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& TECHNOLOGY**

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DEPARTMENT OF MECHANICAL ENGINEERING

LECTURE NOTES

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UNIT – I

CRYSTAL STRUCTURES AND METALLOGRAPHY

Crystal Structures – Solid Solutions – Types - Metallography – Metallurgical Microscopes – Specimen Preparation – Cooling Curves – Allotropy Concept

CRYSTALLINE STRUCTURE

The atoms of the material are arranged in a regular and repeating manner over large atomic distances (long range order). **Unit cell:** is chosen to represent the symmetry of the crystal structure, It is small repeat entity; it is basic structural unit and building block of crystal structure.

The majority of common metals have either Face Center Cubic Structure, , a Body Centered Cubic Structure, or an Hexagonal Close Packed structure. These are usually abbreviated to FCC, BCC or HCP structures respectively. The major differences between these structures are the Unit Cell, the building block. The different cells lead to different physical properties of bulk metals. For example, FCC metals, Cu, Au, Ag, are usually soft and 'ductile', which means they can be bent and shaped easily. BCC metals are less ductile but stronger, e.g. iron, while HCP metals are usually brittle. Zinc is HCP and is difficult to bend without breaking, unlike copper. Many other features depend upon the crystal structure of metals, such as density, deformation processes, alloying behavior, and much more. Thus, it is important to understand metal structures.

Face Centered Cubic Structure

Face Center Cubic Structure consists of an atom at each cube corner and an atom in the center of each cube face. A hard sphere concept can be used to describe atomic packing in unit cells. The FCC structure is shown in fig. 1 (a). The distance along unit cell edges is called the lattice parameter, a_0 . For cubic crystals the lattice parameter is identical in all three crystal axes. If a corner atom of the FCC unit cell is removed, six atoms are revealed in a hexagonal array. These atoms are closed packed, i.e., they cannot be packed any tighter, and each atom touches its neighbor in any direction.

Since a close packed plane such as this can be achieved by removing each of the eight corner atoms and because eight such planes form an octahedron, they are called the 'Octahedral'

planes. Thus the FCC structure has four sets of two parallel planes. As parallel planes with the same atomic arrangement are equivalent the FCC structure has four equivalent close packed planes. Using Miller indices from the previous crystallography experiment show them to be $\{111\}$ planes. Thus the FCC structure has four $\{111\}$ close packed planes. The atomic arrangement is shown in fig.1a. Three close packed directions are shown as well. These correspond to (110) directions diagonally across cube faces. There are three of these for each $\{111\}$ plane. Therefore, FCC structures have twelve possible combinations of $\{111\}$ and (110) .

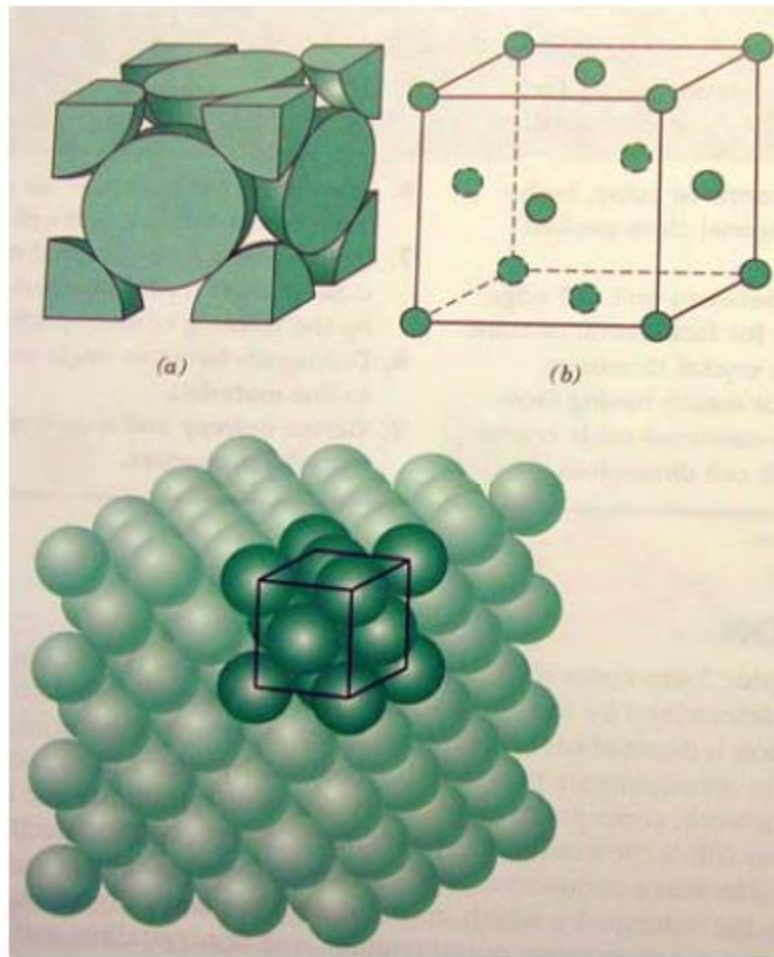


Figure 1 Face Centered Cubic Structure

Body Centered Cubic Structure

In this structure, atoms exist at each cube corner and one atom is at the center of the cube, fig 2a. Comparison of figs, 1a and 1b show that the BCC is much emptier than the FCC structure. In this case there are no close packed planes only close packed directions. Fig.2b shows the atomic arrangement of $\{110\}$ planes in a BCC structure which are the planes of highest atomic

density. There are 6 planes of this type, and each contains two close packed directions. Consideration of fig. 1b and 2b shows the closed packed direction joins diagonally opposite corners of the BCC unit cell. It is therefore a (111) direction. As there are two (111) for each {110} plane there is a total of 12 possible combinations of {110} and (111).

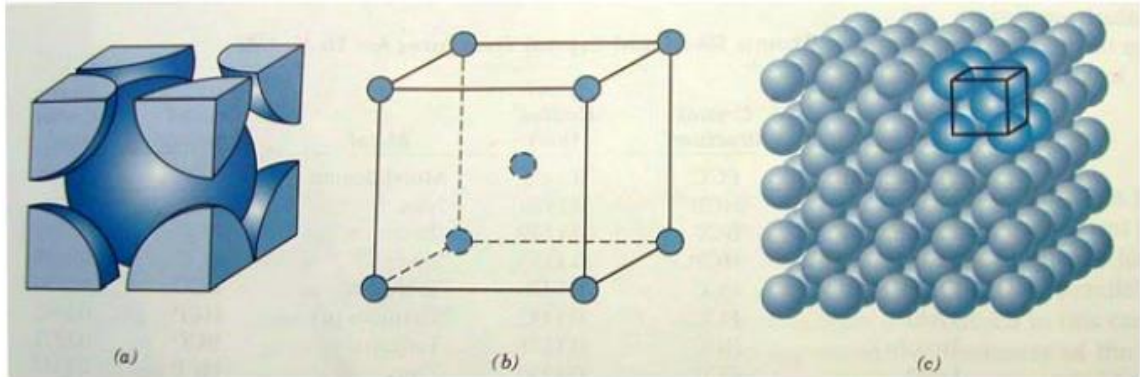


Figure 2 Body Centered Cubic Structure

Hexagonal Close Packed Structure

The hexagonal structure is shown in fig. 3a. A close packed plane at the bottom and top of the unit cell is separated by 3 atoms in the cell center, which are also part of a closed packed plane. Closed packed planes are of the {001} family of which there is only 1 equivalent type. Fig.3a shows the atomic arrangement and directions of close packing. These are of the (2TTO) family and there are three for each {0001}. Thus, hexagonal structures have only three combinations of {0001} and (2TTO). It should be noted that the lattice parameter differs with direction in HCP structures.

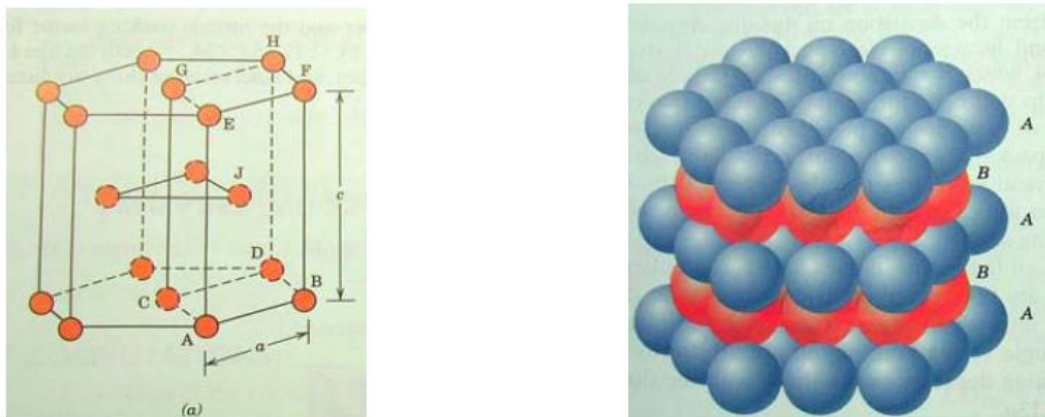


Figure 3 Hexagonal Close Packed Structure

SOLID SOLUTION

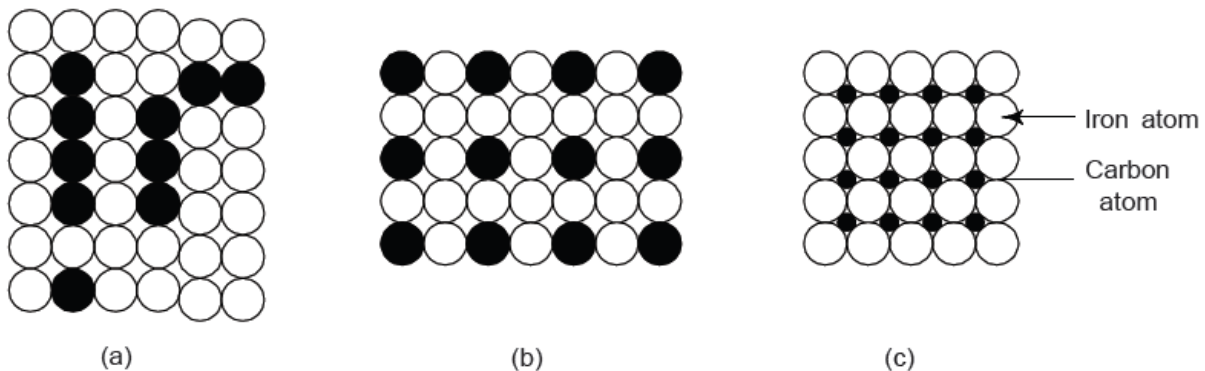
A solid solution forms when, as the solute atoms are added to the host material, the crystal structure is maintained, and no new structures are formed. In other words, when elements completely dissolve in each other in liquid and or solid state the resulting phase is called *solid solution*. Solid solutions form readily when solvent and solute atoms have similar sizes and electron structures, so that it is compositionally or chemically homogeneous and the component atoms of the elements cannot be distinguished physically or separated mechanically. There is a homogeneous distribution of the constituents in the solid state so as to form a single phase or solid solution. Basically, solid solutions are of two types:

Substitutional Solid Solution When the two metals in solid solution form a single face centred cubic lattice, i.e., in general solute or impurity atoms replace or substitute for the host atoms, is called as substitutional solid solution. One may also define solid solutions as crystalline phases of a variable composition. Atoms of a solute *B* can be arranged in the crystal lattice of a solvent *A* either by substituting for some atoms of the latter in the crystal lattice or by occupying the interatomic spaces between atoms, or interstices. We may note that the atoms of the two metals be of almost same size, i.e., the difference in atomic radii between the two atom types be less than about 15%. Otherwise the solute atoms will create substantial lattice distortion and a new phase will form. For appreciable solid solubility the crystal structures for metals of both atoms must be same. If one element has more electropositivity and the other more electronegativity, then there is greater likelihood that they will form an intermetallic compound instead of a substitutional solid solution. It is also observed that other factors being equal, i.e. atomic size, crystal structure and electronegativity, a metal will have more of a tendency to dissolve another metal of higher valency than one of a lower valency. A familiar example of substitutional solid solution is found for copper and nickel to form monel. These two elements are completely soluble in another at all proportions. Brass, an alloy of copper and zinc, is another example, which forms solid solutions most readily as the atoms of these two elements have similar sizes and electronic structure unlimited solubility in the solid state can be observed in copper-gold, and germanium-silicon alloys. Polymorphous metals may possess unlimited solubility within a single modification of the space lattice. For example, Fe_{α} can form a continuous series of solid solutions with Cr (BCC lattices) and Fe_{γ} , a continuous series of solid solutions with Ni (FCC lattices). The formation of solid solutions is always associated with an

increase of electric resistance and decrease of the temperature coefficient of electric resistance. Solid solutions are usually less plastic (except for copper-based solid solutions) and always harder and stronger than pure metals. Substitutional solid solutions are of two types:

(i) Random substitutional solid solutions and (ii) Ordered substitutional solid solutions.

When there is no order in the substitution of the two metal elements, the chance of one metal element occupying any particular atomic site in the crystal is equal to the atomic percent of the element in the alloy. Obviously, in such a situation the concentration of solute atoms can vary considerably throughout the lattice structure. Such type of the resulting solid solution is called a *random* or *disordered* substitutional solid solution.



(a) Solid solutions (b) substitutional solid solutions and (c) interstitial solid solution

Many substitutional solid solutions can be in an ordered state at relatively low temperatures, i.e. unlike atoms of two elements are distributed between the sites of the space lattice not statistically, but in a perfectly definite order. Such solid solutions are called *ordered*; the term '*superstructure*' is also in use. Such ordering is common at low temperatures because greater thermal agitation tends to destroy the orderly arrangement.

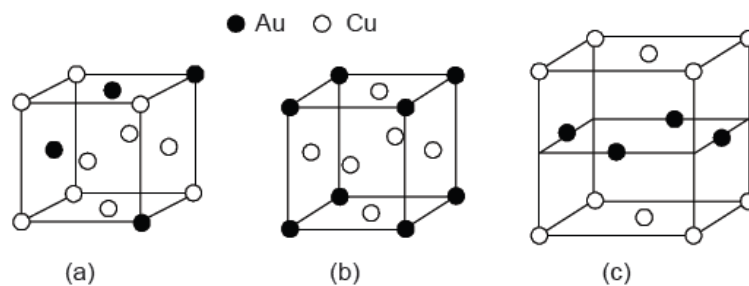
The change from a disordered to ordered state takes place at a definite temperature or in a definite temperature range. The temperature at which a solid solution becomes completely disordered is called the *Kurnakov point* (θ_K). Ordering usually takes place under the conditions when a solid solution is cooled slowly from the temperature region above θ_K .

Ordered solid solutions can be found in systems with either substantial or unlimited solubility in the solid state; in that case complete ordering can occur with concentrations of the solid solution elements corresponding to simple atomic ratios of the components of the type, say *AB* or *AB₃*. Partial ordering may be observed in systems with concentration ratios close to the

indicated ones. The arrangement of atoms in ordered solid solutions of two Cu and Au alloys of the corresponding to AuCu₃ and AuCu are shown in figure below.

The appearance and disappearance of an order in the arrangement of atoms in solid solutions is associated with changes in the properties of an alloy.

Ordering increases the electrical conductivity, temperature coefficient of electric resistance, hardness, and strength, but decreases the ductility of an alloy. In ferromagnetic alloys, it changes magnetic properties; for instance, the magnetic permeability of perm alloys (magnetic iron-nickel alloys) can drop on ordering to a small fraction of the original value. Some alloys are paramagnetic in disordered state, but become ferromagnetic after ordering, such as Heusler (Mn-Cu-Al) alloys.



Crystal lattice of Cu-Au alloys: (a) disordered solid solution; (b) ordered solid solution (AuCu₃ alloy); (c) ordered solid solution (AuCu alloy)

Usually, substitutional solid solutions have a *random arrangement* of the constituent atoms on the atomic sites, especially at elevated temperatures. This is so, as configurational entropy makes a greater contribution in lowering the free energy with increasing temperature, as we have $G = H - TS$. This random arrangement of the constituent atoms in a solid solution may change over to an ordered arrangement on cooling to lower temperatures, if ordering lowers the enthalpy of the crystal sufficiently.

Interstitial Solid Solutions These can form, for instance, on melting together transition metals and non-metals with a small atomic radius (*H, N, C* or *B*).

The possibility of obtaining an interstitial solution is mainly determined by the size factor; i.e., the size of a solute atom must be equal to or slightly smaller than the size of an interstitial void.

Interstitial solid solutions always have a limited solubility and form preferably in solvents having an HCP or FCC lattice with interstices of a radius of $0.41 R$, where R is the radius of a

solvent atom. In BCC lattices, the solubility is low, since the size of interstices does not exceed $0.29 R$.

Examples of interstitial solid solutions of commercial application are solid solution of carbon in Fe_{γ} , and Fe_{α} , Fe_r , which has an FCC lattice, can dissolve upto 2.14% (by mass) of carbon; Fe_{α} (BCC lattice) does not practically dissolve carbon, the maximum solubility being around 0.02 (by mass). *Other elements like:* nitrogen for maintaining stainless steel in austenitic condition for nitriding condition and hydrogen when introduced into steels during welding operations, acid cleaning and plating results in hydrogen embrittlement and causes a sharp decrease in ductility.

Lattice distortions appearing on the formation of interstitial solid solutions are stronger than those in the substitutional solid solutions, because of which the properties of alloys can be changed more drastically. As the concentration of a solute in a solid solution increases, this increases noticeably the electric resistance, coercive force, hardness and strength, but decreases the ductility and toughness.

Interstitial solid solutions usually have very limited solubility and are normally considered of secondary importance. Alloys containing more than two elements can form either substitutional or interstitial solution. For example, when iron is melted together with manganese and carbon, manganese and iron form substitutional solid solution while carbon and iron, interstitial solid solution.

In conclusion we can say that solid solutions are crystals whose properties are close to those of the solvent, since they retain the same crystal lattice and type of bond. In particular, solid solutions of metals are distinguished by high plasticity: they are readily deformable in the hot state and many of them, in the cold state.

Solid solutions are the bases of most commercial structural and special alloys

METALLOGRAPHY

It is the study of the physical structure and components of metals, typically using microscopy.

METALLURGICAL MICROSCOPE

Introduction

The metallurgical microscope is the most important tool of the metallurgist. It consist an objective and an eye-piece. Its primary function is to reveal the details of the object. The clarity

and the extent to which the details are revealed depend on the degree to which these optical systems are created.

Principle

A horizontal beam of light from the light source is reflected by means of a plane glass reflector downwards through the microscope objective on the surface of the specimen some of these incident light reflected from the specimen surface will be magnified and passing through the plane glass reflector and magnified again by upper lens system of the eye-piece.

Constructional Details

The table type microscopes are consist of

1. **Stage:-** A flat movable table supporting specimen. This can be moved up or down by knobs.
2. **Tubes:** - The vertically movable tube containing eyepiece, objective and plane reflector. The tube length varies from 160 mm to 250 mm.
3. **Rough & fine focus Adjustments** - The limbs of microscope carry the coarse & fine adjustments to facilitate the
4. **Objective** – The body tube carries revolving nose piece carrying the three objectives. This enables quick change of the objective which helps for a quick resolving the structure of metal, the magnification of lenses is enlarged on focal length of the lens used

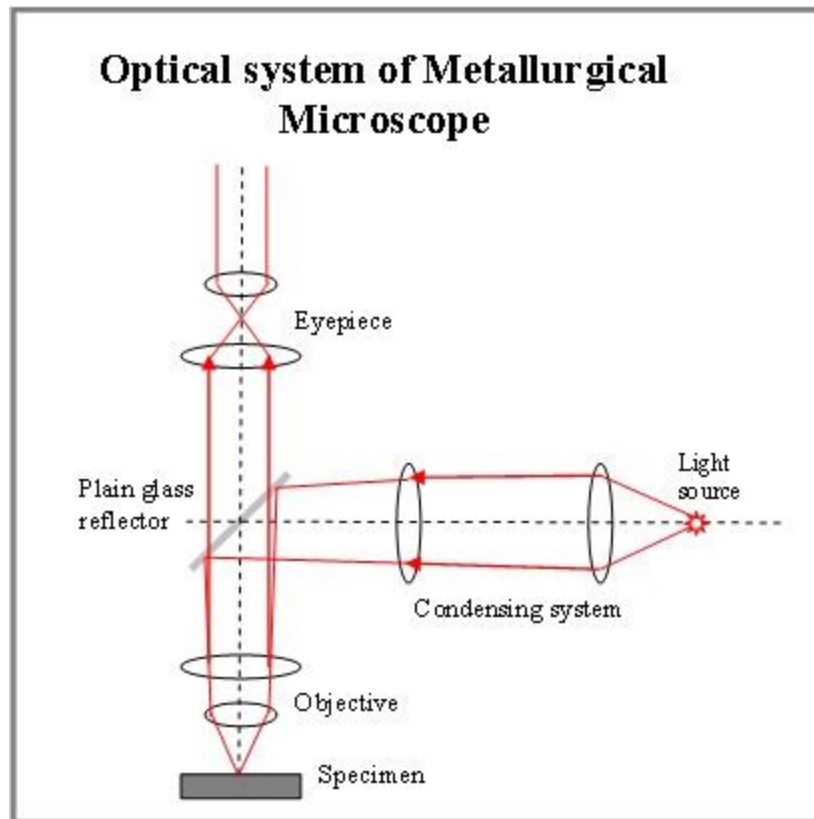
The important properties of an objective are-

1) Magnifying Power

2) Resolving Power

It is the property by which an objective shows distinctly represented two small adjacent bonds in the structure of the object. This is usually expressed as number of lines per mm that can be separated which depends on the numerical operator, the wavelength of the light used. Resolution is particularly important during the microscopy of the micro constituents of metals consisting of fine lamination with core resolution which appears as one uniform area, where as an objective with higher numerical appearance reveals deeper nature of the structure.

5. **Eyepiece** - It is named, as it is near to the eye. It is made up of various Powers such as X5, X10, X15 etc.
6. A photographic camera may be mounted above the eyepiece in order to record permanently the metallographic structure of the alloy.



Uses

The metallurgical microscope is useful in quality control department in Industries to observe & study

- 1) Differential phases
- 2) Porosity or defects.

All these have a great effect on mechanical properties of material.

PREPARING METALLOGRAPHIC SPECIMENS

1. Cutting

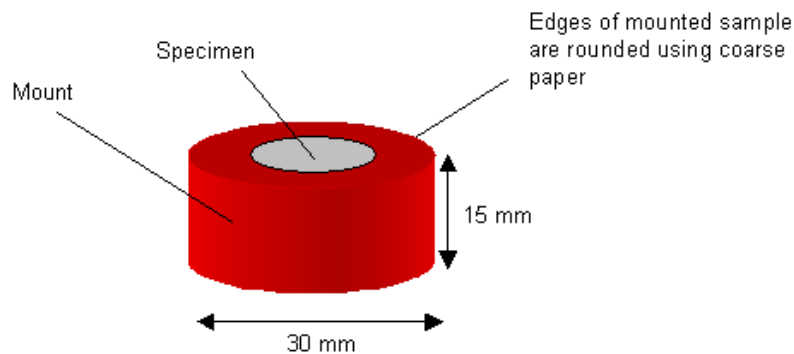
When cutting a specimen from a larger piece of material, care must be taken to ensure that it is representative of the features found in the larger sample, or that it contains all the information required to investigate a feature of interest. One problem is that preparation of the specimen may change the microstructure of the material, for example through heating, chemical attack, or mechanical damage. The amount of damage depends on the method by which the specimen is cut and the material itself. Cutting with abrasives may cause a high amount of damage, while the use of a low-speed diamond saw can lessen the problems. There are many different cutting methods, although some are used only for specific specimen types. MTI

provides the SYJ-150 low speed diamond saw for cutting OM (optical microscope), SEM (scanning electron microscope), and even TEM (transmission electron microscope) specimen.

2. Mounting

Mounting of specimens is usually necessary to allow them to be handled easily. It also minimizes the amount of damage likely to be caused to the specimen itself. The mounting material used should not influence the specimen as a result of chemical reaction or mechanical stresses. It should adhere well to the specimen, and if the specimen is to be electropolished later in the preparation then the mounting material should also be electrically conducting.

Specimens can be hot mounted (about 150 °C) using a mounting press either in a thermosetting plastic, *e.g.* phenolic resin, or a thermosoftening plastic *e.g.* acrylic resin. If hot mounting will alter the structure of the specimen a cold-setting resin can be used, *e.g.* epoxy, acrylic or polyester resin. Porous materials must be impregnated by resin before mounting or polishing, to prevent grit, polishing media or etchant being trapped in the pores, and to preserve the open structure of the material. A mounted specimen usually has a thickness of about half its diameter, to prevent rocking during grinding and polishing. The edges of the mounted specimen should also be rounded to minimize the damage to grinding and polishing discs.



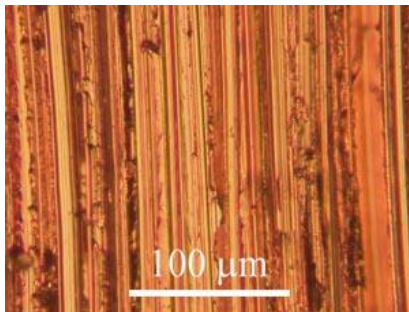
A mounted specimen (shows typical dimensions)

3. Grinding

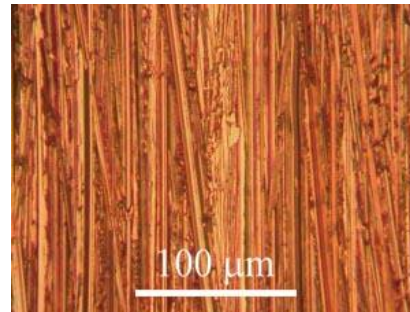
Surface layers damaged by cutting must be removed by grinding. Mounted specimens are ground with rotating discs of abrasive paper, for example wet silicon carbide paper. The coarseness of the paper is indicated by a number: the number of grains of silicon carbide per square inch. So, for example, 180 grit paper is coarser than 1200 grit. The grinding procedure

involves several stages, using a finer paper (higher number) each time. Each grinding stage removes the scratches from the previous coarser paper. This can be easily achieved by orienting the specimen perpendicular to the previous scratches. Between each grade the specimen is washed thoroughly with soapy water to prevent contamination from coarser grit present on the specimen surface. Typically, the finest grade of paper used is the 1200, and once the only scratches left on the specimen are from this grade.

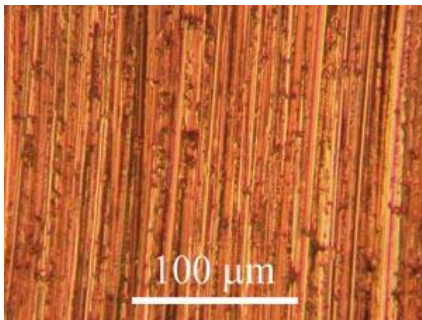
The series of photos below shows the progression of the specimen when ground with progressively finer paper.



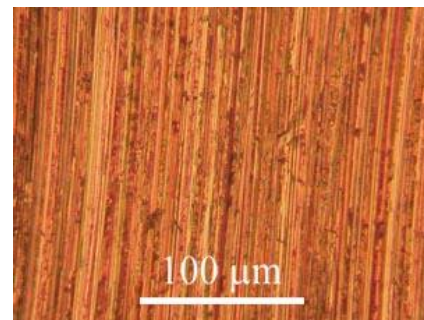
Copper specimen ground with 180 grit paper



Copper specimen ground with 400 grit paper



Copper specimen ground with 800 grit paper



Copper specimen ground with 1200 grit paper

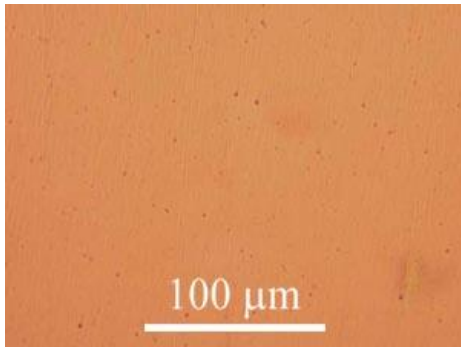
4. Lapping

The lapping process is an alternative to grinding, in which the abrasive particles are not firmly fixed to paper. Instead a paste and lubricant is applied to the surface of a disc. Surface roughness from coarser preparation steps is removed by the micro-impact of rolling abrasive particles.

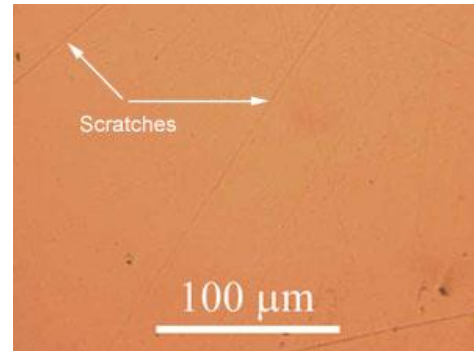
5. Polishing

Polishing discs are covered with soft cloth impregnated with abrasive diamond particles and an oily lubricant or water lubricant. Particles of two different grades are used : a coarser polish - typically with diamond particles 6 microns in diameter which should remove the

scratches produced from the finest grinding stage, and a finer polish – typically with diamond particles 1 micron in diameter, to produce a smooth surface. Before using a finer polishing wheel the specimen should be washed thoroughly with warm soapy water followed by alcohol to prevent contamination of the disc. The drying can be made quicker using a hot air drier.



Copper specimen polished to 6 micron level



Copper specimen polished to 1 micron level

Mechanical polishing will always leave a layer of disturbed material on the surface of the specimen. Electropolishing or chemical polishing can be used to remove this, leaving an undisturbed surface.

6. Etching

Etching is used to reveal the microstructure of the metal through selective chemical attack. In alloys with more than one phase etching creates contrast between different regions through differences in topography or the reflectivity of the different phases. The rate of etching is affected by crystallographic orientation, so contrast is formed between grains, for example in pure metals. The reagent will also preferentially etch high energy sites such as grain boundaries. This results in a surface relief that enables different crystal orientations, grain boundaries, phases and precipitates to be easily distinguished.

The specimen is etched using a reagent. For example, for etching stainless steel or copper and its alloys, a saturated aqueous solution of ferric chloride, containing a few drops of hydrochloric acid is used.

* As a guide the following etchants are commonly used:

Alcoholic Ferric Chloride -copper alloys

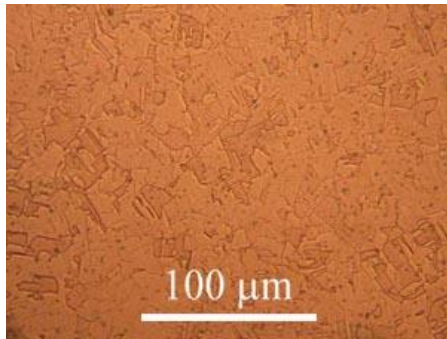
Mixed Acids -aluminum alloys

Nital (ethyl alcohol+ 2% HN03) -iron and steel

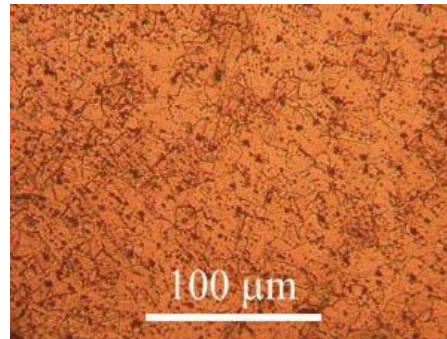
Dilute HCl -zinc alloys

The etchant is applied using a cotton bud wiped over the surface a few of times (Care should be taken not to over-etch - this is a difficult point to determine, however, the photo below may be of some help). The specimen should then immediately be washed in alcohol and dried.

Following the etching process there may be numerous small pits present on the surface. These are etch pits caused by localized chemical attack, and in most cases they do not represent features of the microstructure. They may occur preferentially in regions of high local disorder, for example where there is a high concentration of dislocations. If the specimen is over etched, i.e., etched for too long, these pits tend to grow, and obscure the main features to be observed - as seen in the images below:



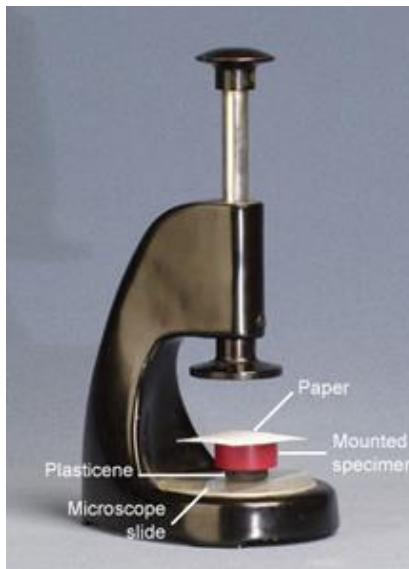
Etched copper specimen



Over etched copper specimen

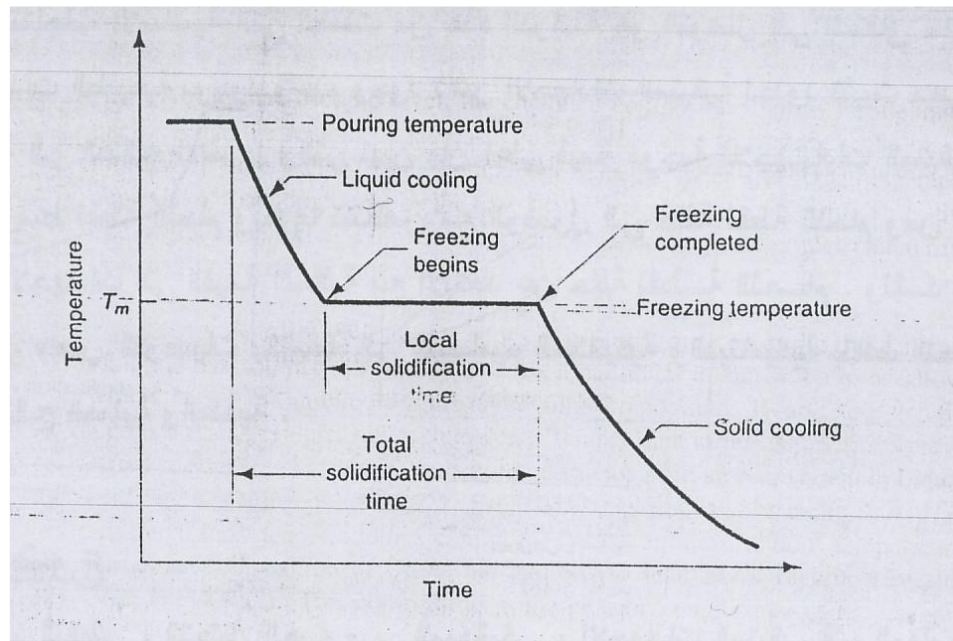
Cleaning specimens in an ultrasonic bath can also be helpful, but is not essential.

Ideally the surface to be examined optically should be perfectly flat and level. If not, then as the viewing area is moved across the surface it will pass in and out of focus. In addition, it will make it difficult to have the whole of the field of view in focus - while the centre is focused, the sides will be out of focus. By using a specimen levelling press (shown below) this problem can be avoided, as it presses the mounted specimen into plasticene on a microscope slide, making it level. A small piece of paper or cloth covers the surface of the specimen to avoid scratching.



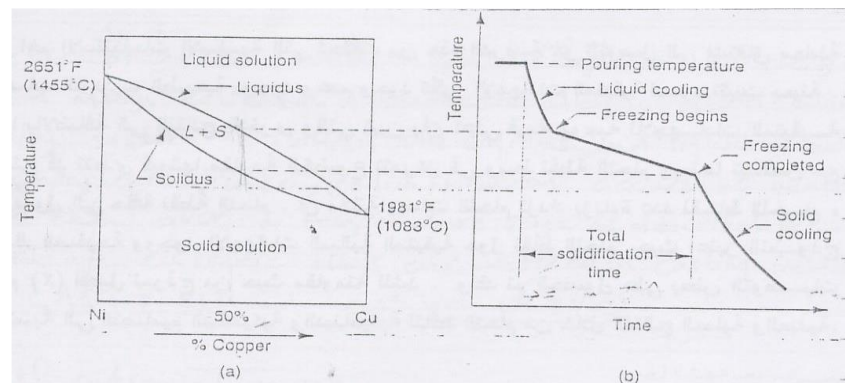
COOLING CURVES

Solidification involves the transformation of the molten metal back into the solid state. The solidification process differs depending on whether the metal is pure element or an alloy. A pure metal solidifies at a constant temperature equal to its freezing point, which is the same as its melting point. The process occurs over and over time as shown in the plot of the below figure called a cooling curve.



Pure metal cooling curve

Most alloys freeze over a temperature range rather than at a single temperature. The exact range depends on the alloy system and the particular composition. Solidification of an alloy can be explained with reference to the below figure, which shows the phase diagram for a particular alloy system and the cooling curve for a given composition.



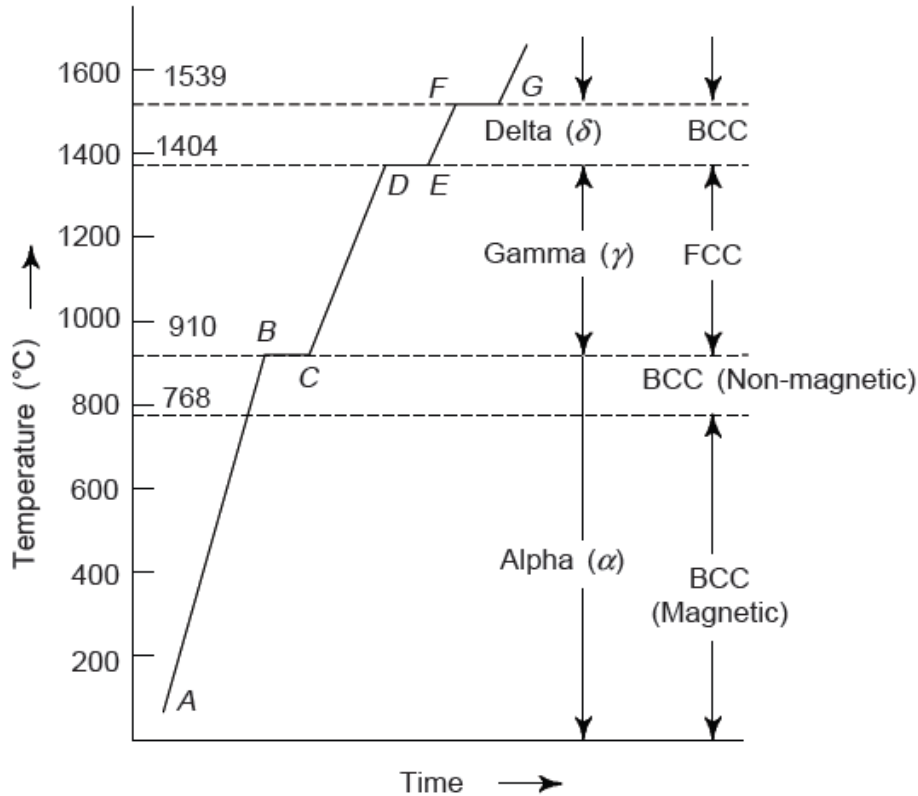
(a) Phase diagram for Cu-Ni alloy. (b) Associated cooling curve for 50% Ni, 50%Cu.

ALLOTROPY CONCEPT

Pure substances may exist in more than one crystalline form and each such crystalline form is stable over more or less well defined limits of temperature and pressure. This is termed as allotropy or polymorphism.

Example:

Pure iron is relatively soft and ductile and its melting point is 1539°C. The pure iron exists in three important allotropic forms, i.e. alpha (α), gamma (γ) and delta (δ) iron. The existence of phases depends upon the temperature to which the iron is heated. An ideal curve for pure iron, showing the temperature ranges over which each of these crystallographic forms are stable at atmospheric pressure is shown in below figure.



From the above figure, it is evident that from room temperature to 910°C pure iron has a BCC structure and is called alpha (α) iron ($\text{Fe } \alpha$). It is highly ferromagnetic and remains so upto 768°C (Curie point). On heating it becomes non-magnetic, i.e., ferromagnetism disappears. However, the crystal structure still remains BCC. Non-magnetic α -iron is stable upto 910°C. The non-magnetic α -iron was earlier known as β -iron. However, the X-ray crystallography

revealed no change of crystal structure at 768°C. In order to avoid confusion, the original naming of the sequence retained with the β -phase deleted. Hence it is known as α -iron (Fe α).

Above 910°C, it is transformed into FCC and allotropic change takes place. It is transformed from α to γ -iron structure. Upon heating to 1404°C, again allotropic change takes place and γ -iron is transformed back into the BCC structure called δ -iron. It is stable upto the melting point, 1539°C of pure iron. The BCC structure δ -iron has a longer cube edge than BCC structure of α -iron.

We may note that the above transformations are reversible. The δ -iron is changed to γ -iron at 1404°C. Evolution of heat takes place on cooling at 910°C and γ -iron changes to α -iron

UNIT -II

PHASE DIAGRAM

Construction and interpretation of binary phase diagrams – Types – Eutectic, Eutectoid, Peritectic and Peritectoid systems – Iron Carbon Equilibrium Diagrams – Classification of Steels and Alloy Steels – Types, Manufacture, Properties and Applications of Cast Irons.

INTRODUCTION

Phase diagrams provide a graphical means of presenting the results of experimental studies of complex natural processes, such that at a given temperature and pressure for a specific system at equilibrium the phase or phases present can be determined.

GIBBS PHASE RULE

For a system at equilibrium the phase rule relates:

P = number of phases

C = number of components

F = degrees of freedom.

Where these three variables are related in the equation

$$P + F = C + 2$$

For practical purpose, in metallurgical and materials field, pressure can be considered as a constant, and thus the *condensed phase rule* is given as follows:

$$P + F = C + 1$$

PHASE DIAGRAM

The phase diagram is a map showing which phases of a material are in equilibrium at any given temperature, composition, and pressure. It is drawn from experimental data and may be used to determine at equilibrium:

number of phases present (P)

composition of each phase (X)

the amount of each phase present as a function of temperature and composition.

Of particular interest to integrated circuit fabrication is the binary partial solid solubility phase diagram. The solidus curve can be used for determining the solid solubility limit (Nsl) used in diffusion problems.

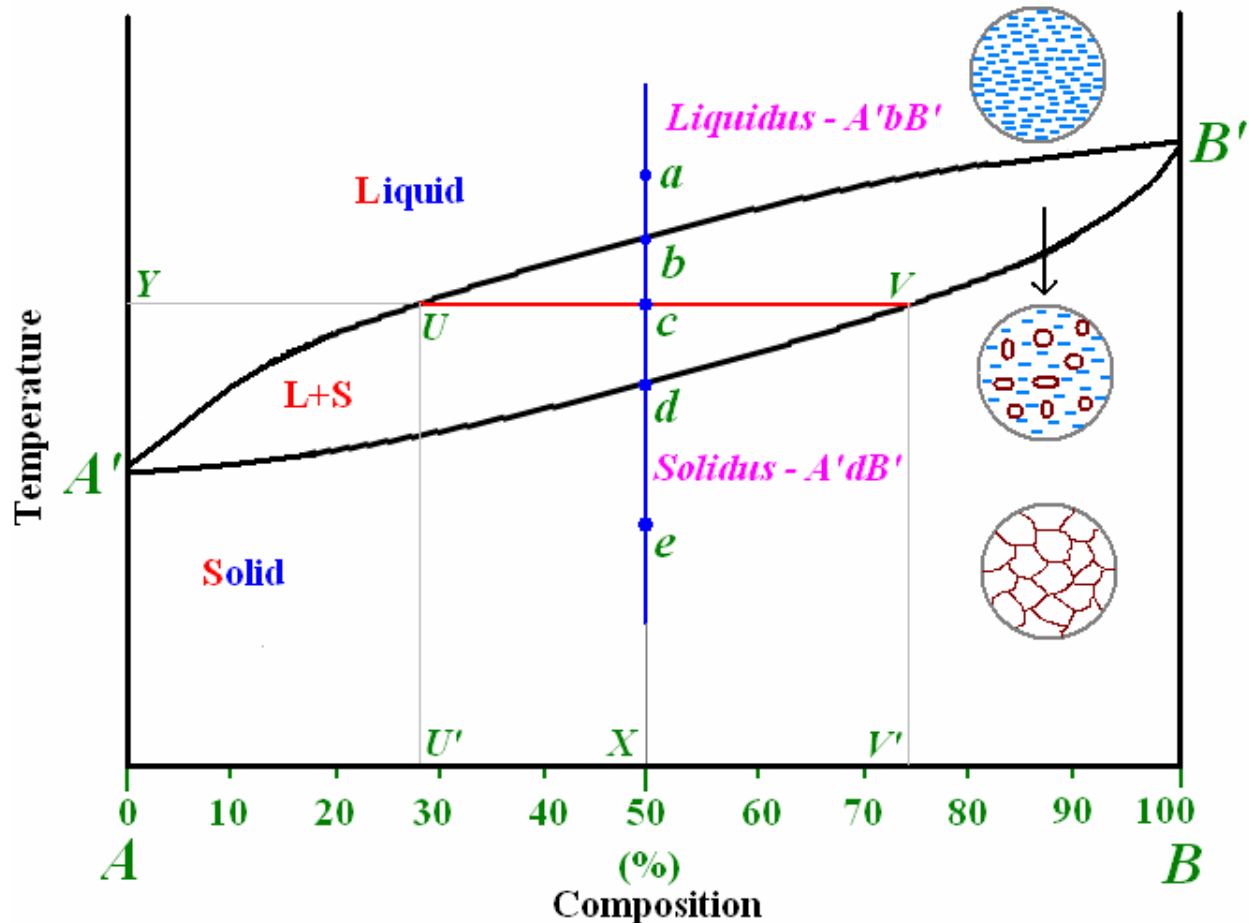


Figure -1 Interpretation of Phase Diagrams

For the interpretation of the phase diagram, let's consider the vertical line *ae* drawn corresponding to composition of 50%A +50%B and assume that the system is undergoing equilibrium cooling. The point *a* on the line *ae* signifies that for that particular temperature and composition, only liquid phase is stable. This is true up to the point *b* which lies on the liquidus line, representing the starting of solidification. Completion of solidification of the alloy is represented by the point, *d*. Point *e* corresponds to single-phase solid region up to the room temperature. Point *c* lies in the two-phase region made of both liquid and solid phases.

Corresponding micro-structural changes are also shown in *figure-1*. As shown in figure-1, above liquidus only a liquid phase exists, and below the solidus single solid phase exists as completely solidified grains. Between these two lines, system consist both solid crystals spread in liquid phase. It is customary to use **L** to represent liquid phase(s) and Greek alphabets (α , β , γ) for representing solid phases.

Between two extremes of the horizontal axis of the diagram, cooling curves for different alloys as a function of time and temperature. Cooling curves represent **A**, **U'**, **X**, **V'** and **B** correspondingly in *figure-2*. Change in slope of the cooling curve is caused by heat of fusion. In fact these changes in slope are nothing but points on either solidus or liquidus of a phase diagram. An experimental procedure where repeated cooling/heating of an alloy at different compositions, and corresponding changes in slope of cooling curves will be used to construct the phase diagram. Another important aspect of interpreting phase diagrams along with phases present is finding the relative amount of phases present and their individual composition.

Procedure to find equilibrium concentrations of phases:

EUTECTIC SYSTEM

Many pairs of elements (e.g., Bi-Cd, Sn-Zn, Ag-Cu, Al-Si etc) do not mix. The bond between the two elements A-B is weaker than the A-A and the B-B bond and each of them can dissolve a limited amount of the other. These pairs solidify in a manner similar to Pb-Sn whose **eutectic** phase diagram is shown in Figure 2. The eutectic is so named for the critical **eutectic point** corresponding to the **eutectic temperature** (183°C in Sn-Pb) and **eutectic composition** (61.9% Sn in Sn-Pb). Above the **eutectic temperature**, it is as though two independent solid solution systems exist - one on the Pb side yielding Pb rich solid solutions (the α phase), the other on the Sn side giving rise to Sn rich solid solutions (the β phase). Their liquidus lines converge at the **eutectic point** (61.9 wt. %Sn and 183°C). This means that the liquid phase of every alloy containing between 19.2 to 97.5 wt% Sn, will eventually reach the eutectic composition (61.9 wt.% Sn) upon cooling from elevated temperature to slightly above 183°C.

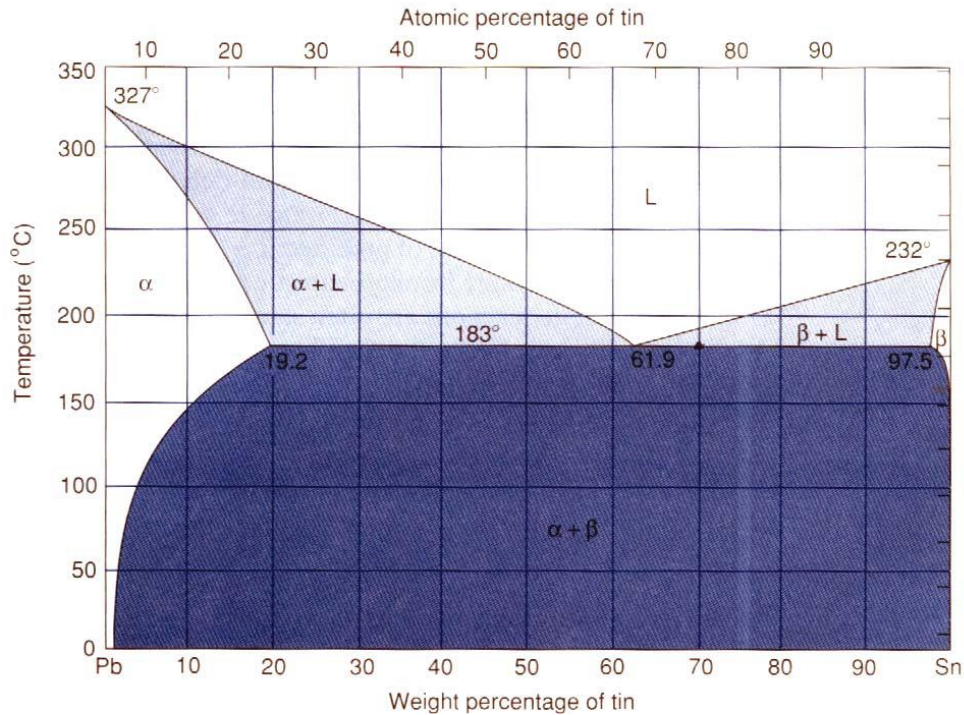


Figure 2. Pb-Sn phase diagram showing eutectic reaction. 2-phase regions are colored.

Liquid at this eutectic composition **decomposes** at 183°C into a mixture of two solid phases: α , a Pb rich solid solution, and β , a Sn rich solid solution. The reaction is invariant; both the temperature and phase compositions remain constant during the transformation of eutectic liquid to $\alpha + \beta$. Consider now the cooling behavior of an alloy of exactly eutectic composition (61.9 wt.% Sn-30.1 wt.% Pb

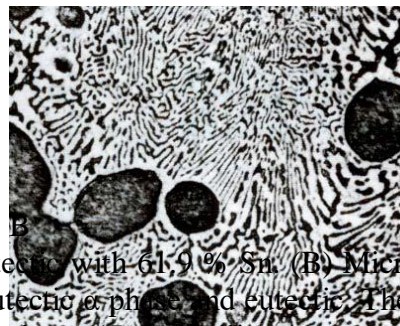


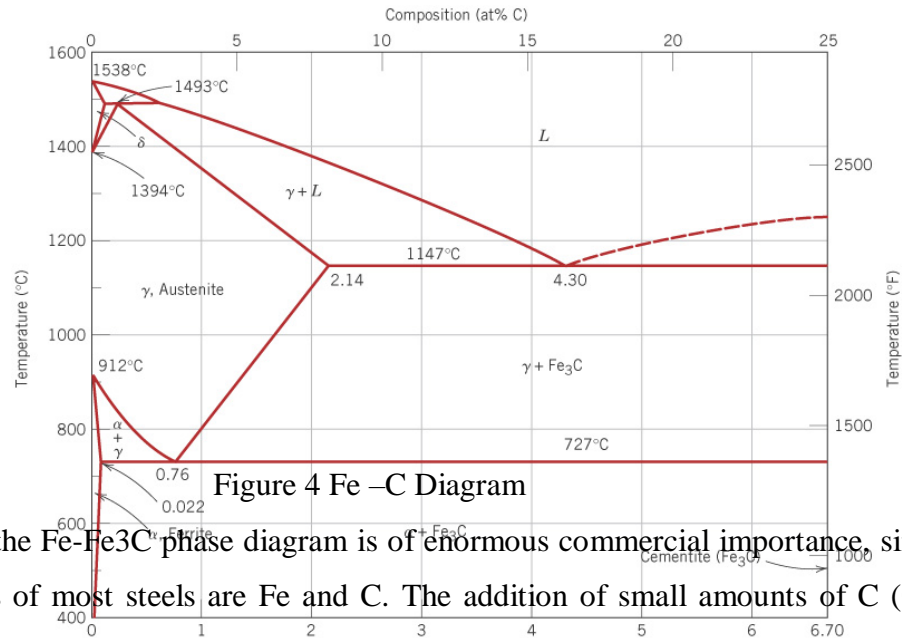
Figure 3. (A) Microstructure of a Pb-Sn eutectic with 61.9% Sn. (B) Microstructure of a Pb-Sn alloy of composition 60 wt.% Sn; with proeutectic α phase and eutectic. The dark regions are Pb-rich α phase; the bright areas are Sn-rich β phase. (From Callister).

The rules of phase analysis in single- and two - phase fields given previously will be applied once again in the example below. First, however, a few additional details of eutectic solidification should be noted. The solid α phase (in equilibrium with L) that forms above the eutectic temperature is known as the **proeutectic or primary α phase**. Similarly, solid

proeutectic β phase separates from the melt in Sn - rich alloys at $T > 183^{\circ}\text{C}$. As the eutectic reaction proceeds, the eutectic mixture of $\alpha + \beta$ adds its presence to the already solidified larger crystals of proeutectic α (or β).

The solvus curve on the Pb – rich side shows that the solubility of Sn in Pb decreases as the temperature is lowered. When the alloy cools below the eutectic temperature, solute is rejected from proeutectic phases because of the lower solubility.

EUTECTOID SYSTEM

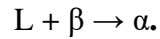


Obviously, the Fe-Fe₃C phase diagram is of enormous commercial importance, since the primary ingredients of most steels are Fe and C. The addition of small amounts of C (0.2-1.0 wt.%) increases the ductility of Fe tremendously and prevents brittle failure. It is not a true phase diagram, since Fe₃C is metastable, gradually degrading to form Fe and C (graphite). However, this reaction is nearly infinitely slow at room temperature, so common practice is to treat Fe₃C as though it were a stable compound. Note that pure Fe has a room-temperature BCC α phase (ferrite) and a higher temperature FCC γ phase (austenite). This is not uncommon, particularly among ceramic materials.

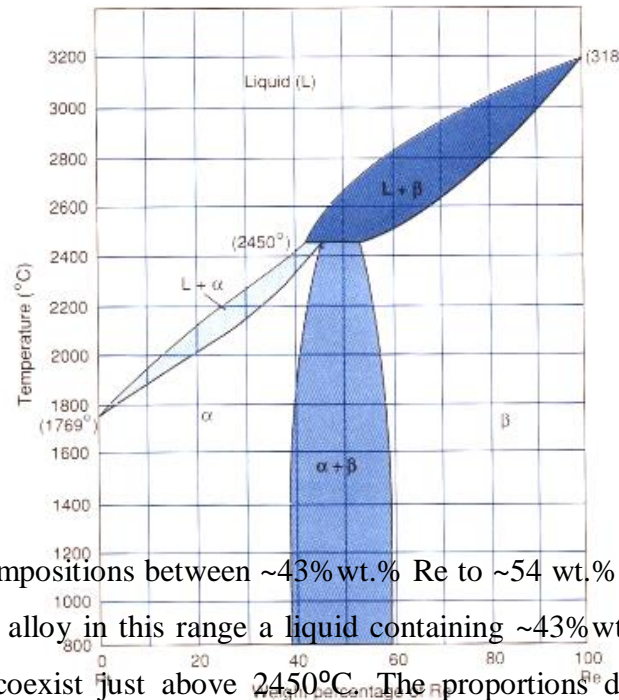
The Fe-Fe₃C phase diagram shows a eutectic reaction, but it also shows a eutectoid reaction, during which $\gamma \rightarrow \alpha + \text{Fe}_3\text{C}$. Any phase transformation during which a solid phase transforms simultaneously to two other solid phases is referred to as a eutectoid reaction. The transformations associated with the eutectoid reaction are similar to those associated with the eutectic reaction. The main difference is that for the eutectoid reaction, the initial reactant is a solid, whereas for the eutectic reaction, the initial reactant is a liquid.

PERITECTIC SYSTEM

Not uncommon in the catalog of solidification sequences is the invariant **peritectic** reaction which can be written in the generic form



Peritectic reactions often occur when there is a large difference in melting point between the two components. The liquid reacts with the higher-temperature solid to form a new solid phase. On the phase diagram the peritectic reaction is characterized by the prominent isotherm, and appears as an upside down eutectic. There are few examples of alloy systems that exhibit only peritectic behavior over the complete temperature range. One is the platinum-rhenium system, whose phase diagram is shown in Fig. 5. Above the peritectic temperature of 2450°C, solid solution solidification (β) prevails in Re – rich alloys. Below this temperature down to the melting point of Pt, liquid exists with Pt – rich compositions which also solidify as solid solutions α .



Only alloys with compositions between ~43% wt.% Re to ~54 wt.% Re participate in the peritectic reaction. For any alloy in this range a liquid containing ~43% wt.% Re and a solid β containing ~54 wt.% Re coexist just above 2450°C. The proportions depend on the initial composition and can be calculated from the Lever Rule. Given sufficient time the β phase will react with the liquid and produce the α phase as shown in above equation suggests. But, as the temperature drops, will be rejected from α and both phases will persist down to lower temperatures. Unlike eutectics, peritectics have no particularly distinguishing microstructural features.

The issue of equilibrium is an important one in peritectic solidification. Since peritectic reactions are sluggish they don't readily proceed to completion unless maintained at high

temperature for long times. During practical cooling rates the peritectic reaction may be bypassed yielding nonequilibrium phases that may not appear on the phase diagram.

PERITECTOID SYSTEM

It is a three-phase reaction similar to peritectic but occurs from two solid phases to one new solid phase ($\alpha + \beta = \gamma$).

THE IRON-CARBON EQUILIBRIUM DIAGRAM

A study of the constitution and structure of all steels and irons must first start with the iron-carbon equilibrium diagram. Many of the basic features of this system (**Fig. 6**) influence the behavior of even the most complex alloy steels. For example, the phases found in the simple binary Fe-C system persist in complex steels, but it is necessary to examine the effects alloying elements have on the formation and properties of these phases. The iron-carbon diagram provides a valuable foundation on which to build knowledge of both plain carbon and alloy steels in their immense variety.

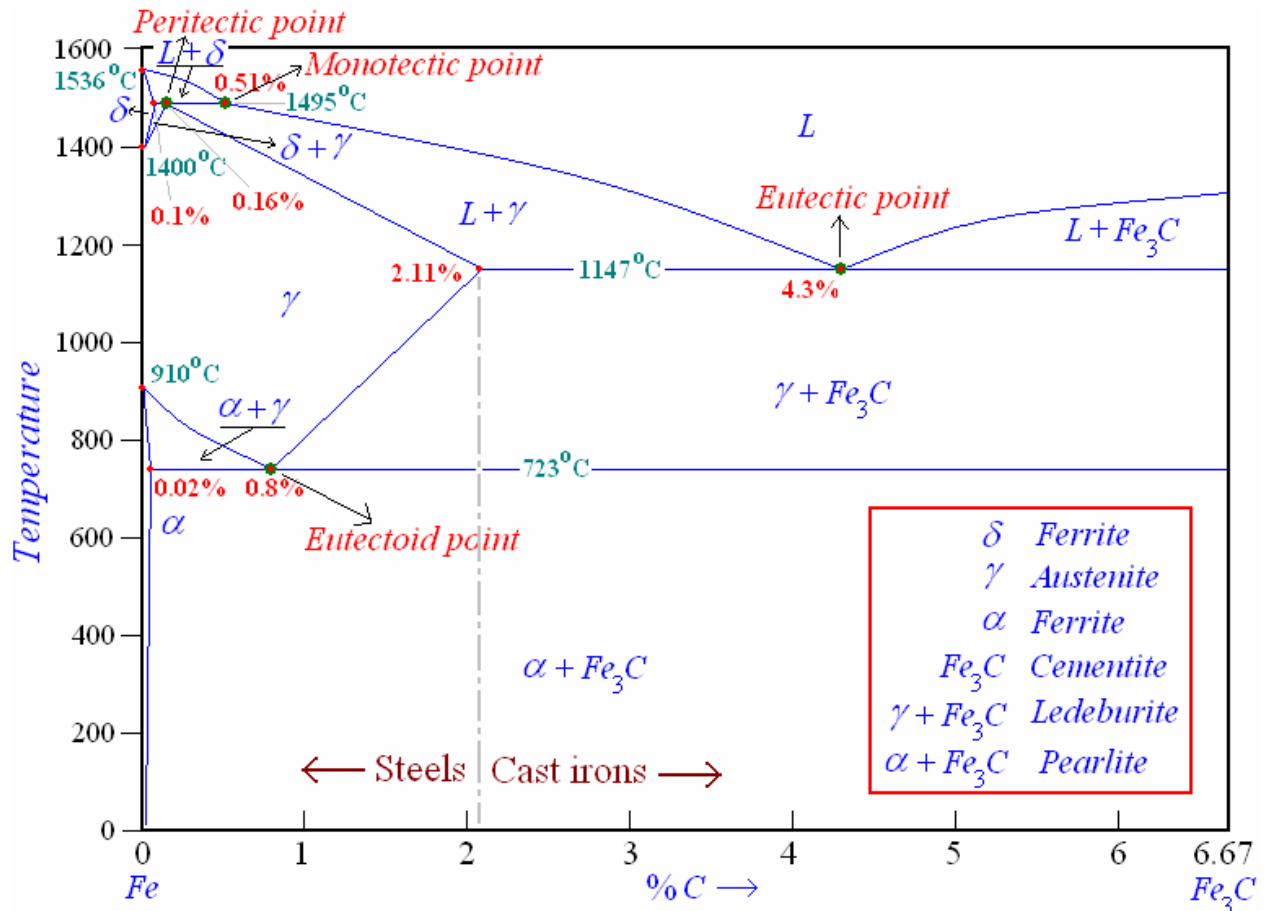


Figure 6. The Iron-Carbon Equilibrium Diagram

It should first be pointed out that the normal equilibrium diagram really represents the metastable equilibrium between iron and iron carbide (cementite). Cementite is metastable, and the true equilibrium should be between iron and graphite. Although graphite occurs extensively in cast irons (2-4 wt % C), it is usually difficult to obtain this equilibrium phase in steels (0.03-

1.5 wt %C). Therefore, the metastable equilibrium between iron and iron carbide should be considered, because it is relevant to the behavior of most steels in practice.

The α -iron phase field is severely restricted, with a maximum carbon solubility of 0.02 wt% at 723°C, so over the carbon range encountered in steels from 0.05 to 1.5 wt%, α -iron is normally associated with iron carbide in one form or another. Similarly, the δ -phase field is very restricted between 1390 and 1534°C and disappears completely when the carbon content reaches 0.5 wt% .

There are several temperatures or critical points in the diagram, which are important, both from the basic and from the practical point of view.

- Firstly, there is the A1, temperature at which the eutectoid reaction occurs, which is 723°C in the binary diagram.
- Secondly, there is the A3, temperature when α -iron transforms to γ -iron. For pure iron this occurs at 910°C, but the transformation temperature is progressively lowered along the line GS by the addition of carbon.
- The third point is A4 at which γ -iron transforms to δ -iron, 1390°C in pure iron, but this is raised as carbon is added. The A2, point is the Curie point when iron changes from the ferro to the paramagnetic condition. This temperature is 769°C for pure iron, but no change in crystal structure is involved. The A1, A3 and A4 points are easily detected by thermal analysis or dilatometry during cooling or heating cycles, and some hysteresis is observed. Consequently, three values for each point can be obtained. Ac for heating, Ar for cooling and Ae (equilibrium), but it should be emphasized that the Ac and Ar values will be sensitive to the rates of heating and cooling, as well as to the presence of alloying elements.

The eutectoid temperature is 723°C while the eutectoid composition is 0.80% C(s). On cooling alloys containing less than 0,80% C slowly, hypo-eutectoid ferrite is formed from austenite in the range 910-723°C with enrichment of the residual austenite in carbon, until at 723°C the remaining austenite, now containing 0.8% carbon transforms to pearlite, a lamellar mixture of ferrite and iron carbide (cementite). In austenite with 0,80 to 2,06% carbon, on cooling slowly in the temperature interval 1147°C to 723°C, cementite first forms progressively

depleting the austenite in carbon, until at 723°C, the austenite contains 0.8% carbon and transforms to pearlite.

The austenite- ferrite transformation

Under equilibrium conditions, pro-eutectoid ferrite will form in iron-carbon alloys containing up to 0.8 % carbon. The reaction occurs at 910°C in pure iron, but takes place between 910°C and 723°C in iron-carbon alloys.

However, by quenching from the austenitic state to temperatures below the eutectoid temperature A_{e1} , ferrite can be formed down to temperatures as low as 600°C. There are pronounced morphological changes as the transformation temperature is lowered, which it should be emphasized apply in general to hypo-and hyper-eutectoid phases, although in each case there will be variations due to the precise crystallography of the phases involved. For example, the same principles apply to the formation of cementite from austenite, but it is not difficult to distinguish ferrite from cementite morphologically.

The austenite-cementite transformation

The Dube classification applies equally well to the various morphologies of cementite formed at progressively lower transformation temperatures. The initial development of grain boundary allotriomorphs is very similar to that of ferrite, and the growth of side plates or Widmanstätten cementite follows the same pattern. The cementite plates are more rigorously crystallographic in form, despite the fact that the orientation relationship with austenite is a more complex one. As in the case of ferrite, most of the side plates originate from grain boundary allotriomorphs, but in the cementite reaction more side plates nucleate at twin boundaries in austenite.

The austenite-pearlite reaction

Pearlite is probably the most familiar micro structural feature in the whole science of metallography. It was discovered by Sorby over 100 years ago, who correctly assumed it to be a lamellar mixture of iron and iron carbide.

Pearlite is a very common constituent of a wide variety of steels, where it provides a substantial contribution to strength. Lamellar eutectoid structures of this type are widespread in metallurgy, and frequently pearlite is used as a generic term to describe them.

These structures have much in common with the cellular precipitation reactions. Both types of reaction occur by nucleation and growth, and are, therefore, diffusion controlled.

Pearlite nuclei occur on austenite grain boundaries, but it is clear that they can also be associated with both proeutectoid ferrite and cementite. In commercial steels, pearlite nodules can nucleate on inclusions.

CLASSIFICATION OF CARBON AND LOW-ALLOY STEELS

The American Iron and Steel Institute (AISI) defines carbon steel as follows: Steel is considered to be carbon steel when no minimum content is specified or required for chromium, cobalt, columbium [niobium], molybdenum, nickel, titanium, tungsten, vanadium or zirconium, or any other element to be added to obtain a desired alloying effect; when the specified minimum for copper does not exceed 0.40 per cent; or when the maximum content specified for any of the following elements does not exceed the percentages noted: manganese 1.65, silicon 0.60, copper 0.60.

Steels can be classified by a variety of different systems depending on:

- The composition, such as carbon, low-alloy or stainless steel.
- The manufacturing methods, such as open hearth, basic oxygen process, or electric furnace methods.
- The finishing method, such as hot rolling or cold rolling
- The product form, such as bar plate, sheet, strip, tubing or structural shape
- The deoxidation practice, such as killed, semi-killed, capped or rimmed steel
- The microstructure, such as ferritic, pearlitic and martensitic
- The required strength level, as specified in ASTM standards
- The heat treatment, such as annealing, quenching and tempering, and thermomechanical Processing
- Quality descriptors, such as forging quality and commercial quality.

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High-Strength Low-Alloy Steels

High-strength low-alloy (HSLA) steels, or microalloyed steels, are designed to provide better mechanical properties and/or greater resistance to atmospheric corrosion than conventional carbon steels in the normal sense because they are designed to meet specific mechanical properties rather than a chemical composition

HSLA Classification:

- **Weathering steels**, designated to exhibit superior atmospheric corrosion resistance
- **Control-rolled steels**, hot rolled according to a predetermined rolling schedule, designed to develop a highly deformed austenite structure that will transform to a very fine equiaxed ferrite structure on cooling
- **Pearlite-reduced steels**, strengthened by very fine-grain ferrite and precipitation hardening but with low carbon content and therefore little or no pearlite in the microstructure
- **Microalloyed steels**, with very small additions of such elements as niobium, vanadium, and/or titanium for refinement of grain size and/or precipitation hardening
- **Acicular ferrite steel**, very low carbon steels with sufficient hardenability to transform on cooling to a very fine high-strength acicular ferrite structure rather than the usual polygonal ferrite structure
- **Dual-phase steels**, processed to a micro-structure of ferrite containing small uniformly distributed regions of high-carbon martensite, resulting in a product with low yield strength and a high rate of work hardening, thus providing a high-strength steel of superior formability.

Low-alloy Steels

Low-alloy steels constitute a category of ferrous materials that exhibit mechanical properties superior to plain carbon steels as the result of additions of alloying elements such as nickel, chromium, and molybdenum. Total alloy content can range from 2.07% up to levels just below that of stainless steels, which contain a minimum of 10% Cr.

- Chemical composition, such as nickel steels, nickel-chromium steels, molybdenum steels, chromium-molybdenum steels
- Heat treatment, such as quenched and tempered, normalized and tempered, annealed.

Because of the wide variety of chemical compositions possible and the fact that some steels are used in more than one heat-treated, condition, some overlap exists among the alloy steel classifications. In this article, four major groups of alloy steels are addressed: (1) low-

carbon quenched and tempered (QT) steels, (2) medium-carbon ultrahigh-strength steels, (3) bearing steels, and (4) heat-resistant chromium-molybdenum steels.

CAST IRON

Cast irons may often be used in place of steel at considerable cost savings. The design and production advantages of cast iron include:

- Low tooling and production cost
- Good machinability without burring
- Ability to cast into complex shapes
- Excellent wear resistance and high hardness (particularly white cast irons)
- High inherent damping capabilities

The properties of the cast iron are affected by the following factors:

- Chemical composition of the iron
- Rate of cooling of the casting in the mold (which depends on the section thickness in the casting)
- Type of graphite formed (if any)

TYPES OF CAST IRON:

Major types of cast iron are shown in Figure 7

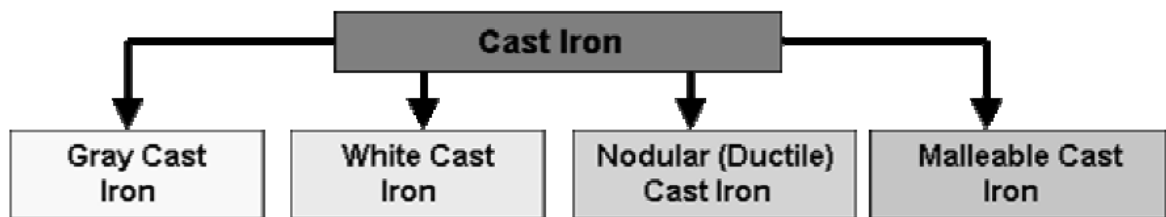


Figure 7. Types of Cast Iron

GRAY CAST IRON:

Gray cast iron is by far the oldest and most common form of cast iron. As a result, it is assumed by many to be the only form of cast iron and the terms "cast iron" and "gray iron" are used interchangeably. Unfortunately the only commonly known property of gray iron- brittleness- is also assigned to "cast iron" and hence to all cast irons. Gray iron, named because its fracture has a gray appearance. It contains carbon in the form of flake graphite in a matrix which consists of ferrite, pearlite or a mixture of the two. The fluidity of liquid gray iron, and its

expansion during solidification due to the formation of graphite, have made this metal ideal for the economical production of shrinkage-free, intricate castings such as motor blocks.

The flake-like shape of graphite in Gray iron, see Figure 1.6, exerts a dominant influence on its mechanical properties. The graphite flakes act as stress raisers which may prematurely cause localized plastic flow at low stresses, and initiate fracture in the matrix at higher stresses. As a result, Gray iron exhibits no elastic behavior but excellent damping characteristics, and fails in tension without significant plastic deformation. The presence of graphite flakes also gives Gray Iron excellent machinability and self-lubricating properties.



Figure 8 Photomicrograph of Gray Cast iron

Advantages of Gray Cast Iron:

- Graphite acts as a chip breaker and a tool lubricant.
- Very high damping capacity.
- Good dry bearing qualities due to graphite.
- After formation of protective scales, it resists corrosion in many common engineering environments.

Disadvantages:

- Brittle (low impact strength) which severely limits use for critical applications.
- Graphite acts as a void and reduces strength. Maximum recommended design stress is 1/4 of the ultimate tensile strength. Maximum fatigue loading limit is 1/3 of fatigue strength.
- Changes in section size will cause variations in machining characteristics due to variation in microstructure.
- Higher strength gray cast irons are more expensive to produce.

LOW ALLOY GRAY CAST IRON:

Enables gray cast iron to be used in higher duty applications without redesign or need for costly materials.

Advantages:

- Reduction in section sensitivity.
- Improvement in strength, corrosion resistance, heat and wear resistance or combination of these properties.

Disadvantages:

- Higher cost.
- Alloy additions can cause foundry problems with reuse of scrap (runners, risers, etc) and interrupt normal production.
- Increase in strength does not bring corresponding increase in fatigue strength.
- Cr, Mo and V are carbide stabilizers which improve strength and heat resistance but impair machinability.

WHITE CAST IRON:

White cast iron is unique in that it is the only member of the cast iron family in which carbon is present only as carbide. Due to the absence of graphite, it has a light appearance. The presence of different carbides, depending on the alloy content, makes white cast irons extremely hard and abrasion resistant but very brittle. An improved form of white cast iron is the chilled cast iron.



Figure 9 Photomicrograph of White Cast Iron

CHILLED CAST IRON:

When localized area of a gray cast iron is cooled very rapidly from the melt, cast iron is formed at the place that has been cooled. This type of white cast iron is called chilled iron. A chilled iron casting can be produced by adjusting the carbon composition of the white cast iron

so that the normal cooling rate at the surface is just fast enough to produce white cast iron while the slower cooling rate below the surface will produce gray iron. The depth of chill decreases and the hardness of the chilled zone increases with increasing carbon content.

Chromium is used in small amounts to control chill depth. Because of the formation of chromium carbides, chromium is used in amount of 1 to 4 percent in chilled iron to increase hardness and improve abrasion resistance. It also stabilizes carbide and suppresses the formation of graphite in heavy sections. When added in amounts of 12 to 35 percent, chromium will impart resistance to corrosion and oxidation at elevated temperatures.

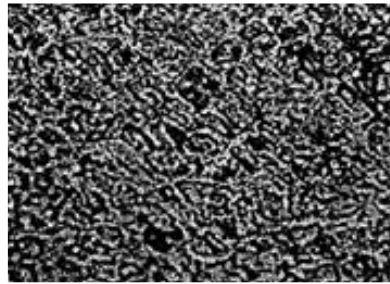


Figure 10 Photomicrograph of Chilled Cast Iron

Fast cooling prevents graphite and pearlite formation. If alloys such as nickel, chromium, or molybdenum are added, much of the austenite transforms to martensite instead of pearlite. The hardness of chilled cast iron is generally due to the formation of martensite.

Chilled cast iron is used for railway-car wheels, crushing rolls, stamp shoes and dies, and many heavy-duty machinery parts.

DUCTILE CAST IRON (NODULAR CAST IRON):

This structure is developed from the melt. The carbon forms into spheres when cerium, magnesium, sodium, or other elements are added to a melt of iron with a very low sulfur content that will inhibit carbon from forming. The control of the heat-treating process can yield pearlitic, ferritic, martensitic matrices into which the carbon spheres are embedded.

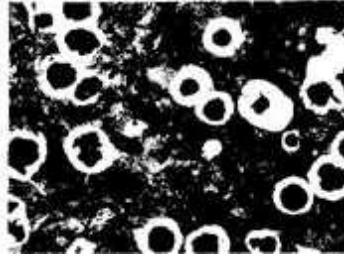


Figure 11 Photomicrograph of Nodular Cast iron

The advantages of ductile cast iron which have led to its success are numerous, but they can be summarized easily- versatility and high performance at low cost. Other members of the ferrous casting family may have superior individual properties which might make them the material of choice in some applications, but none have the versatility of ductile cast iron, which often provides the designer with the best combination of overall properties. This is especially evident in the area of mechanical properties where ductile cast iron offers the designer the option of selecting high ductility, with grades guaranteeing more than 18% elongation (as high as 25 %), or high strength, with tensile strengths exceeding 120 Ksi.

Ductile cast iron is used for many structural applications, particularly those requiring strength and toughness combined with good machinability and low cost. The automotive and agricultural industries are the major users of ductile iron castings. Because of economic advantage and high reliability, ductile iron is used for such critical automotive parts as crankshafts, engine connecting rods, idler arms, wheel hubs, truck axles, front wheel spindle supports, disk brake calipers, suspension system parts, power transmission yokes, high temperature applications for turbo housing and manifolds, and high security valves for many applications. The cast iron pipe industry is another major user of ductile iron.

MALLEABLE CAST IRON:

If cast iron is cooled rapidly, the graphite flakes needed for gray cast iron do not get a chance to form. Instead, white cast iron forms. This white cast iron is reheated to about 1700oF for long periods of time in the presence of materials containing oxygen, such as iron oxide. At the elevated temperatures cementite (Fe_3C) decomposes into ferrite and free carbon. Upon cooling, the combined carbon further decomposes to small compact particles of graphite (instead of flake -like graphite seen in gray cast iron). If the cooling is very slow, more free carbon is

released. This free carbon is referred to as temper carbon, and the process is called malleableizing.

Figure 12 shows ferritic malleable cast iron, which has a ferrite matrix and the tempered carbon particles are embedded into the matrix.

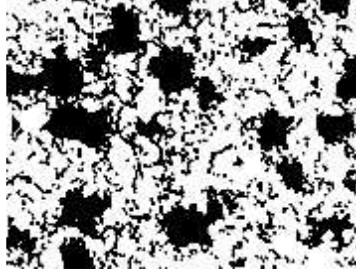


Figure 12 Ferritic Malleable Cast iron

Figure 13 shows pearlite malleable cast iron, which has a pearlite matrix. By adding manganese to the structure, carbon is retained in the form of cementite.

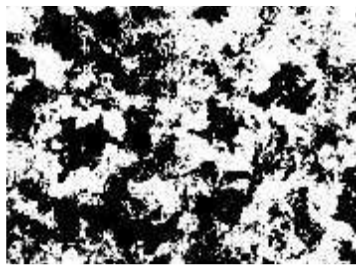


Figure 13 Pearlitic Malleable Cast Iron

Malleable cast iron is used for connecting rods and universal joint yokes, transmission gears, differential cases and certain gears, compressor crankshafts and hubs, flanges, pipe fittings and valve parts for railroad, marine and other heavy-duty applications.

Advantages:

- Excellent machinability
- Significant ductility
- Good shock resistance properties

Disadvantages:

The major disadvantage is shrinkage. Malleable cast iron decreases in volume during solidification, and as a result, requires attached reservoirs (feeders and risers) of liquid metal to offset the shrinkage and prevent the formation of internal or external shrinkage defects.

UNIT- III

HEAT TREATMENT OF STEEL

Heat treatment of steel: critical temperature on heating and cooling , effects off residual stresses, - annealing, normalizing , hardening,hardenbility test- tempering , construction and interpretation of TTT diagram- marten site transformation – sub zero treatment-surface hardening processes.

HEAT TREATMENT

The heat treatment includes heating and cooling operations or the sequence of two or more such operations applied to any material in order to modify its metallurgical structure and alter its physical, mechanical and chemical properties. Usually it consists of heating the material to some specific temperature, holding at this temperature for a definite period and cooling to room temperature or below with a definite rate. Annealing, Normalizing, Hardening and Tempering are the four widely used heat treatment processes that affect the structure and properties, and are assigned to meet the specific requirements from the semi-fabricated and finished components. Steels being the most widely used materials in major engineering fabrications undergo various heat treatment cycles depending on the requirements. Also aluminum and nickel alloys are exposed to heat treatment for enhancement of properties.

CRITICAL TEMPERATURES

The "critical points" of carbon tool steel are the temperatures at which certain changes in the chemical composition of the steel take place, during both heating and cooling. Steel at normal temperatures has its carbon (which is the chief hardening element) in a certain form called *pearlite* carbon, and if the steel is heated to a certain temperature, a change occurs and the pearlite becomes *martensite* or hardening carbon. If the steel is allowed to cool slowly, the hardening carbon changes back to pearlite. The points at which these changes occur are the *decalescence* and *recalescence* or critical points, and the effect of these molecular changes is as follows: When a piece of steel is heated to a certain point, it continues to absorb heat without appreciably rising in temperature, although its immediate surroundings may be hotter than the steel. This is the *decalescence* point. Similarly, steel cooling slowly from a high heat will, at a

certain temperature, actually increase in temperature, although its surroundings may be colder. This takes place at the *recalcescence* point. The recalcescence point is lower than the decalescence point by anywhere from 85 to 215 degrees F., and the lower of these points does not manifest itself unless the higher one has first been fully passed. These critical points have a direct relation to the hardening of steel. Unless a temperature sufficient to reach the decalescence point is obtained, so that the pearlite carbon is changed into a hardening carbon, no hardening action can take place; and unless the steel is cooled suddenly before it reaches the recalcescence point, thus preventing the changing back again from hardening to pearlite carbon, no hardening can take place. The critical points vary for different kinds of steel and must be determined by tests in each case. It is the variation in the critical points that makes it necessary to heat different steels to different temperatures when hardening.

ANNEALING

Annealing refers to a wide group of heat treatment processes and is performed primarily for homogenization, recrystallization or relief of residual stress in typical cold worked or welded components. Depending upon the temperature conditions under which it is performed, annealing eliminates chemical or physical non-homogeneity produced of phase transformations. Few important variants of annealing are full annealing, isothermal annealing, spheroidise annealing, recrystallization annealing, and stress relief annealing.

Full annealing (conventional annealing) Full annealing process consists of three steps. First step is heating the steel component to above A₃ (upper critical temperature for ferrite) temperature for hypoeutectoid steels and above A₁ (lower critical temperature) temperature for hypereutectoid steels by 30-500 C (Figures 3.1 and 3.2). In Figure 3.2, the terms α , γ and Fe₃C refer to ferrite, austenite and cementite phases.

The second step is holding the steel component at this temperature for a definite holding (soaking) period of at least 20 minutes per cm of the thick section to assure equalization of temperature throughout the cross-section of the component and complete austenization. Final step is to cool the hot steel component to room temperature slowly in the furnace, which is also called as furnace cooling. The full annealing is used to relieve the internal stresses induced due to cold working, welding, etc, to reduce hardness and increase ductility, to refine the grain

structure, to make the material homogenous in respect of chemical composition, to increase uniformity of phase distribution, and to increase machinability.

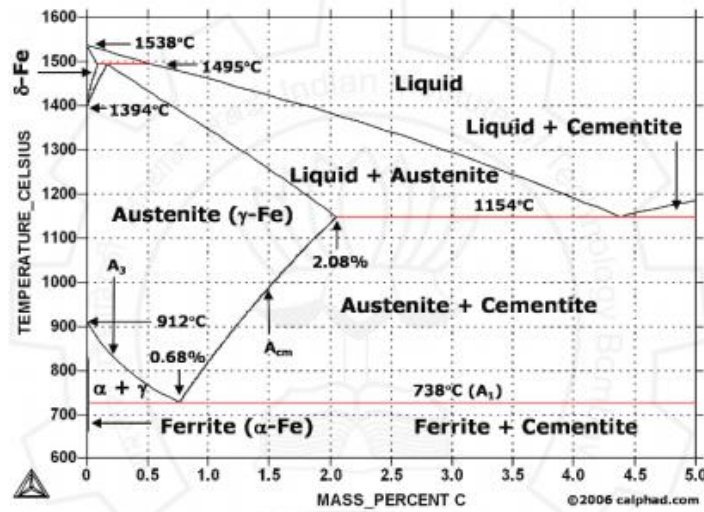


Figure 3.1 Iron Carbon Diagram

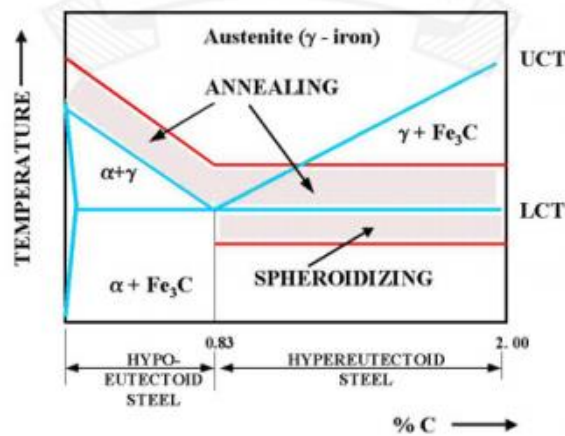


Figure 3.2 Schematic representation of annealing operation

NORMALIZING

Normalizing process consists of three steps. The first step involves heating the steel component above the A₃ temperature for hypoeutectoid steels and above A_{cm} (upper critical temperature for cementite) temperature for hypereutectoid steels by 300 C to 500 C (Figure 3.3). The second

step involves holding the steel component long enough at this temperature for homogeneous austenization. The final step involves cooling the hot steel component to room temperature in still air. Due to air cooling, normalized components show slightly different structure and properties than annealed components. The same are explained in Table 3.1. The properties of normalized components are not much different from those of annealed components. However, normalizing takes less time and is more convenient and economical than annealing and hence is a more common heat treatment in industries. Normalizing is used for high-carbon (hypereutectoid) steels to eliminate the cementite network that may develop upon slow cooling in the temperature range from point A_{cm} to point A_1 . Normalizing is also used to relieve internal stresses induced by heat treating, welding, casting, forging, forming, or machining. Normalizing also improves the ductility without reducing the hardness and strength.

Table 3.1 The variation in the properties of the annealed and normalized components

Annealed	Normalised
<ul style="list-style-type: none"> • Less hardness, tensile strength and toughness. • Pearlite is coarse and usually gets resolved by the optical microscope. • Grain size distribution is more uniform. • Internal stresses are least. 	<ul style="list-style-type: none"> • Slightly more hardness, tensile strength and toughness. • Pearlite is fine and usually appears unresolved with optical microscope. • Grain size distribution is slightly less uniform. • Internal stresses are slightly more.

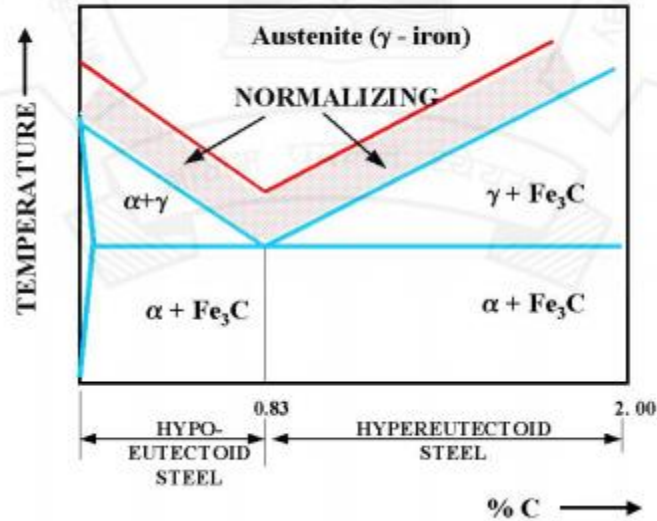


Figure 3.3 Normalizing

HARDENING

Different techniques to improve the hardness of the steels are conventional hardening, martempering and austempering. Conventional hardening process consists of four steps. The first step involves heating the steel to above A_3 temperature for hypoeutectoid steels and above A_1 temperature for hypereutectoid steels by 500. Following are a few salient features in conventional hardening of steel. The second step involves holding the steel components for sufficient soaking time for homogeneous austenization. The third step involves cooling of hot steel components at a rate just exceeding the critical cooling rate of the steel to room temperature or below room temperature. The final step involves the tempering of the martensite to achieve the desired hardness. Detailed explanation about tempering is given in the subsequent sections. In this conventional hardening process, the austenite transforms to martensite. This martensite structure improves the hardness.

1. Proper quenching medium should be used such that the component gets cooled at a rate just exceeding the critical cooling rate of that steel.
2. Alloy steels have less critical cooling rate and hence some of the alloy steels can be hardened by simple air cooling.

3. High carbon steels have slightly more critical cooling rate and has to be hardened by oil quenching.
4. Medium carbon steels have still higher critical cooling rates and hence water or brine quenching is necessary.

Figure 3.4 depicts the conventional hardening process which involves quenching and tempering. During quenching outer surface is cooled quicker than the center. Thinner parts are cooled faster than the parts with greater cross-sectional areas. In other words the transformation of the austenite is proceeding at different rates. Hence there is a limit to the overall size of the part in this hardening process.

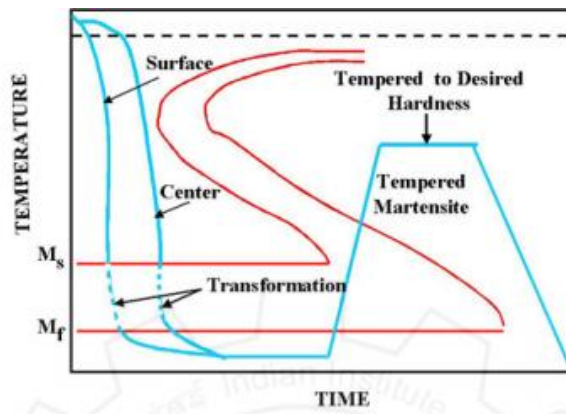


Figure 3.4 Heat treatment cycle for conventional hardening process

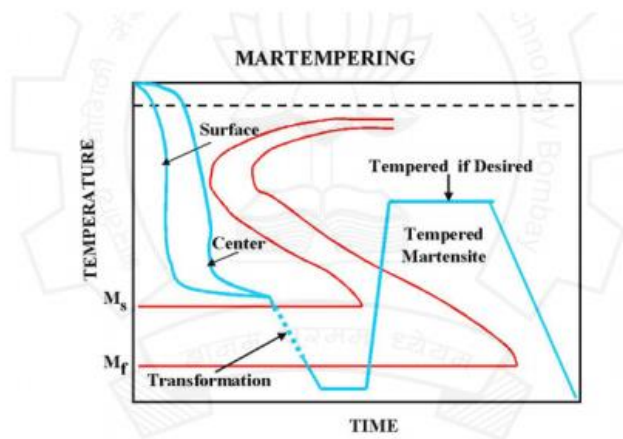


Figure 3.5 Heat treatment cycle for martempering

TEMPERING

The hardened steel is not readily suitable for engineering applications. It possesses following three drawbacks.

- Martensite obtained after hardening is extremely brittle and will result in failure of engineering components by cracking.
- Formation of martensite from austenite by quenching produces high internal stresses in the hardened steel.
- Structures obtained after hardening consists of martensite and retained austenite. Both these phases are metastable and will change to stable phases with time which subsequently results in change in dimensions and properties of the steel in service.

Tempering helps in reduce these problems. Tempering is achieved by heating hardened steel to a temperature below A_1 , which is in the range of 1000 C to 6800 The tempering temperature is decided based on the type of steel. Highly alloyed tool steels are tempered in the range of 500 C, hold the component at this temperature for a soaking period of 1 to 2 hours (can be increases up to 4 hours for large sections and alloy steels), and subsequently cooling back to room temperature. 0 C – 6000 C. Low alloy construction steels are tempered above 4000 C to get a good combination of strength and ductility. Spring steels are tempered between 3000 C – 4000 C to get the desired properties. Figure 3.6 depicts the influence of tempering temperature on the properties of steel. It is observed that the increase in the tempering temperature decreases the hardness and internal stresses while increases the toughness.

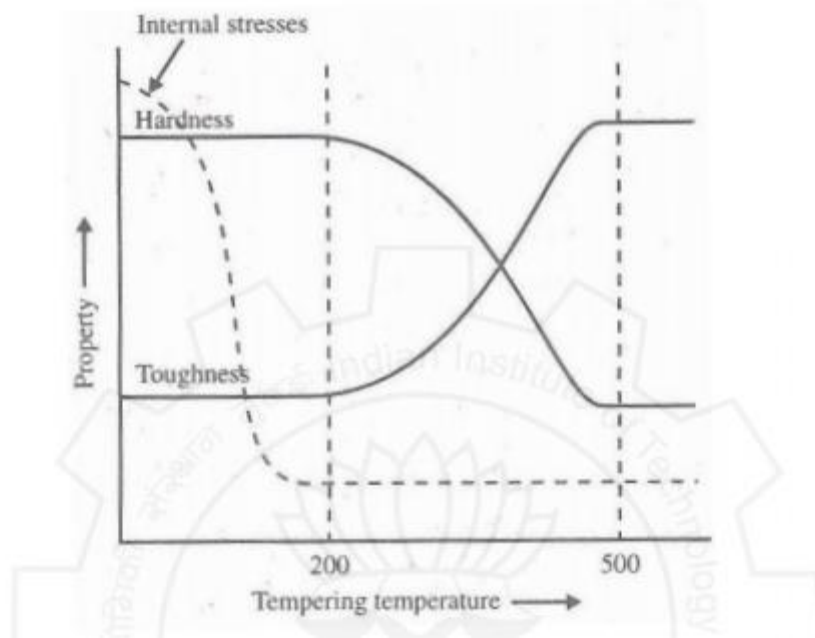


Figure 3.6 Variation in properties with tempering temperature

TIME-TEMPERATURE-TRANSFORMATION (TTT) DIAGRAM

T (Time) T (Temperature) T (Transformation) diagram is a plot of temperature versus the logarithm of time for a steel alloy of definite composition. It is used to determine when transformations begin and end for an isothermal (constant temperature) heat treatment of a previously austenitized alloy. When austenite is cooled slowly to a temperature below LCT (Lower Critical Temperature), the structure that is formed is Pearlite. As the cooling rate increases, the pearlite transformation temperature gets lower. The microstructure of the material is significantly altered as the cooling rate increases. By heating and cooling a series of samples, the history of the austenite transformation maybe recorded. TTT diagram indicates when a specific transformation starts and ends and it also shows what percentage of transformation of austenite at a particular temperature is achieved. Cooling rates in the order of increasing severity are achieved by quenching from elevated temperatures as follows: furnace cooling, air cooling, oil quenching, liquid salts, water quenching, and brine. If these cooling curves are superimposed on the TTT diagram, the end product structure and the time required to complete the

transformation may be found. In Figure 3.7 the area on the left of the transformation curve represents the austenite region. Austenite is stable at temperatures above LCT but unstable below LCT. Left curve indicates the start of a transformation and right curve represents the finish of a transformation. The area between the two curves indicates the transformation of austenite to different types of crystal structures. (Austenite to pearlite, austenite to martensite, austenite to bainite transformation.)

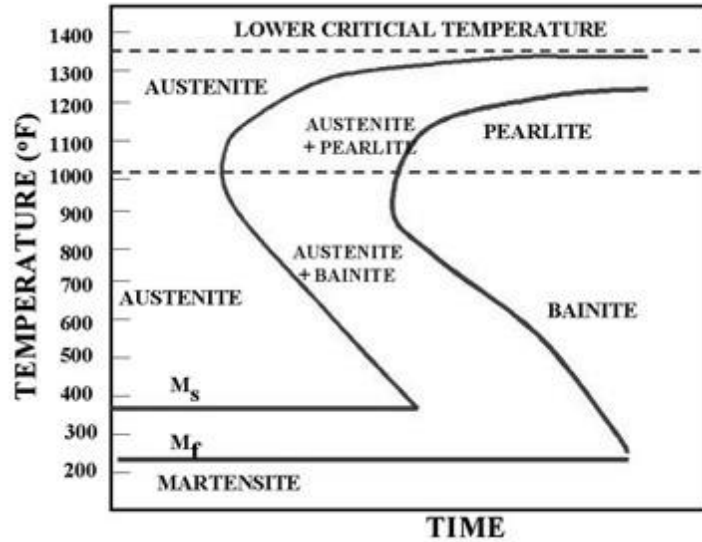


Figure 3.7 TTT diagram

Figure 3.8 represents the upper half of the TTT diagram. As indicated in Figure 3.8, when austenite is cooled to temperatures below LCT, it transforms to other crystal structures due to its unstable nature. A specific cooling rate may be chosen so that the transformation of austenite can be 50 %, 100 % etc. If the cooling rate is very slow such as annealing process, the cooling curve passes through the entire transformation area and the end product of this the cooling process becomes 100% Pearlite. In other words, when slow cooling is applied, all the Austenite will transform to Pearlite. If the cooling curve passes through the middle of the transformation area, the end product is 50 % Austenite and 50 % Pearlite, which means that at certain cooling rates we can retain part of the Austenite, without transforming it into Pearlite.

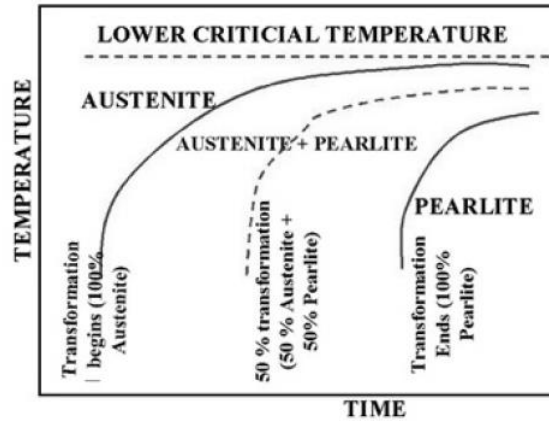


Figure 3.8 Upper half of TTT diagram(Austenite – Pearlite Transformation Area)

Figure 3.8 indicates the types of transformation that can be found at higher cooling rates. If a cooling rate is very high, the cooling curve will remain on the left hand side of the Transformation Start curve. In this case all Austenite will transform to Martensite. If there is no interruption in cooling the end product will be marten site.

HARDENABILITY AND JOMINY END QUENCH TEST

The influence of alloy composition on the ability of a steel alloy to transform to martensite for a particular quenching treatment is related to a parameter called hardenability. For every different steel alloy there is a specific relationship between the mechanical properties and the cooling rate.

Hardenability is used to describe the ability of an alloy to be hardened by the formation of martensite as a result of a given heat treatment. One standard procedure that is widely utilized to determine hardenability is the Jominy end quench test. The heating and cooling treatment of the steel specimens have a great effect on the phase of the microstructure of the steel specimen. The addition of alloys or coarsening of the austenitic grain structure increase the hardenability of steel. Any steel that has low critical cooling rate will harden deeper than one that has a high cooling rate of quenching. The size of the part that is being quenched has a direct effect upon the hardenability of the material. The objective of the experiment is to take readings in the Rockwell C scale along the flat surface of the Jominy specimen and to plot Hardness versus distance from quenched end. Equipment: Electric Furnace, Jominy End Quench Test Fixture, Jominy Specimens (Made as per ASTM standard), Rockwell Hardness Testing Machine.

Procedure:

1. Preheat the furnace to 1700°F.
2. Place the Jominy specimen in the furnace and soak for one hour.
3. Turn the water on at the Jominy sink. Adjust the free water column to about 2.5 in. Swivel the baffle plate to block the water column so that there is no contact between water and the test specimen when the test specimen is initially placed on the fixture.
4. Remove the Jominy specimen from the furnace and place it in the fixture as shown in Figure 3.9. Swivel the baffle out of position so that the water impinges on the bottom of the specimen without wetting the sides of the specimen. Leave water running for about 15 minutes.
5. Remove the Jominy specimen from the fixture and grind a flat on the side of the specimen.
6. Mark points on the ground surface at an interval of 1/16 in. up to 2 in. distance from the quenched end as shown in Figure 3.10.
7. Take readings at an interval of 1/16 in. by measuring the Rockwell C hardness at each point marked in the previous step.
8. Plot the data for Rockwell Hardness versus Distance from quenched end as shown in Figure 3.11.

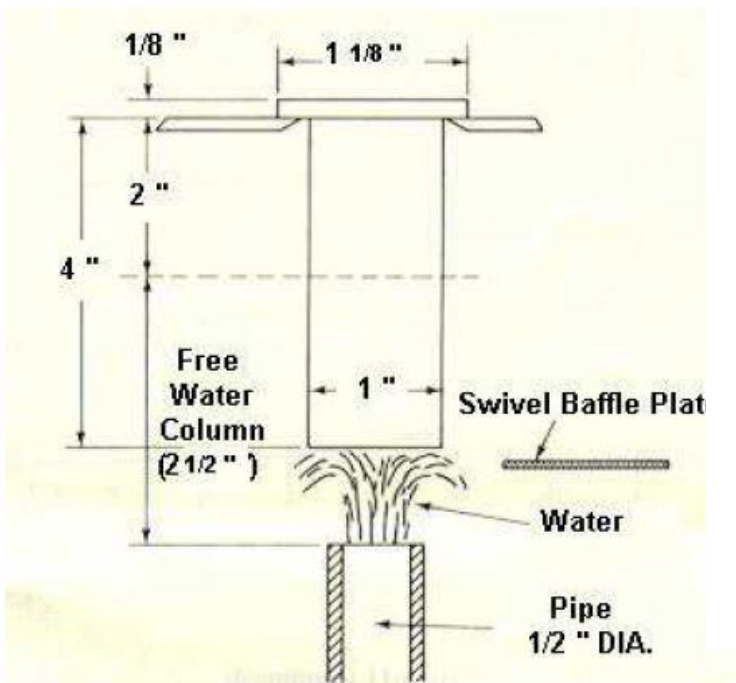


Figure 3.9 Jominy end quench fixture specimen

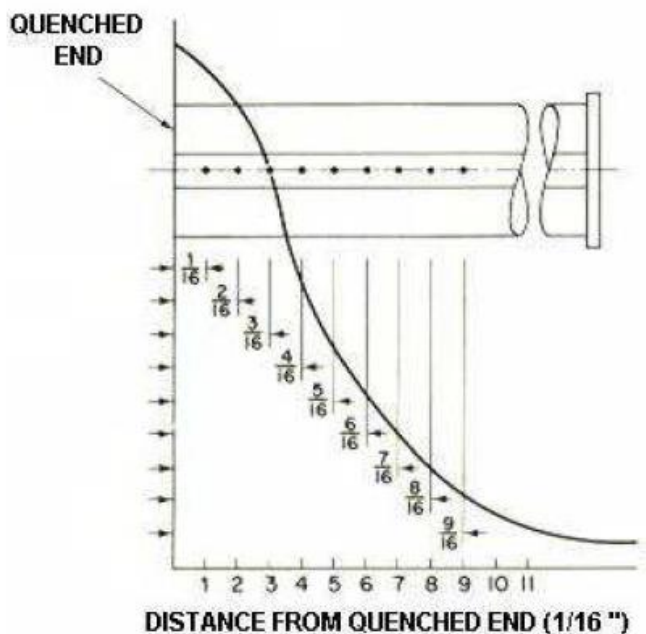


Figure 3.10 Distance marked in

Determining the Hardenability of a Material:

In the Jominy test the quenching medium is eliminated from consideration by standardizing the effect of the quenching medium on a steel sample regardless of the medium. This is designated by the ratio of the heat transfer factor F to the thermal conductivity K of the material. This ratio is called H-factor which indicates the severity of a cooling rate.

$H = F/K$	F= Heat transfer factor	
	H= Thermal conductivity	
H-Factor	Quench Conditions	Agitation
0.20	Poor oil quench	None
0.70	Strong oil quench	Violent
1.00	Poor water quench	None
1.50	Very good water quench	Strong
2.00	Brine quench	None
5.00	Brine quench	Violent

Transformation

During rapid cooling (quenching) of austenite, athermal martensitic transformation begins at the martensite start temperature (M_s). Thereafter, the volume fraction of martensite increases with decreasing temperature and finally, the transformation is completed on reaching the martensite finish temperature (M_f). In the case of stress assisted martensite, the martensite start temperature at a given stress level σ is termed M_s^σ .

Fig. 3.11 shows the microstructural images obtained during an in situ observation, by using laser scanning confocal microscope, of plate martensite formation by means of a thermal transformation during rapid quenching of a high carbon steel with a composition of Fe-0.88%C-4.12 %Cr, expressed in mass % [22]. The real time and temperature can be seen in the upper left corner. Slightly above the M_s , one can see untransformed austenite grains in Fig. 3.11a. Slightly below the M_s , martensitic transformation initiates in a heterogeneous manner, i.e. nucleation occurs at different sites as can be seen in Fig. 3.11b. One can see, in Fig. 3.11b, the untransformed austenite grains as well as partly transformed austenite grains with martensite

plates. At a temperature close to M_f , one can see almost completely transformed steel with complex martensitic microstructure containing several martensite plates oriented in different directions, as shown in Fig. 3.11c. Thus it can be understood that the martensite volume fraction increases with decreasing temperature.

During rapid cooling, a diffusion controlled transformation of austenite to ferrite, with a very low carbon content, does not occur due to lack of time. However as the temperature is reduced below the T_0 temperature, i.e. the temperature where the Gibbs energies of ferrite and austenite are the same, there exists a thermodynamic driving force available for the formation of ferrite (martensite) with the same composition as that of austenite, i.e. occurrence of a diffusionless phase transformation. Martensitic transformation leads to the crystallographic transformation of face centered cubic (FCC) austenite into body centered cubic (BCC) martensite. The carbon atoms that are randomly distributed on the interstitial sites in FCC do not have time to migrate to the BCC in a random manner and hence move in a coordinated motion. This increases the tetragonality of the BCC lattice and thus the carbon containing martensite is of body centered tetragonal (BCT) structure. The tetragonality of martensite increases with increasing carbon content.

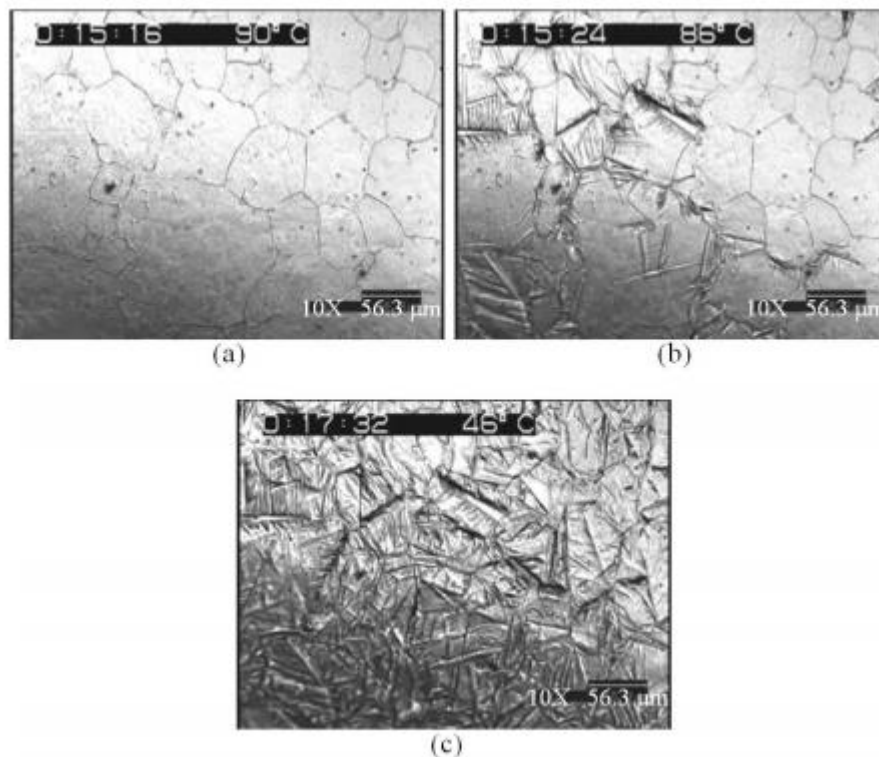


Figure 3.11: In situ observation, by using laser scanning confocal microscope, of plate martensite formation in a high carbon steel, where the real transformation time and temperature are marked in the upper left corner. (a) Microstructure at a temperature slightly above M_s . (b) Microstructure at slightly below M_s . (c) Final martensitic microstructure at a temperature close to M_f .

SUB ZERO TREATMENT OF STEEL

A Certain amount of retained Austenite may always be found in hardened steel. Retained Austenite reduces the hardness, wear resistance and thermal conductivity of steel and makes its dimensions unstable.

‘A Sub Zero Treatment’ has been devised to reduce the retained Austenite in hardened steel. It consists in cooling the metal to Sub Zero Temperature. This treatment is suitable only when the temperature at which the Martensite transformation is completed (M_f) is below Zero. Cooling to M_f transforms the retained austenite into Martensite. This increases the hardness of the part and its dimensions will become more stable. There is no purpose in cooling below M_f since no additional transformation of retained austenite occurs below this temperature.

Sub Zero Treatment is usually conducted in the defined temperature and holding time at this temperature from 1 to 1.5 hrs. Prolonged holding at room temperature after hardening will stabilize the austenite of many grades of steels and reduce the effect if sub zero Treatment directly following the hardening operation. Sub Zero Treatment is most frequently used for HSS tools, Measuring tools and also for carburized gears and other machined components.

SURFACE HARDENING PROCESS,

Surface hardening a process that includes a wide variety of techniques, is used to improve the wear resistance of parts without affecting the softer, tough interior of the part. This combination of hard surface and resistance to breakage upon impact is useful in parts such as a cam or ring gear, bearings or shafts, turbine applications, and automotive components that must have a very hard surface to resist wear, along with a tough interior to resist the impact that occurs during operation. Most surface treatments result in compressive residual stresses at the surface that reduce the probability of crack initiation and help arrest crack propagation at the case-core interface. Further, the surface hardening of steel can have an advantage over through hardening

because less expensive low-carbon and medium carbon steels can be surface hardened with minimal problems of distortion and cracking associated with the through hardening of thick sections. There are two distinctly different approaches to the various methods for surface hardening. Methods that involve an intentional buildup or addition of a new layer Methods that involve surface and subsurface modification without any intentional buildup or increase in part dimensions The first group of surface-hardening methods includes the use of thin films, coatings, or weld overlays (hard-facings). Films, coatings, and overlays generally become less cost-effective as production quantities increase, especially when the entire surface of workpieces must be hardened. The fatigue performance of films, coatings, and overlays may also be a limiting factor, depending on the bond strength between the substrate and the added layer. Fusion welded overlays have strong bonds, but the primary surface-hardened steels used in wear applications with fatigue loads include heavy case-hardened steels and flame- or induction hardened steels. Nonetheless, coatings and overlays can be effective in some applications. With tool steels, for example, TiN and Al₂O₃ coatings are effective not only because of their hardness but also because their chemical inertness reduces crater wear and the welding of chips to the tool. Some overlays can impart corrosion-resistant properties. Overlays can be effective when the selective hardening of large areas is required.

This introductory article on surface hardening focuses exclusively on the second group of methods, which is further divided into diffusion methods and selective-hardening methods (Table 1). Diffusion methods modify the chemical composition of the surface with hardening species such as carbon, nitrogen, or boron. Diffusion methods may allow effective hardening of the entire surface of a part and are generally used when a large number of parts are to be surface hardened. In contrast, selective surface-hardening methods allow localized hardening. Selective hardening generally involves transformation hardening (from heating and quenching), but some selective-hardening methods (selective nitriding, ion implantation, and ion beam mixing) are based solely on compositional modification.

UNIT – IV

NON FERROUS ALLOYS

Non ferrous alloys : copper , aluminium, nickel, zinc and lead based alloys – concepts and applications of metal matrix composites.

Mechanical properties of materials and testing of materials: tensile, compression, torsion, hardness, impact testing

COPPER ALLOY

In general, most copper alloys eventually weather to the gray-green patina. There are, however, significant variations in their natural colors and in the rate at which they form a patina. The last two columns in Table 4.1 contain information about the natural and weathered colors of the alloys. Table 4.2 is a color matching table. It depicts which alloys, in various forms, are reasonably well matched in color with the sheet, strip, and plate copper alloys.

Copper Alloy Table

Table 4.1 Common Copper Alloys				
Alloy	Common Term	Composition	Color	
			Natural	Weathered
C11000 / C12500	Copper	99.90% Copper	Salmon Red	Reddish-Brown to Gray-Green Patina
C12200	Copper	99.90% Copper 0.02% Phosphorous	Salmon Red	Reddish-Brown to Gray-Green Patina
C22000	Commercial Bronze	90% Copper 10% Zinc	Red Gold	Brown to Gray-Green Patina in Six Years
C23000	Red Brass	85% Copper 15% Zinc	Reddish Yellow	Chocolate Brown to Gray-Green Patina
C26000	Cartridge Brass	70% Copper 30% Zinc	Yellow	Yellowish, Gray-Green
C28000	Muntz Metal	60% Copper 40% Zinc	Reddish Yellow	Red-Brown to Gray-Brown
C38500	Architectural Bronze	57% Copper 3% Lead 40% Zinc	Reddish Yellow	Russet Brown to Dark Brown

Alloy	Common Term	Composition	Color	
			Natural	Weathered
C65500	Silicon Bronze	97% Copper 3% Silicon	Reddish Old Gold	Russet Brown to finely mottled Gray-Brown
C74500	Nickel Silver	65% Copper 25% Zinc 10% Nickel	Warm Silver	Gray-Brown to finely mottled Gray-Green
C79600	Leaded Nickel Silver	45% Copper 42% Zinc 10% Nickel 2% Manganese 1% Lead	Warm Silver	Gray-Brown to finely mottled Gray-Green

ALUMINUM (Al)

Aluminium and its alloys are used in many fields, whether in daily life or industrially. The reasons why aluminium and its alloys are common use is because they have low density, they are easy to work with, they have high electrical conductivity, and they have high heat conductivity. However, aside from the advantages listed above, the engineering applications for aluminium and alloys are limited due to poor surface properties, and low abrasion resistance. For many commercial Al alloys, the desirable mechanical properties are developed by adding alloys and applying heat treatment to heterogeneous microstructures. It is possible that adding alloying elements affects the wear properties of Al-Si-Mg, as it strengthens them through solid solution and hardening precipitation. Ce, Cu, Cr, Fe, Mn, Ti, Zn, and Zr are some of the alloying elements that are added to these alloys. The added alloying elements either dissolve or form compounds within the microstructure.

Strongest and most frequently used deoxidiser and degasifier, favors insensibility to aging. Added in small amounts, it helps fine grain formation. Since it combines with nitrogen to form very hard nitride, it is a favorable alloy constituent in nitriding steels. Aluminum - killed steels exhibit a high order of fracture toughness.

Applications

The properties of the various aluminium alloys has resulted in aluminium being used in industries as diverse as transport, food preparation, energy generation, packaging, architecture, and electrical transmission applications. Depending upon the application, aluminium can be used to replace other materials like copper, steel, zinc, tin plate, stainless steel, titanium, wood, paper, concrete and composites.

NICKEL

Nickel (Ni) is classified as a borderline element between hard and soft acid acceptors in chemical interactions toward donor atoms. This is reflected in its abundance in the earth's crust as oxides, carbonates, silicates with iron, magnesium, and as sulphides, arsenides and tellurides. Nickel is one of the major elemental constituents of the earth, constituting approximately 2% by mass. However, it is a minor constituent (0,01%) on the earth's crust.

Nickel is silvery white, malleable and ductile. It possesses good thermal and electrical conductivity, moderate strength, and hardness. It takes and retains high polish. Although nickel can achieve oxidation states from -1 to $+4$, compounds of the $+2$ state are most common. Nickel alloys have been known to man since 3 500 BC. The use of alloys for coinage dates back to 327 BC in the Bactrian Kingdom (North of Afghanistan). Therapeutic uses were discontinued in the early part of this century after clear demonstration of its acute and chronic toxicity.

Production

The demand for nickel in coinage, electroplating, and alloys has increased strongly since 1850, resulting in an exponential increase in the world mine production of the metal. Nickel continues to be a vital commodity in every area of industrial activity. It is essential that the growth in demand will moderate to 3,5 – 4,5% in the last two decades of this century due to the awareness of the finite nature of world resources.

Uses

The physical properties of nickel, such as corrosion resistance, high strength and durability over a wide range of temperatures, pleasing appearance, good thermal and electrical conductivity, and alloying ability are the main advantages in almost all uses of the metal. More than 75% of nickel produced is consumed in the production of alloys. There are more than 3 000 different alloys including stainless steel and alloy steels, ductile and cast iron, cupronickels and high nickel alloys. Stainless steel is the largest single outlet, followed by plating and high nickel alloys. Addition of nickel to ferrous alloys maximises the mechanical, physical and chemical properties of the product. It also enhances the flexibility of the alloy during fabrication. Stainless steel is primarily used in the field of rapid transit and railway car manufacture, in chemical industries including fertiliser manufacture and food processing machinery, petroleum refining, and in architectural applications.

ZINC AND ITS ALLOYS

- Zinc can be extracted from zinc sulphide (ZnS) or zinc blende or sphalerite.
- Found in many countries such as USA, Mexico, Peru, etc., and also in Thailand.

Ores are found in the forms of

- 1) Smithsonite (ZnCO_3) – 67% Zn
- 2) Hemimorphite or ($\text{Zn}_4\text{Si}_2\text{O}_7(\text{OH})_2\cdot\text{H}_2\text{O}$). – 54.2% Zn

3) Zincite (ZnO)

4) Willemite (Zn_2SiO_4) – 58.5%.

There are two methods of zinc extraction;

1) Pyrometallurgy

2) Hydrometallurgy

Physical properties of zinc

- Crystal structure HCP HCP
 - c/a ratio 1.856
 - Density (g.cm^{-3}) 7.14
 - Atomic weight 65.39
 - Atomic number 30
 - Melting point ($^{\circ}\text{C}$) 419.6
 - Boiling point ($^{\circ}\text{C}$) 906
- Zinc recrystallises and creeps near room temperature so it cannot be strain-hardened significantly.
 - Most structural zinc is used in the form of die casting (has advantage of a low melting point).
 - Good strength but low toughness and low creep strength. Cannot be used for high temperature applications.
 - Anisotropic properties due to HCP structure.

Classification of zinc alloys

Zinc alloys can be mainly classified into to

1) Zinc casting alloys

- Conventional zinc casting alloys (4% Al)
- Zn-Al (ZA) casting alloys

2) Wrought zinc alloys

- Zn-Pb alloys
- Zn-Cd alloys
- Zn-Cu alloys

Advantages of zinc alloys

- 1) Ability of zinc to die cast at high productivity rates due to zinc's relatively low melting point (419°C).
- 2) Ability to produce near-net shapes of intricate designs with close dimensional tolerance and good surface finishes.
- 3) Zinc die castings can be machined, bent, swaged or coined for finishing.
- 4) Zinc die castings can be riveted, welded, and soldered in assembly operations.
- 5) Relatively good atmospheric corrosion resistance, especially in Cr solution (forming surface passive film).
- 6) Sufficient strength for some applications.
- 7) Cost of Zn is competitive with Al and Cu alloys for many applications.

Applications

- Used for automobile parts such as handles, locks mechanical and electrical components.
- Body hardware, light fittings, instruments.
- Galvanic coating on steels.

Metal Matrix Materials

Metal matrix composites, at present though generating a wide interest in research fraternity, are not as widely in use as their plastic counterparts. High strength, fracture toughness and stiffness are offered by metal matrices than those offered by their polymer counterparts. They can withstand elevated temperature in corrosive environment than polymer composites. Most metals and alloys could be used as matrices and they require reinforcement materials which need to be stable over a range of temperature and non-reactive too. However the guiding aspect for the choice depends essentially on the matrix material. Light metals form the matrix for temperature application and the reinforcements in addition to the aforementioned reasons are characterized by high moduli.

Most metals and alloys make good matrices. However, practically, the choices for low temperature applications are not many. Only light metals are responsive, with their low density proving an advantage. Titanium, Aluminium and magnesium are the popular matrix metals

currently in vogue, which are particularly useful for aircraft applications. If metallic matrix materials have to offer high strength, they require high modulus reinforcements. The strength-to-weight ratios of resulting composites can be higher than most alloys.

The melting point, physical and mechanical properties of the composite at various temperatures determine the service temperature of composites. Most metals, ceramics and compounds can be used with matrices of low melting point alloys. The choice of reinforcements becomes more stunted with increase in the melting temperature of matrix materials.

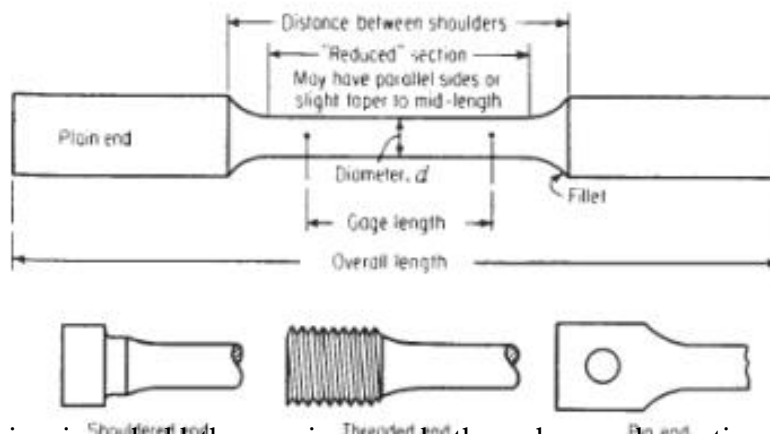
MECHANICAL PROPERTIES OF MATERIALS AND MECHANICAL TESTS

Static tensile and compressive testing are the most fundamental tests to define material properties. Typically, the tests are carried out by increasing the uniaxial load gradually, i.e., statically, until failure occurs. Properties to be defined through testing include:

- Strengths: yield, ultimate, rupture, etc.
- Strains
- Elastic modulus,
- Poisson's ratio
- Elongation, and shortening
- Uniaxial stress - strain relationships

Tensile Test

A tensile test specimen for metal has three portions, the central testing portion and two dummy ends for setting in the testing machine, as shown in Figure 4.1. A gradual fillet transit is typically shaped between the testing portion and the end to avoid stress concentration. The ends may be of any shape, plain or threaded, to fit the holders of the testing machine in such a way that the load is axial.



The gripping jaws hold the specimen ends through a wedge action. A universal testing machine typically can provide two types of outputs for tensile testing, i.e., the load through the built in load cell, and the loading platen displacement. The loading platen displacement, however, cannot be used to determine the strain of the specimen, since it involves the

deformation of the machine system. The true specimen deformation must be detected using the extensometers. Most modern computer controlled universal testing machines allow the connection of extensometers and output the readings.

Compression Test

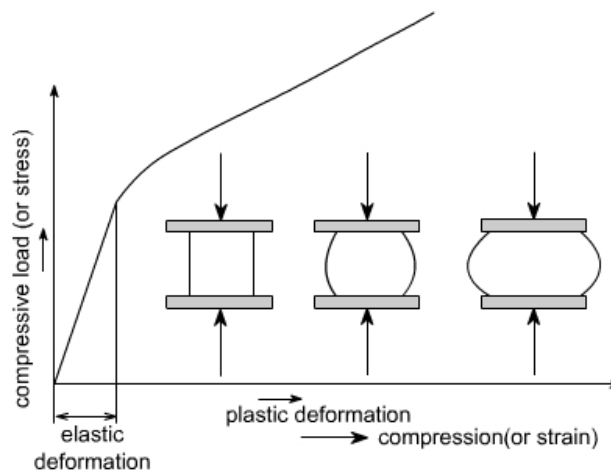
Machines used for compression testing are basically similar to those used for tensile testing often the same machine can be used to perform both tests.

Shape of the specimen: The shape of the machine to be used for the different materials is as follows:

- (i) **For metals and certain plastics:** The specimen may be in the form of a cylinder
- (ii) **For building materials:** Such as concrete or stone the shape of the specimen may be in the form of a cube.

Shape of stress strain diagram

- (a) **Ductile materials:** For ductile material such as mild steel, the load Vs compression diagram would be as follows.

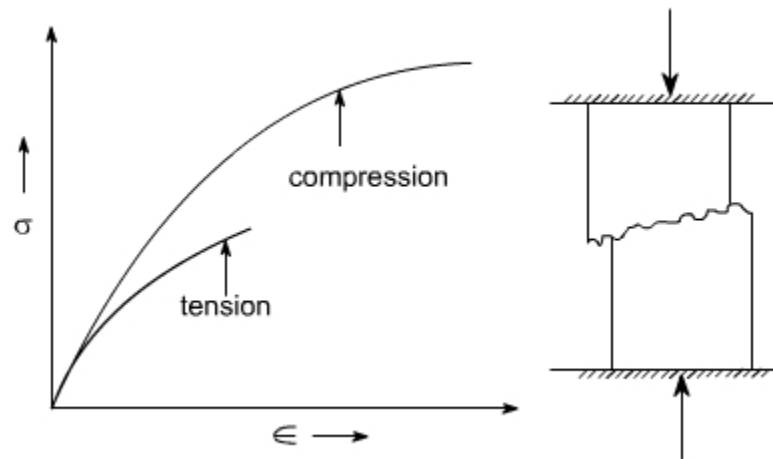


- (1) The ductile materials such as steel, Aluminum, and copper have stress – strain diagrams similar to ones which we have for tensile test, there would be an elastic range which is then followed by a plastic region.
- (2) The ductile materials (steel, Aluminum, copper) proportional limits in compression test are very much close to those in tension.
- (3) In tension test, a specimen is being stretched, necking may occur, and ultimately fracture takes place. On the other hand when a small specimen of the ductile material is compressed,

it begins to bulge on sides and becomes barrel shaped as shown in the figure above. With increasing load, the specimen is flattened out, thus offering increased resistance to further shortening (which means that the stress – strains curve goes upward) this effect is indicated in the diagram.

Brittle materials (in compression test)

Brittle materials in compression typically have an initial linear region followed by a region in which the shortening increases at a higher rate than does the load. Thus, the compression stress – strain diagram has a shape that is similar to the shape of the tensile diagram. However, brittle materials usually reach much higher ultimate stresses in compression than in tension. For cast iron, the shape may be like this.



Brittle materials in compression behave elastically up to certain load, and then fail suddenly by splitting or by cracking in the way as shown in figure. The brittle fracture is performed by separation and is not accompanied by noticeable plastic deformation.

Hardness Testing:

The term 'hardness' is one having a variety of meanings; a hard material is thought of as one whose surface resists indentation or scratching, and which has the ability to indent or cut other materials.

Hardness test: The hardness test is a comparative test and has been evolved mainly from the need to have some convenient method of measuring the resistance of materials to scratching, wear or in dentation this is also used to give a guide to overall strength of a materials, after as an inspection procedure, and has the advantage of being a non – destructive test, in that only small indentations are left permanently on the surface of the specimen.

Four hardness tests are customarily used in industry namely

- (i) Brinell
- (ii) Vickers
- (iii) Rockwell
- (vi) Shore Scleroscopy

The most widely used are the first two.

In the Brinell test the indenter is a hardened steel ball which is pressed into the surface using a known standard load. The diameter of resulting indentation is then measured using a microscope & scale.

Units:

The units of Brinell Hardness number in S.I Unit would have been N/mm^2 or Mpa To avoid the confusion which would have been caused of her wise Hardness numbers are quotes as kgf / mm^2

Brinell Hardness test:

In the Brinell hardness test, a hardened steel ball is pressed into the flat surface of a test piece using a specified force. The ball is then removed and the diameter of the resulting indentation is measured using a microscope.

$$BHN = P / A$$

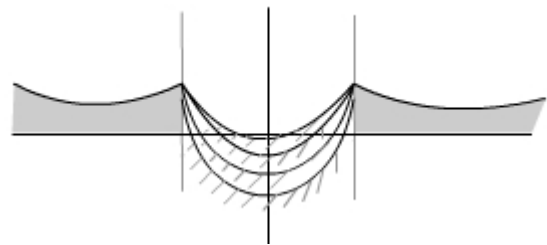
Where P = Force applied to the ball.

A = curved area of the indentation

It may be shown that $A = \frac{1}{2} \pi D \left[D - \sqrt{D^2 - d^2} \right]$

D = diameter of the ball,

d = the diameter of the indentation.



Disadvantage of Brinell Hardness Test: The main disadvantage of the Brinell Hardness test is that the Brinell hardness number is not independent of the applied load. This can be realized from. Considering the geometry of indentations for increasing loads. As the ball is pressed into the surface under increasing load the geometry of the indentation changes.

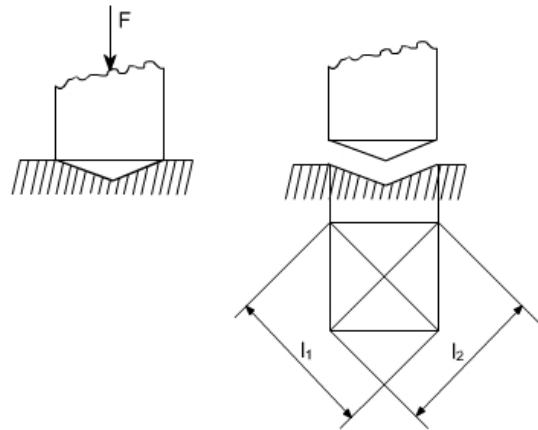
Vickers Hardness test:

The Vicker's Hardness test follows a procedure exactly identical with that of Brinell test, but uses a different indenter. The steel ball is replaced by a diamond, having the form of a square – based pyramid with an angle of 136° between opposite faces. This is pressed into the flat surface of the test piece using a specified force, and the diagonals of the resulting indentation measured are using a microscope. The Hardness, expressed as a Vicker's pyramid number is defined as the ratio F/A , where F is the force applied to the diamond and A is the surface area of the indentation.

$$A = \frac{\frac{1}{2}l^2}{\sin \frac{1}{2}(136^\circ)}$$
$$= \frac{l^2}{.854} \Rightarrow H_V = \frac{F}{.854}$$

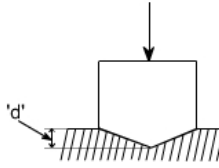
$$H_V = \frac{.854F}{l^2}$$

where l is the average length of the diagonal is $l = \frac{1}{2}(l_1 + l_2)$



Rockwell Hardness Test:

The Rockwell Hardness test also uses an indenter when is pressed into the flat surface of the test piece, but differs from the Brinell and Vicker's test in that the measurement of hardness is based on the depth of penetration, not on the surface area of indentation. The indenter may be a conical diamond of 120° included angle, with a rounded apex. It is brought into contact with the test piece, and a force F is applied.



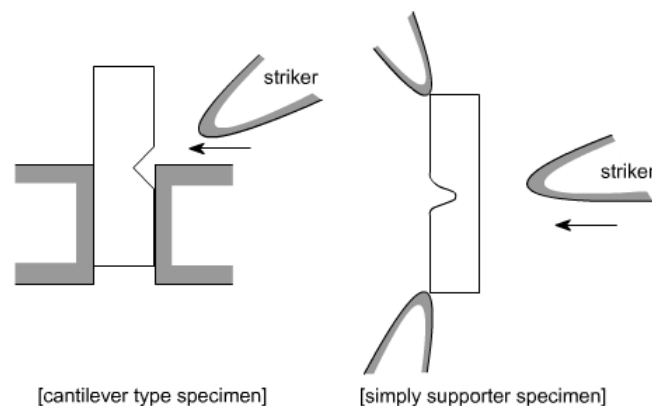
Advantages:

Rockwell tests are widely applied in industry due to rapidity and simplicity with which they may be performed, high accuracy, and due to the small size of the impressions produced on the surface.

Impact testing:

In an 'impact test' a notched bar of material, arranged either as a cantilever or as a simply supported beam, is broken by a single blow in such a way that the total energy required to fracture it may be determined.

The energy required to fracture a material is of importance in cases of "shock loading" when a component or structure may be required to absorb the K.E of a moving object. Often a structure must be capable of receiving an accidental 'shock load' without failing completely, and whether it can do this will be determined not by its strength but by its ability to absorb energy. A combination of strength and ductility will be required, since large amounts of energy can only be absorbed by large amounts of plastic deformation. The ability of a material to absorb a large amount of energy before breaking is often referred as toughness, and the energy absorbed in an impact test is an obvious indication of this property. Impact tests are carried out on notched specimens, and the notches must not be regarded simply as a local reduction in the cross-sectional area of the specimen, Notches – and , in fact, surface irregularities of many kind – give rise to high local stresses, and are in practice, a potential source of cracks.



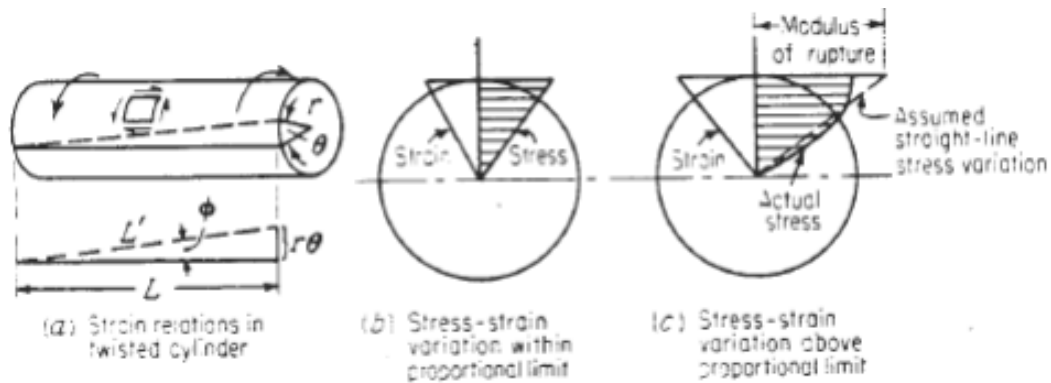
The specimen may be of circular or square cross – section arranged either as a cantilever or a simply supported beam.

Toughness:

It is defined as the ability of the material to withstand crack i.e to prevent the transfer or propagation of cracks across its section hence causing failures. Cracks are propagated due to stress concentration.

Torsion Tests

Torsion, as shown in the figure, often exists in machinery structural members and parts. Since a pure shear stress state can be obtained, shear strain can be easily measured. Torsion test is typically used in determining shear modulus of metal.



As shown in Figure, the following relationships exist for torsion members, stress: $\tau_{max} = Tr/J$ where, the J is the polar moment of inertia and $J = \pi r^4/32$, for circle. angle of twist: $\phi = TL/JG$. Direct torsion test is typically conducted using torsion testing machine, which is capable to apply and measure the torques.

UNIT - V

PLASTIC DEFORMATION

Material deformation can be permanent or temporary. Permanent deformation is irreversible i.e. stays even after removal of the applied forces, while the temporary deformation disappears after removal of the applied forces i.e. the deformation is recoverable. Both kinds of deformation can be function of time, or independent of time.

Temporary deformation is called elastic deformation, while the permanent deformation is called plastic deformation. Time dependent recoverable deformation under load is called anelastic deformation, while the characteristic recovery of temporary deformation after removal of load as a function of time is called elastic aftereffect. Time dependent i.e. progressive permanent deformation under constant load/stress is called creep. For viscoelastic materials, both recoverable and permanent deformations occur together which are time dependent. When a material is subjected to applied forces, first the material experiences elastic deformation followed by plastic deformation. Extent of elastic- and plastic- deformations will primarily depend on the kind of material, rate of load application, ambient temperature, among other factors.

ELASTIC DEFORMATION

Elastic deformation is reversible i.e. recoverable. Up to a certain limit of the applied stress, strain experienced by the material will be the kind of recoverable i.e. elastic in nature. This elastic strain is proportional to the stress applied. The proportional relation between the stress and the elastic strain is given by Hooke's law, which can be written as follows:

$$\sigma \propto \varepsilon$$

$$\sigma = E\varepsilon$$

where the constant E is the modulus of elasticity or Young's modulus,

PLASTIC DEFORMATION

When the stress applied on a material exceeds its elastic limit, it imparts permanent non recoverable deformation called plastic deformation in the material. Microscopically it can be said of plastic deformation involves breaking of original atomic bonds, movement of atoms and the restoration of bonds i.e. plastic deformation is based on irreversible displacements of atoms through substantial distances from their equilibrium positions. The mechanism of this deformation is different for crystalline and amorphous materials. For crystalline materials, deformation is accomplished by means of a process called slip that involves motion of dislocations. In amorphous materials, plastic deformation takes place by viscous flow

mechanism in which atoms/ions slide past one another under applied stress without any directionality.

MECHANISMS OF PLASTIC DEFORMATION IN METALS

Plastic deformation, as explained in earlier section, involves motion of dislocations. There are two prominent mechanisms of plastic deformation, namely slip and twinning. Slip is the prominent mechanism of plastic deformation in metals. It involves sliding of blocks of crystal over one other along definite crystallographic planes, called slip planes. In physical words it is analogous to a deck of cards when it is pushed from one end.

Slip occurs when shear stress applied exceeds a critical value. During slip each atom usually moves same integral number of atomic distances along the slip plane producing a step, but the orientation of the crystal remains the same. Steps observable under microscope as straight lines are called slip lines. Slip occurs most readily in specific directions (slip directions) on certain crystallographic planes. This is due to limitations imposed by the fact that single crystal remains homogeneous after deformation. Generally slip plane is the plane of greatest atomic density, and the slip direction is the close packed direction within the slip plane. It turns out that the planes of the highest atomic density are the most widely spaced planes, while the close packed directions have the smallest translation distance. Feasible combination of a slip plane together with a slip direction is considered as a slip system.

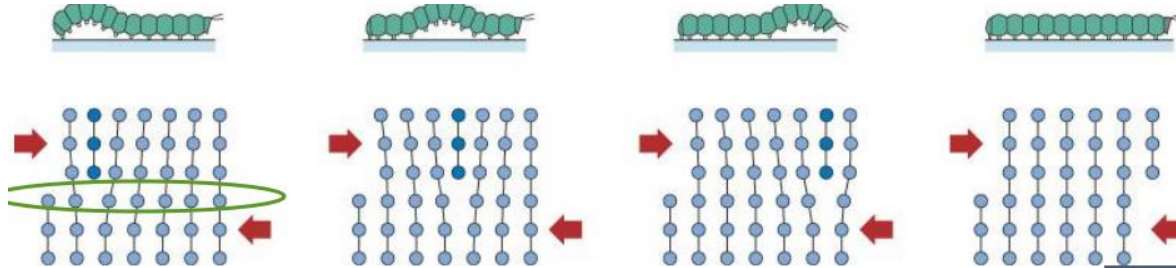


Figure 5.1 Slip

Twinning occurs as atoms on one side of the boundary (plane) are located in mirror image positions of the atoms on the other side. The boundary is called twinning boundary.

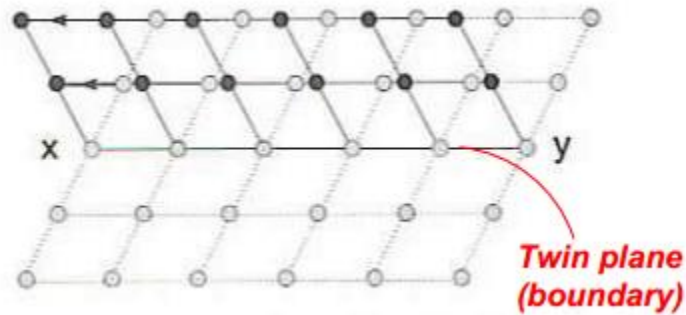


Figure 5.2 Twinning

Twin results from atomic displacements produced from;

- 1) Applied mechanical shear force (mechanical twin) : in BCC, HCP
- 2) During annealing heat treatment (annealing twin) : in FCC

Comparisons of twinning and slip:

Slip	Twinning
Similar orientations of the crystal above and below the slip plane	Different orientations of the crystal above and below the twinning plane
Slip normally occurs in discrete multiples of the atomic spacing.	Atom movements in twinning are much less than an atomic distance
Slip occurs on relatively widely spaced plane	Twinning occurs in a region of a crystal of every atomic plane involved in the deformation.

Other characteristics of twins:

- Does not produce large amount of gross deformation due to small lattice strain. HCP metals therefore have low ductility.
- Does not largely contribute to plastic deformation but change the orientations which may place new (favorable) slip systems. Additional slips can take place.
- Twins do not extends beyond grain boundaries.
- The driving force for twinning is the applied shear stress.

DEFORMATION PROCESSING

The ultimate goal of a manufacturing engineer is to produce steel components with required geometrical shape and structurally optimized for a given application. One of the method is the deformation processing. Deformation processing exploits the ability of steel to flow plastically without altering the other properties. The required forces are often very high. Cast ingots, slabs, blooms and billets are reduced in size and converted into plates, sheets, rods and others. These forms experience further deformation to produce the desired products formed by processes such as forging, extrusion and other sheet metal forming. The deformation may be bulk flow in three dimensions, simple shearing, simple bending, or any combination of these and other processes. The stresses could either be tensile or compressive or shear or combination of them. In this connection the steel chemistry and cleanliness are important factors for deformation processing. In the following, some aspect of deformation processing is discussed. This is given to appreciate the efforts of steelmakers in producing quality steels. The readers should also understand the reverse engineering approach and to appreciate the steelmaking. Deformation processing can be carried out either under hot or cold condition. In the following general features of hot and cold working are described. Details can be obtained in any text book on deformation processing.

HOT WORKING

It is plastic deformation of metals above their recrystallization temperatures. Hot working of steel requires to heat steel near 1000o C for plastic deformation. Hot working of steel involves the deformation of fcc austenite.

- Hot working does not produce strain hardening. Hence no increase in either yield strength or hardness occurs. In addition yield strength decreases as temperature increases and the ductility improves.
- Hot working can be used to drastically alter the shape of metals without fear of fracture and excessively high forces.
- Elevated temperatures promote diffusion that can remove chemical in homogeneties; pores can be welded or reduced in size during deformation.
- The dendritic grain structure, small gas cavities and shrinkage porosity formed during solidification in large sections can be modified by hot working to produce a fine, randomly oriented, spherical-shaped grain structure which results in a net increase in strength, ductility and toughness.
- Hot working results in reorientation of inclusions or impurity particles in the metal with the result that an impurity originally oriented so as to aid crack movement through the metal can be reoriented into a “crack arrestor” configuration. The various hot working processes are rolling, extrusion, forging, hot drawing etc.

Cold working

Cold working is plastic deformation of metals below the recrystallization temperature and is generally performed at room temperature. Some *advantages* are:

- No heating is required
- Better surface finish and superior dimensional control are achieved
- Strength, fatigue, and wear properties are improved
- Directional properties can be imparted

Disadvantages:

- Heavier forces are required
- Strain hardening occurs (may require intermediate annealing treatment to relieve internal stresses)
- Residual stresses may be produced

Spring back

Spring back is also present in cold working operations. In the elastic region, the strained material returns to its original size and shape. Thus, in cold working the deformation must be carried out beyond the desired point by an amount equal to the spring back. The various cold working processes are squeezing, bending, shearing and drawing.

Recovery

Recovery is a process that kicks in at low temperatures; in this stage, the excess defects are annealed out, dislocations of opposite signs annihilate each other, and dislocations align to form low energy configurations, namely tilt and twist boundaries. In Fig. 1 for example, we show how a wall of edge dislocations form a tilt boundary. In the recovery stage, however, the energy released through the annihilation and rearrangement of dislocations is not considerable.

Recrystallisation

Recrystallisation is the process in which deformed grains are replaced by strain-free grains. It is generally observed that higher cold work and smaller initial grain size lead to finer recrystallized grains. The driving force for recrystallisation is the stored strain energy in the material. For recrystallisation to take place, a minimum of cold working is needed; if the deformation is very low, recrystallisation does not occur. During recrystallisation, the stress-free grains nucleate and grow. In a recrystallised system (after more than about 90% deformation) the resultant microstructure is textured; that is, most of the grains have similar orientation.

The temperature at which a given material completely recrystallises in an hour is defined as the recrystallisation temperature. The recrystallisation temperature is low if the degree of deformation is high and/or if the temperature of deformation is low and/or if the initial grain size is small. The recrystallisation temperature is also very sensitive to the purity of the material; an addition of 0.01 at % of Te to pure copper, for example, can increase the recrystallisation temperature by about 240°C.

Fracture, Ductile and Brittle fracture

Fracture

Fracture is a form of failure, and is defined as the separation or fragmentation of a solid body into two or more parts under the action of stress. Fracture that occurs over a very short time period and under simple loading conditions (static i.e. constant or slowly changing) is considered here. Fracture under complex condition, for example alternating stress, is considered in later sections.

The process of fracture can be considered to be made up of two components, crack initiation followed by crack propagation. Fractures are classified w.r.t. several characteristics, for example, strain to fracture, crystallographic mode of fracture, appearance of fracture, etc. Table - 5.1 gives a brief summary of different fracture modes.

Table – 5.1 Different fracture modes

<i>characteristic</i>	<i>terms used</i>	
Strain to fracture	Ductile	Brittle
Crystallographic mode	Shear	Cleavage
Appearance	Fibrous and gray	Granular and bright
Crack propagation	Along grain boundaries	Through grains

Shear fracture, promoted by shear stresses, occurs as result of extensive slip on active slip plane. On the other hand, cleavage fracture is controlled by tensile stresses acting normal to cleavage plane. A shear fracture surface appears gray and fibrous, while a cleavage fracture surface appears bright or granular. Actual fracture surfaces often appear as mixture of fibrous and granular mode. Based on metallographic examination of fracture surfaces of polycrystalline materials, they are classified as either transgranular or intergranular. Transgranular fracture, as the name go by, represents crack propagation through the grains, whereas intergranular fracture represents the crack that propagated along the grain boundaries. The fracture is termed ductile or brittle depending on the ability of a material to undergo plastic deformation during the fracture. A ductile fracture is characterized by considerable amount of plastic deformation prior to and during the crack propagation. On the other hand, brittle fracture is characterized by micro-

deformation or no gross deformation during the crack propagation. Plastic deformation that occurs during ductile fracture, if monitored, can be useful as warning sign to the fracture that may occur in later stages. Thus brittle fracture shall be avoided as it may occur without warning!

Figure-5.1 depicts characteristic macroscopic fracture profiles. The profile shown in figure-5.1(a) is representative of very high ductility represented by close to 100% reduction in cross-sectional area. This kind of failure is usually called rupture. It is observed in very soft metals such as pure gold and lead at room temperature and other metals, polymers, glasses at elevated temperatures. Most ductile metals fracture preceded by a moderate amount of necking, followed by formation of voids, cracks and finally shear. This gives characteristic cup-and-cone fracture as shown by figure-5.1(b). In this central interior region has an irregular and fibrous appearance. Figure-5.1(c) presents the typical profile of brittle fracture which is usually transgranular. It occurs in most ceramics and glasses at room temperature, long-chain polymers below their glass transition temperatures, certain metals and alloys below their ductile-to-brittle transition temperatures

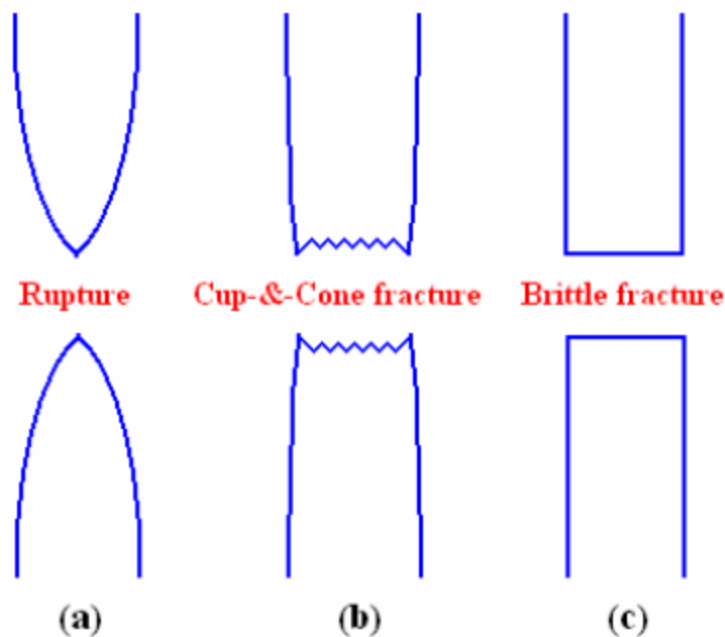


Figure – 5.1 Fracture profiles

Ductile fracture

Most often ductile fracture in tension occurs after appreciable plastic deformation. It occurs by a slow tearing of the metal with the expenditure of considerable energy. It can be said that ductile fracture in tension is usually preceded by a localized reduction in cross-sectional area, called necking. Further it exhibits three stages - (1) after on set of necking, cavities form, usually at inclusions at second-phase particles, in the necked region because the geometrical changes

induces hydrostatic tensile stresses, (2) the cavities grow, and further growth leads to their coalesce resulting in formation of crack that grows outward in direction perpendicular to the application of stress, (3) final failure involves rapid crack propagation at about 45° to the tensile axis. This angle represents the direction of maximum shear stress that causes shear slip in the final stage. During the shear slip, crack propagates at a rapid speed around the outer perimeter of neck leaving one surface in form of cup, and the other in form of cone. Thus it is known as cup-and-cone fracture. In this central interior region has an irregular and fibrous appearance, which signifies plastic deformation. Different progressive stages of ductile fracture are shown in figure-5.2.

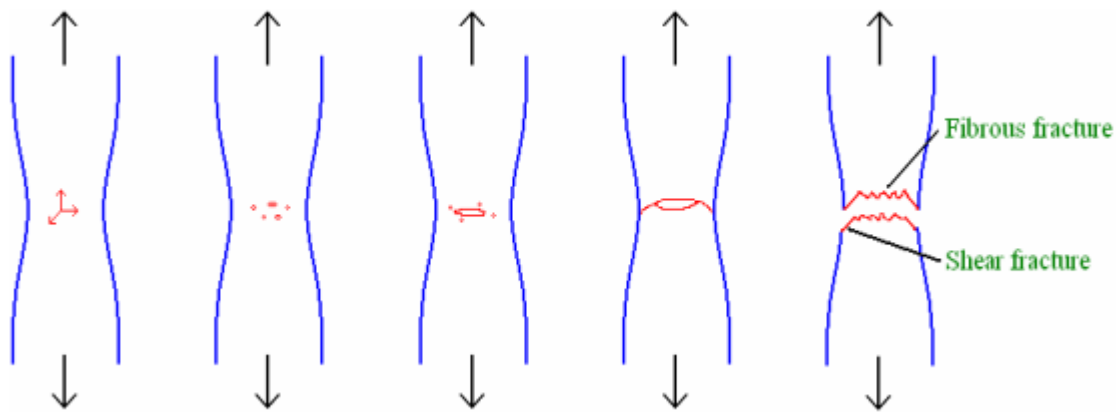
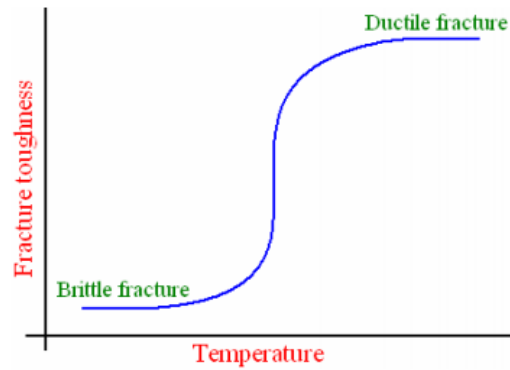


Figure – 5.2 Stages of ductile tensile fracture

Brittle fracture

The other common mode of fracture is known as brittle fracture that takes place with little or no preceding plastic deformation. It occurs, often at unpredictable levels of stress, by rapid crack propagation. The direction of crack propagation is very nearly perpendicular to the direction of applied tensile stress. This crack propagation corresponds to successive and repeated breaking to atomic bonds along specific crystallographic planes, and hence called cleavage fracture. This fracture is also said to be transgranular because crack propagates through grains. Thus it has a grainy or faceted texture. Most brittle fractures occur in a transgranular manner. However, brittle fracture can occur in intergranular manner i.e. crack propagates along grain boundaries. This happens only if grain boundaries contain a brittle film or if the grain-boundary region has been embrittled by the segregation of detrimental elements.

In analogy to ductile fracture, as supported by number of detailed experiments, the brittle fracture in metals is believed to take place in three stages - (1) plastic deformation that causes dislocation pile-ups at obstacles, (2) micro-crack nucleation as a result of build-up of shear stresses, (3) eventual crack propagation under applied stress aided by stored elastic energy.



Creep failure:

- Deformation that occurs under constant load/stress and elevated temperatures which is time-dependent is known as creep.
- Creep deformation (constant stress) is possible at all temperatures above absolute zero. However, it is extremely sensitive to temperature.
- Hence, creep is usually considered important at elevated temperatures (temperatures greater than $0.4 T_m$, T_m is absolute melting temperature).
- Creep test data is presented as a plot between time and strain known as creep curve.
- The slope of the creep curve is designated as creep rate

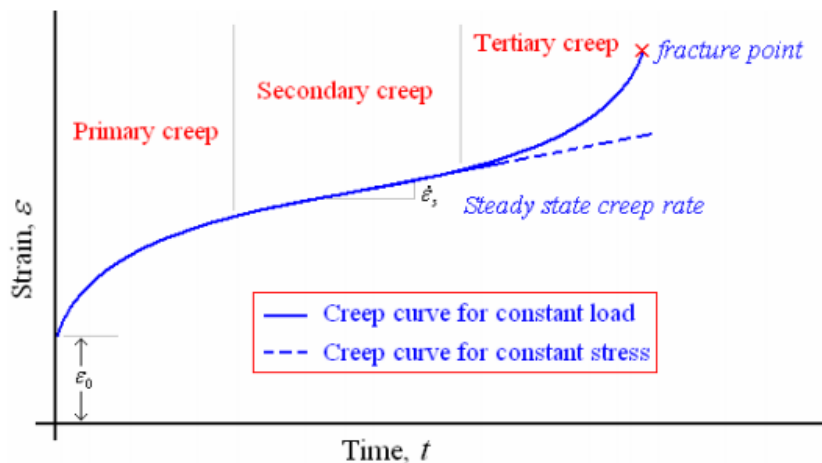


Figure 5.3 Typical Creep Curve

- Creep curve is considered to consist of three portions. After initial rapid elongation, ϵ_0 , the creep rate decreases continuously with time, and is known as primary or transient creep.
- Primary creep is followed by secondary or steady-state or viscous creep, which is characterized by constant creep rate. This stage of creep is often the longest duration of the three modes.

- Finally, a third stage of creep known as, tertiary creep occurs that is characterized by increase in creep rate.
- First stage creep is associated with strain hardening of the sample.
- Constant creep rate during secondary creep is believed to be due to balance between the competing processes of strain hardening and recovery. Creep rate during the secondary creep is called the minimum creep rate.
- Third stage creep occurs in constant load tests at high stresses at high temperatures. This stage is greatly delayed in constant stress tests. Tertiary creep is believed to occur because of either reduction in cross-sectional area due to necking or internal void formation. Third stage is often associated with metallurgical changes such as coarsening of precipitate particles, recrystallization, or diffusional changes in the phases that are present.
- Two most important parameters that influence creep rate are: stress and temperature.

Fatigue failure

Failures occurring under conditions of dynamic or alternating loading are called fatigue failures, presumably because it is generally observed that these failures occur only after a considerable period of service. Fatigue failure usually occurs at stresses well below those required for yielding, or in some cases above the yield strength but below the tensile strength of the material. These failures are dangerous because they occur without any warning. Typical machine components subjected to fatigue are automobile crank-shaft, bridges, aircraft landing gear, etc. Fatigue failures occur in both metallic and non-metallic materials, and are responsible for a large number fraction of identifiable service failures of metals.

A typical fatigue-fracture surface looks like the one shown in figure-5.4. The fatigue crack nucleates at the stress concentration. Generally, the fatigue fracture surface is perpendicular to the direction of an applied stress. A fatigue failure can be recognized from the appearance of the fracture surface, which shows a smooth and polished surface that corresponds to the slow growth of crack, when the crack faces smoothen out by constant rubbing against each other and a rough/granular region corresponds to the stage of fast growth, after critical conditions is attained where member has failed in a ductile manner when cross section was no longer able to carry the applied load. The region of a fracture surface that formed during the crack propagation step may be results in characteristic pattern of concentric rings spread over the smooth region of the fracture surface, known as beach marks or striations, radiating outward from the point of initiation of the failure, as shown in figure-5.4. Beach marks (also known as clamshell pattern) are macroscopic dimensions and may be observed with the unaided eye. These markings are found for components that experienced interruptions during the crack propagation stage. Each beach mark band represents a period of time over which crack growth occurred. On the other hand fatigue striations are microscopic in size and subject to observation with the electron microscope (either TEM or SEM). The relatively widely spaced striations are caused by

variations in the stress amplitude during the life of the component. On a much finer level, a large number of striations may be sometimes being seen. The width of each striation here is equal to the distance by which the crack grows during one cycle. Any point with stress concentration such as sharp corner or notch or metallurgical inclusion can act as point of initiation of fatigue crack.

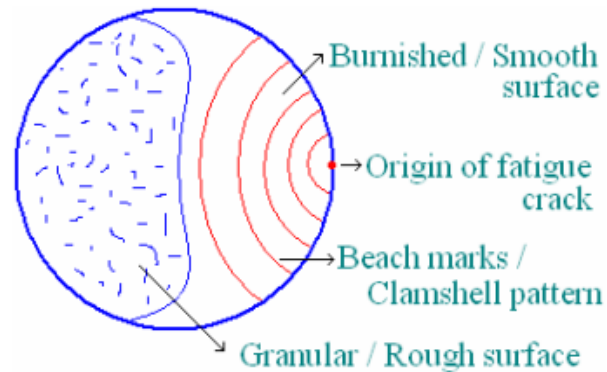


Figure 5.4 Schematic of fatigue fracture surface

Three basic requisites for occurrence of fatigue fracture are: (a) a maximum tensile stress of sufficiently high value (b) a large enough variation or fluctuation in the applied stress and (c) a sufficiently large number of cycles of applied stress. The stress cycles that are evident in fatigue studies are characterized using many parameters, such as mean stress, alternating stress, stress ratio and amplitude ratio.