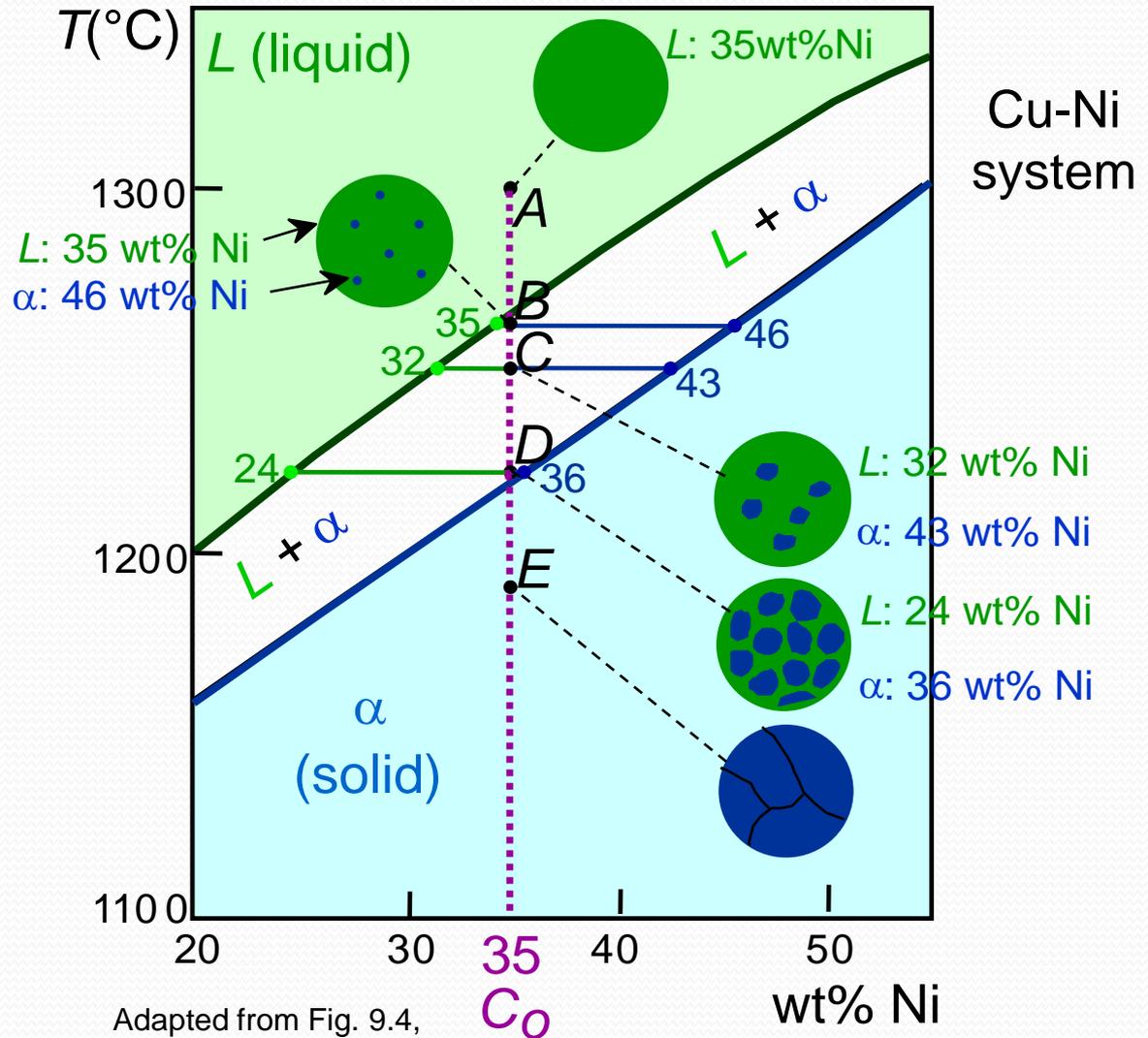
At temperature  $T_y$  the solidification is completed and the solid has same composition as last remaining liquid which is 93% Bi. Solidification in the two-phase region does not take place everywhere, but continuous on the previous nucleation sites.

Thus, further solidification with a different composition produces a ring around the previous one. As cooling continues the first solids having composition of 8 % Bi and the last having 93 % Bi homogenize with each other due to high temperature diffusion and a uniform composition of 50 % prevails in the solid at room temperature. This indeed is the ideal case, and in practice, areas of segregation of alloying elements are observed which is known as **coring**.



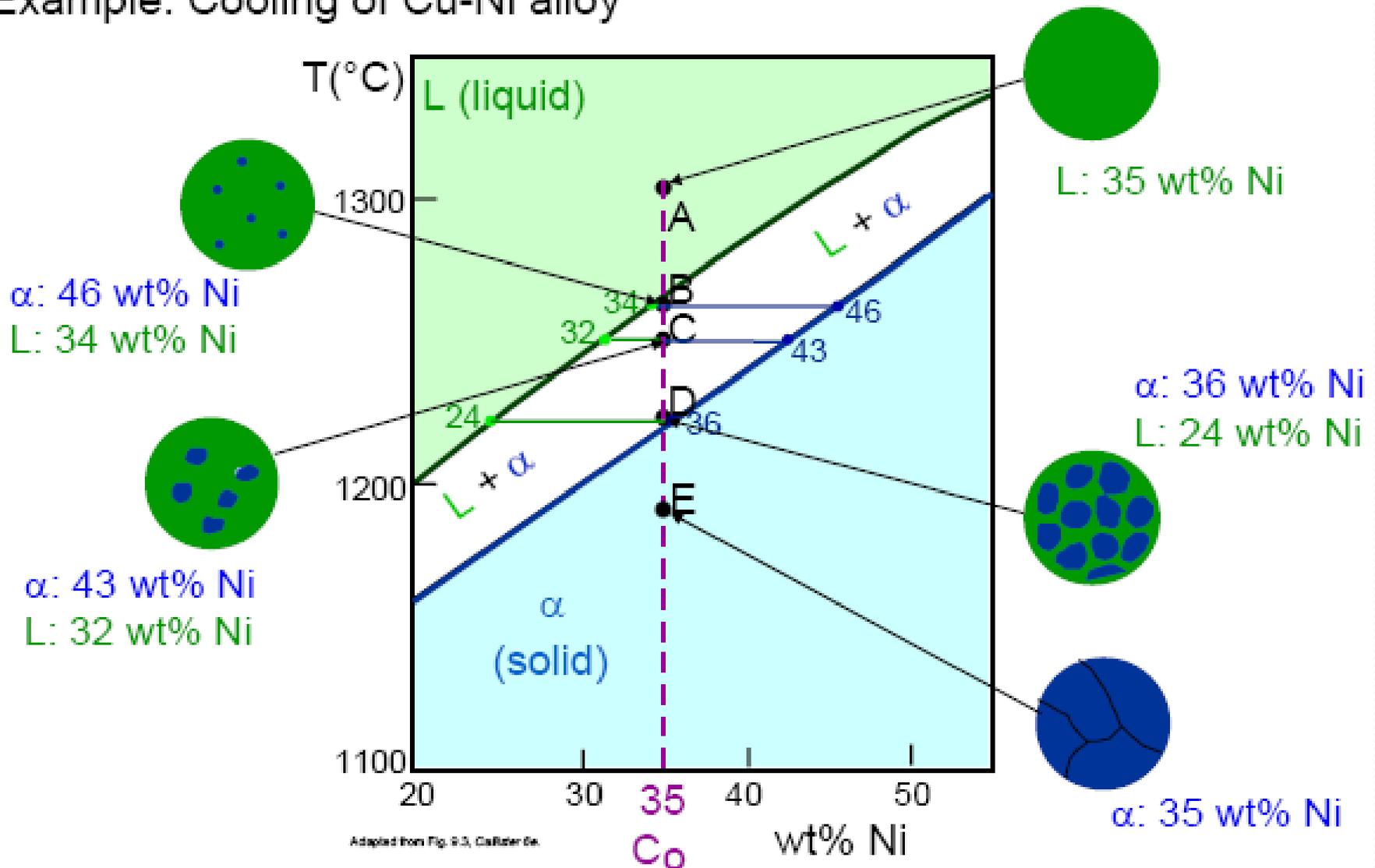
# Ex: Cooling in a Cu-Ni Binary

- Phase diagram: Cu-Ni system.
- System is:
  - binary  
i.e., 2 components: Cu and Ni.
  - isomorphous  
i.e., complete solubility of one component in another;  $\alpha$  phase field extends from 0 to 100 wt% Ni.
- Consider  $C_0 = 35 \text{ wt\%Ni}$ .



# MICROSTRUCTURAL DEVELOPMENT

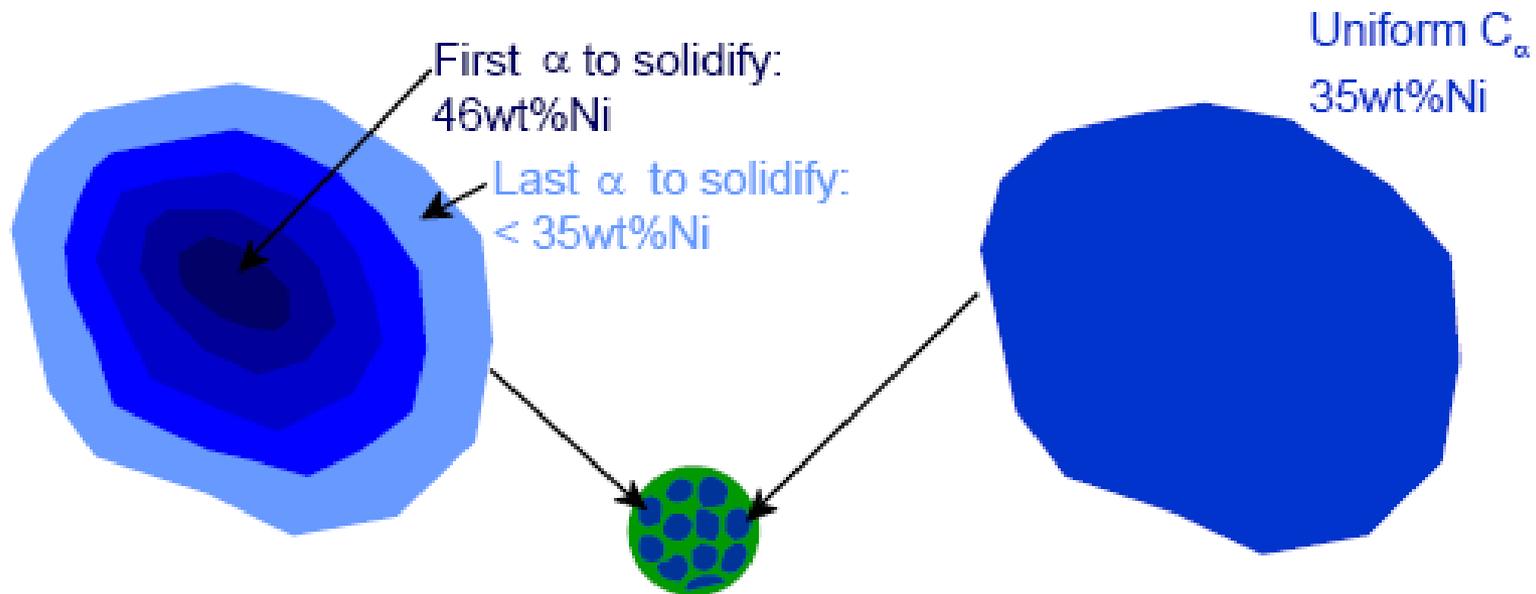
- Example: Cooling of Cu-Ni alloy



# CORED VS EQUILIBRIUM PHASES

- Fast rate of cooling:  
Cored structure

- Slow rate of cooling:  
Equilibrium structure

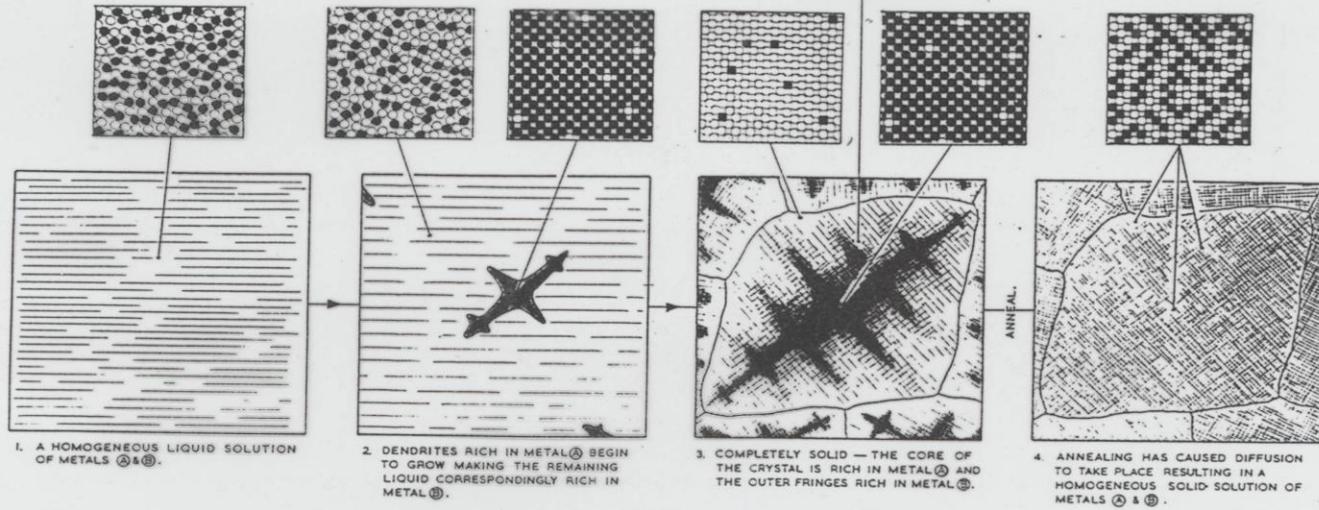


- $C_\alpha$  changes during solidification.
- Cu-Ni case, at  $C_0 = 35$  wt% Ni:  
First  $\alpha$  to solidify has  $C_\alpha = 46$  wt% Ni.  
Last  $\alpha$  to solidify has  $C_\alpha < 35$  wt% Ni.

- $C_\alpha$  composition is equal to  $C_0$  throughout.

## THE CORING OF SOLID SOLUTIONS.

DIAGRAMS INDICATING THE RELATIVE DISTRIBUTIONS OF ATOMS OF METALS (A) & (B) AT VARIOUS STAGES DURING THE SOLIDIFICATION AND ANNEALING OF A SOLID SOLUTION CONTAINING 50% OF EACH METAL.



—The variations in composition which are possible in a solid solution.

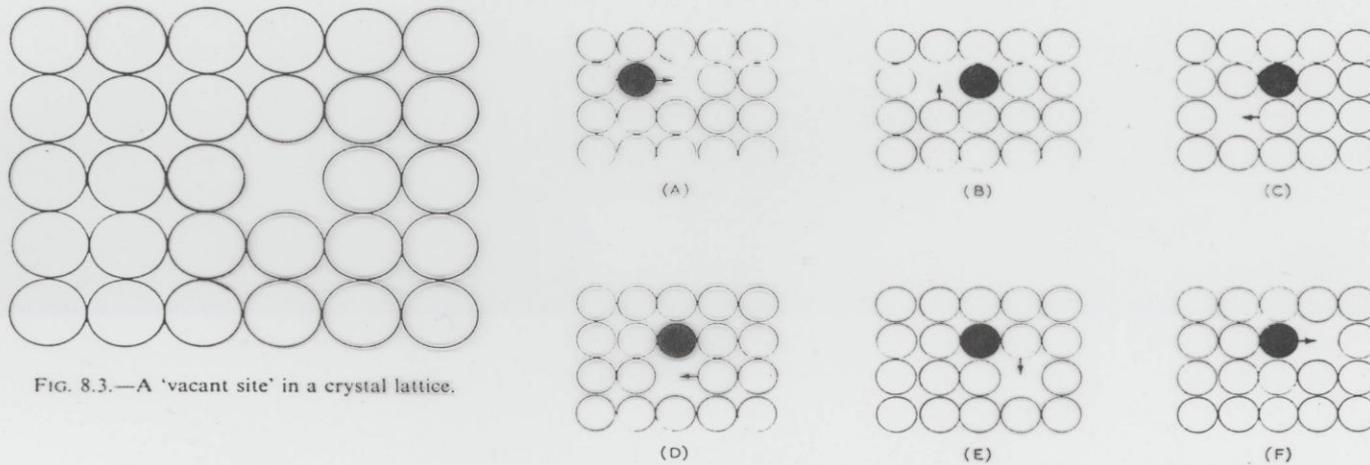


FIG. 8.3.—A 'vacant site' in a crystal lattice.

—The diffusion of a solute atom which is associated with a vacant site.

# PHASE DIAGRAMS: composition and phases

If we know  $T$  and  $C_0$ , then we know the composition of each phase.

- Examples:

$$C_0 = 35 \text{ wt\%Ni}$$

At  $T_A$ : Only Liquid (L)

$$C_L =$$

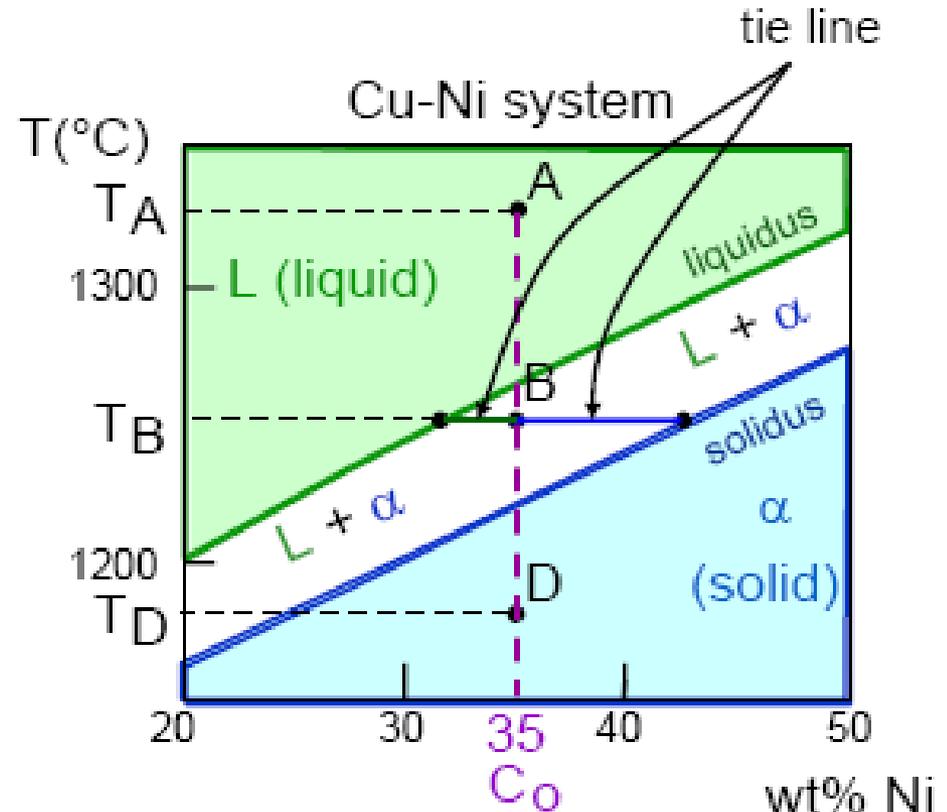
At  $T_D$ : Only Solid ( $\alpha$ )

$$C_\alpha =$$

At  $T_B$ : Both  $\alpha$  and L

$$C_L = C_{\text{liquidus}}$$

$$C_\alpha = C_{\text{solidus}}$$



# PHASE DIAGRAMS: weight fractions of phases

If we know  $T$  and  $C_0$ , then we know the amount of each phase (wt%).

- Examples:

$$C_0 = 35\text{wt\%Ni}$$

At  $T_A$ : Only Liquid (L)

$$W_L = 100 \text{ wt\%}, W_\alpha = 0$$

At  $T_D$ : Only Solid ( $\alpha$ )

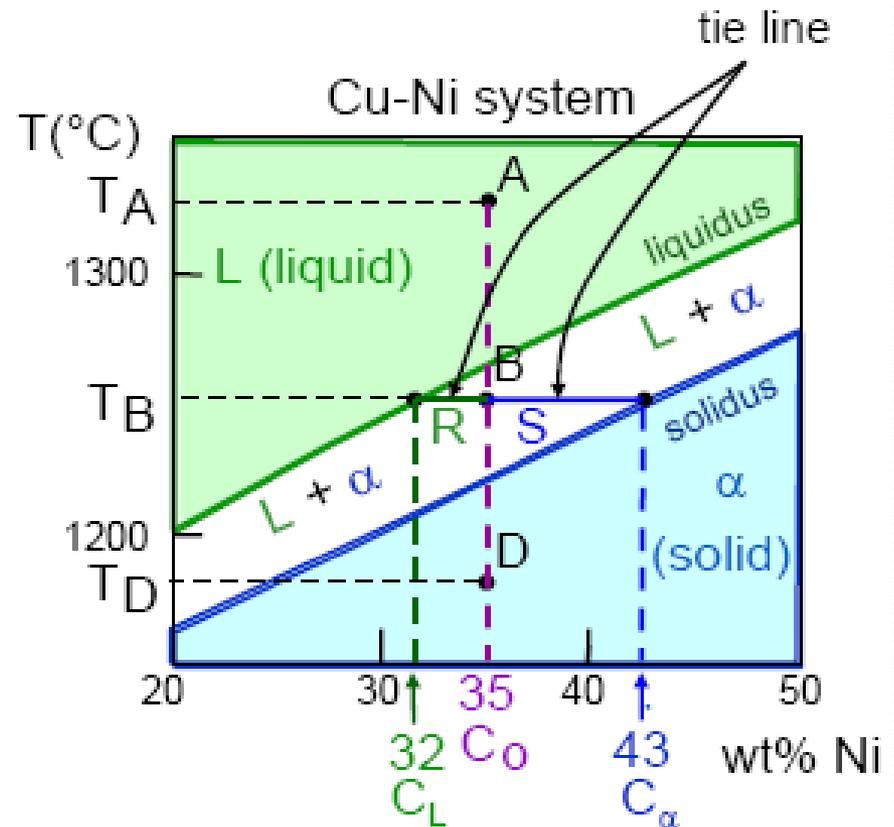
$$W_L = 0, W_\alpha = 100 \text{ wt\%}$$

At  $T_B$ : Both  $\alpha$  and L

Lever Rule:

$$W_L = \frac{C_\alpha - C_0}{C_\alpha - C_L}$$

$$W_\alpha = \frac{C_0 - C_L}{C_\alpha - C_L}$$



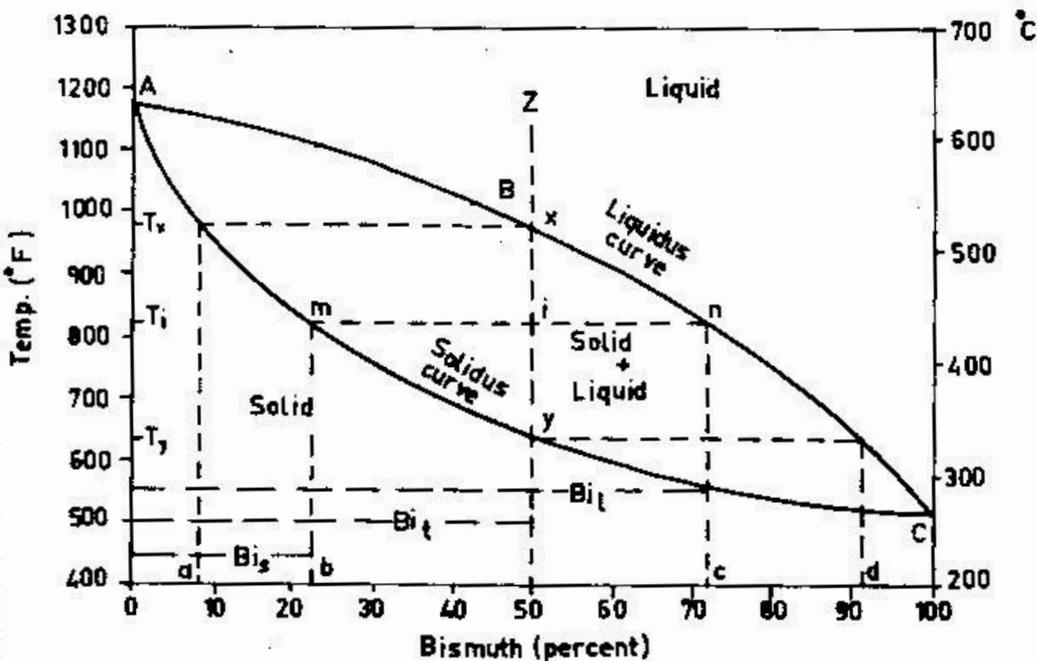
Adapted from Fig. 9.2(b), Callister 6e.  
 (Fig. 9.2(b) is adapted from Phase Diagrams of Binary Nickel Alloys, P. Nash (Ed.), ASM International, Materials Park, OH, 1991.)

# Interpretation of Phase Diagrams : Lever Rule

- Finding the amounts of phases in a two phase region:
  1. Locate composition and temperature in diagram
  2. In two phase region draw the tie line or isotherm
  3. Fraction of a phase is determined by taking the length of the tie line to the phase boundary for the other phase, and dividing by the total length of tie line
- The lever rule is a mechanical analogy to the mass balance calculation. The tie line in the two-phase region is analogous to a lever balanced on a fulcrum.
- Proof

## 4.5.1. Lever Arm Principle

Relative weight fractions of the two phases (liquid and solid) can also be obtained from the diagram at any temperature using the lever arm principle. Let us consider  $T_i$  for this analysis. Just above  $T_x$  the phase is 100 % liquid. At  $T_x$  solidification begins and the weight fraction of solids is very small compared to liquid. At  $T_i$  the weight fraction of solid has increased and that of liquid has decreased. To determine the weight fraction, a horizontal line is drawn at  $T_i$  such as  $mn$  passing through  $i$  (Fig 4.3). The weight fraction of solid phase is the ratio  $in/mn$  and that of liquid is  $mi/mn$ . In present case at  $T_i$ , therefore, the weight fraction of solid is;



$$\text{Wt \% of solid} = (in/mn) \times 100$$

$$in = 73 \% - 50 \% = 23 \text{ and}$$

$$mn = 73 \% - 23 \% = 50$$

$$\text{Wt \% of solid} = (23/50) \times 100 = 46 \%$$

$$\text{Wt \% of liquid} = (mi/mn) \times 100$$

$$mi = 50 \% - 23 \% = 27$$

$$\text{Wt \% of liquid} = (27/50) \times 100 = 54 \%$$

hence at  $T_i$ , there is 46 % solid and 54 % liquid phase present. This analysis can be carried out for any diagram at any temperature.

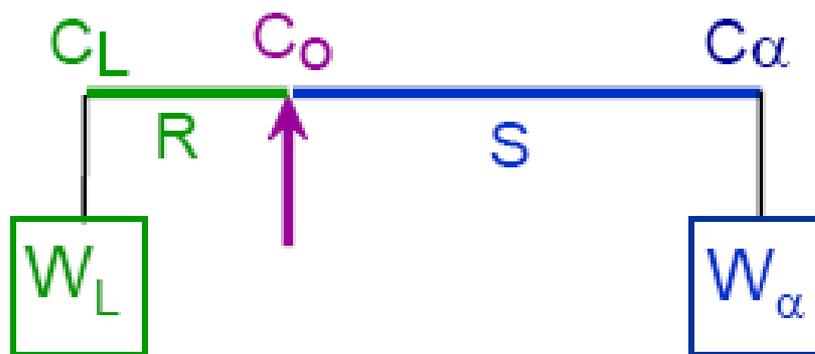
# THE LEVER RULE: A PROOF

- Sum of weight fractions:
- Conservation of mass (Ni):
- Combine above equations:

$$W_L = \frac{C_\alpha - C_0}{C_\alpha - C_L}$$

$$W_\alpha = \frac{C_0 - C_L}{C_\alpha - C_L}$$

- A geometric interpretation:



moment equilibrium:

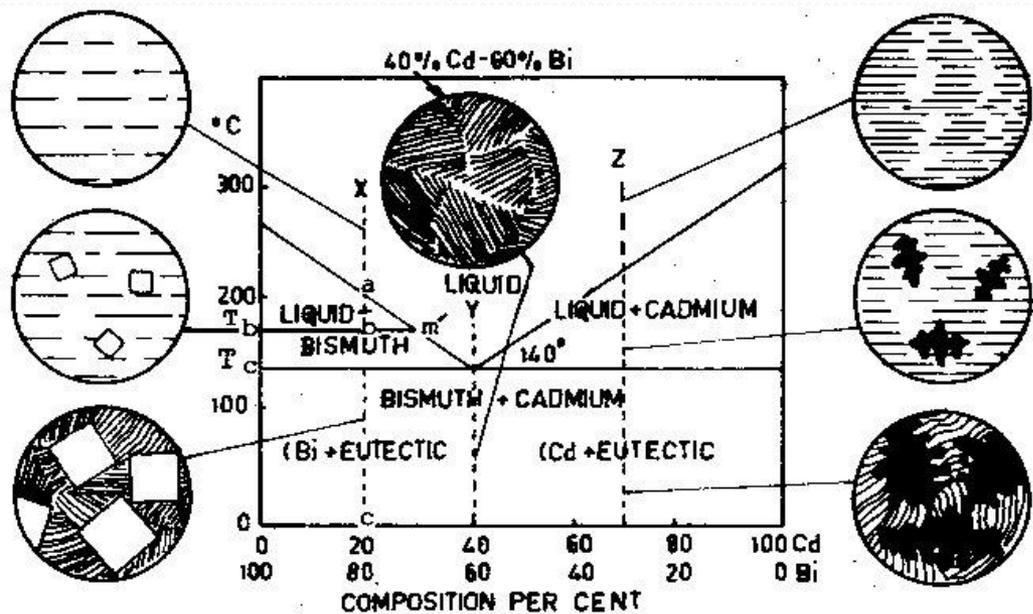
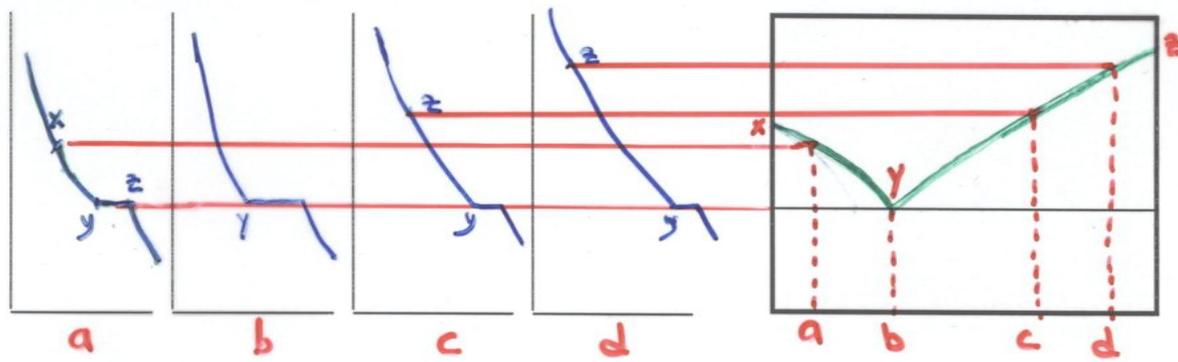
$$W_L R = W_\alpha S$$

$1 - W_\alpha$

solving gives Lever Rule

# 4.6. SYSTEMS INSOLUBLE AT SOLID STATE

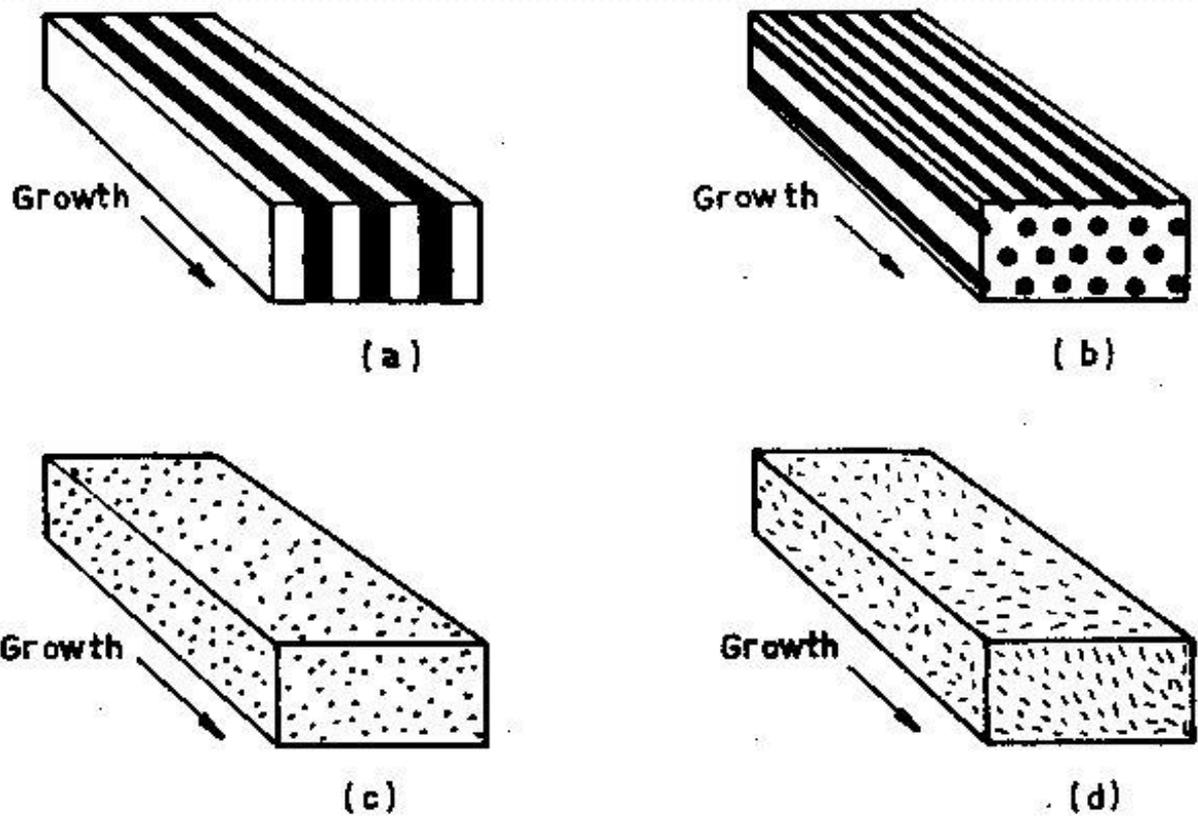
For binary alloys which are completely insoluble in solid state the diagram looks like that of bismuth and cadmium shown in Fig 4.4. Construction of the phase diagram is identical to the one explained in Fig.4.1.



All the rules described above are applicable to this type of system as well. There is one significant difference, however, and that occurs for an alloy Y which behaves like a pure metal in so far as solidification is concerned. As shown in Fig 4.4, this alloy solidifies at a constant temperature of  $T_c$  (just like pure metal). Unlike pure metal, though, the solidification product is not a single phase but a mixture of two phases, solid Bi and solid Cd, which are completely insoluble in each other.

Fig 4.4 Phase diagram of bismuth and cadmium

The two phases exist side by side with various structures as shown in Fig 4.5. The nucleation of phase Bi produces a plate. The liquid next to it becomes enriched in Cd because nucleation of Bi changes liquid composition as already explained. Due to enrichment of Cd, the liquid next to Bi solidifies as Cd in the plate form. The sequence of events continues until whole of the liquid is transformed to solid at constant temperature of  $T_c$ . Such a transformation is called a **eutectic transformation**, the temperature  $T_c$  being the **eutectic temperature**, and the alloy Y is known as **eutectic alloy**. At eutectic, it can be seen that **one phase (liquid) decomposes to produce two phases (Bi and Cd)**.



*Fig.4.5 Various eutectic structures:  
 (a) lamellar,  
 (b) rodlike,  
 (c) globular, and  
 (d) acicular.*

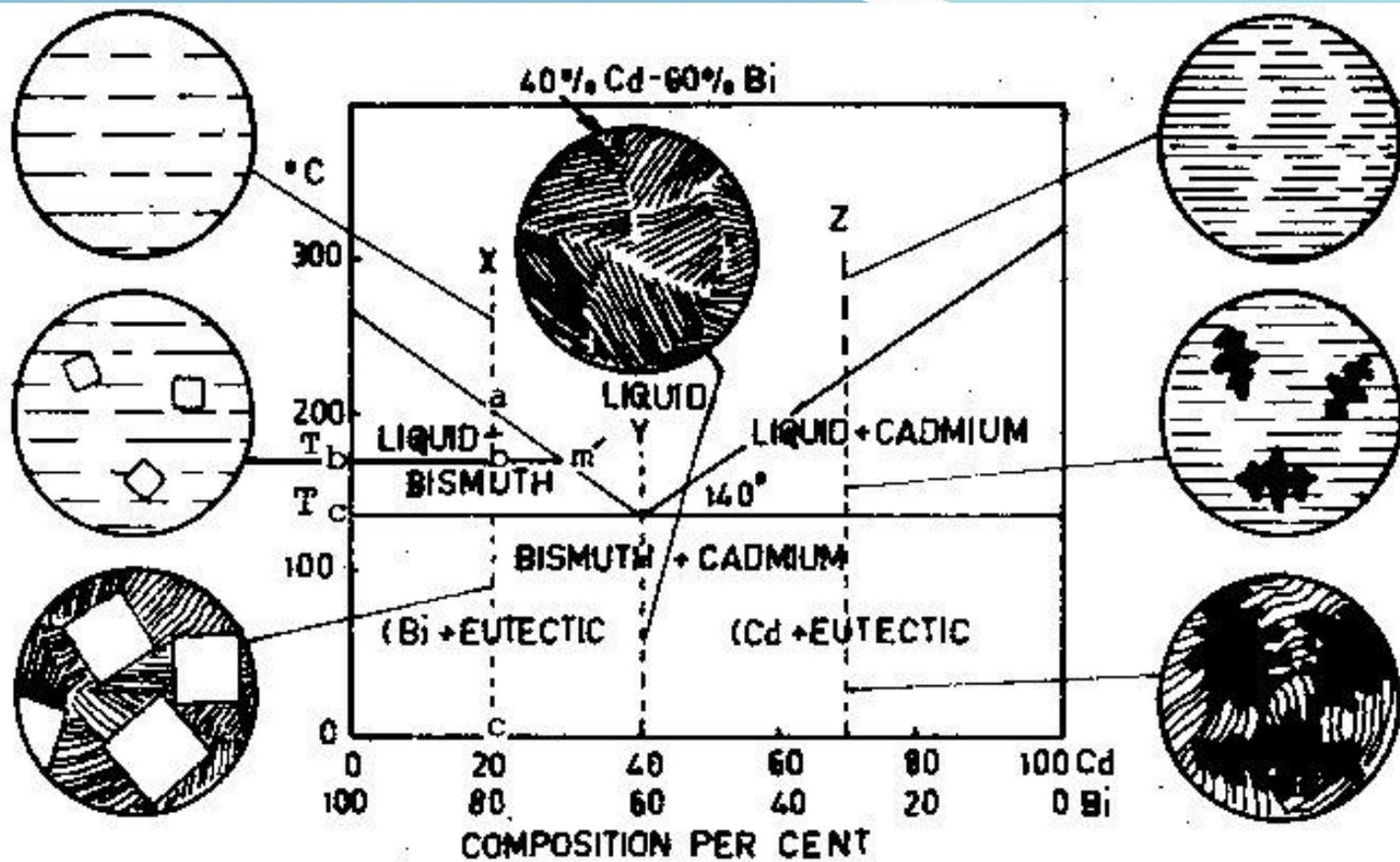


Fig.4.4 Phase diagram of bismuth and cadmium

An alloy other than Y in this type of system would solidify to produce either pure Bi or pure Cd followed by, the eutectic lamellar structure. Consider, for example, alloy X cooling from 300 °C in liquid state. At “a” it start to solidify and pure Bi begins to form. At point “b” more Bi has been formed and liquid composition is given by  $m'$  which is 30 % Cd.

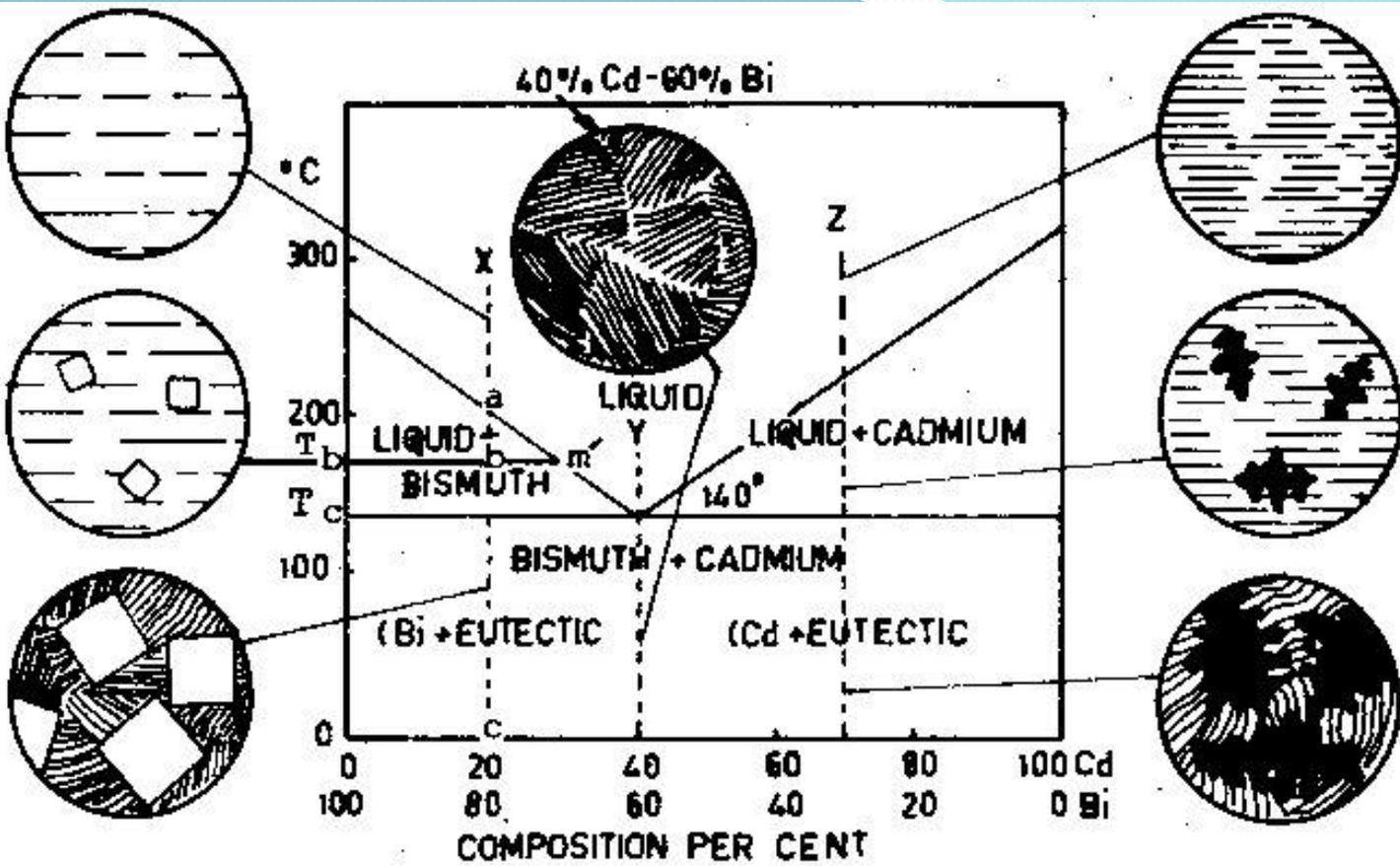


Fig.4.4 Phase diagram of bismuth and cadmium

The weight fraction of pure Bi at b is given by lever arm principle to be:

$$\frac{bm'}{T_b m'} = \frac{(30 - 20) \times 100}{30 - 0} = 33\%$$

At just above "c" the liquid composition is 40 % Cd which is eutectic composition. This remaining liquid will solidify as lamellar eutectic structure at a constant temperature  $T_c$ . Similarly alloy Z will solidify to give pure Cd followed by lamellar eutectic structure.

## 4.7. SYSTEMS PARTIALLY SOLUBLE AT SOLID STATE

The third type of alloy system which is the most common one and in which steel system falls is where the two metals are partially soluble in solid state. Copper-Silver system is an example of such a system whose equilibrium diagram is shown in Fig 4.6. Solid solution  $\alpha$  is silver rich whereas  $\beta$  is copper rich and  $\alpha + \beta$  is the mixture of the two. Again the rules and interpretation of these type of diagrams is the same as that discussed for previous types of systems. At temperatures below eutectic, solubility decreases as cooling continues. This gives rise to precipitation of new solid solutions which is the basic of age or precipitation hardening.

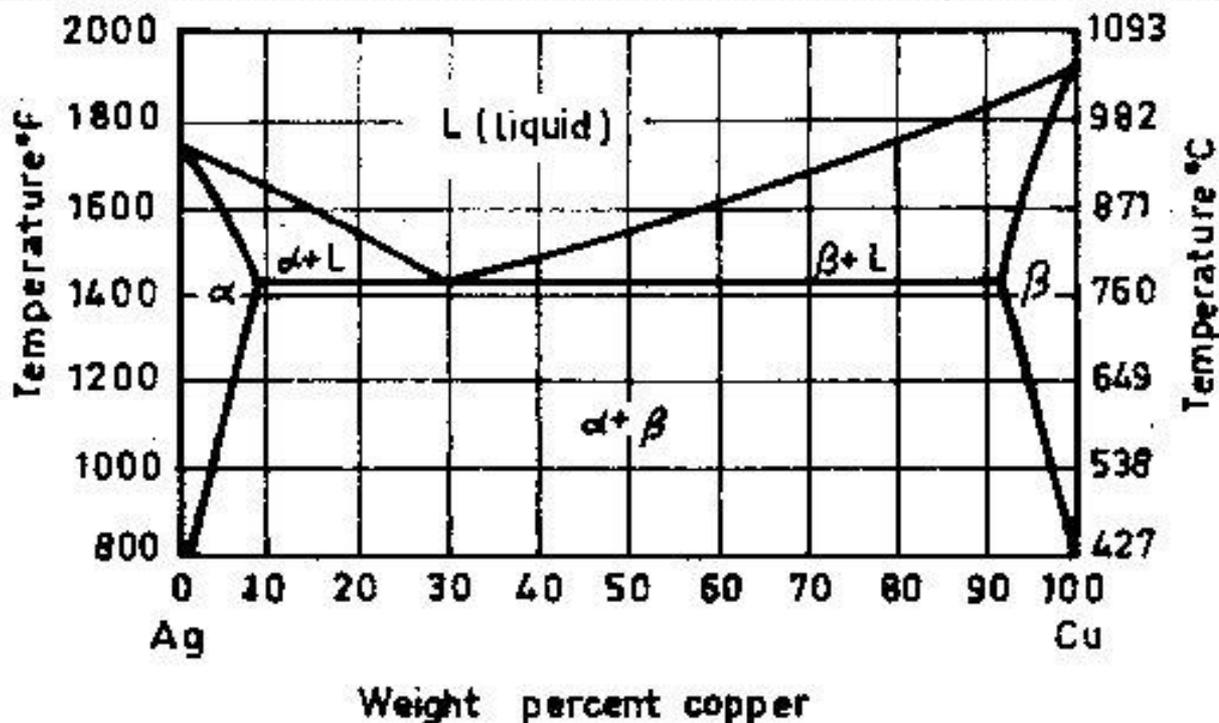


Fig.4.6 Phase diagram for silver and copper

# Binary-Eutectic Systems

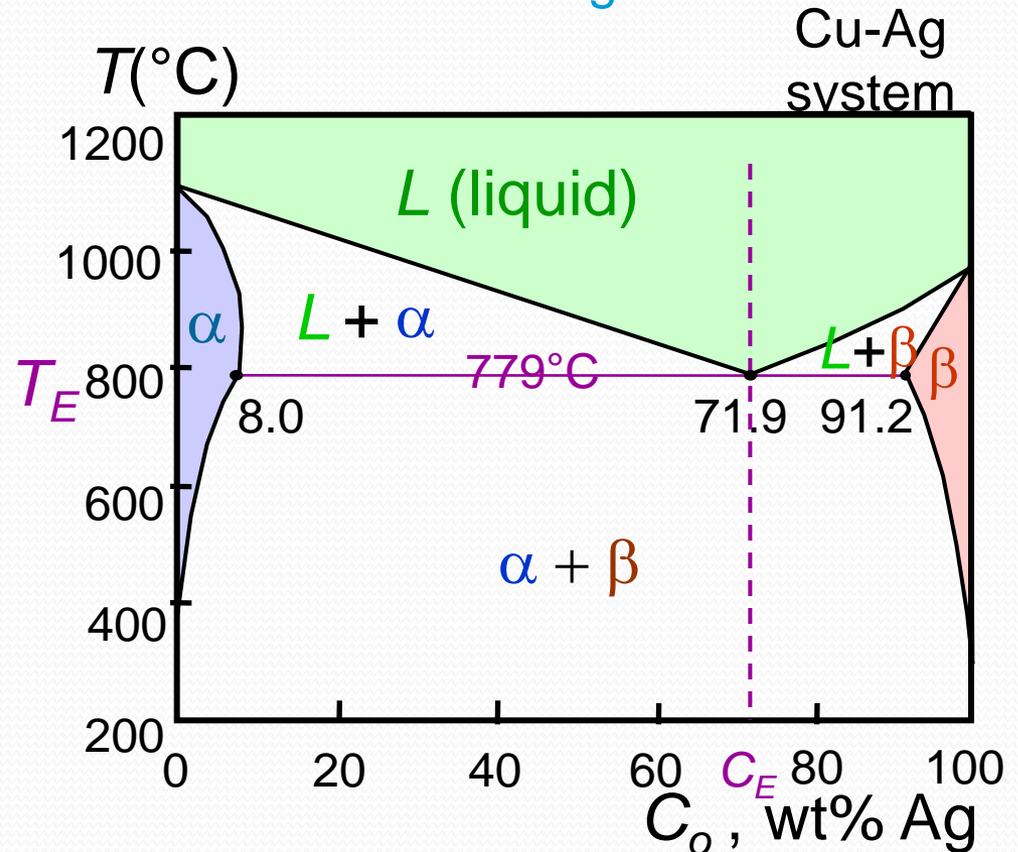
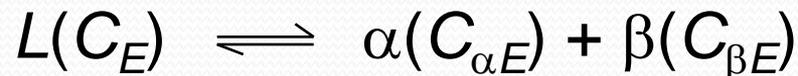
2 components

has a special composition with a min. melting T.

Ex.: Cu-Ag system

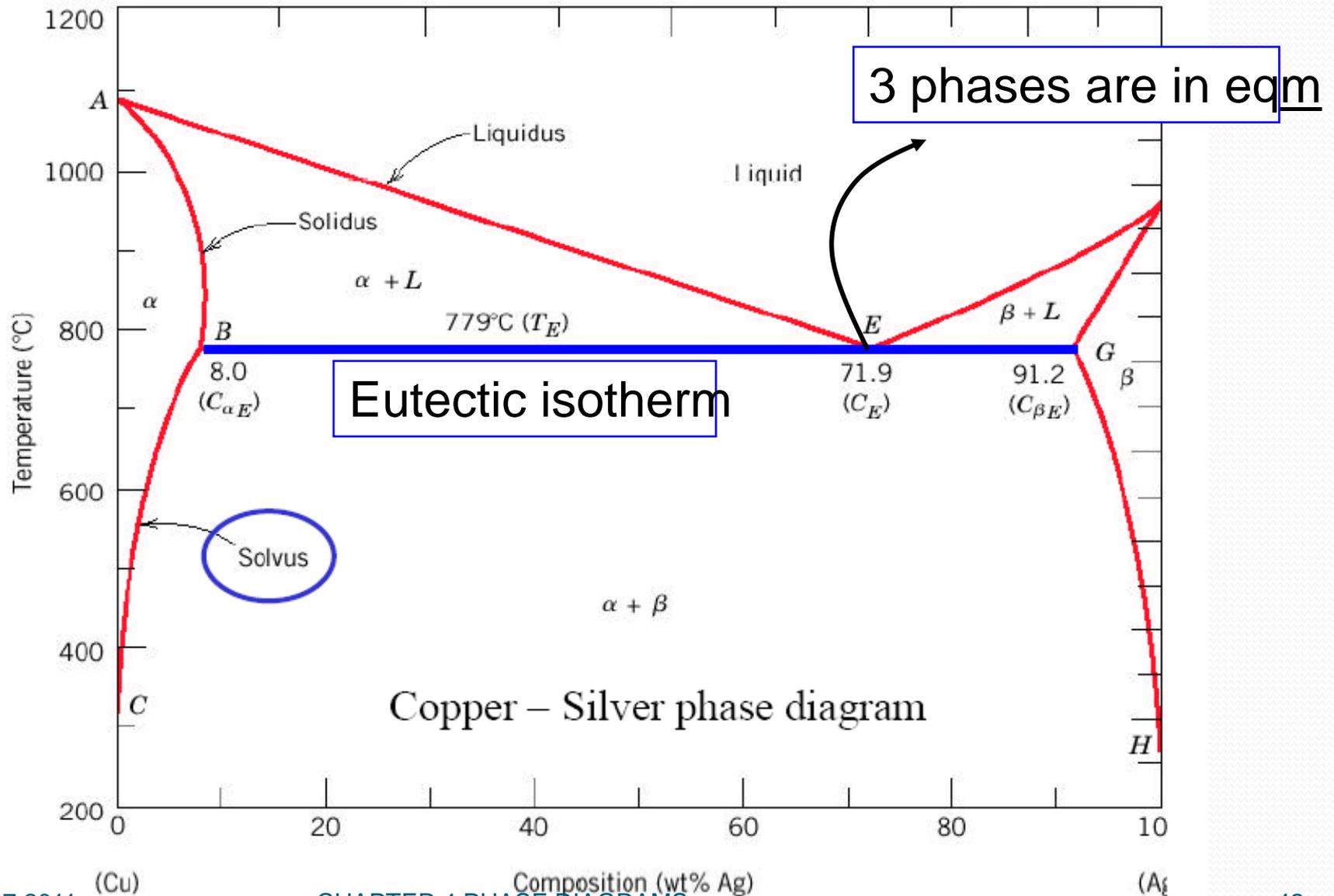
- 3 single phase regions ( $L$ ,  $\alpha$ ,  $\beta$ )
- Limited solubility:
  - $\alpha$ : mostly Cu
  - $\beta$ : mostly Ag
- $T_E$ : No liquid below  $T_E$
- $C_E$ : Min. melting  $T_E$  composition

## • Eutectic transition



Adapted from Fig. 9.7, Callister 7e.

# More Information on Eutectic Systems (I)



## More Information on Eutectic Systems (II)

- **Eutectic reaction** – transition between liquid and mixture of two solid phases,  $\alpha + \beta$ , at eutectic concentration  $C_E$ .
  - The melting point of the eutectic alloy is lower than that of the components (*eutectic = easy to melt in Greek*).
- At most two phases can be in equilibrium within a phase field. Three phases (L,  $\alpha$ ,  $\beta$ ) may be in equilibrium only at a few points along the eutectic isotherm.
- Single phase regions are separated by 2-phase regions.

# EX: Pb-Sn Eutectic System (1)

- For a 40 wt% Sn-60 wt% Pb alloy at 150°C, find...

--the phases present:  $\alpha + \beta$

--compositions of phases:

$$C_o = 40 \text{ wt\% Sn}$$

$$C_\alpha = 11 \text{ wt\% Sn}$$

$$C_\beta = 99 \text{ wt\% Sn}$$

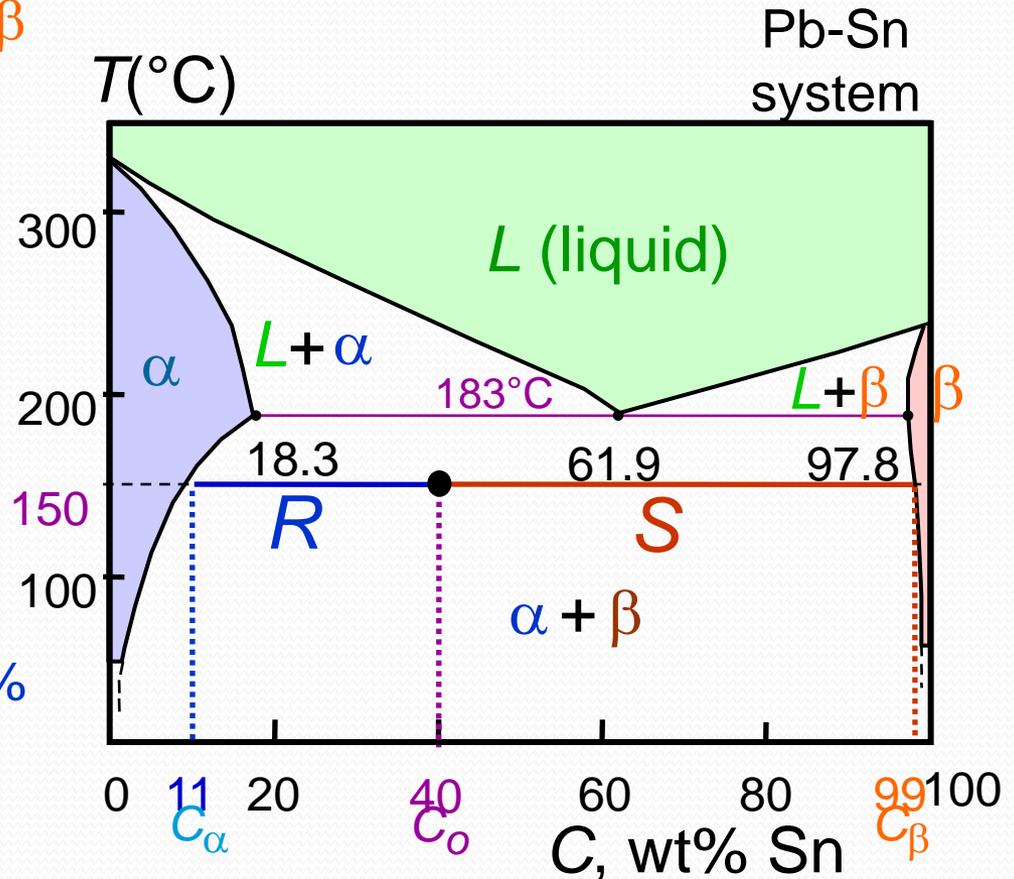
--the relative amount of each phase:

$$W_\alpha = \frac{S}{R+S} = \frac{C_\beta - C_o}{C_\beta - C_\alpha}$$

$$= \frac{99 - 40}{99 - 11} = \frac{59}{88} = 67 \text{ wt\%}$$

$$W_\beta = \frac{R}{R+S} = \frac{C_o - C_\alpha}{C_\beta - C_\alpha}$$

$$= \frac{40 - 11}{99 - 11} = \frac{29}{88} = 33 \text{ wt\%}$$



Adapted from Fig. 9.8, Callister 7e.

THE TIN-LEAD EQUILIBRIUM DIAGRAM.

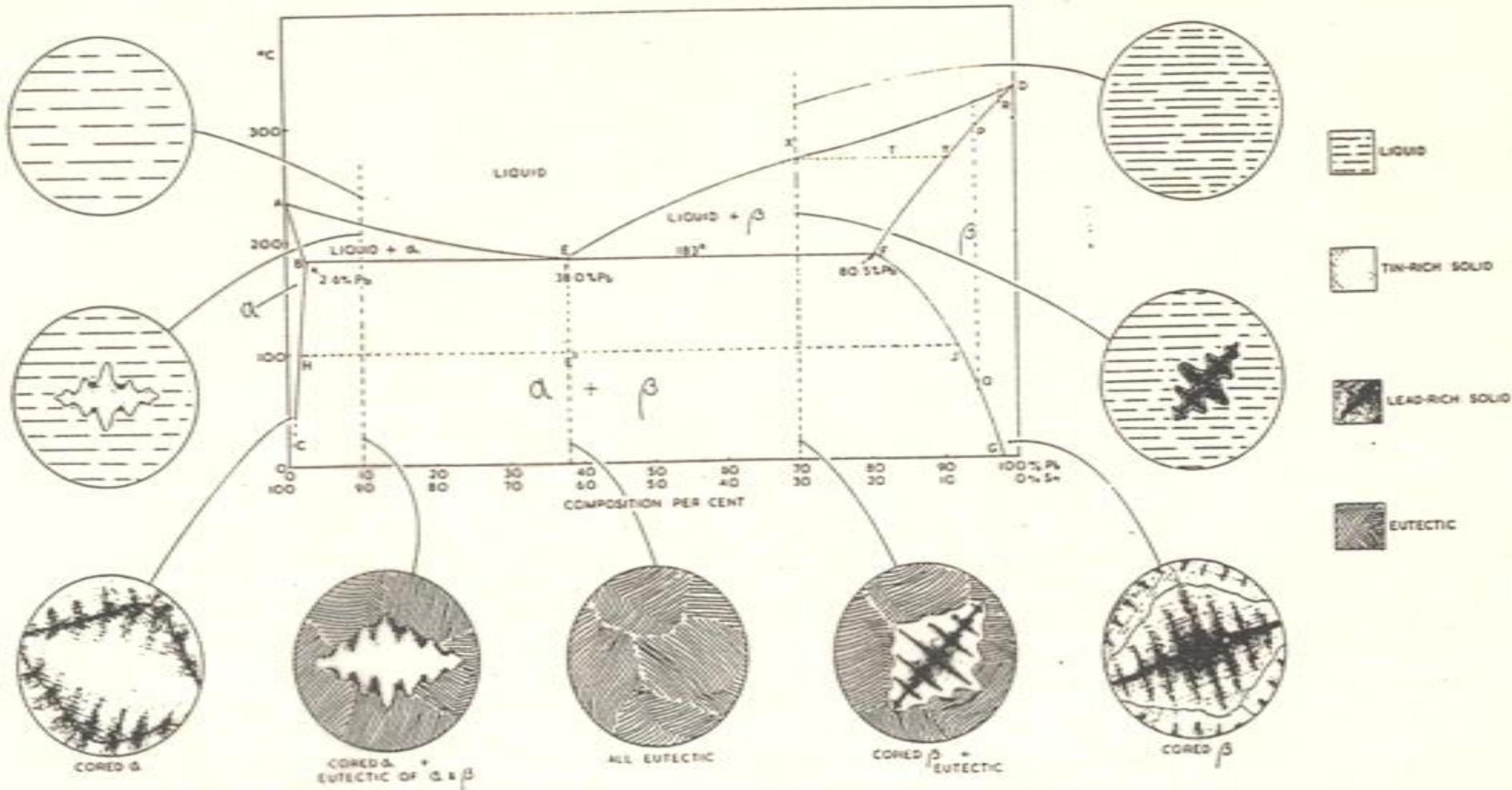
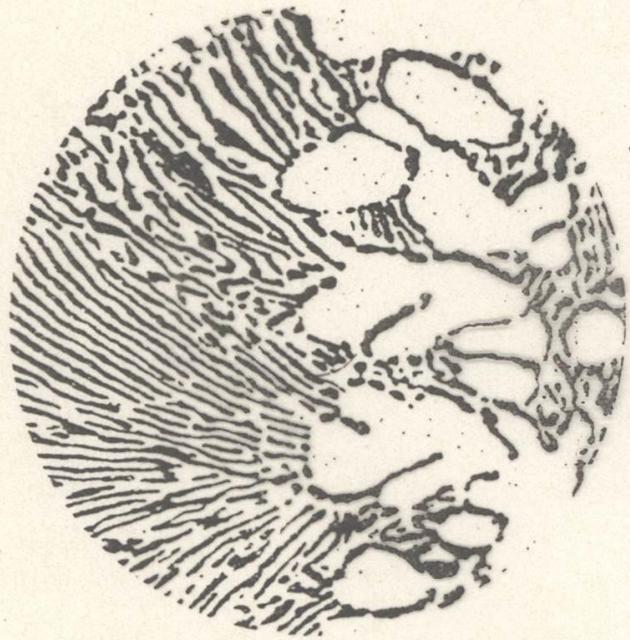
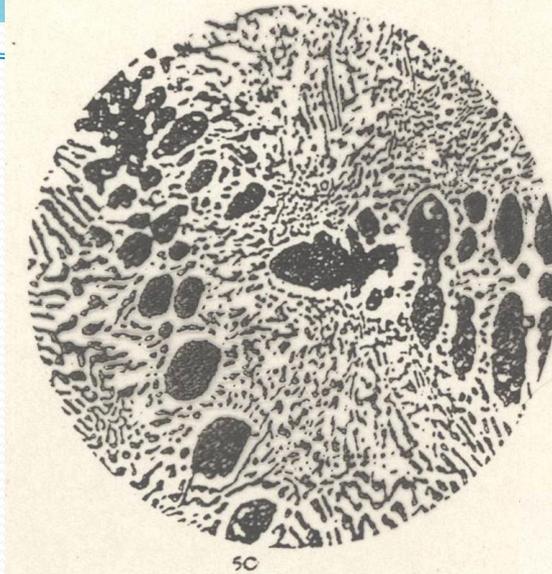


FIG. 9.12.—The tin-lead equilibrium diagram. The microstructures indicated are those obtained under non-equilibrium conditions of solidification.

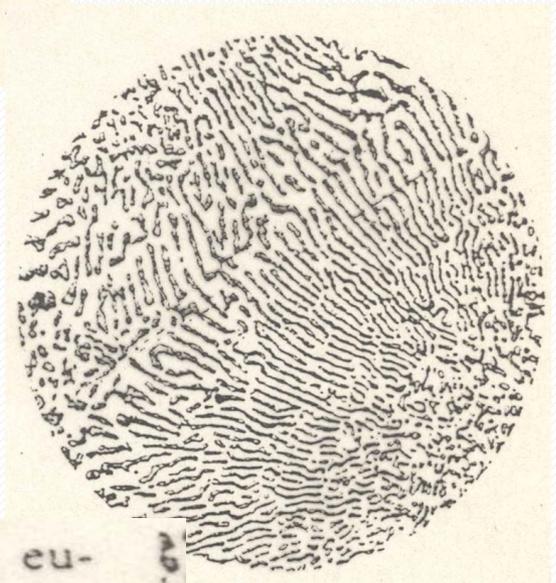


(i) 75 tin–25 lead. Primary crystals of  $\alpha$  (light) in a matrix of eutectic consisting of layers of  $\alpha$  (light) and  $\beta$  (dark).



(ii) 62 tin–38 lead. Completely eutectic in structure—layers of  $\alpha$  (light) and  $\beta$  (dark).

(iii) 50 tin–50 lead. Primary crystals of  $\beta$  (dark) in a matrix  $\alpha + \beta$  eutectic as in (i) and (ii). Note the small 'islands' of  $\alpha$  within the primary  $\beta$  crystals in (iii). These were precipitated as the alloy cooled slowly from 183°C to ambient temperature and the  $\beta$  changed in composition along the steeply-sloping solvus FG (Fig. 9.12).



# EX: Pb-Sn Eutectic System (2)

- For a 40 wt% Sn-60 wt% Pb alloy at 200°C, find...

--the phases present:  $\alpha + L$

--compositions of phases:

$$C_o = 40 \text{ wt\% Sn}$$

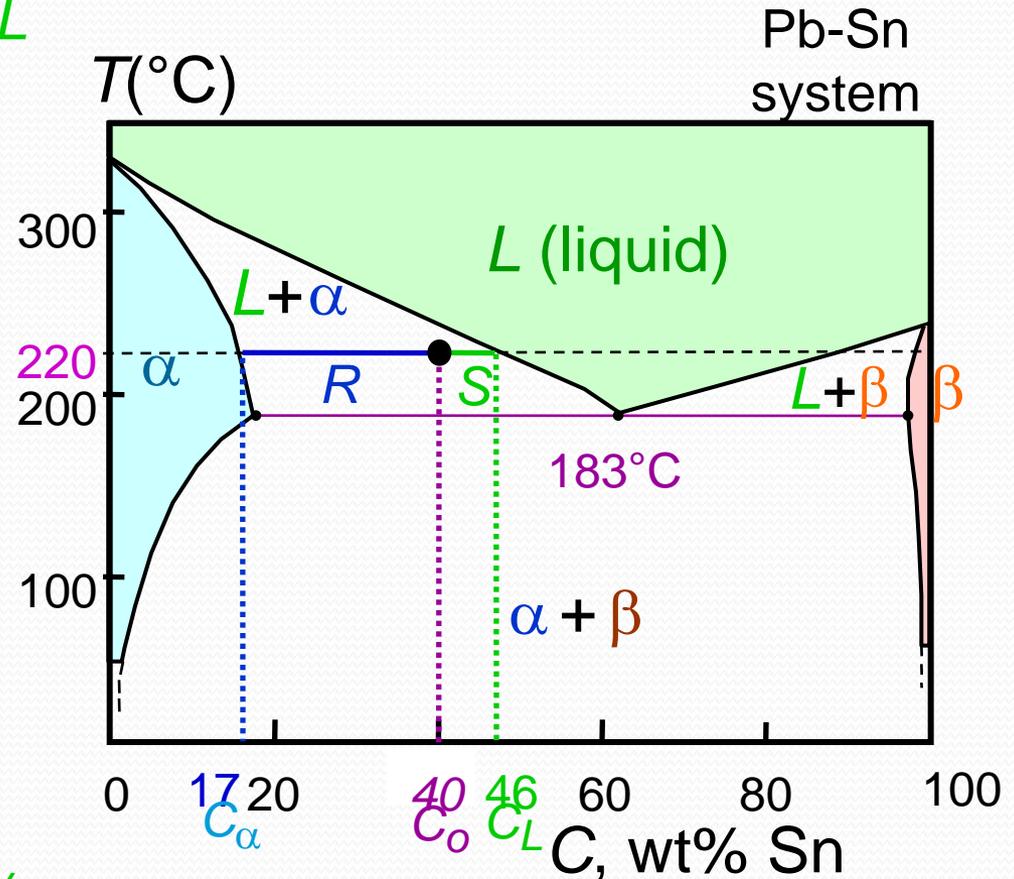
$$C_\alpha = 17 \text{ wt\% Sn}$$

$$C_L = 46 \text{ wt\% Sn}$$

--the relative amount of each phase:

$$W_\alpha = \frac{C_L - C_o}{C_L - C_\alpha} = \frac{46 - 40}{46 - 17} = \frac{6}{29} = 21 \text{ wt\%}$$

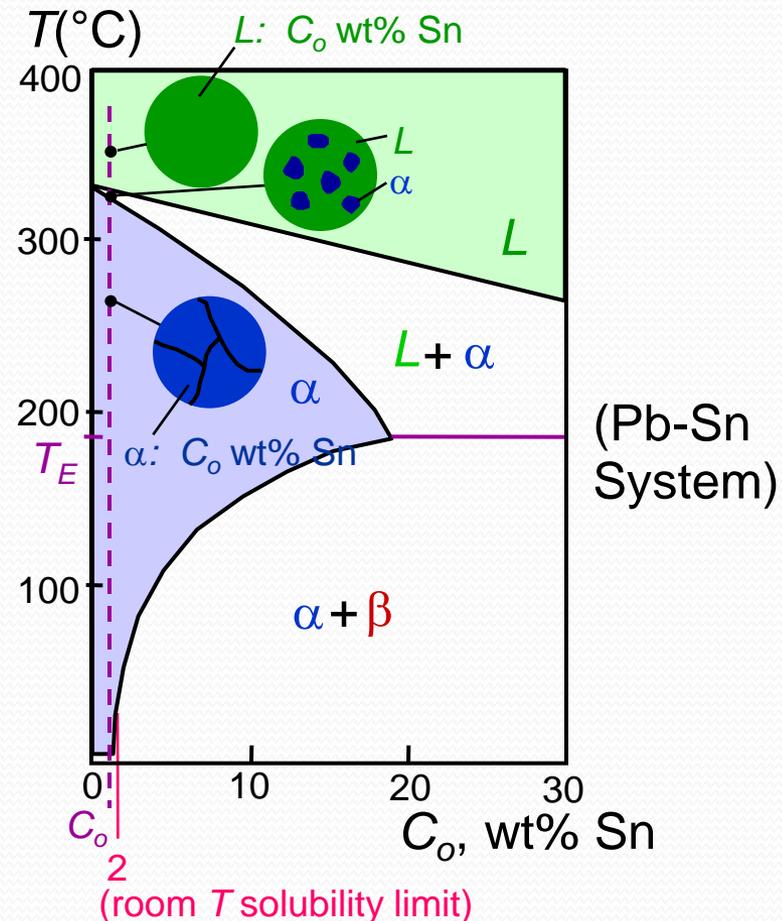
$$W_L = \frac{C_o - C_\alpha}{C_L - C_\alpha} = \frac{23}{29} = 79 \text{ wt\%}$$



Adapted from Fig. 9.8, Callister 7e.

# Microstructures in Eutectic Systems: I

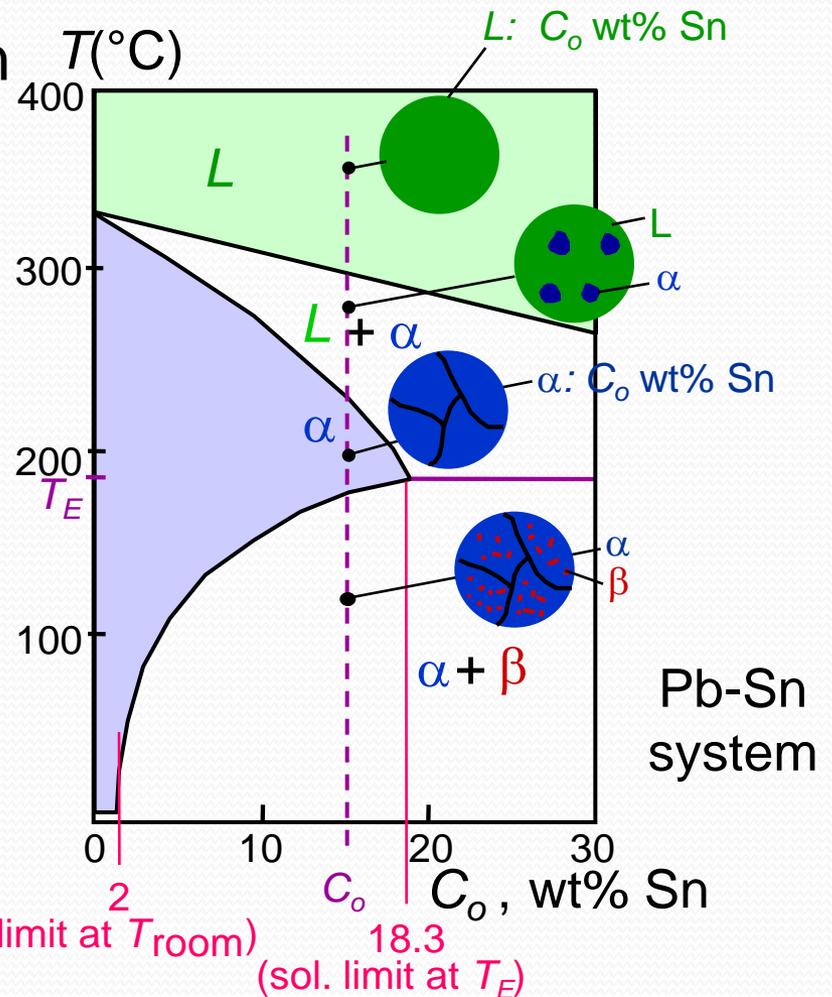
- $C_0 < 2 \text{ wt\% Sn}$
- Result:
  - at extreme ends
  - polycrystal of  $\alpha$  grains  
i.e., only one solid phase.



Adapted from Fig. 9.11,  
Callister 7e.

# Microstructures in Eutectic Systems: II

- $2 \text{ wt\% Sn} < C_0 < 18.3 \text{ wt\% Sn}$
- Result:
  - Initially liquid +  $\alpha$
  - then  $\alpha$  alone
  - finally two phases
    - $\alpha$  polycrystal
    - fine  $\beta$ -phase inclusions



Adapted from Fig. 9.12, Callister 7e.

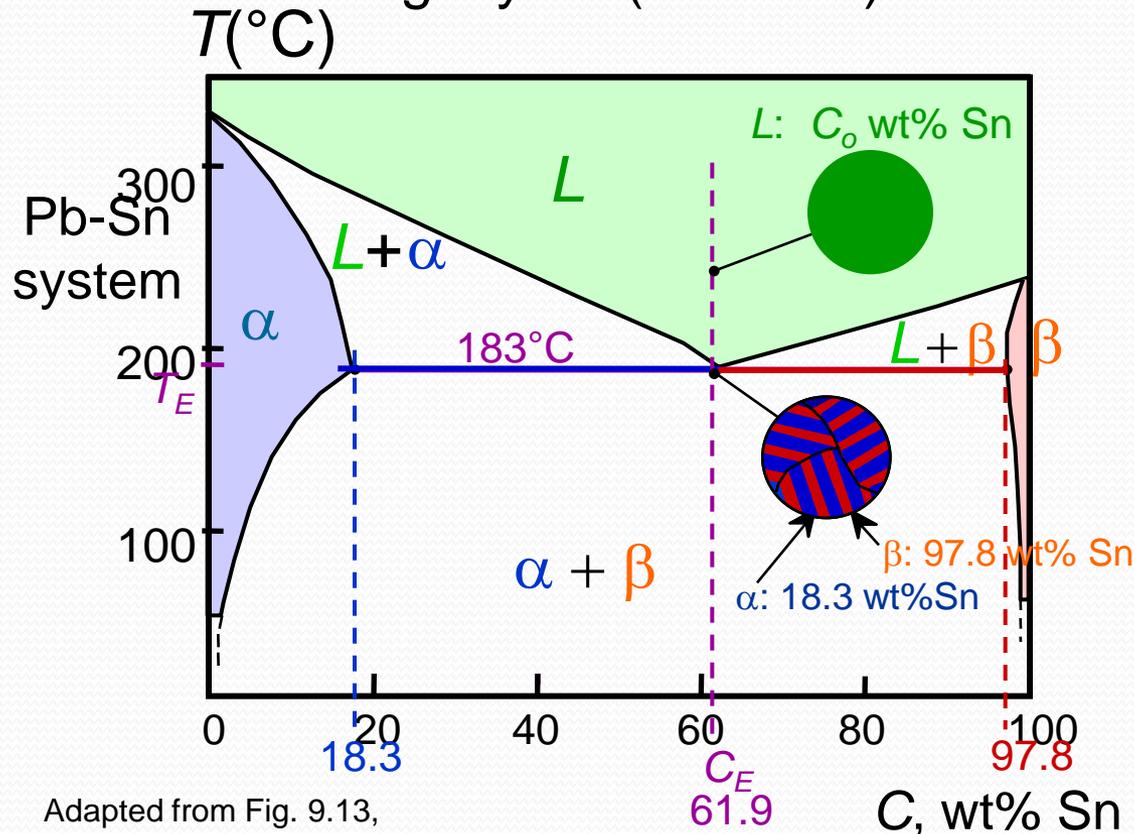
(sol. limit at  $T_{\text{room}}$ )

18.3  
(sol. limit at  $T_E$ )

# Microstructures

## in Eutectic Systems: III

- $C_0 = C_E$
- Result: Eutectic microstructure (lamellar structure)  
--alternating layers (lamellae) of  $\alpha$  and  $\beta$  crystals.



Adapted from Fig. 9.13,  
*Callister 7e.*

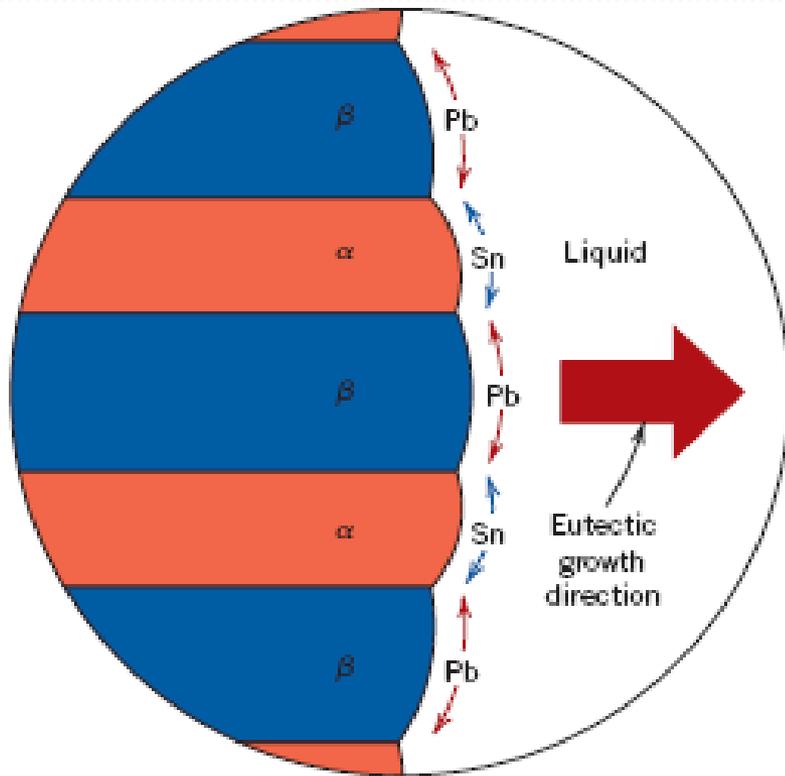
Micrograph of Pb-Sn  
eutectic  
microstructure



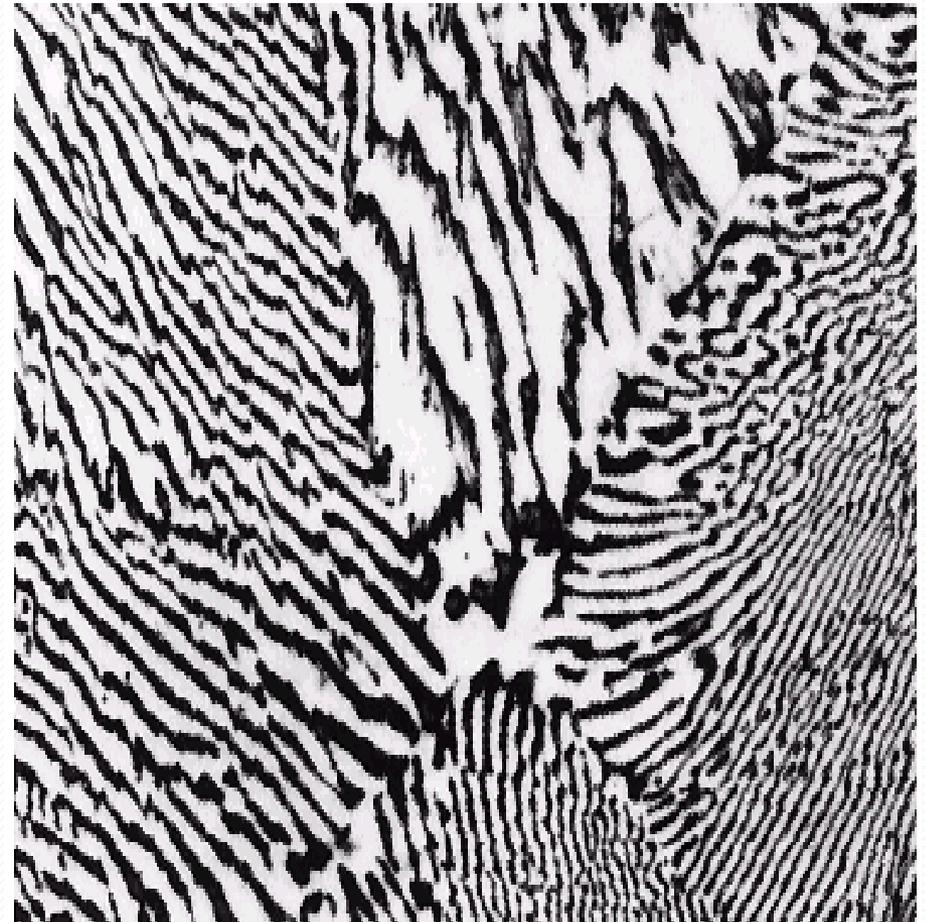
160  $\mu\text{m}$

Adapted from Fig. 9.14, *Callister 7e.*

# Lamellar Eutectic Structure

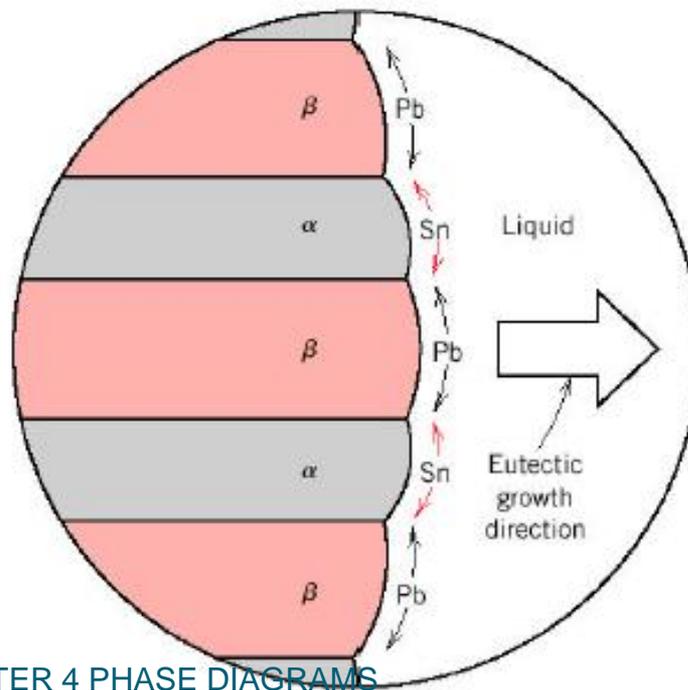


Adapted from Figs. 9.14 & 9.15, *Callister 7e*.



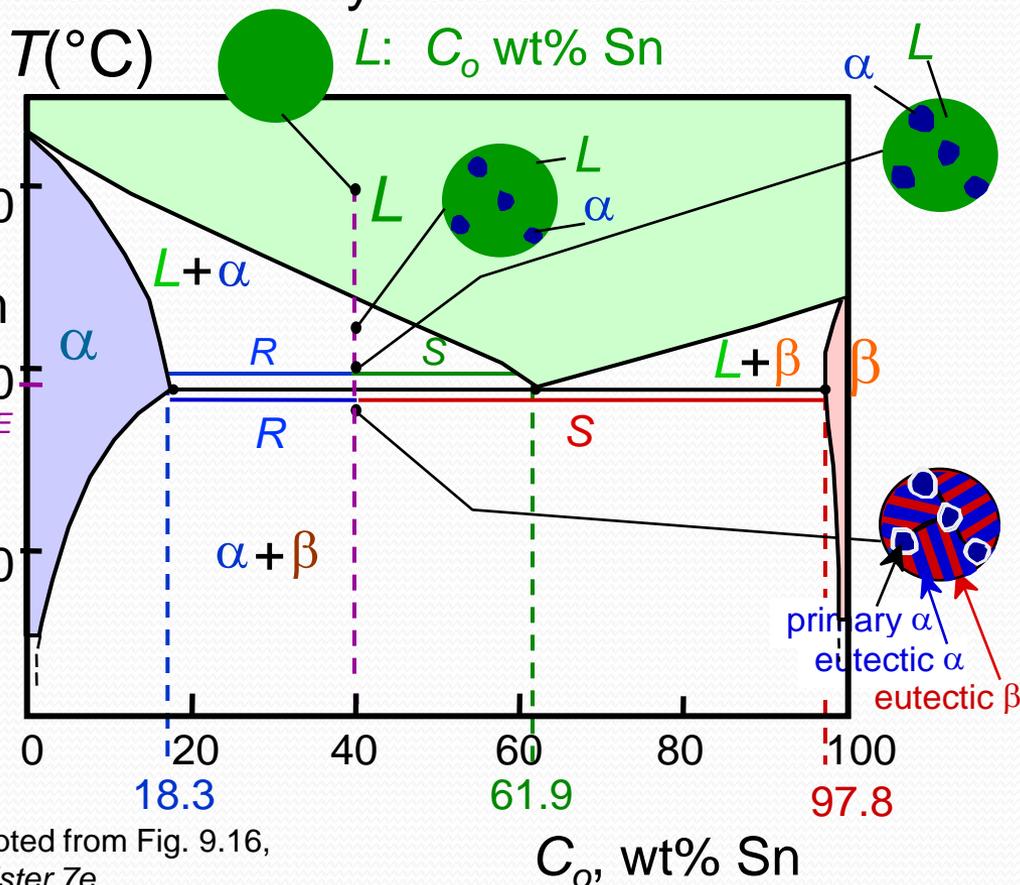
# Development of microstructure in eutectic alloys (IV)

- Compositions of  $\alpha$  and  $\beta$  phases are very different:
  - eutectic reaction involves redistribution/diffusion of Pb and Sn atoms by atomic diffusion. WHY ?
  - simultaneous formation of  $\alpha$  and  $\beta$  phases result in a layered (lamellar) microstructure that is called **eutectic s**



# Microstructures in Eutectic Systems: IV

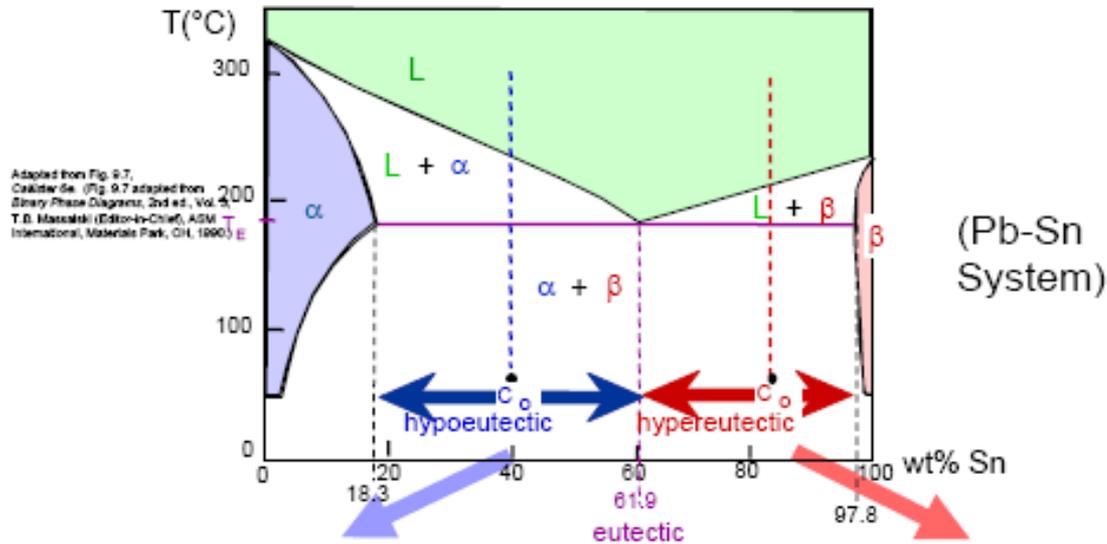
- 18.3 wt% Sn <  $C_0$  < 61.9 wt% Sn
- Result:  $\alpha$  crystals and a eutectic microstructure



Adapted from Fig. 9.16,  
Callister 7e.

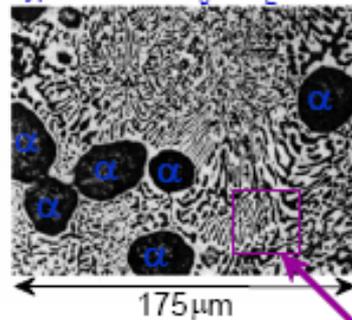
- Just above  $T_E$ :  
 $C_\alpha = 18.3$  wt% Sn  
 $C_L = 61.9$  wt% Sn  
 $W_\alpha = \frac{S}{R+S} = 50$  wt%  
 $W_L = (1 - W_\alpha) = 50$  wt%
- Just below  $T_E$ :  
 $C_\alpha = 18.3$  wt% Sn  
 $C_\beta = 97.8$  wt% Sn  
 $W_\alpha = \frac{S}{R+S} = 73$  wt%  
 $W_\beta = 27$  wt%

# HYPOEUTECTIC & HYPEREUTECTIC



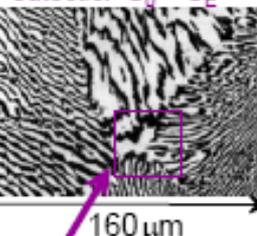
hypoeutectic:  $C_0 < C_E$

$\alpha$  and eutectic



Adapted from Fig. 9.15, Callister 6e.

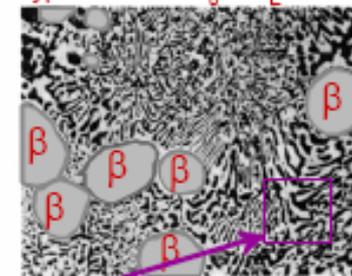
eutectic:  $C_0 = C_E$



eutectic micro-constituent

hypereutectic:  $C_0 > C_E$

$\beta$  and eutectic



## 4.8. ISOTHERMAL REACTIONS

The constant temperature transformation reactions taking place in a binary system in liquid or solid states are as follows:

1. **Eutectic** is the reaction whereby a liquid changes to two solid phases at a constant temperature :



as already explained in the previous section.

2. **Eutectoid** is the reaction whereby a solid changes to two different solid phases at a constant temperature :



This is essentially the same as eutectic except that all phases involved in reaction are solids. Example of such a reaction is given in Fe-C system and is depicted schematically in Fig 4.7.

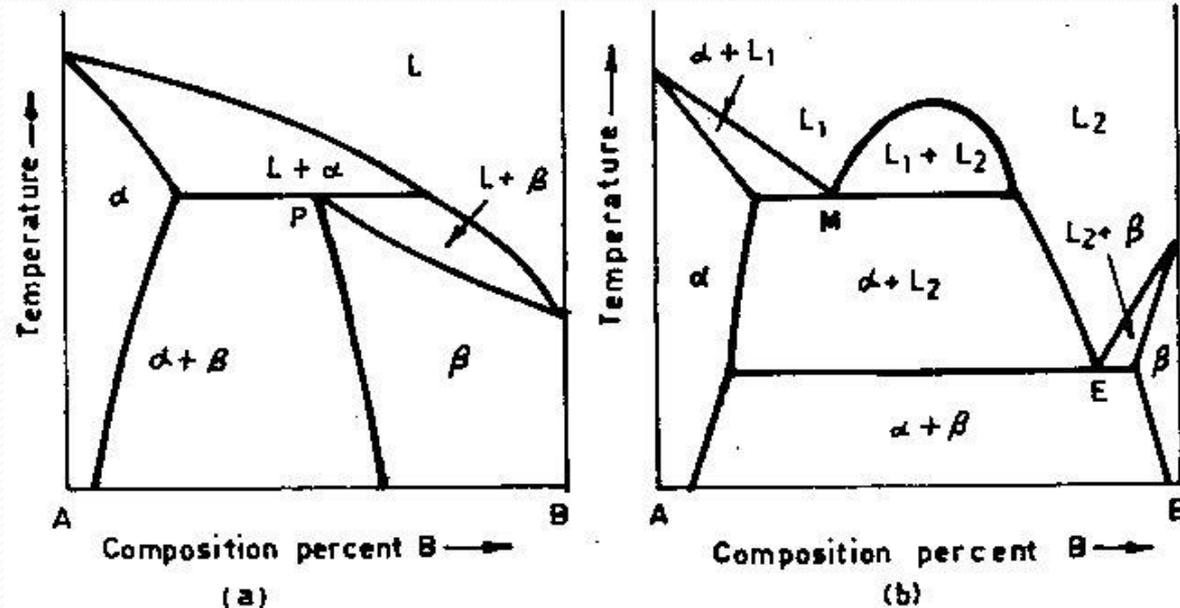


Fig.4.7 (a) Peritectic, and  
(b) Monotectic reactions

**3. Peritectic** is the reverse of eutectic in that in peritectic reaction one solid phase and liquid phase combine to produce another solid phase :  $\alpha + L \rightarrow \beta$

This reaction occurs when the solidification temperature of two phases has a large difference. Fig 4.7 depicts it schematically and it occurs in Fe-C system

**4. Peritectoid** is the same reaction as peritectic except that it is a solid state reaction :  $\alpha + \beta \rightarrow \gamma$

It is found in Ni-Zn, Fe-Nb systems etc.

**5. Monotectic** is a reaction which depends upon a gap in liquid solubility just as eutectic, peritectic etc are based on a gap in solid solubility. Monotectic is similar to eutectic except that on cooling one liquid transforms to a solid phase and another liquid phase as depicted in Fig 4.7. The reaction is  $L1 \rightarrow \alpha + L2$

This reaction is found in Zn-Pb, Cu-Pb systems etc.

**6. Monotectoid** is same as monotectic. except that it is in solid state. Al-Zn and other systems show such a feature . The use of this term, however, is not widespread as it could be argued that it is same as eutectoid. The reaction is written as  $u1 \rightarrow \alpha + U2$

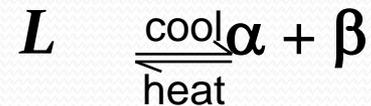
which is the same as eutectoid

**7. Syntectic** is a reaction of peritectic type in which two liquids combine to form one solid :  $L1 + L2 \rightarrow \beta$

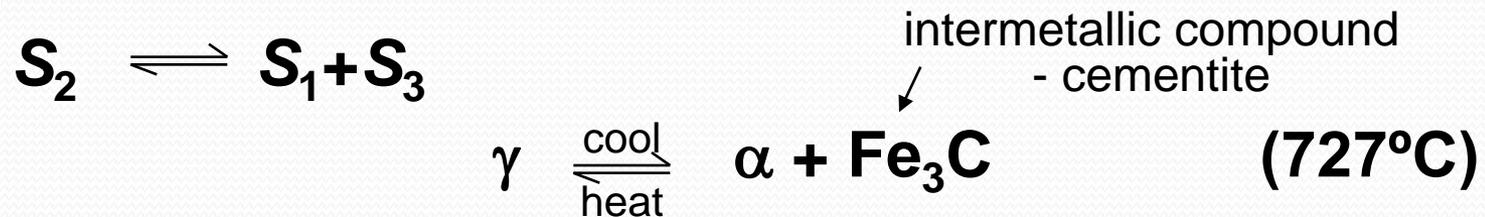
The best example of this reaction is found in Na-Zn system

# Eutectoid & Peritectic

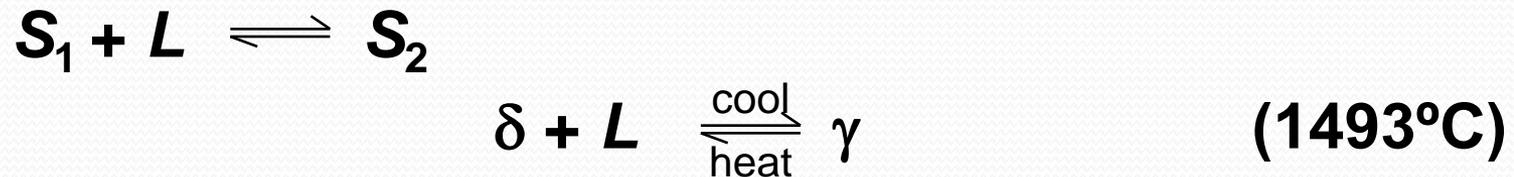
- **Eutectic** - liquid in equilibrium with two solids



- **Eutectoid** - solid phase in equilibrium with two solid phases



- **Peritectic** - liquid + solid 1  $\rightarrow$  solid 2 (Fig 9.21)



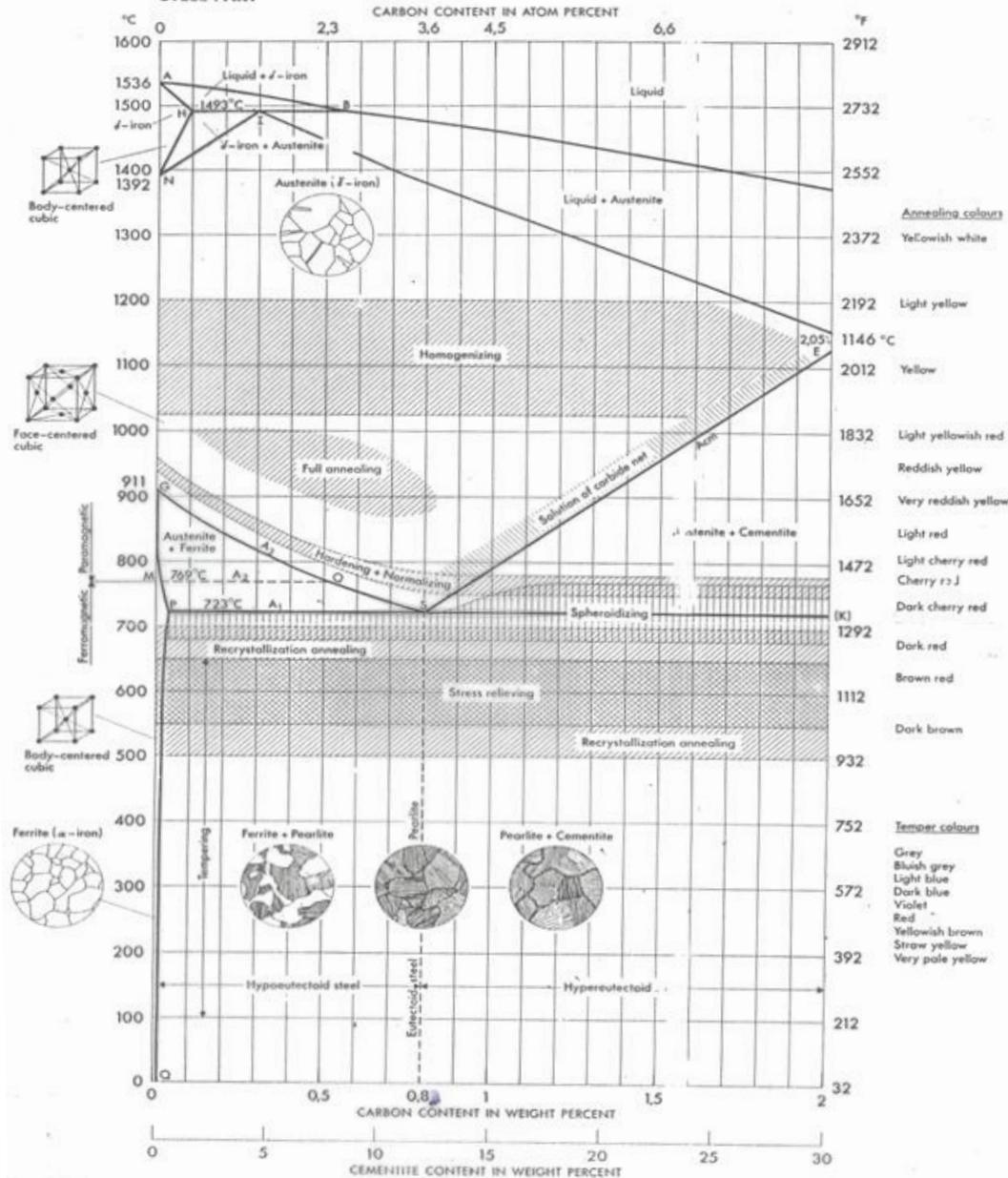


TO BE CONTINUED

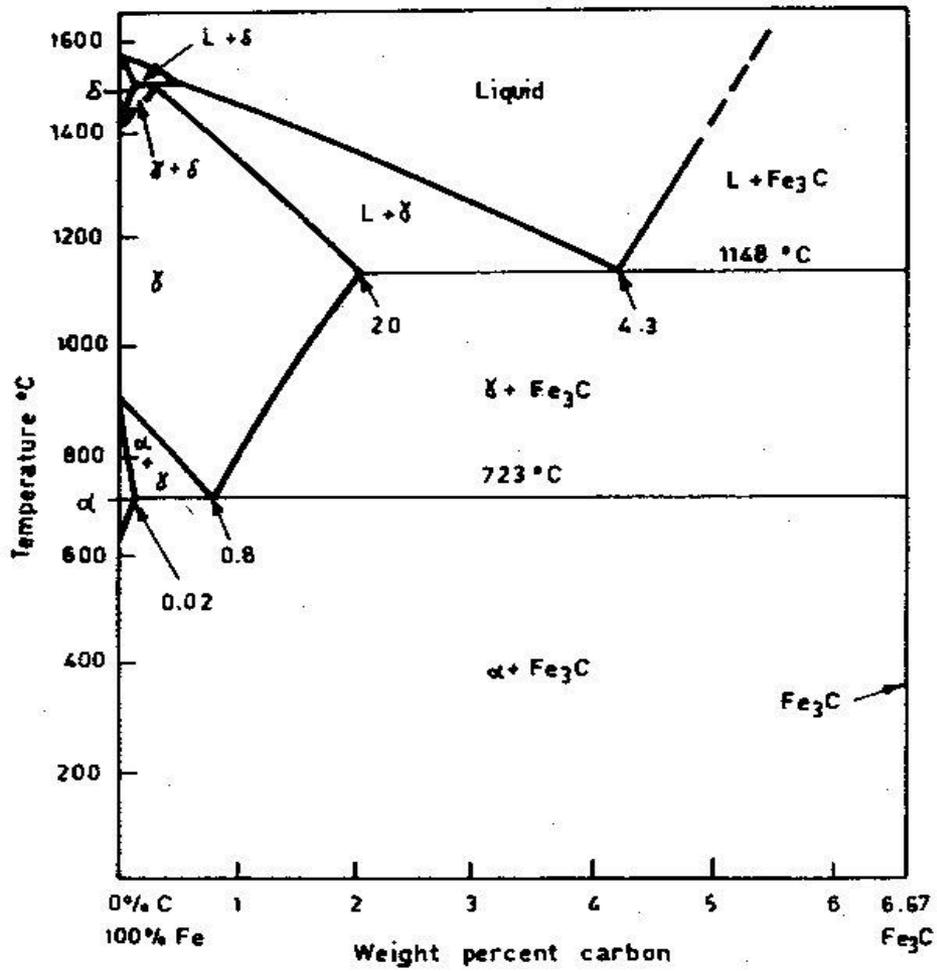
**CHAPTER 4**  
**PHASE DIAGRAMS-II**

# IRON-CARBON EQUILIBRIUM DIAGRAM

STEEL PART



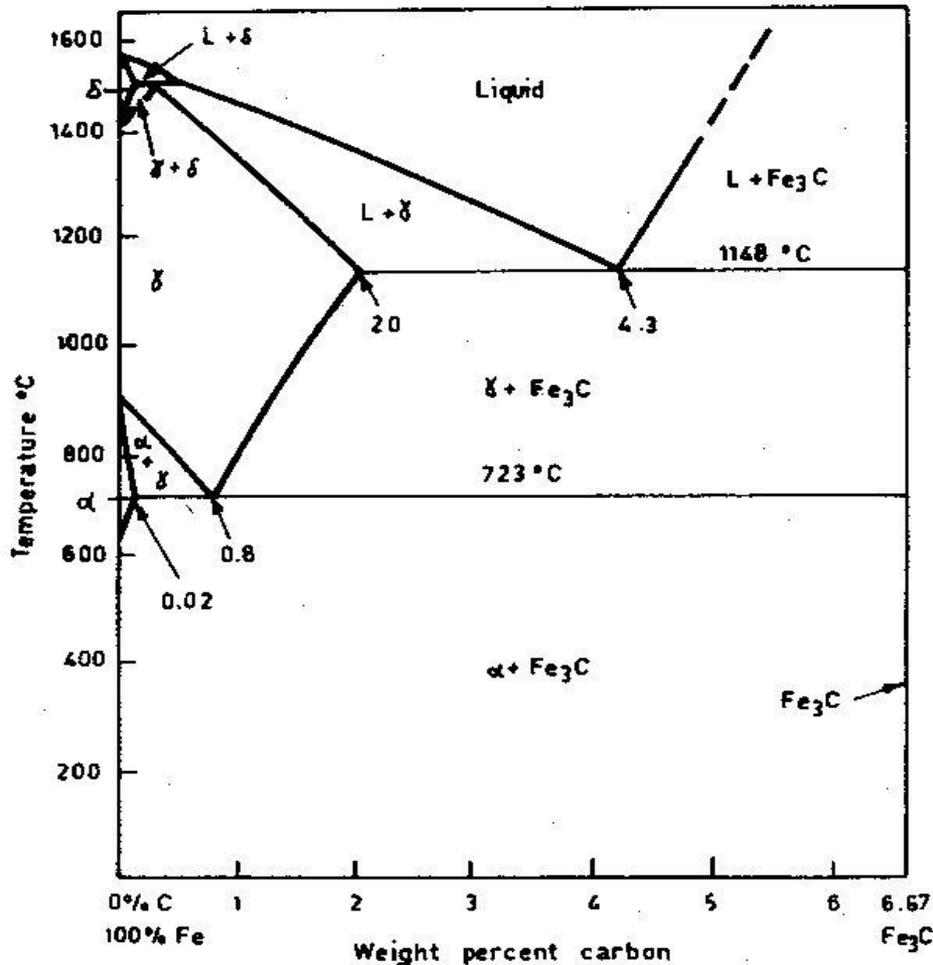
# 4.9. IRON-CARBON DIAGRAM



Iron being an **allotropic** metal exists in more than one crystal structures depending upon temperature. At 1534 °C it solidifies to a BCC structure called delta iron. All the remaining changes involve change of lattice structures in solid state iron. At 1390 °C delta iron transforms to a FCC structure called austenite and at 910 °C austenite transforms to a BCC structure called ferrite. The next transformation is not a structural change when non-magnetic ferrite ( $\beta$ -iron) changes to magnetic ferrite ( $\alpha$ -iron).

Fig.4.8 Iron-carbon phase diagram

## 4.9. IRON-CARBON DIAGRAM



Iron carbon phase diagram, which forms the basis of steels and cast irons, is the most important phase diagram for engineers. A large variety of structures can be obtained by varying carbon content, rate of transformation and transformation temperature, which makes steel the most fascinating and widely used engineering material.

In order to utilize this versatility of steel for a specific purpose, it is imperative for an engineer to have an understanding of the iron-carbon diagram which underlies any treatment of steels and cast irons.

Fig.4.8 Iron-carbon phase diagram

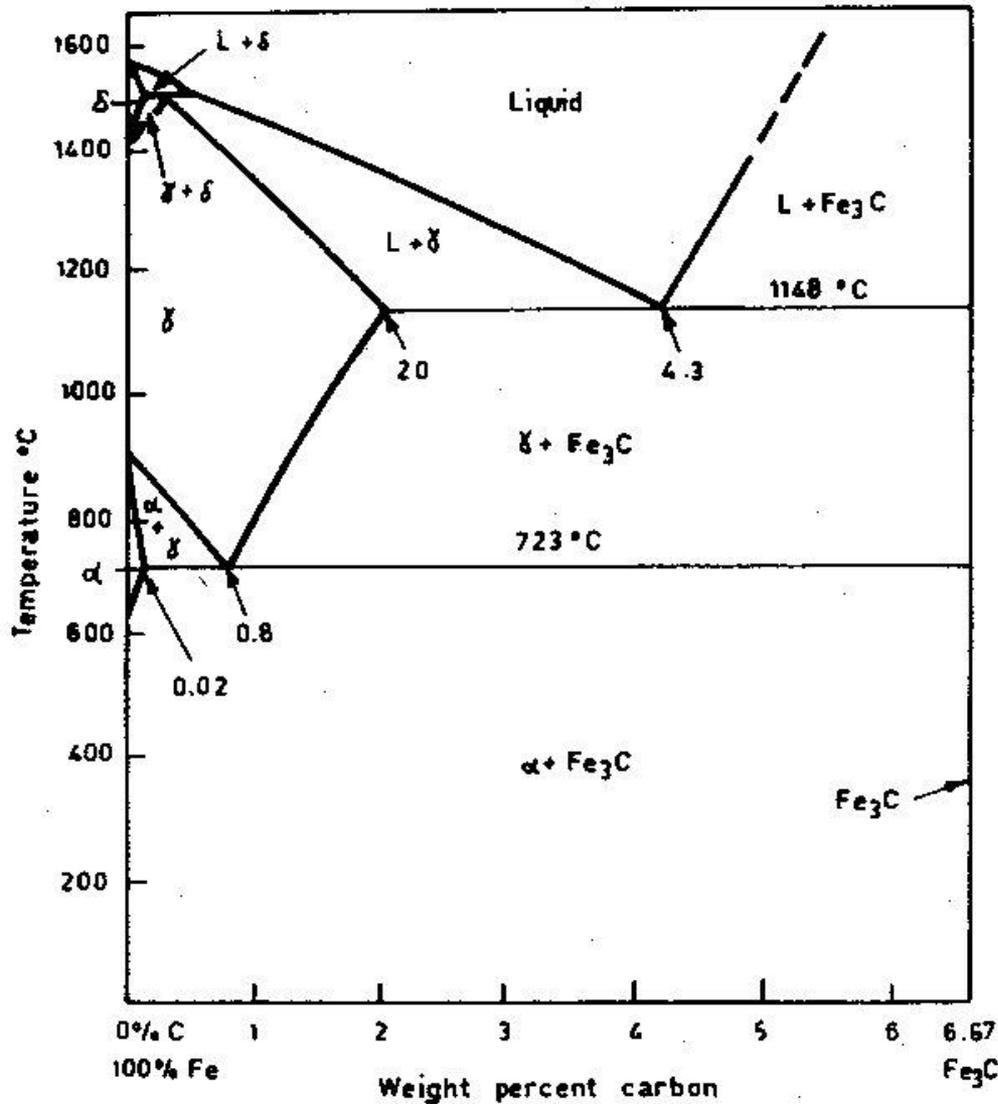


Fig.4.8 Iron-carbon phase diagram

A simplified version of this diagram is shown in Fig 4.8. This diagram is essentially the same as phase diagrams discussed in the preceding. It has more lines which represents the various solid state reactions. It ends at 6.67 % carbon because the weight percent of carbon in iron carbide is 6.67 % (see Example 4.3).

Iron containing up to 2 % carbon is classified as steel whereas cast irons contain between 2-4 % carbon..

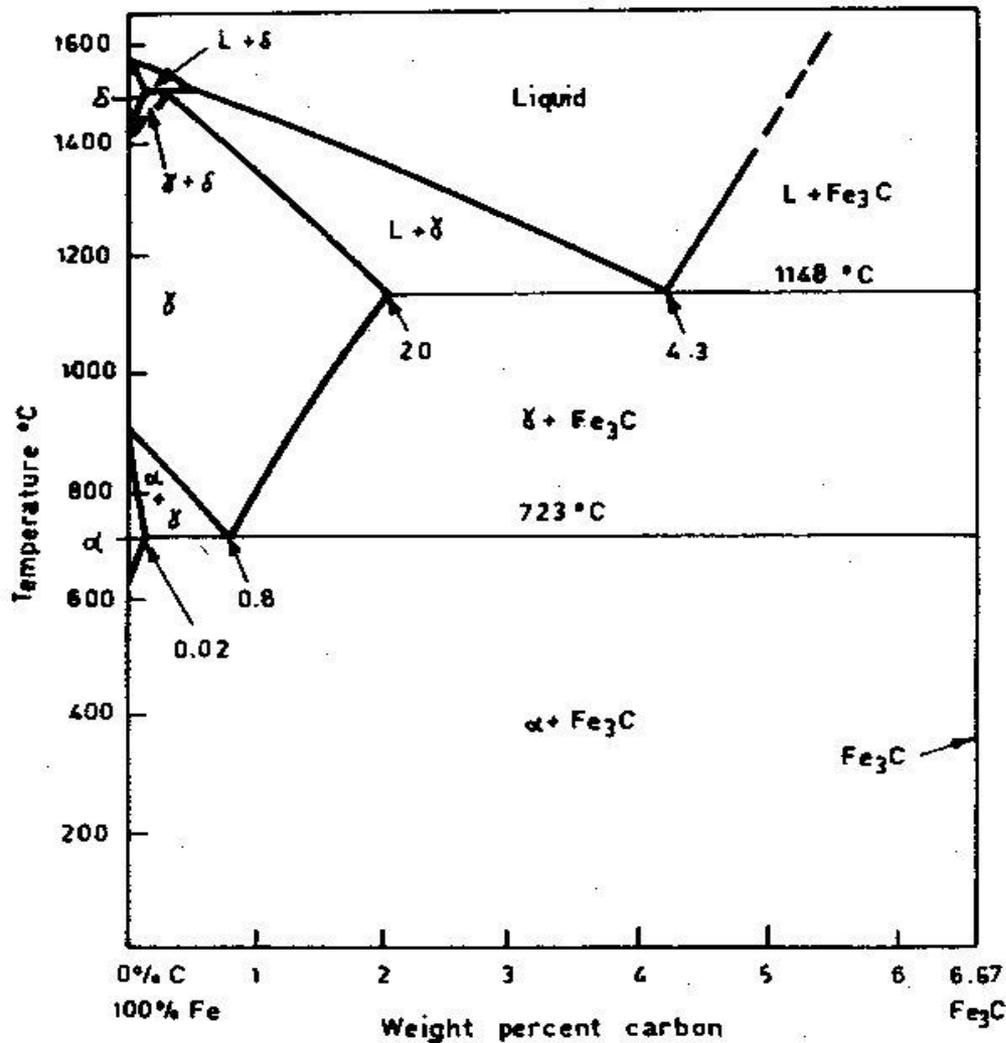
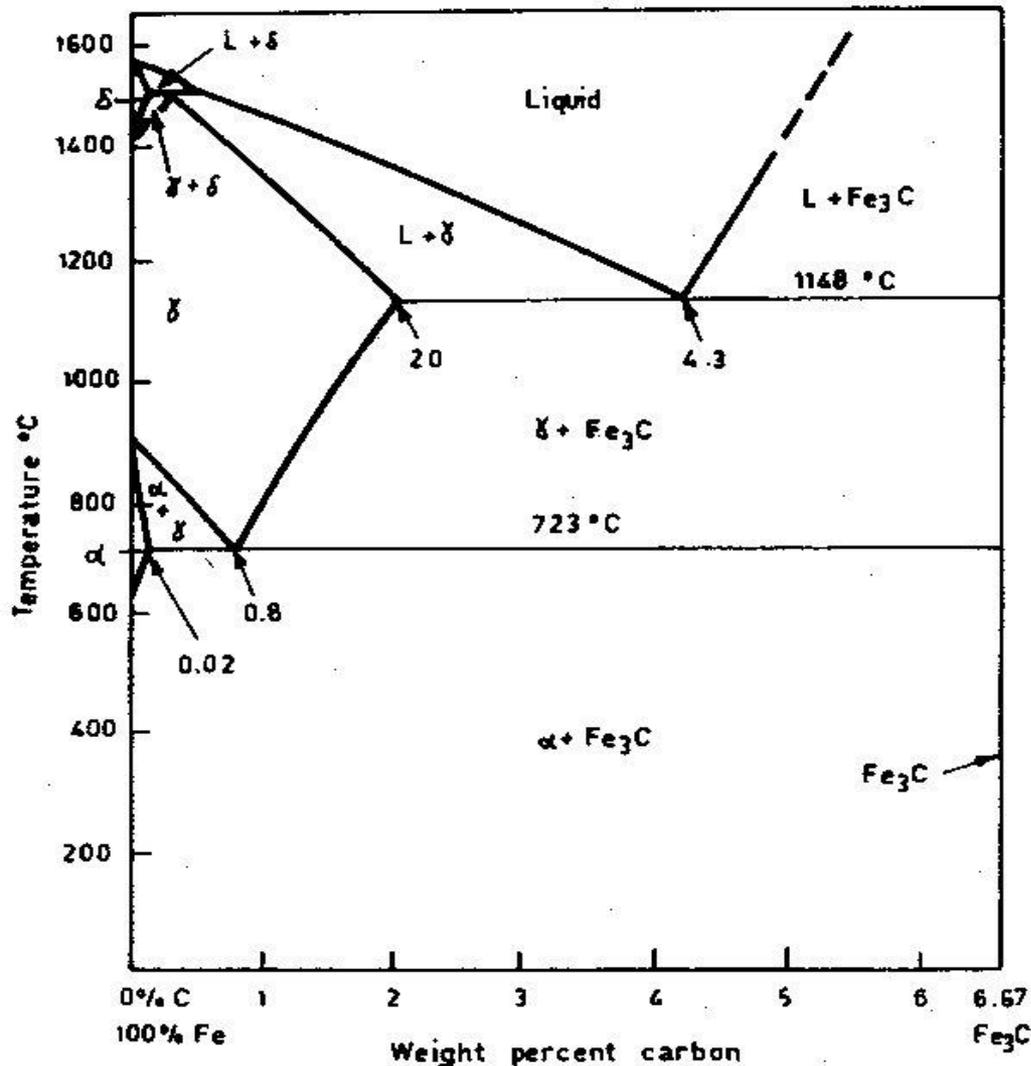


Fig.4.8 Iron-carbon phase diagram

A eutectic reaction takes place at 1,147 °C where liquid of composition 4.3 % carbon solidifies into a **eutectic mixture of austenite and cementite**. This eutectic mixture is known as **ledeburite**

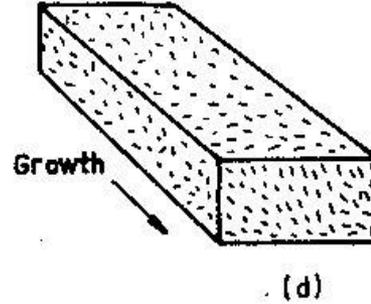
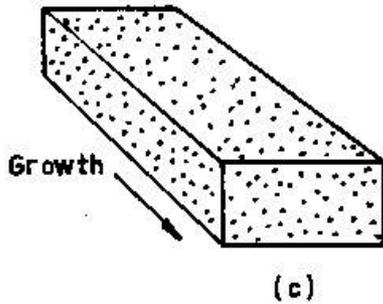
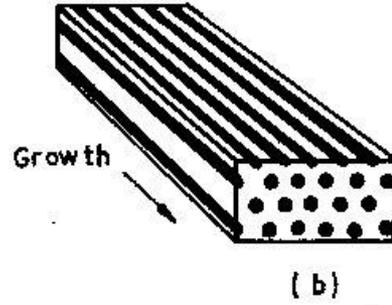
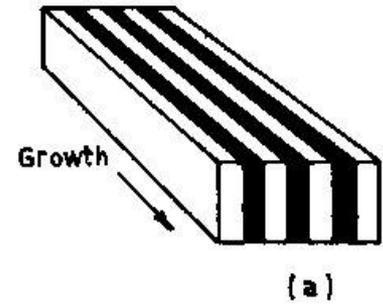
Delta iron which is stable between 1390 °C and 1534°C changes to FCC austenite below 1390°C. Austenite is a solid solution of iron and carbon. It can dissolve maximum of 2% carbon interstitially at 1147°C. At 910°C austenite transforms to ferrite which is a BCC solid solution of iron and carbon.



At room temperature ferrite can dissolve a maximum of 0.008% carbon interstitially whereas at 723°C it can dissolve up to 0.025% carbon. Steel containing 0.83% carbon changes from **austenite** to **ferrite + cementite** at a constant temperature of 723 °C which is a **eutectoid reaction**.

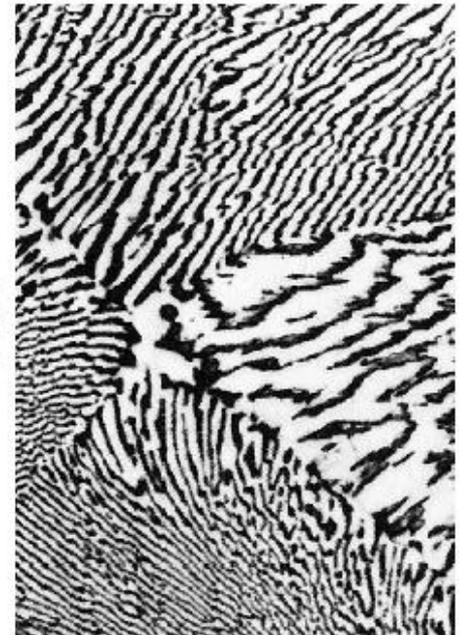
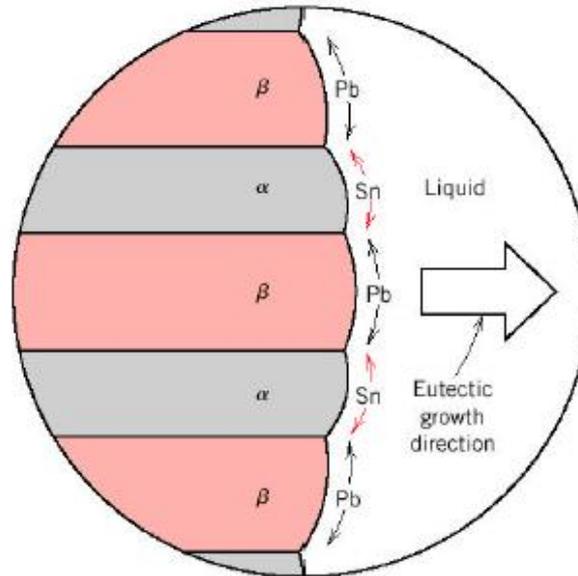
The lines  $A_3$  and  $A_{cm}$  are called **upper critical temperatures** at which the decomposition of austenite begins. The temperatures represented by lines  $A_1$  and  $A_{3,1}$  is **lower critical temperature** at which the transformation of austenite is complete.

Fig.4.8 Iron-carbon phase diagram



The eutectoid product consists of a lamellar structure called pearlite which is the same as that shown in Fig 4.5; one plate is ferrite and the other is cementite. Ferrite which nucleates before eutectoid is called pro-eutectoid ferrite as against the eutectoid ferrite produced by the eutectoid reaction as explained above.

*Fig.4.5 Various eutectic structures:  
 (a) lamellar,  
 (b) rodlike,  
 (c) globular, and  
 (d) acicular.*



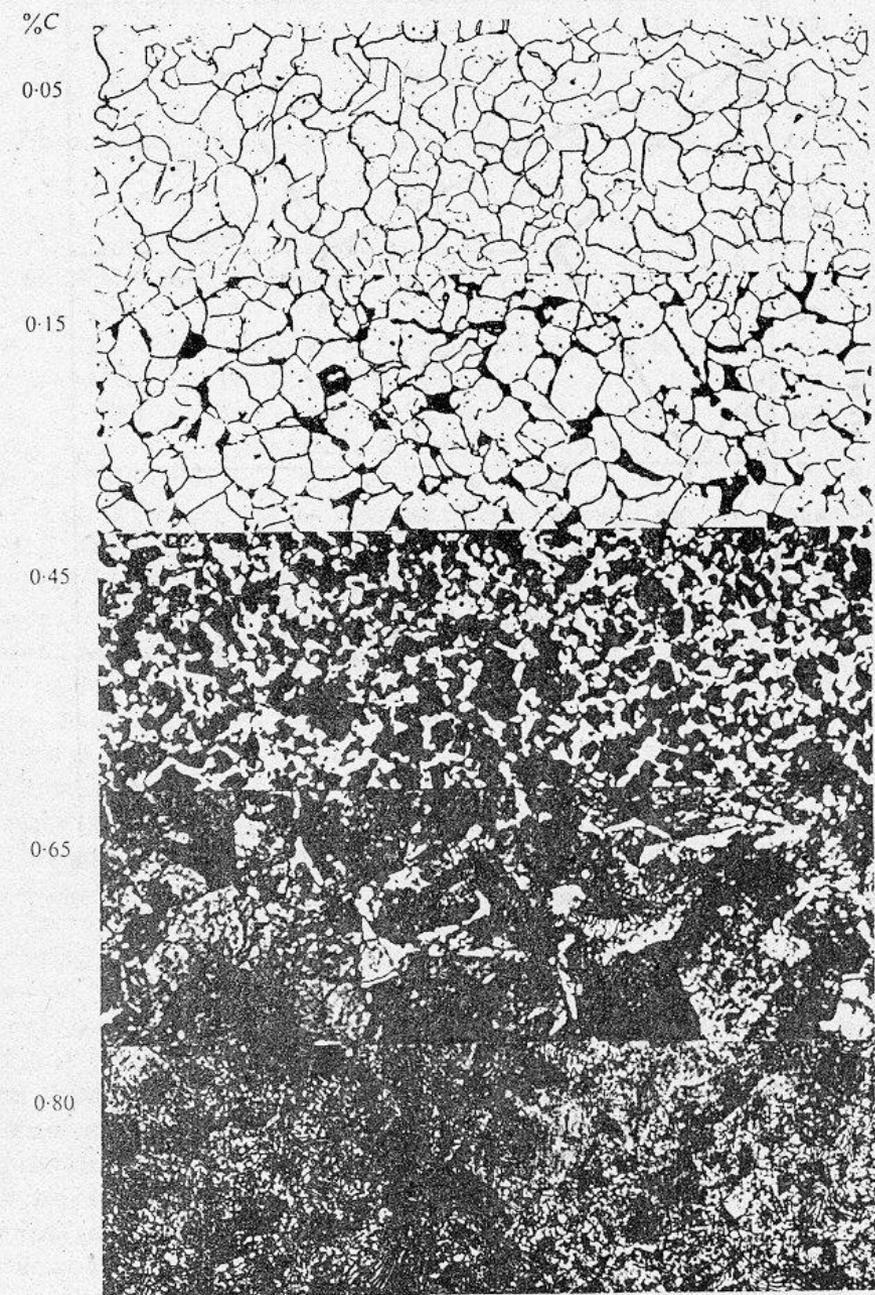


Fig 4.9 is a compendium of microstructures of a range of steels with increasing amounts of carbon in them. It can be seen that the area of pearlite and cementite increases with amount of carbon.

*Fig.4.9 Micrographs of steels with increasing carbon contents.*

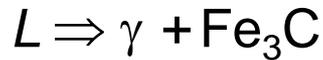
# Info on Fe phases

- **$\alpha$ -ferrite - solid solution of C in BCC Fe**
  - Stable form of iron at room temperature.
  - The maximum solubility of C is 0.022 wt%
  - Transforms to FCC  $\gamma$ -austenite at 912 °C
- **$\gamma$ -austenite - solid solution of C in FCC Fe**
  - The maximum solubility of C is 2.14 wt %.
  - Transforms to BCC  $\delta$ -ferrite at 1395 °C
  - Is not stable below the eutectic temperature (727 °C) unless cooled rapidly (Chapter 10)
- **$\delta$ -ferrite solid solution of C in BCC Fe**
  - The same structure as  $\alpha$ -ferrite
  - Stable only at high T, above 1394 °C
  - Melts at 1538 °C
- **Fe<sub>3</sub>C (iron carbide or cementite)**
  - This intermetallic compound is metastable, it remains as a compound indefinitely at room T, but decomposes (very slowly, within several years) into  $\alpha$ -Fe and C (graphite) at 650 - 700 °C

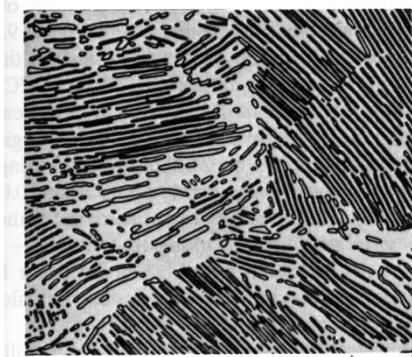
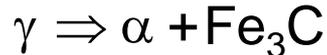
# Iron-Carbon (Fe-C) Phase Diagram

- 2 important points

-Eutectic (A):

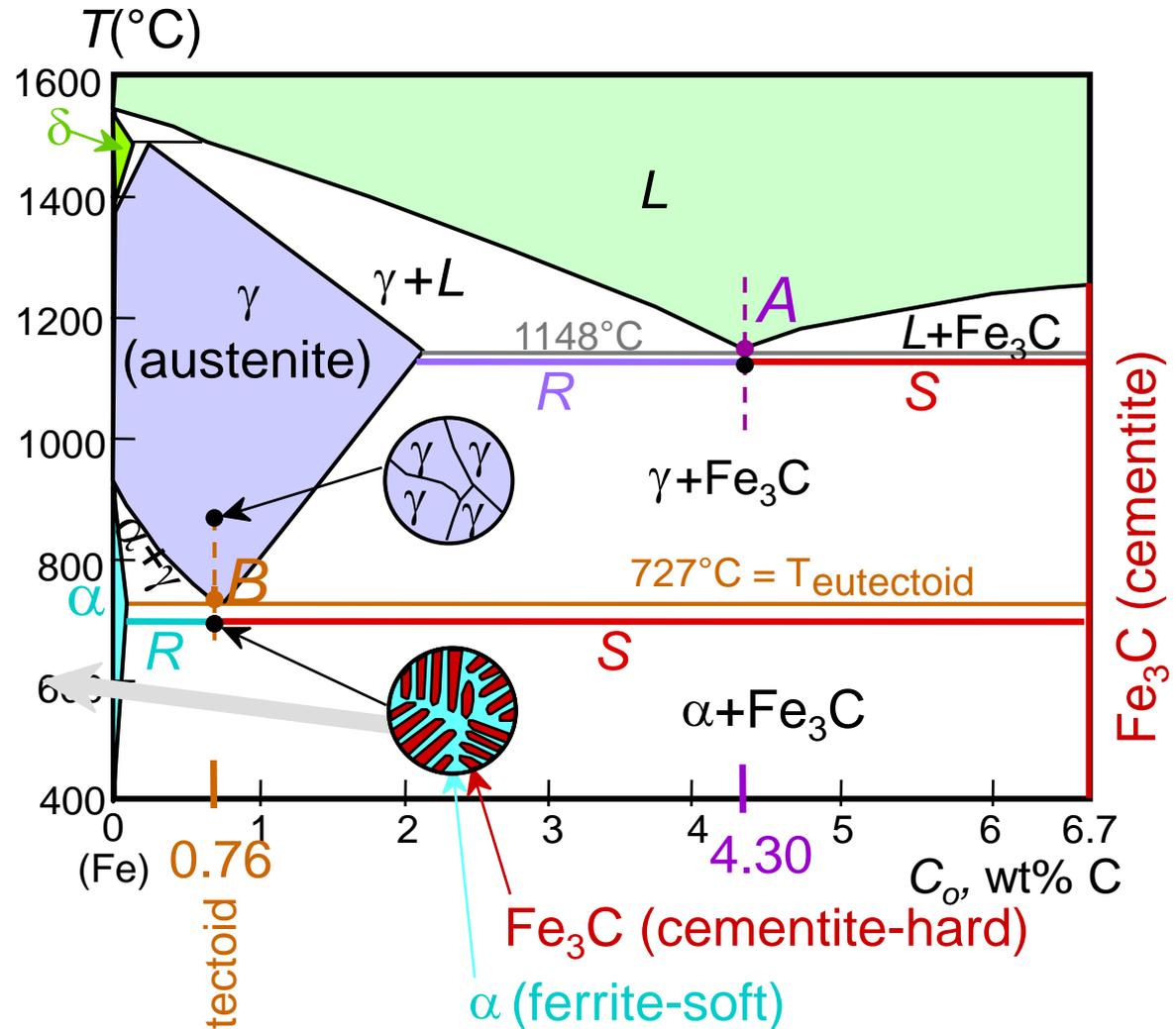


-Eutectoid (B):



120 μm

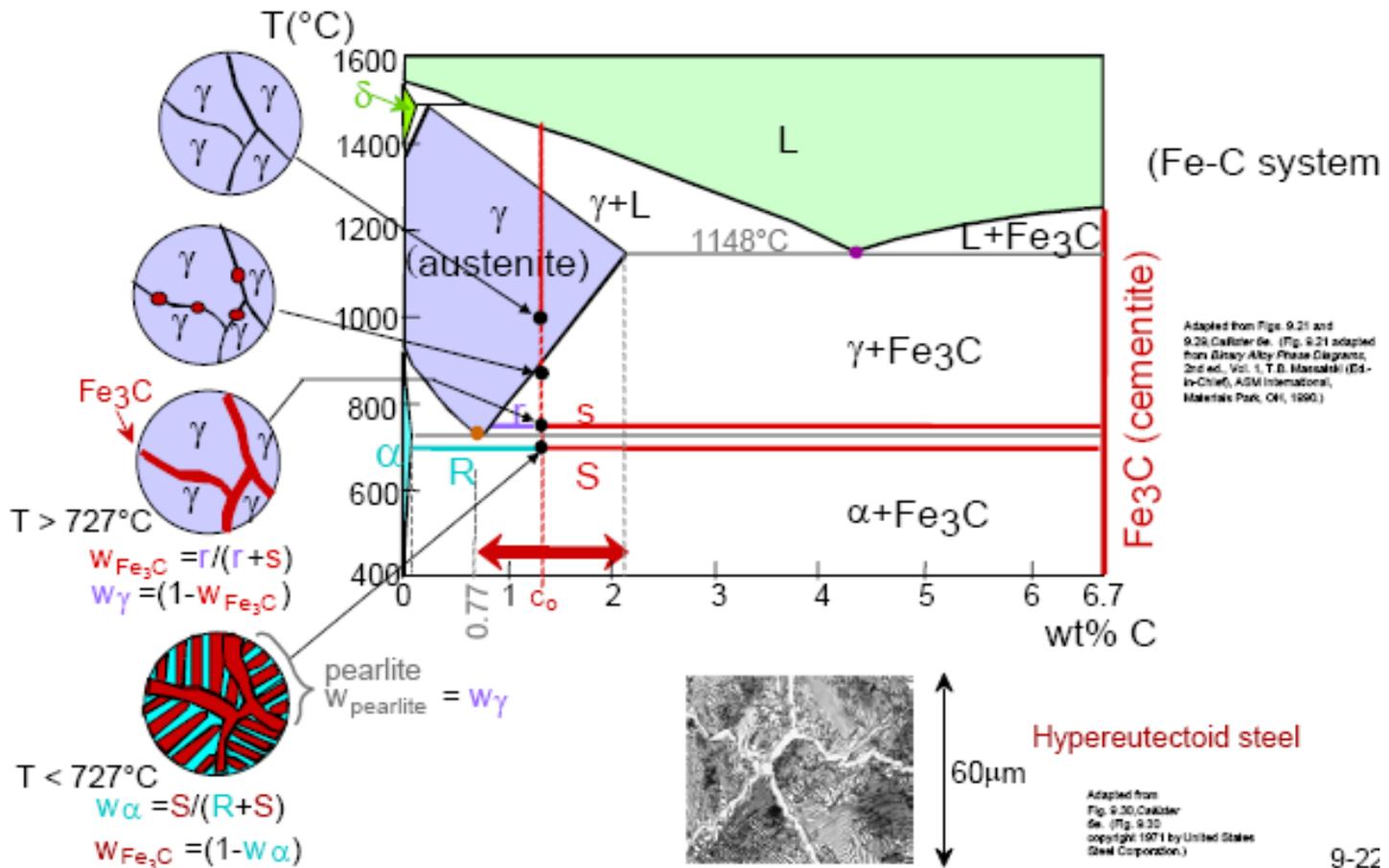
Result: Pearlite = alternating layers of α and Fe<sub>3</sub>C phases





# HYPEREUTECTOID STEEL

Pearlite and Fe<sub>3</sub>C form on slow cooling



## 4.10. PROPERTY VARIATION WITH SOLUBILITY

The properties of an alloy depends upon two factors:

1. The properties of the phases of which it is composed
2. The manner in which the several phases are associated

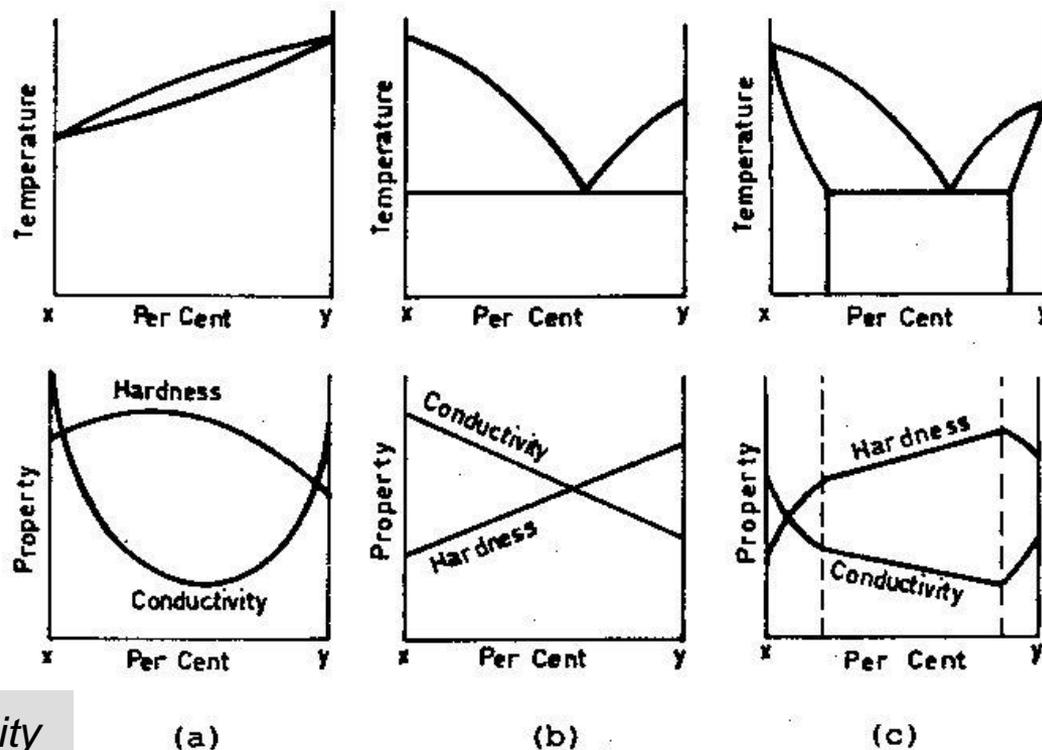


Fig.4.10 Variation of properties with solubility

A general idea of how the properties will vary within a given system can be secured from the phase diagram. A system in which the components are completely soluble in solid state will exhibit a variation in hardness and conductivity as depicted in Fig 4.10(a). The presence of small amounts of solute atoms has a tremendous influence in decreasing conductivity. The variation of strength and conductivity for systems exhibiting insolubility in solid state is depicted in Fig 4.10 (b)

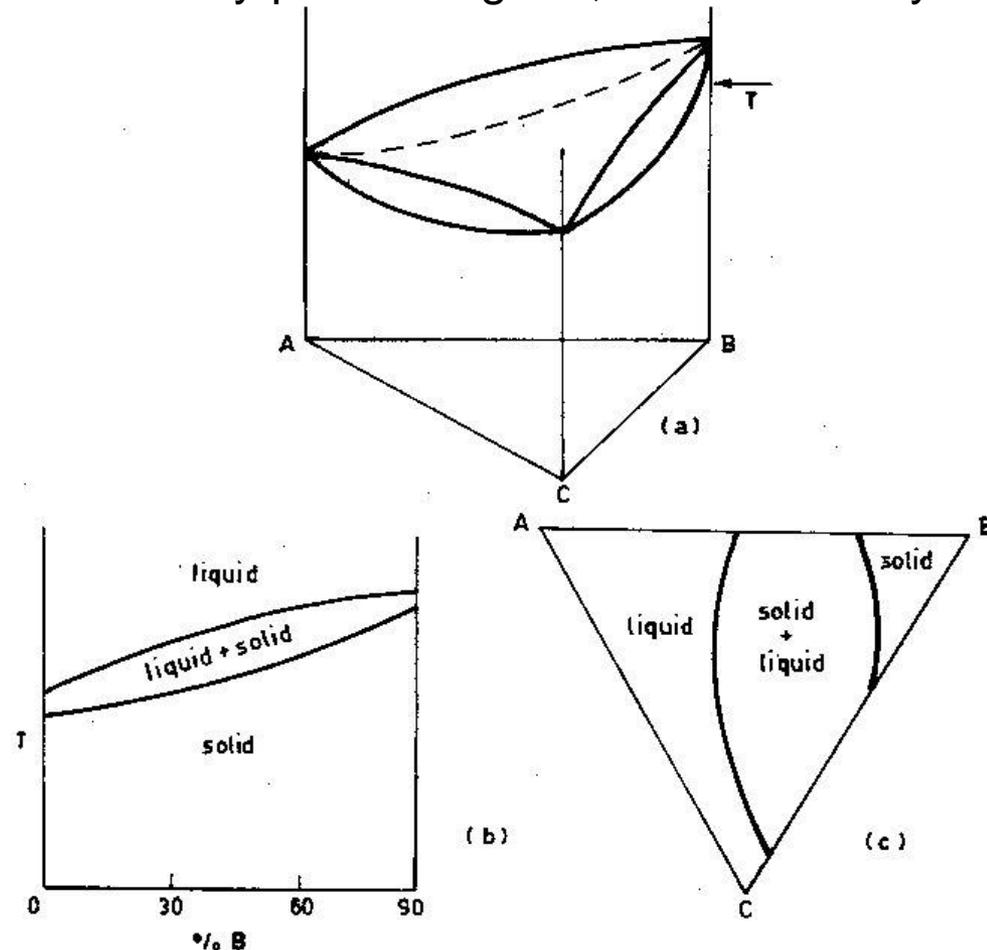
## 4.11. TERNARY SYSTEMS

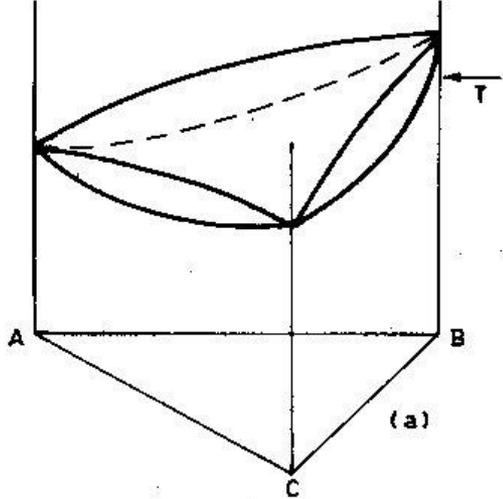
An improvement in properties of a binary alloy is frequently gained by adding a third element. Addition of nickel to steel (Fe-C) to improve toughness and addition of lead to brass (Cu-Zn) to improve machinability are two commercial examples. The presence of third element, however, alters the binary phase diagram, often markedly.

In principle, use and interpretation of ternary phase diagrams are same as binary diagrams and phase rule and lever arm principle are valid. In practice, however, ternary systems are more complex than binary systems.

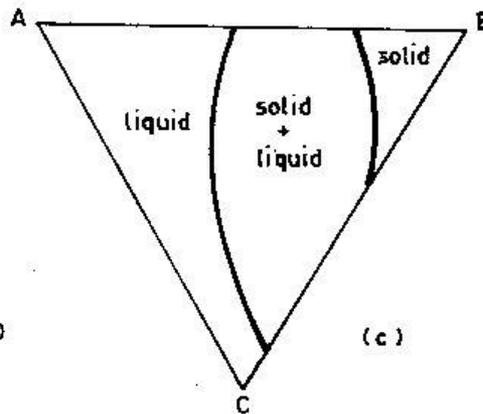
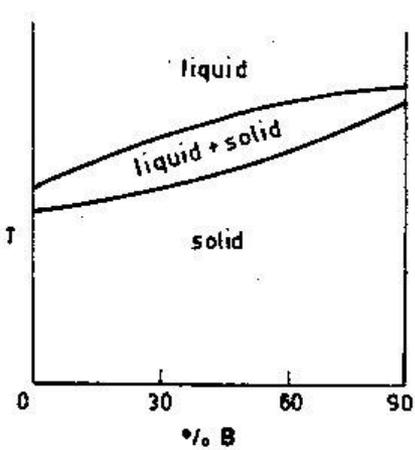
Constant pressure ternary systems are three dimensional as against two dimensional binary systems. They consist of an equilateral composition triangle while the temperature is plotted vertically as shown in Fig 4.11.

*Fig.4.11 Ternary phase diagram for a system with complete solid solubility*





To facilitate interpretation, a two dimensional plot is customarily obtained by sectioning the diagram at constant temperatures (isothermals) or at constant composition of one phase or a constant ratio of compositions, isopleths.



Isopleths (4.11.c) on the other hand do not give true compositions but are useful in predicting the changes expected on heating or cooling.

(b)

(c)

Fig.4.11 Ternary phase diagram for a system with complete solid solubility

Mechanical properties of alloys can be changed by changing their structures. Phase diagrams are essential tools for such treatments and enable an engineer to produce desired structures by various heat treatments. This chapter provides adequate background for an engineer to be able to use and interpret a phase diagram.

# SUMMARY

- **Phase diagrams** are useful tools to determine:
  - the number and types of phases,
  - the wt% of each phase,
  - and the **composition** of each phasefor a given T and composition of the system.
- Alloying to produce a solid solution usually
  - increases the tensile strength (TS)
  - decreases the ductility.
- Binary **eutectics** and binary **eutectoids** allow for a range of microstructures.

## EXAMPLE 4.1.

Determine the weight percentages of austenite, ferrite and pearlite upon slow cooling of a 0.4 % C steel from 900 °C to room temperature.

As can be seen from the iron-carbon diagram, at 900 °C the steel is composed of austenite only. Upon slow cooling it intersects the A3 line where ferrite begins to form in increasing quantity until reaching to A1. Just before A1 the weight fraction of ferrite and austenite can be determined by the lever arm principle as follows:

$$\text{wt. \% } \alpha = [(0.83-0.4) \times 100] / (0.83-0.025) = 53.4 \%$$

$$\text{wt. \% } \gamma = [(0.4-0.025) \times 100] / (0.83-0.025) = 46.6 \%$$

The austenite will contain 0.83 % carbon as can be seen from the diagram. Upon slight further cooling, this austenite will decompose into ferrite and cementite (pearlite). This pearlite will contain following fractions of ferrite and cementite according to lever arm principle (austenite composition used in this calculation would be 0.83 % C not the original 0.4 % C):

$$\text{wt. \% } \alpha = [(6.67-0.83) \times 100] / (6.67-0.025) = 87.9 \%$$

$$\text{wt. \% Fe}_3\text{C} = [(0.83-0.025) \times 100] / (6.67-0.025) = 12.1 \%$$

Total weight fraction of ferrite in the final microstructure would, therefore, be:

$$\text{proeutectoid ferrite} = 53.4 \%$$

$$\text{eutectoid ferrite} = 87.9 \% \text{ of } 46.6 \% = 40.9 \%$$

$$\text{total ferrite} = 94.3 \%$$

$$\text{total cementite} = 12.1 \% \text{ of } 46.6 \% = 5.7 \%$$

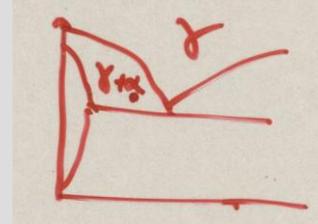
$$\text{Total Ferrite} = \frac{6.67 - 0.4}{6.67 - 0.025} = 94.3\%$$

## EXAMPLE 4.2.

In the iron-carbon diagram, the austenite-pearlite reaction can only take place at one constant temperature whereas the austenite -ferrite reaction can take place at a range of temperatures, why?

Let us consider the austenite-ferrite reaction. The number of components in the system is two (Fe & C) and the number of phases is also two (austenite & ferrite) hence from the phase rule we have

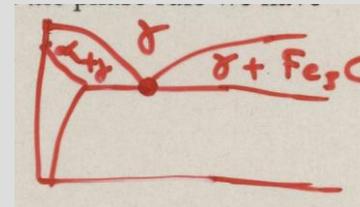
$$2 - 2 = 1 - F$$



so that the degree of freedom is one and hence the temperature is variable for this reaction.

For the austenite-pearlite reaction, however, the number of components remains two but the number of phases is three ( austenite, ferrite & cementite), so that from the phase rule we have

$$3 - 2 = 1 - F$$



and  $F$  is zero. The temperature is, therefore, not variable for this reaction and consequently the reaction must take place at a constant temperature.

## EXAMPLE 4.3.

Determine the weight percentage of carbon in cementite.

Iron carbide is  $\text{Fe}_3\text{C}$  which consists of 3 atoms of iron and 1 atom of carbon in its molecule. The total atomic weight of  $\text{Fe}_3\text{C}$  is, therefore

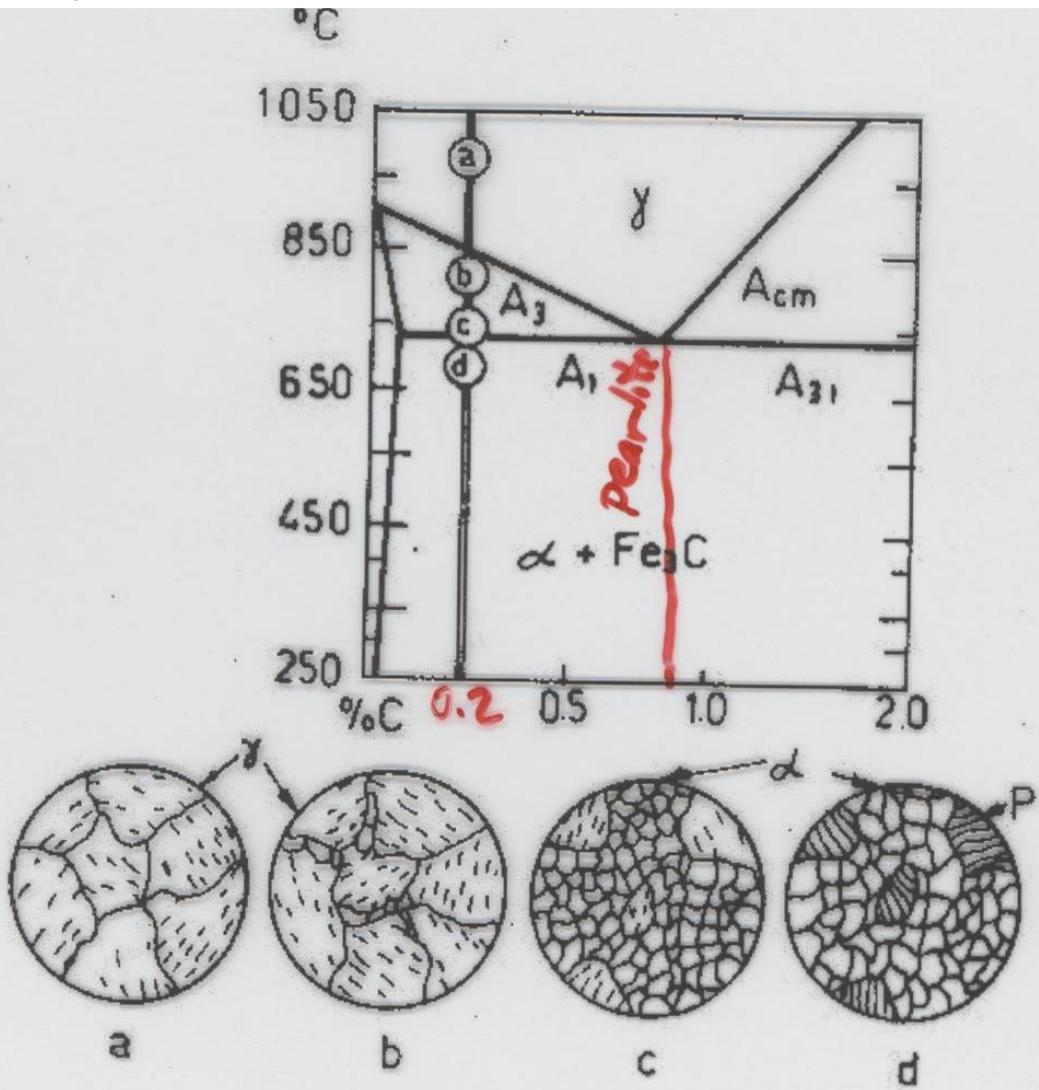
3 x atomic weight of iron + 1 x atomic weight of carbon =

$$\begin{aligned} &= 3 \times 56 + 1 \times 12 \\ &= 168 + 12 = 180 \end{aligned}$$

Hence weight percentage of carbon in  $\text{Fe}_3\text{C}$  would be  $(12/180) \times 100 = 6.67 \%$

## EXAMPLE 4.4.

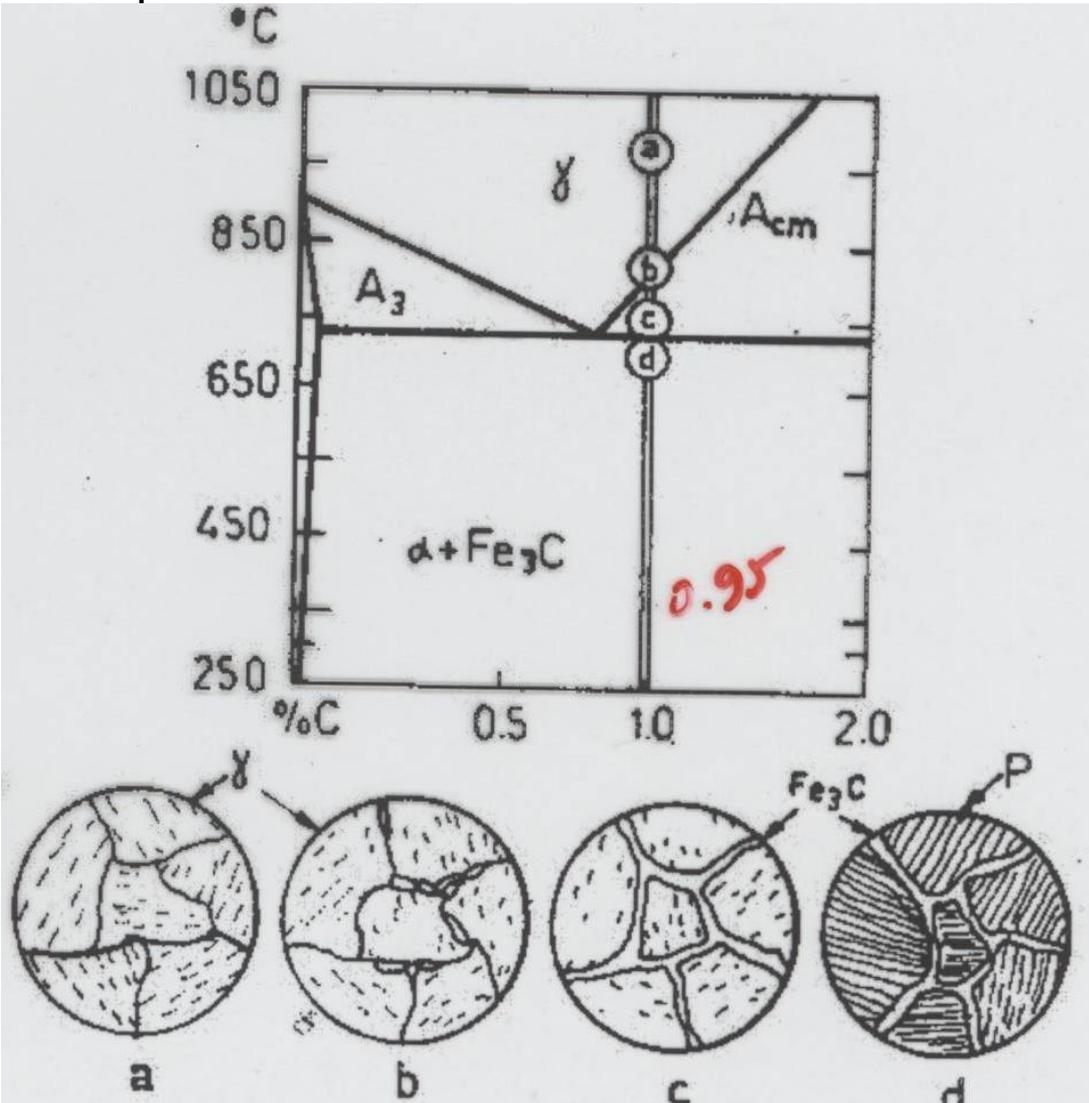
Consider slow cooling of a 1020 steel from austenite to room temperature. Step by step draw the microstructures of the transformation products in each region.



In Fig.4.12 transformation products at various points for 1020 steel are drawn. At point (a) it is in austenite form and just above (b) ferrite begins to nucleate in increasing amounts until point (c) where the remaining austenite of 0.83 % C content will transform to pearlite and the final microstructure will be  $\alpha$  + pearlite given at (d).

## EXAMPLE 4.4.

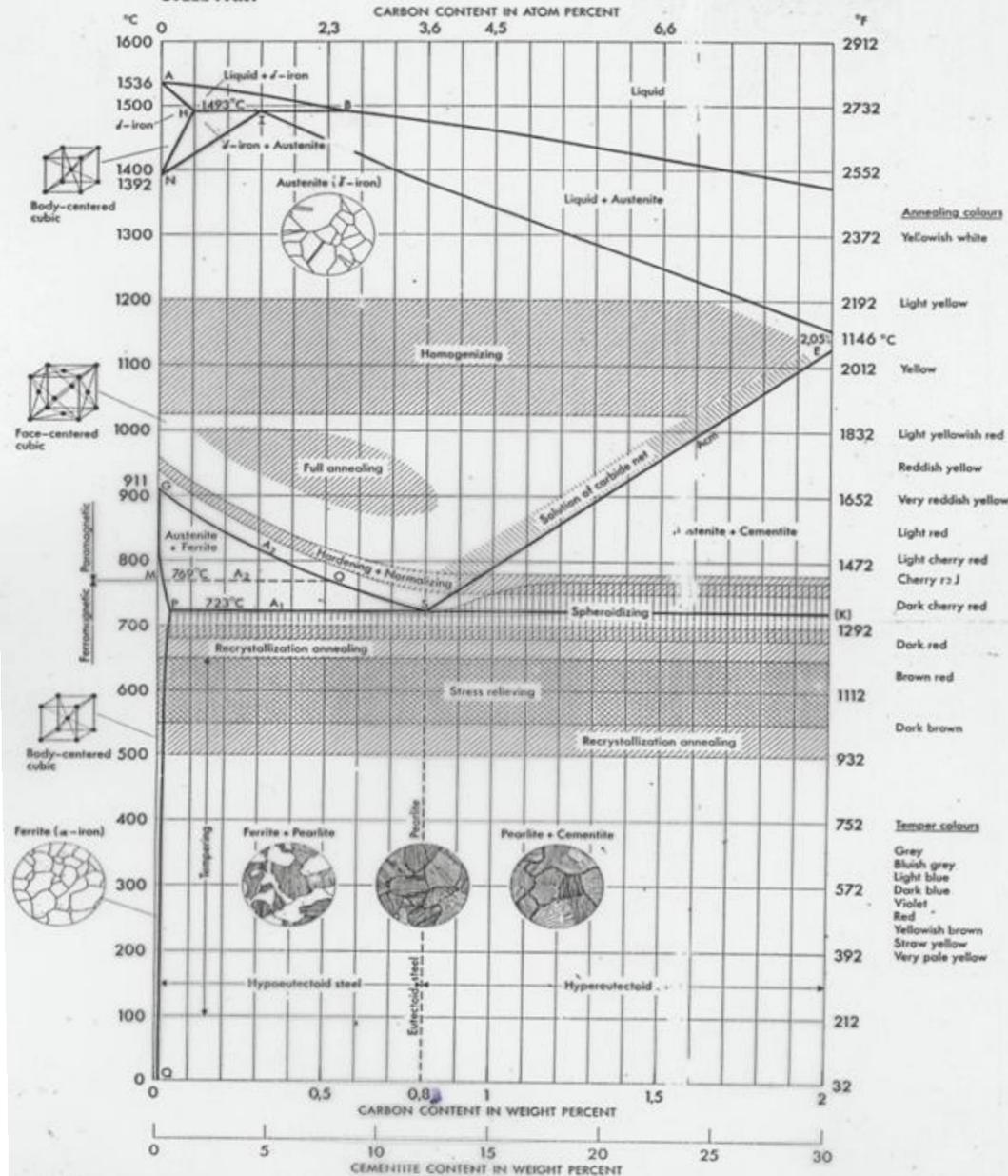
Consider slow cooling of a 1095 steel from austenite to room temperature. Step by step draw the microstructures of the transformation products in each region.



In Fig.4.12 transformation products at various points for 1095 steel are drawn. Similarly, at point (b) transformation is to cementite and the remaining austenite at (c) will transform to pearlite to give a final structure of cementite + pearlite at(d).

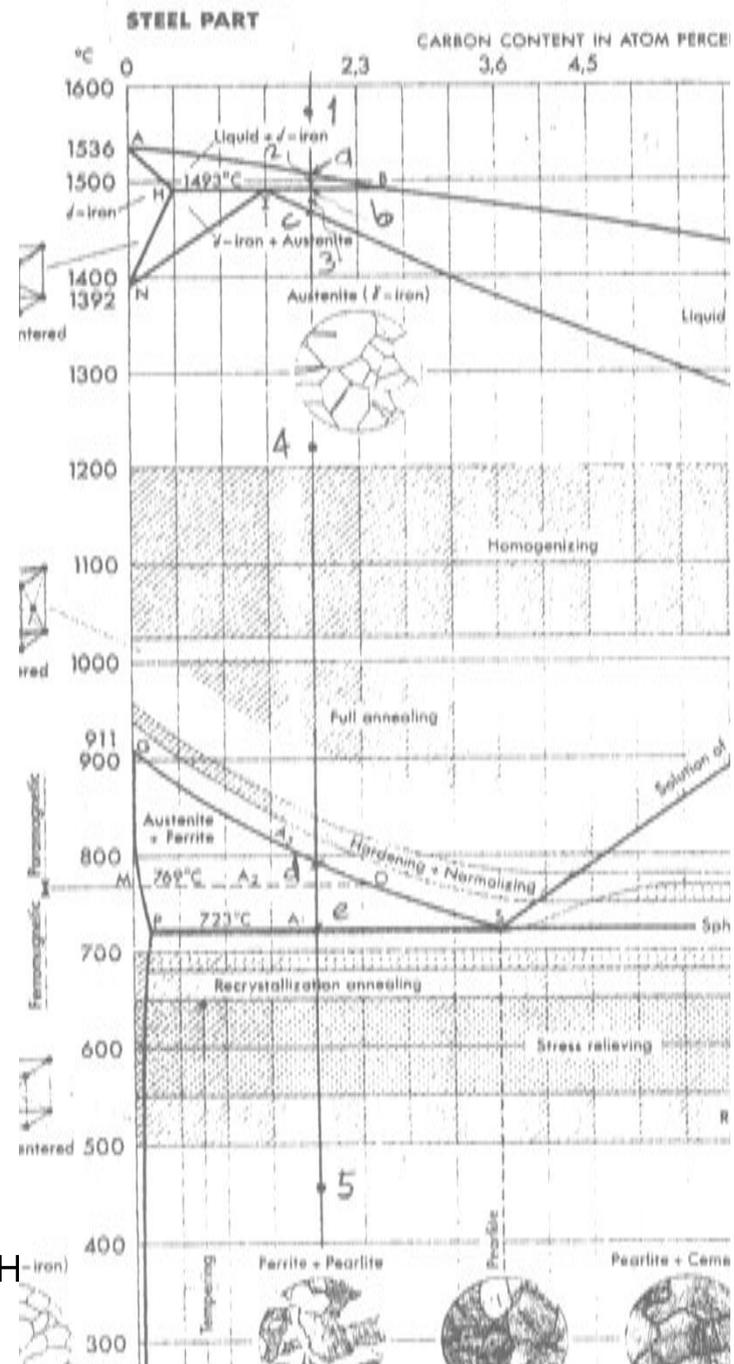
# IRON-CARBON EQUILIBRIUM DIAGRAM

STEEL PART



# EXAMPLE 4.1 (Expanded Solution)

## IRON-CARBON EQUILIBRIUM



## 0.4 % C Steel

Point (1) at 1600 °C,  
Phase: only liquid,  
Composition: 0.4 % C

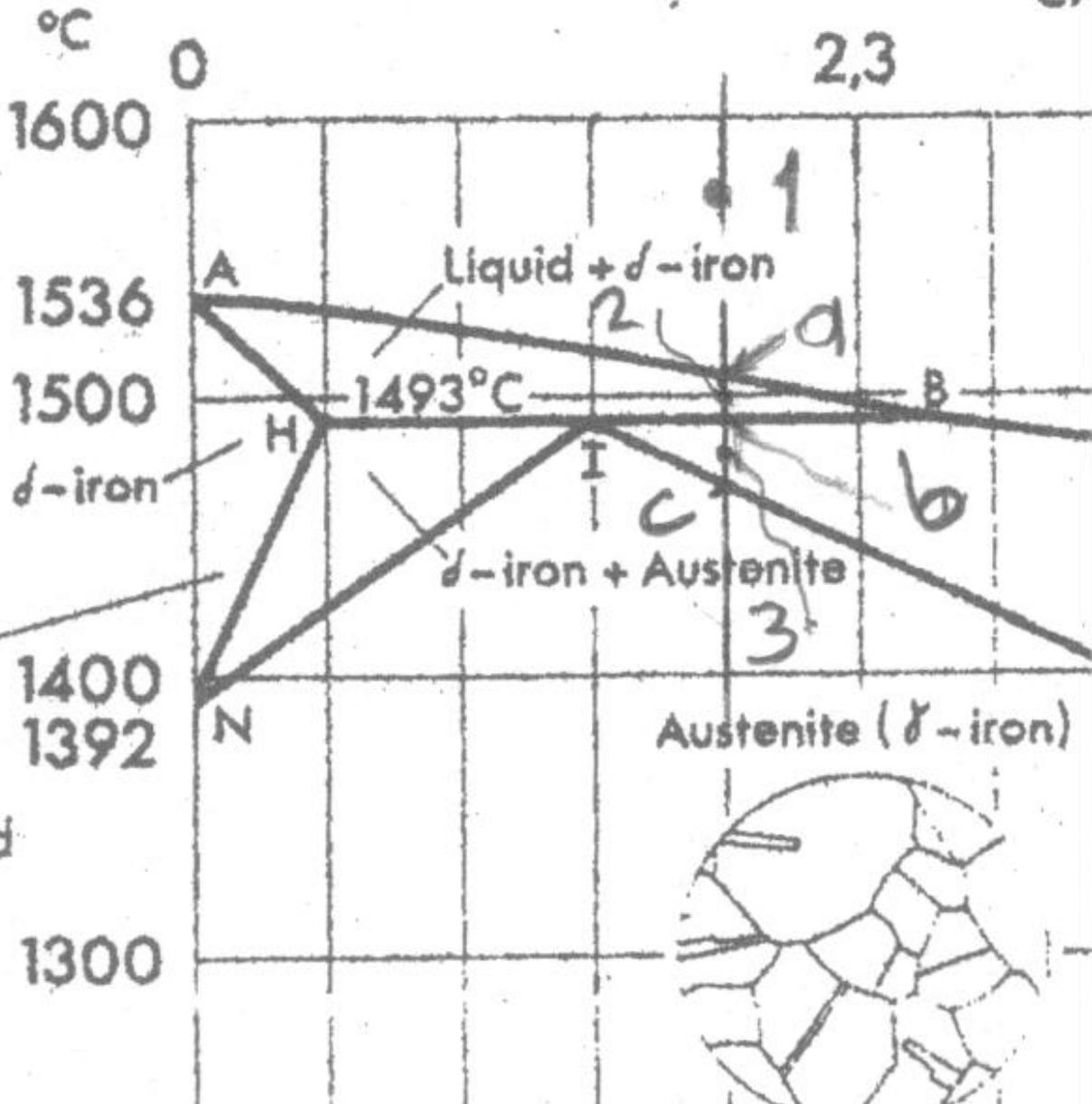
Point (2) at 1500 °C,  
Phase:  $\delta$  + liquid

$\delta$  \_\_\_\_\_ L

0.08       $\Delta$       0.45

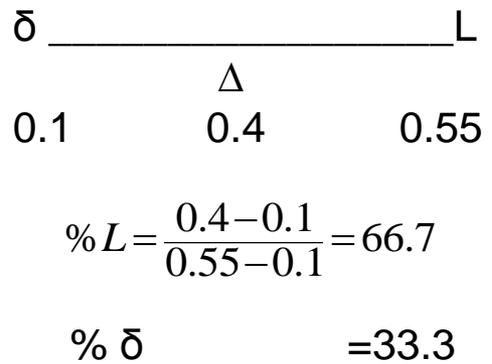
$$\%L = \frac{0.4 - 0.08}{0.45 - 0.08} = 86.5$$

$$\% \delta = 13.5$$

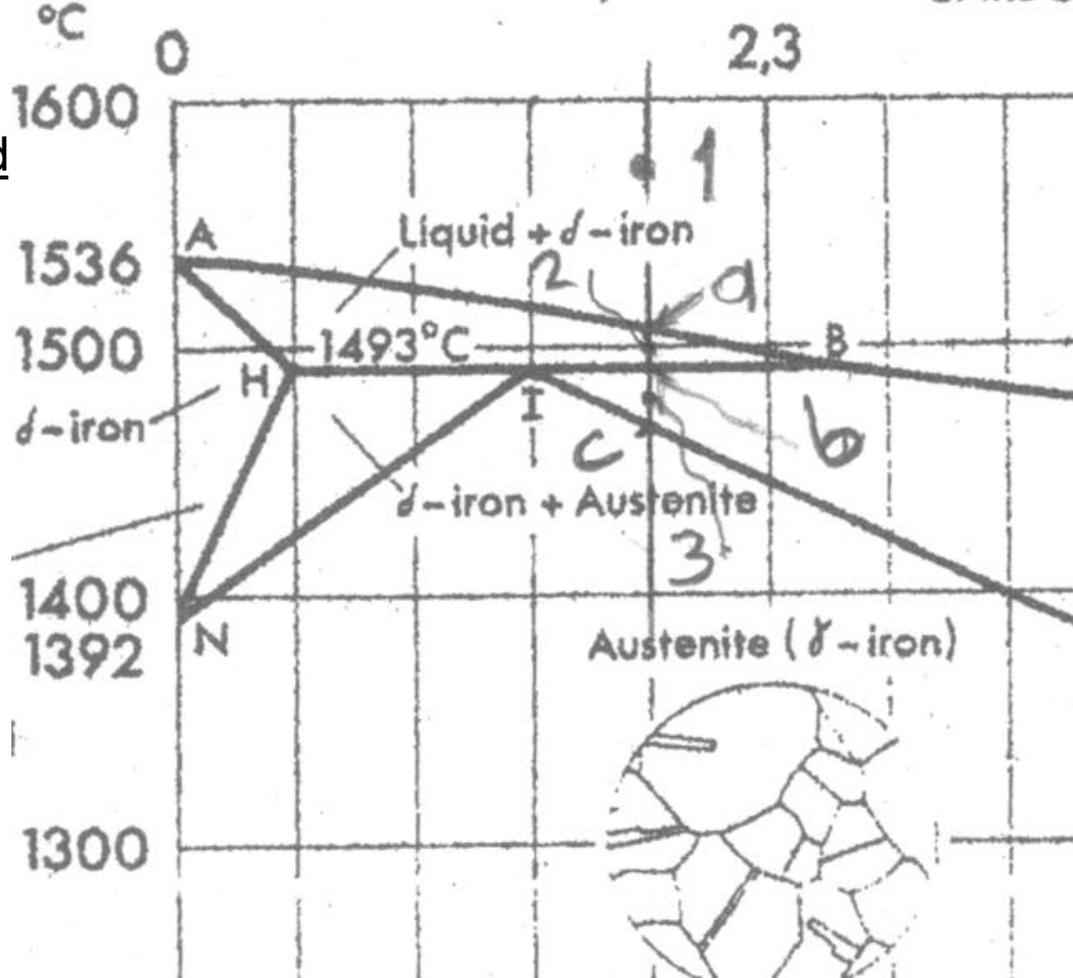
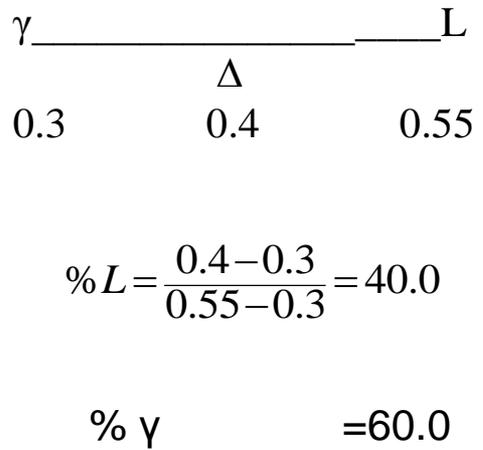


Point (b) at 1493 °C,

Before transformation: Phase:  $\delta + \text{liquid}$



After transformation: Phase:  $\gamma + \text{liquid}$



Point (e) at 723 °C,

Before transformation:

Phase:  $\alpha + \gamma$

$\alpha$  \_\_\_\_\_  $\gamma$

$\Delta$   
0.025      0.4      0.83

$$\% \alpha = \frac{0.83 - 0.4}{0.83 - 0.025} = 53.4$$

$$\% \gamma = 46.6$$

After transformation:

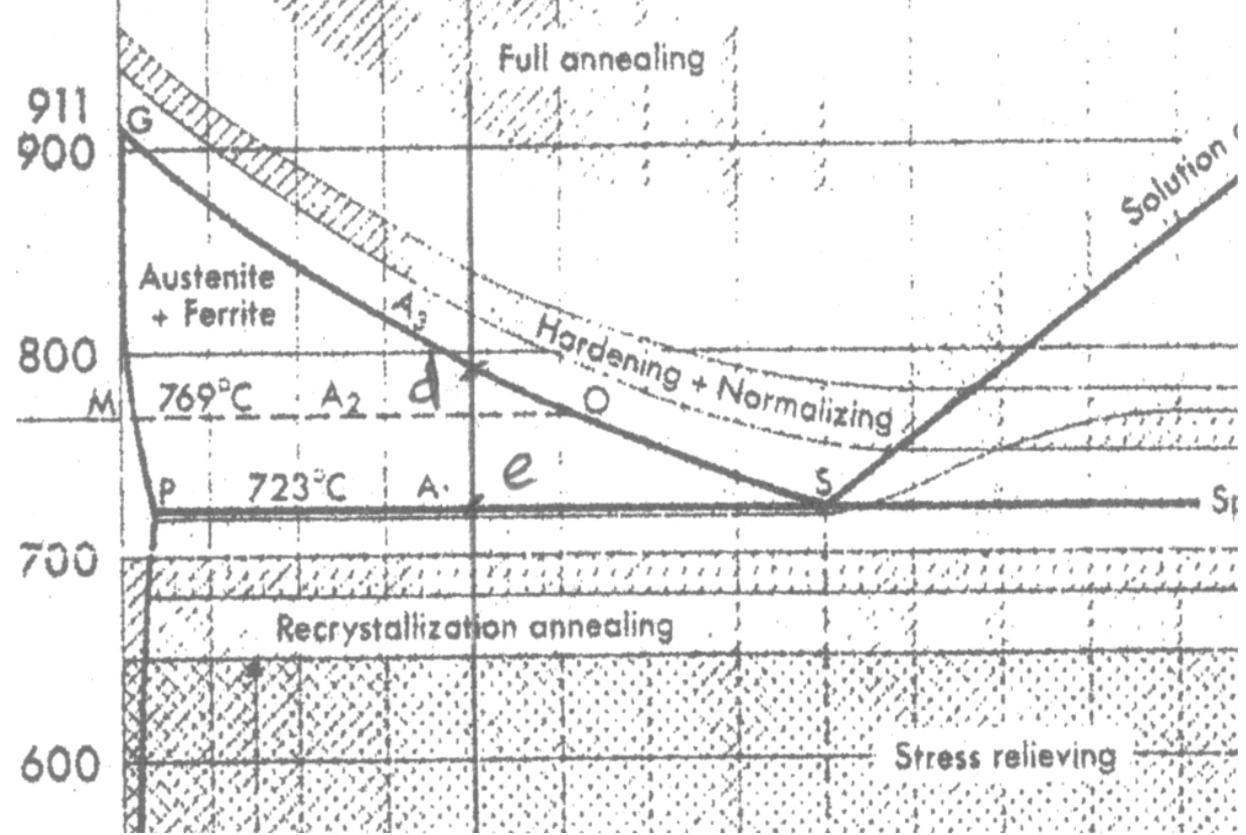
Phase:  $\alpha + \text{Fe}_3\text{C}$

$\alpha$  \_\_\_\_\_  $\text{Fe}_3\text{C}$

$\Delta$   
0.025      0.4      6.67

$$\% \alpha = \frac{6.67 - 0.4}{6.67 - 0.025} = 94.3$$

$$\% \text{Fe}_3\text{C} = 5.7$$



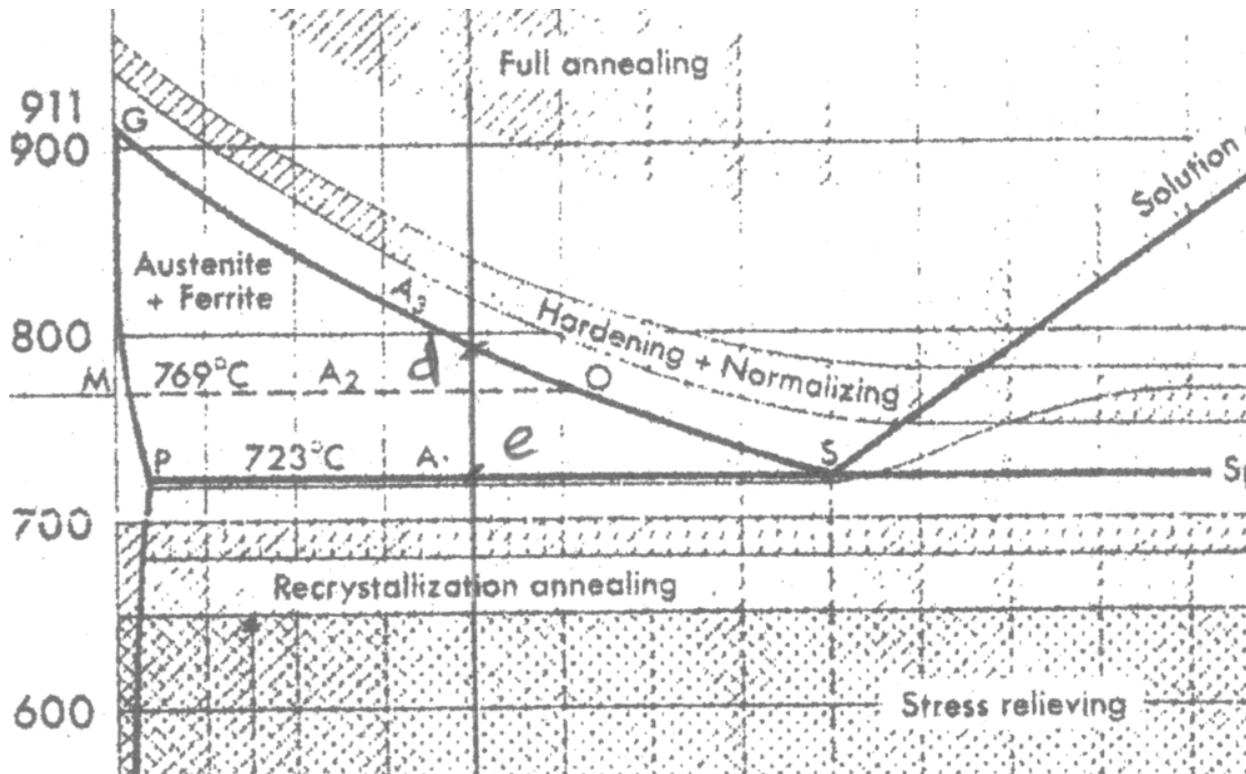
# Eutectoid Reaction at 723 °C,

Phase:  $\alpha + \text{Fe}_3\text{C}$

$\alpha$  \_\_\_\_\_  $\text{Fe}_3\text{C}$   
 $\Delta$   
 0.025      0.83      6.67

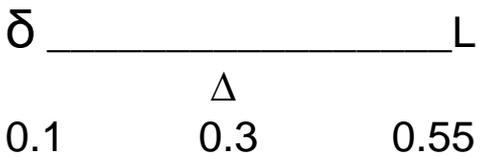
$$\% \alpha = \frac{6.67 - 0.83}{6.67 - 0.025} = 87.9$$

$$\% \text{Fe}_3\text{C} = 12.1$$



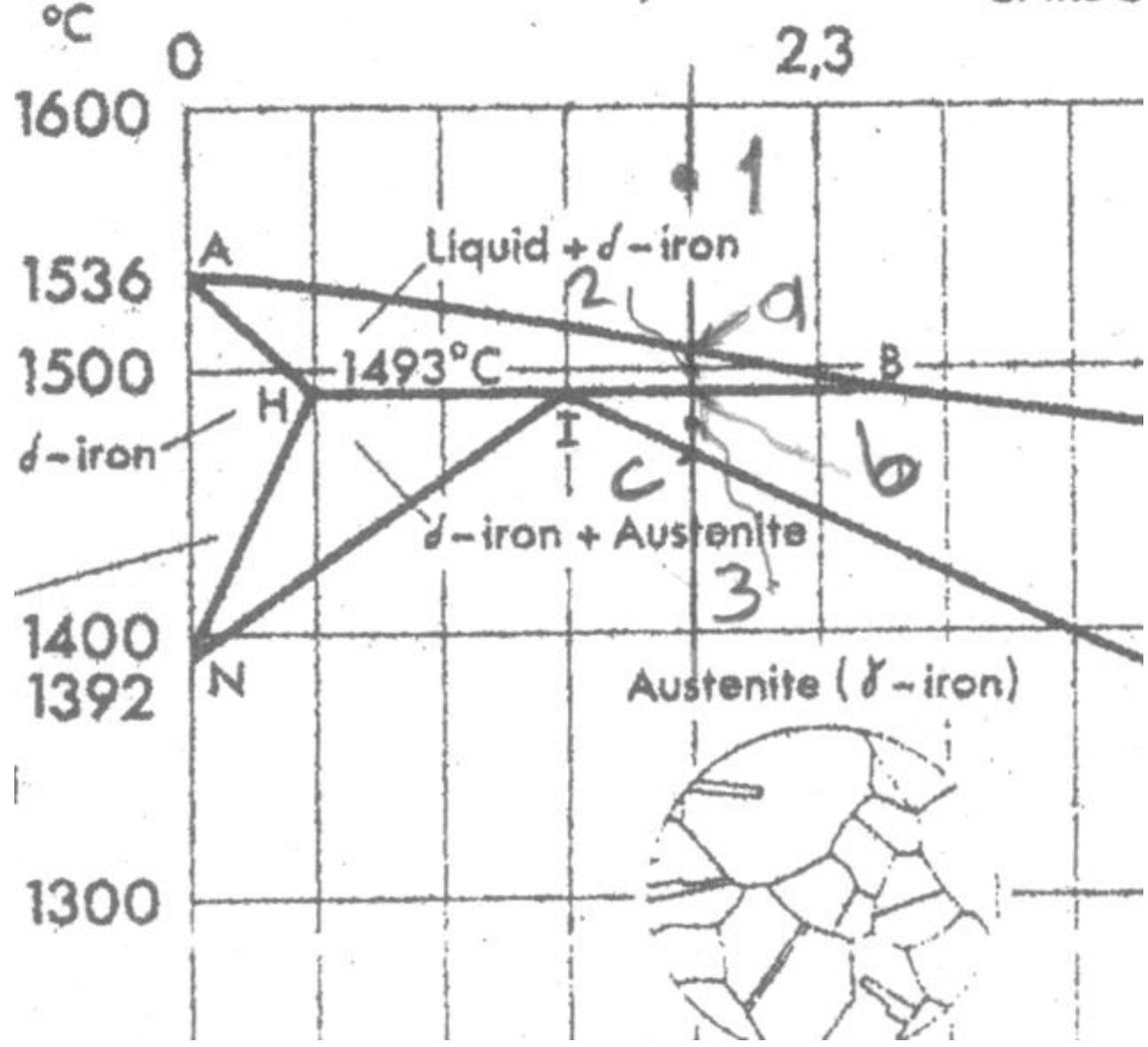
Peritectic Reaction at 1493 °C,

Phase:  $\delta$  + liquid



$$\%L = \frac{0.3 - 0.1}{0.55 - 0.1} = 44.5$$

$$\% \delta = 55.5$$



THE END

## CHAPTER 5

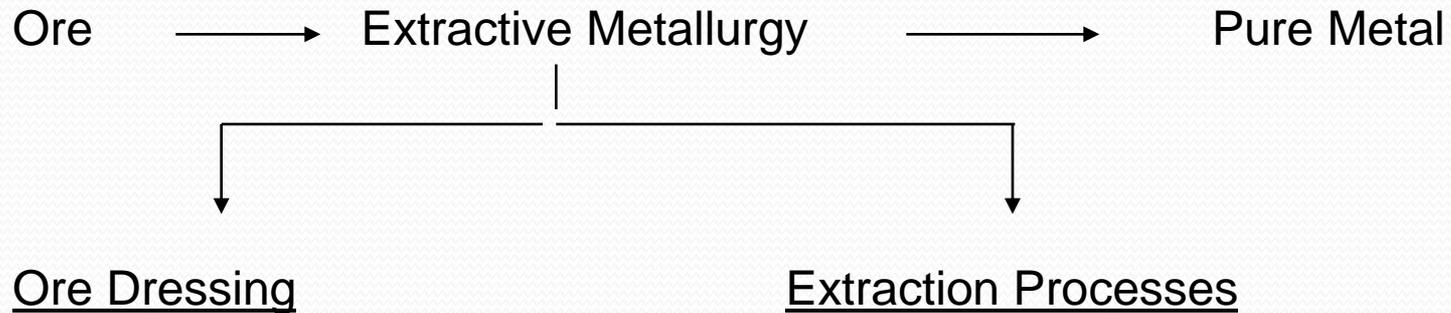
# EXTRACTIVE METALLURGY

## 5.1 INTRODUCTION

Extractive metallurgy is the science of converting ores to pure metals. It begins with the procurement of ores from mines and culminates in the form of pure metal through various processes. The ores are generally concentrated after mining through ore dressing. It may need to be agglomerated to reduce losses in transportation. The concentrated ore is then put through extraction processes involving chemical reactions, which release the pure metal from the rest of the impurities; the pure metal is collected separately.

# Extractive Metallurgy

Extractive metallurgy is the science of converting ores to pure metals.



- 1.) Crushing and Grinding
- 2.) Sizing and Sorting
  - a) Screening
  - b) Sorting
    - Classification
    - Flotation
    - Magnetic Separation
- 3.) Agglomeration
  - a) Pelletizing
  - b) Sintering
  - c) Nodularizing

Physical

- 1.) Calcination
- 2.) Roasting
- 3.) Smelting
- 4.) Electrolysis
- 5.) Fire Refining
- 6.) Distillation

Chemical

## 5.2 ORES

Almost all metals, with the possible exception of magnesium and plutonium, are derived from ores, which are concentrations of appropriate minerals situated at or near the earth's crust. Ores contain various important engineering metals as parts of **chemical compounds**. They are removed from the earth crust (mined) by a method appropriate to the size of the ore deposit, its shape and depth below the surface of earth.

## 5.2 ORES

In general, the ores contain the valuable mineral in a banded array; the valuable mineral being sandwiched between bands of other minerals. Chemically, an ore may contain **three groups of minerals**:

1. **The valuable mineral,**
2. **compounds of this mineral,** which may be of secondary value, and
3. **useless gangue material.**

**Native metal** rarely occurs in nature as pure substance, but is found as a compound. **The most common ore compounds are oxides, oxy salts and sulphides.** Oxide ores are often a result of oxidation of sulphides, although a few oxides such as  $\text{Fe}_3\text{O}_4$  do occur as primary oxide deposits. The minerals in this class often associate in families, iron being almost always presents; zinc and lead are always found together, lead is seldom found without silver.

## 5.3 ORE-DRESSING

**Ore dressing** is the preparation of ores for the principle chemical treatment by a series of relatively cheap processes, mainly physical rather than chemical in nature. They are designed to concentrate the valuable mineral and separate it from useless gangue and to render the enriched material into the most suitable physical condition for the subsequent operations.

In general these processes involve:

**First, breaking the ore** to such a small size that the precious mineral is released or exposed from the gangue;

**Secondly, a sorting operation** to separate the precious mineral from the gangue, and sometimes to distinguish more than one valuable mineral from one another; **and**

**Thirdly, if necessary, to agglomerate (combine)** mineral particles to produce large particles.

### 5.3.1 Crushing and Grinding

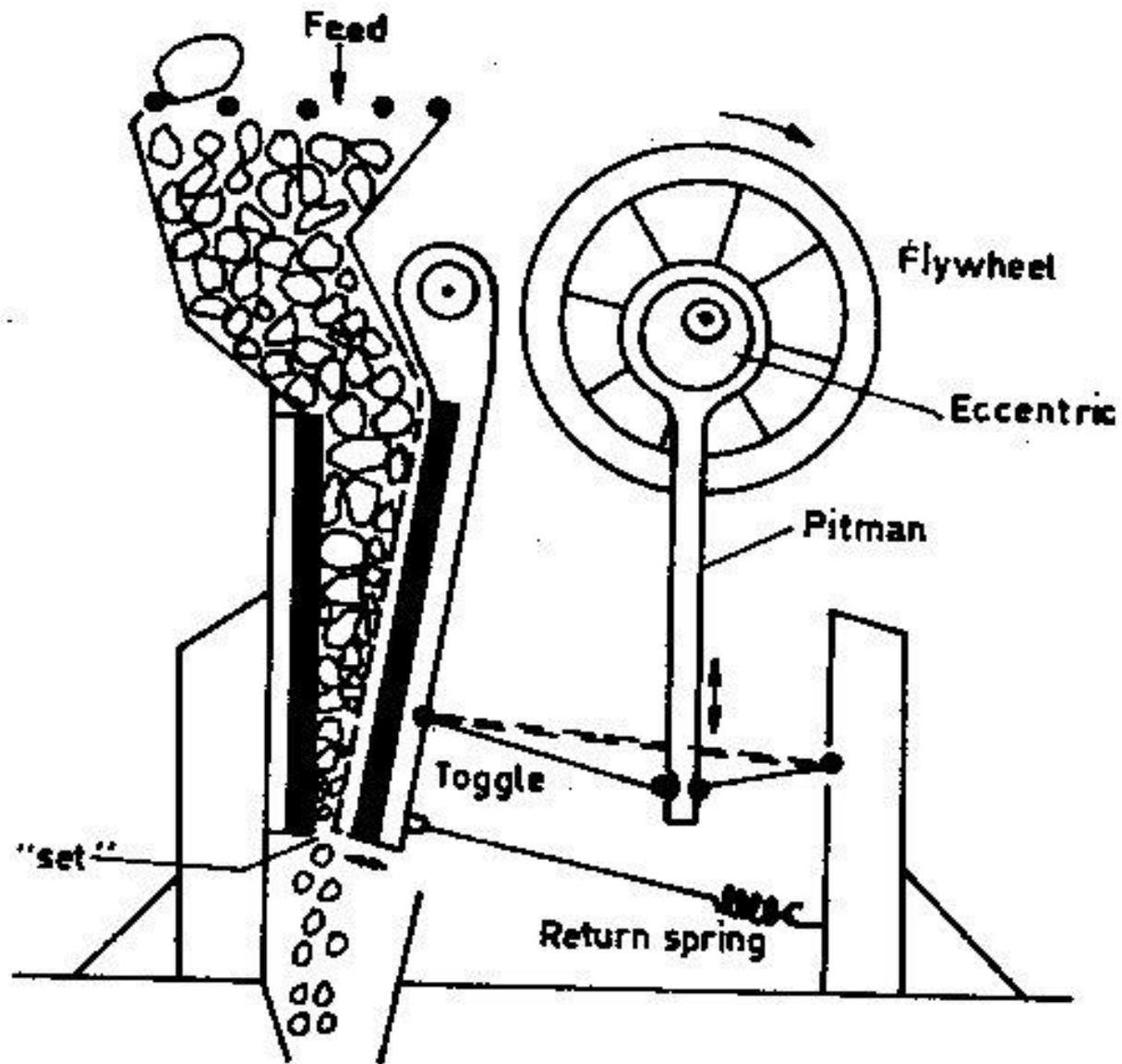
The size to which ores should be crushed is dictated by the requirements of the next stage of ore-dressing. Ideally the ore would be broken down until every particle is either the valuable mineral or the gangue particle. In practice, however, the ore is broken down to a satisfactory fineness; a range of sizes are inevitably obtained which are separated and processed or re-crushed, depending on the state of mineral/gangue association.

**There are two types of comminution:**

crushing down to about 1 mm maximum, and

grinding to smaller sizes.

**Primary crushing** is carried out in Jaw, Gyratory or roll crushers. In jaw and gyratory crushers, the ore is put between a fixed plate and a moving one, the mechanism of movement of plate being translational or gyrational. Fig 5.1 shows a Jaw crusher schematically. Rolls break the ores by crushing between two rolls; whose diameters and the gap between the rolls determine the size of final particles.



*Fig.5.1 Schematic diagram of a jaw crusher*

## Secondary crushing

down to 1 mm is carried out in cone crusher shown in Fig 5.2. The movement of interior cone crushes the ore particles as depicted schematically in the figure.

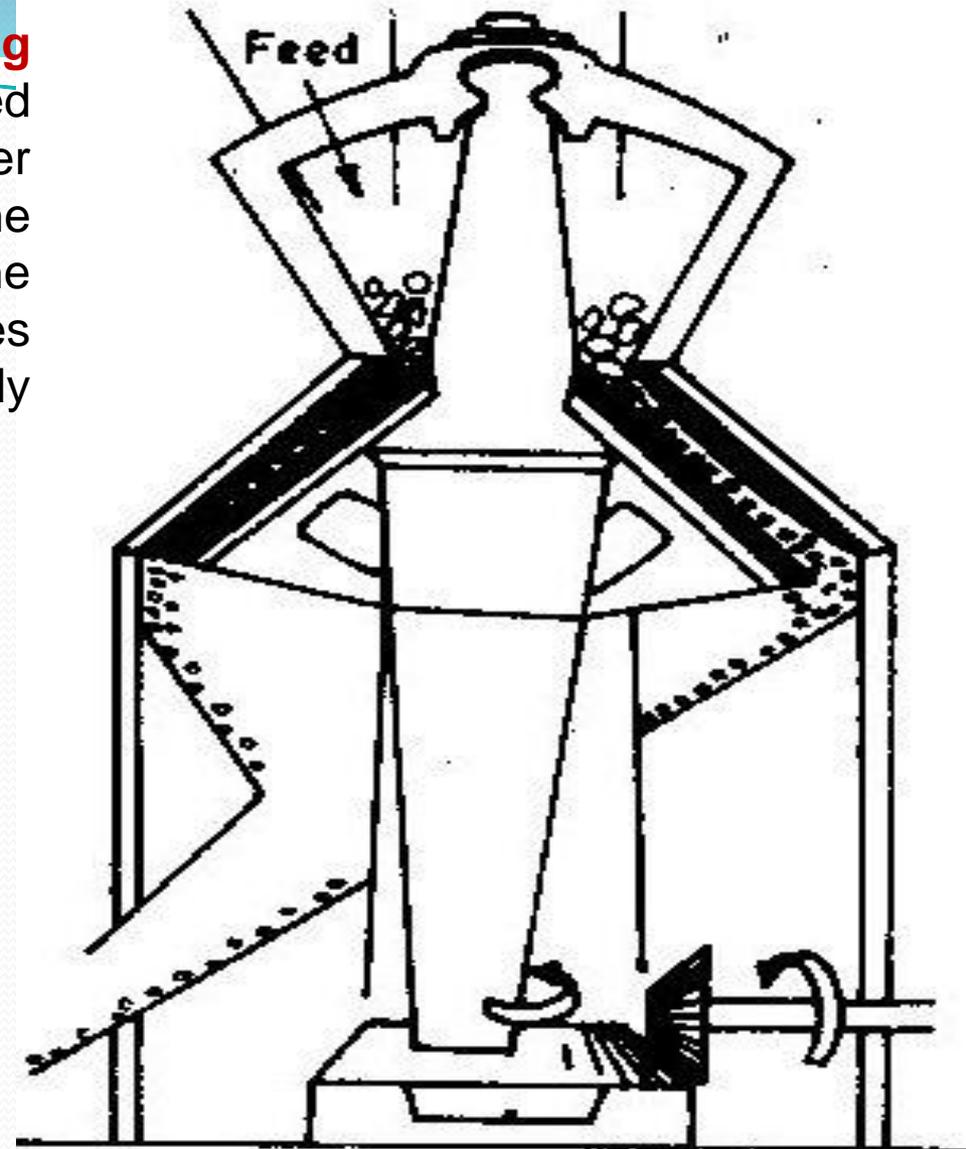
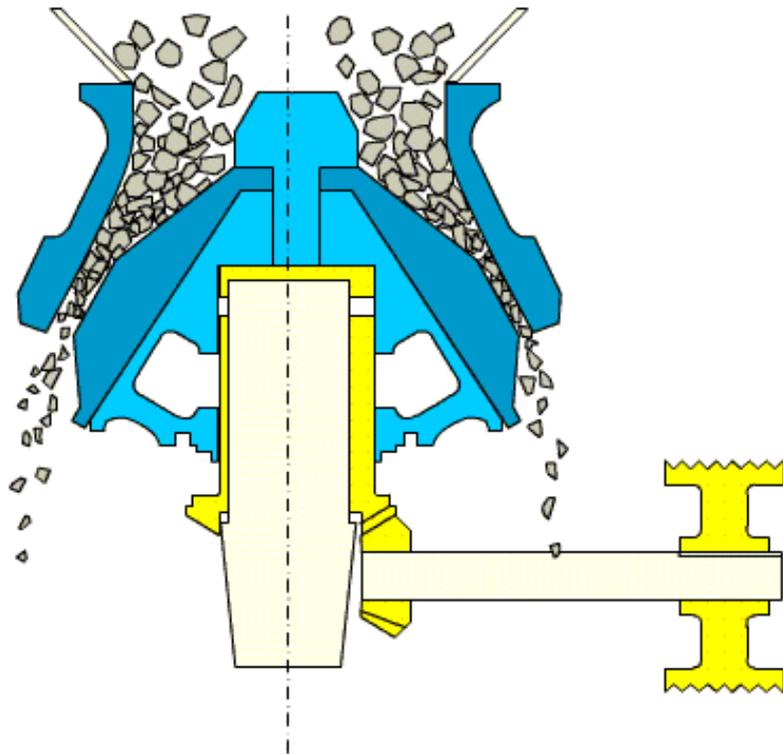
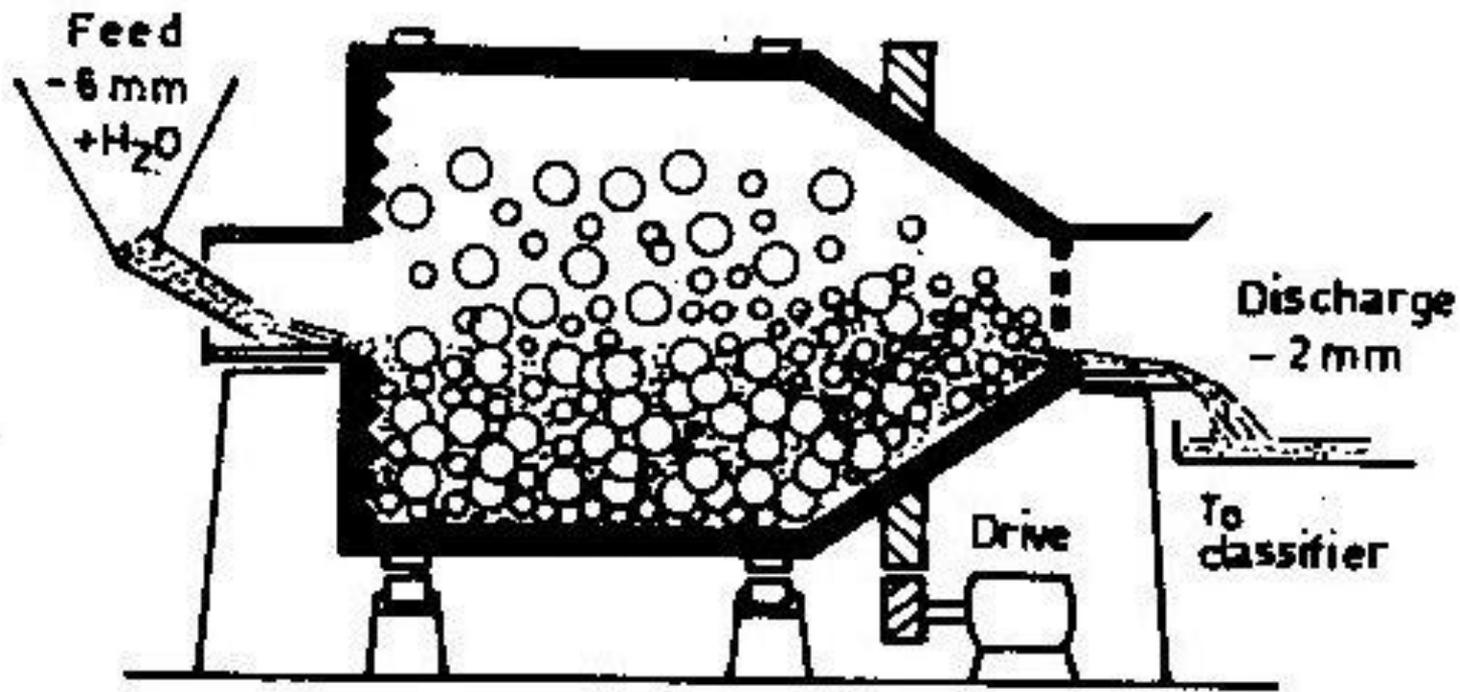


Fig.5.2 Schematic diagram of a cone crusher

**Grinding** is mainly carried out in ball, tube, pebble or rod mills. The principle is to place crushed ore particles in a pear shaped vessel rotating on horizontal axis (Fig 5.3).



*Fig.5.3 Schematic diagram of a ball mill.*

The vessel contains balls (or tubes, pebbles or rods) of steel or cast iron and a pulp of crushed ore and water is fed into the vessel. Ore is ground due to smashing by balls and the ground product overflows axially out of the mouth of the vessel.

Another type of tumbling mill is the cascade (taşırma) or aerofall mill. No balls are used in this system and the crushing is carried out by the large blocks of ores hitting and grinding smaller particles. The diameter is much larger than the length of the mill, and an air current carries small particles to the cyclone for collection.

## 5.3.2 Sizing and Sorting

Sorting operations are carried out to separate minerals for further processing. In principle, any physical property might be used as basis for distinguishing and separating mineral particles from gangue particles. **Screening is used to group particles together according to size**, which may or may not separate mineral from gangue.

### SCREENING

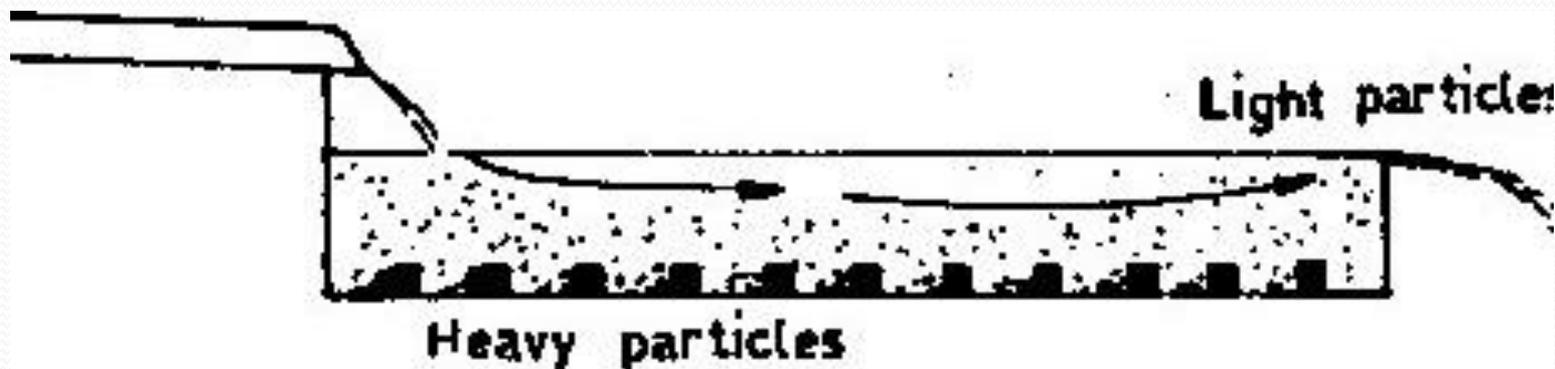
The simplest, most direct sizing process is screening or sieving. Particles are passed through an aperture of appropriate size to separate undersize particles (which pass through the opening) from oversize particles. This process can be carried out using a range of aperture sizes to separate particles of various sizes. A screen is an assembly of such apertures of square shapes woven from fine wires. Aperture sizes range down to about 50  $\mu\text{m}$ , below which accurate fabrication of cloth is difficult.

### SORTING

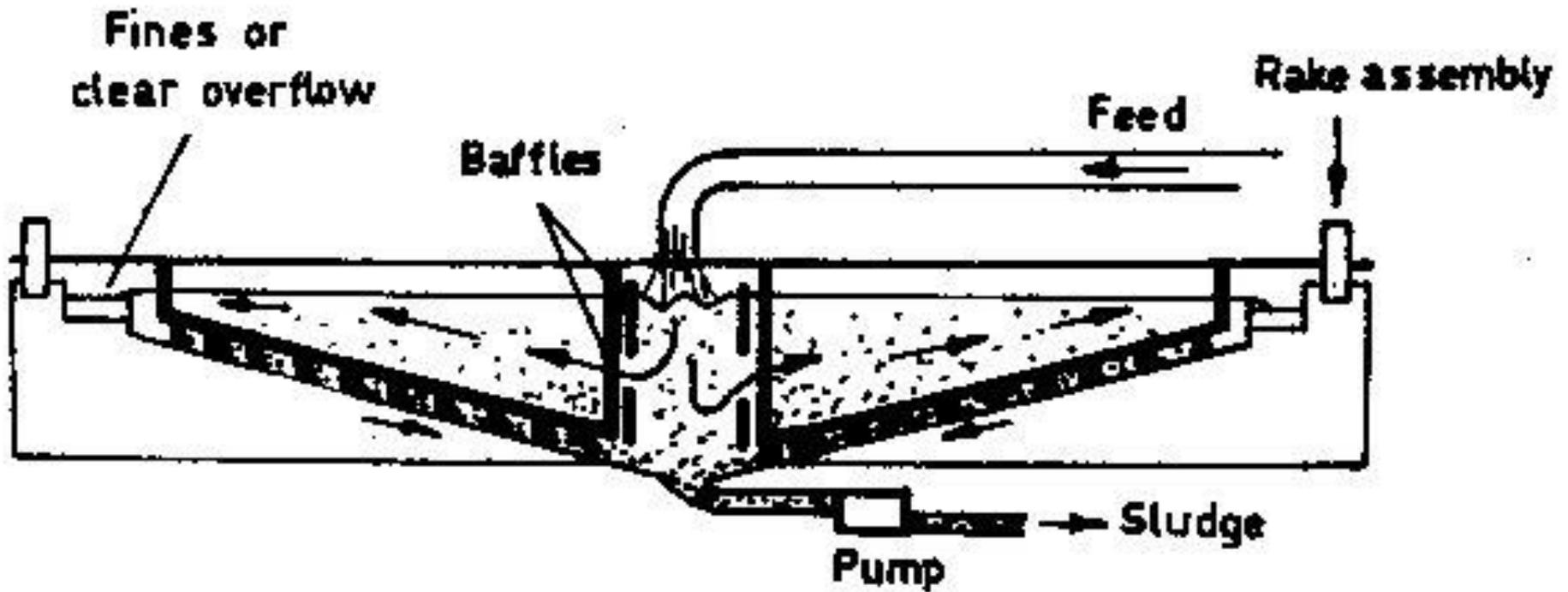
Sorting processes separate the valuable mineral from gangue, or in some cases also affect a separation of different types of minerals. They are classified according to the physical property, which forms the basis of separation. **Classification takes into account the rate of travel of particles through fluid media; Flotation uses differences in flow properties and Magnetic methods distinguish between magnetic and non-magnetic materials.**

Classification is based on difference of rate of fall of particles through water, and in some cases through air. **These are gravity separation processes.** Panning or Humphrey's spiral is a method in which mineral particles and water are put in a conical dish and swirled around. Dense particles stratify in the bottom while lighter minerals, being more buoyant, remain partly in suspension and can be decanted with water from time to time.

**Selective settling is another method** in which particles are allowed to settle down against a current of water. Dense particles settle nearer to the entrance, whereas lighter particles are carried to some distance, depending upon their specific gravities. Fig 5.4 shows a sluice box in which a pulp of particles and water is fed through a launder; heavy particles settle near the entrance, and particles with a range of specific gravities can be separated as shown.



*Fig.5.4 A simple sluice box*



*Fig.5.5 A bowl classifier*

For large scale sorting operations, bowl classifiers (thickeners) shown in Fig.5.5 are used. They are shallow cones with diameters as large as 50 m. Rotating rake assembly assists the solids to the central outlet.

# FLOTATION

Froth flotation is the most specific of the sorting processes, as it operates through the sensitive surface characteristics of the individual minerals. It can be applied to very fine particles, and is capable of distinguishing minerals from each other as well as from the gangue. In principle, conditions are arranged so that when a pulp is agitated and air is blown through it, certain minerals attach themselves to the bubbles and are floated out in a froth, which is skimmed off and discharged of its mineral burden.

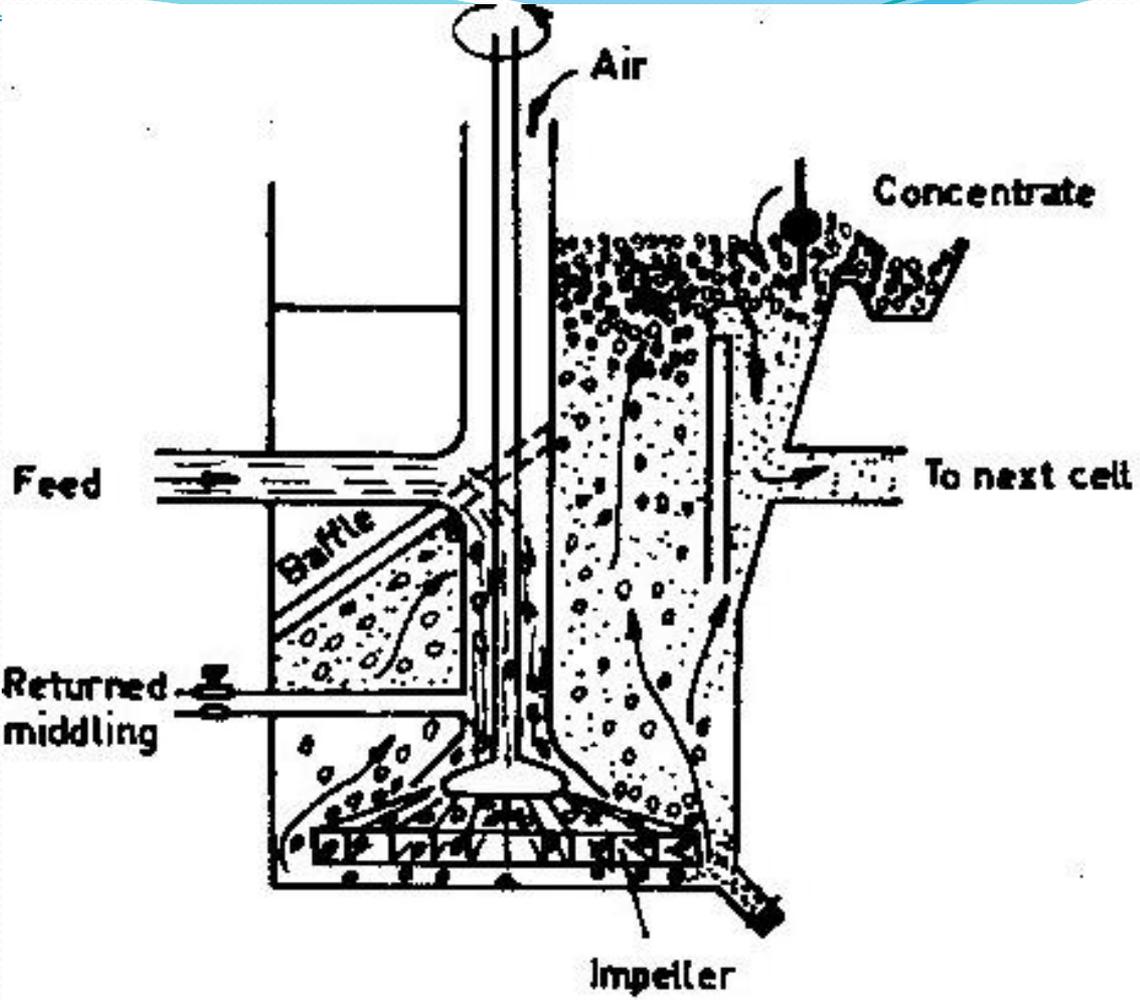


Fig.5.7 Essentials of a floatation cell.

# MAGNETIC SEPARATION

Only a few minerals are commonly separated magnetically, although many more are moderately susceptible to magnetic attraction. Magnetic fields are obtained using permanent magnets, but the most intense fields require electro-magnets. Mineral particles are placed on a conveyer belt which moves towards a magnet as shown in Fig 5.8. The magnetic separators provide two paths; one gravitational path for non-magnetic particles which fall on the near side, and one path for magnetic particles which cling to the magnet and collect at the farther end as shown in the figure. Minerals of progressively weaker magnetic susceptibility may also be separated by diminishing the magnetic field in several steps.

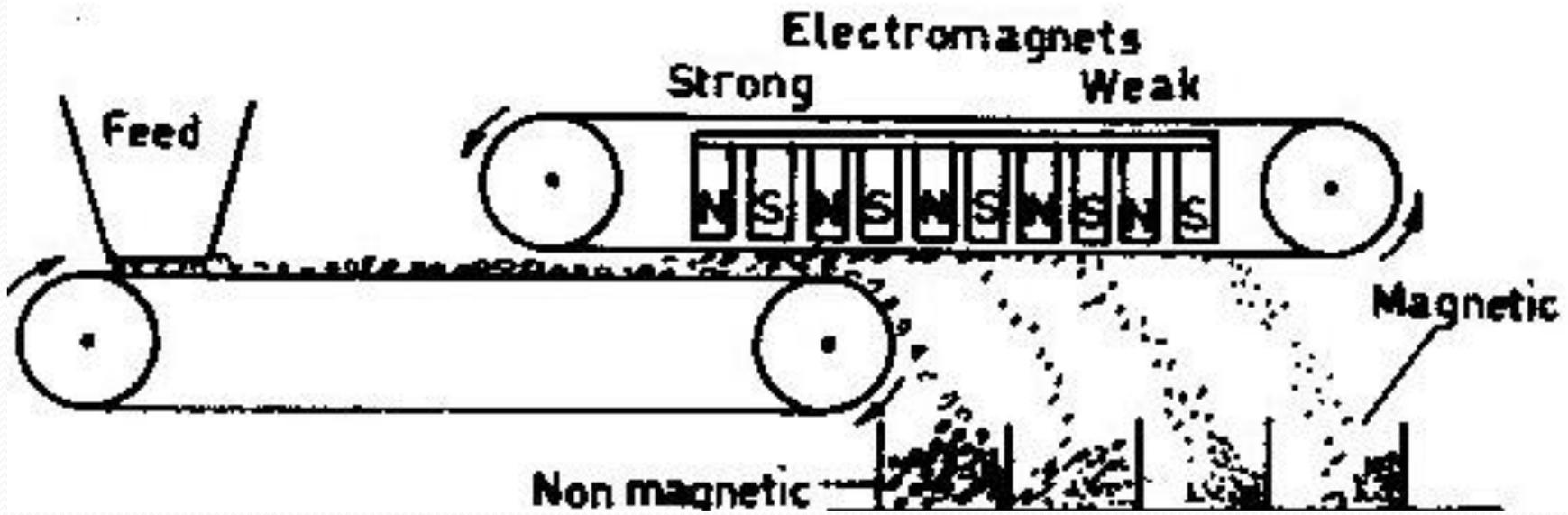


Fig.5.8 Magnetic separation process.

### 5.3.3 Agglomeration

When a particle size after concentration is too small to be suitable for a subsequent process, (for blast furnace, for example), it must be reformed into lumps of appropriate size and strength. This may be done by pelletizing or briquetting at ordinary temperatures or by sintering or nodularizing at very high temperatures. Pelletizing and sintering are the most common processes and sometimes they are used together whereby pellets are fed to the sintering plant.

#### PELLETIZING

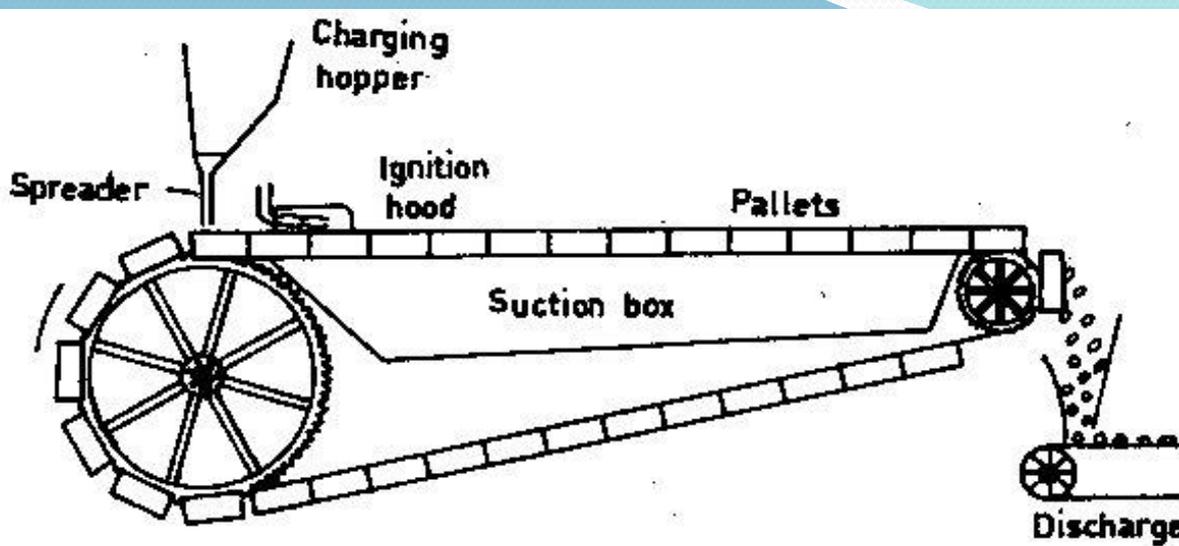
Pellets are made by rolling ore particles, moistened to a critical level, in a drum or on a rotating inclined disc. The particles join together by the capillary and surface tension forces in the moisture between them. A small pressure is also necessary which is supplied by the weight of particles themselves. The pellets may be used green (in moist condition), but are usually dried or fired together to obtain greater strengths.

The strength is derived from a clay bond or from a glassy silicate bond replacing the water bond, and clay or flux may be deliberately added for this purpose. Pellets are mainly used in iron-making. They may be made large (up to 4 cm diameter) for feeding to the blast furnace, but about 1 cm diameter pellets are preferred for iron-making.

The process of sintering is conducted at very high temperature, but below the melting point, to allow diffusion to take place between particles at the points of contact, so that they can grow together to produce a rigid entity. It also involves chemical reactions which produce new chemical species, whose crystallization provides the main mechanism for the formation of bridges between particles. In most cases sintering is used for roasting as well as agglomeration.

The components of the charge, including coke dust as fuel if necessary, are prepared to small size ( $<1/2$  mm), and thoroughly mixed and tempered with water in a drum or a pug mill. The charge is fed onto the grate of the sintering machine to the depth of 25 - 50 cm, and ignited with a flame on the top. Air is drawn down through the bed, whereby a combustion front passes slowly downwards accompanied by a series of physical and chemical changes which produce the sinter.

First the charge is dried out by hot gases, followed by the ignition of the particles as the combustion front approaches. Combustion provides oxidizing conditions so that sulphides and reduced oxides are oxidized by the combustion process. The re-formation of oxides produces new crystals at the points of contact, which form permanent bonds between particles.



*Fig.5.9 Dwight-Lloyd sintering machine.*

Sintering machines are of two types, continuous and batch. Continuous machines are more common and Fig 5.9 shows a Dwight-Lloyd type continuous sintering machine. A good sinter should be large in size and strong. It should also be chemically reactive, with a large available surface area.

## **NODULARIZING**

Fine ores may also be agglomerated in a rotary kiln if heated to such temperatures that some of the components just begin to melt. The process is rather like pelletizing, but with a slag for bond instead of water. The main difficulty is the tendency of materials to build up on the lining of the kiln. This method was formerly very popular in iron-works in Europe, but in recent years sintering is preferred.

## 5.4. EXTRACTION PROCESSES

Extraction processes alter the ore chemically. They may produce:

a single oxide of metal or decompose an ore (**calcination**), or

convert sulphide ore to oxide (**roasting**), or

form a matte (**smelting**), or

refine a metal (**electrolysis and fire refining**), or

volatilise a metal (**distillation**).

## 5.4.1 Calcination

Calcination is a process by which an ore is decomposed into its constituents, or the volatile component (water or CO<sub>2</sub>) of the ore is removed.

The process is carried out in shaft or rotating kilns, applying counter flow principle for efficient heat transfer. The kiln temperature is governed by the chemical reactions.

For CaCO<sub>3</sub>, for example, the decomposition takes place at 850 °C so that the kiln temperature is maintained at 1000 °C, whereby CaO and CO<sub>2</sub> are produced:



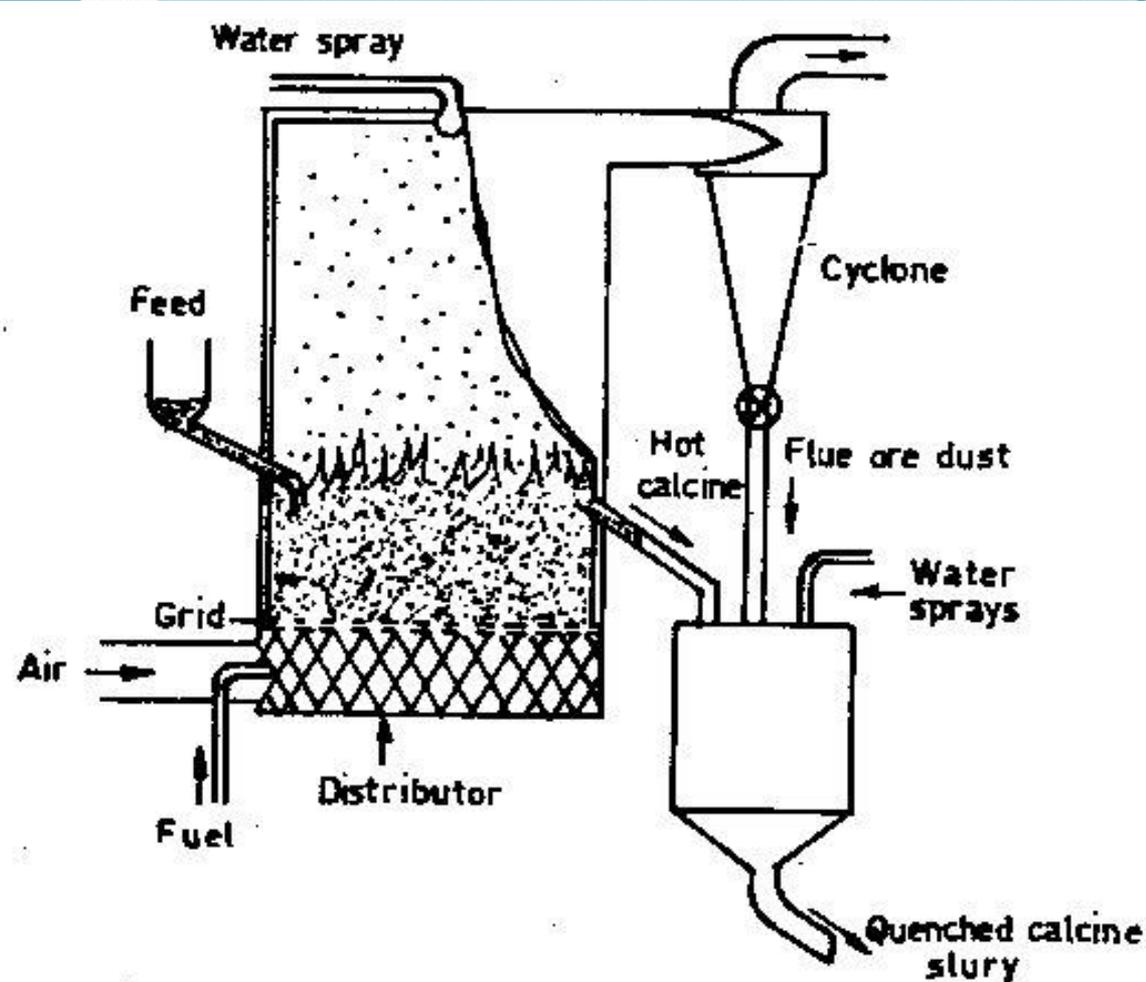
## 5.4.2 Roasting

Roasting is of many types, depending on the objective of the process. It may be

- (1) oxidizing roasting to convert sulphides to oxides,
- (2) volatilizing roasting to eliminate volatile oxides,
- (3) chloridising roasting for converting certain metals to chlorides,
- (4) sulphating roasting to convert sulphides to sulphates,
- (5) magnetizing roasting to convert hematite to magnetite,
- (6) reducing roasting to reduce oxides to metals prior to leaching or smelting,
- (7) carburising roasting to prepare calcine for chlorination, and
- (8) sintering roasting to sinter as well as oxidize ore particles.

Roasting involves chemical changes other than decomposition, usually by reaction with the furnace atmosphere, and depends on diffusion of chemical species through the product to the reaction front in each particle. A roast may cause drying and calcination in passing, however.

Roasting in present days is carried out in multi-hearth furnaces. Flash roasting is a more modern development in which the pre-heated ore is injected through a "burner" with pre-heated air, rather like pulverised fuel. This process is most appropriate for roasting sulphides to oxides which is an exothermic reaction not requiring any additional fuel. Fluidised bed roasting (Fig 5.10) is also used in which the oxidizing gas is passed through a bed of fine concentrate. Sulphating roast occurs under oxidizing conditions at high  $\text{SO}_2$  pressure, whereas chloridising and magnetising roasts are usually reducing in character and require good control of furnace atmosphere.



*Fig.5.10 A fluidized bed roasting furnace*

### 5.4.3 Smelting

Smelting is a reduction process which is employed to produce a matte or metal.

Matte smelting follows roasting; the undesirable sulphides are removed by roasting process which only leaves the desirable sulphides and iron sulphide (which is always present in sulphide ore). When this product of roasting is melted with a flux, a rich matte (containing sulphide of the desired metal) is obtained along with a slag containing impurity metals.

**Smelting, therefore, is a process of melting and separating.** The slag must be fluid enough to allow the separation of the matte easily, and this factor determines the operating temperature

Matte smelting can be carried out in a blast furnace if the ore is lumpy, or in a reverberatory furnace as shown in Fig 5.11, if a fine concentrate is being treated (e.g. copper matte smelting). Flash smelting is a pyritic smelting process which combines the operations of flash roasting and smelting; fine concentrate is mixed with auxiliary fuel ( $\text{FeS}_2$ ) and burnt like pulverised fuel to create enough heat to melt the matte and slag which settles in the settling hearth in the bottom of the furnace.

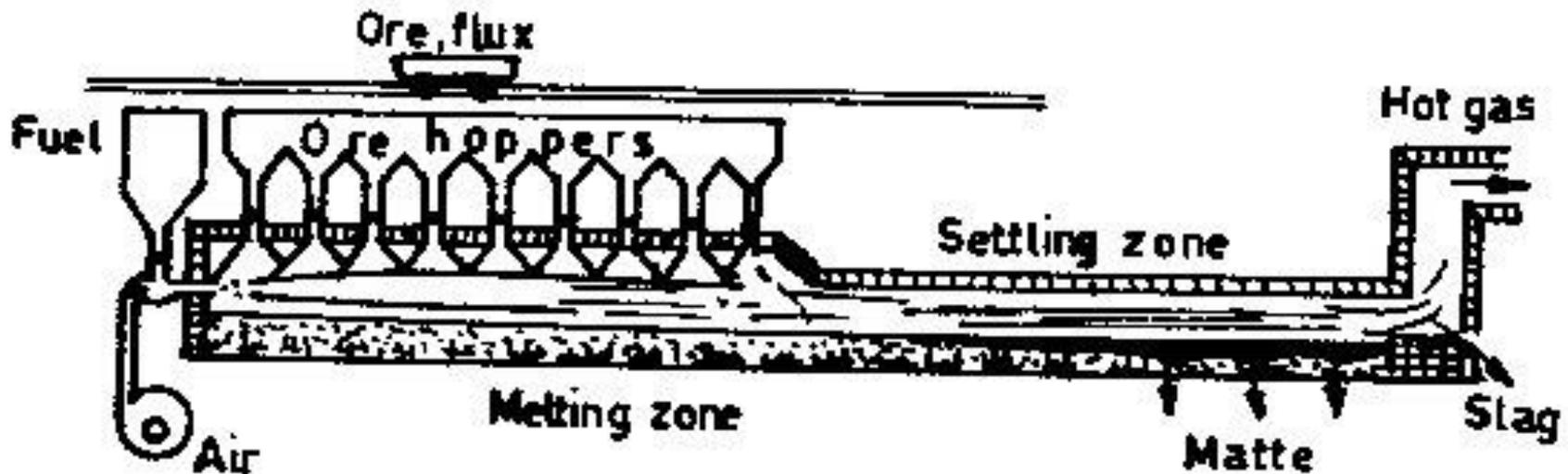


Fig.5.11 A reverberatory furnace

Smelting for metal, on the other hand, involves reduction, usually by carbon as coal or coke, but sometimes by ferrosilicon, and may be performed in a blast furnace, hearth, reverberatory, or electric arc furnace.

The coke is burnt to produce  $\text{CO}_2$  which reacts with further coke to produce CO. The CO reacts with metal oxide to produce the metal. The stack reactions amount to drying, calcination and reduction roasting. The metal melts and the slag forms by combining flux and gangue in the bottom, and floats on top of the metal. Metal and slag are removed separately, the metal obtained being crude and needs subsequent refining.

**Production of pig iron is an example of such smelting and will be discussed in detail in the next chapter.**

## 5.4.4 Electrolysis

Electrolysis is a hydrometallurgical process used for both extraction and refining, the electrolyte being a solution or a mixture of fused salts.

In extraction process the metal is in solution in the electrolyte from which it is deposited on the cathode by passing a current through the solution, the anode being an insoluble conductor.

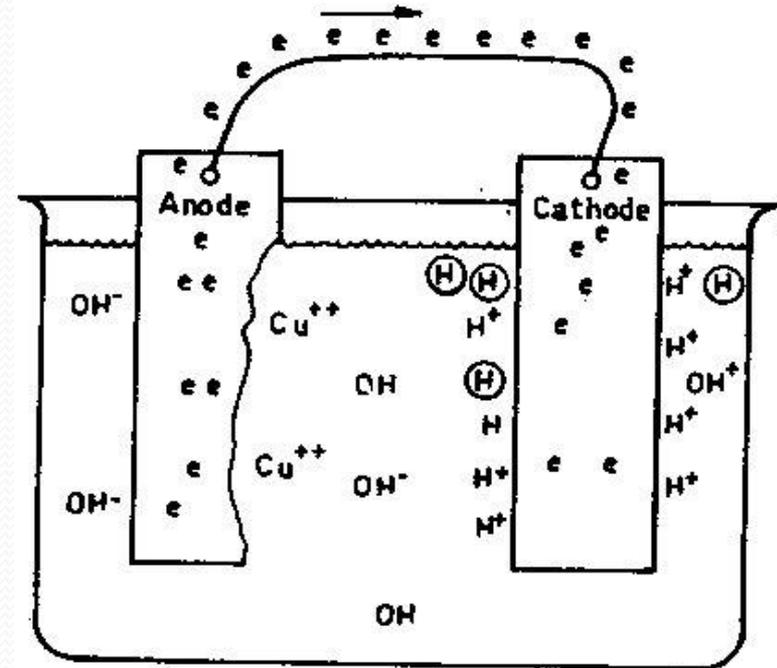
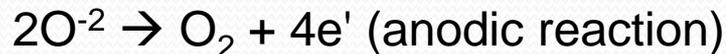
In refining, however, the impure metal is made the anode which dissolves in the solution and redeposit on the cathode as pure metal by passage of current through the solution.

## 5.4.4 Electrolysis

The principle involved is simple. The metal to be extracted is first dissolved to form a solution, whereby the ions of that metal ( $M^+$ ) are free to move in the solution. When an electric current is passed through the solution, cathode acquires a negative charge and anode becomes positive. The  $M^+$  ions are attracted to cathode where they acquire an electron and are deposited as pure metal atoms:



To balance this transfer of electron, an ion of a different species is oxidised at anode whereby it releases its electron to the anode, which in turn is transferred to the cathode by the battery and the electrical balance is maintained.



*Fig.5.12 Principles of electrolytic refining*

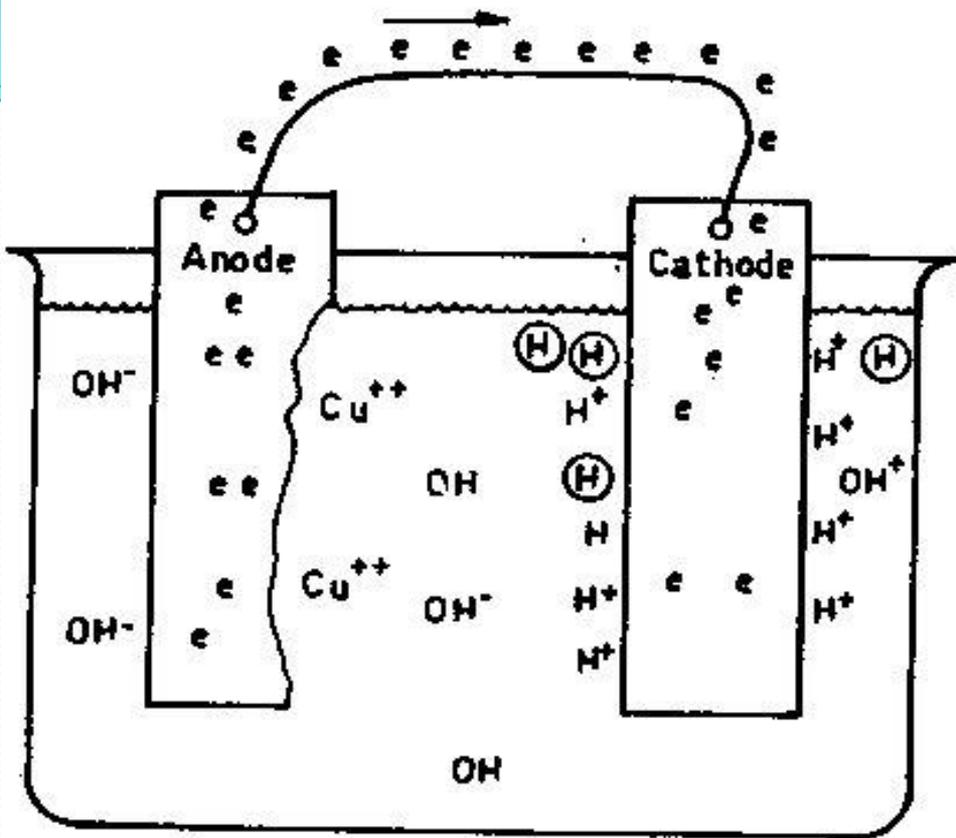
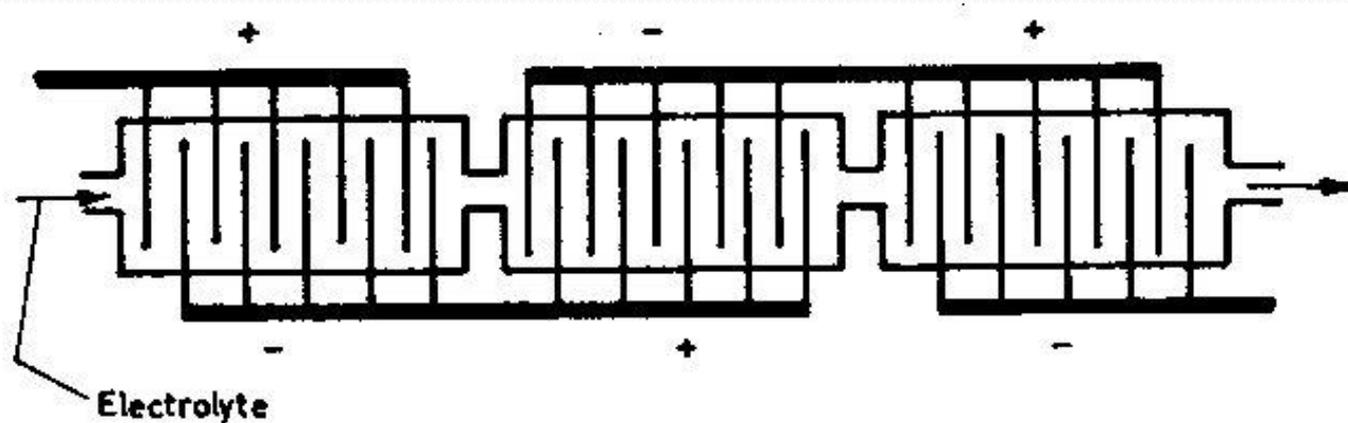


Fig.5.12 Principles of electrolytic refining

The process is depicted in Fig 5.12 for refining of copper. The important requirement for this process, therefore, is that the metal should, be soluble in electrolyte. Furthermore, only those metals are processable whose ions are discharged with a lower electro motive force (emf) than that required to discharge hydrogen ions; otherwise on passage of electric current  $\text{H}^+$  ions will be reduced at cathode to produce hydrogen gas instead of the metal ions to produce pure metal.

Those metals which can not be electrolyzed from aqueous solutions may be deposited from fused salts or "igneous melts". Fused salts are capable of decomposing metal compounds to free metal ions, which move freely in fused salt baths and are separated at cathodes on passing electric current, as in the case of aluminum extraction.

In electrolytic extraction plants, electrodes are usually arranged in parallel in each tank, while large number of tanks are arranged in series, as shown in Fig 5.13. Tanks typically hold about forty to fifty anodes and cathodes, each with an area of about 1 m<sup>2</sup>. Current densities usually lie in the range 100-300 A/m<sup>2</sup>.



*Fig.5.13 Typical layout of electrolytic plant.*

## 5.4.5 Fire Refining

Fire refining works on the principle that impurities are removed by heating the metal to its melting point. In some cases the cathodically entrained hydrogen is removed by diffusion, in others volatile impurities are drawn off under reduced pressure. In cases such as steel, most impurities are removed by selective oxidation, which makes the impurity oxides insoluble in molten steel and are thus removed. Oxygen is the most common reagent for this purpose, but S, Cl, C, lime or Zn may be used for particular cases.

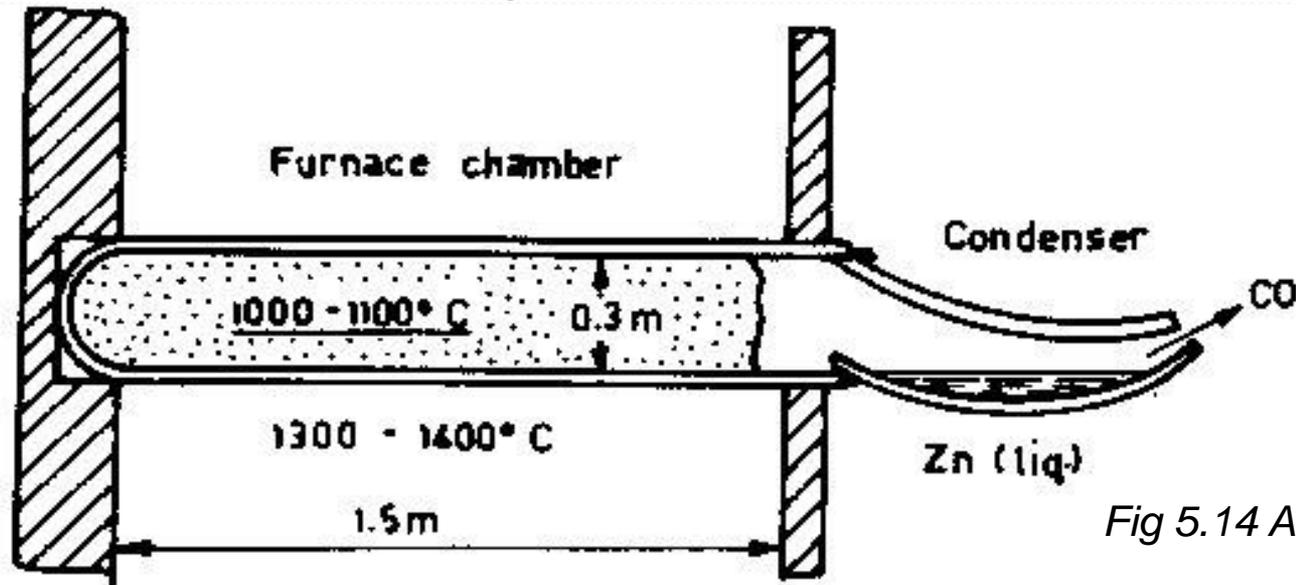
Most common of these mechanisms is oxidation refining in which air or an oxidizing slag is used to oxidize impurities whose oxides are insoluble in the principle metal. These insoluble oxides then combine with the flux to form a slag which is separated from the refined metal. Gaseous impurities can be removed by vacuum degassing or by bubbling an inert gas through the melt.

Liquation is a variant of fire refining in which impure metal is heated to its melting temperature on an inclined surface. Upon reaching its melting point the pure metal is viscous and, therefore, drains off leaving impurities behind. Conversely the impurities may be lower melting and drain off leaving the pure metal.

## 5.4.6 Distillation

In only a few cases are metals amenable to extraction or refinement by distillation at normal pressures. Only those metals which have low boiling points at normal pressures are distillable. In this process the metal is heated to its boiling point and its vapours are condensed to obtain pure metal. Metals such as zinc, mercury and cadmium are distilled.

The impure metal is placed in a retort, which is a tubular vessel, and retort is placed in a furnace. Desirable metal is vapourised by the heat of the furnace and is removed through the nose of the retort, and condensed to produce the pure metal. In case of zinc, ZnO sinter is briquetted with coke before placing it in retort. Fig 5.14 shows such an arrangement.



*Fig 5.14 A typical zinc retort*



Distillation can also be carried out at lower pressures, which allows the process to be carried out at lower temperatures because the boiling point is reduced at low pressure. This is particularly useful for the more highly reactive metals.

This chapter has described the basic processes which are required to produce metals from their ores. The important engineering metals, ferrous and non-ferrous, are produced using some of the techniques described herein. Next two chapters will discuss the production of important metals in greater details.

Culminate: sonuçlanmak

Agglomeration: yığma, yığın, toplanma, toplama

Pebble: parlak taş

Bowl: kase, çanak

Froth: köpük

Sluice: oluk kanal

Pine oil: çam yağı

Kiln: ocak

Cascade: taşırma; şelale

Rod: sopa

Lumpy: yumrulu, topaklı

Pellet: A small sphere (yumak, ufak top, topakla vurmak, topak, top, saçmayla vurmak, saçma tanesi, hap)

Smelting: maden eritme, döküm.

Fused salts: erimiş tuzlar

Igneous melts: ateşe ait, ateşten, ateş gibi, volkanik ateş ısıyla meydana gelmiş (kaya), volkanik; ateşe ait; ateş gibi, ateşli.

Aqueous solution: sulu çözeltiler

Calcination: The conversion of metals into their oxides as a result of heating to a high temperature. (yakarak toz haline getirme veya gelme)

Roasting: Cooking (meat) by dry heat in an oven

Mining: a. Heating an ore to effect some chemical change that will facilitate smelting,

b. The operation of heating sulfide ores in air to convert to oxide or sulfate c. Calcination, usually with oxidation.

Leach: süzmek

Fused: eriyip karışmış

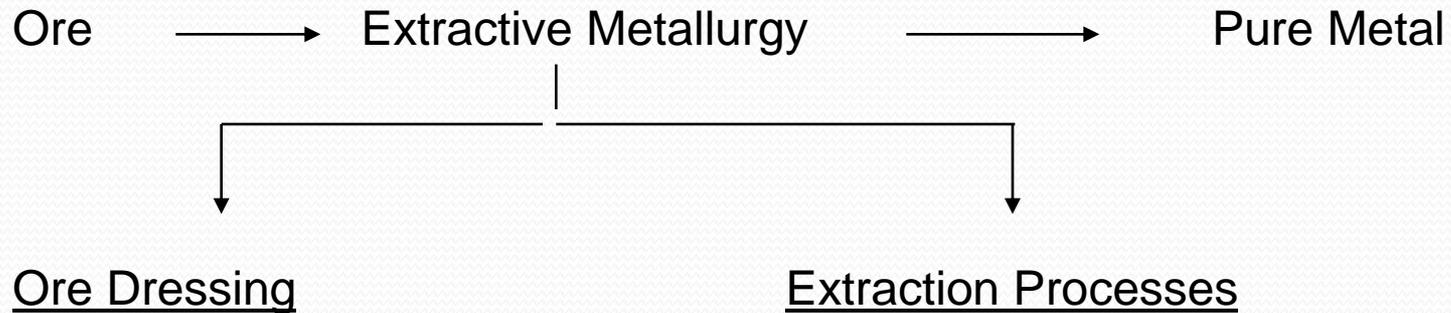
Rake: tırmık, taramak

Stack: istiflemek, dizmek

Pyrites: a natural compound of SULPHUR with any one of certain metals, esp. iron (iron pyrites) or copper (copper pyrites), found in the earth and having a shiny yellow look, like gold.

# Extractive Metallurgy

Extractive metallurgy is the science of converting ores to pure metals.

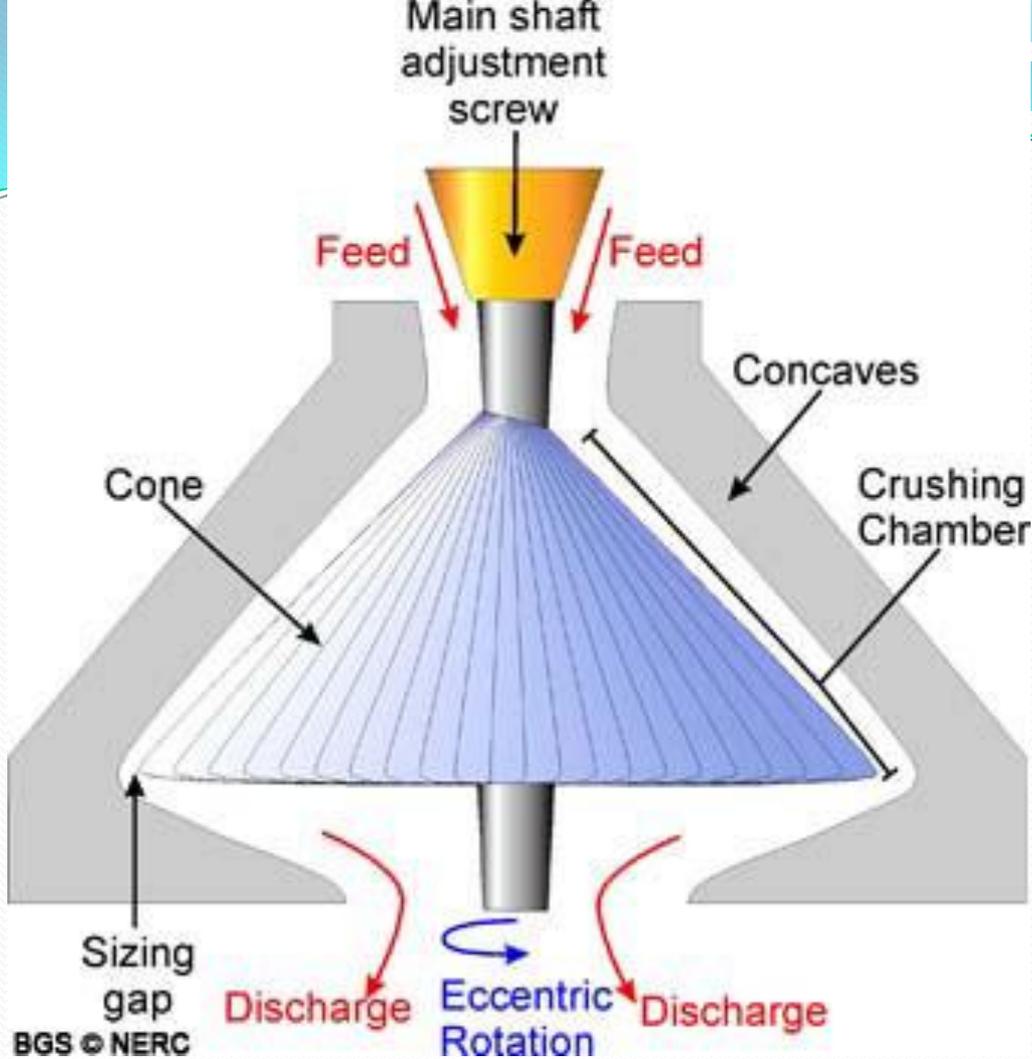


- 1.) Crushing and Grinding
- 2.) Sizing and Sorting
  - a) Screening
  - b) Sorting
    - Classification
    - Flotation
    - Magnetic Separation
- 3.) Agglomeration
  - a) Pelletizing
  - b) Sintering
  - c) Nodularizing

Physical

- 1.) Calcination
- 2.) Roasting
- 3.) Smelting
- 4.) Electrolysis
- 5.) Fire Refining
- 6.) Distillation

Chemical



THE END

# CHAPTER 6

## PRODUCTION OF IRON AND STEEL

### 6.1 INTRODUCTION

Ferrous metals comprising of steels and cast irons are the most widely used materials for engineering. A wide variety of structures and properties can be obtained from steels, and to some extent from cast irons, by changing carbon content, by adding alloying elements, by heat treatments or by processing. In order to make the most of these metals it is important for an engineer to know ferrous metals technology which includes production and processing of irons and steels. The objective is to understand iron and steel making processes and to familiarize with the constituents of ferrous metals to facilitate the study of their physical metallurgy in later chapters.

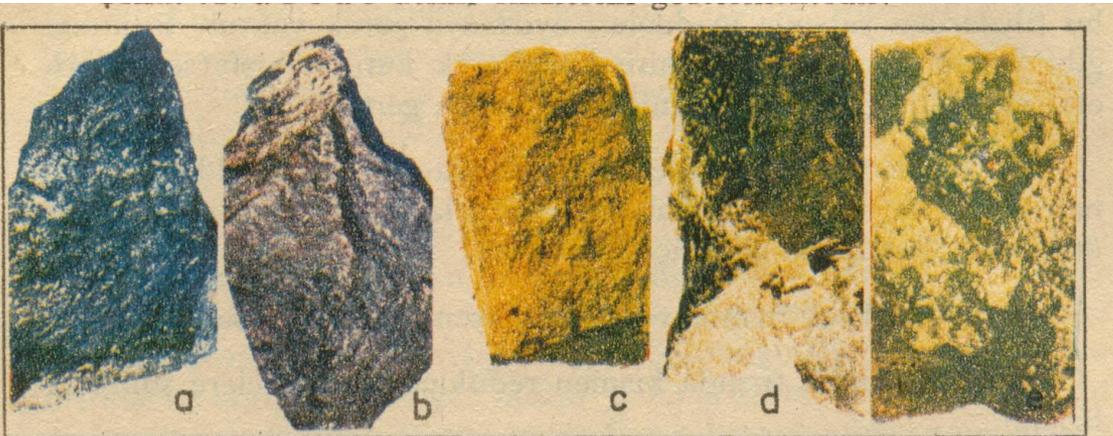
**In this chapter** processing and conversion of **iron ore** into **irons and steels** will be described. Latest technology used to produce optimum quality steels will be discussed. Various types of steels and cast irons will be dealt with so that a general background is created and the relationship between processing parameters and resulting qualities of ferrous metals is appreciated by the students.

# 6.2 IRON ORES

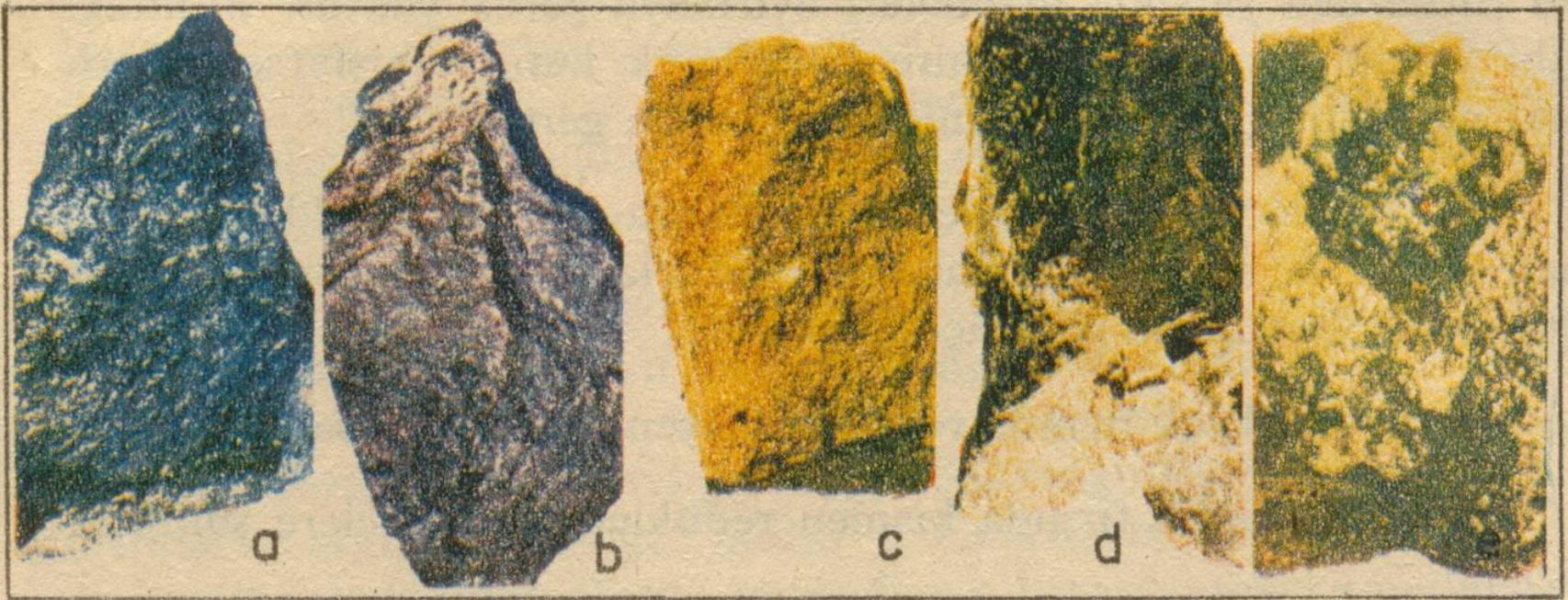
Iron is the fourth most plentiful element in earth's crust. It is almost never found in its native or metallic state. Iron ores are found all over the world in the form of various compounds, mainly oxides. Depending on the type of ore, the iron content of the ore ranges from 25 % up to 70 % as shown in Table 6.1.

Ore	Compound	Content(%)
Magnetite(a)	$Fe_3O_4$	72.4
Hematite(b)	$Fe_2O_3$	70.0
Goethite	$Fe_2O_3 \cdot H_2O$	62.9
Limonite(c)	$2Fe_2O_3 \cdot 3H_2O$	59.8
Siderite (d)	$FeCO_3$	48.2
Taconite	$Fe_3O_3$	25-35
Pirite (e)	$FeS_2$	46.6

Until recently ores containing less than 30% iron were not considered viable. A shortage in iron supply has, however, changed the scenario and taconite is now readily mined for iron.



- a) Magnetite
- b) Hematite
- c) Limonite
- d) Siderite
- e) Pirite



(Sakil 72)

(a) Magnetite, (b) Hematite, (c) Limonite, (d) Siderite, (e) Pyrite.

These ores are removed by open-pit mining as against the more costly and hazardous underground mining. The ore once removed from pits are then separated from the worthless material called gangue and refined to produce iron.

**The sequence of operations is:**

- mining
- concentration
- purification
- reduction

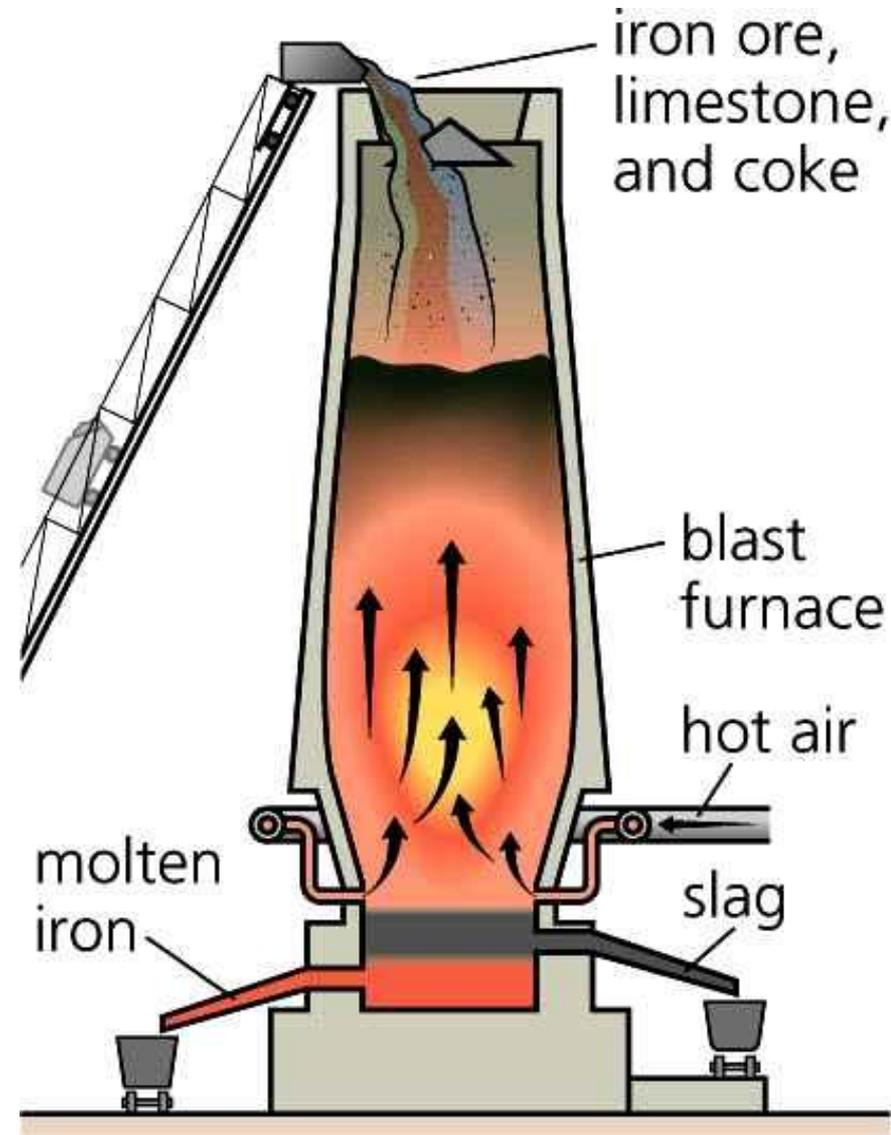
20.07.2011 refining.

## 6.3 PRODUCTION OF PIG IRON

The modern story of iron and steel begins with the raw materials:

1. iron ore,
2. coal and
3. limestone.

From these ingredients **pig iron** is produced in a **blast furnace**. Pig iron is the source of almost all ferrous metals. The steel mill then refines it in furnaces to produce steel, after which it is cast into ingots which are turned into **slabs, billets, blooms and bars**. The ingots and blooms are processed by various techniques to produce the many steel products in contemporary use.



These cast ingots are preheated at 1200 °C (the process is known as *soaking*). Then, they are rolled into one of the three intermediate shapes called *slabs*, *blooms*, or *billets*.

- \* *Slab* (40/250 mm or more) is rolled from an ingot or a bloom
- \* *Bloom* has a square cross section of 150/150 mm or more
- \* *Billet* (40/40 mm or more) is rolled from a bloom

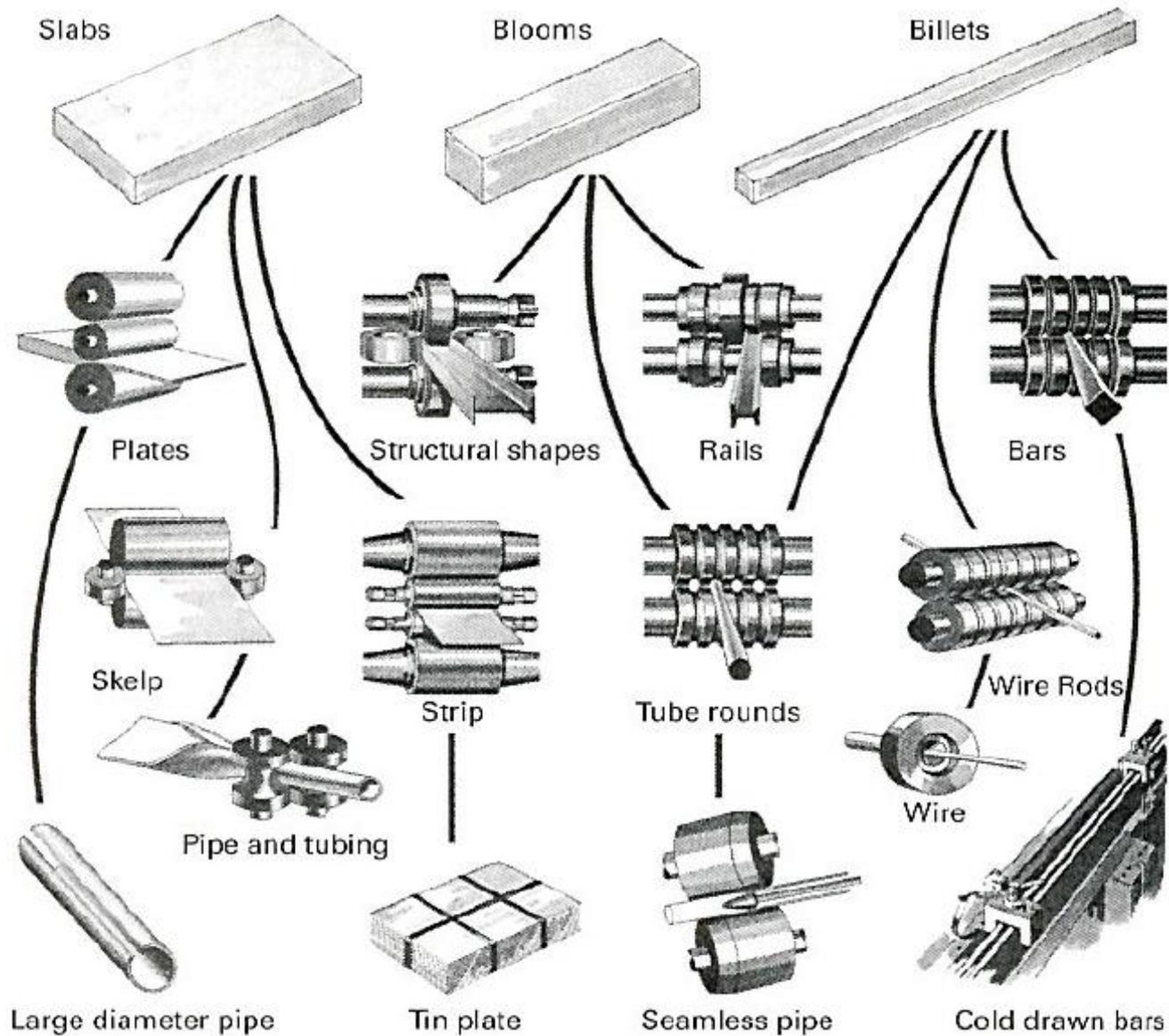
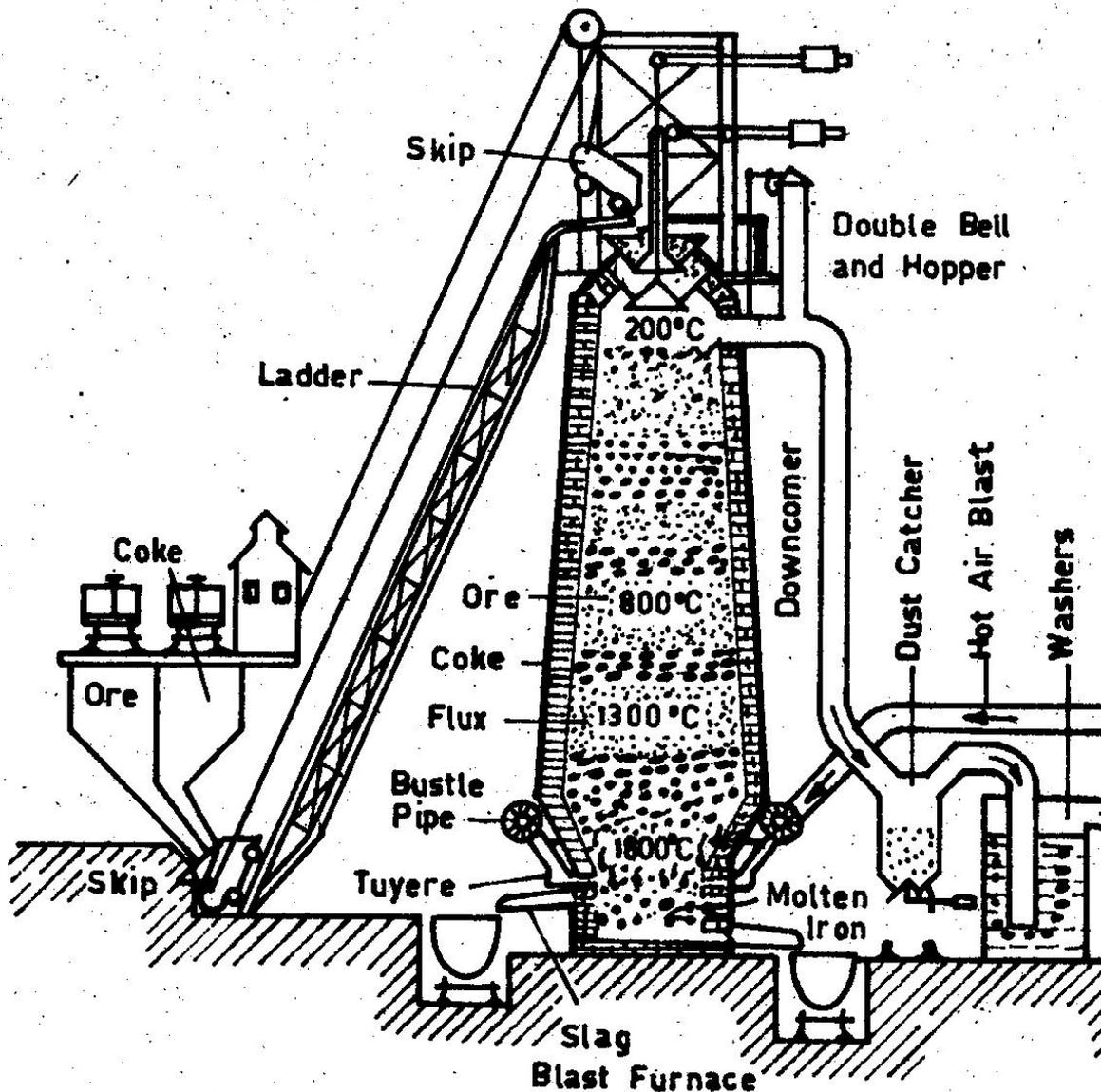


Fig.6.9 Flow diagram for steel processing.

## 6.3 PRODUCTION OF PIG IRON



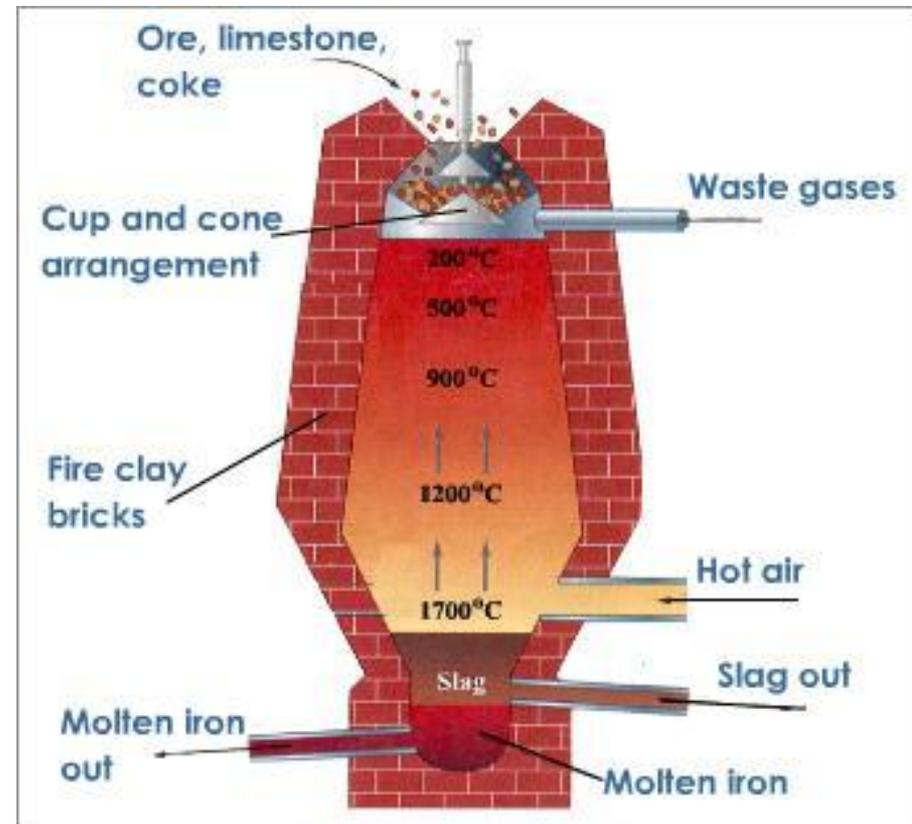
The concentrated iron ore is converted into pig iron in a blast furnace. Fig.6.1 summarizes the operation of a blast furnace. **The three raw materials, iron ore, coke and limestone** are put into the furnace alternately making it a continuous process. About 7 tons of raw materials of

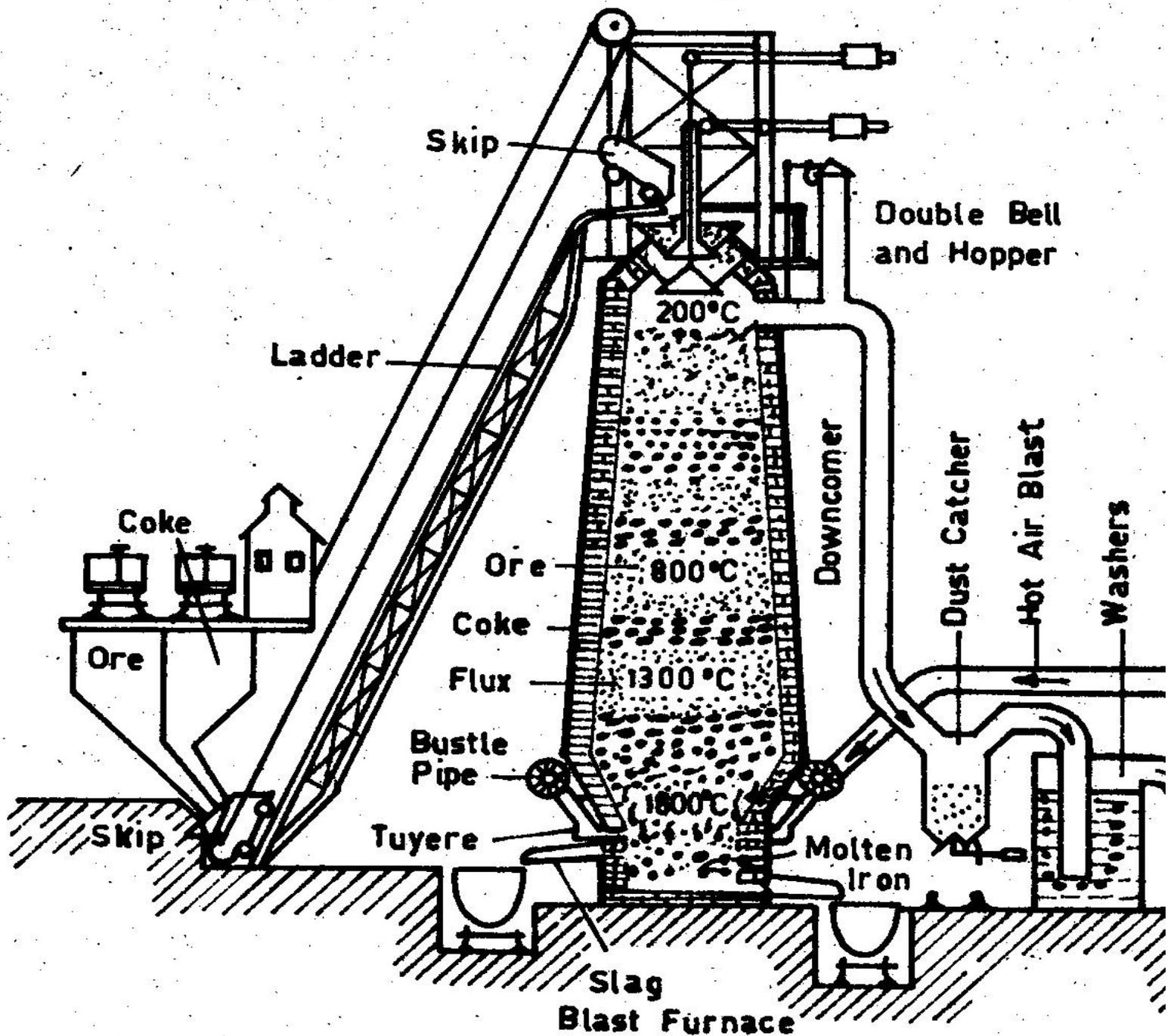
2 tons of **iron ore**,  
1 ton of **coke**  
1/2 tons of **limestone** and  
3.5 tons of **gases**  
(CO, H<sub>2</sub>, CO<sub>2</sub>, H<sub>2</sub>O, N<sub>2</sub>, O<sub>2</sub>)

are required to produce one ton of pig iron.

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Fig 6.1 Blast furnace and accessories.

- BLAST FURNACE is a refractory lined chamber with a diameter of 9 to 11 m at its widest and a height of 40 m.
- To produce: **1 ton of Pig Iron,**
- 7 tons of raw materials are required:
- 2 tons of Iron Ore
- 1 ton of Coke
- 0.5 tons of Limestone
- 3.5 tons of gases
- ( CO, H<sub>2</sub>, CO<sub>2</sub>, H<sub>2</sub>O, N<sub>2</sub>, O<sub>2</sub>)



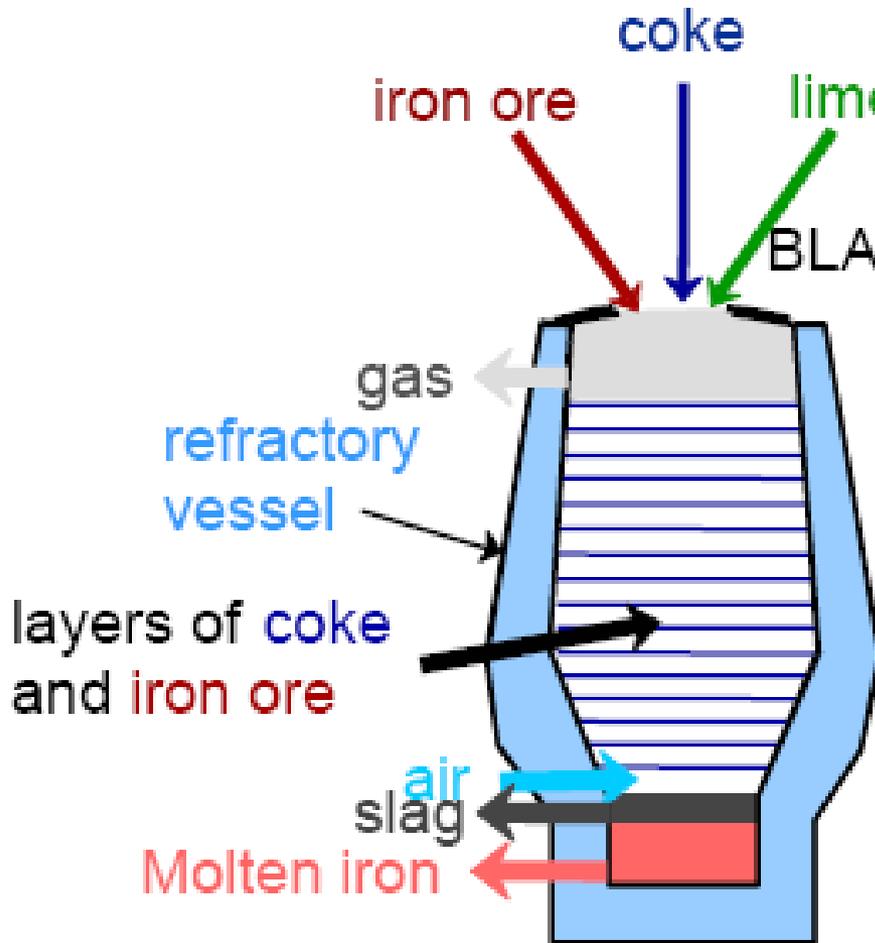


**LIMESTONE** is a rock containing high proportions of calcium carbonate( $\text{CaCO}_3$ ). The limestone is used in the process as a flux to react with and remove impurities present in the molten iron as slag.

**COKE** is a high-carbon fuel produced by heating bituminous coal in a limited oxygen atmosphere for several hours, followed by water spraying in special quenching towers.

- Coke serves two functions in the reduction process:
- 1. It is a fuel that supplies heat for the chemical reactions, and
- 2. It produces carbon monoxide (CO) to reduce the iron ore.

# REFINEMENT OF STEEL FROM ORE

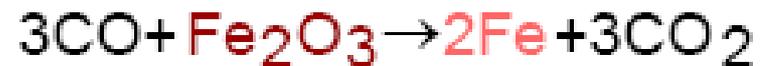


BLAST FURNACE

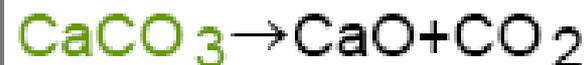
heat generation



reduction of iron ore to metal



purification



One of the three major ingredients is **coke**, a residue left after burning certain soft coals in the absence of air. When coal is heated in coke ovens and the exhaust gases are driven off, coke is the resulting product. **Coke is a hard, brittle, porous material containing from 85-90% carbon, together with some ash, sulphur and phosphorous.** An older type of coke oven called the **bee hive oven** (due to its shape) is now obsolete because it wasted the exhaust gases from the cooking process. Many useful products such as fuel gas, ammonia, sulphur, oils and coal tar can be made from waste gases. Coal tar in turn can be used to produce dyes, plastics, synthetic rubbers, perfumes, soda drags and aspirin.

**Reduction is a process** by which **oxygen is removed** from a compound, such as iron ore, **and combined with carbon**. Hence in the production of iron in the blast furnace, the iron ore is reduced by combining it with coke. Metallic iron is released from its oxides.

Raw materials enter the blast furnace through the hopper at the top. The charge is raised to the rotating hopper by skip cars on inclined rails. Rotating hopper distributes the charge evenly onto the gas tight bells. When the bells are lowered, the charge enters the furnace. Cross section of the furnace increases towards the bosh region and whole of the furnace is filled with charge. Weight of the charge is carried by the charge in the lower bosh region which has a smaller cross section. The charge here is compressed due to smaller cross section and this compression supports the weight of the material above.

Air is blasted in at the bottom through tuyeres. In the latest blast furnaces this air is preheated to 600-800 °C by the waste gases to increase the efficiency of production. Air is heated in stoves composed of refractory bricks before it enters the furnace. In order to reduce erosion the shell of blast furnace is water cooled.

Blast furnace is a counter current process whereby the reducing gases rise and the charge descends. The fuel burns near the bottom and the heat rises to meet the descending charge. At very high temperature (about 1650 °C) the coke unites with the oxygen of air blast and is converted into CO gas



The CO gas rises to near the top of the charge in the furnace where it reacts with the iron oxide to produce ferrous oxide



The CO<sub>2</sub> combines with some of the remaining coke to produce CO again



Lower down the bosh region, a direct reduction takes place whereby some iron oxide reacts with coke to produce iron



As the process continues, iron is released to the bottom of the furnace where it remains a molten mass.

Here the **limestone is used to segregate impurities** (mostly silica) from the iron by combining to form a lower melting temperature compound called **slag**. The flux first decomposes to form lime and CO<sub>2</sub>



Lime (basic) combines with SiO<sub>2</sub> in iron (acidic) to form the slag



Lime also helps remove sulphur from the iron



Since this waste slag is lighter than iron in weight, it floats on top of iron and is drawn off periodically to be hauled away in slag cars. The slag is sometimes ground into an aggregate which is used for asphaltic roads and in concrete building blocks. The molten mass of slag also helps protect the iron from oxidation by floating on top of iron and insulating it.

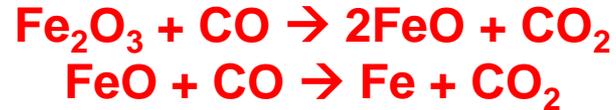
Molten iron in the bottom of blast furnace contains from 3-4.5 % carbon, 4 % silicon and up to 1 % manganese as well as some other unwanted impurities such as sulphur and phosphorous. These are later removed to some extent by steel making process.

Production of pig iron is an intermediate stage in the manufacture of steel. The iron is tapped at intervals and collected in a transfer car which is insulated to keep iron hot. It is then removed to the steel furnace and added to the charge of steel scrap and limestone.

Sometimes the iron is not made into steel but is instead poured directly into moulds. Before the introduction of pig casting machines the iron was poured in open sand moulds consisting of a groove or trough with many small moulds on each side, reminding one of the **sow and pigs**, hence the name pig iron. Iron pigs are melted in cast iron foundries and in steel mills.

## 6.4 DIRECT REDUCTION OF IRON

Iron from the ore can also be directly reduced to produce sponge iron in a solid state reduction at 750 °C. The reactions which take place are:



The iron so produced has a spongy appearance giving it its name. It can then be converted to steel using an electric process. The advantage of this process is that a solid state, low temperature reaction makes it possible to mine and produce iron from very remote areas and in very small quantities. Considerable research has gone into the development of this technology and smaller sized steel plants have been constructed as a result in various countries:

The HyL, Midrex, SL/RN and Accar shaft systems are some of the many processes developed to produce pellets of sponge iron from ore by using either natural gas or some other reductant. Natural gas acts as a fuel and reducing agent simultaneously. The ore is mixed with the reducing gas at 750 °C and is thoroughly mixed to produce sponge iron. A further recent development is based on the 20th century method of converting sponge iron into useful shapes by sintering and pressing (as depicted in Fig.6.2).

In this method the sponge from direct reduction process is not cooled and fed to electric steel making furnace but instead it is fed directly to a large diameter horizontal rolling mill stand. After complete gaseous reduction the loose tumbling mass of hot sponge (1100-1200 °C) is passed under atmospheric protection into the roll gap; a single heavy pass giving a reduction in thickness of approximately 80 % fully consolidates the sponge iron into hot rolled strip or, if preferred, a bar or light section. The finished product has mechanical properties very similar to those of conventional low carbon steel but the structure is quite different. This method promises to be very economical and viable and may become widely used.

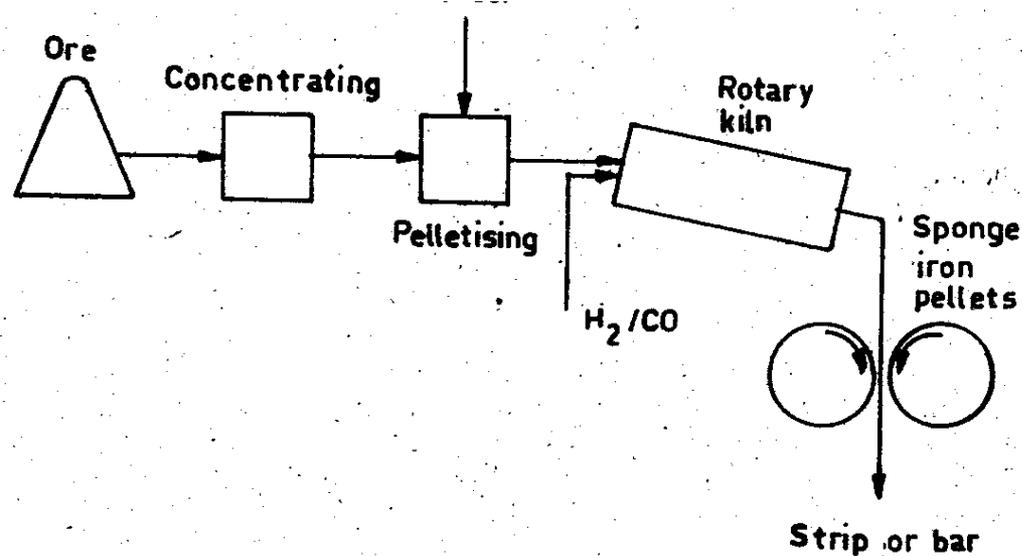


Fig.6.2 Direct reduction of iron ore to produce structural shapes

## 6.5 WROUGHT IRON

In ancient times before the advent of steel and pig iron, iron was produced by a direct process whereby the ore was heated in a forge to white heat to remove impurities and to produce iron. The charcoal fire in the forge did not get hot enough to melt the iron; the result then was a pasty mass of spongy iron (similar to sponge iron) which was then hammered to remove the molten gangue or slag.

Wrought iron was, however, used extensively before the introduction of modern steel making processes. Bars, plates, rails and structural shapes for bridges, boilers and many other applications used wrought iron. Even after the advent of steel wrought iron is used especially where the parts are to be forged or welded. Wrought iron is never cast, it is hammered or pressed or forged.

## 6.5 WROUGHT IRON

Wrought iron was made by a puddling process in which pig iron was melted in an open hearth type of furnace. Iron oxide was then added to form a slag. The iron was stirred with rabble arms by hands. Carbon and other impurities were removed by the iron oxide slag. The mass of iron was removed and squeezed to remove the slag; much of it, however, remained in the iron. The result was a very low carbon fibrous, (due to trapped slag), soft iron. This process is now obsolete and Aston process is used to produce wrought iron nowadays. Molten pig iron and steel are poured into an open hearth furnace in a prepared slag; this cools the metal to a pasty mass which is later squeezed in a hydraulic press. The slag in wrought iron is distributed in the iron matrix as threads and fibers in the rolling direction. This imparts excellent ductility to wrought iron. In addition it has good machineability and corrosion resistance.

# SUMMARY

- PRODUCTION OF IRON
- 1. Pig Iron → Blast Furnace
- 2. Sponge Iron → Direct Reduction  
(Solid State at 750 °C)
- 3. Wrought Iron → Direct Process

## 6.6 STEEL MAKING

Since pig iron contains too many impurities to be useful, it must be refined to produce steel or cast iron of various types. Steel is simply an alloy of iron with most of its impurities removed; it contains 0.03-2 % carbon plus any other alloying elements. Over 90 % of all steels is **plain carbon steel** containing less than 1 % carbon with little manganese to control sulphur and other impurities. All other alloy steels make up the other 10%.

### **Major steel making processes are**

<b>Bessemer-Thomas,</b>	0 %
<b>Basic Oxygen Furnace (BOF),</b>	60 %
<b>Open Hearth (Siemens-Martin) and</b>	15 %
<b>Electric Processes.</b>	25 %

Sixty percent of all steels is produced by BOF whereas electric processes account for 25% and open hearth 15%. Bessemer process is not generally used at present due to inferior steel produced from it.

These processes are classified as either **acid or basic** processes.

In the acid process **non-metallic oxides** are used to initially oxidize iron into FeO and Fe<sub>2</sub>O<sub>3</sub> which subsequently oxidizes C, Mn and Si thereby producing steel. The reactions taking place are as follows:



These oxides form a slag which floats over molten steel protecting it from excessive oxidation.

Slag producing reactions are:



Oxidation conditions are not sufficient to oxidize phosphorous in steel (and even if P was oxidized it would again be reduced in the presence of  $\text{SiO}_2$ ). **The refractory lining is acidic (silica)** because otherwise it would react with the bath producing cracks.

In the **basic process** **metallic oxides** oxidize impurities. Limestone is added and sometimes iron ore (to provide FeO) is also added as an oxidizing agent unless oxygen is blown in the process (as in Bessemer process). The reactions are as follows:



The last reaction only takes place if the slag is very basic and only slightly oxidizing (presence of silicon reduces the phosphorous and it goes back to steel). Sulphur can be partially reduced as:



**The refractory lining is magnetite or dolomite.**

In both acid and basic processes the oxidizing agent is FeO but in acid process it is produced early and so the **time required for refining is shorter in acid process.**

Basic process has much more severe oxidizing condition so it is likely that some of the FeO is present in steel which forms cellular structure around ferrite crystals reducing the strength markedly.

**All being equal, therefore, acid steel is probably more desirable.**

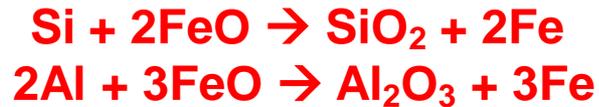
In most cases too much carbon is burnt out during refining. Carbon content of steel is therefore raised by adding ferromanganese. (72-80% Mn, 6-8% C) or spiegeleisen (15-20% Mn, 4-6% C). In acid process it may be added during refining while in basic process it is added in the ladle rest it reduces the phosphorous. Carburisers also act as deoxidisers.

## 6.6.1 Deoxidation and Rimming

The refined steel is produced through oxidation and as a result it may (and in most cases it does) contain oxygen in the form of iron oxide and dissolved gas. This can be tackled either by:

deoxidation (killed steel) or  
by rimming.

**Killing** is done by adding silicon (in the form of ferrosilicon) or aluminum which form  $\text{SiO}_2$  or  $\text{Al}_2\text{O}_3$  by reacting with iron oxide or oxygen viz:



In acid process deoxidation is carried out in the furnace in the presence of slag so that the time available for  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$  is sufficient to rise to the surface and be removed with the slag.

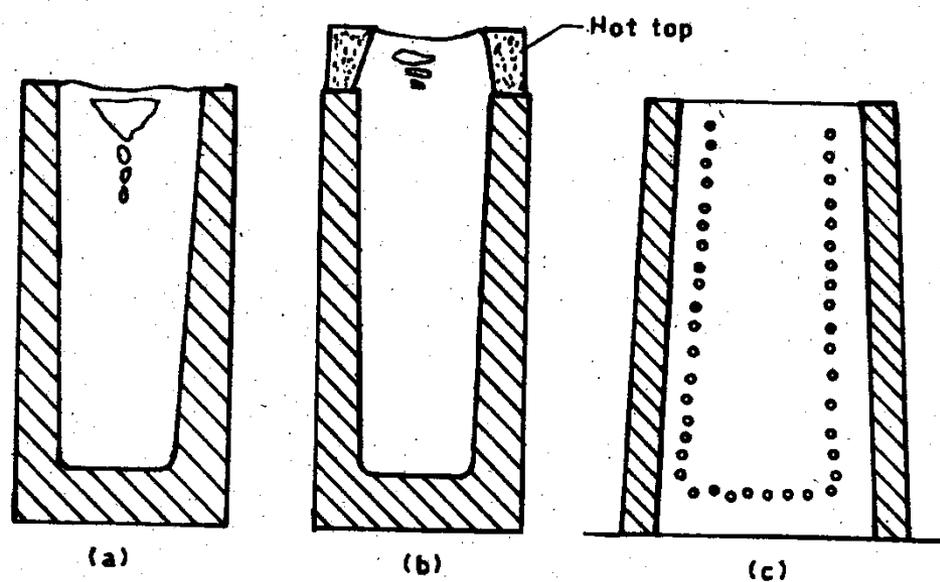
In the basic process, however, the deoxidation cannot be carried out in the presence of the slag which also contains  $\text{P}_2\text{O}_3$ , if deoxidation is carried out in the presence of the slag then  $\text{P}_2\text{O}_5$  would be deoxidised as well and phosphorous will go back into steel which is not desirable.



Deoxidation, therefore, has to be carried out in the ladle (out of the furnace), after removing the slag. This reduces the time available for  $\text{Al}_2\text{O}_3$  and  $\text{SiO}_2$  to rise to the surface before the temperature of the steel is very low. Consequently some of the oxides cannot rise to the surface and are trapped in the solidified metal impairing its properties.

**Steel from basic process is, therefore, inferior to the steel from the acid process.**

In **rimming**, manganese is added in the form of ferromanganese which forms manganese iron oxide. During solidification pure iron solidifies at the surface of the mold leaving the molten steel in the middle enriched with carbon. Manganese iron oxide reacts with carbon to form CO gas.



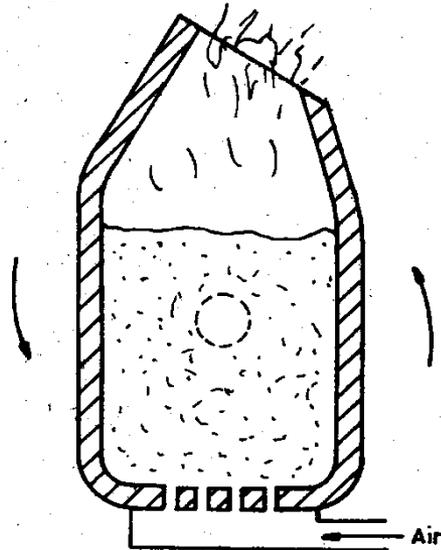
*Fig.6.3 Steel ingots: (a) killed, (b) killed with hot top, (c) rimmed.*

Some of this gas escapes to the atmosphere where it reacts with oxygen to produce  $\text{CO}_2$  (visible sparks). Most of the CO, however, remains inside the mold and counteracts the effect of shrinkage so that rimmed steels do not show as deep a pipe as killed steels as shown in the Fig.6.3.

**Rimming** is only suitable for steels with carbon content up to 0.15% as more carbon would react with oxygen required for rimming and consequently rimming could not be completed. Rimming steels are used for cold and deep drawing because the top surface of pure iron allows stretching without cracking. The deep seated blow holes weld together and disappear during rolling.

## 6.6.2 Bessemer-Thomas Process

This process uses a pear shaped converter shown in Fig 6.4 which is filled with molten pig iron when in horizontal position. Pig iron is usually melted in a cupola before charging in the converter. Converter is then turned to vertical position and compressed air (about 125 atm.) is blown through tuyers which oxidize all impurities to produce steel. Its capacity is 15-20 tons. Oxidation of carbon and silicon is an exothermic reaction whose heat keeps the steel molten. For low phosphorous iron **acid process** is used which takes about 10 minutes to oxidize the impurities. **The quality of steel from this process is not very high and consequently this process is not commonly used.**



*Fig.6.4 Bessemer converter*

## 6.6.3 Basic Oxygen Process

Use of air in Bessemer process leads to high nitrogen steels which are not desirable for certain applications. Basic oxygen process is developed to use 98% **pure oxygen instead of air**. The converter resembles Bessemer converter except that it is closed at the bottom (Fig 6.5). The molten metal in the converter is refined by blowing pure oxygen at greater than 800 atm. pressure into the melt using water cooled lances. The agitation ensures a thorough refining and oxygen oxidizes the impurities which form a slag. **It is a basic process**. It has the advantage of using 25% scrap as raw material to avoid excessive heat and it is faster than open hearth process (about 300 tons per hour).

**The quality of steel is very good** with low hydrogen and nitrogen contents. A further modification of the process is to add lime powder to oxygen jets when using high phosphorous charge.

**Lintz-Dowatz (L/D)** process is commonly used for steel making.

**The Kaldo and Rotor processes** are the same as L/D except that the converter works in horizontal position instead of vertical. Largest proportion of steel is produced by this process.

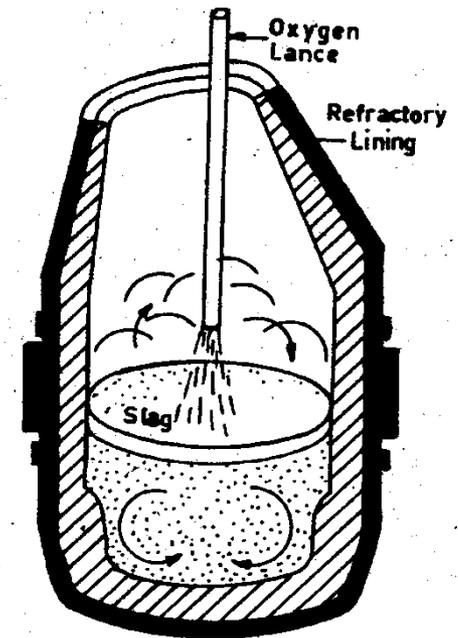


Fig.6.5 Oxygen steel making process

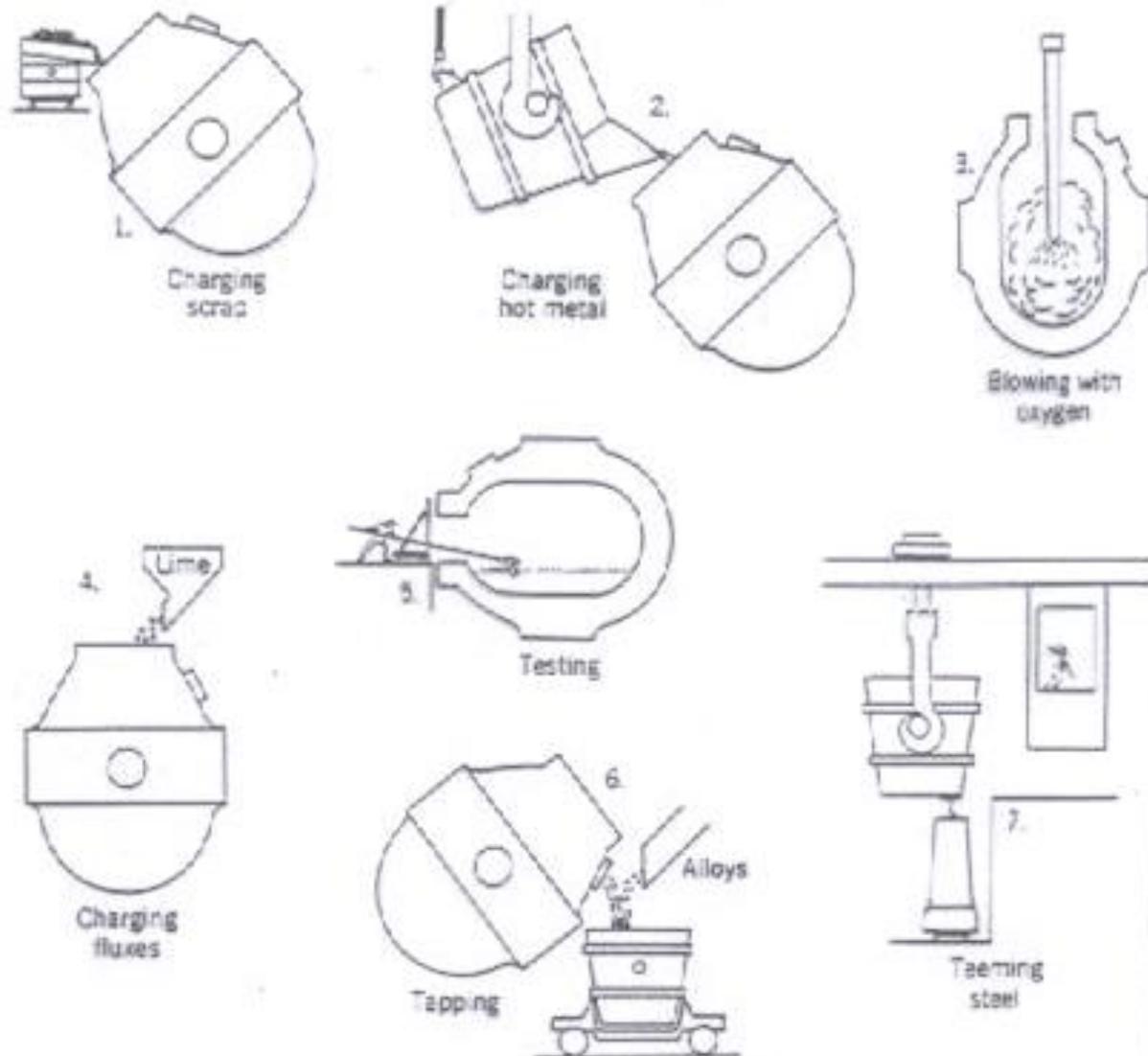
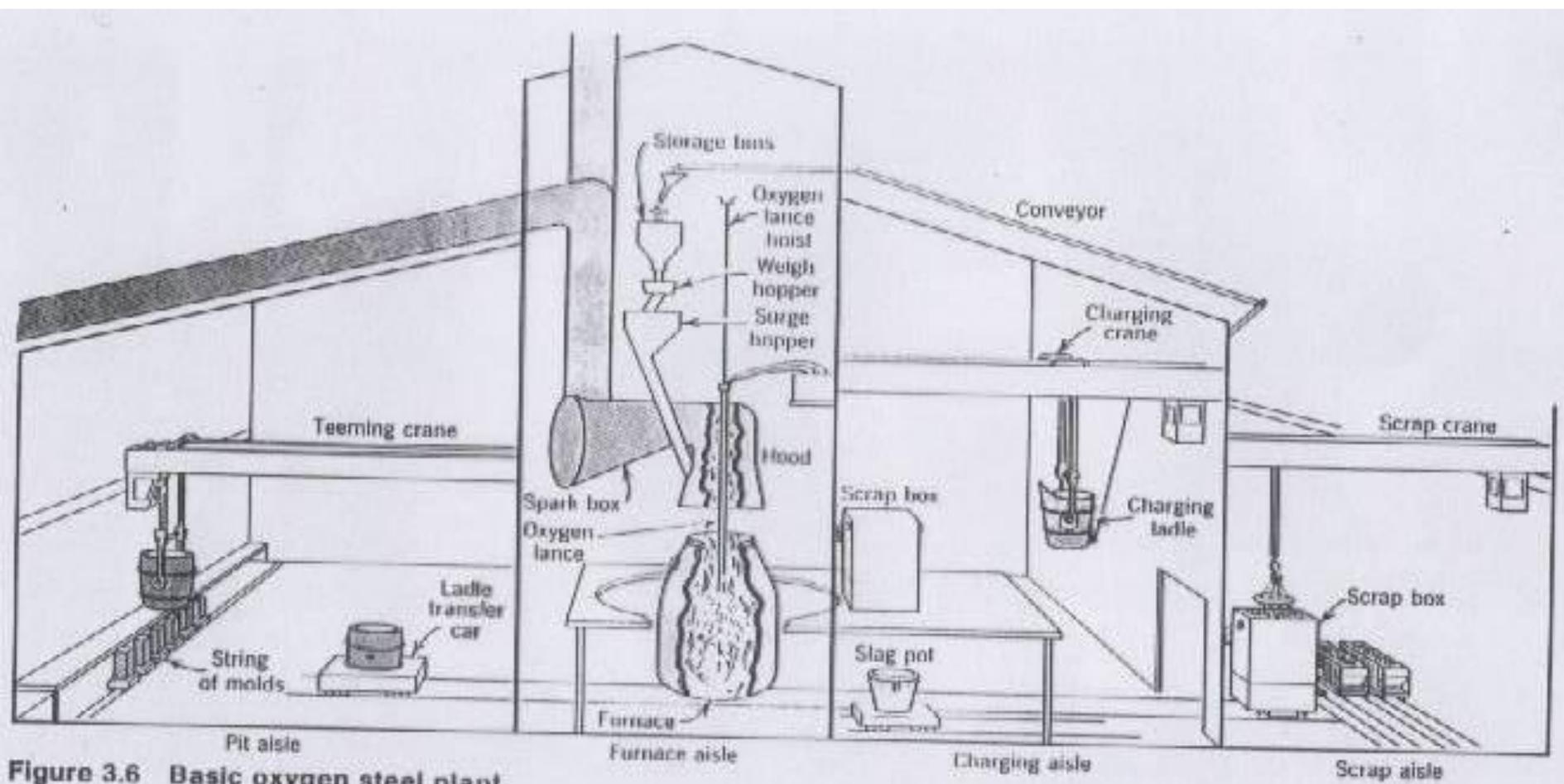


Figure 3.5 Ladle positions in the production of steel by the basic oxygen furnace (BOF).

## Furnaces for Ferrous Metals

Type of Furnace	Primary Fuel	Predominant Metal Charge	Special Atmosphere Available	Product
Air or reverberatory	Pulverized coal, oil	Molten or solid pig iron, scrap		Gray cast iron, white cast iron
Basic oxygen	Oxygen	Molten pig iron and scrap		Steel
Converter	Air	Molten pig iron or molten cupola iron		Raw material for wrought iron and steel
Crucible	Gas, coke, oil	Select scrap		Small quantities steel and cast irons
Cupola	Coke	Solid pig iron and scrap		Gray cast iron, nodular iron
Electric furnace	Electricity	Scrap	Vacuum or inert gas	Steel, gray iron
Induction	Electricity	Select scrap	Vacuum or inert gas	Steel
Open-hearth furnace	Natural gas, coke oven gas, pulverized coal, oil	Molten pig iron		Steel



**Figure 3.6 Basic oxygen steel plant.**

## 6.6.4 Open Hearth Process (Siemens-Martin)

Steel in this process is produced by heating molten pig iron, scrap, iron ore and other elements such as ferrosilicon and flourspar (to make slag viscous) in the hearth of the furnace as shown in Fig.6.6. It is superior to Bessemer process because it is not restricted to low phosphorous pig iron and also because it uses steel scrap as charge. Sufficiently high temperatures are obtained by using regenerative furnaces; the exhaust gases are used to heat up the brick work which in turn supplies its heat to the incoming gases and air when the flow direction of air is reversed. The flow of gases and air is alternated every 15-20 minutes. These furnaces produce 100-375 tons per heat of 8-10 hours. Mostly basic process is used with limestone as flux. The quality of steel is good but a limited amount of steel is produced by this process. Sometimes a duplex process is used whereby acid Bessemer and basic open hearth processes are combined. Impurities such as Mn and Si are removed by the Bessemer process followed by the removal of S and P in open hearth. This process is, however not very common.

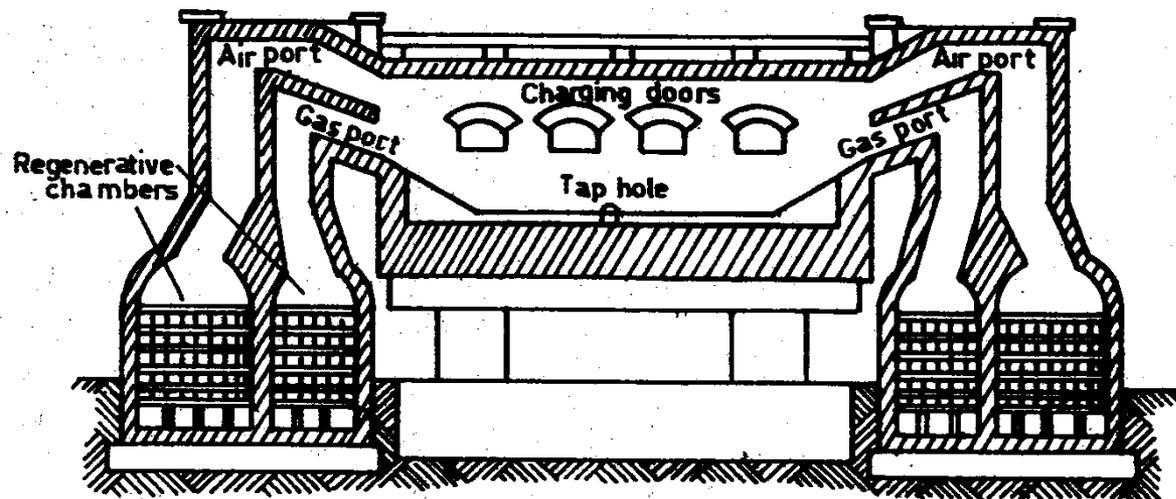
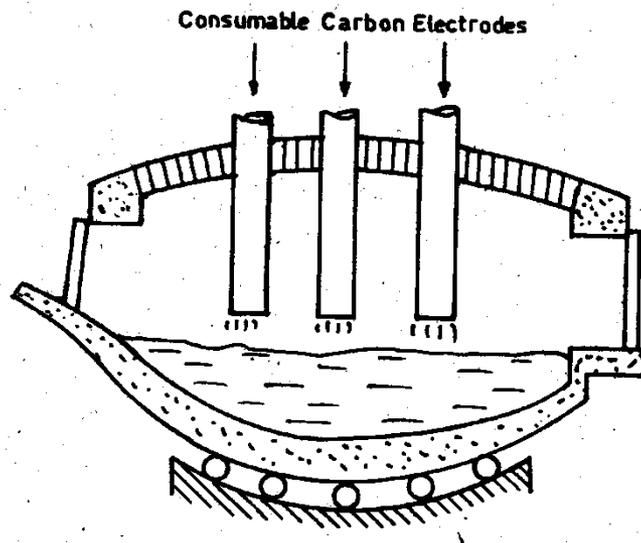


Fig.6.6 Open hearth furnace

## 6.6.5 Electric Processes

When extremely high quality steel is required and electrical energy is cheap and plentiful, electric steel making is employed. In the electric process, the pig iron and cold scrap are added as usual with any other desired elements. The heat is provided by electrical energy in one of few ways. The atmosphere and temperature can be controlled precisely and there is no excessive oxidation from furnace gases so that the steel composition can be manipulated accurately. **Alloy and tool steels and stainless steels** are produced by electric processes as well as steel castings. The electrical energy is converted into heat.



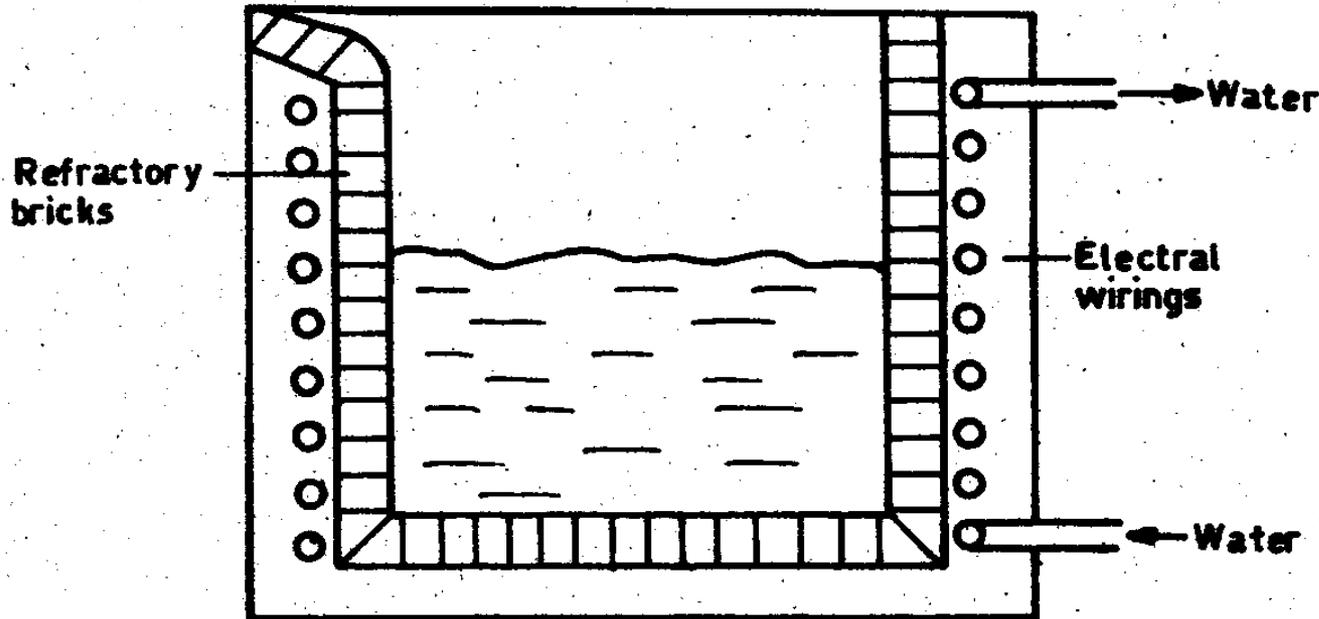
*Fig 6.7 Electric arc furnace*

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**Electric Arc** in which electricity from one electrode passes through an arc into the charge and then through another arc to the other electrode as shown in Fig 6.7. Usually a charge of graded steel scrap is melted under a basic slag (lime) to remove P. A second basic slag is used to remove S and to deoxidize the steel in the furnace. Capacity of such furnaces may be 200 tons with a production rate of 40 tons/hour with 50,000 Kwh power. Graphite electrodes upto 760 mm diameter and over 24m long are used. Operating potential is 40 V and current exceeds 12,000 amperes.

35

**Induction Furnace** whereby a coil is wound around a crucible and a high current in the coil heats the metal which forms the secondary of a transformer as shown in Fig 6.8. Alternating current in the primary coil creates a magnetic field and produces an eddy current in the metal. The penetration of eddy current depends upon the frequency and a frequency of 500-2000 Hertz is generally used. Capacity of these furnaces usually range from a few kilograms to 5 tons and high quality bearing and tool steels are produced by this process.



*Fig.6.8 Induction furnace*

A third method of heating the charge which is sometimes used is to make the charge a carrier of electricity. The charge is, therefore, heated due to its electrical resistivity when electricity is passed through it just as an electrical coil heater is heated when current is passed through it.

## 6.7 IMPURITIES IN STEEL

As a result of deoxidation and incomplete removal of impurities, the molten steel cast into moulds has either dissolved impurities such as Mn, Si, P and gases or suspended non-metallic inclusions. These impurities remain in their positions through cooling and transformation to ferrite and pearlite structures. The dissolved impurities may strengthen ferrite or may react with other elements to form inclusions and other phases depending upon the nature of the impurity.

**Manganese** confers depth of hardening but is also liable to quench cracking. It may dissolve in ferrite to give solid solution strengthening or it may form carbides, sulphites or Mn-silicate inclusions.

**Silicon** is present in most steels and is generally beneficial. The amount is usually less than 0.2%.

**Sulphur** exists either as MnS or ferrous sulphide, FeS. The FeS forms a brittle low melting point yellowish brown film around the solid steel crystals and causes the metal to split when forged. MnS is a dove grey colored inclusion which is only slightly soluble in iron and segregates into large globules irregularly distributed throughout steel. It is plastic at high temperatures and elongates into fibers during rolling without impairing mechanical properties. It may even improve fatigue characteristics of steel by enveloping the brittle oxides.

**Phosphorous** has a powerful tendency to segregate and in steels containing 0.05% or more P, there are areas containing 0.1% P which is dangerous and should be avoided by keeping the phosphorous content below 0.05%. Phosphorous forms a compound which dissolves in iron up to 1.7% but in the presence of 3.5% C its solubility is reduced to 0.3% and the excess forms a brittle eutectic found in cast irons. In rolled steels, areas containing high P are elongated into bands, called ghost bands, which are characterized by the absence of pearlite and are weak due to presence of P. In some specific cases P is beneficial such as in tin plates and for fire welding of spades.

Dissolved **carbon** and **nitrogen** cause strain aging after cold rolling in mild steels. They also affect the ductility as shown through impact tests.

The steel produced from steel making process is teemed or poured into ingot moulds to solidify. Ingots are then formed into either slabs, blooms or billets and are then processed into various shapes and forms as depicted in Fig.6.9. Recent technology in steel processing is direct continuous casting of liquid steel into slabs, blooms or billets.

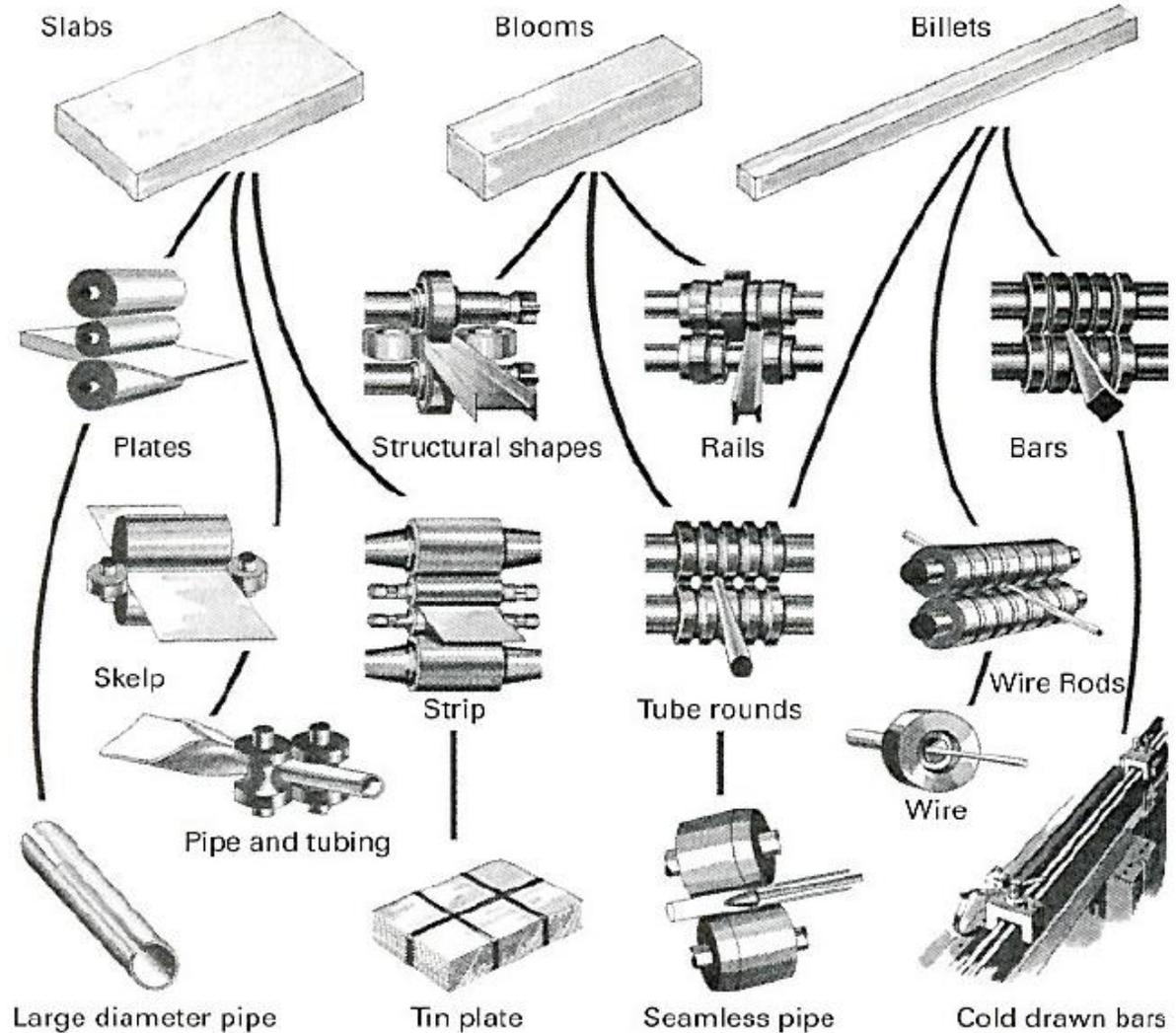
Fig.6.9 Flow diagram for steel processing.

These cast ingots are preheated at 1200 °C (the process is known as *soaking*). Then, they are rolled into one of the three intermediate shapes called *slabs, blooms, or billets*.

\* *Slab* (40/250 mm or more) is rolled from an ingot or a bloom

\* *Bloom* has a square cross section of 150/150 mm or more

\* *Billet* (40/40 mm or more) is rolled from a bloom



# SUMMARY

- **PRODUCTION OF IRON**

- 1. Pig Iron → Blast Furnace
- 2. Sponge Iron → Direct Reduction  
(Solid State at 750 °C)
- 3. Wrought Iron → Direct Process

- **STEEL PRODUCTOIN METHODS**

- Bessemer –Thomas Process 0 %
- Basic Oxygen Furnace (BOF) 60 %
- Open Hearth (Siemens-Martin) Process 15 %
- Electric Process 25 %

Impair: to spoil or to weaken

Inferior: lower in position

Spade: Kürek

Sow: Mature Female pig

Coal Tar: Zift, Kömür asfaltı

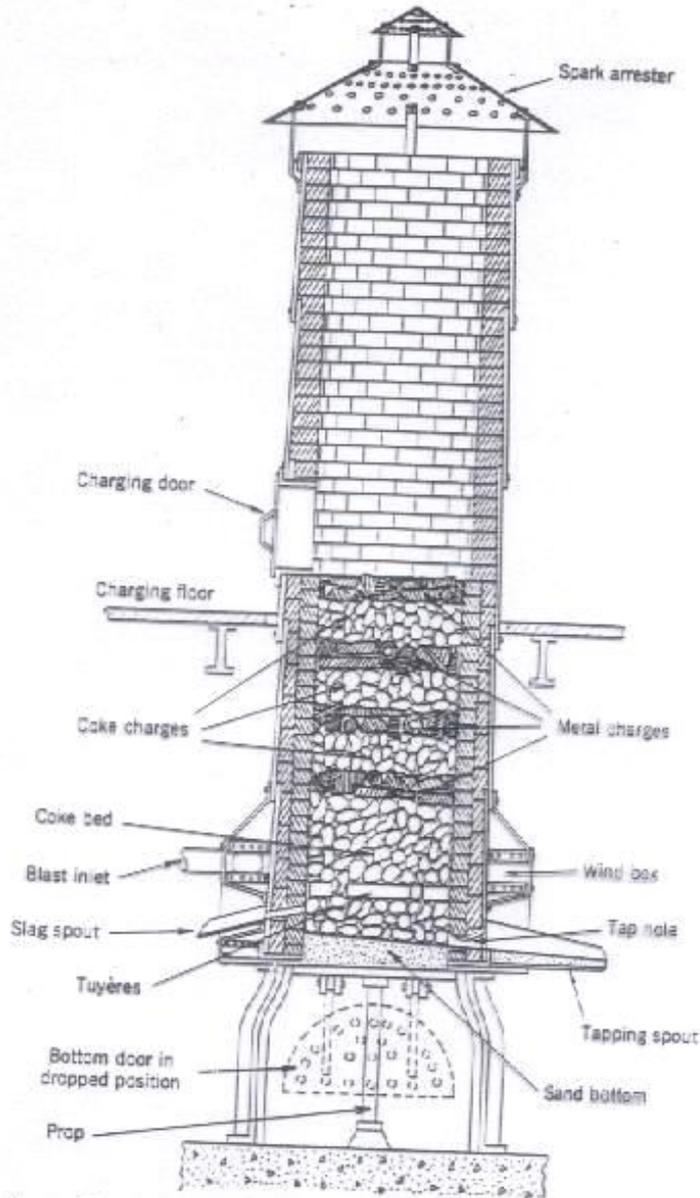


Figure 3.9 Sectional view of cupola.

### Furnaces for Ferrous Metals

Type of Furnace	Primary Fuel	Predominant Metal Charge	Special Atmosphere Available	Product
Air or reverberatory	Pulverized coal, oil	Molten or solid pig iron, scrap		Gray cast iron, white cast iron
Basic oxygen	Oxygen	Molten pig iron and scrap		Steel
Converter	Air	Molten pig iron or molten cupola iron		Raw material for wrought iron and steel
Crucible	Gas, coke, oil	Select scrap		Small quantities steel and cast irons
Cupola	Coke	Solid pig iron and scrap		Gray cast iron, nodular iron
Electric furnace	Electricity	Scrap	Vacuum or inert gas	Steel, gray iron
Induction	Electricity	Select scrap	Vacuum or inert gas	Steel
Open-hearth furnace	Natural gas, coke oven gas, pulverized coal, oil	Molten pig iron		Steel

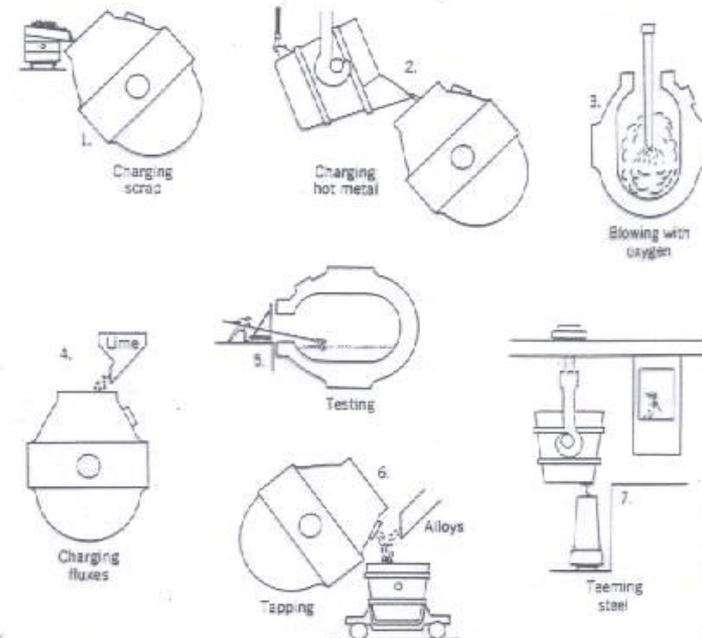


Figure 3.5 Ladle positions in the production of steel by the basic oxygen furnace (BOF).

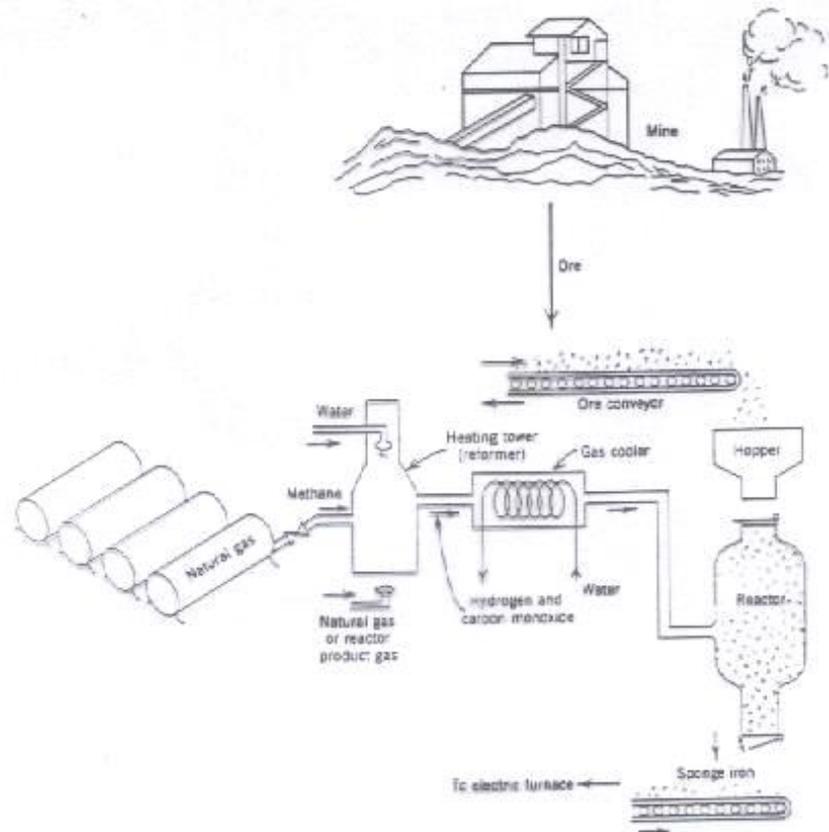
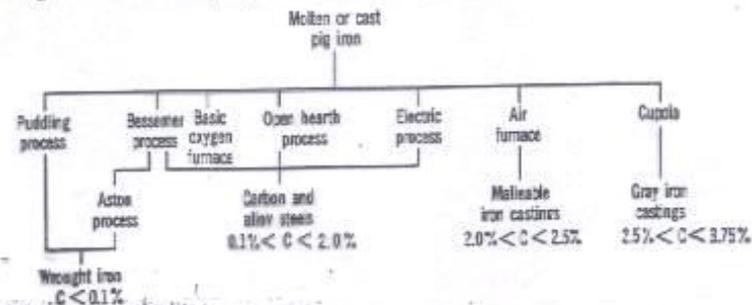


Figure 3.3 Schematic diagram of direct-reduction process for producing sponge iron from iron ore.

Figure 3.4 Principal processes for remelting or refining pig iron.



# ÜLKEMİZİN HAMMADDE POTANSİYELİ VE DEĞERLENDİRİLMESİ

- Ülkemizde üretilen maden ürünleri sanayide ve inşaat sektöründe hammadde olarak tüketilmektedir. **Bor, krom, mermer, pomza, sodyum feldspat** genel olarak ihraç edilen madenlerimizdir. Ülkemizin maden varlığınının 4350 Katrilyon TL değerinde olduğu ifade edilmektedir. Buna karşın yıllık maden üretimi 3,45 Katrilyon TL, ihracatı ise 0,75 Katrilyon TL kadardır.

# DEMİR VE ÇELİK

## UZAYDAN GELEN METAL

- Yeryüzünün en kıymetli metali zannedilen altın yeryüzünde olmasa idi insan hayatında hiç bir anormallik olmazdı, ancak demir yeryüzünde olmasa idi insan hayatı altüst olurdu. Bu bakımdan demir yeryüzünün en kıymetli metalidir.
- Demir yeryüzü metali değildir. Demirin yeryüzüne daha sonra yoğunlaşarak veya gök taşları ile uzaydan inerek geldiği sanılmaktadır.
- Aya ilk adımını atan Armstron'a göre demir metalinde güneş enerjisinin 4-5 misli bir enerji yüklenmiş olduğundan çok sert ve dayanıklı bir metal davranışı göstermektedir.

# DEMİR ALTINDAN DEĞERLİDİR

- Doğal olarak bir şeye ihtiyaç ne kadar çoksa, o da o nispette çok yaratılmıştır.
- Tabiatta bulunması en zor olana ihtiyaç daha azdır.
- Akciğerlere hava bir an ulaşmasa insan derhal ölür.
- İnsanın en fazla havaya, sırası ile suya, ekmeğe, yiyeceğe ve diğer şeylere ihtiyacı vardır.
- İnsan vücudunda kan hücrelerinde demir oksijen taşıyıcı rol oynamaktadır.
- Demirin insanlar için çok faydalı ve insanların demire ihtiyaçlarının altına olan ihtiyaçlarından daha fazla olmasından dolayı, demir altından çok ve kolay bulunabilir yaratılmıştır.
- Demir yerkabuğunun % 5,1 ini oluşturmakta olup , alüminyumdan sonra yerkabuğunda en çok bulunan ikinci metaldir.

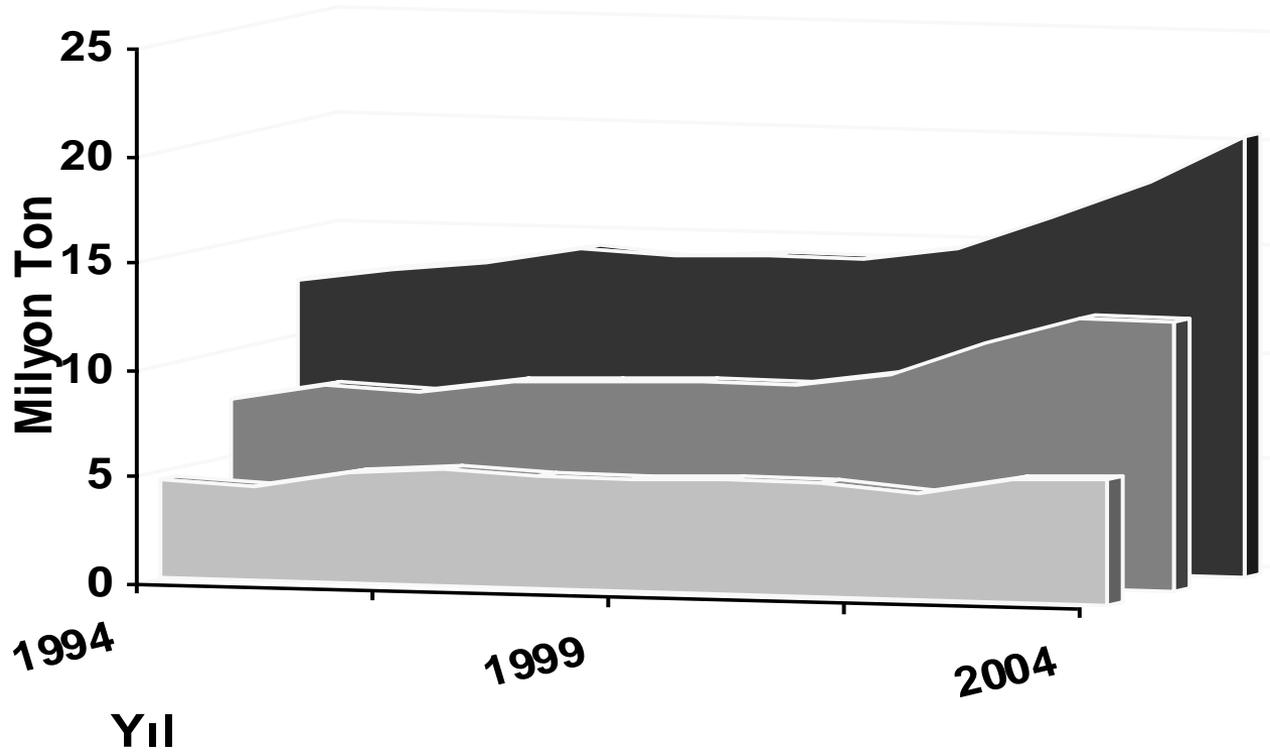
# DEMİR ALTINDAN DEĞERLİDİR

- Arkeolojik arařtırmalara gre demirin M.. 3000 yıllarında kullanıldıđı belirlenmektedir.
- İlk çağlardan beri en fazla kullanılan metaldir. İnsanlıđın kullandıđı malzemenin  $\frac{3}{4}$ ' ü demir esastır. Dnyada yılda yaklaşık 1 milyar ton demir ve çelik üretilmekte ve tüketilmektedir.
- Demir karbon ile alařım oluřturarak stn mekanik zellikler kazanmakta, ısıl iřleme yapısı ve zellikleri kolayca deđiřtirilebilmektedir.
- Oturduđumuz binaların betonundaki donatılar, bindiđimiz araçların gvdeleri çeliktendir.
- 21. Yz yıla girerken plastik ve kompozit malzemelerin demir ve çeliđin yerini alacađı beklentisi bořa çıkmıř olup, demir-çelik endstride saltanatını korumakta ve kıyamete kadar koruyacađa benzemektedir.

# DÜNYADA VE TÜRKİYE'DE ÇELİK ÜRETİMİ

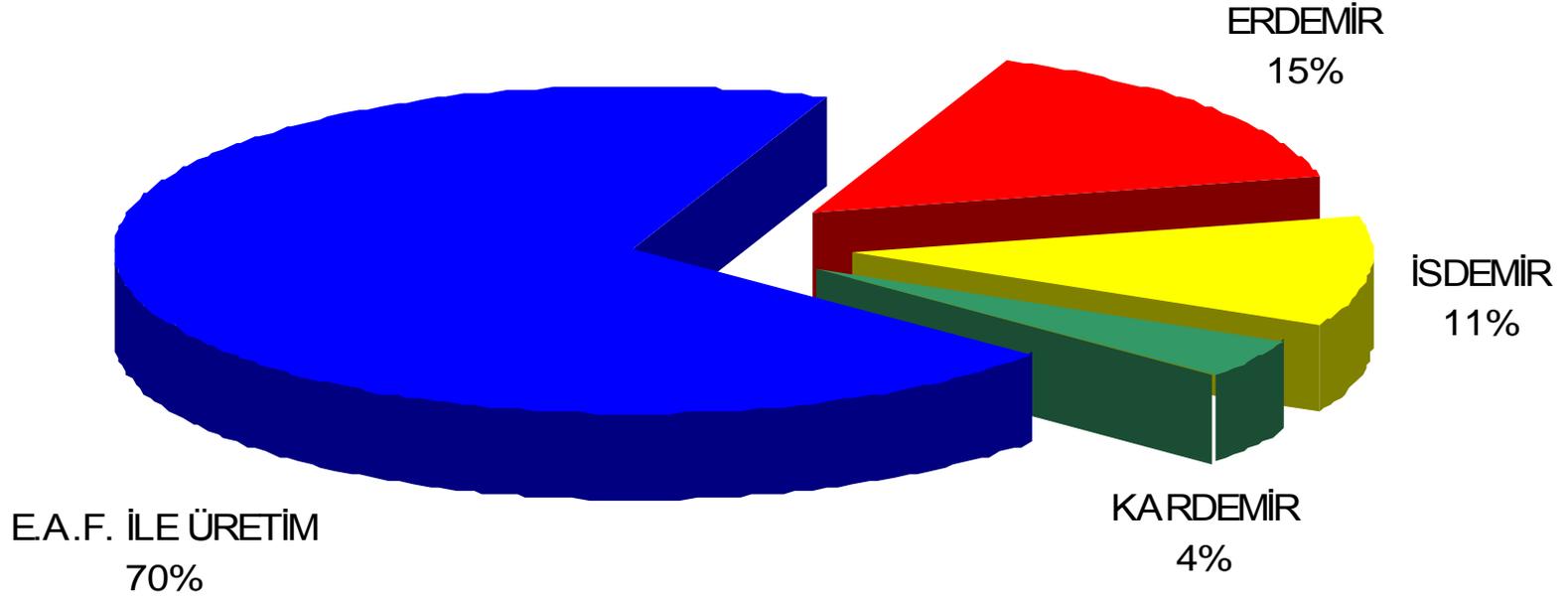
- 1950 yılında dünya çelik üretimi 190 Mt civarındaydı. Bu 190 Mt çelik üretiminin %80'i Yüksek Fırın - Siemens Martin yöntemiyle, %10'u Yüksek Fırın - Thomas Konverter yöntemiyle, %10'u da E.A.F.'ı ile üretilmekteydi. 1970'te 700 Mt'a ulaşan sıvı çelik üretiminde E.A.F.'nın payı %20'ye çıkmıştır. 1990 yılı itibariyle dünya ham çelik üretimi 770 Mt olarak gerçekleşmiş, 1994'te bu rakam 702 Mt'na düşmüştür. 2004 yılı için verilen rakam ise 1030 Mt'dur.

# Türkiye Ham Çelik Üretiminin Yıllara Göre Değişimi ve E.A.F.'nın Payı.



- Türkiye Pik Demir Üretimi
- Türkiye Çelik Üretiminde E.A.F. Payı
- Türkiye Ham Çelik Üretimi (Net Milyon Ton)

# Türkiye'nin 2004 Yılı Ham Çelik Üretiminin Yöntemlere Göre Dağılımı



# HURDANIN HAMMADDE OLARAK DEĞERLENDİRİLMESİNİN ÖNEMİ

- **HAMMADDE TASARRUFU:**Hurdanın ikincil bir hammadde olarak değerlendirilmesi, tabiatta bulunan birincil doğal hammadde kaynaklarının korunması açısından önemlidir.
- **ENERJİ TASARRUFU:**Hurdadan malzeme üretimi doğal hammaddelerden malzeme üretimine göre daha az enerji gerektirdiğinden enerji tasarrufu elde edilir. Örnek olarak alüminyum ve demir hurdadan elde edildiğinde sırası ile 1/15 ve 1/3 oranında enerji gerekmektedir.
- **ÇEVRE KİRLİLİĞİNİN ORTADAN KALDIRILMASI:**Hurdanın değerlendirilmesi çevre kirliliğinin ortadan kaldırılması açısından önemlidir.
- **EKONOMİK KAZANÇ:**Hurdanın değerlendirilmesi ekonomik kazanç elde etmek bakımından önemlidir.

# DEMİR-ÇELİK HURDASININ ÜSTÜNLÜKLERİ

- Demir cevheri kaynaklarının sınırlı ve düşük kaliteli olması,
- Hurdadan çelik üretiminin cevhere oranla daha az enerji gerektirmesi(1/3),
- Gelişen teknolojiye paralel olarak daha fazla metal tüketimi ve hurda oluşumu,
- Hurda kullanımının çevre sorunlarını ortadan kaldırması,
- Hurdanın stoklama ve nakliye kolaylığı,
- Hurdanın yüksek ısı geçirgenliği sebebi ile ergitme kolaylığı,
- Hurdanın değerlendirilmesinin ekonomik kazanç sağlaması.

# CHAPTER 7

## PRODUCTION OF NON-FERROUS METALS

### 7.1 INTRODUCTION

Even though ferrous metals and alloys are the most important and widely used engineering materials, nonferrous metals and alloys also find significance in engineering construction. They have a wide range of properties which often adapt them to uses for which ferrous alloys would not be suitable. In general non-ferrous metals and alloys are **more expensive** than any iron or steel substitute, but they hold their place in industry because they meet special requirements; copper is most useful due to its electrical properties; **aluminum and magnesium** are very light and provide very high strength/weight ratios, **tin and lead** have good corrosion resistance.

Most of the useful engineering alloys are made from two or more of the following metals:

1. Aluminum,
2. Copper,
3. Lead,
4. Magnesium,
5. Nickel,
6. Tin and
7. Zinc.

This chapter will discuss the production of above mentioned metals from their ores. Various types and grades of these metals obtained from refining processes will be described to familiarize the students with the variety of these metals available for engineering applications.

## 7.2 FURNACES

The furnaces used for smelting non-ferrous metals are different from those used for iron and steel. The blast furnace, similar to but smaller than those used for iron smelting, is used for reducing oxide ores of non-ferrous metals such as copper, tin, lead and zinc. Some ores contain sulphides which are converted in roasting ovens which drive off sulphur leaving the oxide. A reverberatory furnace, similar to an open-hearth furnace, is often used to smelt non-ferrous metals.

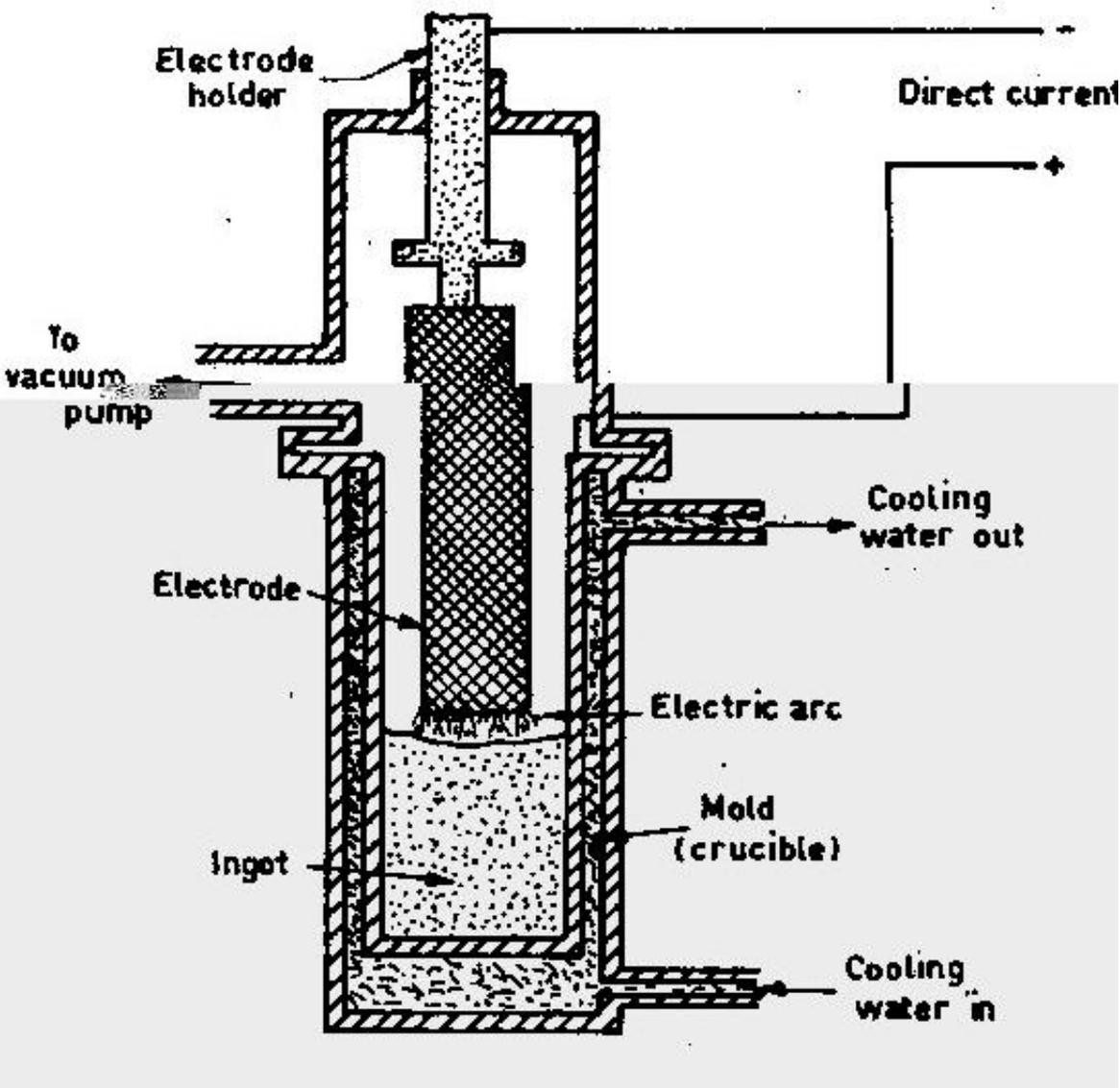


Fig 7.1 Operating principle of a vacuum arc furnace.

Another type of electric furnace in use today is the consumable electrode unit shown in Fig 7.1. Two basic designs of such furnaces are the vacuum arc and the vacuum induction models. High purity steels, titanium, zirconium and various other non-ferrous metals are melted by these units. The metal used to charge the furnace is fashioned into long rods by such methods as briquetting (e.g. titanium), and then welding these briquettes into an electrode. The vacuum in the furnace is constantly maintained to remove any gases before they are absorbed by the metal. By this method of melting in water-cooled mold at the base of the furnace, an ingot is gradually formed.

## 7.3 ALUMINUM

Of all the structural metals, aluminum is by far the most abundant in the earth's crust. Approximately 7.5 % of earth's crust is made up of aluminum. Many of the earth ores contain aluminum, but the ore most used in the production of aluminum is bauxite, which is found in relatively few places: Bauxite is a mixture of gibbsite ( $\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$ ) and diaspore ( $\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$ ).

### 7.3.1 Bayer Process

The bauxite ore basically goes through two refining processes. First, the Bayer process breaks down the ore into its components (as shown in Fig. 7.2), silicon, iron, titanium oxide, water and aluminum oxide.

In this process, dried, finely ground **bauxite** is charged into a digester where it is mixed with **soda ash, crushed lime, sodium hydroxide and hot water** under pressure at a temperature well above 100 °C. Live steam and agitators stir the mixture to bring all the materials into close contact, forming **sodium aluminate**, which is soluble in the liquor. Iron oxide, silicon and other impurities settle to the bottom and are removed. The sodium aluminate is then pumped through filters to precipitators, where it, is mixed with aluminum hydrate. This seeding converts sodium aluminate to aluminum hydrate.

As the mixture cools, **aluminum hydrate** settles to the bottom, and **sodium hydroxide** rises to the top. Sodium hydroxide is pumped back to the precipitator for re-use, and **aluminum hydrate** is calcined (heated) in rotary kiln to about 1100 °C where it becomes 99.4 % pure alumina. About 2 kg of bauxite converts to 1 kg of alumina; which in turn converts to about 0.5 kg of pure aluminum.

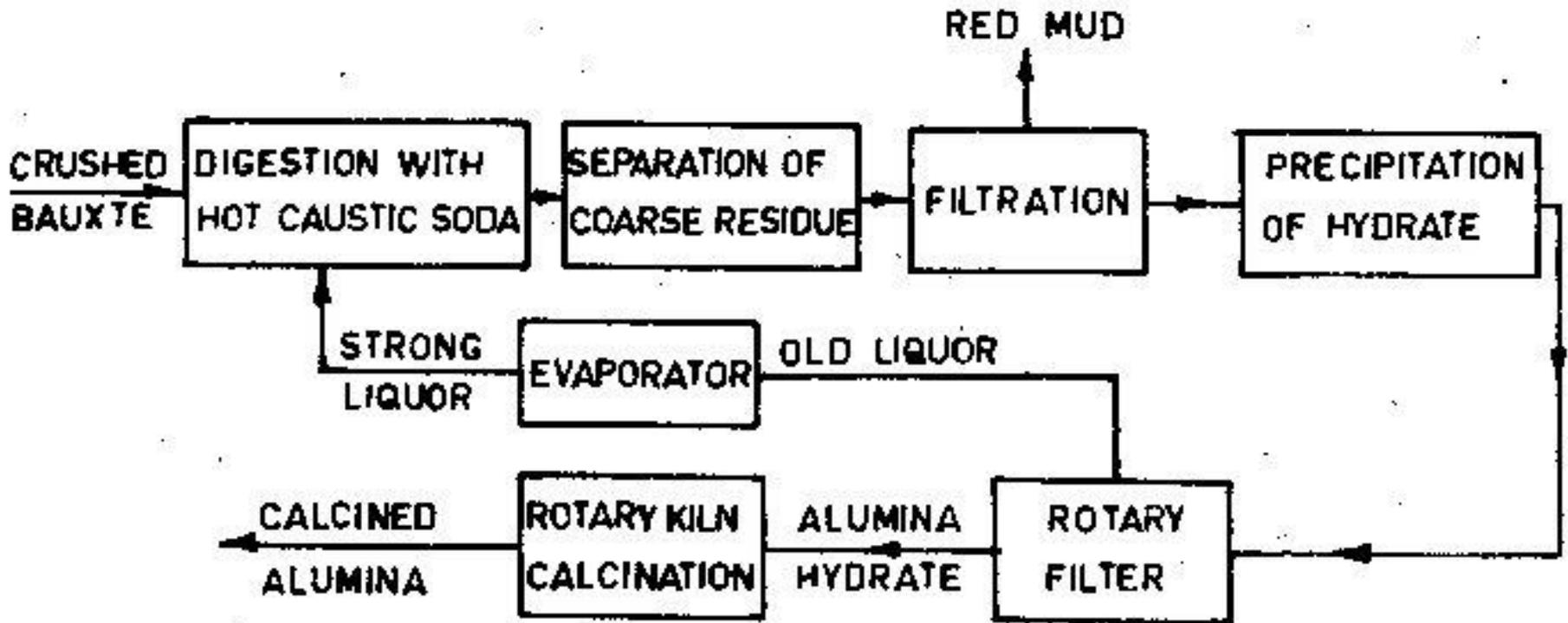
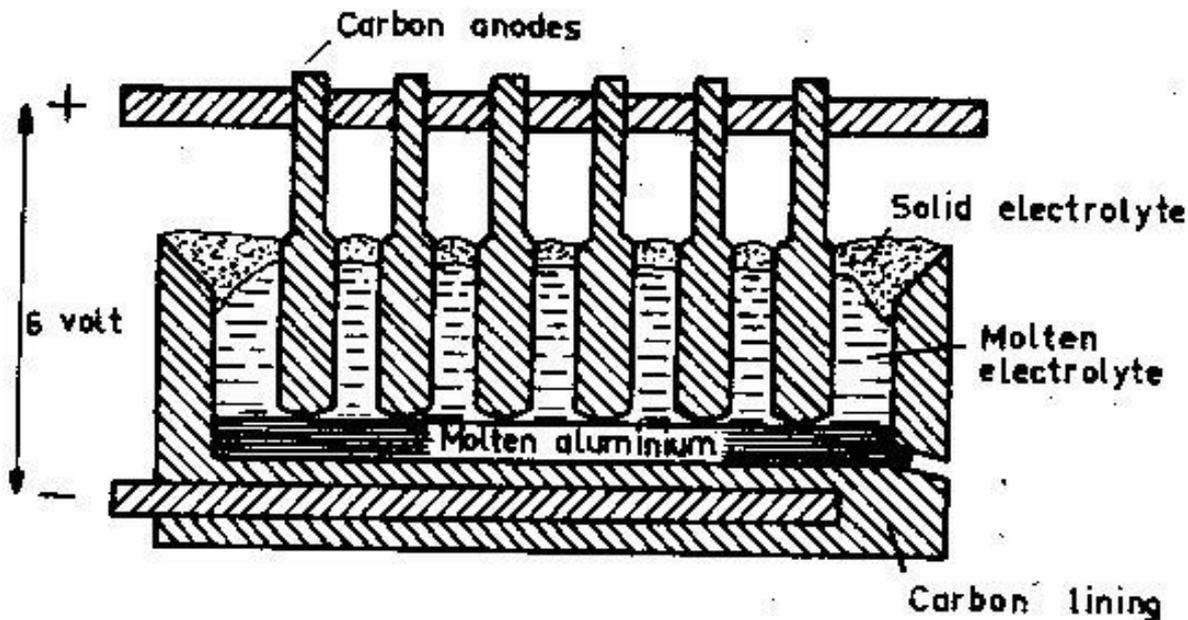


Fig.7.2 The Bayer process.

## 7.3.2 Electrolytic Process

In the second stage, pure alumina is refined into metallic aluminium by the electrolytic reduction process, the **Hall-Heroult** process. The electrolytic cell consists of a large steel tank lined with carbon (made from petroleum coke) which acts as cathode for the electrolysis process. The anodes are also made of carbon and are dipped into the electrolytic cell as shown in Fig. 7.3. The tank is filled with cryolite ( $\text{Na}_3\text{AlF}_6$ ), a rare fluoride of aluminium, which is found in Iceland and Greenland. The outstanding characteristic of cryolite is that it dissolves alumina and does not take part in the electrolytic process and hence does not get consumed during electrolysis. Cryolite is melted in the cell with an electric current, and then alumina is placed in the molten cryolite bath. The cell temperature is maintained at  $960^\circ\text{C}$  to keep both cryolite and aluminium melted.



*Fig.7.3 Electrolytic cell for aluminum.*

The reaction taking place in the cell is simple; on passage of an electric current of 7000 amperes at 6V potential, positive aluminium ions are attracted towards the cathodic carbon cell lining where they are reduced to produce aluminium viz:



Aluminium thus produced is heavier than the cryolite and, therefore, sinks to the bottom of the cell where it is siphoned off at intervals and cast into ingots. Negative oxygen ions, on the other hand are attracted towards the carbon anodes and are oxidized to form oxygen gas which combines with carbon to form CO<sub>2</sub> gas:



This anodic reaction is very important, both in providing heat to the cell due to its exothermic nature as well as in the thermodynamics of the reaction. Carbon anodes, therefore, are used up during the process and are replaced continuously, whereas cryolite is not decomposed and does not need replacing. The overall reaction is:



A typical cell produces about 300 kg of aluminium daily and consumes 26 kwh of electricity per kg produced, and about 0.5 kg of anode is used up. The aluminium produced is about 99.6 % pure.

Further refining is often carried out to obtain 99.99 % purity in **a three-Layer electrolytic cell** the **Hoopess cell**. In this process the bottom layer is the aluminium from **Hall - Heroult** process, alloyed with copper and silicon to form a heavy liquid of low melting point which acts as anode. The middle layer is the electrolyte containing sodium fluoride and aluminium with addition of barium fluoride to make it heavier than pure aluminium. The top layer is pure aluminium, which, being the lightest of the three, floats to the surface and is periodically ladled out for casting. The cell lining acts as a cathode and, on passing current through the electrolyte, positive aluminium ions are reduced to 99.99 % pure aluminium which floats to the surface for removal.

Pure aluminium is white or grey-white in color having a tensile strength of about 500 MPa, and specific gravity of about  $2.7 \text{ gr/cm}^3$ , which gives it a better strength/weight ratio than carbon steel. It is very ductile and malleable and possesses good thermal and electrical conductivity. The melting temperature of aluminium is  $660 \text{ }^\circ\text{C}$ .

# SUMMARY

## ALUMINUM

Bauxite  $\longrightarrow$  Bayer process  $\xrightarrow[99,4\% \text{ Pure Alumina}]{99,4\% \text{ Al}_2\text{O}_2}$  *Electrolytic Process*  $\longrightarrow$  99,6 % *Pure Aluminum*  
*Hall Heroult*

$\xrightarrow{\text{further electrolysis}}$  *Three Layer Electrolytic Cell*  $\longrightarrow$  99,99 % *Pure Al*  
*Hoopes Cell*

### BAYER PROCESS

Boxite Powder

+

Coastic Soda  
(NaOH)

mixed with pressurized  
Water vapor above 100 °C

(Sodium Aluminate) formed

Pumped Through Filter

Aluminum Hydrate Settle to Bottom

Sodium Hydroxide rises to the top

And Pumped for re-use

Aluminum Hydrate

Calcinated (Heated in rotary kiln at 1100 °C)

99,4 % Pure Alumina (  $99,4\% \text{ Al}_2\text{O}_2$  )

## 7.4 COPPER

Copper ores are widely distributed in the earth. The main source of copper is the sulphide ore, generally with large excess of iron sulphide. Ore concentration enables low grade ores with less than 2 % copper to be mined successfully. The principal ores are **chalcocite** ( $\text{Cu}_2\text{S}$ ) with 79.8 % copper, and **chalcopyrite** ( $\text{CuFeS}_2$ ) with 34.5 % copper.

A simple method of producing copper from sulphide ores, as practiced in old days, is to roast the sulphide ore to convert it to oxide and then reduce it with carbon to produce copper. The metal produced in this fashion was very impure and the process was not economical due to large losses of metal in the slag.

The modern method of producing copper uses the greater affinity of oxygen for iron and of sulphur for copper at high temperatures; copper tends to form sulphide and iron tends to form oxide at high temperatures. Some of the excess iron (in the form of iron sulphide) can, therefore, be removed by high temperature oxidation, which would convert iron sulphide to iron oxide, which could then be fluxed with silica to form iron silicate slag.

## 7.4.1 Blister Copper

The first stage of refining copper is, therefore; to concentrate the sulphide ore by removing some of the iron by matte smelting as shown in Fig. 7.4. The prepared ore is melted in a reverberatory furnace with silica flux. A small blast furnace also used to be employed for the purpose but was found to be uneconomical. Some of the iron is converted to iron oxide, which combines with the flux to form iron silicate slag, which floats on top of molten heavy copper matte. The copper matte contains 40-45 % copper and is run off separately to be charged into a converter for further refining.

The converter is an adaptation of the Bessemer converter for steel making (Fig 6.4), being a large pear shaped vessel open at top with tuyeres for introducing an air blast in the side near the bottom. The molten matte is charged into the converter and air is blown in the converter, the temperature being maintained at 1250°C by the heat of the reaction.

Silica rich copper ore is added as flux. Iron is converted to FeO, which combines with silica of the ore to form iron silicate slag, which floats on top.



The slag is removed by tilting the converter, and more matte is added to the converter. The process is continued until the entire converter is full of molten copper sulphide only (all iron having been removed as silicate slag). Air is then blown through the melt to produce crude copper, known as **blister copper**, which is about 98 % pure



Up to 200 tons of matte is refined in a 24 hour heat by this process.

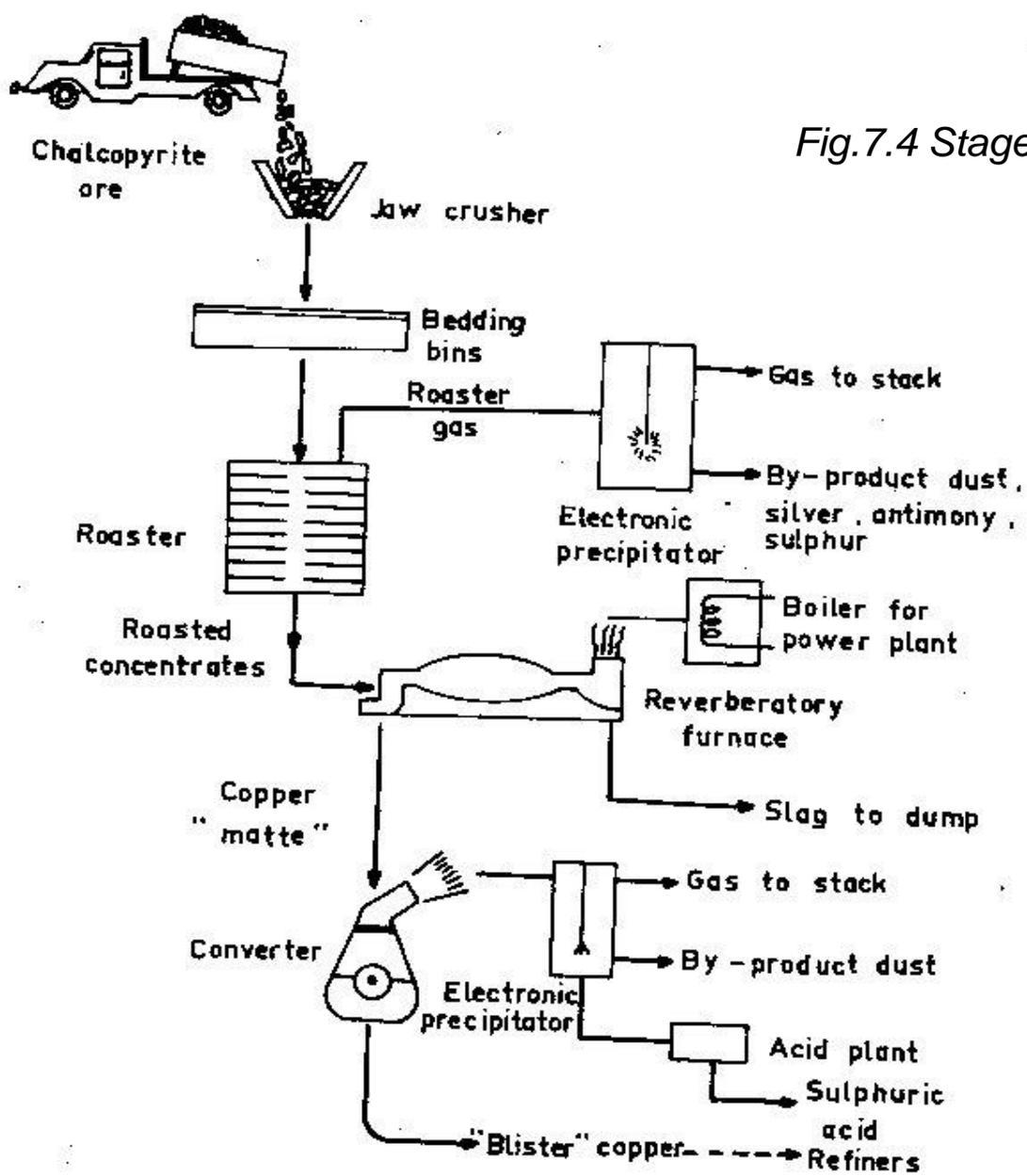


Fig.7.4 Stages during copper refining.

## 7.4.2 Refining Processes

The purification of blister copper consists of furnace refining followed by electrolytic refining. The first stage of refining exploits the low affinity of copper for oxygen at high temperatures. Blister copper is run into a reverberatory furnace and is refined by selective oxidation. Air is blown through the melt and the stirring action agitates the melt to affect oxidation of iron, sulphur, zinc, lead and other impurities, and forms a slag of mixed oxides. The addition of soda ash (sodium carbonate), lime and sodium nitrate to the slag helps to remove arsenic, antimony and tin. Extensive oxidation is required to remove the last traces of sulphur, leaving the copper with up to 0.9 % dissolved oxygen. The oxygen combines with copper to form cuprous oxide, which makes the metal weak and brittle. It is, therefore, necessary to remove dissolved oxygen by deoxidizing copper following the removal of the slag.

**Charcoal or powdered coal** is placed on top of the molten bath, and **green hardwood logs** are thrown into the molten metal. This process, known as **poling** releases hydrocarbon gases on stirring the bath. These reducing gases combine with dissolved oxygen to deoxidize copper. This is a critical operation in which the oxygen content is to be reduced to between 0.03-0.05 %. If the process is not completed then some oxygen in the form of cuprous oxide will weaken the metal, and if it is taken too far then steam pockets are developed inside the metal due to the reaction of hydrogen with cuprous oxide during solidification. The optimum point is indicated by the surface of metal, which remains level during solidification due to a balance between evolution of steam and shrinkage due to solidification. The copper obtained is called **tough-pitch copper** and is about 99 % pure.

Tough-pitch copper is further refined through electrolysis to obtain 99.95 % pure copper. The process, as explained in chapter 5 and shown in Fig 5.12, is simple; tough-pitch copper is made into 1 square meter anodes weighing 250 kg and cathodes are made of pure sheet copper, the electrolyte is copper sulphate in dilute sulphuric acid, and on passing electric current through the solution tough-pitch copper dissolves and redepot on pure copper cathodes. The electrodes are lined alternatively as shown in Fig 5.13.

The tank is lined with lead. The cell is operated at 50 °C, 0.3V potential and current density of 180 amp/sq,m of cathode. Impurities less noble than copper stay in solution whereas those more noble form anode mud, which is removed for reprocessing. Some of the electrolyte is removed and purified at intervals to reduce the concentration of soluble impurities.

The refined copper at cathode is usually 99.9 to 99.99 % pure and is known as **cathode copper**, which is melted to produce billets wire-bars and cakes for further working into rough products or for use in making castings or alloys. Electrolytic copper usually contains between 0.03-0.06 % oxygen. If these cathode coppers are melted; cast and solidified under protective atmosphere to exclude oxygen, an improved quality of copper is produced. This material is called **Oxygen Free High Conductivity (OFHC)** copper.

Copper is a soft heavy metal of reddish color. It is very ductile and in pure form it possesses excellent thermal and electrical conductivity. The melting temperature is 1083 °C and specific gravity is 8.9 gr/cm<sup>3</sup>.

# COPPER

Copper Ore Concentrated by removing iron with matte smelting in → Reverberatory Furnace →

Copper Matte contains 40~45% Cu → Converter (Iron taken as Silicate slag) →

Blister Copper (98 % pure) → Refining Process →

Reverberatory Furnace  
(Poling) tough pitch Cu 99 % pure → *Electrolytic Process* →  
*99,95% Pure Cu (CathodeCu)*

Electrolytic Refined Cu is 99.9 to 99.99 % pure Cu

This copper contains 0.03-0.06 % Oxygen  
If these coppers melted under protective atmosphere and  
Oxygen excluded

Oxygen Free High Conductivity Copper(OFHC )

## 7.5 LEAD

The most common and worked lead ore is galena (PbS), which is a dark heavy mineral often associated with zinc and sometimes with silver and other metals. The initial PbS content is about 1-10 % lead which is concentrated by flotation to about 60-80 % lead and this process also separates ZnS which is the main outside compound.

Very rich concentrates are sometimes converted directly to lead by roast-reduction, which is a process of combining PbS with oxygen, which reduces lead due to its strong affinity for sulphur. The reactions taking place are:



The presence of FeS<sub>2</sub> impurity in the ores, however, makes it difficult to control this process and therefore the process of complete roasting followed by reduction is preferred instead.

The ore is first roasted by heating the powdered sulphide ore to 600-1000 °C (the temperature being below the melting points of both PbS and PbO) in good contact with air. The sulphide is converted entirely to oxide viz:



Roasting reaction is exothermic and the heat released provides much of the heat to keep up the temperature during roasting. The oxide is then reduced with carbon in a blast furnace to obtain lead. A small blast furnace running at about 900 °C is used, with coke as fuel and reducing agent, CaO and FeO as flux for silica. Crude lead is produced at the bottom of the furnace



## 7.5.1 Refining of Lead

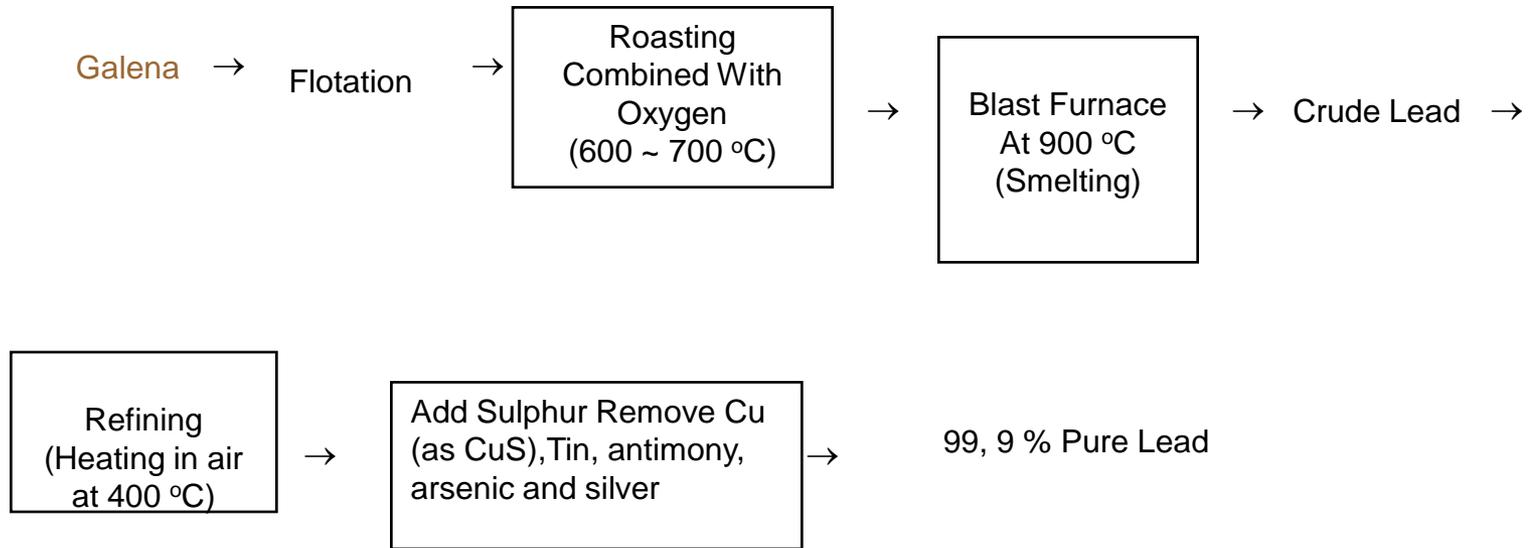
The lead so produced is first refined by heating in air at 400 °C and stirring; insoluble oxides and other compounds float to the surface and are skimmed off. Sulphur is sometimes added to help eliminate copper by forming copper sulphide. Next step is to remove tin, antimony and arsenic by selective oxidation in a reverberatory furnace. An alternate method of purification is to add an oxidizing mixture of sodium nitrate, salt and caustic soda to lead.

Silver is an important precious metal, which is present in lead ore. It is removed from lead in a tall vessel, fed from the top, the lower half of which is filled with lead and the upper half with zinc. The bottom of the vessel is held at melting point of lead (327 °C) whereas the top is held at 600 °C. Molten zinc and lead are insoluble in each other and therefore remain on top of each other. Furthermore, silver has a much stronger tendency of dissolving in zinc compared to lead; silver dissolves in zinc compared to lead by a ratio of 300:1. Hence, all the silver leaves lead and transfers to zinc. The desilverised lead is siphoned off from the bottom of the vessel. Silver is recovered from zinc by distillation by volatilising zinc at 907 °C. The process of producing lead is described in Fig 7.5.

Lead is a heavy metal of greyish complexion due to oxidation. It possesses low strength and low ductility but high malleability and good corrosion resistance. Its melting point is 327 °C.



# LEAD



## 7.6 MAGNESIUM

Magnesium is extracted from deposits of:

Magnesite ( $\text{MgCO}_3$ ),

Dolomite ( $\text{MgCO}_3 \cdot \text{CaCO}_3$ ),

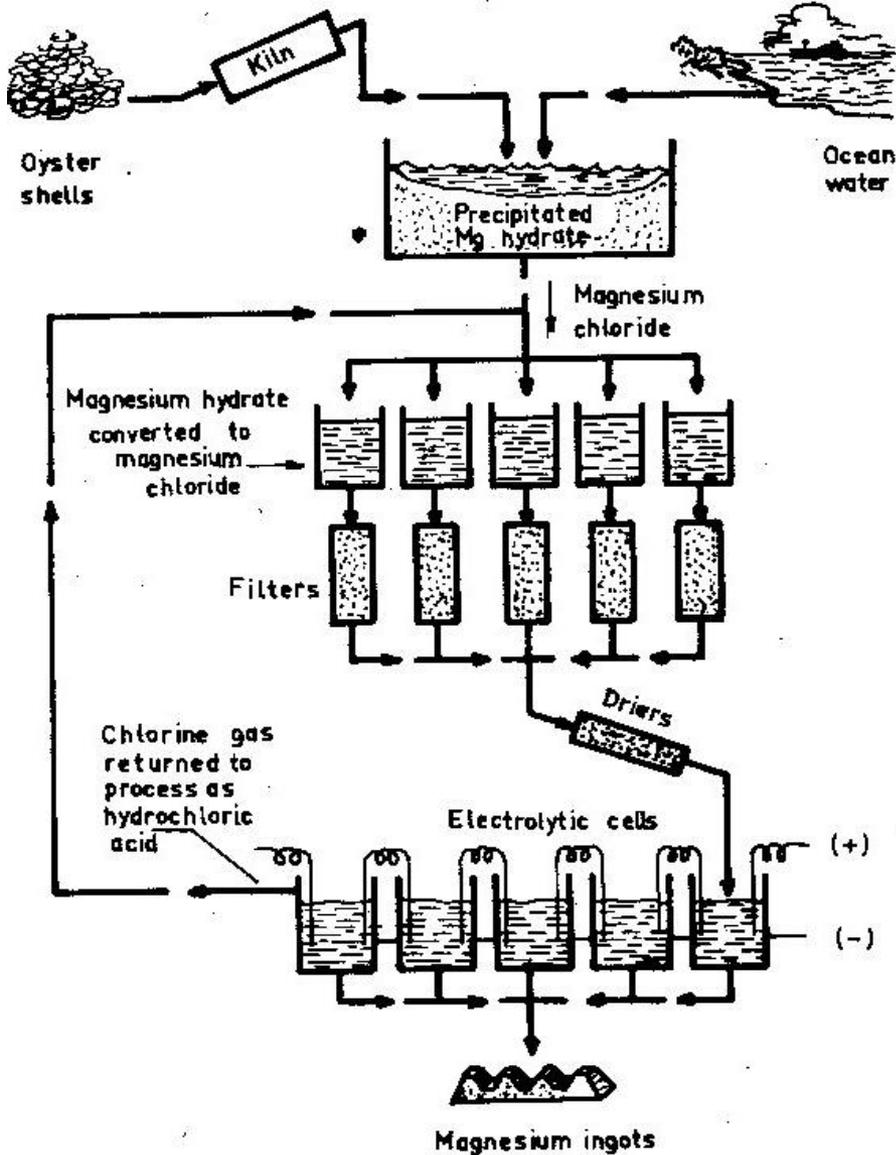
Brucite ( $\text{MgO} \cdot \text{H}_2\text{O}$ ),

Carnallite ( $\text{MgCl}_2 \cdot \text{KCl} \cdot 6\text{H}_2\text{O}$ ) and

from SEAWATER which contains 1300 ppm magnesium.

Magnesium is refined using electrolysis, as in the case of aluminium. Magnesium chloride is used for the process and, therefore, the oxide ores are first converted to chloride by heating with carbon and chlorine, or by treatment with hydrochloric acid.

Magnesium is a soft silver-white metal like aluminium, but lighter than aluminium with a specific gravity of  $1.74 \text{ gr/cm}^3$ . It is a chemically active metal with a melting temperature of  $650 \text{ }^\circ\text{C}$ .



Seawater is first mixed with **milk of lime** whereby **magnesium hydrate** precipitates to the bottom as a slurry and is drawn away. The slurry is filtered to obtain a more concentrated hydrate, which is converted to **magnesium chloride** by treatment with HCl.

The **magnesium chloride** is dissolved in an electrolyte of mixed calcium and sodium chlorides, in a cell with carbon anodes and steel cathodes. A direct current of 60,000 amperes causes the magnesium ions to be reduced to magnesium metal at cathodes and, being light, magnesium floats to the surface where it is periodically removed. The cell is kept at a temperature of 700 °C to keep magnesium molten. Chlorine gas evolves at the anodes. Fig. 7.6 describes the process of producing magnesium from seawater.

Fig.7.6 Production of magnesium from the seawater.

## MAGNESIUM

Sea water + Milk of Lime → Magnesium Hydrate → Add HCl →

Magnesium Chloride → By Electrolysis Magnesium is obtained

## 7.7 NICKEL

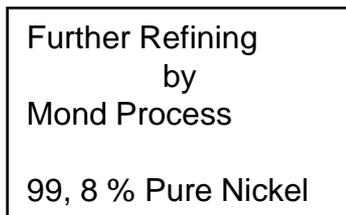
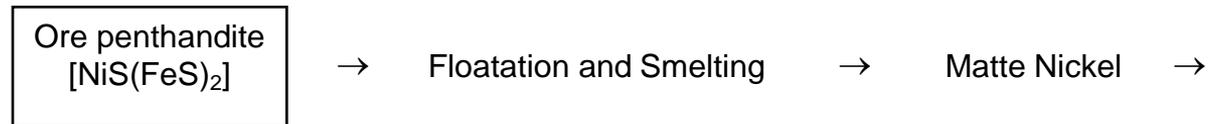
Nickel is extracted from its ore pentlandite  $[\text{NiS} \cdot (\text{FeS})_2]$ . First the ore is concentrated by flotation and smelted to obtain matte nickel containing copper and iron sulphides. If the iron content is high, however, then the matte is treated in a converter to remove iron as iron silicate slag (same as in case of copper). Further refining is carried out by the Mond process.

In this process, the nickel sulphide matte is crushed and heated to drive off sulphur and convert nickel sulphide to  $\text{NiO}$ . It is then treated with sulphuric acid to remove some of the copper as copper sulphate, and dried. The residue is exposed to water gas (hydrogen+CO), in a reducing tower at  $300\text{ }^\circ\text{C}$ . This reduces the  $\text{NiO}$  to nickel. The charge is then taken to a volatilising tower where it is exposed to water gas at  $50\text{ }^\circ\text{C}$  and the volatile nickel carbonyl  $[\text{Ni}(\text{CO})_4]$  is formed. This vapor is then passed to a decomposing tower at  $180\text{ }^\circ\text{C}$  where the carbonyl decomposes to Ni and CO, and the nickel is deposited on nickel shot. By this method 99.8 % pure nickel is obtained.

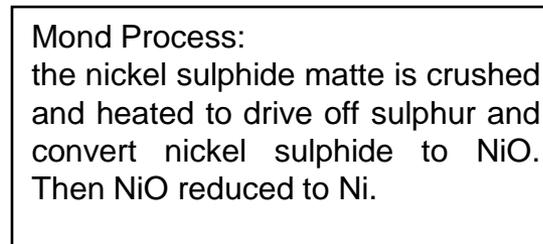
An important recent development is a hydrometallurgical process called Sherritt-Gordon process, for mixed sulphide ores of nickel, cobalt and iron. These sulphides are dissolved in ammonia in the presence of oxygen. The metals are selectively reduced from ammoniacal solution by treatment with hydrogen at about  $170\text{ }^\circ\text{C}$  under a pressure of 30 atmospheres. Powdered nickel, copper and cobalt are now produced in this way.

Nickel is a whitish metal with good corrosion and oxidation resistance. Its melting point is  $1452\text{ }^\circ\text{C}$ . It is magnetic up to  $360\text{ }^\circ\text{C}$  with a specific gravity of  $8.8\text{ gr/cm}^3$ .

## NICKEL



→



## 7.8 TIN

The chief ore of tin is cassiterite ( $\text{SnO}_2$ ), commonly known as tin stone, containing from 1-5 % tin as mined. Impurities are removed by washing the powdered ore, leaving the heavy tin oxide behind.

Purification of tin by smelting is straightforward in principle. The washed and dried ore is heated with powdered coal, together with lime to form a slag, in a reverberatory furnace at  $1200\text{ }^\circ\text{C}$ . This temperature is needed to melt the slag and to increase the rate of reaction, even though the reduction, can take place at as low a temperature as  $600\text{ }^\circ\text{C}$ . The mixture is stirred and when fully molten, it is run off into a pot where the slag is allowed to overflow leaving the tin behind.

Tin is not fully recovered by the smelting process, however, due to it being amphoteric. Some of it tends to remain absorbed in the slag; as silicate in acid slag and as stannate in basic slag. These slags are themselves, therefore, smelted afterwards to recover tin.

**Amphoteric:** (chemistry) having characteristics of both an acid and a base and capable of reacting as either.

(mining): Having both acidic and basic properties

**Silicate:** silisik asit tuzu, silikat.

A salt or ester derived from silicic acid.

A compound whose crystal structure contains  $\text{SiO}_4$  tetrahedra, either isolated or joined through one or more of the oxygen atoms to form groups, chains, sheets, or three-dimensional structures with metallic elements. Silicates were once classified according to hypothetical oxyacids of silicon (see metasilicate and orthosilicate) but are now classified according to crystal structure (see nesosilicate, sorosilicate, cyclosilicate, inosilicate, phyllosilicate, tectosilicate).

In chemistry, a **silicate** is a compound consisting of silicon and oxygen ( $\text{Si}_x\text{O}_y$ ), one or more metals, and possibly hydrogen. It is also used to denote the salts of silica or of one of the silicic acids. Silicate minerals are noted for their tetrahedral form.

**Stannate:** A salt of stannic acid.

stannic acid: (a) A hypothetical substance,  $\text{Sn}(\text{OH})_4$ , analogous to silicic acid, and called also normal stannic acid. (b) Metastannic acid.

The smelted tin is refined in two stages. First stage makes use of low melting point of tin, to remove impurities such as copper, iron and arsenic by liquation process. The second stage is selective oxidation. Impurities are oxidized by melting the metal in an open crucible (kettle) and stirring by injecting compressed air and steam (poling), whereas tin is not oxidized due to its little affinity for oxygen: Oxidized impurities such as zinc float on the surface and are skimmed off as a dross. Tin obtained thus is more than 99 % pure, which may be, if required, purified to 99.9 % purity by electrolysis.

Tin is a white colored metal with a blue tinge. It is whiter than silver or zinc. Its specific gravity is  $7.3 \text{ gr/cm}^3$  and melting point is  $232 \text{ }^\circ\text{C}$ . It is very malleable and highly resistant to corrosion. Its strength is low tough.

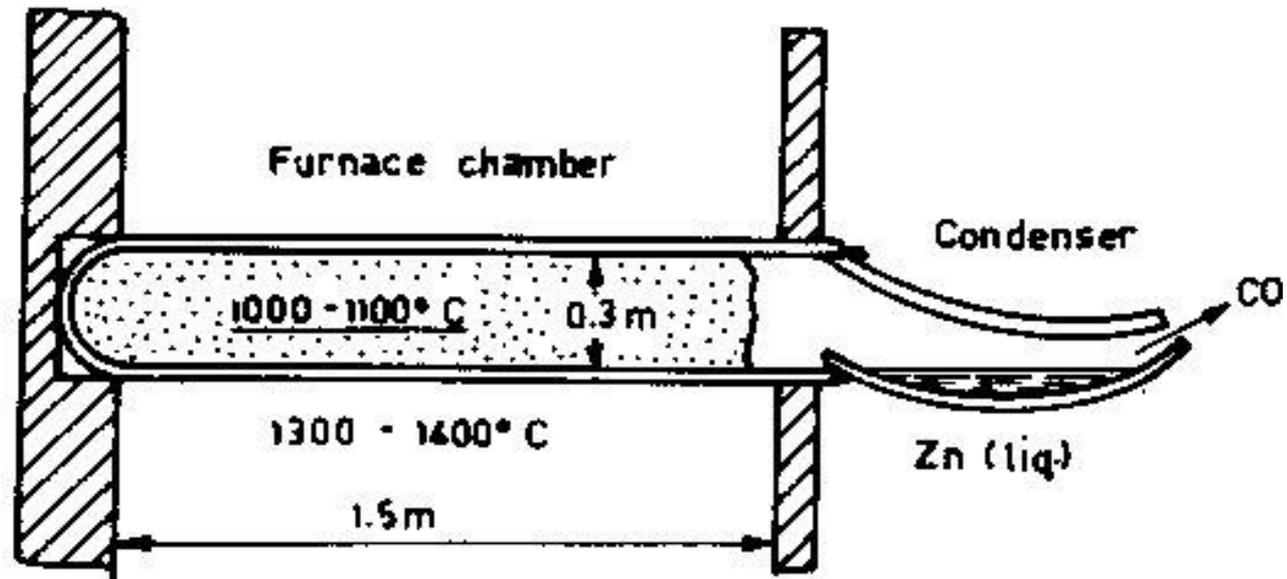
## 7.9 ZINC

The principal ores of zinc are sulphides, carbonates, silicates and oxides. The most commonly used ore is zincblende or sphalerite (ZnS), which contains lead, copper and iron sulphides as impurities. These impurities are first removed by flotation. Resulting zinc concentrate is then thickened and roasted to oxide and is then ready for reduction to metal.

There are two basic methods of converting the oxide into metal. In the first method, reduction takes place at atmospheric pressure in retorts and zinc is condensed as shown in Fig 5.14. Direct reduction using carbon is not possible because the reduction temperature is above the melting temperature of zinc. In this process, the zinc oxide is mixed with coke or powdered coal and pressed into briquettes, which are subsequently placed inside fireclay retorts, about 1.2 m long and 20 cm in diameter. Retorts are placed in a furnace at 1200-1400 °C. The reaction taking place is



Fig 5.14 A typical zinc retort



The mouth of the retort projects out of the furnace (Fig 5.14) and is fitted with a clay condenser. Due to reaction in furnace zinc is produced which is in vapour form because the reaction takes place above the boiling point. Zinc vapours are condensed in the condenser at about 500 °C and any vapours which escape the condenser are caught by the prolong. Zinc is then cast into slabs for shaping and forming.

The reduction has to be performed at high temperature so that enough CO is not present in the retort, otherwise it would oxidize the zinc back to ZnO. The use of a vertical retort process in which a 10 m tall narrow retort is used, alleviates some of the inefficiencies of a small retort process, which arise due to inefficient thermal transfer. The zinc produced from this process is fairly pure but needs to be purified further to 99.99 % purity by either fractional distillation or electrolytic refining.

Zinc may also be produced by electrolysis. Zinc concentrate is roasted and leached (soluble particles are removed) with a weak solution of sulphuric acid. Other metals are filtered out, and the solution (zinc sulphate) is then pumped into electrolytic tanks. Cathodes of pure aluminium and anodes of lead or lead-silver alloys are lowered into the tanks and electric current is passed through the solution. Pure zinc is deposited on the cathodes, from which it is stripped off and cast into slabs for further processing.

Zinc is a bluish white metal characterized by low strength and brittleness. It is readily attacked by alkalis and acids, but is resistant to corrosion by water. It is formable and machinable. Its melting temperature is 419 °C.

## 7.10 REFRACTORY METALS

The melting points of some of the main refractory metals are as follows: W 3410 °C, Re 3170 °C, Os 3000 °C, Ta 2980 °C, Mo 2610 °C, Nb 2470 °C. W and Mo are reduced from their oxides. Nb and Ta are more reactive and it is usual to reduce their fluorides with sodium. **Conventional crucible methods are not possible at the high temperatures needed to produce these metals as liquids.** Inevitably, then, the method is to reduce the metal direct to the metal powder. Later, metallic powder is consolidated by sintering in solid state.

Tungsten is obtained mainly from scheelite,  $\text{CaWO}_2$  and molybdenum from molybdenite,  $\text{MoS}_2$ . In both cases the first stage is to prepare pure oxide powder by chemical treatments. This is then reduced to the metal by heating in a stream of hydrogen gas. Hydrogen is an effective reducing agent for these metals. It gives a clean metal and there is no problem of carbide formation.

This chapter has described, in sufficient details, the production processes for some important non-ferrous metals. These metals are generally alloyed to provide some very versatile alternatives to ferrous materials.

**Refractory:** Lining consisting of material with a high melting point; used to line the inside walls of a furnace.

: **ısıya dayanıklı**

Fired articles having the special property of resisting high temperatures as met in metallurgy, the glass industry etc.

(e. g. of the order of 1500 degree and higher)

**Reactive:** participating readily in reactions,  
: **tepkili** (jet propelled, jet-prop), **tepki gösteren, duyarlı.**

Liquor: içki, sert içki, salgı, çözelti

# THE END

# CHAPTER 8

## ALLOY STEELS AND CAST IRONS

### 8.1 INTRODUCTION

Plain carbon steels are the most plentiful and economical class of steels. They do not, however, comply with some of the requirements for engineering applications. Alloy steels have, therefore, been developed to provide such characteristics. Specific alloying elements are added to steels which impart the required characteristics to them. Consequently these steels become more expensive and are therefore employed where plain carbon steels are inadequate.

Plain carbon steels with relatively low carbon content and virtual absence of alloying elements lack following characteristics:

1. Hardenability,
2. Softens on tempering,
3. High temperature/ low temperature strength,
4. Corrosion resistance,
5. Special properties such as ferromagnetism.

1. Hardenability,
2. Softens on tempering,
3. High temperature/ low temperature strength,
4. Corrosion resistance,
5. Special properties such as ferromagnetism

Alloy steels, therefore, provide one or more of above properties. This is achieved by the effect of alloying elements on iron-carbon system, which can be in many ways. The way in which Fe-C system is influenced depends upon the nature of the alloying element.

*In this chapter the effects of alloying elements on Fe-C system will be discussed so that an insight is provided to an engineer as to how and why alloy steels possess certain characteristics. Such understanding will be of valuable assistance to an engineer in making a correct choice of steel for a desired application. Various **alloy steels** and **cast irons** will be described in detail and finally the identification of various steels will be discussed.*

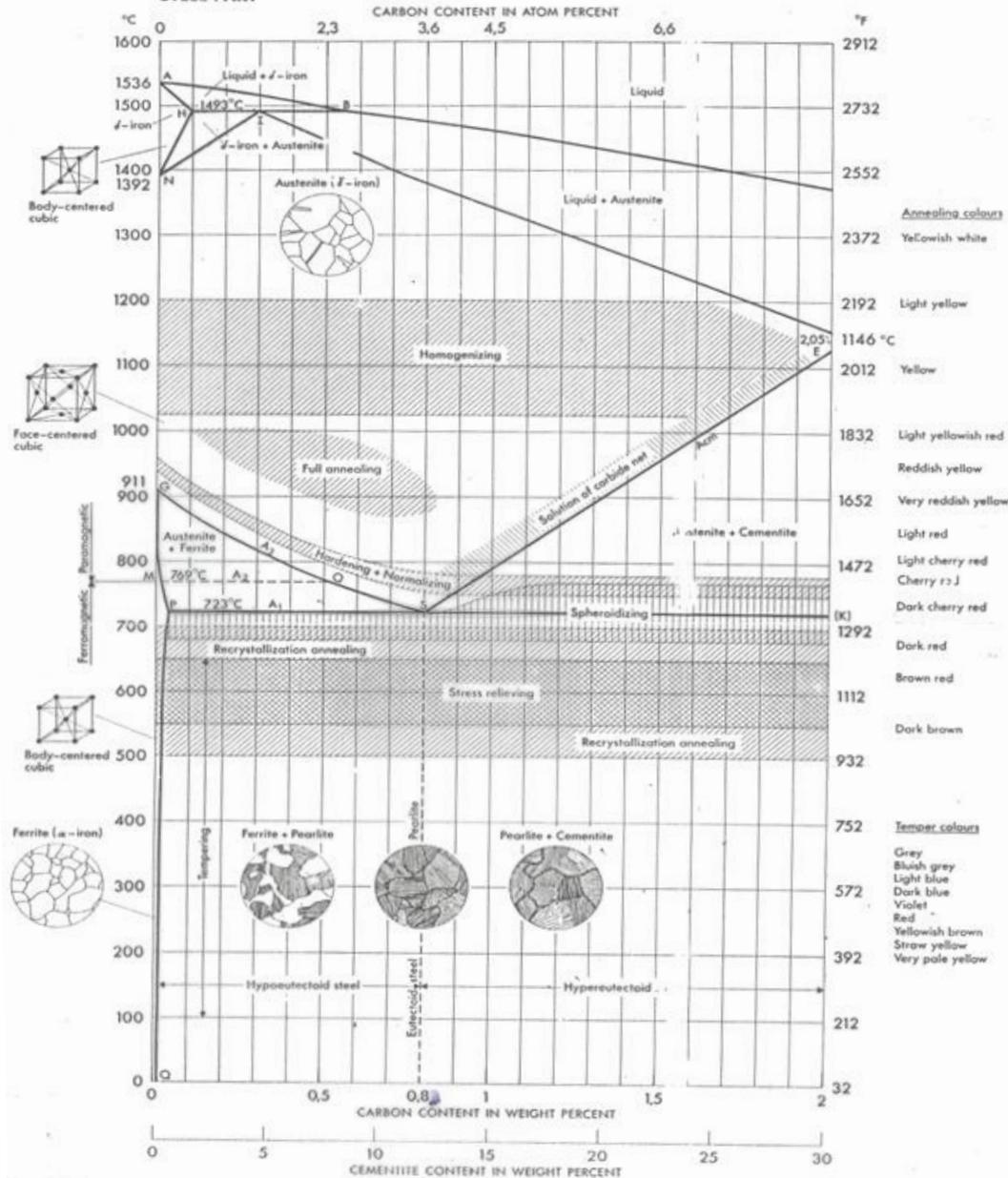
## 8.2 EFFECTS OF ALLOYING ELEMENTS

Three most important equilibrium constituents of steel are ferrite, austenite and cementite. Alloying elements influence the properties of steels by, among other things, altering the behavior of one or more of these phases in one or more of the following ways:

- 1. It may alter the Fe-C phase diagram by either changing the eutectoid temperature or eutectoid carbon content.*
- 2. It may dissolve in ferrite to increase its strength.*
- 3. It may form complex carbides such as  $Cr_{23}C_6$  which are hard and brittle and which always increase the strength of steels.*
- 4. It may form an intermediate compound with iron such as FeCr or  $Fe_2W_2$ . These compounds may increase strength due to dispersion hardening.*
- 5. It may alter the isothermal transformation diagram so that martensite could be formed by slower cooling, thereby increasing hardenability.*
- 6. It may reduce the volume change during  $\gamma - \alpha$  transformation which would reduce dimensional changes.*
- 7. It may clean steel by combining with impurities; V, Mn and Zn combine with sulphur to form sulphides.*
- 8. It may form surface oxide film for corrosion protection; Cr, Cu, Al and Si provide such protection, chromium oxide gives the characteristic corrosion resistance to stainless steels. .*
- 9. It may increase creep resistance by dispersion of fine carbides such as MoC.*

# IRON-CARBON EQUILIBRIUM DIAGRAM

STEEL PART





## 8.2.1 Alteration of Iron-Carbon Diagram

Iron-carbon binary system falls into four main categories of open, closed, expanded and contracted fields as shown in Fig 8.1. The alloying elements can, therefore, influence the diagram in two ways:

(a) **by expanding the  $\gamma$  - field** and encouraging the formation of austenite over wider compositional and temperature limits. These elements are called  $\gamma$  - stabilisers.

(b) **by contracting the  $\gamma$  - field** and encouraging the formation of ferrite over a wider range of composition and temperature. These elements are called  $\alpha$  - stabilisers.

The form of the diagram depends upon the electronic structure of the alloying element to some degree.

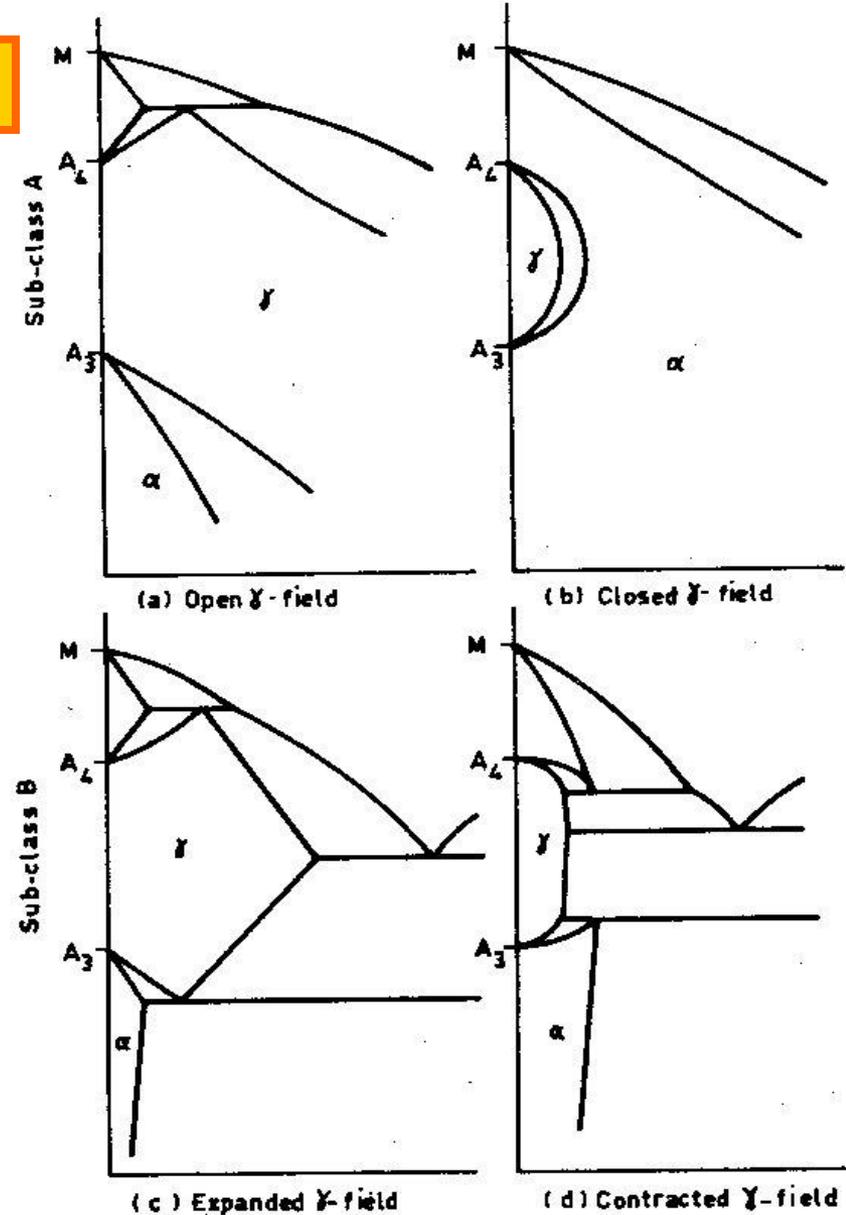
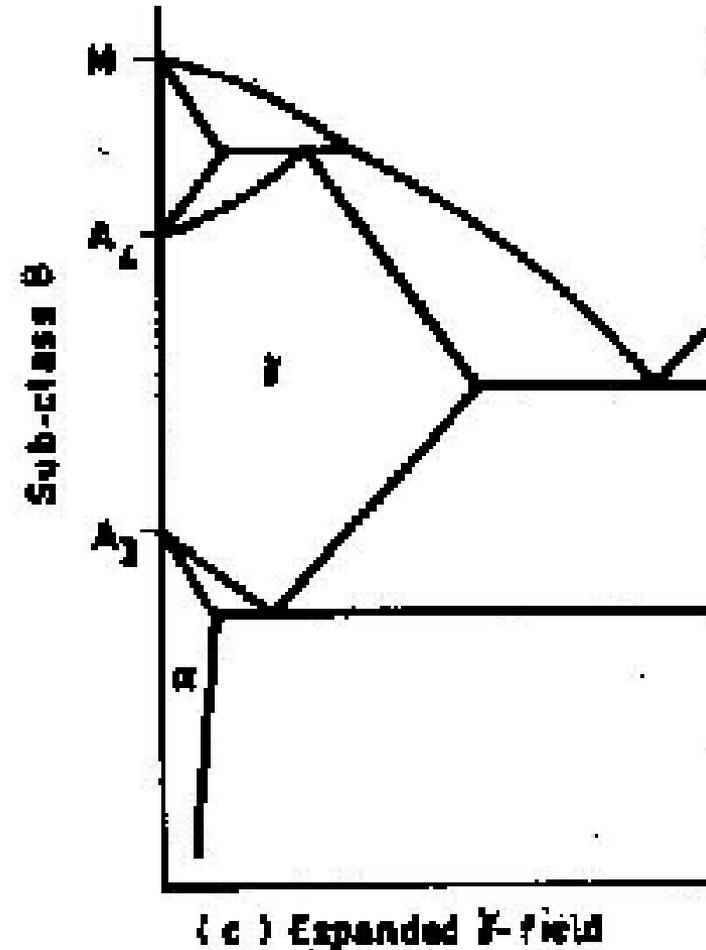


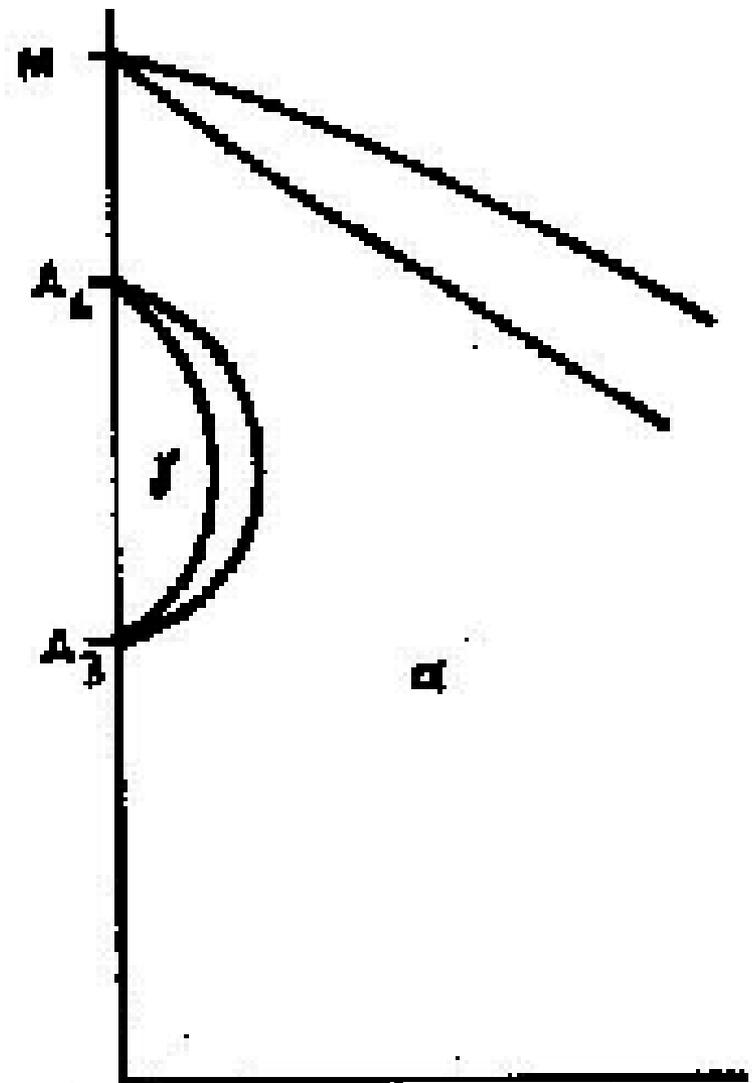
Fig 8.1 Classification of iron alloy phase diagram.



**Class 2 Expanded  $\gamma$ -field:** Carbon and nitrogen are the most important elements in this class. The  $\gamma$  field is expanded but its range is limited by formation of compounds (8.1,c); cementite is formed above 2% carbon. The expansion of  $\gamma$  field by carbon and nitrogen underlies the whole of the heat treatment of steels, by allowing the formation of austenite upto 2 % C and 2.8 % N.



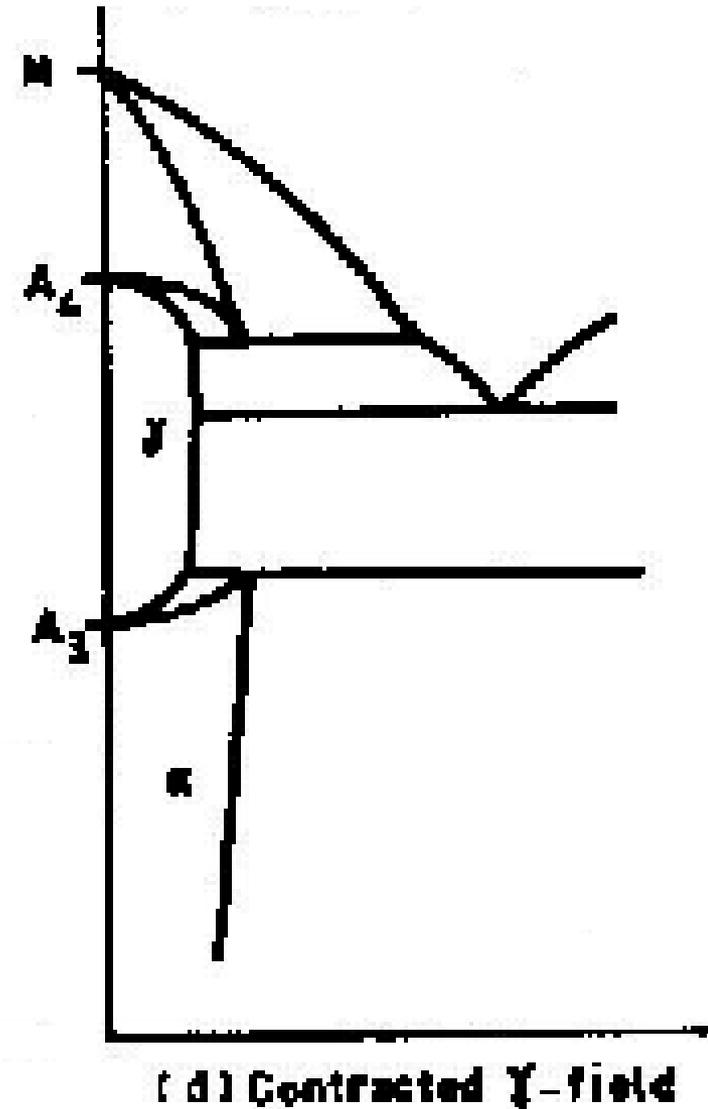
**Class 3 Closed  $\gamma$ -field:** Many elements restrict the formation of  $\gamma$  and restrict its field to a very small area known as  $\gamma$ -loop, as shown in Fig. 8.1(b). These elements encourage the formation of  $\alpha$  and one result of this is that  $\delta$  and  $\alpha$  fields become continuous. Such alloys are, therefore, not amenable to normal heat treatments involving  $\gamma \rightarrow \alpha$  phase transformation. Si, Al, Be and P fall into this category together with strong carbide formers Ti, V, Mo and Cr.



(b) Closed  $\gamma$ -field

### Class 4 Contracted $\gamma$ -field:

Boron is the most significant element of this group, together with the carbide forming elements tantalum, niobium and zirconium. The  $\gamma$ -loop is strongly contracted but is accompanied by compound formation (8.1.d).



Changes in  $\gamma$  phase fields are accomplished by the alloying elements through a change in either the eutectoid temperature or the eutectoid carbon composition.

Fig 8.2 (a) shows the change in eutectoid temperature by various alloying elements whereas 8.2 (b) shows the variation in eutectoid carbon composition due to the alloying elements.

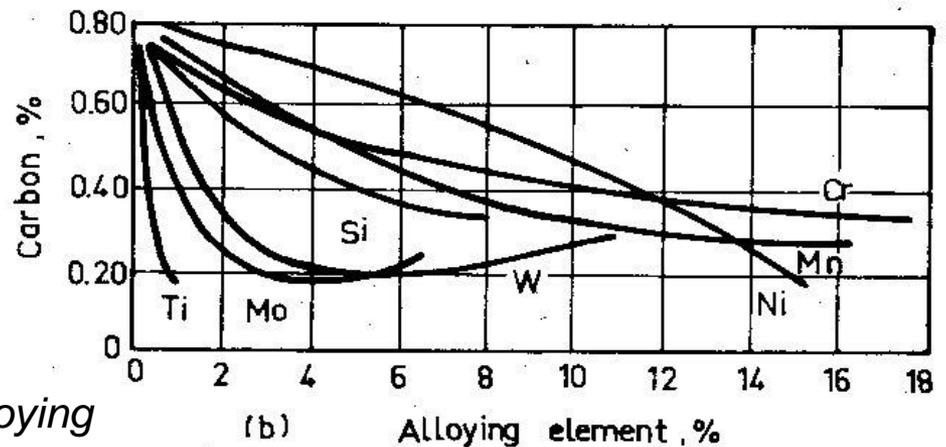
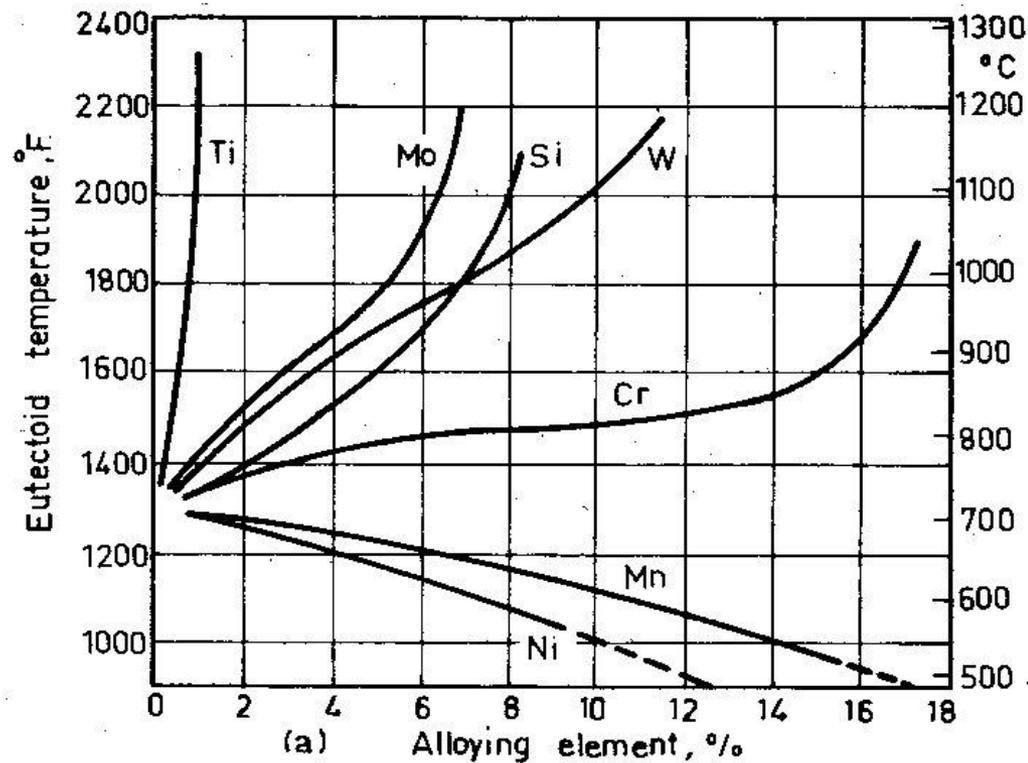
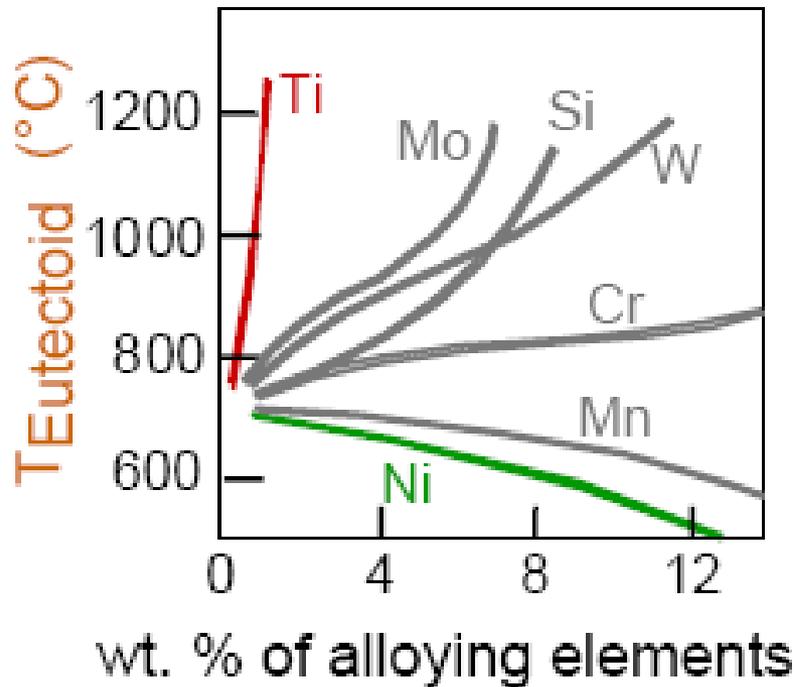


Fig 8.2 (a) Eutectoid temperature, and (b) eutectoid composition as influenced by alloying elements .

- $T_{\text{eutectoid}}$  changes:



- $C_{\text{eutectoid}}$  changes:

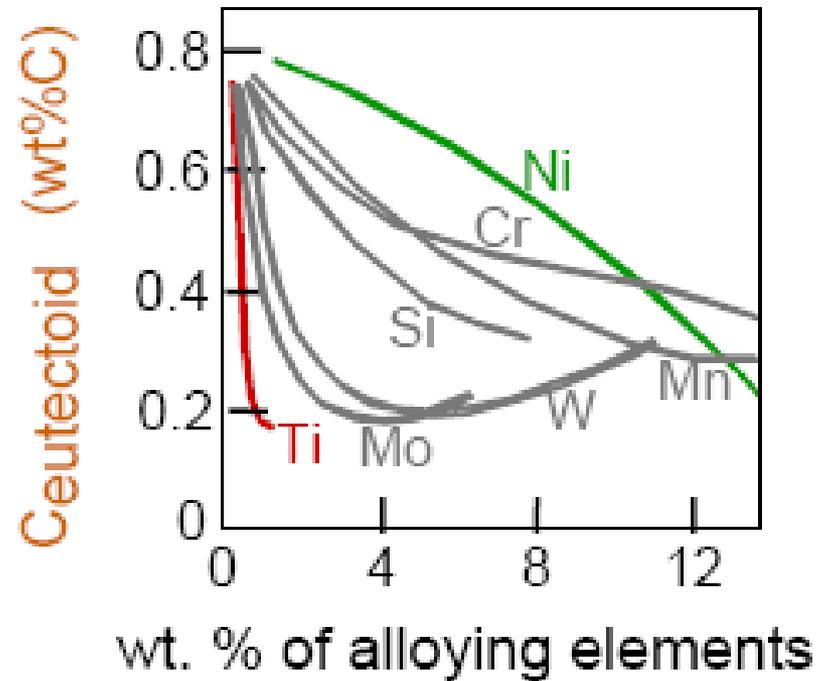


Fig 8.2.1 (a) Eutectoid temperature, and (b) Eutectoid composition as influenced by alloying elements .

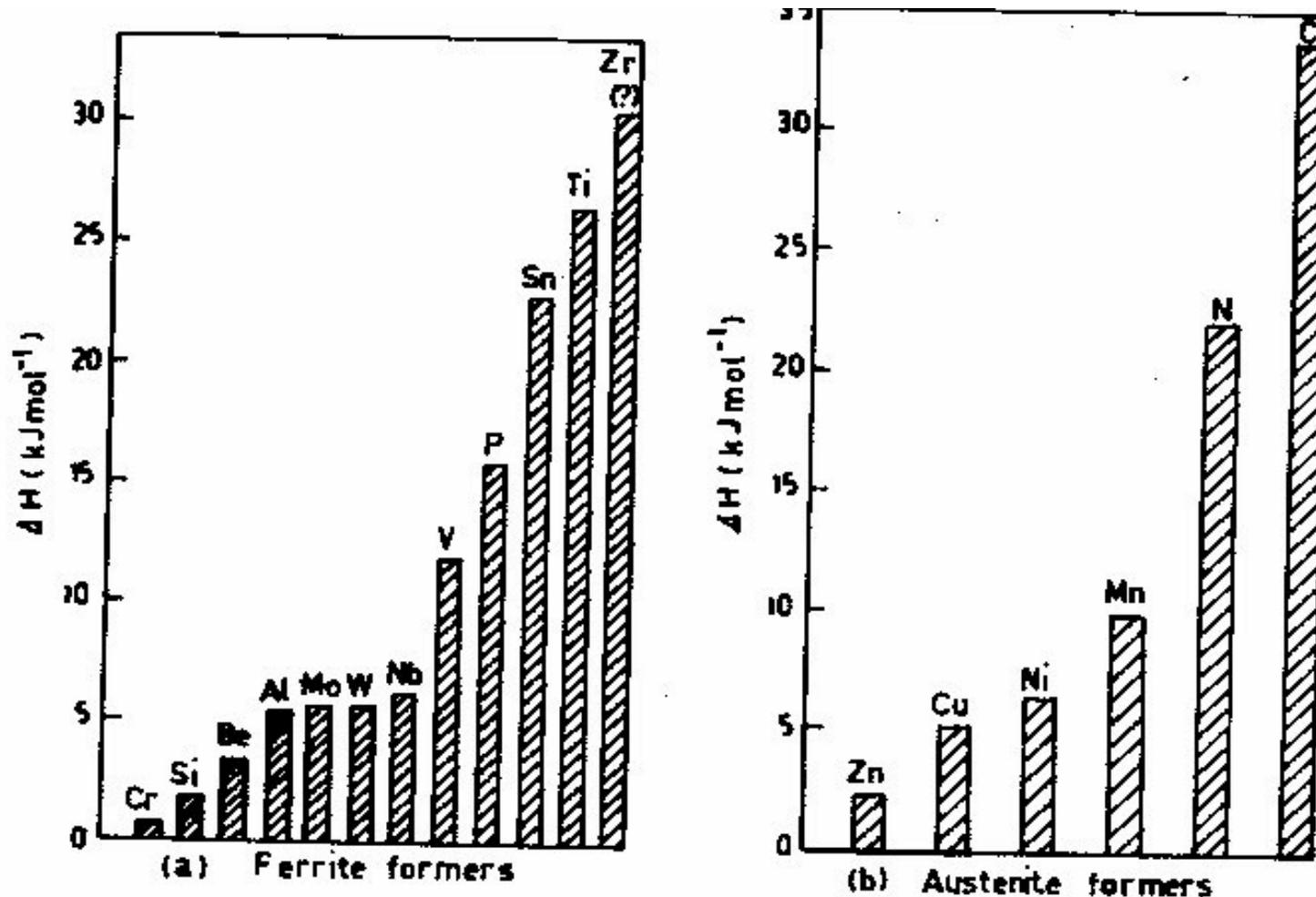


Fig 8.3 Relative strengths of  $\alpha$  and  $\gamma$  formers.

Relative strength of various alloying elements as ferrite or austenite formers is depicted in Fig 8.3. It can be seen from these three figures that Ti reduces the austenite field very strongly compared to Cr.

## 8.2.2 Distribution in Steel

If only the steels in which austenite transforms to ferrite and cementite on slow cooling are considered, the alloying elements can be divided into four categories:

- (1) elements which only dissolve in  $\alpha$ ,
- (2) elements which dissolve in  $\alpha$  as well as form carbides,
- (3) elements which only form stable carbides,
- (4) elements which promote graphitization by decomposing carbides.

1. In the first category elements such as Ni, P and Si are present which do not form carbides and are only soluble in  $\alpha$ . They increase the strength of ferrite as shown in Fig 8.4. Their overall contribution to strength is, however, not significant as ferrite is a weak phase in steels.

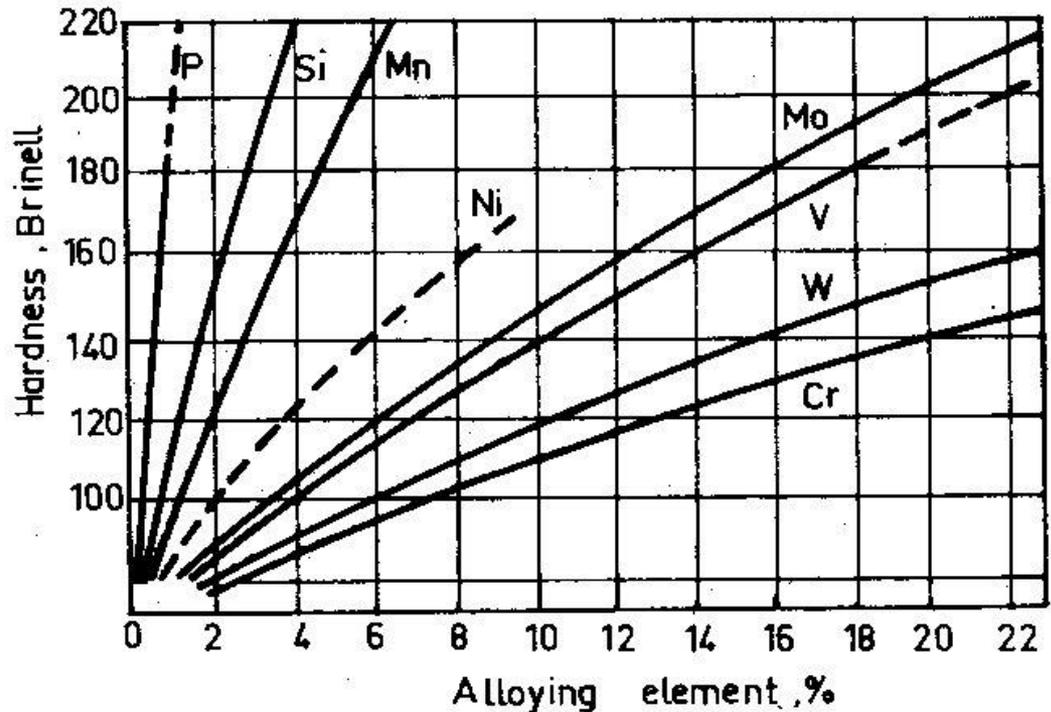


Fig 8.4 Strengthening effects of elements on ferrite  
CHAPTER 8 ALLOY STEELS  
AND CAST IRONS

2. Great majority of steel alloying elements, however, fall into the second category whereby they are carbide formers as well as soluble in ferrite. These elements go into solid solution in cementite and ferrite at low concentrations, whereas at high concentrations they form carbides which are more stable than iron carbide.

Most of these alloying elements occur in steels in amounts larger than that required for carbide forming (due to amount of available carbon depending on composition of steel). Excess of these elements goes into solution with ferrite.

Carbides are hard and brittle and they always increase the room temperature strength of steels. Some of these carbides provide secondary hardening during tempering, as shown in Fig.8.5.

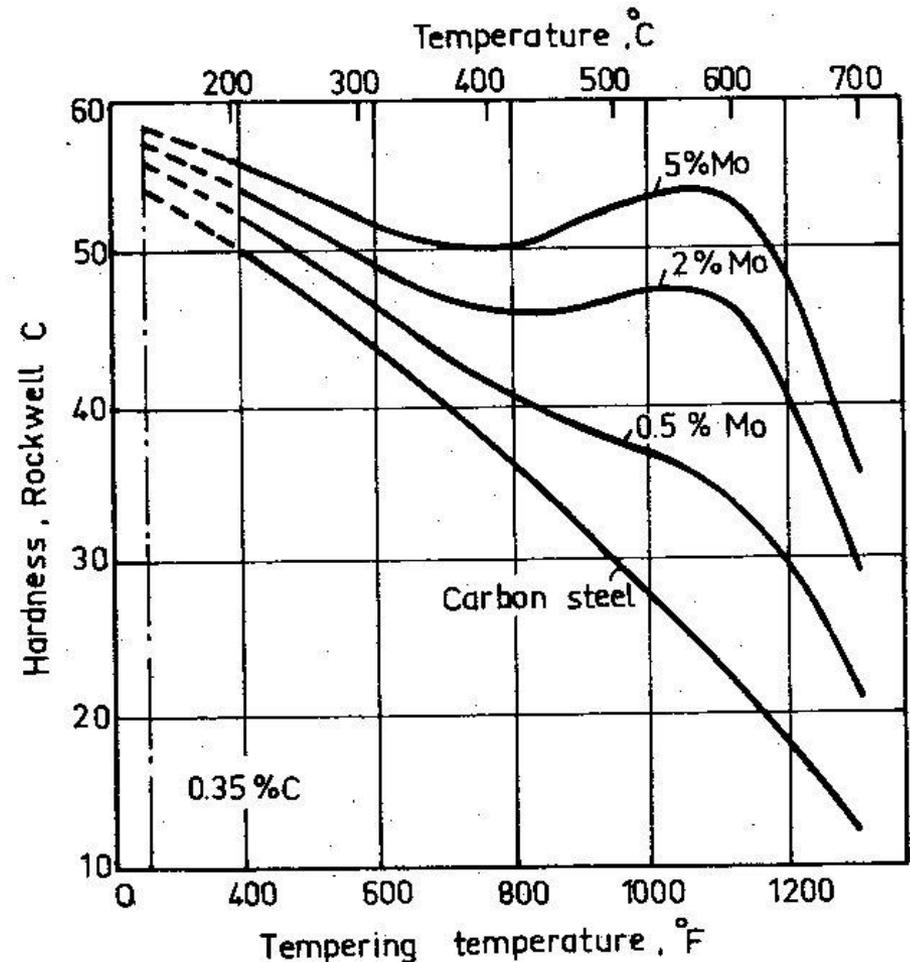


Fig 8.5 Secondary hardening due to alloying elements in steel.  
 CHAPTER 8 ALLOY STEELS  
 AND CAST IRONS

## 8.2.2 Distribution in Steel

If only the steels in which austenite transforms to ferrite and cementite on slow cooling are considered, the alloying elements can be divided into four categories:

- (1) elements which only dissolve in  $\alpha$ ,
- (2) elements which dissolve in  $\alpha$  as well as form carbides,
- (3) elements which only form stable carbides,
- (4) elements which promote graphitization by decomposing carbides.

3. Few elements are only in the third category as carbide formers, such as nitrogen which forms carbonitrides. In the presence of certain strong nitride forming elements like Ti and Al, however, separate nitride phases may occur in steels.

4. Fourth category comprises of elements such as Si, Co, Ni and Al which tend to form graphite, thus decomposing carbides and reducing the strength of steels drastically. Carbide formers are added in steels containing these elements to counter their effects.

## 8.3 STEELS

Plain carbon steels containing upto 1 % carbon are the most economic and commonly used steels; 90 % of steels produced are plain carbon steels. Their applications are, however, limited to routine ambient temperature uses, and are replaced by a variety of alloy steels to meet stringent demands. There are over 70,000 types of steels and more are being continually developed, so that a classification is essential to make it easier for an engineer to select them for particular applications.

The classification is based on **the composition** and **functions of steels**.

# STEELS

## Plain Carbon S.

C<1%  
90% of steel produced  
Applications are limited to routine ambient temp.

## Tool Steels

Very clean,  
High quality  
High strength  
  
Classified according to Cooling medium and Applications  
  
Water Hardening (W)  
Shock Resisting (S)  
Cold Work (A,D,O,M)  
Hot Work (H)  
High Speed (HSS)  
Special Purpose (L,F,P)

## Stainless Steels

Low Carbon  
App. 10.5%Cr  
Corrosion and heat resistant  
  
Austenitic (200,300)  
Ferritic (405,430,446)  
Martensitic (403,410,416, 420,501,502)  
Precipitation hardening

## HSLA

C<0.2%  
Fine grains  
High strength

## Other Steels

Classified acc. to major alloying element

Manganese	(13xx)
Nickel	(2xxx)
Ni-Cr	(3xxx)
Molybdenum	(4xxx)
Cr-Mo	(40xx)
Cr-Ni-Mo	(43xx)
Ni-Mo	(46xx)
Chromium	(5xxx)
Cr-Vanadium	(6xxx)
Tungsten	(7xxx)
Cr-Ni-Mo	(8xxx)
Silicon-Mang	(9xxx)
Superalloys	

## Maraging S.

(Martensite-Aging)  
High strength

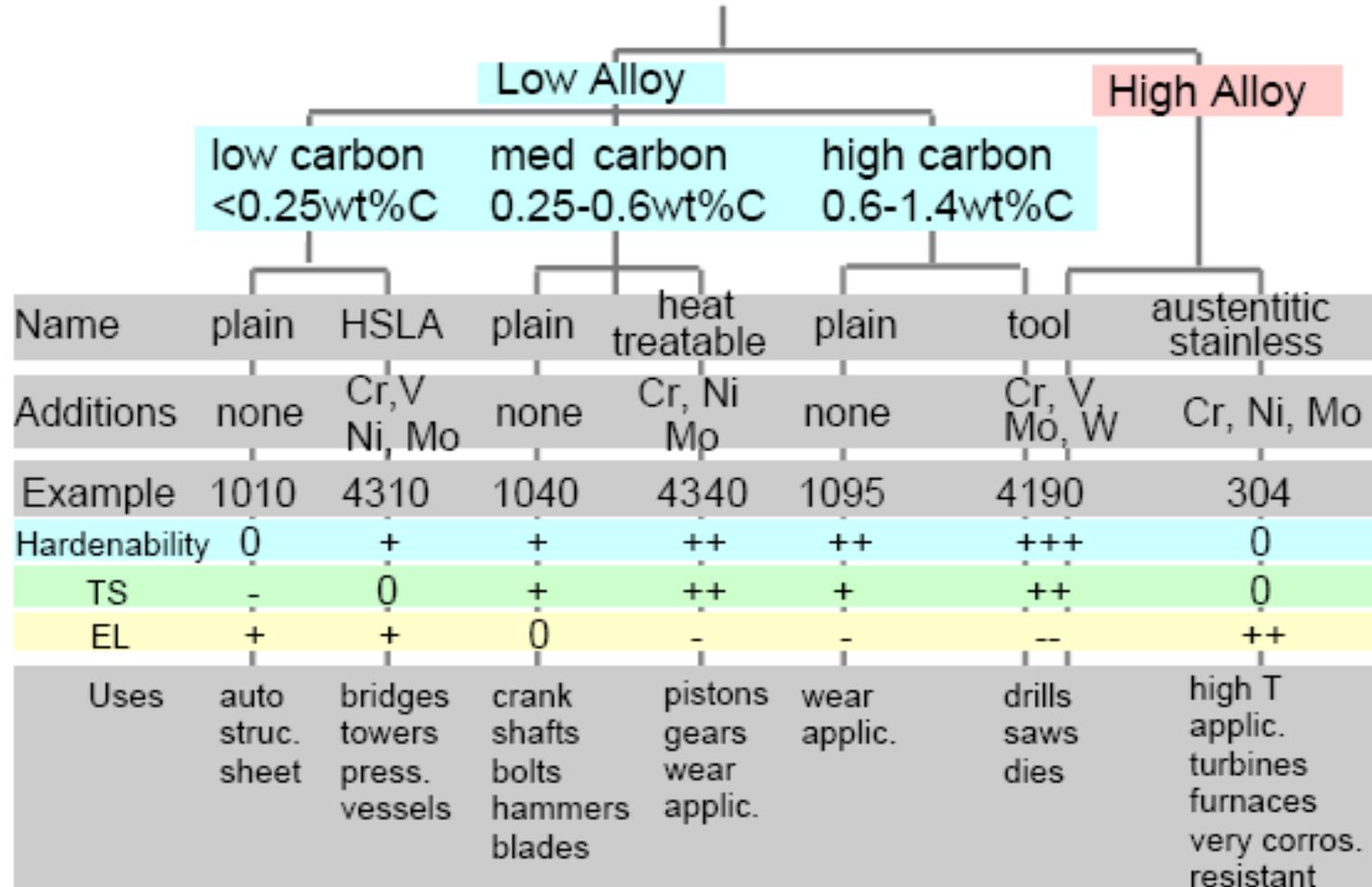
## CUTTING MATERIALS

*Satellites: Co-Cr-W alloys 40-60 HRC*

*Cemented Carbides: Tungsten or Ti-Tantalum type 67 HRC*

*Ceramic tools: Aluminum oxides (very good resistance to wear)*

# STEELS



### 8.3.1 Tool Steels

Tool steels are very clean high quality special purpose steels produced by electric processes making them very expensive commodity. They are characterized by high strength and are used for machine tools for cutting and forming. These steels either have high carbon content (water hardening type) or they rely upon carbide forming elements W, Mo, Cr and V for their strength. The later type has medium carbon content to provide enough carbon for alloy carbide formation.

**Tool steels are classified either according to the quenching media used** such as water, oil etc., or according to alloy content such as carbon tool steels, low alloy tool steels etc., or **according to their applications** such as hot-work steels, shock-resisting steels etc. The method adopted by AISI (American Iron & Steel Institute) for classification includes quenching media, application, special characteristics and steels for special industries as shown in Table 8.2.

Table 8.2 lists the essential properties of tool steels. These steels are rated relative to each other.

**Depth of hardening** is related to hardenability.

**Nondeforming properties** describe the distortion obtained during hardening (quenching) from the hardening temperature.

The term **toughness** is the ability to resist breaking rather than the ability to absorb energy, as usually defined.

**Wear resistance** is the resistance to abrasion or the resistance to loss of dimensional tolerances.

**Red hardness** is the resistance of steels to the softening effects of heat, whereas

**Machinability** is the ability to be cut freely and produce a good finish.

**Resistance to de-carburisation** is the ability not to lose carbon when heated above about 600 °C, as de-carburisation softens the metal.

**TABLE 8.2 Comparative Properties of Some Tool Steels.**

STEEL TYPE °C	HARDEING °C	HARDENING MEDIUM	TEMPERING °C	HARDNESS HRC	DEPTH OF HARDENING
W1	750-850	Brine or water	150-350	65-50	Shallow
W2	750-850	Brine or water	150-350	65-50	Shallow
S1	900-1000	Oil	200-650	58-40	Medium
S5	875-925	Oil	175-425	60-50	Medium
O1	B00-820	Oil	150-250	62-57	Medium
A2	925-1000	Air	175-550	62-57	Deep
A4	820-875	Air	175-925	62-54	Deep
D2	975-1075	Air	200-550	61-59	Deep
D3	925-975	Oil	200-550	61-59	Deep
D9	950-1000	Air	200-550	61-54	Deep
H11	1000-1025	Air	550-650	54-3B	Deep
H19	11.00-1200	Air or Oil	550-700	59-40	Deep
H21	1100-1200	Air or Oil	600-675	54-36	Deep
H23	1200-1300	Air or Oil	650-820	47-30	Deep
H26	1175-1250	Salt/Oil/Air	560-675	58-43	Deep
H41	1100-1200	Salt/Oil/Air	560-650	60-50	Deep

STEEL TYPE °C	HARDEING °C	HARDENING MEDIUM	TEMPERING °C	HARDNESS HRC	DEPTH OF HARDENING
T1	1250-1300	Oil/Air/Salt	550-600	65-60	Deep
T4	1250-1300	Oil/Air/Salt	550-600	66-62	Deep
T6	1275-1320	Oil/Air/Salt	550-600	65-60	Deep
M1	1175-1225	Oil/Air/Salt	550-600	65-60	Deep
M2	1200-1230	Oil/Air/Salt	550-600	65-60	Deep
M6	1175-1200	Oil/Air/Salt	550-600	66-61	Deep
M41	1100-1220	Oil/Air/5alt	550-600	70-65	Deep
L2	800-850	Water	175-550	63-45	Medium
	850-925	Oil			
L6	800-850	Oil	175-550	62-45	Medium
F2	800-875	Water or brine	150-250	66-62	Shallow
P2	825-850	Oil	150-250	64-58	Shallow
P20	820-875	Oil	425-600	37-28	Shallow

## **WATER-HARDENING TOOL STEELS (Group W)**

These are essentially plain carbon steels containing 0.60 to 1.40 % carbon. They must be water quenched for high hardness and are therefore subject to considerable distortion. They have the best machinability, but their resistance to heat is poor. These steels must be used at low speeds and light cuts on relatively soft materials.

## **SHOCK-RESISTING TOOL STEELS (Group S)**

These steels are developed for the applications where toughness and ability to withstand repeated shock are paramount. Their carbon content is between 0.45 to 0.65 %. The principal alloying elements are Si, Cr, W and sometimes Mo. Most of these steels are oil hardening.

## COLD-WORKING TOOL STEELS

This is considered to be the most important tool steel group. The oil-hardening type (group O) contains Mn, Cr and W. They have very good nondeforming properties and are less likely to bend, sag, twist, distort, or crack during heat treatment. The air-hardening type (group A) contains 1 % C, up to 3 % Mn, up to 5 % Cr, and 1 % Mo. The increased alloy content, particularly Mn and Mo, confers marked air-hardening properties and increased hardenability. The high alloyed types (group D) contain up to 2.25 % C and 12 % Cr. They also contain Mo, V, and Co. The combination of high carbon and high chromium gives excellent wear resistance and nondeforming during hardening makes these steels popular for **blanking and piercing dies**.

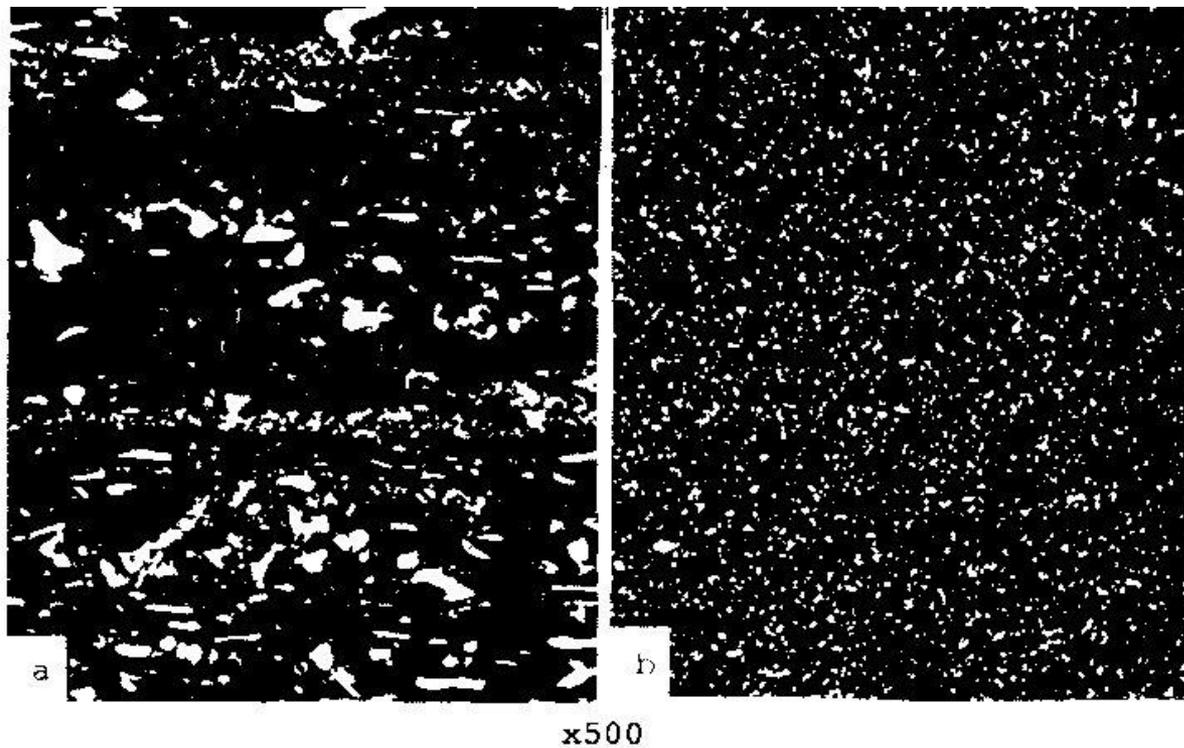
## **HOT-WORKING TOOL STEELS (Group H)**

In many applications, the tool is subjected to excessive heat because the material is being hot worked, as in hot forging. They have good red-hardness. The alloying elements noted for red-hardness are Cr, Mo, and W. The sum of these elements must be at least 5 %. They are subdivided into three groups: chromium base containing min. 3.25 % Cr (H11 to H19), tungsten base containing min. 9 % W and 2 to,12 % Cr (H21 to H26), and molybdenum base containing 8 % Mo and 4 % Cr. These steels as a group have good toughness because of low carbon content, excellent red-hardness, fair wear resistance and machinability.

## **HIGH-SPEED STEELS (HSS)**

They are among the most highly alloyed of the tool steels and usually contain large amounts of W and Mo with Cr, V, and sometimes Co. The carbon content varies between 0.70 to 1.50%.

The major application of HSS is for **cutting tools**, but they are also used for making **extrusion dies, blanking and piercing dies and punches**. They are subdivided into two groups: molybdenum base (group M) and tungsten base (group T). The most widely used one is known as 18-4-1 (T1), the numerals denoting the content of W, Cr, and V respectively. Both groups have excellent red-hardness and reasonably good shock resistance.



*Fig.8.6 Microstructures of HSS steels: (a) Conventional cast and wrought, (b) powder metallurgy processed*

**Red-hardness** of HSS steels is due to stable carbide distribution which are produced during double-tempering. For improved red-hardness, carbides should be very fine and homogeneously distributed. However, even during double-tempering, some carbides grow very large as shown in Fig.8.6(a). Similar alloy produced through powder metallurgy processing shows very fine distribution of carbides, Fig.8.6(b), thus much improved red-hardness

## **SPECIAL-PURPOSE TOOL STEELS**

Many tool steels do not fall into the usual categories and are therefore designated as special-purpose tool steels. The low-alloy types (group L) contain chromium as the principal alloying element. The carbon-tungsten type (group F) are generally shallow-hardening, water-quenching steels with high carbon and tungsten contents. Mold steels (group P) contain Cr and Ni, with Mo and Al as additives.

## **SPECIAL CUTTING MATERIALS**

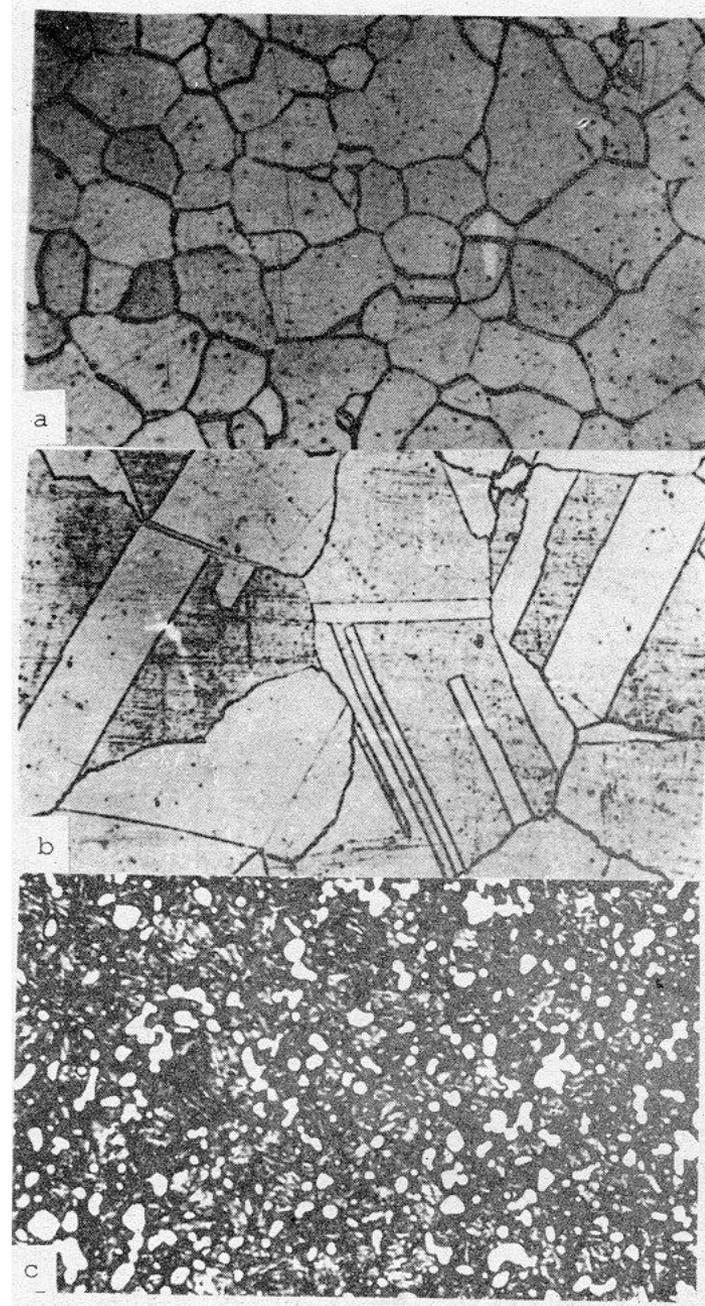
**Stellites** are essentially Co-Cr-W alloys. They contain from 25 to 35 % Cr, 4 to 25 % W, 1 to 3 % C, and the remainder Co. The hardness varies from HRC 40 to 60, depending upon the tungsten and carbon content. Their outstanding properties are high hardness, high resistance to wear and corrosion, and excellent red-hardness. This combination of properties makes them very suitable for **cutting applications**.

**Cemented Carbides** are made of very finely divided carbide particles of the refractory metals, cemented together with cobalt, forming a body of very high hardness and high compressive strength. Cemented carbides are manufactured by powder metallurgy techniques (Section 15.4). They are classified into two categories: (1) tungsten carbide grades, used primarily for machining cast irons and nonferrous materials; and (2) the grades containing major amounts of titanium and tantalum carbides, used primarily for **machining steels**. Recently, cemented carbides are coated with titanium nitride which reduces coefficient of friction, and thus improves tool life considerably. The exceptional tool performance of sintered carbides result from high hardness (HRC 67) and high compressive strength combined with unusual red-hardness.

**Ceramic Tools** are manufactured primarily from aluminum oxide. After consolidation into a useful shape, they are sintered at 1700 °C. Ceramic tools are commonly used as disposable inserts which are available in many shapes. Alumina is very stable at metal cutting temperatures and has very good resistance to wear. Unfortunately, **they are brittle and must be properly mounted in suitable holders.**

### 8.3.2 Stainless Steels

Stainless steels are very low carbon steels with a minimum of 10.5 % Cr, although 501 and 502 steels have 4-6 % Cr. The corrosion and heat resistance of these steels is superior to other steels, and is proportional to Cr content. **Corrosion resistance is provided by an adherent film of chromium oxide on the surface.** The high temperature strength does not rely on carbides but is provided by Cr metal itself. They have considerably higher strengths than plain carbon steels. Stainless steels are classified into series 300 and 400, in addition to a few steels in series 200 and 500. Series 300 is basically austenitic stainless steels whereas series 400 contains ferritic and martensitic steels. Fig.8:7 shows microstructures of various stainless steels.



*Fig.8.7 Microstructure of various stainless steels, x100:  
(a) Ferritic, (b) Austenitic, 18-8, and (c) Precipitation hardening*

## AUSTENITIC STAINLESS STEELS

These steels are Cr-Ni (type 300) and Cr-Ni-Mn (type 200) steels. They are essentially non-magnetic in annealed condition, and **they do not harden by heat treatment**. The total content of Ni and Cr is at least 23 %. They can be hot worked easily and can be cold worked when an allowance is made for their rapid work hardening. The steels may become slightly magnetic in cold worked condition. They are extremely shock resistant and difficult to machine. Austenitic stainless steels possess best high temperature strength and resistance to scaling among stainless steels. Their corrosion resistance is usually better than ferritic or martensitic stainless steels.

## FERRITIC STAINLESS STEELS

These are straight Cr steels containing approximately 14-27 % Cr and includes types 405, 430, and 446., They are not hardened by heat treatment and only moderately hardened by cold working. Ferritic stainless steels are magnetic and they possess maximum softness, ductility and corrosion resistance in annealed condition. Their strength in annealed condition is about 50 % higher than plain carbon steels, and they are superior to martensitic stainless steels in corrosion resistance and machinability. These steels are easily cold formed and consequently extensively used for **deep drawing** such as **vessels for chemical and food industries and for architectural and automotive trims**.

## **MARTENSITIC STAINLESS STEELS**

These steels are also straight Cr steels containing between 11.5 and 18 % Cr. Some examples are 403, 410, 416, 420, 501 and 502. Types 410 and 416 are the most popular alloys in this group. They are magnetic and can be cold worked without difficulty, especially with low carbon content. They can be easily machined, have good toughness and corrosion resistance to weather and some chemicals. They attain their best corrosion resistance when hardened, but are not as good as ferritic or austenitic stainless steels in this respect.

## **PRECIPITATION HARDENING STEELS**

This type of stainless steels were developed during world war II. They contain about 17 % Cr, 7 % Ni with Mo and some other elements such as Cu, Al, Nb and P. These steels are supplied in solution annealed condition and after forming they are aged to attain an increase in hardness and strength due to precipitation.

### 8.3.3 High Strength Low Alloy (HSLA) Steels

HSLA steels have been developed about 50 years ago to replace plain carbon steels. They contain small additions of Nb, V, Ti and Al and upto 0.2 % C. They provide high strength due to extremely fine grain size. Strength is improved without heat treatment, as a result of, pinning action of fine dispersion of intermetallic compounds which impede grain growth to yield very small grains.

They are generally available in sheet or strip form; they are inherently anisotropic or directionally sensitive. The grades known as improved formability, developed primarily for the **automotive and construction industry** are 2-3 times stronger than plain carbon steels.

### 8.3.4 Maraging Steels

These steels are capable of providing extremely high strengths by a process of martensitic transformation followed by aging (maraging). They contain 18-25 % Ni together with Ti, Mo and Co. Aging of martensite produces fine dispersion of intermetallic precipitates which impart ultra high strength to these steels.

They are considered to be martensitic as annealed and attain ultra high strength on being aged in the annealed martensitic condition. The martensite formed is soft and tough rather than the hard, brittle martensite of conventional low alloy steels. This ductile martensite has a low work hardening rate and can be cold worked to a high degree. There are two grades of maraging steels developed thus far; the 18 % Ni grade contains Co and Mo additions with small amounts of Ti and Al, whereas the 20 and 25 % Ni grade uses Ti-Al-Nb additions.

### 8.3.5 Other Steels

Other alloy steels are classified according to the major alloying element which is responsible for their characteristics.

**Manganese Steels (13xx series)** containing more than 0.8 % Mn are classified as alloy steels. They are tough, hard and strong; fine grained manganese steels attain unusual toughness and strength. These steels are used for gears, spline shafts etc. With moderate additions of V they are used for **large forgings** which must be air cooled. Steels containing more than 10 % Mn remain austenitic after slow cooling. **Hadfield steels** containing about 12 % Mn is a special steel which can undergo severe service conditions of abrasion and wear.

**Nickel Steels (2xxx series)** are characterized by strength consistent with toughness, plasticity and fatigue resistance. They are highly suited for high strength structural applications as large forgings. The 3.5 % Ni steels are used for **carburising of automotive parts** and the 5 % Ni steels are used for **heavy duty applications** due to their increased toughness.

### 8.3.5 Other Steels

**Nickel - Chromium Steels (3xxx series)** contain Ni and Cr in the ratio 2.5:1. They are tough and wear resistant. Low carbon steels are used for worm gear, piston.etc. while for heavy duty applications such as **aircraft parts**, the Ni content is raised to 3.5 % and Cr is kept at 1.5 %. In many cases, these steels have been replaced by the tripple-alloy steels of the 87xx and 88xx series because of lower cost.

**Molybdenum Steels (4xxx series)** are characterized by good hardenability and high temperature strength. Low carbon steels are used for transmission gear, spline shaft etc. and high carbon steels are suitable for automotive coil and leaf spring. The Cr-Mo steels possess good deep hardening characteristics as well. as ductility and weldability and are used for pressure vessels and aircraft parts. Ni-Mo steels have good toughness, wear and fatigue resistance and are used for **bearings, gears and shafts**.

**Chromium Steels (5xxx series)** contain between 0.15 and 0.64 % C and between 0.7 and 1.15 % Cr. They are wear resistant steels. Medium carbon steels are oil hardening and are used for springs, axles etc. whereas high C high Cr steels are hard and wear resistant and extensively employed for **ball and roller bearings**.

### 8.3.5 Other Steels

**Vanadium Steels (6xxx series)** are characterized by hardenability and strength on air cooling. The C-V steels are, therefore, used for heavy locomotive and machinery forgings which are normalized. The low carbon Cr-V steels are used in the case hardened condition in the manufacture of **pins and crankshaft**. The medium carbon Cr-V steels, having good toughness and strength are used for axles and springs. High carbon grades with high hardness and wear resistance are used for **bearings and tools**.

**Tungsten Steels (7xxx series)** are more expensive but similar in characteristics to Mo steels. Due to their higher cost, however, they are not extensively used in engineering applications, but instead W is used as an alloying element for tool steels.

**Silicon Steels (9xxx series)** are those containing more than 0.6 % Si. A steel containing 1 - 2% Si, known as navy steel, is used for structural applications requiring high yield strength. **Hadfield Si steel** with less than 0.01 % C and about 3 % Si has excellent magnetic properties for use in the **cores and poles of electrical machinery**.

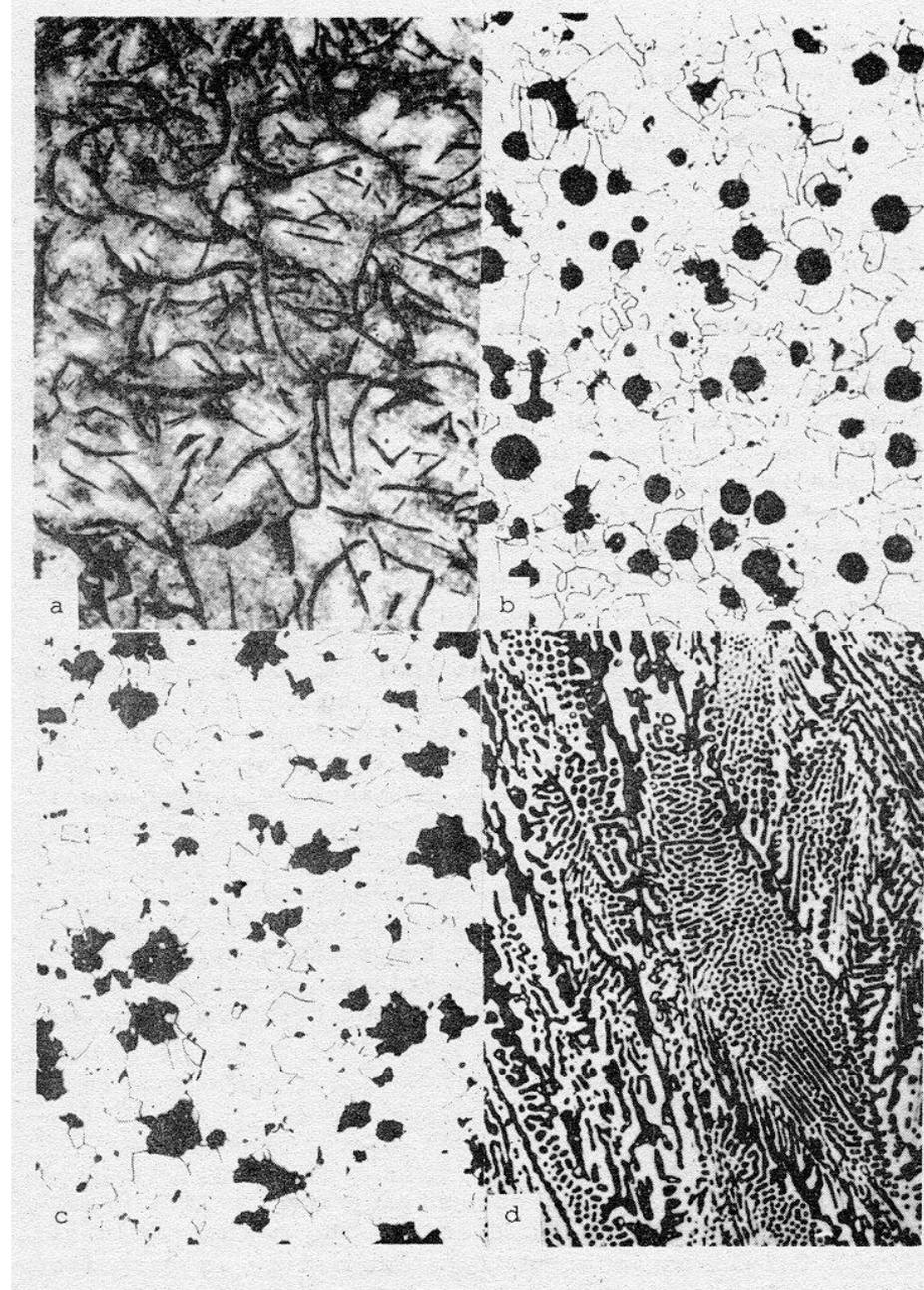
**Super Alloys** are mainly alloys of Fe, Ni and Co which are developed for high temperature applications. They are either iron based, nickel based or cobalt based. Fe - based alloys are cheaper than the other two types, however.

## 8.4 CAST IRONS

Commercial cast irons contain from 2 - 4 % C with some additions of Si, Mn, S and P. The maximum solubility of C in iron is about 2 %. Extra **Carbon** in cast iron is, therefore, present as super saturated solid solution and it precipitates out as either graphite in various forms or as iron carbide, as depicted in Fig 8.8. Cast irons are, consequently, classified according to the type of precipitated carbon.

*Fig.8.8 Microstructures of various cast irons, x100:*

- (a) Gray cast iron,*
- (b) Nodular cast iron,*
- (c) Malleable cast iron,*
- (d) Eutectic white cast iron.*



# CAST IRONS

## Gray Cast Iron

Gray C.I. contains more than 1 % Si in addition to 1.7 - 3.5 % C.

Freshly fractured surface of this cast iron has a grayish color giving it the name.

Gray C.I. possesses almost no ductility

It is widely used for **furnace doors, guards and frames, housings, cylinder liners and camshafts.**

## White Cast Iron

White C.I. contains most of iron as iron carbide.

It has a whitish appearance on fracture surface and hence it is termed white C.I.

It is very hard, abrasion resistant and brittle material containing pearlite grains. It is not machinable or weldable.

It is used for applications where wear resistance is important, such as **liners for concrete mixers, ball mills, drawing dies and extrusion nozzles.**

## Malleable Cast Iron

Malleable C.I. contains graphite as nodules which are produced as a result of a two stage heat treatment to give tempered carbon nodules.

It may have ferritic, pearlitic or even martensitic matrix, depending upon heat treatment.

The yield strength and ductility are same as soft steel.

Tempered nodules act as lubricants during machining making it very machinable.

It has been widely used for **automotive, agricultural, and railroad equipments.**

## Nodular Cast Iron

Nodular or ductile C.I. is a special type of gray C.I. which possesses tensile strength with increased ductility.

It is a C.I. in which the graphite is present as tiny balls or spheroids.

Ductility is increased by inoculation with small amounts of magnesium, in the form of Ni-Mg alloy

The matrix can be ferritic, pearlitic, martensitic or even austenitic, depending upon the alloying elements.

Nodular C.I. is used where tough and high strength material is required; for **fluid conducting applications and agricultural machinery parts.** It is machinable and produces good finish.

### 8.4.1 Gray Cast Iron

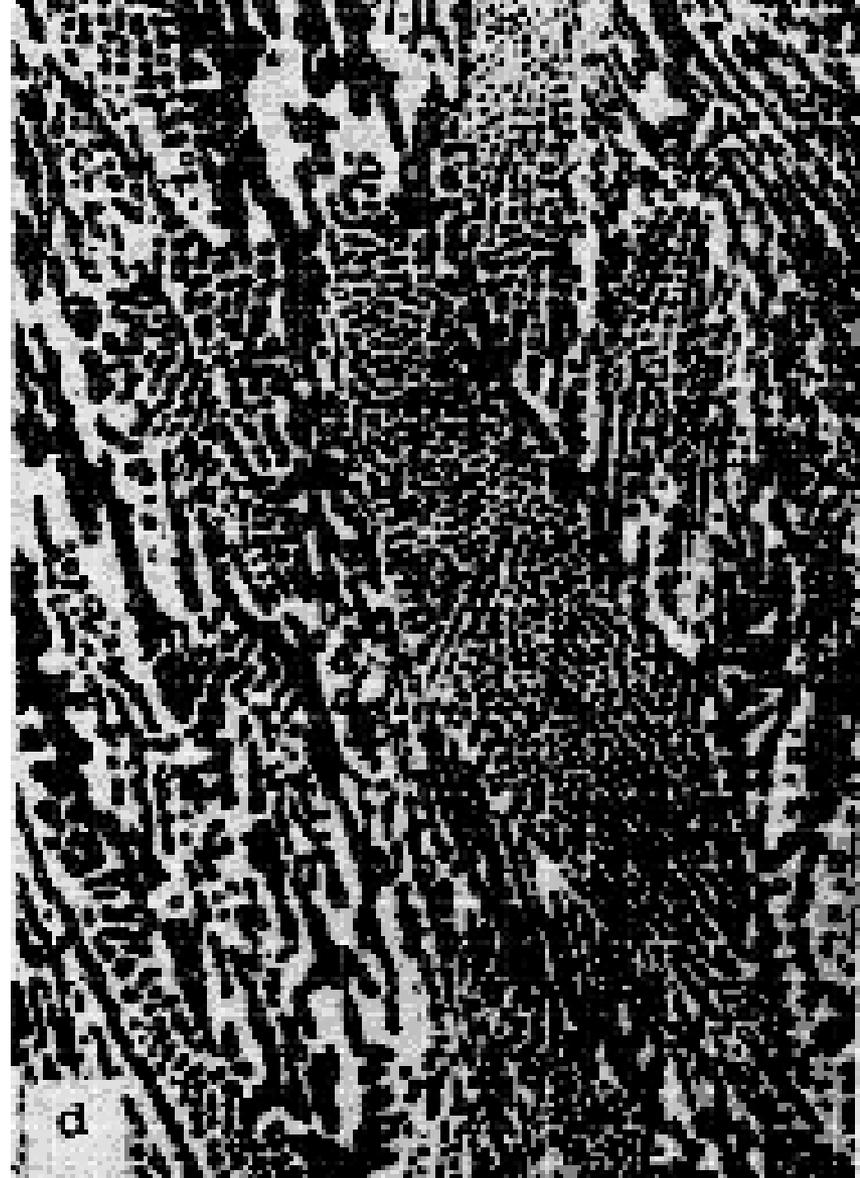
Gray cast iron contains more than 1 % Si in addition to 1.7 - 3.5 % C. The addition of Si enhances graphitization of carbon, the graphite being present as flakes as shown in micrograph of Fig 8.9. Freshly fractured surface of this cast iron has a grayish color giving it the name. Gray cast iron possesses almost no ductility. It has lower modulus of elasticity and lower tensile strength compared to steel. It is, however, lower melting iron and is, therefore, easily castable into complex shapes. It can withstand higher temperatures than steel without warping or oxidizing and is used for **furnace doors** etc., due to this characteristic. Graphite network provides good corrosion resistance and good vibration damping making it one of the most widely used alloys of iron. It is widely used for **furnace doors, guards and frames, housings, cylinder liners and camshafts.**



(a) Gray cast iron,

## 8.4.2 White Cast Iron

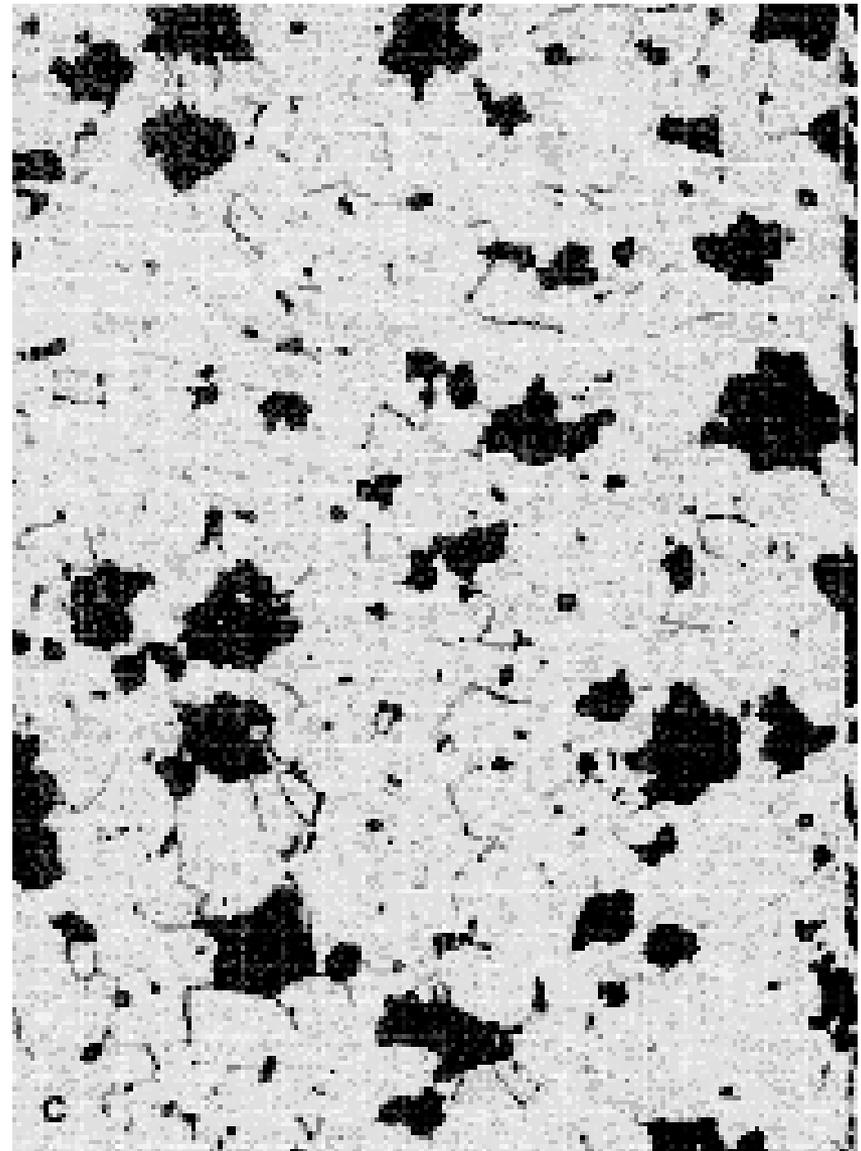
White cast iron contains most of iron as iron carbide as shown in Fig 8.8. It has a whitish appearance on fracture surface and hence it is termed white cast iron. It is very hard, abrasion resistant and brittle material containing pearlite grains. It is not machinable or weldable. It is produced by very fast cooling (chilling) process which suppresses precipitation of graphite. White cast iron can be produced by chilling from gray or malleable cast iron. It is used for applications where wear resistance is important, such as **liners for concrete mixers, ball mills, drawing dies and extrusion nozzles.**



*(d) Eutectic white cast iron.*

### 8.4.3 Malleable Cast Iron

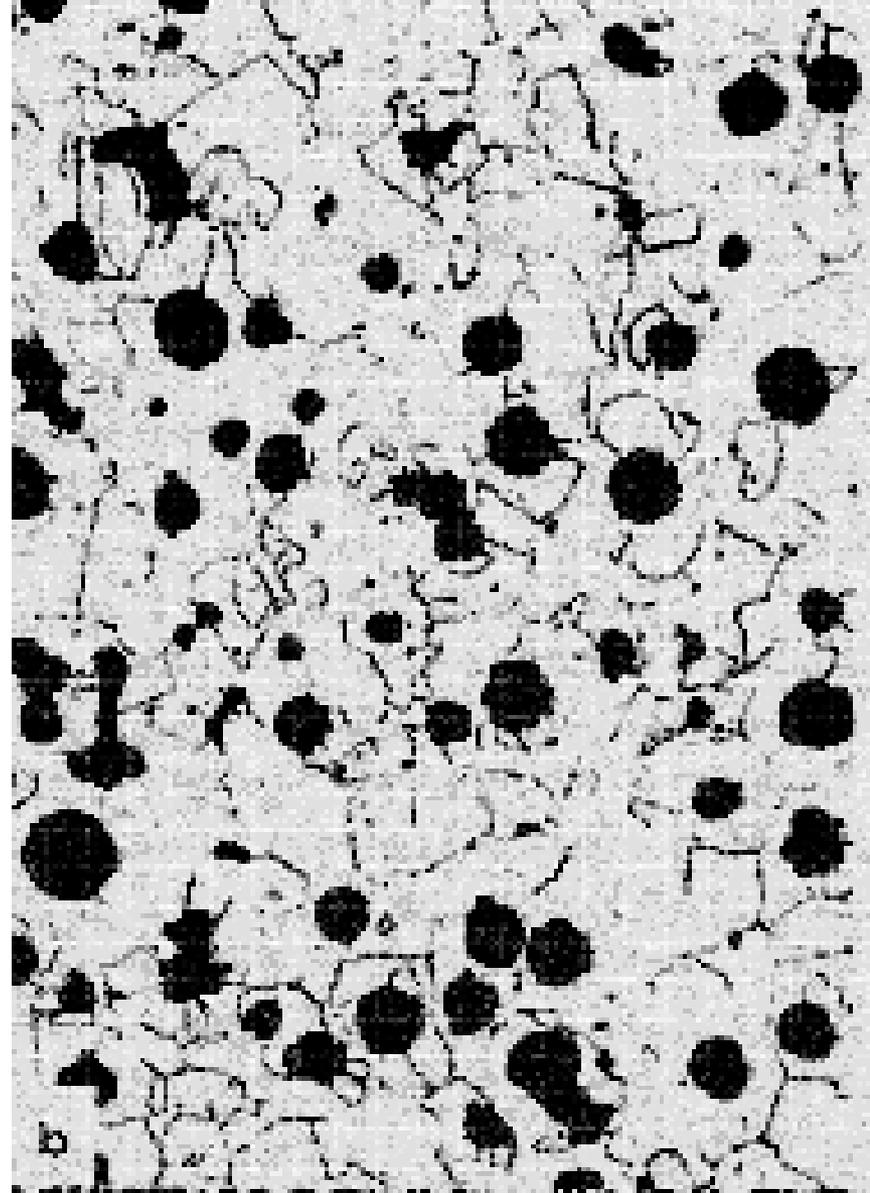
Malleable cast iron contains graphite as nodules which are produced as a result of a two stage heat treatment to give tempered carbon nodules (Fig 8.8 (c)). It may have ferritic, pearlitic or even martensitic matrix, depending upon heat treatment. The yield strength and ductility are same as soft steel. Tempered nodules act as lubricants during machining making it very machinable. It has been widely used for **automotive, agricultural, and railroad equipments.**



*(c) Malleable cast iron,*

## 8.4.4 Nodular Cast Iron

Nodular or ductile cast iron is a special type of gray cast iron which possesses tensile strength with increased ductility. It is a cast iron in which the graphite is present as tiny balls or spheroids. Ductility is increased by inoculation with small amounts of magnesium, in the form of Ni-Mg alloy, in the ladle. Magnesium causes the graphite to take a spherical (nodular) shape, as shown in Fig 8.8, which increases the ductility. The matrix can be ferritic, pearlitic, martensitic or even austenitic, depending upon the alloying elements. Its properties are similar to steel but it is cheaper. Nodular cast iron is used where tough and high strength material is required; for **fluid conducting applications and agricultural machinery parts**. It is machinable and produces good finish.



*(b) Nodular cast iron,*

### **8.4.5 High Alloy Irons**

These are ductile, gray or white irons containing more than 3 % alloying additions. These alloy irons have properties significantly different from other cast irons and are usually produced by special foundries for specific purposes. nickel resist, for example, contains 15 % Ni for corrosion resistance, and for wear resistance the alloy nickel hard is employed.

### **8.4.6 Industrial Iron**

Pure iron is more corrosion resistant than its alloys and its ductility is unusually high. Tensile strength is, however, much less than steel. Iron powder is pressed and sintered in molds to produce finished small parts of various structural shapes demanding low strength.

This chapter does not attempt to provide an exhaustive survey of effects of all alloying elements, but it does give a reader a sense and feel for the important aspects of alloying to alter the properties of steels. It also covers the range of ferrous metals adequately, giving an idea of the variety and diversity of ferrous materials. It enables an engineer to judge a steel regarding its characteristics and functions, through its alloy concentrations.

# CHAPTER 9

## NON-FERROUS INDUSTRIAL ALLOYS

### 9.1 INTRODUCTION

Almost all non-ferrous metals used for engineering applications are alloys, with the possible exception of copper, lead and zinc. Although not as common as steel, these alloys are important for specific purposes and are indispensable in their own rights.

These alloys are classified, in general, according to the predominant metal;

Aluminum Alloys,

Copper Alloys,

Lead Alloys,

Magnesium Alloys,

Nickel alloys

Titanium alloys and

as well as some special purpose alloys.

# NONFERROUS ALLOYS

## Cu Alloys

**Brass:** Zn is substitutional impurity

- costume jewelry, coins; corrosion resistant

**Bronze:** Sn, Al, Si, Ni substitutional impurities

- bushings, landing gear

**Cu-Be:** precipitation hardened for strength

## Ti Alloys

- lower  $\rho$ : 4.5 g/cm<sup>3</sup> vs. 7.9 g/cm<sup>3</sup> for steel
- reactive at high T
- space applications

## NonFerrous Alloys

## Al Alloys

- lower  $\rho$ : 2.7 g/cm<sup>3</sup>
- Cu, Mg, Si, Mn, Zn additions
- Solid solution or precipitation strengthened
  - Structural aircraft parts & packaging

## Mg Alloys

- very low  $\rho$ : 1.7 g/cm<sup>3</sup>
- ignites easily
- aircraft, missiles

## Refractory metals

- high melting T
- Nb, Mo, W, Ta

## Noble metals

- Ag, Au, Pt
- oxid/corr. resistant

## 9.2 ALUMINUM ALLOYS

Aluminium alloys have come into great use in reducing weight in machine parts, especially in the aeronautical and automotive industries, and to a certain degree in the construction industry. The most significant advantage of these alloys is their low density and good corrosion resistance coupled with sound mechanical properties.

In commercial alloys aluminum is alloyed with Si, Mg, Mn, Cu, Zn and Cr. Cu and Zn alloys are heat treatable and can develop strengths up to 500 MPa. The other types of alloys are hardened by cold working. While only small percentages of alloying elements is used in wrought aluminum alloys, the casting alloys may contain as much as 17 % Si, 11 % Cu, or 10 % Mg. The hard alloys containing copper are the best machining aluminum alloys, but they have limited ductility for forming and bending.

The aluminum alloys are classified into two groups: **the casting alloys** and **the wrought alloys**. Wrought formulations are those used for rolling, extruding, drawing and forging. Aluminum casting alloys are formulated for sand casting, permanent mould casting and die-casting.

## 9.2.1 Casting Alloys

There are several processes of casting aluminum alloys. Molten Al alloys may be poured into sand moulds or metal moulds. Plaster moulds may be used to produce plaster-process and investment castings. In die casting the molten alloy is forced into steel moulds under pressure.

Aluminum alloys used for casting are designated by a two or three digit number indicating their composition. Number designations are sometimes followed by a letter indicating the temper. Perhaps the most common designation system is that of Aluminum Association in which:

Pure Al (Min 99.0 %)	1xx.x;
Al-Cu	2xx.x;
Al-Si, Cu, Mg	3xx.x;
Al-Si	4xx.x;
Al-Mg	5xx.x;
unused series	6xx.x;
Al-Zn	7xx.x;
Al-Sn	8xx.x and
other elements	9xx.x.

Aluminum-copper alloys are preferred for their hardness when machinability is a factor; aluminum-silicon alloys are useful when **fluidity to follow intricate shapes** is desired. The high magnesium alloys require care during melting to prevent excessive oxidation loss of the magnesium content.

Most aluminum casting alloys are not notably strong in tension; only a few exceeding 400 MPa at room temperature. This low strength, which drops rapidly with temperature, coupled with a high coefficient of thermal expansion, indicates a tendency towards hot shortness the susceptibility to cracking and tearing when hot. Aluminum also has a propensity to pick up hydrogen in molten form, and this is a cause of porosity in castings and welds. Moreover, aluminum castings are not **pressure-tight**, and to obtain pressure-tightness they must be impregnated with sodium silicate, epoxy or other material.

## 9.2.2 Wrought Alloys

Aluminium alloys used in the production of sheet products and extruded shapes are heat treatable or non-heat treatable alloys. Heat treatable ones attain maximum strength through a controlled heat treatment to provide precipitation hardening, either before or after forming operations. These are the highest strength alloys; they are hard, retain their appearance and generally have good resistance to abrasion and corrosion. They are particularly suited to structural applications and are commercially produced in the form of extrusions or forgings. Non-heat treatable alloys acquire maximum strength, beyond the annealed condition, through work hardening as a result of cold rolling. They possess high corrosion resistance, good formability, pleasing appearance, and good weldability, and are widely used for manufactured products and general sheet applications.

The Aluminum Association has devised a four digit number designation system for wrought aluminum alloys:

Pure Al (Min 99.6%)	1xxx;
Al-Cu	2xxx;
Al-Mn	3xxx;
Al-Si	4xxx;
Al-Mg	5xxx;
Al-Mg, Si	6xxx; and
Al-Zn	7xxx.

Temper designations for wrought aluminum alloys follow the alloy designation and are separated by a hyphen (for example, 1100-O). Subdivisions of a basic temper are indicated by one or more digits and follow the letter of the basic designation (for example, 1100-H14). Basic temper designations are:

F-as fabricated,  
O-annealed and recrystallized,  
H-strain hardened, and  
T- heat treated.

## **STRAIN-HARDENED SUBDIVISIONS**

H1- Strain-hardened only. The degree of strain hardening is indicated by the second digit. It varies from quarter-hard (H12) to full hard (H18).

H2- Strain-hardened and partially annealed. Tempers ranging from quarter-hard to full-hard obtained by partial annealing of cold-worked materials. Tempers are H22, H24, H26, and H28.

H3- Strain-hardened and stabilized. Tempers for age softening aluminium-magnesium alloys. Tempers are H32, H34, H36, and H38.

## **HEAT-TREATED SUBDIVISIONS**

T1- Naturally aged. It is applied to hot worked products.

T3- Solution treated, cold worked and naturally aged.

T4- Solution treated and naturally aged.

T5- Artificially aged. It is applied to hot worked products.

T6- Solution treated and artificially aged.

T7- Solution treated and stabilized.

T8- Solution treated, cold-worked and artificially aged.

## 9.2.3 Commercial Alloys

**Aluminium - Copper alloys (type 2xxx)** are heat treatable alloys of high strength, used in aircraft applications and for parts requiring high strength or hardness. Maximum solubility of copper in aluminium occurs in solid solution at 548 °C, and decreases with decreasing temperature (as shown in Fig. 12.20), allowing precipitation hardening. These alloys may contain smaller amounts of silicon, iron, magnesium, manganese, chromium, and zinc.

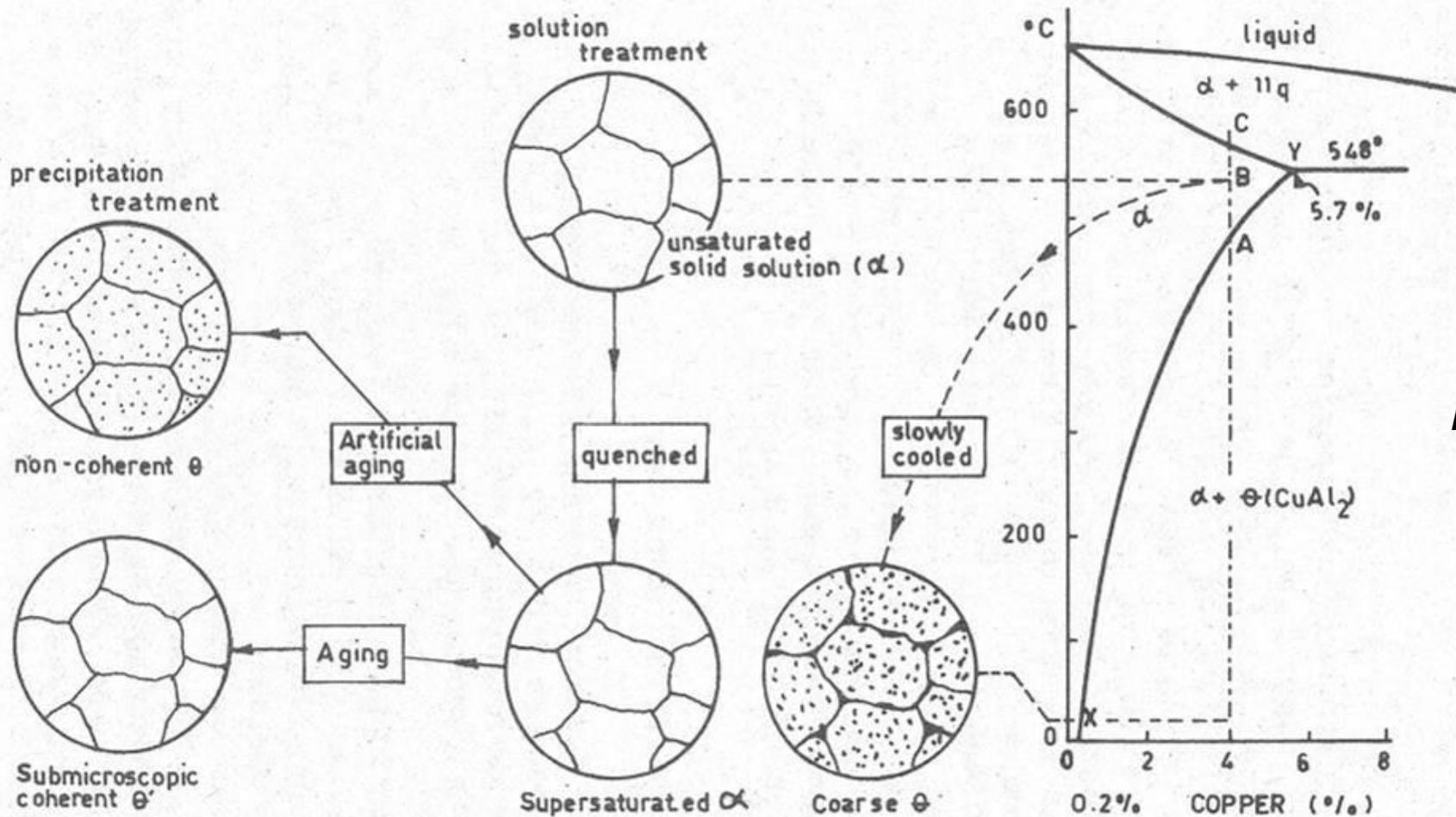


Fig. 12.20

# PRECIPITATION HARDENING

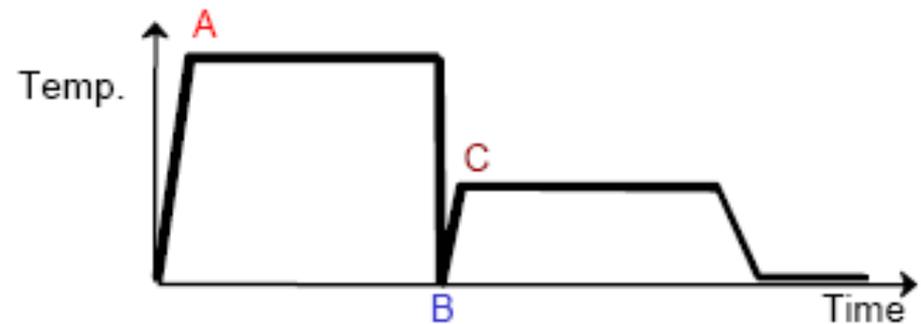
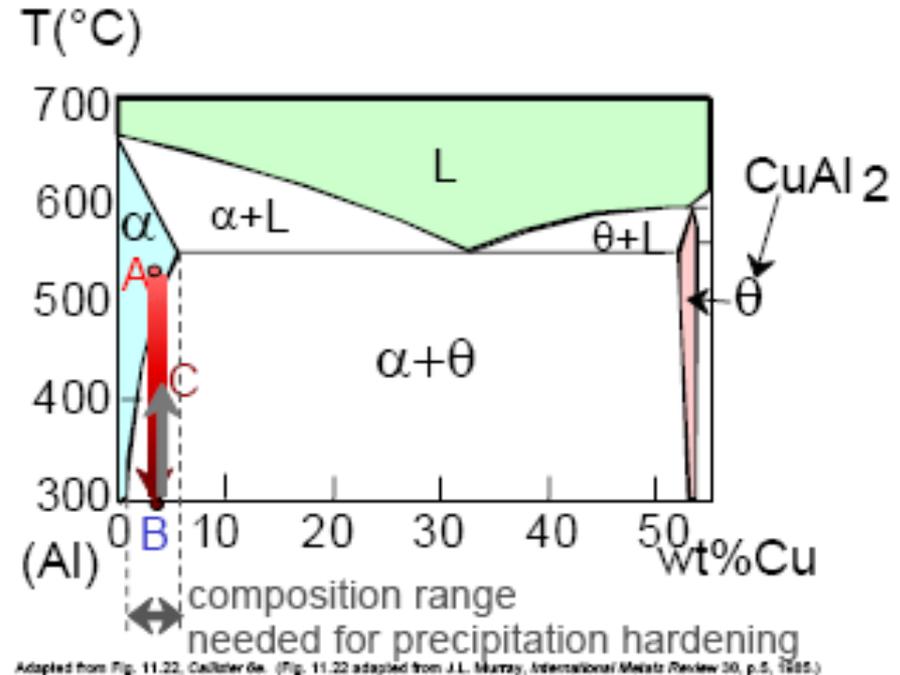
- Particles impede dislocations.
- Ex: Al-Cu system
  - **Point A:** solution heat treatment

- **Point B:** rapid quench

- **Point C:** aging

- Other precipitation systems:

- Cu-Be, Cu-Sn, Mg-Al

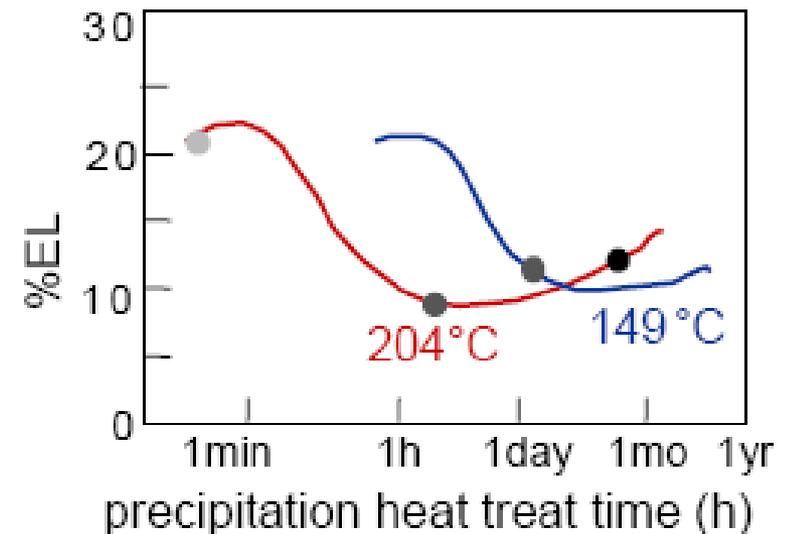
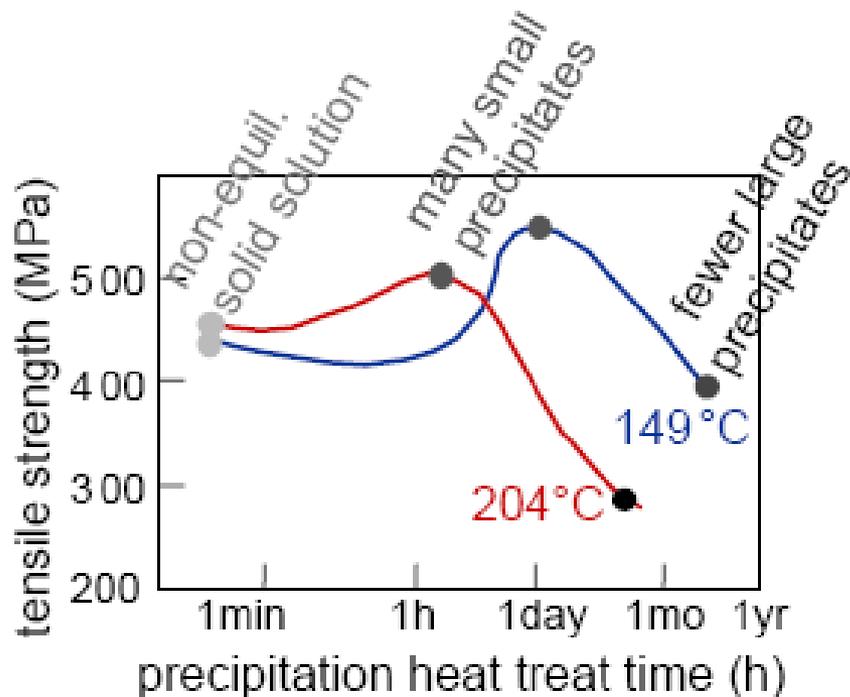


# PRECIPITATE EFFECT ON TS, %EL

- 2014 Al Alloy:

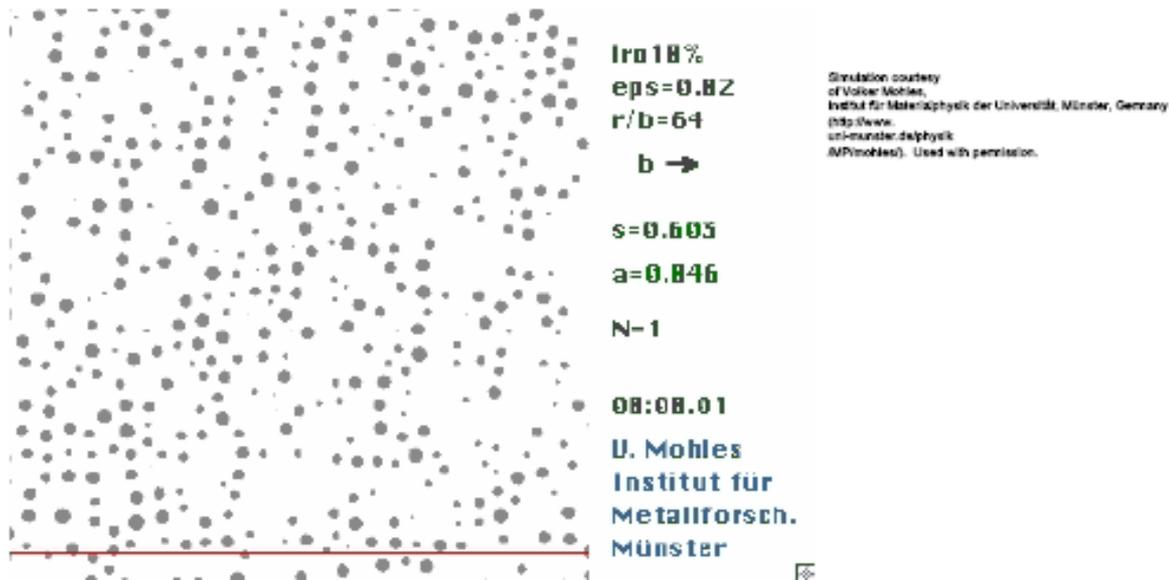
- TS peaks with precipitation time.
- Increasing T accelerates process.

- %EL reaches minimum with precipitation time.



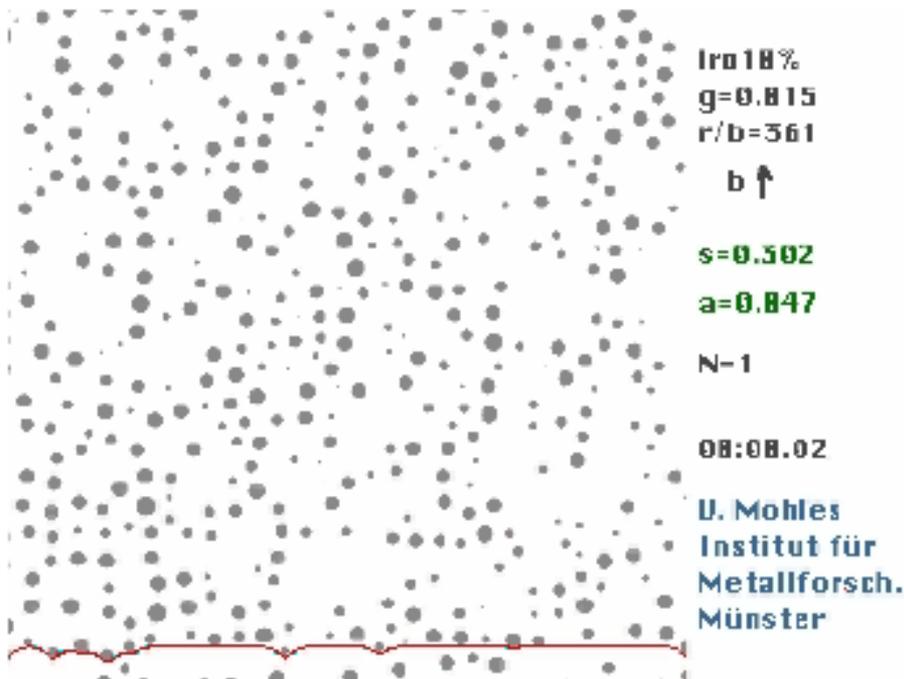
# SIMULATION: DISLOCATION MOTION PEAK AGED MATERIAL

- Peak-aged
  - avg. particle size =  $64b$
  - closer spaced particles efficiently stop dislocations.



# SIMULATION: DISLOCATION MOTION OVERAGED MATERIAL

- Over-aged
  - avg. particle size =  $361b$
  - more widely spaced particles not as effective.



Simulation courtesy  
of Volker Mohles,  
Institut für Materialphysik der Universität Münster, Germany  
(<http://www.uni-muenster.de/physik/IMP/mohles/>). Used with permission.

**2017:** It contains 4 % Cu and is used as **rivets in aircraft**. It is stored in refrigerators after solution treatment. After riveting, the temperature of the alloy increases to room temperature allowing precipitation to take place, which increases the strength of the rivets. 2017 is the oldest of all the heat treatable aluminium alloys, called as **duralumin**.

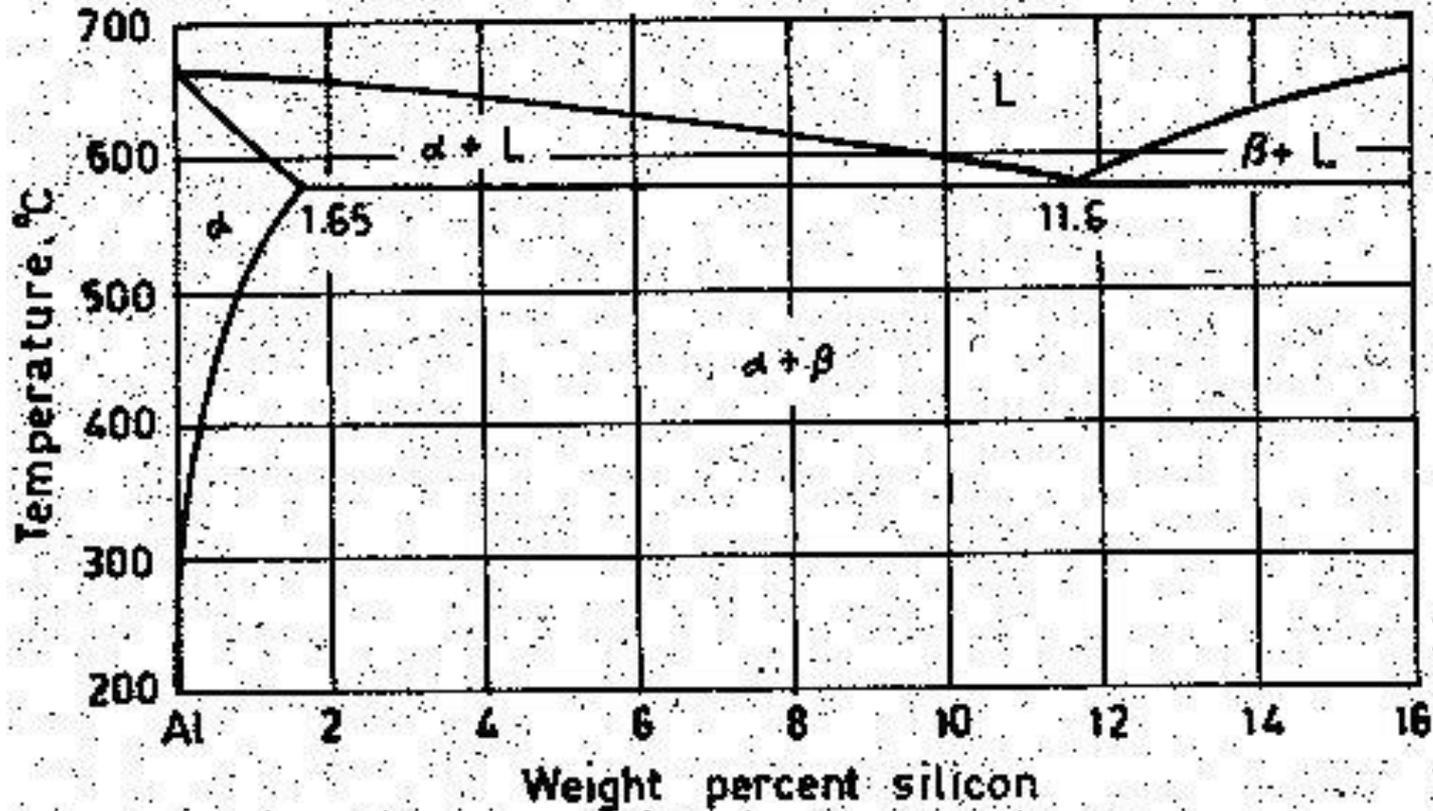
**2014:** It has higher copper and manganese content than 2017 and is susceptible to artificial aging. It is stronger than 2017 and is used for **heavy-duty forgings, aircraft fittings, truck frames** etc.

**2024:** It contains 4.5 % Cu and 1.5 % magnesium. It develops the highest strengths of any natural aged aluminium-copper type of alloy. Fabrication of 2024 is more difficult.

A series of casting alloys such as 85, 108, 319, and 380, classed as aluminium-copper-silicon alloys, have been developed containing less than 5 % copper and from 3 to 8 % silicon. Copper provides higher strength and better machining properties than the straight aluminium-silicon alloys, while silicon provides better casting and pressure-tightness than the aluminium-copper alloys. Typical applications include **brackets, typewriter frames, manifolds, valve bodies, oil pans, and gasoline and oil tanks**.

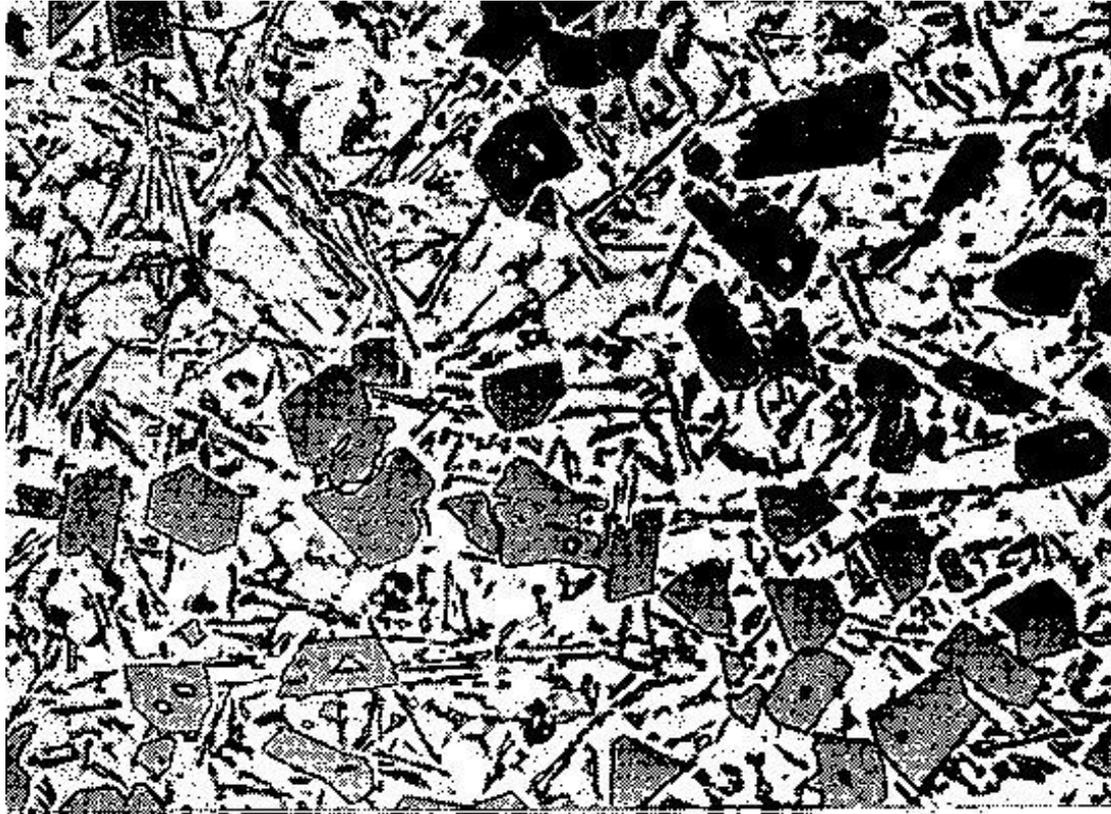
**Aluminium-Manganese Alloys (type 3xxx)** are not heat treatable. Because of limited solubility, manganese is not used as a major alloying element in any casting alloys and is used in only a few wrought alloys. 3003 is the popular alloy in this group, which has good formability, very good resistance to corrosion, and good weldability. Typical applications are **cooking utensils, food and chemical handling and storage equipment, gasoline and oil tanks, pressure vessels, and piping.**

**Aluminium - Silicon Alloys (type 4xxx)** are not heat treatable. Higher silicon alloys are very suitable for castings. Maximum solubility of silicon in aluminium is 1.65 % at 577 °C as shown in Fig. 9.1. 4032 alloy contains 12.5 % Si and has good formability as well as **low coefficient of thermal expansion**. It is used for **forged automotive pistons**.



*Fig.9.1 Al-Si phase diagram.*

Aluminium-silicon casting alloys have excellent castability and resistance to corrosion. Alloy 13 containing 12 % silicon and alloy 43 containing 5% silicon are used for **intricate castings, food handling equipment, and marine fittings**. Fig. 9.2 shows microstructures of die-cast, and artificially aged alloy 13.

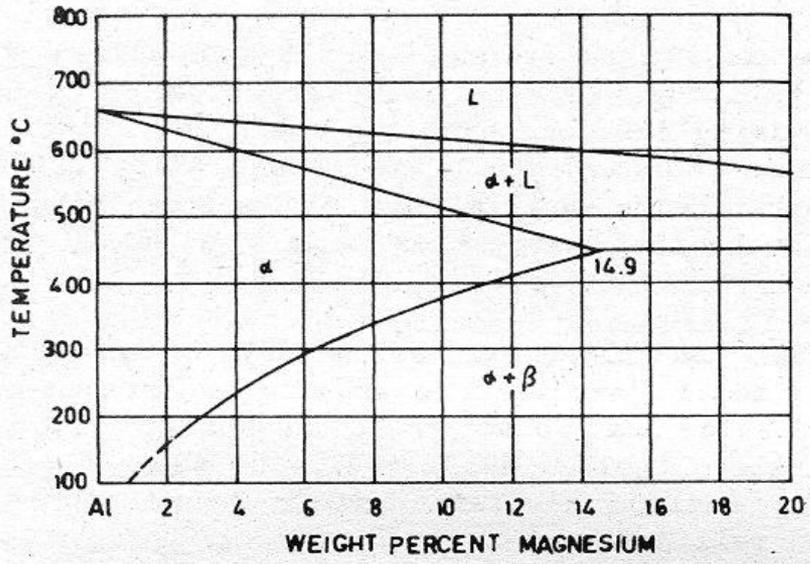


*Fig.9.2 Microstructure of die cast alloy 13, x100.*

**Aluminium-Magnesium Alloys (type 5xxx)** are not heat treatable although phase diagram shows decreasing solubility as seen in Fig. 9.3. The maximum solubility of magnesium in the alpha solid solution is 14.9 % at the eutectic temperature of 450 °C.

Wrought alloys contain less than 5 % Magnesium. They are characterized by good corrosion resistance, and moderate strength. Alloy 5005 is used for **architectural extrusions**; alloy 5050 for **aircraft fuel and oil lines**; alloy 5083 for **marine and welded structural applications**.

The aluminium-magnesium casting alloys include alloy 214, alloy 218, and alloy 220. The first two are used for **dairy and food handling equipment, fittings for marine use, and aircraft brake shoes**. Alloy 220 is the only age-hardening one in this group, resulting in the highest mechanical properties of any aluminium-casting alloy.



*Fig. 9.3 Al-Mg phase diagram.*

**Aluminium-Silicon-Magnesium Alloys (type 6xxx)** are characterised by excellent corrosion resistance and are more workable than other heat treatable alloys. The wrought alloys include 6053, 6061, and 6063. Typical applications include **aircraft landing mats, canoes, tubings, and railings.**

Aluminium-silicon-magnesium casting alloys 355, 356, and 360 provide a desirable combination of castability, pressure-tightness, strength, and corrosion resistance. They are widely used in **aircraft applications, and general-purpose castings.**

**Aluminium-Zinc Alloys (type 7xxx)** have high strength and good corrosion resistance. Aluminium rich portion of the aluminium-zinc alloy system is shown in Fig. 9.4. Alloy 7075, alloy 7079, and alloy 7178 develop the highest tensile strengths obtainable in aluminium alloys.

Aluminium-zinc casting alloy known as 40E provides high mechanical properties without solution treatment. This alloy has fair casting characteristics, good corrosion resistance, and very good machinability. It is used for **aircraft fittings**.

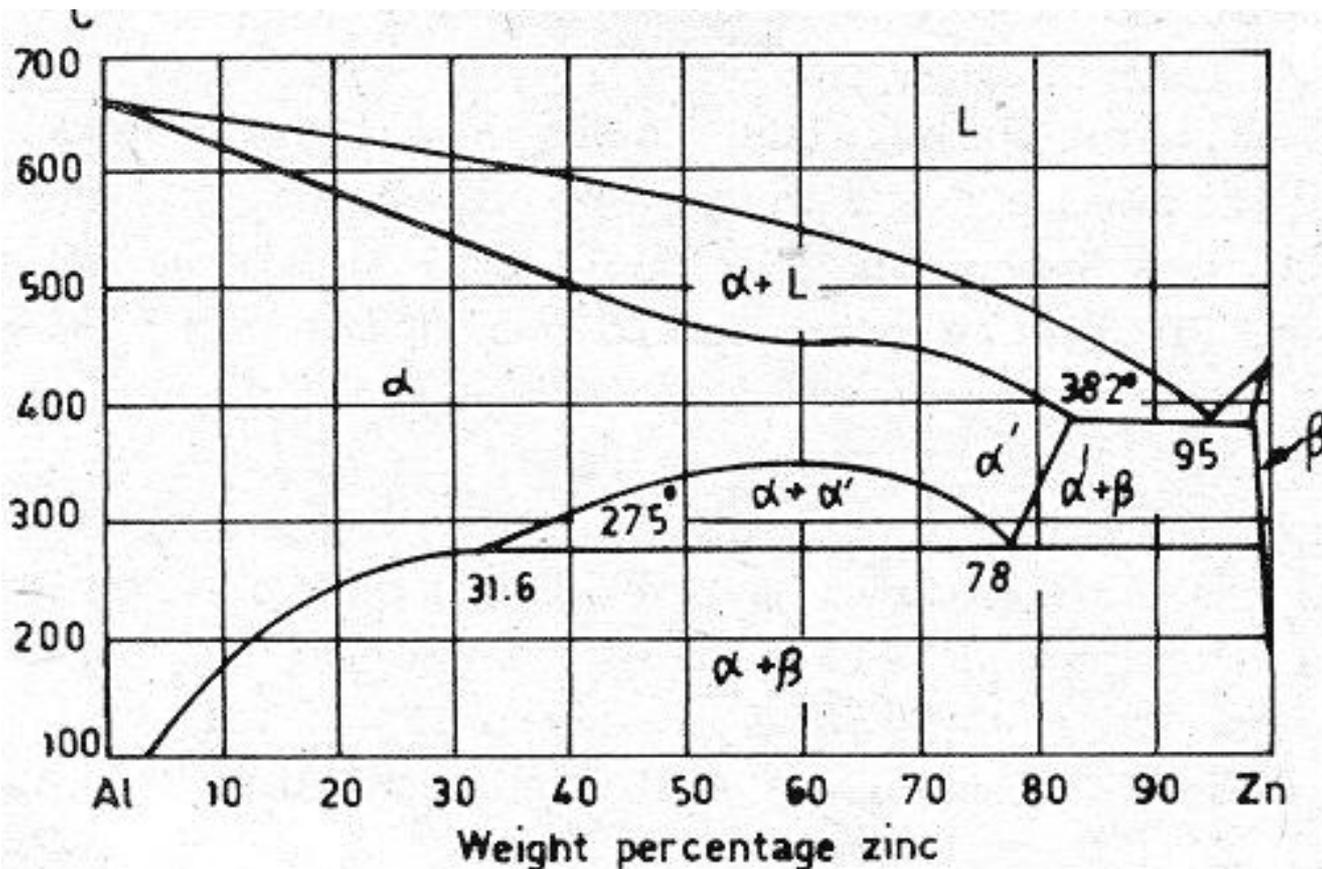


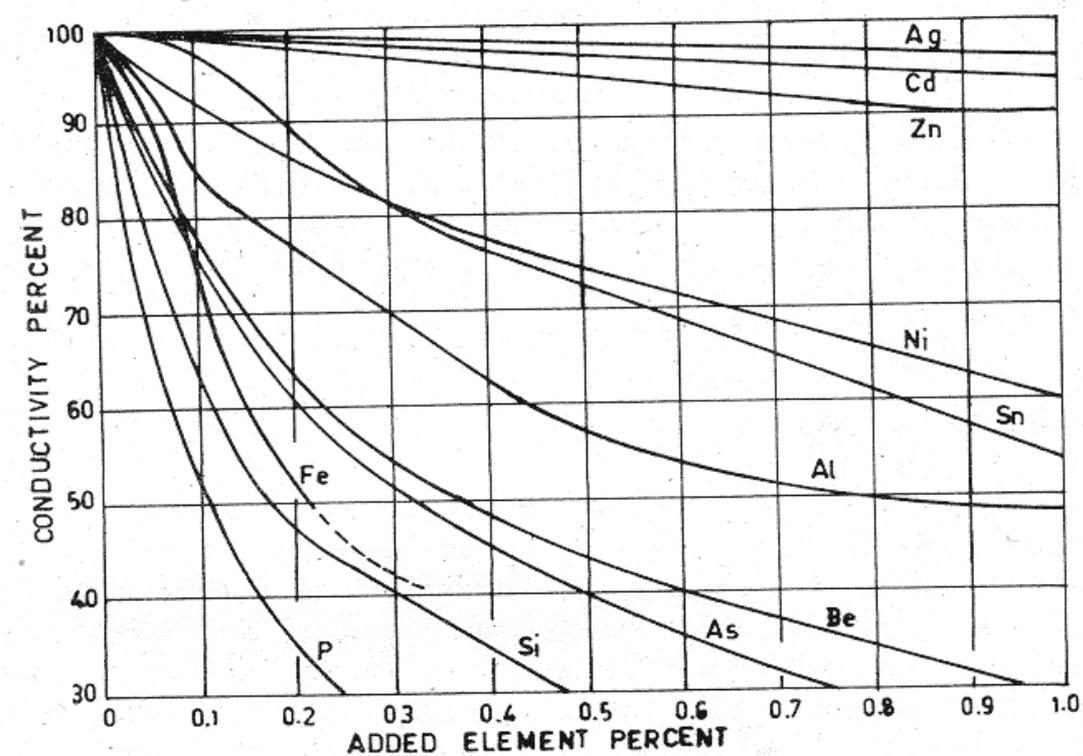
Fig. 9.4 Al-Zn phase diagram.

## 9.3 COPPER ALLOYS

Copper is an important engineering metal and is widely used in the pure condition as well as alloys. The copper alloys are numerous indeed, but their nomenclature is often inconvenient and confusing. Zinc, tin, aluminium and silicon all serve as solid solution hardeners in Copper alloys. The more important copper alloys may be classified as **brasses, bronzes and cupro-nickels.**

### 9.3.1 Pure Copper

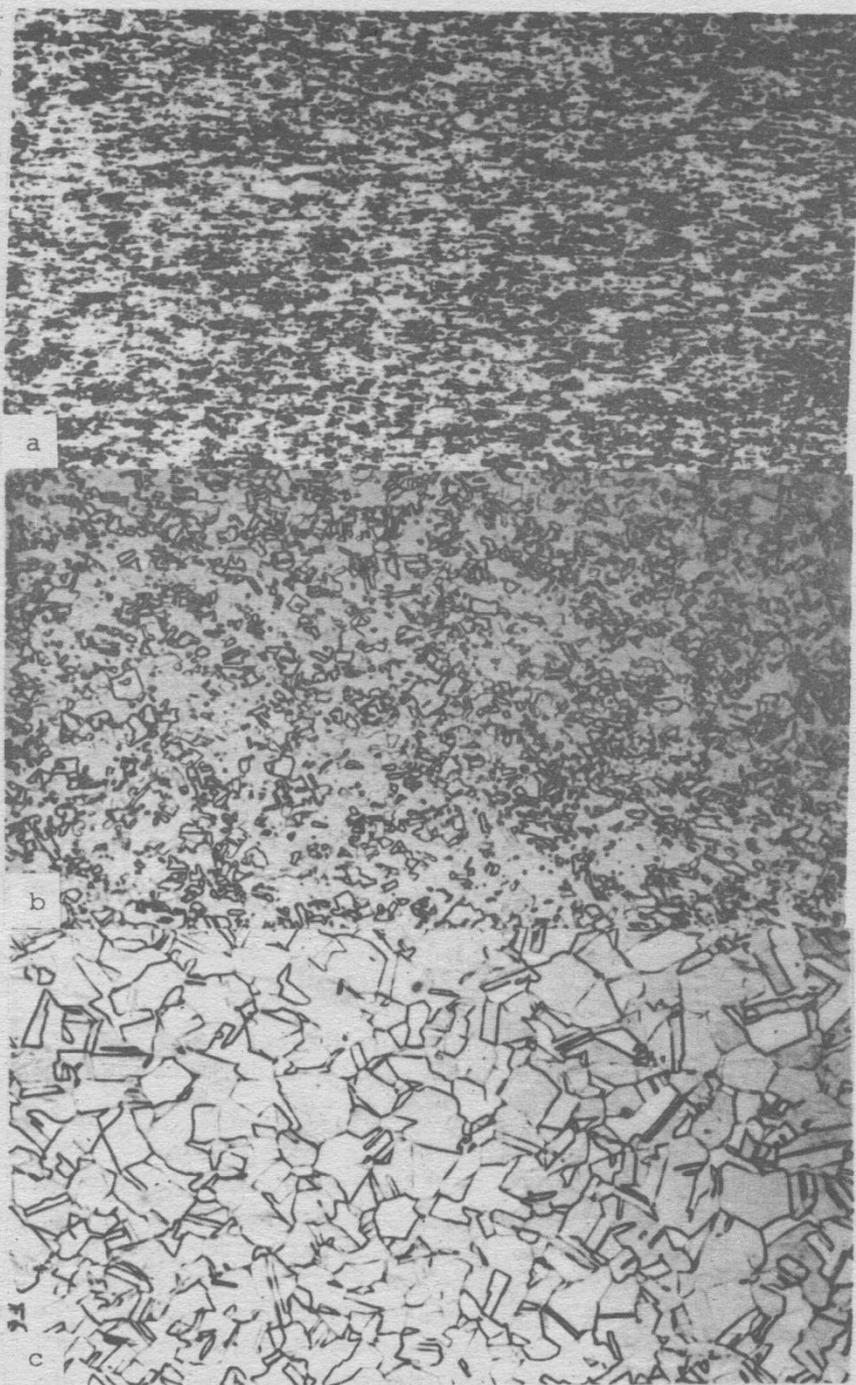
Unalloyed copper has high electrical and thermal conductivity, and so it is used to a large extent in the electrical industry. Electrolytic tough-pitch Copper (ETPC) is the least expensive of the industrial coppers and is used for the production of wire, rod, plate and strip.



*Fig. 9.5 The effect of impurities on the electrical conductivity of copper.*

As indicated in Fig. 9.5, the presence of impurities reduces electrical conductivity. To a less degree, cold-working has the same effect. The International Annealed Copper Standard (IACS) was adopted by the International Electrochemical Commission on 1913. It specifies that for conductivity applications, annealed copper wire 1 m long and 1 mm square cross-section should not have resistance of more than 0.017241 ohms at 20 °C. Such a wire is said to have a conductivity of 100 %. As shown in the figure, in small amounts while some elements like silver, cadmium and zinc do not reduce conductivity to a large extent, others like phosphorus, silicon and iron dramatically reduce conductivity.

Although pure copper has only a moderate tensile strength, it is a metal with very high malleability and ductility. It is very suitable for both hot and cold working. After cold working, ductility can be recovered by annealing. Microstructures of cold worked, partially annealed and fully annealed copper are shown in Fig. 9.6.



*Fig. 9.6 Microstructures of 99.9 % pure copper, x100:*

- (a) cold worked, hard;*
- (b) half-hard;*
- (c) annealed, ductile*

## 9.3.2 Brasses

The term brass represents alloys of Cu and Zn, with small additions of Pb, Sn or Al. The phase diagram for this system is shown in Fig. 9.7. The left half of this diagram, up to 50 % Zn, includes practically all the Cu-Zn alloys of commercial importance. The exceptional feature of this system is the remarkable combination of strength and ductility, which both increase simultaneously with zinc content as shown in the figure. The ductility, however, decreases with the appearance of  $\beta$  phase. The ductility is maximum for 30 % Zn. The strength falls rapidly in the  $\gamma$  phase and commercial alloys avoid occurrence of  $\gamma$  phase.

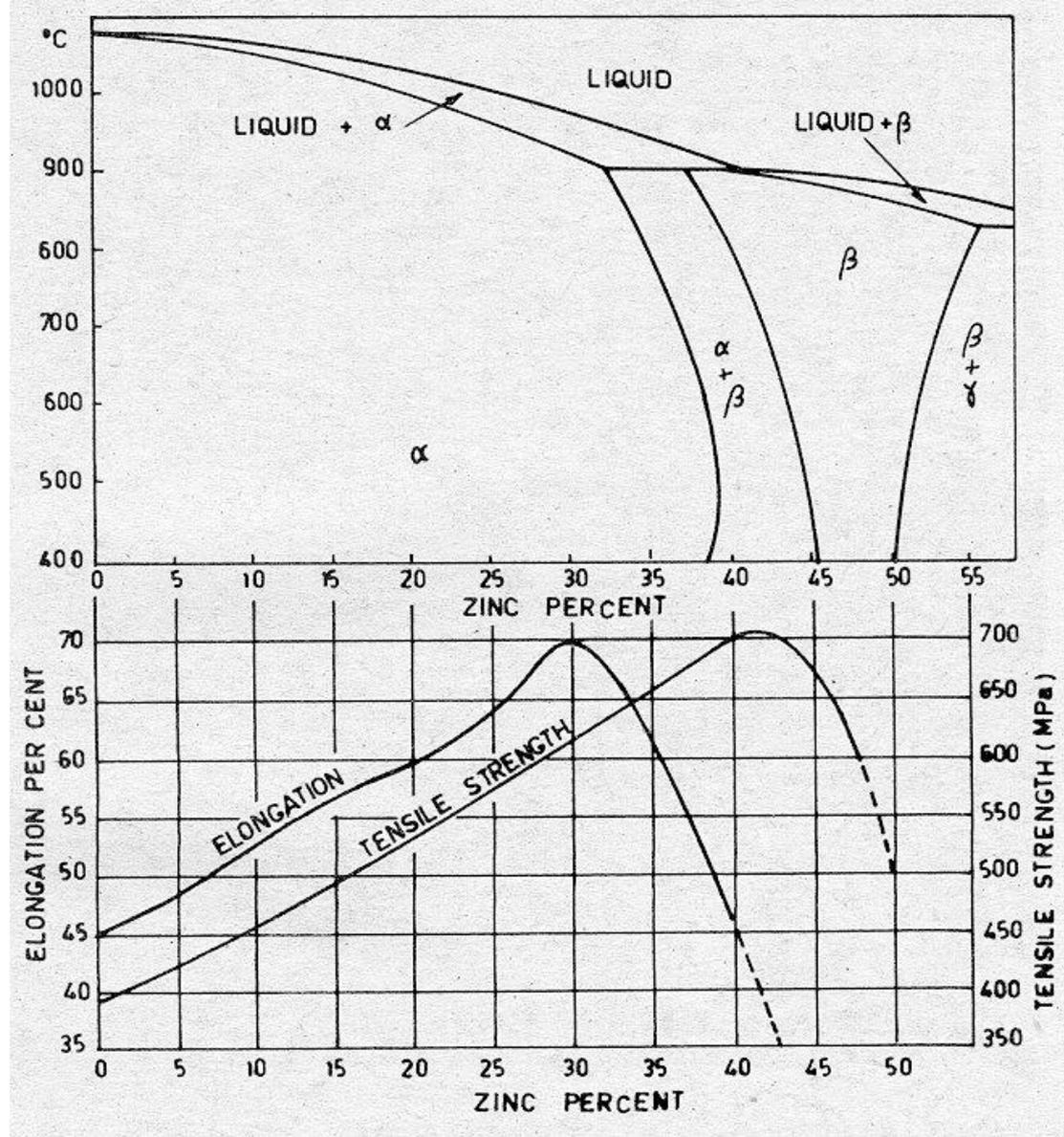


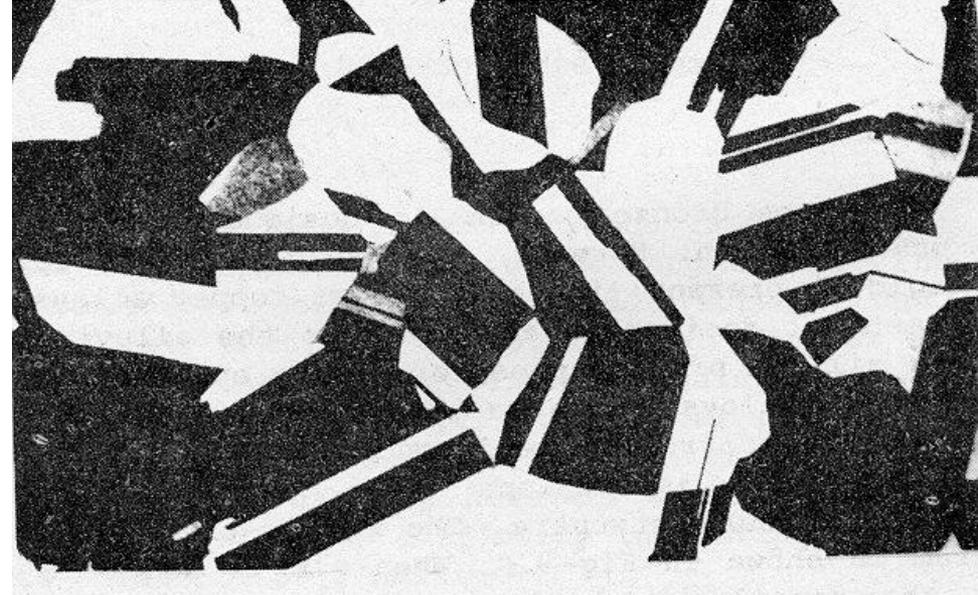
Fig. 9.7 Cu-Zn phase diagram and change of properties with zinc content

Brasses offer a range of mechanical properties, ease of working and resistance to atmospheric corrosion. Corrosion resistance, combined with strength and hardness makes *brass* one of the more important groups of engineering alloys. The brasses present difficulties in welding, though, due to loss of zinc, which boils at 907 °C. They are, therefore, gas welded or brazed rather than arc-welded.

**Cap Copper:** It contains 2-5 % Zn, is very ductile and is used for **ammunition priming cases**. It has a red complexion.

**Gilding Metal:** Contains 5 % Zn, and has a golden color. It is used for **deep drawing, jewellery, coins and medals** etc.

**Cartridge Brass:** It has 30 % Zn. It possesses maximum ductility and is, therefore, very suitable for deep drawing. It is used as cartridge cases as well as in a wide range of applications such as **electric sockets, flash light casings** etc. It has a yellow color. Fig. 9.8 shows the microstructure of annealed cartridge brass.



*Fig. 9.8 Microstructure of annealed cartridge brass, x100*

**Muntz Metal:** With 40 % Zn, it is an  $\alpha+\beta$  alloy which is very suitable for hot working. It is formulated for corrosion resistance and is commonly used in **sheet form; for condenser heads, architectural works** etc.

**Naval Brass:** Also known as **admiralty brass**, it contains 39 % Zn with 1 % Sn. It has very good resistance to seawater corrosion and consequently it is used for **propellers, shafts, condenser plates** etc.

All the brasses can be hot worked those with less than 15 % Zn being capable of extensive hot working. Severe cold working frequently develops intergranular cracking which appears after a delay. It is sometimes referred to as season cracking, and can be avoided by proper annealing. Al, Fe, Mn, Sn and Ni are frequently added to increase the tensile strength; lead improves the machinability and tin increases resistance to corrosion.

### 9.3.3 Bronzes

The term bronze originally designated the alloys of copper and tin. However, the usage of this term is not rigid at present; it now includes copper alloys with other metals, designated according to the alloying element as silicon bronze, phosphor bronze etc. Bronzes are rich brown alloys suitable for casting, where their dense grains, corrosion resistance and ability to take delicate mould impressions make them particularly suitable for **cast statuary**. The Copper-tin equilibrium diagram is shown in Fig. 9.9. When tin is added to copper, the tensile strength and hardness are increased somewhat up to about 20 % Sn; beyond this range bronzes are very brittle.

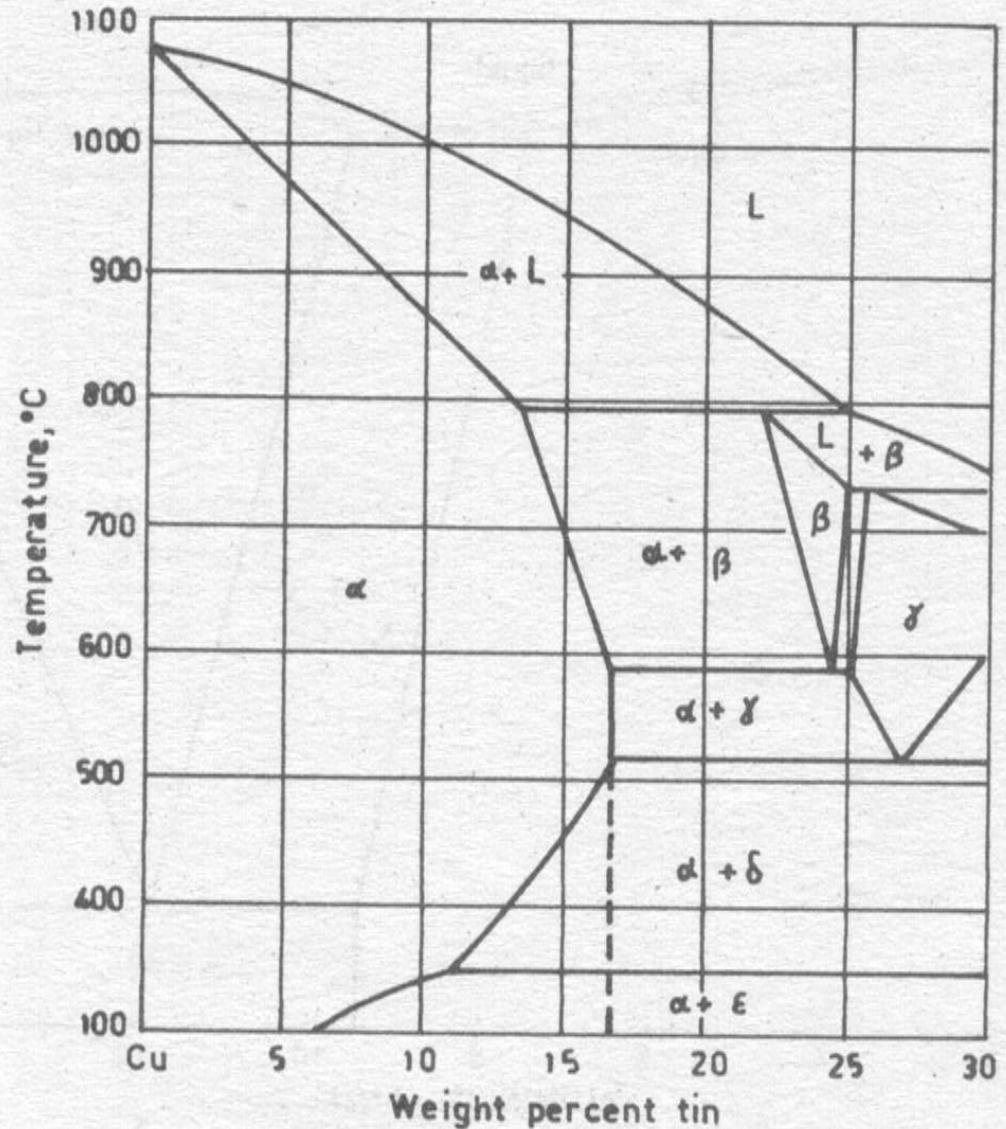


Fig. 9.9 Cu-Sn phase diagram.

Practically all commercial bronzes contain less than 12 % Sn and more than 80 % Cu. Bronzes have good corrosion properties and good strength and wear qualities. The addition of up to 10 % lead provides lubricating properties for the bearing alloys. Phosphorous additions increase the tensile strength up to 680 MPa with fair ductility in rolled condition, as well as provide high corrosion resistance against salt water. Aluminium can be used as principal metal instead of tin, providing desirable shock resistance and fatigue characteristics. Its use is, however, limited due to high cost of production and difficulty in melting and pouring due to oxidation of aluminum.

**Phosphor Bronzes** are actually tin bronzes containing 1-11 % tin. P is added as deoxidizer to remove tin and copper oxides. These bronzes are used in sheet and bar form for their high tensile strength, toughness, formability, fatigue strength and corrosion resistance. They are frequently specified for instrument parts such as **diaphragms, bellows, springs and electrical contacts**.

**Silicon Bronzes** are more familiarly known by their trade names, such as Everdur and Herculoy. These are also high strength alloys with strengths as high as 750 MPa.

**Aluminium Bronzes** contain from 4-11% Al. Copper-aluminium phase diagram is shown in Fig.9.10. As can be seen from the diagram, it reveals similarities with iron-carbon phase diagram. The two  $\alpha$  phases are analogous,  $\beta$ -phase corresponds to austenite, and eutectoid of copper-aluminium is similar to pearlite. Similarly, a 10% aluminium bronze can be heat treated similar to steel so that martensite transformation occurs as shown in Fig. 9.11. Aluminium bronzes are used for wide range of applications, including *electrical hardware, marine hardware, propellers, tubings and pumps*. Their strength after heat treatment may exceed 680 MPa but ductility is minimal.

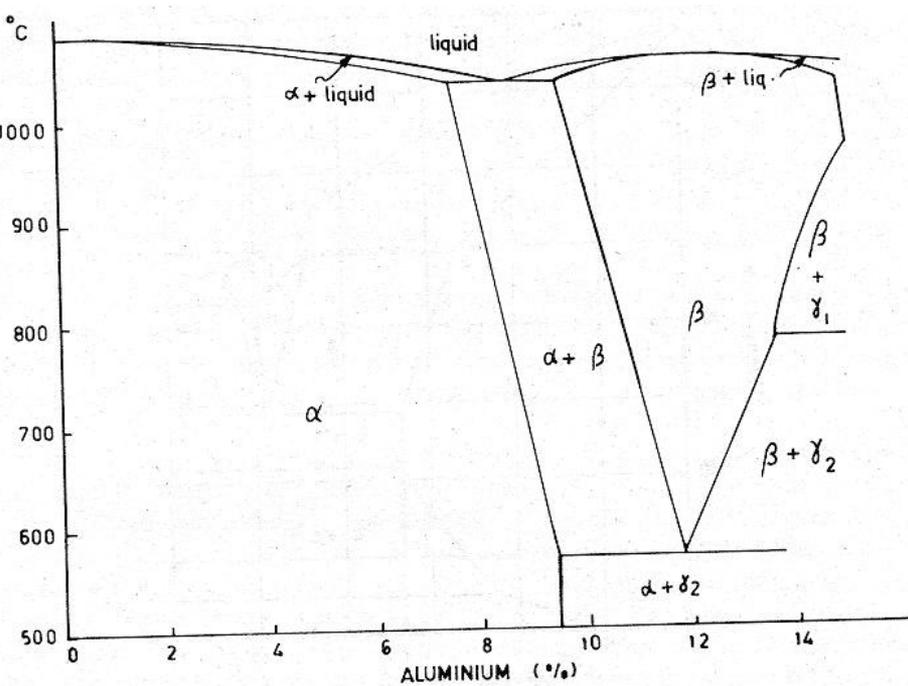


Fig. 9.10 Cu-Al phase diagram.

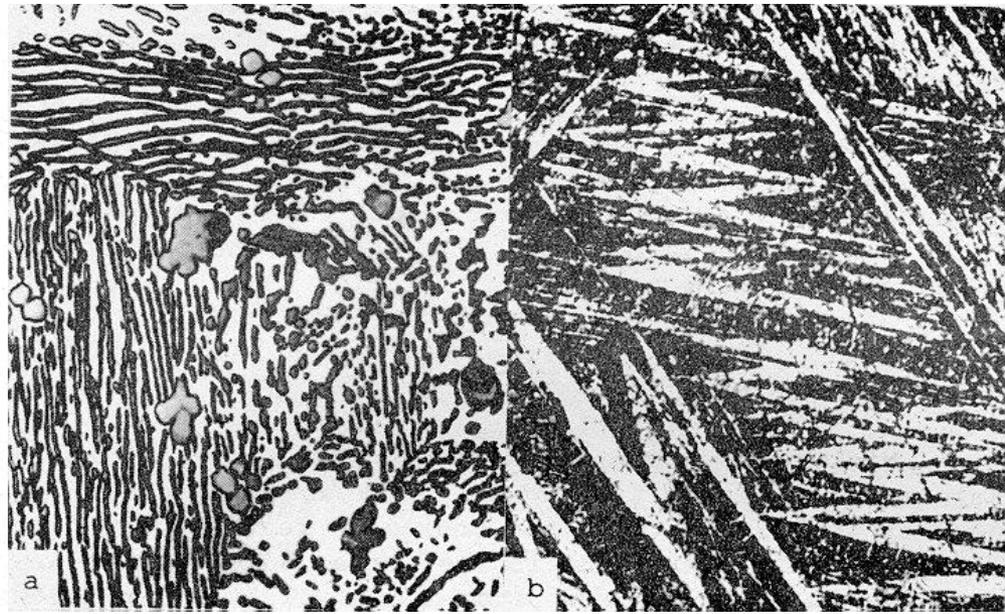


Fig. 9.11 Microstructures of 10% aluminium bronze, x100:  
 (a) slow cooling, a plus eutectoid;  
 (b) fast cooling, martensite.

**Beryllium Copper** is another heat treatable bronze, giving the highest strength of all copper alloys, together with remarkable fatigue strength, formability, corrosion and wear resistance. It is put to a range of uses including **instrument parts, electrical hardware** and, due to its **hardness, non-sparking hand tools such as wrenches**. A maximum hardness of HRC 42 is possible. A range of beryllium bronzes is available, containing from 0.4 to 1.9 % Be. Co and Ni are added to give grain refinement.

**Zirconium Copper and Chromium Copper** are heat treatable. They are used chiefly for instrument work and electrical hardware such as **resistance welding tips and switch parts**.

Other bronzes are produced for specific applications such as Bell metal containing 20-25 % Sn which is used as **bells** due to its ringing qualities and Speculum metal with 33 % Sn, used as **reflectors** due to white polished appearance.

### 9.3.4 Cupronickels

Nickel and copper form a complete series of solid solutions. Ni lends its color, thus whitening the copper, as well as improves the corrosion resistance. These alloys contain small additions of other elements and are ductile. Those containing from 15 to 20 % Ni are used for condenser tubes handling seawater. An alloy of 40 to 45 % Ni finds considerable use in the form of wire for **electrical resistance and thermocouples**. Ambrac is an alloy of 75 % Cu, 20 % Ni and 5 % Zn used for **condenser tubes**.

Nickel Silver is an alloy of copper and nickel used for **ornamental work** and for parts to resist corrosion. It contains from 5 to 30 % Ni with varying small amounts Zn and the remainder is copper. It has a silvery colour giving it its name. It is used as a base for silver plating and for a wide variety of ornamental work such as **domestic equipment and soda fountain fixtures**. German silver contains 52 % Cu, 26 % Zn and 22 % Ni and possesses extremely low thermal conductivity.

## 9.4 LEAD ALLOYS

In general lead does not form useful alloys except with other metals of low melting point. In the free machining leaded alloys, lead is not an alloy ingredient but an inclusion. For corrosion resistance and for **gamma ray shielding**, pure lead gives best performance.

To increase the low strength of lead, two types of alloys are in use; the tellurium lead and the antimony lead alloys. Addition of less than 0.1 % Te improves the work hardening capacity of lead. Pure lead has a tensile strength of only 17 MPa, but Sb improves this strength. A maximum of 11 % Sb may be used which increases, the strength three times. Alloying, however, reduces the already low melting temperature of lead.

The solders are alloys of lead and tin, tin content ranging from 5 to 50 %.

The equilibrium diagram for these solders is given in Fig 9.12. Tin additions are necessary, as it enables lead to wet the metal to be joined. The lead based babbitt bearing alloys are somewhat similar to solders, containing about 10 % Sn and 10 % Sb. Lead is also present in soft and hard type copper based bearing alloys, in which it is usually in suspension in copper. **Terne plate** used for **gasoline tanks in automobiles, and other mobile equipment**, is steel sheet coated with a lead solder alloy of about 20 % tin.

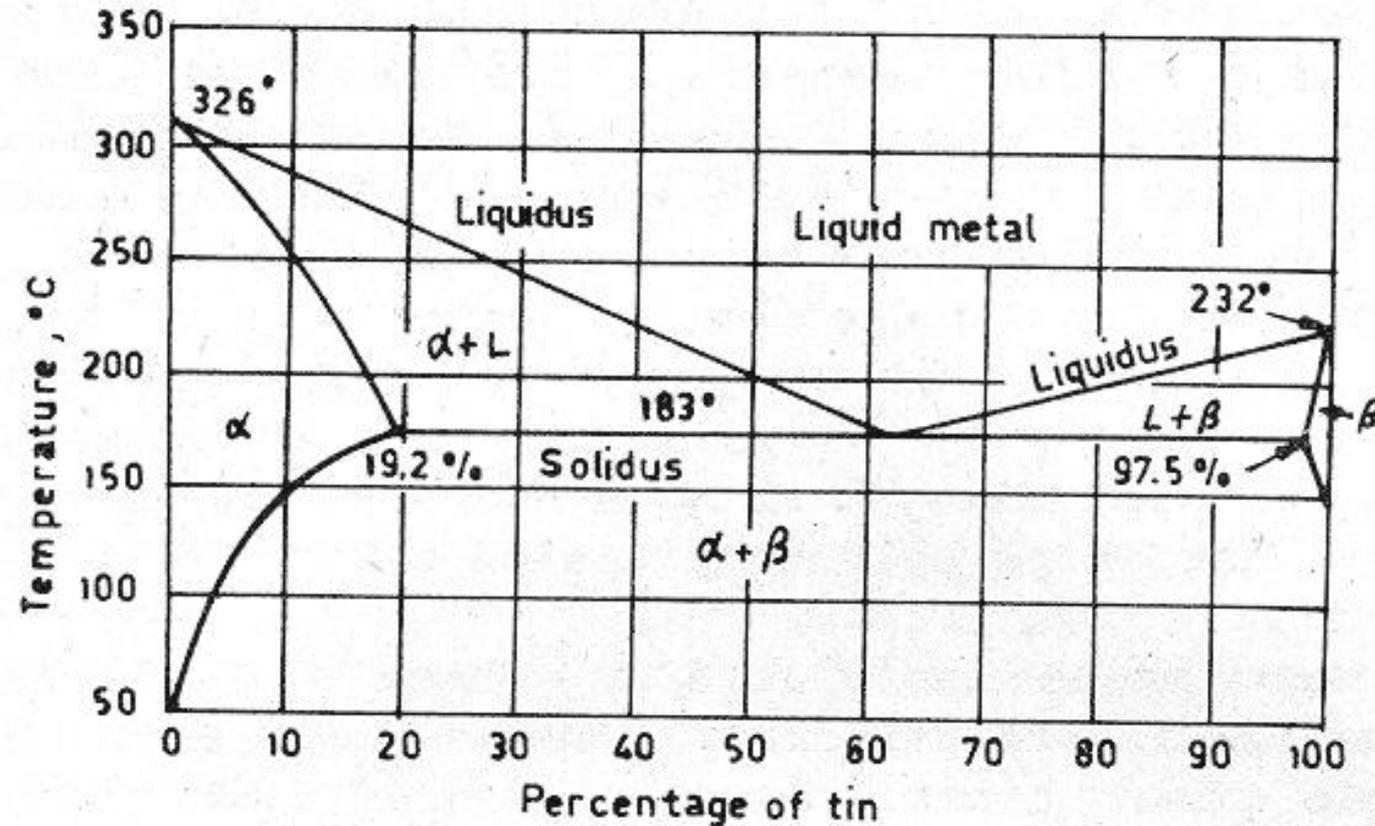


Fig. 9.12 Pb-Sn phase diagram

## 9.5 MAGNESIUM ALLOYS

Magnesium alloys find considerable applications where lightweight materials are required under non-corrosive conditions. The specific gravity of magnesium alloys varies between 1.76 and 1.84. Unlike aluminium, magnesium does not form an impervious protective film at the surface, and consequently parts made of Mg alloys have to be protected either by painting or anodizing. These alloys may be divided into two classes; wrought alloys and cast alloys. Many of these alloys are susceptible to hardening by precipitation treatment.

Most magnesium alloys are used for lightweight equipment, as in **aircraft, space vehicles, ladders, portable power tools, luggage or the dock boards etc.** The large **stiffening rings of moon rockets**, as large as 10 m in diameter, are produced with Mg alloys. Currently the lightest commercial alloy is a magnesium alloy containing 14 % lithium and 1.25 % aluminium.

Magnesium has recently taken a place among the **tooling materials**. Magnesium's light weight, weldability and ease of machining greatly reduces the cost of manufacture and **Mg tools** are easy to handle and are durable.

Alloy AZ31B, containing 3 % Al and 1 % Zn is used for tooling.

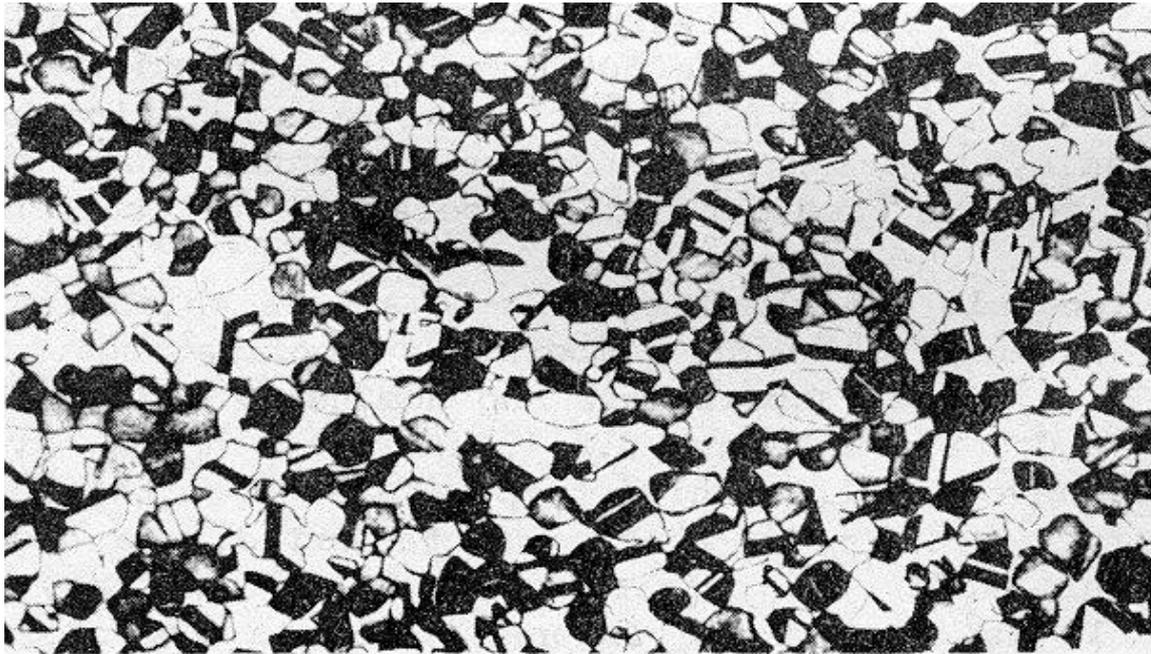
Alloy designations for magnesium alloys are simple. Two letters represent the chief ingredients, followed by two numbers giving respective percentages to the nearest whole number. A serial letter follows the designation. These designations apply to both the wrought and cast alloys. The letter code is as follows: A-aluminium, E-rare earth, H-thorium, K-zirconium, M-manganese, Z-zinc and T-tin.

Most of magnesium alloys are Al-Zn type. Rare earth and thorium additions give improved strength at temperatures above 300°C. Usually about 3 % thorium is used which does not produce any radiation hazards. Addition of about 0.5 to 0.7 % zirconium provides grain refinement. Alloy AZ92A is usually for normal temperature applications, including **sand casting and welding wire**.

The alloy of highest strength may have ultimate tensile strength as high as 380 MPa in extruded articles. Elongation (ductility) is, however, limited in all magnesium alloys



The names are slightly confusing but if nickel content exceeds copper content then the alloys are called **Monels**. Nickel coinage contains 75 % Ni and 25 % Cu but it is not called a monel, its microstructure is shown in Fig. 9.13. The monels may be considered to be two thirds nickel and one third copper with some iron, manganese, silicon and carbon. Monels are a series of alloys which are more resistant to reducing chemicals such as HCl than pure copper or nickel. They have better corrosion resistance under **the action of salt solution, foods and food acids, strong alkalis, dry gases and most atmospheres**. They are, however, attacked by strong oxidizing acids such as nitric acid, and by oxidizing acid salts such as cupric and ferric chlorides. Monels are readily workable and are available in rods, sheets, wires or strip forms, and can be successfully joined by welding or soldering.



*Fig. 9.13 Microstructure of nickel coinage alloy, x100.*

**The standard monel** is monel 400 containing 66 % Ni, 31.5 % Cu and about 1 % each of Fe and Mn. It is used for sinks, kitchen equipment, washing machines and marine equipments. The R-monel (monel R-405) contains 66 % Ni, 31.5 % Cu and 0.05 % S which is added to improve machinability. Permanickel contains 98.6 % Ni and 0.5 Ti, whereas Duranickel contains 4.5 % Al and 0.5 % Ti, the rest being nickel. Both these alloys are heat treatable to produce precipitation hardening by an intermetallic compound. The 500 monels, K-500 and 501 both contain 2.8 % Al and 0.5 % Ti. These precipitation hardening alloys possess much greater strengths than common monels, and are used for **high temperature applications**.

**Inconels** are complex Ni-Cr-Fe alloys which are extensively used in high temperature applications. They are called nickel superalloys and nominally contain 78 % Ni, 14 % Cr, 6.5 % Fe and 0.2 % Cu, with some Mn, Si and C. They have excellent high temperature strength, resistance to corrosion by food products and dilute organic acids as well as oxidising acid salts. They are available in sheet form. Inconel X-750 is used for **gas turbine blades** and after **burner combustion chambers**. It is used for high stress applications at temperatures as high as 1000 °C or more. **The fuselage of Bell X-15** rocket was also fabricated with inconel X-750. Ultimate tensile strengths of these alloys may exceed 1400 MPa at room temperature after hardening.

**Hastelloys** are Ni-Cr-Fe or Ni-Mo-Fe alloys developed for high corrosion resistance to chemicals, especially acids, but also used as super alloys. Hastelloy A (Ni, Mo, Fe) is austenitic and not heat treatable.

**Constantan, Alumel and Chromel P** are Ni alloys with 45 % Ni & 55 % Cu, 95.3 % Ni, 1.75 % Mn & 1.2 % Si, and 90 % Ni, 9.5 % Cr respectively. They are used as thermocouple materials for industrial furnaces. A range of high Ni alloys with high specific resistance are used as heating elements; Nichrome with 73 % Ni, 20 % Cr for small wire wound resistors, Karma with 80 % Ni, 20 % Cr for **precision miniature resistors**.

**Nilvar and Invar** with 36 % Ni and iron have the lowest coefficient of thermal expansion of all known materials. By altering the Ni content the coefficient can be changed to a desired value. Elinvar is used for **watch components** due to its constant E-value over considerable temperature range. **Alnico** is an alloy of Ni, Al, Cr and Co used as **permanent magnet**.

**Beryllium nickel** is an alloy containing 1.95 % Be, 0.5 % Ti and marketed as Berylco Nickel 440. It is hardenable to remarkable strength, fatigue and wear resistance, with a maximum hardness of HRC 50. It is used in the field of instrumentation.

Special Ni alloys are produced for fabrication, especially useful for welding and brazing of metals other than Ni. Cast iron is usually welded or repaired by Ni-rod (95 % Ni) or Ni-rod 55 (53 % Ni).

Inco-weld A is similar to an inconel, but developed for welding dissimilar metals, such as ferritic stainless steel to high Ni alloys. Brazed joints which must resist high temperature are made from Ni base alloys, usually Ni-Cr alloys.

## 9.7 TITANIUM ALLOYS

Although titanium is the fourth most abundant structural metal in the earth's crust, quantities sufficiently large for engineering purposes have only become available in the last twenty years or so. The development by W. J. Kroll in 1940 of a method of reducing titanium tetra- chloride with molten magnesium to produce a cake like mass of titanium known as sponge, marked the beginning of the widespread use of the material.

The density of titanium ( $4.51 \text{ g/cm}^3$ ) is mid-way between that of light metals like aluminium and magnesium, and that of steels and nickel alloys. It retains useful strength and temperatures substantially higher than those considered safe for the light alloys. Thus, it is an attractive structural metal for applications demanding high specific strength at temperatures ranging from sub-zero to more than  $500 \text{ }^\circ\text{C}$ . Alloys now in service offer guaranteed strengths up to  $1150 \text{ MPa}$ , which compete with the strength levels of many steels.

Titanium is also resistant to attack by a wide range of natural and chemical environments and has extremely high resistance to pitting and stress-corrosion cracking. In many applications, its corrosion resistance is superior to that of stainless steel.

It is the combination of high strength, low density, and excellent corrosion resistance which has lead to the expansion of the use of titanium that has taken place over the past 25 years in **the aircraft, chemical, and engineering industries.**

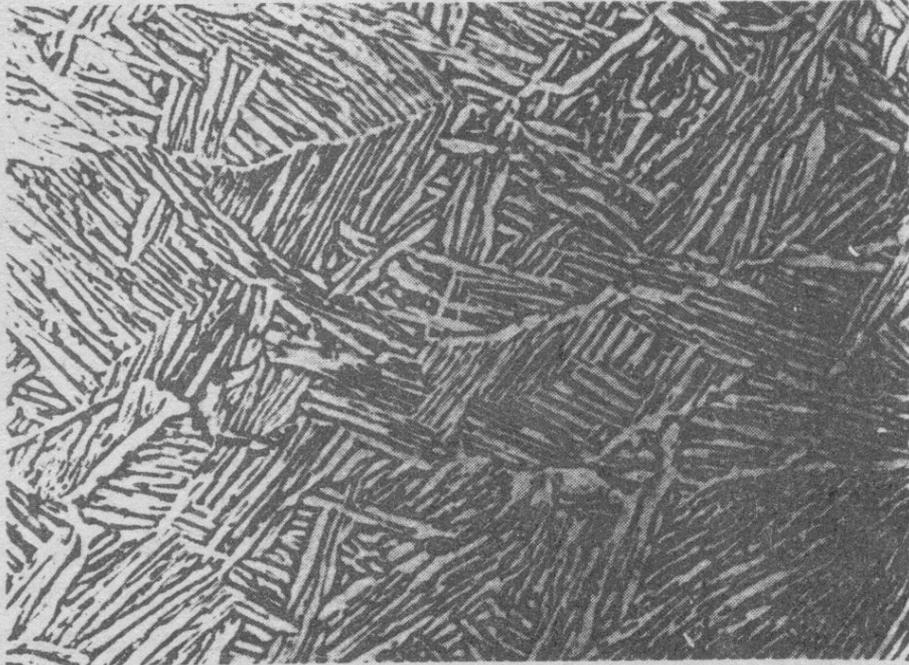
## 9.7.1 Titanium Alloys

Titanium metal has a HCP crystal structure, called alpha, at room temperature. This structure transforms to BCC beta at 882 °C. The addition of alloying elements influences the transformation temperature and in many alloys results in beta phase being retained at room temperature. Thus, titanium alloys can be alpha, alpha plus beta or even whole beta. The relative amounts of alpha and beta phases significantly affect the mechanical properties.

Single-phase alloys are weldable with good ductility. Two-phase alpha-beta alloys are stronger than one phase alpha alloys. Most important, two-phase alloys can be strengthened by heat treatment because the microstructure can be manipulated by controlling heating, quenching, and aging cycles.

**Alpha Alloys** contain some beta stabilizing elements. The compositions of these alloys are balanced by high aluminium content so that the alloys are essentially one-phase alpha. The alpha alloys have two main attributes: weldability and retention of strength at high temperatures. The first results from the one-phase structure, the second from the presence of aluminium. Aluminium is the most important strengthener of alpha alloys, and its effect persists to high temperatures. Applications of alpha alloys include **aircraft tailpipe assemblies, missile fuel tanks and structural parts** operating for short runs up to 550 °C.

**Alpha-Beta Alloys** contain beta-stabilizing elements to cause the beta phase to persist down to room temperature, and they are stronger than alpha alloys. The alpha alloys can be further strengthened by heat treatment. Best alpha-beta alloy is Ti-6Al-4V alloy which can be quenched to produce martensitic structure. Typical applications of Ti-6Al-4V alloy include **aircraft compressor blades and disks, forged airframe fittings**. Recently this alloy replaces stainless steels as **hip joint prostheses**. Mill annealed microstructure of Ti-6Al-4V alloy is shown in Fig. 9.14.



*Fig. 9.14 Microstructure of mill annealed  
Ti-6Al-4V alloy, x100*

**Beta Alloys** can also be strengthened by heat treatment. Aging after solution treatment results in the precipitation of fine compounds. Beta alloys have been used for **high strength fasteners and for aerospace components** requiring high strength at moderate temperatures.

## 9.8 ZINC ALLOYS

The principal use of zinc is as a coating for steel to prevent corrosion. It is more highly anodic than steel, and in a corrosive atmosphere the zinc coating acts as the sacrificial anode. Thus, zinc is consumed while protecting the steel from any attack.

Zinc can be easily worked into various shapes and forms by common fabrication methods. Pure zinc has a recrystallization temperature below room temperature, so that it self-anneals and can not be work-hardened at room temperature.

The major use of zinc as a structural material is in the form of alloys for **die-casting**. The zinc die-casting alloys are low in cost and easy to cast and have greater strength than the die-casting metals except the copper alloys.

The Al-Zn phase diagram is shown in Fig. 9.4. A lamellar eutectic forms at 382 °C and 5 % Al, containing alpha prime and beta solid solutions. The alpha prime constituent of the eutectic is stable only at temperatures above 275 °C. At that temperature, it transforms by a eutectoid reaction into alpha and beta phases. Commercial die-casting alloys are cooled fast enough to prevent the eutectoid transformation and retain the eutectic mixture. When die-castings are aged at room temperature, a precipitation reaction occurs in the zinc rich beta solid solution. During 5-week room temperature aging period, minute alpha particles appear within the beta structure.

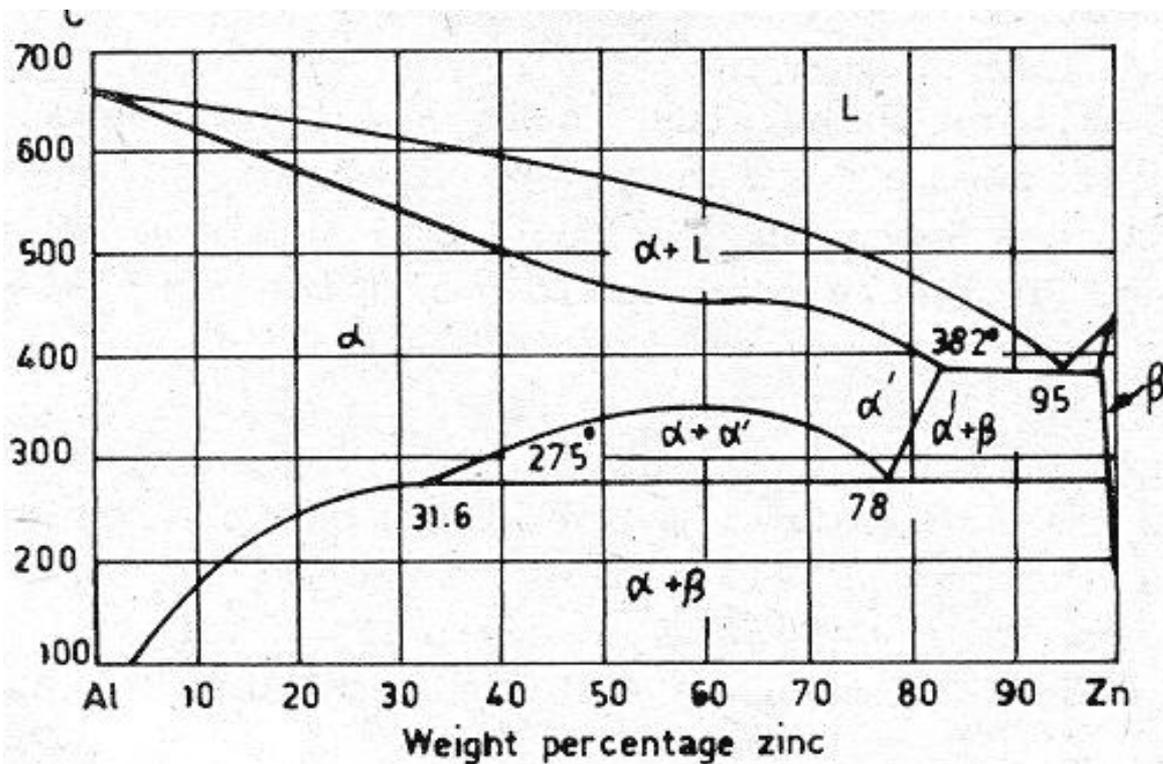
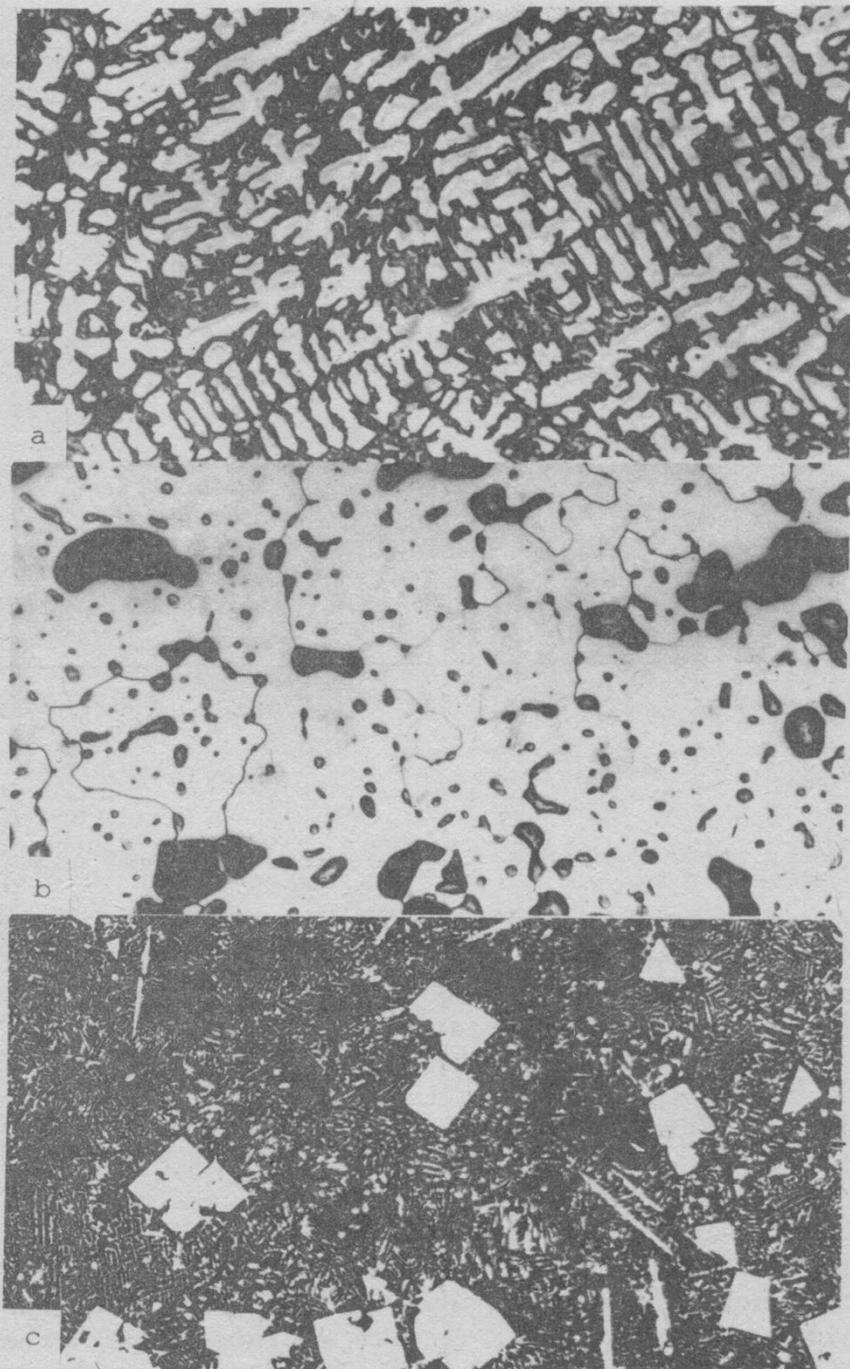


Fig. 9.4 Al-Zn phase diagram.

## 9.9.2 Bearing Alloys

Bearings are devices used to transmit loads between relatively moving surfaces. They may be plain bearings involving sliding contact between surfaces or more complex antifriction bearings of ball or roller components. This section considers only alloys used for plain bearings.

Bearing alloy should be relatively soft so that it will align itself to the journal when under pressure (**conformability**). This prevents the built-up of stress at any high spots on the surface. Also, soft bearing material removes away any small chip or dirt left on the journal during running in period (**embeddability**). Nevertheless the bearing must be strong enough and hard enough (compressive strength, fatigue strength), with low friction and wear resistant surface. This set of properties is generally not obtained in a single-phase alloy.



Hence, traditionally, bearing metals have been two-phase alloys. In these materials harder, low friction particles are held in a malleable, soft, solid solution (or eutectic) matrix. Fig. 9.15 shows the microstructures of bearing materials.

*Fig. 9.15 Microstructures of various bearing alloys, x100.  
(a) Tin bronze,  
(b) lead bronze,  
(c) babbitt.*

Bearing alloys are divided into two groups, the hard and the soft alloys. The hard type is composed principally of copper. The soft bearing alloys include the well-known babbitts and the cadmium-silver alloys.

Some common bearing material compositions and their hardness's are listed in Table 9.2.

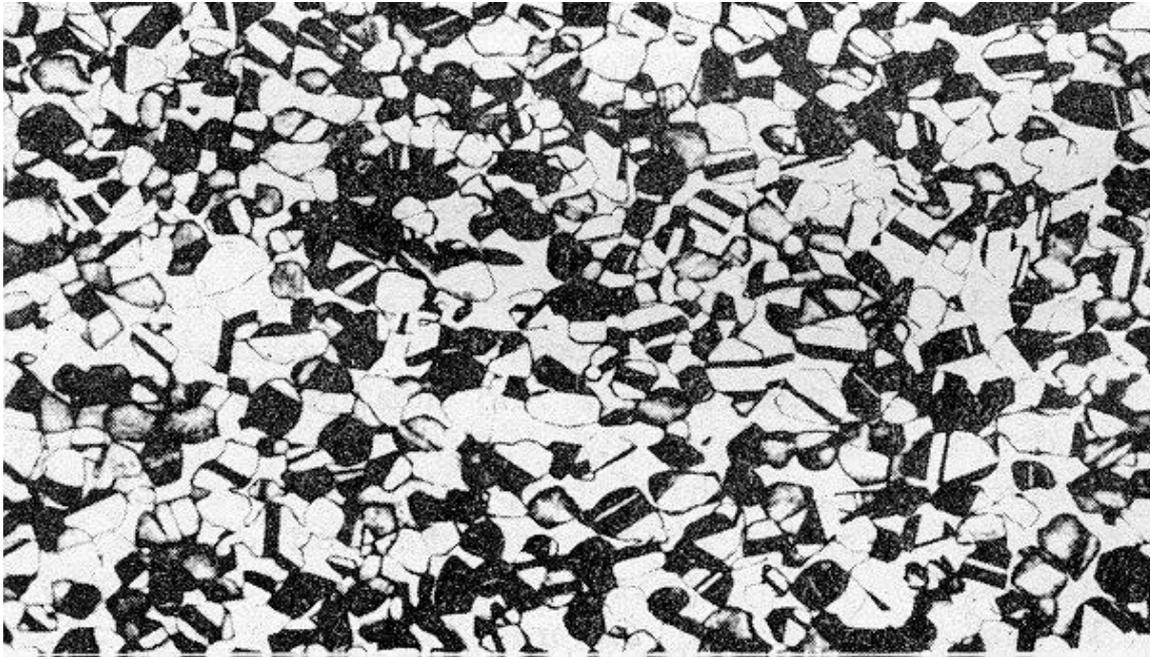
**TABLE 9.2 Bearing Materials**

Type	Composition					Bearing Hardness, HV	Recommended Journal, HV
	Cu	Sn	Pb	Sb	Al		
Tin base	3.5	89	-	7.5	-	23-25	140
Babbitt	4	87	-	9	-	27-32	150
Lead base	1	12	74	13	-	26	140
Babbitt							
Lead	70	-	30	-	-	35-45	
bronze	74	4	22	-	-	40-45	
	75	5	20	-	-	45-70	25-500
	80	10	10	-	-	65-90	
	85	5	10	-	-	45-70	
Phosphor	Rem	10		0.5min		70-150	500
bronze							
Aluminum	1	6	-	(1%Ni)	Rem	45-60	250
alloys	1	20	-	-	Rem	40	250

Rem: Remainder

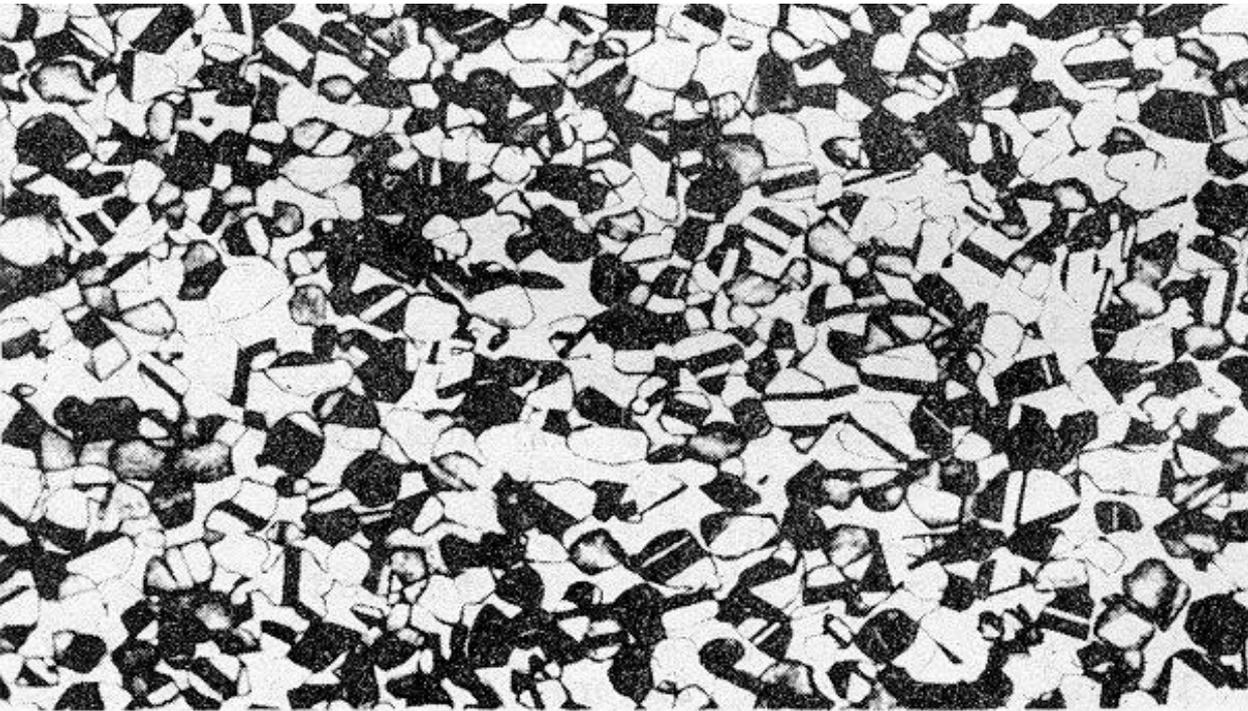
**Copper-Base Bearing Alloys** include the phosphor bronzes and the plain tin bronzes. Both types of bronze satisfy the structural requirements of a bearing metal, since they contain particles of the hard inter metallic compound embedded in a tough matrix of the solid solution alpha, as shown in Fig. 9.13. These alloys are very widely used for bearings where the loading is heavy.

**Leaded bronzes** are used for main bearings in aero engines, and for automobile and diesel crankshaft bearings. They have a high resistance to wear, and good thermal conductivity enables them to keep cool when running. Should lubrication fail, lead is extruded under pressure, and forms a lubricating film, which prevents seizure.



*Fig. 9.13 Microstructure of nickel coinage alloy, x100.*

**White Bearing Metals** may be either tin-base or lead-base. Tin-base bearing alloys are often called Babbitt metals, after Isaac Babbitt, their original patentee. All of these alloys contain antimony, which combines with tin to form an intermetallic compound,  $SbSn$ . This compound forms cubic crystals, usually called cuboids (Fig. 9.13), which are hard and low-friction properties. Lead is added in the interest of cheapness, and these form solid solutions of limited solubility with both tin and antimony. These solid solutions form a eutectic structure.



*Fig. 9.13 Microstructure of nickel coinage alloy, x100.*

**Aluminium-Tin Bearing Alloys** are recent developments, and contain about 20 % tin. Bearing shells of this type are generally carried on a steel-backing strip and have been widely used in automobile design for main and big end bearings.

**P.T.F.E. and Nylon** as non-metallic bearing materials are competing with metals in many fields. The coefficient of friction of PTFE is smaller than any other solid material. Unfortunately, its mechanical properties are poor so that it has to be strengthened by the use of fillers. PTFE and Nylon can be reinforced with bronze particles through powder metallurgy techniques, which is explained in section 15.4. Self-lubricating bearings are also in this group and their characteristics are given in Table 15.5.

### 9.9.3 Solders and Brazing Alloys

Solders and brazing alloys are used to join metals by melting at a lower temperature than the metals to be joined. Brazing is used where joints require higher strength, whereas solders are used principally for joining sheet iron, electrical work and plumbing.

Brazing alloys, or hard solders, are usually copper-based or silver-based alloys, although for special applications Au based or Al based alloys may be employed. Various compositions are employed to give a range of melting temperatures and suitable flow characteristics, depending upon the applications. Brazing temperatures range from 600 °C to 1100 °C. The colour of the alloy varies with composition from pure white for silver alloys to a yellow for copper ones.

Soft solders are composed of Sn and Pb and, therefore, their melting temperatures are very low. They contain 5-70 % Sn and 30-98 % Pb. The temperature of liquification can be varied in the range 190-275 °C by changing composition (Fig. 9.12), depending on application. For most soldering operations, however, a 50/50 alloy of Sn and Pb is used.

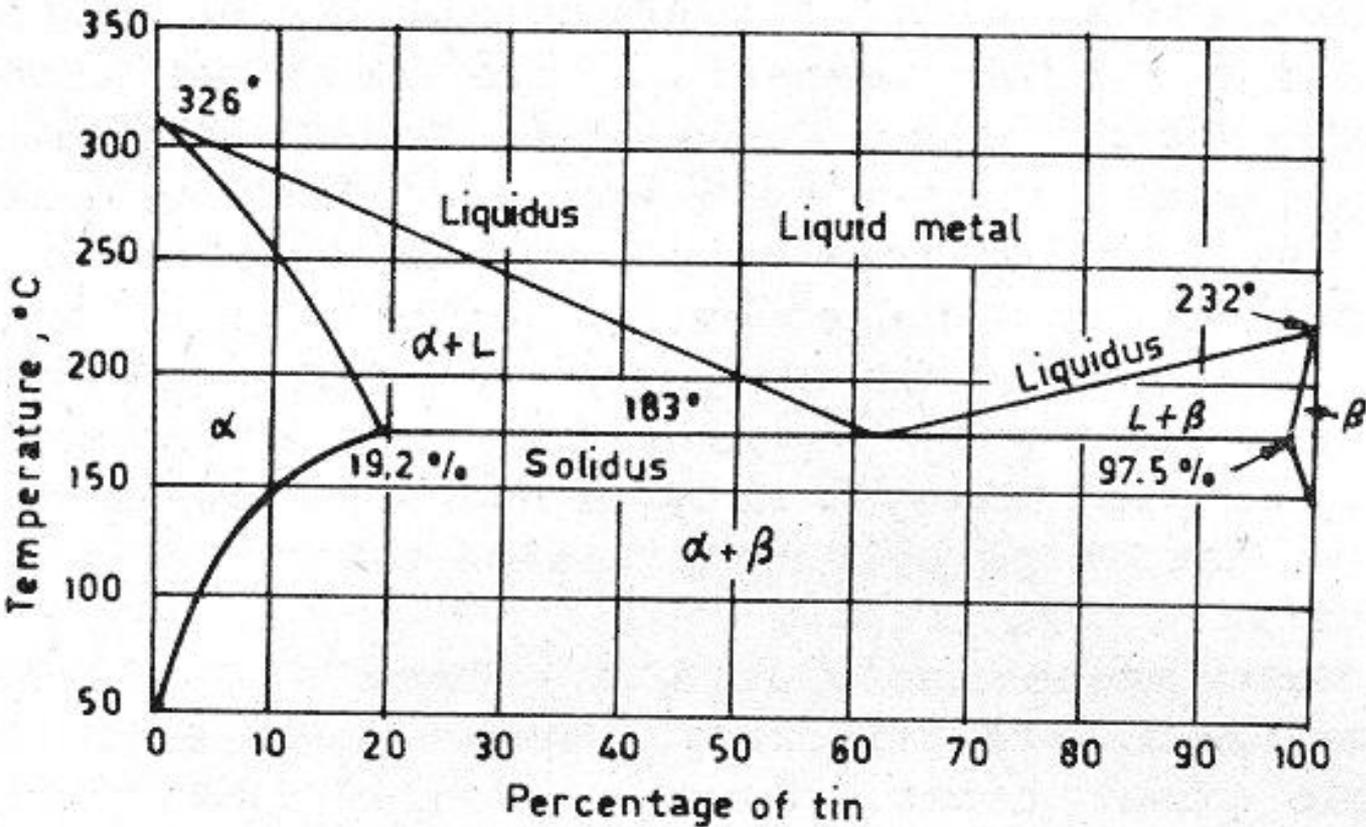


Fig. 9.12 Pb-Sn phase diagram

## 9.9.4 Fusible Alloys

Alloys containing lead, tin, bismuth and cadmium are used in automatic sprinklers, in safety plugs in boilers, and for fillers in bending tubes. By varying the composition, alloys can be obtained with melting temperatures far below those of their constituents. They are known by trade names such as Lipowitz's alloy containing 50 % Bi, 27 % Pb, 13 % Sn and 10 % Cd with 65 °C melting point, and Wood's alloy with 50 % Bi, 25 % Pb, 12.5 % Sn and 12.5 % Cd having a melting point of 68 °C and Rose's alloy having 50 % Bi, 28 % Pb and 22 % Sn with a melting point of 100 °C.

## 9.9.5 Cladding Metals

Clad metals can effectively combine the best qualities of two or more metals, frequently at a lower cost than the metals themselves. A clad metal is not, strictly speaking, an alloy as it is not a mixture of two metals, but is obtained by forming a metallurgical bond between layers of dissimilar metals.

Aluminium Cladding is produced by rolling a corrosion resistant layer of nearly pure Al on both sides of Al alloy or carbon steel. These clads are used as roof decks, sidings, building panels, and other applications requiring corrosion resistance.

Copper Cladding comprises of a heavy copper layer covering carbon steel or stainless steel. They are used where a strong, lightweight, easily formed, corrosion resistant material is required.

Lead cladding is performed on copper to produce a strong and workable material, which is easy to join. It is used where copper might stain metals or wood surfaces, and in industrial applications where the patina of copper might be objectionable.

## 9.9.6 Other Alloys

There are many other non-ferrous alloys of engineering importance. Important groups are those, which are used as cutting tools and for the purpose of resisting abrasion. Included in this group are stellite, the Co-Cr alloys, tungsten carbide and tantalum carbide. Tungsten carbide is marketed by trade name Carboly. Tantalum carbide is sintered with nickel, which gives a material little softer than tungsten carbide but with the same cutting properties. Stellite is a trade name for a Co-Cr-W alloy. It is extremely hard, brittle and non-corrosive alloy. It is specially suited for high speed turning and for cutting a wide variety of alloys.

# CHAPTER 10

## DEFORMATION OF METALS

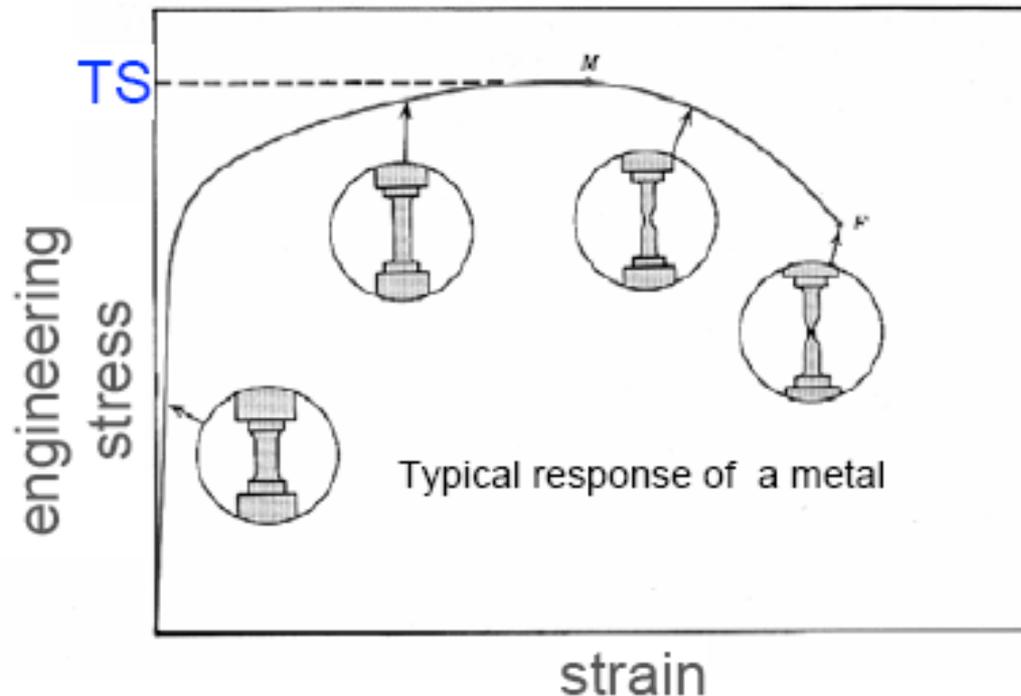
### 10.1 INTRODUCTION

Deformation of metals is one of the most important aspects of metallurgy, as it not only the formability of metals but also their integrity under service conditions. While some materials are elastic up to the point of fracture (e.g. elastomers and most ceramics), many useful engineering materials such as metals can undergo substantial plastic deformation prior to fracture which makes processing operations possible.

Deformation of metals takes place by the agency of movement of **dislocations** to cause **slip**, or in some cases **twinning**. In few cases grain boundary sliding and diffusional creep may also take place. **Dislocations play a vital role in the deformation process**, and will be discussed in detail followed by the processes of slip and twinning. Finally various forming processes will be described which make use of the deformability of metals to shape them for various useful applications.

# TENSILE STRENGTH, TS

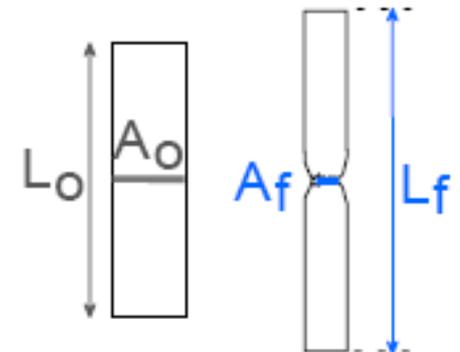
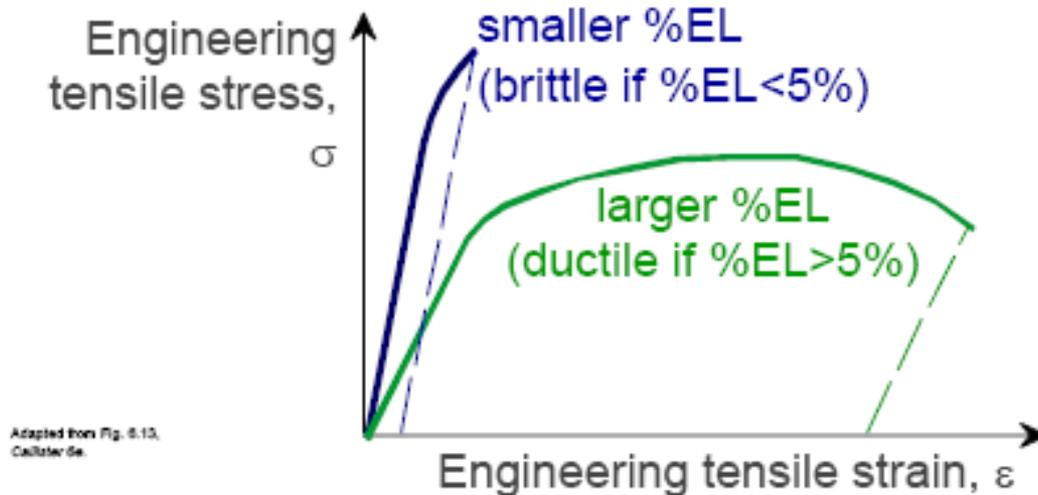
- Maximum possible engineering stress in tension.



- Metals: occurs when noticeable **necking** starts.
- Ceramics: occurs when **crack propagation** starts.
- Polymers: occurs when **polymer backbones** are aligned and about to break.

# DUCTILITY, %EL

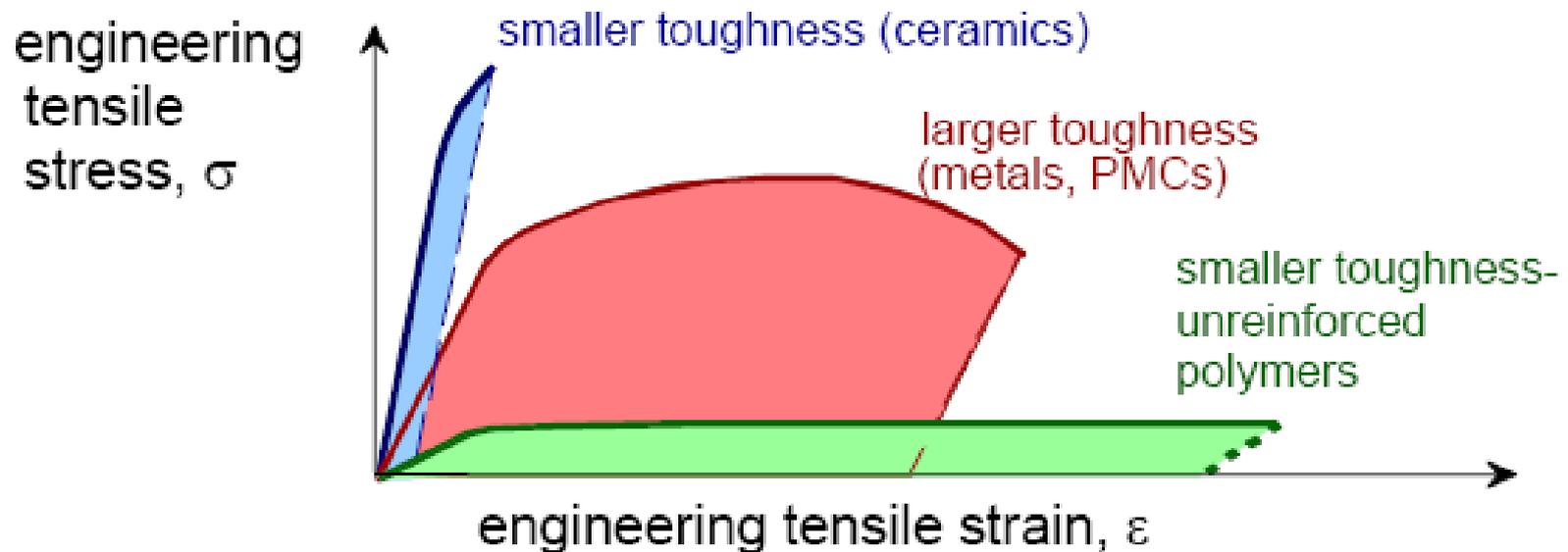
- % Elongation:  
(Plastic tensile strain *at failure*)



- % Area reduction:
  - Note: %AR and %EL are often comparable.
    - Reason: crystal slip does not change material volume.
    - %AR > %EL possible if internal voids form in neck.

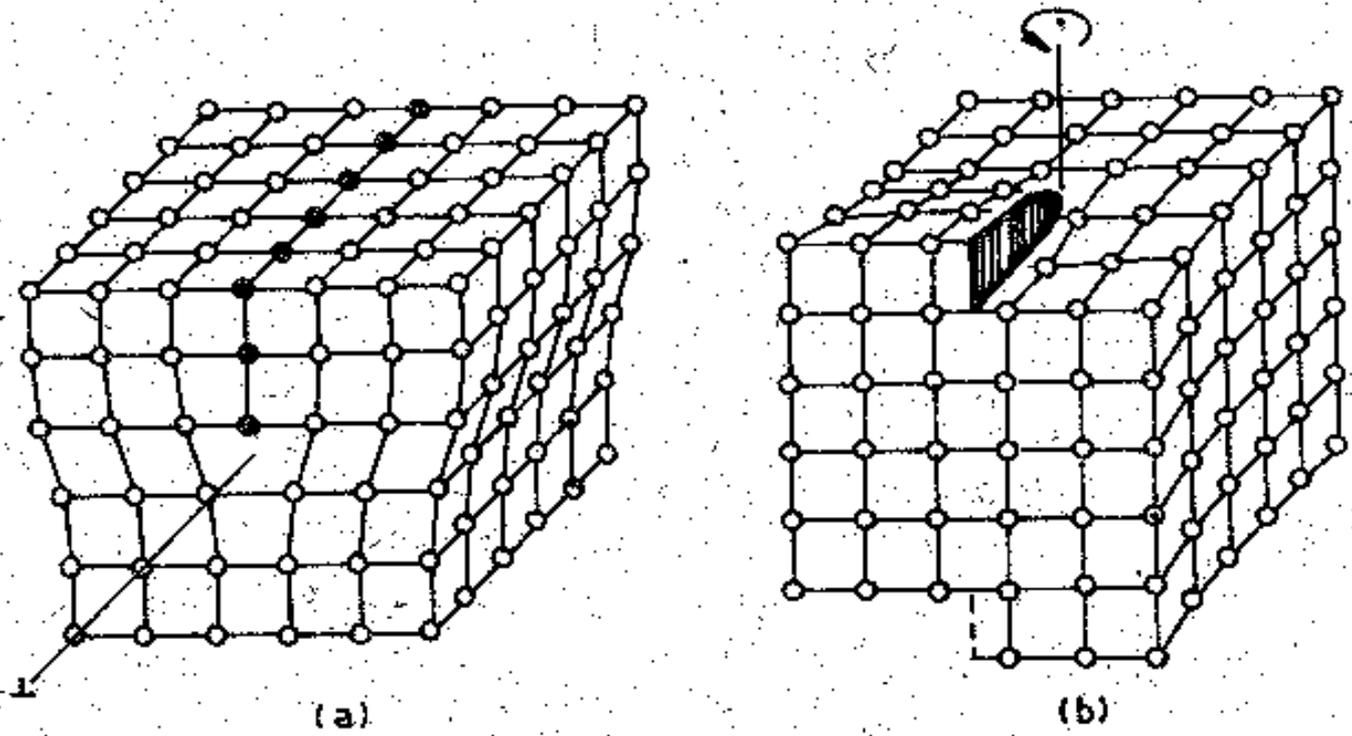
# TOUGHNESS

- Energy to break a unit volume of material
- Area under the stress-strain curve (“strain energy”)



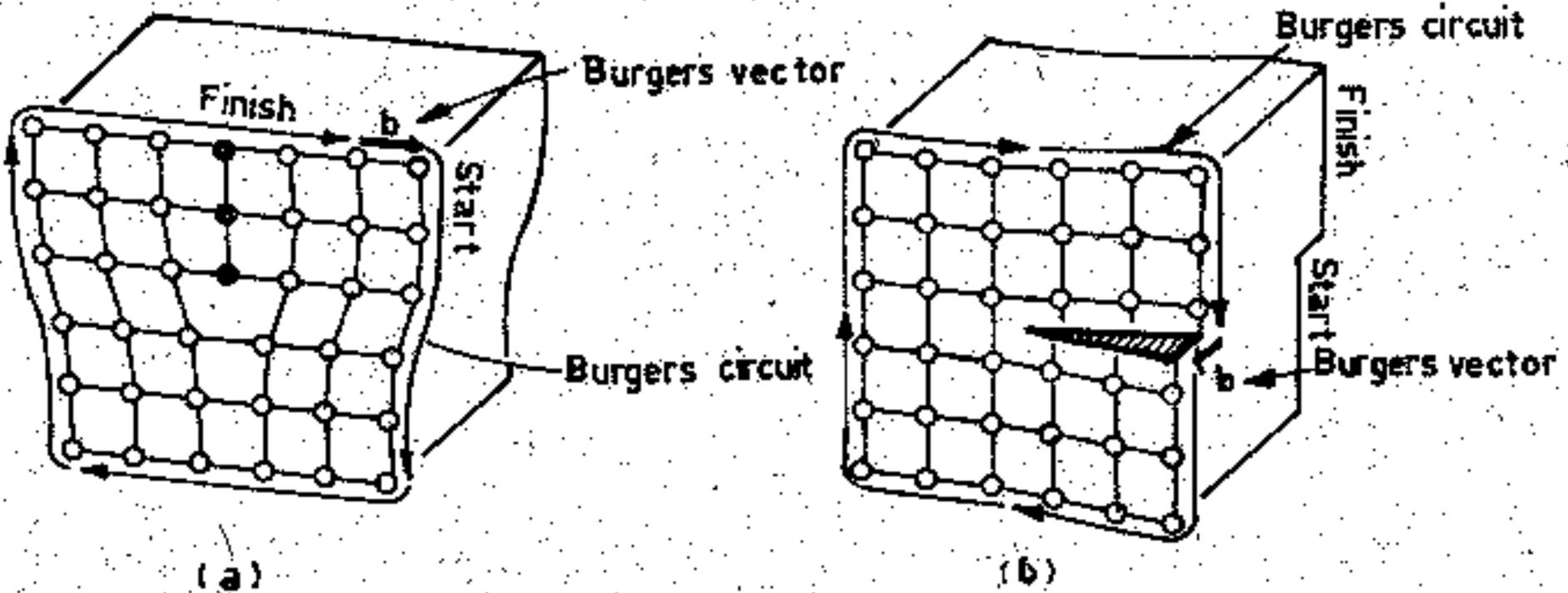
# 10.2 DISLOCATIONS

The theoretical strength of metals is generally about 10,000 times more than the actual practically observed value. The cause of this discrepancy is **dislocations, which are line defects inherent in crystals of materials**. A dislocation is an extra half plane of atoms embedded in a perfect crystal. It may be considered to have two components, an **edge** component and a **screw** component. These two components or kinds of dislocations are shown in Fig 10.1. Dislocations are characterized by **Burger's vector  $b$** , which describes both **the magnitude and direction of motion** of these dislocations under an applied force

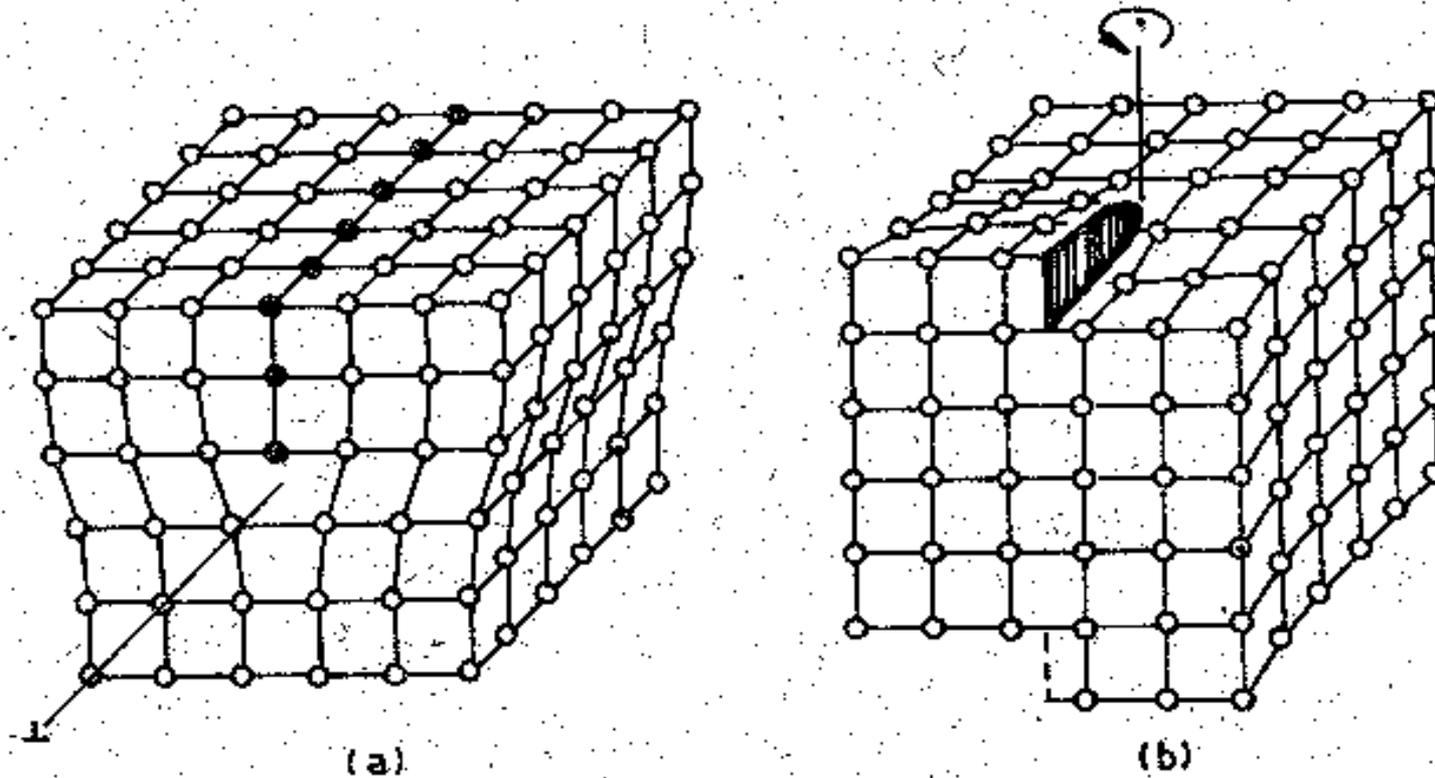


*Fig.10.1 Geometry of (a) edge, and (b) screw dislocations*

An atom by atom circuit around the dislocation fails to close due to the presence of dislocation as shown in Fig 10.2. The direction and magnitude of the vector which completes the circuit gives the Burger's vector for that dislocation. It can further be seen that  $b$  for an edge dislocation is perpendicular to the line of dislocation, while that of a screw dislocation is parallel to dislocation line.



*Fig.10.2 Burger's vectors for (a) edge, and (b) screw dislocations*

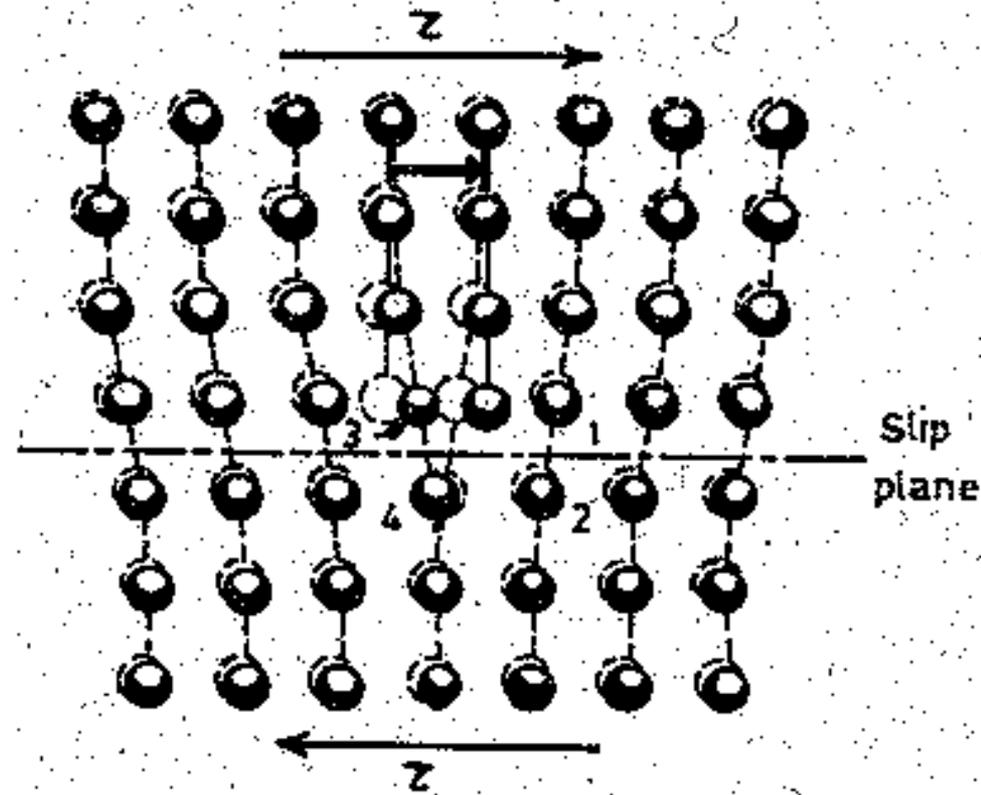


*Fig.10.1 Geometry of  
(a) edge, and  
(b) screw dislocations*

The edge dislocation shown in Fig 10.1 (a) is called a positive type having a compressive region in the top half with extra plane of atoms, and a tensile region in the bottom half. An **opposite dislocation** (T) with extra half plane in the bottom half is called a **negative type dislocation**. The dislocation line may wander through a crystal, being pure edge in some places, screw in others, and a mixture or hybrid of both the types in yet other places. The Burger's vector of a mixed dislocation makes an angle with dislocation line. In addition, dislocations may be only partial and not unit dislocations.

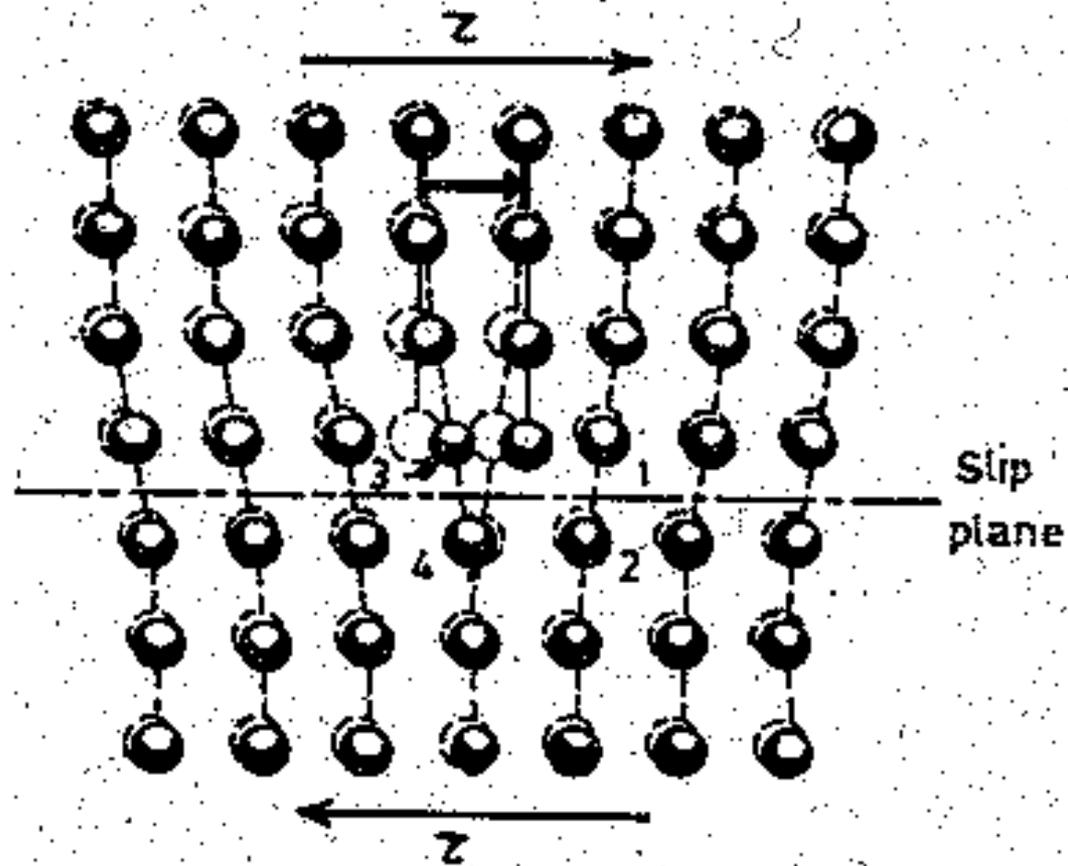
## 10.2.1 Dislocation Motion

The ability of dislocations to move readily in metals at small applied stresses arises from the fact that atomic bonds are not truly broken in the process. When a dislocation (extra half plane of atoms) moves through a crystal, atomic bonds with an atom "being left behind" must be broken and new bond with an atom "being approached" must be established. This process is, however, made easy by the fact that metallic bonding is relatively non-directional, being held by a cloud of electrons around nuclei, which allows a new bond with the atom "being approached" to be formed before the existing bond with the atom "being left behind" is completely broken.

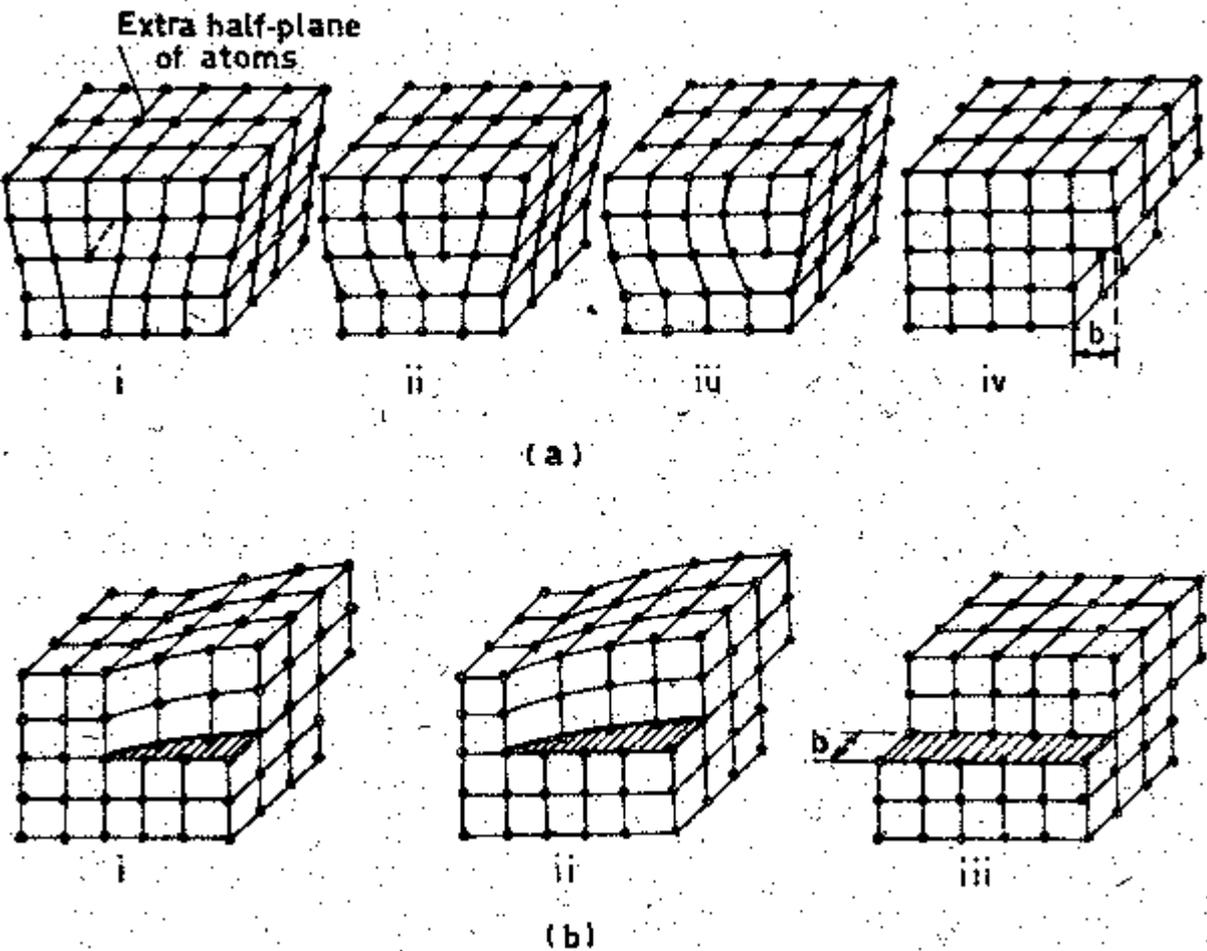


*Fig.10.3 Movement of edge dislocation under shear stress*

For simplicity, consider the movement of an edge dislocation under an applied shear stress (Fig 10.3). The shear stress, in trying to move the dislocation, must first break the bond between atoms 1 and 2 so that atom 1 is pulled away from atom 2. At the same time atom 3 moves towards its equilibrium position with respect to atom 4; in the process it releases stored elastic strain energy. Hence the process of moving atom 1 becomes easier due to the release of strain energy by atom 3 and, therefore, the movement of dislocation carries on one step at a time, until the dislocation moves completely to the right and emerges to produce a slip step.



*Fig. 10.3 Movement of edge dislocation under shear stress*



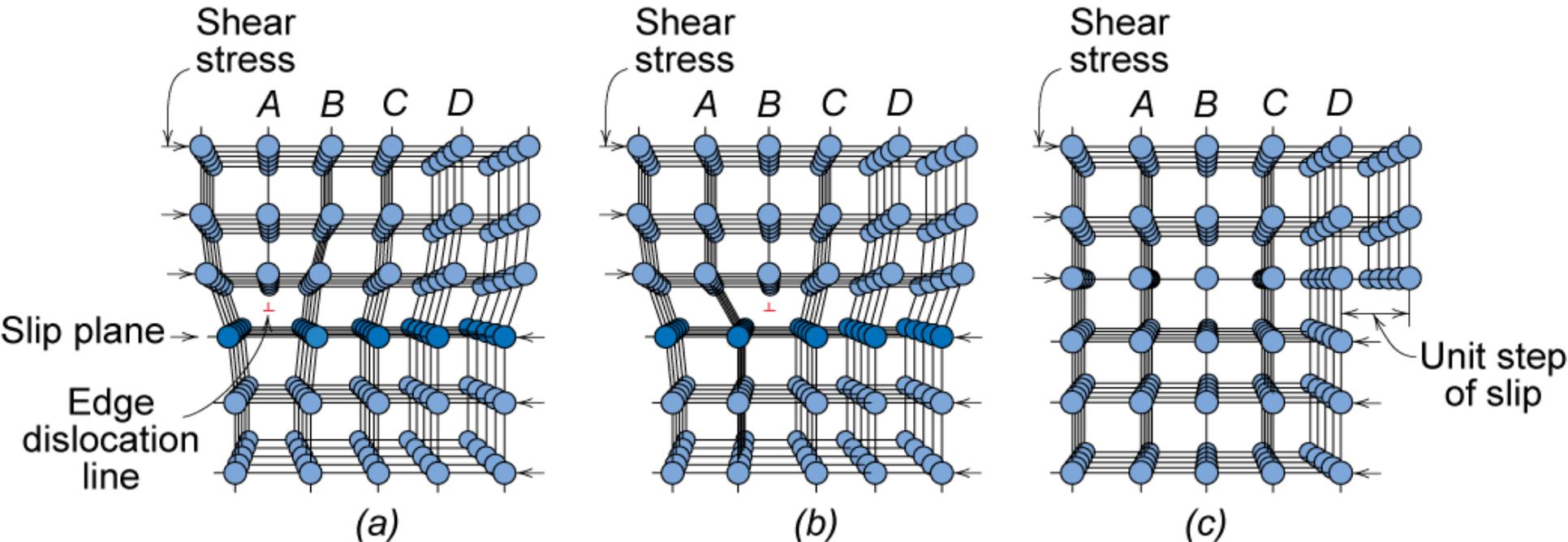
*Fig. 10.4 Atomic representation of movement:  
 (a) in edge dislocation,  
 (b) in screw dislocation*

Fig. 10.4 shows the same process on atomic scale and it could be seen from it that the movement of edge dislocation is in the direction of  $b$  and the slip step produced is of the same magnitude (length) as  $b$ . On the other hand, to produce same amount of slip in a block with screw dislocation the screw dislocation will have to move perpendicular to the direction of  $b$ , the magnitude of slip being same as  $b$ .

# Dislocation Motion

## Dislocations & plastic deformation

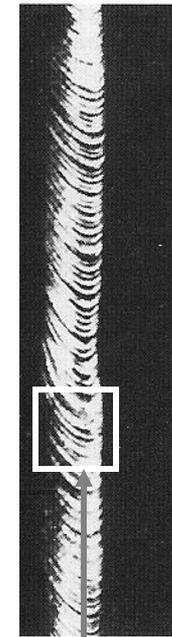
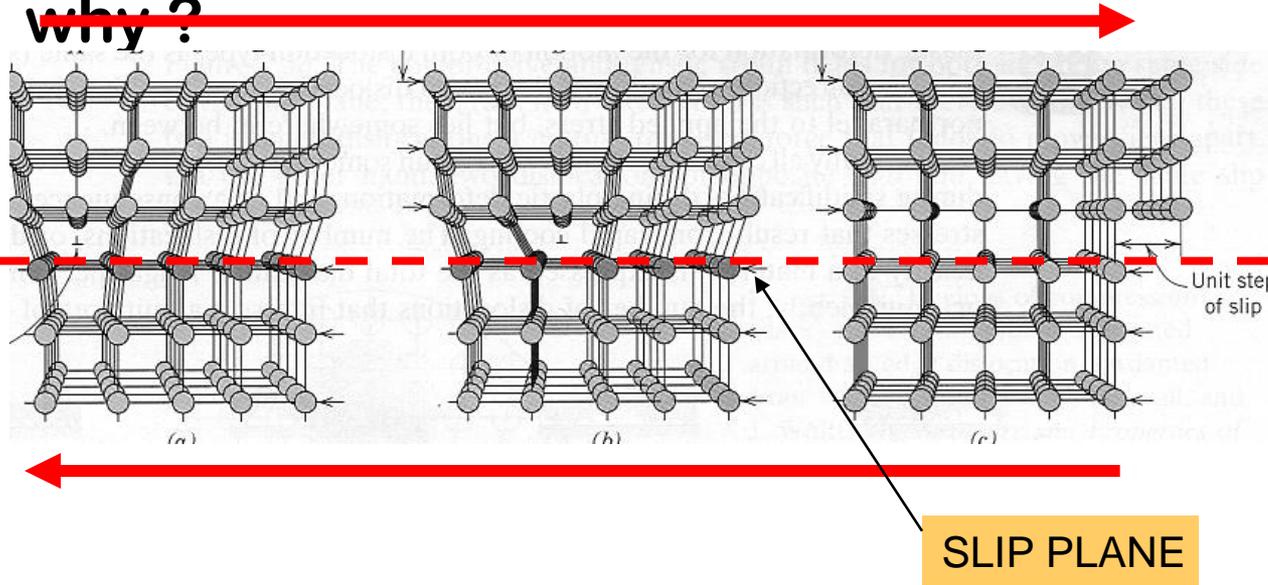
- Cubic & hexagonal metals - plastic deformation by **plastic shear or slip** where one plane of atoms slides over adjacent plane by defect motion (dislocations).



- If dislocations don't move, deformation doesn't occur!

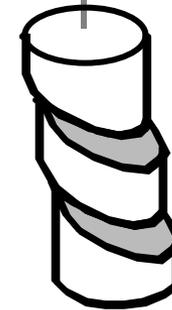
# DISLOCATION MOTION

- Produces plastic deformation !
- Bonds are incrementally broken and re-formed. Much less force is needed ,  
~~why ?~~



Plastically stretched zinc single crystal.

Adapted from Fig. 7.9, *Callister 6e*. (Fig. 7.9 is from C.F. Elam, *The Distortion of Metal Crystals*, Oxford University Press, London, 1935.)

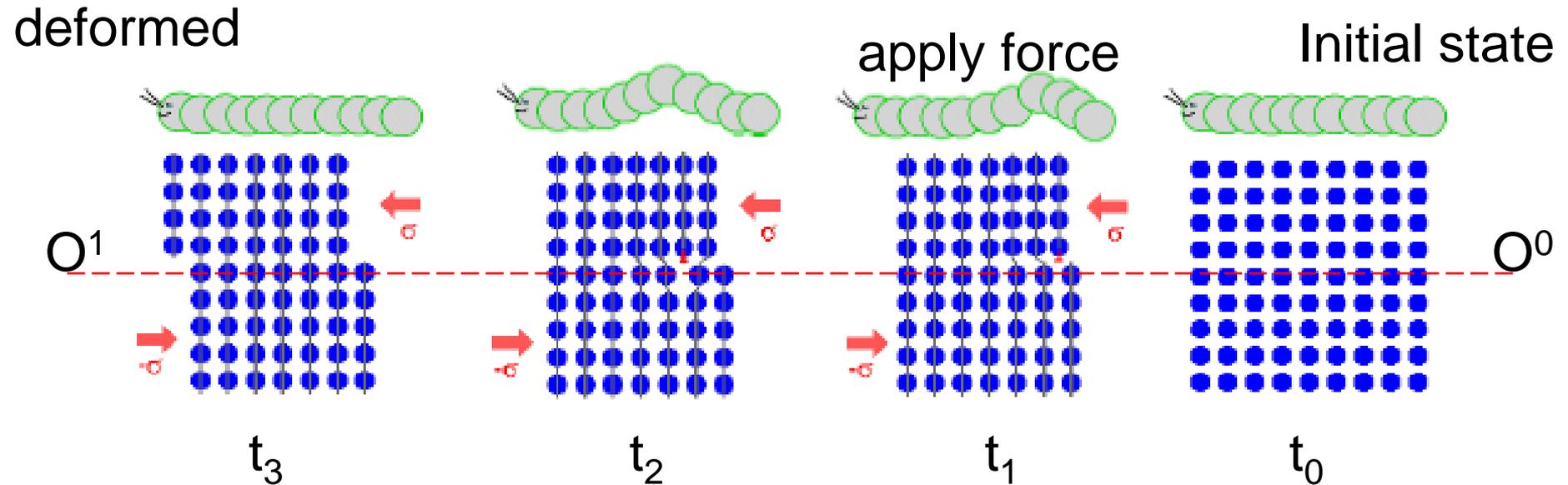


Adapted from Fig. 7.8, *Callister 6e*.

- If dislocations don't move, plastic deformation doesn't happen!

How do we generate the dislocation motion ?

# DISLOCATION MOTION



The motion of a single dislocation across the plane causes the top half of the crystal to move (**to slip**) with respect to the bottom half but we can not have to break all the bonds across the middle plane simultaneously (which would require a very large force).

**The slip plane ( $O^0$ - $O^1$ )**– the crystallographic plane of dislocation motion.

## DISLOCATIONS, STRENGTH, & DUCTILITY

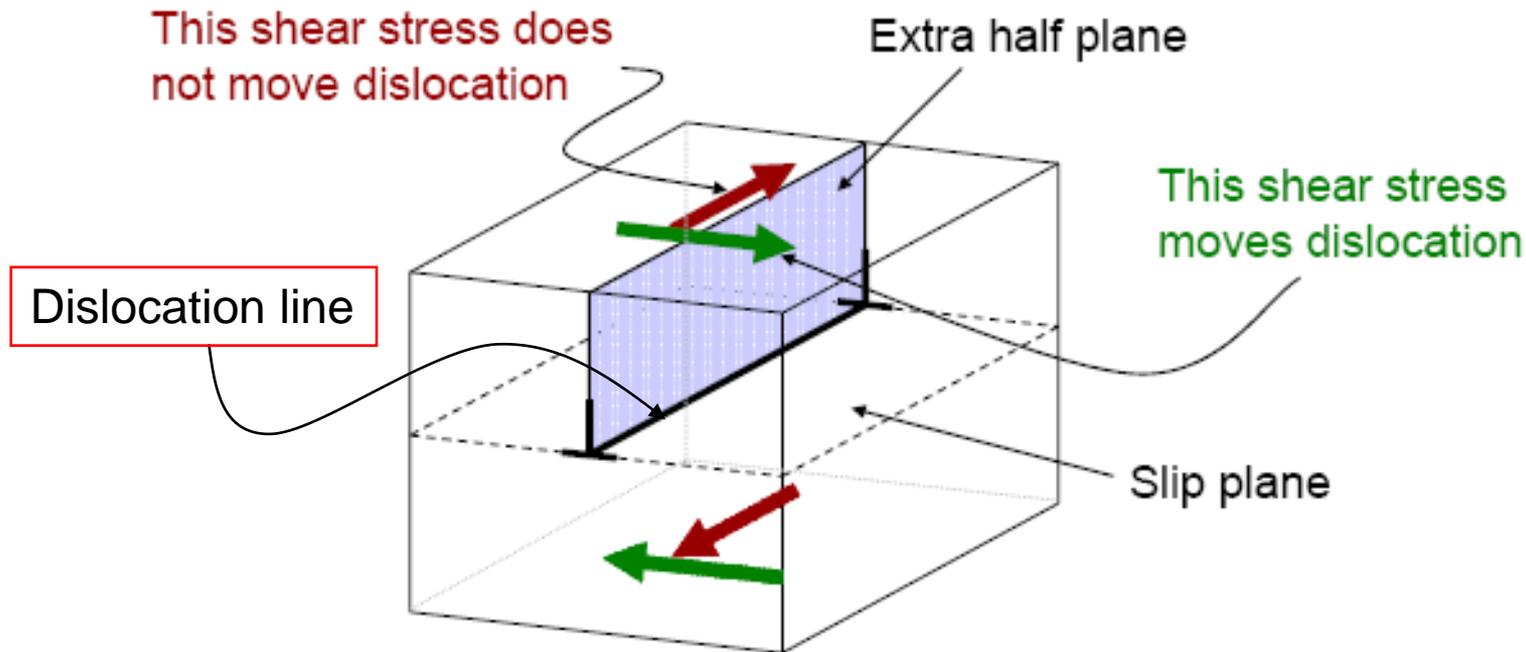
**How are dislocations, strength, and ductility related?**

- Onset of dislocation motion limits strength
- Strengthening techniques impede dislocation motion
- Heat treatment techniques restore ductility

Onset: The beginning or early stages; "the onset of pneumonia".

# STRESS AND DISLOCATION MOTION

In 3D, multiple shear stresses are possible:  $\tau = F_s/A$



To move the edge dislocation, the shear stress MUST:

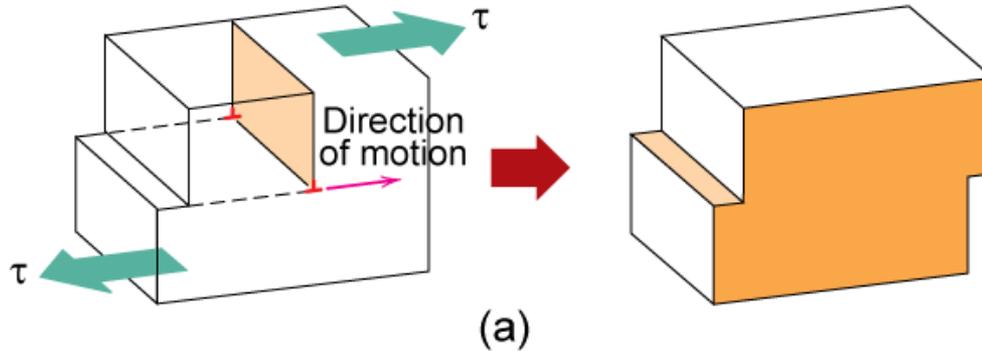
**NOT be parallel to the dislocation line !**

- Act parallel to slip plane
- Act perpendicular to dislocation line

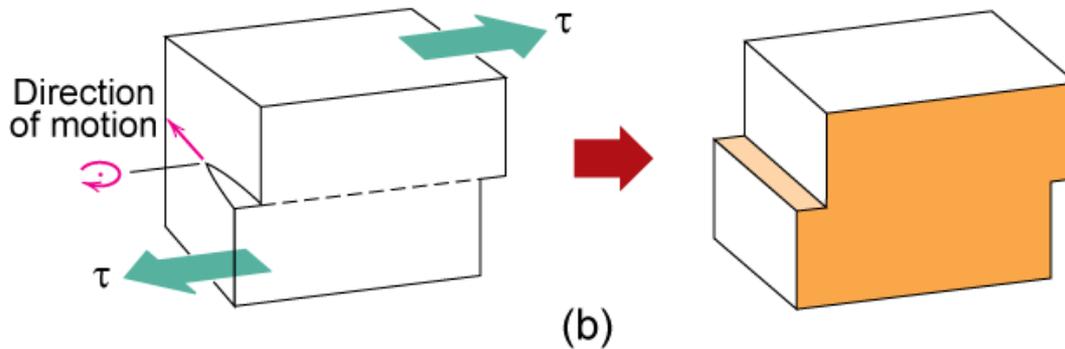
need right stress component

# Dislocation Motion

- Dislocation moves along **slip plane** in **slip direction** perpendicular to dislocation line
- Slip direction same direction as **Burgers vector**

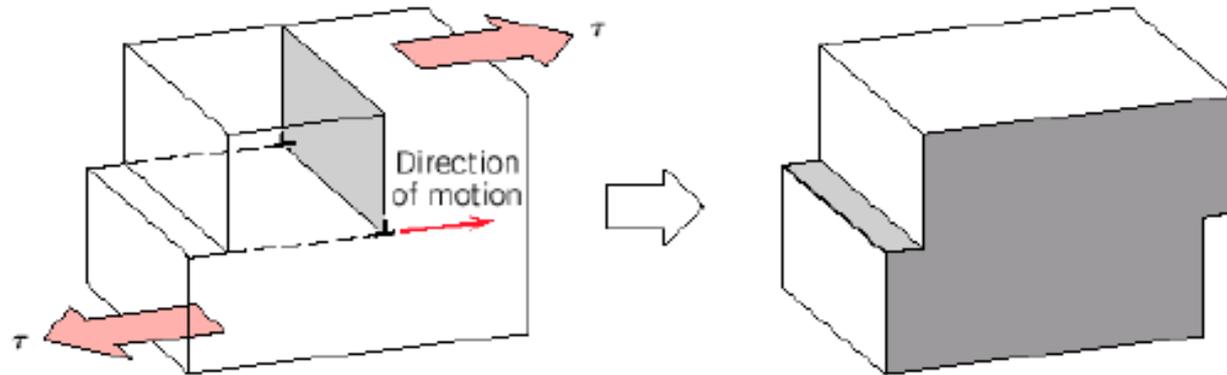


**Edge dislocation**

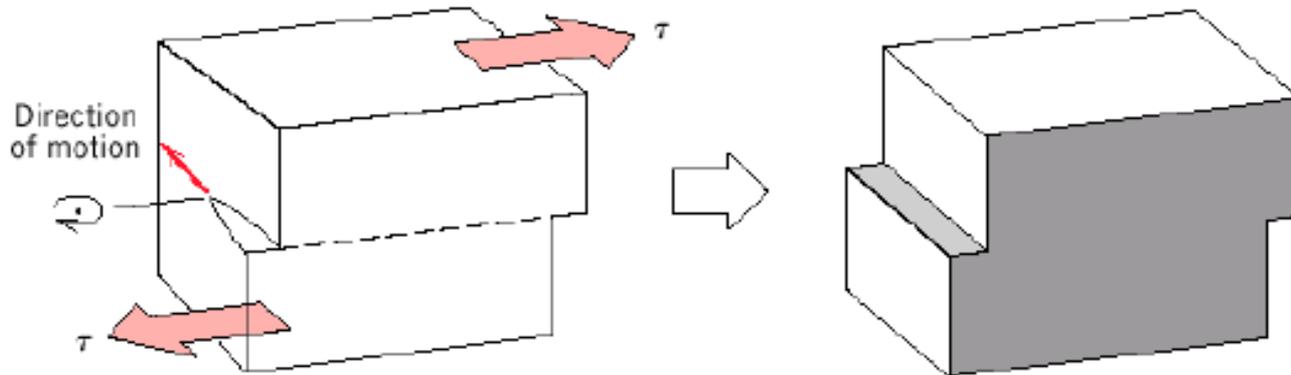


**Screw dislocation**

# STRESS AND DISLOCATION MOTION

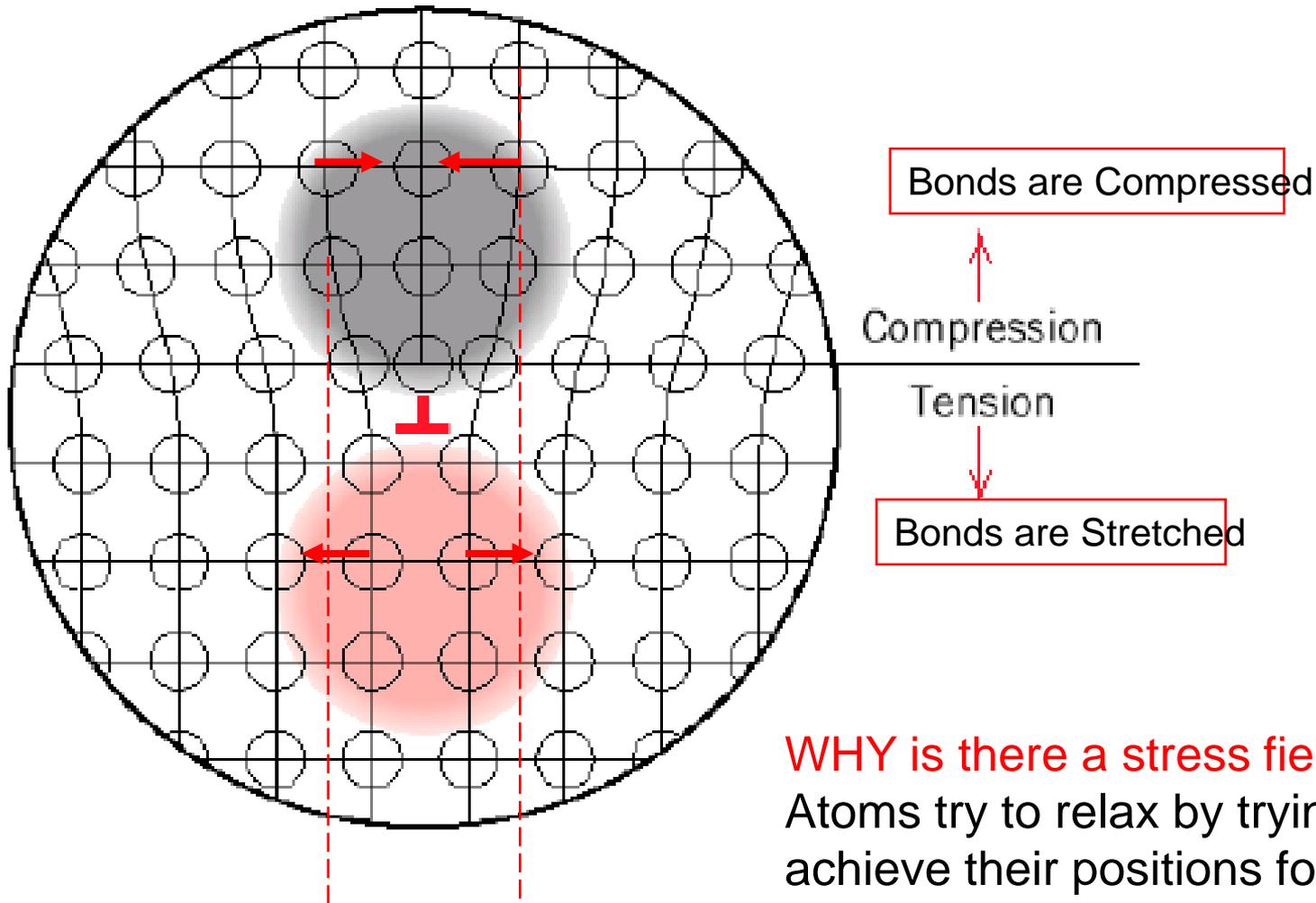


**Edge dislocation line moves parallel to applied stress**



**Screw dislocation line moves perpendicular to applied stress**

# STRESS field around dislocations



**WHY is there a stress field ?**

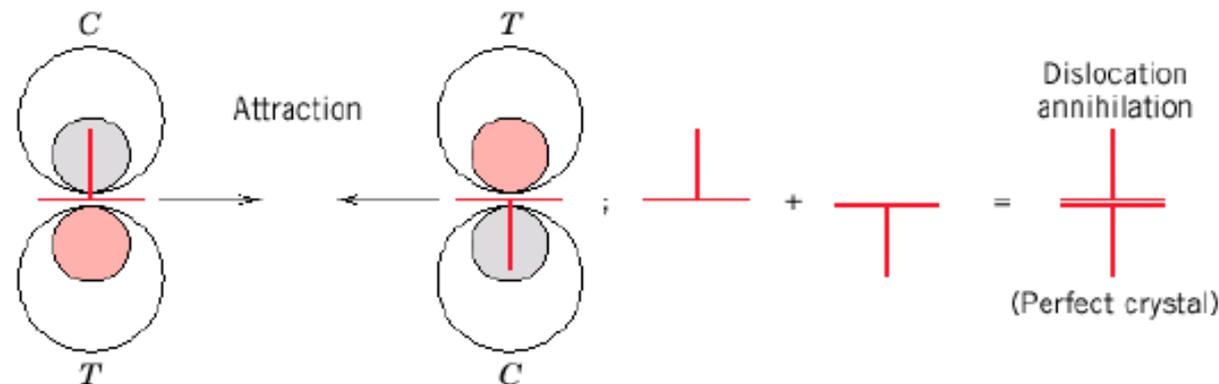
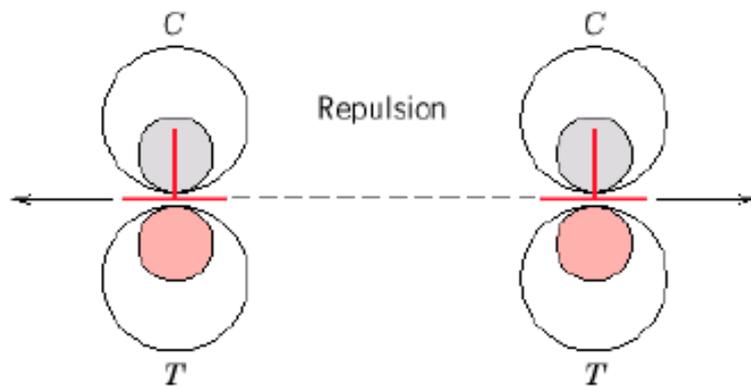
Atoms try to relax by trying to achieve their positions for the case if there was not a dislocation in the vicinity !

# Stress fields of dislocations interacting !

The strain fields around dislocations interact with each other. Hence, they exert force on each other.

Edge dislocations, when they are in the same plane, they repel each other if they have the same sign (direction of the Burgers vector). WHY ?

They can attract and annihilate if they have opposite signs. PROVE !



# Dislocation Density

- The number of dislocations in a material is expressed using the term **dislocation density** - the total dislocation length per unit volume or the # of dislocations intersecting a unit area. Units are mm / mm<sup>3</sup>, or just / mm
- Dislocation densities can vary from 10<sup>3</sup> mm<sup>-2</sup> in carefully solidified metal crystals to 10<sup>10</sup> mm<sup>-2</sup> in heavily deformed metals.

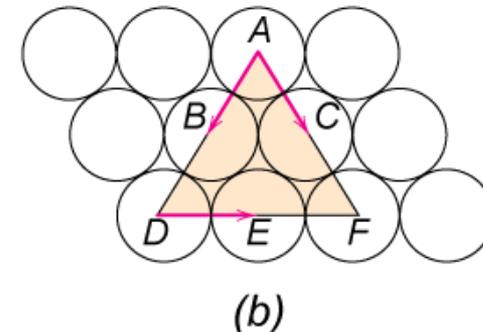
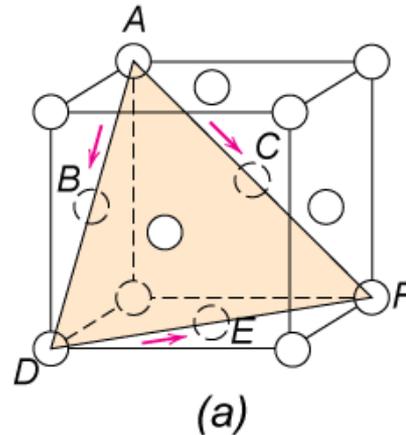
## Where do Dislocations come from, what are their sources ?

- Most crystalline materials, especially metals, have dislocations in their as-formed state, mainly as a result of stresses (mechanical, thermal...) associated with the manufacturing processes used.
- The number of dislocations increases dramatically during plastic deformation.
- Dislocations spawn from existing dislocations, grain boundaries and surfaces and other “defects” .

# Deformation Mechanisms

## Slip System

- **Slip plane** - plane allowing easiest slippage
  - Wide interplanar spacings - highest planar densities
- **Slip direction** - direction of movement - Highest linear densities



ed from Fig.  
Hallister 7e.

- **FCC Slip occurs on  $\{111\}$  planes (close-packed) in  $\langle 110 \rangle$  directions (close-packed)**
  - => total of 12 slip systems in FCC**
- **in BCC & HCP other slip systems occur**

# SLIP SYSTEMS !!!

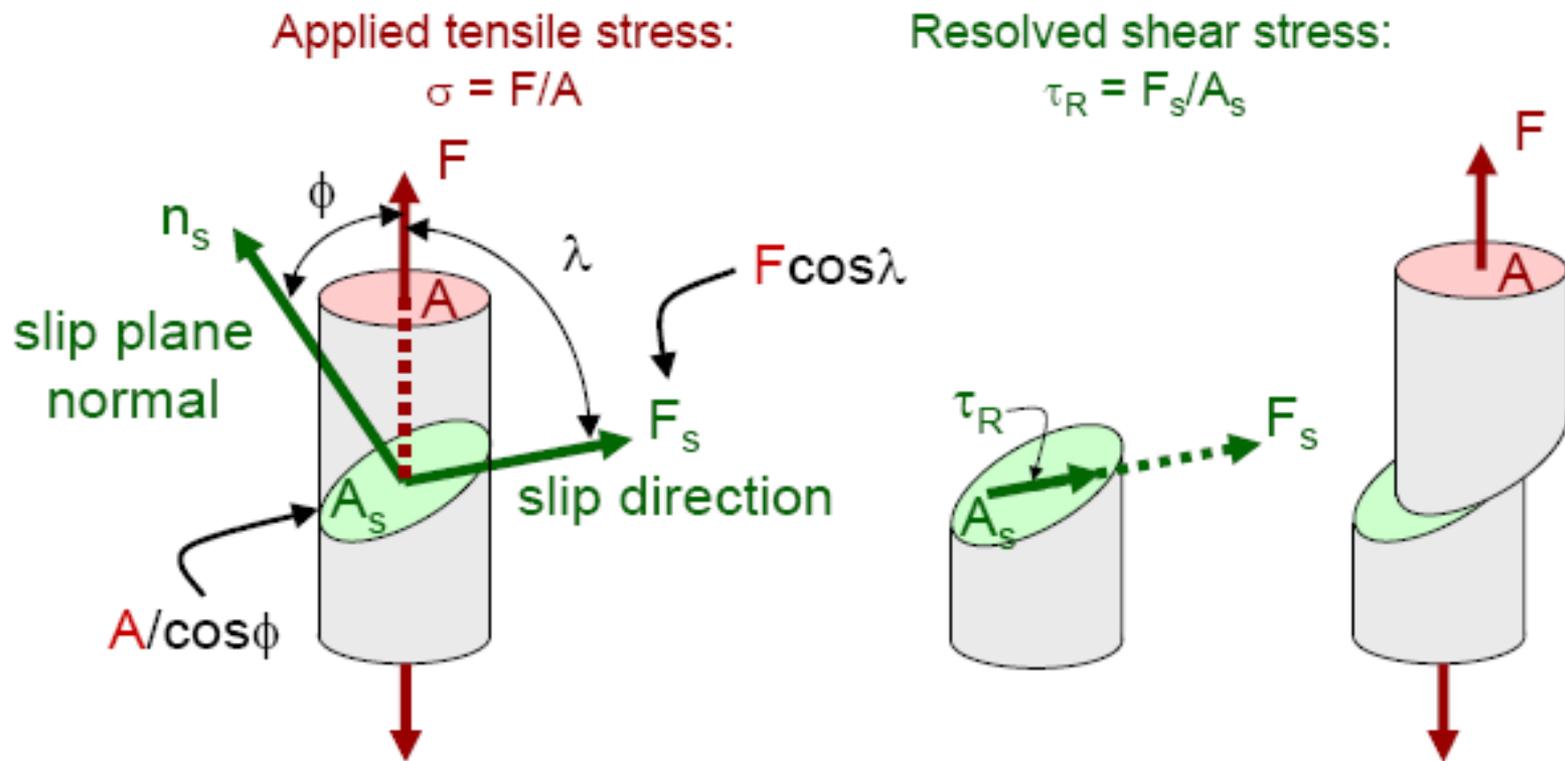
- Dislocations move with ease on certain crystallographic planes and along certain directions on these planes !
  - The plane is called a slip plane
  - The direction is called a slip direction
  - Combination of the plane of slip and direction is a slip system
- The slip planes and directions are those of highest packing density.
  - The distance between atoms is shorter than the average...High number of coordination along the planes also important !

# Concept Check

<i>Metals</i>	<i>Slip Plane</i>	<i>Slip Direction</i>	<i>Number of Slip Systems</i>
	<b>Face-Centered Cubic</b>		
Cu, Al, Ni, Ag, Au	{111}	$\langle 1\bar{1}0 \rangle$	12
	<b>Body-Centered Cubic</b>		
$\alpha$ -Fe, W, Mo	{110}	$\langle \bar{1}11 \rangle$	12
$\alpha$ -Fe, W	{211}	$\langle \bar{1}11 \rangle$	12
$\alpha$ -Fe, K	{321}	$\langle \bar{1}11 \rangle$	24
	<b>Hexagonal Close-Packed</b>		
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

# STRESS AND DISLOCATION MOTION

- Dislocation motion occurs and crystals slip as a result of a **resolved shear stress**,  $\tau_R$ , acting on dislocations moving on slip planes in the slip direction.
- Applied tension can produce resolved shear stresses!



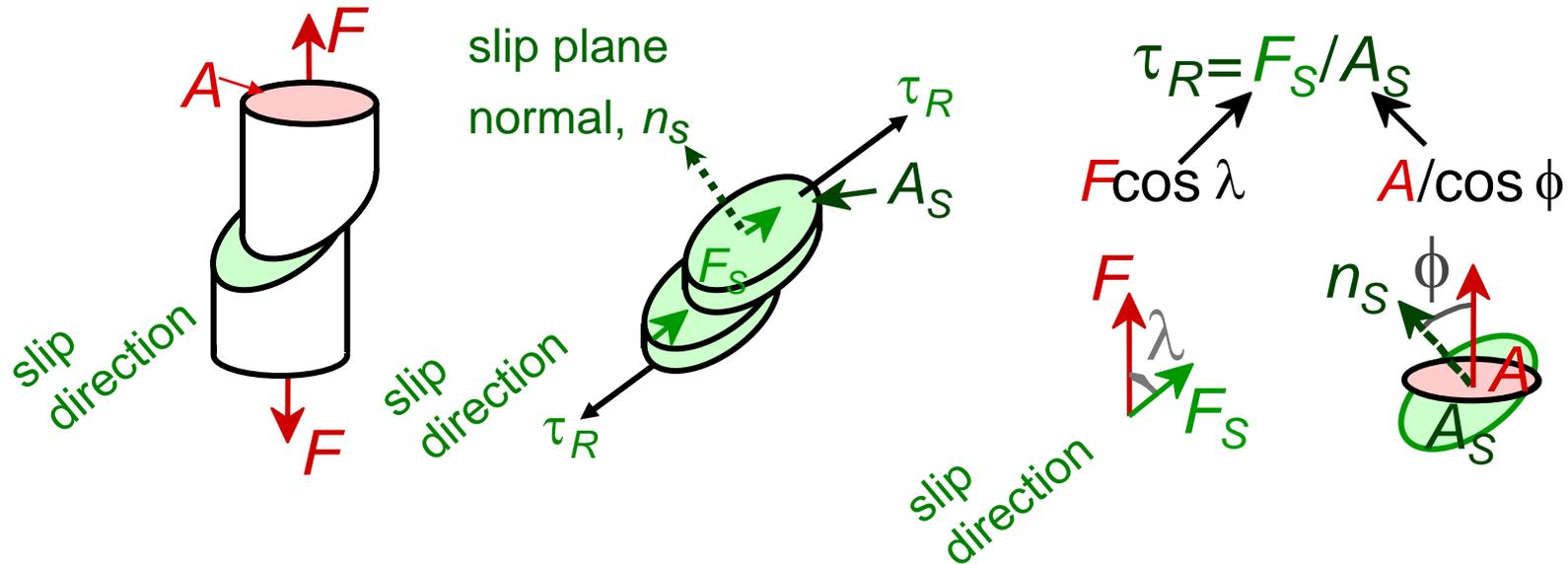
# Stress and Dislocation Motion

- Crystals slip due to a **resolved shear stress**,  $\tau_R$ .
- Applied tension can produce such a stress.

Applied tensile stress:  $\sigma = F/A$

Resolved shear stress:  $\tau_R = F_S/A_S$

Relation between  $\sigma$  and  $\tau_R$



$$\tau_R = \sigma \cos \lambda \cos \phi$$

$$\lambda + \phi \neq 90$$

# Critical Resolved Shear Stress

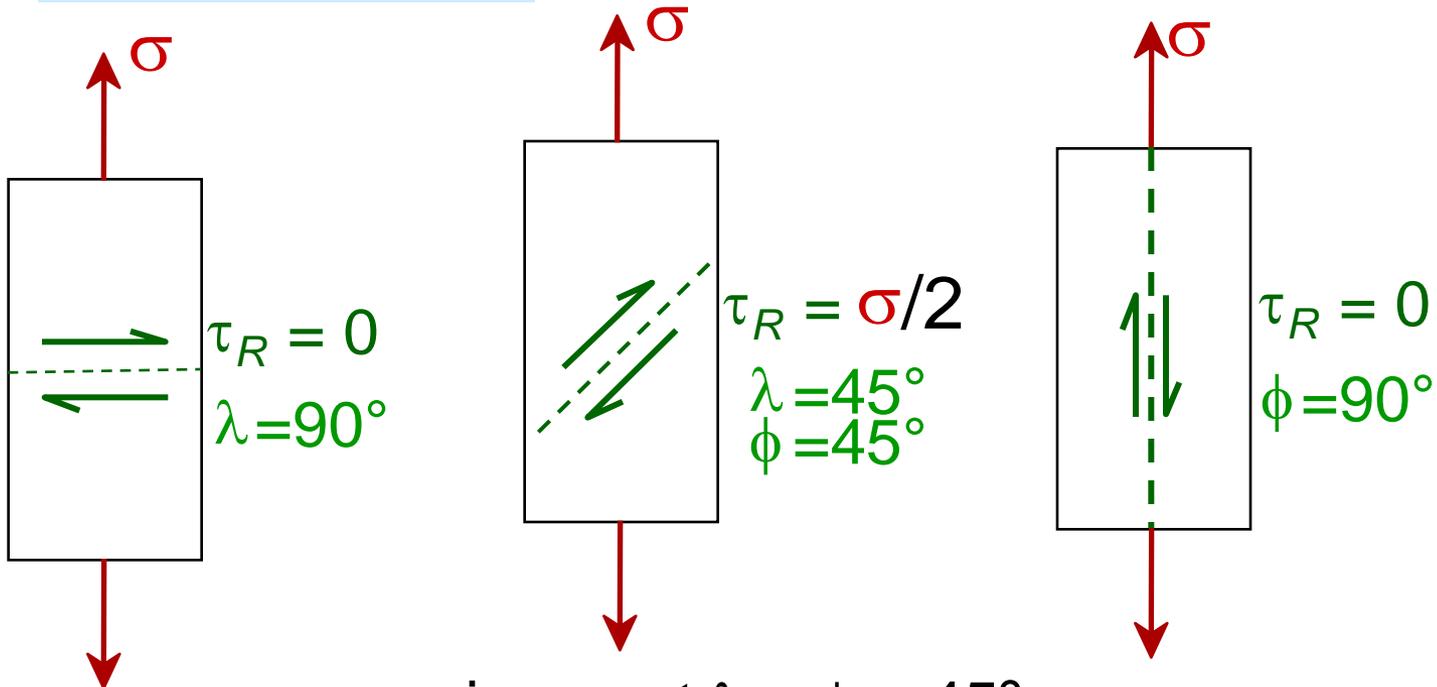
- Condition for dislocation motion:
- Crystal orientation can make it easy or hard to move dislocation

$$\tau_R > \tau_{CRSS}$$

typically

$10^{-4}$  GPa to  $10^{-2}$  GPa

$$\tau_R = \sigma \cos \lambda \cos \phi$$



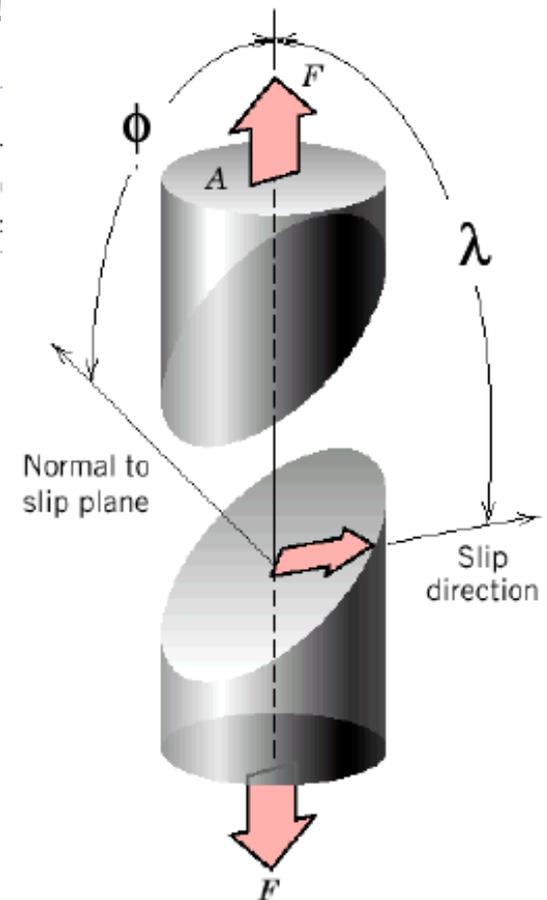
$\tau$  maximum at  $\lambda = \phi = 45^\circ$

# Resolving the Applied Stress on a SLIP PLANE !

- Shear Stress has to be **resolved** on to the slip planes as;
  - Shear Stress is needed for dislocations to move / slip
  - Dislocations can only move on slip planes, and these planes are rarely on axis with the applied force

We should resolve the force applied in a tensile test,  $F$ , on to the cross-sectional area  $A$  where the slip is going to take place;

$$\tau_R = \sigma \cos \phi \cos \lambda$$



# Critical Resolved Shear Stress => Slip in Single X'tals

Macroscopically;

Q: when do materials plastically deform / yield ?

Stress > YS

Q: How does plastic deformation take place ?

Dislocation Motion ( Elastic deformation ??)

Q: On what planes does dislocations move ?

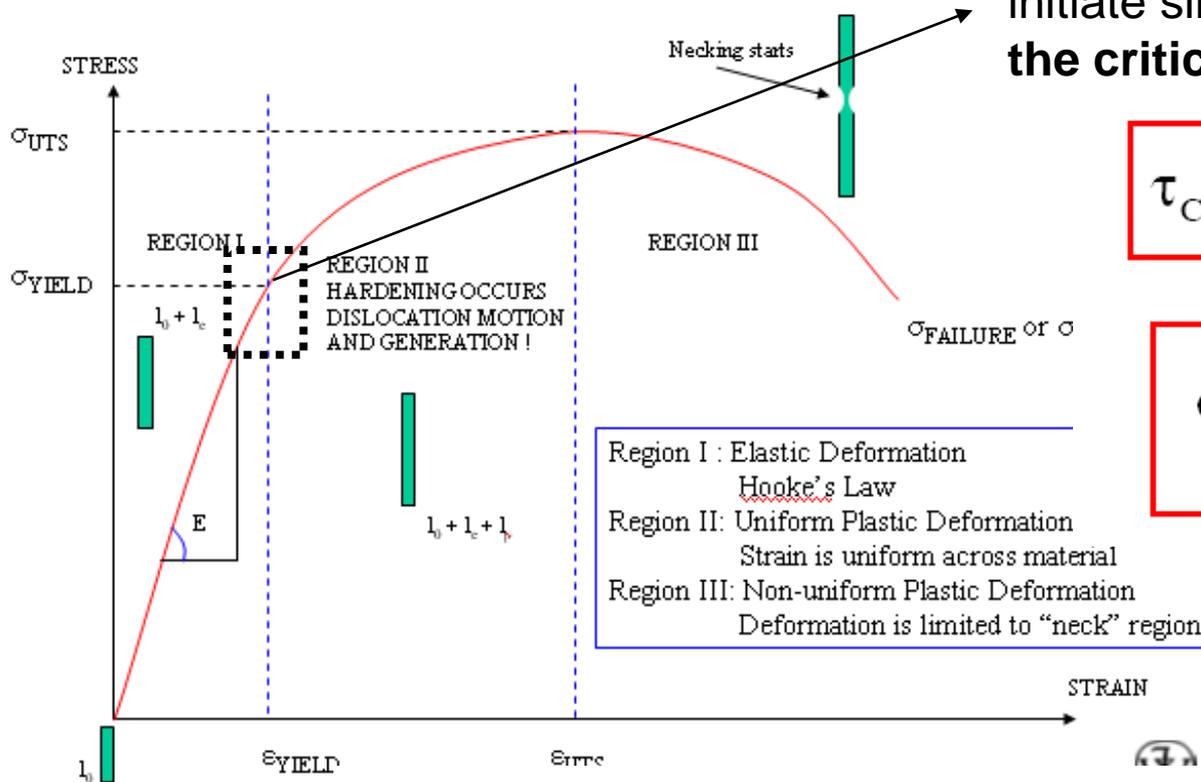
Slip Planes

Q: At stress = YS, what would be the minimum resolved shear stress needed to act on dislocations to initiate dislocation motion, onset of yield/plastic deformation ?

**HIMMM ! Lets think !!!**

# The Critical Resolved Shear Stress

The minimum shear stress required to initiate slip is termed:  
**the critical resolved shear stress**



$$\tau_{CRSS} = \sigma_y (\cos \phi \cos \lambda)_{MAX}$$

$$\sigma_y = \frac{\tau_{CRSS}}{(\cos \phi \cos \lambda)_{MAX}}$$

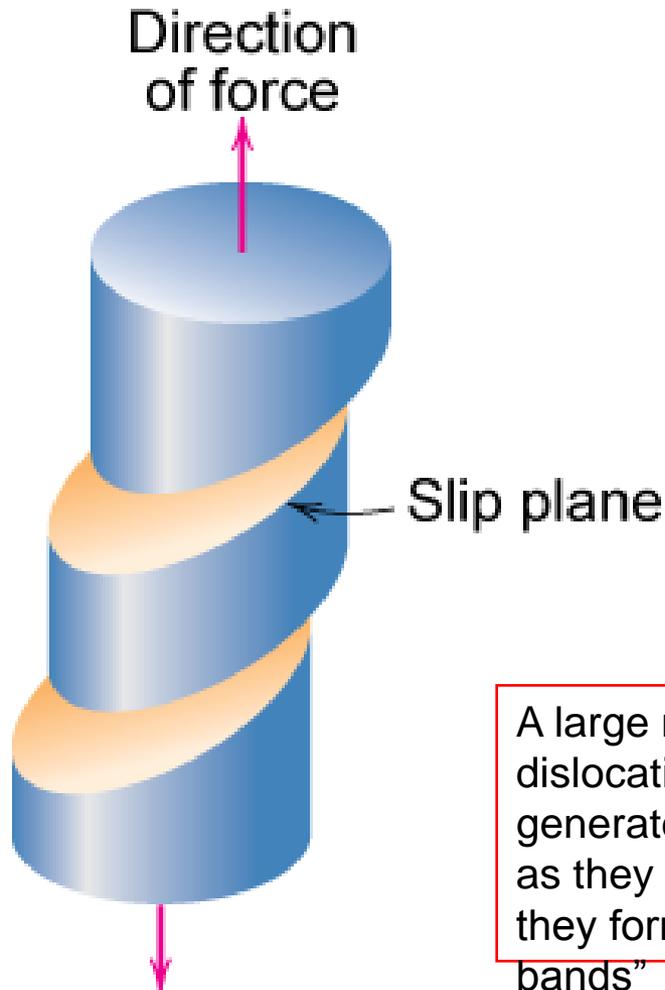
- Region I : Elastic Deformation  
Hooke's Law
- Region II: Uniform Plastic Deformation  
Strain is uniform across material
- Region III: Non-uniform Plastic Deformation  
Deformation is limited to "neck" region

Maximum value of  $(\cos \phi \cos \lambda)$  corresponds to

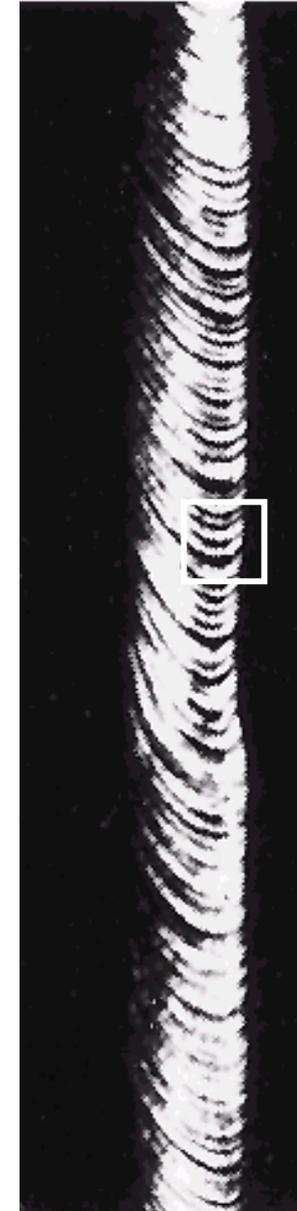
$$\phi = \lambda = 45^\circ \Rightarrow \cos \phi \cos \lambda = 0.5 \Rightarrow \sigma_y = 2\tau_{CRSS}$$

Slip will occur first in slip systems oriented close to this angle ( $\phi = \lambda = 45^\circ$ ) with respect to the applied stress

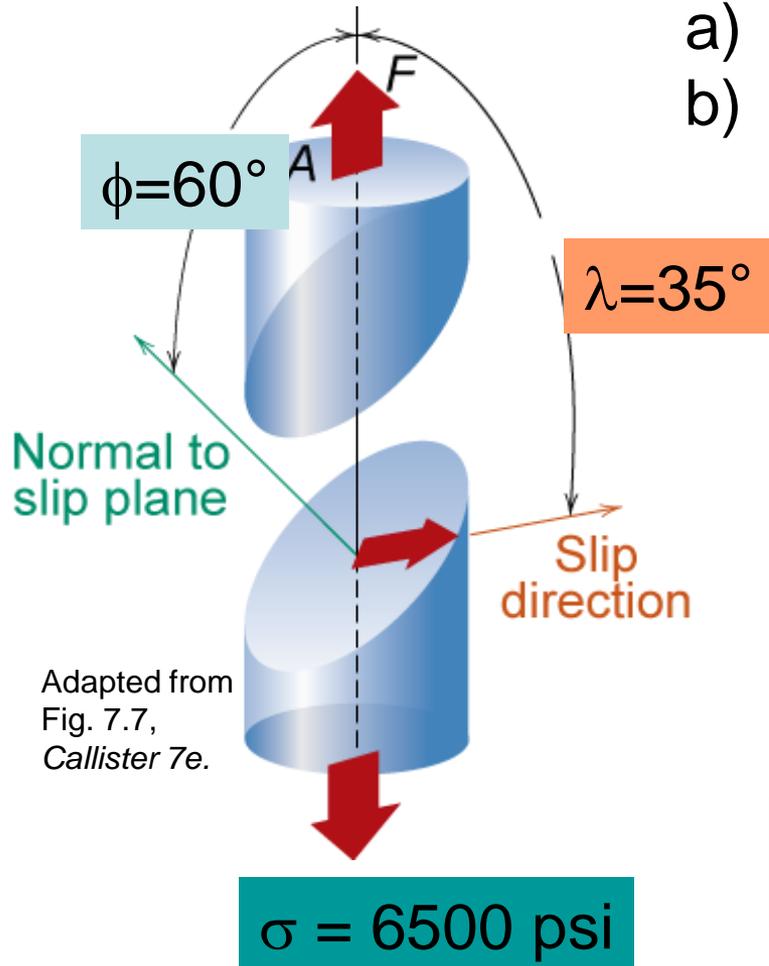
# Single Crystal Slip



Adapted from Fig. 7.9, *Callister 7e*.



# Ex: Deformation of single crystal



- Will the single crystal yield?
- If not, what stress is needed?

$$\tau_{\text{crss}} = 3000 \text{ psi}$$

$$\tau = \sigma \cos \lambda \cos \phi$$

$$\sigma = 6500 \text{ psi}$$

$$\begin{aligned} \tau &= (6500 \text{ psi}) (\cos 35^\circ) (\cos 60^\circ) \\ &= (6500 \text{ psi}) (0.41) \end{aligned}$$

$$\tau = 2662 \text{ psi} < \tau_{\text{crss}} = 3000 \text{ psi}$$

**So the applied stress of 6500 psi will not cause the crystal to yield.**

# Ex: Deformation of single crystal

What stress *is* necessary (i.e., what is the yield stress,  $\sigma_y$ )?

$$\tau_{\text{crss}} = 3000 \text{ psi} = \sigma_y \cos \lambda \cos \phi = \sigma_y (0.41)$$

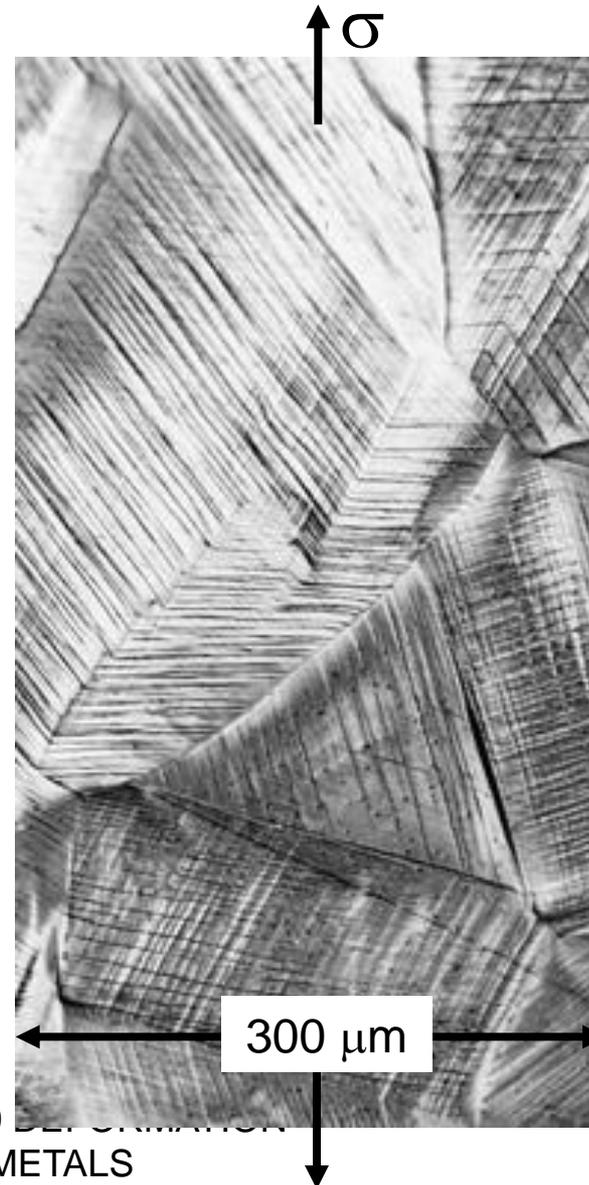
$$\therefore \sigma_y = \frac{\tau_{\text{crss}}}{\cos \lambda \cos \phi} = \frac{3000 \text{ psi}}{0.41} = \underline{\underline{7325 \text{ psi}}}$$

So for deformation to occur the applied stress must be greater than or equal to the yield stress

$$\sigma \geq \sigma_y = 7325 \text{ psi}$$

# Slip Motion in Polycrystals

- Stronger - grain boundaries pin deformations
- Slip planes & directions ( $\lambda$ ,  $\phi$ ) change from one crystal to another.
- $\tau_R$  will vary from one crystal to another.
- The crystal with the largest  $\tau_R$  yields first.
- Other (less favorably oriented) crystals yield later.



Adapted from Fig. 7.10, *Callister 7e*. (Fig. 7.10 is courtesy of C. Brady, National Bureau of Standards [now the National Institute of Standards and Technology, Gaithersburg, MD].)

# Plastic Deformation in Polycrystalline Materials

- Slip directions vary from crystal to crystal  $\Rightarrow$  Some grains are unfavorably oriented with respect to the applied stress (i.e.  $\cos\phi \cos\lambda$  low)
- Even those grains for which  $\cos\phi \cos\lambda$  is high may be limited in deformation by adjacent grains which cannot deform so easily
- Dislocations cannot easily cross grain boundaries because of changes in direction of slip plane and disorder at grain boundary
- **As a result, polycrystalline metals are stronger than single crystals** (the exception is the perfect single crystal without any defects, as in whiskers)

# **FORMS OF HARDENING OR STRENGTHENING STRATEGIES OF METALS**

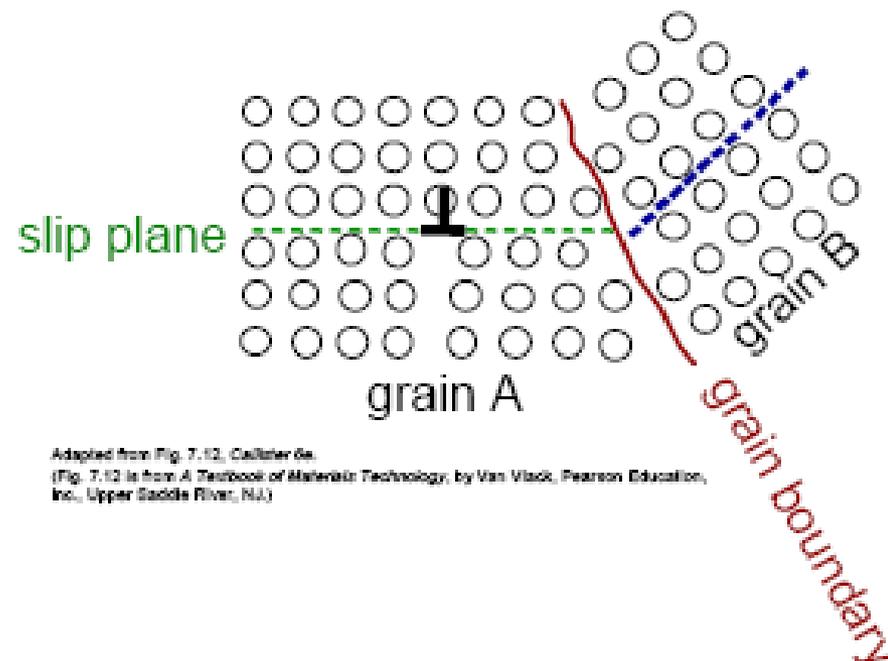
- 1. Smaller Grain Size (increase grain boundaries)**
- 2. Solution Treatment, Solid Solution Hardening (Add impurity atoms)**
- 3. Precipitation (Dispersion) Strengthening (hard 2<sup>nd</sup> phase particles)**
- 4. Work or Strain Hardening (cold working)**
- 5. Phase Transformation (hardening)**
- 6. Fiber Reinforcement**

# STRENGTHENING STRATEGIES

- To strengthen a metal: make it harder for dislocations to move!
- There are 4 strategies for strengthening:

## 1. REDUCE GRAIN SIZE

- Obstacle: Grain boundaries
- Obstacle "strength" increases with misorientation.
- Smaller grain size  
⇒ more barriers to slip.

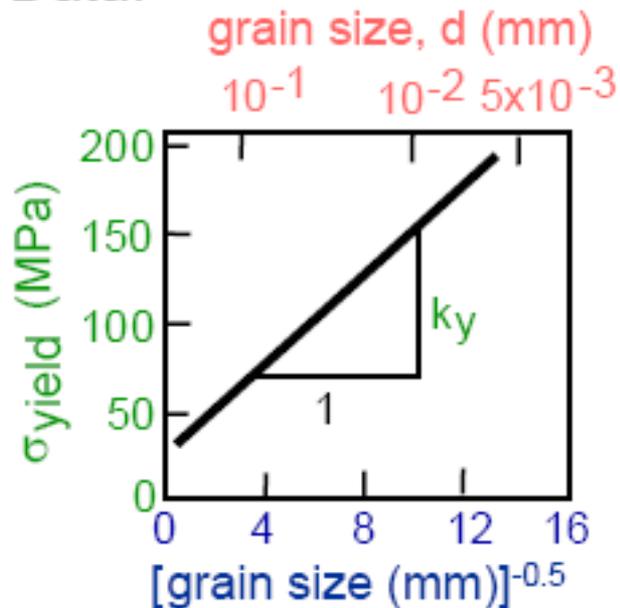


# GRAIN SIZE STRENGTHENING: AN EXAMPLE

- Cu - 30 wt% Zn brass alloy

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

- Data:



Adapted from Fig. 7.13, Callister 6e.  
(Fig. 7.13 is adapted from H. Suzuki, "The Relation  
Between the Structure and Mechanical Properties of  
Metals", Vol. II, National Physical Laboratory  
Symposium No. 15, 1963, p. 524.)

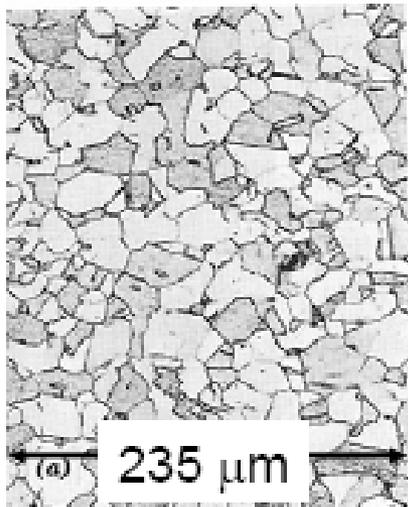


Adapted from Fig. 4.11(c), Callister 6e. (Fig. 4.11(c) is  
courtesy of J.E. Burke, General Electric Co.)

# ANISOTROPY in $\sigma_y$

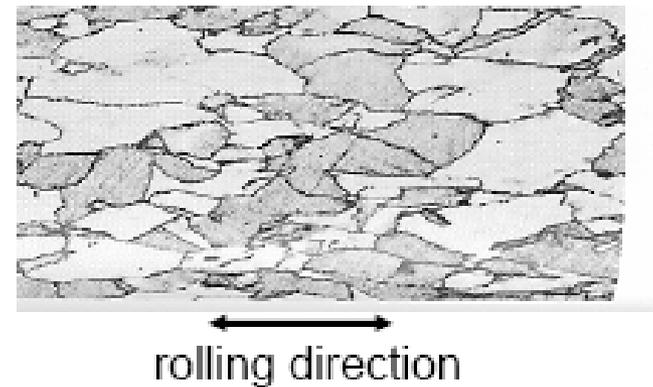
- Definition: different values in different directions.
- Can be induced by rolling a polycrystalline metal.

before rolling



Isotropic:

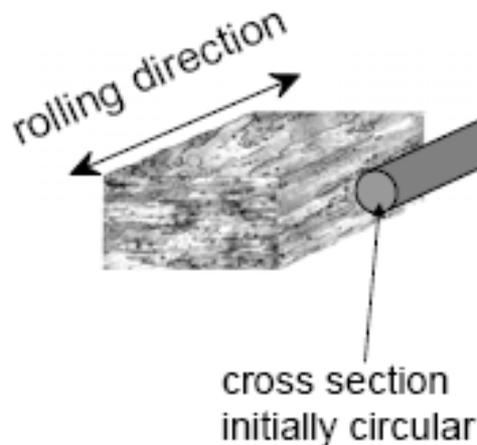
after rolling



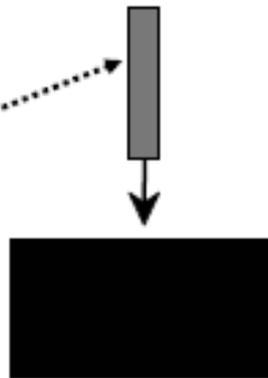
Anisotropic:

# ANISOTROPY IN DEFORMATION

1. Cylinder of tantalum machined from a rolled plate:



2. Fire cylinder at a target.



3. Deformed cylinder

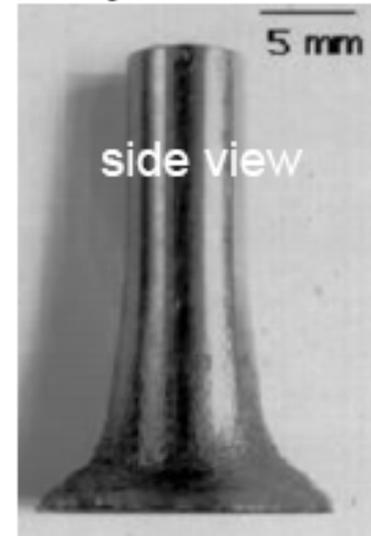
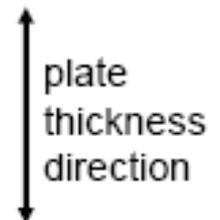
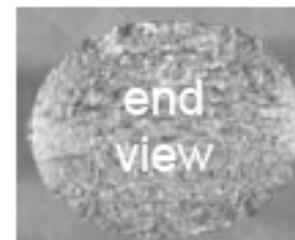
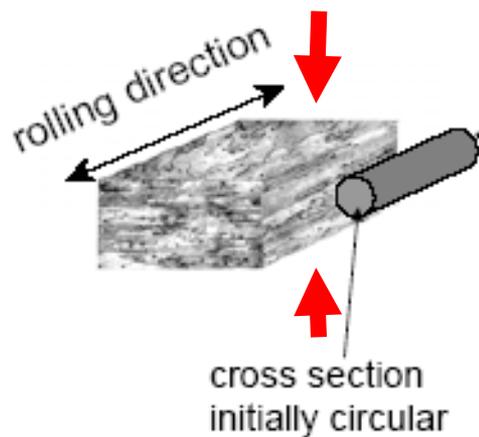


Photo courtesy of G.T. Gray II, Los Alamos National Lab. Used with permission.

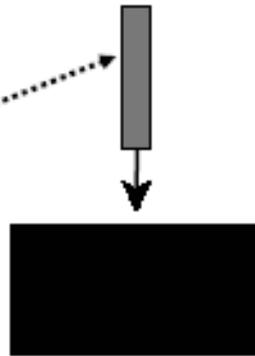


# ANISOTROPY IN DEFORMATION

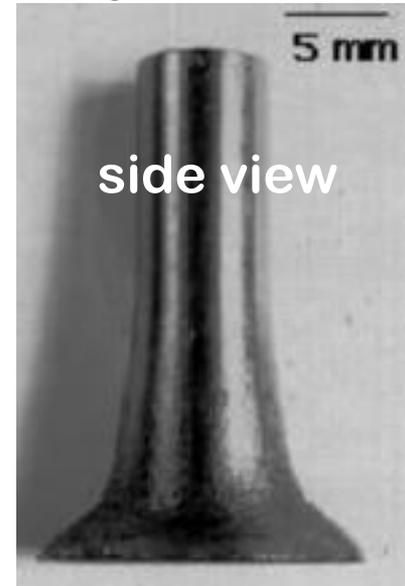
1. Cylinder of Tantalum machined from a rolled plate:



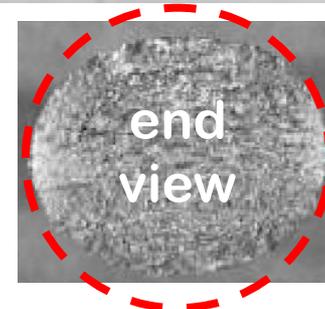
2. Fire cylinder at a target.



3. Deformed cylinder



Photos courtesy of G.T. Gray III, Los Alamos National Labs. Used with permission.

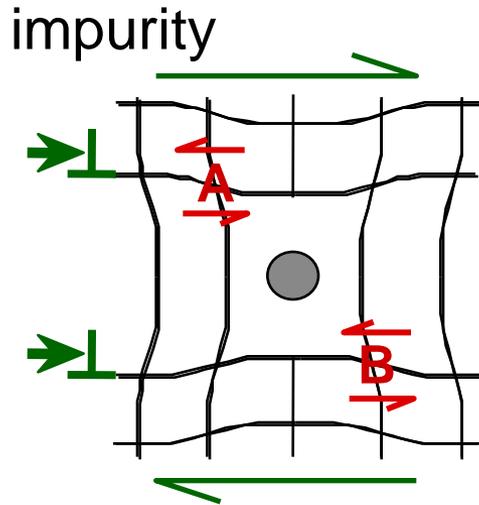


↑  
plate thickness direction  
↓

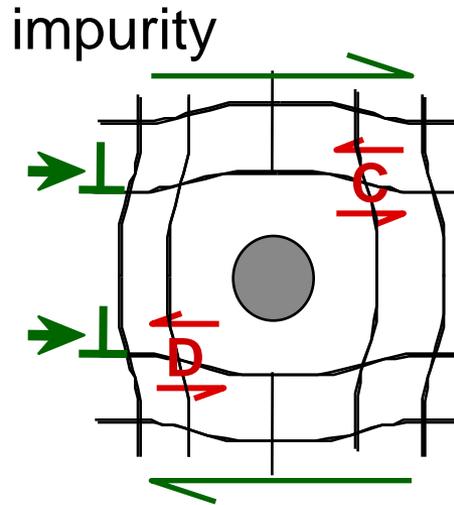
- The noncircular end view shows: anisotropic deformation of rolled material.

# 4 Strategies for Strengthening: 2: Solid Solutions

- Impurity atoms distort the lattice & generate stress.
- Stress can produce a barrier to dislocation motion.
- Smaller substitutional impurity
- Larger substitutional impurity



Impurity generates local stress at **A** and **B** that opposes dislocation motion to the right.



Impurity generates local stress at **C** and **D** that opposes dislocation motion to the right.

## Strategy #2: Solid Solutions

- **Alloyed metals are usually stronger than their pure base metals counter parts.**

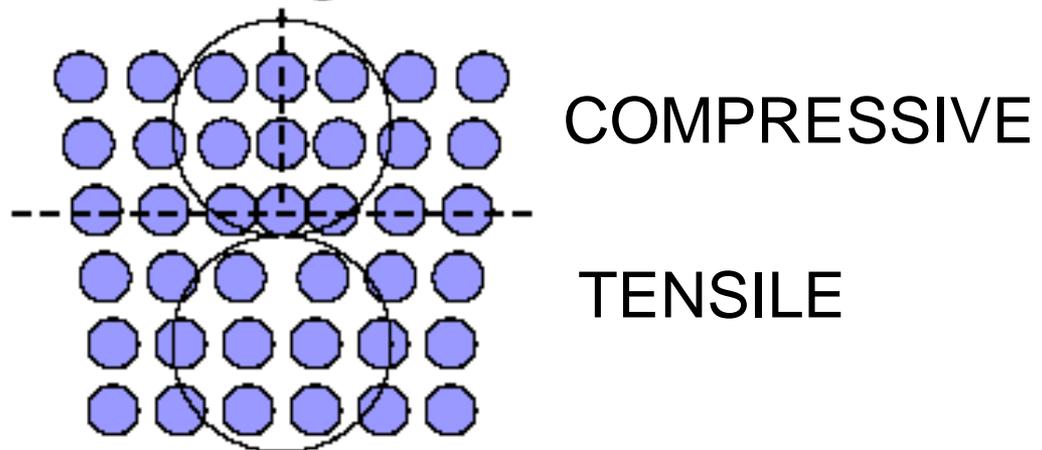
**Why ?** Interstitial or substitutional impurities in a solution cause lattice strain, aka *distortions in the lattice*

**Then ?**

- Strain field around the impurities interact with dislocation strain fields and *impede dislocation motion*.
- Impurities tend to diffuse and *segregate around the dislocation core* to find atomic sites more suited to their radii. This reduces the overall strain energy and “*anchor*” the dislocation. Motion of the dislocation core away from the impurities moves it to a region of lattice where the atomic strains are greater, where lattice strains due to dislocation is no longer compensated by the impurity atoms.

# Interactions of the Stress Fields

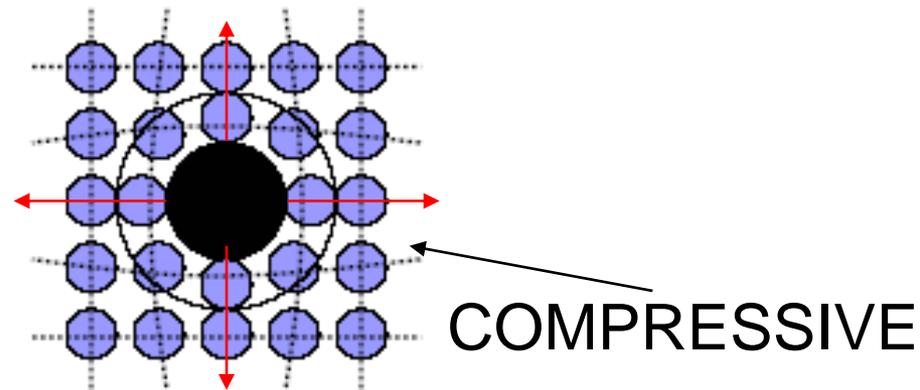
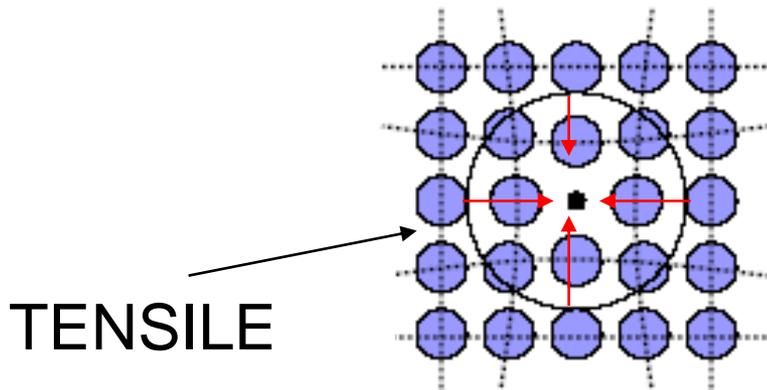
- Consider the stresses around an edge dislocation...
  - Extra half plane acts like wedge



- Consider the stresses around an impurity atom...

Small substitutional atom

Large substitutional atom



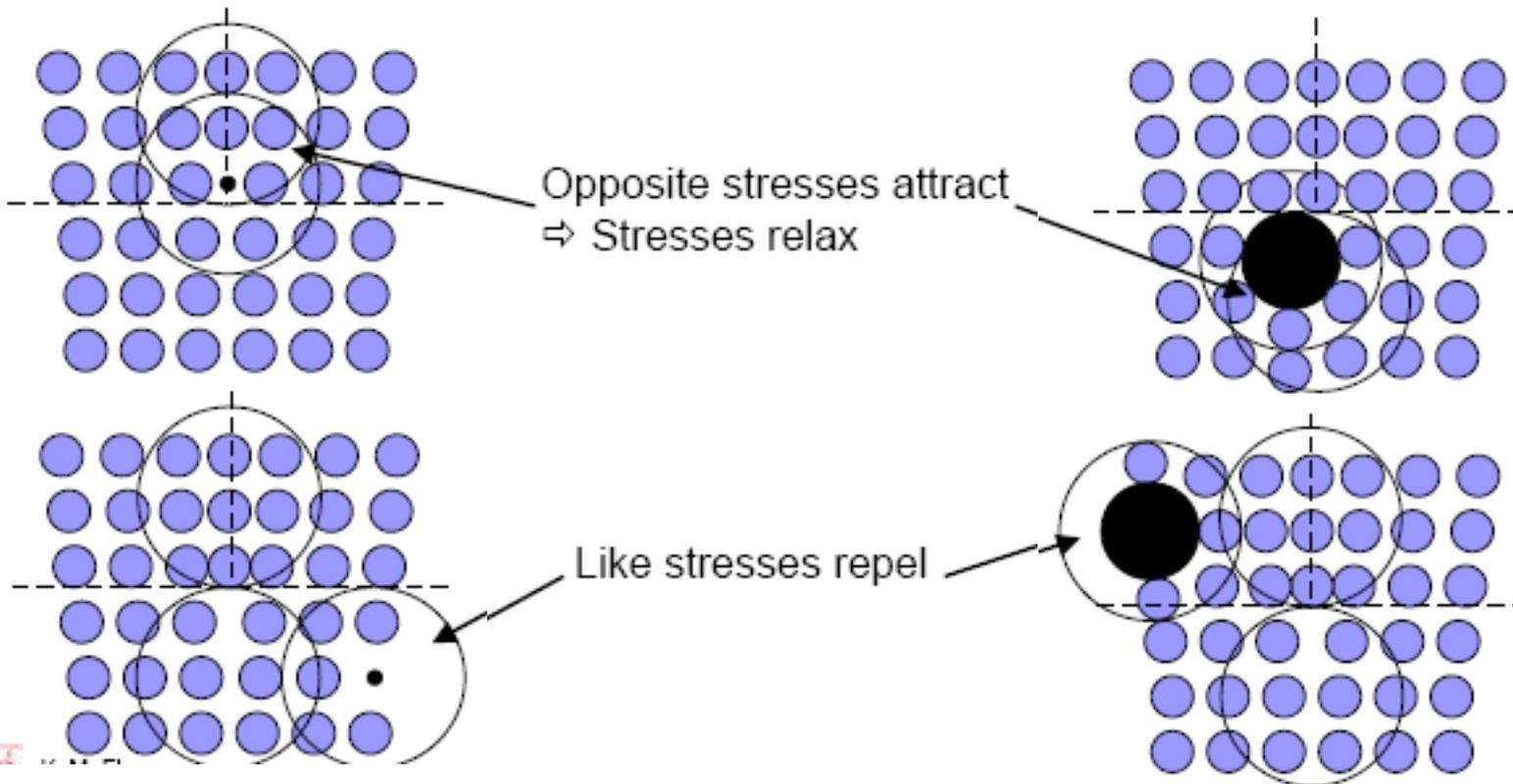
# STRENGTHENING STRATEGIES

## 2. SOLID SOLUTIONS

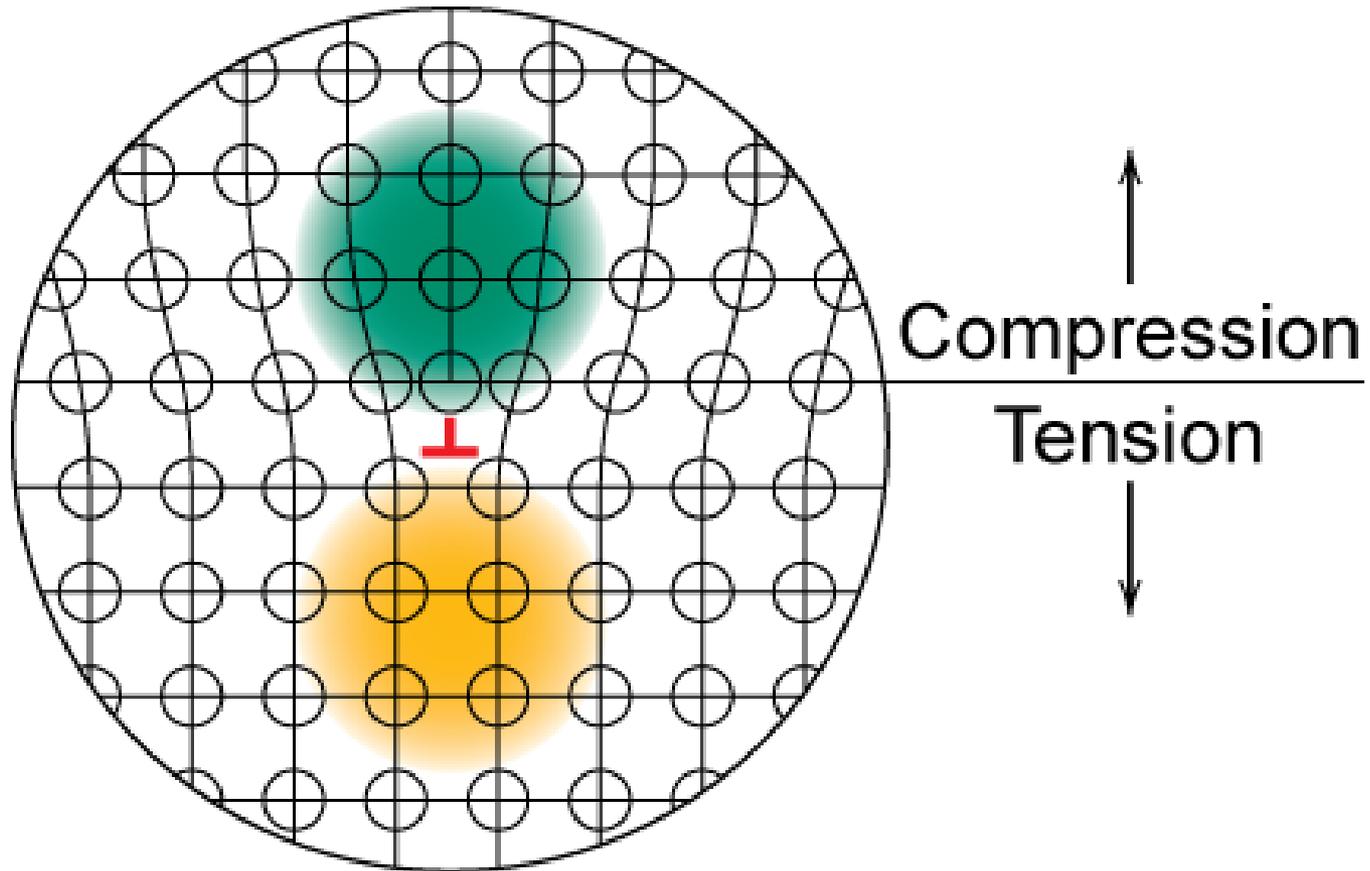
- Overlapping stresses produce an obstacle to dislocation motion
- Moving dislocation past impurity *increases strain energy*

Small substitutional atom

Large substitutional atom

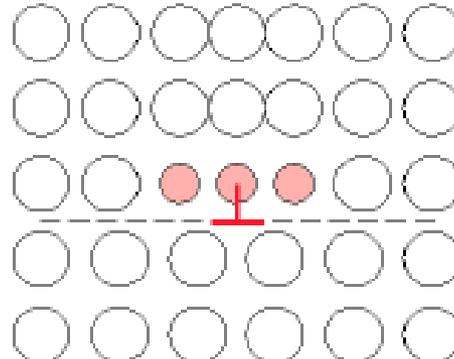
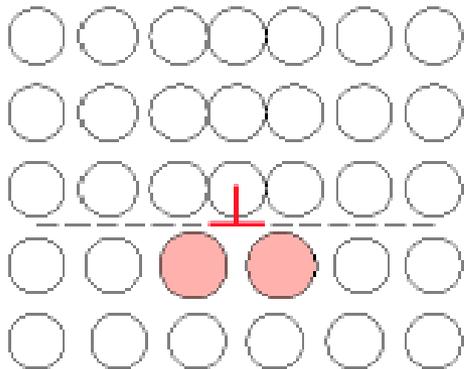
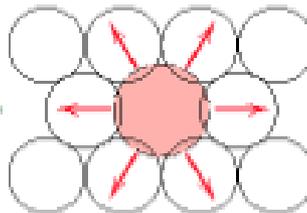
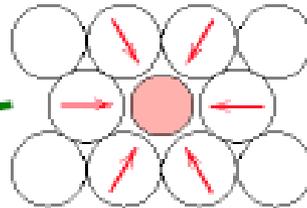
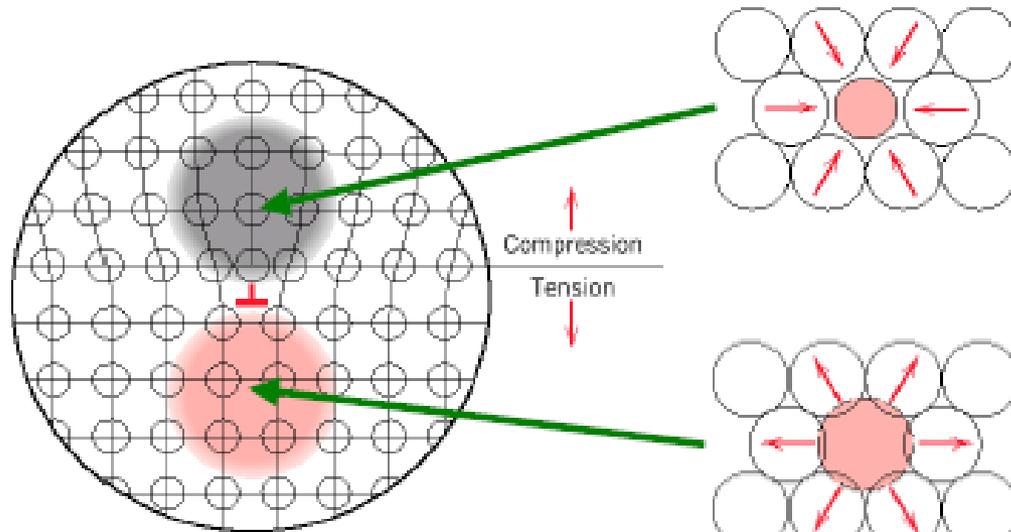


# Stress Concentration at Dislocations



Adapted from Fig. 7.4,  
*Callister 7e.*

# Impurity Segregation

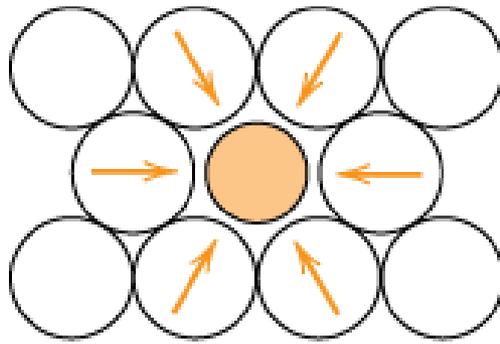


Impurities tend to segregate at energetically favorable areas around the dislocation core and partially decrease the overall stress field generated around the dislocation core.

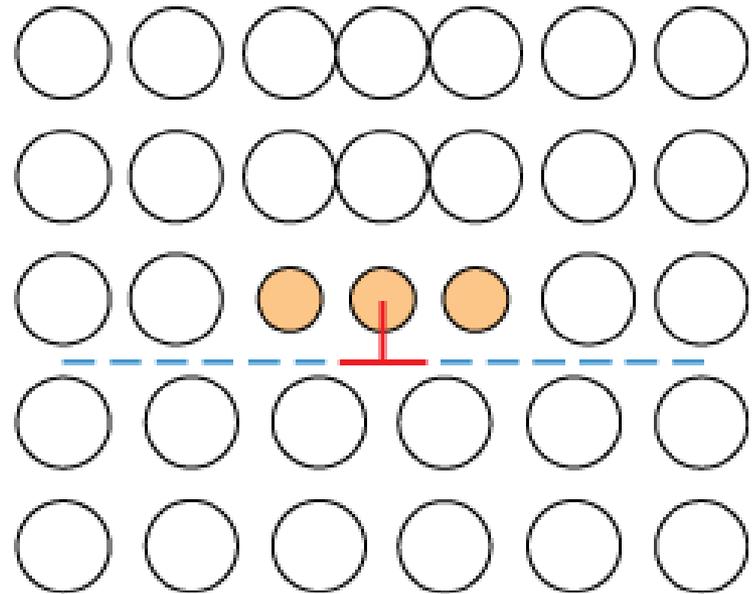
However, when stress is applied more load is needed to move dislocations with impurity atoms segregated to its core !

# Strengthening by Alloying

- small impurities tend to concentrate at dislocations
- reduce mobility of dislocation  $\therefore$  increase strength



(a)

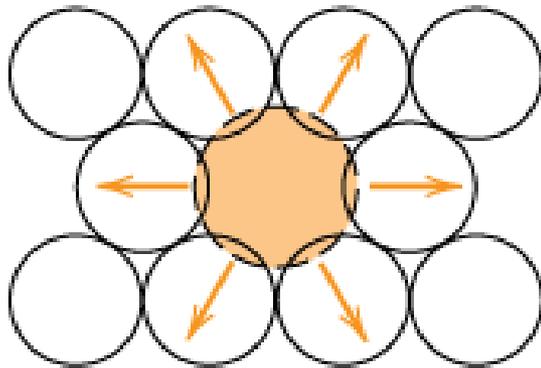


(b)

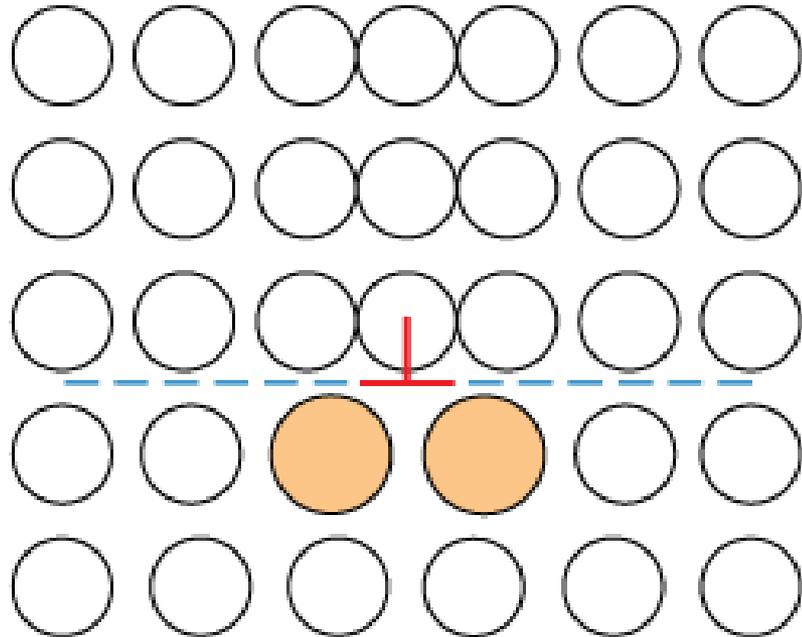
Adapted from Fig.  
7.17, Callister 7e.

# Strengthening by alloying

- large impurities concentrate at dislocations on low density side



(a)

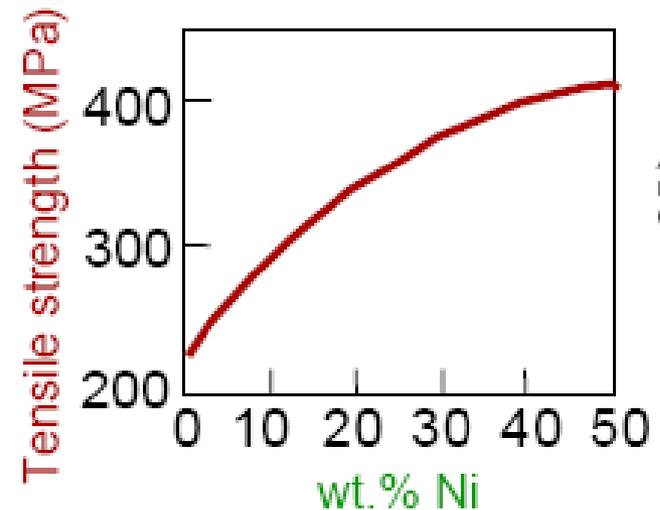
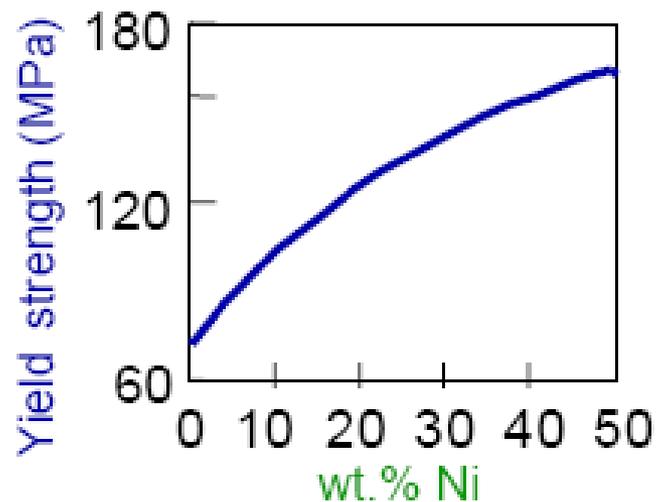


(b)

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

# EXAMPLE OF SOLID SOLUTION STRENGTHENING IN COPPER

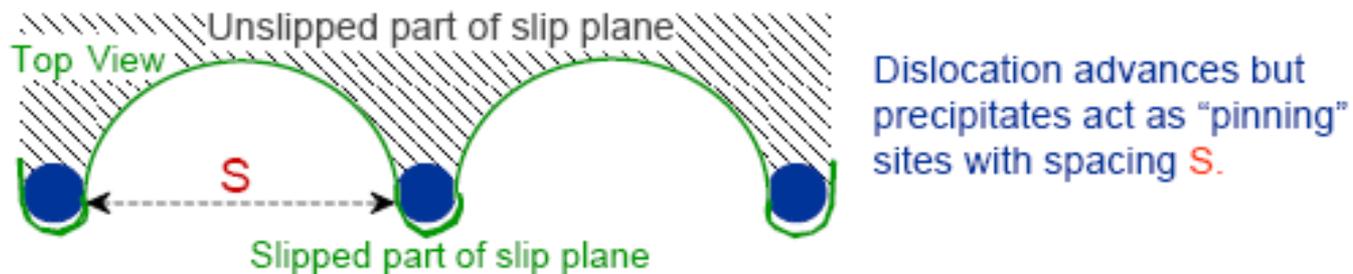
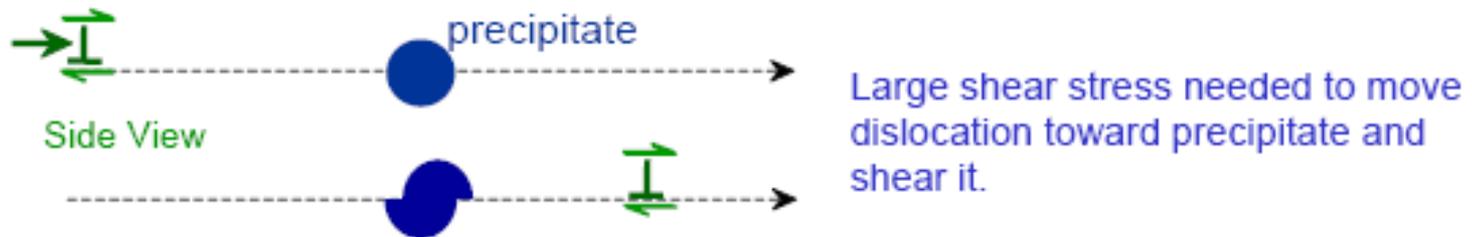
- Alloying with Ni increases  $\sigma_y$  and TS.



# STRENGTHENING STRATEGIES

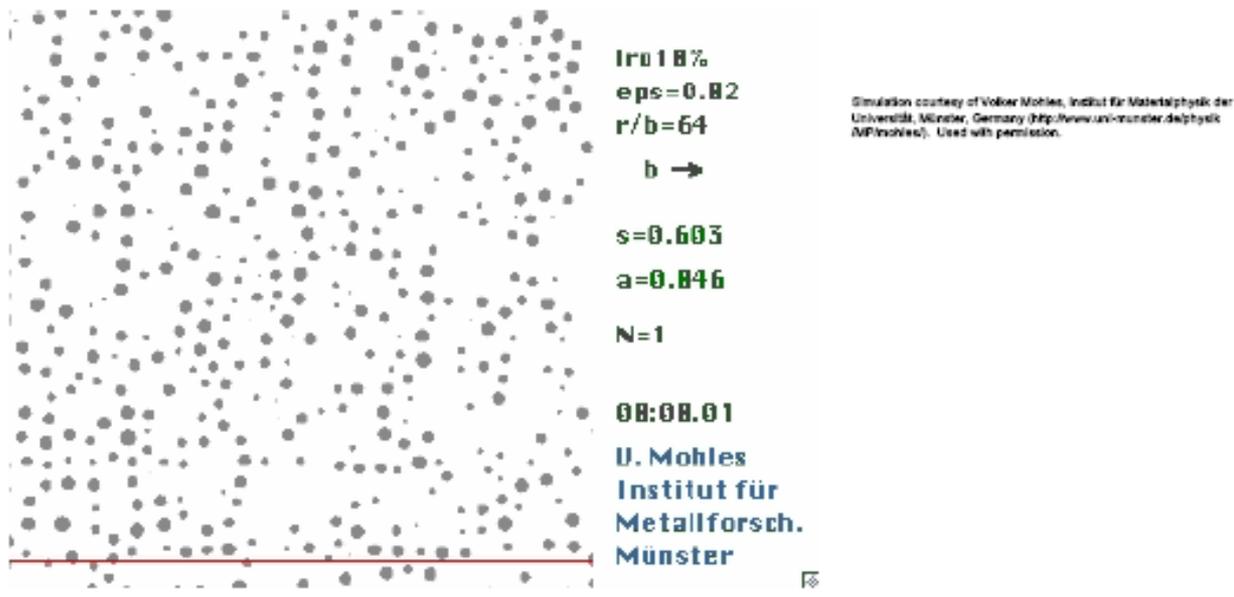
## 3. PRECIPITATION STRENGTHENING

- **Obstacle: hard particles (2<sup>nd</sup> phase)**  
Ex: Ceramics in metals (SiC in Iron or Aluminum).
- Hard precipitates are difficult to shear.



# SIMULATION: PRECIPITATION STRENGTHENING

- View onto slip plane of Nimonic PE16 (nickel alloy)
- Precipitate volume fraction: 10%
- Average precipitate size: 64 b (b = 1 atomic slip distance)



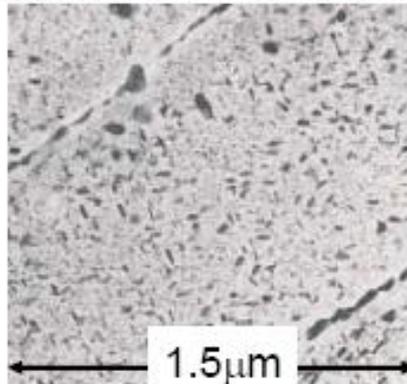
# APPLICATION: PRECIPITATION STRENGTHENING

- Fuselage and wing material



Adapted from Fig. 11.0, Callister 6e.  
(Fig. 11.0 is courtesy of G.H. Narayanan  
and A.G. Miller, Boeing Commercial  
Airplane Company.)

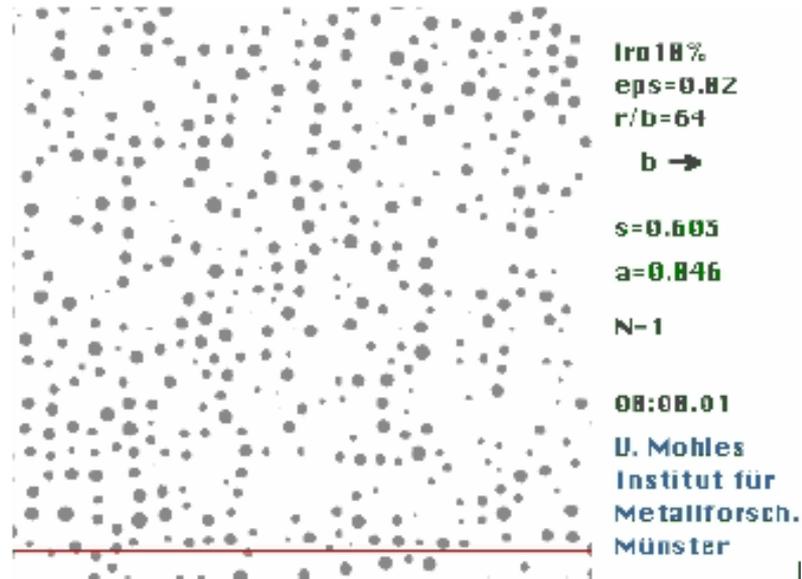
- Aluminum is strengthened with precipitates formed by alloying.



Adapted from Fig. 11.24, Callister 6e.  
(Fig. 11.24 is courtesy of G.H. Narayanan  
and A.G. Miller, Boeing Commercial  
Airplane Company.)

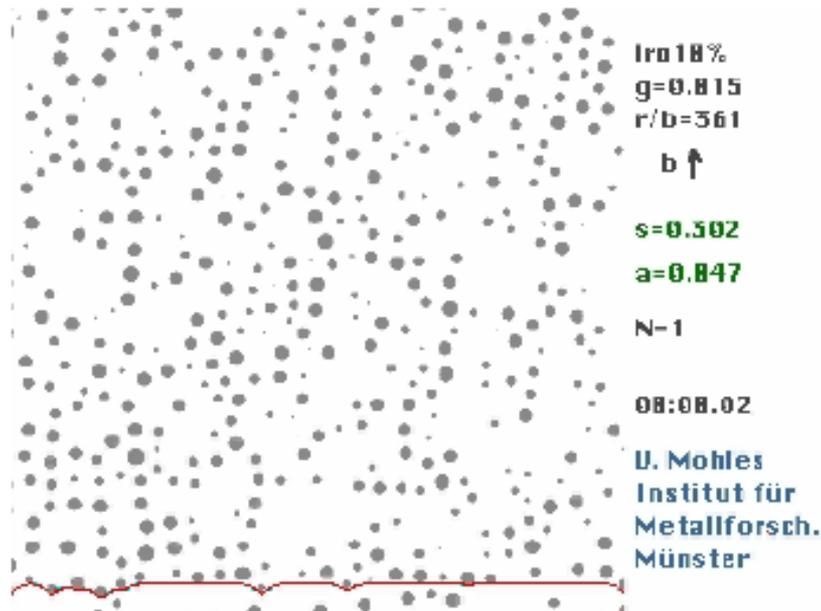
# SIMULATION: DISLOCATION MOTION PEAK AGED MATERIAL

- Peak-aged
  - avg. particle size =  $64b$
  - closer spaced particles efficiently stop dislocations.



# SIMULATION: DISLOCATION MOTION OVERAGED MATERIAL

- Over-aged
  - avg. particle size =  $361b$
  - more widely spaced
  - particles not as effective.



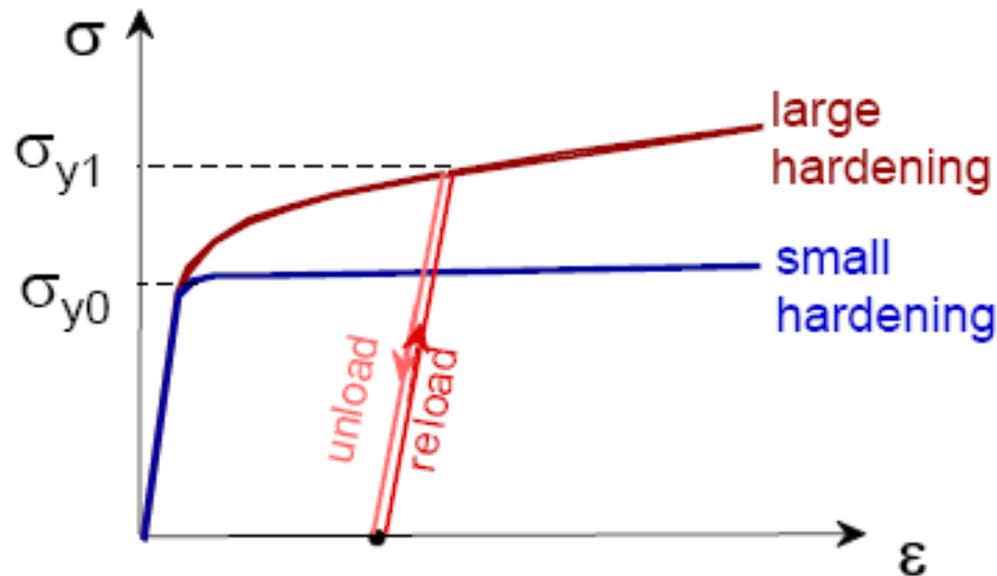
# STRENGTHENING STRATEGIES

## 4. COLD WORK (%CW)

(aka WORK or STRAIN HARDENING)

*aka: also known as*

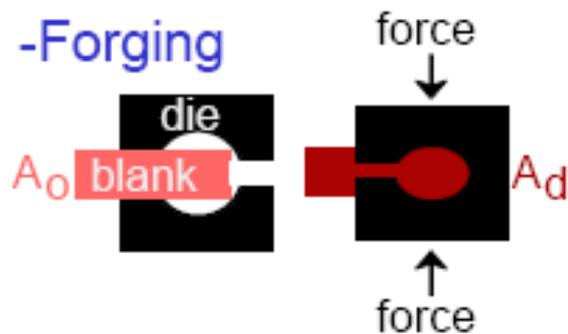
- Obstacle: other dislocations
- $\sigma_y$  for plastically deformed sample is higher than for annealed sample (strength increases with strain) due to **hardening**



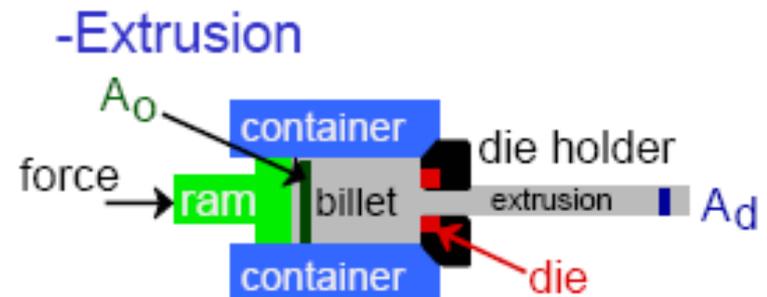
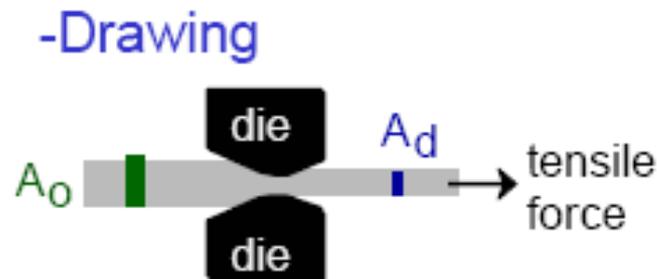
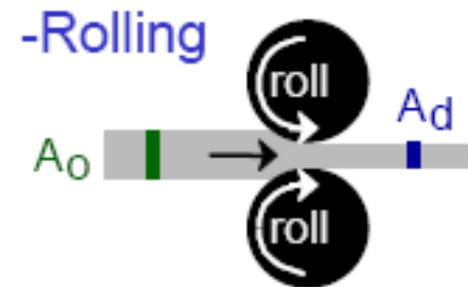
# STRENGTHENING STRATEGIES

## 4. COLD WORK (%CW)

- Room temperature deformation
- Common forming operations change the cross sectional area:



Adapted from Fig. 11.7, Callister 6e.

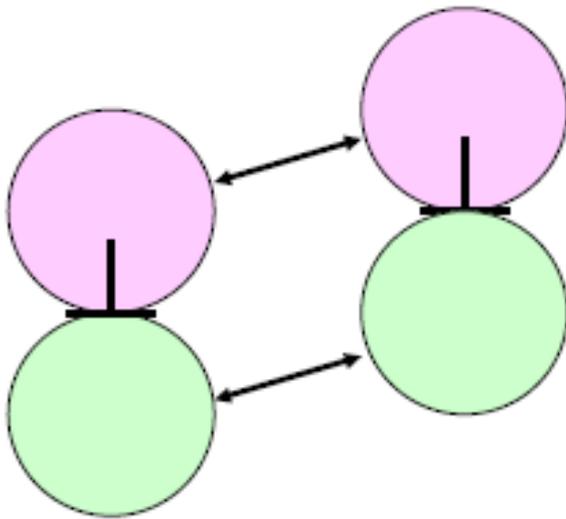


# ORIGIN OF WORK HARDENING

## DISLOCATION-DISLOCATION TRAPPING

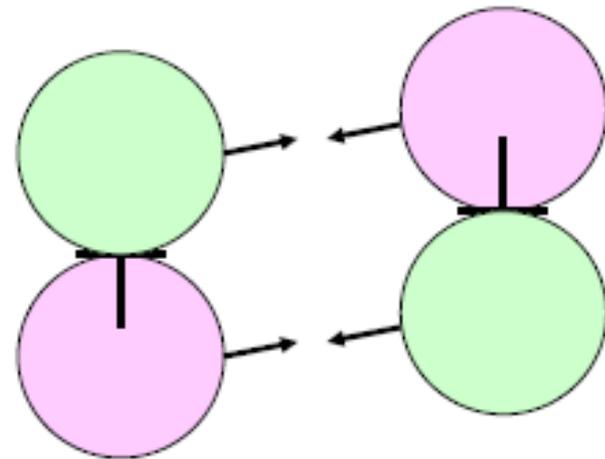
Like dislocations repel

⇒ Overlapping extra half planes would increase lattice strain, cost energy



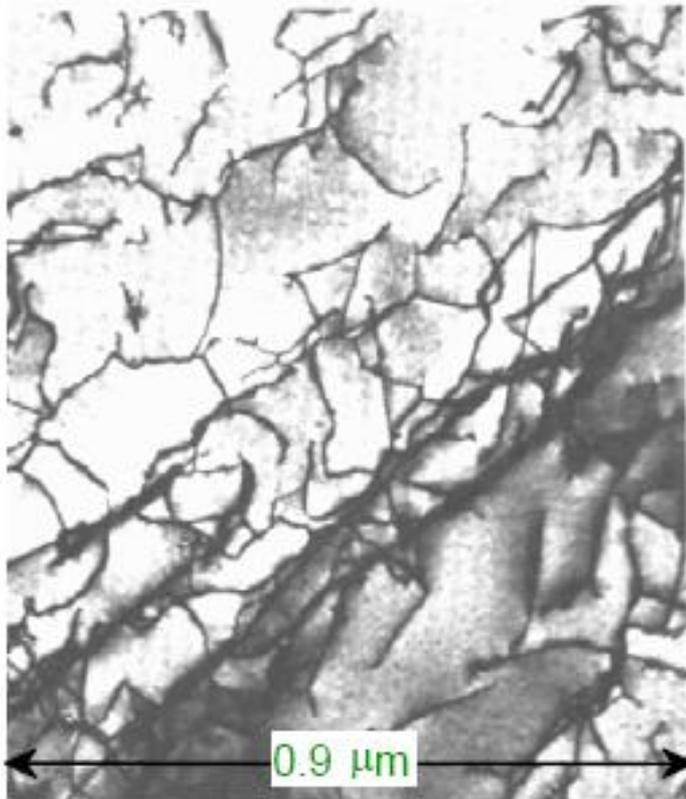
Opposite dislocations attract

⇒ Could overlap and “annihilate” extra half planes!



# DISLOCATIONS DURING COLD WORK

- Ti alloy after cold working:



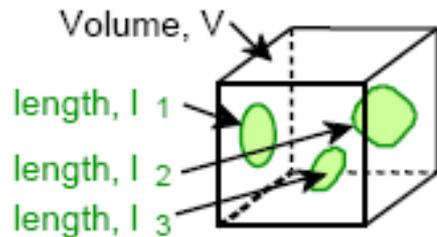
Adapted from Fig. 4.6, Callister 6e.  
(Fig. 4.6 is courtesy of M.R. Pichler,  
Michigan Technological University.)

- Dislocations become entangled with one another during **cold work**.
- More dislocations are generated.
- Dislocation motion becomes more difficult.

# RESULT OF COLD WORK

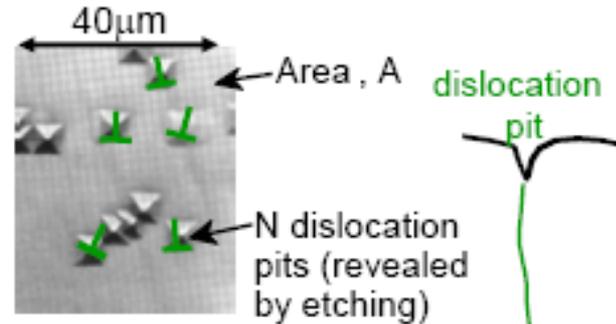
- Dislocation density ( $\rho_d$ ) goes up:  
Carefully prepared sample:  
Heavily deformed sample:

- Ways of measuring dislocation density:



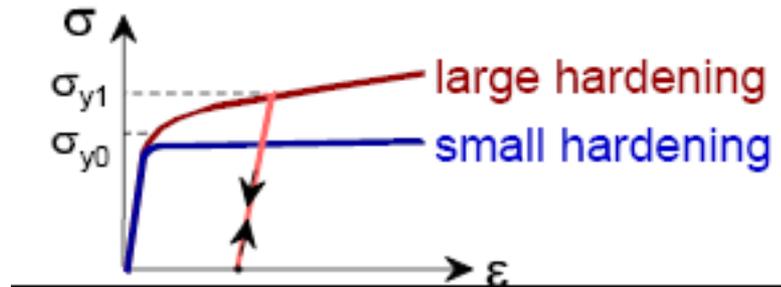
$$\rho_d = \frac{l_1 + l_2 + l_3}{V} = \frac{\sum l}{V}$$

OR

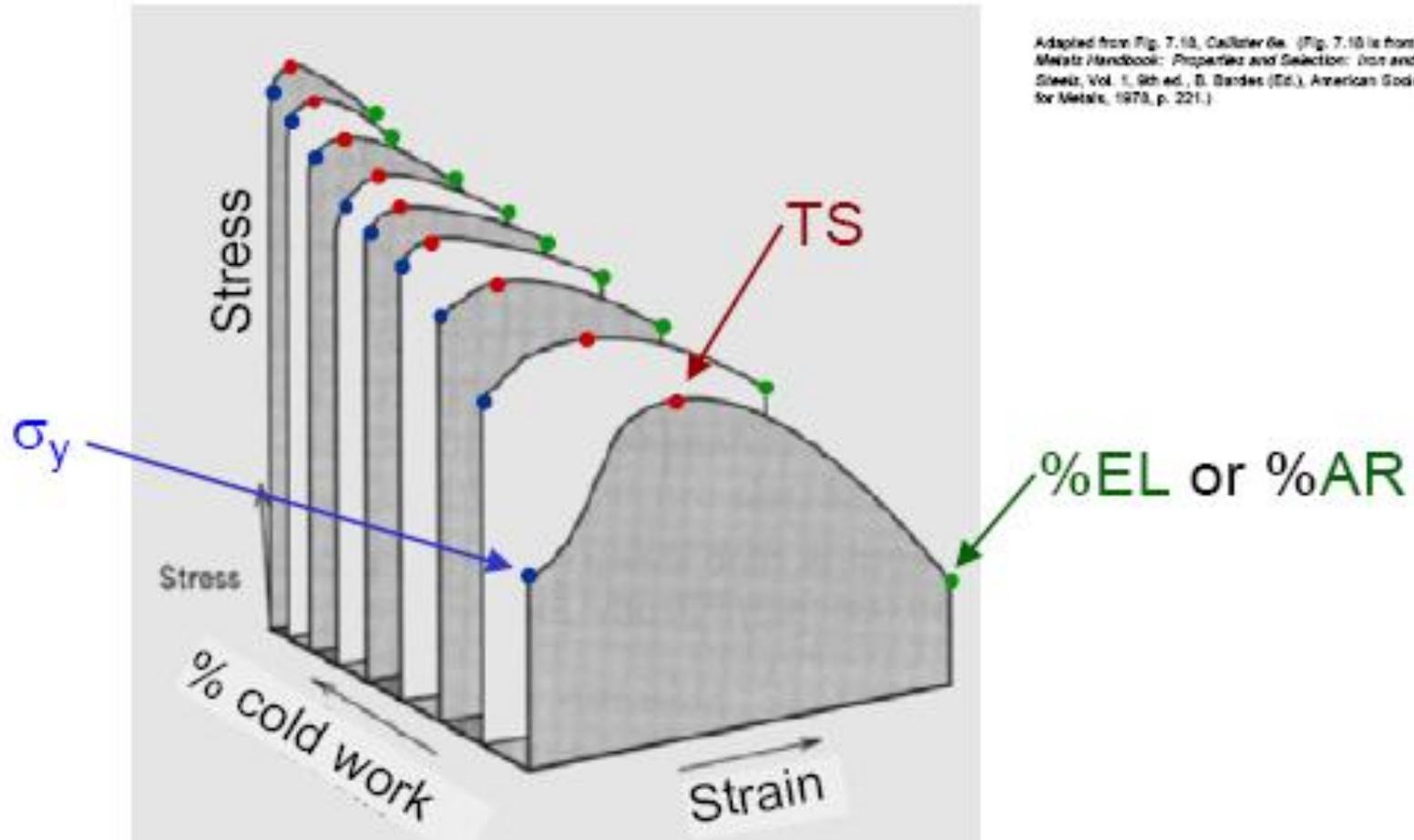


$$\rho_d = \frac{N}{A}$$

- Yield stress increases as  $\rho_d$  increases:



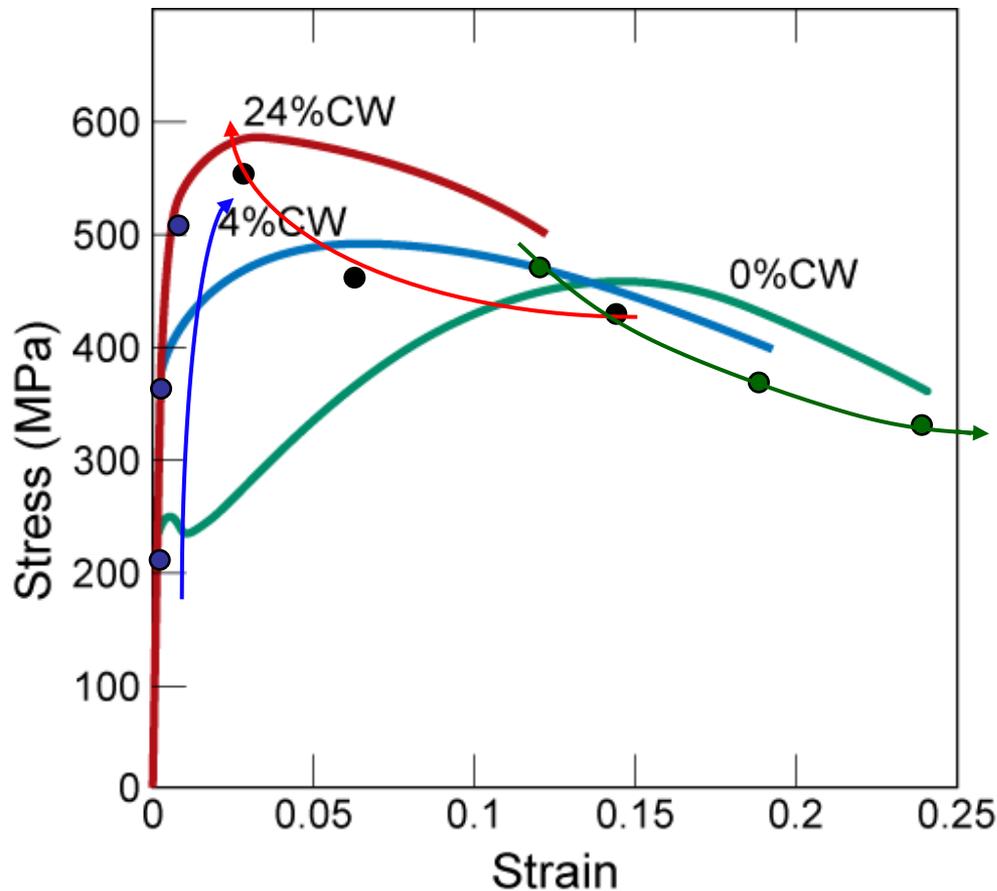
# IMPACT OF COLD WORK



# Impact of Cold Work

As cold work is increased

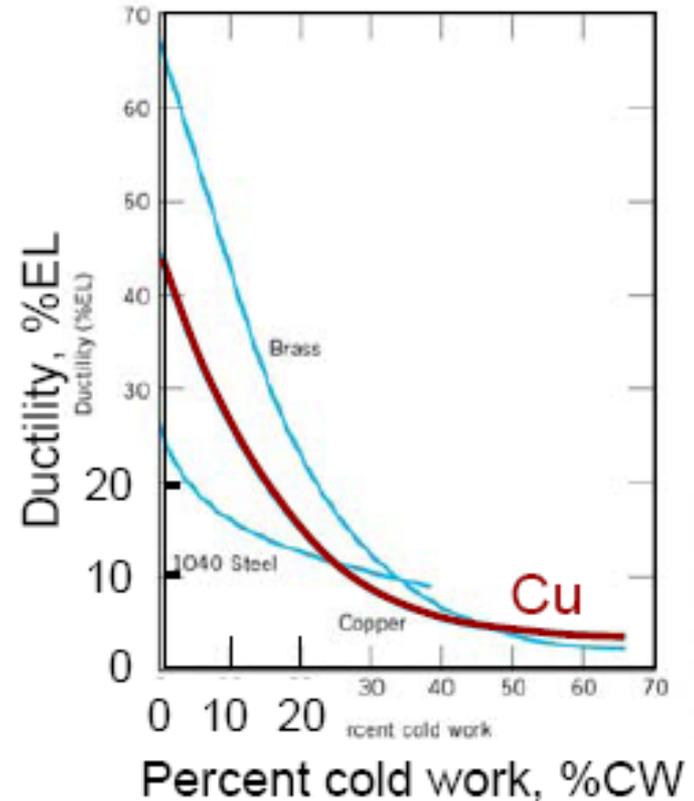
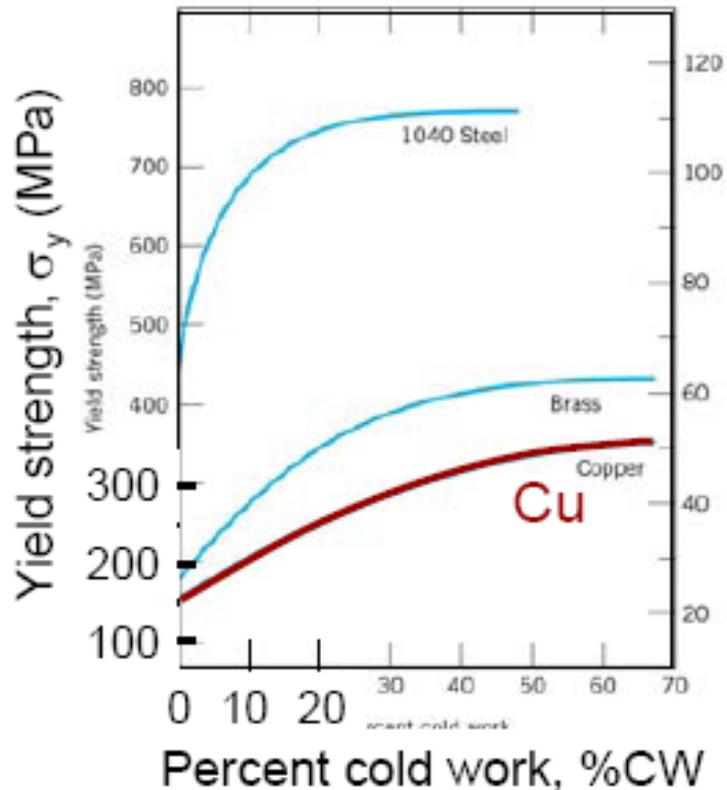
- Yield strength ( $\sigma_y$ ) increases.
- Tensile strength ( $TS$ ) increases.
- Ductility ( $\%EL$  or  $\%AR$ ) decreases.



Adapted from Fig. 7.20, Callister 7e.

# COLD WORK ANALYSIS

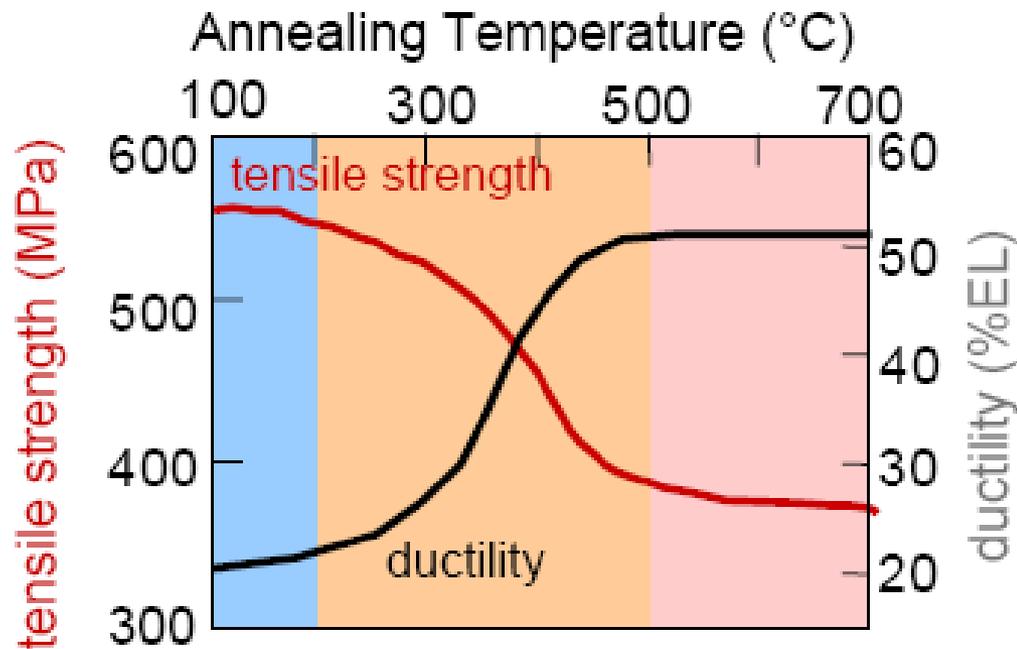
Problem: Produce a Cu bar with  $\sigma_y > 200$  MPa and %EL > 15%



Design guideline:

# RESTORING DUCTILITY

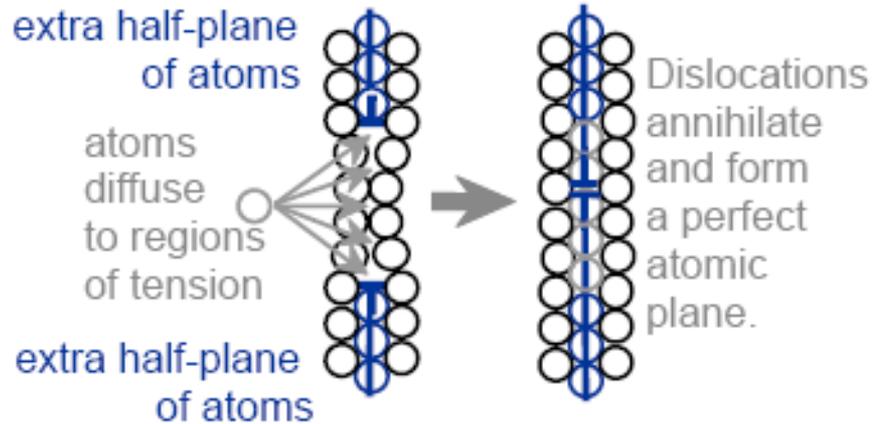
- 1 hour “heat treatment” at different annealing temperatures:  
⇒  $TS \downarrow$  and  $\%EL \uparrow$
- Effects of cold work are reversed!



# RECOVERY

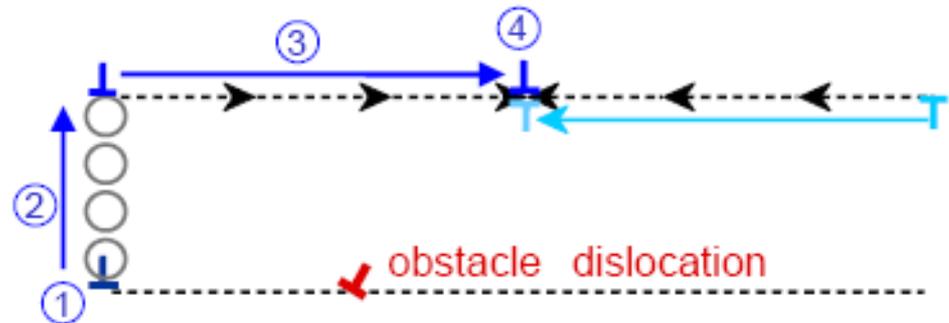
**Annihilation** reduces dislocation density.

- Scenario 1



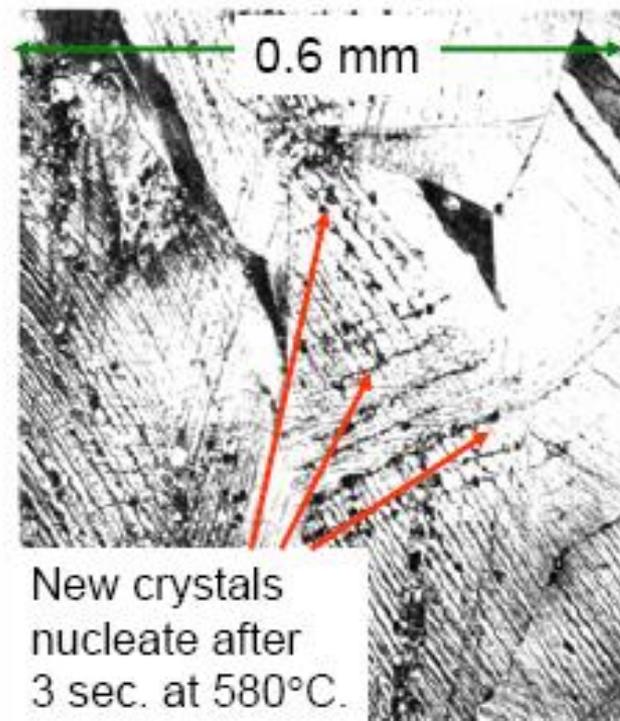
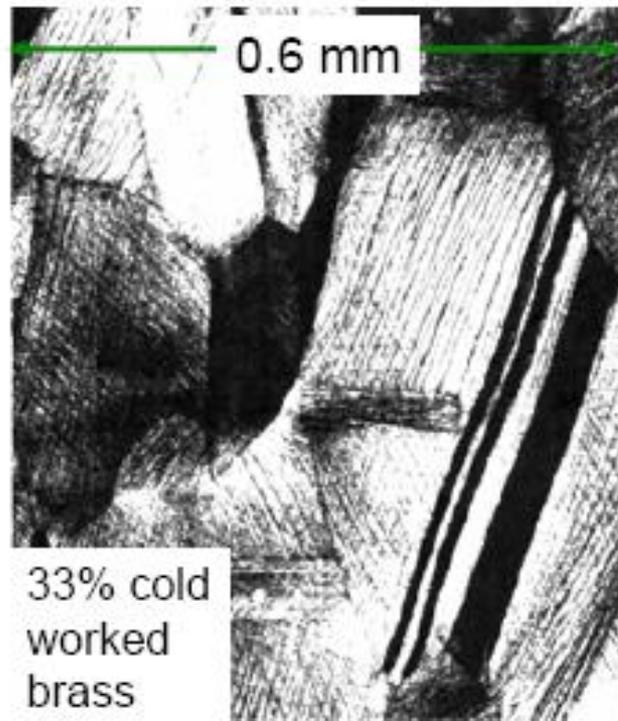
- Scenario 2

1. Dislocation blocked; can't move to the right
2. Grey atoms leave by vacancy diffusion (dislocation climb)
3. "Climbed" dislocation moves on new slip plane
4. Opposite dislocations meet and annihilate



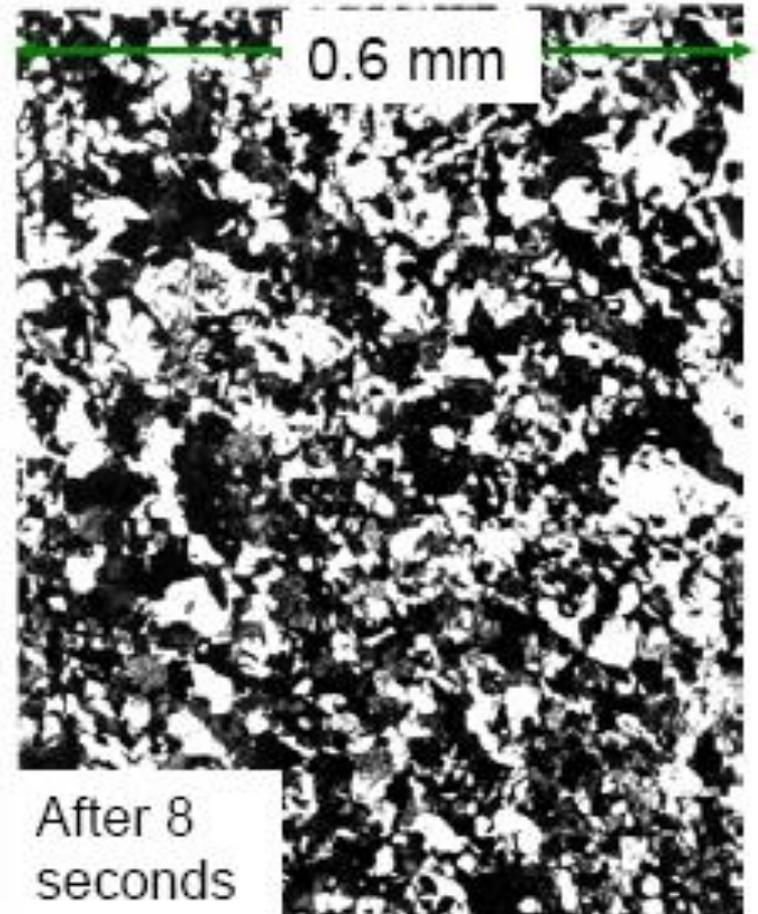
# RECRYSTALLIZATION

- New crystals are formed
  - have a small disl. density
  - are small
  - consume cold-worked crystals.



# FURTHER RECRYSTALLIZATION

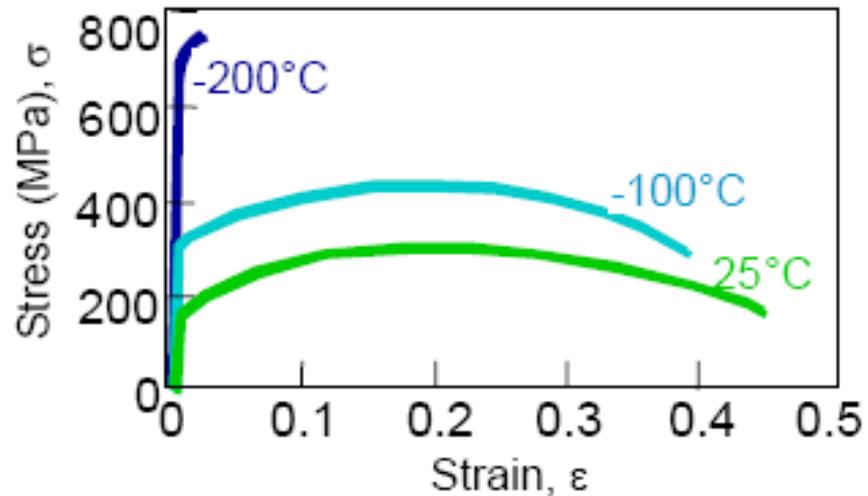
- All cold-worked crystals are consumed.



# OTHER FACTORS THAT AFFECT STRENGTH/DUCTILITY

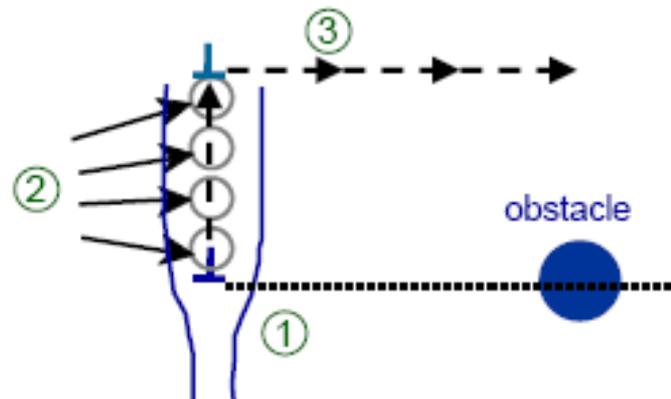
## 1. TEMPERATURE

- Results for polycrystalline iron:



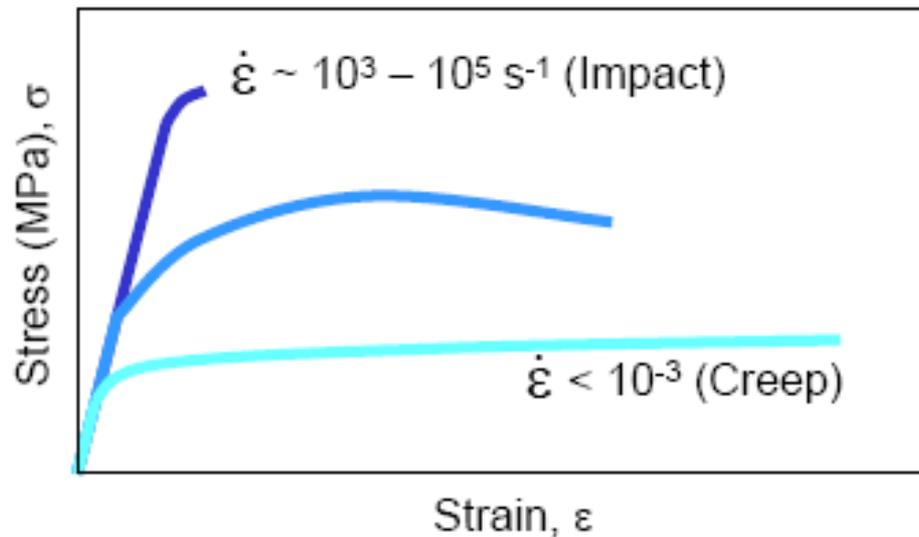
- Why?** Vacancies help dislocations move past obstacles.

- Dislocation trapped by obstacle
- Vacancies replace atoms on half plane (dislocation climb)
- Dislocation glides past obstacle



# OTHER FACTORS THAT AFFECT STRENGTH/DUCTILITY

## 2. STRAIN RATE



$$\sigma = K\dot{\epsilon}^m$$

$m$  = strain rate sensitivity exponent

- **Why?** Moving atoms takes time!

# SUMMARY

- Dislocations are observed primarily in metals and alloys.
- Making dislocation motion difficult increases strength.
- Strengthening strategies:
  - decrease grain size
  - add solid solution impurities
  - precipitate second phase particles
  - cold work
- Heating (**annealing**) can reduce dislocation density and increase grain size, which decreases strength.
- Temperature and strain rate also affect strength and ductility!

### 10.2.3 Work-Hardening and Recrystallization

A very low stress is required to move a single, isolated dislocation through a crystal. The strain produced when it runs out of the crystal is also small. Clearly, then, the generation of macroscopic strain requires the cooperative motion of a very large number of dislocations. The initial dislocation density in a metal is usually many orders of magnitude lower than that required to produce the fracture strain. Therefore, some mechanism must exist by which dislocations can be produced during plastic deformation.

In many commercial metal-working processes (section 10. 6), there is a limit to the amount of strain to which a part may be subjected without danger of cracking or tearing. For this reason, the material is often **annealed** or heated above its **recrystallization temperature** for a predetermined period of time. As shown in Fig.10.9, new, strain free grains are produced by this treatment. The softened material is then capable of further deformation. Annealing and recrystallization account for the elimination of a large number of dislocations.

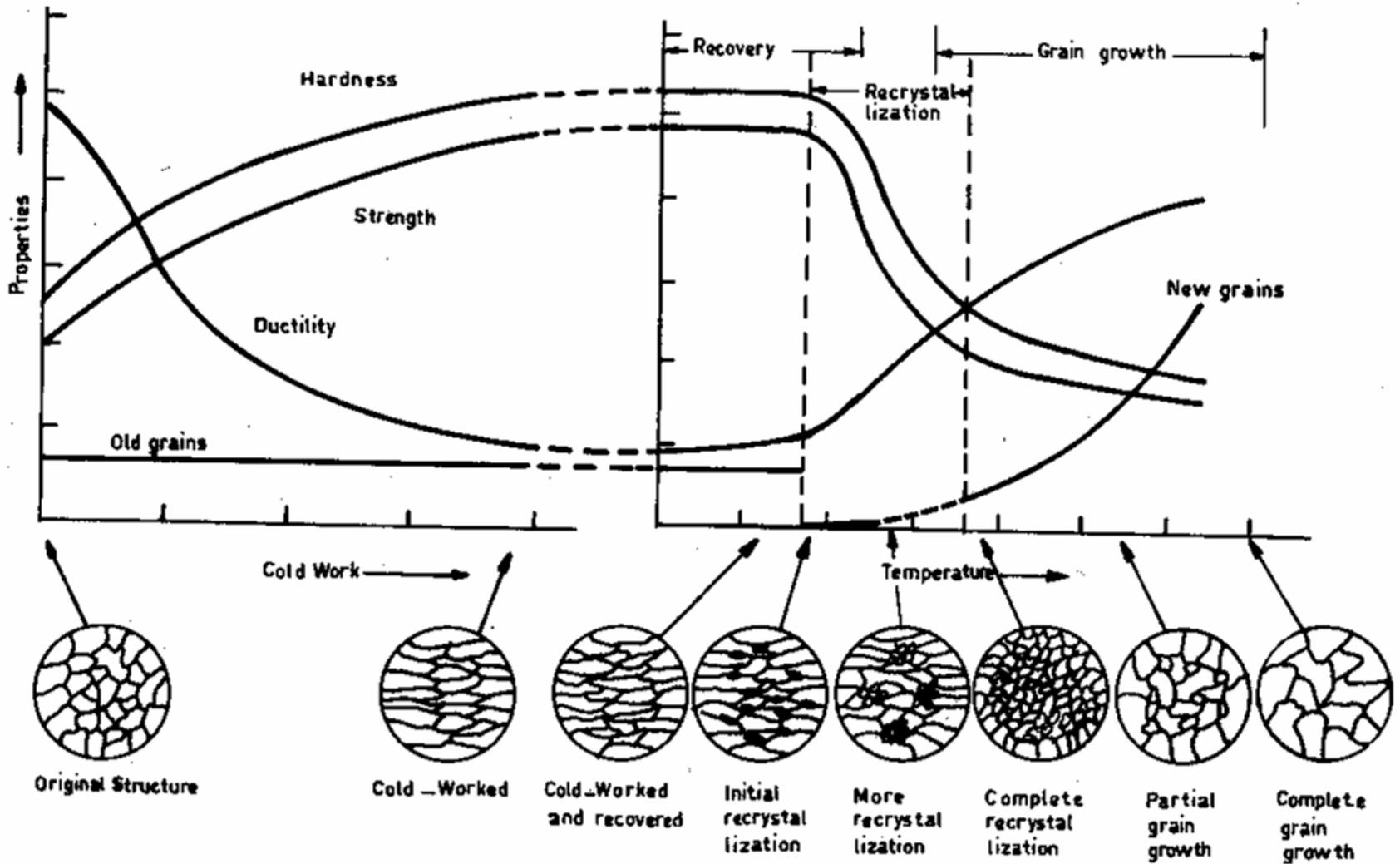
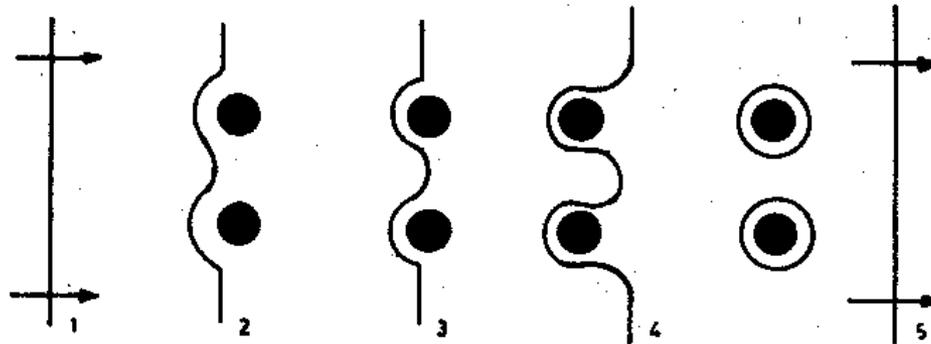


Fig.10.9 Annealing of cold-worked structured

## 10.2.4 Precipitation-or Dispersion-Hardening

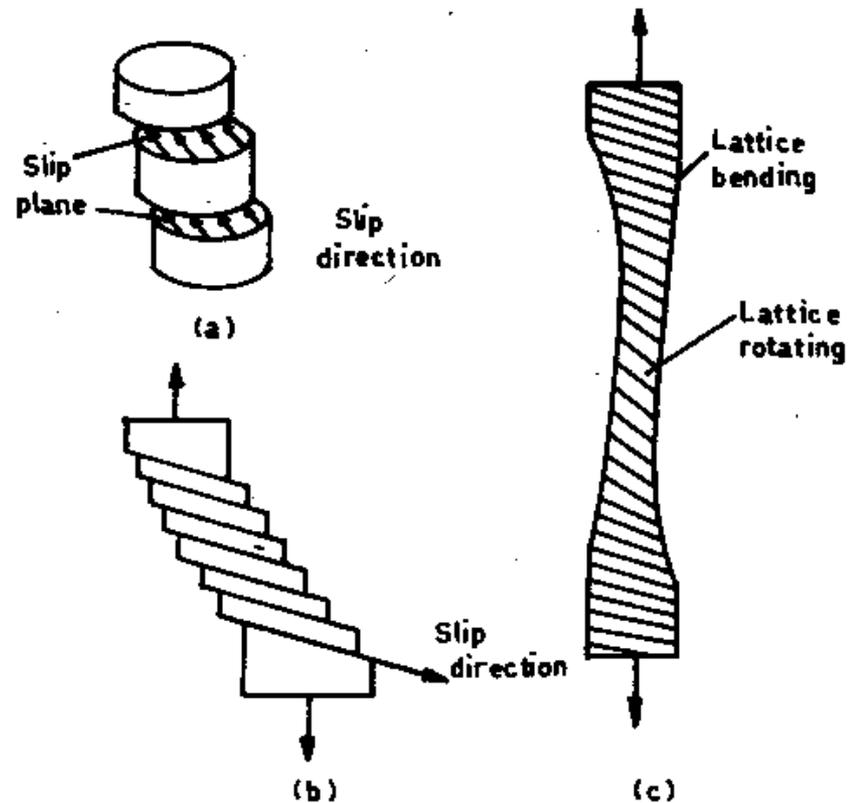
As explained in previous sections, interstitial and substitutional atoms affect movement of dislocations. Hard, second-phase particles distributed in a matrix behave similarly but to a very large extent. A dislocation moving in a matrix, under the influence of a resolved shear stress, arrive at a hard particle which does not shear as easily as the matrix (Fig.10.10). The dislocation, on being arrested in its motion at the hard particle, starts to bulge through between them. After bulging through between the particles, the dislocation line re-forms, leaving a dislocation loop around the particle. Each additional dislocation leaves another loop around the particle, effectively increasing its size and decreasing the spacing between them, so that an ever-increasing stress is required to push successive dislocations through. This mechanism is called **precipitation or dispersion hardening**. Precipitation-hardening is most effective when the particles are small and coherent with the matrix lattice.



*Fig.10.10 Dislocation loop formation around hard second-phase particles.*

## 10.3 SLIP

Slip marks the onset of plasticity in metals. Under the action of applied stress the metal first undergoes elastic deformation whereby it regains its original size on the removal of the stress. Once a critical stress is reached, however, the metal becomes permanently deformed; plastic deformation takes place which is caused predominantly by slip. Such a plastic flow involves the sliding of atomic planes relative to each other in a crystallographically organised fashion. Plastic deformation by slip occurs as a result of the relative movement of lamellae in the crystal, where movement is concentrated in a succession of planes or in a very thin block of planes as shown in Fig 10.11 (a) and (b). Intervening blocks are left undeformed, much like the movement of cards in a pack when the pile is distorted. Displacement takes place on specific crystallographic planes in specific crystallographic directions.



*Fig.10.11 Slip process in a single crystal.*

### 10.3.1 Slip Systems

A study of the orientation of slip lines has revealed that slip takes place in specific planes and directions. X-ray analysis has shown **that slip takes place in most closely packed planes in most closely packed directions**. Fig 10.12 shows the stacking of atomic layers for closely packed planes and non-closely packed planes. Slip occurs by the sliding of these layers upon each other. In the case 10.12 (a), it can be seen that due to the close packing nature of atoms, the distance that top layer has to travel so that atoms of this layer are transferred from one trough to the next trough in the bottom layer is small compared to 10.12 (b). Also the height to which atoms of top layer have to travel to move from one trough to the next is less in 10.12(a). Therefore, the energy required to slide top layers of atoms is less for closely packed atomic planes compared to non-closely packed planes. Slip, therefore, is concentrated on closely packed planes in closely packed directions

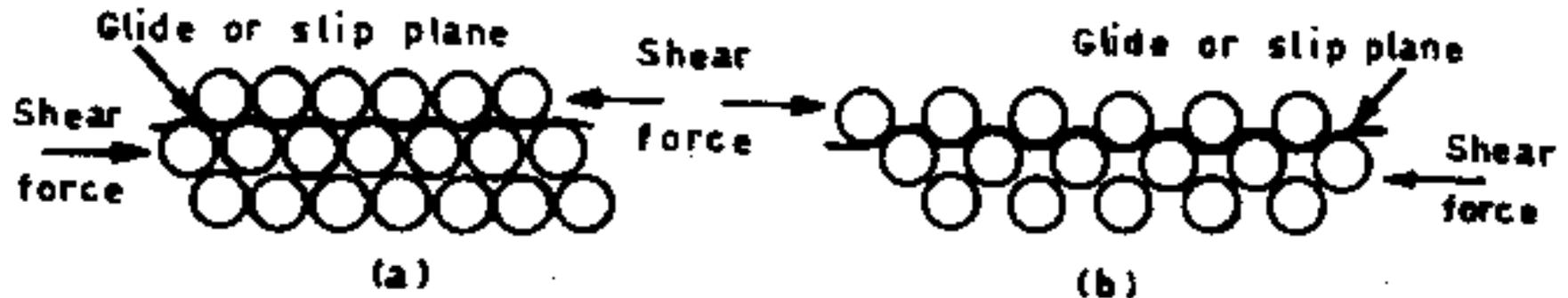
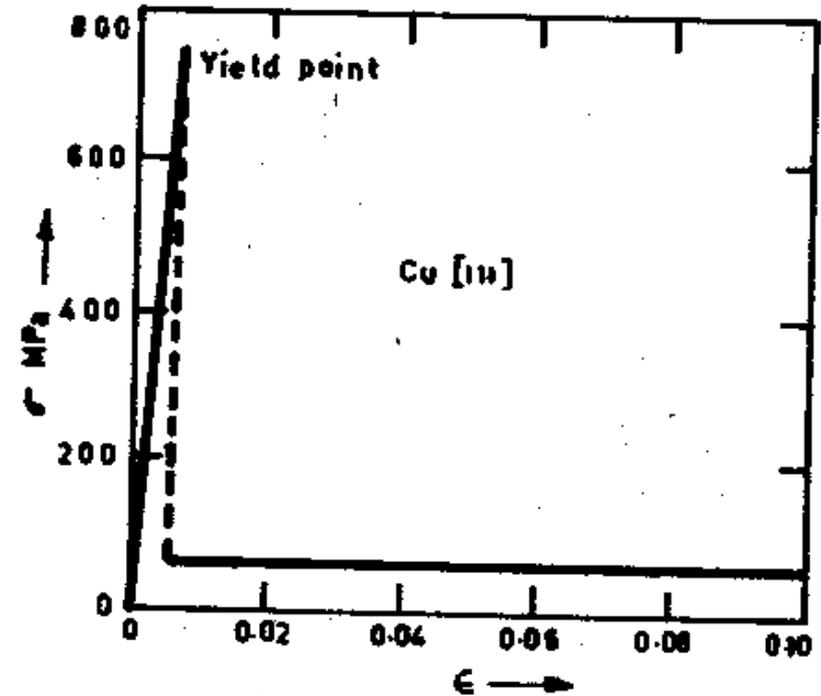


Fig.10.12 Sliding of atomic layers to produce slip.

### 10.3.3 Slip in Single Crystals

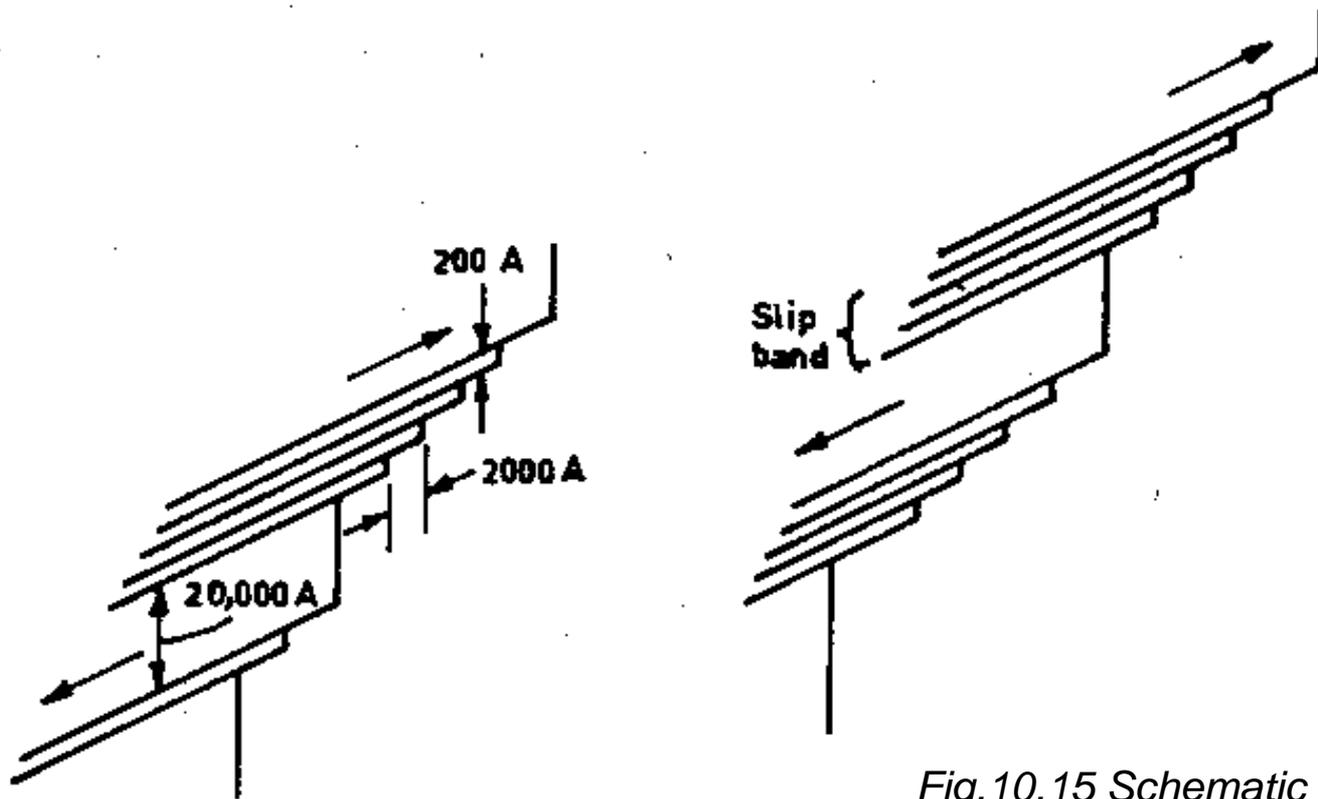
An understanding of the fundamental process of plastic deformation is provided by experiments on single crystals only, because if a polycrystalline sample is used, the results obtained would be an average behavior of all the differently oriented grains in the material.

Single crystals are especially developed by metallurgists, an example of which are whiskers which are fine fibers having diameters of the order of  $1\ \mu\text{m}$ . Whiskers are essentially dislocation free and a study of a Copper whisker under tensile loading demonstrates the role of dislocations in causing slip in metals. Fig10.14 shows that the dislocation free whisker does not flow plastically up to an applied stress of about 800 MPa when dislocations are created due to high stress levels though, a large discontinuous drop in applied stress results due to yielding assisted by the motion of these dislocations.



*Fig.10.14 Tensile behavior of a copper whisker.*

Slipping, on a microscopic scale, is not uniform but is localised on slip planes and within slip bands (Fig 10.15). The spacing between slip planes in a slip band may be of the order of 200A (about 100 atomic diameters), whereas the separation of adjacent bands may be 100 times greater. Slip on each plane may be of the order of several micrometers. As the magnitude of applied stress increases, the number of active slip planes and the distance of slip along these planes also increases.



*Fig.10.15 Schematic representation of slip*

### 10.3.4 Slip in Polycrystalline material

Deformation in polycrystalline material is far more complicated than in a single crystal, although the process is similar. Complicating factors come from the grain boundaries in terms of constraints imposed on the flow of a given grain by its neighbors, and by the flow of the aggregate. One result of this complication is that the stress required to initiate flow in a polycrystal is increased; although some grains may be favorably oriented for slip, yielding can not occur unless the unfavorably oriented neighboring grains are also able to slip. In a polycrystalline aggregate, therefore, individual grains provide a mutual geometrical constraint on one another, and this precludes plastic yielding at low applied stresses. Once yielding has occurred, continued plastic deformation is possible only if enough slip systems are simultaneously operative so as to accommodate grain shape changes while maintaining grain boundary integrity as slip continues, slip planes change their orientation towards the tensile axis and consequently grains begin to elongate. **It has been shown that at least five independent slip systems must be mutually operative for a polycrystalline solid to exhibit ductility.** Thus polycrystalline zinc, with only three slip systems at room temperature, fractures after a very small amount of plastic strain, whereas polycrystalline copper, with 12 slip systems, displays extensive plastic flow prior to fracture. **The yield strength of polycrystals increases with decreasing grain size, since grain boundaries act as internal obstructions to dislocation motion.**

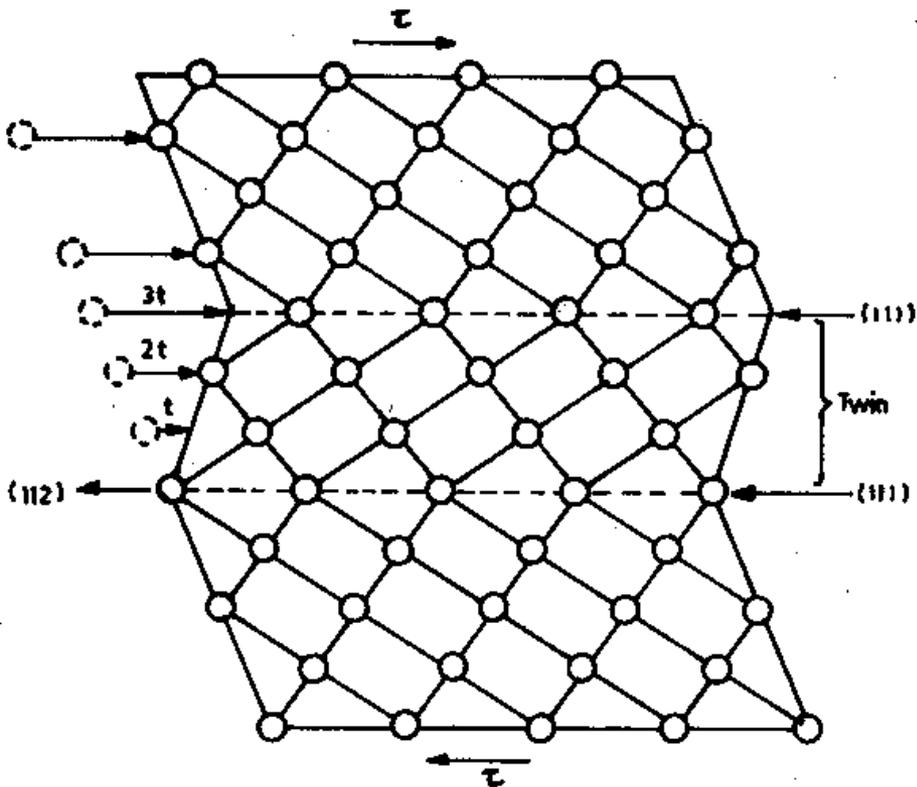
## 10.4 TWINNING

A second mechanism of plastic deformation, which is important in some materials, is deformation twinning. **A crystal is said to be twinned when one portion of its lattice is a mirror image of the other** (Fig 10.16). The crystallographic plane of reflection is known as the **twin plane**. Twins may be formed during growth of a crystal or may be produced mechanically, which occurs by a homogeneous shear of successive planes of atoms by the amount of twinning vector, parallel to the twin plane.

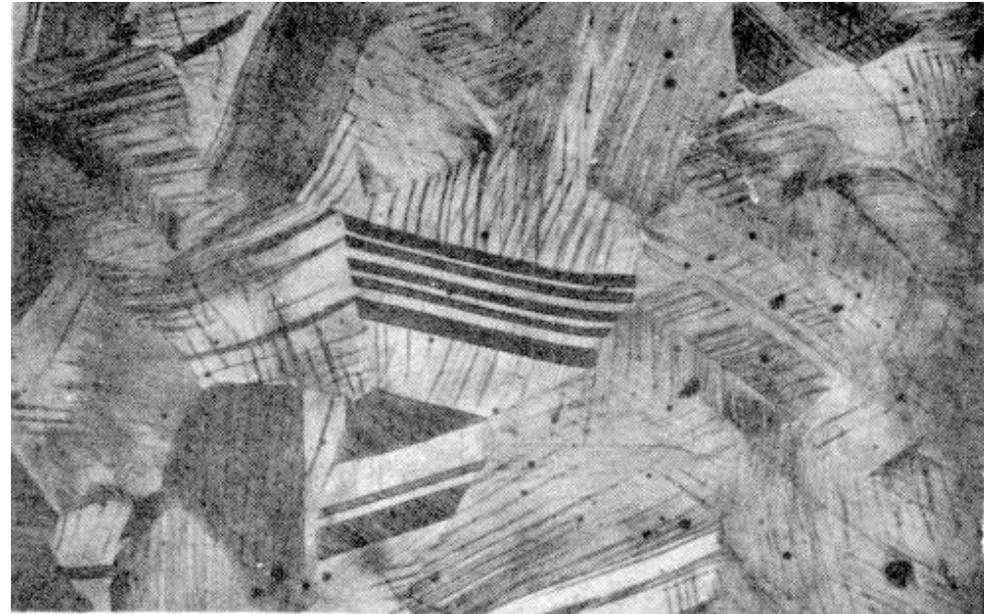
### Mechanical twinning differs from slip in the following ways:

- (1) the twinning portion of a grain is the mirror image of the original lattice, whereas the slipped portion of a grain has the same orientation as the original grain,
- (2) slip consists of shear displacement of an entire block of crystal, whereas twinning is a uniform shear strain,
- (3) the direction of slip may be either positive or negative, while the direction of twinning is limited to that which produces the mirror image.

**The stress required for twinning is higher than that required for slip, and is less sensitive to temperature.** There is evidence to suggest that there is a critical resolved shear stress for twinning as well. The stress required to grow a twin is less than that required to initiate it.



*Fig.10.16 Crystallograph of twinning in BCC crystal*



*Fig.10.17 Appearance of deformation slippings and twinnings in a brass, x100*

## **10.6 WORKING OF METALS**

Deformability of metals makes it possible to turn them into useful shapes and contours by forming processes. These processes are divided into two groups, hot working and cold working. Hot working is carried out above the recrystallisation temperature (see chapter 13) whereas cold working is performed below it.

### **10.6.1 Hot Working**

Hot working is exercised above the recrystallisation temperature, which varies from metal to metal. Most hot working is carried out at temperatures well above this temperature, however, because of ease of forming at high temperatures. Hot working operations include rolling, forging, extrusion and drawing.

Hot working produces fine, strain free grains which may grow if the temperature is too high. Consequently these operations are arranged to finish just above the recrystallisation temperature. Hot working produces uniform properties by eliminating porosity and inclusion segregation; in rolled and forged structures these segregations are elongated to give strong fibrous structures. On the other hand, surface finish is not very good, and close dimensional tolerances can not be maintained. High temperature causes oxidation and scaling. These processes are, however, suitable for rapid production and are, therefore, economical.

## 10.6.2 Cold working

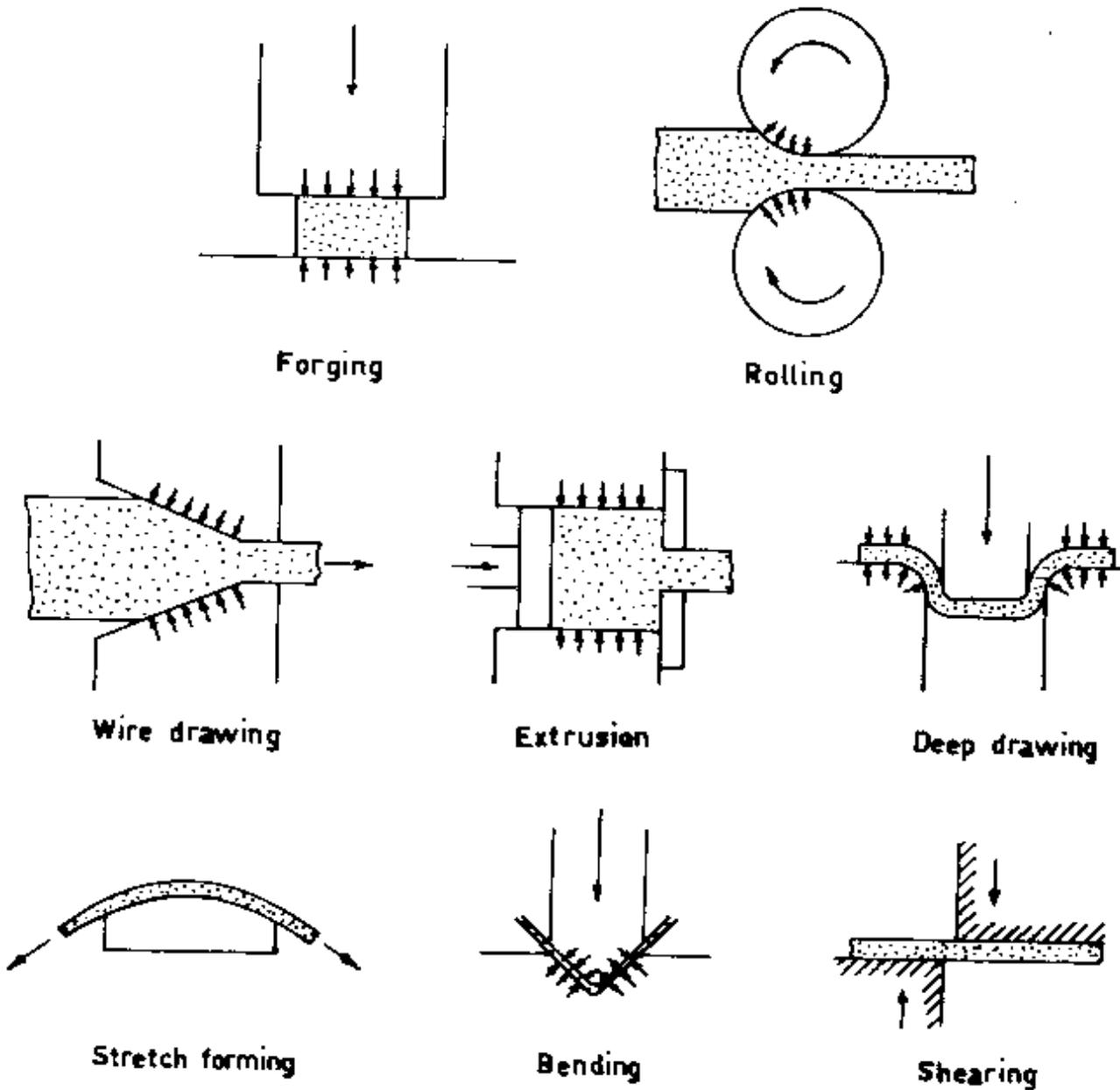
Cold working processes are broadly classified as:

- (1) squeezing, such as rolling and impact extrusion,
- (2) shearing, such as blanking,
- (3) drawing, such as wire and tube drawing and spinning, and
- (4) bending, such as roll forming and seaming.

The distinction lies in the character of stress which is compressive in squeezing, shear in shearing, tensile in drawing and a combination of the three in bending.

Cold forming causes an increase in strength and reduction in ductility due to low temperature of operation. Fig 10.9 shows the effect of cold working on properties of a 0.12 % C steel. Cold working severely distorts the structure and leaves it in a state of high strain, which is removed by annealing. Cold working can be carried out on ductile and malleable metals such as copper, iron etc. Cold working produces good finish, close dimensional tolerances and high strength, but it has slower production rate and is more costly.

# 10.6.3 Forming Processes



*Fig. 10.19 Principal metal working processes*

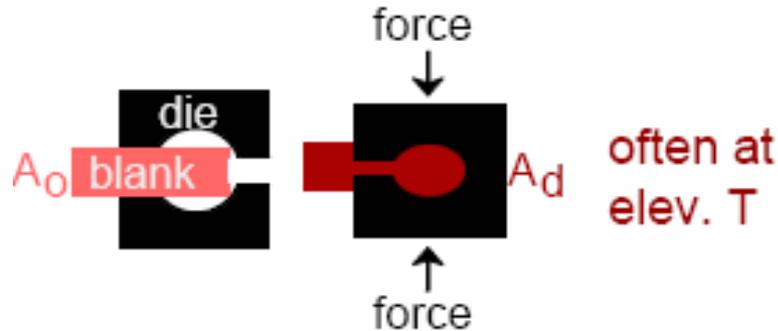
# METAL FABRICATION METHODS-I

FORMING

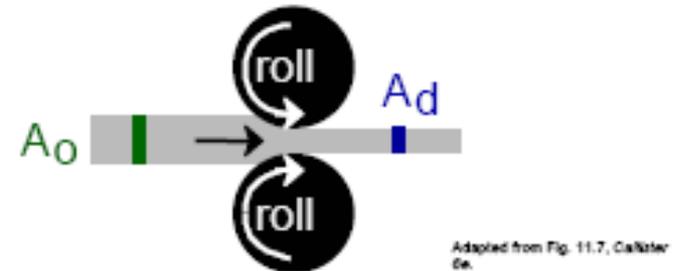
CASTING

JOINING

- wrenches, crankshafts



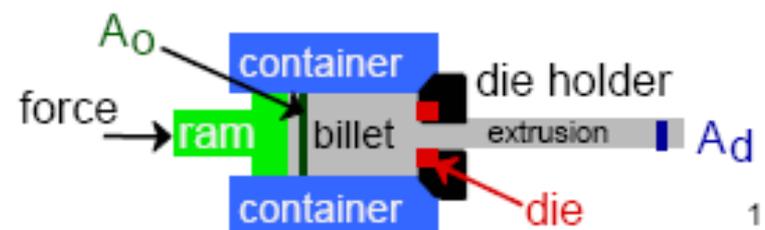
- I-beams, rails



- rods, wire, tubing



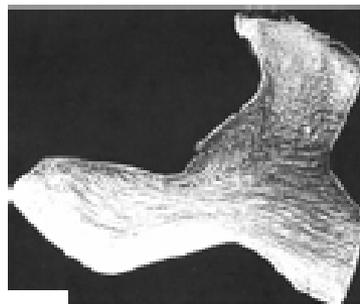
- rods, tubing



# FORMING TEMPERATURE

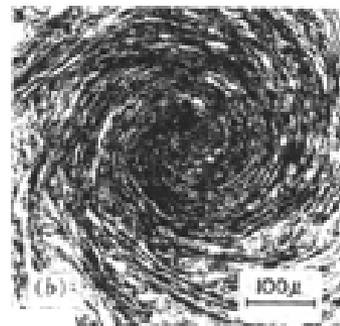
- **Hot working**
  - recrystallization
  - less energy to deform
  - oxidation: poor finish
  - lower strength
- **Cold working**
  - work hardening
  - more energy to deform
  - good finish
  - higher strength
- **Cold worked microstructures**

--Forged



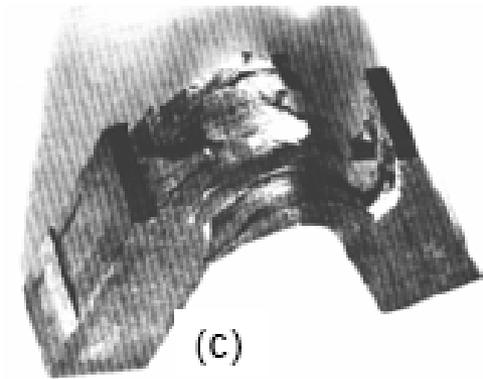
(a)

--Swaged



(b)

--Fracture resistant!

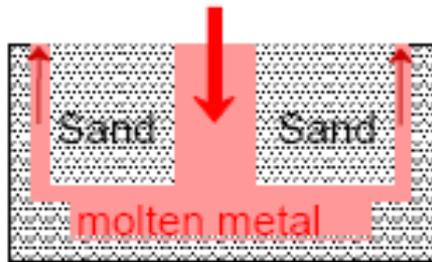


(c)

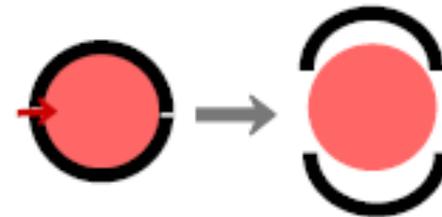
# METAL FABRICATION METHODS-II



- large parts, e.g., auto engine blocks



- high volume, low T alloys



- low volume, complex shapes, e.g. jewelry, turbine blades



- simple slab shapes



# METAL FABRICATION METHODS-III

FORMING

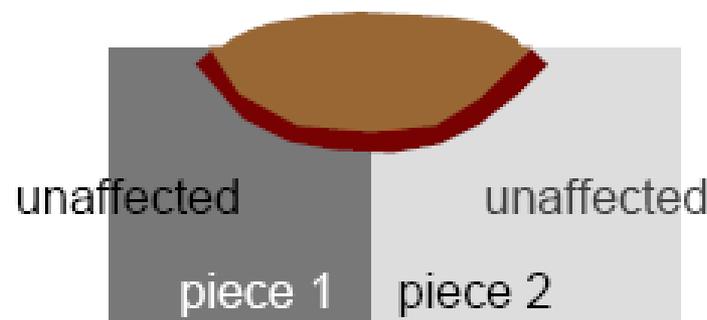
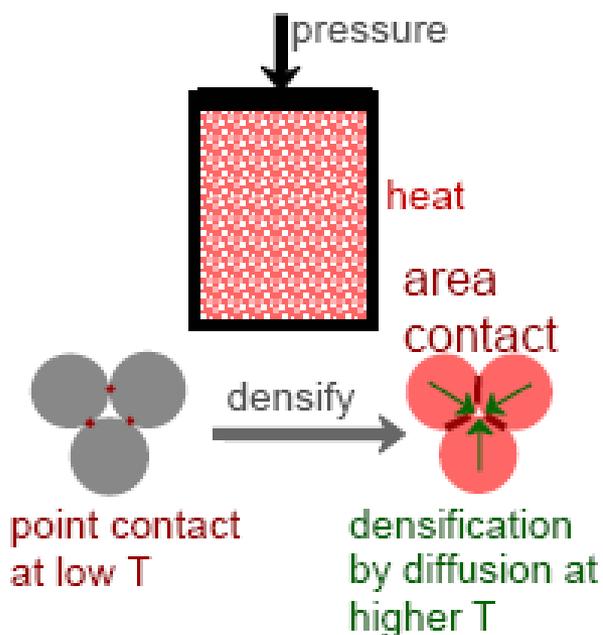
CASTING

JOINING

- Powder Processing

- Welding

when one large part is impractical



Heat affected zone (HAZ):

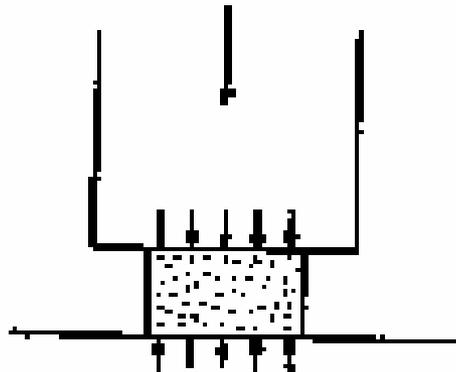
- region in which the microstructure and/or properties have been changed.

### 10.6.3 Forming Processes

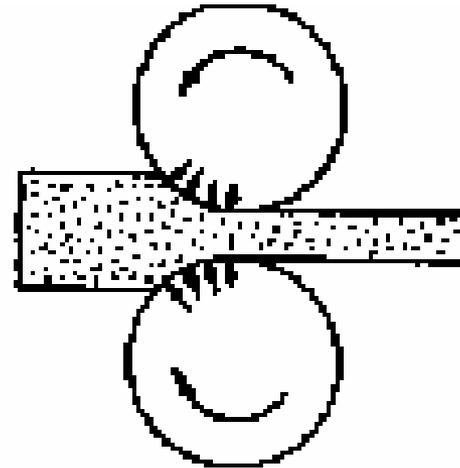
Forming processes are used either hot or cold, depending upon material and applications. The most common of these are rolling, forging, extrusion, drawing, piercing, punching and spinning (Fig.10.19).

**Rolling** is carried out in structural rolling mills to produce I beams, channels, angles, wide flange beams as well as special shapes such as tees etc. Ordinary structural shapes are produced from low carbon steels.

**Forging** is a process whereby metal is heated and then pressed or hammered into a desired shape. It is used for the production of tools and crank shaft etc. Material is sized and heated prior to forcing it into a die. Forging gives a continuous grain structure which yields better properties compared to machined parts.



**Forging**



**Rolling**

**Extrusion** is a process in which metal is forced through a die under extremely high pressures, causing the metal to deform plastically and flow through the die taking on its shape. Soft metals such as lead can be extruded with pressures of 20 to 30 tons, whereas aluminium requires much higher pressures.

**Impact extrusion** is used for soft metals such as aluminium to produce hollow shapes such as collapsible tubes (tooth paste tubes). The operation is simple, a thick metal slug is forced to flow between the ram and the die to produce a hollow shape.

**Drawing** is used to produce wires, rods and shafts etc. Wire is produced by drawing a metal rod through a succession of dies of smaller diameters. Hot rolled steel bars are converted to any shaped rods or shafts by a similar process. Cold drawing produces superior products compared to cold rolling because of uniform density obtained during drawing.

**Tubular products** are obtained by piercing a round billet and rolling it over a tube mandrel to produce seamless tubes. Welded pipes are not made this way, however, but are produced from flat sheets by welding the edges.

**Metal spinning** is a cold forming operation in which a blank is placed in a spinning lathe, and is forced over a mandrel which has the shape of the desired product. Missile cones etc are made in this fashion.

**THE END**

# CHAPTER 11 FAILURE AND TESTING

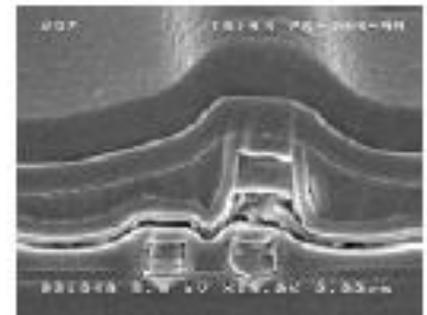
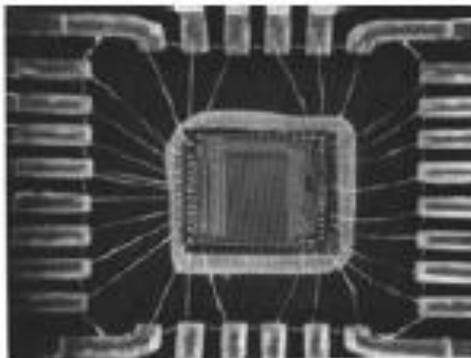
## 11.1 INTRODUCTION

Plastic deformation begins imperceptibly, as a result of slip or other mechanisms discussed in the previous chapter. If continued for long enough, however, it can end with relative suddenness and finality in fracture. **Fracture is the breaking of material into two or more pieces.** The plastic deformation, if continued, leads to the formation of "emptiness" in materials which is termed a crack, which continues to grow as the material is stressed. At a critical load, the crack acquires a large enough length so that the material can not sustain the applied load any longer, and the material fails or fractures.

Fractures are classified as brittle or ductile, depending upon whether or not they are associated with plastic deformation. In addition, fatigue failures are those caused by a repeated stress, and creep failures are generally caused by high temperature. Presence of corrosive environment also serves to cause failure by weakening the materials. Various types of testing are carried out to assess the susceptibility of materials to fracture in any of the above mentioned modes. This chapter deals with a simplified presentation of the mechanisms of fracture in different modes as well as the various methods of testing to evaluate material behavior.

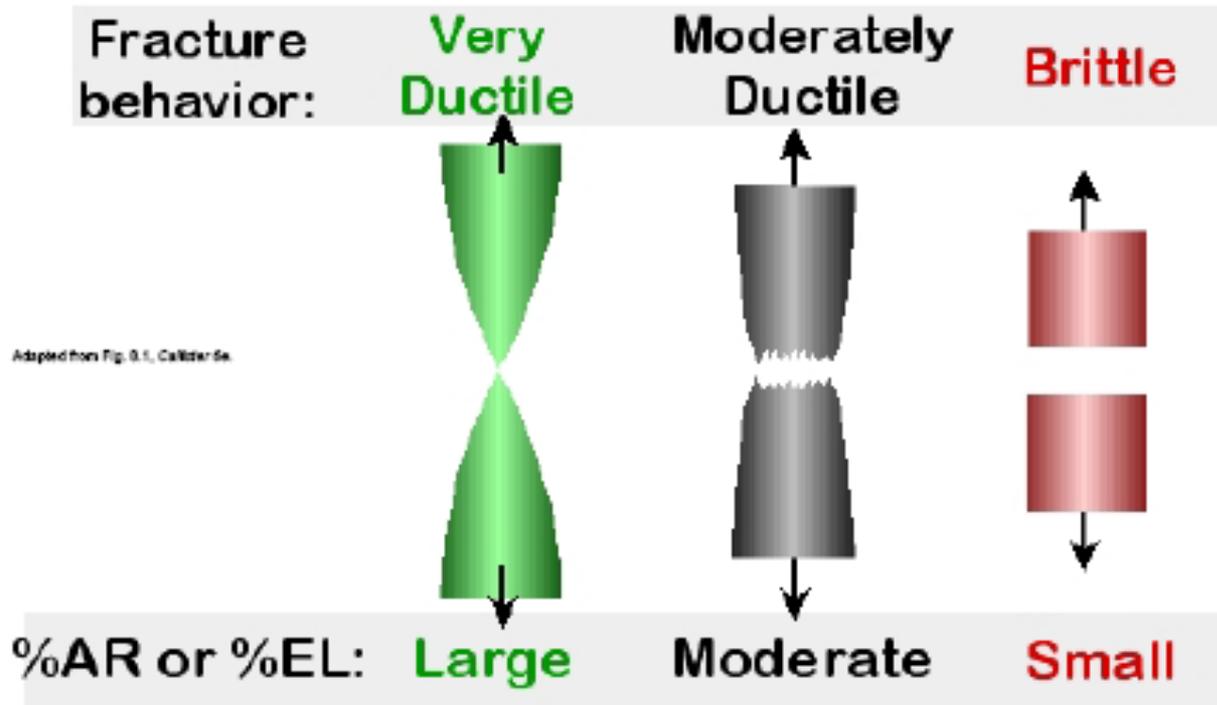
# How do structures fail?

- Fracture: crack growth to rupture at a critical load
- Fatigue: crack growth due to cycling loads
- Creep: high temperature plastic deformation



# DUCTILE VS BRITTLE FRACTURE

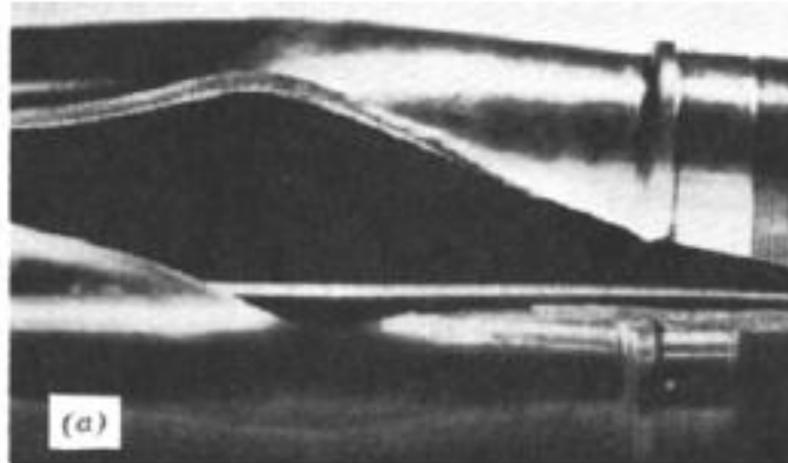
- Classification:



Ductile fracture is desirable!

# EXAMPLE: FAILURE OF A PIPE

- **Ductile** fracture:
  - one piece
  - large deformation



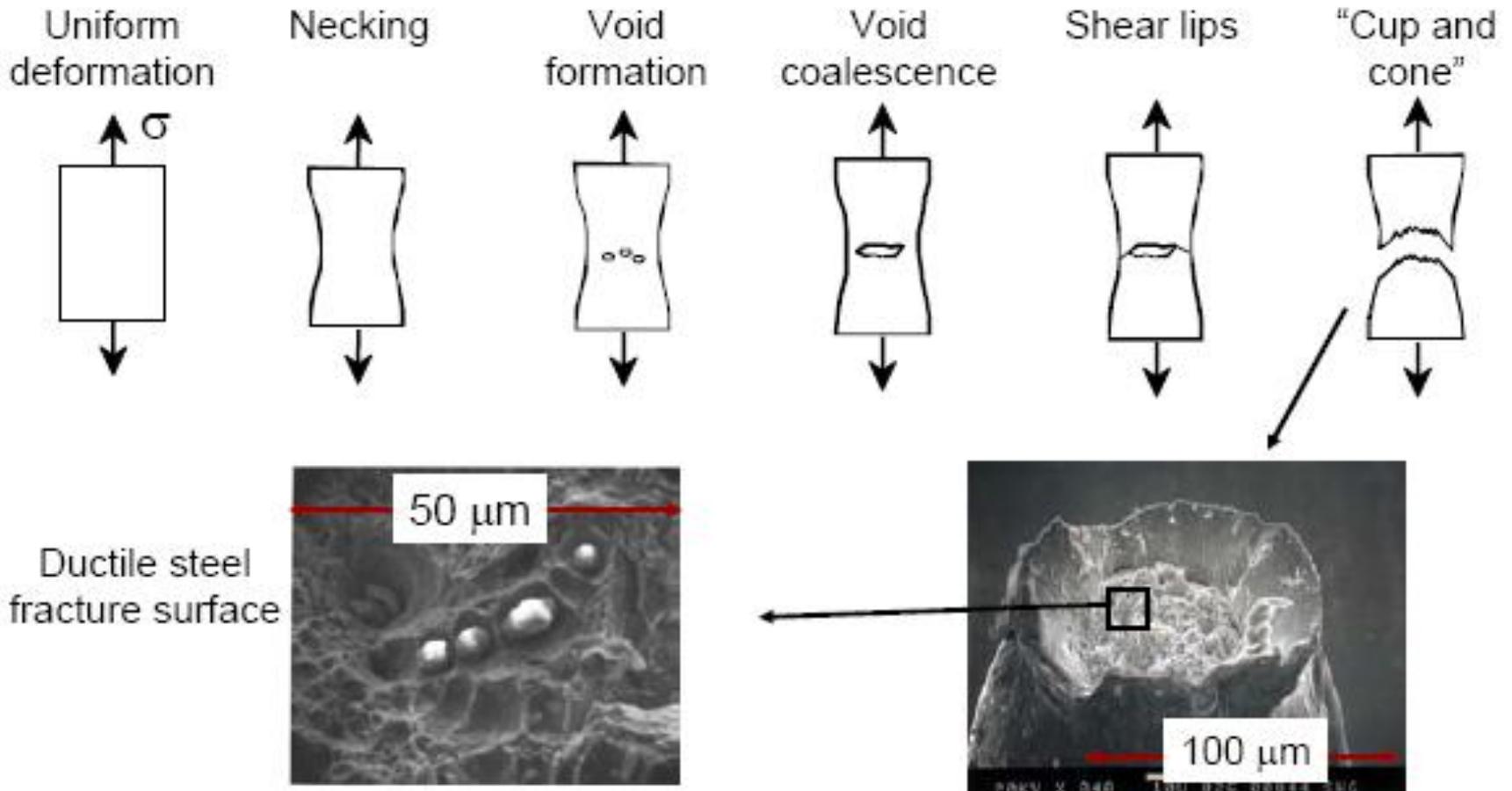
- **Brittle** fracture:
  - many pieces
  - small deformation



Figures from V.J. Colangelo and F.A. Heiser, *Analysis of Metallurgical Failures* (2nd ed.), Fig. 4.1(a) and (b), p. 69 John Wiley and Sons, Inc., 1997. Used with permission.

# MODERATELY DUCTILE FAILURE

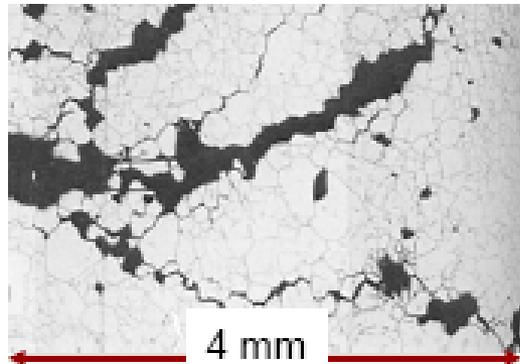
- Evolution to failure:



# BRITTLE FRACTURE SURFACES

- Intergranular

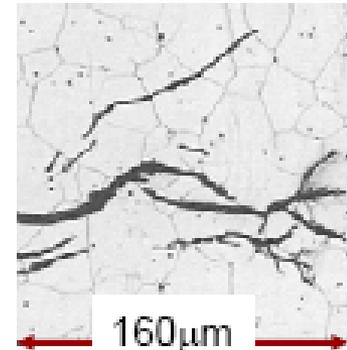
- Transgranular



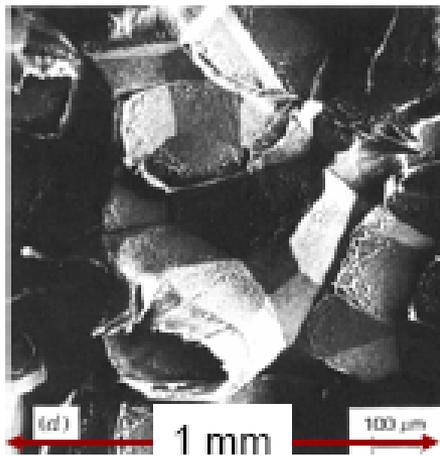
304 S. Steel  
(metal)

Reprinted w/permission from "Metals Handbook", 8th ed. Fig. 633, p. 650. Copyright 1995, ASM International, Materials Park, OH. (Micrograph by J.R. Keiser and A.R. Olson, Oak Ridge National Lab.)

316 S. Steel  
(metal)



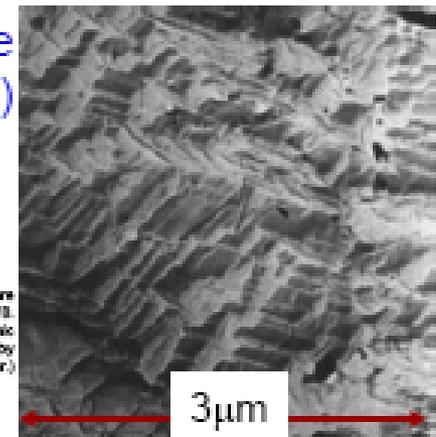
Reprinted w/permission from "Metals Handbook", 9th ed. Fig. 650, p. 327. Copyright 1995, ASM International, Materials Park, OH. (Micrograph by D.R. Dircks, Argonne National Lab.)



Polypropylene  
(polymer)

Reprinted w/permission from R.W. Hertzberg, "Deformation and Fracture Mechanics of Engineering Materials", (4th ed.) Fig. 7.35(d), p. 303, John Wiley and Sons, Inc., 1996.

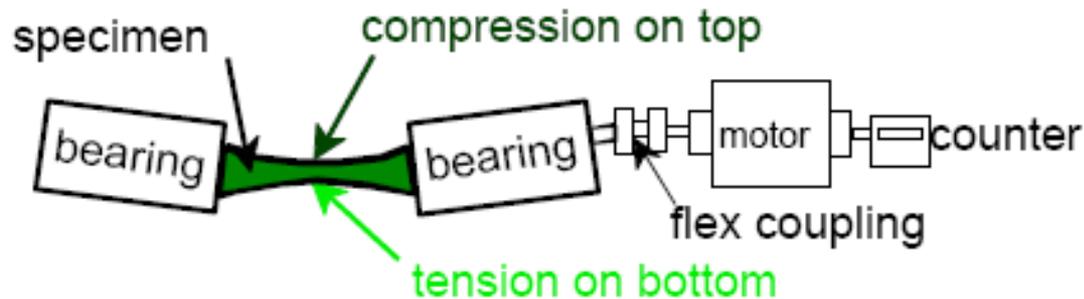
Al Oxide  
(ceramic)



Reprinted w/permission from "Failure Analysis of Brittle Materials", p. 70. Copyright 1990, The American Ceramic Society, Westerville, OH. (Micrograph by R.M. Geaver and H. Kirschner.)

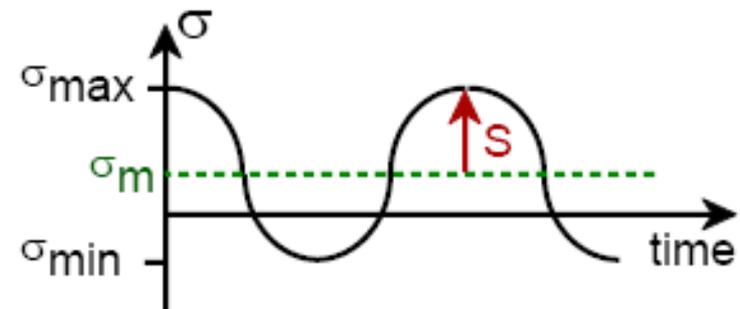
# FATIGUE

- **Fatigue** = failure due to cyclic stress.



Adapted from Fig. 8.16, Callister 8e.  
(Fig. 8.16 is from *Materials Science in Engineering, 4E* by Calli. A. Kittler, Pearson Education, Inc., Upper Saddle River, NJ.)

- Stress varies with time.

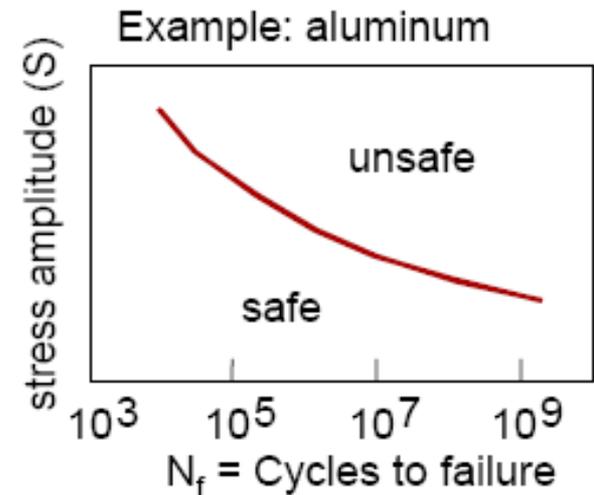
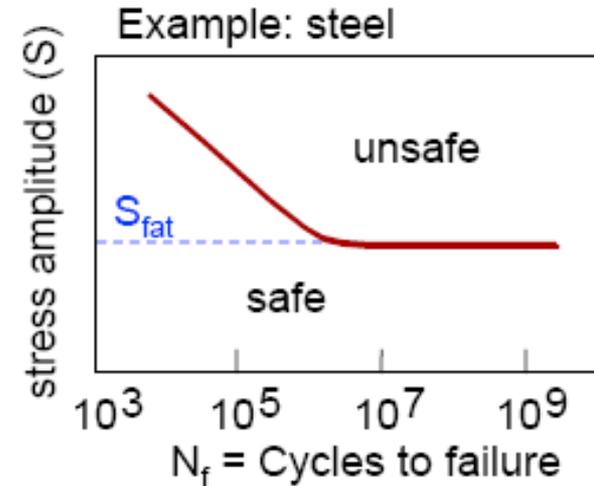


- Key points: Fatigue...
  - can cause part failure, even though  $\sigma_{\max} < \sigma_{\text{critical}}$ .
  - causes ~ 90% of mechanical component failures!

# FATIGUE DESIGN PARAMETERS

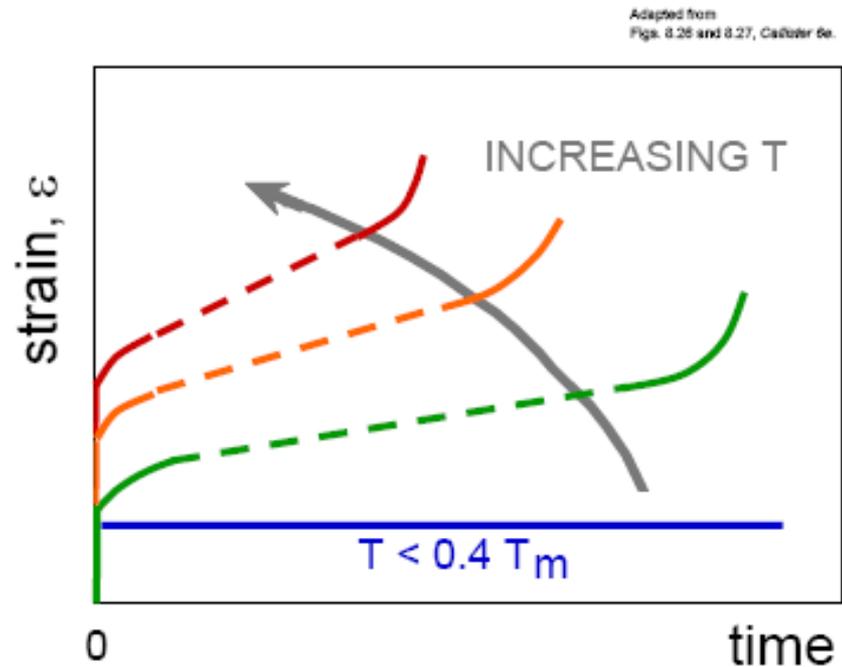
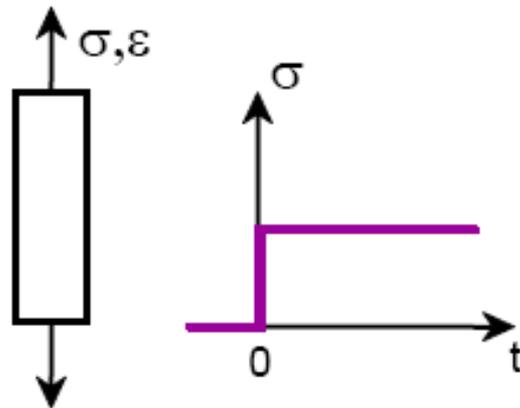
Fatigue endurance limit,  $S_{fat}$ :

For some materials, the  
fatigue limit is zero!



# CREEP

- Occurs at elevated temperature,  $T > 0.4 T_{\text{melt}}$
- Deformation changes with time.



## 11.8 TESTING

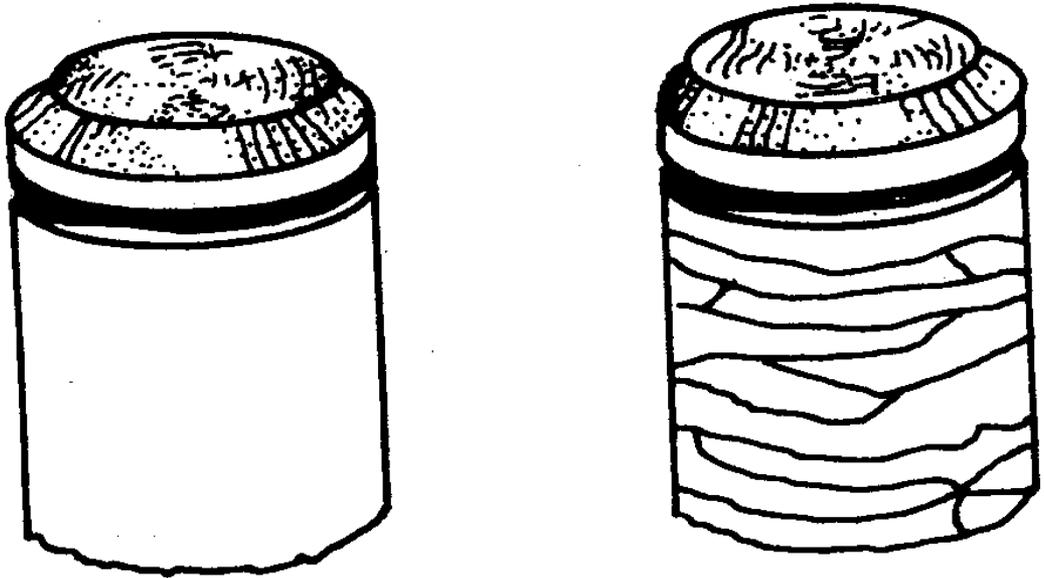
Various tests can be carried out to assess mechanical behaviour of engineering components under different types of applied loads.

### 11.8.1 Non- Destructive Testing (NDT)

NDT is carried out to examine cracks and other defects in a metal without breaking the material. They are very useful for detecting such things as cracks in weldments etc. The most basic NDT examination is that carried out by the naked eye to observe any surface features. However, for interior examinations various techniques are available.

# MAGNAFLUX EXAMINATION = *Magnetic Particle Inspection*

This test can only be performed on **ferromagnetic materials**. The component is magnetised and coloured magnetic powder is sprayed on the surface. Cracks etc. possess higher magnetic intensity and, therefore, attract magnetic powder, making them detectable. This is **dry method**, as against **wet method** in which fluorescent magnetic powder in a low viscosity oil is used. Cracks are observed under ultraviolet light. Fig.11.22 shows the revealing of cracks in a pin by magnaflux method.



( a ) Visual inspection

( b ) Magnaflux process.

*Fig.11.22 Magnaflux examination of a crack in a pin.*

# DYE PENETRATION = *Liquid Penetrant Inspection*

Inspection with a penetrating dye is used for **nonmagnetic materials**. The part is first sprayed with a red coloured dye which penetrates in defects. Next, the oil is washed from the surface leaving the residue in defects. Finally, a white coating is sprayed over the surfaces the oil in the defects gradually oozes out on the white surface delineating them (Fig.11.23)

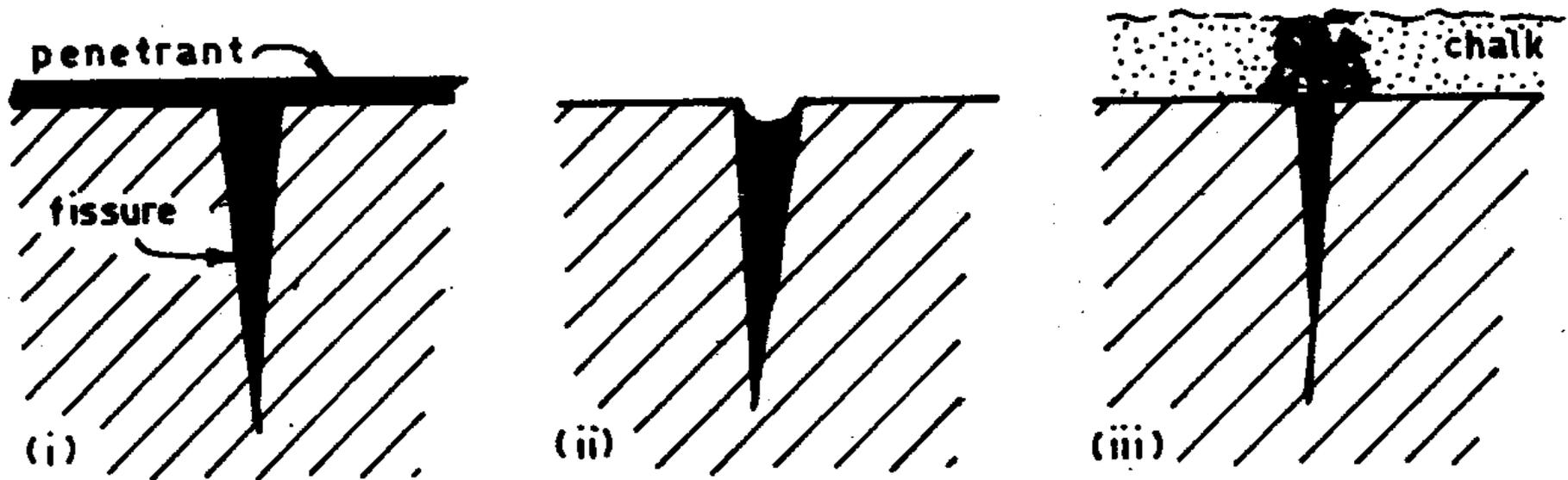
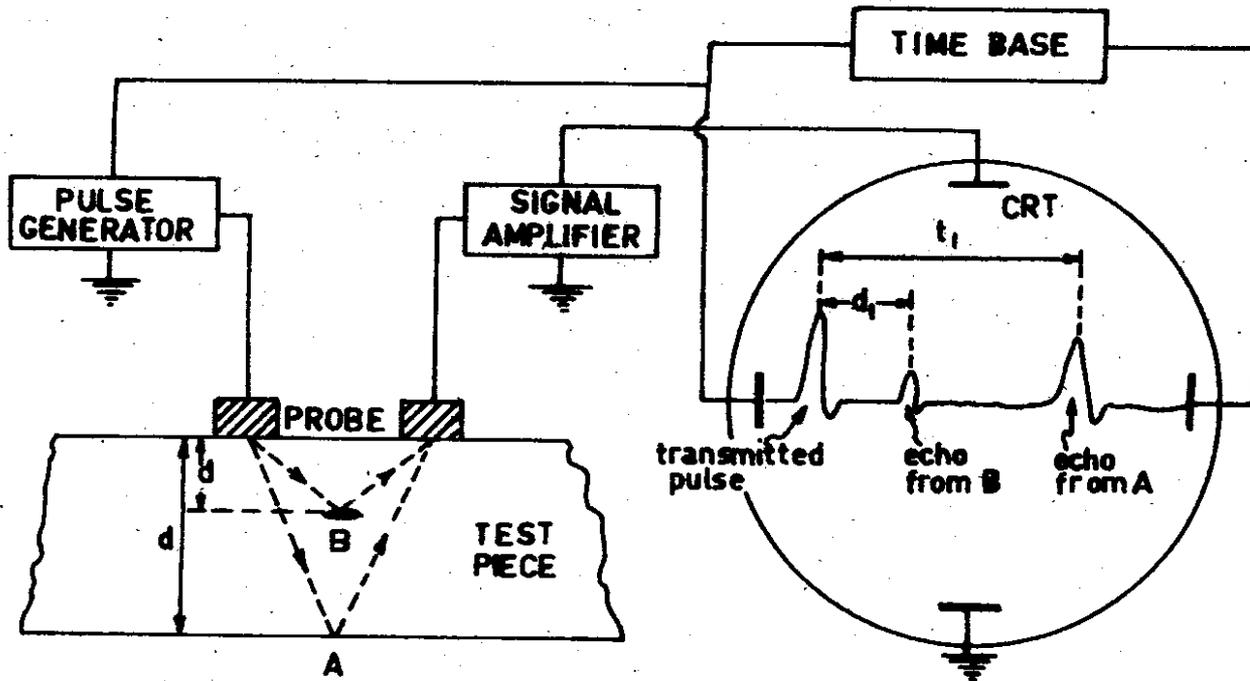


Fig.11.23 Delineation of a crack by penetrating dyes

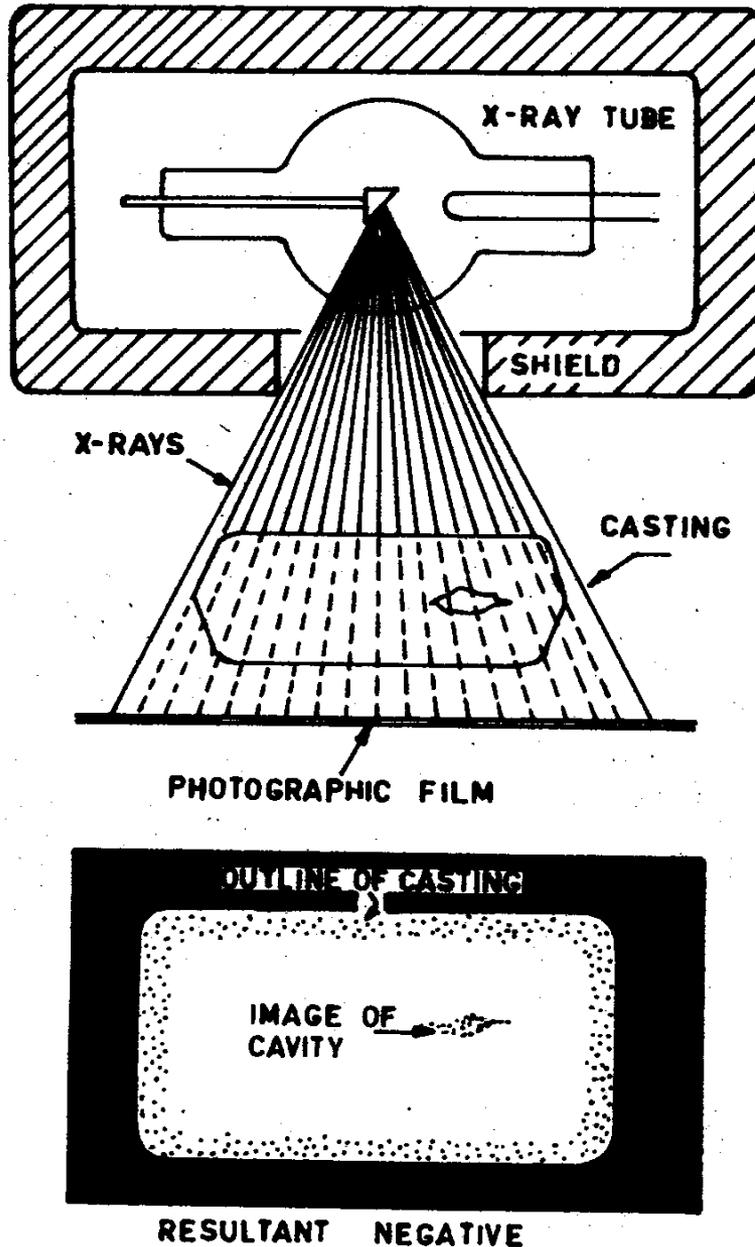
# ELECTRICAL AND SONIC METHODS

These methods depend upon a variety of techniques. In **ultrasonic testing**, sound waves are transmitted into the part from a vibrating crystal pressed against the part as shown in Fig.11.24. These sound waves are then received and displayed on an oscilloscope. One can determine discontinuities and variations in structure from the oscilloscope trace, as the defects reflect the sound waves in a different manner compared to normal metal. Other methods involve evaluating hysteresis and eddy current losses as well as acoustic emission from the part.



*Fig.11.24 Operation diagram of ultrasonic testing.*

# RADIOGRAPHY



Radiography is carried out by using X-rays, cobalt 60 or other high energy sources to produce radiation which penetrates the metal. The radiation is received on a photographic plate, which shows any defects in a manner analogous to X-ray radiographs used for medical purposes. Radiographic examination of a casting is shown in Fig.11.25.

*Fig.11.25 Detection of a cavity in a casting by X-ray radiographs*

**THE END**

# CHAPTER 12 HEAT TREATMENT

## 12.1 INTRODUCTION

Heat treatment is the operation of heating and cooling a metal in its solid state to change its physical properties. According to the procedure used, metals can be made **hard** to resist cutting action and abrasion or it can be **softened** to permit further machining. With the proper heat treatment, internal stresses may be removed, **grain size** reduced, toughness increased, or a hard surface produced on a ductile interior.

The fact that phases and microstructures in a material can be modified permits the engineer to choose a combination of the properties most suitable for a given application.

The microstructures of single-phase metals can be adjusted by:

*Plastic deformation,*

*Recrystallization,*

*Solid solution additions, and*

*Crystal orientation.*

Multiple-phase materials can have their properties modified through these same procedures. Furthermore, there are additional means of control of microstructures in materials with more than one phase present:

*(1) The relative amounts of the phases may be varied.*

*(2) The grain size may be varied.*

*(3) The shape and distribution of the phases can be modified.*

Each of these three **microstructural variations** provides means of modifying the properties of materials.

In a multiple-phase material, the phases never have completely identical properties, because each is structurally different. Certain of these properties are additive and may be determined by suitably weighed averages of the properties of each of the individual phases. Other properties are interactive, because the behaviour of each phase depends on the nature of the adjacent phase. **Strength and hardness are interactive properties.** A finely dispersed rigid phase inhibits slip and prevents shear of a ductile matrix. This interdependence of the mechanical properties of phases makes it possible to strengthen materials by the addition of fillers. For example, carbon in rubber, sand in clay, sand in asphalt. Mixtures of ferrite and carbide in steel are equally common. Carbide is harder than the accompanying ferrite, and so it increases the resistance of steel to deformation.

For the aggregates of cementite and ferrite found in annealed, normalized, and spheroidized steels the flow strength is inversely proportional to the logarithm of the mean interparticle spacing (mean free ferrite path) as shown in Fig.12.1. The same relationship is valid for finer cementite particles in tempered martensite, coarse particles in over aged aluminium copper alloys, and cobalt - tungsten carbide sintered products. The most common method of altering microstructures is by various heat treatments, each designed to produce a particular phase relationship. Although heat treatments are commonly developed for steels, they are receiving increasing industrial applications for nonferrous alloys as well.

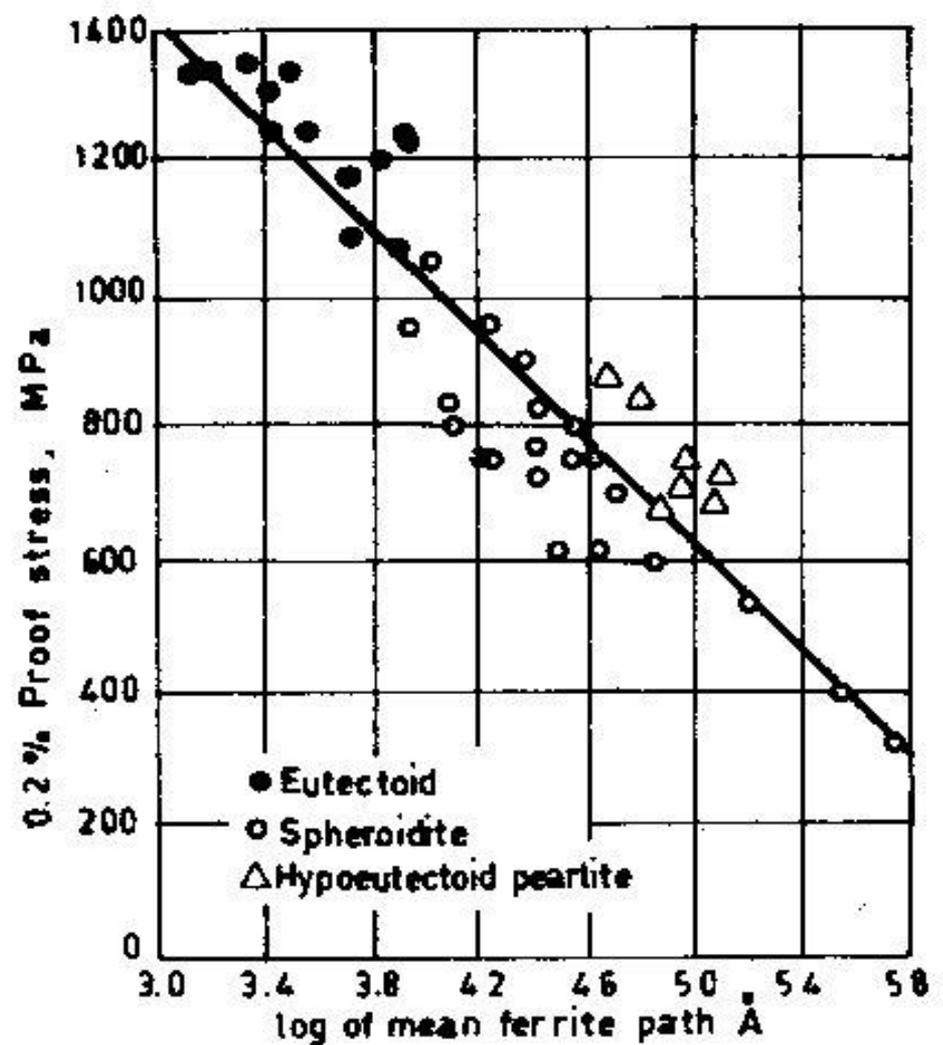


Fig.12.1 Flow Stress versus Mean Free Ferrite Path in Steel

# **FORMS OF HARDENING OR STRENGTHENING STRATEGIES OF METALS**

- 1. Smaller Grain Size (increase grain boundaries)**
- 2. Solution Treatment, Solid Solution Hardening (Add impurity atoms)**
- 3. Precipitation (Dispersion) Strengthening (hard 2<sup>nd</sup> phase particles)**
- 4. Work or Strain Hardening (cold working)**
- 5. Phase Transformation (hardening)**
- 6. Fiber Reinforcement**

# PHASE TRANSFORMATIONS

## How can we control phase formation?

- Transforming one phase into another takes time!



- Time – Temperature – Transformation Diagrams
- Processing  $\rightarrow$  Structure  $\rightarrow$  **Properties**
- How does the rate of transformation depend on time and  $T$ ?
- How can we slow down the transformation so that we can engineering non-equilibrium structures?
- Are the mechanical properties of non-equilibrium structures better?

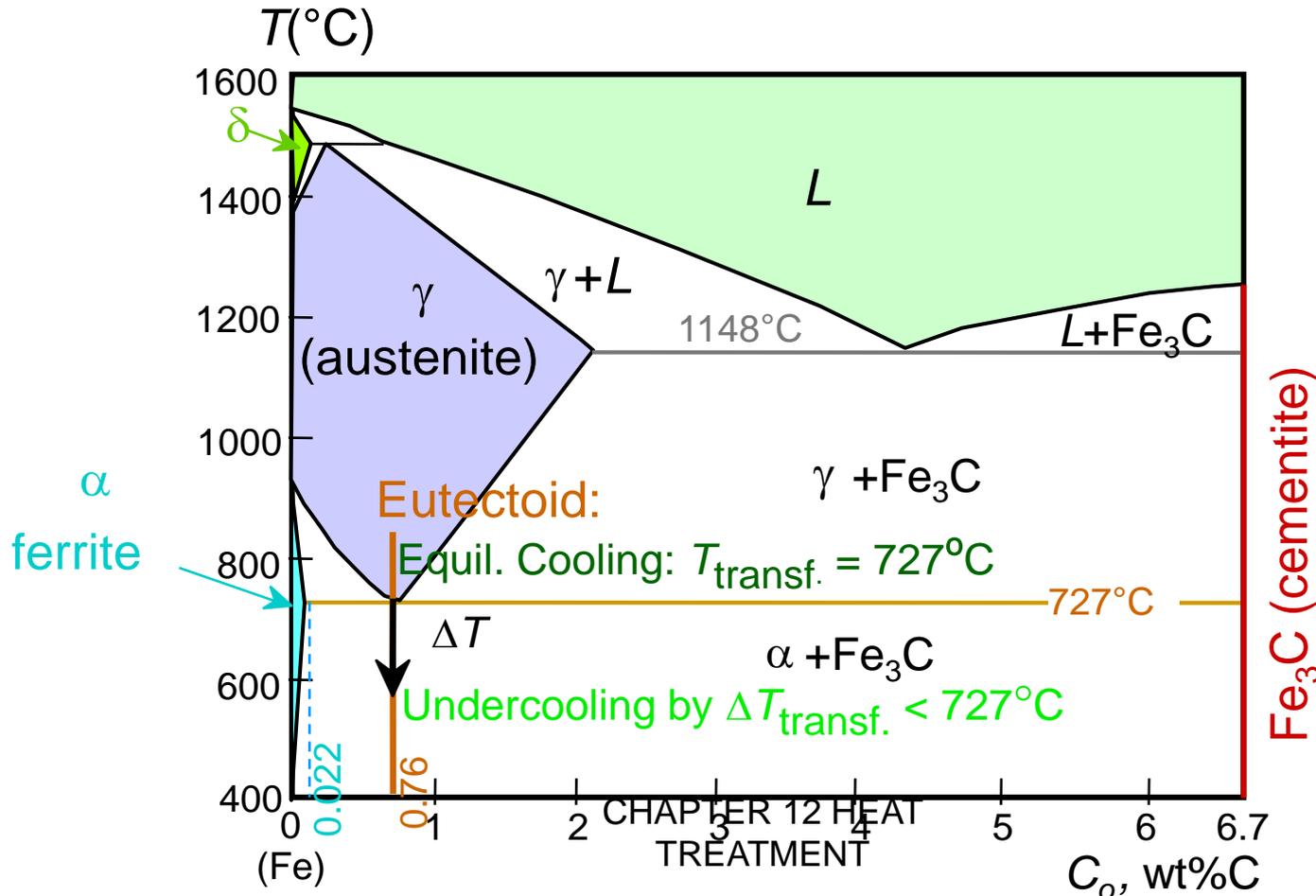
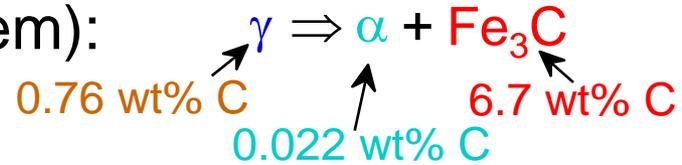
# TRANSFORMATIONS & UNDERCOOLING

- Eutectoid transf. (Fe-C System):

- Can make it occur at:

...727°C (cool it slowly)

...below 727°C (“undercool” it!)

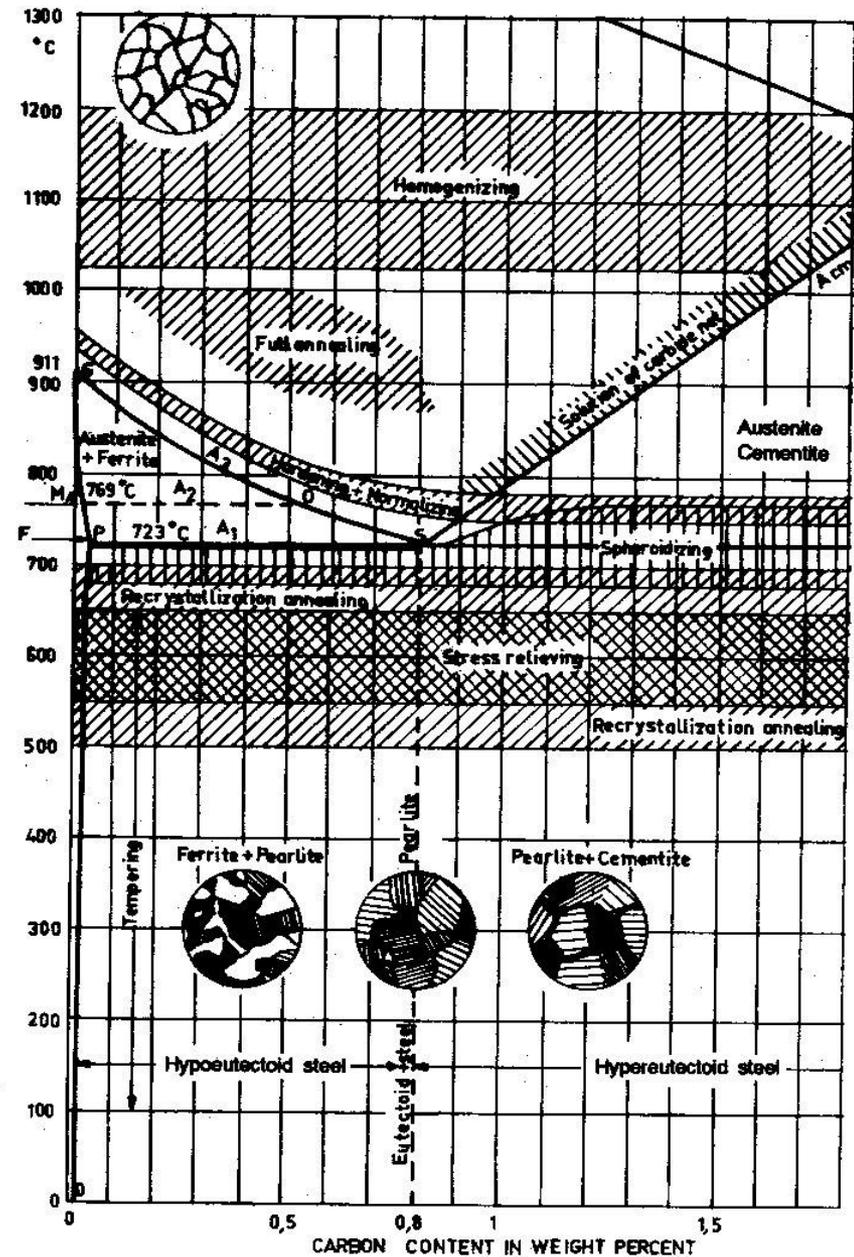


## 12.2 BASIC CONCEPTS

On heating pure iron from room temperature to its melting point it undergoes **allotropic** modifications. On cooling molten iron to room temperature the transformations take place in the reverse order and at approximately the same temperatures as on heating. Ferrite or  $\alpha$ -iron is stable below 911 °C, austenite or  $\gamma$ -iron is stable between 911 °C and 1392 °C, and  $\delta$ -iron is stable between 1392 °C and melting point. Iron is ferromagnetic at room temperature, but its magnetism vanishes completely at 769 °C.

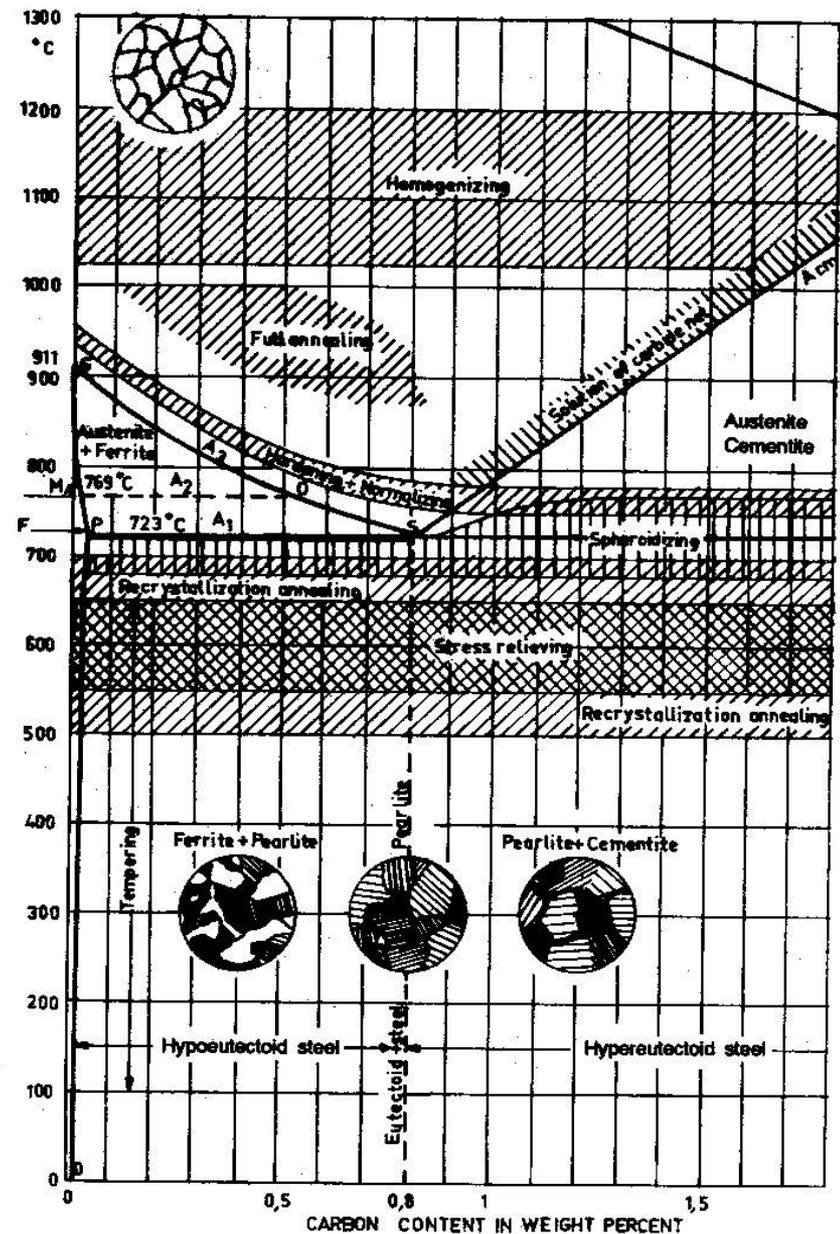
The most important alloying element in steel is carbon. Its presence is largely responsible for the wide range of properties that can be obtained. At room temperature the solubility of carbon in  **$\alpha$ -iron** is almost zero. So, it separates from the crystal structure and forms a chemical compound with iron known as **cementite**. Cementite and ferrite may show a lamellar structure, which is known as **pearlite**.

When iron is alloyed with carbon the transformation will take place within a temperature range, which is dependent on the carbon content as shown in iron-carbon equilibrium diagram in Fig. 12.2. Solubility of carbon in austenite is much greater than in ferrite, 2.0 % C at 1193°C.



## 12.3 TIME-TEMPERATURE-TRANSFORMATION (TTT)

The iron-carbon equilibrium diagram is unquestionably of fundamental importance to heat-treatment processing. However, it only describes the situation when **equilibrium** has been established between the components iron and carbon. In the great majority of heat treatments the **time parameter** is one of the determinative factors.



## 12.3.1 Heating

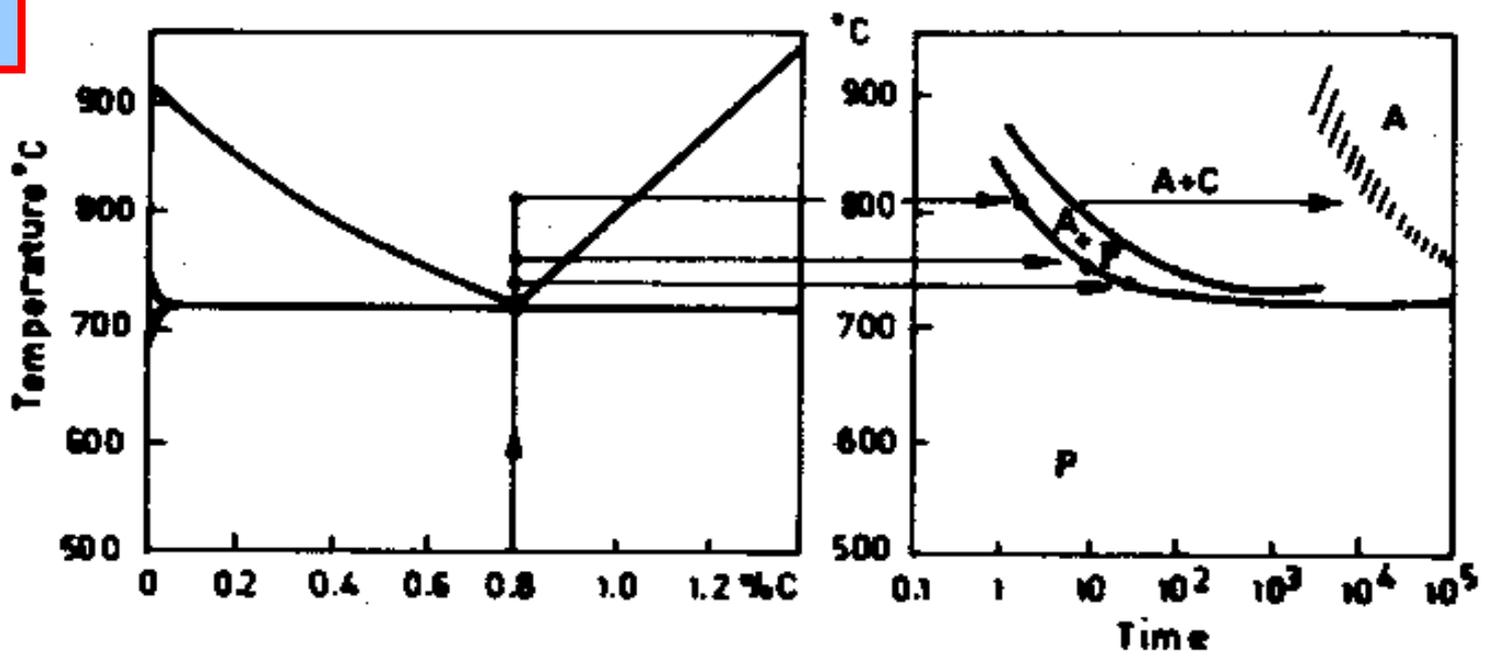
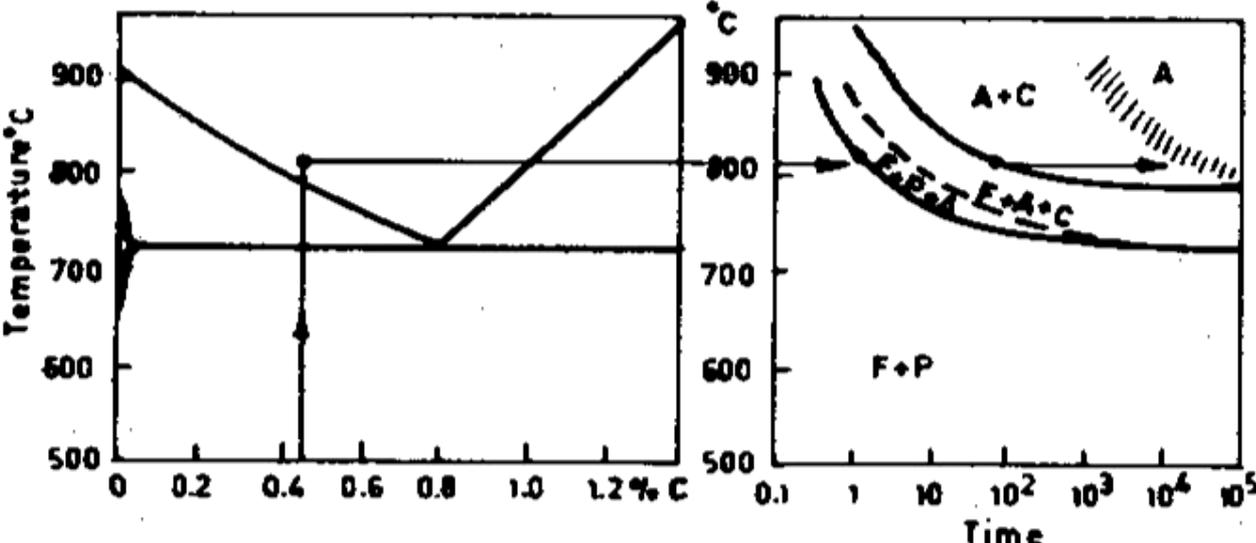


Fig.12.3 Structural transformation on heating steels containing: (a) 0.8 % C.

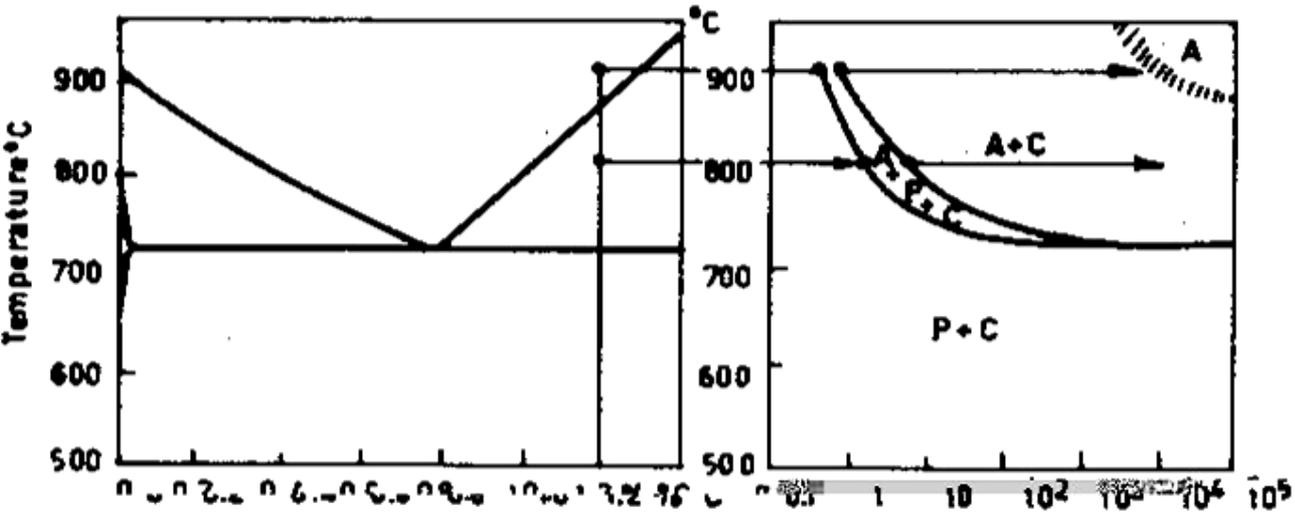
The influence of time is best explained by means of the diagrammatic illustrations in Fig.12.3. On heating steel with 0.80 % C, Fig.12.3 (a), phase diagram shows that transformation to austenite occurs at 723 °C. However, the phase diagram tells us nothing about how long this transformation will take to start and complete. From heating curve it can be predicted that when the temperature is 730 °C, the transformation starts in 30 seconds. If steel is heated to 750 °C, the transformation will begin in 10 seconds, and if heated to 810 °C, in 1 second. The transformation of pearlite to austenite and cementite is completed in about 6 seconds at 810 °C. If steel is to be fully austenitic it must be held at this temperature for about 5 hours.

## 12.3.1 Heating(cntd.)

Figure 12.3(b) shows the transformation of 0.45 % C steel on heating. Similarly transformation of a hyper-eutectoid steel containing 1.2 % C is shown in Fig.12.3 (c).



(b)



(c)

*Fig.12.3 Structural transformation on heating steels containing:  
(b) 0.45 % C,  
(c) 1.2 % C.*

## 12.3.2 Cooling

The general appearance of the structure created during cooling is dependent on the transformation temperature and on the time taken for the transformation. The transformation of steel at a certain temperature may be investigated by cooling it from the austenite state to the temperature concerned, letting the transformation take place and then quenching to room temperature as shown in Fig.12.4. This is best explained by the construction of TTT (Time Temperature Transformation) diagrams.

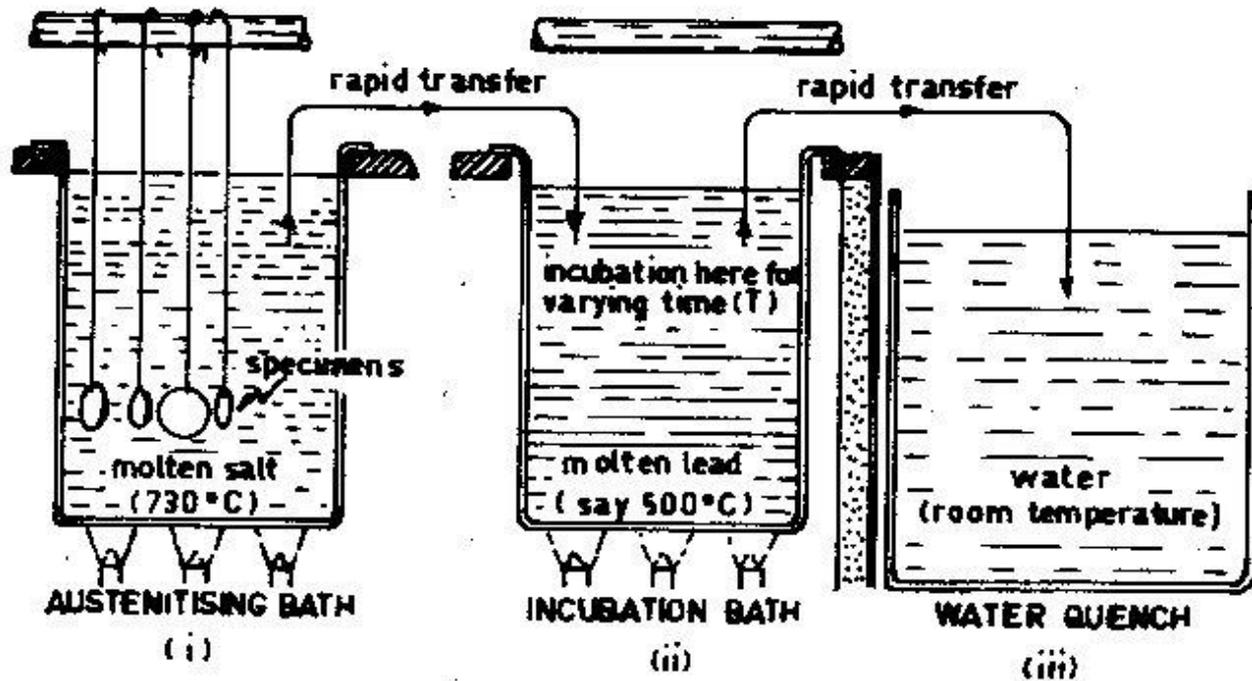


Fig.12.4 Experimental procedure for obtaining TTT diagrams

# The steps usually followed to determine a TTT diagram are:

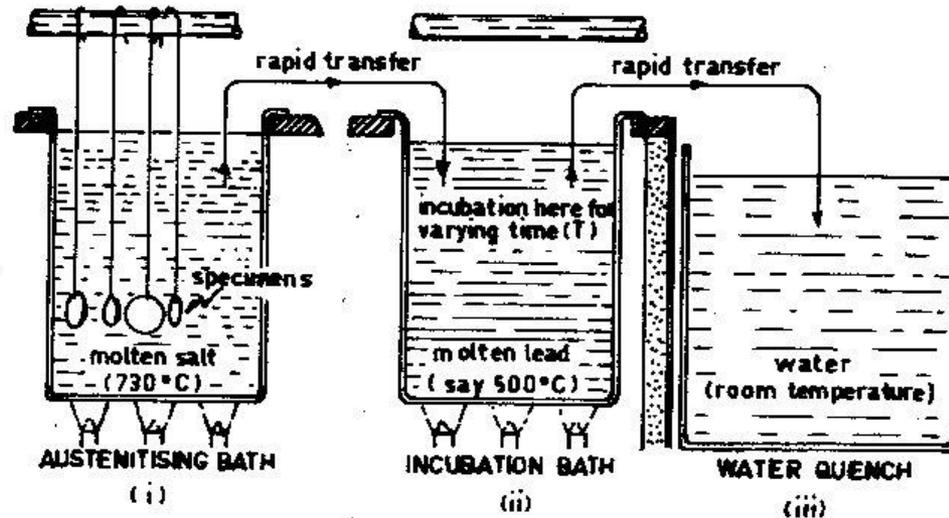
**Step 1** Prepare large number of samples cut from the same bar. The cross-section has to be small in order to react quickly to changes in temperature.

**Step 2** Place the samples in a furnace or molten salt bath at the proper austenitizing temperature. They should be left at the given temperature long enough to become completely austenite (Fig.12.4i).

**Step 3** Place the samples in a molten salt bath which is held at a constant subcritical temperature (Fig.12.4ii).

**Step 4** After varying time intervals in the salt bath, each sample is quenched in cold water or iced brine (Fig.12.4iii).

**Step 5** After cooling each sample is checked for hardness and studied microscopically.



TREATMENT

# TTT diagrams

As a result of this experiment, **two points** may be plotted at this subcritical temperature, **the time for the beginning and the end of transformation**. It is also common practice to plot the time for 50 % transformation. Construction of a reasonably accurate diagram requires the heat treatment and metallographic study of more than one hundred individual samples. TTT diagrams for three different steels are shown in Fig.12.5.

TTT diagram for steel containing 0.80 % C is shown in Fig.12.5 (a)

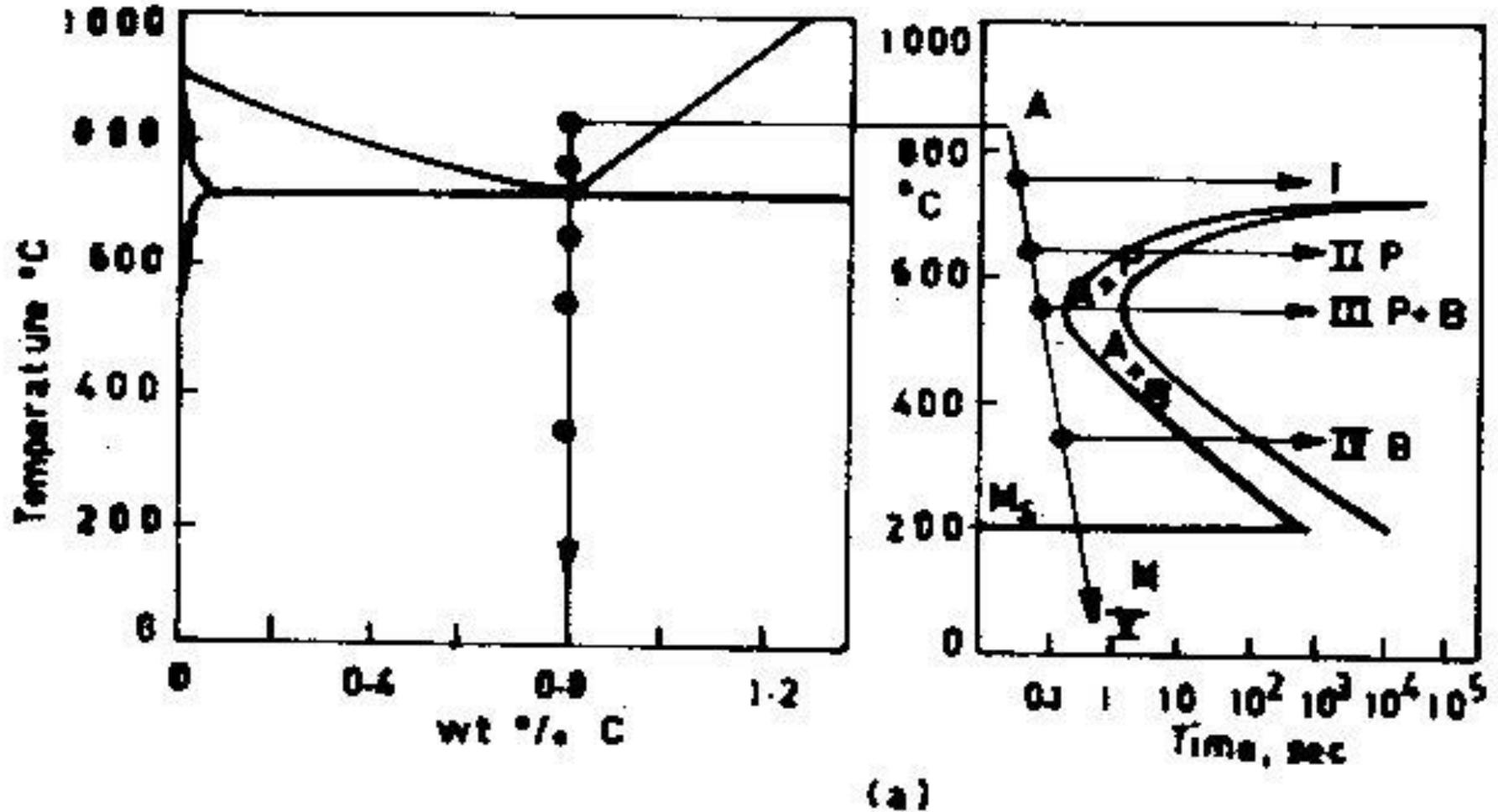


Fig.12.5 Structural Transformations on Cooling Steel Containing: (a) 0.80 % C

TTT diagram for steel containing 0.45 % C is shown in Fig.12.5 (b)

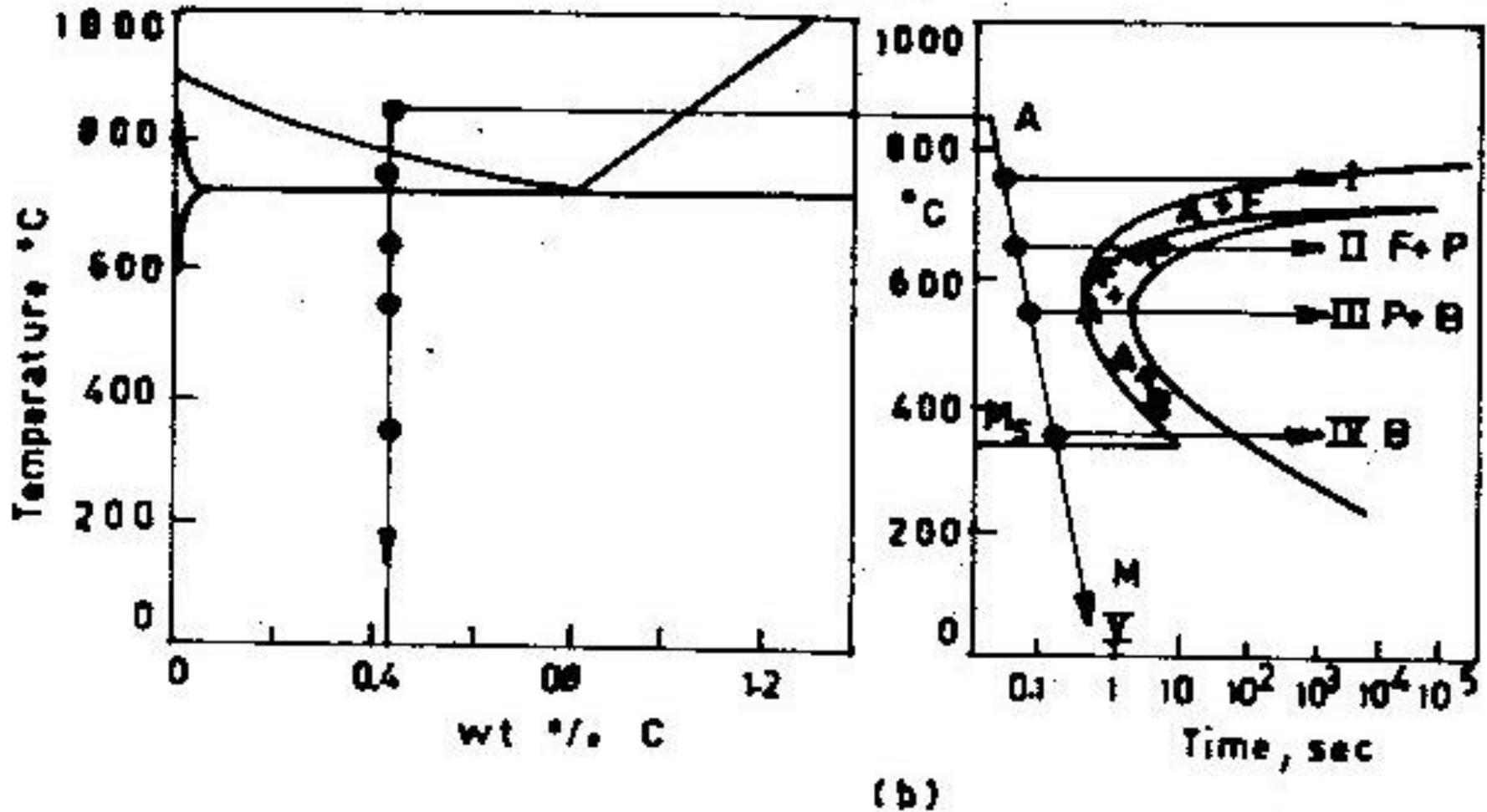


Fig.12.5 Structural Transformations on Cooling Steel Containing: (b) 0.45 % C.

TTT diagram for steel containing 1.0 % C is shown in Fig.12.5 (c)

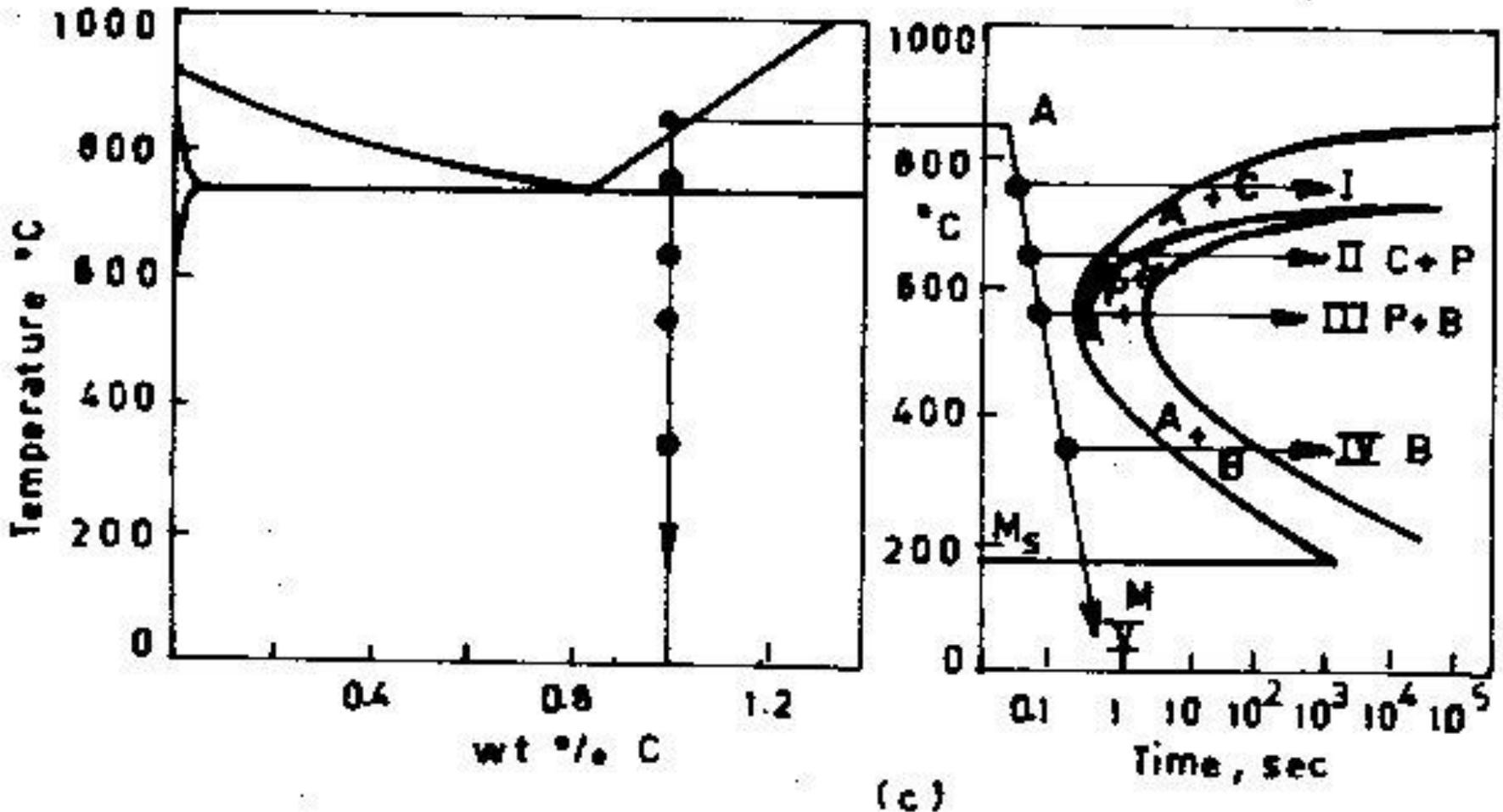


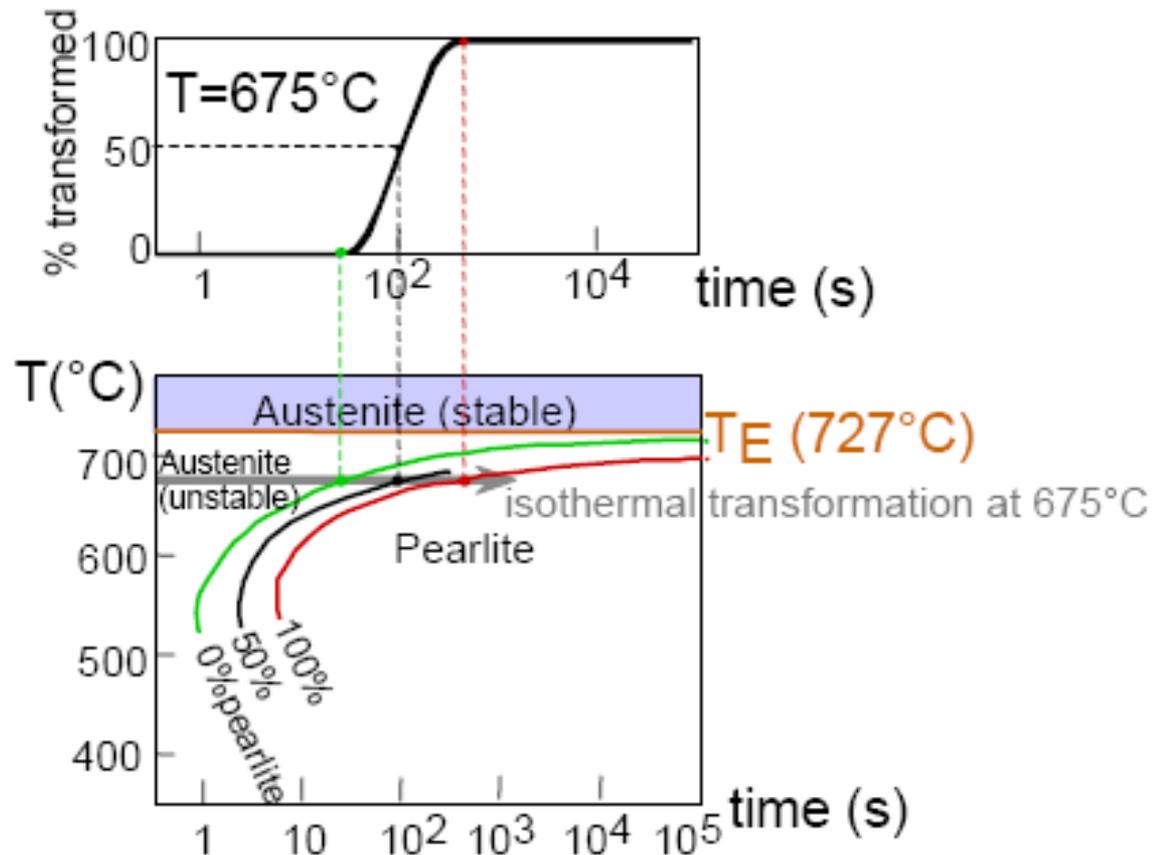
Fig.12.5 Structural Transformations on Cooling Steel Containing: (c) 1.0 % C

# TTT DIAGRAMS

- The family of S-shaped curves at different T are used to construct the TTT diagrams.
- The TTT diagrams are for the **isothermal** (constant T) transformations (material is cooled quickly to a given temperature before the transformation occurs, and then keep it at that temperature).
- At low temperatures, the transformation occurs sooner (it is controlled by the rate of nucleation) and grain growth (that is controlled by diffusion) is reduced.
- Slow diffusion at low temperatures leads to fine-grained microstructure with thin-layered structure of pearlite (**fine pearlite**).
- At higher temperatures, high diffusion rates allow for larger grain growth and formation of thick layered structure of pearlite (**coarse pearlite**).
- At compositions other than eutectoid, a proeutectoid phase (ferrite or cementite) coexist with pearlite.
- Additional curves for proeutectoid transformation must be included on TTT diagrams.

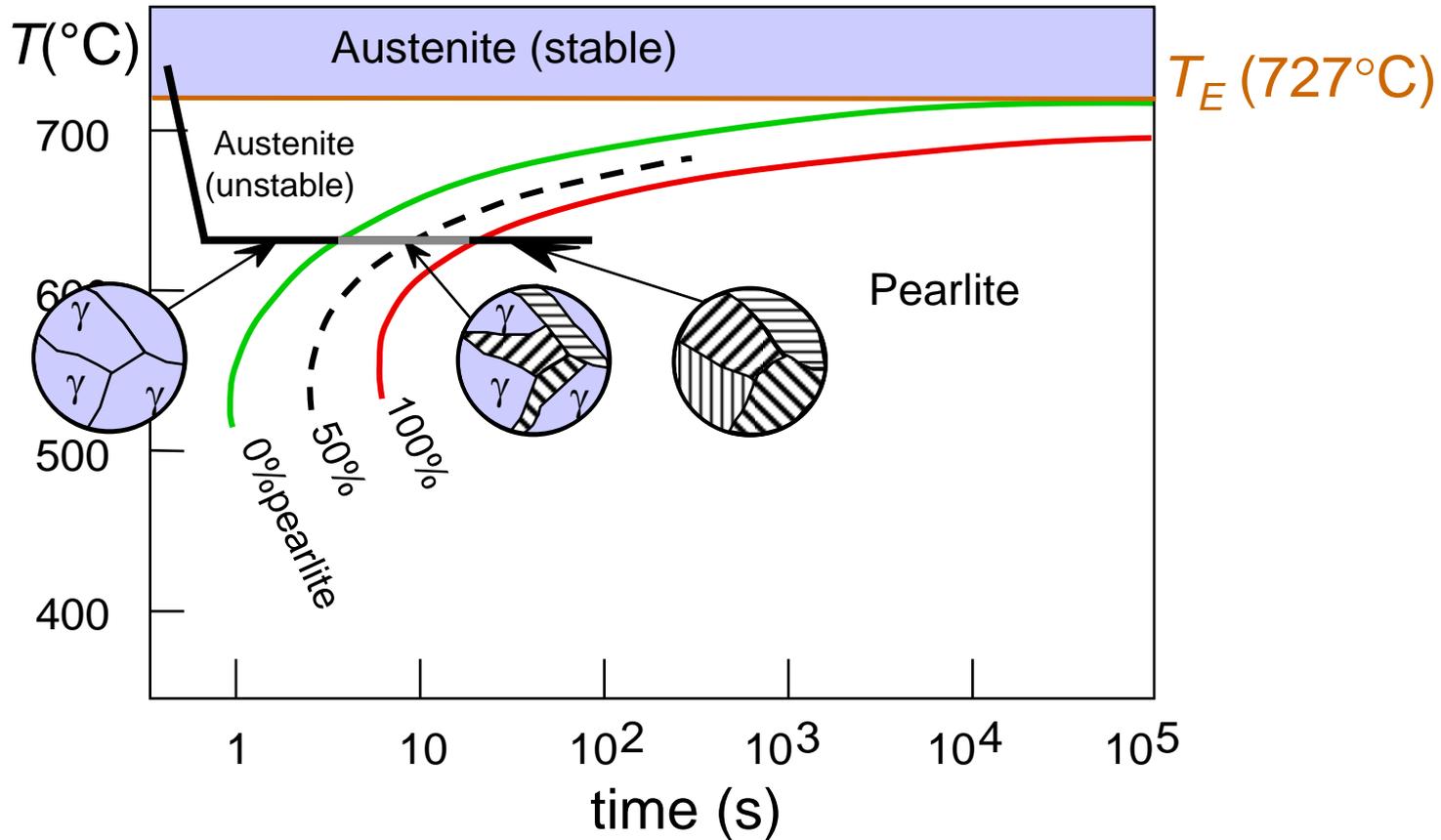
# ISOTHERMAL TRANSFORMATION DIAGRAMS

- Fe-C system,  $C_0 = 0.77\text{wt}\%C$
- Transformation at  $T = 675^\circ\text{C}$ .



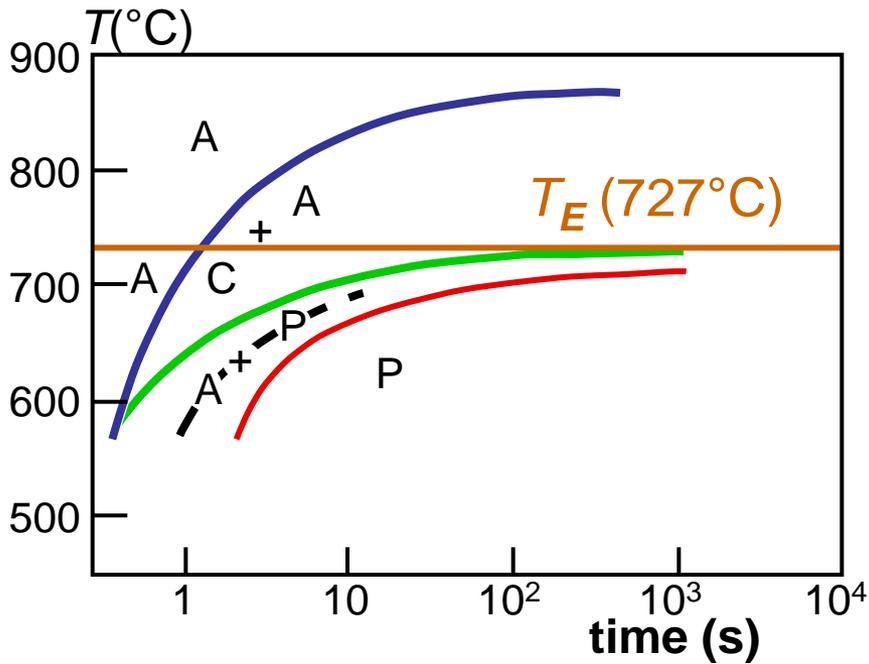
# EFFECT OF COOLING HISTORY IN FE-C SYSTEM

- Eutectoid composition,  $C_o = 0.76 \text{ wt\% C}$
- Begin at  $T > 727^\circ\text{C}$
- Rapidly cool to  $625^\circ\text{C}$  and hold isothermally.

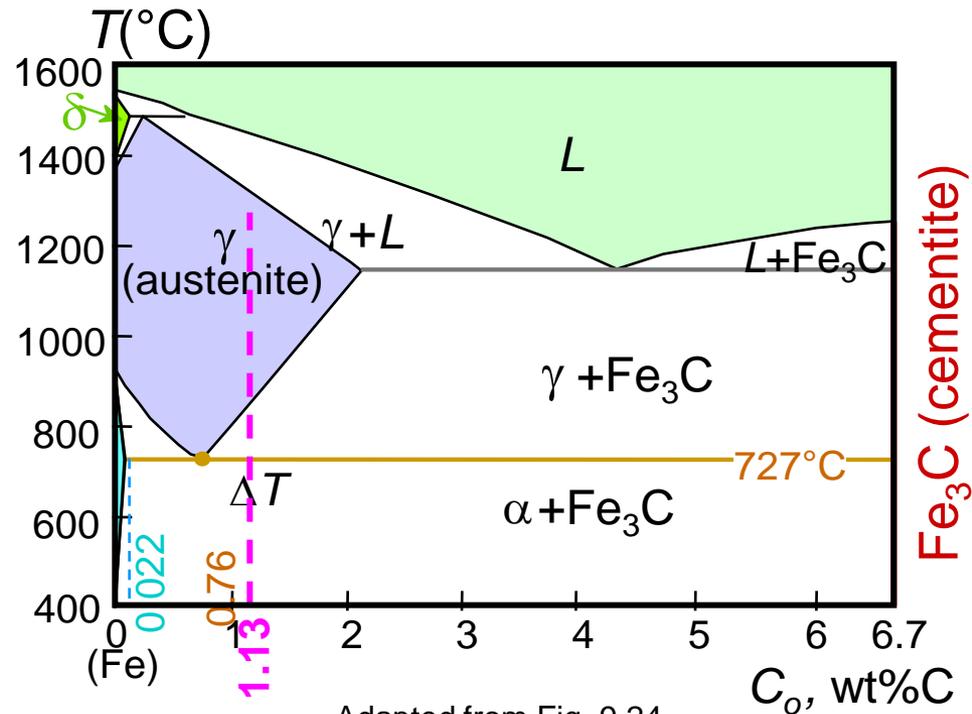


# TRANSFORMATIONS WITH PROEUTECTOID MATERIALS

$C_0 = 1.13 \text{ wt\% C}$



Adapted from Fig. 10.16, Callister 7e.

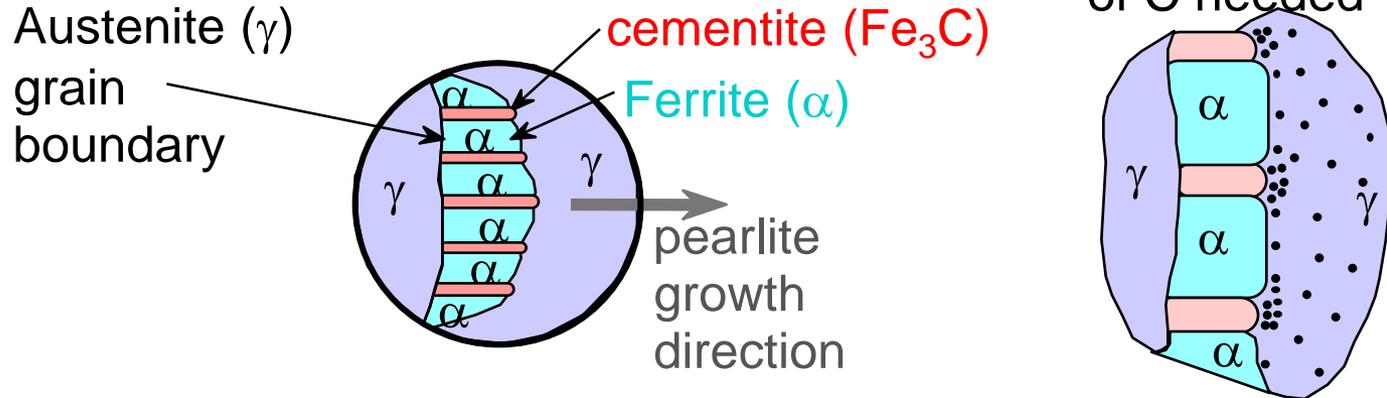


Adapted from Fig. 9.24, Callister 7e.

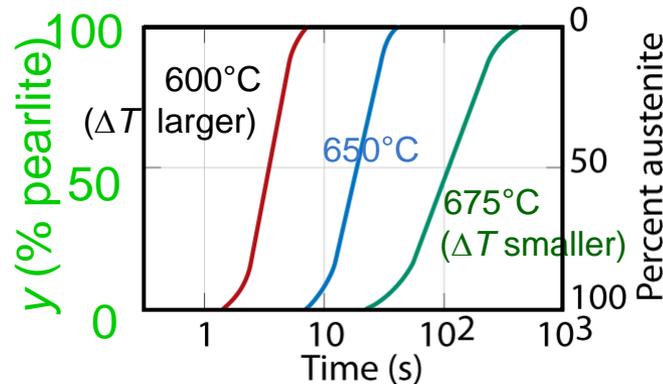
Hypereutectoid composition – proeutectoid cementite

# EUTECTOID TRANSFORMATION RATE

- Growth of pearlite from austenite:



- Recrystallization rate increases with  $\Delta T$ .

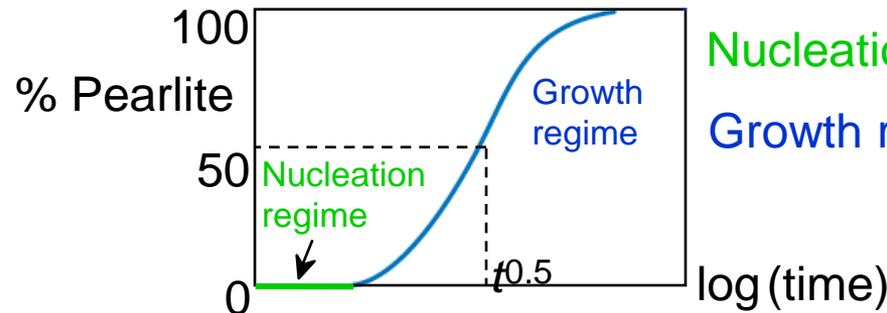


Course pearlite → formed at higher  $T$  - softer

Fine pearlite → formed at low  $T$  - harder

# NUCLEATION AND GROWTH

- Reaction rate is a result of nucleation and growth of crystals.

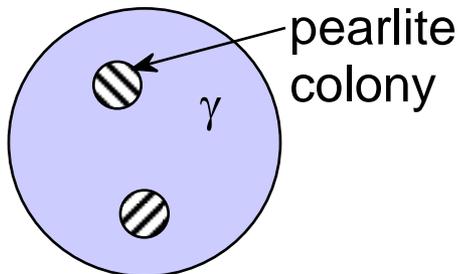


Nucleation rate increases with  $\Delta T$

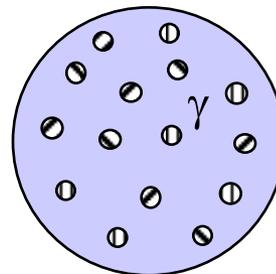
Growth rate increases with  $T$

Adapted from  
Fig. 10.10, Callister 7e.

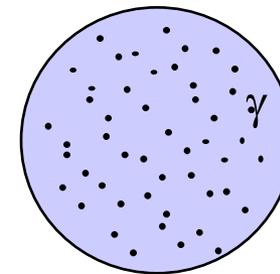
- Examples:



$T$  just below  $T_E$   
Nucleation rate low  
Growth rate high



$T$  moderately below  $T_E$   
Nucleation rate med.  
Growth rate med.

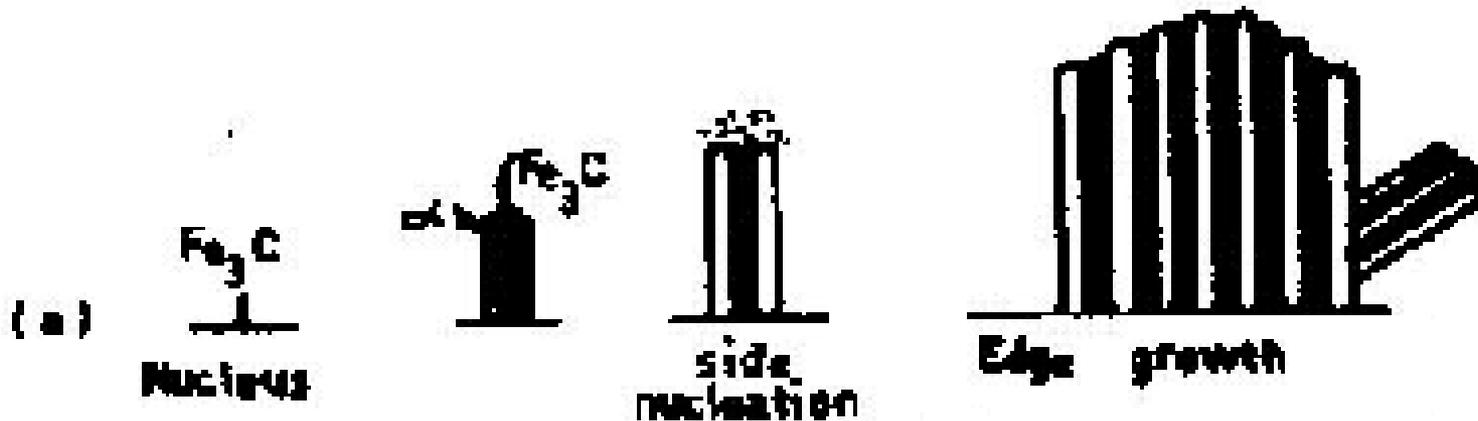


$T$  way below  $T_E$   
Nucleation rate high  
Growth rate low

## (i) Formation of Pearlite

The pearlite microstructure is the characteristic lamellar structure of alternate layers of ferrite and cementite as described in chapter 4. Just below 723 °C line, coarse lamellar pearlite is formed with a hardness of about 15 HRC. As the transformation temperature decreases, pearlite lamellae become increasingly finer and the whole structure becomes harder.

Pearlite formation is initiated at the austenite grain boundaries or at some other disarray in the austenite grains. First cementite is initiated causing carbon depletion in the adjacent region which is transformed to ferrite platelets, as shown in Fig. 12.6(a). Further transformation continues by branching.



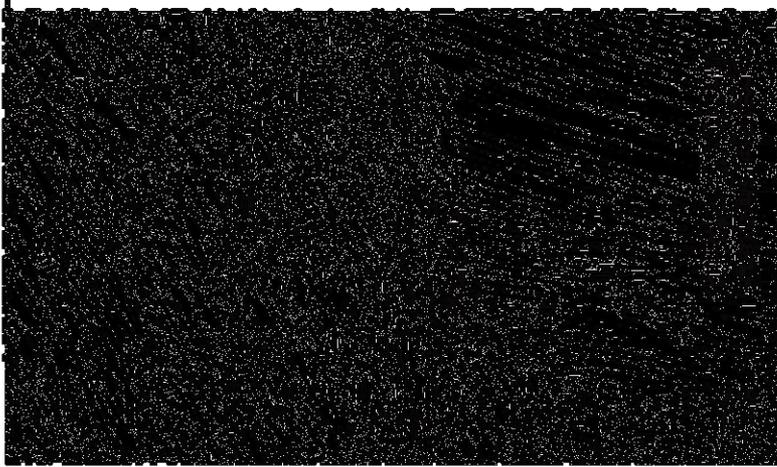
*Fig.12.6 Transformation of austenite into: (a) pearlite,*

# PEARLITE MORPHOLOGY

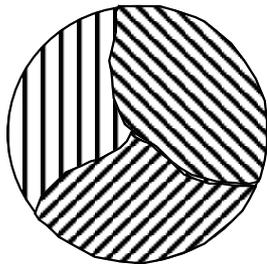
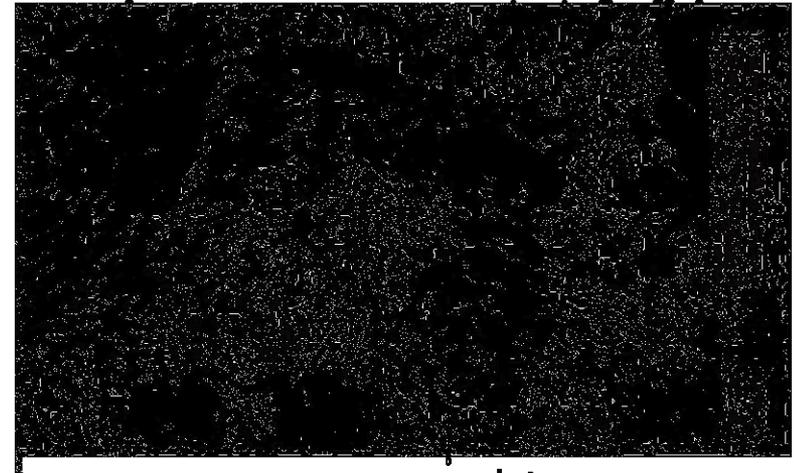
## Two cases:

- $T_{\text{transf}}$  just below  $T_E$  (650-700)
  - Larger  $T$ : diffusion is faster
  - Pearlite is coarser.

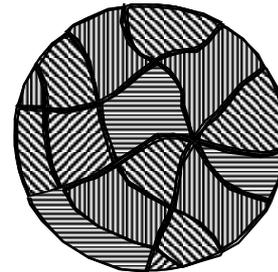
- $T_{\text{transf}}$  well below  $T_E$  (650-700)
  - Smaller  $T$ : diffusion is slower
  - Pearlite is finer.



10  $\mu\text{m}$



- Smaller  $\Delta T$ :  
colonies are  
larger



- Larger  $\Delta T$ :  
colonies are  
smaller

# NON-EQUILIBRIUM TRANSFORMATION PRODUCTS

## (ii) Formation of Bainite

At temperatures below about 550 °C another constituent, bainite, starts to separate along with the pearlite. Its formation is assumed to be initiated on ferrite nuclei, Fig. 12.6(b) which grows as platelets from the grain boundaries. The carbon content of the surrounding austenite increases continuously and then forms platelets of cementite. Bainite structure is not regularly lamellar as that of pearlite.

Depending on the temperature of formation of bainite it is classified as upper or lower bainite. The hardness of bainite varies from about **40 HRC: for upper bainite** to about **60 HRC for lower bainite**. This hardness increase, as with pearlite, is a reflection of the decrease in size and spacing of the carbide platelets as the transformation temperature decreases.

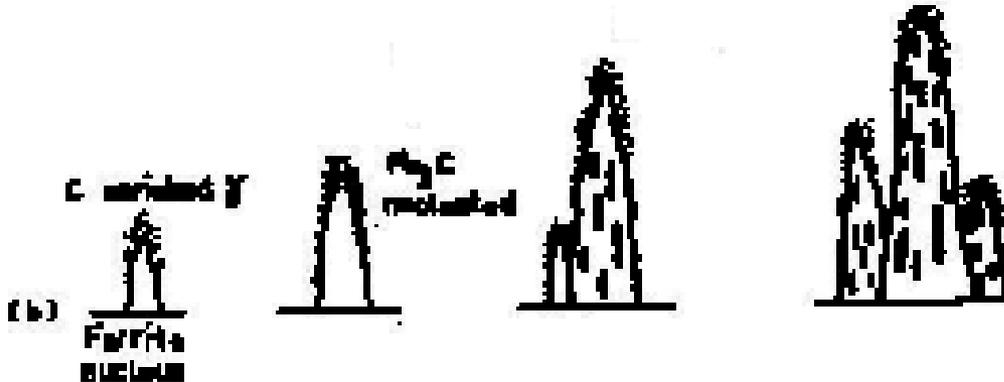
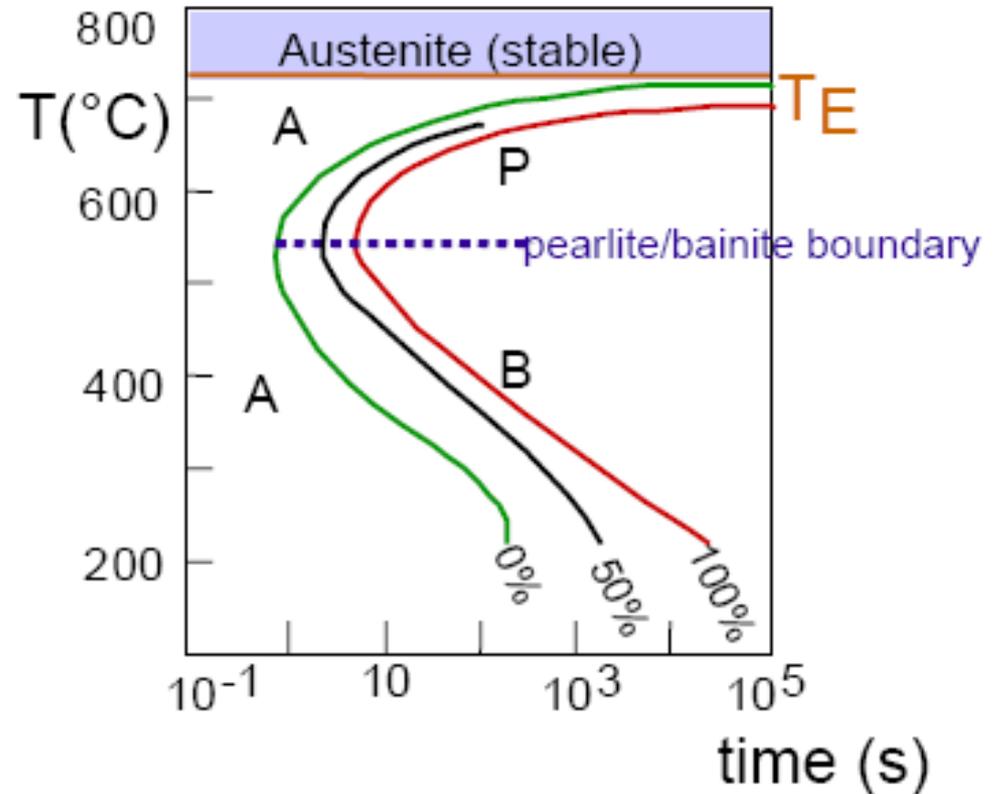
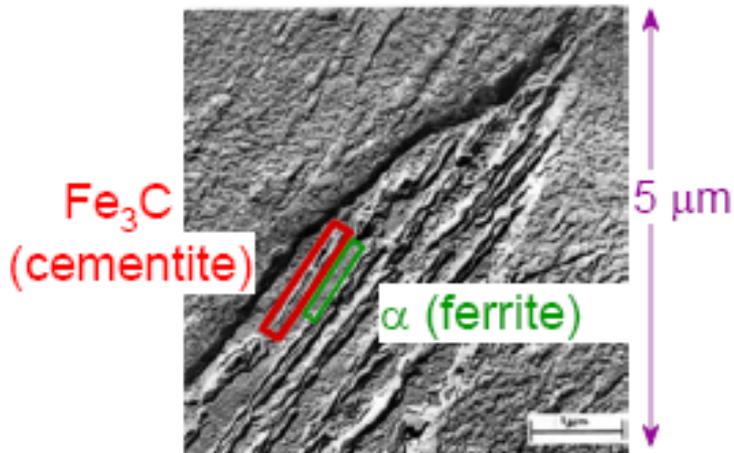


Fig.12.6 Transformation of austenite into: (b) bainite.

# NON-EQUIL TRANSFORMATION PRODUCTS

- **Bainite:**  $T_{\text{transf}} = 250 - 550^{\circ}\text{C}$

$\alpha$  lathes (strips) with long particles/rods of  $\text{Fe}_3\text{C}$



# NON-EQUILIBRIUM TRANSFORMATION PRODUCTS

## (iii) Formation of Martensite

Referring to Fig. 12.5, if cooling takes place as represented by curve V, austenite will start to transform on reaching martensite start line. As the cooling continues below this line there is very little carbon migration while the austenite is transforming. Thus the carbon atoms remain in solid solution in the  $\alpha$ -iron. Since the space available for the carbon atoms is less in  $\alpha$ -iron than in  $\gamma$ -iron the carbon atoms will expand the lattice. The resulting state of stress increases the hardness of the steel. The new constituent is called martensite and is a super-saturated solution of carbon in  $\alpha$ -iron.

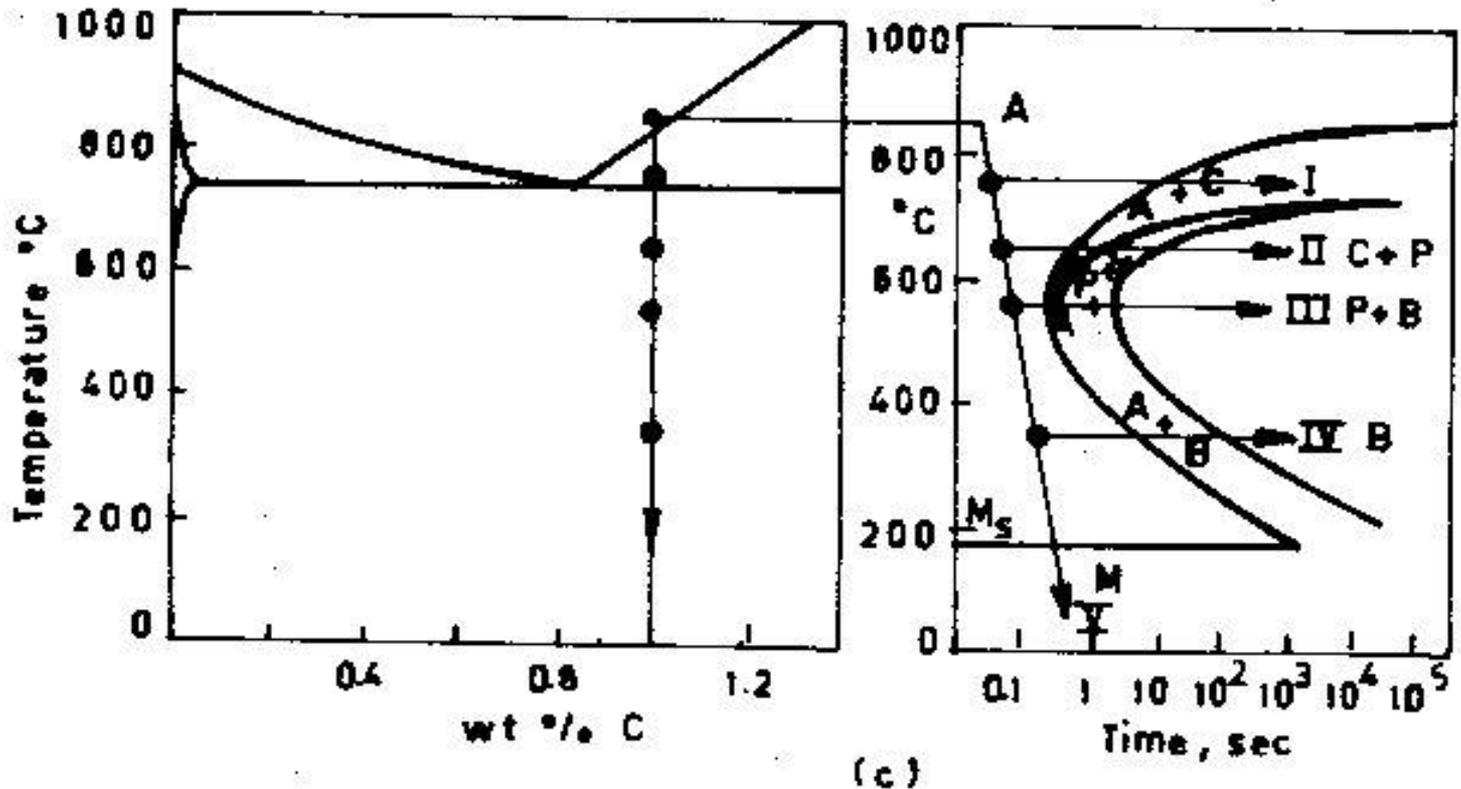


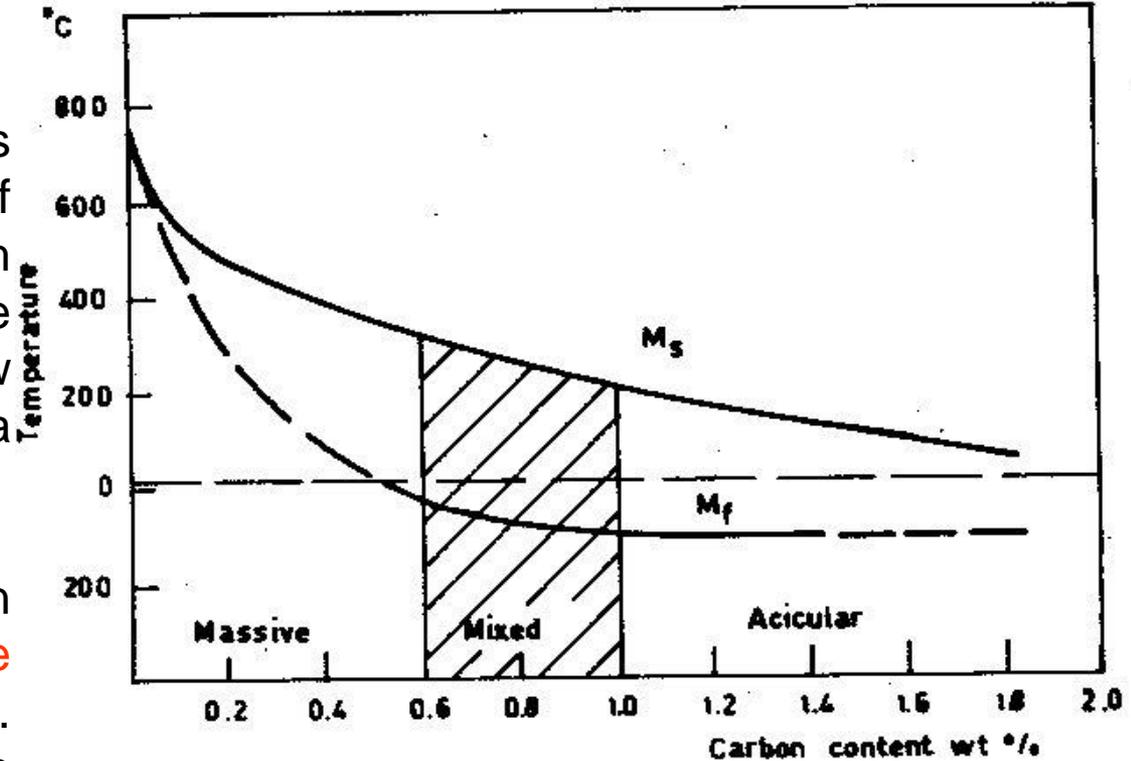
Fig.12.5  
Structural  
Transformations  
on Cooling Steel  
Containing: (c)  
1.0 % C

# NON-EQUILIBRIUM TRANSFORMATION PRODUCTS

## (iii) Formation of Martensite

From the transformation diagrams it will be seen that the formation of pearlite and bainite progresses with time whereas that of martensite does not. Each temperature below martensite start corresponds to a definite proportion of martensite.

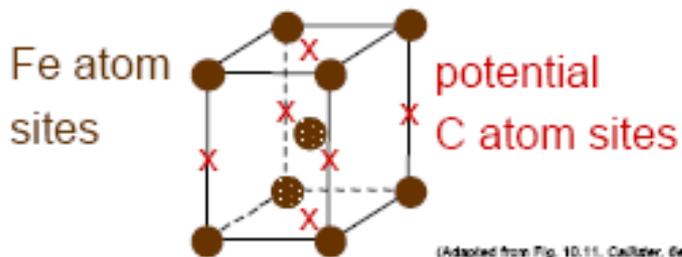
The structure of martensite in steels is classified as **massive martensite** and **acicular martensite**. The range of composition in which only massive martensite exists extends up to 0.6 % C. This type of martensite consists of packets of parallel platelets which can only be resolved in the electron microscope. The more familiar acicular martensite is found only in steels containing 1 % C and more.



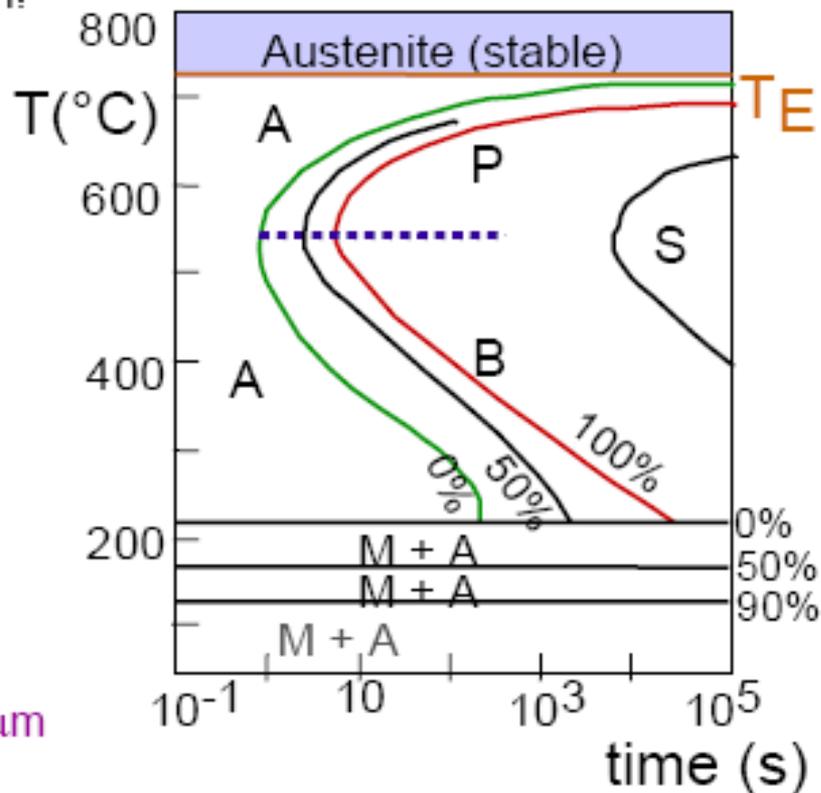
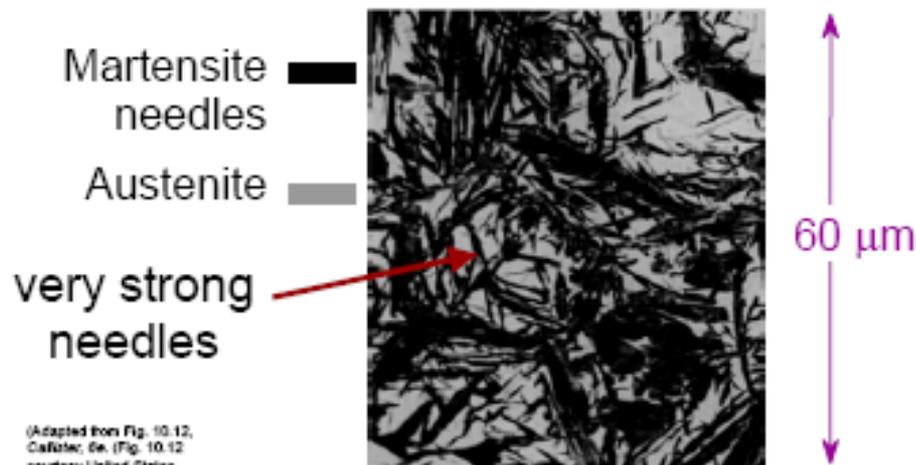
*Fig.12.7 Influence of carbon content on the martensite start and finish temperatures in unalloyed steels.*

# NON-EQUIL TRANSFORMATION PRODUCTS

- **Martensite**:  $T_{\text{transf}} < 250^{\circ}\text{C}$   
 --  $\gamma(\text{FCC}) \rightarrow \text{Martensite (BCT)}$   
 Involves single atom jumps, not diffusion!



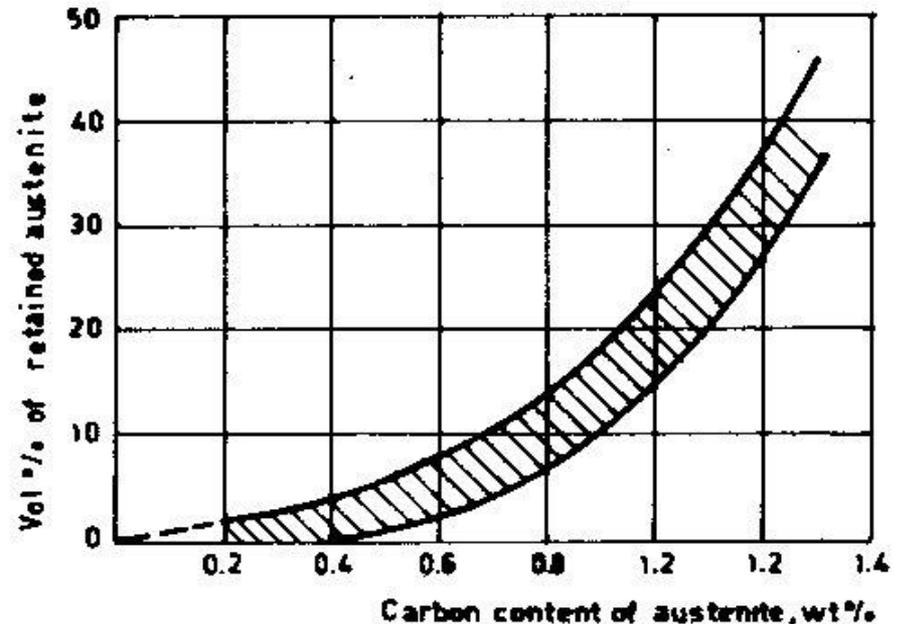
- $\gamma$  to M transformation..



#### (iv) Retained Austenite

Most of the austenite in steel will transform to martensite during quenching to room temperature. **The untransformed part is called retained austenite.** Fig.12.8. shows how the amount of retained austenite in unalloyed steel varies with the carbon content. If the temperature is lowered below room temperature the transformation to martensite continues. This method of increasing the amount of martensite is called **sub-zero treatment.**

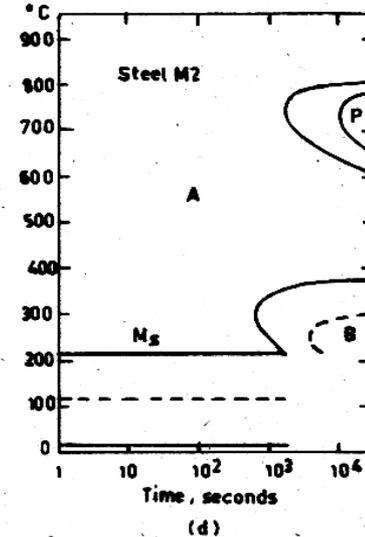
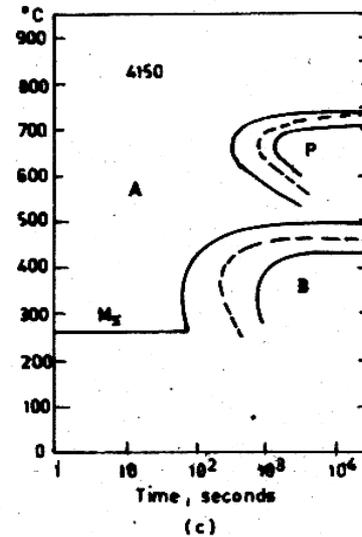
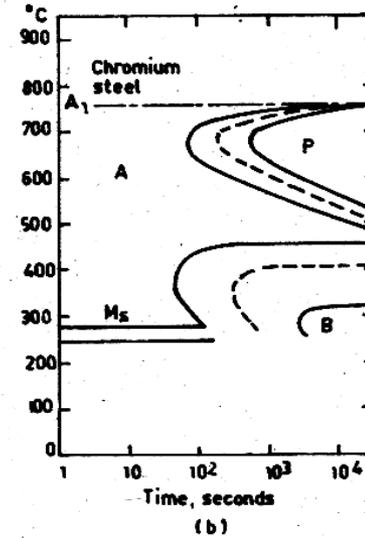
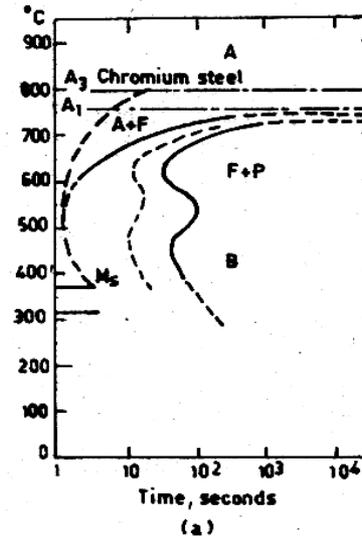
In the martempering process, the cooling is interrupted just above martensite start temperature and then the steel is allowed to cool to room temperature. This interruption in the cooling stabilizes the austenite somewhat; which causes the martensite formation to start at a lower temperature, thereby resulting in a higher proportion of retained austenite at room temperature. Hence a martempered or air-hardened steel has in general a larger amount of retained austenite than an oil hardened one.



*Fig.12.8 Dependence of retained austenite to austenitic carbon content.*

### 12.3.3 Affect of Alloying Elements on TTT Curves

All alloying elements delay the formation of ferrite and cementite, i.e. the transformation curves in the TTT diagram are displayed to the right. It is very difficult to formulate any general rules regarding the influence exerted by the various alloying elements. Carbon, nickel, manganese and silicon move both pearlite and bainite curves to the right but do not separate them appreciably on the temperature scale. Molybdenum, chromium and vanadium move the pearlite curve markedly to the right and also displace it upwards to higher temperatures; the bainite curve is not moved so much to the right but is depressed to lower temperatures. The transformations are affected to a much greater extent by the simultaneous presence of several alloying elements as shown in Fig.12.9.



The bainite transformation start temperature is changed by alloying elements according to the following empirical equation:

$$B_s (\text{°C}) = 830 - 270\%C - 90\%Mn - 37\%Ni - 70\%Cr - 83\%Mo \quad (12.1)$$

Where as the martensite start temperature is altered according to the following empirical equation:

$$M_s (\text{°C}) = 539 - 423\%C - 30.4\%Mn - 17.7\%Ni - 12.1\%Cr - 7.5\%Mo \quad (12.2)$$

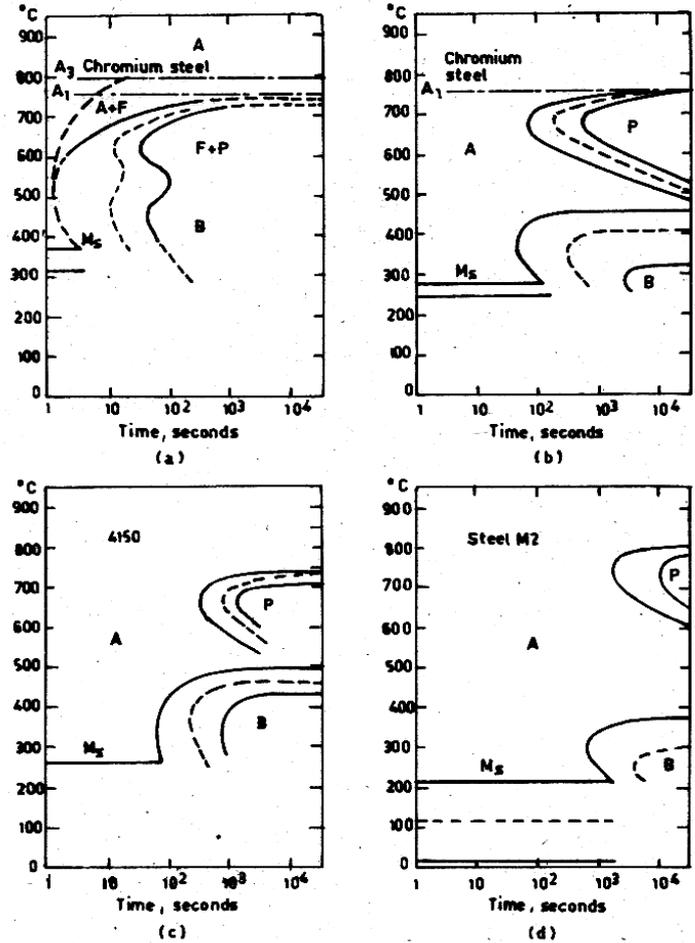


Fig.12.9 TTT Diagrams of Some Alloy Steels:  
 (a) 0.5 % Cr, (b) 3.1 % Cr, (c) AISI 4150, and (d) Tool Steel M2

# PHASE TRANSFORMATIONS OF ALLOYS

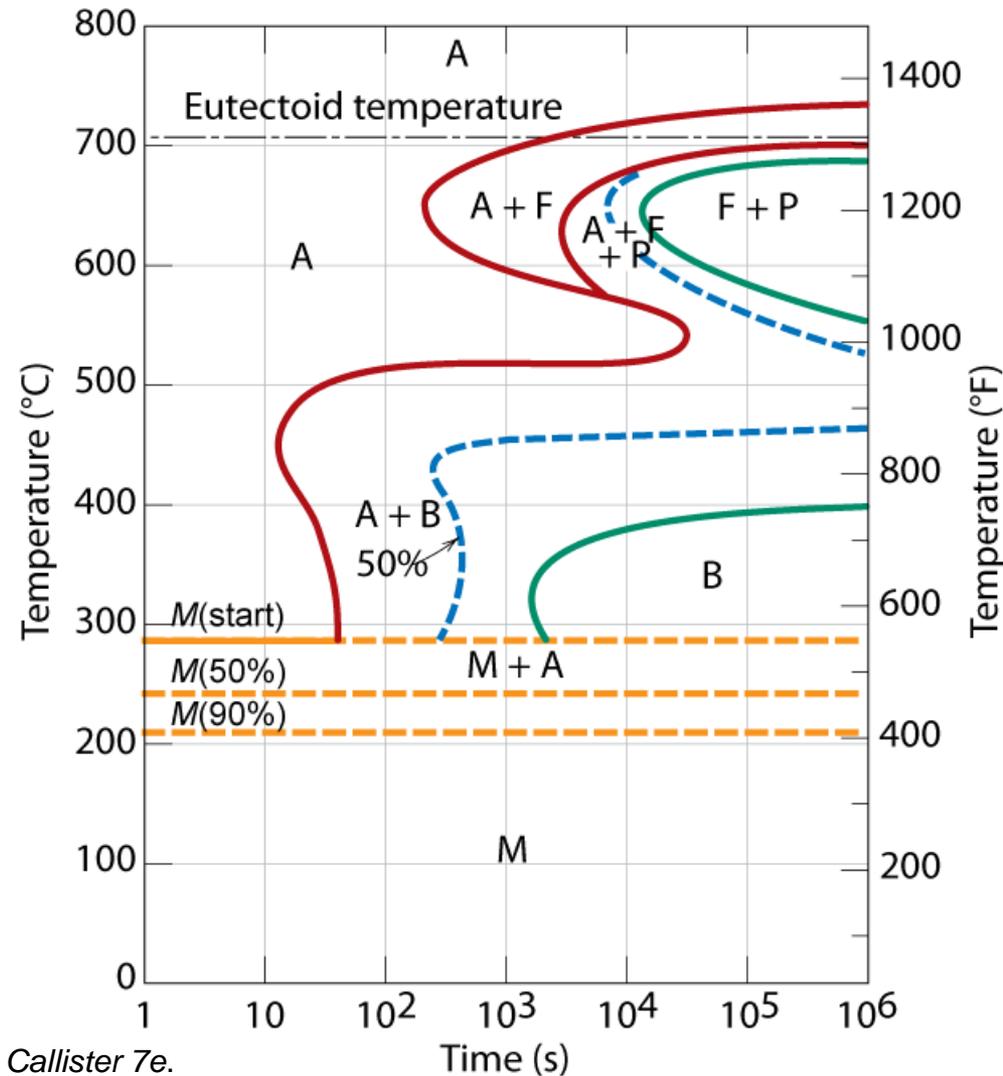
Effect of adding other elements

Change transition temp.

Cr, Ni, Mo, Si, Mn

retard  $\gamma \rightarrow \alpha + \text{Fe}_3\text{C}$

transformation



Adapted from Fig. 10.23, *Callister 7e*.

## 12.3.4 Transformation on Continuous Cooling

The TTT curves refer specifically to transformation at a constant temperature, whereas most heat treatment operations involve continuous cooling. The effects of continuous cooling on the transformation behaviour can be derived from Fig.12.10, which shows superimposed on the TTT curves number of cooling curves, each representing a different rate of continuous cooling.

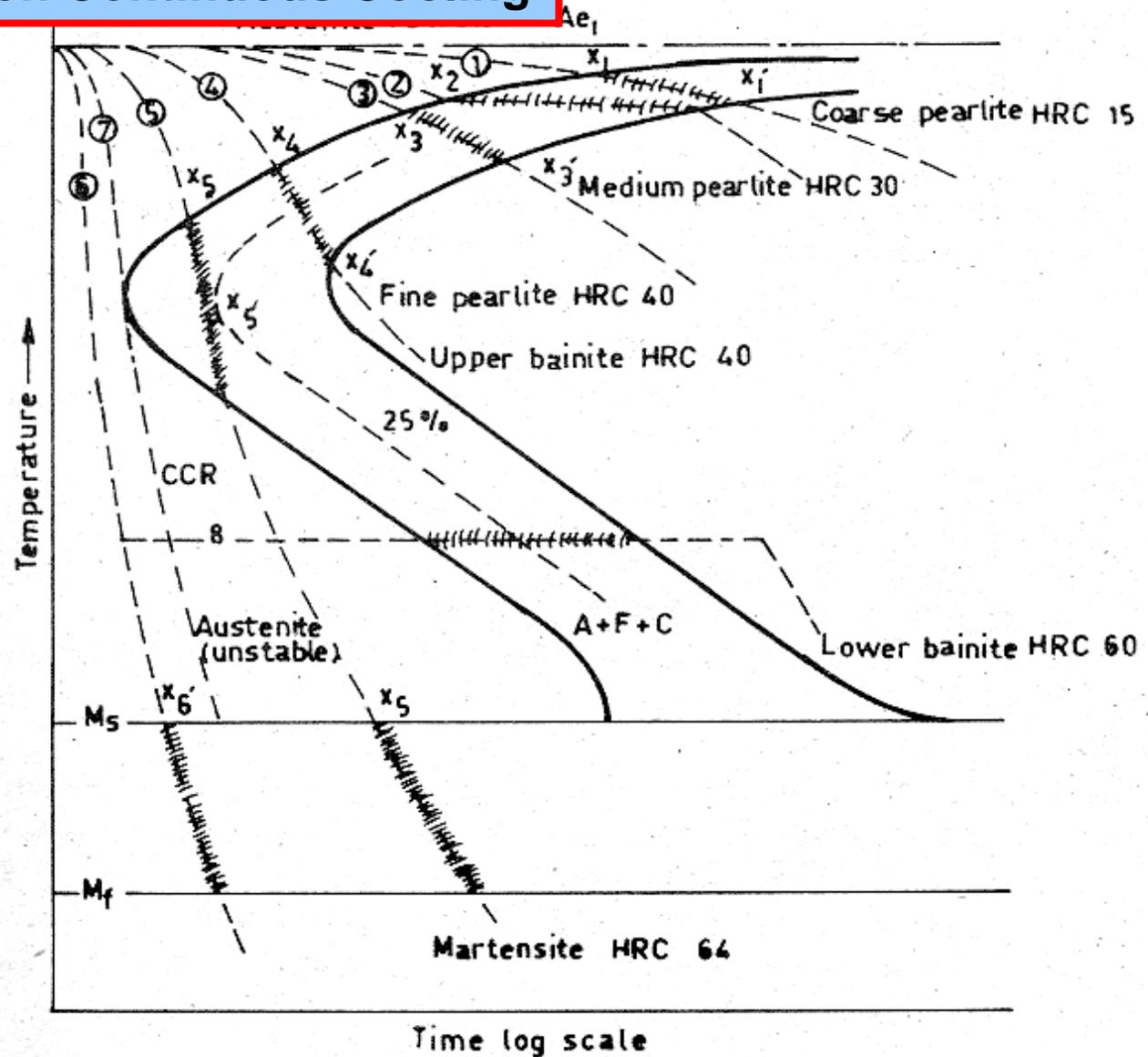


Fig.12.10 Cooling curves superimposed on TTT diagram of a eutectoid steel.

## 12.3.4 Transformation on Continuous Cooling

Curve 1 indicates a very slow cooling rate typical of annealing allowing transformation to coarse pearlite. Transformation starts at  $X_1$ , point and completed at  $X_1'$  after which the material may be cooled without any change occurring.

Curve 2 illustrates isothermal annealing which results in a more uniform microstructure.

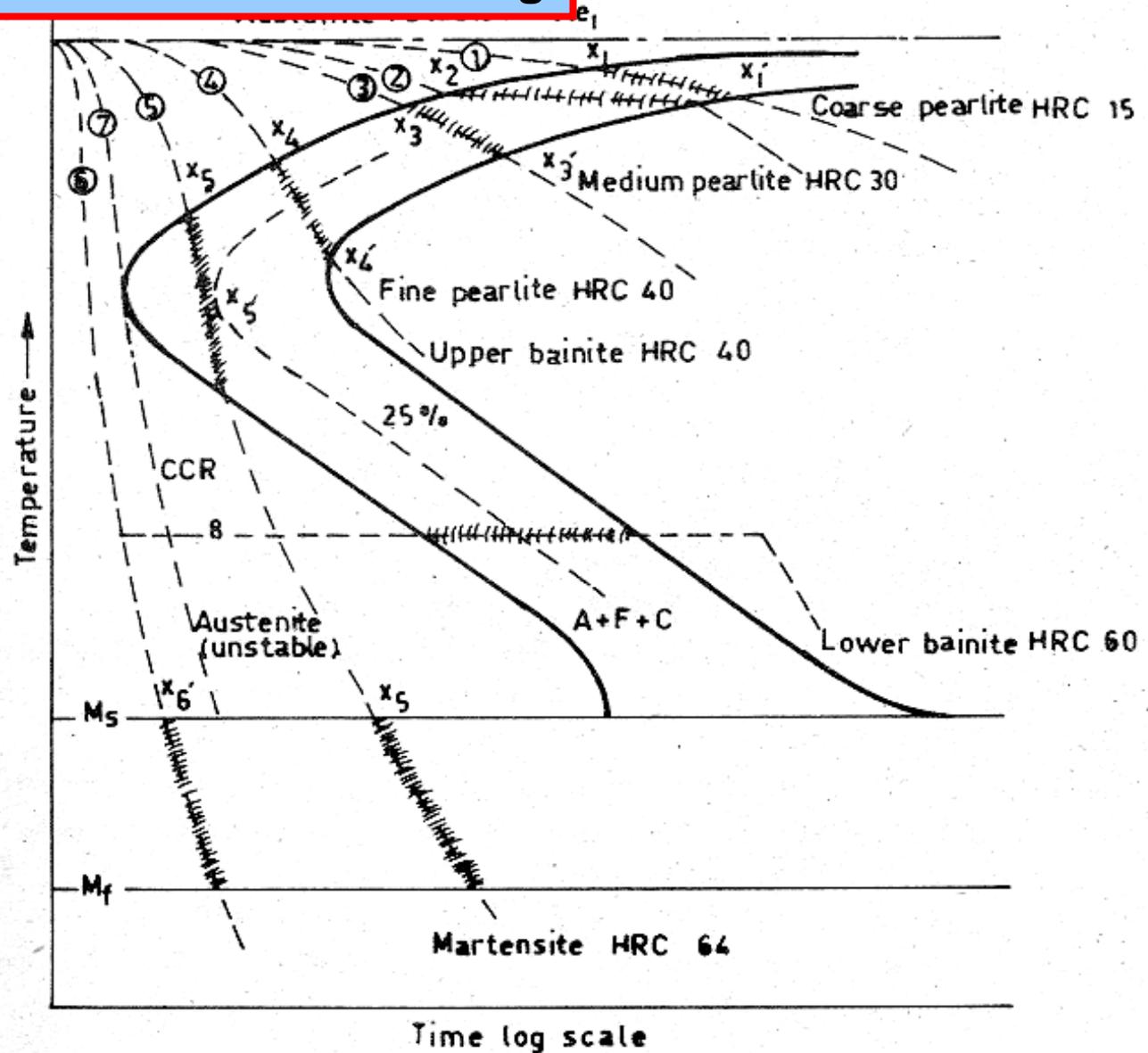


Fig. 12.10 Cooling curves superimposed on TTT diagram of a eutectoid steel.

Curve 3 represents cooling rate of normalizing: Transformation starts at X3 and completed at X'3. Time difference between these two points are shorter than X1 and X1', so structure will show more variation in the fineness of pearlite. Curve 4 is slow oil quench and results in fine pearlite. Curve 5 is fast oil quenching, transformation to fine pearlite starts at X5 and stops at X5'. Below this temperature, no transformation takes place till X5'' which is on martensite start line. The remaining austenite now transform to martensite. Final microstructure is 25 % fine pearlite and 75 % martensite.

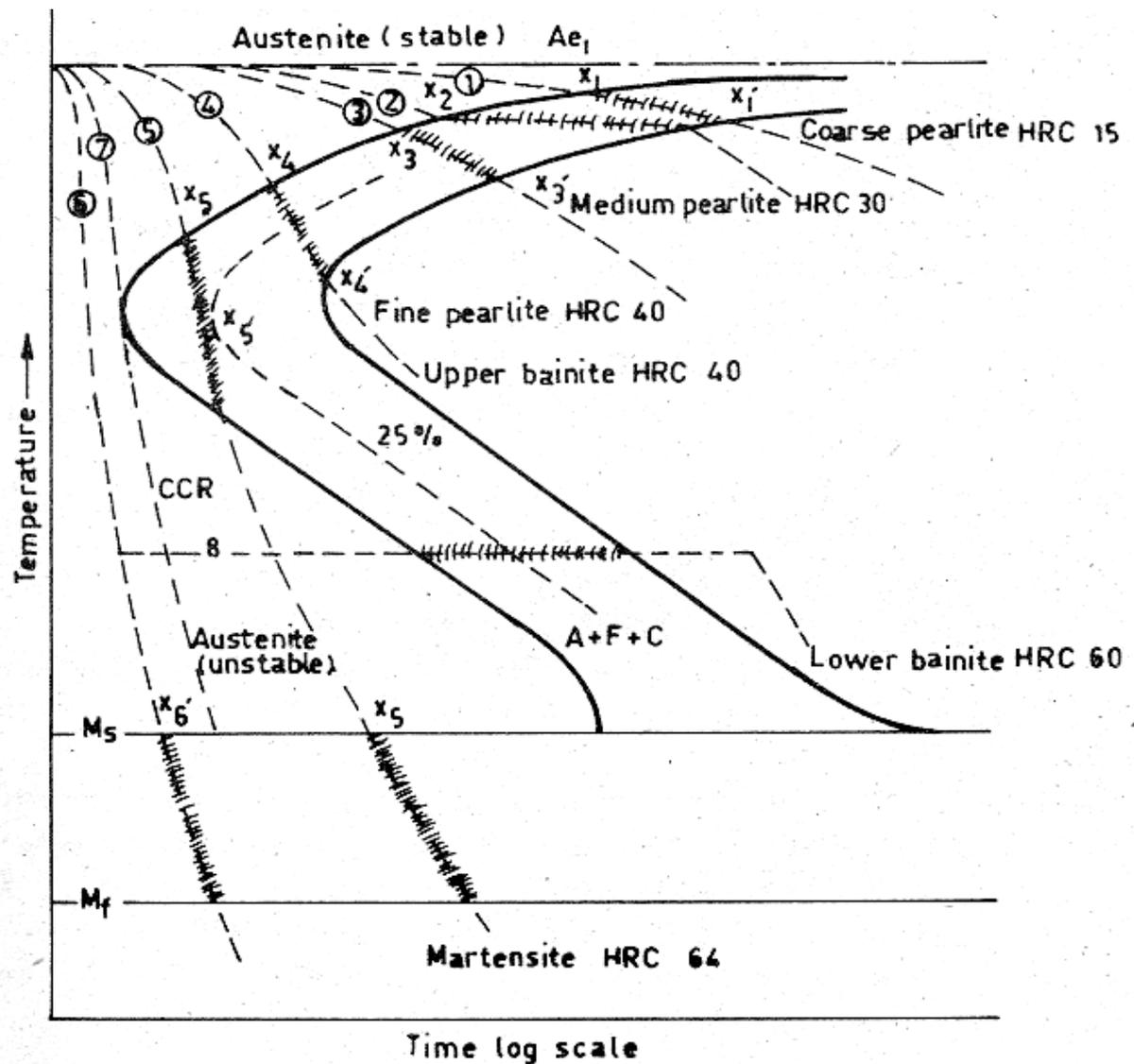


Fig.12.10 Cooling curves superimposed on TTT diagram of a eutectoid steel.

Curve 6 represents a fast water quench, which avoids the nose of pearlite transformation. It remains austenitic until the martensite start line is reached at X6. Transformation to martensite will take place between the martensite start and finish lines. The final microstructure will be entirely martensite of high hardness. Curve 7 is tangent to top pearlite nose region which does not transform to pearlite at all. This is called **Critical Cooling Rate**. Any cooling rate slower than critical cooling rate will enter pearlite region and complete martensitic transformation will not take place. Any cooling rate faster than the critical cooling rate will form only martensite.

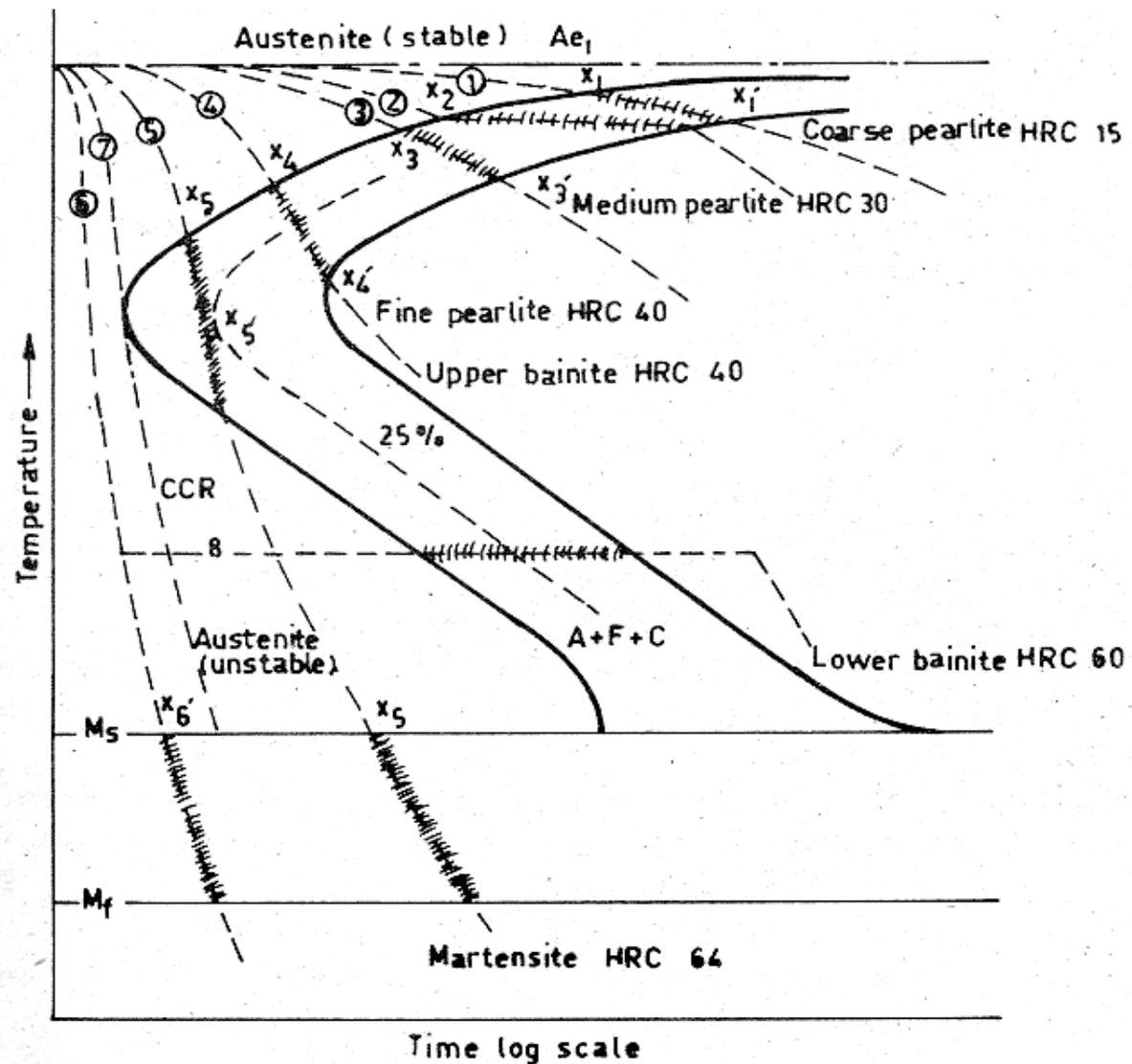


Fig.12.10 Cooling curves superimposed on TTT diagram of a eutectoid steel.

It is possible to derive from the TTT diagram another diagram which will show the transformation under continuous cooling. This is called as CCT (**Continuous Cooling Transformation**) diagram. In most cases, transformation is delayed when continuous cooling is employed. So, CCT diagrams are derivations of TTT diagrams where the transformation curves are pushed downward and to the right. The derivation of CCT diagrams are tedious task and not essential provided that TTT diagrams are well understood. TTT diagram is very useful in planning heat treatments and in understanding why steel responds as it does to a particular heat treatment.

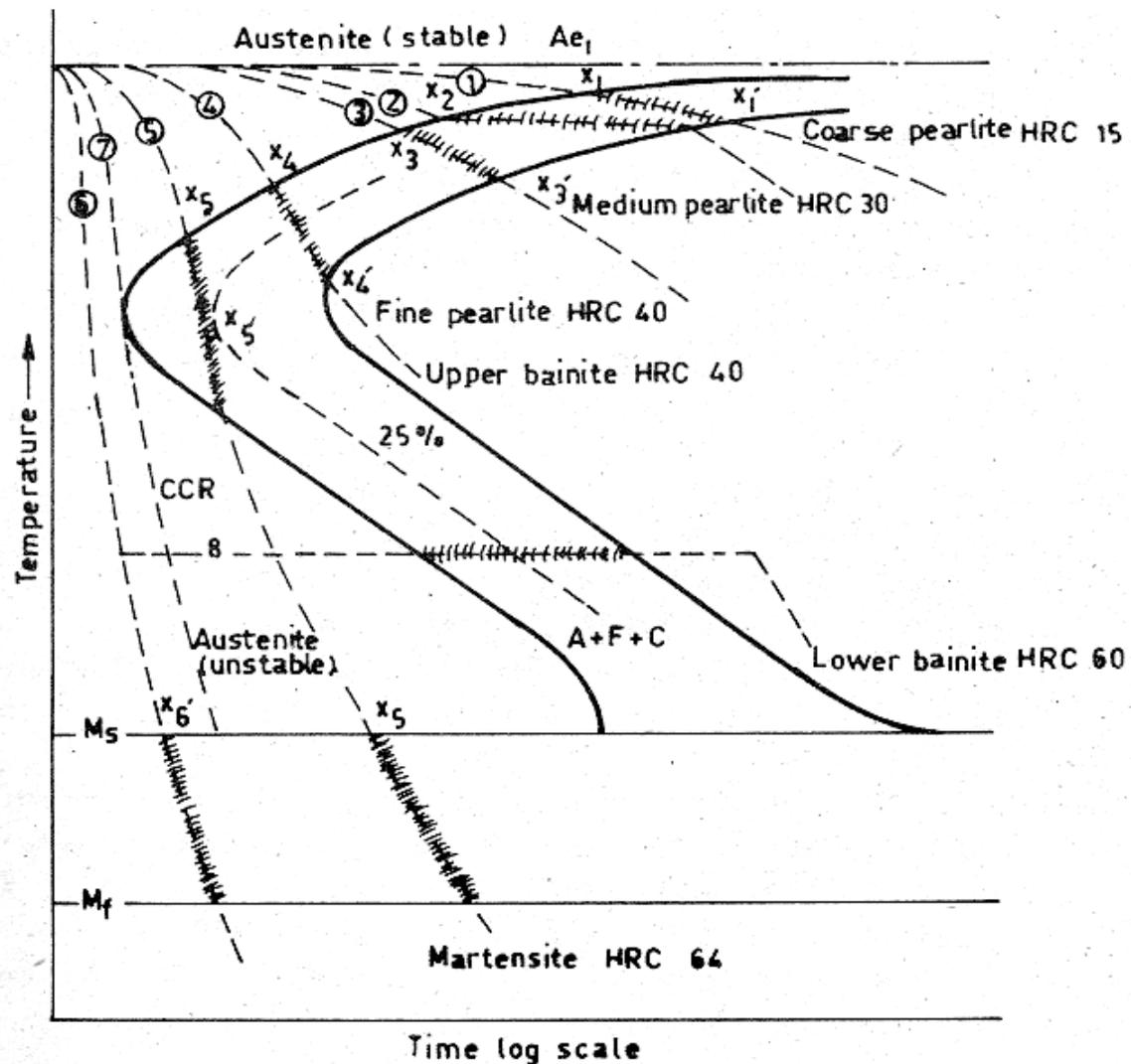
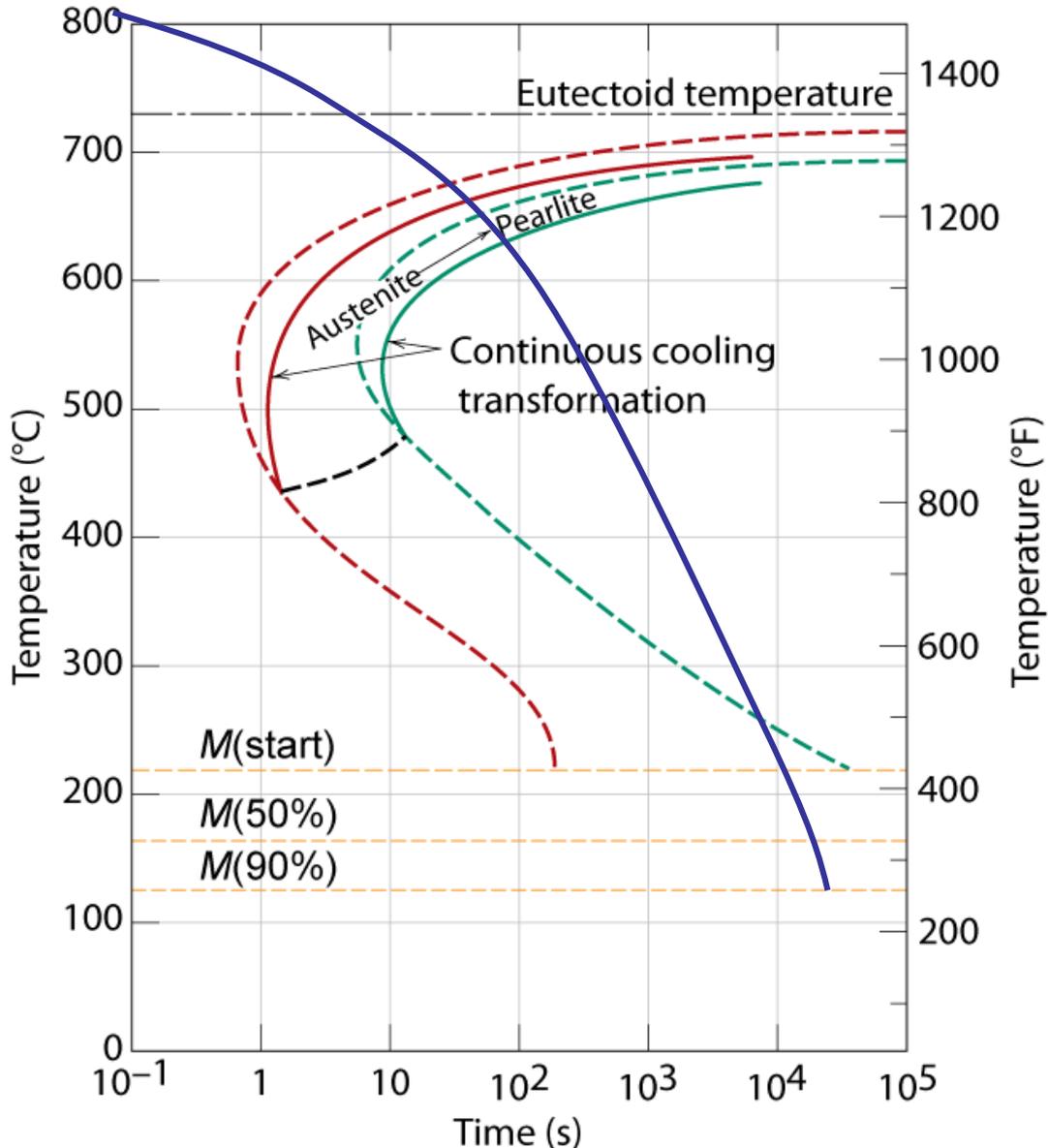


Fig.12.10 Cooling curves superimposed on TTT diagram of a eutectoid steel.

# CONTINUOUS COOLING CURVE

plot temp vs. time



# Dynamic Phase Transformations

**On the isothermal transformation diagram for 0.45 wt% C Fe-C alloy, sketch and label the time-temperature paths to produce the following microstructures:**

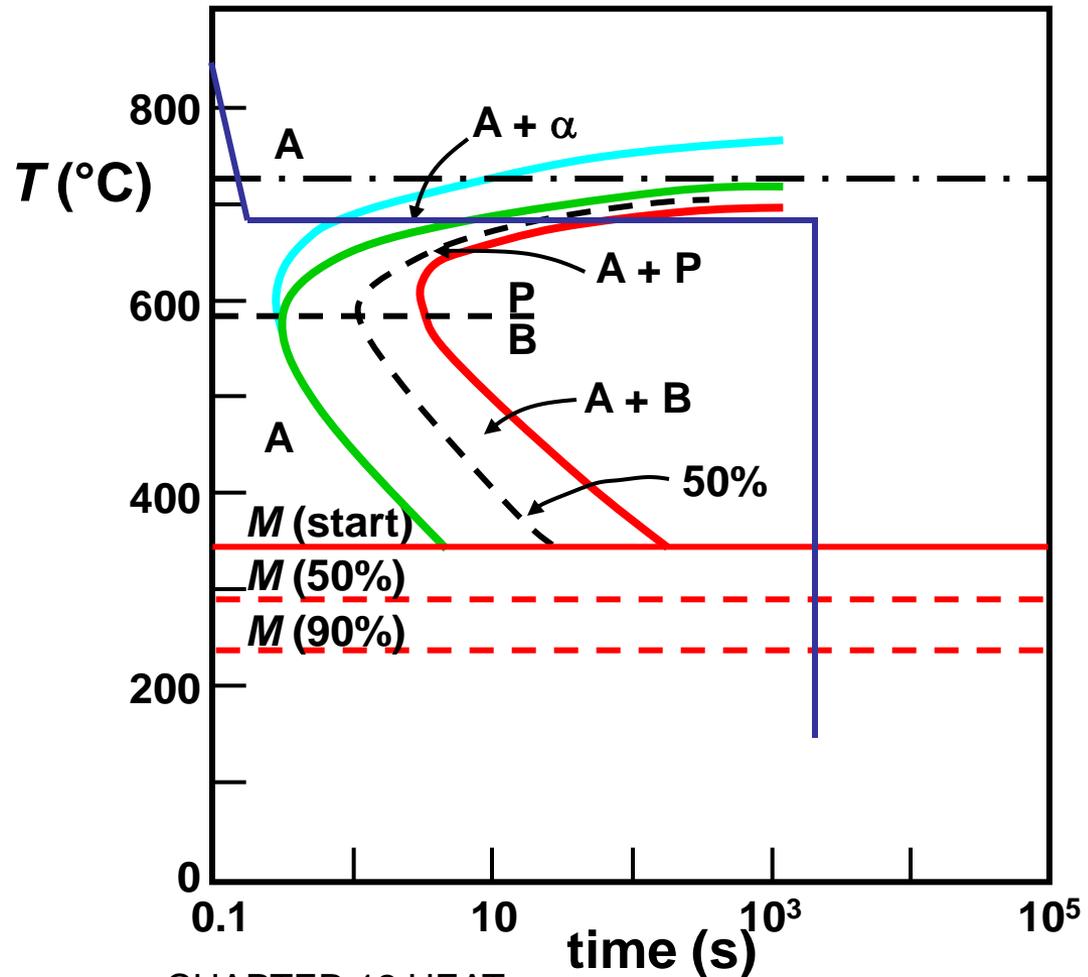
- a) 42% proeutectoid ferrite and 58% coarse pearlite**
- b) 50% fine pearlite and 50% bainite**
- c) 100% martensite**
- d) 50% martensite and 50% austenite**

## Example Problem for $C_o = 0.45 \text{ wt}\%$

a) 42% proeutectoid ferrite and 58% coarse pearlite

first make ferrite  
then pearlite

course pearlite  
 $\therefore$  higher  $T$

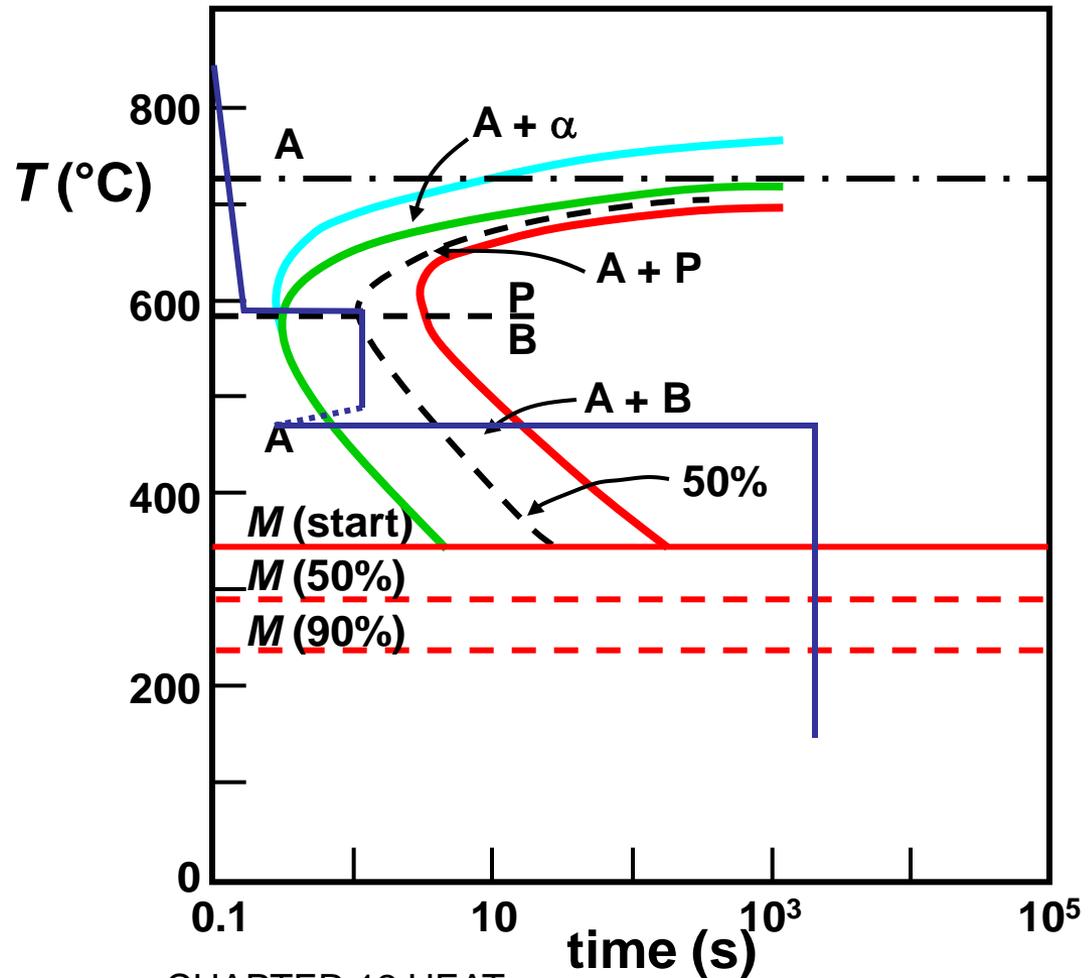


# Example Problem for $C_o = 0.45 \text{ wt}\%$

b) 50% fine pearlite and 50% bainite

first make pearlite then bainite

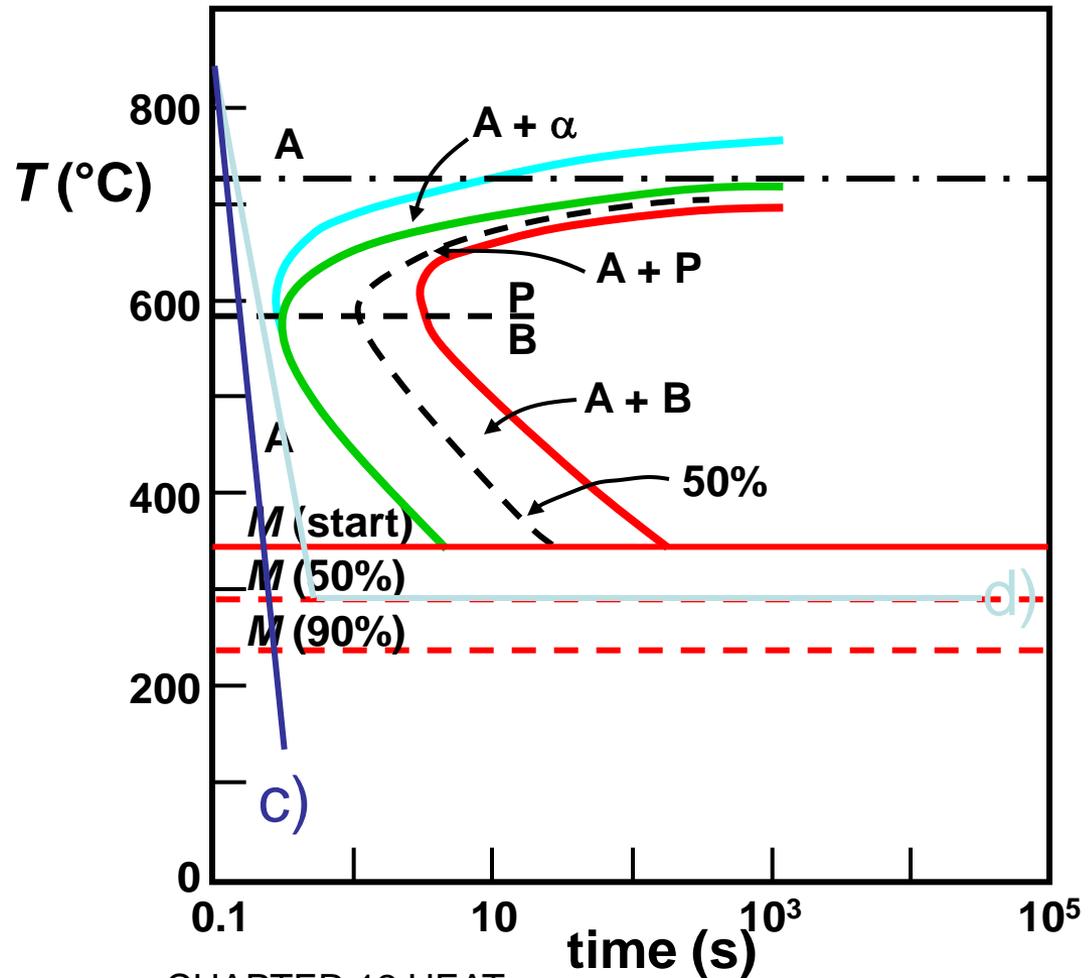
fine pearlite  
 $\therefore$  lower  $T$



## Example Problem for $C_o = 0.45 \text{ wt}\%$

c) 100 % martensite – quench = rapid cool

d) 50 % martensite  
and 50 % austenite



## 12.4 HARDENABILITY

Provided the rate of cooling is greater than the critical cooling rate, the hardness obtained on quenching depends principally on the carbon content of the steel. If the cooling rate is slower than the critical cooling rate the amount of martensite is reduced, thus lowering the overall hardness of the steel. The relationship between the hardness, carbon content and amount of martensite is shown in Fig.12.11.

Hardenability is the ability of the steel to harden by the formation of martensite on quenching.

Hardenability determines the depth of hardening obtained on quenching, which is usually specified as the distance below the surface where the amount of martensite has been reduced to 50 %.

Hardenability of steel depends on:

- (1)The quenching medium and method of quenching.
- (2)Composition of the steel.
- (3)Section size of the steel

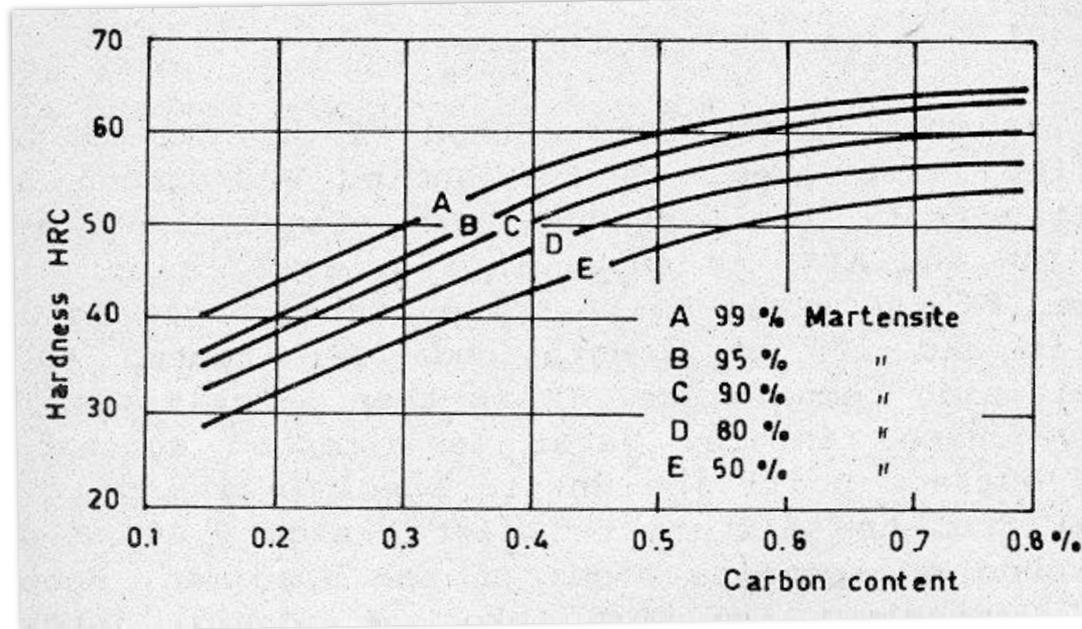


Fig.12.11 Relationship between hardness, carbon content and amount of martensite.

The most widely used method of determining hardenability of steel is the **Jominy end-quench hardenability test**. The test has been standardized by the ASTM, SAE and AISI as shown in Fig.12.12. A normalized specimen of the steel to be tested is machined to 25 mm diameter and 100 mm length and then heated to its austenitizing temperature. It is then quickly placed in the quenching fixture. Water is directed against the bottom surface until the entire specimen is cool. Upon removal from the fixture two flats, each 0.40 mm deep, are ground on opposite sides of the specimen. Rockwell hardness readings are then taken at regular intervals from the bottom of the specimen and plotted as shown in the figure.

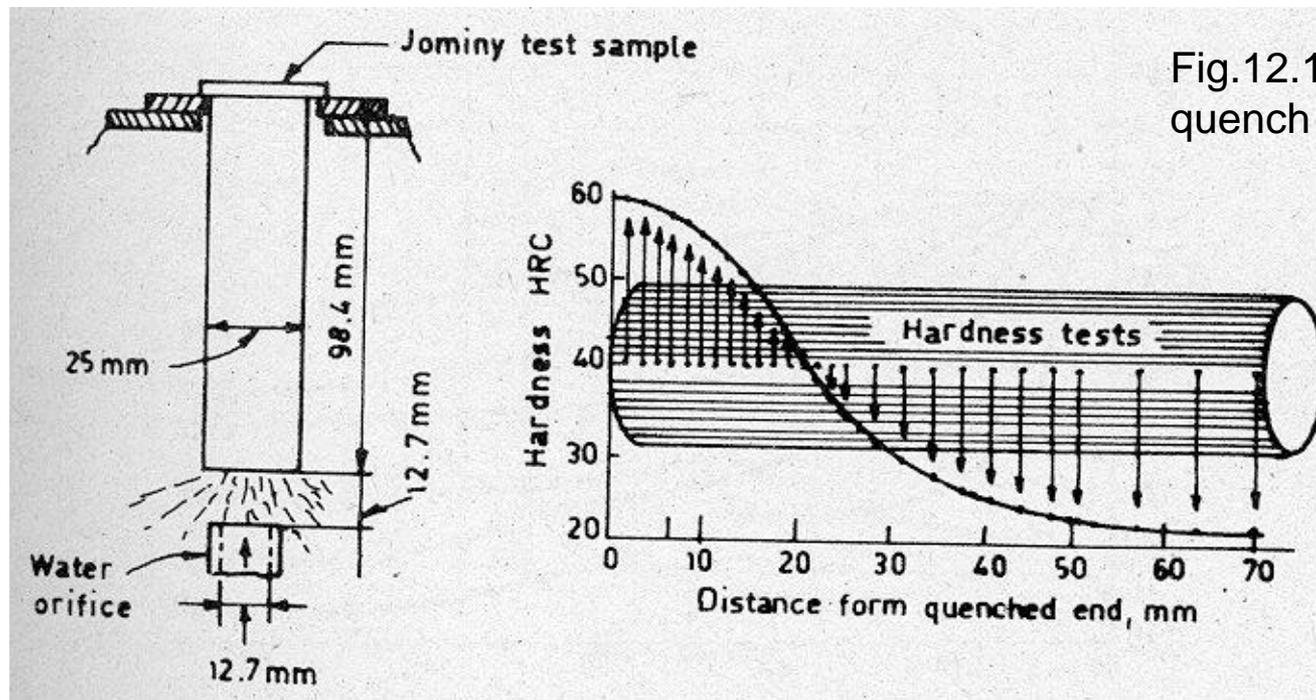
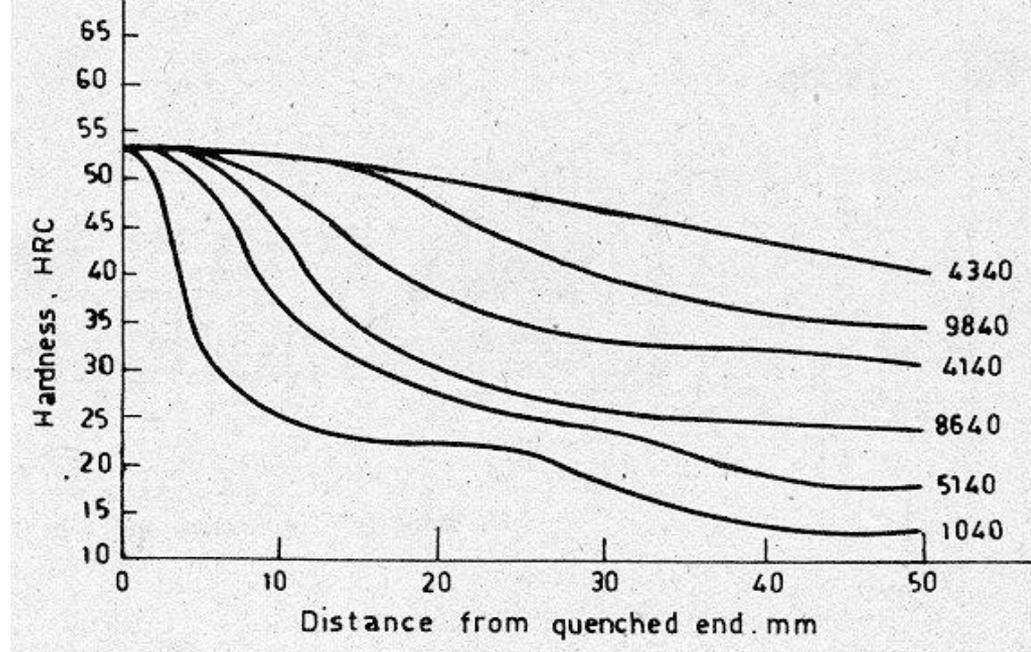


Fig.12.12 The Jominy end-quench hardenability test.

Each location on the Jominy test piece represents a certain cooling rate, and since the thermal conductivity of all steels is assumed to be the same, this cooling rate is the same for a given position on the test piece regardless of the composition of the steel. Each specimen is thus subjected to a series of cooling rates varying continuously from very rapid at the quenched end to very slow at the air-cooled end.



*Fig.12.13 Jominy hardenability curve for some steels.*

Since each distance along the quenched bar is equivalent to a certain actual cooling rate, hardness versus distance graph is equivalent to hardness versus cooling rate graph.

The end-quench curves of six steels, each containing 0.40 % carbon but of different hardenability are shown in Fig 12.13. All six steels develop the same maximum hardness at the water quenched end, since this is primarily a function of carbon content only. However, in the high-hardenability steel 4340, this hardness is maintained for a considerable distance, whereas in the lower-hardenability steel 1040 the hardness drops off almost immediately

## 12.4.1 Quenching medium

The structure and hardness resulting from a quenching operation are determined by the actual cooling rate of the medium. Characteristics of the cooling media and the mechanism of heat removal are the controlling parameters. Every cooling media has a characteristic cooling curve as shown in Fig.12.14. Instead of showing a constant cooling rate throughout the quench, the cooling curve shows three stages:

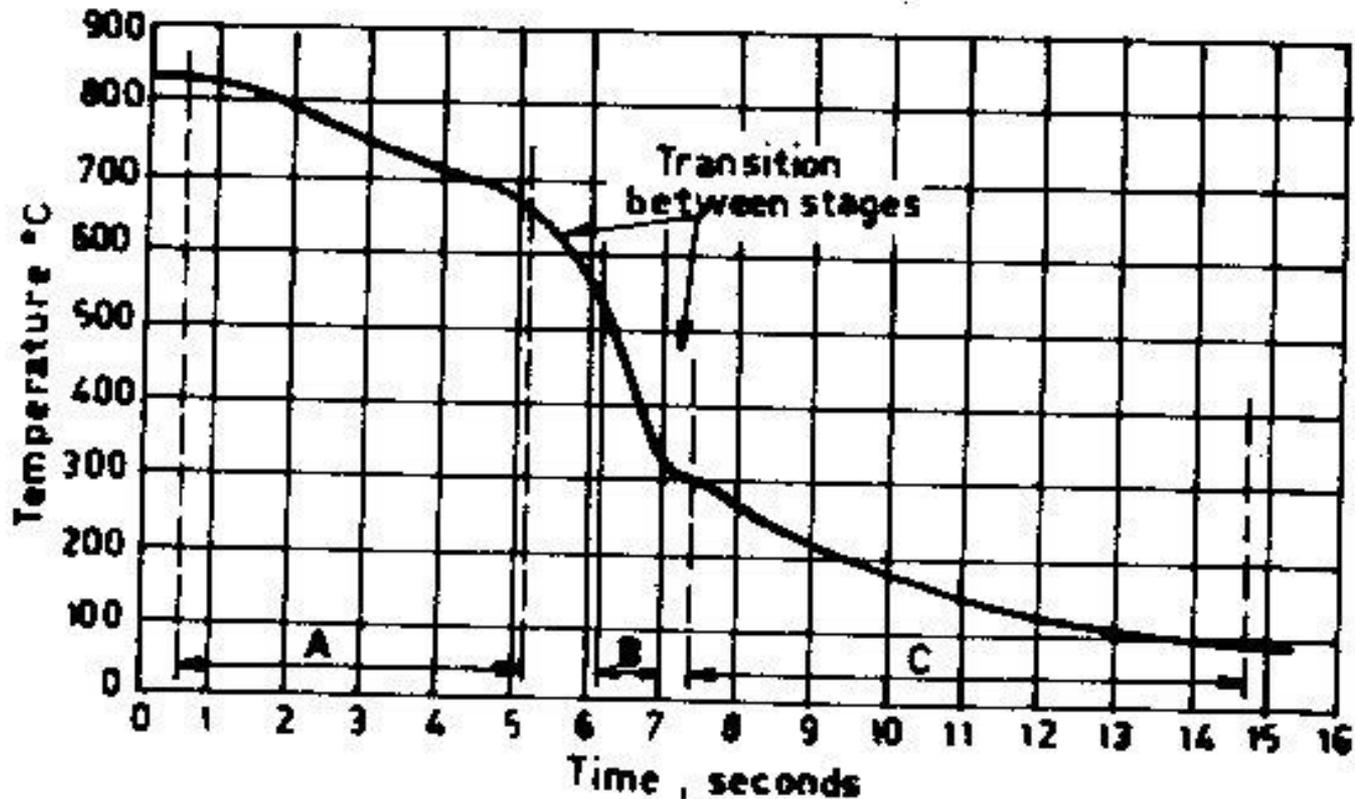
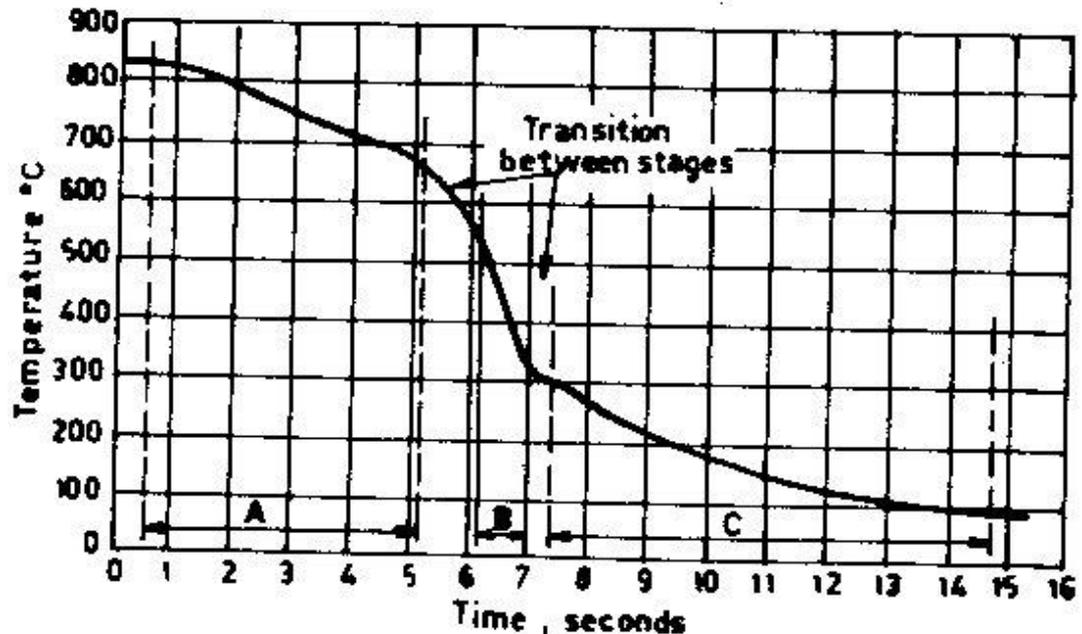


Fig.12.14 Typical cooling curve of water.

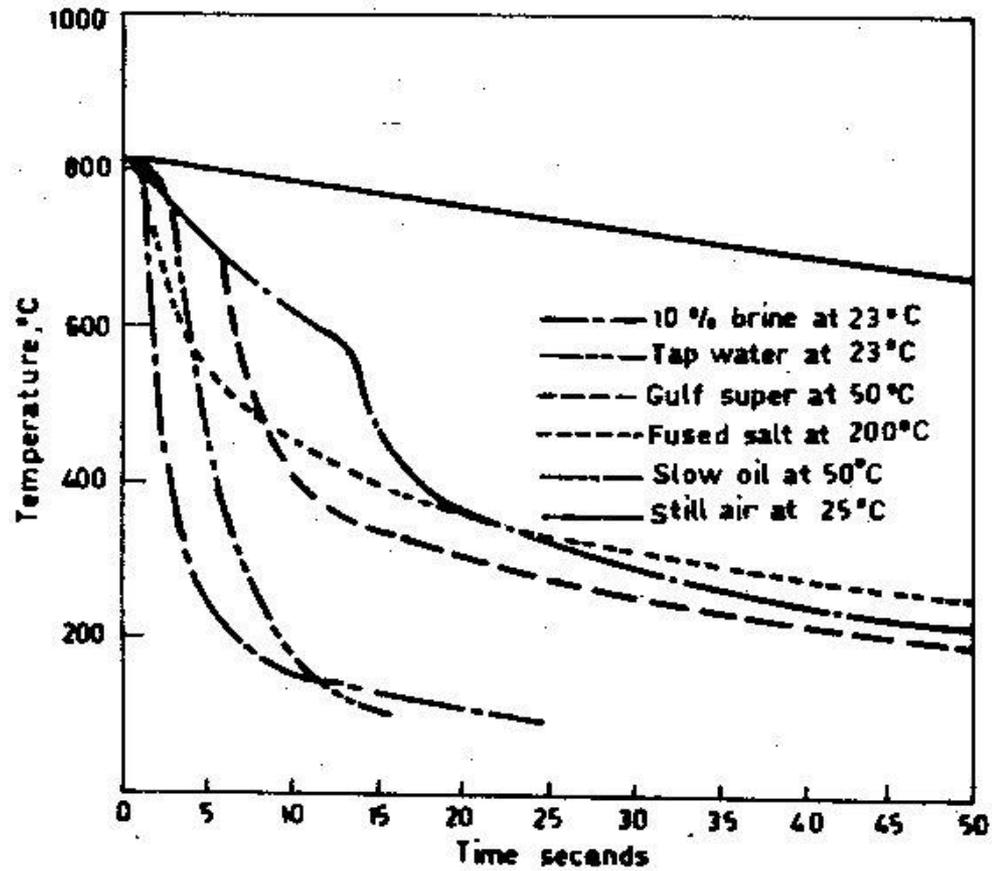
**(a) Stage A-Vapor-Blanket Cooling Stage:** In this stage, the temperature of the metal is so high that the quenching medium is vaporised at the surface of the metal and a thin stable film of vapor surrounds the hot metal. Cooling is by conduction and radiation through the gaseous film, and since vapor films are poor heat conductors, the cooling rate is relatively slow through this stage.

**(b) Stage B-Vapor-Transport Cooling Stage:** This stage starts when the metal has cooled to a temperature at which the vapor film is no longer stable. Wetting of metal surface by the quenching medium and violent boiling occur. Heat is removed from the metal very rapidly as the latent heat of vaporization. this is the fastest stage of cooling.

**(c) Stage C-Liquid Cooling Stage:** This stage starts when the surface temperature of the metal reaches the boiling point of the quenching liquid. Vapor no longer forms, so cooling is by conduction and convection through the liquid. The rate of cooling is slowest in this stage.



In view of the mechanism of heat removal, the ideal quenching medium would show a high initial cooling rate to avoid transformation in the nose region of the TTT diagram and then a slow cooling rate throughout the lower temperature range to minimize distortion. Unfortunately, there is no quenching medium that exhibits these ideal properties. Water and water solutions of inorganic salts have high initial cooling rates through the A and B stages, but these high cooling rates persist to low temperatures where distortion and cracking tend to occur. Oils have a longer A and a shorter B with a slower rate of cooling. The cooling curves obtained by different media in the center of a 12.5 mm diameter austenitic stainless steel bar are shown in Fig.12.15.



*Fig.12.15 Cooling curves of various quenching media*

As the temperature of the medium rises, the cooling rate decreases. This is particularly true of water and brine. However, oils show an increase in cooling rate with a rise in medium temperature. **The cooling rate may be improved and the temperature of the medium kept constant by circulation of the medium and agitation of the workpiece.** This effectively wipes off the vapor films as quickly as it forms and results in faster cooling. The quenching severity, relative to still water as 1.0 is shown in Table 12.1 for various conditions of quench.

**TABLE 12.1 Quenching Severity (H-value) of Various Media**

Method of Quenching	Air	Oil	Water	Brine
No circulation	0.02	0.25-0.30	0.90-1.0	2.0
Mild circulation		0.30-0.35	1.0-1.1	2.0-2.2
Moderate circulation		0.35-0.40	1.2-1.3	
Good circulation		0.40-0.50	1.4-1.5	
Strong circulation	0.05	0.50-0.80	1.6-2.0	
Violent circulation		0.80-1.1	4.0	5.0

## 12.4.2 Size and Mass

Since it is only the surface of a part which is in contact with the quenching medium, **the ratio of surface area to mass** is an important factor in determining the actual cooling rate. This ratio is a function of the geometric shape of the part and is smallest for a spherical part. Thin plates and small diameter wires have a large ratio of surface area to mass and therefore rapid cooling rates. Consider a long cylinder so that the surface area of the ends is negligible.

The ratio is,

$$\text{Surface area / Mass} = (\pi DL) / [(\pi/4)D^2 L\rho] = 4 / D \rho$$

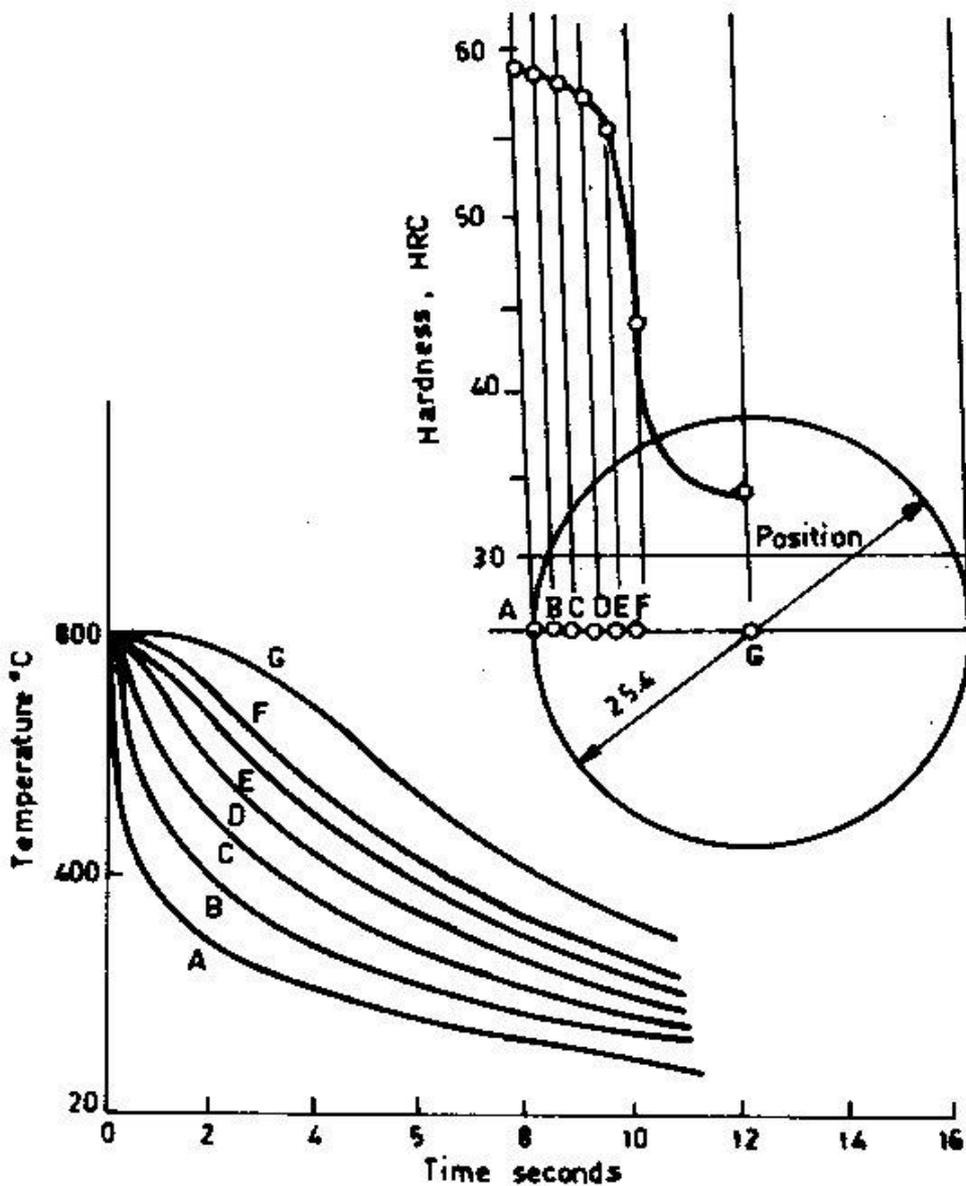
Where

D = diameter of the cylinder

L = length of the cylinder

$\rho$  = density

So, the ratio is inversely proportional to diameter. If the diameter is increased, the ratio of surface area to mass decreases and the cooling rate decreases.



*Fig.12.15 Time - Temperature Cooling Curves in a 25 mm diameter bar quenched in water*

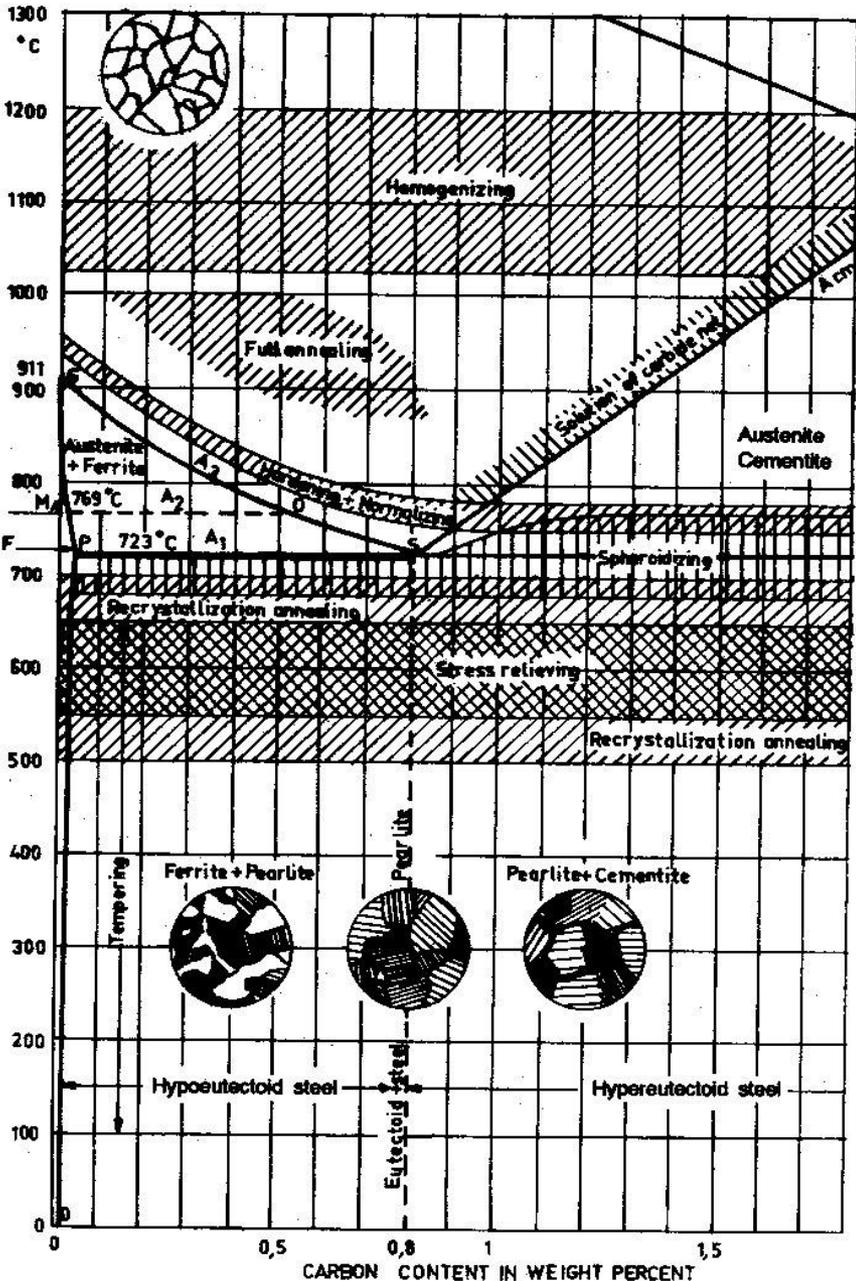
Cooling of the interior of the work piece takes place only by conduction, through the body of the piece reaching the surface and quenching medium. Therefore, the cooling rate in the interior is less than that at the surface. Fig. 12.16 shows the time-temperature cooling curves at different positions in a 25 mm diameter cylinder during a drastic quench. if such a variation in cooling rates exists across the radius of a bar during cooling, it is to be anticipated that variations in hardness would be evident across the section.

# 12.5 ANNEALING

The purpose of annealing may be to refine the grain, induce softness, improve electrical and magnetic properties, homogenize the structure and improve machinability. It is usually accomplished by heating the steel to slightly above the critical range, holding it there until the temperature of the piece is uniform throughout, and then cooling slowly.

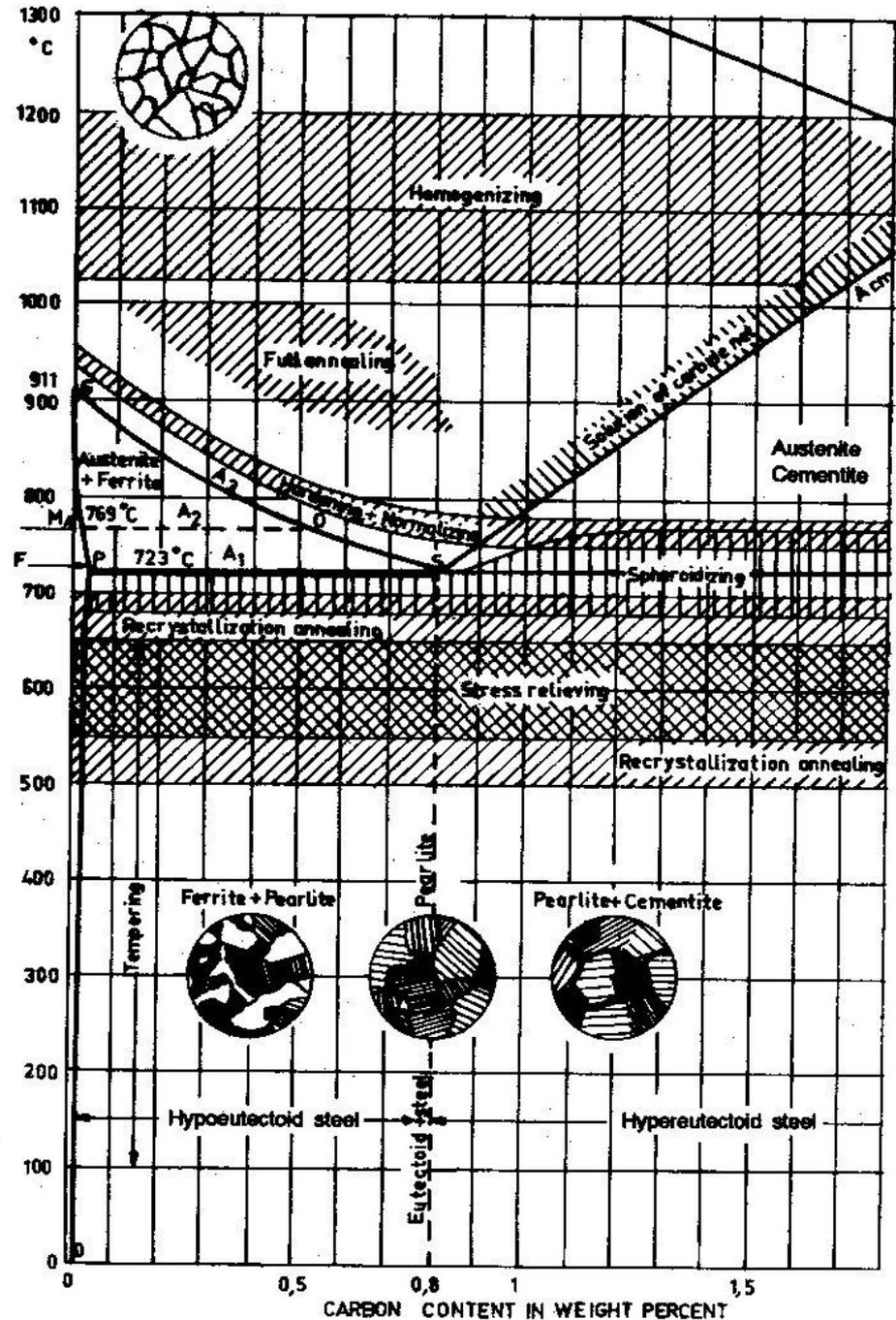
## TYPES OF ANNEALING

1. Spheroidizing Annealing
2. Full Annealing
3. Isothermal Annealing
4. Process Annealing
5. Stress-relief Annealing
6. Quench Annealing
7. Normalizing



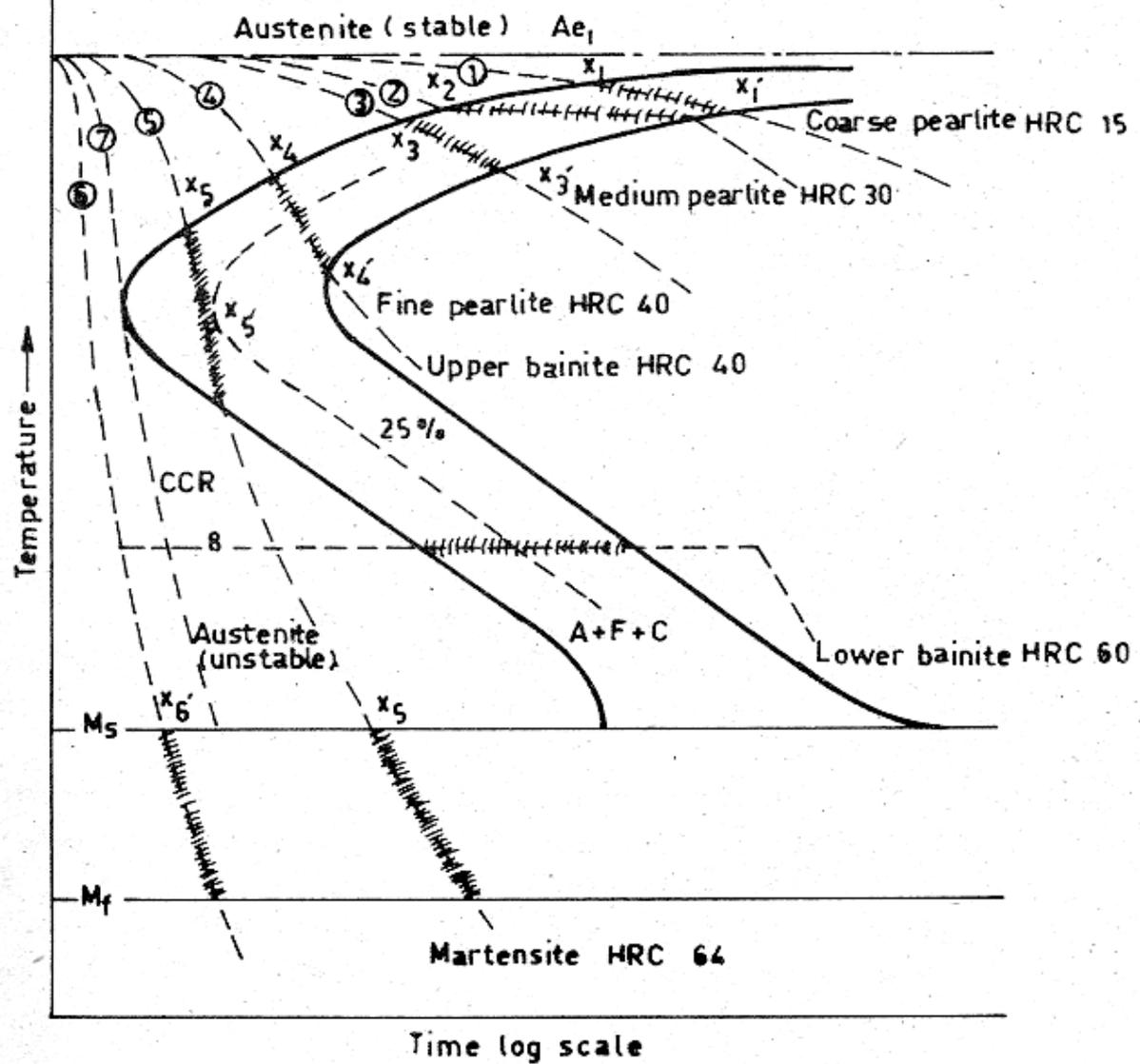
## 12.5.1 Spheroidizing Annealing

Spheroidizing annealing produces the maximum reduction in hardness. The major rule to apply when undertaking a spheroidizing anneal may be summarized as: austenize at a temperature not more than 50 °C above A<sub>1</sub> and transform at a temperature not more than 50 °C below A<sub>1</sub>. For the majority of steels the annealing time is between 2 and 6 hours. The resulting microstructure is spherical carbides embedded in ferrite.



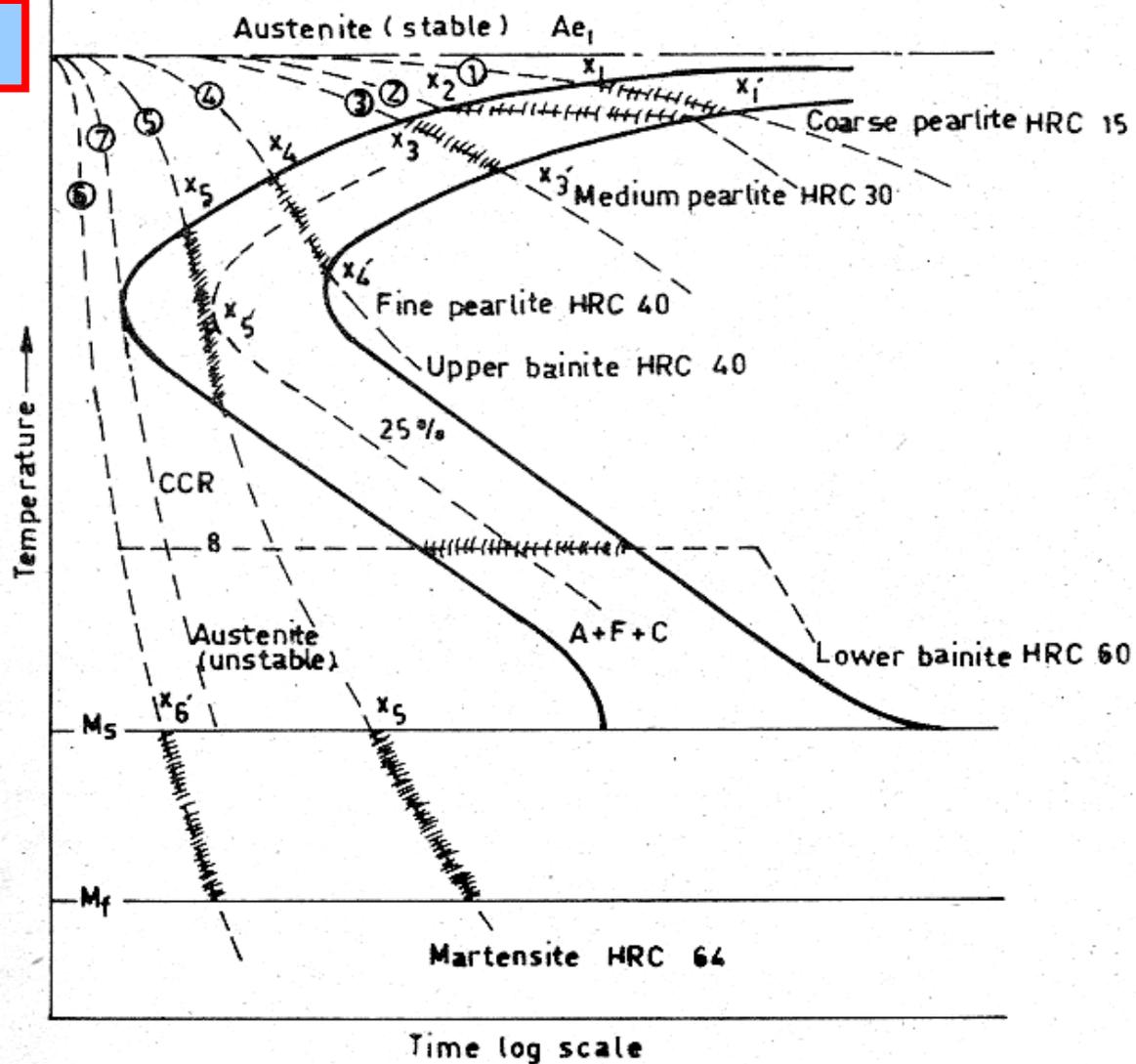
## 12.5.2 Full Annealing

This process consists in heating the steel 50 °C above the critical range and then cooling very slowly through the transformation range, preferably in the furnace or in any good heat insulating material. The slow cooling is generally continued to low temperatures. Full annealing is illustrated in Fig.12 .10 by Curve 1. Since the entire mass of the furnace must be cooled down along with the material, full annealing comes closest to following the iron-carbon equilibrium diagram. Full annealing generally refines the grain size. It is performed on high C steels in general.



## 12.5.3 Isothermal Annealing

Isothermal annealing, as shown in Fig.12.10 by **Curve 2**, provides a short annealing cycle. Steel is heated 50 °C above the critical range and then quickly transferred to a second furnace at a temperature about 50 °C below A<sub>1</sub>. It is then held for the time necessary to completely transform the austenite to pearlite. After the transformation is complete, the part may be cooled in any manner. Isothermal annealing results in giving pearlite a more uniform structure than that obtained by other annealing process. Fineness depends upon the transformation temperature used.



## 12.5.4 Process Annealing

This is also called as recrystallization annealing. It is practiced in the sheet and wire industry between cold working operations. **Steel is heated about 50 °C below  $A_1$  and then cooled slowly. Holding time is about 1 hour.** After annealing new, stress-free grains are formed which grow at the expense of the deformed original grains. Since the temperature involved are low, there is less tendency for the steel to scale or decarburise. It is essentially the same as *stress* relief annealing.

## 12.5.5 Stress-Relief Annealing

This process, sometimes called **subcritical annealing** is useful in removing residual stresses due to heavy machining or other cold working processes. It is usually carried out at a temperature below  $A_1$ . This treatment will not cause any phase changes, but recrystallization may take place. In order that thermal *stresses* are not induced during cooling, it is good practice to allow the parts to cool slowly in the furnace. **It is generally carried out for low C steels as it only recrystallises  $\alpha$ -grains without affecting cementite morphology.**

## 12.5.6 Quench Annealing

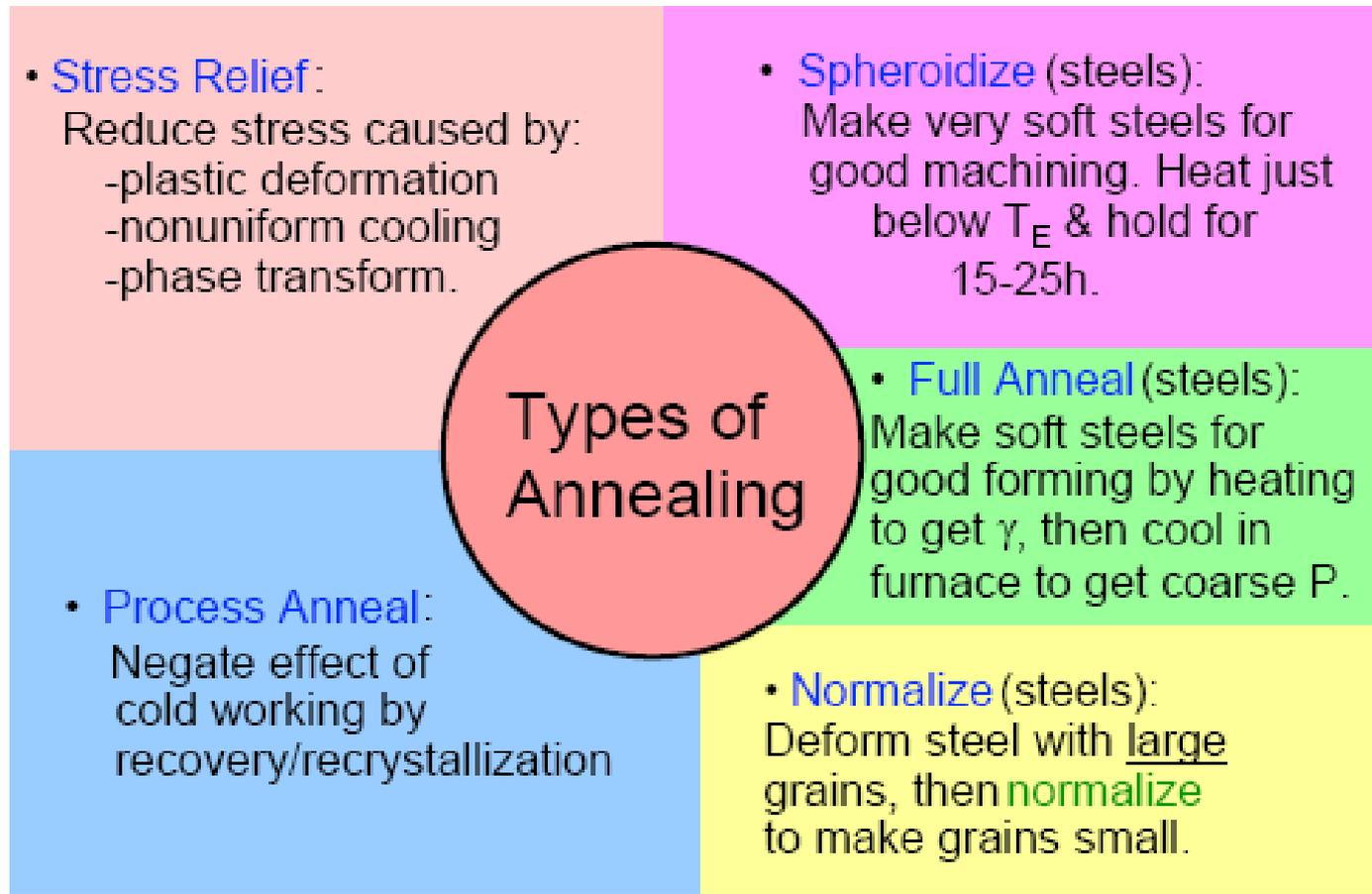
This treatment is used for austenitic steels only and consists in fact of a homogenizing anneal. Slow cooling will cause carbides to precipitate in austenite grain boundaries. This gives the steel low impact strength. Solution treatment around 1000-1100 °C, followed by rapid cooling in water eliminates carbide precipitation and increase toughness of the steel.

## 12.5.7 Normalizing

It consists of heating the steel to its hardening temperature, 50°C above its critical range, holding it there for 10-20 minutes, and then cooling **it in free still air**. The normalizing treatment refines the grain of steel which was coarsened due to forging or welding. **This treatment is applied mainly to plain medium carbon and low alloy steels**. Normalizing may also be used to improve machinability, modify and refine cast dendritic structures.

# THERMAL PROCESSING OF METALS

**Annealing:** Heat to  $T_{\text{anneal}}$ , then cool slowly.



## 12.6 HARDENING

Hardening is the process of heating a steel to a temperature 50 °C above its critical range and then cooling it rapidly. The rate of heating is important. If the steel is heated too fast, homogeneous heating cannot be obtained. If the workpiece is irregular in shape, slow heating is more essential to eliminate warping and cracking. The heavier the section, the longer must be the heating time to achieve uniform results. Even after reaching the correct temperature for a sufficient time to permit its thickest section to attain a uniform temperature. The soaking time in furnace is customarily taken as **1 hour for every 25 mm in diameter or thickness** of the workpiece. To prevent oxidation and decarburisation, either furnaces should have controlled atmospheres or protective measures such as burying in cast-iron chips or coke powder should be carried out.

The basic purpose of hardening is to produce a fully martensitic structure. To achieve this result, a cooling rate faster than **critical cooling rate** should be selected otherwise transformation will continue in pearlite region. The cooling methods used for hardening depend on the grade of steel, the shape of the part and the properties desired in the steel.

Three cooling methods are: direct quenching, martempering and austempering.

## 12.6.1 Direct Quenching

Direct quenching is the oldest hardening method and it is still the commonest one. According to this method the steel is cooled or quenched straight from the hardening temperature to room temperature as shown in Fig 12.17. The medium may be water, oil or air depending upon steel composition.

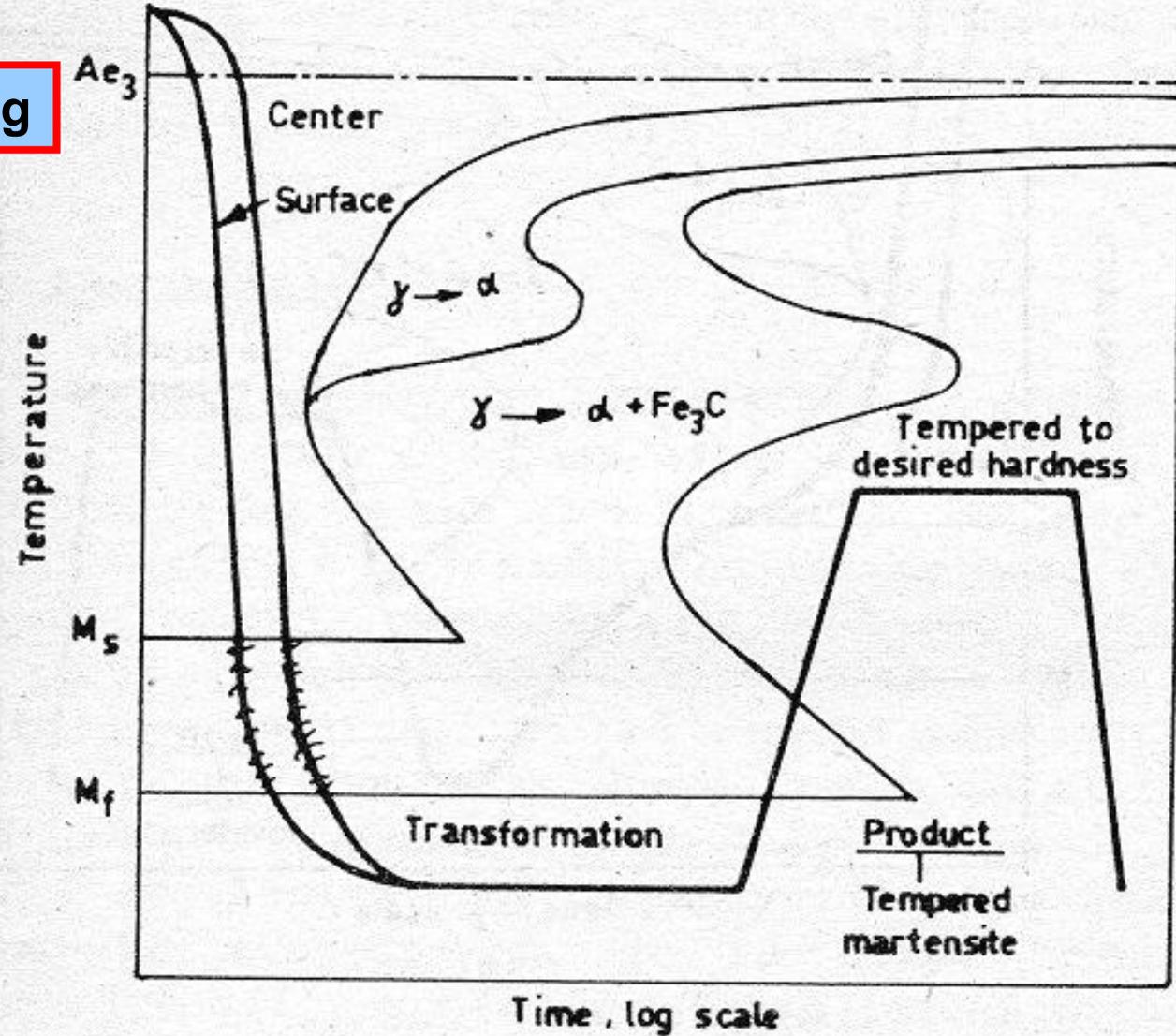


Fig. 12.17 Transformation diagram showing direct quenching

## 12.6.2 Martempering

The principle underlying martempering is most clearly understood by examining Fig.12.18. In this hardening treatment the cooling takes place in two stages. First the steel is quenched in a molten salt bath or metal bath kept at a temperature just above the martensite start temperature. The steel is held there until the temperature difference between the surface and the centre is eliminated. Then, it is cooled freely in air, which results in the formation of martensite. Consequently the austenite transforms to martensite practically simultaneously throughout the cross-section. As a result there is less residual stress and minimum distortion.

Martempering is applicable to oil hardening and air hardening steel grades only.

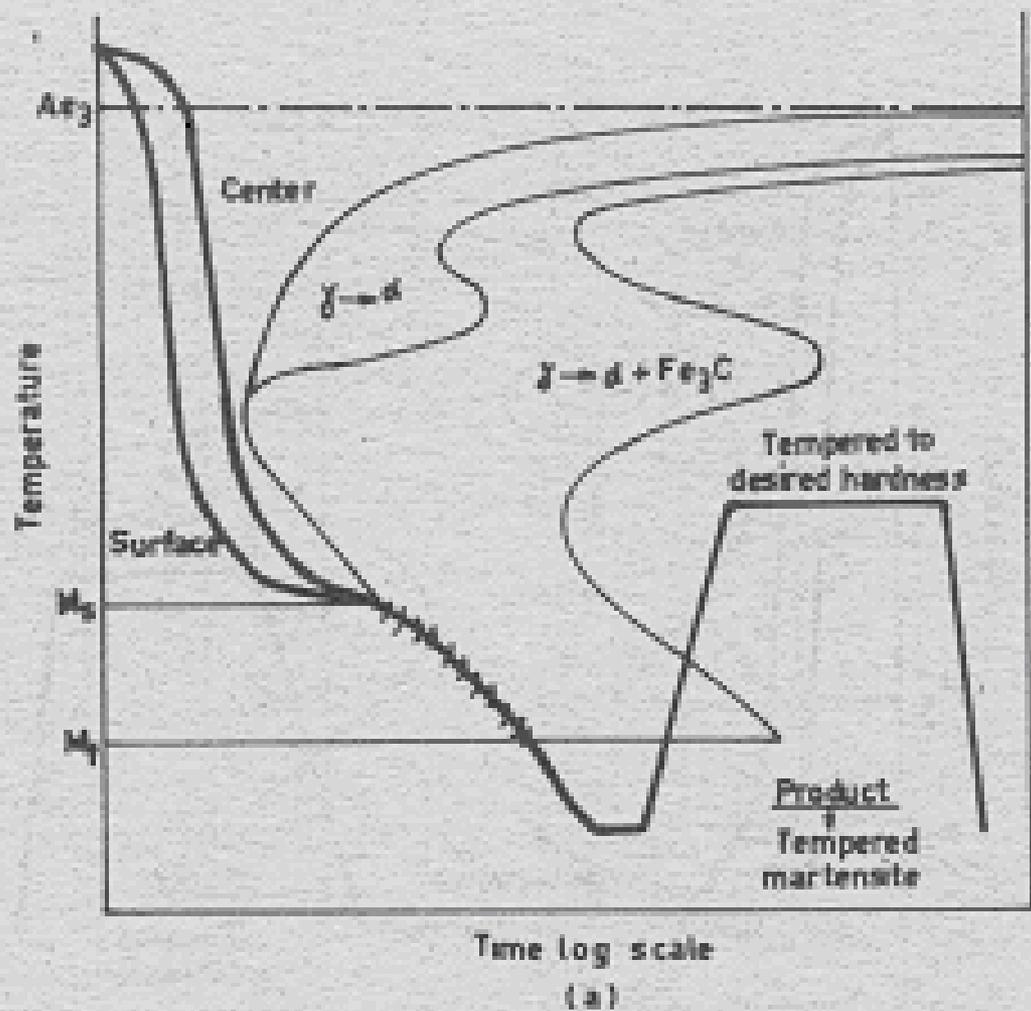


Fig.12.18 Transformation diagram showing:  
(a) Martempering

### 12.6.3 Austempering

By austempering, it is possible to obtain greater toughness than that obtained after conventional hardening and tempering to the same hardness. Residual stresses and distortion are minimum. As in the case of martempering, the part is quenched in a salt bath, which is at a temperature slightly above martensite start, and kept there till all austenite is transformed to bainite (Fig.12.18). Cooling takes place freely in air. The resulting hardness depends on the temperature of the salt bath. **All steels that are capable of being martempered can also be austempered.** It is common practice to austemper low alloy steels and plain carbon steels. **High alloy steels can not be austempered due to their very long transformation times.**

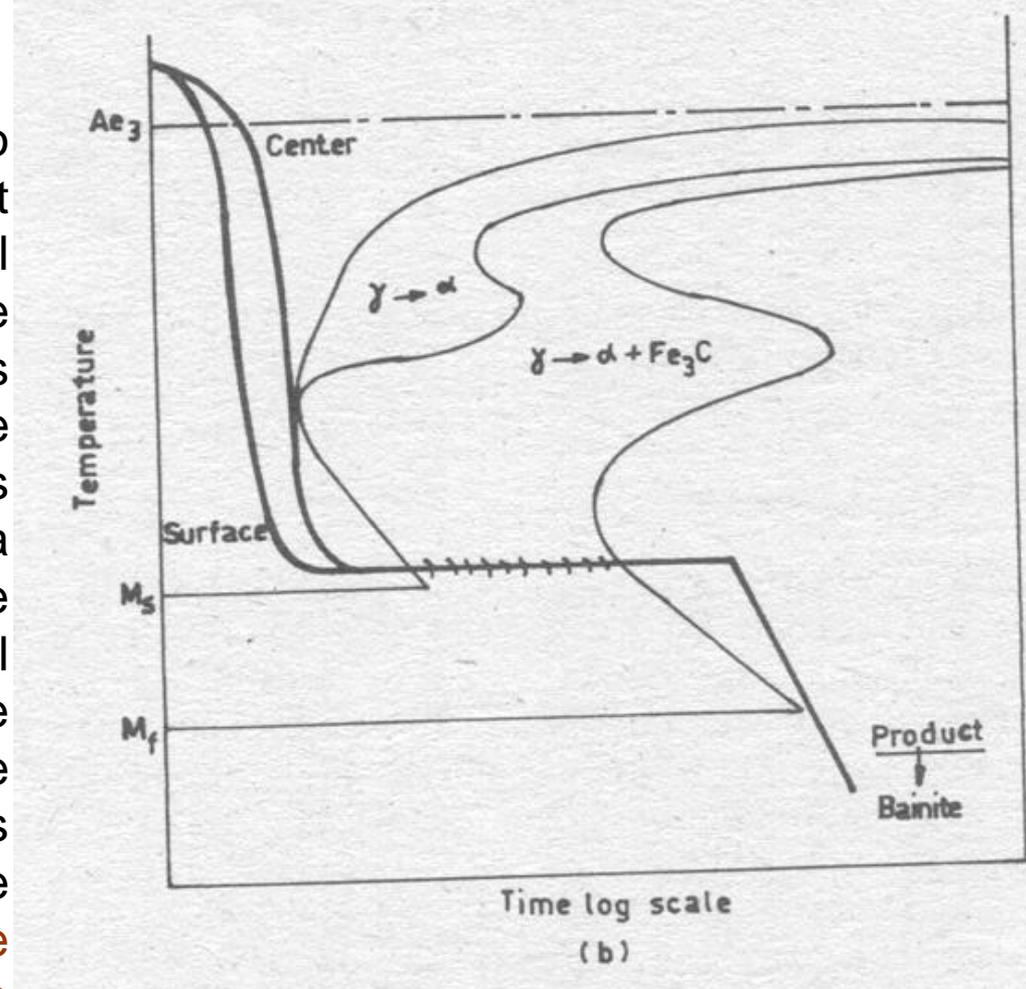


Fig.12.18 Transformation diagram showing:  
(b) Austempering

## 12.7 TEMPERING

The martensite formed during hardening is generally too brittle for the steel to be put to practical use without first tempering it. Tempering usually results in an increase in toughness and a simultaneous reduction in hardness. Although this process softens steel, it differs considerably from annealing:

Firstly tempering does not soften the steel to the extent that annealing would.

Secondly tempering mechanism has a close similarity to those of precipitation hardening. Tempering takes place in four stages as shown in Fig.12.19.

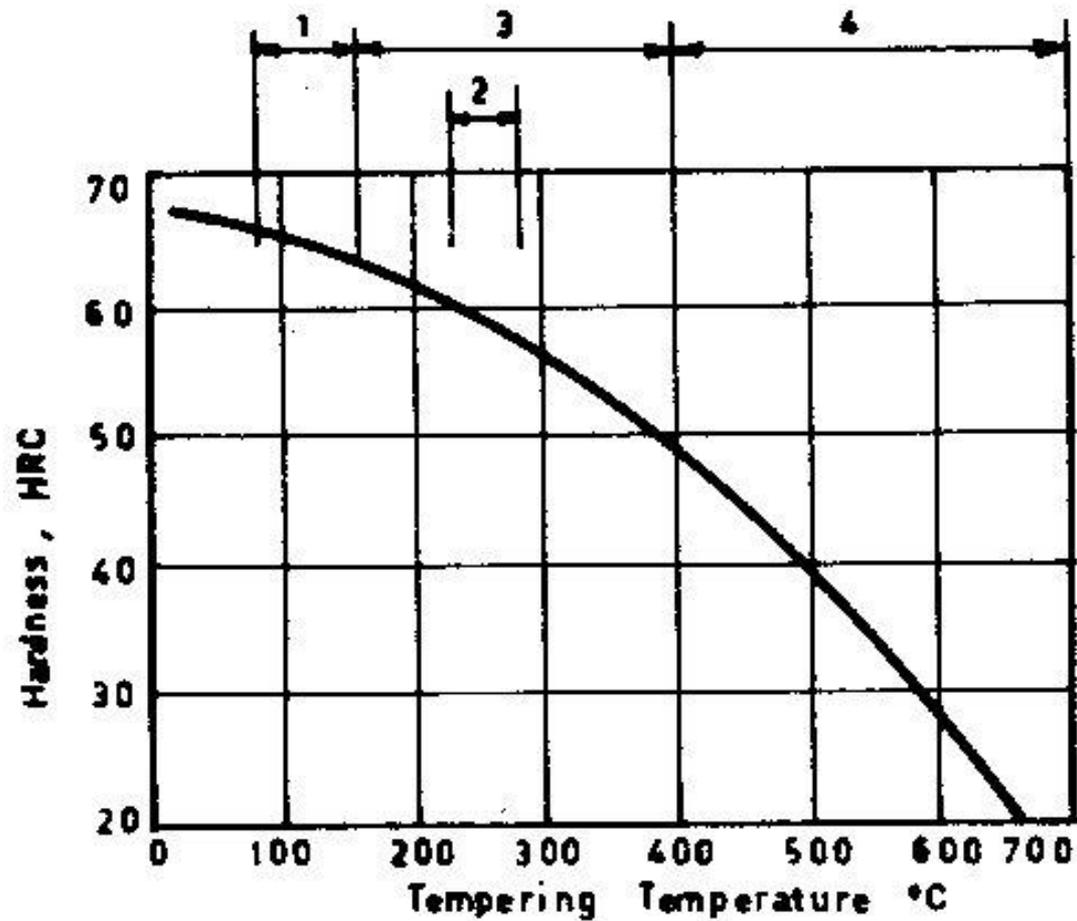


Fig.12.19 Tempering stages of a 1 % C steel

## 12.7 TEMPERING

### Stage 1: 80 - 160 °C.

Martensite breaks down to a transition precipitate known as  $\epsilon$ -carbide which results in slight dispersion hardening. The product is called black martensite due to its darker colour.

### Stage 2: 230 - 280 °C.

Decomposition of retained austenite to bainite and decrease in hardness. It is called troostite.

### Stage 3: 160 - 400 °C.

Conversion of  $\epsilon$ -carbide into cementite which gradually coarsens to give visible particles and rapid softening. It is called sorbite.

### Stage 4: 400 - 700 °C.

Carbide changes in alloy steels. Product is called spherodite.

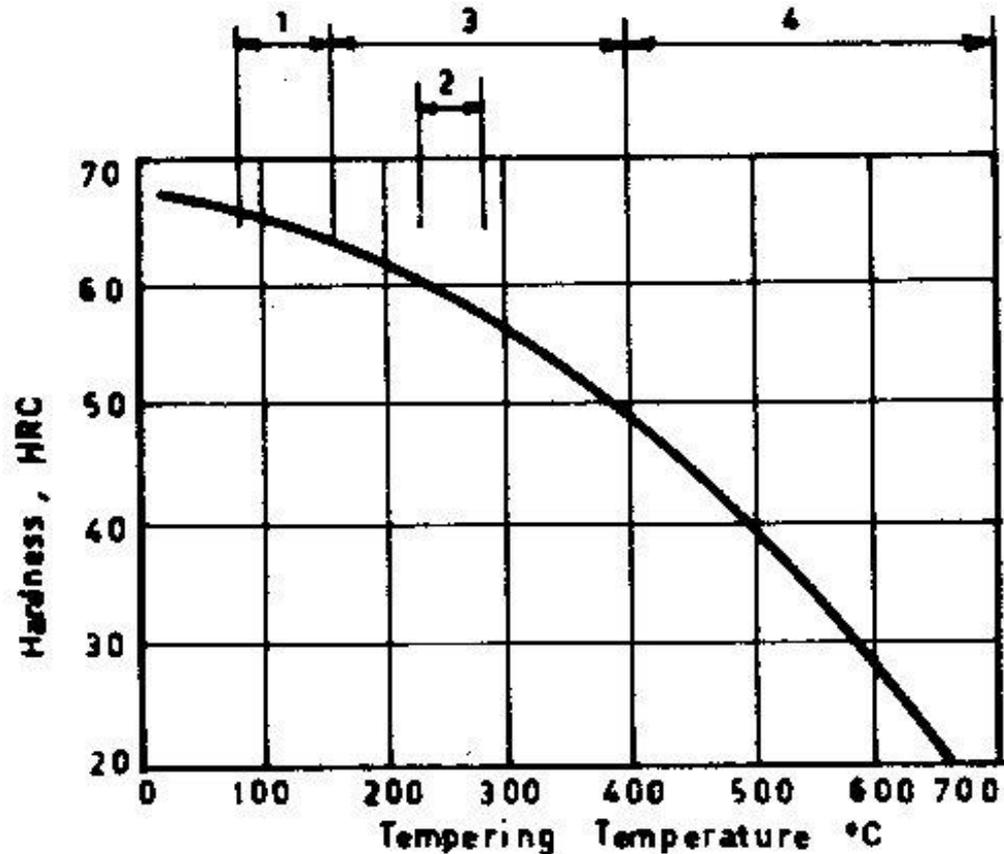


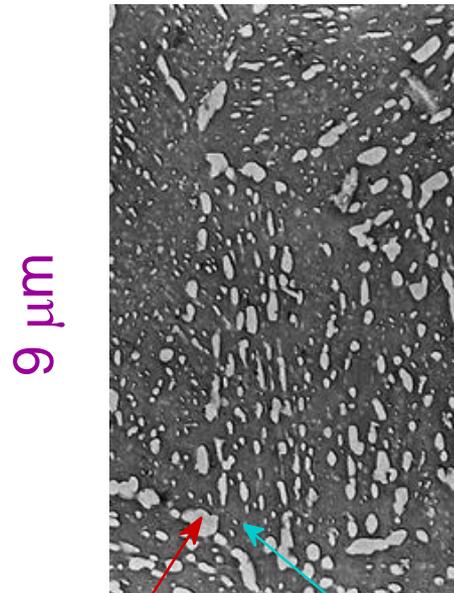
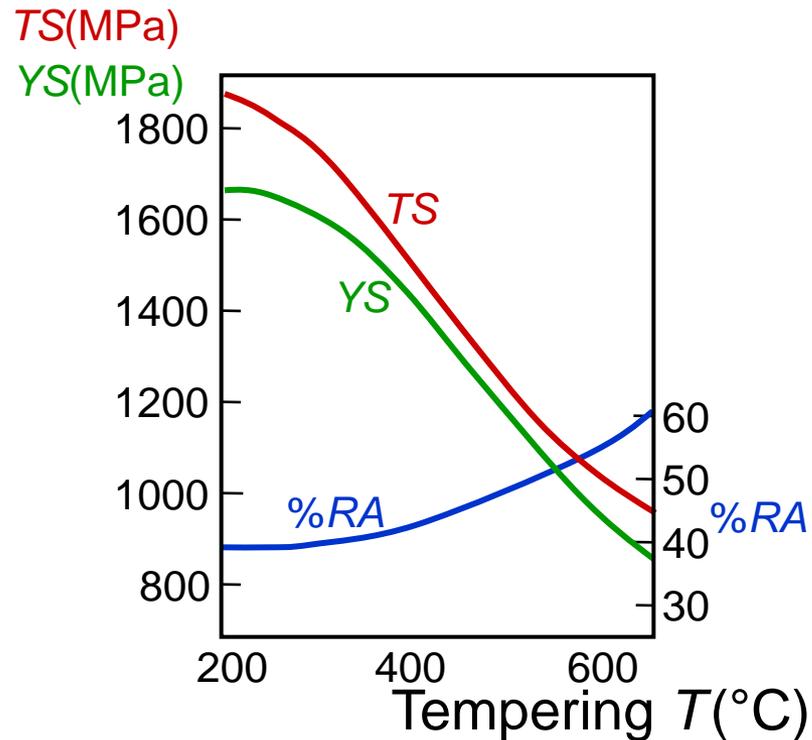
Fig.12.19 Tempering stages of a 1 % C steel

All these products are however termed tempered martensite by metallurgists. In steels containing one alloying addition cementite forms first and the alloy diffuses to it. Complex alloy carbides are produced in this way. By resolution of existing iron carbides, fresh nucleation of coherent alloy carbides take place which causes considerable hardening. In some alloy steels therefore, the hardness is maintained constant up to about 500 °C or in some cases it rises to a peak followed by a gradual drop. This age hardening process is known as **secondary hardening** and it enhances high temperature creep properties of steel. Vanadium and molybdenum form a fine dispersion of coherent precipitates in a ferrite matrix with considerable hardening.

The reactions in tempering occur slowly and time as well as temperature of heating is important. Tempering is carried out in oil, salt, lead baths and also in furnaces in which the air is circulated by fans. After tempering, the piece may be cooled either rapidly or slowly except in the case of steels susceptible to **temper brittleness**. Some steels, however, shows a reduction rather than increase in ductility upon tempering in temperature range 200-420°C. This phenomenon is called **blue brittleness** and for steels with blue brittleness above temperature range should be avoided. On the other hand some steels containing Cr, Mn and P show loss of ductility upon tempering in range 450-670°C. This is called **temper embrittlement** which can be alleviated by the addition of Mo to such steels.

# TEMPERING MARTENSITE

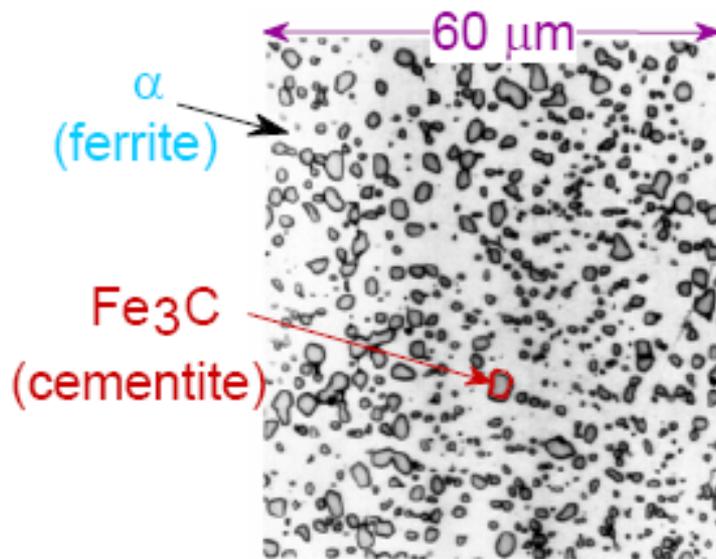
- reduces brittleness of martensite,
- reduces internal stress caused by quenching.



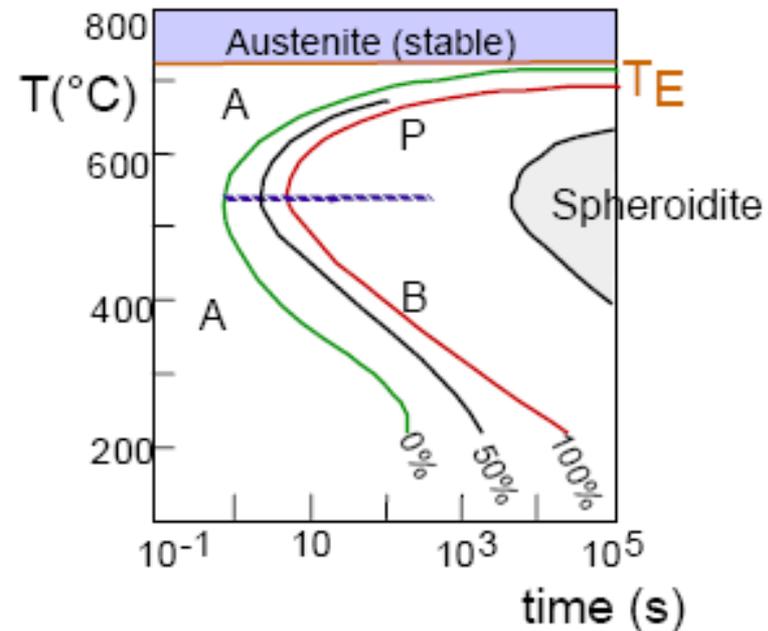
- produces extremely small **Fe<sub>3</sub>C particles** surrounded by  $\alpha$ .
- decreases **TS**, **YS** but increases **%RA**

# ANOTHER MICROSTRUCTURE IN THE Fe-C SYSTEM

- Spheroidite:
  - $\alpha$  crystals with spherical  $\text{Fe}_3\text{C}$  particles
  - growth is diffusion controlled
  - formed by heating bainite or pearlite for long time at about  $700^\circ\text{C}$



(Adapted from Fig. 10.10, Callister, 6e. (Fig. 10.10 copyright United States Steel Corporation, 1971.)



Adapted from Fig. 10.9, Callister 6e. (Fig. 10.9 adapted from H. Boyer (Ed.) Atlas of Isothermal Transformation and Cooling Transformation Diagrams, American Society for Metals, 1967, p. 28.)

## 12.8 PRECIPITATION HARDENING

Precipitation hardening, often called age hardening, can be achieved only with those alloys in which there is a **decreasing solubility** of one material in another as the **temperature is reduced**.

Precipitation hardening is generally applied to nonferrous industrial alloys. It can also be applied to low carbon unalloyed steels or to some high alloyed heat resisting steels.

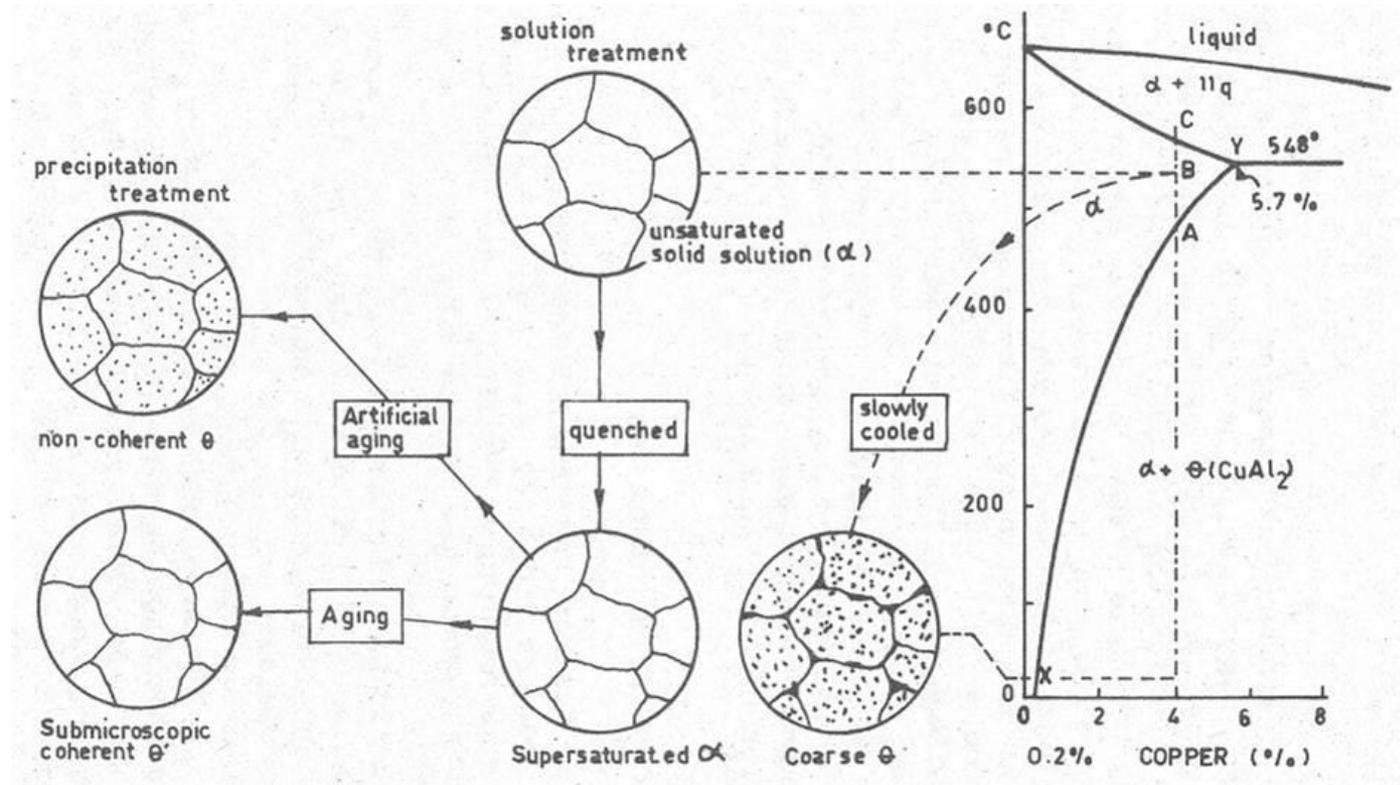
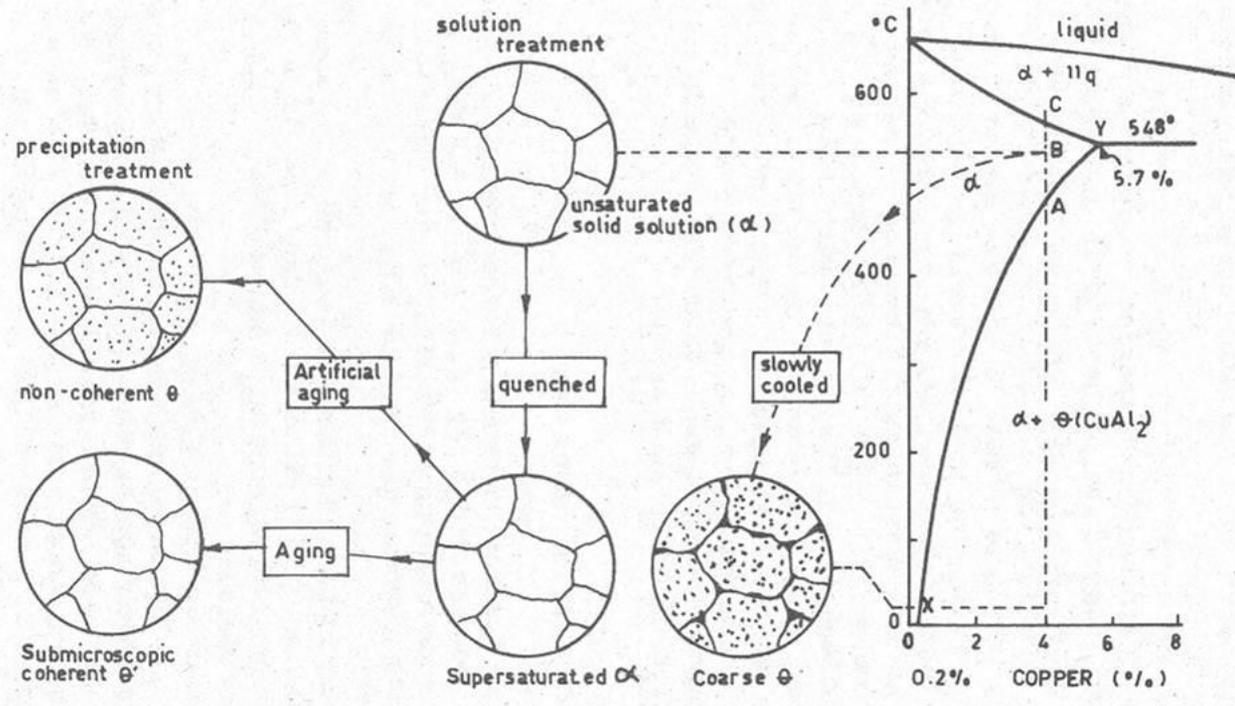


Fig. 12.20  
Precipitation  
hardening of  
aluminum-copper  
alloy.

Fig.12.20 shows the falling solubility curve of all alloys which age harden, and the aluminum-copper alloys can be used as a typical example. When an alloy containing 4% copper is heated to 500°C for a sufficient time, all compounds  $\text{CuAl}_2$  is dissolved to form a homogeneous solid solution.



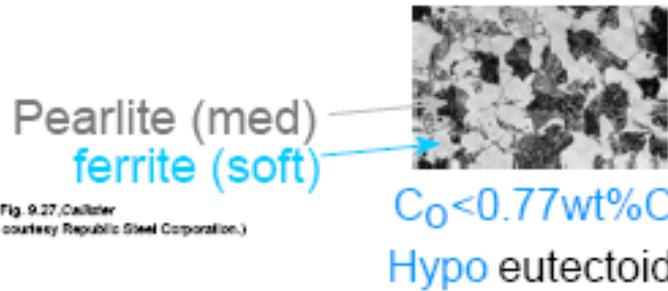
When the alloy is slow cooled from 500°C, the compound is precipitated as relatively coarse particles and no hardening is produced. If the alloy is quenched from 500°C, a supersaturated solid solution is retained at room temperature which is slightly harder but more ductile than the slowly cooled sample. This condition is unstable and precipitation of very fine particles will take place at room temperature which produces maximum hardness. Artificial aging at temperatures up to 200°C will accelerate the precipitation but particles will be coarser than natural aging and resulting hardness will be lower. To prevent natural aging of quenched alloy, it must be stored at temperatures down to -20 °C.

The actual causes of age hardening is the obstruction to slip set up by a critical dispersion of fine particles.

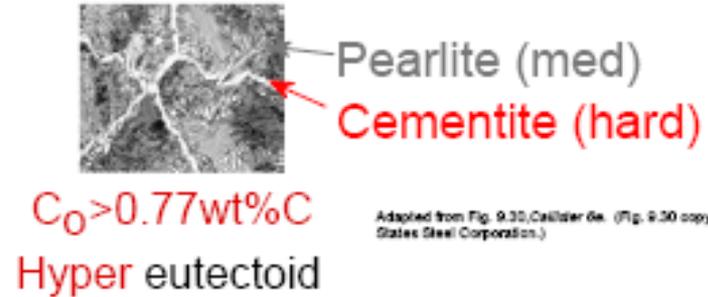
Instead of producing these fine precipitates by aging, they can be introduced as insoluble particles by powder metallurgy processes. Insoluble particles such as oxides, nitrides and carbides can be dispersed in metallic matrixes and properties are then retained to temperatures well above the normal softening temperatures of precipitation hardened alloys. Creep properties of dispersion hardened materials are much higher.

# Fe-C SYSTEM - MECHANICAL PROPERTIES

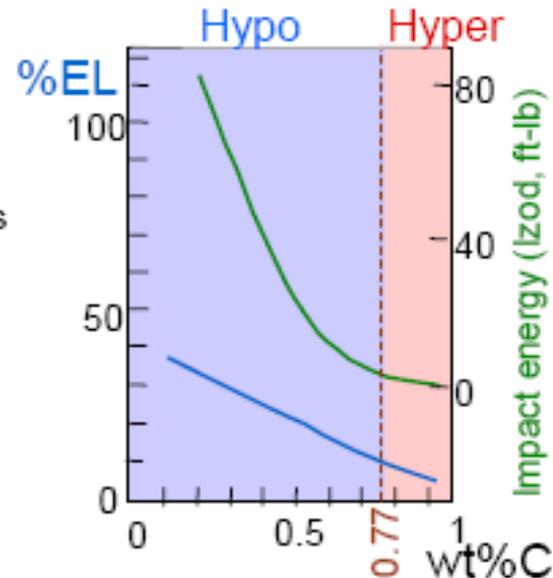
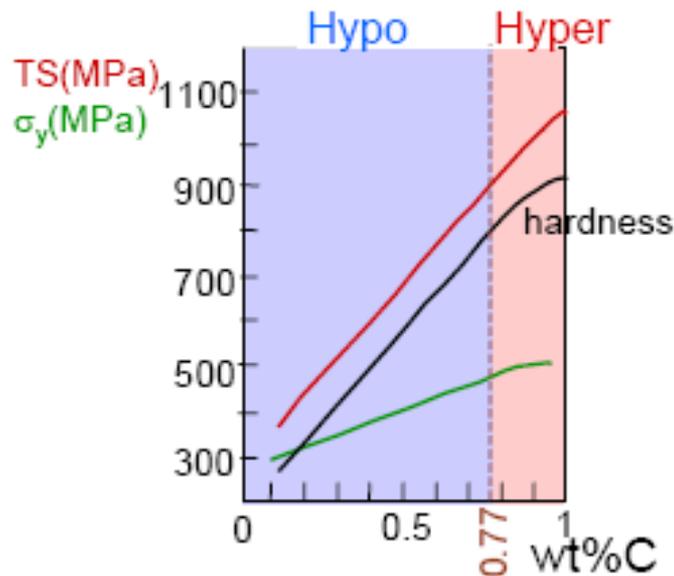
- Effect of wt%C:



Adapted from Fig. 9.27, Callister 6e. (Fig. 9.27 courtesy Republic Steel Corporation.)



Adapted from Fig. 9.30, Callister 6e. (Fig. 9.30 copyright 1971 by United States Steel Corporation.)

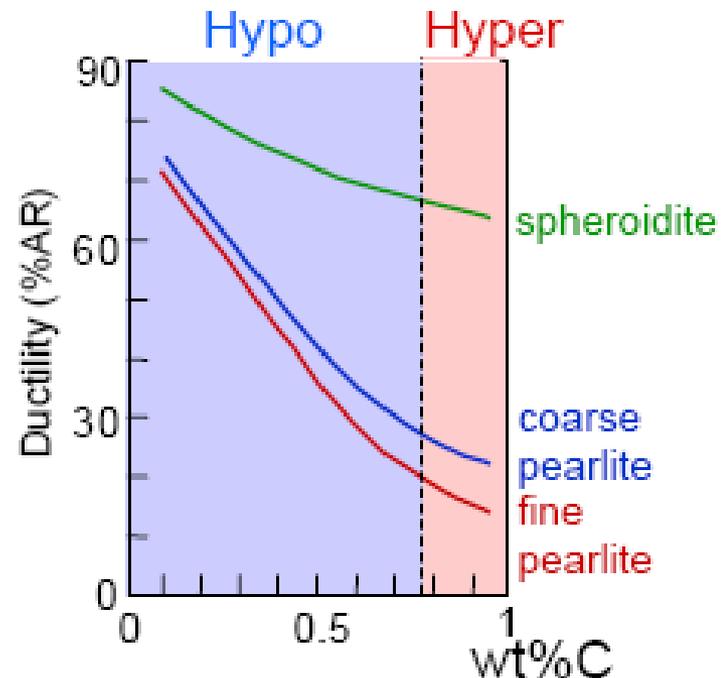
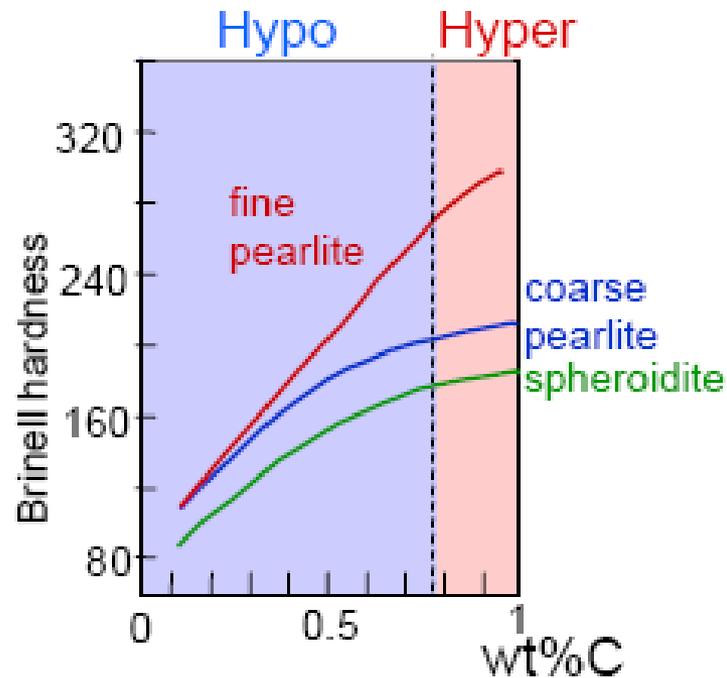


Adapted from Fig. 10.20, Callister 6e. (Fig. 10.20 based on data from Metals Handbook: Heat Treating, Vol. 4, 9th ed., V. Maspero (Managing Ed.), American Society for Metals, 1991, p. 9.)

- More wt% C: *TS* and *YS* increase, *%EL* decreases.

# Fe-C SYSTEM - MECHANICAL PROPERTIES

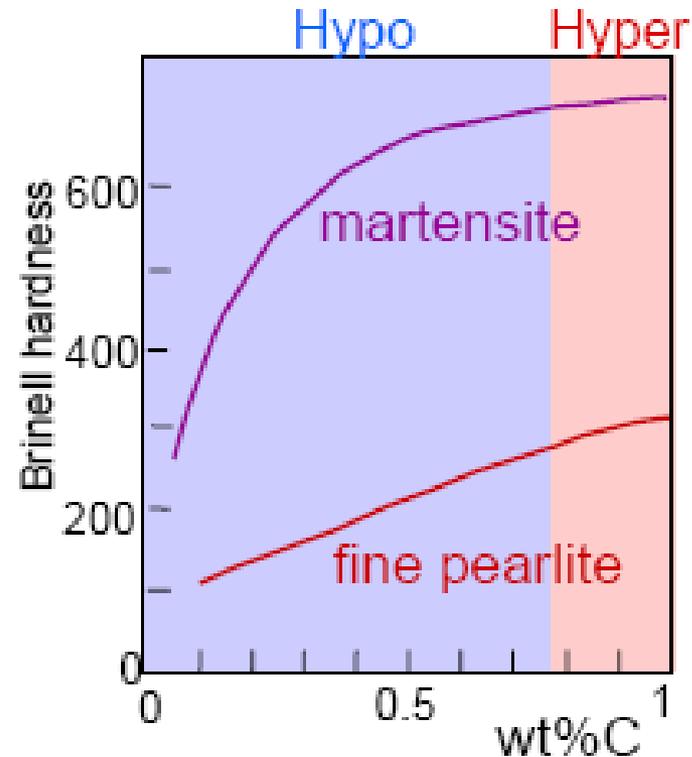
- Fine vs coarse pearlite vs spheroidite:



- Hardness: fine > coarse > spheroidite
- %RA : fine < coarse < spheroidite

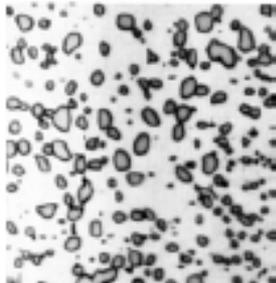
# Fe-C SYSTEM - MECHANICAL PROPERTIES

Fine Pearlite vs Martensite:

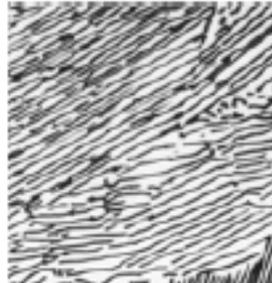


- Hardness: fine pearlite  $\ll$  martensite.

# MICROSTRUCTURE – MECHANICAL PROPERTIES



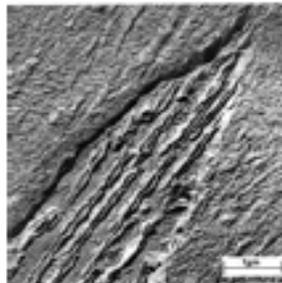
Spheroidite



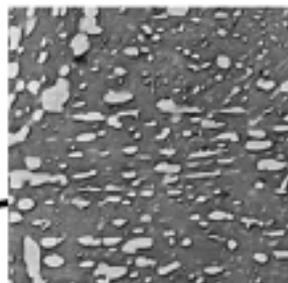
Coarse Pearlite



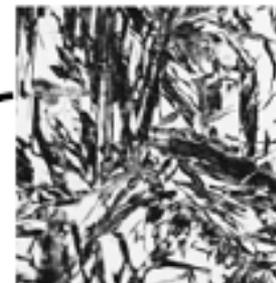
Fine Pearlite



Bainite



Tempered Martensite

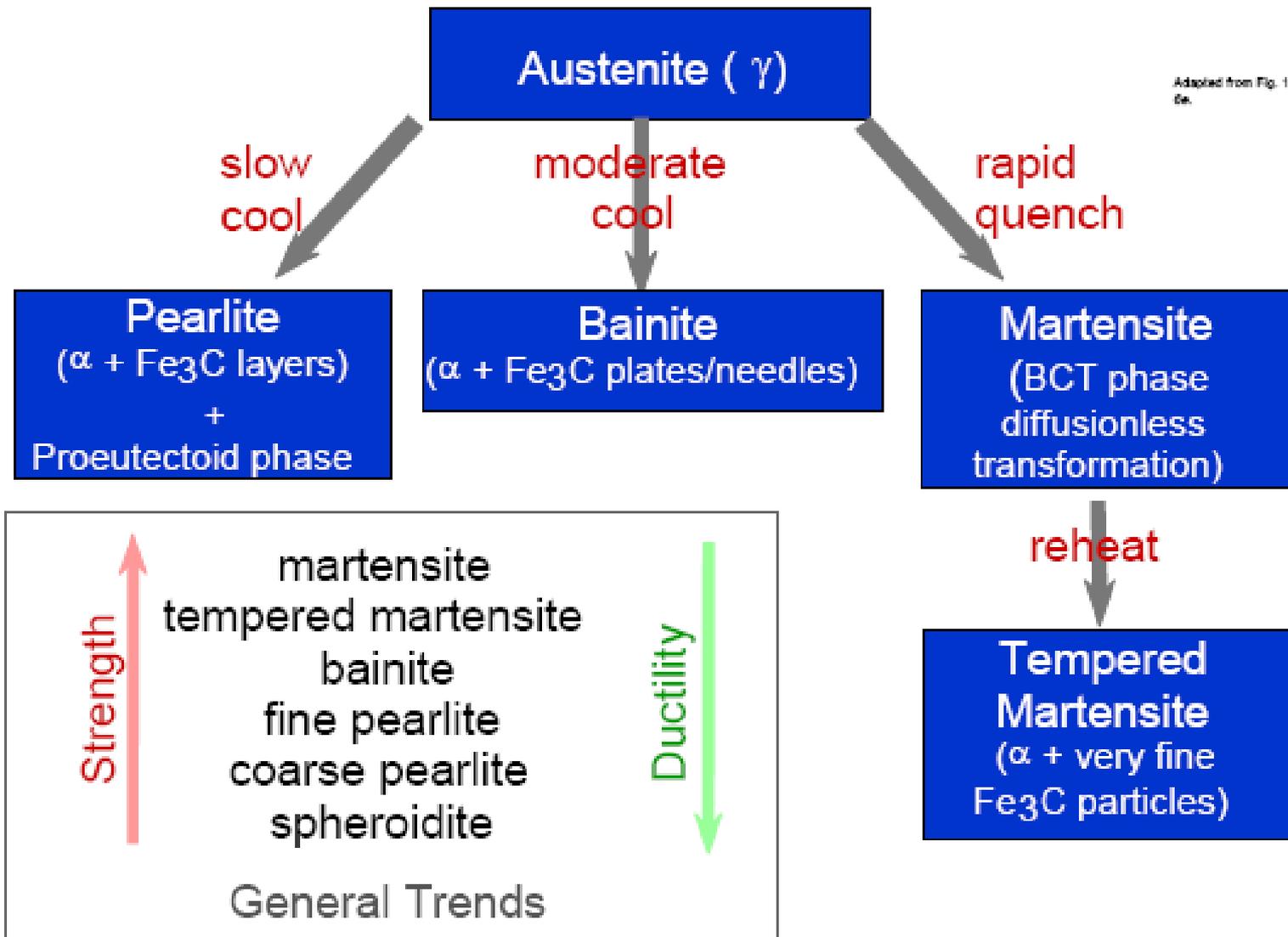


Martensite

**finer**  
**harder/stronger**  
**less ductile**

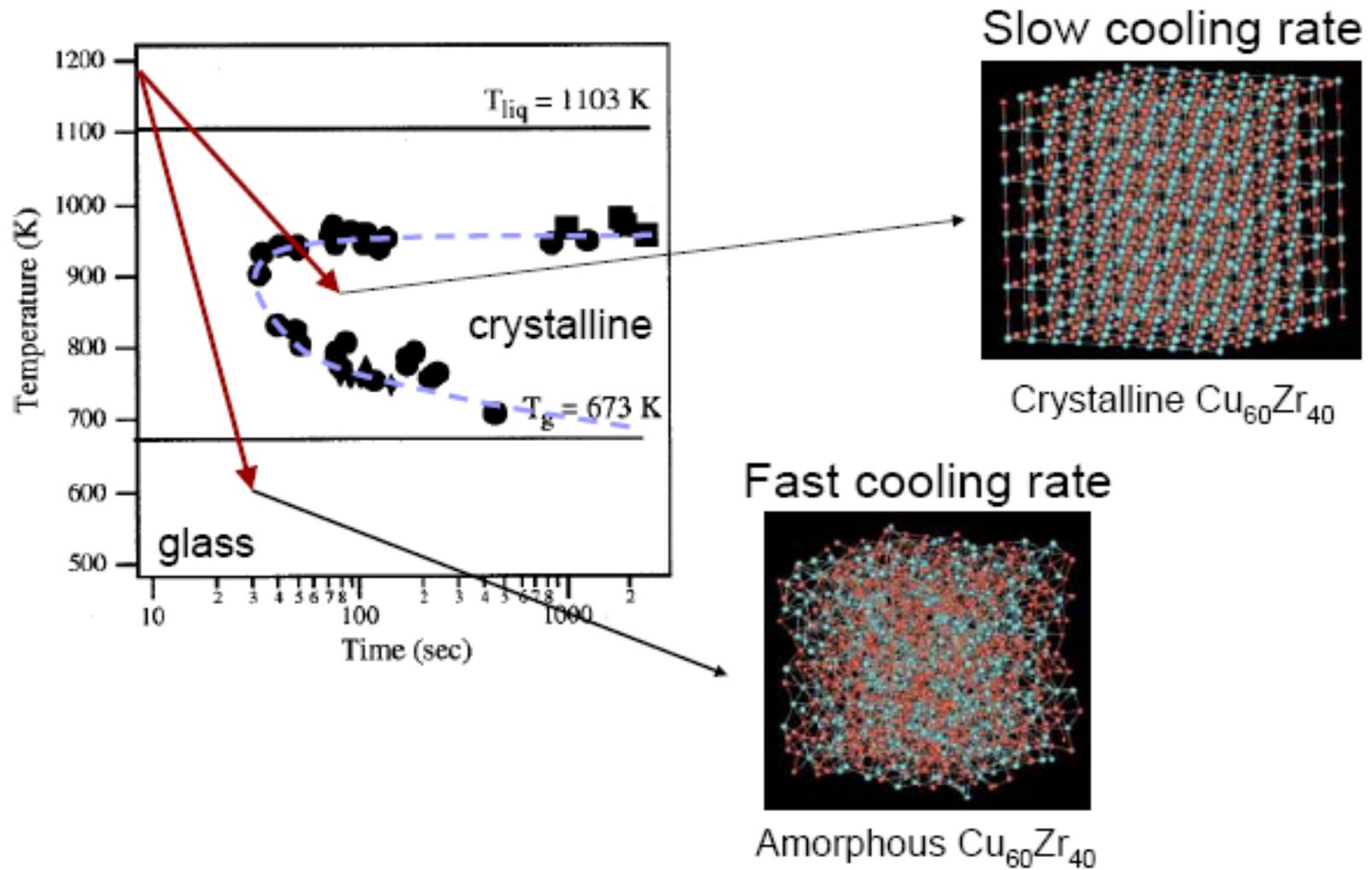
# SUMMARY: STEEL PROCESSING OPTIONS

Adapted from Fig. 10.27, Callister 6e.



# TTT: OTHER MATERIALS

## Amorphous Metals



## 12.9 SURFACE HARDENING

Numerous industrial applications require a hard wear resistant surface called the case and a relatively soft, tough inside called the core. There are four principal methods of case hardening:

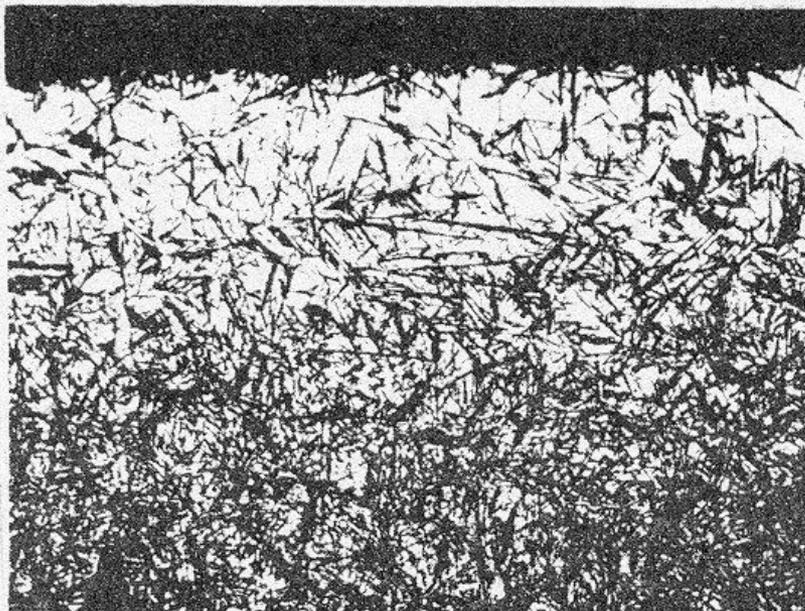
1. Carburizing
2. Nitriding
3. Flame hardening
4. Induction hardening

The first two methods change the **chemical composition**, carburizing by the addition of carbon, nitriding by the addition of nitrogen.

The last two methods do not change the chemical composition of the steel and are essentially shallow-hardening methods. In flame and induction hardening the steel must be capable of being hardened, therefore, the carbon content must be about 0.30% or higher.

## 12.9.1 Carburizing

This is the oldest and one of the cheapest methods of case hardening. A low carbon steel, usually about 0.20% carbon or lower is placed in an atmosphere rich in carbon monoxide. The usual carburizing temperature is 900°C. At this temperature the carbon is absorbed into the metal to form a solid solution with iron and converts the outer surface into high carbon steel. As the operation continues, the carbon is gradually diffused to, the interior of the part. The depth of the case depends upon the time and temperature of the treatment. The microstructure of carburized steel is shown in Fig.12.21.



*Fig. 12.21 Microstructure of carburized 8620 steel (white areas are retained austenite), x100.*

## 12.9.1 Carburizing

Commercial carburizing may be accomplished by means of pack carburizing, gas carburizing, and liquid carburizing:

**In pack carburizing**, the work is surrounded by a carburizing compound such as charcoal or coke, and about 20% barium carbonate as an energizer. It is a long process and used to produce fairly thick cases of from 0.75 to 4 mm in depth. Pack carburizing is used principally for large parts.

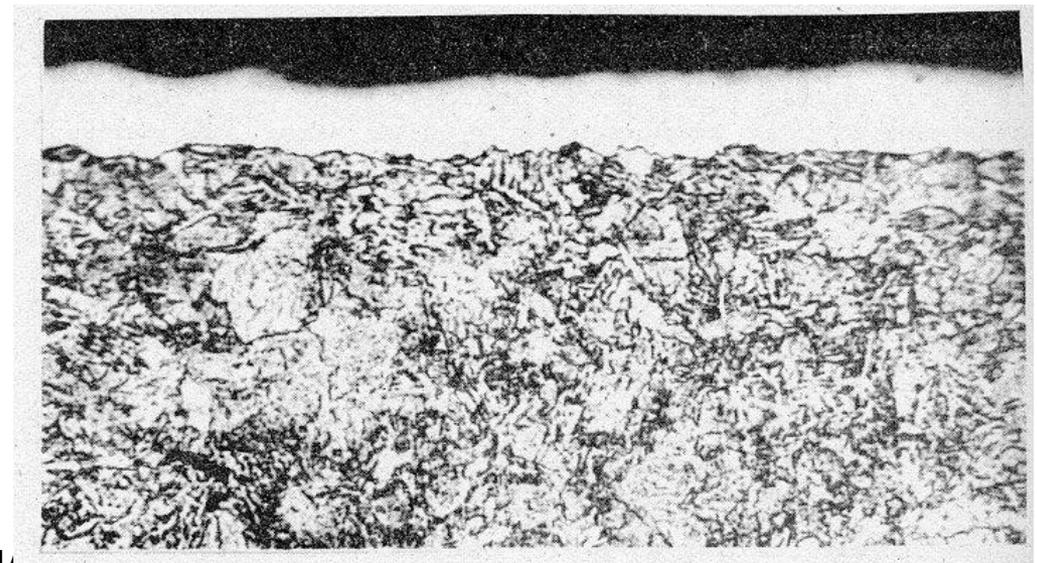
**Gas carburizing** may be either batch or continuous and very suitable to production heat treatments. It is adapted to the case hardening of small parts and direct quenching at the end of the cycle is possible. Case depth is shallow, between 0.10 to 0.75 mm. Carburizing is done in hydrocarbon fuels such as natural gas or propane.

**Liquid carburizing** is performed in cyanide salt bath causing the carbon and some nitrogen to diffuse into the case. The depth can easily be varied and ranges from 0.50 to 6.50 mm. This method is best suited for small and medium size parts but **the cyanide salts are poisonous**.

## 12.9.2 Nitriding

This is a process for case hardening of alloy steels in dissociated ammonia atmosphere. Temperature is around  $550^{\circ}\text{C}$  and there is no phase change, so minimum distortion is produced. The effectiveness of the process depends on the **formation of nitrides** in the steel by reaction of nitrogen with certain alloying elements. These are aluminum, chromium, titanium and molybdenum. Aluminum in the range of 1 to 1.5% has proved to be especially suitable in steel. Case thicknesses up to 0.50 mm are possible. Nitriding develops extreme hardness in the surface of steel. This hardness ranges from 900 to 1100 HV, which is considerably higher than that obtained by other case hardening operations. Fatigue and wear resistance of nitrided steels are excellent. Microstructure of a nitrided steel is shown in Fig.12.22.

*Fig.12.22 Microstructure of a nitrided steel, x500*



## 12.9.3 Flame Hardening

Flame hardening is based on rapid heating and quenching of the surface to be hardened. The heating is done by an oxyacetylene flame which is applied for enough time to heat the surface above the critical temperature range of the steel. Integral with the flame head are water connections that cool the surface by spraying as soon as the desired temperature is reached. The depth of hardening may be controlled by the adjustment of the flame intensity, heating time and speed of travel. Skill is required in adjusting and handling manually operated equipment to avoid overheating the work because of high flame temperature. Overheating can result in cracking after quenching.

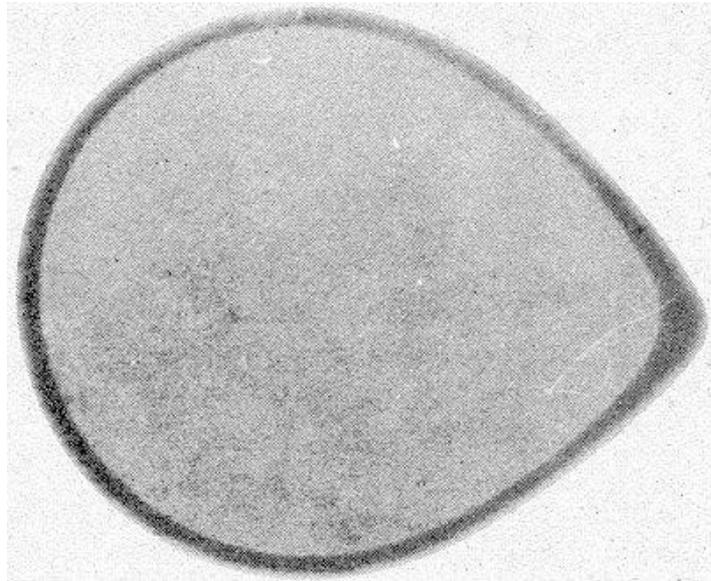
Flame hardening is adaptable to large pieces. The hardened zone is generally much deeper than that obtained by carburizing, ranging from 3.0 to 7.0 mm depth. Four methods are in general use for flame hardening: (1) stationary, (2) progressive, (3) spinning, and (4) progressive spinning. In the first, both torch and the work are stationary. In progressive method, the torch moves over the stationary work piece. In spinning method, the torch is stationary while the work rotates. In progressive spinning method, the torch moves over the rotating work piece.

## 12.9.4 Induction Hardening

Induction hardening depends for its operation on localized heating produced by currents induced in a metal placed in a rapidly changing magnetic field. An inductor block, acting as a primary coil of a transformer, is placed around the part to be hardened. A high frequency current is passed through this block, inducing a current in the surface of the part. The heating effect is due to induced eddy currents and hysteresis losses in the surface material. The inductor block surrounding the heated surface has water connections. As soon as the steel has been brought up to the proper temperature, it is automatically spray quenched under pressure.

The high frequency induced currents tend to travel at the surface of the metal. This is known as skin effect. Therefore, it is possible to heat a shallow layer of the steel without heating the interior. The surface layer is heated practically instantaneously to a depth which is inversely proportional to the square root of the frequency. The range of frequencies commonly used is between 10,000 and 500,000 Hz. Greater case depths may be obtained at each frequency by increasing the time of heating.

The case obtained by induction hardening is similar to that obtained by flame hardening, and thinner cases are possible. Induction hardening equipment can be fitted into the production line and used by relatively unskilled labor. Macrostructure of an induction hardened camshaft lobe is shown in Fig.12.23.



*Fig.12.23 Macrostructure of an induction hardened cam lobe, x2.*

# SUMMARY

Diagram	For
Fe-C	Equilibrium condition, slow cooling
TTT	Constant temperature (isothermal) transformation
CCT	Continuous cooling transformation

## Forms of Hardening of Metals

1. Solid solution hardening
2. Strain (work) hardening
3. Precipitation (dispersion) hardening
4. Phase transformation
5. Finer grains
6. Fiber reinforcement

## HEAT TREATMENTS

### I. Annealing

1. Spheroidizing
2. Full
3. Isothermal
4. Process
5. Stress-relief
6. Quench
7. Normalizing

*Purpose: refine the grain, induce softness, improve elec. & magnetic properties, homogenize structure, improve machinability*

Chemical-thermal treatment

### II. Hardening

1. Direct quenching
2. Martempering
3. Austempering

### III. Tempering

*Differ from annealing by:*

1. *Does not soften the steel to the extent that annealing would*
2. *Mechanism is similar to precipitation annealing*

### V. Surface Hardening

1. Carburizing (pack, gas, liquid)
2. Nitriding (gas, liquid)
3. Flame hardening (stationary, progressive, spinning, progressive-Spin.)
4. Induction hardening

### IV. Precipitation (Age) H.

Precipitation (age) hardening, can be achieved only with those alloys in which there is a **decreasing solubility** of one material in another as the **temperature is reduced**.

Thermal treatment %C > 0.3

# **CHAPTER 13**

## **METALLURGY OF METAL WORKING AND FABRICATION**

### **13.1 INTRODUCTION**

Thus far all various metallurgical aspects have been discussed which impart an understanding of the characteristics of metals and the relationship between structures and mechanical properties. However, all this may have little practical value if it is not applied to form a material into desired internal structure and external shape, i.e. to fabricate the actual hardware. This chapter, therefore, deals with **the application of metallurgical knowledge to the various processes for forming and fabrication of metals**, so that an understanding is developed which would assist in producing a desired structure and characteristics for a specific material. Details of fabrication processes will not be indulged into, however, as these can be obtained from reference books.

# **METAL WORKING AND FABRICATION PROCESSES**

- 1. CASTING PROCESSES**
- 2. MECHANICAL WORKING OF METALS**
- 3. MACHINING OF METALS**
- 4. WELDING PROCESSES**

## 13.2 CASTING

Casting is the oldest process known for forming materials. In essence, it consists of making a mould of desired shape and pouring liquid metal into it which takes up the shape of the mould upon solidification. There are practically no limits to the shapes and sizes which can be obtained by casting and they range from tiny dental inlays of rare metals to complicated steel castings exceeding 200 tons.

## 13.2.0 CASTING PROCESSES

In general casting processes are classified according to the material used for the mould.

**Sand casting** uses various types of sands and binders, such as fireclay and bentonite, to make the mould. Plaster of Paris castings use plaster moulds which provide better surface finish to the cast shape, as well as better dimensional accuracy, finer details and a more solid structure, but at a higher cost compared to sand casting.

**Permanent and semi-permanent mould castings** are used when a large number of a shape has to be cast and an even better finish is required. Metal moulds are used for these castings.

**Die and cold chamber pressure castings** use metallic moulds in which fluid metal is solidified under sustained pressure, which gives close tolerances, sharp outlines and contours, and a fine smooth surface.

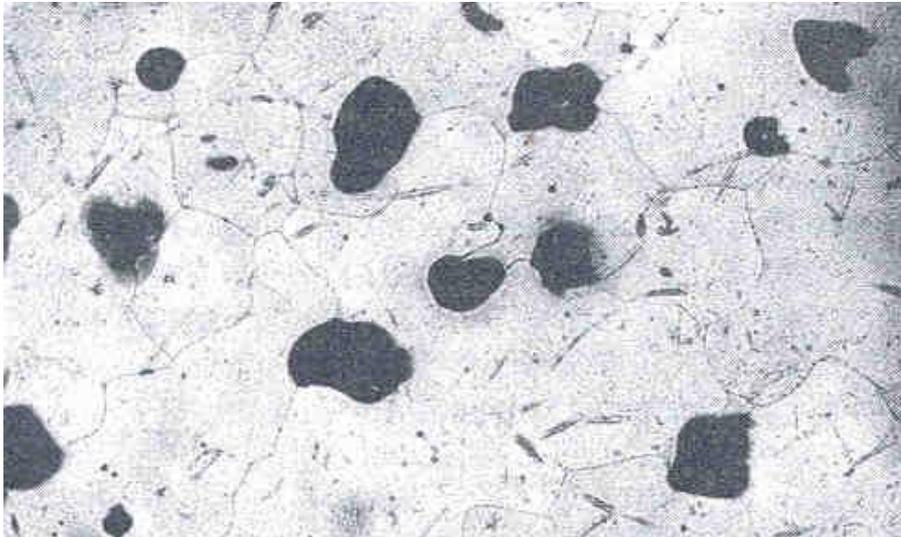
**Centrifugal castings** are produced by pouring molten metal into a revolving mould, made of sand, clay or metal. Centrifugal action forces the metal tightly against the mould, which gives finer grain size, slightly increased density and uniform distribution of alloying elements. It is essentially a pressure casting process.

**Investment or Precision or lost wax casting** is a versatile method of producing complicated/small parts. Firstly a plaster or glue mould is made for the desired shape from which wax parts are then produced. Investment material (special sand) is then placed around the wax part and is allowed to harden and then baked in an oven whereby wax melts and runs out leaving a hard permanent mould for casting. It makes small, intricate parts which can not be machined economically.

**Shell Mould casting** is a variant of sand casting in which thin shell moulds are produced by mixing sand with a thermosetting resin. Sand and resin are sprinkled over the heated pattern, which partially sets the resin to provide a thin shell mould, which is then removed from the pattern and baked at about 200 °C to completely set the resin and produce a hard mould. It eliminates the problems of handling vast amounts of sand required in sand casting.

## 13.2.1 Metallurgical Aspects of Casting

Metal for casting may come directly from reduction of ore (for example from blast furnace) or from re-melting and alloying. In either case the surface is covered with slag or protective coating to avoid or minimize evaporation losses, oxidation and contamination of the metal. Gases tend to dissolve in metals at high temperatures, and the gas content increases with time elapsed at high temperature. Dissolved gases, if remain trapped, cause porosity and produce unsound castings (Fig.13.1). To avoid it, therefore, casting is carried out at minimum possible temperature and with least possible delay.



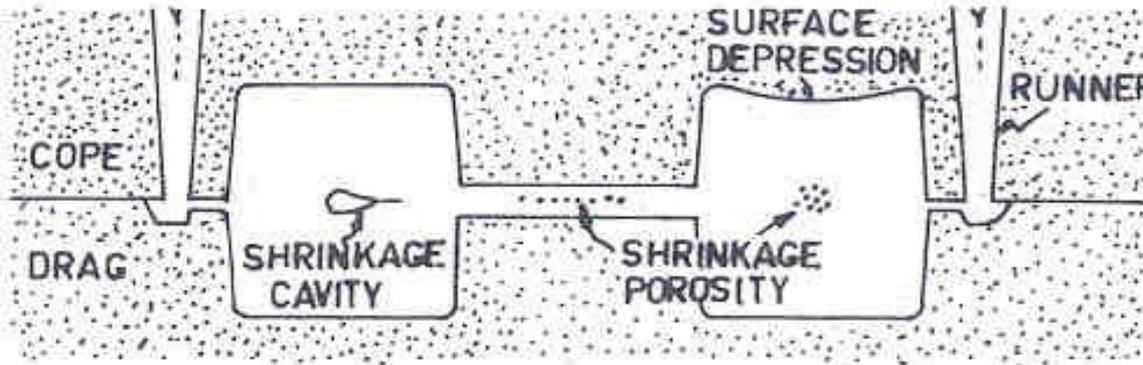
*Fig.13.1 Micrograph of gas holes in a cast copper, x50.*

## 13.2.1 Metallurgical Aspects of Casting

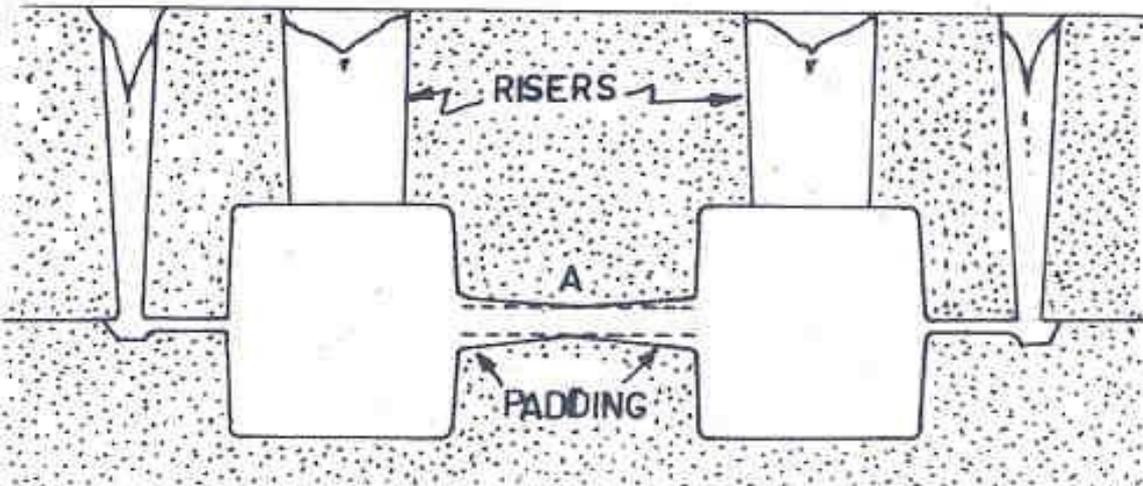
Vacuum casting makes it possible to use high casting temperatures which increase the fluidity of metals enabling them to completely fill the mould; as well as low dissolved gas concentrations. These, processes are, however, expensive and are used when no other alternative is possible.

During solidification a casting generally freezes on the exterior while the centre is still liquid. Since metals contract on solidification, this leads to a shrinkage cavity in the centre. This problem can be avoided by **directional solidification** of the casting whereby the casting solidifies progressively without leaving any liquid regions behind; all sections of the casting will then have continuous access to the liquid metal and hence no cavity can form. Directional solidification can be achieved in many ways. A thick section can, for example, be solidified rapidly (chilled) with a metallic mould, whereas a thin section can be cast in a pre-heated mould or a mould made of poor heat conductivity material.

Fig.13.2 shows the way how casting defects are eliminated. In the web area directional solidification eliminates shrinkage porosities, and in thick sections risers supply sufficient fresh liquid so that no cavity is formed.



(i)



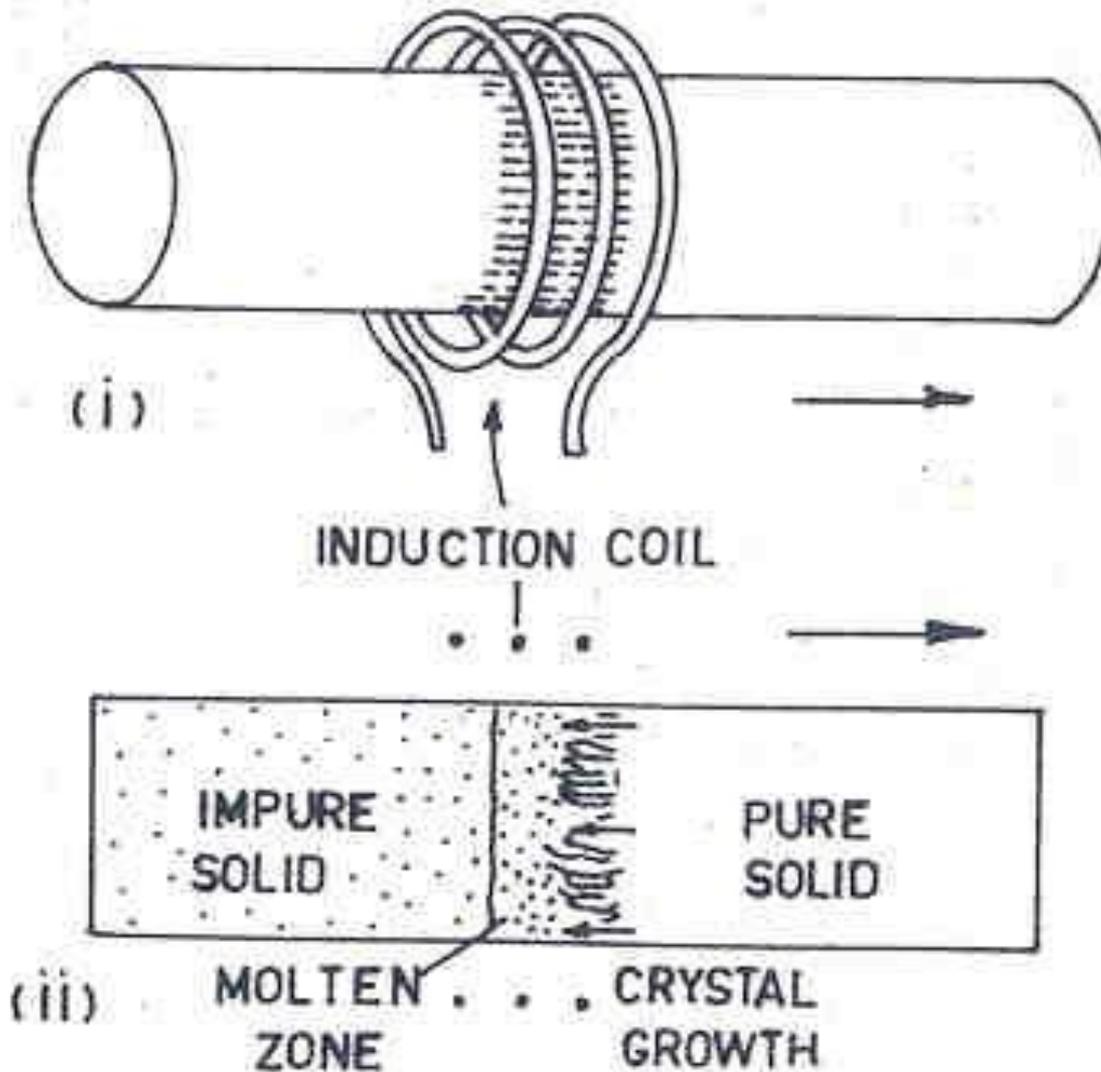
(ii)

*Fig.13.2 Elimination of casting defects by controlling solidification..*

Many impurities are soluble in liquid metal but insoluble in solid metal. Thus, as metal freezes, these impurities are rejected by the solid and remain in the liquid with slag etc. **A difference in the impurity level between the first solidified metal and the last metal to solidify is,** therefore, established which is known as **ingot segregation**. Ingot segregation gives different properties between these areas of the castings and is, therefore, undesirable. It can be minimized by providing a hot dip on the ingot mould or a riser on the casting. This reservoir is the last to freeze and hence contains most of the impurities and is discarded.

**Grain boundary segregation** is a specific case of segregation in which impurities accumulate in a film at the grain boundaries making them brittle. Sulphur in excess of few hundredths of one percent in iron, for example, produces FeS film on iron grain boundaries to make the metal brittle.

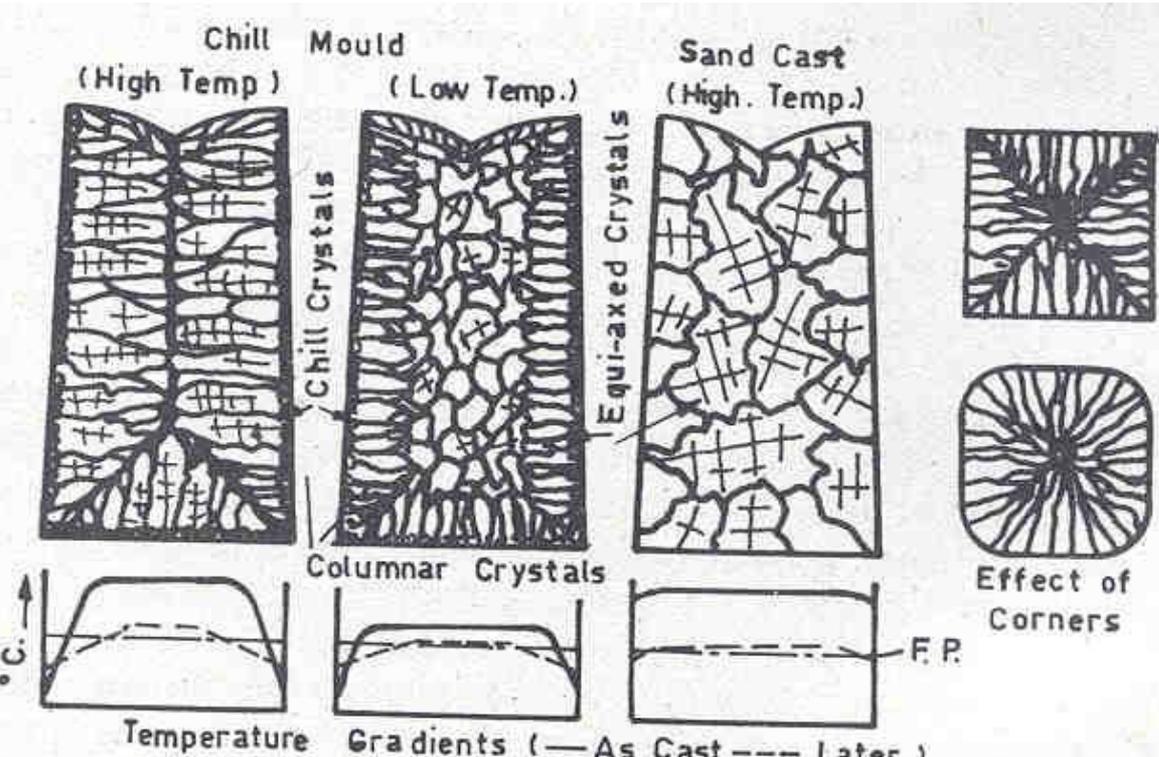
**Zone refining** can be applied in some cases to produce high purity material. Here metallurgist encourages the segregation to work for him in sweeping or squeezing out impurities.



*Fig. 13.3 The principle of zone refining*

In zone refining, an ingot of the material is melted progressively along its length, a narrow zone at a time (Fig. 13.3). In this manner, the molten zone moves progressively from one end of the ingot to the other and collects much of the impurity. Multiphase can be necessary in some cases. Much of the impurity is then concentrated in the last 20 % of the ingot which is cut off later.

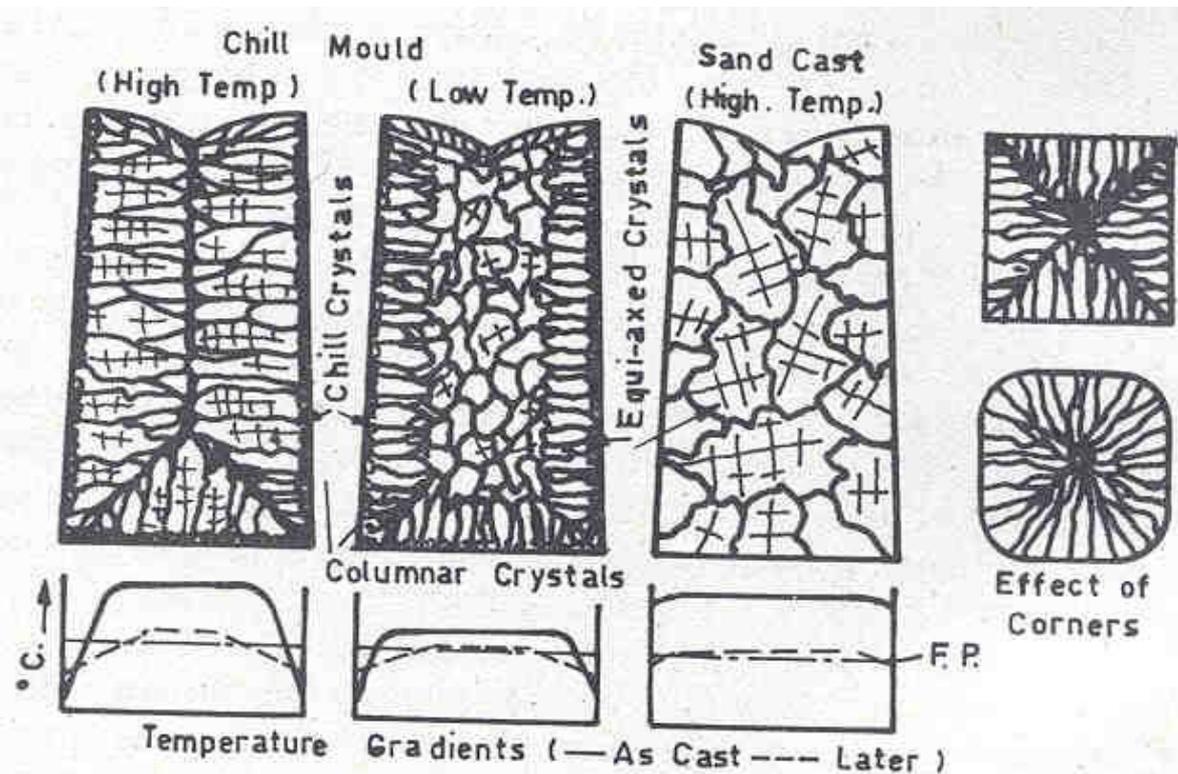
During solidification under quasi-equilibrium conditions, equiaxed grains are obtained which, however, is not the case in practice. If molten metal is poured into a relatively cold mould (e.g. an ingot mould), the metal nearest to the wall cools first and solidifies. The first crystals, therefore, nucleate on the mould wall and begin to grow in all directions. Their circumferential growth is obstructed by each other, and they continue to grow inwards. The final structure is, therefore, columnar on the surface with the columns almost normal to the surface, while the inside having randomly oriented grains due to slower cooling (Fig 13.4). Columnar structure has a preferred orientation, as in chilling which has a predominantly columnar structure. Columnar structure can be reduced to a minimum thin "skin" area on the surface of the mould by using a sand mould or a preheated metal mould or a large mould.



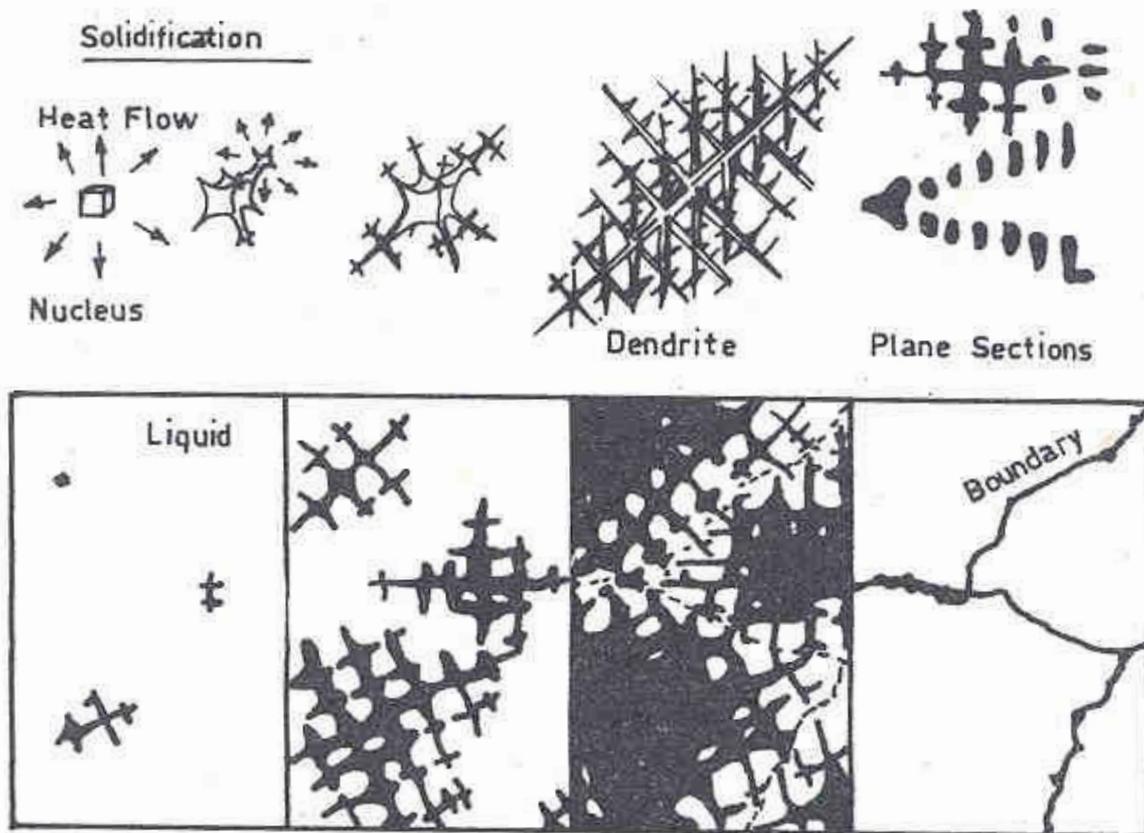
*Fig.13.4 Columnar and equiaxed grains and planes of weakness in casting.*

The rest of the interior structure is then randomly oriented equiaxed grains. In mould containing a sharp corner, a plane of weakness is developed at the corner since it contains bulk of impurities rejected by the growing columnar crystals. Such corners should be rounded to alleviate the problem.

In case of sand casting which cools slowly due to low rate of heat dissipation, a few nuclei are activated due to slow cooling and the growth of these nuclei is roughly the same in all directions. The result is a coarse equiaxed grain structure with grains of about the same size but differing orientations.



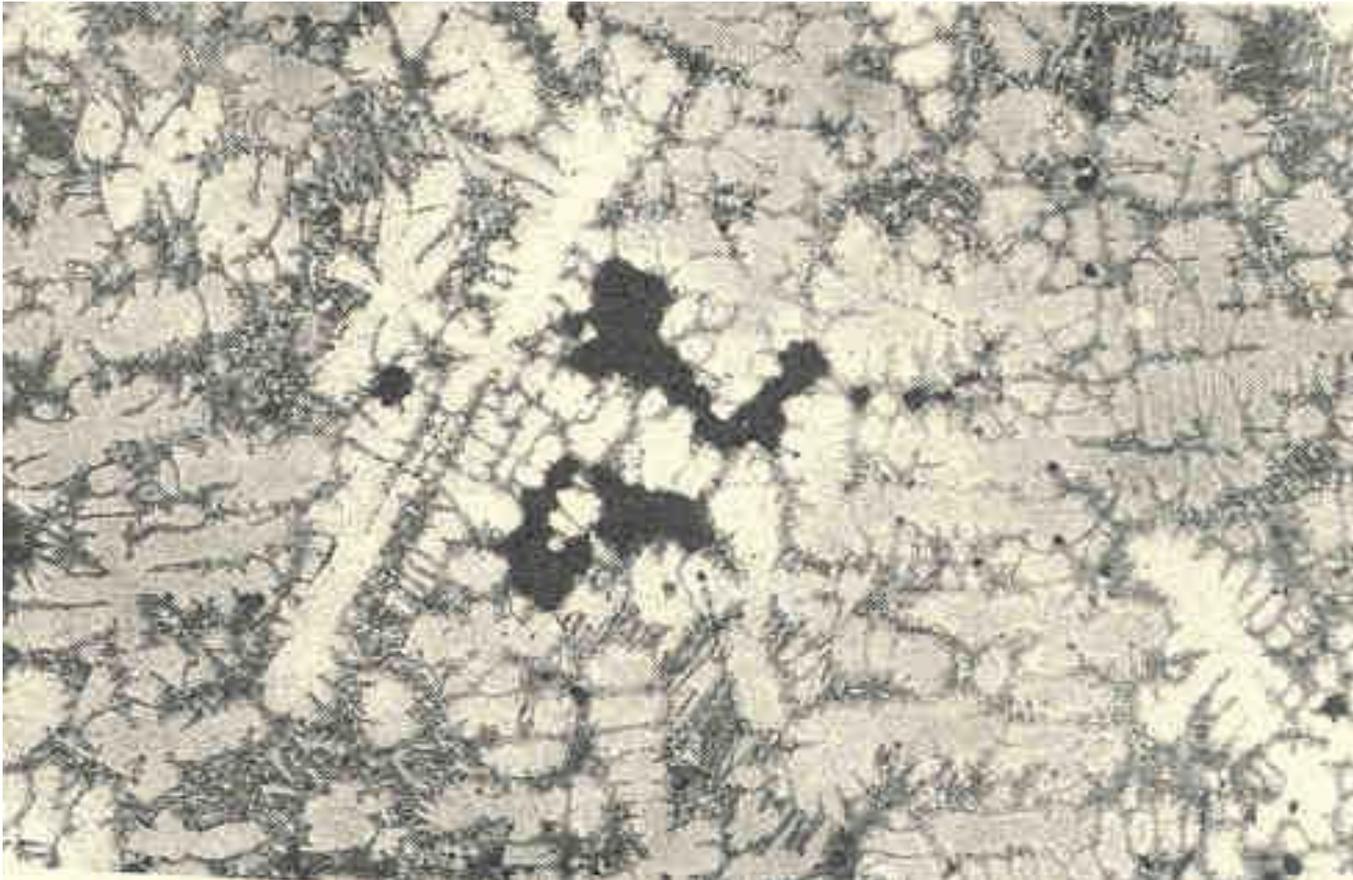
*Fig. 13.4 Columnar and equiaxed grains and planes of weakness in casting.*



In some instances, crystals growing during solidification develop rapidly along certain crystallographic directions and slowly along others, resulting in formation of long branchlike arms or **dendrites**, as shown in Fig 13.5. As these dendrites grow into grains, they must accommodate themselves to their neighbors which makes the exterior irregular while preserving the regular arrangement of atoms in the interior.

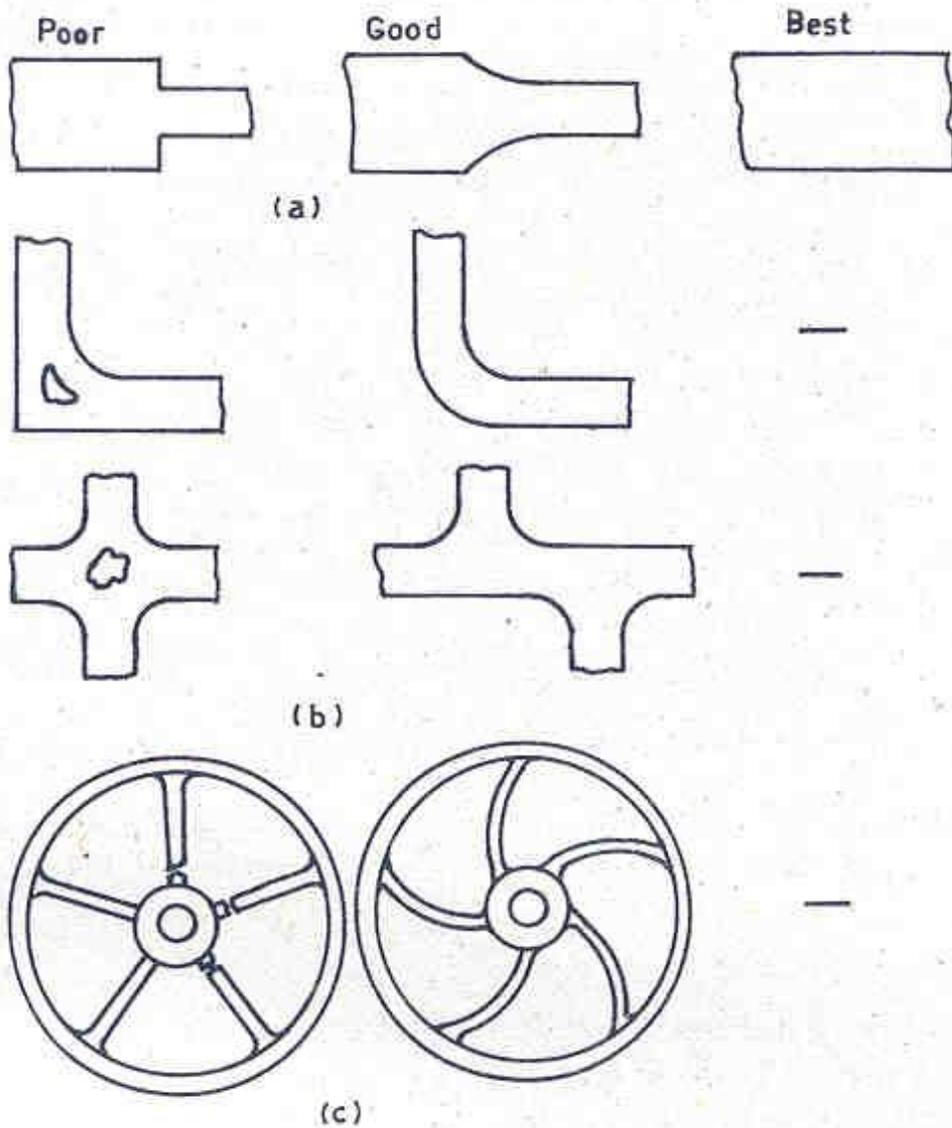
*Fig. 13.5 Development of dendritic structure during solidification.*

Fig. 13.6 shows dendritic structure and shrinkage cavities in a cast copper alloy



*Fig. 13.6 Micrograph showing shrinkage cavity and dendrites in a cast copper alloy, x50*

In the melting and casting of metals or alloys many factors have to be considered in order to reduce the incidence of defects. A number of defects may arise from faults in mould construction or from poor quality sand. Experienced staff will easily avoid moulding problems. However, shape of the component is generally decided by the design engineers who knows little about casting problems. It is the shape of the component which produces casting defects in most of the cases.



The shape of the component should allow orderly solidification. When wall-thickness variations are essential, transition must be made by generous radii. Localized heavy cross sections should be avoided. A material that has a high solidification shrinkage is susceptible to hot tear. In Fig.13.7 some of the common casting defects due to shape and their practical solutions are given.

*Fig. 13.7 Design features to avoid casting defects:*

- (a) Thickness change,*
- (b) hot spots, and*
- (c) hot tear.*

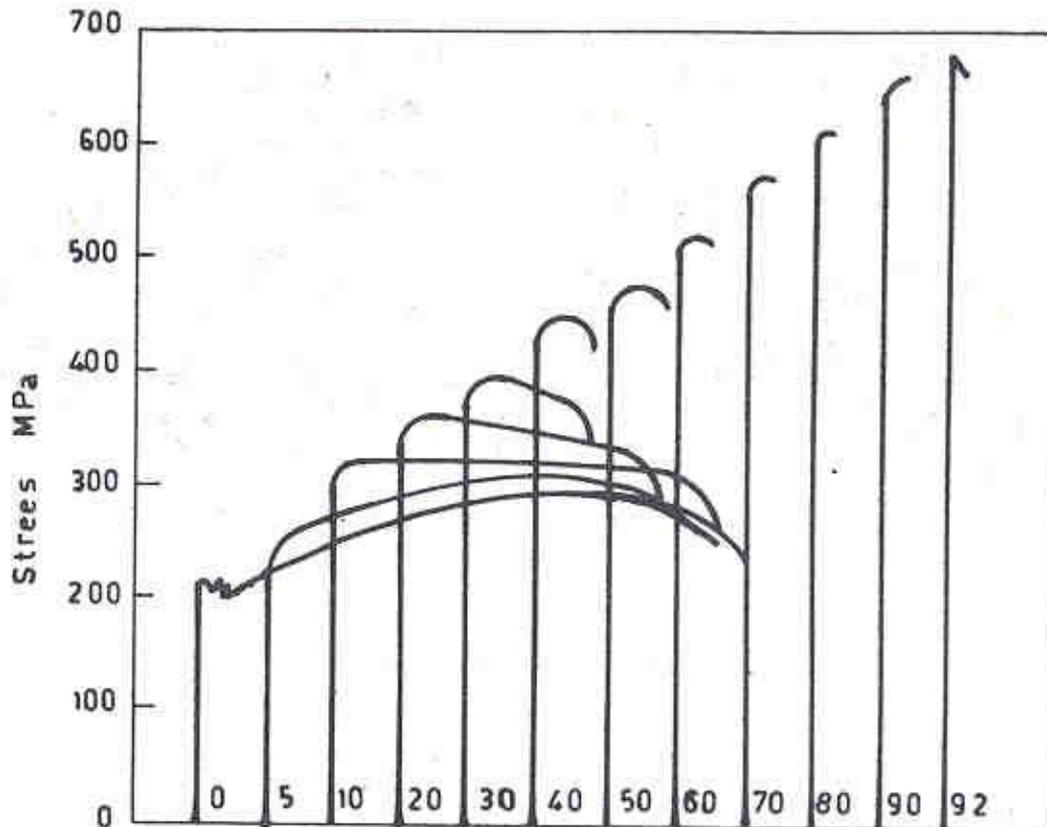
## 13.3 MECHANICAL WORKING OF METALS

The principals of working of metals has already been discussed in Chapter 10. Metals could be worked below the recrystallization temperature (cold working) or above it but below melting point (hot working). Both have certain advantages and disadvantages as explained before.

Control of mechanical properties during shaping by plastic deformation is very important. Blow-holes and porosities produced during casting may be eliminated by hot deformation which improves ductility and fracture toughness. In many products the mechanical properties depend upon the control of strain hardening during processing, while in other instances precise control of deformation, temperature, and strain rate during processing is required to develop the optimum structure and properties.

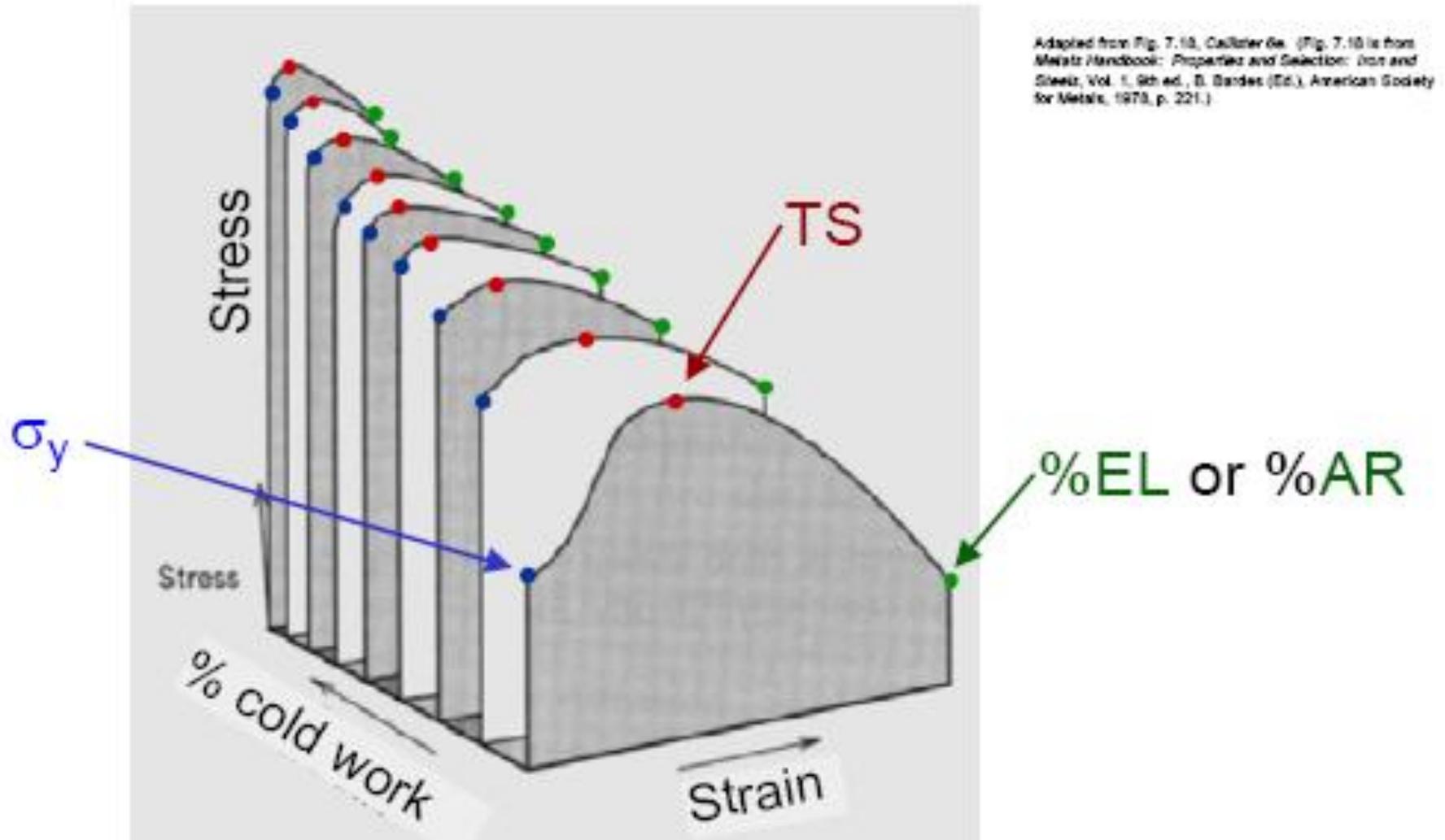
## 13.3.1 Cold Working

The marked strengthening that results from cold working an iron wire is shown in Fig.13.8.



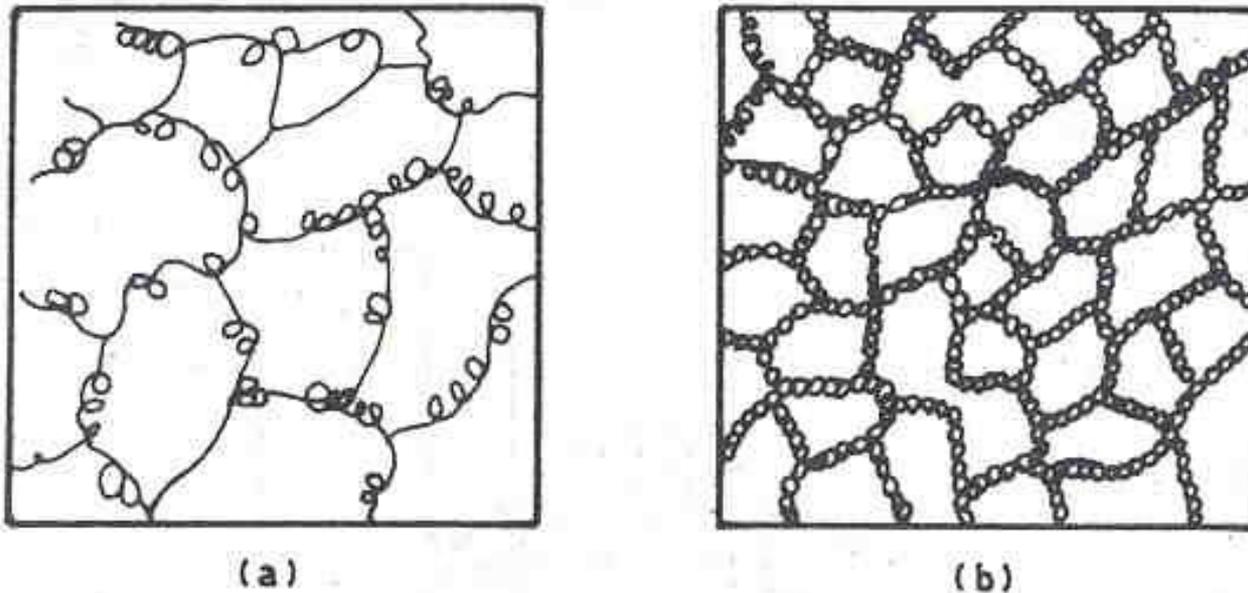
*Fig.13.8 Stress-strain diagrams for a low carbon steel cold worked to different amounts*

# IMPACT OF COLD WORK



The dislocation structure of cold worked metals consists of a cellular substructure with the cell walls composed of tight-packed tangles of dislocations (Fig.13.9). For the large plastic strains characteristics of wire drawing and rolling, structure consists of highly elongated grains (as shown in Fig.9.6).

On macroscopic scale, the structure of severely cold-worked metal is characterized by the development of a strong crystallographic texture the presence of preferred orientation causes anisotropy of mechanical properties this is of particular importance in determining the deep-drawing properties of rolled sheet.



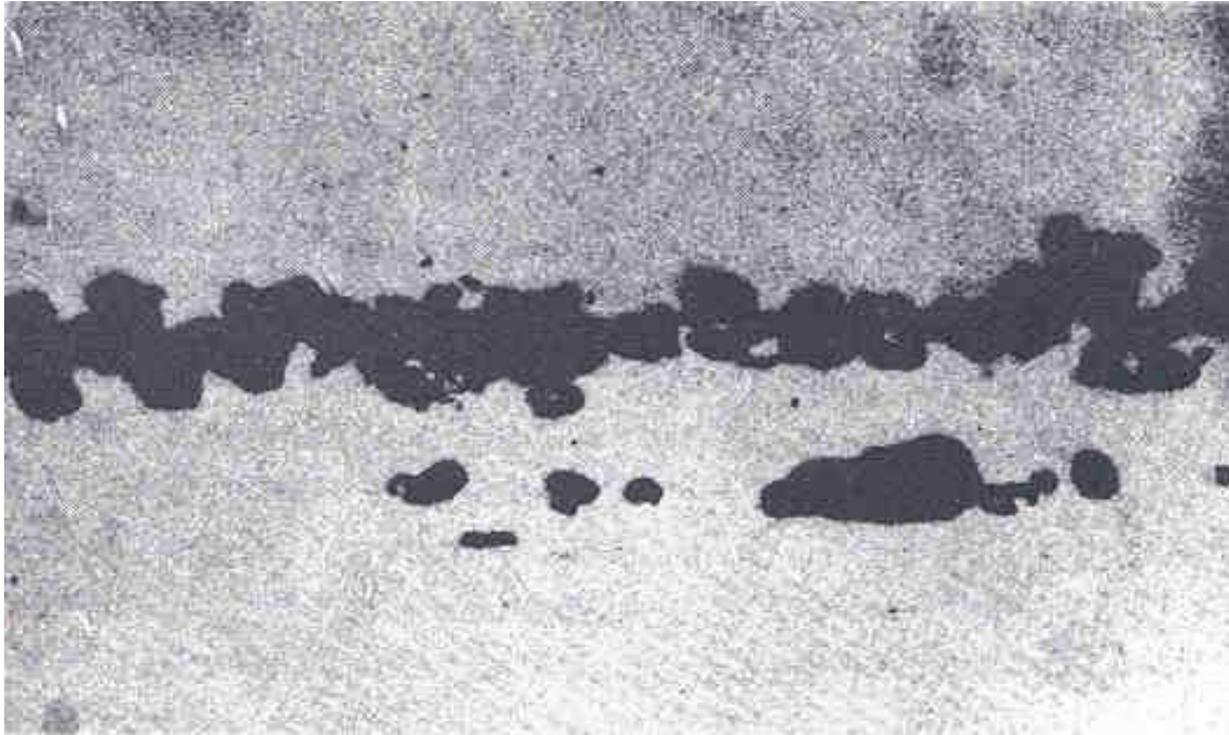
*Fig. 13.9 Formation of cellular dislocation structure:  
(a) 10 % deformation, (b) 50 % deformation.*

## 13.3.2 Hot Working

The predominant softening mechanism in hot-working is dynamic recovery. Dynamic recovery is the sole softening mechanism in metals where climb and cross-slip of the dislocations are relatively easy. This occurs in metals of high stacking-fault energy such as aluminium, alpha iron and most BCC metals. When climb and crossslip are not easy processes another mechanism intrudes at larger strains. This occurs in metals with low stacking-fault energy such as copper, nickel, austenitic iron, and their alloys. When the misorientation between subgrains reaches high values, the subgrains act as recrystallization nuclei and dynamic recrystallization occurs as the softening mechanism.

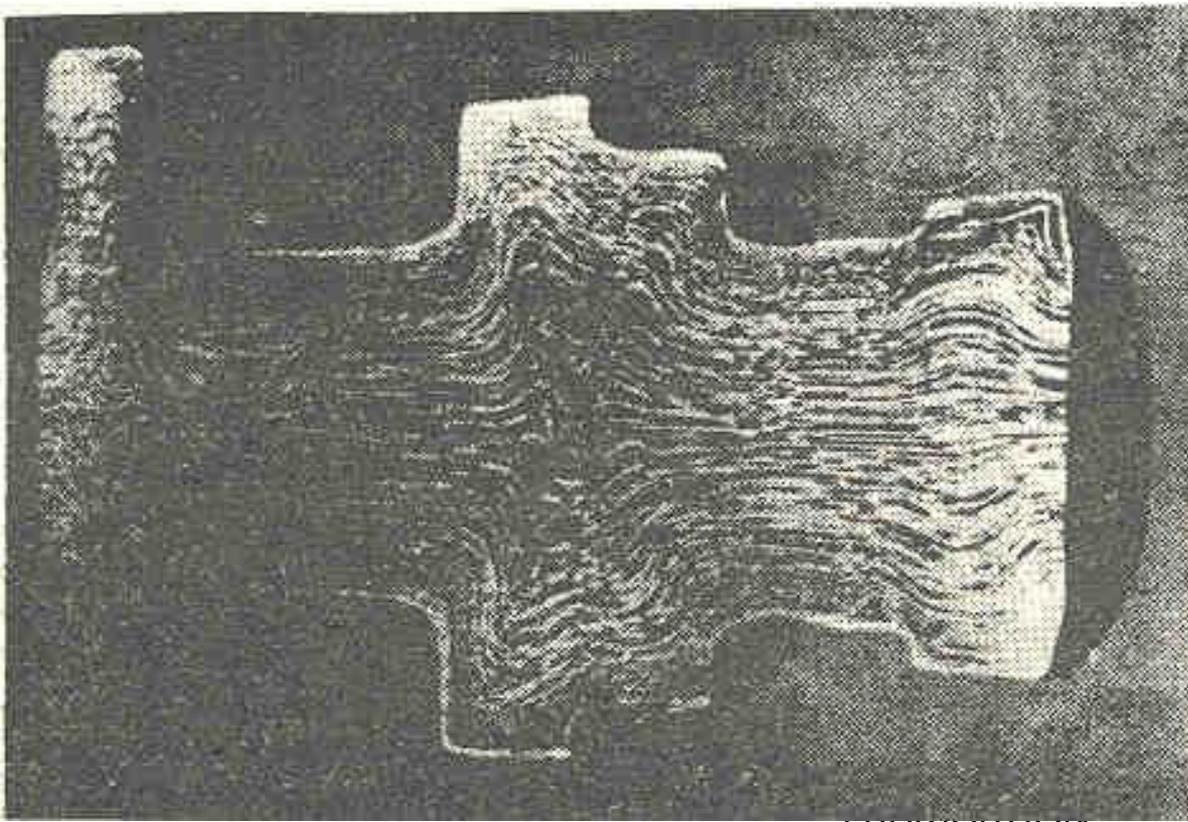
Hot working greatly accelerates diffusional processes. Two examples of practical importance are the elimination of compositional inhomogenities, such as a cored structure, and coarsening of a second-phase structure, such as the spheroidization of a pearlitic steel. Diffusion is greatly enhanced by dynamic recovery process.

As the result of mechanical working operation second-phase particles will tend to assume a shape and distribution which roughly correspond to the deformation of the body as a whole. Second-phase particles or primarily inclusions which are originally spheroidal will be distorted in the working direction into an ellipsoidal shape if they are softer and more ductile than the matrix. If the inclusions are brittle, they will be broken into fragments which will be oriented parallel to working direction as shown in Fig.13.10.



*Fig.13.10 Fragmentation and then orientation of brittle inclusions during hot rolling of a heat resisting steel, x100*

If the particles are harder and stronger than the matrix, they will be essentially undeformed but cracks around them can be initiated due to deformation. As a result of mechanical deformation (both hot and cold) fibrous structure may be produced which is due to orientation of grains and second-phase particles in the working direction. The fiber structure may be observed after macroetching as shown in Fig.13.11. Microscopic examination of wrought products frequently shows the results of this mechanical fibering ((i) in Fig.13.24). An important consequence of mechanical fibering is that the mechanical properties are anisotropic. In general, ductility, fatigue properties, and impact properties will be lower in the transverse direction than in the longitudinal direction.



*Fig.13.11 Macrograph of an upset forging showing fiber structure, x1*

### 13.3.3 Workability and Prevention of Defects

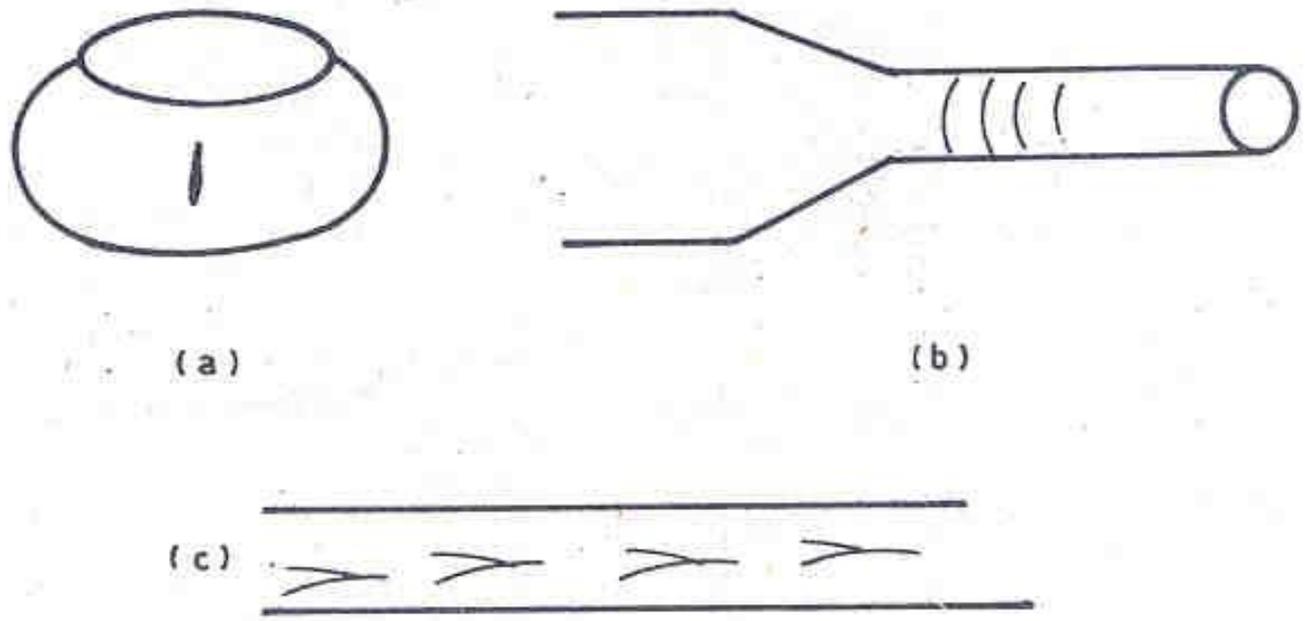
Workability is concerned with the extent to which a material can be deformed in a specific metalworking process without the formation of cracks. Workability is a complex technological concept that depends not only on the fracture resistance (ductility) of the material but also on the specific details of the process such as the reduction, friction, temperature, and strain rate.

There is no widely accepted workability test, but industry uses some empirical tests for rating workability.

The complete analysis of workability involves first establishing the ductile fracture criterion for the material. Then, complete analysis of the deformation mechanics in terms of the process geometry, reduction, friction, etc., is needed to compute the stress and strain histories at the critical points of fracture.

The cracks that occur in metalworking process can be grouped into three broad categories as shown in Fig.13.12:

1. Cracks at a free surface, such as at the bulge in upsetting a cylinder or in edge cracking in rolling,
2. Cracks that develop in a surface where interface friction is high, such as extrusion,
3. Internal cracks, such as chevron cracks in drawn bars.



*Fig.13.12 Metalworking cracks: (a) surface cracks in upsetting, (b) surface cracks in extrusion due to friction, (c) center burst cracks in a drawn rod.*

Kobayashi was able to calculate these parameters for the slow speed upsetting of steel cylinders at room temperature. The resulting workability diagram is shown in Fig.13.13.

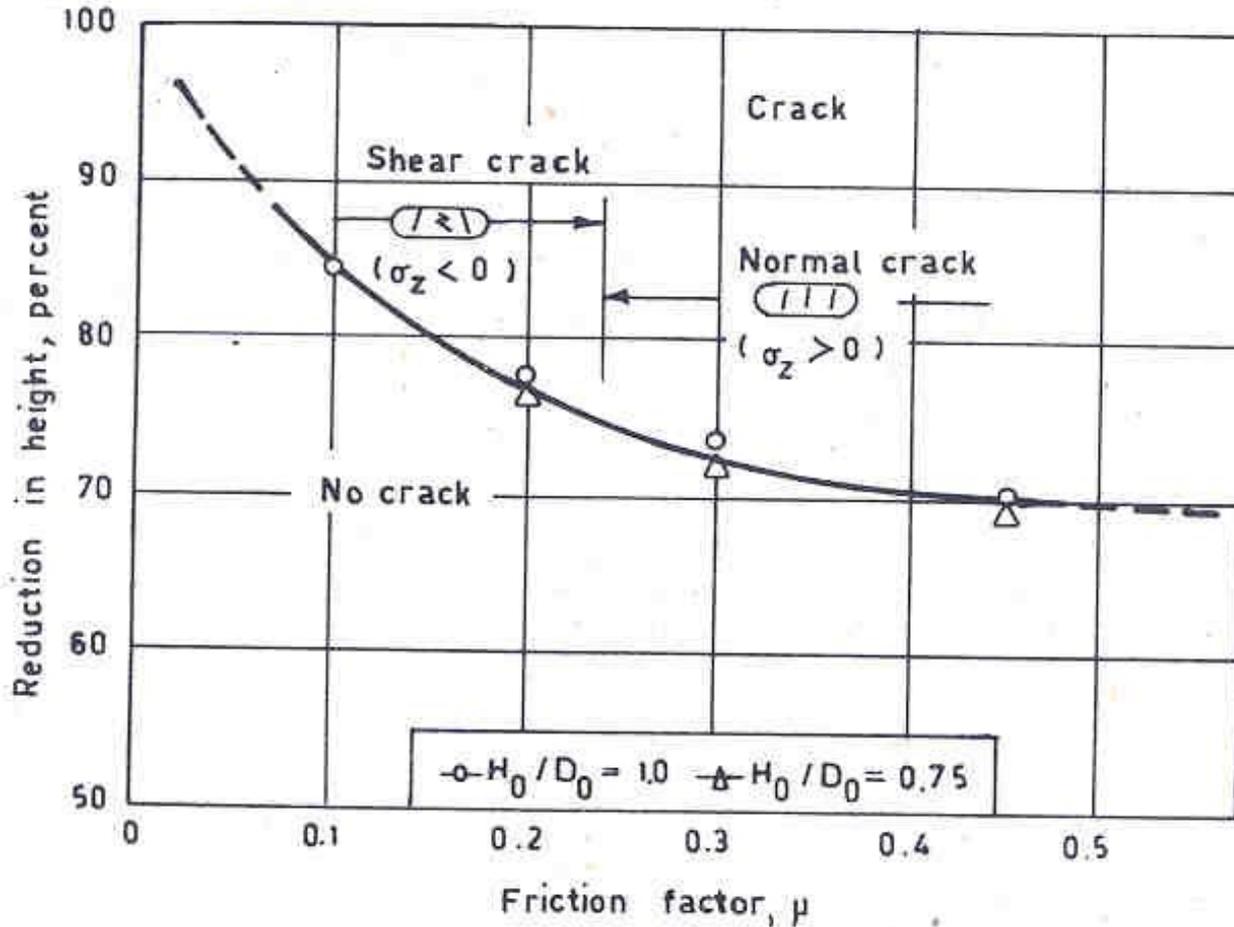
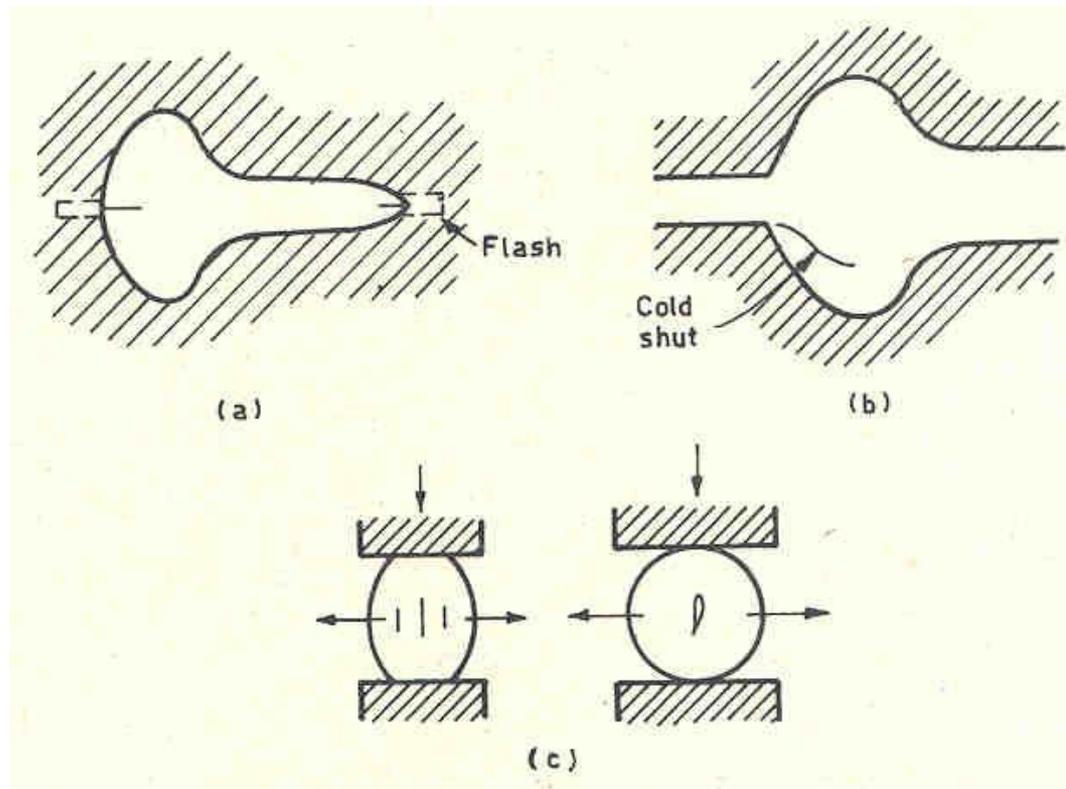


Fig.13.13 Workability of SAE 1040 steel in upsetting (S. Kobayashi et al., AFML-TR-73-192, 1973).

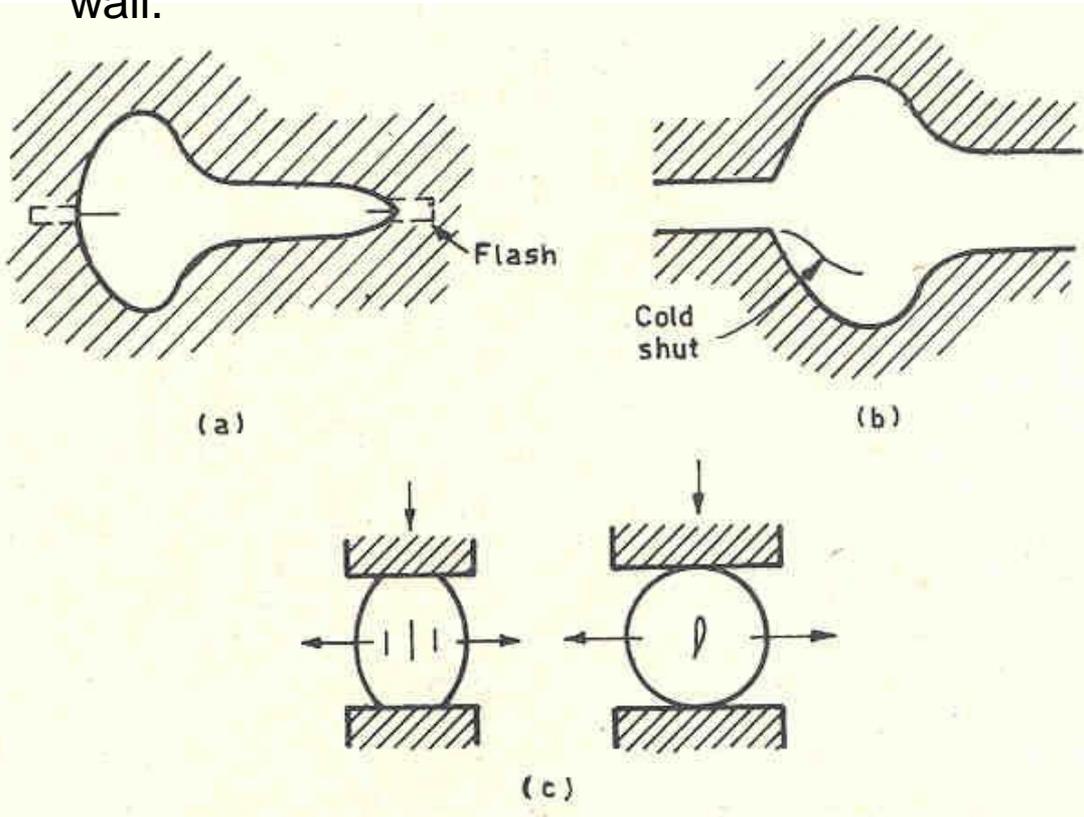
## FORGING DEFECTS

Forging defects are illustrated in Fig.13.14. Surface cracking can occur as a result of excessive working of the surface at too low a temperature or as a result of hot shortness. A high sulfur concentration in the furnace atmosphere can produce hot shortness in steel and nickel. Flash cracking (Fig.13.14a) can be avoided by increasing the flash thickness or by relocating the flash to a less critical region of the forging. It also may be avoided by hot trimming or stress relieving prior to cold trimming of the flash. **Cold shut**, or **fold** (Fig.13.14b) are usually caused by poor die design. Secondary tensile stresses can develop during forging, and cracking can thus be produced.



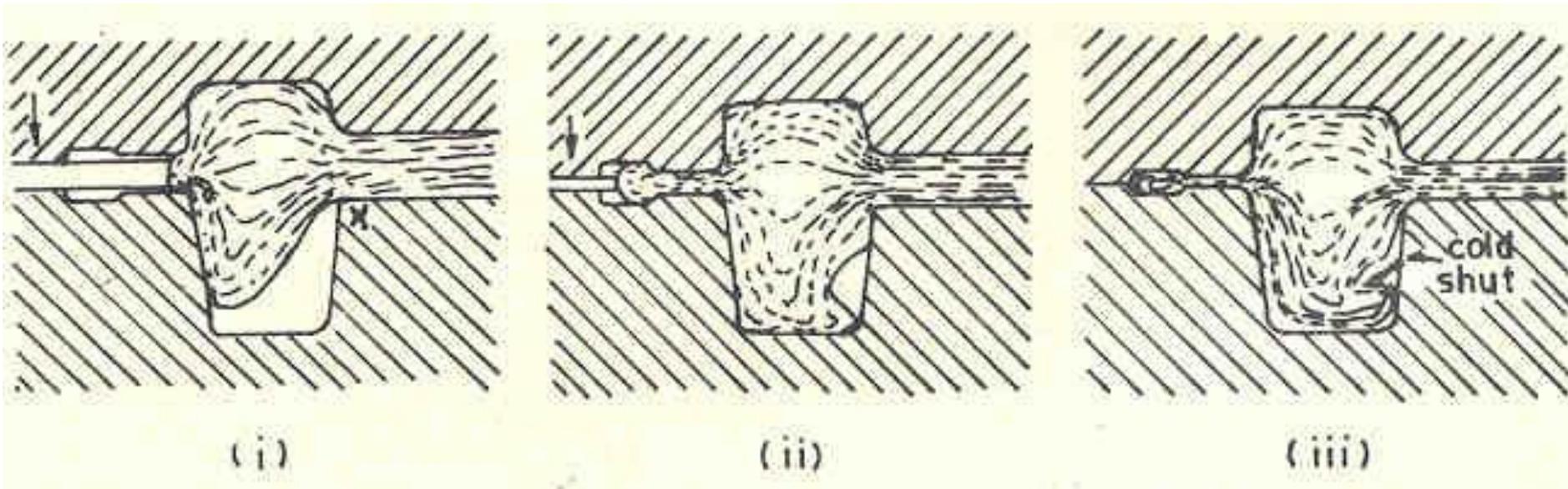
*Fig.13.14 Typical forging defects:  
(a) Cracking at the flash,  
(b) cold shut, and  
(c) internal cracking due to  
secondary tensile stresses.*

Internal cracks can develop during the upsetting of a cylinder or a round (Fig.13.14c). Proper design of the dies can minimize this type of cracking. Internal cracking is less prevalent in closed-die forging because lateral compressive stresses are developed by the reaction of the work with the die wall.

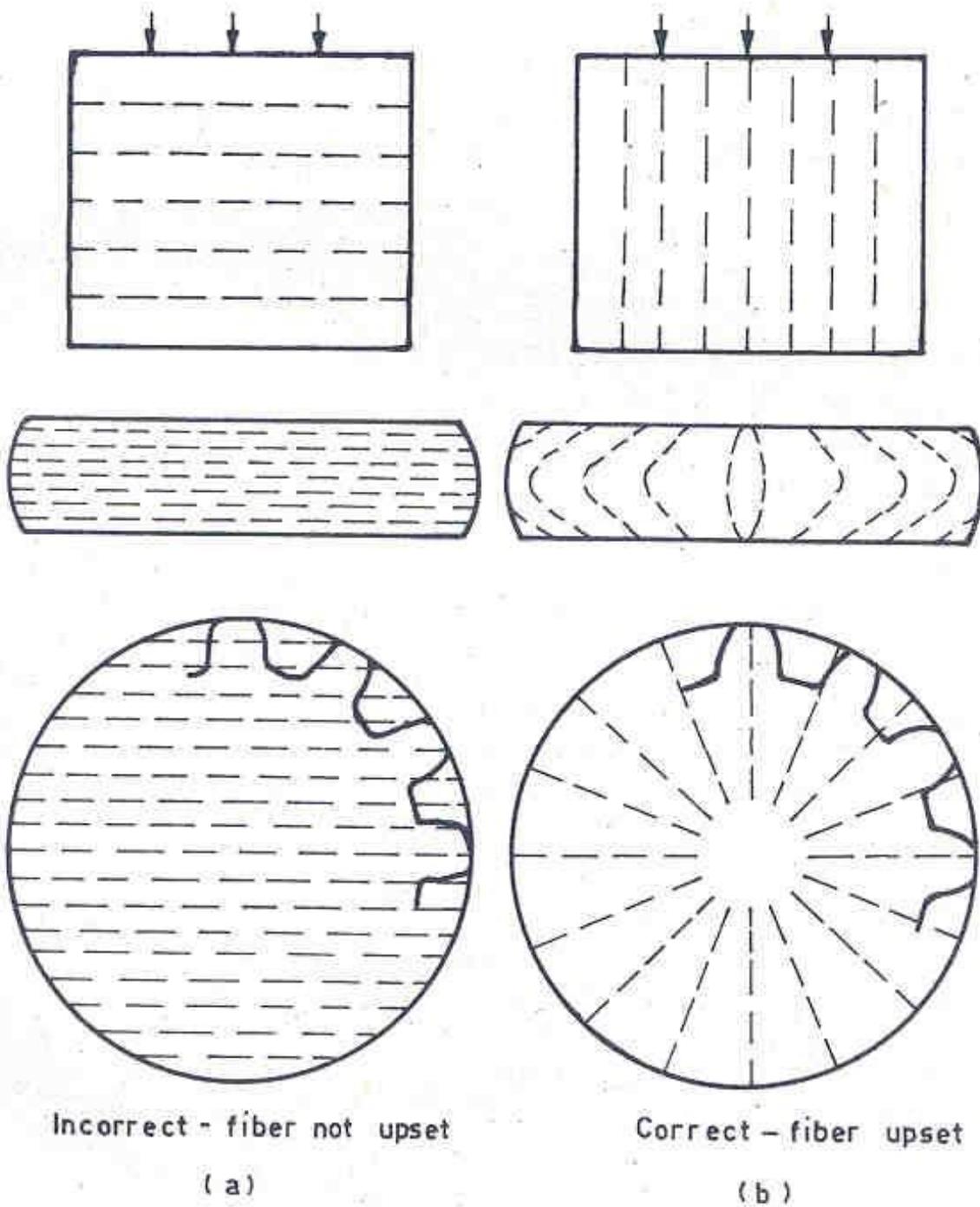


*Fig.13.14 Typical forging defects:  
(a) Cracking at the flash,  
(b) cold shut, and  
(c) internal cracking due to  
secondary tensile stresses.*

The metal flows past part of the die cavity instead of following the die wall due to a sharp corner as shown in Fig.13.15. As the die closes a fold is produced in the metal, giving rise to **cold shut** as indicated. To prevent cold shut generous radius should be given to every corner and intricate shapes.



*Fig.13.15 Formation of a cold shut.*



Flow lines, or fiber structure is beneficial if correctly oriented. Fibre lines should not be broken in a forging. Forging of a gear blank is given as an example in Fig.13.16.

In (a) original fibres are incorrectly located and after upsetting flow lines are not following the gear profile and they will be cut during machining.

In (b) proper location is illustrated and flow lines are correctly oriented after upsetting.

*Fig.13.16 Fiber flow patterns in forged gear blanks*

# ROLLING DEFECTS

A variety of problems in rolling, leading to specific defects, can arise depending on the interaction of the plastically deformed workpiece with the elastically deforming rolls and rolling mill.

The roll gap must be perfectly parallel, otherwise one edge of the sheet will be decreased more in thickness than the other. Since volume and the width remain constant, this edge of the sheet elongates more, and the sheet bows. The rolling process is very sensitive to flatness. A difference in elongation of one part in ten thousand between different locations in the sheet can give rise to waviness in a sheet. **Bowing out and waviness** are shown in Fig.13.17a

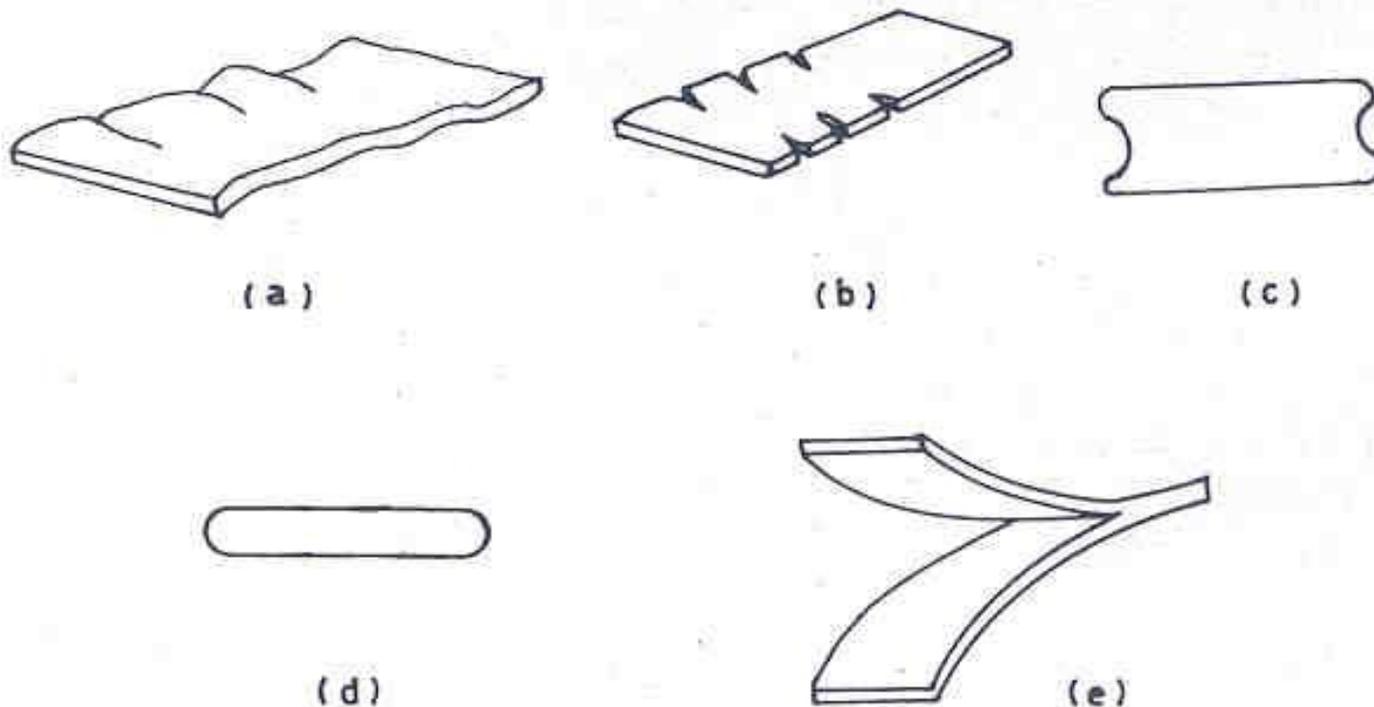
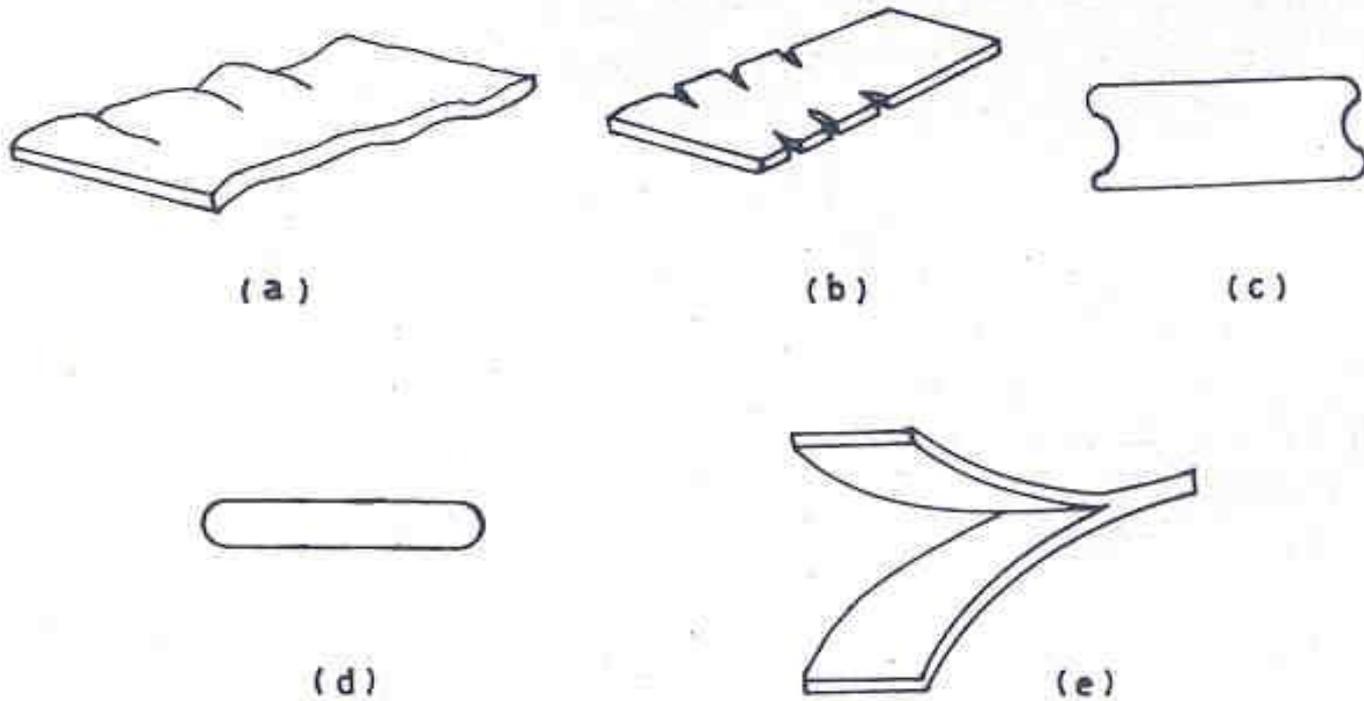


Fig.13.17 Rolling defects:  
(a) *Bowing and waviness,*  
(b) *edge cracking,*  
(c) *edge inward,*  
(d) *edge barrelling,*  
(e) *alligatoring*



*Fig.13.17 Rolling defects:*  
 (a) *Bowing and waviness,*  
 (b) *edge cracking,*  
 (c) *edge inward,*  
 (d) *edge barrelling,*  
 (e) *alligatoring*

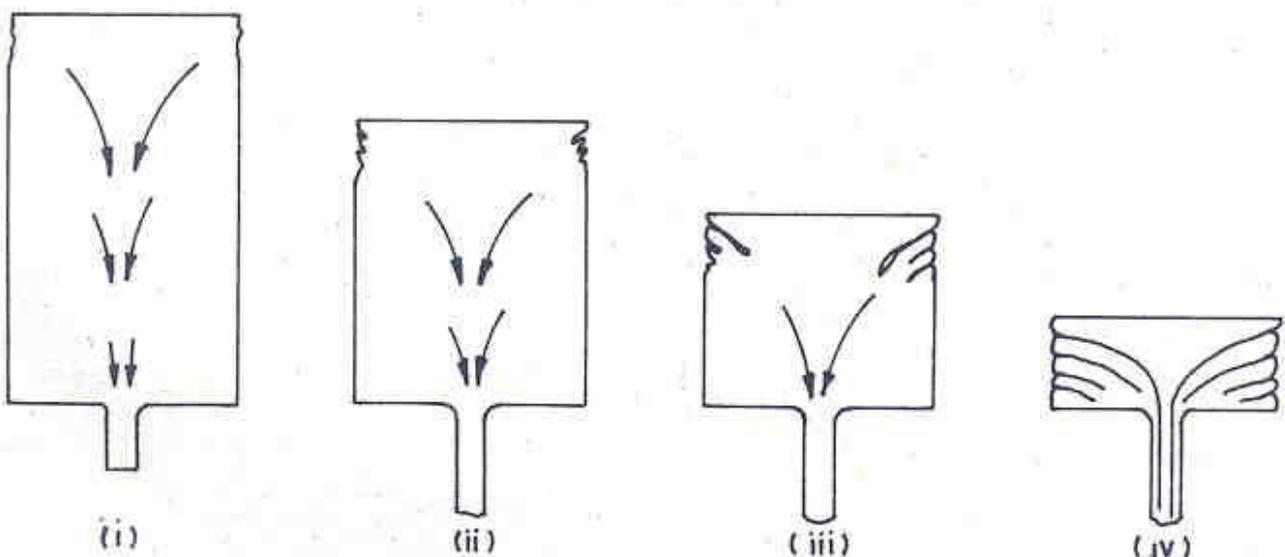
**Edge cracking** can be caused due to friction hill development during rolling (Fig.13.17b). It can also be caused by inhomogenous deformation in the thickness direction. With light reductions only the surface is deformed and sheet takes the shape shown in Fig.13.17c. In later passes it causes edge cracking. With heavy reductions, all sheet is deformed and the side of the sheet is **barreled** (Fig.13.17d) which can lead to edge cracking. If there is metallurgical weakness along the center line of the slab, fracture will occur as shown in Fig.13.17e. This is called **alligatoring**. Edge cracking can be minimized by using vertical edge rolls which restrict deformation in this direction.

# EXTRUSION DEFECTS

In hot extrusion, when the billet is placed in the chamber its outside skin becomes chilled and does not deform easily. The core of the billet is therefore more easily extruded as shown in Fig.13.18. As extrusion proceeds, outer skin begins to buckle and ultimately extruded which results in piped length. This is also called as **back-end defect**. To eliminate it, 10 to 15 % of the billet, which corresponds to back-end, should be discarded.

Transverse cracking in an extruded section is nearly always caused by frictional forces between the die and the work piece (Fig.13.12b). Too rapid extrusion will produce the same affect.

There is likely to be some variation in grain size along the length of an extruded section. The leading end of the rod undergoes little deformation and thus coarse grained as compared to the back end of the rod which suffers considerable plastic flow.



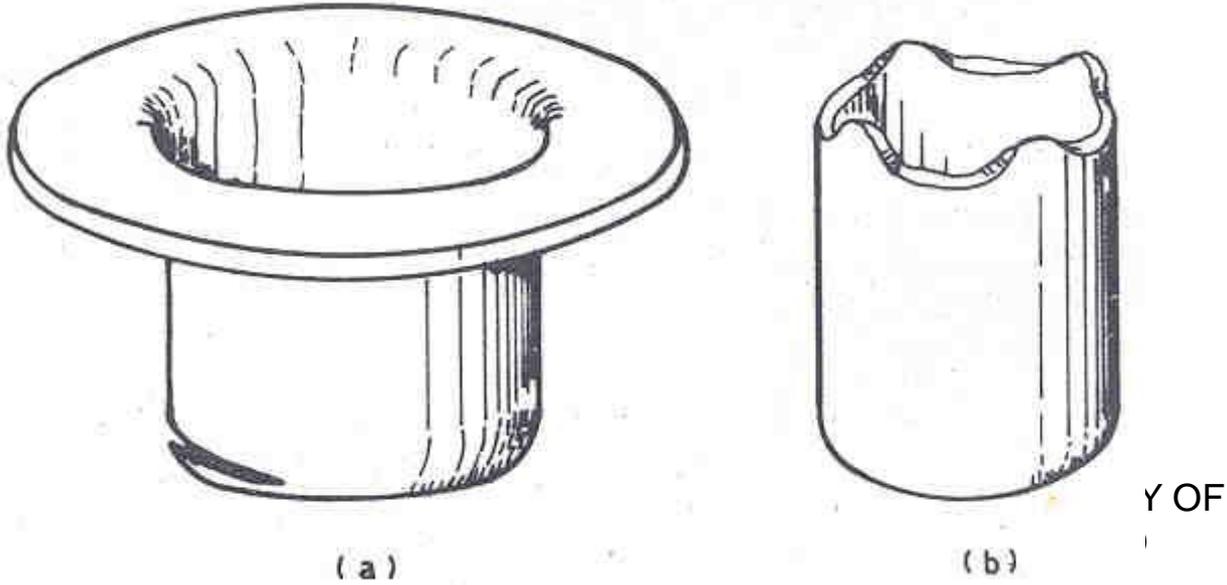
*Fig.13.18 Back-end defect formation in extrusion.*

# DEEP DRAWING DEFECTS

During deep drawing, the blank is hold flat on the die surface by the pressure pad. The pressure applied must be sufficient to prevent wrinkling. There are, however, several other faults which may develop during deep drawing.

Fig.13.19a shows a cup which has failed at the punch radius. This occurs when thinning of the wall in that region has taken place to such an extent that drawing force has exceeded its tensile strength. Excessive blank holding pressure, insufficient clearance between punch and die or inadequate radius of punch or die may lead to failure of this type.

**Ear formation** on a drawn cup (Fig.13.19b) may sometimes be encountered. Such ears are caused by directional properties in the sheet from which the cup was drawn. Ear formation can be minimized by avoiding excessive deformation in the deep drawing process, or by locating the most suitable axes relative to the sheet.



*Fig.13.19 Deep drawing defects: (a) Torn cup, (b) ear formation.*

The need for assessment of the suitability of a metal for deep drawing led to the development of the **Erichsen** cupping tests. In this test a specimen of the sheet to be drawn is clamped between a pressure pad and a die face. A load is then applied to the sheet by means of a standard steel ball so that the sheet is drawn through the die aperture until failure. The depth of the cup in mm till failure begins gives the **Erichsen Number**. It is a comparative test and results depends on sheet thickness, pad pressure and surface quality.

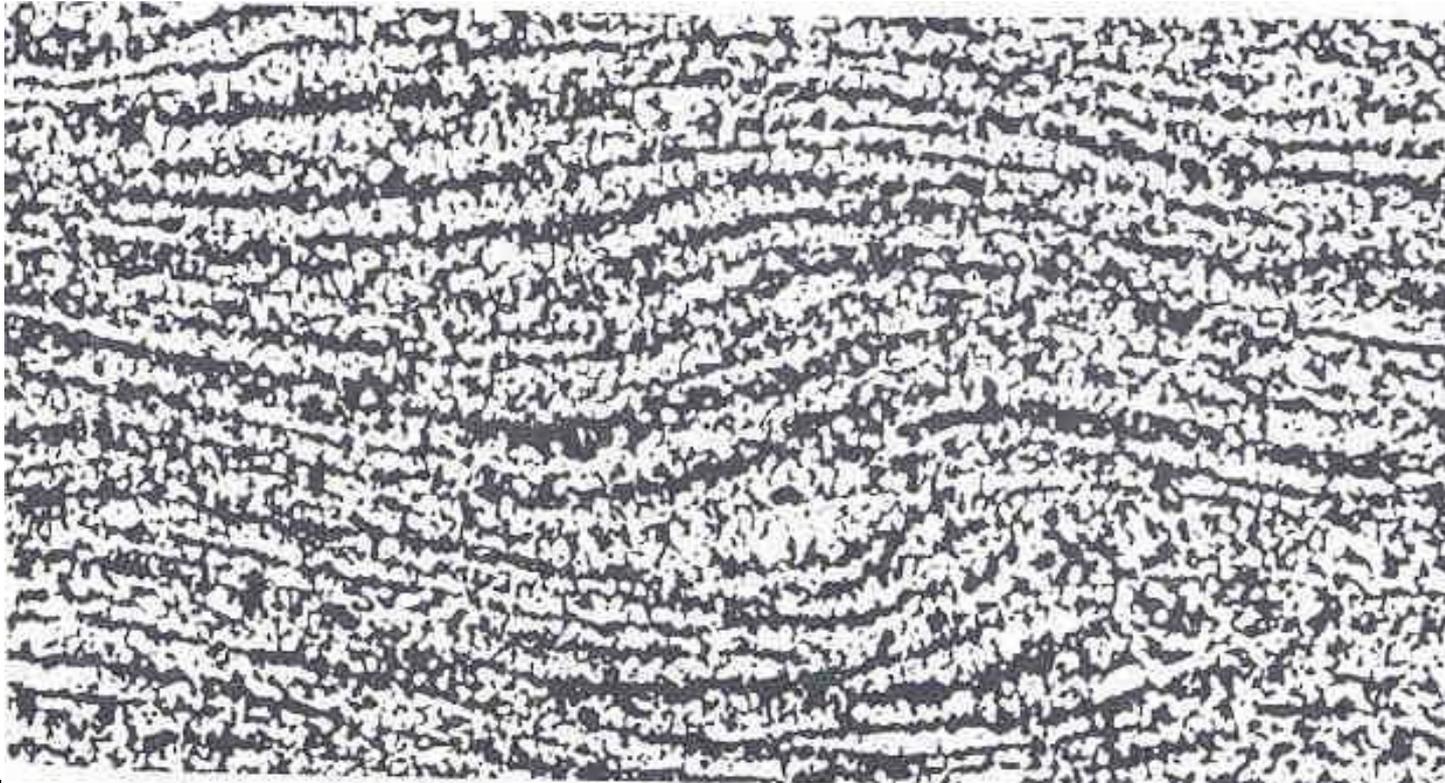
## 13.4 MACHINING OF METALS

Machining is carried out to cut a metal part to a required shape and size. Machining practices can have a profound effect on the grain structure, usefulness, and working life of a metal part. This can be the result of **distortion, notches** produced by machining, and by the **disturbance of the surface** while the metal is being cut. On the other hand, the composition and cleanliness of the metal being cut is important in determining the quality of cut and final finish, as well as the life of the cutting machine tool.

The surface finish of a machined article determines the level of surface smoothness and lack of notches and irregularities on the surface. In addition to the rake of the cutting tool, the use of lubricants effects the surface finish. In the absence of the lubricants, pressure welding of the chips is a problem, especially for softer metals such as aluminium and low carbon steels. Pressure welding produces a built up edge which makes the surface of the part rough and torn.

The speed of cutting influences the surface finish as well as the near surface grain structure of the work piece. **Too slow** a speed leads to the formation of built up edge. **High speeds** give a better surface finish and produce less disturbance of the grain structure. At lower speeds the metal structure is disturbed to a greater depth and the grains flow in the direction of the cut.

The grains become distorted and the surface becomes torn in places, which could lead to fatigue failures in service. Fig.13.20 shows a micrograph of a piece after milling showing distortion of microstructure. At higher speeds, the depth of distortion is reduced by as much as 80 %, and the distortion is much less severe.



26.07.

39

Fig.13.20 Micrograph of milled part showing grain distortion during chip formation, x100.

Sulphur is usually added to improve the machinability of metals. Sulphur additions produce sulphides which are not hard enough to reduce machining. On the other hand, the presence of hard inclusions or constituents not only impairs machining but also makes cutting edges of tools dull, reduces their working life. Annealed high carbon steel (0.9-1.1 % C) is difficult to machine because of the hard, brittle carbide sheaths which surround the grains of the metal. The problem can, however, be overcome by spheroidising as the carbides then become distributed throughout the mass as tiny spherical particles.

## 13.5 METALLURGY OF WELDING

**Welding is the localised union of metals by fusion, diffusion or surface alloying, accomplished by applying heat and/or pressure with or without a filler material.** It is a joining process as well as forming process. As a forming process it competes with casting, working and machining; and as a joining process it competes with riveting, bolting and other mechanical methods. In welding, however, the parts are held together by inter atomic forces. Brazing and Soldering processes are variants of welding in which the filler material has a lower melting point than the base metals, and the joint is secured by the adhesion of molten brazing or soldering alloy while the base metals remain in solid state. If the melting temperature of the filler material is above 450 °C, the process is called brazing whereas if it is below 450 °C the process is called soldering.

## 13.5.1 Welding Processes

### ARC WELDING

A number of welding processes are available which are generally classified according to the source of heat.

**Arc welding** processes accomplish local union by heating with an electric arc and with or without a filler metal.

**In shielded arc welding** the filler is covered with a flux and made into an electrode, the flux providing protection against the atmosphere.

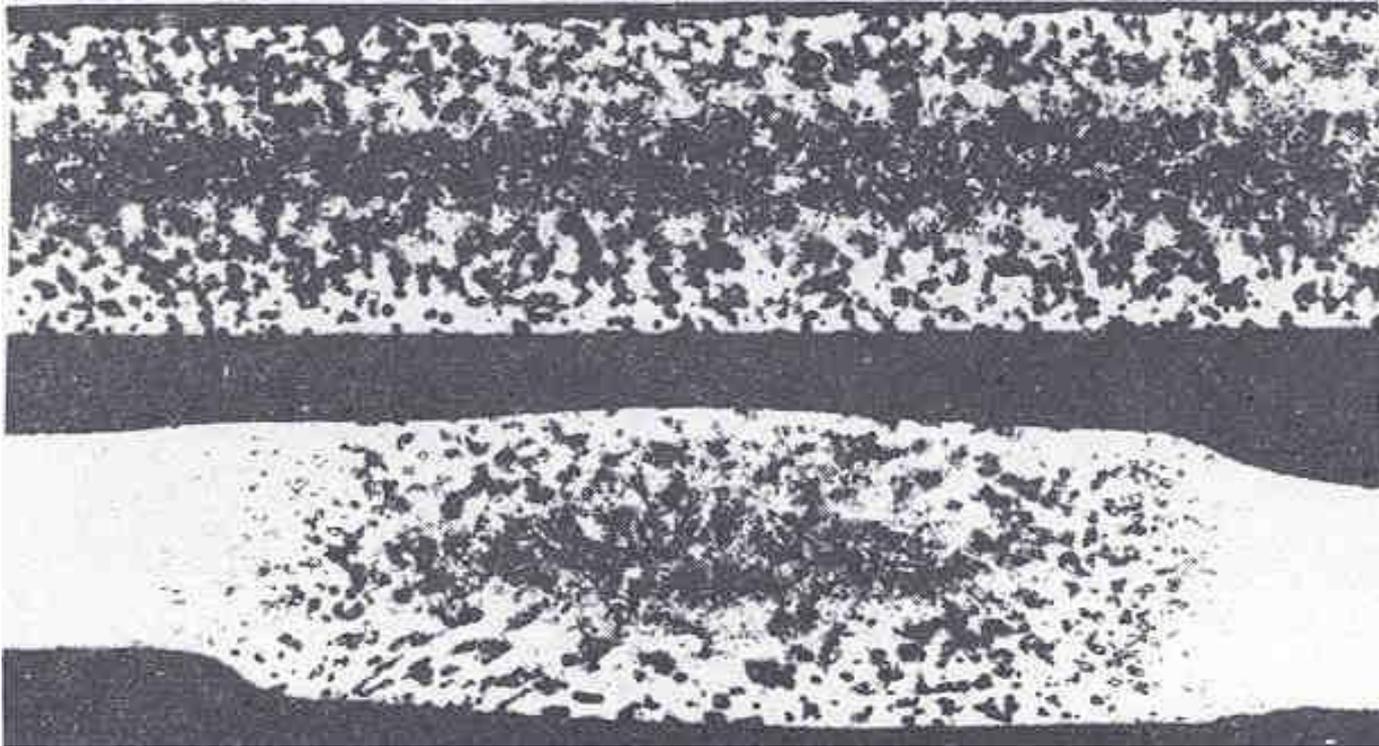
**Submerged arc welding** uses fused and unfused flux to cover the weld area.

**Tungsten arc welding** uses a non-consumable tungsten electrode with inert gas atmosphere.

**Plasma arc welding** is a special variation in which an ionised gas (plasma) is used to direct the flow of heat from the electrode to the metal making the process more heat efficient.

# RESISTANCE WELDING

Resistance welding incorporates processes in which heat for welding is generated by the electrical resistance of base metal. Welding is obtained by application of pressure to the heated material. Most common method is **spot welding**, but **projection welding**, **seam welding** and **butt welding** are also used. Microstructure of a seam welded steel sheet is shown in Fig.13.21.

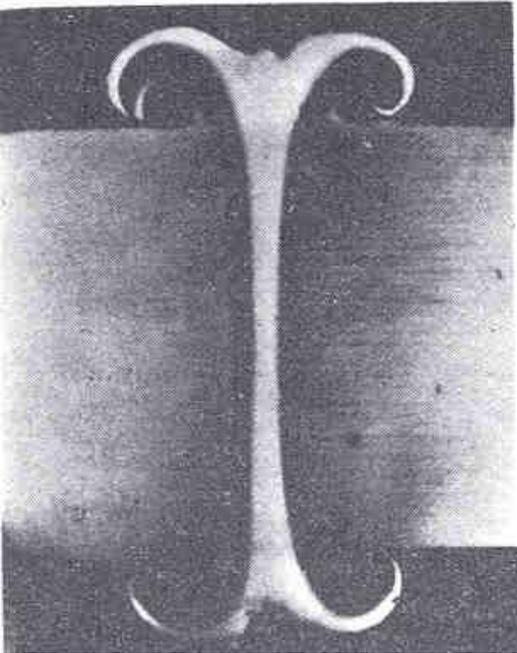


*Fig.13.21 Longitudinal and cross-sectional microstructures of seam weld in a steel, x12.5.*

## OXY-FUEL GAS WELDING

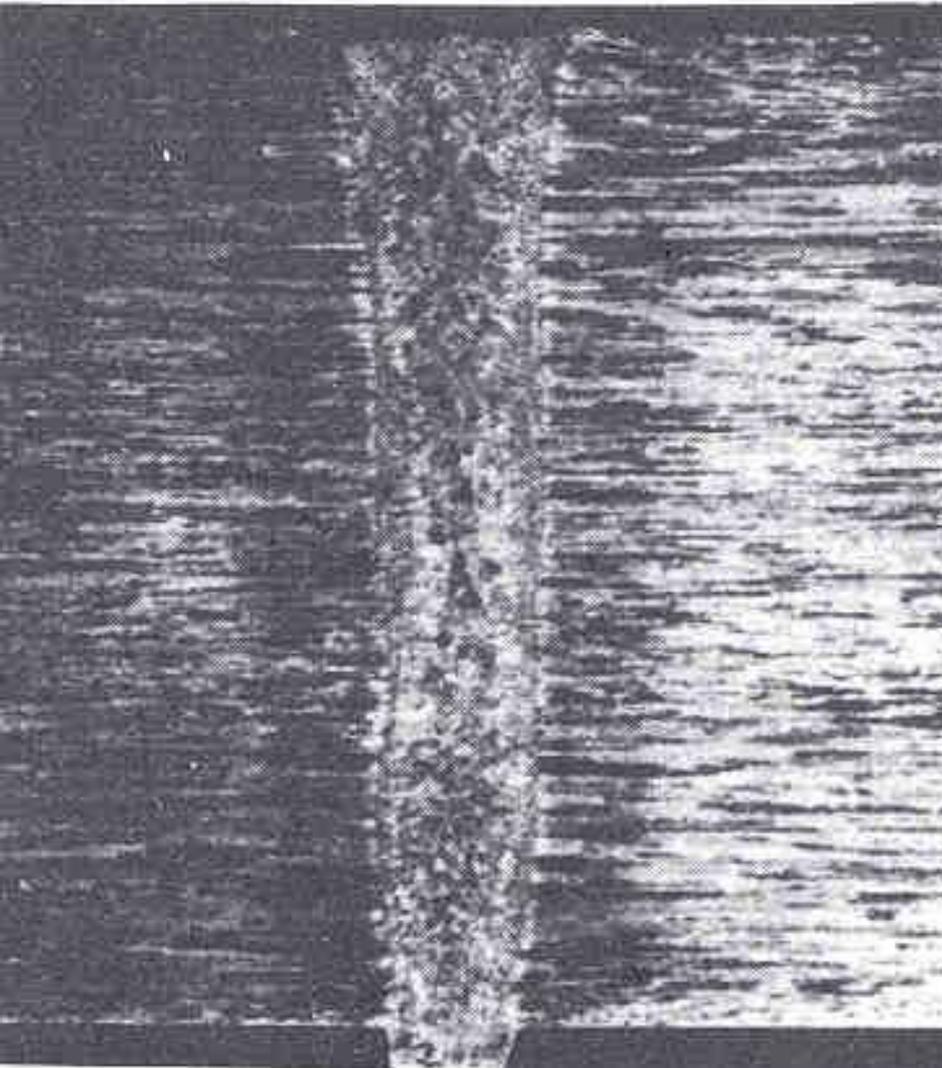
Oxy-fuel gas welding defines a group of welding processes which use a fuel flame to generate heat for welding. Oxy-acetelene is the oldest and most common of these processes, which uses acetelene as fuel. However hydrogen is the also used in oxy-hydrogen welding

Welding can also be carried out without melting the base metals. This produces excellent dimensional tolerances and much less distortion. Diffusion welding relies on high temperature diffusion between the two parts to secure a joint: Sometimes a filler material is placed in between the two parts and a slight pressure is applied together with heat; diffusion of atoms between the base and filler metals produces a weld.



In friction welding one part is stationary while a second circular or quasi-circular part is made to revolve on it at high speeds. The heat generated by friction softens the metal which is welded due to the pressure between the two parts. The microstructure of a friction welded engine valve stem is shown in Fig.13.22.

*Fig.13.22 Microstructure of a friction welded engine valve stem (see example in Chap.1 for material), x10*



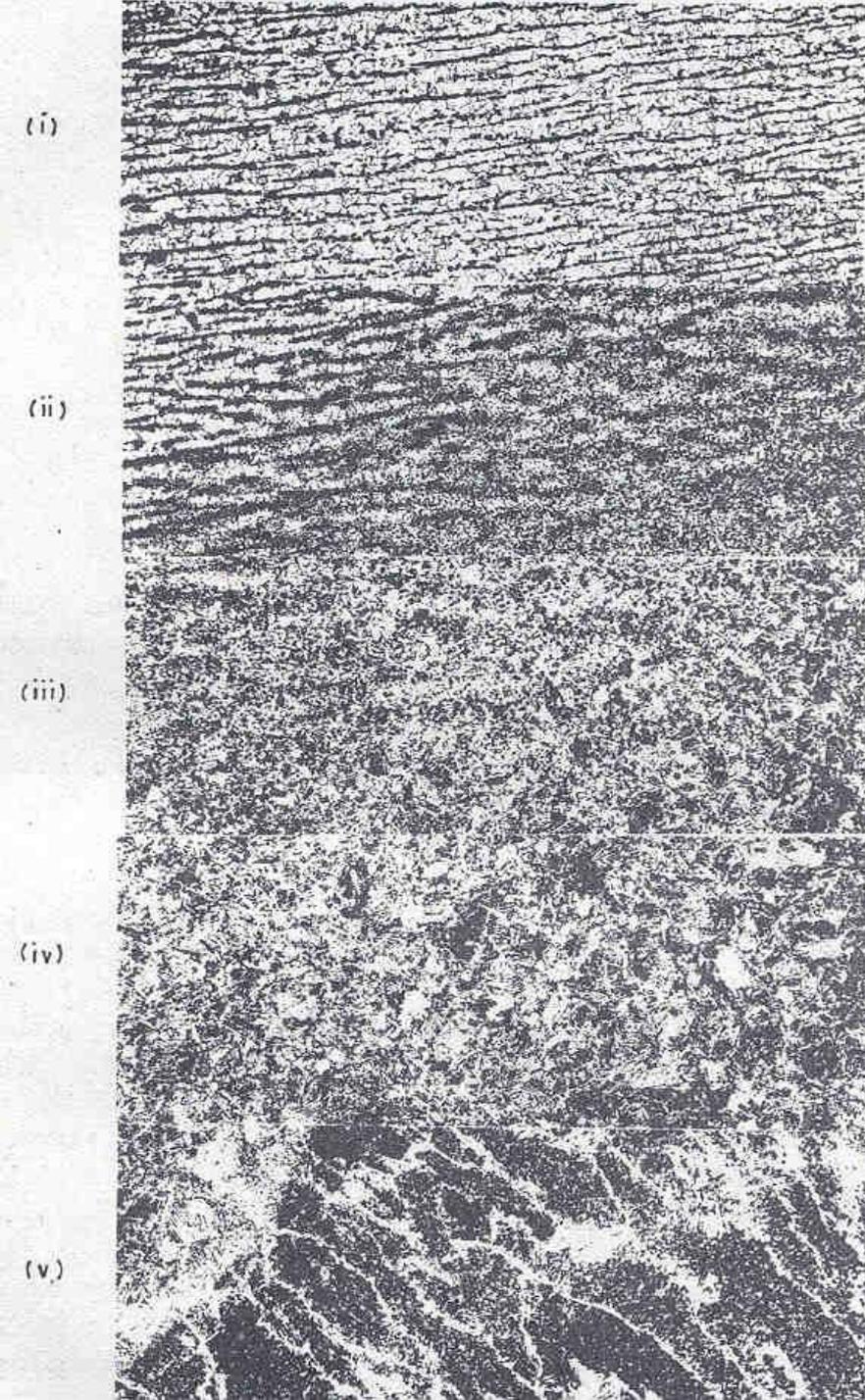
High energy electron and laser beams are used to melt metal very locally and produce a weld which has a minimum area and small heat affected zone. These welds are sound but expensive and are used in special circumstances. Fig.13.23 shows the microstructure of an electron beam welded joint almost without a heat affected zone.

*Fig. 13.23 microstructure of an electron beam welded 2024 - T4 aluminium joint, x4. (Amstead and Begeman, book cited).*

## 13.5.2 Structure of Fusion Welds

The ideal weld is the one in which the deposited metal and the parent metal would have exactly the same composition and structure; that is there would be no discontinuity at the joint. In practice, the attainment of this condition is never realized, as the weld is quickly cooled cast structure.

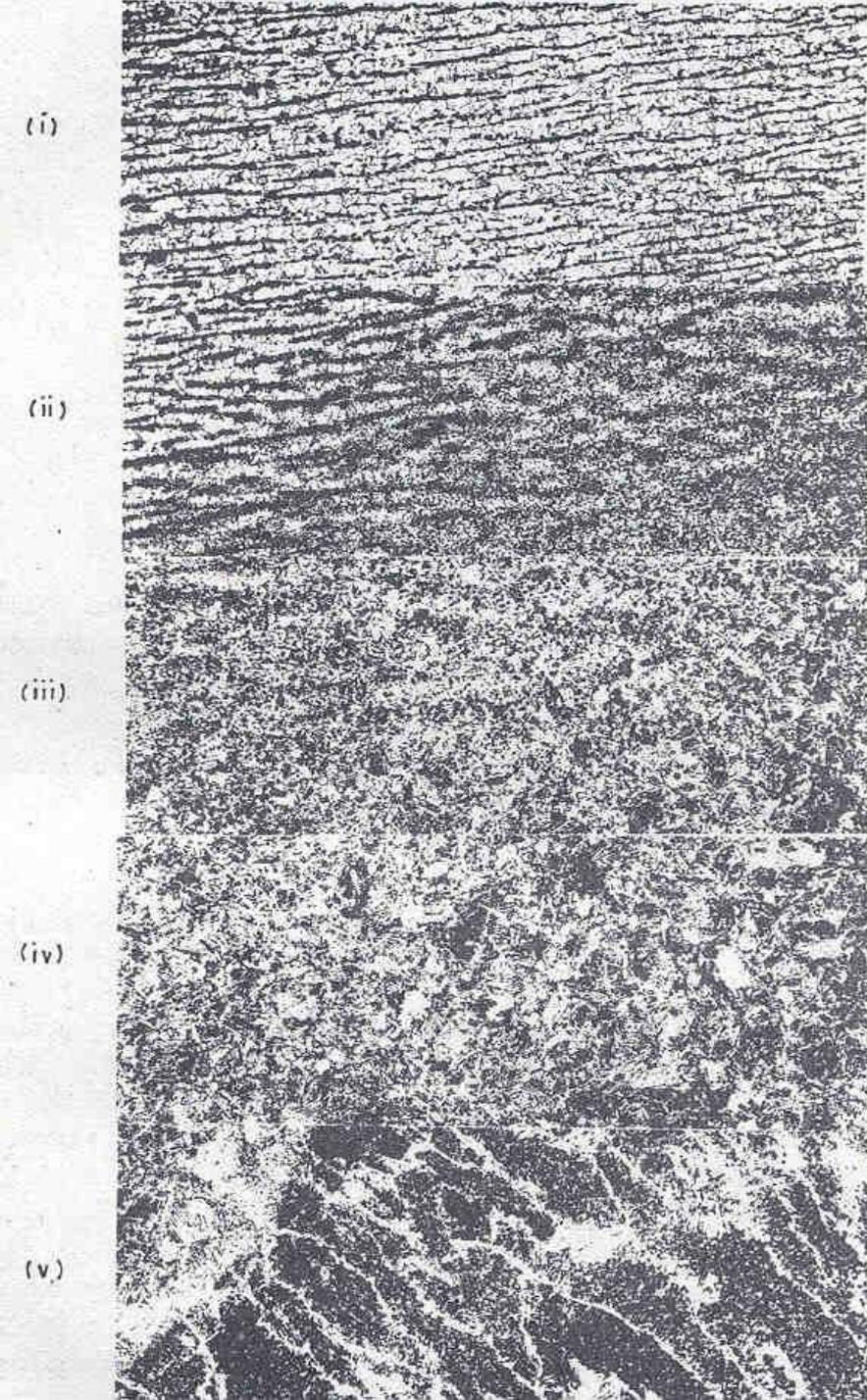
If a section of a weld is metallographically examined, structures similar to those shown in Fig.13.24 will be observed.



The grain structure of the original material is fairly fine, and it has been unaffected by the heat supplied during the welding process. This zone, is referred to as the **unaffected zone (i)**. Nearer the weld, a region will exist in which the steel has been heated to a temperature within the critical range of the steel. This zone is called **transition zone (ii)**.

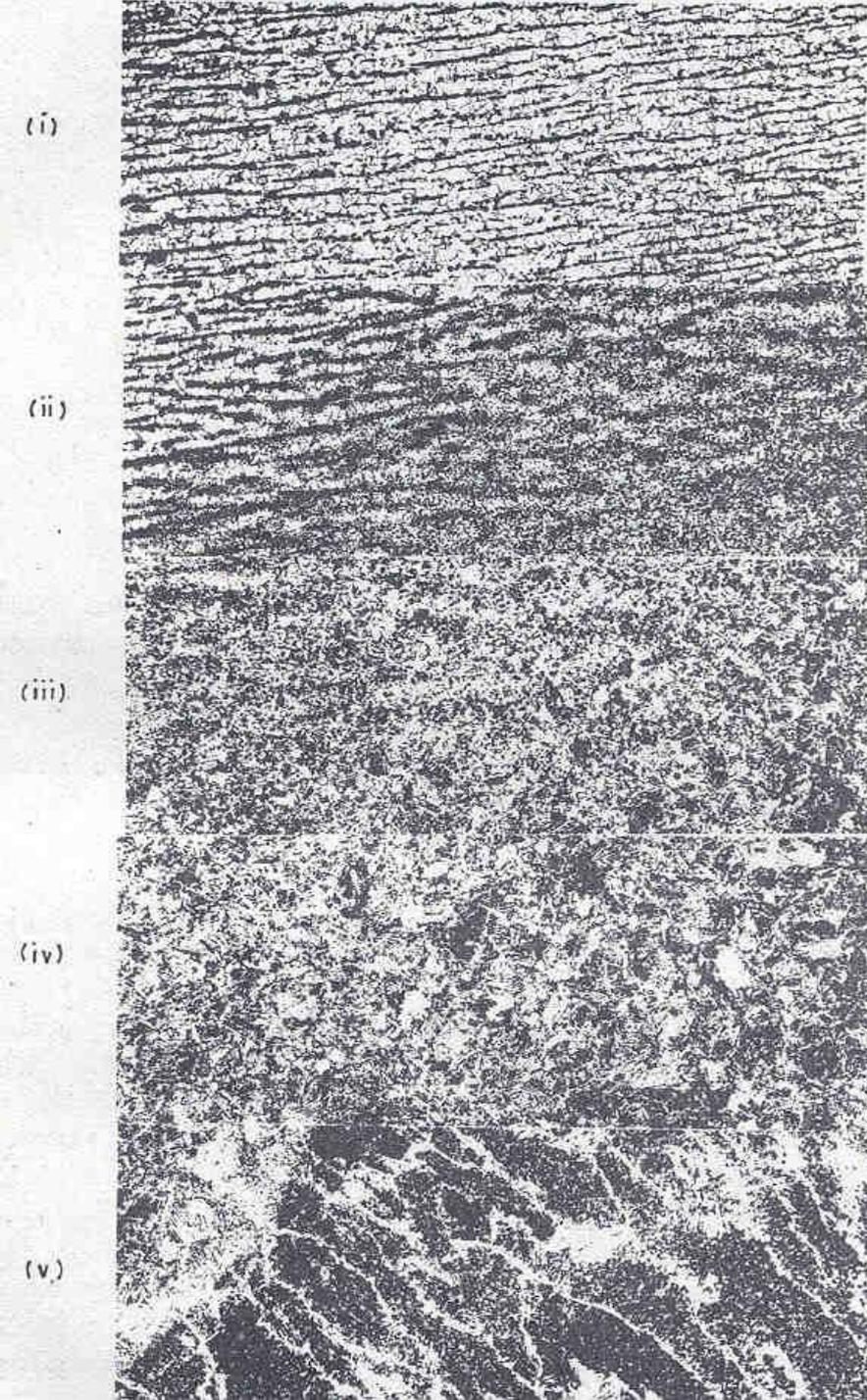
As shown in the figure; pearlite band is broken in this zone. Adjacent to this zone, the steel has been heated to a temperature just above the upper critical temperature, with complete **grain refinement (iii)**.

*Fig. 13.24 Microstructure in various zones of an arc welded low carbon steel plate: Materials used in construction of penstock pipes of Ataturk Dam, x50.*



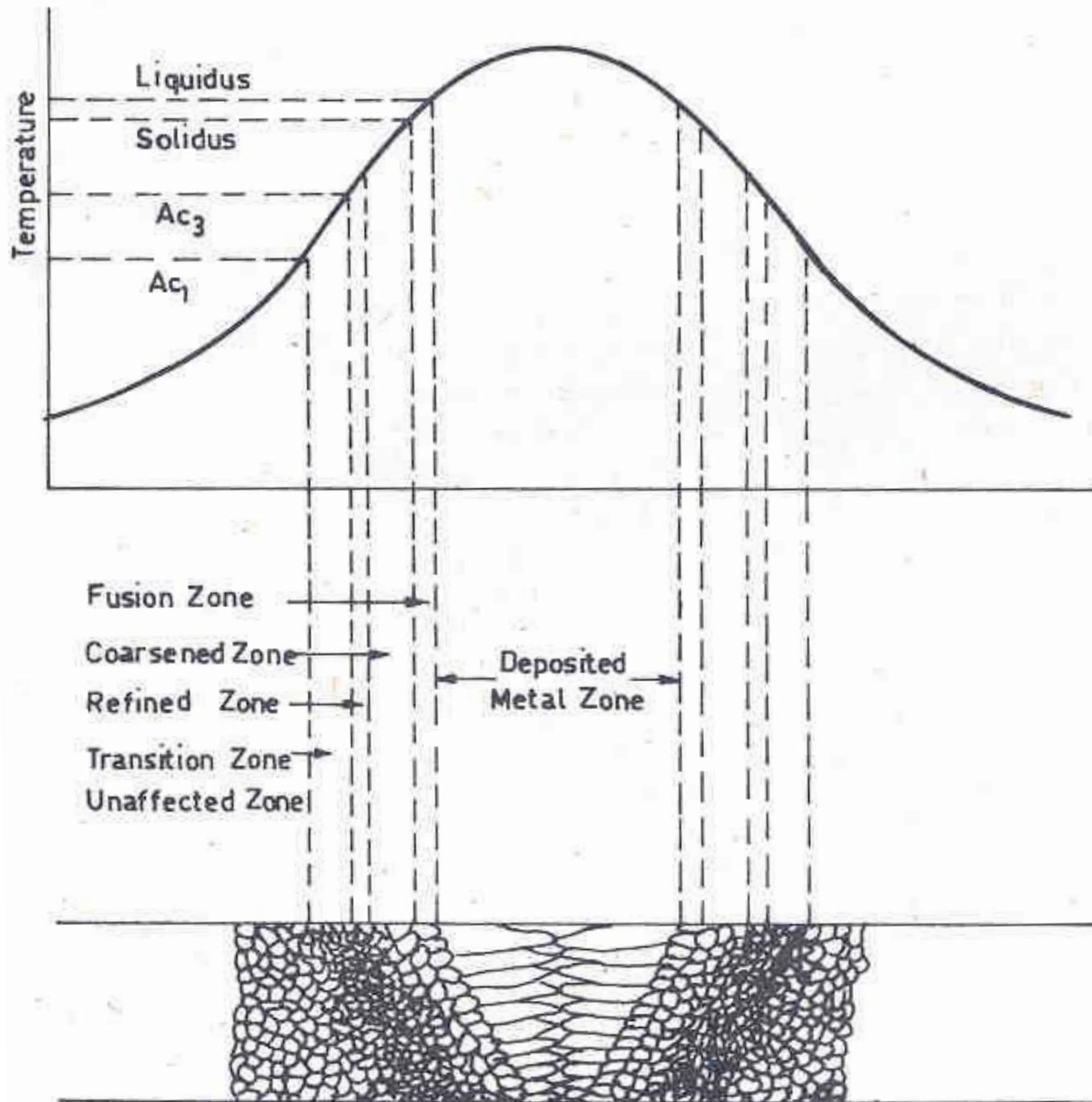
The grain structure is even finer than that of the original steel plate in the refined zone. Still nearer to the weld, the grain size increases; immediately adjacent to the weld it becomes very coarse (iii and iv in Fig.13.24). It is in this area that steel has been heated to temperatures considerably above the critical range. This zone is called the **coarsened zone**. The parent metal that has been in contact with the molten metal in the weld has been fused and will have some of the characteristics of a cast material. This is called the **fusion zone**.

*Fig. 13.24 Microstructure in various zones of an arc welded low carbon steel plate: Materials used in construction of penstock pipes of Ataturk Dam, x50.*



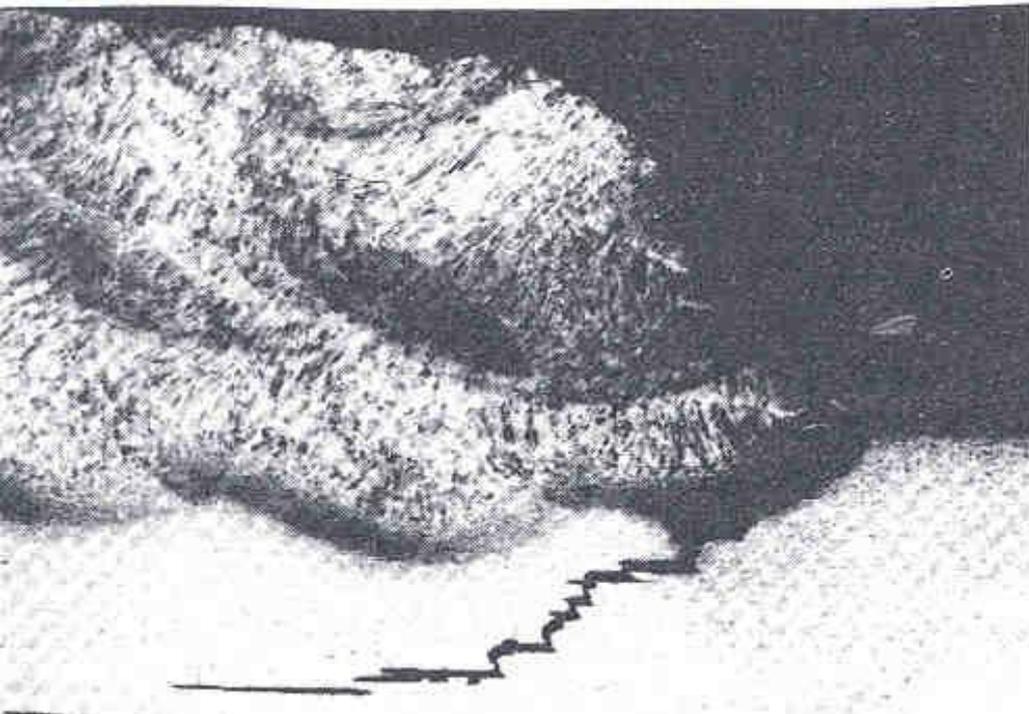
The metal that has been deposited into the weld from the filler rod takes a cast structure (v), and this area is called the **deposited zone**. The grains grow in the direction of heat flow to yield a columnar structure as shown in the figure.

*Fig.13.24 Microstructure in various zones of an arc welded low carbon steel plate: Materials used in construction of penstock pipes of Ataturk Dam, x50.*



The relation of these zones to the temperature across the weld during welding is shown schematically in Fig.13.25.

*Fig.13.25 Zones in welded steel joint*



*Fig.13.26 Formation of cracks during welding, x10*

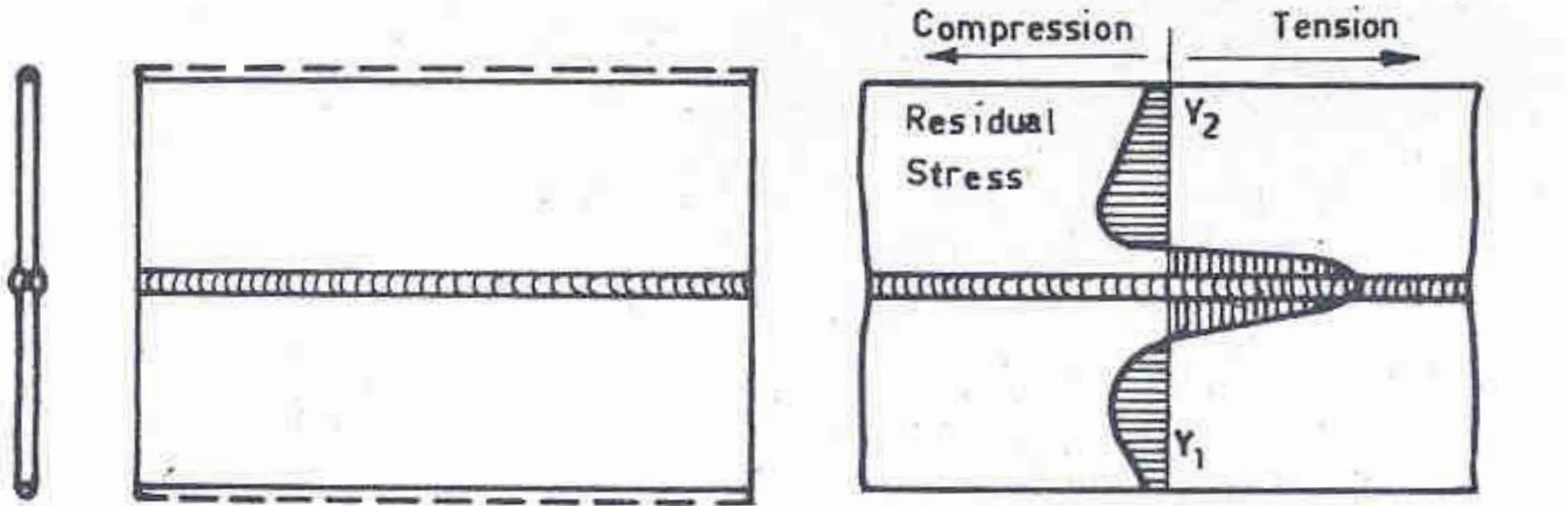
In general, steels of relatively low carbon content (below 0.3 %C) are readily welded. However, it must be remembered that, as the carbon content increases, steel becomes sensitive to rapid cooling.

In welding operation the heat is abstracted from the weld area by the cooler parent metal which causes rapid cooling in the weld area. Such rapid cooling may lead to the formation of martensite or some other hard transition structure as shown in Fig.13.26. This may induce cracking in the weld, which will interfere with the strength of the part. Likewise, if alloy steels are welded, difficulties may be encountered unless the carbon content is sufficiently low. A complete discussion of this problem is not within the scope of this book and further reading should be consulted. It is possible to weld the higher carbon steels and alloy steels, provided they are preheated to a sufficiently high temperature that the cooling rate will be decreased enough to prevent the formation of the harder structural constituents.

## 13.5.3 Distortion

Welding process causes two thermal processes of heating and solidification. Both of these are associated with a change in volume which causes distortion of the welded assembly due to constraints applied by the cold base metal remote from the weld. For example steel *expands* on heating and shrinks by 1.5 % on solidification. Such volume changes cause distortion of the welded joint and also produce residual stresses in the weld which could have disastrous consequences in service.

The distortion is caused by three fundamental dimensional changes taking place during welding: (1) Transverse shrinkage which occurs perpendicular to the weld line. (2) Longitudinal shrinkage occurring parallel to the weld line. (3) An angular change consisting of rotation around the weld line as shown in Fig.13.27. Angular change is caused by the non-uniformity of transverse shrinkage in the thickness direction. The actual distortion phenomena are more complex than those shown in the figure as a result of combination thereof.



a. Transverse shrinkage in a butt weld. b. Longitudinal shrinkage in a butt weld.



c. Angular change in a butt weld.

d. Angular change in a fillet weld.

*Fig.13.27 Types of shrinkages causing distortion.*

## 13.5.4 Design Against Distortion

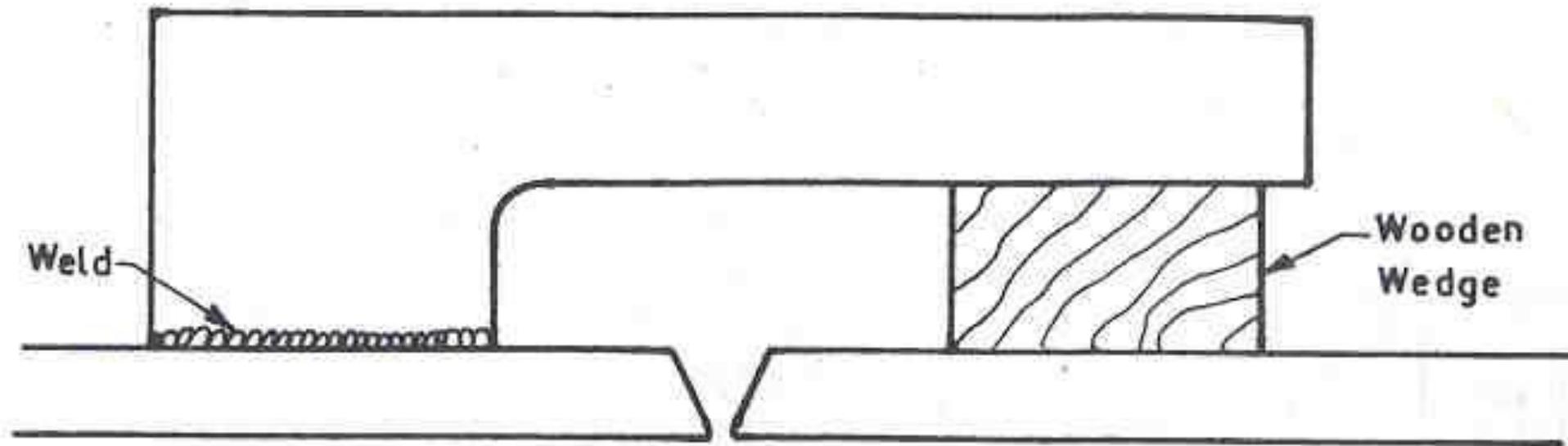
Distortion is caused by change in volume and can, therefore, be minimized by proper design. Furthermore, a proper design may take into account possible distortion and hence avoid any consequences of distortion on service life of the welded structure.

One of the most effective way of reducing distortion and residual stresses is to reduce the amount of weld metal, since distortion is caused by thermal strains due to welding. For example, use of U-groove instead of V-groove reduces the amount of weld metal and consequently distortion.

The most economical design for a welded fabrication is the one requiring fewest number of parts and a minimum welding which also reduces distortion. The type of joint preparation is important as it can influence the amount of angular distortion resulting from welding. Good design, however, can not remove distortion altogether, but makes the magnitude of distortion less and makes it easy to control it.

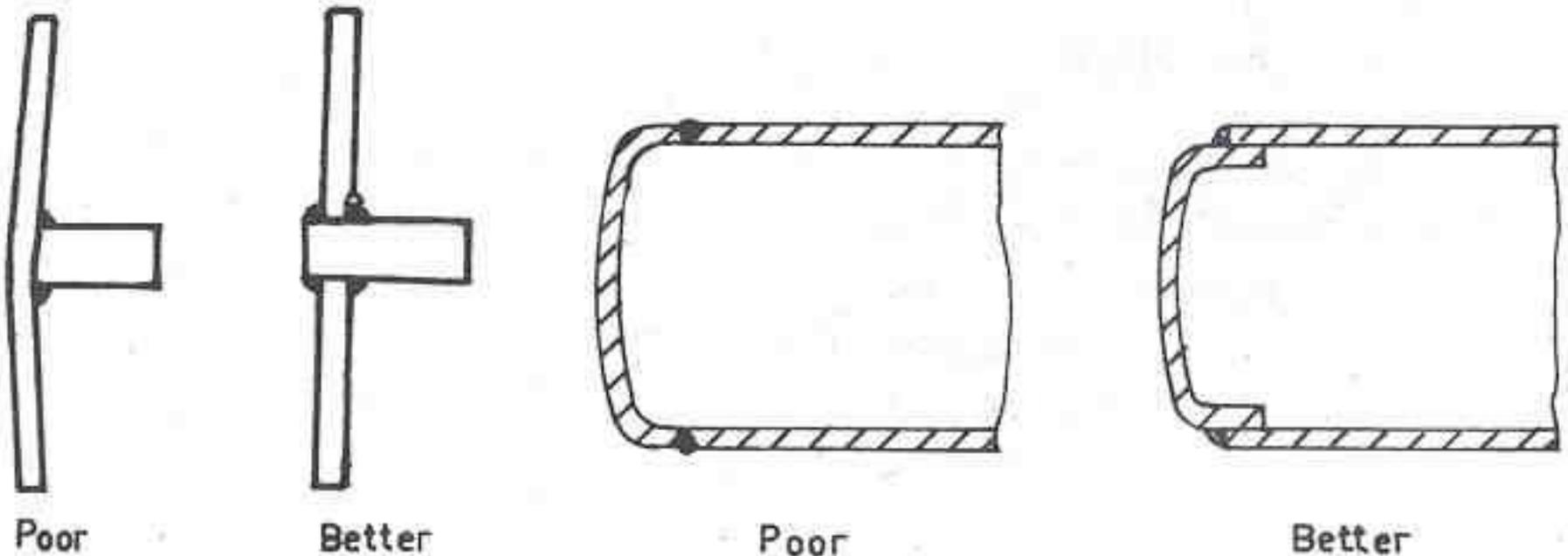
The control of the inevitable distortion can be affected in one of two, ways:

- (1) By estimating the amount of distortion likely to occur and then assembling the job to compensate for distortion. This is an attractive method in so far as it allows complete freedom of movement during welding which results in minimum residual stresses. It is, however, difficult to apply except in simple fabrications.
- (2) By assembling the job so that it is nominally correct before welding and by employing some sort of restraint to minimize distortion. This method, however, generates large residual stresses. Fig.13.28 shows an example whereby distortion is impeded by placing a block of wood under the part.



*Fig.13.28 Tackling distortion by applying restraint*

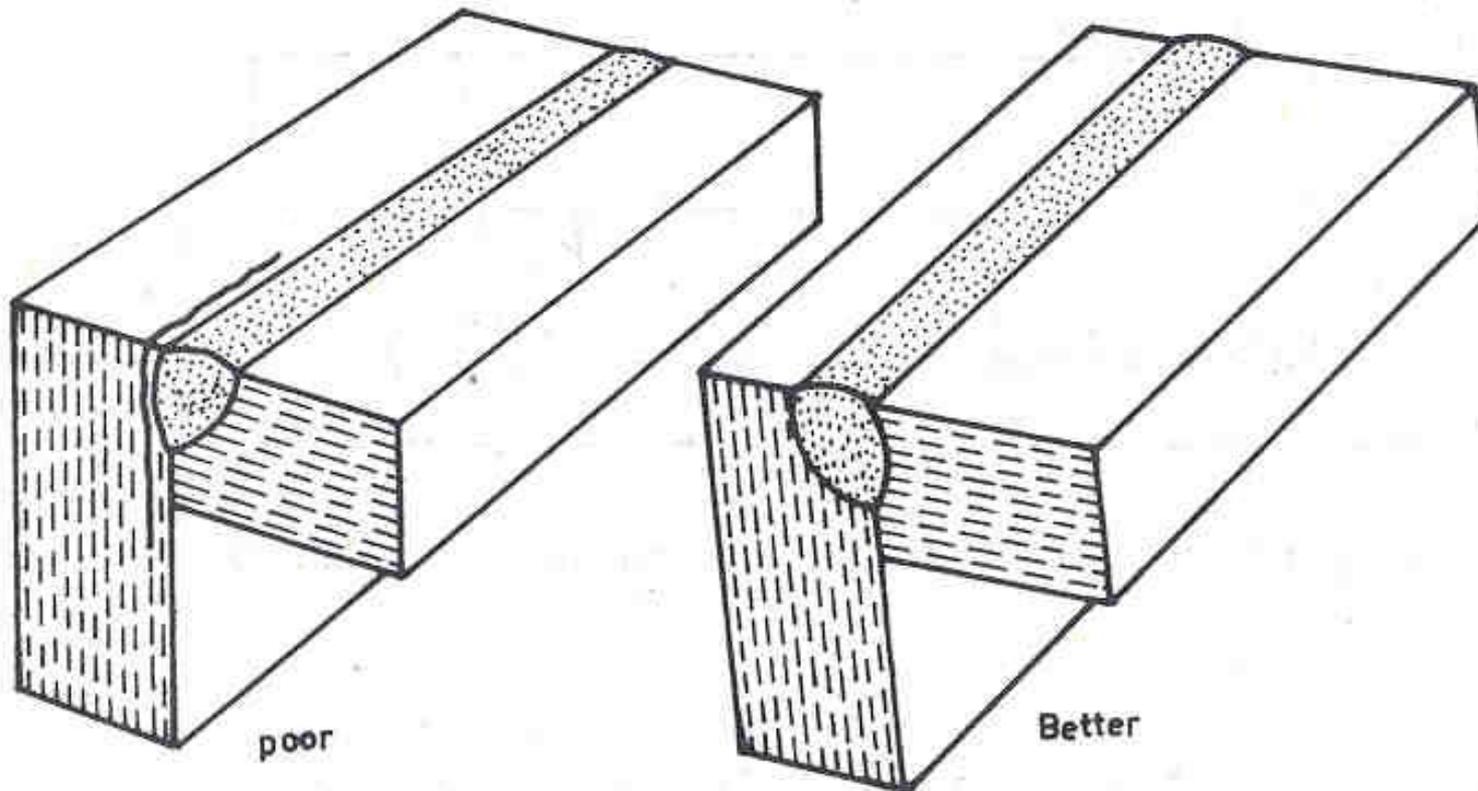
The usual method is to breakdown the welding job into many sub-assemblies which are welded in method (1) or (2) to keep distortion to a minimum. After the application of method (2), it may become necessary to heat treat the part to remove residual stresses, depending upon the service requirements. Distortion can also be avoided or minimized by designing so that welding of a part in different positions neutralize the effects of distortion as shown in Fig.13.29.



*Fig.13.29 Design to neutralize distortion.*

An engineer dealing with welding also has to take into account other factors such as structure of metal when designing or applying a weld. As shown in Fig.13.30, a weld may crack in **HAZ** (**H**eat **A**ffected **Z**one) due to residual stresses which are directed along weak orientation in the metal. A change in orientation of welding may be the solution, as shown.

Once distortion has set into a weld, there are various ways of removing or controlling it to acceptable level. Thermal or flame straightening is very successfully used in shipbuilding industry whereby distorted section is heated to 595-650 °C and quenched in water.



*Fig.13.30  
Change in  
welding  
groove to  
avoid  
cracking.*

## 13.5.5 Weldability

**Weldability** is the capacity of a metal or combination of metals to be welded under fabrication conditions into a specific, suitably designed structure, and to perform satisfactorily in the intended service. It encompasses metallurgical compatibility of a metal or alloy with any specific welding process, the ability of the metal to be welded with mechanical soundness, and the serviceability of the resulting welded joint.

Metallurgical compatibility implies that the base metals and weld metal can be combined within the degree of dilution (mixing) encountered in a specific process without the production of harmful constituents or phases. The mechanical soundness must meet the requirements of satisfaction and engineering standards. The serviceability factor concerns the ability of the finished weldment to meet special requirements such as low temperature impact, high temperature stability or other designated qualities.