M.I.E.T. ENGINEERING COLLEGE

(Approved by AICTE and Affiliated to Anna University Chennai)
TRICHY – PUDUKKOTTAI ROAD, TIRUCHIRAPPALLI – 620 007

DEPARTMENT OF MECHANICAL ENGINEERING

COURSE MATERIAL

ME 6403 Engineering Materials and Metallurgy

II YEAR - IV SEMESTER
### ME6403 ENGINEERING MATERIALS AND METALLURGY

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#### UNIT I ALLOYS AND PHASE DIAGRAMS

#### UNIT II HEAT TREATMENT

#### UNIT III FERROUS AND NON-FERROUS METALS

#### UNIT IV NON-METALLIC MATERIALS
Polymers – types of polymer, commodity and engineering polymers – Properties and applications of various thermosetting and thermoplastic polymers (PP, PS, PVC, PMMA, PET,PC, PA, ABS, PI, PAI, PPO, PPS, PEEK, PTFE, Polymers – Urea and Phenol formaldehydes)- Engineering Ceramics – Properties and applications of Al2O3, SiC, Si3N4, PSZ and SIALON –Composites-Classifications-Metal Matrix and FRP - Applications of Composites.

#### UNIT V MECHANICAL PROPERTIES AND DEFORMATION MECHANISMS

**TOTAL: 45 PERIODS**
COURSE OBJECTIVE
1. To bring in the necessary principles of materials science for mechanical and associated engineering applications.
2. Spot and pick suitable materials for various engineering applications.
3. Understand structure of various materials and properties relationship.
4. Understand structure of nan-metalic materials and properties relationship.
5. To be test hardness of various materials.

COURSE OUTCOMES
1. Describe the various phase diagram for engineering metals
2. Identify the different types of engineering materials in industrial applications
3. Understand the various isothermal transformation in heat treatment process
4. Understand the effects of alloying elements on Ferrous and Non-Ferrous materials.
5. Discuss the properties and applications of Polymers, Ceramics and Composite materials
6. Identify the mechanical properties and deformation using various mechanical testing methods.

Prepared by
RAMKUMAR.T
AP/MECH

Verified By
HOD

Approved by
PRINCIPAL
UNIT I ALLOYS AND PHASE DIAGRAMS

Materials play an important role for our existence, for our day to day needs, and even for our survival. In the stone age, the naturally accessible materials were stone, wood, bone, fur, etc. Gold was the 1st metal used by the mankind followed by copper. In the bronze age, copper and its alloy like bronze was used and in the iron age, they discovered iron (sponge iron & later pig iron). According to Webster’s dictionary, materials are defined as ‘substances of which something is composed or made’.

Material Engineering is mainly concerned with the use of fundamental and applied knowledge of materials, so that they may be converted into products, as needed or desired by the society (bridges materials knowledge from basic sciences to engineering disciplines).

1.1.1. Introduction

Mechanical engineers search for high temp material so that gas turbines, jet engines, etc, can operate more efficiently, and wear resistance materials to manufacture bearing materials. Electrical engineers search for materials by which electrical devices or machines can be operated at a faster rate with minimum power losses. Aerospace & automobile engineers search for materials having high strength-to-weight ratio. Electronic engineers search for materials that are useful in the fabrication & miniaturization of electronic devices. Chemical engineers search for highly corrosion-resistant materials. All these demands may be fulfilled when the internal structure and engineering properties are known to an engineer or technologist.

The world dimensions are used to describe basic concepts like mass, length, time, temperature, and force. Units are the means of expressing the value of these dimensions quantitatively or numerically.

1.1.2. General classification of materials

a. According to General Properties
   (a). Metals (e.g., iron, aluminium, copper, zinc, lead, etc)
       Iron as the base metal, and range from plain carbon (> 98% Fe) to (i). Ferrous: high alloy steel (< 50% alloying elements), e.g., cast iron, wrought iron, steel, alloys like high-speed steel, spring steel, etc.
       (ii). Non-Ferrous: Rest of the all other metals and their alloys, e.g., copper, aluminium, zinc, lead, alloys like brass, bronze, duralumin, etc.
   (b). Non-Metals (e.g., leather, rubber, asbestos, plastics, etc)

b. According to Nature of Materials
   (a). Metals: e.g., Iron & Steel, Alloys & Superalloys, Intermetallic Compounds, etc.
   (b). Ceramics: e.g., Structural Ceramics (high-temperature load bearing), Refractories (corrosion-resistant, insulating), Whitewares (porcelains), Glass, Electrical Ceramics (capacitors, insulators, transducers), Chemically Bonded Ceramics (cement & concrete).
   (c). Polymers: e.g., Plastics, Liquid Crystals, Adhesives.
   (d). Electronic Materials: e.g., Silicon, Germanium, Photonic materials (solid-state lasers, LEDs).
   (e). Composites: e.g., Particulate composites (small particles embedded in a different material), Laminate composites (golf club shafts, tennis rackets), Fiber reinforced composites (fiberglass).
   (f). Biomaterials: e.g., Man-made proteins (artificial bacterium), Biosensors, etc.
   (g). Advanced / Smart Materials: e.g., materials in computers (VCRs, CD Players, etc).

c. According to Applications
   a) Electrical Materials: e.g., conductors, dielectrics, etc.
   b) Electronic Materials: e.g., conductors, semi-conductors, etc.
   c) Magnetic Materials: e.g., ferromagnetic, paramagnetic & diamagnetic materials, etc.
   d) Optical Materials: e.g., glass, quartz, etc.
   e) Bio Materials: e.g., man-made proteins, artificial bacterium.
Crystalline Solid Vs Amorphous Solids

1.2.1. Crystalline

Crystalline solids totally differ from amorphous solid in every aspect, for example: crystalline solids have a fixed geometric pattern while amorphous solids have no definite pattern. Crystalline solids have a very sharp melting point and amorphous solids don’t have sharp melting point. Crystalline solid a type of solid which is made up of atoms or molecules that are arranged in a highly ordered manner which is termed as crystal lattice. Crystal lattice is basically a three-dimensional symmetrical arrangement of molecules or atoms inside a crystal. Crystalline solids have a definite internal structure which in turn leads to a definite flat faces or surfaces.

1.2.2. Amorphous

Amorphous solid is another type of solid which is made up of atoms or molecules that are not arranged in a fixed geometric pattern like crystal. Amorphous solids have two characteristics. When they are cleaved they produce fragments which have irregular or conchoidal surfaces and when exposed to x-ray they have very ill-defined patterns because the atoms in amorphous solid are not arranged in a regular array. Amorphous solid do not have very sharp melting point because of its atoms that are not arranged at the same distance from the same neighboring atoms.

1.2.3. Crystal structure

In crystallography, crystal structure is a description of the ordered arrangement of atoms, ions or molecules in a crystalline material. Ordered structures occur from the intrinsic nature of the constituent particles to form symmetric patterns that repeat along the principal directions of three-dimensional space in matter. The smallest group of particles in the material that constitutes the repeating pattern is the unit cell of the structure. The unit cell completely defines the symmetry and structure of the entire crystal lattice, which is built up by repetitive translation of the unit cell along its principal axes. The repeating patterns are said to be located at the points of the Bravais lattice.

The crystal structure of a material (the arrangement of atoms within a given type of crystal) can be described in terms of its unit cell. The unit cell is a box containing one or more atoms arranged in three dimensions. The unit cells stacked in three-dimensional space describe the bulk arrangement of atoms of the crystal. The unit cell is represented in terms of its lattice parameters.
1.3. Types of crystal structure
Crystal structure the manner in which atoms, ions, or molecules are spatially arranged. Lattice is 3D array of points coinciding with atom positions (center of spheres) crystals may be Cubic, Monoclinic, Triclinic, Tetragonal, Orthorhombic, Rhombohedral and Hexagonal

Simple Cubic Lattice
➢ Most elementary crystal structure with three mutually perpendicular axes arbitrarily placed through one of the corners of a cell
➢ Each corners occupied with one atom

Example: alpha polonium

1.3.1. B.C.C Body Centered Cubic (BCC) Structure
✓ BCC cell has an atom at each corner and another atom at body center of cube
✓ Each atom at corner is surrounded by eight adjacent atoms
  Example: alpha iron, chromium, molybdenum & tungsten

1.3.2 Face Centered Cubic (FCC) Structure
Atoms at each corner of cube, and in addition there is an atom at the center of each cube’s face

Example: aluminium, copper, gold, lead, silver and nickel
1.3.3 Hexagonal Close-packed (HCP) Structure
Unit cell has an atom at each of twelve corners of hexagonal prism, with one atom at centre of each of two hexagonal faces and three atoms in body of cell

Example: zinc, lithium, magnesium, beryllium

![Hexagonal Close-packed (HCP) Structure](image)

1.3.4 Miller indices
Miller indices form a notation system in crystallography for planes in crystal (Bravais) lattices. Any of a set of three numbers or letters used to indicate the position of a face or internal plane of a crystal and determined on the basis of the reciprocal of the intercept of the face or plane on the crystallographic axes.

![Miller indices](image)

1.4 TYPES OF BONDING
Chemical bonds are some of the most basic topics one must study in chemistry. As early as junior high, students take part in studying the bonds of these compounds because it aids them in understanding the structure of a certain compound. Chemical bonds are defined as the likeness of atoms that will allow them to form substances that have two or more atoms. One of the two types of chemical bonds are covalent bond and ionic bond.

1.4.1 Ionic Bonding
This is the bond when one of the atoms is negative (has an extra electron) and another is positive (has lost an electron). Then there is a strong, direct Coulomb attraction. An example is NaCl. In the molecule, there are more electrons around Cl, forming Cl and less around Na, forming Nalonic bonds are the strongest bonds.

1.4.2 Covalent Bonding
In covalent bonding, electrons are shared between the molecules, to saturate the valency. The simplest example is the H molecule, where the electrons spend more time in between the nuclei than outside, thus producing bonding.
1.4.3 Metallic Bonding
2In the metallic bond encountered in pure metals and metallic alloys, the atoms contribute their outer-shell electrons to a generally shared electroncloud for the whole block of metal.

1.5. SOLID SOLUTIONS
A solid solution occurs when we alloy two metals and they are completely soluble in each other. If a solid solution alloy is viewed under a microscope only one type of crystal can be seen just like a pure metal. Solid solution alloys have similar properties to pure metals but with greater strength but are not as good as electrical conductors.

1.5.1 Substitution solid solution
The name of this solid solution tells you exactly what happens as atoms of the parent metal (or solvent metal) are replaced or substituted by atoms of the alloying metal (solute metal). In this case, the atoms of the two metals in the alloy, are of similar size. Eg Gropper and Zinc, Copper and Nickel

1.5.2 Interstitial solid solutions:
In interstitial solid solutions the atoms of the parent or solvent metal are bigger than the atoms of the alloying or solute metal. In this case, the smaller atoms fit into interstices i.e spaces between the larger atoms. Eg Carbon, Nitrogen, Oxygen

1.5.3 Isomorphic phase diagrams
A phase diagrams show what phases exist at equilibrium and what phase transformations we can expect when we change one of the parameters of the system (T, P, composition). Isomorphous
binary phase diagrams are found in a number of metallic and ceramic systems. In the isomorphous systems, only one solid phase forms; the two components in the system display complete solid solubility.

Typically, the isomorphous system has a liquid area, a solid area, and an area that is a mixture of both liquid and solid. Typically, a binary isomorphous phase diagram consists of two phase boundaries: the liquids and the solidus and it shows complete solid solubility of the two components (both in the liquid and solid phases).

\[ \alpha \text{ is the solid phase, can also be represented by } S \]
\[ L \text{ is the liquid phase} \]
\[ \alpha + L \text{ is a phase region which is a mixture of solid and liquid} \]
\[ A \text{ and } B \text{ are separate components of the system} \]

### 1.6.1. Eutectic

A eutectic or eutectic mixture is a mixture of two or more phases at a composition that has the lowest melting point. It is where the phases simultaneously crystallize from molten solution. The proper ratios of phases to obtain a eutectic is identified by the eutectic point on a binary phase diagram. The term comes from the Greek 'eutektos', meaning 'easily melted.'

**Eutectic:** 4.30 wt% C, 1147 °C

\[ L \text{ (4.30% C) } \leftrightarrow \gamma \text{ (2.14% C) } + \text{FeC} \]
1.6.2. Eutectoid Reaction

In eutectoid reaction, the austenite transforms into a phase mixture of ferrite (containing 0.76% C) and cementite. This phase mixture is known as pearlite. The average carbon content in pearlite is 0.76%. The eutectoid reaction occurs at a constant temperature. This is known as eutectoid temperature and is 727°C. Eutectoid reaction is very important in heat treatment of steels.

At 0.76% C and 727 °C
\[ \gamma(0.76\%\ C) \leftrightarrow \alpha(0.022\%\ C) + Fe_3C \]

1.6.3 Peritectic Reaction

In peritectic reaction, the liquid and δ iron transforms into austenite (containing 0.16% C). The peritectic reaction occurs at a constant temperature. This is known as peritectic temperature and is 1493°C.

Peritectic reaction: at 0.16% C and 1493°C
\[ \delta(0.11\%\ C) + L(0.51\%\ C) \leftrightarrow \gamma(0.16\%\ C) \]

Iron-Carbon System

1.7.1. Introduction

Pure iron when heated experiences 2 changes in crystal structure before it melts. At room temperature the stable form, ferrite (α iron) has a BCC crystal structure. Ferrite experiences a polymorphic transformation to FCC austenite (γ iron) at 912 °C (1674 °F). At 1394°C (2541°F) austenite reverts back to BCC phase δ ferrite and melts at 1538 °C (2800 °F). Iron carbide (cementite or FeC) an intermediate compound is formed at 6.7 3wt%. Typically, all steels and cast irons have carbon contents less than 6.7 wt% C. Carbon is an interstitial impurity in iron and forms a solid solution with the α, γ, δ phases.

1.7.2 Concepts and demonstration

In eutectoid steel, pearlite is formed at eutectoid temperature. The austenite gets converted into pearlite which is a mechanical mixture of ferrite and cementite. This transformation occurs at 727°C (at constant temperature).
- Firstly, there is the A₁, temperature at which the eutectoid reaction occurs (P-S-K), 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 ferromagnetic 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 great difference in carbon solubility between γ- and α-iron leads normally to the rejection of carbon as iron carbide at the boundaries of the γ phase field. The transformation of γ to α- iron occurs via a eutectoid reaction, which plays a dominant role in heat treatment.

When alloy of eutectoid composition (0.76 wt % C) is cooled slowly it forms pearlite, a lamellar or layered structure of two phases: α-ferrite and cementite (Fe₃C). The layers of alternating phases in pearlite are formed for the same reason as layered structure of eutectic structures: redistribution of C atoms between ferrite (0.022 wt%) and cementite (6.7 wt%) by atomic diffusion. Mechanically, pearlite has properties intermediate to soft, ductile ferrite and hard, brittle cementite.

Relative amounts of proeutectoid phase (α or Fe and pearlite can be calculated by the lever rule with tie line that extends from the eutectoid composition (0.76 % C) to α – (α + Fe C) boundary (0.022 % C) for hypoeutectoid alloys and to (α + Fe boundary (6.7 % C) for hypereutectoid alloys. Fraction of total α phase is determined by application of the lever rule across the entire (α + Fe₃C) phase field. Iron is allotropic; at room temperature pure iron exists in the Body Centered Cubic crystal form but on heating transforms to a Face Centered Cubic crystal. The temperature that this first transformation takes place is known as a critical point and it occurs at 910 degrees Celsius. This change in crystal structure is accompanied by shrinkage in volume, since the atoms in the face centered crystal are more densely packed together than in the body centered cubic crystal. At the second critical point the F.C.C crystal changes back to a B.C.C crystal and this change occurs at 1390 degrees Celsius.

- Iron above 1390 degrees is known as delta iron
- Iron between 1390 and 910 degrees is known as gamma iron, Iron below 910 degrees is known as alpha iron.
**Critical temperatures**

Upper critical temperature (point) \( A_3 \) is the temperature, below which ferrite starts to form as a result of ejection from austenite in the hypoeutectoid alloys. Upper critical temperature (point) \( A \) is the temperature, below which cementite starts to form as a result of ejection from austenite in the hypereutectoid alloys. Lower critical temperature (point) \( A_C \) is the temperature of the austenite-pearlite eutectoid transformation. Below this temperature, austenite does not exist.
1.8. STEEL
1.8.1. Introduction
All the different metals and materials that we use in our trade, steel is by far the most important. When steel was developed, it revolutionized the American iron industry. With it came skyscrapers, stronger and longer bridges, and railroad tracks that did not collapse. Steel is manufactured from pig iron by decreasing the amount of carbon and other impurities and adding specific amounts of alloying elements. Do not confuse steel with the two general classes of iron: cast iron (greater than 2% carbon) and pure iron (less than 0.15% carbon). In steel manufacturing, controlled amounts of alloying elements are added during the molten stage to produce the desired composition. The composition of a steel is determined by its application and the specifications that were developed by the following: American Society for Testing and Materials (ASTM).

1.8.2 Classification
Low-carbon steels contain up to 0.30% C. The largest category of this class of steel is flat-rolled products (sheet or strip), usually in the cold-rolled and annealed condition. The carbon content for these high-formability steels is very low, less than 0.10% C, with up to 0.4% Mn. Typical uses are in automobile body panels, tin plate, and wire products.

Medium-carbon steels are similar to low-carbon steels except that the carbon ranges from 0.30 to 0.60% and the manganese from 0.60 to 1.65%. Increasing the carbon content approximately 0.5% with an accompanying increase in manganese allows medium carbon steels to be used in the quenched and tempered condition. The uses of medium carbon-manganese steels include shafts, axles, gears, crankshafts, couplings, and forgings. Steels in the 0.40 to 0.60% Cr range are also used for rails, railway wheels, and rail axles.

High-carbon steels contain from 0.60 to 1.00% C with manganese content ranging from 0.30 to 0.90%. High-carbon steels are used for spring materials and high-strength wires.

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 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.

Low-carbon quenched and tempered steels combine high yield strength (from 350 to 1035 MPa) and high tensile strength with good notch toughness, ductility, corrosion resistance, or weldability. The various steels have different combinations of these characteristics based on their intended applications. However, a few steels, such as HY-80 and HY-100, are covered by military specifications. The steels listed are used primarily as plate. Some of these steels, as well as other, similar steels, are produced as forgings or castings.

Medium-carbon ultrahigh-strength steels are structural steels with yield strengths that can exceed 1380 MPa. Many of these steels are covered by SAE/AISI designations or are proprietary compositions. Product forms include billet, bar, rod, forgings, sheet, tubing, and welding wire.

Bearing steels used for ball and roller bearing applications are comprised of low carbon (0.10 to 0.20% C) case-hardened steels and high carbon (-1.0% C) through-hardened steels. Many of these steels are covered by SAE/AISI designations.

Chromium-molybdenum heat-resistant steels contain 0.5 to 9% Cr and 0.5 to 1.0% Mo. The carbon content is usually below 0.2%. The chromium provides improved oxidation and corrosion resistance, and the molybdenum increases strength at elevated temperatures. They are generally supplied in the normalized and tempered, quenched and tempered or annealed condition. Chromium-molybdenum steels are widely used in the oil and gas industries and in fossil fuel and nuclear power plants.

1.9. cast Iron
1.9.1 Introduction
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 cats 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)

1.9.2 Micro structures and application
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.

![Gray Cast Iron Diagram](image)

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.

![White Cast Iron Diagram](image)

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.

![Ductile Cast Iron Diagram](image)

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 1700°F for long periods of time in the presence of materials containing oxygen, such as iron oxide. At the elevated temperatures cementite (Fe₃C) 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.
UNIT II
HEAT TREATMENT

2.1.1. Introduction
Heat treatment is the heating and cooling of metals to change their physical and mechanical properties, without letting it change its shape. Heat treatment could be said to be a method for strengthening materials but could also be used to alter some mechanical properties such as improving formability, machining, etc. The most common application is metallurgical but heat treatment can also be used in manufacture of glass, aluminum, steel and many more materials. The process of heat treatment involves the use of heating or cooling, usually to extreme temperatures to achieve the wanted result. It is very important manufacturing processes that can not only help manufacturing process but can also improve product, its performance, and its characteristics in many ways

2.2.2 Definition
Process in which a metal is heated to a certain temperature and the cooled in a particular manner to alter its internal structure for obtaining desired degree of physical and mechanical properties such as brittleness, hardness, and softness

2.2. Annealing classification
Annealing involves treating steel up to a high temperature, and then cooling it very slowly to room temperature, so that the resulting microstructure will possess high ductility and toughness, but low hardness. Annealing is performed by heating a component to the appropriate temperature, soaking it at that temperature, and then shutting off the furnace while the piece is in it. Steel is annealed before being processed by cold forming, to reduce the requirements of load and energy, and to enable the metal to undergo large strains without failure

Annealing

The purpose of annealing may involve one or more of the following aims:

1. To soften the steel and to improve machinability.
2. To relieve internal stresses induced by some previous treatment (rolling, forging, uneven cooling).
3. To remove coarseness of grain.

The treatment is applied to forgings, cold-worked sheets and wire, and castings. The operation consists of:

a. Heating the steel to a certain temperature,
b. "Soaking" at this temperature for a time sufficient to allow the necessary changes to occur,
c. Cooling at a predetermined rate.

2.2.1. Full annealing
The process involves heating the steel to 30 to 50 degrees Centigrade above the critical temperature of steel and maintaining the temperature for a specified period of time, then allowing the material to slowly cool down inside the furnace itself without any forced means of cooling. Hot Worked sheets, forgings, and castings made from medium and high carbon steels need full annealing. Example In full annealing of hypoeutectoid steels less than 0.77% is heated to 723 to 910 C above A3 line convert to single phase austenite cooled slowly in room temperature. Resulting structure is coarse pearlite with excess of ferrite it is quite soft and more ductile cooling rate of full annealing is 30-40 C
Process annealing
Process annealing is a heat treatment process that restores some of the ductility to a product being cold-worked so it can be cold-worked further without breaking. The temperature range for process annealing ranges from 260 °C (500 °F) to 760 °C (1400 °F), depending on the alloy in question. This process is mainly suited for low-carbon steel. The material is heated up to a temperature just below the lower critical temperature of steel. Cold-worked steel normally tends to possess increased hardness and decreased ductility, making it difficult to work.

2.2.2. Stress relief
It is an annealing process below the transformation temperature A with subsequent slow cooling, the aim of which is to reduce the internal residual stresses in a workpiece without intentionally changing its structure and mechanical properties.

Causes of Residual Stresses
1. Thermal factors (e.g., thermal stresses caused by temperature gradients within the workpiece during heating or cooling)
2. Mechanical factors (e.g., cold-working)
3. Metallurgical factors (e.g., transformation of the microstructure)

The process is limited to steels in excess of 0.5% carbon and consists of heating the steel to temperature about A1 (727°C). At this temperature any cold worked ferrite will recrystallize and
the iron carbide present in pearlite will form as spheroids or “ball up”. As a result of change of carbides shape the strength and hardness are reduced. To remove coarse pearlite and making machining process easy. It forms spheroids structure of maximum soft and ductility easy to machining and deforming.

Objectives
☐ To soften steels
☐ To increase ductility and toughness
☐ To improve machinability and formability

2.2.3. Recrystallization
Recrystallization is a process by which deformed grains are replaced by a new set of undeformed grains that nucleate and grow until the original grains have been entirely consumed.

Recrystallisation annealing is an annealing process applied to cold-worked metal to obtain nucleation and growth of new grains without phase change. This heat treatment removes the results of the heavy plastic deformation of highly shaped cold formed parts. The annealing is effective when applied to hardened or cold-worked steels, which recrystallise the structure to form new ferrite grains.

Recrystallization is usually accompanied by a reduction in the strength and hardness of a material and a simultaneous increase in the ductility.

Thus, the process may be introduced as a deliberate step in metals processing or may be an undesirable byproduct of another processing step.

The most important industrial uses are the softening of metals previously hardened by cold work, which have lost their ductility, and the control of the grain structure in the final product.

Recrystallization is defined as the process in which grains of a crystal structure come in new structure or new crystal shape.

A precise definition of recrystallization is difficult to state as the process is strongly related to several other processes, most notably recovery and grain growth.

2.2.4 Spheroidizing
The process is limited to steels in excess of 0.5% carbon and consists of heating the steel to temperature about A1 (727°C). At this temperature any cold worked ferrite will recrystallize and the iron carbide present in pearlite will form as spheroids or “ball up”. As a result of change of carbides shape the strength and hardness are reduced.

☐ To remove coarse pearlite and making machining process easy.
☐ It forms spheroidite structure of maximum soft and ductility easy to machining and deforming.

Objectives
☐ To soften steels
☐ To increase ductility and toughness
☐ To improve machinability and formability

2.3. Heat treatment classification

2.3.1. Hardening
Hardening involves heating of steel, keeping it at an appropriate temperature until all pearlite is transformed into austenite, and then quenching it rapidly in water or oil. The temperature at which austenitizing rapidly takes place depends upon the carbon content in the steel used. The heating time should be increased ensuring that the core will also be fully transformed into austenite. The microstructure of a hardened steel part is ferrite, martensite, or cementite.
Normalizing
Normalizing involves heating steel, and then keeping it at that temperature for a period of time, and then cooling it in air. The resulting microstructure is a mixture of ferrite and cementite which has a higher strength and hardness, but lower ductility. Normalizing is performed on structures and structural components that will be subjected to machining, because it improves the machinability of carbon steels.

2.4.1. Definition
Tempering involves heating steel that has been quenched and hardened for an adequate period of time so that the metal can be equilibrated. The hardness and strength obtained depend upon the temperature at which tempering is carried out. Higher temperatures will result into high ductility, but low strength and hardness. Low tempering temperatures will produce low ductility, but high strength and hardness. In practice, appropriate tempering temperatures are selected that will produce the desired level of hardness and strength. This operation is performed on all carbon steels that have been hardened, in order to reduce their brittleness, so that they can be used effectively in desired applications.

Caution: Tempering can, in some circumstances, make the steel brittle which is the opposite of what it is intended to achieve.

There are two forms of this brittleness
Temper Britteness which affects both carbon and low alloy steels when either, they are cooled too slowly from above 575°C, or are held for excessive times in the range 375 to 575°C. The embrittlement can be reversed by heating to above 575°C and rapidly cooling. Blue Brittness affects carbon and some alloy steels after tempering in the range 230 to 370°C. The effect is not reversible and susceptible steels should not be employed in applications in which they sustain shock loads. If there is any doubt consult with the heat treater or in house metallurgical department about the suitability of the steel type and the necessary heat treatment for any application

2.4.2. Austempering
Austempering also involves an isothermal hold in the quenching operation, but the structure formed, whilst hard and tough, does not require further tempering. The process is mostly applied to high carbon steels in relatively thin sections for springs or similar parts. These processes are shown schematically in the TTT Curves

2.4.3. Martempering
It will be readily appreciated that the quenching operation used in hardening introduces internal stresses into the steel. These can be sufficiently large to distort or even crack the steel. Martempering is applied to steels of sufficient hardenability and involves an isothermal hold in the quenching operation. This allows temperature equalization across the section of the part and more uniform cooling and structure, hence lower stresses. The steel can then be tempered in the usual way.
2.5. Isothermal transform diagram

Isothermal transformation diagrams (also known as time-temperature-transformation (TTT) diagrams) are plots of temperature versus time (usually on a logarithmic scale). They are generated from percentage transformation-vs time measurements, and are useful for understanding the transformations of an alloy steel at elevated temperatures. An isothermal transformation diagram is only valid for one specific composition of material, and only if the temperature is held constant during the transformation, and strictly with rapid cooling to that temperature. Though usually used to represent transformation kinetics for steels, they also can be used to describe the kinetics of crystallization in ceramic or other materials. Time-temperature-precipitation diagrams and time-temperature-embrittlement diagrams have also been used to represent kinetic changes in steels.

The C-curve is associated with mechanical properties, microconstituents/microstructures, and heat treatments in carbon steels. Diffusional transformations like austenite transforming to a cementite and ferrite mixture can be explained using the sigmoidal curve; for example the beginning of pearlitic transformation is represented by the pearlite start (Ps) curve. This transformation is complete at Pf curve. Nucleation requires an incubation time. The rate of nucleation increases and the rate of microconstituent growth decreases as the temperature decreases from the liquidus temperature reaching a maximum at the bay or nose of the curve. Thereafter, the decrease in diffusion rate due to low temperature offsets the effect of increased driving force due to greater difference in free energy. As a result of the transformation, the microconstituents, Pearlite and Bainite, form; Pearlite forms at higher temperatures and bainite at lower. The specimen is cooled rapidly to 433 K and left for 20 minutes. The cooling rate is too rapid for pearlite to form at higher temperatures; therefore, the steel remains in the austenitic phase until the Ms temperature is passed, where martensite begins to form. Since 433 K is the temperature at which half of the austenite transforms to martensite, the direct quench converts 50% of the structure to martensite. Holding at 433 K forms only a small quantity of additional martensite, so the structure can be assumed to be half martensite and half retained austenite. The specimen is held at 523 K for 100 seconds, which is not long enough to form bainite. Therefore, the second quench from 523 K to room temperature develops a martensitic structure. An isothermal hold at 573 K for 500 seconds produces a half-bainite and half-austenite structure. Cooling quickly would result in a final structure of martensite and bainite. Austenite converts completely to fine pearlite after eight seconds at 873 K. This phase is stable and will not be changed on holding for 100,000 seconds at 873 K. The final structure, when cooled, is fine pearlite.
Cooling curve 1 shows a very slow cooling rate typical of conventional annealing. The diagram indicates that the material will remain austenitic for a relatively long period of time. Transformation will start when the cooling curve crosses the beginning of transformation at point x1. The transformation product at that temperature will be very coarse pearlite. Transformation will continue until point \( x_1^{TM} \). Since there is a slight difference in temperature at the beginning and end of transformation, there will be a slight difference in the fineness of pearlite formed at the beginning and at the end. The overall product will be coarse pearlite with low hardness. Below the temperature of \( x_1^{TM} \) the rate of cooling will have no effect on the microstructure or properties. The material may now be cooled rapidly without any change occurring. This is very important for companies doing commercial annealing, since the diagram indicates that it is not necessary to cool in the furnace to room temperature but that the material may be removed at a relatively high temperature after transformation and cooled in air.

2.5.1 Cooling curves

Cooling curve 1 shows a very slow cooling rate typical of conventional annealing. The diagram indicates that the material will remain austenitic for a relatively long period of time. Transformation will start when the cooling curve crosses the beginning of transformation at point x1. The transformation product at that temperature will be very coarse pearlite. Transformation will continue until point \( x_1^{TM} \). Since there is a slight difference in temperature at the beginning and end of transformation, there will be a slight difference in the fineness of pearlite formed at the beginning and at the end. The overall product will be coarse pearlite with low hardness. Below the temperature of \( x_1^{TM} \) the rate of cooling will have no effect on the microstructure or properties. The material may now be cooled rapidly without any change occurring. This is very important for companies doing commercial annealing, since the diagram indicates that it is not necessary to cool in the furnace to room temperature but that the material may be removed at a relatively high temperature after transformation and cooled in air.

Cooling curve 2 illustrates isothermal or cycle annealing and was developed directly from the I-T diagram. The process is carried out by cooling the material rapidly from above the critical range to a predetermined temperature in the upper portion of the I-T diagram and holding for the time indicated to produce complete transformation. In contrast to conventional
annealing, this treatment produces a more uniform microstructure and hardness, in many cases with a shorter time cycle.

Cooling curve 3 is a faster cooling rate than annealing and may be considered typical of normalizing. The diagram indicates that the transformation will start at x3, with the formation of coarse pearlite, in a much shorter time than annealing. Transformation will be complete at xα^TM3 with the formation of medium pearlite. Since there is a greater temperature difference between x3 and xα^TM3 than there is between x1 and xα^TM1, the normalized microstructure will show a greater variation in the fineness of pearlite and a smaller proportion of coarse pearlite than the annealed microstructure.

Cooling curve 4, typical of a slow oil quench, is similar to the one just described, and the microstructure will be a mixture of medium and fine pearlite.

Cooling curve 5, typical of an intermediate cooling rate, will start to transform (at x5) to fine pearlite in a relatively short time. The transformation to fine pearlite will continue until the curve becomes tangent to some percentage transformed, say 25 percent, at xα^TM5. Below this temperature, the cooling curve is going in a direction of decreasing percent transformed. Since pearlite cannot form from austenite on cooling, the transformation must stop at xα^TM5. The microstructure at this point will consist 25 percent of fine, nodular pearlite largely surrounding the existing austenitic grains. It will remain in this condition until the Ms line is crossed at xα^TM5. The remaining austenite now transforms to martensite. The final microstructure at room temperature will consist of 75 percent martensite and 25 percent fine nodular pearlite largely concentrated along the original austenite grain boundaries.

Cooling curve 6, typical of a drastic quench, is rapid enough to avoid transformation in the nose region. It remains austenitic until the Ms line is reached at x6. Transformation to martensite will take place between Ms and Mf lines. The final microstructure will be entirely martensite of high hardness.

It is apparent that to obtain fully martensite structure it is necessary to avoid transformation in the nose region. Therefore, cooling rate 7, which is tangent to the nose, would be approximate critical cooling rate (CCR) for this steel. Any cooling rate slower than the one indicated will cut the curve above the nose and form some softer transformation product. Any cooling rate faster than the one illustrated will form only martensite. Thus different steels may be compared on the basis of their critical cooling rates.

It may be noted that it is possible to form 100 percent pearlite or 100 percent martensite by continuous cooling, but it is not possible to form 100 percent bainite. A complete bainite structure may be formed only by cooling rapidly enough to miss the nose of the curve and then holding it in the temperature range at which bainite is formed until transformation is complete.
2.5.2 CCR
When cooling curve tangent to the nose of TTT curve, it is called as critical cooling rate (CCR). CCR can be defined by two ways ‘The slowest cooling rate at which unstable austenite can be transformed into martensite.’ or ‘The faster cooling rate or within minimum time at which unstable austenite can be transformed into perlite.’
2.6. Hardenability

2.6.1 Difference between hardness and hardenability

Hardness:
Measure of resistance of material to deformation or to surface indentation. It is a function of stress required to produce specific deformation. Hardness is a property that represents an effect of complex elastic and plastic stress fields set up in the material being tested. To express hardness quantitatively, there are different hardness scales. Different hardness test methods like Brinell, Rockwell, Vickers, etc., are used to measure hardness.

Hardenability:
Relative ability of material to achieve targeted hardness to certain depth, e.g., alloy steel can be hardened or can achieve specific hardness at greater depth than plain carbon steel. Hardenability is a measurement of depth from surface where specific hardness is achieved. Jominy end quench test is commonly used to test hardenability. This hardenability test uses Rockwell C scale for hardness evaluation.

2.6.2 Jominy-end quench test

The Jominy End Quench Test measures Hardenability of steels. As we already discussed, hardenability is a measure of the capacity of a steel to be hardened in depth when quenched from its austenitizing temperature.

First, a sample specimen cylinder either 100 mm in length and 25 mm in diameter, or alternatively, 102 mm by 25.4 mm is obtained. Second, the steel sample is normalized to eliminate differences in microstructure due to previous forging, and then it is austenitized. This is usually at a temperature of 800 to 900°C. Next, the specimen is rapidly transferred to the test machine, where it is held vertically and sprayed with a controlled flow of water onto one end of the sample. This cools the specimen from one end, simulating the effect of quenching a larger steel component in water. Next, the specimen is ground flat along its length to a depth of .38 mm (15 thousandths of an inch) to remove decarburized material.

6. The hardness is measured at intervals along its length beginning at the quenched end. For alloyed steels, an interval of 1.5 mm is commonly used where as with carbon steels an interval of .75 mm is
typically employed. The Rockwell or Vickers hardness values are plotted versus distance from the quenched end.

![Hardness versus distance from the quenched end](image)

### 2.7. Case hardening techniques

#### Reasons to Surface Harden

- Increase wear resistance
- Increase surface strength for load carrying (crush resistance)
- Induce suitable residual and compressive stresses
- Improve fatigue life
- Impact resistance

#### 2.7.1. Carburizing

- Low-carbon steel is heated in a carbon-rich environment—Pack carburizing - packing parts in charcoal or coke - makes thick layer (0.025 - 0.150 in)—Gas carburizing - use of propane or other gas in a closed furnace - makes thin layer (0.005 - 0.030 in)—Liquid carburizing - molten salt bath containing sodium cyanide, barium chloride - thickness between other two methods Followed by quenching, hardness about HRC 60

#### 2.7.2. Nitriding

- Nitrogen diffused into surface of special alloy steels (aluminum or chromium) Nitride compounds precipitate out Gas nitriding - heat in ammonia Liquid nitriding - dip in molten cyanide bath Case thicknesses between 0.001 and 0.020 in. with hardness up to HRC 70

#### 2.8.1. Carbonitriding

- Use both carbon and nitrogen Carbonitriding is a surface-hardening heat treatment that introduces carbon and nitrogen into the austenite of steel. This treatment is similar to carburizing in that the austenite composition is changed and high surface hardness is produced by quenching to form martensite. However, because nitrogen enhances hardenability, carbonitriding makes possible the use of low-carbon steel to achieve surface hardness equivalent to that of high-alloy carburized steel without the need for drastic quenching, resulting in less distortion and minimizing potential for cracks. In some cases, hardening may be dependent on nitride formation. Although the process of carbonitriding can be performed with gas atmospheres or salt baths, the term carbonitriding often refers solely to treatment in a gas atmosphere (see the article “Carbonitriding of Steels” in this Volume). Basically, carbonitriding in a salt bath is the same as cyanide bath hardening. In both processes, nitrogen enhances hardenability and case hardness but inhibits the diffusion of carbon. In many instances, carbonitriding of coarse-grained steels is more appropriate than carburizing, because of the lower temperatures and shorter cycle times

#### 2.8.2. Cyaniding

- Nitriding is a surface-hardening heat treatment that introduces nitrogen into the surface of steel at a temperature range (500 to 550°C or 930 to 1020°F), while it is in the ferritic condition. Because nitriding does not involve heating into the austenite phase with quenching to form martensite, nitride components exhibit minimum distortion and excellent dimensional control. Nitriding has the additional advantage of improving corrosion resistance in salt spray tests. The mechanism of nitriding is generally known, but the specific reactions that occur in different steels and with different nitriding media are not always known. Nitrogen has a partial solubility in iron. It can form a solid solution with ferrite at nitrogen contents up to approximately 6%.
2.8.3 Flame hardening
Flame hardening consists of austenitizing the surface of a steel by heating with an oxy-acetylene or oxyhydrogen torch and immediately quenching with water or water-based polymer. The result is a hard surface layer of martensite over a softer interior core with a ferrite-pearlite structure. There is no change in composition, and therefore, the flame-hardened steel must have adequate carbon content for the desired surface hardness. The rate of heating and the conduction of heat into the interior are more important in establishing case depth than the use of steel of high hardenability. Flame-heating equipment may be a single torch with a specially designed head or an elaborate apparatus that automatically indexes, heats, and quenches parts. Large parts such as gears and machine tool ways, with sizes or shapes that would make furnace heat treatment impractical, are easily flame hardened. With improvements in gas-mixing equipment, infra-red temperature measurement and control, and burner design, flame hardening has been accepted as a reliable heat treating process that is adaptable to general or localized surface hardening for small and medium to high production requirements.

2.9.1 Induction hardening
Induction heating is an extremely versatile heating method that can perform uniform surface hardening, localized surface hardening, through hardening, and tempering of hardened pieces. Heating is accomplished by placing a steel ferrous part in the magnetic field generated by high-frequency alternating current passing through an inductor, usually a water-cooled copper coil. The depth of heating produced by induction is related to the frequency of the alternating current, power input, time, part coupling and quench delay. The higher the frequency, the thinner or more shallow the heating. Therefore, deeper case depths and even through hardening are produced by using lower frequencies. The electrical considerations involve the phenomena of hysteresis and eddy currents. Some of the benefits of induction hardening are faster process, energy efficiency, less distortion, and small footprints. Care must be exercised when holes, slots, or other special geometric features must be induction hardened, which can concentrate eddy currents and result in overheating and cracking without special coil and part designs. For details, see the articles “Induction Surface Hardening of Steels” and “Induction Heat Treating Systems” in this Volume.

2.9.2 Vacuum and Plasma hardening
In combination with diffused nitrogen, iron and nitride forming elements present in the material (Cr, Mo, Al, V, Ti, W) form nitrides and thus increase the hardness. Depending on the alloy, a hardness of up to 1,200 HV can be reached. The resulting increase in hardness of the surface layer improves the running properties, wear resistance as well as antifriction properties. This method can also be used for hardening of austenitic stainless steels. This process is also known as pulse plasma nitriding or ion nitriding. If, in addition, carbon is diffused into the surface layer, this method is referred to as plasma nitro carburizing. An optional subsequent oxidation can significantly increase corrosion resistance of low-alloy and no alloyed nitrided steels. A partial nitriding can be better implemented than other methods since covering of the material is relatively simple. Although the process temperature of between 350 and 500 °C is lower compared to other methods, it minimizes the distortion and mostly allows short treatment times.

UNIT III FERROUS AND NON FERROUS METALS
Carbon
The basic metal, iron, is alloyed with carbon to make steel and has the effect of increasing the hardness and strength by heat treatment but the addition of carbon enables a wide range of hardness and strength.
Manganese
Manganese is added to steel to improve hot working properties and increase strength, toughness and hardenability. Manganese, like nickel, is an austenite forming element and has been used as a substitute for nickel in the A.I.S.I.1200 Series of Austenitic stainless steels (e.g. A.I.S.I 202 as a substitute for I.S.I 304).

Chromium
Chromium is added to the steel to increase resistance to oxidation.

Nickel
Nickel is added in large amounts, over about 8%, to high chromium stainless steel to form the most important class of corrosion and heat resistant steels. These are the austenitic stainless steels, typified by 18-8, where the tendency of nickel to form austenite is responsible for a great toughness and high strength at both high and low temperatures. Nickel also improves resistance to oxidation and corrosion. It increases toughness at low temperatures when added in smaller amounts to alloy steels.

Molybdenum
Molybdenum, when added to chromium-nickel austenitic steels, improves resistance to pitting corrosion especially by chlorides and sulphur chemicals. When added to low alloy steels, molybdenum improves high temperature strengths and hardness. When added to chromium steels it greatly diminishes the tendency of steels to decay in service or in heat treatment.

Titanium
The main use of titanium as an alloying element in steel is for carbide stabilisation. It combines with carbon to form titanium carbides, which are quite stable and hard to dissolve in steel, this tends to minimise the occurrence of inter-granular corrosion.

Phosphorus
Phosphorus is usually added with sulphur to improve machinability in low alloy steels, phosphorus, in small amounts, aids strength and corrosion resistance. Experimental work shows that phosphorus present in austenitic stainless steels increases strength. Phosphorus additions are known to increase the tendency to cracking during welding.

Sulphur
When added in small amounts sulphur improves machinability but does not cause hot shortness. Hot shortness is reduced by the addition of manganese, which combines with the sulphur to form manganese sulphide. As manganese sulphide has a higher melting point than iron sulphide, which would form if manganese were not present, the weak spots at the grain boundaries are greatly reduced during hot working.

Silicon
Silicon is used as a deoxidising (killing) agent in the melting of steel, as a result, most steels contain a small percentage of silicon. Silicon contributes to hardening of the ferritic phase in steels and for this reason silicon killed steels are somewhat harder and stiffer than aluminium killed steels.

Cobalt
Cobalt becomes highly radioactive when exposed to the intense radiation of nuclear reactors, and as a result, any stainless steel that is in nuclear service will have a cobalt restriction, usually approximately 0.2% maximum. This problem is emphasised because there is residual cobalt content in the nickel used in producing these steels.

3.3 Classification of steel

3.3.1 Stainless steel:
It is defined as a steel alloy with a minimum of 11.5 wt% chromium content. Stainless steel does not stain, corrode or rust as easily as ordinary steel (it “stains less”), but it is not stain-proof. It is also called corrosion resistant steel when the alloy type and grade are not detailed, particularly in the aviation industry. There are different grades and surface finishes of stainless steel to suit the environment to which the material will be subjected in its lifetime. Common uses of stainless steel are cutlery and watch straps. Stainless steel differs from carbon steel by amount of chromium present. Carbon steel rusts when exposed to air and moisture. This iron oxide film is active and accelerates corrosion by forming more iron oxide. Stainless steels have sufficient amount of chromium present so that a passive film of chromium oxide forms which prevents further corrosion. Mild steels
Carbon steel is sometimes referred to as ‘mild steel’ or ‘plain carbon steel’. The American Iron and Steel Institute defines a carbon steel as having no more than 2% carbon and no other appreciable alloying element. Carbon steel makes up the largest part of steel production and is used in a vast range of applications. Typically, carbon steels are stiff and strong. They also exhibit ferromagnetism (i.e., they are magnetic). This means they are extensively used in motors and electrical appliances. Welding carbon steels with a carbon content greater than 0.3% requires that special precautions be taken. However, welding carbon steel presents far fewer problems than welding stainless steels. The corrosion resistance of carbon steels is poor (i.e., they rust) and so they should not be used in a corrosive environment unless some form of protective coating is used.

3.3.2 Tool steel
Tool and die steels are high carbon steels (either carbon or alloy) possessing high hardness, strength and wear resistance. Tool steels are heat treatable. In order to increase hardness and wear resistance of tool steels, alloying elements forming hard and stable carbides (chromium, tungsten, vanadium, manganese, molybdenum) are added to the composition. Designation system of one-letter in combination with a number is accepted or tool steels. The letter means: W - Water hardened plain carbon tool steels Applications: chisels, forging dies, hummers, drills, cutters, shear blades, cutters, drills, razors.

3.3.3 HSLA
High-strength low-alloy steel (HSLA) is a type of alloy steel that provides better mechanical properties or greater resistance to corrosion than carbon steel. HSLA steels vary from other steels in that they are not made to meet a specific chemical composition but rather to specific mechanical properties. They have a carbon content between 0.05–0.25% to retain formability and weldability. Other alloying elements include up to 2.0% manganese and small quantities of copper, nickel, niobium, nitrogen, vanadium, chromium, molybdenum, titanium, calcium, rare earth elements, or zirconium. Copper, titanium, vanadium, and niobium are added for strengthening purposes. These elements are intended to alter the microstructure of carbon steels, which is usually a ferrite-pearlite aggregate, to produce a very fine dispersion of alloy carbides in an almost pure ferrite matrix. This eliminates the toughness-reducing effect of a pearlitic volume fraction yet maintains and increases the material’s strength by refining the grain size, which in the case of ferrite increases yield strength by 50% for every halving of the mean grain diameter. Precipitation strengthening plays a minor role, too. Their yield strengths can be anywhere between 250–590 megapascals (36,000–86,000 psi). Because of their higher strength and toughness HSLA steels usually require 25 to 30% more power to form, as compared to carbon steels. Copper, silicon, nickel, chromium, and phosphorus are added to increase corrosion resistance. Zirconium, calcium, and rare earth elements are added for sulfide-inclusion shape control which increases formability. These are needed because most HSLA steels have directionally sensitive properties. Formability and impact strength can vary significantly when tested longitudinally and transversely to the grain. Bends that are parallel to the longitudinal grain are more likely to crack around the outer edge because it experiences tensile loads. This directional characteristic is substantially reduced in HSLA steels that have been treated for sulfide shape control. They are used in cars, trucks, cranes, bridges, roller coasters and other structures that are designed to handle large amounts of stress or need a good strength-to-weight ratio. HSLA steel cross-sections and structures are usually 20 to 30% lighter than a carbon steel with the same strength. HSLA steels are also more resistant to rust than most carbon steels because of their lack of pearlite – the fine layers of ferrite (almost pure iron) and cementite in pearlite. Non-stainless varieties of maraging steel are moderately corrosion-resistant, and resist stress corrosion and hydrogen embrittlement. Corrosion-resistance can be increased by cadmium plating or phosphating.

3.3.4 Maraging steel
Maraging steels offer good weldability, but must be aged afterward to restore the properties of heat affected zone. When heat-treated the alloy has very little dimensional change, so it is often machined to its final dimensions. Due to the high alloy content maraging steels have a high hardenability. Since ductile FeNi martensites are formed upon cooling, cracks are non-existent or negligible. The steels can be nitrided to increase case hardness, and polished to a fine surface finish. Non-stainless varieties of maraging steel are moderately corrosion-resistant, and resist stress corrosion and hydrogen embrittlement. Corrosion-resistance can be increased by cadmium plating or phosphating.

3.5. Copper and Copper alloys
Copper is a chemical element with symbol Cu (from Latin: cuprum) and atomic number 29. It is a soft, malleable, and ductile metal with very high thermal and electrical conductivity. A freshly exposed surface of pure copper has a reddish-orange color. Copper is used as a conductor of heat and electricity, as a building material, and as a constituent of various metal alloys, such as sterling silver used in jewelry, cupronickel used to make marine hardware and coins, and constantan used in strain gauges and thermocouples for temperature measurement.

3.5.1 Brass
- Brasses contain zinc as the principle alloying element. Brasses are subdivided into three groups:
  - CuZn alloys
  - CuPb-Zn alloys or leaded brasses
  - CuZn-Sn alloys or tin brasses
- Brasses are high resistance to corrosion and it is easily machinable. It also acts as a good bearing material. Zinc in the brass increases the ductility along with strength. Brass possesses greater strength than copper, however it has a lower thermal and electrical conductivity.

Types of brass
1) Gilding metal
   - 5% to Zn (balance copper) and possesses shades of color from the red of a brassy yellow. Gliding metal is used for making coins, medals, tokens, fuse caps etc.
2) Cartridge brass
   - 70% Copper and 30% zinc. In the fully annealed condition, it has strength of over 300N/mm² caps of electric lamp bulbs, door furniture, etc. This brass, harden when deformed in the cold. An annealing temperature of about 600°C is satisfactory in the most cases.
3) Admiralty brass
   - Cu 71%, Zn 28%, and Sn 1%. Used for the tubes and other parts of condenser cooled by fresh water and for many other purposes.

3.5.2 Bronze
- An alloy of copper and elements other than nickel or zinc. Bronze is basically an alloy of copper and tin.
- It possesses superior mechanical properties and corrosion resistance than brass.
- It is comparatively hard and it resists surface wear.
- It can be rolled into wire, rod, and sheets.

Types of bronze
1) Phosphor bronze
   - The most important copper-tin alloys are those which have been deoxidized with phosphorus during the refining process and hence are known as phosphor bronze. A phosphor bronze:
   - Aluminum bronze: 89% Cu, 7% Al, and 3.5% Sn. It possesses the following properties, good strength, high corrosion resistance, good heat resistance, good cold working properties, etc.
2) Silicon bronze
   - 4% Si, 0.5-1.0% iron, 0.25-1.25% Mn, and balance amount of copper. When lead added as 0.05% improves machinability. It possesses high strength and toughness as that of mild steel and corrosion resistance as that of copper.

3.5.3 Cupronickel
- Cupronickel (also referred to as "cupernickel" or copper-nickel alloy) refers to a group of copper-nickel alloys that are used in saltwater environments due to their corrosion resistant properties.
- The most common cupronickel alloys are:
  - 90/10 Cupro-nickel (copper-nickel-iron)
  - 70/30 Cupro-nickel (copper-nickel-iron)
- These alloys have good working properties, are readily weldable and considered insensitive to stress corrosion. Cupronickel is also resistant to biofouling, crevice corrosion, stress corrosion cracking, and hydrogen embrittlement. Slight differences in corrosion resistance and strength generally determine which alloy grade is used for a particular application. Cupronickel has been made and used for over a thousand years. Its first known use was in China in about 300 BCE. Chinese records describe the process for making "white copper," which involved heating and mixing copper, nickel, and saltpeter. Cupronickel was also used to make Greek coins. Later European "rediscovery" of cupronickel involved alchemical experiments.

3.6 Aluminium and alloy
- An aluminum alloy is a chemical composition where other elements are added to pure aluminum in order to enhance its properties, primarily to increase its strength. These other elements include iron, silicon, copper, magnesium, manganese, and zinc at levels that combined may make up as much as
15 percent of the alloy by weight. Alloys are assigned a four-digit number, in which the first digit identifies a general class, or series, characterized by its main alloying elements.

Commercially Pure Aluminum

1xxx Series
The 1xxx series alloys are comprised of aluminum 99 percent or higher purity. This series has excellent corrosion resistance, excellent workability, as well as high thermal and electrical conductivity. This is why the 1xxx series is commonly used for transmission, or power grid, lines that connect the national grids across the United States. Common alloy designations in this series are 1350, for electrical applications, and 1100, for food packaging trays.

Heat-Treatable Alloys
Some alloys are strengthened by solution heat-treating and then quenching, or rapid cooling. Heat treating takes the solid, alloyed metal and heats it to a specific point. The alloy elements, called solute, are homogeneously distributed with the aluminum putting them in a solid solution. The metal is subsequently quenched, or rapidly cooled, which freezes the solute atoms in place. The solute atoms consequently combine into a finely distributed precipitate. This occurs at room temperature which is called natural aging or in a low temperature furnace operation which is called artificial aging.

xxx Series
In the 2xxx series, copper is used as the principle alloying element and can be strengthened significantly through solution heat-treating. These alloys possess a good combination of high strength and toughness, but do not have the levels of atmospheric corrosion resistance as many other aluminum alloys. Therefore, these alloys are usually painted or clad for such exposures. They’re generally clad with a high-purity alloy or a 6xxx series alloy to greatly resist corrosion. Alloy 2024 perhaps the most widely known aircraft alloy.

6xxx Series
The 6xxx series are versatile, heat treatable, highly formable, weldable and have moderately high strength coupled with excellent corrosion resistance. Alloys in this series contain silicon and magnesium in order to form magnesium silicide within the alloy. Extrusion products from the 6xxx series are the first choice for architectural and structural applications. Alloy 6061 is the most widely used alloy in this series and is often used in truck and marine frames. Additionally, the iPhone 6 extrusion was made from 6xxx series alloy.

7xxx Series
Zinc is the primary alloying agent for this series, and when magnesium is added in a smaller amount, the result is a heat-treatable, very high strength alloy. Other elements such as copper and chromium may also be added in small quantities. The most commonly known alloys are 7050 and 7075, which are widely used in the aircraft industry. Apple®’s aluminum Watch, released in 2015, was made from a custom 7xxx series alloy.

Non Heat-Treatable Alloys
Non-heat treated alloys are strengthened through cold-working. Cold working occurs during rolling or forging methods and is the action of “working” the metal to make it stronger. For example, when rolling aluminum down to thinner gauges, it gets stronger. This is because cold working builds up dislocations and vacancies in the structure, which then inhibits the movement of atoms relative to each other. This increases the strength of the metal. Alloying elements like magnesium intensify this effect, resulting in even higher strength.

3xxx Series
Manganese is the major alloying element in this series, often with smaller amounts of magnesium added. However, only a limited percentage of manganese can be effectively added to aluminum. 3003 is a popular alloy for general purpose because it has moderate strength and good workability and may be used in applications such as heat exchangers and cooking utensils. Alloy 3004 and its modifications are used in the bodies of aluminum beverage cans.

4xxx Series
4xxx series alloys are combined with silicon, which can be added in sufficient quantities to lower the melting point of aluminum, without producing brittleness. Because of this, the 4xxx series produces excellent welding wire and brazing alloys where a lower melting point is required. Alloy 4043 is one of the most widely used filler alloys for welding 6xxx series alloys for structural and automotive applications.
5xxx Series
Magnesium is the primary alloying agent in the 5xxx series and is one of the most effective and widely used alloying elements for aluminum. Alloys in this series possess moderate to high strength characteristics, as well as good weldability and resistance to corrosion in the marine environment. Because of this, aluminum-magnesium alloys are widely used in building and construction, storage tanks, pressure vessels and marine applications. Examples of common alloy applications include: 5052 in electronics, 5083 in marine applications, anodized 5005 sheet for architectural applications and 5182 makes the aluminum beverage can lid. The U.S. military’s Bradley Fighting Vehicle is made with 5083 and the 7xxx series aluminum

3.7. Precipitation hardening treatment

Precipitation hardening, also called age hardening or particle hardening, is a heat treatment technique used to increase the yield strength of malleable materials, including most structural alloys of aluminium, magnesium, nickel, titanium, and some steels and stainless steels. In superalloys, it is known to cause yield strength anomaly providing excellent high-temperature strength. Precipitation hardening relies on changes in solid solubility with temperature to produce fine particles of an impurity phase, which impede the movement of dislocations, or defects in a crystal's lattice. Since dislocations are often the dominant carriers of plasticity, this serves to harden the material. The impurities play the same role as the particle substances in particle-reinforced composite materials. Just as the formation of ice in air can produce clouds, snow, or hail, depending upon the thermal history of a given portion of the atmosphere, precipitation in solids can produce many different sizes of particles, which have radically different properties. Unlike ordinary tempering, alloys must be kept at elevated temperature for hours to allow precipitation to take place. This time delay is called "aging". Solution treatment and aging is sometimes abbreviated "STA" in metals specs and certs.

Note that two different heat treatments involving precipitates can alter the strength of a material: solution heat treating and precipitation heat treating. Solid solution strengthening involves formation of a single-phase solid solution via quenching. Precipitation heat treating involves the addition of impurity particles to increase a material’s strength. Precipitation hardening via precipitation heat treatment is the main topic of discussion in this article
3.8 Bearing alloys
Bearing alloys, are any bearing that is using a metal alloy as its running surface, either lubricated by fluids/greases or running on smooth surfaces. For example, the big-end shells or crankshaft bearing shells in an internal combustion engine (amongst other devices) use all sorts of metal alloys in their structure.

Babbitt (metal)
Babbitt, also called Babbitt metal or bearing metal, is any of several alloys used for the bearing surface in a plain bearing. The original Babbitt alloy was invented in 1839 by Isaac Babbitt in Taunton, Massachusetts, United States. He disclosed one of his alloy recipes but kept others as trade secrets. Other formulations were later developed. Like other terms whose eponymous origin is long since deemphasized (such as diesel engine or eustachian tube), the term babbitt metal is frequently styled in lowercase. It is preferred over the term "white metal", because the latter term may refer to various bearing alloys, lead- or tin-based alloys, or zinc die-casting metal.

Microstructure of babbitt
Babbitt metal is most commonly used as a thin surface layer in a complex, multi-metal structure, but its original use was as a cast-in-place bulk bearing material. Babbitt metal is characterized by its resistance to galling. Babbitt metal is soft and easily damaged, which suggests that it might be unsuitable for a bearing surface. However, its structure is made up of small hard crystals dispersed in a softer metal, which makes it a metal matrix composite. As the bearing wears, the softer metal erodes somewhat, which creates paths for lubricant between the hard high spots that provide the actual bearing surface. When tin is used as the softer metal, friction causes the tin to melt and function as a lubricant, which protects the bearing from wear when other lubricants are absent. Internal combustion engines use Babbitt metal which is primarily tin-based because it can withstand cyclic loading. Lead-based Babbitt tends to work-harden and develop cracks but it is suitable for constant-turning tools such as sawblades.

3.9.1 Mg alloy
Magnesium alloys are mixtures of magnesium with other metals (called an alloy), often aluminum, zinc, manganese, silicon, copper, rare earths and zirconium. Magnesium is the lightest structural metal. Magnesium alloys have a hexagonal lattice structure, which affects the fundamental properties of these alloys. Plastic deformation of the hexagonal lattice is more complicated than in cubic latticed metals like aluminium, copper and steel; therefore, magnesium alloys are typically used as cast alloys, but research of wrought alloys has been more extensive since 2003. Cast magnesium alloys are used for many components of modern automobiles have been used in some high-performance vehicles; die-cast magnesium is also used for camera bodies and components in lenses.
Practically, all the commercial magnesium alloys manufactured in the United States contain aluminum (3 to 13 percent) and manganese (0.1 to 0.4 percent). Many also contain zinc (0.5 to 3 percent) and some are hardenable by heat treatment. All the alloys may be used for more than one product form, but alloys AZ63 and AZ92 are most used for sand castings, AZ91 for die castings, and AZ92 generally employed for permanent mold castings (while AZ63 and A10 are sometimes also used in the latter application as well). For forgings, AZ61 is most used, and here alloy M1 is employed where low strength is required and AZ80 for highest strength. For extrusions, a wide range of shapes, bars, and tubes are made from M1 alloy where low strength suffices or where welding to M1 castings is planned. Alloys AZ31, AZ61 and AZ80 are employed for extrusions in the order named, where increase in strength justifies their increased relative costs.

Magnox (alloy), whose name is an abbreviation for 'magnesium non-oxidizing', is 99% magnesium and 1% aluminum, and is used in the cladding of fuel rods in magnox nuclear power reactors.

Magnesium alloys are referred to by short codes (defined in ASTM B275) which denote approximate chemical compositions by weight. For example, AS41 has 4% aluminum and 1% silicon; AZ81 is 7.5% aluminum and 0.7% zinc. If aluminium is present, a manganese component is almost always also present at about 0.2% by weight which serves improve grain structure; if aluminum and manganese are absent, zirconium is usually present at about 0.8% for this same purpose.

3.9.2 Ni based super alloy
A superalloy is a metallic alloy which can be used at high temperatures, often in excess of 0.7 of the absolute melting temperature. Creep and oxidation resistance are the prime design criteria. Superalloys can be based on iron, cobalt or nickel, the latter being best suited for aeroengine applications. The essential solutes in nickel based superalloys are aluminium and/or titanium, with a total concentration which is typically less than 10 atomic percent.

A listing of some of the super alloys, with information on their composition and some of the uses is provided here.

- Inconel Alloy 600 (76Ni-15Cr-8Fe) is a standard material of construction for nuclear reactors, also used in the chemical industry in heaters, stills, evaporator tubes and condensers,
- Nimonic alloy 75 (80/20 nickel-chromium alloy with additions of titanium and carbon) used in gas turbine engineering, furnace components and heat-treatment equipment
- Alloy 601. Lower nickel (61%) content with aluminium and silicon additions for improved oxidation and nitriding resistance chemical processing, pollution control, aerospace, and power generation
- Alloy X750. Aluminium and titanium additions for age hardening. Used in gas turbines, rocket engines, nuclear reactors, pressure vessels, tooling, and aircraft structures.
- Alloy 718. (55Ni-21Cr-5Nb-3Mo). Niobium addition to overcome cracking problems during welding. Used in aircraft and land-based gas turbine engines and cryogenic tankage
- Alloy X (48Ni-22Cr-18Fe-9Mo + W). High-temperature flat-rolled product for aerospace applications
- Waspaloy (60Ni-19Cr-4Mo-3Ti-1.3Al). Proprietary alloy for jet engine applications
- ATI 718Plus. A lower cost alloy which exceeds the operating temperature capability of standard 718 alloy by 100 °F (55 °C) allowing engine manufacturers to improve fuel efficiency.
- Nimonic 90. (Ni 54% min Cr 18-21% Co 15-21% Ti 2-3% Al 1-2%) used for turbine blades, discs, forgings, ring sections and hot-working tools
- Rene' N6. (4Cr-12Co-1Mo-W6-Ta7- Al5.8 - Hf 0.2 -Re5- BalNi) 3rd generation single crystal alloy used in jet engines
- TMS 162 (3Cr- 6Co-4Mo-6W-6Ta-6Al-5Re-6Ru-balance Ni) 5th generation single crystal alloy for turbine blades

3.9.3 Titanium alloys
Titanium alloys are metals that contain a mixture of titanium and other chemical elements. Such alloys have very high tensile strength and toughness (even at extreme temperatures). They are light in weight, have extraordinary corrosion resistance and the ability to withstand extreme temperatures. However, the high cost of both raw materials and processing limit their use to military applications, aircraft, spacecraft, medical devices, highly stressed components such as
connecting rods on expensive sports cars and some premium sports equipment and consumer electronics. Although "commercially pure" titanium has acceptable mechanical properties and has been used for orthopedic and dental implants, for most applications titanium is alloyed with small amounts of aluminium and vanadium, typically 6% and 4% respectively, by weight. This mixture has a solid solubility which varies dramatically with temperature, allowing it to undergo precipitation strengthening. This heat treatment process is carried out after the alloy has been worked into its final shape but before it is put to use, allowing much easier fabrication of a high-strength product.

Ti 6Al-4V (Grade 5)

Ti-6AL-4V is the most commonly used of the titanium alloys. It is therefore commonly referred to as the titanium alloy “workhorse.” It is believed to be used in half of the usage of titanium around the world.

These desirable properties make Ti-6AL-4V a popular choice in several industries including medical, marine, aerospace and chemical processing. Ti 6AL-4V is commonly used to make:

- Aircraft turbines
- Engine components
- Aircraft structural components
- Aerospace fasteners
- High-performance automatic parts
- Marine applications
- Sports equipment

Ti 6AL-4V ELI (Grade 23)

Ti 6AL-4V ELI is commonly referred to surgical titanium because of its use in surgery. It is a more pure version of Grade 5 (Ti 6AL-4V) titanium alloy. It can be easily molded, and cut into small strands, coils, and wires. It has the same strength, and high corrosion resistance as Ti 6AL-4V. It is also light-weight and is highly tolerant to damage by other alloys. Its use is highly desirable in the medical and dental fields for uses in complex surgical procedures not only because of these properties but also because of the unique surgical properties Ti 6AL-4V ELI has. It has superior biocompatibility making it easy to graft in and attach to bone all the while being accepted by the human body. Some of the more common surgical procedures Ti 6AL-4V ELI is used in include:

- Orthopedic pins and screws
- Orthopedic cables
- Ligature clips
- Surgical staples
- Springs
- Orthodontic appliances
- In joint replacements
- Cryogenic vessels
- Bone fixation devices

Ti 3Al 2.5 (Grade 12)

Ti 3Al 2.5 is the titanium alloy with the best weldability. It is also strong at high temperatures like the other titanium alloys. This grade 12 titanium alloy is unique in that it exhibits characteristics of stainless steel (one of the other strong metals), such as being heavier than the other titanium alloys.

Ti 3Al 2.5 is most commonly used in the manufacturing industry, specifically in equipment. It is highly resistant to corrosion and can be formed by heat or cold. Grade 12 titanium alloy is used the most in the following industries and applications:

- Shell and heat exchangers
- Hydrometallurgical applications
- Elevated temperature chemical manufacturing
- Marine and airfare components

Ti 5Al-2.5Sn (Grade 6)

Ti 5Al-2.5Sn is a non-heat treatable alloy that can achieve good weldability with stability. It also possesses high temperature stability, high strength, and good corrosion resistance. It has a uniquely high creep (plastic-like strain over long periods of time, usually caused by extreme temperatures)
resistance. Ti 5Al-25Sn is mostly used in aircraft and airframe applications. Titanium as a whole is a highly durable and strong metal. In its pure form it has many uses. It alloys add greater malleability and flexibility to the already strong metal, opening up doors to many more applications. Each titanium alloy shares the same strength and corrosion resistance. They vary on flexibility, making a specific alloy ideal for specific industries and applications. At the Titanium Processing Center, you can find a large selection of both pure and titanium alloy grades for your project. Call us today to schedule your order or to ask a question.
UNITIV. NON-METALLIC MATERIALS

4.1. Introduction to polymers

4.1.1 Definition
Appearance of real linear polymer chains as recorded using an atomic force microscope on surface under liquid medium. Chain contour length for this polymer is ~204 nm; thickness is ~0.4 nm.

A polymer is a large molecule (macromolecule) composed of repeating structural units. These subunits are typically connected by covalent chemical bonds. Although the term polymer is sometimes taken to refer to plastics, it actually encompasses a large class of natural and synthetic materials with a wide variety of properties.

Because of the extraordinary range of properties of polymeric materials, they play an essential and ubiquitous role in everyday life. This role ranges from familiar synthetic plastics and elastomers to natural biopolymers such as nucleic acids and proteins that are essential for life.

Natural polymeric materials such as shellac, amber, and natural rubber have been used for centuries. A variety of other natural polymers exist, such as cellulose, which is the main constituent of wood and paper. The list of synthetic polymers includes synthetic rubber, Bakelite, neoprene, nylon, PVC, polystyrene, polyethylene, polypropylene, polyacrylonitrile, PVB, silicone, and many more.

Most commonly, the continuously linked backbone of a polymer used for the preparation of plastics consists mainly of carbon atoms. A simple example is polyethylene, whose repeating unit is based on ethylene monomer. However, other structures do exist; for example, elements such as silicon form familiar materials such as silicones, examples being silly putty and waterproof plumbing sealant. Oxygen is also commonly present in polymer backbones, such as those of polyethylene glycol, polysaccharides (in glycosidic bonds), and DNA (in phosphodiester bonds).

Polymers are studied in the fields of polymer chemistry, polymer physics, and polymer science.

4.1.2 Types of polymers
There are three general groups of polymer materials:
- Elastomers
- Thermoplastics
- Thermosets

Elastomers
Elastomers are polymers possessing high elasticity - may be reversibly stretched at high degree. Elastomers consists of long lightly cross-linked molecules.
Common elastomers are:
- Polyisoprene (natural rubber)
Elastomers may be strengthened by vulcanization process (heat treatment in presence of chemical agents). Vulcanization results in increase of cross-linking of the molecules. Vulcanized elastomers are elastic for small deformations.

**Thermoplastics**

Thermoplastics are polymers, which soften (becomes pliable and plastic) and melt when heated. In the melted conditions thermoplastics may be formed by various methods (injection molding, extrusion, Thermoforming). No new cross-links form (no chemical curing) when a thermoplastic cools and harden. Thermoplastics may be reprocessed (remelt) many times.

Common thermoplastics are:
- Thermoplastic Low Density Polyethylene (LDPE)
- Thermoplastic High Density Polyethylene (HDPE)
- Polypropylene (PP)
- Acrylonitrile Butadiene-Styrene (ABS)
- Polyvinyl Chloride (PVC)
- Polymethylmethacrylate (PMMA)
- Polytetrafluoroethylene (PTFE)
- Polyethylene Terephthalate (PET)
- Nylon 6 (N6)
- Polymide (PI)
- Polycarbonate (PC)
- Polysulfone (PSF)

**Thermosets**

Thermosets are polymers which do not melt when heated. Thermosets molecules are cross-linked by strong covalent intermolecular bonds, forming one giant molecule. Cross-linking is achieved in curing process initiated by heat, chemical agents or radiation.

Thermosets are stronger and stiffer than thermoplastics. Common thermosets are:
- Epoxies (EP)
- Unsaturated Polyesters (UP)
- Phenolics (PF)
- Urea Formaldehyde (UF)
- Melamine Formaldehyde (MF)
- Alkyds (AMC)

4.1.3 Commodity and engineering polymers

The polymers which are used in engineering applications are called as engineering or commodity polymers.

4.2. Introduction of thermoplastics and thermo setting plastics

4.2.1 Properties and applications of PE, PP, PS, PVC, PMMA, PET, PC, PA, ABS

**Polypropylene (PP)** (thermoplastic, melting temperature: 174oC; glass transition temperature: -17oC) is a versatile commodity polymer. It serves double duty, both as a plastic and as a fiber. As a plastic it's used to make things like dishwasher-safe food containers. It can do this because it doesn't melt below 160oC, or 320oF. Polyethylene, a more common plastic, will anneal at around 100oC,
which means that polyethylene dishes will warp in the dishwasher. As a fiber, polypropylene is used to make indoor-outdoor carpeting, used around swimming pools and miniature golf courses. It works well for outdoor carpet because it is easy to make colored polypropylene, and because polypropylene doesn't absorb water, like nylon does.

It is slightly more susceptible than polyethylene to strong oxidizing agents. It offers the best stress-crack resistance of the polyolefins. Products made of polypropylene are brittle at 0°C and may crack or break if dropped from benchtop height. Polypropylene can be made from the monomer propylene by Ziegler-Natta polymerization and by metallocene catalysis polymerization.

**Polyethylene (PE)** is probably the polymer seen mostly in daily life. Polyethylene is the most popular plastic in the world. This is the polymer that makes grocery bags, shampoo bottles, children's toys, and even bullet proof vests. For such a versatile material, it has a very simple structure, the simplest of all commercial polymers. A molecule of polyethylene is nothing more than a long chain of carbon atoms, with two hydrogen atoms attached to each carbon atom.

Sometimes it's a little more complicated. That is some of the carbons, instead of having hydrogens attached to them, will have long chains of polyethylene attached to them. This is called branched, or low-density polyethylene, or LDPE. When there is no branching, it is called linear polyethylene, or HDPE. Linear polyethylene is much stronger the branched polyethylene, but branched polyethylene is cheaper and easier to make. Linear polyethylene is normally produced with molecular weights in the range of 200,000 to 500,000, but it can be made even higher.

**Polystyrene (PS)** is normally a solid thermoplastic, but can be melted at higher temperature for molding or extrusion, then resolidified. It is an amorphous and its glass transition temperature is 100°C. Polystyrene is an aromatic polymer. Polystyrene is also used as a building material, with electrical appliances (light switches and plates), and in other household items. Polystyrene can be transparent or can be made to take on various colors. It is economical and is used for producing plastic model assembly kits, plastic cutlery, CD "jewel" cases, and many other objects where a fairly rigid, economical plastic of various colors is desired. For architectural and engineering modelling, polystyrene is extruded into forms of standard modelling scale with the cross-sections of a miniature I-beam as well as rods and tubes. It is also formed into sheets with various patterns for this purpose as well. The blank sheets of polystyrene are referred to as "plasticard". Polystyrene fabricated into a sheet can be stamped (formed) into economic, disposable cups, glasses, bowls, lids, and other items, especially when high strength, durability, and heat resistance are not essential. A thin layer of transparent polystyrene is often used as an infra-red spectroscopy standard.
Polyvinyl chloride (PVC) is obtained by suspension or bulk free radical polymerization of vinyl chloride. It is an amorphous polymer (thermo plastic) having glass transition temperature around 87°C. It is an unstable polymer compared to the other commodity polymers like PE, PP etc. Its commercial success is attributed to the discovery of suitable stabilizers and other additives. Lead compounds (lead stearate etc), organo tin compounds (dibutyl tin dilaurate etc) etc are used as stabilizers.

About 50% of produced PVC is used as rigid resins (ex in PVC pipes etc). Flexible PVC is made via plasticization using plasticizers such as dioctyl phthalate, dioctyl adipate, tricresyl phosphate etc. Building construction market account for 30% of its production, which include pipe and fittings, siding, carpet backing, windows gutters, wall coverings etc. Bottles and packaging sheet are also major rigid markets. Flexible vinyl is used in wire and cable insulation, film and sheet, floor coverings, synthetic leather products, coatings, blood bags, medical tubing and many other applications. Plasticized PVC is melt processed. PVC has a good resistance to hydrocarbons. Its application is widened using fillers, pigments, impact modifiers etc.

- \([-\text{CH}_2\text{-CH(Cl)}\text{-}]_n-\)

Poly methyl methacrylate (PMMA) is an amorphous (glass transition 105°C), transparent and colourless thermoplastic that is hard and stiff but brittle and notch-sensitive. It has good abrasion and UV resistance and excellent optical clarity but poor low temperature, fatigue and solvent and scratch resistances. Though flammable, it has low smoke emission. General purpose grades can be extruded and injection moulded. Monomer casting is also used to achieve much higher molecular weights - which are not melt processable because of their extremely high melt viscosity - with somewhat improved properties. The monomer cast items most commonly encountered are sheets and novelty displays in which e.g. insects or watch parts are embedded. Thin films are normally made from impact modified grades, which incorporate a small proportion of elastomer(s), in order to improve their flexibility.

Perspex CQ is a particular example of monomer cast sheet which was, until recently, made for intraocular use and they are additive-free and the purest (and probably the highest molecular weight) grade of PMMA available. Applications include sinks, baths, displays, signs, glazing (especially aircraft), lenses and light covers. Cast sheet is also used for guards and the like.

POLYCARBONATE (PC)

It is an amorphous engineering thermoplastic with excellent combination of properties. It is one of the engineering plastic to compete with die cast metals. Polycarbonate, or specifically polycarbonate of bisphenol A, is a clear plastic used to make shatterproof windows, lightweight eyeglass lenses.
Polycarbonate is a tough, dimensionally stable, transparent thermoplastic that has many applications which demand high performance properties. This versatile thermoplastic maintains its properties over a wide range of temperatures, from -40°F to 280°F. It is available in three types: machine grade; window and glass-filled. It has the highest impact of any Thermoplastic, transparent up to 2” in special grades, outstanding dimensional and thermal stability, and exceptional machinability, stain resistant and non-toxic with low water absorption. Machine Grade is relatively stress free to permit the most demanding machining. It is also available in glass-filled. This polycarbonate is perfect for high performance uses in tough applications over a broad temperature range. Window Grade is optically clear, providing total luminous transmittance and very low haze factor. The high impact strength makes it resistant to repeated blows, shattering and spalling. Polycarbonate is excellent for electrical applications, because of its high dielectric strength and high volume resistivity which decreases only slightly as temperature or humidity is increased.

ABS Plastics

It is a tercopolymer containing styrene, acrylonitrile and butadiene comonomers. The earliest materials were the physical blends of styrene-acrylonitrile copolymer(SAN) and acrylonitrilebutadiene copolymers. Today the ABS refers to a product consisting of discrete cross-linked polybutadiene rubber particles that are grafted with SAN and embedded in a SAN matrix. ABS materials are important for their widespread use as quality housings for equipments. It possesses the following important properties such as, high impact resistance, good stiffness, excellent surface quality, high dimensional stability at elevated temperatures & good heat distortion temperature, good chemical and stress cracking resistance, good low temperature properties etc. It can be electroplated.

Eventhough polypropylene is cheaper than ABS, ABS is preferred where the extreme toughness and superior heat distortion resistance is required. But its main disadvantages are i) lack transparency, ii) poor weathering resistance and iii) poor flame resistance.

4.3. Properties and applications of PAI,PPO,PPS,PEEK,PTFE

POLY ETHER ETHER KETONE(PEEK)

PEEK (Tg : 145°C) is an abbreviation for PolyEtherEther-Ketone, a high performance engineering thermoplastic and is an excellent material for a wide spectrum of applications where thermal, chemical, and combustion properties are critical to performance. The tensile properties of PEEK™ exceed those of most engineering plastics and can be reinforced with carbon fiber resulting in a tensile strength of over 29,000 psi (200 MPa) with excellent properties being retained up to 570°F(300°C). The exceptional stiffness of PEEK™ is reflected in its flexural modulus which is among the best of any thermoplastic. Glass or carbon fiber reinforcement gives further improvement up to very high temperatures.

PEEK combines excellent tribological properties with moldability and outstanding performance at high temperatures. Carbon fiber-reinforced PEEK is probably the only injection moldable bearing material that has a measurable wear factor at over 500°F (260°C), all the thermoplastics fail at or below this temperature. PEEK can retain its flexural and tensile properties at very high temperatures -
- in excess of 250°C (482°F). The addition of glass fiber and carbon fiber reinforcements enhances the mechanical and thermal properties of the basic PEEK material.
Superior chemical resistance has allowed them to work effectively as a metal replacement in harsh environments. They are inert to all common solvents and resist a wide range of organic and inorganic liquids. When extensive machining is required, a secondary annealing process should be considered.

Polytetrafluoroethylene (PTFE)

Polytetrafluoroethylene [Teflon, \((\text{CF}_2-\text{CF}_2)_n\)] is obtained by polymerizing (emulsion polymerization) tetrafluoroethylene (i.e., When all the hydrogen atoms in polyethylene have been replaced by fluorine, polytetrafluoroethylene (PTFE) is obtained). It is a tough, flexible, nonresilient material of moderate tensile strength but with excellent resistance to heat, chemicals and to the passage of electric current. It is resistant to many chemicals, including acetic acid, ammonia, sulfuric acid, and hydrochloric acid. It remains ductile in compression at temperatures as low as 4K (-269°C). The coefficient of friction is low and is reported to be lower than that of any other solid. PTFE is an outstanding insulator over a wide range of temperature and frequency.

Polyamides (NYLONS)

Polyamides are a group of thermoplastic polymers containing amide groups in the main chain. They are popularly known as nylons. They may be aliphatic (nylon 66, nylon66 etc) or aromatic (Kevlar, nomex etc). Commercially important polyamides are PA-66, PA-6, PA-11, PA-12, PA-610, PA-612 etc. Polyamides have good strength and toughness with excellent fatigue resistance.

However, they are prone to absorb moisture, ranging from 8 - 10% for PA6 and PA66 to 2 - 3% for PA11 and PA12 at saturation. Mechanical properties are affected by moisture, with toughness improving with the absorption of moisture whereas modulus is reduced. Polyamides are resistant to hydrocarbons, esters and glycols, but swell and dissolve in alcohols. They are also attacked by acids but generally stable to alkalis.

\[
\begin{align*}
\text{H} & \text{H} & \text{H} & \text{H} & \text{H} & \text{O} \\
\text{N} & \text{C} & \text{C} & \text{C} & \text{C} & \text{C} \\
\text{H} & \text{H} & \text{H} & \text{H} & \text{H} & \text{H}
\end{align*}
\]

the repeat unit of nylon 6-6

Hard and tough thermoplastic, good abrasion resistance, low coefficient of friction, high tensile strength, good dimensional stability, low tendency to warp, smooth appearance of surface, average to high surface gloss, resistant to lubricants, engine fuels, grease etc, good resistance to coolants, refrigerants, paint solvent cleaners, resistant to aqueous solution of many inorganic chemicals.

Nylon fibres are used in textiles, fishing line and carpets. Nylon films are used for food packaging, offering toughness and low gas permeability, and coupled with its temperature resistance, for boil-in-the-bag food packaging. Moulding and extrusion compounds find many applications as replacements for metal parts, for instance in car engine components. Intake manifolds in nylon are tough, corrosion resistant, lighter and cheaper than aluminium (once tooling costs are covered) and offer better air flow due to a smooth internal bore instead of a rough cast one. Its self-lubricating properties make it useful for gears and bearings.

Polyethylene terephthalate (PET)

Polyethylene terephthalate (PET) and polybutylene terephthalate (PBT) are the most common thermoplastic polyesters. They are similar to PA6 and PA66 in many respects but with much lower water absorption. However, they are prone to hydrolysis, and prolonged contact with water at temperatures as low as 50°C has a detrimental effect on properties. Polyethylene terephthalate
PET is often called just “polyester”. Polybutylene terephthalate (PBT) also a (thermoplastic) polyester, the most common resin system used in glass reinforced plastic (GRP) is also a polyester system.

Polyethylene terephthalate (PET) is a hard, stiff, strong, dimensionally stable material that absorbs very little water. It has good gas barrier properties and good chemical resistance except to alkalis (which hydrolyse it). Its crystallinity varies from amorphous to fairly high crystalline. It can be highly transparent and colourless but thicker sections are usually opaque and off-white. The “Mylar®-type” films are used for capacitors, graphics, film base and recording tapes etc. PET is also used for fibres for a wide variety of textile and industrial uses (Dacron®, Trevira®, Terylene®). Other applications include bottles and electrical components.

Polymide (PI)
Polymeric compounds containing multiple imides, i.e., NH groups derived from ammonia (NH₃) by replacement of two hydrogen atoms by metals or equivalents of acid groups.

Polyimides are a very interesting group of incredibly strong and astoundingly heat and chemical resistant polymers. Their strength and heat and chemical resistance are so great that these materials often replace glass and metals, such as steel, in many demanding industrial applications. Polyimides are even used in many everyday applications. They are used for the struts and chassis in some cars as well as some parts under-the-hood because they can withstand the intense heat and corrosive lubricants, fuels, and coolants cars require. They are also used in the construction of many appliances as well as microwave cookware and food packaging because of their thermal stability, resistance to oils, greases, and fats and their transparency to microwave radiation. They can also be used in circuit boards, insulation, fibers for protective clothing, composites, and adhesives. These polymers have excellent resistant to oxidative degradation, chemicals, strong bases and high energy radiation. It possesses good flame and abrasion resistances. But unfortunately these polymers cannot be moulded by conventional thermoplastic techniques. They are used as wire enamels, insulating varnishes, as coatings for glass cloth etc. Polyimide foams have been used for sound deadening of jet engines. They are used in space craft construction, rockets and weapons technology.

Polyamide-imide (PAI)
Polyamide-imides are amorphous thermoplastic materials with excellent mechanical properties, especially at elevated temperatures. Trimellitic anhydrides react with aromatic diamines to produce polyamide-imides. Polyamide-imides are applied in demanding engineering applications. Solvay Advanced Polymer's Torlon® is a well-known example of a polyamide-imide engineering resin that is also used to molded, extruded or machined plastic parts or shape stock.

It is used for fabricating valves, pumps bearings, electrical connectors, gears and general mechanical components, Parts for jet engines, internal combustion engines, Printed circuit boards, accessories for refrigeration plants etc. Polyamideimide (PAI) was initially developed as a high temperature enamel but was later modified for processing by injection and compression techniques. No other commercially available unreinforced thermoplastic is as strong as PAI over its operating range. Applications include valves, bearings, gears, electrical connectors, jet engine parts labyrinth seals, car mandrel, bearing cages, etc.

Polyetherimides (PEI)
Polyetherimides are thermally stable at high temperatures and exhibit good optical properties making them useful in high temperature processing applications, in the fabrication of...
optoelectronics devices, and in optical applications. Polyetherimides (PEI) are amorphous, high performance thermoplastics with a continuous use temperature of around 170°C. PEI resins can also be melt processed using typical equipment for high volume production. The strength, creep and impact properties of PEIs make them ideal for under bonnet components. They are also used in high temperature switchgear and electrical connectors.

A number of medical equipment components are manufactured using PEIs, taking advantage of their excellent resistance to repeated sterilisation using steam, autoclave, gamma radiation or ethylene oxide. Microwave cookware is another application. They exhibit very high tensile strength without reinforcement, high glass transition (215°C), deflection (200°C) and softening (219°C) temperatures. PEIs are competitive with PAI, polysulphones, polycarbonates, polyphenylene sulphides etc. It is used in microwave equipment, printed circuit boards, wire insulation etc.

Polyphenylene Oxide (PPO)

PPO is prepared by oxidative coupling of phenylene oxide monomer using oxygen and a copper-based catalyst. PPO is a high strength, tough and heat resistant polymer, but in the unmodified state it is extremely difficult to process. It is also relatively expensive.

Fortunately, it is miscible with polystyrene, and the resulting amorphous blends are easily processed and cheaper than PPO, with little loss in mechanical properties. Stiffness and strength are approximately 50% higher than high impact ABS, with similar creep behaviour. Modified PPO grades are also self extinguishing when ignited. Resistance to solvents is poor, a characteristic of styrene-based polymers. As well as glass fibre reinforced grades, these materials are available in structural foam grades.

Consumer goods: Power tool housings, portable mixers, hairdryers.

Automotive: Instrument panels and seat backs, spoilers, wheel trims, external mirror housings.

Electrical: Electrical terminal housings, cable connectors, bulb sockets, coil formers.

Miscellaneous: Plastic parts in central heating systems.

Polyphenylene sulphide (PPS)

Poly phenylene sulfide or PPS, is one of those really high-performance plastics that is very strong and can resist very high temperatures. PPS doesn't melt until around 300°C. It's also flame resistant.

PPS is an engineering thermoplastic. PPS is expensive, so it's used only when good heat resistance is needed. Electrical sockets, and other electrical components are made of PPS. So are certain parts of cars, microwave ovens, and hairdryers. Its melting point 300°C. Glass transition temperature 90°C.

PPS is a crystalline material, usually supplied reinforced with glass fibres or glass fibres and mineral fillers.

The chemical and ionising radiation resistance of PPS is excellent and the maximum recommended service temperature for PPS is about 200°C, although it will withstand 350°C for short periods of time. While PPS will burn and char in the presence of a flame, it is self extinguishing and any
smoke that does form is lower in toxicity compared to that given off by many polymers. There are some similarities between PPS and polysulphones, with PPS usually the cheaper option. Uses of PPS include chemically resistant coatings, chemical pumps and electrical components.

4.4. Urea, Phenol Formaldehydes

UREA-FORMALDEHYDE RESIN

It is a thermosetting resin prepared by heating urea and formaldehyde in the presence of mild alkalies, such as pyridine or ammonia. The urea and formaldehyde undergo a condensation reaction in which they combine to form a water-soluble polymer. This polymer is used to formulate adhesives and coatings agents or is mixed.

Urea formaldehyde resin is a colourless to milky viscous liquid, with faint formaldehyde odour. It is soluble in water and alcohol. The free formaldehyde content of UF resins is less than 5 per cent and usually less than 0.5 per cent depending on grade.

It is most commonly used for commercially produced interior and exterior particle boards. UF polymers have proven to be very good adhesives for wooden materials. Due to their high reactivity and cost efficiency, they are the most popular binders for interior products. Adhesives based on formaldehyde are used as binders in the production of reconstituted wood panels such as particleboard, plywood, medium density fibreboard, laminated veneer lumber, finger joints and laminated beams. UF resins and other related formaldehyde resins are also used in resin impregnated decorative paper laminates, glass fibre insulation binders, foundry cores, pulp and papers processing aids, paper sizing, textile treatments, paints and enamels, and miscellaneous joinery applications.

PF RESIN (Phenol-formaldehyde resin, phenolic resin, Bakelite)

It is a thermoset resin prepared by condensation polymerization of phenol and formaldehyde. If acid catalyst is used the resin is called Novolac and if base catalyst is employed the resulting resin is termed as resol. PF is mainly used in mouldings and laminates. Phenolics have poor tracking resistance under conditions of high humidity. This means phenolics have a tendency to form a conductive path through carbonization along a surface between two electrodes at differing potential.

The most well known application of PF resin is in domestic plugs and switches. But now a days they are replaced by UF resins (amino resins) because of their better anti-tracking properties. In car industry PF mouldings are used in fuse-box covers, distribution heads. Heat resistance PF resins are used in sauce pan handles and knobs, lamp housings, cooker handles, welding tongs. Bottle caps and closures are made from PF mouldings. PF mouldings continue to be used in many industrial applications where heat resistance, low cost and shock resistance are important features. PF resins is also used as matrix in composite industry with fibre reinforcements. Phenolic-paper laminates are used for high-voltage insulation applications. PF-cotton laminates are used in the manufacture of gear wheels. Phenolic resins are useful surface coating material. Resols are useful for storing lacquers, for coating chemical plant, textile equipment, razor blades, brasswares and food cans. PF resin is also used in formulating different adhesives for plywoods.

4.5. Ceramics

4.5.1. Introduction

Ceramic materials are inorganic, nonmetallic materials. Most ceramics are compounds between metallic and nonmetallic elements for which the interatomic bonds are either totally ionic or predominantly ionic but having some covalent character. The term ceramic comes from the Greek word keramikos, which means burnt stuff, indicating that desirable properties of these materials are normally achieved through a high-temperature heat treatment process called firing.
Ceramic materials are important in today's society. Consider the ceramic engine and what advantages it offers in terms of fuel economy, efficiency, weight savings and performance. Below are three gif's showing a montage of a prototype ceramic engine and some of the internal automotive components made from ceramics.

4.6 Properties and applications of \( \text{Al}_2\text{O}_3, \text{SiC}, \text{Si}_3\text{N}_4 \)

**Aluminum Oxide, \( \text{Al}_2\text{O}_3 \)**

Alumina is the most cost effective and widely used material in the family of engineering ceramics. The raw materials from which this high performance technical grade ceramic is made are readily available and reasonably priced, resulting in good value for the cost in fabricated alumina shapes. With an excellent combination of properties and an attractive price, it is no surprise that fine grain technical grade alumina has a very wide range of applications.

**Key Properties**
- Hard, wear-resistant
- Excellent dielectric properties from DC to GHz frequencies
- Resists strong acid and alkali attack at elevated temperatures
- Good thermal conductivity
- Excellent size and shape capability
- High strength and stiffness

Available in purity ranges from 94%, an easily metallizable composition, to 99.5% for the most demanding high temperature applications.

**Typical Uses**
- Gas laser tubes
- Wear pads
- Seal rings
- High temperature electrical insulators
- High voltage insulators
- Furnace liner tubes
- Thread and wire guides
- Electronic substrates
- Ballistic armor
- Abrasion resistant tube and elbow liners
- Thermometry sensors
- Laboratory instrument tubes and sample holders
- Instrumentation parts for thermal property test machines
- Grinding media

**Silicon Carbide**

Sintered alpha silicon carbide is produced by initially mixing fine (sub-micron) and pure silicon carbide powder with non-oxide sintering aids. The powdered material is formed or compacted by using most of the conventional ceramic forming processes such as die pressing, isostatic pressing and injection moulding. Following the forming stage the material is sintered in an inert atmosphere at temperatures above 2000°C. The sintered silicon carbide can then be machined to precise tolerances using a range of precision diamond grinding or lapping techniques. As with most advanced ceramics the cost of the component is reduced if the amount of diamond grinding is reduced i.e. either the material manufacturer can achieve the required tolerances “as sintered” or the designer removes unnecessary tolerances.

**Key Properties**
- The major properties of sintered silicon carbide of interest to the engineer or designer, are as
follows:
High hardness (second only to diamond)
Low density 40% the density of steel – approximately the same as aluminium
Low porosity
Good wear resistance in sliding and abrasive environments
Excellent corrosion resistance in most chemical environments
Low thermal expansion and high thermal conductivity leading to excellent thermal shock resistance.

**Silicon Nitride, Si₃N₄**

Silicon nitride is a man made compound synthesized through several different chemical reaction methods. Parts are pressed and sintered by well developed methods to produce a ceramic with a unique set of outstanding properties. The material is dark gray to black in color and can be polished to a very smooth reflective surface, giving parts with a striking appearance. High performance silicon nitride materials were developed for automotive engine wear parts, such as valves and cam followers and proven effective. The cost of the ceramic parts never dropped enough to make the ceramics feasible in engines and turbochargers. The very high quality bodies developed for these demanding high reliability applications are available today and can be used in many severe mechanical, thermal and wear applications.

**Key Properties**

- High strength over a wide temperature range
- High fracture toughness
- High hardness
- Outstanding wear resistance, both impingement and frictional modes
- Good thermal shock resistance
- Good chemical resistance

**Typical Uses**

- Rotating bearing balls and rollers
- Cutting tools
- Engine moving parts — valves, turbocharger rotors
- Engine wear parts — cam followers, tappet shims
- Turbine blades, vanes, buckets
- Metal tube forming rolls and dies
- Precision shafts and axles in high wear environments

**4.7. Properties and applications of PSZ and SIALON**

**PSZ**

Pure zirconia exists in three crystal phases at different temperatures. At very high temperatures (>2370°C) the material has a cubic structure. At intermediate temperatures (1170 to 2370°C) it has a tetragonal structure. At low temperatures (below 1170°C) the material transforms to the monoclinic structure. The transformation from tetragonal to monoclinic is rapid and is accompanied by a 3 to 5 percent volume increase that causes extensive cracking in the material. This behavior destroys the mechanical properties of fabricated components during cooling and makes pure zirconia useless for any structural or mechanical application. Several oxides which dissolve in the zirconia crystal structure can slow down or eliminate these crystal structure changes. Commonly used effective additives are MgO, CaO, and Y2O3. With sufficient amounts added, the high temperature cubic structure can be maintained to room temperature. Cubic stabilized zirconia is a useful refractory and technical ceramic material because it does not go through destructive phase transitions during heating and cooling.
The volume expansion of the tetragonal to monoclinic inversion is used to produce very high strength, hard, tough varieties of zirconia for mechanical and structural applications. There are several different mechanisms that lead to strengthening and toughness in zirconias that contain tetragonal grains. This is a complex subject matter. Simplistically, these depend on the grain sizes, the thermal history and the kind and amount of stabilizing additive in the body. These variations lead to two strong materials identified as TZP and PSZ ceramics. The PSZ is the more common commercial material and is made as a MgO partially stabilized zirconia. The second variety, TZP, is a pure tetragonal very fine grain material. This material, which is challenging to produce, has found uses in cutting and wear resistant applications due to its reliable and outstanding hardness and toughness. TZP properties degrade rapidly when the material is exposed to water vapor at 200 to 300°C, so controlled use conditions are important for good performance. All of the toughened zirconias show a degrading of properties with increasing temperature, and this class of high strength, tough materials is generally limited to use temperatures below 800°C.

Key Properties
Use temperatures up to 2400°C
High density
Low thermal conductivity (20% that of alumina)
Chemical inertness
Resistance to molten metals
Ionic electrical conduction
Wear resistance
High fracture toughness
High hardness

Typical Uses
Precision ball valve balls and seats
High density ball and pebble mill grinding media
Rollers and guides for metal tube forming
Thread and wire guides
Hot metal extrusion dies
Deep well down-hole valves and seats
Powder compacting dies
Marine pump seals and shaft guides
Oxygen sensors
High temperature induction furnace susceptors

Sialon
Sialon, a fine grain nonporous technical grade engineering material, is a silicon nitride ceramic with a small percentage of aluminum oxide added. Sialon is outstanding in nonferrous metal contact. It is highly thermal shock resistant, strong, and is not wet or corroded by aluminum, brass, bronze, and other common industrial metals.

Key Properties
Excellent thermal shock resistance
Not wetted or corroded by nonferrous metals
High strength
Good fracture toughness
Good high temperature strength
Low thermal expansion
Good oxidation resistance

Typical Uses
Thermocouple protection tubes for nonferrous metal melting
Immersion heater and burner tubes
Degassing and injector tubes in nonferrous metals
Metal feed tubes in aluminum die casting
Welding and brazing fixtures and pins

4.8. Composites.
A composite material is a multiphase material, which is composed of at least two basic elements working together to produce material properties that are different to the properties of those elements on their own. In practice, most composites consist of a bulk material (the ‘matrix’), and a reinforcement of some kind, added primarily to increase the strength and stiffness of the matrix. This reinforcement is usually in fibre form. Composites maintain an interface between components and act in concert to provide improved specific or synergistic characteristics not obtainable by any of the original components acting alone. The definition will allow the inclusion of natural materials such as wood which consists of cellulose fibers bonded together with lignin and other carbohydrate constituents, as well as the silk fiber spun by a spider which is as strong as steel on a weight basis consisting of a gel core encased in a solid protein structure as composite materials. Composites include: (1) fibrous (composed of fibers, and usually in a matrix), (2) laminar (layers of materials), (3) particulate (composed of particles or flakes, usually in a matrix), and (4) hybrid (combinations of any of the above).

Overall, the properties of the composite are determined by the, 1) properties of the fibre, 2) properties of the resin, 3) ratio of fibre to resin in the composite (Fibre Volume Fraction (FVF)) and 4) geometry and orientation of the fibres in the composite.

The ratio of the fibre to resin derives largely from the manufacturing process used to combine resin with fibre. However, it is also influenced by the type of resin system used, and the form in which the fibres are incorporated. In general, since the mechanical properties of fibres are much higher than those of resins, the higher the fibre volume fraction (FVF) the higher will be the mechanical properties of the resultant composite. In practice there are limits to this, since the fibres need to be fully coated in resin to be effective, and there will be an optimum packing of the generally circular cross-section fibres. In addition, the manufacturing process used to combine fibre with resin leads to varying amounts of imperfections and air inclusions. Typically, with a common hand lay-up process as widely used in the boat-building industry, a limit for FVF is approximately 30-40%. With the higher quality, more sophisticated and precise processes used in the aerospace industry, FVF’s approaching 70% can be successfully obtained.

The geometry of the fibres in a composite is also important since fibres have their highest mechanical properties along their lengths, rather than across their widths. This leads to the highly anisotropic properties of composites, where, unlike metals, the mechanical properties of the composite are likely to be very different when tested in different directions. This means that it is very important when considering the use of composites to understand at the design stage, both the magnitude and the direction of the applied loads. When correctly accounted for, these anisotropic properties can be very advantageous since it is only necessary to put material where loads will be applied, and thus redundant material is avoided.

It is also important to note that with metals the material supplier largely determines the properties of the materials, and the person who fabricates the materials into a finished structure can do almost nothing to change those ‘in-built’ properties. However, a composite material is formed at the same
time, as the structure is itself being fabricated. This means that the person who is making the
structure is creating the properties of the resultant composite material, and so the manufacturing
processes they use have an unusually critical part to play in determining the performance of the
resultant structure.

Today, the most common man-made composites can be divided into three main groups:
1. Polymer Matrix Composites (PMC’s) – These are the most common and will be discussed here. Also known as FRP - Fibre Reinforced Polymers (or Plastics) – these materials use a polymer-based
resin as the matrix, and a variety of fibres such as glass, carbon and aramid as the reinforcement.
2. Metal Matrix Composites (MMC’s) - Increasingly found in the automotive industry, these materials use a metal such as aluminium as the matrix, and reinforce it with fibres such as silicon carbide.
3. Ceramic Matrix Composites (CMC’s) - Used in very high temperature environments, these materials use a ceramic as the matrix and reinforce it with short fibres, or whiskers such as those made from silicon carbide and boron nitride.

Manufacturing processes forming microstructure of ceramics

Powder preparation
Powder characteristics such as particle shape (spherical, irregular), average particle
size, size distribution determine the ceramic grain size and the amount and size of the pores.

Compaction (shape forming)
The value of the applied pressure the method of its application (Uniaxial (Die) Pressing, Isostatic
Pressing, Injection Molding, Extrusion, Slip Casting, etc.) and the amount of binders and
other additives (plasticizers, lubricants, deflocculants, water etc.) determine the pores size and the
residual internal stresses.

Sintering
Diffusion proceeding during sintering process causes the pores to diminish or
even to close up resulting in densification of the ceramic material. The bonding and other second
phases are distributed between the grains of the main ceramic phase. The matrix grains may grow
during the sintering process. Thus sintering process determines the final grains and pores size and
the physical and chemical homogeneity.

Characterization of ceramics properties
In contrast to metallic bonding neither ionic nor covalent bonding form free electrons,
therefore ceramic materials have very low electric conductivity and thermal
conductivity. Since both ionic and covalent bonds are stronger than metallic bond, ceramic materials are stronger and harder than metals.

Strength of ionic and covalent bonds also determines high melting point, modulus of elasticity
(rigidity), temperature and chemical stability of ceramic materials. Motion of dislocations
through a ceramic structure is impeded therefore ceramics are generally brittle that limits their
use as structural materials.

Ceramics may have either crystalline or amorphous structure. There are also ceramic materials,
consisting of two constituents: crystalline and amorphous.

4.8.1. Metal Matrix Composites
Increasingly found in the automotive industry, these materials use a metal such as aluminium as the
matrix, and reinforce it with fibres such as silicon carbide.

4.8.2 Fibre Reinforced Composites
Used in very high temperature environments, these materials use a ceramic as the matrix and
reinforce it with short fibres, or whiskers such as those made from silicon carbide and boron nitride.
UNIT 5  MECHANICAL PROPERTIES AND DEFORMATION MECHANISM

5.1. Plastic deformation of materials

Plastic deformation is a change of the material dimensions remaining after removal of the load caused the deformation. Plastic deformations in metals occur by “slip” mechanism, illustrated in the picture:

When the yield stress is achieved one plane of atoms in crystal lattice glides over another. Few parallel slip planes form a block, neighboring with another block. Thus movement of the crystal planes is resulted in a series of steps, forming slip bands - black lines viewed under optical microscope.

In polycrystalline material directions of slips are different in different crystals. If a grain is oriented unfavorably to the stress direction its deformation is impeded. In addition to this grain boundaries are obstacles for the slip movement as the slip direction should be changed when it crosses the boundary. As a result of the above strength of polycrystalline materials is higher, than that of mono-crystals.

Slip and twinning processes, occurring during plastic deformation result in formation of preferred orientation of the grains. If the stress value required for a slip is higher than cohesion strength, metal fracture occurs. Stress-strain relations are considered in Tensile test and Stress-Strain Diagram.

5.2. Deformation of Mechanism

5.2.1. Slip
Slip occurs when the share resolved stress along the gliding planes reaches a critical value. This critical resolved shear stress is a characteristic of the material.

Microscopically, plastic deformation is a result of permanent distortion of lattice by extensive rearrangement of atoms within it. There is an irreversible shear displacement of one part of the crystal relative to another in a definite crystallographic direction. This process is known as slip. Slip follows the path of least energy. It coincides to the direction in which atoms are most closely packed.

In a lattice, crystalline array of atoms are having linear imperfection, called dislocation. Slip is considered as step-by-step movement of dislocation within a crystal. In well-annealed metals, density of dislocation is not high enough to cause such macroscopic deformation. Therefore, there must be some mechanism that causes dislocations to multiply to a large number. Slip is one of such mechanisms in which dislocations reproduce themselves.

There are two types of dislocations: edge dislocation and screw dislocation. The edge dislocation moves across the slip plane in the direction of applied shear force. The direction of movement of screw dislocation is normal to the direction of slip step. When slip occurs by combination of the two types of dislocations, it results in a curved dislocation.
5.2.2. Twinning

Certain metals (Zn and Sn) deform by a process of twinning, differing from the normal slip mechanism, where all atoms in a block move the same distance. In the deformation by twinning atoms of each slip plane in a block move different distances, causing half of the crystal lattice to become a mirror image of another half.

Another mechanism of plastic deformation that occurs in certain metals under certain circumstances is by twinning. In this process, atoms in each successive plane within a block move different distances. As a result the direction of the lattice is altered so that each half of the crystal becomes a mirror image of the other half along a twinning plane. In case of BCC structure, twinning occurs after some plastic deformation or when stress is applied quickly.

5.3. Determination of fracture

5.3.1. Definition

Fracture is an inhomogeneous process of deformation that makes regions of material to separate and load-carrying capacity to decrease to zero. It can be viewed on many levels, depending on the size of the fractured region that is of interest. At the atomistic level fracture occurs over regions whose dimensions are of the order of the atomic spacing (10^-7 mm); at the microscopic level fracture occurs over regions whose dimensions are of the order of the grain size (about 10^-3 mm); and at the macroscopic level fracture occurs over dimensions that are of the order of the size of flaws or notches (1 mm or greater).

At each level there are one or more criteria that describe the conditions under which fracture can occur. For example, at the atomistic level fracture occurs when bonds between atoms are broken across a fracture plane and new crack surface is created. This can occur by breaking bonds perpendicular to the fracture plane, a process called cleavage, or by shearing bonds across the fracture plane, a process called shear. At this level the fracture criteria are simple; fracture occurs...
when the local stresses build up either to the theoretical cohesive strength $\sigma_c \approx E/10$ or to the theoretical shear strength $\gamma_c \approx G/10$, where $E$ and $G$ are the respective elastic and shear module. The high stresses required to break atomic bonds are concentrated at the edges of inhomogeneities that are called micro cracks or macro cracks (flaws, notches, cracks). At the microscopic and macroscopic levels fracture results from the passage of a crack through a region of material. The type of fracture that occurs is characterized by the type of crack responsible for the fracture. Few structural materials are completely elastic; localized plastic strain usually precedes fracture, even when the gross fracture strength is less than the gross yield strength. Fracture in these instances is initiated when a critical amount of local plastic strain or plastic work occurs at the tip of a flaw. From the principles of fracture mechanics it is possible to determine macroscopic fracture criteria in terms of the nominal fracture strength, the flaw length, and the critical amount of plastic work required to initiate unstable fracture -- the fracture toughness.

5.3.2 Classification

Cleavage fractures occur when a cleavage crack spreads through a solid under a tensile component of the externally applied stress. The material fractures because the concentrated tensile stresses at the crack tip are able to break atomic bonds. In many crystalline materials certain crystallographic planes of atoms are most easily separated by this process and these are called cleavage planes.

Under uniaxial tensile loading the crack tends to propagate perpendicularly to the tensile axis. When viewed in profile, cleavage fractures appear "flat" or "square", and these terms are used to describe them.

Most structural materials are polycrystalline. The orientation of the cleavage plane(s) in each grain of the aggregate is usually not perpendicular to the applied stress so that, on a microscopic scale, the fractures are not completely flat over distances larger than the grain size.

In very brittle materials cleavage fractures can propagate continuously from one grain to the next. However, in materials such as mild steel the macroscopic cleavage fracture is actually discontinuous on a microscopic level; most of the grains fracture by cleavage but some of them fail in shear, causing the cleaved grains to link together by tearing.

Shear fracture, which occurs by the shearing of atomic bonds, is actually a process of extremely localized (inhomogeneous) plastic deformation. In crystalline solids, plastic deformation tends to be confined to crystallographic planes of atoms which have a low resistance to shear. Shear fracture in pure single crystals occurs when the two halves of the crystal slip apart on the crystallographic glide planes that have the largest amount of shear stress resolved across them. When the shear occurs on only one set of parallel planes, a slant fracture is formed.

In polycrystalline materials the advancing shear crack tends to follow the path of maximum resolved shear stress. This path is determined by both the applied stress system and the presence of internal stress concentrators such as voids, which are formed at the interface between impurity particles (e.g., nonmetallic inclusions) and the matrix material. Crack growth takes place by the formation of voids and their subsequent coalescence by localized plastic strains.

Shear fracture in thick plates and round tensile bars of structural materials begins in the center of the structure (necked region) and spreads outwards. The macroscopic fracture path is perpendicular to the tensile axis. On a microscopic scale the fracture is quite jagged, since the crack advances by shear failure (void coalescence) on alternating planes inclined at 30-45° to the tensile axis. This form of fracture is commonly labeled normal rupture (since the fracture path is normal to the tensile axis) or fibrous fracture (since the jagged fracture surface has a fibrous or silky appearance).

Normal rupture forms the central (flat) region of the familiar cup-cone pattern. The structure finally fails by shear rupture (shear lip formation) on planes inclined at 45° to the tensile
axis. This form of fracture is less jagged, appears smoother, and occurs more rapidly than the normal rupture which precedes it. Similarly no cleavage fracture in thin sheets of engineering materials occurs exclusively by shear rupture and the fracture profile appears similar to the slant fracture.

Under certain conditions the boundary between adjacent grains in the poly-crystalline aggregate is weaker than the fracture planes in the grains themselves. Fracture then occurs intergranularly, by one of the processes mentioned above, rather than through the grains (transgranular fracture). Thus there are six possible modes of fracture: transgranular cleavage, transgranular shear rupture, transgranular normal rupture, and intergranular cleavage, intergranular shear rupture, intergranular normal rupture.

Fracture takes place by that mode which requires the least amount of local strain at the tip of the advancing crack. Both the environmental fracture exclusively by one particular mode over a large variety of conditions and the state of applied (nominal) stress mid strain determine the type of fracture which occurs, and only a few materials and structures operating conditions (i.e., service temperature, corrosive environment, and so on).

Furthermore, under any given condition more than one mode of fracture can cause failure of a structural member and the fracture is described as "mixed". This implies that the relative ease of one type of crack propagation can change, with respect to another type, as the overall fracture process takes place. For example, normal rupture, cleavage, and shear rupture are all observed on the fracture surfaces of notched mild steel specimens broken in impact at room temperature.

In order to analyze the fracture process under various types of stress systems, it is necessary to establish a coordinate system with respect to both the fracture plane, the direction of crack propagation, and the applied stress system.

One of the difficulties encountered by engineers and scientists who are interested in a particular aspect of the fracture problem is the large mass of notation and coordinate systems used by other workers who have investigated similar problems. Three distinct modes of separation at the crack tip can occur:

- **Mode I** -- The tensile component of stress is applied in the y direction, normal to the faces of the crack, either under plane-strain (thick plate, t large) or plane-stress (thin plate, t small) conditions.
- **Mode II** -- The shear component of stress is applied normal to the leading edge of the crack either under plane-strain or plane-stress conditions.
- **Mode III** -- The shear component of stress is applied parallel to the leading edge of the crack (antiplane strain).

### 5.4. Testing of Materials

#### 5.4.1. Tensile load

A tensile test, also known as tension test, is probably the most fundamental type of mechanical test you can perform on material. Tensile tests are simple, relatively inexpensive, and fully standardized. By pulling on something, you will very quickly determine how the material will react to forces being applied in tension. As the material is being pulled, you will find its strength along with how much it will elongate.

**Why Perform a Tensile Test or Tension Test?**

You can learn a lot about a substance from tensile testing. As you continue to pull on the material until it breaks, you will obtain a good, complete tensile profile. A curve will result showing how it reacted to the forces being applied. The point of failure is of much interest and is typically called its "Ultimate Strength" or UTS on the chart.

**Hooke's Law**

For most tensile testing of materials, you will notice that in the initial portion of the test, the relationship between the applied force, or load, and the elongation the specimen exhibits is linear. In this linear region, the line obeys the relationship defined as "Hooke's Law" where the ratio of stress to strain is a constant, or . $E$ is the slope of the line in this region where stress ($\sigma$) is proportional to strain ($\varepsilon$) and is called the "Modulus of Elasticity" or "Young's Modulus".
Modulus of Elasticity
Select image to enlarge The modulus of elasticity is a measure of the stiffness of the material, but it only applies in the linear region of the curve. If a specimen is loaded within this linear region, the material will return to its exact same condition if the load is removed. At the point that the curve is no longer linear and deviates from the straight-line relationship, Hooke's Law no longer applies and some permanent deformation occurs in the specimen. This point is called the "elastic, or proportional, limit". From this point on in the tensile test, the material reacts plastically to any further increase in load or stress. It will not return to its original, unstressed condition if the load were removed.

Yield Strength
A value called "yield strength" of a material is defined as the stress applied to the material at which plastic deformation starts to occur while the material is loaded.

Offset Method
For some materials (e.g., metals and plastics), the departure from the linear elastic region cannot be easily identified. Therefore, an offset method to determine the yield strength of the material tested is allowed. These methods are discussed in ASTM E8 (metals) and D638 (plastics). An offset is specified as a % of strain (for metals, usually 0.2% from E8 and sometimes for plastics a value of 2% is used). The stress (R) that is determined from the intersection point "r" when the line of the linear elastic region (with slope equal to Modulus of Elasticity) is drawn from the offset "m" becomes the Yield Strength by the offset method.

Alternate Moduli
The tensile curves of some materials do not have a very well-defined linear region. In these cases, ASTM Standard E111 provides for alternative methods for determining the modulus of a material, as well as Young's Modulus. These alternate moduli are the secant modulus and tangent modulus.

Strain
You will also be able to find the amount of stretch or elongation the specimen undergoes during tensile testing. This can be expressed as an absolute measurement in the change in length or as a relative measurement called "strain". Strain itself can be expressed in two different ways, as "engineering strain" and "true strain". Engineering strain is probably the easiest and the most common expression of strain used. It is the ratio of the change in length to the original length.

Ultimate Tensile Strength
One of the properties you can determine about a material is its ultimate tensile strength (UTS). This is the maximum load the specimen sustains during the test. The UTS may or may not equate to the strength at break. This all depends on what type of material you are testing...brittle, ductile, or a substance that even exhibits both properties. And sometimes a material may be ductile when tested in a lab, but, when placed in service and exposed to extreme cold temperatures, it may transition to brittle behavior.

5.4.2 Compressive load
A compression test determines behavior of materials under crushing loads. The specimen is compressed and deformation at various loads is recorded. Compressive stress and strain are calculated and plotted as a stress-strain diagram which is used to determine elastic limit, proportional limit, yield point, yield strength and, for some materials, compressive strength.

Why Perform a Compression Test?
The ASM Handbook®, Volume 8, Mechanical Testing and Evaluation states: "Axial compression
Testing is a useful procedure for measuring the plastic flow behavior and ductile fracture limits of a material. Measuring the plastic flow behavior requires frictionless (homogenous compression) test conditions, while measuring ductile fracture limits takes advantage of the barrel formation and controlled stress and strain conditions at the equator of the barreled surface when compression is carried out with friction.

Axial compression testing is also useful for measurement of elastic and compressive fracture properties of brittle materials or low-ductility materials. In any case, the use of specimens having large L/D ratios should be avoided to prevent buckling and shearing modes of deformation.

The image at right shows variation of the strains during a compression test without friction (homogenous compression) and with progressively higher levels of friction and decreasing aspect ratio L/D (shown as h/d).

The figure to the right illustrates the modes of deformation in compression testing. (a) Buckling, when L/D > 5. (b) Shearing, when L/D > 2.5. (c) Double barreling, when L/D > 2.0 and friction is present at the contact surfaces. (d) Barreling, when L/D < 2.0 and friction is present at the contact surfaces. (e) Homogenous compression, when L/D < 2.0 and no friction is present at the contact surfaces. (f) Compressive instability due to work-softening material.

The following materials are typically subjected to a compression test.
- Concrete
- Metals
- Plastics
- Ceramics
- Composites

5.4.3 Shear load
The load applied to make the shear (or) cut in the specimen is called as shear load.

5.5. Basic mechanical properties
**Modulus of Elasticity**
In this linear region, the line obeys the relationship defined as "Hooke's Law" where the ratio of stress to strain is a constant, or . $E$ is the slope of the line in this region where stress ($\sigma$) is proportional to strain ($\varepsilon$) and is called the "Modulus of Elasticity" or "Young's Modulus".

**Yield Strength**
A value called "yield strength" of a material is defined as the stress applied to the material at which plastic deformation starts to occur while the material is loaded.

**Strain**
Strain itself can be expressed in two different ways, as "engineering strain" and "true strain". Engineering strain is probably the easiest and the most common expression of strain used. It is the ratio of the change in length to the original length.

### 5.6. Testing of Hardness

#### 5.6.1. Brinell

The Brinell hardness test method consists of indenting the test material with a 10 mm diameter hardened steel or carbide ball subjected to a load of 3000 kg. For softer materials the load can be reduced to 1500 kg or 500 kg to avoid excessive indentation. The full load is normally applied for 10 to 15 seconds in the case of iron and steel and for at least 30 seconds in the case of other metals. The diameter of the indentation left in the test material is measured with a low powered microscope. The Brinell harness number is calculated by dividing the load applied by the surface area of the indentation.

The diameter of the impression is the average of two readings at right angles and the use of a Brinell hardness number table can simplify the determination of the Brinell hardness. A well structured Brinell hardness number reveals the test conditions, and looks like this, "75 HB 10/500/30" which means that a Brinell Hardness of 75 was obtained using a 10mm diameter hardened steel with a 500 kilogram load applied for a period of 30 seconds. On tests of extremely hard metals a tungsten carbide ball is substituted for the steel ball. Compared to the other hardness test methods, the Brinell ball makes the deepest and widest indentation, so the test averages the hardness over a wider amount of material, which will more accurately account for multiple grain structures and any irregularities in the uniformity of the material. This method is the best for achieving the bulk or macro-hardness of a material, particularly those materials with heterogeneous structures.

#### 5.6.2 Rockwell

The Rockwell hardness test method consists of indenting the test material with a diamond cone or hardened steel ball indenter. The indenter is forced into the test material under a preliminary minor load $F_0$ (Fig. 1A) usually 10 kgf. When equilibrium has been reached, an indicating device, which follows the movements of the indenter and so responds to changes in depth of penetration of the indenter is set to a datum position. While the preliminary minor load is still applied an additional major load is applied with resulting increase in penetration (Fig. 1B). When equilibrium has again been reach, the additional major load is removed but the preliminary minor load is still maintained. Removal of the additional major load allows a partial recovery, so reducing the...
depth of penetration (Fig. 1C). The permanent increase in depth of penetration, resulting from the application and removal of the additional major load is used to calculate the Rockwell hardness number.

\[ HR = E - e \]

\[ F_0 = \text{preliminary minor load in kgf} \]
\[ F_1 = \text{additional major load in kgf} \]
\[ F = \text{total load in kgf} \]
\[ e = \text{permanent increase in depth of penetration due to major load } F_1 \]
\[ E = \text{a constant depending on form of indenter: 100 units for diamond indenter, 130 units for steel ball indenter} \]
\[ D = \text{diameter of steel ball} \]

**TYPICAL APPLICATION OF ROCKWELL HARDNESS SCALES**

HRA . . . . Cemented carbides, thin steel and shallow case hardened steel
HRB . . . . Copper alloys, soft steels, aluminium alloys, malleable iron, etc.
HRC . . . . Steel, hard cast irons, case hardened steel and other materials harder than 100 HRB
HRD . . . . Thin steel and medium case hardened steel and pearlitic malleable iron
HRE . . . . Cast iron, aluminium and magnesium alloys, bearing metals
HRF . . . . Annealed copper alloys, thin soft sheet metals
HRG . . . . Phosphor bronze, beryllium copper, malleable iron
HRH . . . . Aluminium, zinc, lead
HRK . . . . }
HRL . . . . }
HRM . . . . Soft bearing metals, plastics and other very soft materials
HRP . . . . }
HRR . . . . }
HRS . . . . }
HRV . . . . }

Advantages of the Rockwell hardness method include the direct Rockwell hardness number readout and rapid testing time. Disadvantages include many arbitrary non-related scales and possible effects from the specimen support anvil (try putting a cigarette paper under a test block and take note of the effect on the hardness reading! Vickers and Brinell methods don't suffer from this effect).

5.6.3 Vicker

The Vickers hardness test method consists of indenting the test material with a diamond indenter, in the form of a right pyramid with a square base and an angle of 136 degrees between opposite faces subjected to a load of 1 to 100kgf. The full load is normally applied for 10 to 15 seconds. The two diagonals of the indentation left in the surface of the material after removal of the load are measured using a microscope and their average calculated. The area of the sloping surface of the indentation is calculated. The Vickers hardness is the quotient obtained by dividing the kgf load by the square mm area.

\[ F = \text{Load in kgf} \]
\[ d = \text{Arithmetic mean of the two diagonals, } d_1 \text{ and } d_2 \text{ in mm} HV = \text{Vickers hardness} \]
\[ HV = \text{Vickers hardness} \]
When the mean diagonal of the indentation has been determined the Vickers hardness may be calculated from the formula, but is more convenient to use conversion tables. The Vickers hardness should be reported like 800 HV/10, which means a Vickers hardness of 800, was obtained using a 10 kgf force. Several different loading settings give practically identical hardness numbers on uniform material, which is much better than the arbitrary changing of scale with the other hardness testing methods. The advantages of the Vickers hardness test are that extremely accurate readings can be taken, and just one type of indenter is used for all types of metals and surface treatments. Although thoroughly adaptable and very precise for testing the softest and hardest of materials, under varying loads, the Vickers machine is a floor standing unit that is more expensive than the Brinell or Rockwell machines.

5.7. Testing of Impact

5.7.1. Charpy

The Charpy impact test, also known as the Charpy v-notch test, is a standardized high strain-rate test which determines the amount of energy absorbed by a material during fracture. This absorbed energy is a measure of a given material's toughness and acts as a tool to study temperature-dependent brittle-ductile transition. It is widely applied in industry, since it is easy to prepare and conduct and results can be obtained quickly and cheaply. But a major disadvantage is that all results are only comparative.

The apparatus consists of a pendulum axe swinging at a notched sample of material. The energy transferred to the material can be inferred by comparing the difference in the height of the hammer before and after a big fracture.

The notch in the sample affects the results of the impact test, thus it is necessary for the notch to be of regular dimensions and geometry. The size of the sample can also affect results, since the dimensions determine whether or not the material is in plane strain. This difference can greatly affect conclusions made.

Quantitative results

The quantitative result of the impact tests the energy needed to fracture a material and can be used to measure the toughness of the material and the yield strength. Also, the strain rate may be studied and analyzed for its effect on fracture. The ductile-brittle transition temperature (DBTT) may be derived from the temperature where the energy needed to fracture the material drastically changes. However, in practice there is no sharp transition and so it is difficult to obtain a precise transition temperature. An exact DBTT may be empirically derived in many ways: a specific absorbed energy, change in aspect of fracture (such as 50% of the area is cleavage), etc.

Qualitative results

The qualitative results of the impact test can be used to determine the ductility of a material. If the material breaks on a flat plane, the fracture was brittle, and if the material breaks with jagged edges or shear lips, then the fracture was ductile. Usually a material does not break in just one way or the other, and thus
comparing the jagged to flat surface areas of the fracture will give an estimate of the percentage of ductile and brittle fracture.

**Sample Sizes**
According to ASTM A370, the standard specimen size for Charpy impact testing is 10mm×10mm×55mm.
Subsize specimen sizes are:
- 10mm×7.5mm×55mm,
- 10mm×6.7mm×55mm,
- 10mm×5mm×55mm
- 10mm×3.3mm×55mm,
- 10mm×2.5mm×55mm.
Details of specimens as per ASTM A370 (Standard Test Method and Definitions for Mechanical Testing of Steel Products).

5.7.2 Izod

During the first part of the 20th century, a metallurgist named Izod invented an impact test for determining the suitability of various metals to be used as cutting tools. The test involved a pendulum with a known weight at the end of its arm swinging down and striking the specimen as it stood clamped in a vertical position.

Pendulum machines remained popular with those testing to Izod and Charpy while more high speed, product oriented impact applications became the dominion of the drop tower.

**Specimens for Izod Testing**
While still used, pendulum impact testing has inherent weaknesses. In notched Izod testing, samples are mounted in a vise fixture with the notch facing a pendulum. A weighted pendulum, fixed at a point directly above the sample vise, is swung up and held stationary. This height and thus the speed of the pendulum at impact is a constant for this test. When released, the pendulum swings through the path where the sample is fixed. As the sample breaks, energy is absorbed by the sample. The height the pendulum attains after impact is measured by an indicator on a fixed scale which reads in joules (ft-lb). The impact strength is the loss of momentum in the pendulum while breaking the sample off at the notch.

![Izod pendulum](image)

In the beginning.
The Izod pendulum test configuration served as the standard in impact testing in the plastics and metals industry for many years. The problems with the Izod pendulum test involve several parameters which can drastically alter the results if not strictly controlled.

First the radius of the notch is critical. It is meant to simulate conditions which might exist in applications where the features such as internal corner on an enclosure will act as a stress concentrator upon impact. In a pendulum test, the radius cannot be varied. The notch radius has a significant effect on the ability of a sample to absorb impact. Most polymers, especially polycarbonate and nylon have critical notch radii below which their impact strength falls off dramatically. In a fixed radius test, the data can give a false impression about the relative impact resistance of different polymers.

In addition, the creation of the notch in the sample has been a problem. Notch consistency has been difficult so comparison between testing labs is difficult. Notching blades can overheat polymers and degrade the material around the notch thus resulting in inaccurate test results. Industry round robin studies have shown that test results among participants were impossible to correlate because of the tremendous variations in notches.

5.8. Testing of Fatigue

5.8.1. Introduction
In materials science, fatigue is the progressive and localized structural damage that occurs when a material is subjected to cyclic loading. The nominal maximum stress values are less than the ultimate tensile stress limit, and may be below the yield stress limit of the material.

Fatigue occurs when a material is subjected to repeated loading and unloading. If the loads are above a certain threshold, microscopic cracks will begin to form at the surface. Eventually a crack will reach a critical size, and the structure will suddenly fracture. The shape of the structure will significantly affect the fatigue life; square holes or sharp corners will lead to elevated local stresses where fatigue cracks can initiate. Round holes and or fillets are smooth transitions therefore important to increase the fatigue strength of the structure.

Characteristics of fatigue

Fatigue is a stochastic process, often showing considerable scatter even in controlled environments.
Some materials (e.g., some steel and titanium alloys) exhibit a theoretical fatigue limit below which continued loading does not lead to structural failure.
In recent years, researchers have found that failures occur below the theoretical fatigue limit at very high fatigue lives (10^9 to 10^10 cycles).

Factors that affect fatigue-life

Cyclic stress state:
Depending on the complexity of the geometry and the loading, one or more properties
of the stress state need to be considered, such as stress amplitude, mean stress, biaxiality, in-phase or sequence, Out-of-phase shear stress, and load.

Geometry:
Notches and variation in cross section throughout a Part lead to stress Concentrations where fatigue cracks initiate.

Surface quality:
Surface roughness cause microscopic stress concentrations that lower the fatigue strength.

Compressive residual stresses can be introduced in the surface by e.g. shot peening to increase fatigue life.

Material Type:
Fatigue life, as well as the behavior during cyclic loading, varies widely for different materials, e.g. composites and polymers differ markedly from metals.

Grain size:
For most metals, smaller grains yield longer fatigue lives, however, the presence of surface defects or scratches will have a greater influence than in a coarse grained alloy.

There are three principal approaches to life assurance for mechanical parts that display increasing degrees of sophistication:

1. Design to keep stress below threshold of fatigue limit (infinite lifetime concept);
2. Design (conservatively) for a fixed life after which the user is instructed to replace the part with a new one (a so-called lifed part, finite lifetime concept, or "safe-life" design practice);
3. Instruct the user to inspect the part periodically for cracks and to replace the part once a crack exceeds a critical length. This approach usually uses the technologies of nondestructive testing and requires an accurate prediction of the rate of crack-growth between inspections.

STOPPING FATIGUE
Fatigue cracks that have begun to propagate can sometimes be stopped by drilling holes, called drill stops, in the path of the fatigue crack. This is not recommended as a general practice because the hole represents a stress concentration factor which depends on the size of the hole and geometry. There is thus the possibility of a new crack starting in the side of the hole. It is always far better to replace the cracked part entirely.

MATERIAL CHANGE
Changes in the materials used in parts can also improve fatigue life. For example, parts can be made from better fatigue rated metals. Complete replacement and redesign of parts can also reduce if not eliminate fatigue problems. Thus helicopter rotor blades and propellers in metal are being replaced by composite equivalents. They are not only lighter, but also much more resistant to fatigue. They are more expensive, but the extra cost is amply repaid by their greater integrity, since loss of a rotor blade usually leads
to total loss of the aircraft. A similar argument has been made for replacement of metal fuselages, wings and tails of aircraft.

5.9. Testing of Creep

5.9.1. Introduction
Method for determining creep or stress relaxation behavior. To determine creep properties, material is subjected to prolonged constant tension or compression loading at constant temperature. Deformation is recorded at specified time intervals and a creep vs. time diagram is plotted. Slope of curve at any point is creep rate. If failure occurs, it terminates test and time for rupture is recorded. If specimen does not fracture within test period, creep recovery may be measured. To determine stress relaxation of material, specimen is deformed a given amount and decrease in stress over prolonged period of exposure at constant temperature is recorded.

Viscoplasticity is a theory in continuum mechanics that describes the rate-dependent inelastic behavior of solids. Rate-dependence in this context means that the deformation of the material depends on the rate at which loads are applied. The inelastic behavior that is the subject of viscoplasticity is plastic deformation which means that the material undergoes unrecoverable deformations when a load level is reached. Rate-dependent plasticity is important for transient plasticity calculations. The main difference between rate-independent plastic and viscoplastic material models is that the latter exhibit not only permanent deformations after the application of loads but continue to undergo a creep flow as a function of time under the influence of the applied load.

In general, viscoplasticity theories are useful in areas such calculation of permanent deformations, the prediction of the plastic collapse of structures, the investigation of stability, crash simulations, systems exposed to high temperatures such as turbines in engines, e.g. a power plant, dynamic problems and systems exposed to high strain rates. Models of rate-independent plasticity that have a rate-dependent yield stress.

5.9.2 Failure mechanisms
Creep is the tendency of a solid material to slowly move or deform permanently under constant stresses. Creep tests measure the strain response due to a constant stress as shown in Figure 3. The classical creep curve represents the evolution of strain as a function of time in a material subjected to uniaxial stress at a constant temperature. The creep test, for instance, is performed by applying a constant force/stress and analyzing the strain response of the system. In general, as shown in Figure 3b this curve usually shows three phases or periods of behavior.
A primary creep stage, also known as transient creep, is the starting stage during which hardening of the material leads to a decrease in the rate of flow which is initially very high. The secondary creep stage, also known as the steady state, is where the strain rate is constant. A tertiary creep phase in which there is an increase in the strain rate up to the fracture strain.