PHS 362

INTRODUCTORY MATERIAL SCIENCE

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Course Outline

1. Introduction
2. Atomic and Molecular Structure, Crystals and Defects in Crystals
3. Mechanical or Engineering Properties of Materials
4. Failure – Fracture, Fatigue and Creep
5. Heat Treatment – Annealing

CHAPTER ONE

1.0 INTRODUCTION

Materials are so important that it is more deep seated in our culture than most of us realized. If you consider transportation, housing, clothing, communication, recreation and food production you will realized that virtually every segment of our everyday lives is influenced to one degree or another by materials.

Historically, the development and advancement of societies have been initially tied to the members’ ability to produce and manipulate materials to fill their needs. In fact, early civilizations have been designed by the level of their materials development (that is, Stone Age (ended 5000years ago), Bronze Age (Alloy), Iron Age began about 3000 years ago and continue till today). Use of iron and steel, a stronger and cheaper material changed drastically daily life of a common person. We are presently in age of advanced material.

Human beings in the Stone Age had access to only a very limited number of materials, those that occur naturally, stone, wood, clay, skins and so on. With time they discovered techniques for producing materials that had properties superior to those of the natural ones: these new materials included pottery and various metals. It was later discovered that the properties of a material could be altered by heat treatments and by addition of other substances. It was not until relatively recent times that Scientists came to understand the relationship between the structural elements of materials and their properties. This knowledge led to production of different materials with specialized characteristics which meet the needs of our modern and complex society; this includes metals, plastics, glasses and fibers. For example, automobiles would not have been possible without the availability of inexpensive steel or some other comparable substitute. All those sophisticated electronic devices rely on components that are made from what are called semi-conducting materials.

1.1 What is Material Science?

Material science is the investigation of the relationship that exists among the process, structure, property and performance of material.

The discipline of material science involves investigating the relationships that exist between the structures and properties of materials. In contrast, materials engineering is, on the basis of these structure – property correlations, designing or engineering the structure of a material to produce a predetermined set of properties.

The structure of a material usually relates to the arrangement of its internal components. Subatomic structure involves electrons within the individual atoms and interactions with their nuclei.

1.2 Process

This is to initiate a series of actions directed at producing modified or new materials. This is to prepare a material in a series of steps. It is also to create existing or novel materials according to an established or experimental procedure. This includes smelting, chemical synthesis, refining, solidification, deformation, sintering, machining, heat treating, atomization, hot working, joining and composition.

1.3 Structure

This is a system that is comprised of many parts. This is the manner in which the different parts of the material/system are put together. The parts of the system that is distinguishable through composition, size, shape, etc. This is the physical disposition of the parts of the system. The hierarchy of structure is given as:

1. Electronic structures
2. Atomic/Crystallographic structures
3. Defect structure
4. Nanostructures
5. Microstructures
6. Macrostructures

1.4 Property

All materials are exposed to external stimuli that evoke some type of response. For example, a specimen subjected to forces will experience deformation, or a polished metal surface will reflect light.

Property is a material trait in terms of the kind and magnitude of response to a specific imposed stimulus. Properties of solids are grouped into six different categories: mechanical, electrical, thermal, magnetic, optical and deteriorative. For each there is a characteristic type of stimulus capable of provoking different responses. Mechanical properties relate deformation to an applied load or force; examples include elastic modulus and strength. Electrical properties such as electrical conductivity and dielectric constant, the stimulus is an electric field. The thermal behaviour of solids can be represented in terms of heat capacity and thermal conductivity. Magnetic properties demonstrate the response of a material to the application of a magnetic field. For optical properties, the stimulus is electromagnetic or light radiation: index of refraction and reflectivity are representative optical properties. Deteriorative characteristics indicate the chemical reactivity of materials.

1.5 Performance

This is the manner in which something functions or operates. This is the effectiveness of a material or artifact. This is usually determined by a non-linear combination of properties, including cost.

The structure of a material depends on how it is processed. Furthermore, a material’s performance will be a function of its properties.

CHAPTER TWO

2.0 ATOMIC AND MOLECULAR STRUCTURE, CRYTALS STRUCTURE

Some of the important properties of solid materials depend on geometrical atomic arrangements and also, the interactions that exist among constituent atoms or molecules.

2.1 Atomic Structure

Each atom consists of a very small nucleus composed of protons and neutrons, which is encircled by moving electrons. Both electrons and protons are electrically charged, with magnitude 1.60 x 10^{-19}C. Neutrons are electrically neutral.
M_p and M_n = 1.67 x 10^{-27} and M_e = 9.11 x 10^{-31} Kg.

2.1.1 Atomic Number Z

This is the number of protons in the nucleus of an atom. Each chemical element is characterized by the number of protons in the nucleus.

2.1.2 Atomic Mass A

This is the sum of the masses of protons and neutrons within the nucleus.
$A = Z + N$

2.1.3 Atomic Weight

This corresponds to the weighted average of the atomic masses of the atom's naturally occurring isotopes. Atomic weight of an element or the molecular weight of a compound may be specified on the basis of amu's per atom (molecules) or mass per mole of material. In one mole of a substance there are 6.023 x 10^{23} (Avogadro's number) atoms or molecules. 1amu/atom (or molecule) = 1 g/mol.

2.1.4 Atomic Mass Unit (amu)

This is used for computation of atomic weight. 1amu. is defined as the $\frac{1}{12}$ of the atomic mass of the most common isotope of carbon atom that has 6 protons (Z = 6) and six neutrons (N = 6). $M_{proton} \approx M_{neutron} = 1.66x10^{-24}g = 1amu$. The atomic mass of the ^{12}C atom is 12amu

The number of atoms per volume or cm^3, n, for material of density ρ (g/cm^3) and atomic mass M (g/mol) is given as $n = N_{av} x \frac{\rho}{M}$

2.2 Atomic Models

2.2.1 Bohr Atomic Model

In this model electrons are assumed to revolve around the atomic nucleus in discrete orbital and the position of any particular electron is more or less well defined in terms of its orbital. In this model, energies of electrons are quantized, that is, electrons are permitted to have only specific values of energy. Here we talk about energy level or states.

Bohr model was found to have some significant limitations because of its inability to explain several phenomena involving electrons. A resolution was reached with a Wave Mechanical model, in which electron is considered to exhibit both wave-like and particle-like characteristics. In this model, an electron is no longer treated as a particle moving in a discrete orbital, but rather, position is considered to be the probability of an electron being at various locations around the nucleus. In other words, position is described by a probability distribution or electron cloud.

2.2.2 Quantum Numbers

Using wave mechanics, every electron in an atom is characterized by four parameters called quantum numbers. Bohr energy levels separate into electron sub-shells and quantum numbers dictate the number of states within each sub shell. Shells are specified by a principal quantum number n, which may take an integral values beginning with unity; sometimes these shells are designated by the letters K, L, M, N, O and so on, which corresponds respectively to n = 1, 2, 3, 4, 5 . The second quantum number, l. signifies the sub-shell, which is denoted by an s, p, d, f and it is related to the shape of the electron sub-shell. $k = n^2$

2.2.3 Electronic Configuration

This deals with the manner in which electron states are filled with electron. Pauli exclusion principle is used. This principle stipulates that each electron state can hold no more than two electrons, which must have opposite spins. Thus s, p, d, f sub-shells may each accommodate respectively a total of 2, 6, 10 and 14 electrons. For example Sodium Na - $1s^2 2s^2 2p^6 3s^1$

Valence Electron: These are electron that occupy the outermost filled shell.

2.2.4 Electropositive Elements

These are elements that are capable of giving up their few valence electrons to become positively charged ions.

2.2.5 Electronegative Elements

These are electrons that readily accept electrons to form negatively charged ions or sometimes they share electrons with other atoms.

2.3 Atomic Bonding in Solids

2.3.1 Bonding Forces

An understanding of many of the physical properties of materials is predicated on the knowledge of the inter-atomic forces that bind the atoms together. If we consider the interaction between two isolated atoms as they are brought into close proximity from an infinite separation, at large distances, the interactions are negligible, but as the atoms approach, each exerts forces on the other. These forces are of two types, attractive and repulsive, and the magnitude of each is a function of the separation or inter-atomic distance. We have attractive force F_A and repulsive force F_R and the net force FN between the two atoms is $F_N = F_A + F_R$. There is no net force when $F_A + F_R = 0$.

It is more convenient at times to work with the potential energies between two atoms instead of forces. Mathematically, energy (E) and force (F) are related as

$$E = \int F dr$$

$$E_N = \int_{\infty}^{r} F_N dr$$

$$E_N = \int_{\infty}^{r} F_A dr + \int_{\infty}^{r} F_R dr$$

$$E_N = E_A + E_R,$$

where E_N is the net energy, E_A is attractive energy and E_R is repulsive.

2.3.2 Types of Bonding

We have mainly two types of bonding: Primary and Secondary.

2.3.2.1 Primary Bonding

This is the type of bond in which electrons are transferred or shared. Three different types of primary or chemical bond are found in solids – Ionic, Covalent and Metallic. Ionic bond this is a kind of bond which involves the transfer of electron. In Ionic bond mutual ionization occurs by electron transfer and ions are attracted by strong Coulombic interaction. An ionic bond is non-directional (ions may be attracted to one another in any direction). For example, Sodium Chloride (NaCl), Sodium, Na has 11 electrons, 1 more than needed for a full outer shell (Neon). So, Na donates an electron to Chorine, Cl which has 17 electrons which is 1 less than needed for a full outer shell (Argon). In covalent bonding, electrons are shared between the molecules, to saturate the valency. The simplest example is H_2 molecule, where the electrons spend more time in between the nuclei than outside, thus producing bonding. In covalent bond there is cooperative sharing of valence electrons. Covalent bond can be described by orbital overlap and they are highly directional. We have covalent bond model which gives us how an atom can covalently bond with at most "8 – N" where N is the number of valence electrons. For example Cl_2 molecule can form only one covalent bond, N = 7, 8 – 7 = 1. In metallic bonding, valence electrons are detached from atoms and spread in an "electron sea" that glues the ions together. A metallic bond is non-directional (bonds form in any direction) atoms pack closely.

2.3.2.2 Secondary Bonding

This type of bond is physical as opposite to chemical bonding that involves electron transfer or electron sharing. It is a type of bond that result from interaction of atomic or molecular dipoles and is weak. We have three different types of secondary bond and these are Fluctuating Induced Dipole, Permanent dipole bonds and Polar molecule-induced dipole bonds. In electrically symmetric molecules/atoms an electric dipole can be created by fluctuations of electron density distribution. Fluctuating electric field in one atom is felt by the electrons of an adjacent atom and induce a dipole momentum in this atom. This bond due to fluctuating induced dipole is the weakest and this is most exhibited by Inert gases, H_2 Hydrogen molecule and Cl_2 chlorine molecule. Permanent dipole moments exist in some molecules (called polar molecules) due to the asymmetrical arrangement of positively and negatively regions (HCl, H_2O). Bonds between adjacent polar molecules – permanent dipole bonds are strongest among secondary bonds. Polar molecules can induce dipoles in adjacent non-polar molecules and bond is formed due to the attraction between the permanent and induced dipoles.

2.4 Crystal Structure

To understand crystalline structures it is useful to consider atoms as being hard spheres with well defined radii. In this hard sphere model, the shortest distance between two like atoms is one diameter. It is also necessary to consider crystalline structure as a lattice of points at atom/sphere centers. There are mainly three types of crystal structures: Face-Centered Cubic (FCC) Crystal Structure, Body-Centered Cubic (BCC) Crystal Structure and Hexagonal Close-Packed (HCP) Crystal Structure.

2.4.1 Face-Centered Cubic (FCC) Crystal Structure

In FCC atoms are located at each of the corners and on the centers of all the faces of cubic unit cell. The hard spheres or ion cores touch one another across a face diagonal with the cube edge length, $a = 2R\sqrt{2}$. The coordination number CN which is the number of closest neighbors to which an atom is bonded or number of touching atoms is 12. Number of atoms per unit cell, n = 4. Atomic packing factor, APF is 0.74. In FCC corner and face atoms in the unit cell are equivalent.

2.4.2 Body-Centered Cubic (BCC) Crystal Structure

Here atoms are located at each corner and at center of cubic unit cell. The hard spheres touch one another along cube diagonal with the cube edge length, $a = \frac{4R}{\sqrt{3}}$. The coordination number CN is 8. Number of atoms per unit cell n = 2. Atomic packing factor APF is 0.68. In BCC corner and center atoms are equivalent.

2.4.3 Hexagonal Close-Packed (HCP) Crystal Structure

This is one common structure of metallic crystals. Six atoms form regular hexagon, surrounding one atom in center. Another plane is situated halfway up unit cell (c-axis), with three (3) additional atoms situated at interstices of hexagonal (close-packed) planes. Unit cell has two lattice parameters a and c with an ideal ratio $\frac{c}{a} = 1.633$. The coordination number CN = 12. Number of atoms per unit cell n = 6. Atomic packing factor, APF is 0.74. In HCP all atoms are equivalent.

Density computation – since the entire crystal can be generated by the repetition of the unit cell, the density of a crystalline material is given as

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

, where n is the number of atoms per unit cell, A is atomic weight in a.m.u or g/mol, V_c is volume of cell and N_A is the Avogadro's Number.

2.5 Defects in Crystals

Here, we will look at different types of imperfections or defects in the ideal arrangement of atoms in a crystal. Defects have a profound impact on the macroscopic properties of materials and the processing determines the defects. Defects may be classified into four categories depending on their dimension: Point defects, Linear defects, Planar defects and Volume defects.

2.5.1 Point Defects

We have a point defect when atoms are missing or in irregular places in the lattice. There are three types of point defect: vacancy, interstitial and impurity. Vacancy this is a lattice position that is vacant because the atom is missing. How many vacancies are there? The higher is the temperature, more often atoms are jumping from one equilibrium position to another and larger number of vacancies can be found in a crystal. Actually, the number of vacancies, N_v, increases exponentially with the absolute temperature, T, and can be estimated using the equation:

$$N_v = N_s \exp\left(\frac{-Q_v}{K_B T}\right)$$

where N_s is the number of regular lattice sites, K_B is the Boltzmann constant, Q_v is the energy needed to form a vacant lattice site in a perfect crystal and T is the temperature in Kelvin.

Using this equation we can estimate that at room temperature in Copper there is one vacancy per 10^{15} lattice atoms, whereas at high temperature, just below the melting point there is one vacancy for every 10,000 atoms.

Interstitial this is an atom that occupies a place outside the normal lattice position. If the interstitial atom is of the same species as the lattice atoms, it is called self-interstitial. Creation of a self-interstitial causes a substantial distortions in the surrounding lattice and costs more energy as compared to the energy for creation. Foreign, usually smaller atoms (carbon, nitrogen, hydrogen, oxygen) are called interstitial impurities. They introduce less distortion to the lattice and are more common in real materials and more mobile. If the foreign atom replaces or substitutes for a matrix atom, it is called a substitutional impurity.

2.5.2 Linear Defects

These are group of atoms in irregular positions. Dislocations can be introduced and thought of as extra lattice planes inserted in the crystal, but not extending through all of the crystal but ending in the dislocation line. Dislocations are linear defects – the inter-atomic bonds are significantly distorted only in the immediate vicinity of the dislocation line. This area is called the dislocation core. Dislocations also create small elastic deformations of the lattice at large distances. We have three types of dislocation edge dislocation, screw dislocation and mixed/partial dislocations. We have edge dislocation when the burgers vector is directed perpendicular to the dislocation line. We have screw dislocation when the burgers vector is directed parallel to the dislocation line and we have mixed/partial dislocation when the burgers vector is directed either parallel/perpendicular to the dislocation line.

2.5.3 Planar Defects

This is an interfacial defects. Polycrystalline material comprised of many small crystals or grains. The grains have different crystallographic orientation. There exist atomic mismatch within the regions where grains meet. These regions are called grain boundaries. Surfaces and interfaces are reactive and impurities tend to segregate there. Since energy is associated with interfaces, grains tend to grow in size at the expense of smaller grains to minimize energy. These occur by diffusion which is accelerated at high temperatures. We have three types of grain boundaries – tilt and twist grain boundaries and twin boundaries. Tilt grain boundaries is a low angle grain boundary which is an array of aligned edge dislocations. Twist grain boundaries is a high angle grain boundaries which is an array of screw dislocations. Twin boundaries is a low energy twin boundaries with mirrored atomic positions across boundary. This gives rise to shape memory metals, which can recover their original shape if heated to a high temperature. Shape-memory alloys are twinned and when deformed they untwin. At high temperature the alloy returns back to the original twin configuration and restore the original shape.

2.5.4 Volume Defects

This is an extended defect and this includes pores, cracks and foreign inclusions. Pores can greatly affect optical, thermal and mechanical properties. Cracks can greatly affect mechanical properties and foreign inclusions can greatly affect electrical, mechanical and optical properties.

CHAPTER THREE

3.0 MECHANICAL PROPERTIES

Materials deform (elongate, compress, twist) or break as a function of applied load, time, temperature and other conditions. There are different types of loading: tensile, compressive, shear and torsion.

3.1 Stress and Strain

Engineering Stress: $\sigma = \frac{F}{A_o}$, where F is load applied perpendicular to specimen cross-section; A_o is cross-sectional area (perpendicular to the force) before application of the load.

Engineering Strain: $\varepsilon = \frac{\Delta l}{l_o}\left(x100\%\right)$, where Δl is change in length and l_o is the original length.

Stress and Strain are positive for tensile loads and negative for compressive loads.

Shear Stress: $\tau = \frac{F}{A_o}$, where F is load applied parallel to the upper and lower faces each of which has an area A_o.

Shear Strain: $\gamma = tg\theta\left(x100\%\right)$, where θ is strain angle.

3.2 Elastic Deformation

This is a deformation which is reversible. When the stress is removed, the material returns to the dimension it had before the loading. In elastic deformation strains are usually small and stress is always proportional to strain ($\sigma = E\varepsilon$).

3.3 Plastic Deformation

This is a deformation that is irreversible. When the stress is removed, the material does not return to its previous dimension. In plastic deformation, stress and strain are not proportional, deformation occurs by breaking and re-arrangement of atomic bonds and strains are usually large.

3.4 Tensile Properties

These are yield stress, tensile stress, ductility, toughness and hardness.

Yield Stress - this is a measure of resistance to plastic deformation.

Tensile strength is the maximum stress.

Ductility is a measure of the deformation at fracture and it is defined by percent elongation $\%EL = \left(\frac{l_f - l_o}{l_o}\right)x100$ or percent reduction in area, $\%RA = \left(\frac{A_o - A_f}{A_o}\right)x100$.

Toughness is the ability of a material to absorb energy up to fracture.

Hardness is a measure of the material's resistance to localized plastic deformation (e.g. dent or scratch). A qualitative Moh's scale, determined by the ability of a material to scratch another material: from 1 (softest = talc to 10 (hardest = diamond).

CHAPTER FOUR

4.0 FAILURE

4.1 Fracture

This is the separation of a body into pieces due to stress, at temperatures below the melting point. Fracture takes place in two steps, step one is crack formation and step two is crack propagation. Depending on the ability of material to undergo plastic deformation before the fracture two fracture modes can be defined – ductile or brittle.

4.1.1 Ductile Fracture

This is found mostly in metals. There is extensive plastic deformation ahead of crack and crack is stable, that is, it resists further extension unless applied stress is increased.

4.1.2 Brittle Fracture

This is found in ceramics, ice and cold metals. There is relatively little plastic deformation and crack is unstable, that is, it propagates rapidly without increase in applied stress. Crack propagation is very fast and crack propagates nearly perpendicular to the direction of the applied stress. Crack often propagates by cleavage that is, breaking of atomic bonds along specific crystallographic planes (cleavage planes). We have two types of brittle fracture: Transgranular fracture – fracture cracks pass through grains. Fracture surface have faceted texture because of different orientation of cleavage planes in grains. Intergranular fracture – fracture crack propagation is along grain boundaries (grain boundaries are weakened or embrittled by impurities segregation).

4.1.3 Stress Concentration

Fracture strength of a brittle solid is related to the cohesive forces between atoms. One can estimate that the theoretical cohesive strength of a brittle material should be $\approx \frac{E}{10}$. But experimental fracture strength is normally $\frac{E}{100} - \frac{E}{10{,}000}$. This much lower fracture strength is explained by the effect of stress concentration at microscopic flaws. The applied stress is amplified at the tips of micro-cracks, voids, notches, surface scratches, corners, e.t.c., that are called stress raisers. The magnitude of this amplification depends on micro-crack orientations, geometry and dimensions.

For long crack oriented perpendicular to the applied stress the maximum stress near the crack tip is $\sigma_m \approx 2\sigma_o \left(\frac{a}{\rho_t} \right)^{\frac{1}{2}}$, where σ_o is the applied external stress, a is the half-length of the crack, and ρ_t is the radius of curvature of the crack tip. (Note that a is half-length of the internal flaw, but the full length for a surface flaw).

The stress concentration factor is $K_t = \frac{\sigma_m}{\sigma_o} \approx 2\left(\frac{a}{\rho_t} \right)^{\frac{1}{2}}$

4.2 Fatigue

This is a failure under fluctuating/cyclic stresses. Under fluctuating/cyclic stresses, failure can occur at loads considerably lower than tensile or yield strengths of material under a static load. Fatigue is estimated to cause 90% of all failures of metallic structures (bridges aircraft, machine components, etc). Applied stresses causing fatigue may be axial (tension or compression), flextural (bending) or torsional (twisting). Fatigue failure proceeds in three distinct stages: crack initiations in the areas of stress concentration (near stress raisers), incremental crack propagation, final catastrophic failure.

Cyclic stresses are characterized by maximum, minimum and mean stress, the range of stress the stress amplitude, and the stress ratio.

Mean stress: $\sigma_m = \frac{(\sigma_{\max} + \sigma_{\min})}{2}$

Range of stress: $\sigma_r = (\sigma_{\max} - \sigma_{\min})$

Stress amplitude: $\sigma_a = \frac{\sigma_r}{2} = \frac{(\sigma_{\max} - \sigma_{\min})}{2}$

Stress ratio: $R = \frac{\sigma_{\min}}{\sigma_{\max}}$

We have two types of fatigue; low cycle fatigue which is characterized by high loads, plastic and elastic deformation. High cycle fatigue which is characterized by low loads and elastic deformation.

We also have three fatigue properties of a material; fatigue limit, fatigue strength and fatigue life. Fatigue limit is maximum stress amplitude below which the material never fails, no matter how large the number of cycles is. Fatigue strength is stress at which fracture occurs after specified number of cycles. Fatigue life is the number of cycles to fail at specified stress level.

4.2.1 Factors that affect Fatigue Life

1. Magnitude of stress
2. Quality of the surface (scratches, sharp transitions and edges) – this is solved by polishing the surface, introducing compressive stresses into thin surface layer, case hardening and optimizing geometry.
3. Thermal fatigue – thermal cycling causes expansion and contraction, hence thermal stress, if component is restrained and this solved by eliminating restraint by design and use of materials with low thermal expansion coefficients.
4. Corrosion fatigue – chemical reactions induce pits which act as stress raisers. Corrosion also enhances crack propagation. This is solved by decrease corrosiveness of medium, if possible, add protective surface coating and add residual compressive stresses.

4.3 Creep

This is a time-dependent and permanent deformation of materials when subjected to a constant load at high temperature (>$0.4T_m$). Examples include turbine blades, steam generators. Creep failure proceeds in four distinct stages, instantaneous deformation, primary/transient creep, secondary/steady-state creep and tertiary.

4.3.1 Parameters of Creep Behaviour

The most important parameter of the creep behaviour in long-life applications is the steady-state creep rate, $\dot{\varepsilon}_s = \frac{\Delta\varepsilon}{\Delta t}$. Another parameter, especially important in short-life creep situations, is time to rupture, or rupture lifetime, t_r

4.3.2 Effects of Stress and Temperature on Creep

With increasing stress or temperature the instantaneous strain increases, the steady-state creep rate increases and the time to rupture decreases. The stress/temperature dependence of the steady-state creep rate can be described by

$\dot{\varepsilon}_s = K_2\sigma^n \exp\left(-\frac{Q_c}{RT}\right)$, where Q_c is the activation energy for creep, K_2 and n are material constants.

4.3.3 Mechanisms of Creep

Different mechanisms are responsible for creep in different materials and under different loading and temperature conditions. The mechanisms include: stress-assisted vacancy diffusion, grain boundary diffusion, grain boundary sliding and dislocation motion. Different mechanisms result in different values of n and Q_c.

4.3.4 How to Minimize Creep

Creep is generally minimized in materials with high melting temperature, high elastic modulus and large grain sizes.

CHAPTER FIVE

5.0 ANNEALING

This is heat treatment in which a material is taken to an elevated temperature, kept there for some time and then cooled. Annealing proceed in three stages; stage one is heating to required temperature, stage two is holding (soaking) at constant temperature and the third stage cooling.

5.1 Purposes of Annealing

1. To relieve internal stresses.
2. To increase ductility, toughness and softness
3. To produce specific microstructure.

5.2 Process Annealing and Stress Relief Annealing

5.2.1 Process Annealing

This is an example of heat treatment and it is used to revert effects of work-hardening (by recovery and recrystallization) and to increase ductility. Heating is usually limited to avoid excessive grain growth and oxidation.

5.2.2 Stress Relief Annealing

This is an example of heat treatment which is used to eliminate/minimize stresses arising from plastic deformation during machining, nonuniform cooling and phase transformations between phases with different densities. Stress relief annealing allows these stresses to relax. Annealing temperatures are relatively low so that useful effects of cold working are not eliminated.

5.3 Hardenability

This is the ability of the Fe-C alloy to be hardened by forming martensite. Hardenability is not hardness. It is a qualitative measure of the rate at which hardness decreases with distance from the surface because of decreased martensite content. High hardenability means the ability of the alloy to produce a high martensite content throughout the volume of specimen.