



COURSE PLAN

Name of the Faculty	Mr S.Rajkumar			
Designation/Department	Assistant Professor / Aeronautical Engineering			
Course Code/Name	AE8007 / Aircraft Materials			
Year/Section/Department	IV / Aeronautical Engineering			
Credits Details	L: 3	T: 0	P: 0	C: 3
Total Contact Hours Required	45			

SYLLABUS:

UNIT I	ELEMENTS OF AEROSPACE MATERIALS	9
Structure of solid materials – Atomic structure of materials – crystal structure – miller indices – density – packing factor – space lattices – x-ray diffraction – imperfection in crystals – physical metallurgy - general requirements of materials for aerospace applications		
UNIT II	MECHANICAL BEHAVIOUR OF MATERIALS	9
Linear and non linear elastic properties – Yielding, strain hardening, fracture, Bauchinger's effect – Notch effect testing and flaw detection of materials and components – creep and fatigue - comparative study of metals, ceramics plastics and composites.		
UNIT III	CORROSION & HEAT TREATMENT OF METALS AND ALLOYS	10
Types of corrosion – effect of corrosion on mechanical properties – stress corrosion cracking – corrosion resistance materials used for space vehicles heat treatment of carbon steels – aluminium alloys, magnesium alloys and titanium alloys – effect of alloying treatment, heat resistance alloys – tool and die steels, magnetic alloys,		
UNIT IV	CERAMICS AND COMPOSITES	9
Introduction – powder metallurgy - modern ceramic materials – cermets - cutting tools – glass ceramic –production of semi fabricated forms - plastics and rubber – carbon/carbon composites, fabrication processes involved in metal matrix composites - shape memory alloys – applications in aerospace vehicle design, open and close mould processes.		
UNIT V	HIGH TEMPERATURE MATERIALS CHARACTERIZATION	9
Classification, production and characteristics – methods and testing – determination of mechanical and thermal properties of materials at elevated temperatures – application of these materials in thermal protection systems of aerospace vehicles – super alloys – high temperature material characterization.		

COURSE OBJECTIVE:

The student should be made:

- To study the types of mechanical behavior of materials for aircraft applications

TEXT BOOK:

T1. Titterton.G., "Aircraft Materials and Processes", V Edition, Pitman Publishing Co., 1995.

REFERENCE:

R1. Raghavan.V., "Materials Science and Engineering", Prentice Hall of India, New Delhi, 1993.

R2. O.P.Khanna., "Materials science and Metallurgy", Dhanpat Rai Publications

WEB RESOURCES:

W1. <https://www.britannica.com/science/crystal/Structure>

W2. <https://fractory.com/heat-treatment-methods/>

W3. <https://www.aopa.org/go-fly/aircraft-and-ownership/maintenance-and-inspections/aircraft-corrosion>

ONLINE MODE OF STUDY:

NPTEL : <https://nptel.ac.in/courses/113/102/113102080/>

MIT OCW : <https://ocw.mit.edu/courses/materials-science-and-engineering/>

COURSE PLAN:

Topic No	Topic	Reference Detail	Page Number	Mode of teaching	Number of Periods Required	Cumulative Period
UNIT 1		ELEMENTS OF AEROSPACE MATERIALS				
1	Structure of solid materials	R2 W1	35.4 – 35.5	PPT	1	1
2	Atomic structure of materials	R2 W1	35.6 – 35.8	PPT	1	2
3	Crystal structure – miller indices	R2 W1	35.34 – 35.38	BB	1	3
4	Density – packing factor	R2 W1	35.26 – 35.30	BB	1	4
5	Space lattices	R2 W1	35.14 – 35.15	BB	1	5
6	X-ray diffraction	R2 W1	35.44 -35.47	BB	1	6
7	Imperfection in crystals	R2 W1	37.1 – 37.11	PPT	1	7
8	Physical metallurgy	R2 W1	35.1-35.2	BB	1	8
9	General requirements of materials for aerospace applications	R2 W1	4.2 – 4.7	BB	1	9
OUTCOMES:						
At the end of unit, students should be able to						
➤ Explain about the crystal structures and its application in aerospace.						
UNIT 2		MECHANICAL BEHAVIOUR OF MATERIALS				
10	Linear and non linear elastic properties	W2	-	BB	1	10
11	Yielding, strain hardening	W2	-	BB	1	11
12	Fracture,	R2	55.3 – 55.6	BB	1	12
13	Bauchinger's effect	R2	54.21-54.22	BB	1	13
14	Notch effect testing and flaw detection of materials and components	R2	49.10 -49.12	BB	1	14
15	Creep	R2	55.19-55.25	BB	1	15

16	Fatigue	R2	55.12-55.18	BB	1	16
17	Comparative study of metals	R1	244 - 246	BB	1	17
18	Ceramics plastics and composites.	R1	156 - 158	BB	1	18

OUTCOMES:

At the end of unit, students should be able to

- Illustrate the metallurgical factor of materials over the temperature.
- Identify various hardening process on ductile and brittle materials.

UNIT 3**CORROSION & HEAT TREATMENT OF METALS AND ALLOYS**

19	Types of corrosion	T1 W3	120 -125	PPT	1	19
20	Effect of corrosion on mechanical properties	T1 W3	240 -244	BB	1	20
21	Stress corrosion cracking	T1 W3	122-123	BB	1	21
22	Corrosion resistance materials used for space vehicles heat treatment of carbon steels	T1 W3	124-126	PPT	1	22
23	Aluminium alloys	R2	11.2-11.3	BB	1	23
24	Magnesium alloys and Titanium alloys	R2	6.11-6.13	BB	1	24
25	Effect of alloying treatment	R2	40.9-40.11	BB	1	25
26	Heat resistance alloys	R2	7.4-7.7	BB	1	26
27	Tool and Die steels,	R2	8.1-8.3	BB	1	27
28	Magnetic alloys,	R2	36.7-36.9	BB	1	28

OUTCOMES:

At the end of unit, students should be able to

- Interpret oxidation and hot corrosion.

UNIT 4**CERAMICS AND COMPOSITES**

29	Introduction – powder metallurgy	T1	263-265	BB	1	29
30	Modern ceramic materials	T1	131-133	BB	1	30
31	Cermets - Cutting tools – Glass	T1	276-277	BB	1	31

	Ceramic					
32	Production of semi fabricated forms	T1	147-148	BB	1	32
33	Plastics and Rubber	T1	282-284	BB	1	33
34	Carbon/carbon composites	T1	323-326	PPT	1	34
35	Fabrication processes involved in metal matrix composites	T1	315-317	BB	1	35
36	Shape memory alloys	T1	175-178	BB	1	36
37	Applications in aerospace vehicle design, open and close mould processes.	T1	185-187	BB	1	37

OUTCOMES:

At the end of unit, students should be able to

- Explain the composite materials and ceramic materials

UNIT 5

HIGH TEMPERATURE MATERIALS CHARACTERIZATION

38	Classification	R1	466-467	BB	1	38
39	Production and characteristics	R1	473-475	BB	1	39
40	Methods and testing	R1	493-495	BB	1	40
41	Determination of mechanical of materials at elevated temperatures	R1	472-474	BB	1	41
42	Determination of thermal properties of materials at elevated temperatures	R1	452-454	BB	1	42
43	Application of these materials in thermal protection systems of aerospace vehicles	R1	431-433	BB	1	43
44	Super alloys	R2	6.16-6.19	BB	1	44
45	High temperature material characterization	R2	7.1-7.4	BB	1	45

OUTCOMES:

At the end of unit, students should be able to

- Utilize super alloys and ceramic material on high temperature.

COURSE OUTCOMES:

At the end of course students should be able to do:

CO1: Explain about the crystal structures and its application in aerospace.

CO2: Illustrate the metallurgical factor of materials over the temperature.

CO3: Identify various hardening process on ductile and brittle materials.

CO4: Interpret oxidation and hot corrosion.

CO5: Utilize super alloys and ceramic material on high temperature.

Course Outcome Vs Program Outcome Mapping:

CO	PO1	PO2	PO3	PO4	PO5	PO6	PO7	PO8	PO9	PO10	PO11	PO12
CO 1	1		1		1	1	1					
CO 2	1	1		1		1	1					
CO 3	1		1		1	1				1		
CO 4	1		1	1		1	1				1	
CO 5	1	1		1		1					1	1

CONTENT BEYOND THE SYLLABUS

- Fracture Maps For Different Alloys
- Phase diagram for metals

ASSIGNMENT**Assignment 1**

Batch Details	Register Number	Total Number	Mode of Assignment	Topics
Batch 1	814317101001 - 020	17	Seminar	Materials requirements for aerospace application
Batch 2	814317101021 - 039	16	PPT	Testing methods of materials
Batch 3	814317101040 - 059	16	MCQ	Atomic structures

Assignment 2

Batch Details	Register Number	Total Number	Mode of Assignment	Topics
Batch 1	814317101001 - 020	17	MCQ	Corrosion and its effects
Batch 2	814317101021 - 039	16	Seminar	Compare Metal, ceramics plastics and composites
Batch 3	814317101040 - 059	16	PPT	Alloy and its effects

Assignment 3

Batch Details	Register Number	Total Number	Mode of Assignment	Topics
Batch 1	814317101001 - 020	17	PPT	Open and Close mould processes
Batch 2	814317101021 - 039	16	MCQ	Composite and application
Batch 3	814317101040 - 059	16	Seminar	Thermal application of Materials

SIM QUESTIONS:**SIM 1**

1. Classify solid materials based upon their atomic / crystalline structure and give the examples (MAY/JUNE 2016)
2. Explain the X-ray diffraction technique and explain its role in the study of materials (MAY/JUNE 2016)
3. Explain the structure of solid materials
4. Explain the different types of point defects (NOV/DEC 2016)
5. Explain about the crystallography miller indices.
6. Derive and show that the packing efficiency of FCC crystal structure is more than BCC crystal structure (NOV/DEC 2016)
7. List the general requirements of materials used in aerospace applications. (NOV/DEC 2016)
8. With the help of neat stress – strain curve, contrast the mechanical behavior of brittle and ductile material in a tensile test (MAY/JUNE 2016)
9. Explain the bauchinger effect in the mechanical behavior of a material (MAY/JUNE 2016)
10. Explain the following (i) Bauchinger's effect, (ii) strain hardening (NOV/DEC 2016)
11. What are the typical elastic constant of the mechanical behavior of a material
12. Draw and explain the linear and non linear curve for ductile and brittle

SIM 2

1. Explain the properties of ceramic materials
2. What are the various types of fracture? Classify the fracture on the basis of type of loading extent of deformation and appearance.
3. What are the structural changes involved during creep? Explain in detail.
4. Describe fatigue, its mechanism, its consequences and what can be done to the material in order to improve fatigue resistance.
5. Give a comparative study of materials used in aviation industries
6. Briefly explain the three steps of creep with a creep curve
7. What is super plasticity? Explain super plastic forming of aluminium alloys.
(MAY/JUNE 2016)
8. Describe different heat treatment processes available for aluminium alloys and state their respective purposes. (MAY/JUNE 2016)
9. Write short note on the following topics
 - i. Corrosion and different types of corrosion
 - ii. Stress corrosion cracking
 - iii. Corrosion resistance materials used for air and space vehicles and their properties (MAY/JUNE 2016)
10. Explain the various types of corrosion that occurs in metallic materials. (NOV/DEC 2016)
11. Discuss the hardening and normalizing heat treatment processes that are applied to carbon steels. (NOV/DEC 2016)
12. What are the effect of corrosion on mechanical properties of materials? (NOV/DEC 2016)

SIM 3

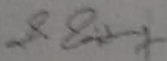
1. Describe the shape memory effect and give examples of shape memory alloys
(MAY/JUNE 2016)
2. List a few examples of the use of metal matrix composite materials in air/space vehicles. Explain a fabrication process for a metal matrix composite part (MAY/JUNE 2016)
3. What do you mean by composites and the classification of composites?

4. Explain the open mould process of composite materials (MAY/JUNE 2016)
5. Explain the close mould process of composite materials (MAY/JUNE 2016)
6. How is high temperature materials classified? And explain the methods of production. (NOV/DEC 2016)
7. Discuss the various methods employed to determine the mechanical properties of materials at high temperature. (NOV/DEC 2016)
8. Explain strengthening of cobalt-base super alloys.
9. Briefly explain the major phases of nickel-base alloys
10. Analyze how the processing parameters can influence the mechanical properties of super alloys at high temperatures.
11. Explain the different types of alloying and effects alloy treatment
12. Explain in detail about the factors influencing functional life of components at elevated temperatures.

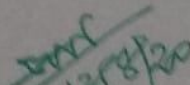
Submission Details:

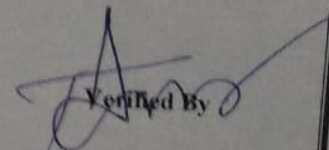
Phase 1 (Before AT 1)		Phase 2 (Before AT 2)		Phase 3 (Before AT 3)	
Assignment 1	SIM 1	Assignment 2	SIM 2	Assignment 3	SIM 3

Google Class Code Details: qbapd2t



Prepared By


13/8/20
Approved By


Verified By

UNIT-1- ELEMENTS OF AEROSPACE MATERIALS

Structure of solid materials – Atomic structure of materials – crystal structure – miller indices – density – packing factor – space lattices – x-ray diffraction – imperfection in crystals – physical metallurgy - general requirements of materials for aerospace applications

Importance of Materials

A material is defined as a substance (most often a solid, but other condensed phases can be included) that is intended to be used for certain applications. There are a myriad of materials around us—they can be found in anything from buildings to spacecrafts. Materials can generally be divided into two classes: crystalline and non-crystalline. The traditional examples of materials are metals, ceramics and polymers. New and advanced materials that are being developed include semiconductors, nanomaterials, biomaterials etc.

The material of choice of a given era is often a defining point. Phrases such as Stone Age, Bronze Age, Iron Age, and Steel Age are great examples. Originally deriving from the manufacture of ceramics and its putative derivative metallurgy, materials science is one of the oldest forms of engineering and applied science. Modern materials science evolved directly from metallurgy, which itself evolved from mining and (likely) ceramics and the use of fire. A major breakthrough in the understanding of materials occurred in the late 19th century, when the American scientist Josiah Willard Gibbs demonstrated that the thermodynamic properties related to atomic structure in various phases are related to the physical properties of a material. Important elements of modern materials science are a product of the space race: the understanding and engineering of the metallic alloys, and silica and carbon materials, used in the construction of space vehicles enabling the exploration of space. Materials science has driven, and been driven by, the development of revolutionary technologies such as plastics, semiconductors, and biomaterials.

AE8007 / Aircraft Materials

Before the 1960s (and in some cases decades after), many materials science departments were named metallurgy departments, reflecting the 19th and early 20th century emphasis on metals. The field has since broadened to include every class of materials, including ceramics, polymers, semiconductors, magnetic materials, medical implant materials, biological materials and nanomaterials (materiomics).

Historical Perspective

Materials are so important in the development of civilization that we associate ages with them. In the origin of human life on earth, the Stone Age, people used only natural materials like stone, clay, skins, and wood. When people found copper and how to make it harder by alloying, the bronze Age started about 3000 BC. The use of iron and steel, stronger materials that gave advantage in wars started at about 1200 BC. The next big step was the discovery of a cheap process to make steel around 1850, which enabled the railroads and the building of the modern infrastructure of the industrial world.

Classification of Materials

Like many other things, materials are classified in groups, so that our brain can handle the complexity. One could classify them according to structure, or properties, or use. The one that we will use is according to the way the atoms are bound together:

Metals: The valence electrons are detached from atoms, and spread in an 'electron sea' that "glues" the ions together. Metals are usually strong, conduct electricity and heat well and are opaque to light (shiny if polished). Examples: aluminum, steel, brass, gold.

Semiconductors: The bonding is covalent (electrons are shared between atoms). Their electrical properties depend extremely strongly on minute proportions of contaminants. They are opaque to visible light but transparent to the infrared. Examples: Si, Ge, GaAs.

Ceramics: Atoms behave mostly like either positive or negative ions, and are bound by Coulomb forces between them. They are usually combinations of metals

AE8007 / Aircraft Materials

or semiconductors with oxygen, nitrogen or carbon (oxides, nitrides, and carbides). Examples: glass, porcelain, many minerals.

Polymers: are bound by covalent forces and also by weak van der Waals forces, and usually based on H, C and other non-metallic elements. They decompose at moderate temperatures (100 – 400 C), and are lightweight. Other properties vary greatly. Examples: plastics (nylon, teflon, polyester) and rubber. Other categories are not based on bonding. A particular microstructure identifies

Composites: Composites made of different materials in intimate contact (example: fiberglass, concrete, wood) to achieve specific properties. **Biomaterials** can be any type of material that is biocompatible and used, for instance, to replace human body parts.

Advanced Materials

Materials used in "High-Tec" applications, usually designed for maximum performance, and normally expensive. Examples are titanium alloys for supersonic airplanes, magnetic alloys for computer disks, special ceramics for the heat shield of the space shuttle, etc.

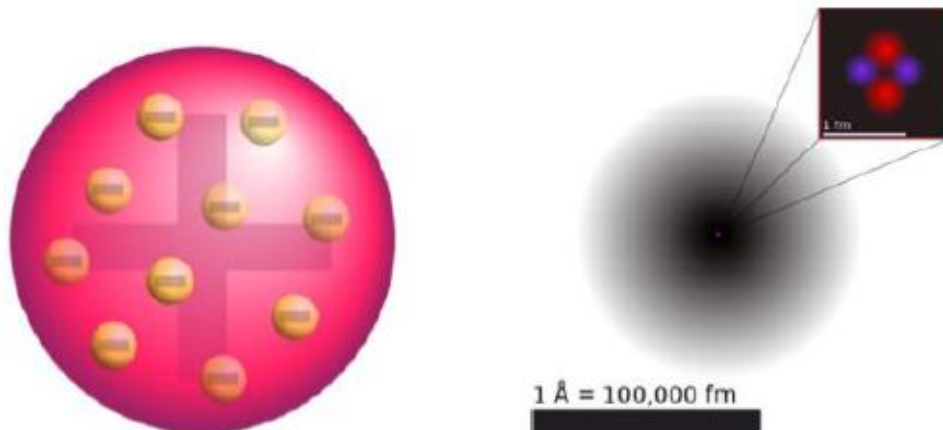
Modern Material's Needs

- Engine efficiency increases at high temperatures: requires high temperature withstanding materials
- Use of nuclear energy requires solving problem with residues, or advances in nuclear waste processing.
- Hypersonic flight requires materials that are light, strong and resist high temperatures.
- Optical communications require optical fibers that absorb light negligibly.
- Civil construction – materials for unbreakable windows.
- Structures: materials that are strong like metals and resist corrosion like plastics.

Atomic models

Thomson atomic model

A schematic presentation of the plum pudding model of the atom; in Thomson's mathematical model the "corpuscles" (or modern electrons) were arranged non-randomly, in rotating rings



The current model of the sub-atomic structure involves a dense nucleus surrounded by a probabilistic "cloud" of electrons

The **plum pudding model** was a model of the atom that incorporated the recently discovered electron, and was proposed by J. J. Thomson in 1904. Thomson had discovered the electron in

1897. The plum pudding model was abandoned after discovery of the atomic nucleus. The plum pudding model of the atom is also known as the "Blueberry Muffin" model.

In this model, the atom is composed of electrons (which Thomson still called "corpuscles", though G. J. Stoney had proposed that atoms of electricity be called electrons in 1894) surrounded by a soup of positive charge to balance the electrons' negative charges, like negatively charged "raisins" surrounded by positively charged "pudding". The electrons (as we know them today) were thought to be positioned throughout the atom, but with many structures possible for positioning multiple electrons, particularly rotating rings of electrons (see below). Instead of a soup, the atom was also sometimes said to have had a "cloud" of positive charge.

AE8007 / Aircraft Materials

With this model, Thomson abandoned his earlier "nebular atom" hypothesis in which the atom was composed of immaterial vortices. Now, at least part of the atom was to be composed of Thomson's particulate negative "corpuscles", although the rest of the positively charged part of the atom remained somewhat nebulous and ill-defined.

The 1904 Thomson model was disproved by the 1909 gold foil experiment of Hans Geiger and Ernest Marsden. This was interpreted by Ernest Rutherford in 1911 to imply a very small nucleus of the atom containing a very high positive charge (in the case of gold, enough to balance about 100 electrons), thus leading to the Rutherford model of the atom. Although gold has an atomic number of 79, immediately after Rutherford's paper appeared in 1911 Antonius Van den Broek made the intuitive suggestion that atomic number is nuclear charge. The matter required experiment to decide. Henry Moseley's work showed experimentally in 1913 (see Moseley's law) that the effective nuclear charge was very close to the atomic number (Moseley found only one unit difference), and Moseley referenced only the papers of Van den Broek and Rutherford. This work culminated in the solar-system-like (but quantum-limited) Bohr model of the atom in the same year, in which a nucleus containing an atomic number of positive charge is surrounded by an equal number of electrons in orbital shells. Bohr had also inspired Moseley's work.

Thomson's model was compared (though not by Thomson) to a British dessert called plum pudding, hence the name. Thomson's paper was published in the March 1904 edition of the Philosophical Magazine, the leading British science journal of the day. In Thomson's view: the atoms of the elements consist of a number of negatively electrified corpuscles enclosed in a sphere of uniform positive electrification.

In this model, the electrons were free to rotate within the blob or cloud of positive substance.

These orbits were stabilized in the model by the fact that when an electron moved farther from the center of the positive cloud, it felt a larger net positive inward force, because there was more material of opposite charge, inside its orbit (see Gauss's law). In Thomson's model, electrons were free to rotate in rings which

AE8007 / Aircraft Materials

were further stabilized by interactions between the electrons, and spectra were to be accounted for by energy differences of different ring orbits. Thomson attempted to make his model account for some of the major spectral lines known for some elements, but was not notably successful at this. Still, Thomson's model (along with a similar Saturnian ring model for atomic electrons, also put forward in 1904 by Nagaoka after James Clerk Maxwell's model of Saturn's rings), were earlier harbingers of the later and more successful solar-system-like Bohr model of the atom.

Rutherford model

Rutherford overturned Thomson's model in 1911 with his well-known gold foil experiment in which he demonstrated that the atom has a tiny, heavy nucleus. Rutherford designed an experiment to use the alpha particles emitted by a radioactive element as probes to the unseen world of atomic structure.

Rutherford presented his own physical model for subatomic structure, as an interpretation for the unexpected experimental results. In it, the atom is made up of a central charge (this is the modern atomic nucleus, though Rutherford did not use the term "nucleus" in his paper) surrounded by a cloud of (presumably) orbiting electrons. In this May 1911 paper, Rutherford only commits himself to a small central region of very high positive or negative charge in the atom.

For concreteness, consider the passage of a high speed α particle through an atom having a positive central charge $N e$, and surrounded by a compensating charge of N electrons.

From purely energetic considerations of how far particles of known speed would be able to penetrate toward a central charge of $100 e$, Rutherford was able to calculate that the radius of his gold central charge would need to be less (how much less could not be told) than 3.4×10^{-14} metres. This was in a gold atom known to be 10^{-10} meters or so in radius—a very surprising finding, as it implied a strong central charge less than 1/3000th of the diameter of the atom.

The Rutherford model served to concentrate a great deal of the atom's charge and mass to a very small core, but didn't attribute any structure to the remaining electrons and remaining atomic mass. It did mention the atomic model of Hantaro

AE8007 / Aircraft Materials

Nagaoka, in which the electrons are arranged in one or more rings, with the specific metaphorical structure of the stable rings of Saturn. The plum pudding model of J.J. Thomson also had rings of orbiting electrons. Jean Baptiste Perrin claimed in his Nobel Lecture that he was the first one to suggest the model in his paper dated 1901.

The Rutherford paper suggested that the central charge of an atom might be "proportional" to its atomic mass in hydrogen mass units u (roughly $1/2$ of it, in Rutherford's model). For gold, this mass number is 197 (not then known to great accuracy) and was therefore modeled by Rutherford to be possibly 196 u . However, Rutherford did not attempt to make the direct connection of central charge to atomic number, since gold's "atomic number" (at that time merely its place number in the periodic table) was 79, and Rutherford had modeled the charge to be about + 100 units (he had actually suggested 98 units of positive charge, to make half of 196). Thus, Rutherford did not formally suggest the two numbers (periodic table place, 79, and nuclear charge, 98 or 100) might be exactly the same.

Bohr model

In the early 20th century, experiments by Ernest Rutherford established that atoms consisted of a diffuse cloud of negatively charged electrons surrounding a small, dense, positively charged nucleus. Given this experimental data, Rutherford naturally considered a planetary-model atom, the Rutherford model of 1911 – electrons orbiting a solar nucleus – however, said planetary model atom has a technical difficulty. The laws of classical mechanics (i.e. the Larmor formula), predict that the electron will release electromagnetic radiation while orbiting a nucleus. Because the electron would lose energy, it would rapidly spiral inwards, collapsing into the nucleus on a timescale of around 16 picoseconds. This atom model is disastrous, because it predicts that all atoms are unstable.

Also, as the electron spirals inward, the emission would rapidly increase in frequency as the orbit got smaller and faster. This would produce a continuous smear, in frequency, of electromagnetic radiation. However, late 19th century experiments with electric discharges have shown that atoms will only emit light (that is, electromagnetic radiation) at certain discrete frequencies.

AE8007 / Aircraft Materials

To overcome this difficulty, Niels Bohr proposed, in 1913, what is now called the Bohr model of the atom. He suggested that electrons could only have certain classical motions:

1. Electrons in atoms orbit the nucleus.
2. The electrons can only orbit stably, without radiating, in certain orbits (called by Bohr the "stationary orbits") at a certain discrete set of distances from the nucleus. These orbits are associated with definite energies and are also called energy shells or energy levels. In these orbits, the electron's acceleration does not result in radiation and energy loss as required by classical electromagnetics.
3. Electrons can only gain and lose energy by jumping from one allowed orbit to another, absorbing or emitting electromagnetic radiation with a frequency ν determined by the energy difference of the levels according to the Planck relation

Where h is Planck's constant. The frequency of the radiation emitted at an orbit of period T is as it would be in classical mechanics; it is the reciprocal of the classical orbit period:

The significance of the Bohr model is that the laws of classical mechanics apply to the motion of the electron about the nucleus only when restricted by a quantum rule. Although rule 3 is not completely well defined for small orbits, because the emission process involves two orbits with two different periods, Bohr could determine the energy spacing between levels using rule 3 and come to an exactly correct quantum rule: the angular momentum L is restricted to be an integer multiple of a fixed unit:

$$L = n \frac{h}{2\pi} = n\hbar.$$

where $n = 1, 2, 3, \dots$ is called the principal quantum number, and $\hbar = h/2\pi$. The lowest value of n is 1; this gives a smallest possible orbital radius of 0.0529 nm known as the Bohr radius. Once an electron is in this lowest orbit, it can get no closer to the proton. Starting from the angular momentum quantum rule, Bohr was able to calculate the energies of the allowed orbits of the hydrogen atom and other hydrogen-like atoms and ions. Other points are:

1. Like Einstein's theory of the Photoelectric effect, Bohr's formula assumes that during a quantum jump a discrete amount of energy is radiated. However, unlike Einstein, Bohr stuck to the classical Maxwell theory of the

AE8007 / Aircraft Materials

electromagnetic field. Quantization of the electromagnetic field was explained by the discreteness of the atomic energy levels; Bohr did not believe in the existence of photons.

2. According to the Maxwell theory the frequency ν of classical radiation is equal to the rotation frequency ν_{rot} of the electron in its orbit, with harmonics at integer multiples of this frequency. This result is obtained from the Bohr model for jumps between energy levels E_n and E_{n-k} when k is much smaller than n . These jumps reproduce the frequency of the k -th harmonic of orbit n . For sufficiently large values of n (so-called Rydberg states), the two orbits involved in the emission process have nearly the same rotation frequency, so that the classical orbital frequency is not ambiguous. But for small n (or large k), the radiation frequency has no unambiguous classical interpretation. This marks the birth of the correspondence principle, requiring quantum theory to agree with the classical theory only in the limit of large quantum numbers.
3. The Bohr-Kramers-Slater theory (BKS theory) is a failed attempt to extend the Bohr model which violates the conservation of energy and momentum in quantum jumps, with the conservation laws only holding on average. Bohr's condition, that the angular momentum is an integer multiple of \hbar was later reinterpreted in 1924 by de Broglie as a standing wave condition: the electron is described by a wave and a whole number of wavelengths must fit along the circumference of the electron's orbit

$$n\lambda = 2\pi r.$$

Substituting de Broglie's wavelength of h/p reproduces Bohr's rule. In 1913, however, Bohr justified his rule by appealing to the correspondence principle, without providing any sort of wave interpretation. In 1913, the wave behavior of matter particles such as the electron (i.e., matter waves) was not suspected.:

Atomic bonding in solids

From elementary chemistry it is known that the atomic structure of any element is made up of a positively charged nucleus surrounded by electrons revolving around it. An element's atomic number indicates the number of positively charged protons in the nucleus.

The atomic weight of an atom indicates how many protons and neutrons in the nucleus. To determine the number of neutrons in an atom, the atomic number is simply subtracted from the atomic weight.

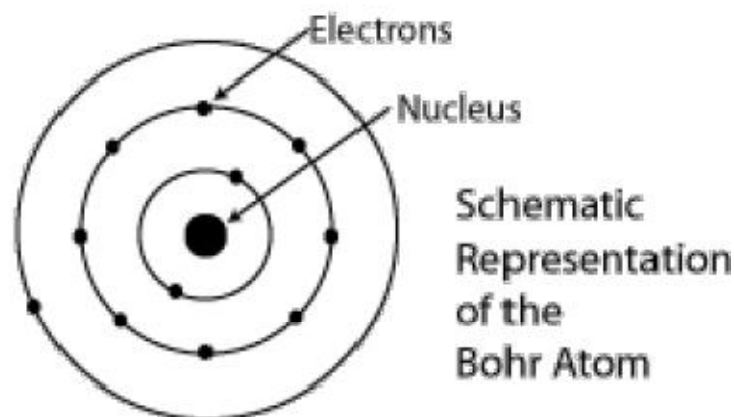
Atoms like to have a balanced electrical charge. Therefore, they usually have negatively charged electrons surrounding the nucleus in numbers equal to the

AE8007 / Aircraft Materials

number of protons. It is also known that electrons are present with different energies and it is convenient to consider these electrons surrounding the nucleus in energy “shells.” For example, magnesium, with an atomic number of 12, has two electrons in the inner shell, eight in the second shell and two in the outer shell.

All chemical bonds involve electrons. Atoms will stay close together if they have a shared interest in one or more electrons. Atoms are at their most stable when they have no partially filled electron shells. If an atom has only a few electrons in a shell, it will tend to lose them to empty the shell. These elements are metals. When metal atoms bond, a metallic bond occurs.

When an atom has a nearly full electron shell, it will try to find electrons from another atom so that it can fill its outer shell. These elements are usually described as nonmetals. The bond between two nonmetal atoms is usually a covalent bond. Where metal and nonmetal atom come together an ionic bond occurs. There are also other, less common, types of bond but the details are beyond the scope of this material. On the next few pages, the Metallic, Covalent and Ionic bonds will be covered in more detail.



The nucleus is composed of protons and neutrons
Atomic number identifies number of protons in the nucleus
Atomic mass is the sum of masses of protons and neutrons
Electrons orbit the nucleus
Protons and electrons have equal and opposite electrical charge

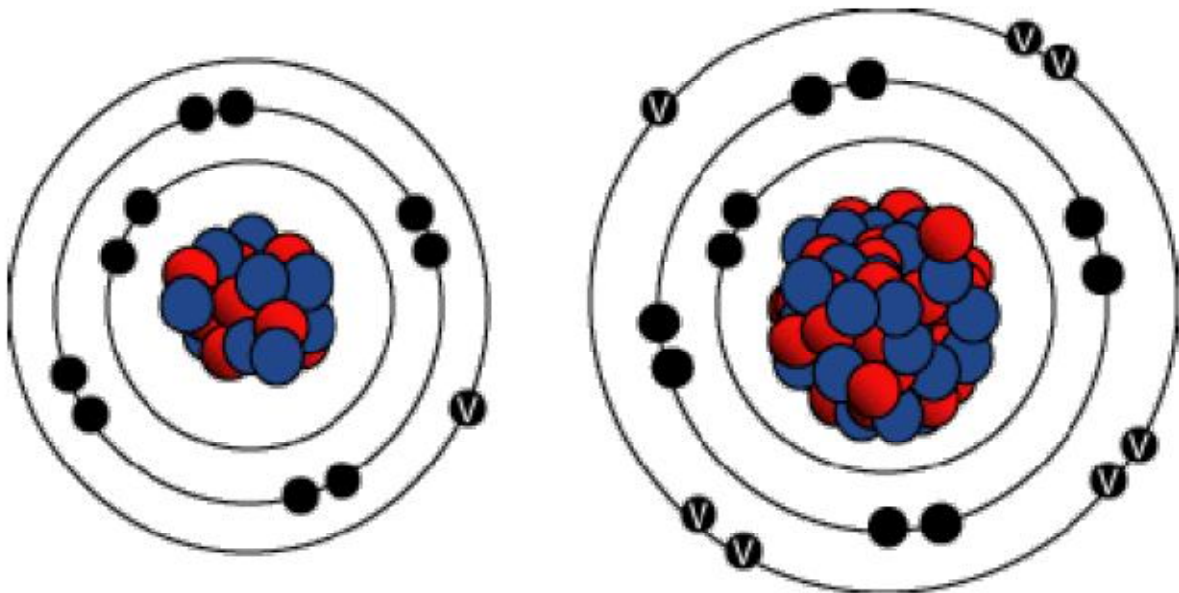
Ionic Bonds

Ionic bonding occurs between charged particles. These may be atoms or groups of atoms, but this discussion will be conducted in terms of single atoms. Ionic bonding occurs between metal atoms and nonmetal atoms. Metals usually have 1, 2, or 3 electrons in their outermost shell. Nonmetals have 5, 6, or 7 electrons in their outer

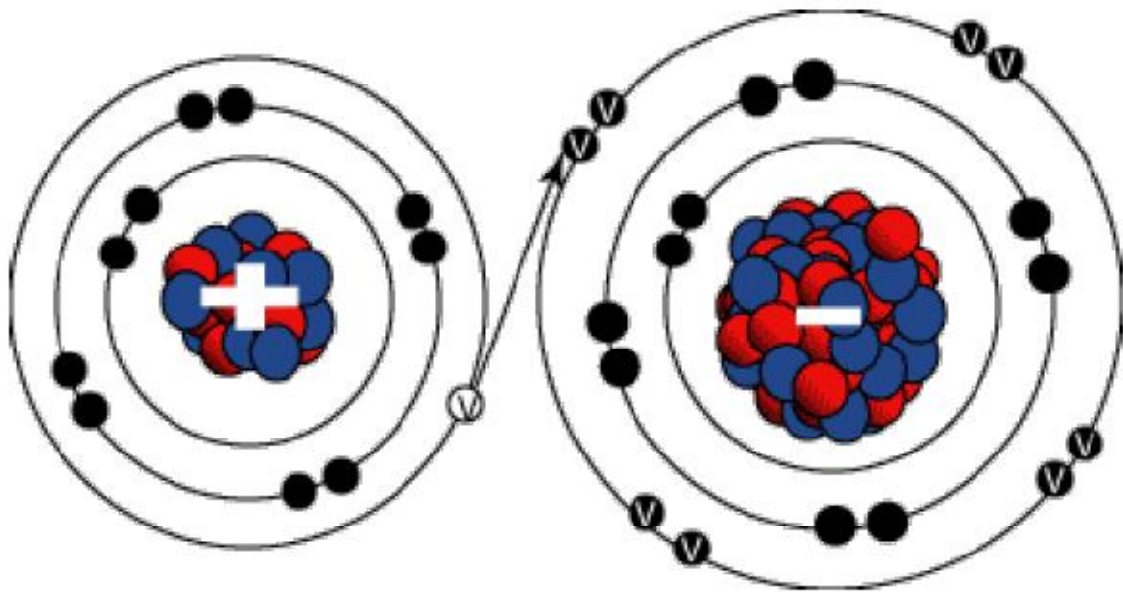
AE8007 / Aircraft Materials

shell. Atoms with outer shells that are only partially filled are unstable. To become stable, the metal atom wants to get rid of one or more electrons in its outer shell. Losing electrons will either result in an empty outer shell or get it closer to having an empty outer shell. It would like to have an empty outer shell because the next lower energy shell is a stable shell with eight electrons.

Since electrons have a negative charge, the atom that gains electrons becomes a negatively charged ions (aka anion) because it now has more electrons than protons. Alternately, an atom that loses electrons becomes a positively charged ion (aka cations). The particles in an ionic compound are held together because there are oppositely charged particles that are attracted to one another.



AE8007 / Aircraft Materials



The images above schematically show the process that takes place during the formation of an ionic bond between sodium and chlorine atoms. Note that sodium has one valence electron that it would like to give up so that it would become stable with a full outer shell of eight. Also note that chlorine has seven valence electrons and it would like to gain an electron in order to have a full shell of eight. The transfer of the electron causes the previously neutral sodium atom to become a positively charged ion (cation), and the previously neutral chlorine atom to become a negatively charged ion (anion). The attraction for the cation and the anion is called the ionic bond.

Generally, *solid materials* with ionic bonds:

- ✓ are hard because particles cannot easily slide past one another.
- ✓ are good insulators because there are no free electrons or ions (unless dissolved or melted).
- ✓ are transparent because their electrons are not moving from atom to atom and less likely to interact with light photons.
- ✓ are brittle and tend to cleave rather than deform because bonds are strong.
- ✓ have high melting point because ionic bonds are relatively strong.

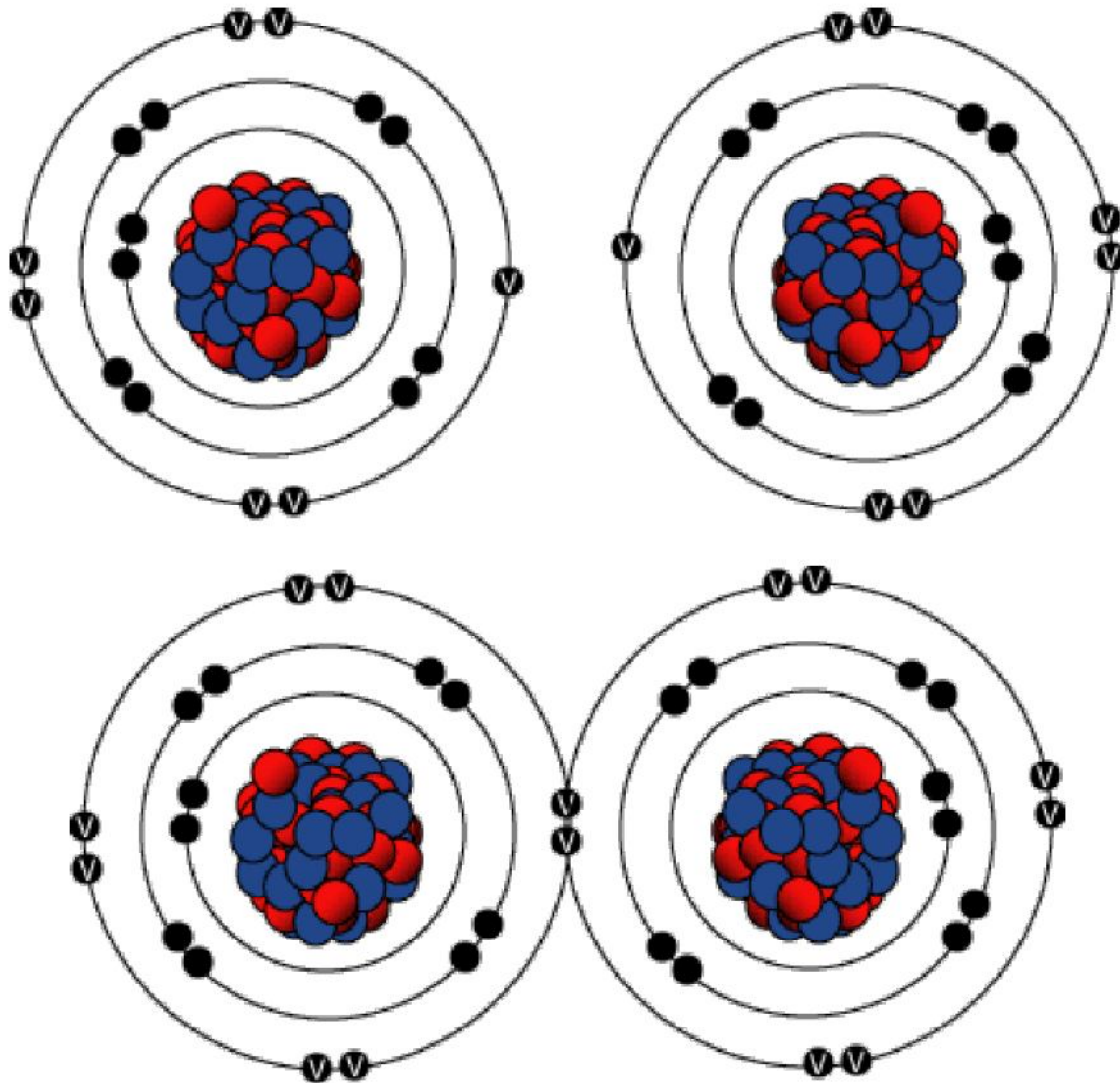
Covalent Bonding

Where a compound only contains nonmetal atoms, a covalent bond is formed by atoms sharing two or more electrons. Nonmetals have 4 or more electrons in their outer shells (except boron). With this many electrons in the outer shell, it would require more energy to remove the electrons than would be gained by making new bonds. Therefore, both the atoms involved share a pair of electrons. Each atom gives one of its outer electrons to the electron pair, which then spends some time with each atom. Consequently, both atoms are held near each other since both atoms have a share in the electrons.

More than one electron pair can be formed with half of the electrons coming from one atom and the rest from the other atom. An important feature of this bond is that the electrons are tightly held and equally shared by the participating atoms. The atoms can be of the same element or different elements. In each molecule, the bonds between the atoms are strong but the bonds between molecules are usually weak. This makes many solid materials with covalent bonds brittle. Many ceramic materials have covalent bonds.

Compounds with covalent bonds may be solid, liquid or gas at room temperature depending on the number of atoms in the compound. The more atoms in each molecule, the higher a compound's melting and boiling temperature will be. Since most covalent compounds contain

AE8007 / Aircraft Materials



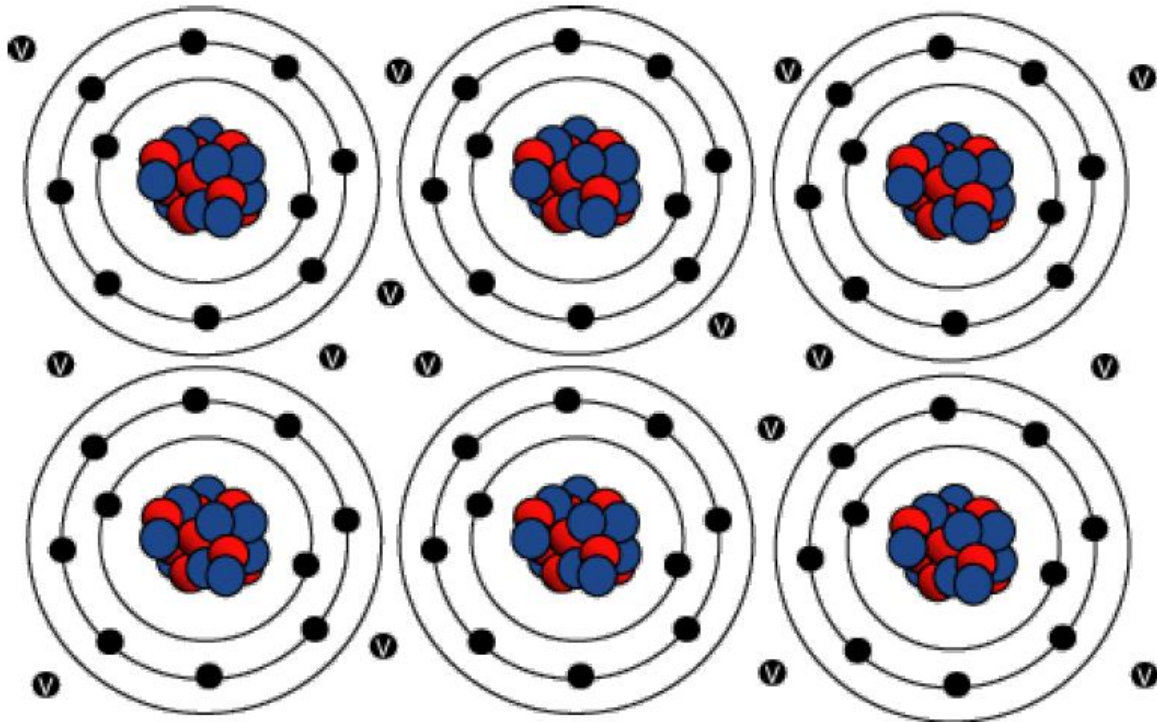
only a few atoms and the forces between molecules are weak, most covalent compounds have low melting and boiling points. However, some, like carbon compounds, can be very large. An example is the diamond in which carbon atoms each share four electrons to form giant lattices.

Some Common Features of Materials with Covalent Bonds:

- ✓ Low enthalpies of fusion and vaporization
- ✓ Good insulators
- ✓ Solids can be soft or brittle
- ✓ If brittle often transparent and cleave rather than deform.

Metallic Bonding

A common characteristic of metallic elements is they contain only one to three electrons in the outer shell. When an element has only one, two or three valence electrons (i.e. electrons in the outer shell), the bond between these electrons and the nucleus is relatively weak. So, for example, when aluminum atoms are grouped together in a block of metal, the outer electrons leave individual atoms to become part of common “electron cloud.” In this arrangement, the valence electrons have considerable mobility and are able to conduct heat and electricity easily. Also, the delocalized nature of the bonds, make it possible for the atoms to slide past each other when the metal is deformed instead of fracturing like glass or other brittle material.



Since the aluminum atoms lose three electrons, they end up having a positive charge and are designated Al^{3+} ions (cations). These ions repel each other but are held together in the block because the negative electrons are attracted to the positively charged ions. A result of the sharing of electrons is the cations arrange themselves in a regular pattern. This regular pattern of atoms is the crystalline structure of metals. In the crystal lattice, atoms are packed closely together to

AE8007 / Aircraft Materials

maximize the strength of the bonds. An actual piece of metal consists of many tiny crystals called grains that touch at grain boundaries.

Some Common Features of Materials with Metallic Bonds:

- ✓ Good electrical and thermal conductors due to their free valence electrons
- ✓ Opaque
- ✓ Relatively ductile

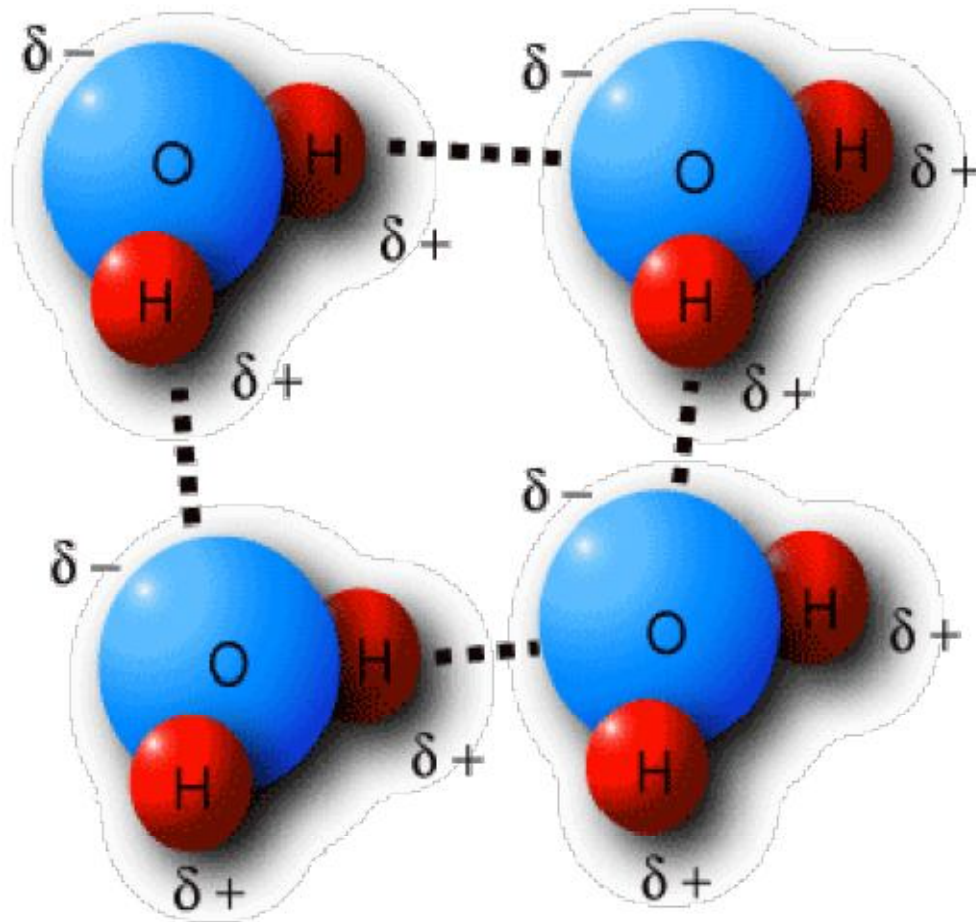
Van der Waals Bond

The van der Waal bonds occur to some extent in all materials but are particularly important in plastics and polymers. These materials are made up of a long string molecules consisting of carbon atoms covalently bonded with other atoms, such as hydrogen, nitrogen, oxygen, fluorine. The covalent bonds within the molecules are very strong and rupture only under extreme conditions. The bonds between the molecules that allow sliding and rupture to occur are called van der Waal forces.

When ionic and covalent bonds are present, there is some imbalance in the electrical charge of the molecule. Take water as an example. Research has determined the hydrogen atoms are bonded to the oxygen atoms at an angle of 104.5° . This angle produces a positive polarity at the hydrogen-rich end of the molecule and a negative polarity at the other end. A result of this charge imbalance is that water molecules are attracted to each other. This is the force that holds the molecules together in a drop of water.

This same concept can be carried on to plastics, except that as molecules become larger, the van der Waal forces between molecules also increases. For example, in polyethylene the molecules are composed of hydrogen and carbon atoms in the same ratio as ethylene gas. But there are more of each type of atom in the polyethylene molecules and as the number of atoms in a molecule increases, the matter passes from a gas to a liquid and finally to a solid.

Polymers are often classified as being either a thermoplastic or a thermosetting material. Thermoplastic materials can be easily remelted for forming or recycling and thermosetting material cannot be easily remelted. In thermoplastic materials consist of long chainlike molecules. Heat can be used to break the van der Waal forces between the molecules and change the form of the material from a solid to a liquid. By contrast, thermosetting materials have a three-dimensional network of covalent bonds. These bonds cannot be easily broken by heating and, therefore, can not be remelted and formed as easily as thermoplastics.



Solid State Structure

In the previous pages, some of the mechanisms that bond together the multitude of individual atoms or molecules of a solid material were discussed. These forces may be primary chemical bonds, as in metals and ionic solids, or they may be secondary van der Waals' forces of solids, such as in ice, paraffin wax and most polymers. In solids, the way the atoms or molecules arrange themselves contributes to the appearance and the properties of the materials.

Atoms can be gathered together as an aggregate through a number of different processes, including condensation, pressurization, chemical reaction, electrodeposition, and melting. The process usually determines, at least initially, whether the collection of atoms will take the form of a gas, liquid or solid. The state usually changes as its temperature or pressure is changed. Melting is the process most often used to form an aggregate of atoms. When the temperature of a melt is

lowered to a certain point, the liquid will form either a crystalline solid or an amorphous solid.

Atomic arrangement



Crystal Structure

Crystal structures may be conveniently specified by describing the arrangement within the solid of a small representative group of atoms or molecules, called the 'unit cell.' By multiplying identical unit cells in three directions, the location of all the particles in the crystal is determined. In nature, 14 different types of crystal structures or lattices are found. The simplest crystalline unit cell to picture is the cubic, where the atoms are lined up in a square, 3D grid. The unit cell is simply a box with an atom at each corner. Simple cubic crystals are relatively rare, mostly because they tend to easily distort. However, many crystals form body-centered-cubic (bcc) or face-centered-cubic (fcc) structures, which are cubic with either an extra atom centered in the cube or centered in each face of the cube. Most metals form bcc, fcc or Hexagonal Close Packed (hcp) structures; however, the structure can change depending on temperature. These three structures will be discussed in more detail on the following page.

Crystalline structure is important because it contributes to the properties of a material. For example, it is easier for planes of atoms to slide by each other if those planes are closely packed. Therefore, lattice structures with closely packed planes allow more plastic deformation than those that are not closely packed. Additionally, cubic lattice structures allow slippage to occur more easily than non-cubic lattices. This is because their symmetry provides closely packed planes in several directions. A face-centered cubic crystal structure will exhibit more ductility (deform more readily under load before breaking) than a body-centered cubic structure. The bcc lattice, although cubic, is not closely packed and forms

AE8007 / Aircraft Materials

strong metals. Alpha-iron and tungsten have the bcc form. The fcc lattice is both cubic and closely packed and forms more ductile materials. Gamma-iron, silver, gold, and lead have fcc structures. Finally, HCP lattices are closely packed, but not cubic. HCP metals like cobalt and zinc are not as ductile as the fcc metals.

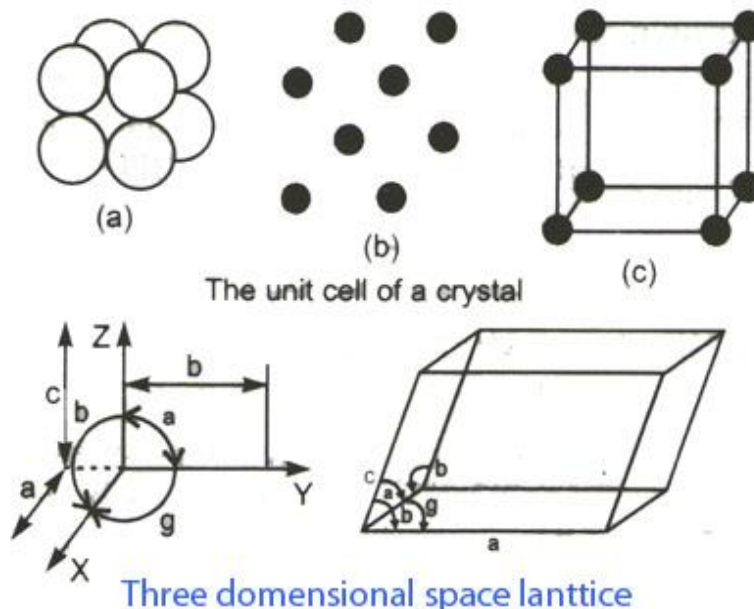
Crystal Lattice is used to represent a three-dimensional periodic array of points coinciding with atom positions.

Unit cell is smallest repeatable entity that can be used to completely represent a crystal structure. It is the building block of crystal structure.

Space Lattice

“A space lattice is an array of points showing how particles (atoms, ions or molecules) are arranged at different sites in three dimensional spaces.”

A crystal is a three dimensional design in which identical points form a 3-dimensional network of cells each representing the unit and through which whole crystal can be built up. The lattice points can be connected by a regular network of lines in various ways. Thus the lattice is broken up into a number of unit cells. This is done by connecting the points by a regular network of lines. The unit cell may be defined as, *“the smallest repeating unit in space lattice which, when repeated over again, results in a crystal of the given substance”*.



Therefore space lattice of a crystal has been likened to a wall-paper on which a single pattern is continuously repeated. Each unit cell requires two vectors a and b

AE8007 / Aircraft Materials

for its description. A three dimensional space lattice can be similarly divided into unit cells described by three vectors. The exact location of particles in a unit cell can be obtained by X-ray diffraction. It should be understood that the choice of unit cell is by no means unique. There are various ways in which a cell can be drawn in a unique space lattice. However, it is usually convenient to choose a parallelepiped whose edges are parallel with the crystallographic axes (a, b and c) and with the

Bravais lattices

When the crystal systems are combined with the various possible lattice centerings, we arrive at the Bravais lattices. They describe the geometric arrangement of the lattice points, and thereby the translational symmetry of the crystal. In three dimensions, there are 14 unique Bravais lattices that are distinct from one another in the translational symmetry they contain. All crystalline materials recognized until now (not including quasicrystals) fit in one of these arrangements. The fourteen three-dimensional lattices, classified by crystal system, are shown above. The Bravais lattices are sometimes referred to as space lattices.

The crystal structure consists of the same group of atoms, the basis, positioned around each and every lattice point. This group of atoms therefore repeats indefinitely in three dimensions according to the arrangement of one of the 14 Bravais lattices. The characteristic rotation and mirror symmetries of the group of atoms, or unit cell, is described by its crystallographic point group.

Crystalline and Non-crystalline materials:

Single Crystals

Crystals can be *single crystals* where the whole solid is one crystal. Then it has a regular geometric structure with flat faces.

Polycrystalline Materials

A solid can be composed of many crystalline grains, not aligned with each other. It is called *polycrystalline*. The grains can be more or less aligned with respect to each other. Where they meet is called a *grain boundary*

Non-Crystalline Solids

In amorphous solids, there is no long-range order. But amorphous does not mean random, since the distance between atoms cannot be smaller than the size of the hard spheres. Also, in many cases there is some form of short-range order. For instance, the tetragonal order of crystalline SiO₂ (quartz) is still apparent in amorphous SiO₂ (silica glass.)

AE8007 / Aircraft Materials

Crystalline Solids

More than 90% of naturally occurring and artificially prepared solids are crystalline. Minerals, sand, clay, limestone, metals, carbon (diamond and graphite), salts (NaCl, KCl etc.), all have crystalline structures. A crystal is a regular, repeating arrangement of atoms or molecules. The majority of solids, including all metals, adopt a crystalline arrangement because the amount of stabilization achieved by anchoring interactions between neighboring particles is at its greatest when the particles adopt regular (rather than random) arrangements. In the crystalline arrangement, the particles pack efficiently together to minimize the total intermolecular energy. The regular repeating pattern that the atoms arrange in is called the crystalline lattice. The scanning tunneling microscope (STM) makes it possible to image the electron cloud associated individual atoms at the surface of a material. Below is an STM image of a platinum surface showing the regular alignment of atoms.

Amorphous Solids

A solid substance with its atoms held apart at equilibrium spacing, but with no long-range periodicity in atom location in its structure is an amorphous solid. Examples of amorphous solids are glass and some types of plastic. They are sometimes described as supercooled liquids because their molecules are arranged in a random manner some what as in the liquid state. For example, glass is commonly made from silicon dioxide or quartz sand, which has a crystalline structure. When the sand is melted and the liquid is cooled rapidly enough to avoid crystallization, an amorphous solid called a glass is formed. Amorphous solids do not show a sharp phase change from solid to liquid at a definite melting point, but rather soften gradually when they are heated. The physical properties of amorphous solids are identical in all directions along any axis so they are said to have isotropic properties, which will be discussed in more detail later

Primary Metallic Crystalline Structures

As pointed out on the previous page, there are 14 different types of crystal unit cell structures or lattices are found in nature. However most metals and many other solids have unit cell structures described as body center cubic (bcc), face centered cubic (fcc) or Hexagonal Close Packed (hcp). Since these structures are most common, they will be discussed in more detail.

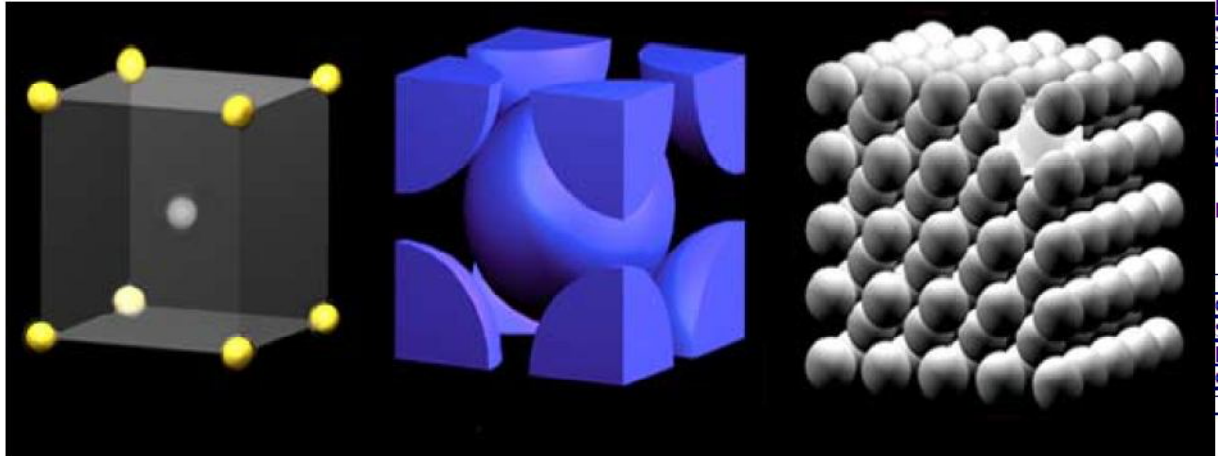
Body-Centered Cubic (BCC) Structure

The body-centered cubic unit cell has atoms at each of the eight corners of a cube (like the cubic unit cell) plus one atom in the center of the cube (left image below). Each of the corner atoms is the corner of another cube so the corner atoms are

AE8007 / Aircraft Materials

shared among eight unit cells. It is said to have a coordination number of 8. The bcc unit cell consists of a net total of two atoms; one in the center and eight eighths from corner atoms as shown in the middle image below (middle image below).

The image below highlights a unit cell in a larger section of the lattice.



The bcc arrangement does not allow the atoms to pack together as closely as the fcc or hcp arrangements. The bcc structure is often the high temperature form of metals that are close-packed at lower temperatures. The volume of atoms in a cell per the total volume of a cell is called the packing factor. The bcc unit cell has a packing factor of 0.68.

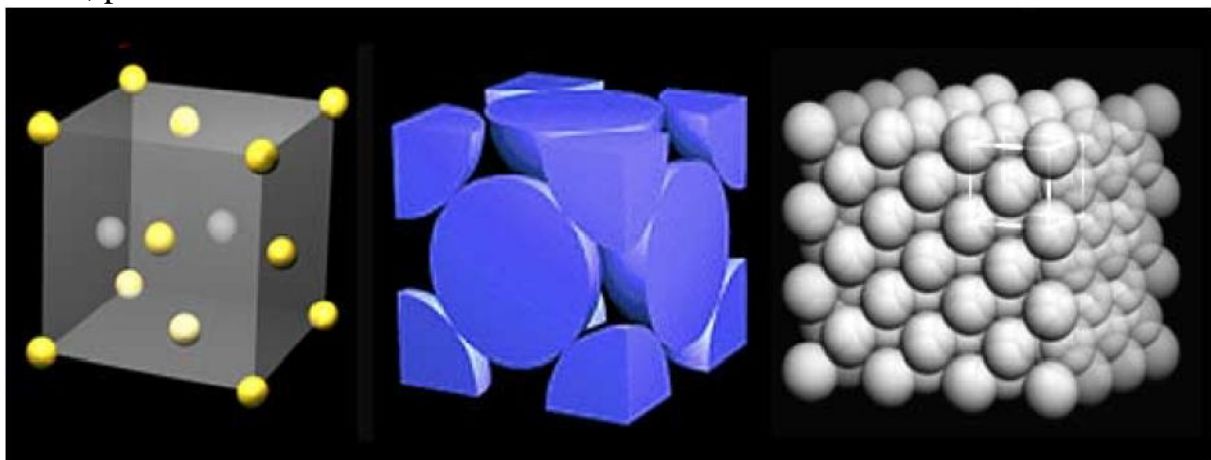
Some of the materials that have a bcc structure include lithium, sodium, potassium, chromium, barium, vanadium, alpha-iron and tungsten. Metals which have a bcc structure are usually harder and less malleable than close-packed metals such as gold. When the metal is deformed, the planes of atoms must slip over each other, and this is more difficult in the bcc structure. It should be noted that there are other important mechanisms for hardening materials, such as introducing impurities or defects which make slipping more difficult. These hardening mechanisms will be discussed later.

Face Centered Cubic FCC Structure

The face centered cubic structure has atoms located at each of the corners and the centers of all the cubic faces (left image below). Each of the corner atoms is the corner of another cube so the corner atoms are shared among eight unit cells. Additionally, each of its six face centered atoms is shared with an adjacent atom. Since 12 of its atoms are shared, it is said to have a coordination number of 12. The fcc unit cell consists of a net total of four atoms; eight eighths from corner atoms and six halves of the face atoms as shown in the middle image above. The image below highlights a unit cell in a larger section of the lattice.

AE8007 / Aircraft Materials

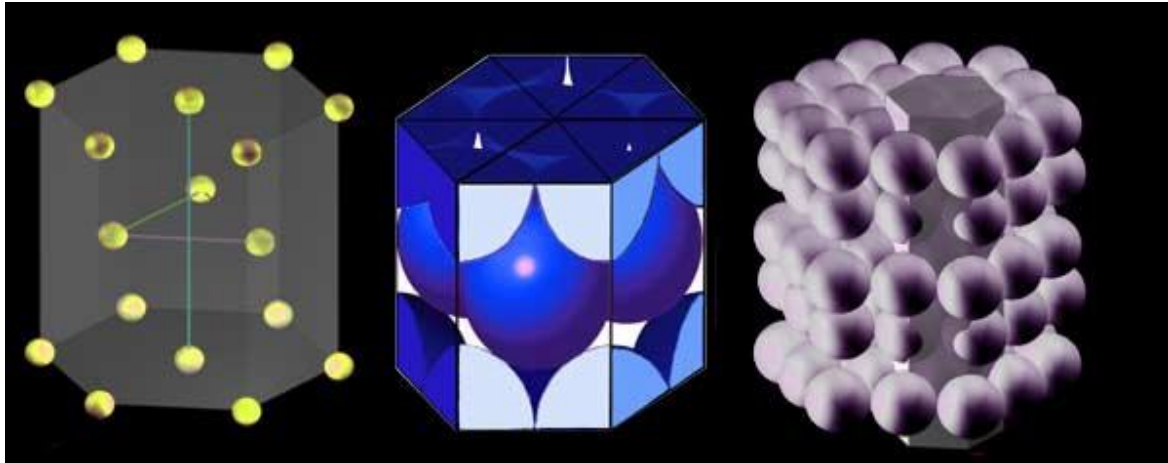
In the fcc structure (and the hcp structure) the atoms can pack closer together than they can in the bcc structure. The atoms from one layer nest themselves in the empty space between the atoms of the adjacent layer. To picture packing arrangement, imagine a box filled with a layer of balls that are aligned in columns and rows. When a few additional balls are tossed in the box, they will not balance directly on top of the balls in the first layer but instead will come to rest in the pocket created between four balls of the bottom layer. As more balls are added they will pack together to fill up all the pockets. The packing factor (the volume of atoms in a cell per the total volume of a cell) is 0.74 for fcc crystals. Some of the metals that have the fcc structure include aluminum, copper, gold, iridium, lead, nickel, platinum and silver.



Hexagonal Close Packed (HCP) Structure

Another common close packed structure is the hexagonal close pack. The hexagonal structure of alternating layers is shifted so its atoms are aligned to the gaps of the preceding layer. The atoms from one layer nest themselves in the empty space between the atoms of the adjacent layer just like in the fcc structure. However, instead of being a cubic structure, the pattern is hexagonal. (See image below.) The difference between the HCP and FCC structure is discussed later in this section.

AE8007 / Aircraft Materials



The hcp structure has three layers of atoms. In each the top and bottom layer, there are six atoms that arrange themselves in the shape of a hexagon and a seventh atom that sits in the middle of the hexagon. The middle layer has three atoms nestle in the triangular "grooves" of the top and bottom plane. Note that there are six of these "grooves" surrounding each atom in the hexagonal plane, but only three of them can be filled by atoms.

As shown in the middle image above, there are six atoms in the hcp unit cell. Each of the 12 atoms in the corners of the top and bottom layers contribute $1/6$ atom to the unit cell, the two atoms in the center of the hexagon of both the top and bottom layers each contribute atom and each of the three atom in the middle layer contribute 1 atom. The image on the right above attempts to show several hcp unit cells in a larger lattice.

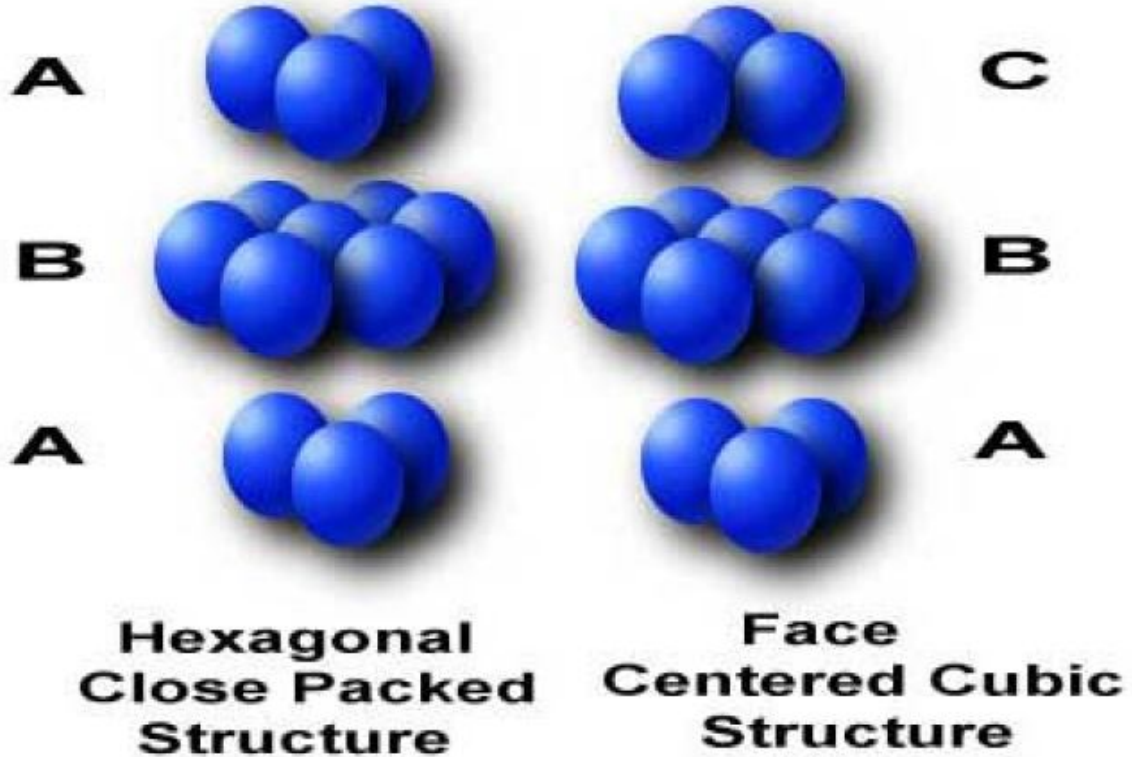
The coordination number of the atoms in this structure is 12. There are six nearest neighbors in the same close packed layer, three in the layer above and three in the layer below. The packing factor is 0.74, which is the same as the fcc unit cell. The hcp structure is very common for elemental metals and some examples include beryllium, cadmium, magnesium, titanium, zinc and zirconium.

Similarities and Difference Between the FCC and HCP Structure

The face centered cubic and hexagonal close packed structures both have a packing factor of 0.74, consist of closely packed planes of atoms, and have a coordination number of 12. The difference between the fcc and hcp is the stacking sequence. The hcp layers cycle among the two equivalent shifted positions whereas the fcc layers cycle between three positions. As can be seen in the image, the hcp structure contains only two types of planes with an alternating ABAB arrangement. Notice how the atoms of the third plane are in exactly the same position as the atoms in the first plane. However, the fcc structure contains three types of planes with a ABCABC arrangement. Notice how the atoms in rows A and C are no longer

AE8007 / Aircraft Materials

aligned. Remember that cubic lattice structures allow slippage to occur more easily than non-cubic lattices, so hcp metals are not as ductile as the fcc metals.



The table below shows the stable room temperature crystal structures for several elemental metals.

Metal	Crystal Structure	Atomic Radius (nm)
Aluminum	FCC	0.1431
Cadmium	HCP	0.1490
Chromium	BCC	0.1249
Cobalt	HCP	0.1253
Copper	FCC	0.1278
Gold	FCC	0.1442
Iron (Alpha)	BCC	0.1241
Lead	FCC	0.1750
Magnesium	HCP	0.1599
Molybdenum	BCC	0.1363
Nickel	FCC	0.1246
Platinum	FCC	0.1387
Silver	FCC	0.1445
Tantalum	BCC	0.1430
Titanium (Alpha)	HCP	0.1445

AE8007 / Aircraft Materials

Tungsten	BCC	0.1371
Zinc	HCP	0.1332

A nanometer (nm) equals 10^{-9} meter or 10 Angstrom units.

Miller Indices: A system of notation is required to identify particular direction(s) or plane(s) to characterize the arrangement of atoms in a unit cell

Rules for Miller Indices (Planes)

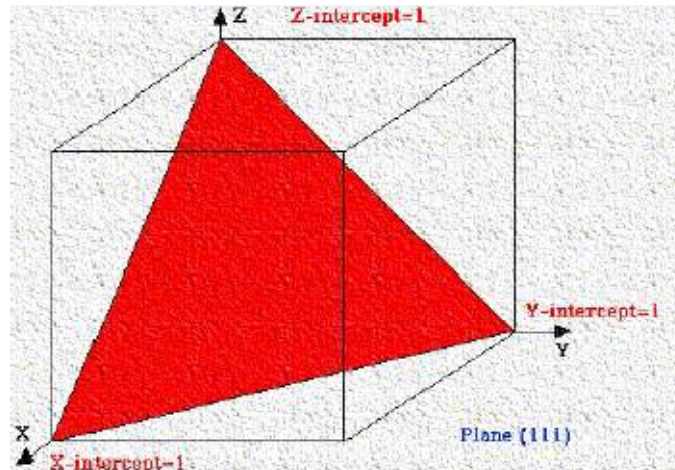
- ✓ Determine the intercepts of the face along the crystallographic axes, *in terms of unit cell dimensions.*
- ✓ Take the reciprocals
- ✓ Clear fractions
- ✓ Reduce to lowest terms
- ✓ For example, if the x-, y-, and z- intercepts are 2, 1, and 3, the Miller indices are calculated as:
- ✓ Take reciprocals: $1/2, 1/1, 1/3$
- ✓ Clear fractions (multiply by 6): 3, 6, 2
- ✓ Reduce to lowest terms (already there)

Thus, the Miller indices are 3,6,2. If a plane is parallel to an axis, its intercept is at infinity and its Miller index is zero. A generic Miller index is denoted by (hkl) . A family of planes is represented by $\{hkl\}$ If a plane has negative intercept, the negative number is denoted by a bar above the number. *Never alter negative numbers.* For example, do not divide -1, -1, -1 by -1 to get 1,1,1. This implies symmetry that the crystal may not have!

Miller Indices - Direction

- A vector of convenient length is placed parallel to the required direction
- The length of the vector projection on each of three axes are measured in terms of unit cell dimensions
- These three numbers are made to smallest integer values, known as indices, by multiplying or dividing by a common factor
- The three indices are enclosed in square brackets, $[uvw]$.
- A family of directions is represented by $\langle uvw \rangle$

AE8007 / Aircraft Materials



Some General Principles

- If a Miller index is zero, the plane is parallel to that axis.
- The smaller a Miller index, the more nearly parallel the plane is to the axis.
- The larger a Miller index, the more nearly perpendicular a plane is to that axis.
- Multiplying or dividing a Miller index by a constant has no effect on the orientation of the plane
- Miller indices are almost always small.

Why Miller Indices?

Using reciprocals spares us the complication of infinite intercepts.

Formulas involving Miller indices are very similar to related formulas from analytical geometry.

Specifying dimensions in unit cell terms means that the same label can be applied to any face with a similar stacking pattern, regardless of the crystal class of the crystal. Face 111 always steps the same way regardless of crystal system.

Crystal Defects

A perfect crystal, with every atom of the same type in the correct position, does not exist. All crystals have some defects. Defects contribute to the mechanical properties of metals. In fact, using the term “defect” is sort of a misnomer since these features are commonly intentionally used to manipulate the mechanical properties of a material. Adding alloying elements to a metal is one way of introducing a crystal defect. Nevertheless, the term “defect” will be used, just keep in mind that crystalline defects are not always bad. There are basic classes of crystal defects:

- ✓ **Point defects**, which are places where an atom is missing or irregularly placed in the lattice structure. Point defects include lattice vacancies, self-interstitial atoms, substitution impurity atoms, and interstitial impurity atoms
- ✓ **Linear defects**, which are groups of atoms in irregular positions. Linear defects are commonly called dislocations.
- ✓ **Planar defects**, which are interfaces between homogeneous regions of the material. Planar defects include grain boundaries, stacking faults and external surfaces.

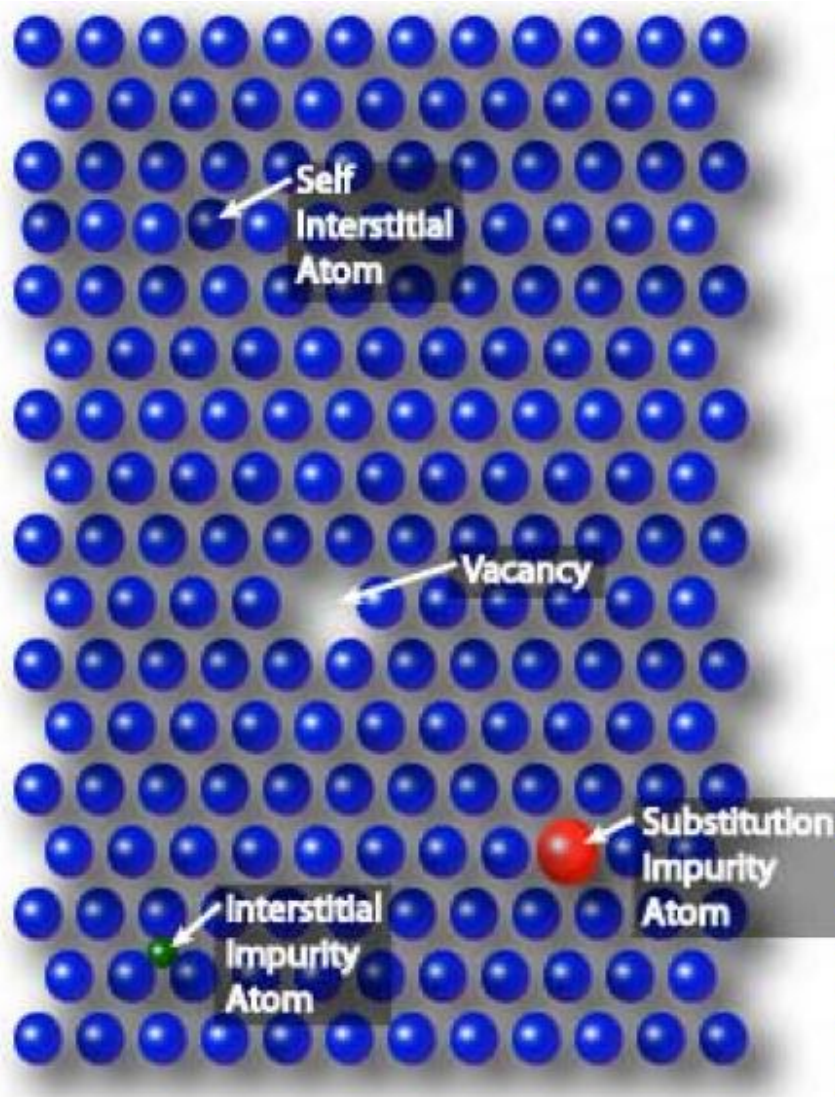
It is important to note at this point that plastic deformation in a material occurs due to the movement of dislocations (linear defects). Millions of dislocations result for plastic forming operations such as rolling and extruding. It is also important to note that any defect in the regular lattice structure disrupts the motion of dislocation, which makes slip or plastic deformation more difficult. These defects not only include the point and planer defects mentioned above, and also other dislocations. Dislocation movement produces additional dislocations, and when dislocations run into each other it often impedes movement of the dislocations. This drives up the force needed to move the dislocation or, in other words, strengthens the material. Each of the crystal defects will be discussed in more detail in the following pages.

Point defects

Point defects are where an atom is missing or is in an irregular place in the lattice structure. Point defects include self interstitial atoms, interstitial impurity atoms, substitutional atoms and vacancies. A *self interstitial atom* is an extra atom that has crowded its way into an interstitial void in the crystal structure. Self interstitial

AE8007 / Aircraft Materials

atoms occur only in low concentrations in metals because they distort and highly stress the tightly packed lattice structure.



A **substitutional impurity** atom is an atom of a different type than the bulk atoms, which has replaced one of the bulk atoms in the lattice. Substitutional impurity atoms are usually close in size (within approximately 15%) to the bulk atom. An example of substitutional impurity atoms is the zinc atoms in brass. In brass, zinc atoms with a radius of 0.133 nm have replaced some of the copper atoms, which have a radius of 0.128 nm.

Interstitial impurity atoms are much smaller than the atoms in the bulk matrix. Interstitial impurity atoms fit into the open space between the bulk atoms of the lattice structure. An example of interstitial impurity atoms is the carbon atoms that

AE8007 / Aircraft Materials

are added to iron to make steel. Carbon atoms, with a radius of 0.071 nm, fit nicely in the open spaces between the larger (0.124 nm) iron atoms.

Vacancies are empty spaces where an atom should be, but is missing. They are common, especially at high temperatures when atoms are frequently and randomly change their positions leaving behind empty lattice sites. In most cases diffusion (mass transport by atomic motion) can only occur because of vacancies.

Linear Defects - Dislocations

Dislocations are another type of defect in crystals. Dislocations are areas where the atoms are out of position in the crystal structure. Dislocations are generated and move when a stress is applied. The motion of dislocations allows slip – plastic deformation to occur.

Before the discovery of the dislocation by Taylor, Orowan and Polyani in 1934, no one could figure out how the plastic deformation properties of a metal could be greatly changed by solely by forming (without changing the chemical composition). This became even bigger mystery when in the early 1900's scientists estimated that metals undergo plastic deformation at forces much smaller than the theoretical strength of the forces that are holding the metal atoms together. Many metallurgists remained skeptical of the dislocation theory until the development of the transmission electron microscope in the late 1950's. The TEM allowed experimental evidence to be collected that showed that the strength and ductility of metals are controlled by dislocations.

There are two basic types of dislocations, the edge dislocation and the screw dislocation. Actually, edge and screw dislocations are just extreme forms of the possible dislocation structures that can occur. Most dislocations are probably a hybrid of the edge and screw forms but this discussion will be limited to these two types.

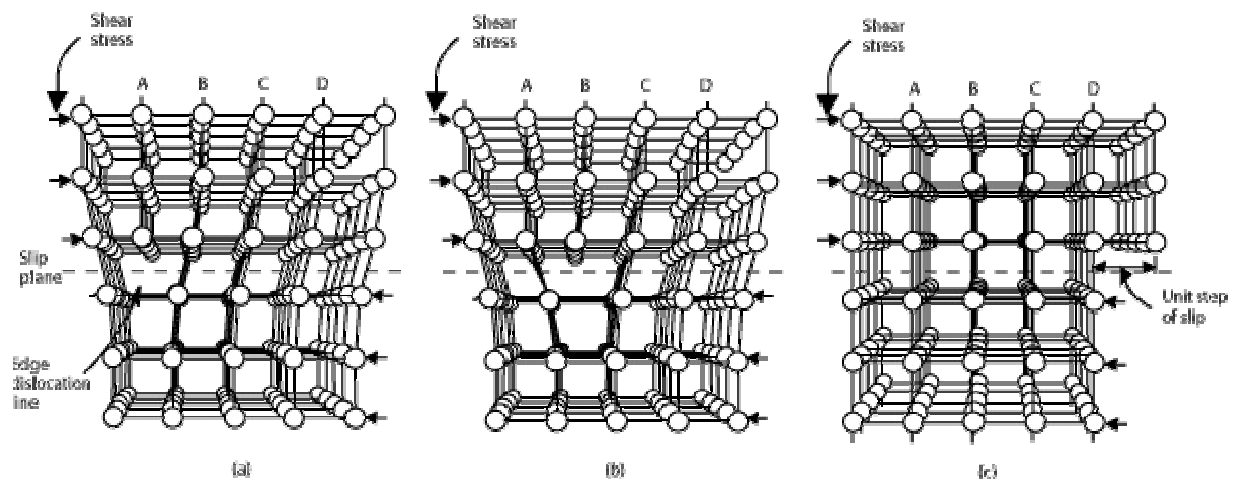
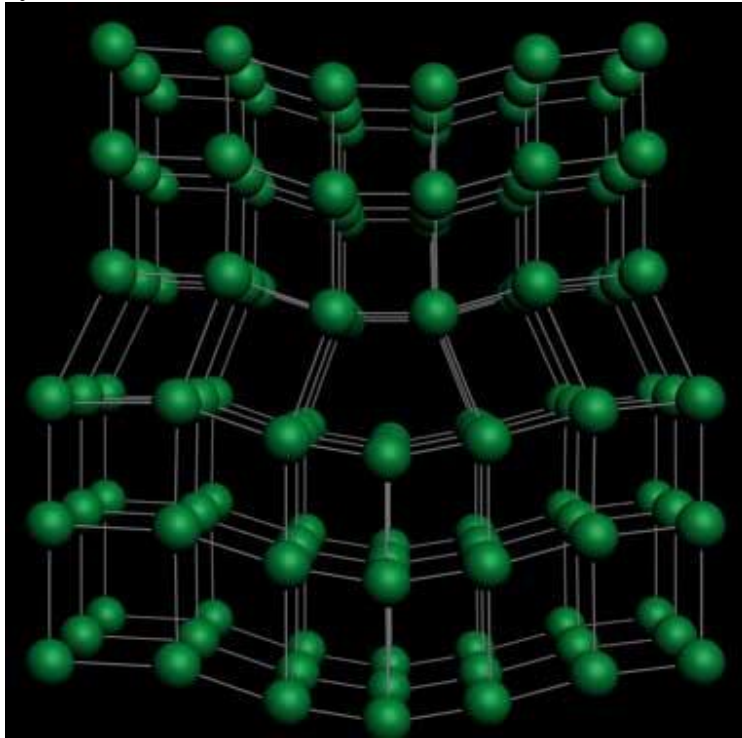
Edge Dislocations

The edge defect can be easily visualized as an extra half-plane of atoms in a lattice. The dislocation is called a line defect because the locus of defective points produced in the lattice by the dislocation lie along a line. This line runs along the top of the extra half-plane. The interatomic bonds are significantly distorted only in the immediate vicinity of the dislocation line.

Understanding the movement of a dislocation is key to understanding why dislocations allow deformation to occur at much lower stress than in a perfect

AE8007 / Aircraft Materials

crystal. Dislocation motion is analogous to movement of a caterpillar. The caterpillar would have to exert a large force to move its entire body at once. Instead it moves the rear portion of its body forward a small amount and creates a hump. The hump then moves forward and eventually moves all of the body forward by a small amount.



As shown in the set of images above, the dislocation moves similarly moves a small amount at a time. The dislocation in the top half of the crystal is slipping one plane at a time as it moves to the right from its position in image (a) to its position in image (b) and finally image (c). In the process of slipping one plane at a time the

AE8007 / Aircraft Materials

dislocation propagates across the crystal. The movement of the dislocation across the plane eventually causes the top half of the crystal to move with respect to the bottom half. However, only a small fraction of the bonds are broken at any given time. Movement in this manner requires a much smaller force than breaking all the bonds across the middle plane simultaneously.

Screw Dislocations

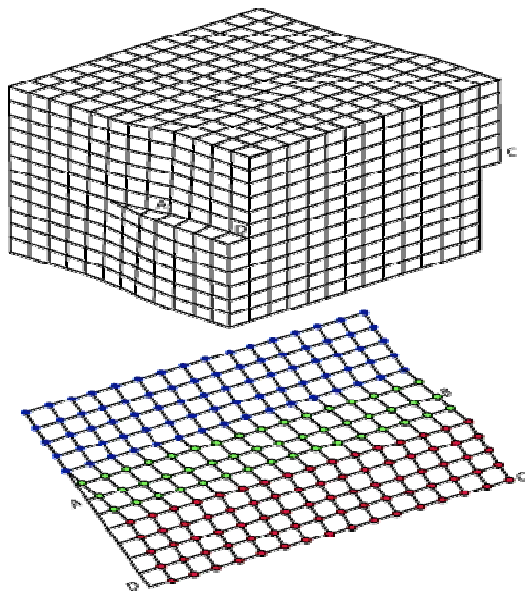
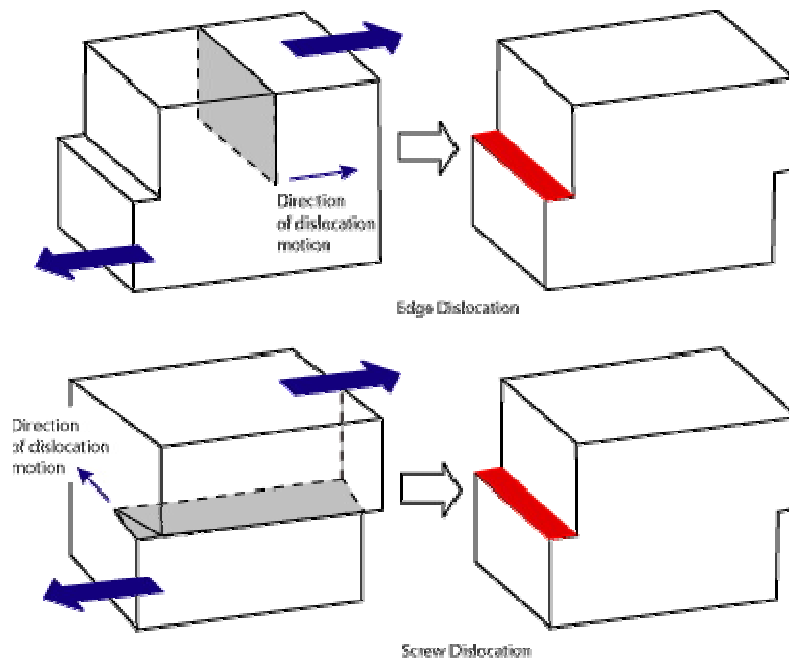
There is a second basic type of dislocation, called screw dislocation. The screw dislocation is slightly more difficult to visualize. The motion of a screw dislocation is also a result of shear stress, but the defect line movement is perpendicular to direction of the stress and the atom displacement, rather than parallel. To visualize a screw dislocation, imagine a block of metal with a shear stress applied across one end so that the metal begins to rip. This is shown in the upper right image. The lower right image shows the plane of atoms just above the rip. The atoms represented by the blue circles have not yet moved from their original position. The atoms represented by the red circles have moved to their new position in the lattice and have reestablished metallic bonds. The atoms represented by the green circles are in the process of moving. It can be seen that only a portion of the bonds are broke at any given time. As was the case with the edge dislocation, movement in this manner requires a much smaller force than breaking all the bonds across the middle plane simultaneously.

If the shear force is increased, the atoms will continue to slip to the right. A row of the green atoms will find there way back into a proper spot in the lattice (and become red) and a row of the blue atoms will slip out of position (and become green). In this way, the screw dislocation will move upward in the image, which is perpendicular to direction of the stress. Recall that the edge dislocation moves parallel to the direction of stress. As shown in the image below, the net plastic deformation of both edge and screw dislocations is the same, however.

The dislocations move along the densest planes of atoms in a material, because the stress needed to move the dislocation increases with the spacing between the planes. FCC and BCC metals have many dense planes, so dislocations move relatively easy and these materials have high ductility. Metals are strengthened by making it more difficult for dislocations to move. This may involve the introduction of obstacles, such as interstitial atoms or grain boundaries, to “pin” the dislocations. Also, as a material plastically deforms, more dislocations are produced and they will get into each others way and impede movement. This is why strain or work hardening occurs.

AE8007 / Aircraft Materials

In ionically bonded materials, the ion must move past an area with a repulsive charge in order to get to the next location of the same charge. Therefore, slip is difficult and the materials are brittle. Likewise, the low density packing of covalent materials makes them generally more brittle than metals



Planar Defects

Stacking Faults and Twin Boundaries

A disruption of the long-range stacking sequence can produce two other common types of crystal defects: 1) a stacking fault and 2) a twin region. A change in the stacking sequence over a few atomic spacings produces a stacking fault whereas a change over many atomic spacings produces a twin region.

A stacking fault is a one or two layer interruption in the stacking sequence of atom planes. Stacking faults occur in a number of crystal structures, but it is easiest to see how they occur in close packed structures. For example, it is known from a previous discussion that face centered cubic (fcc) structures differ from hexagonal close packed (hcp) structures only in their stacking order. For hcp and fcc structures, the first two layers arrange themselves identically, and are said to have an AB arrangement. If the third layer is placed so that its atoms are directly above those of the first (A) layer, the stacking will be ABA. This is the hcp structure, and it continues ABABABAB. However it is possible for the third layer atoms to arrange themselves so that they are in line with the first layer to produce an ABC arrangement which is that of the fcc structure. So, if the hcp structure is going along as ABABAB and suddenly switches to ABABABCABAB, there is a stacking fault present.

Alternately, in the fcc arrangement the pattern is ABCABCABC. A stacking fault in an fcc structure would appear as one of the C planes missing. In other words the pattern would become ABCABCAB_ABCABC.

If a stacking fault does not correct itself immediately but continues over some number of atomic spacings, it will produce a second stacking fault that is the twin of the first one. For example if the stacking pattern is ABABABAB but switches to ABCABCABC for a period of time before switching back to ABABABAB, a pair of twin stacking faults is produced. The red region in the stacking sequence that goes ABCABCACBACBABCABC is the twin plane and the twin boundaries are the A planes on each end of the highlighted region.

Grain Boundaries in Polycrystals

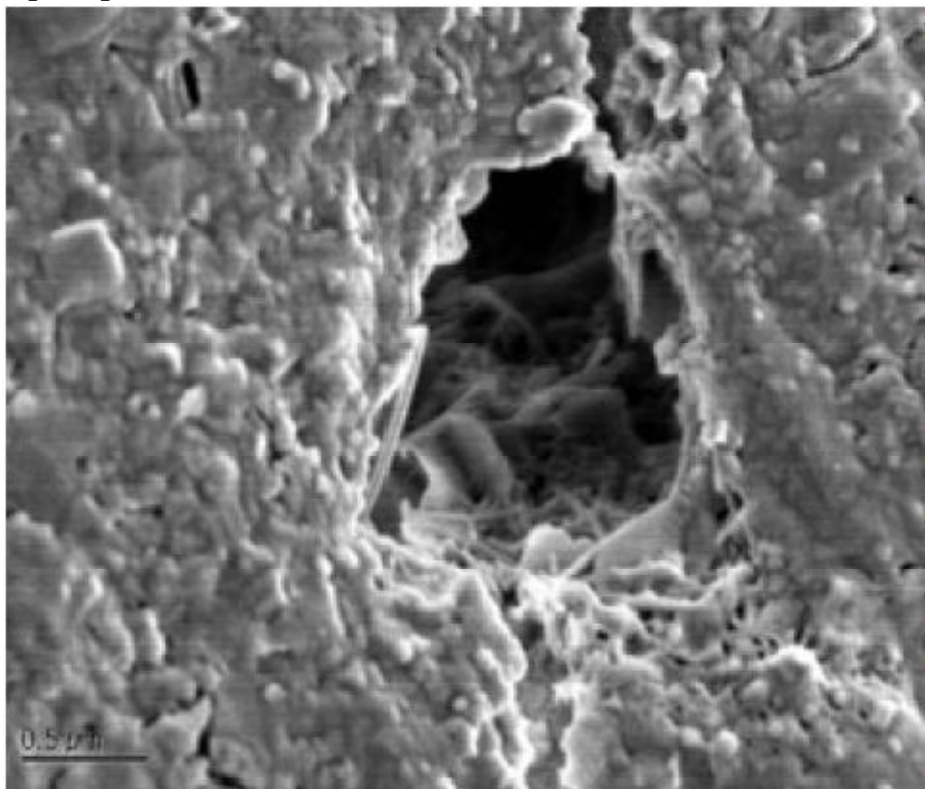
Another type of planar defect is the grain boundary. Up to this point, the discussion has focused on defects of single crystals. However, solids generally consist of a number of crystallites or grains. Grains can range in size from nanometers to millimeters across and their orientations are usually rotated with respect to neighboring grains. Where one grain stops and another begins is known as a grain boundary. Grain boundaries limit the lengths and motions of dislocations. Therefore, having smaller grains (more grain boundary surface area) strengthens a material. The size of the grains can be controlled by the cooling rate when the

AE8007 / Aircraft Materials

material cast or heat treated. Generally, rapid cooling produces smaller grains whereas slow cooling result in larger grains. For more information, refer to the discussion on solidification.

Bulk Defects

Bulk defects occur on a much bigger scale than the rest of the crystal defects discussed in this section. However, for the sake of completeness and since they do affect the movement of dislocations, a few of the more common bulk defects will be mentioned. Voids are regions where there are a large number of atoms missing from the lattice. The image to the right is a void in a piece of metal. The image was acquired using a Scanning Electron Microscope (SEM). Voids can occur for a number of reasons. When voids occur due to air bubbles becoming trapped when a material solidifies, it is commonly called porosity. When a void occurs due to the shrinkage of a material as it solidifies, it is called cavitation. Another type of bulk defect occurs when impurity atoms cluster together to form small regions of a different phase. The term 'phase' refers to that region of space occupied by a physically homogeneous material. These regions are often called precipitates. Phases and precipitates will be discussed in more detail latter.



AE8007 / Aircraft Materials

Atomic packing factor (APF)

Atomic packing factor (APF) or packing efficiency indicates how closely atoms are packed in a unit cell and is given by the ratio of volume of atoms in the unit cell and volume of the unit cell

$$\text{APF} = \text{Volume of atom} / \text{Volume of unit cell}$$

Planar density

Planar density (PD) refers to density of atomic packing on a particular plane.

$$\text{Planar density (PD)} = \text{Number of atoms on a plane} / \text{Area of plane}$$

Linear Density

Linear density (LD) is the number of atoms per unit length along a particular direction

$$\text{LD} = \text{Number of atoms on the direction vector} / \text{Length of the direction vector}$$

X-RAY DIFFRACTION: DETERMINATION OF CRYSTAL STRUCTURES

X-ray diffraction (XRD) relies on the dual wave/particle nature of X-rays to obtain information about the structure of crystalline materials. A primary use of the technique is the identification and characterization of compounds based on their diffraction pattern.

The dominant effect that occurs when an incident beam of monochromatic X-rays interacts with a target material is scattering of those X-rays from atoms within the target material. In materials with regular structure (i.e. crystalline), the scattered X-rays undergo constructive and destructive interference. This is the process of diffraction. The diffraction of X-rays by crystals is described by Bragg's Law, $n(\lambda) = 2d \sin(\Theta)$. The directions of possible diffractions depend on the size and shape of the unit cell of the material. The intensities of the diffracted waves depend on the kind and arrangement of atoms in the crystal structure. However, most materials are not single crystals, but are composed of many tiny crystallites in all possible orientations called a polycrystalline aggregate or powder. When a powder with randomly oriented crystallites is placed in an X-ray beam, the beam will see

AE8007 / Aircraft Materials

all possible interatomic planes. If the experimental angle is systematically changed, all possible diffraction peaks from the powder will be detected.

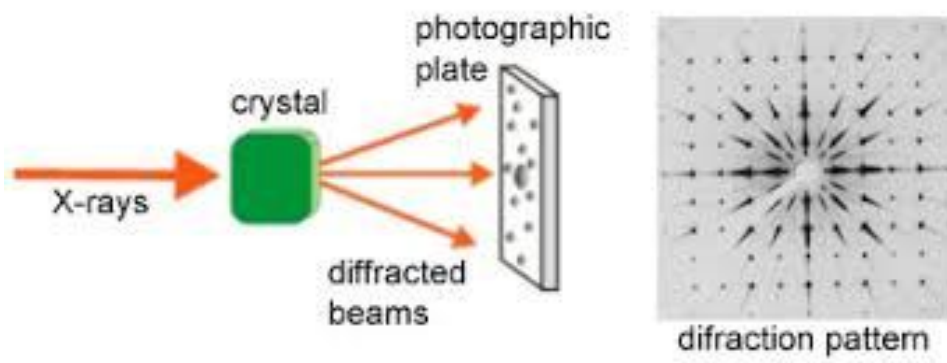
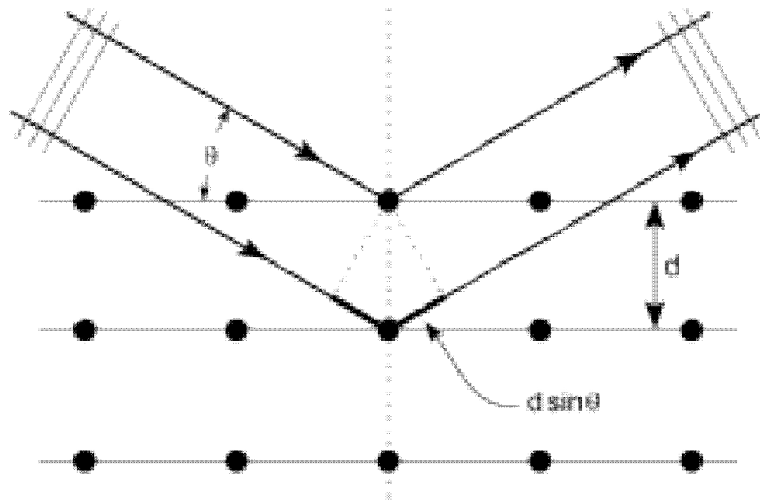
The parafocusing (or Bragg-Brentano) diffractometer is the most common geometry for diffraction instruments.

This geometry offers the advantages of high resolution and high beam intensity analysis at the cost of very precise alignment requirements and carefully prepared samples. Additionally, this geometry requires that the source-to-sample distance be constant and equal to the sample-to-detector distance. Alignment errors often lead to difficulties in phase identification and improper quantification. A mis-positioned sample can lead to unacceptable specimen displacement errors. Sample flatness, roughness, and positioning constraints preclude in-line sample measurement. Additionally, traditional XRD systems are often based on bulky equipment with high power requirements as well as employing high powered X-ray sources to increase X-ray flux on the sample, therefore increasing the detected diffraction signals from the sample. These sources also have large excitation areas, which are often disadvantageous for the diffraction analysis of small samples or small sample features.

Polycapillary X-ray optics can be used to overcome many of these drawbacks and constraints to enhance XRD applications. Polycapillary collimating optics convert a highly divergent beam into a quasi-parallel beam with low divergence. They can be used to form a Parallel Beam XRD instrument geometry which greatly reduces and removes many sources of errors in peak position and intensity inherent to the parafocusing geometry, such as sample position, shape, roughness, flatness, and transparency. Polycapillary focusing optics collect X-rays from a divergent X-ray source and direct them to a small focused beam at the sample surface with diameters as small as tens of micrometers for micro X-ray diffraction applications of small samples or small specimen features. Both types of polycapillary optics direct very high X-ray intensities to the sample surface, such that XRD systems employing optics can use low power X-ray sources, reducing instrument size, cost, and power requirements.

X-ray diffraction using X-ray optics has been applied to many different types of applications including thin film analysis, sample texture evaluation, monitoring of crystalline phase and structure, and investigation of sample stress and strain.

AE8007 / Aircraft Materials



UNIT-2- MECHANICAL BEHAVIOUR OF MATERIALS

Linear and non linear elastic properties – Yielding, strain hardening, fracture, Bauginger’s effect –Notch effect testing and flaw detection of materials and components – creep and fatigue -comparative study of metals, ceramics plastics and composites.

Elastic deformation:

When the stress is removed, the material returns to the dimension it had before the load was applied. Valid for small strains (except the case of rubbers). Deformation is *reversible, non permanent*

Plastic deformation:

When the stress is removed, the material does not return to its previous dimension but there is a *permanent, irreversible* deformation.

In tensile tests, if the deformation is *elastic*, the stress-strain relationship is called Hooke's law:

$$\sigma = E \varepsilon$$

That is, E is the slope of the stress-strain curve. E is *Young's modulus* or *modulus of elasticity*. In some cases, the relationship is not linear so that E can be defined alternatively as the local slope:

$$E = d\sigma/d\varepsilon$$

Shear stresses produce strains according to:

$$\tau = G \gamma$$

where G is the *shear modulus*. Elastic moduli measure the *stiffness* of the material. They are related to the *second* derivative of the interatomic potential, or the first derivative of the force vs. inter nuclear distance. By examining these curves we can

tell which material has a higher modulus. Due to thermal vibrations the elastic modulus decreases with temperature. E is large for ceramics (stronger ionic bond) and small for polymers (weak covalent bond). Since the interatomic distances depend on direction in the crystal, E depends on direction (i.e., it is anisotropic) for single crystals. For *randomly* oriented polycrystals, E is isotropic.

Yield criteria and macroscopic aspects of plastic deformation

Gross plastic deformation of a polycrystalline specimen corresponds to the comparable distortion of the individual grains by means of slip. During deformation, mechanical integrity and coherency are maintained along the grain boundaries; that is, the grain boundaries is constrained, to some degree, in the shape it may assume by its neighboring grains. Before deformation the grains are equiaxed, or have approximately the same dimension in all directions. For this particular deformation, the grains become elongated along the directions. For this particular deformation, the grains become elongated along the direction in which the specimen was extended.

Tensile Properties

Yield point. If the stress is too large, the strain deviates from being proportional to the stress. The point at which this happens is the *yield point* because there the material yields, deforming permanently (plastically).

Yield stress. Hooke's law is not valid beyond the yield point. The stress at the yield point is called *yield stress*, and is an important measure of the mechanical properties of materials. In practice, the yield stress is chosen as that causing a permanent strain of 0.002 *The yield stress measures the resistance to plastic deformation.* The reason for plastic deformation, in normal materials, is not that the atomic bond is stretched beyond repair, but the motion of dislocations, which involves breaking and reforming bonds. *Plastic deformation is caused by the motion of dislocations.*

Tensile strength: When stress continues in the plastic regime, the stress-strain passes through a maximum, called the *tensile strength*, and then falls as the material starts to develop a *neck* and it finally breaks at the *fracture point*.

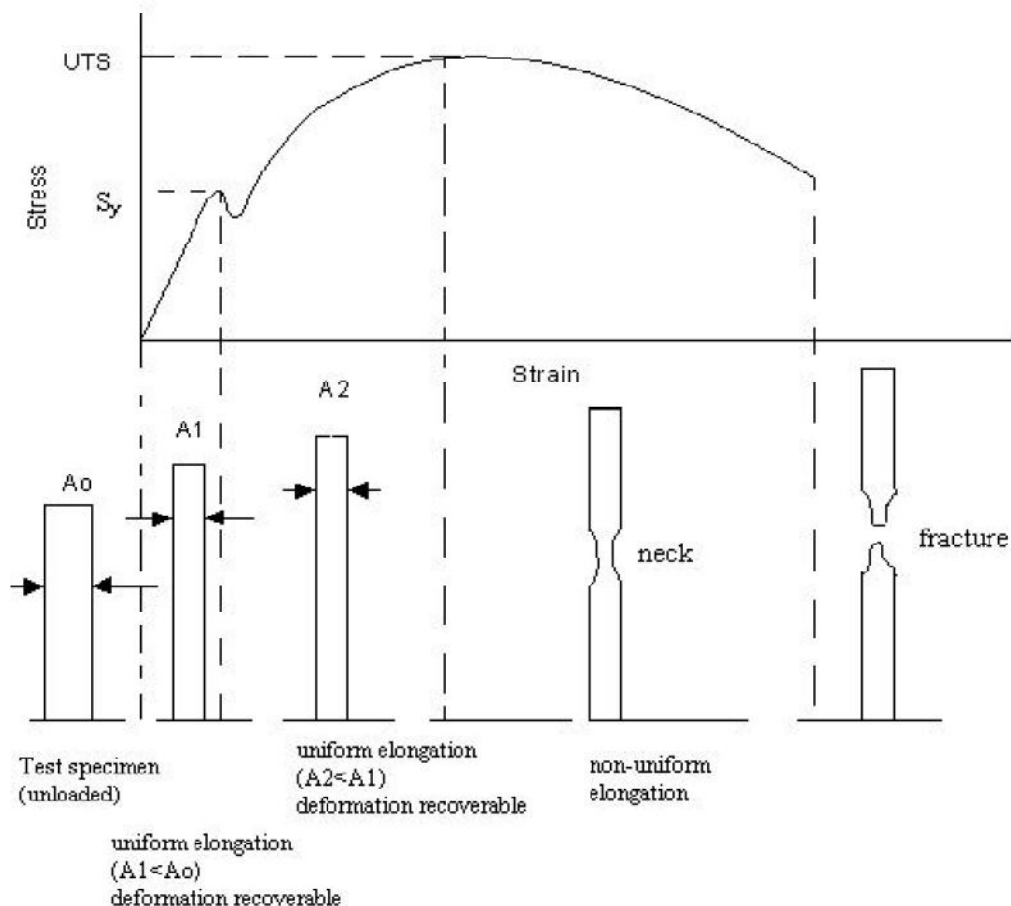
For structural applications, the yield stress is usually a more important property than the tensile strength, since once it is passed, the structure has deformed beyond acceptable limits.

Ductility: The ability to deform before breaking. It is the opposite of **brittleness**. Ductility can be given either as percent maximum elongation \hat{a}_{max} or maximum area reduction.

$$\%EL = \hat{a}_{max} \times 100 \%$$

$$\%AR = (A_0 - A_f)/A_0$$

Stress-Strain curve (Mild Steel)



Resilience: Capacity to absorb energy *elastically*. The energy per unit volume is the *area under the strain-stress curve in the elastic region*.

Toughness: Ability to absorb energy up to fracture. The energy per unit volume is the *total area under the strain-stress curve*. It is measured by an impact test.

True Stress and Strain

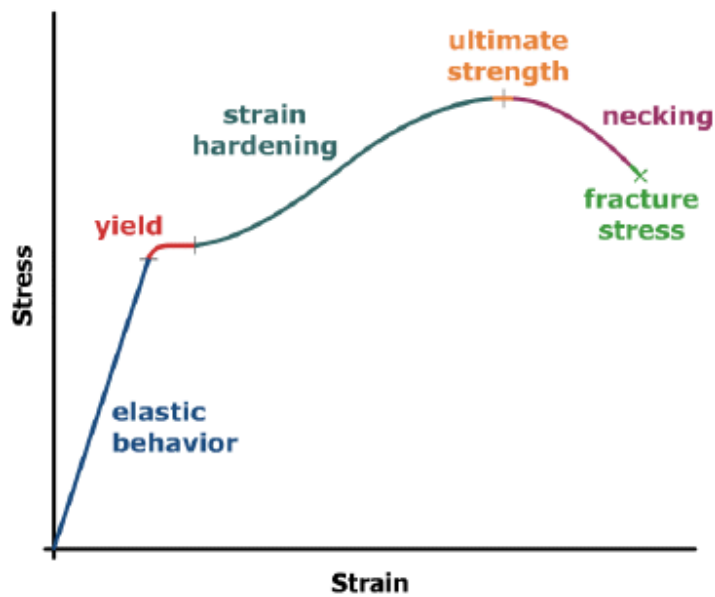
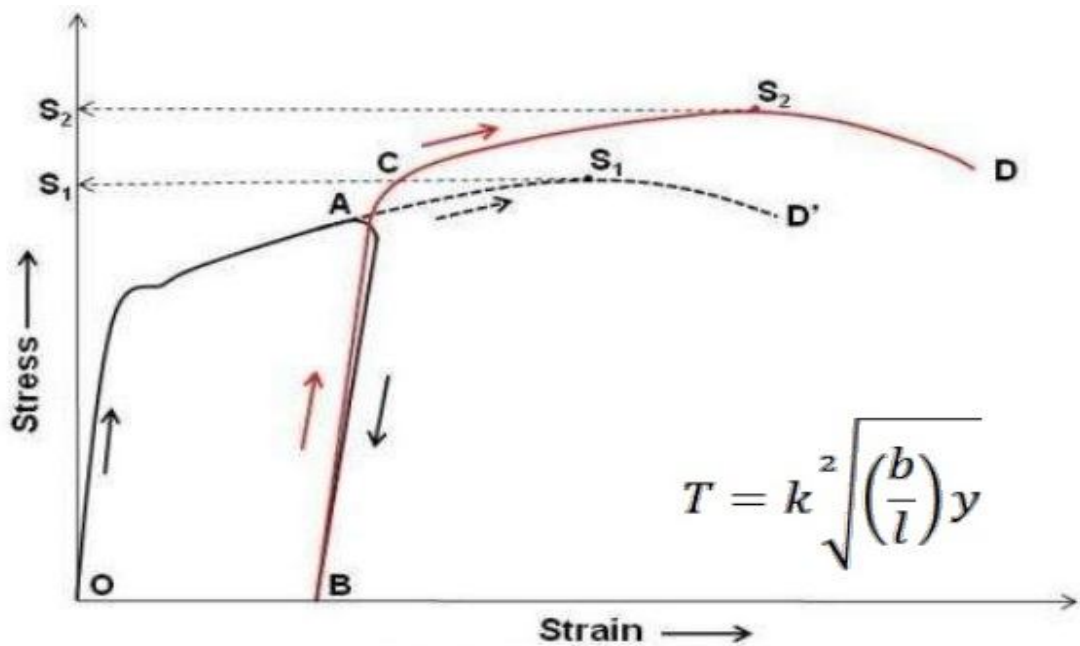
When one applies a constant tensile force the material will break after reaching the tensile strength. The material starts necking (the transverse area decreases) but the stress cannot increase beyond tensile strength. The ratio of the force to the initial area, what we normally do, is called the engineering stress. If the ratio is to the actual area (that changes with stress) one obtains the *true stress*.

Yield criteria and macroscopic aspects of plastic deformation

Gross plastic deformation of a polycrystalline specimen corresponds to the comparable distortion of the individual grains by means of slip. During deformation, mechanical integrity and coherency are maintained along the grain boundaries; that is, the grain boundaries is constrained, to some degree, in the shape it may assume by its neighboring grains. Before deformation the grains are equiaxed, or have approximately the same dimension in all directions. For this particular deformation, the grains become elongated along the directions. For this particular deformation, the grains become elongated along the direction in which the specimen was extended.

Strain Hardening

Phenomenon where ductile metals become stronger and harder when they are deformed plastically is called strain hardening or work hardening. Increasing temperature lowers the rate of strain hardening. Hence materials are strain hardened at low temperatures, thus also called cold working. During plastic deformation, dislocation density increases. And thus their interaction with each other resulting in increase in yield stress. Strain hardening (work hardening) is the reason for the elastic recovery. The reason for strain hardening is that the dislocation density increases with plastic deformation (cold work) due to multiplication. The average distance between dislocations then decreases and dislocations start blocking the motion of each one



Strain hardening (also called cold working) is an important strengthening process for aerospace alloys that involves plastically deforming the material during manufacturing to greatly increase the number of dislocations. During manufacture the metal is deformed into the final component shape (e.g. flat or curved skin panel, cylindrical landing gear strut) by forming processes such as rolling, forging, and extrusion (which are described in chapter 7). The metal must be plastically

deformed to permanently change shape, and this deformation creates dislocations which increase the strength.

Bauschinger effect

The Bauschinger effect refers to a property of materials where the material's stress/strain characteristics change as a result of the microscopic stress distribution of the material. For example, an increase in tensile yield strength occurs at the expense of compressive yield strength. The effect is named after German engineer Johann Bauschinger.

While more tensile cold working increases the tensile yield strength, the local initial compressive yield strength after tensile cold working is actually reduced. The greater the tensile cold working, the lower the compressive yield strength.

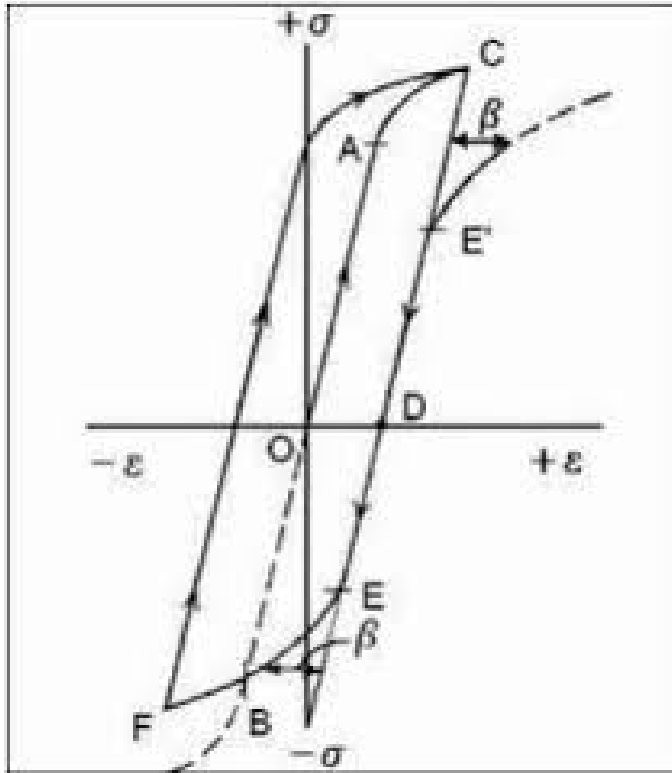
The Bauschinger effect is normally associated with conditions where the yield strength of a metal decreases when the direction of strain is changed. It is a general phenomenon found in most polycrystalline metals. The basic mechanism for the Bauschinger effect is related to the dislocation structure in the cold worked metal. As deformation occurs, the dislocations will accumulate at barriers and produce dislocation pile-ups and tangles. Based on the cold work structure, two types of mechanisms are generally used to explain the Bauschinger effect.

Region OA -This region is Elastic Region in tension. Within this region, if we unload the material it will follow the same path in the reverse direction i. e. From A to O.

Region OB- This region is Elastic Region in compression. Within this region, if we unload the material it will follow the same path in the reverse direction i.e. From B to O.

Region AC- Due to increase in load, tensile stresses overcome the bond strength. Dislocation starts moving towards grain boundary. Material starts yielding due to movement of these dislocations. Accumulation of dislocations near grain boundary creates a back pressure, because same type of dislocations repel each other.

Region CD- Immediate unloading will take curve from C to D. Elastic recovery takes place in this region. Length OD represents the permanent deformation of material.



Region DE- Compression of material takes place from D to E.

Region EB- As in case of tension, back pressure opposes the movement of dislocations i. e. this back pressure resists the tensile load. Same back pressure will now assist the compressive load. Due to combined effect of compression and this back pressure, a curvature is observed from D to Z.

Region EF- Due to further increase in compressive load, material starts yielding in compression. Again a back pressure is created. Now this back pressure will resist the compressive load but will assist the tensile load.

Region FG - Represents removal of compressive load.

Region GA- Again we apply a tensile load.

Failure

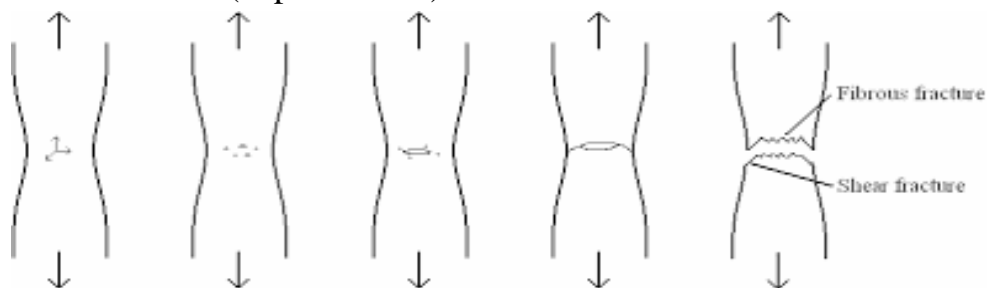
Fundamentals of Fracture

Fracture is a form of failure where the material separates in pieces due to stress, at temperatures below the melting point. The fracture is termed ductile or brittle depending on whether the elongation is large or small. Steps in fracture (response to stress):

- Crack formation
- Crack propagation

Ductile Fracture

- Stages of ductile fracture
- Initial necking
- Small cavity formation (micro voids)
- Void growth (ellipsoid) by coalescence into a crack
- Fast crack propagation around neck. Shear strain at 45°
- Final shear fracture (cup and cone)

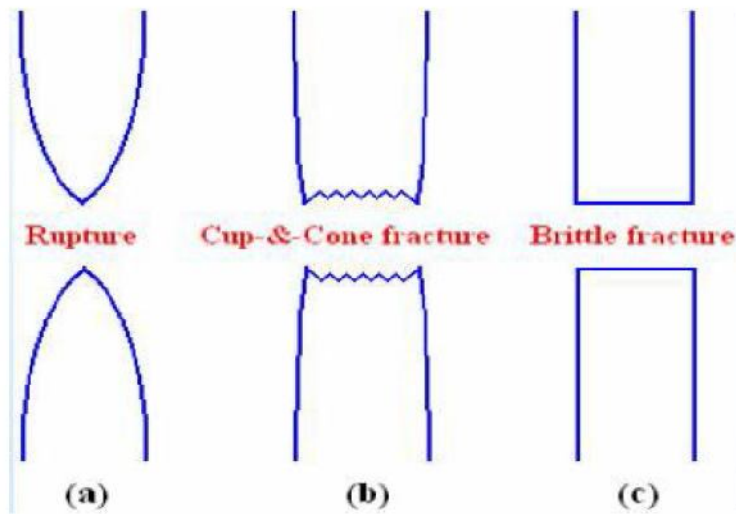


The interior surface is fibrous, irregular, which signify plastic deformation.

Brittle Fracture

There is no appreciable deformation, and crack propagation is very fast. In most brittle materials, crack propagation (by bond breaking) is along specific crystallographic planes (*cleavage* planes). This type of fracture is transgranular (through grains) producing grainy texture (or faceted texture) when cleavage direction changes from grain to grain. In some materials, fracture is intergranular.

Fracture occurs due to *stress concentration* at flaws, like surface scratches, voids,



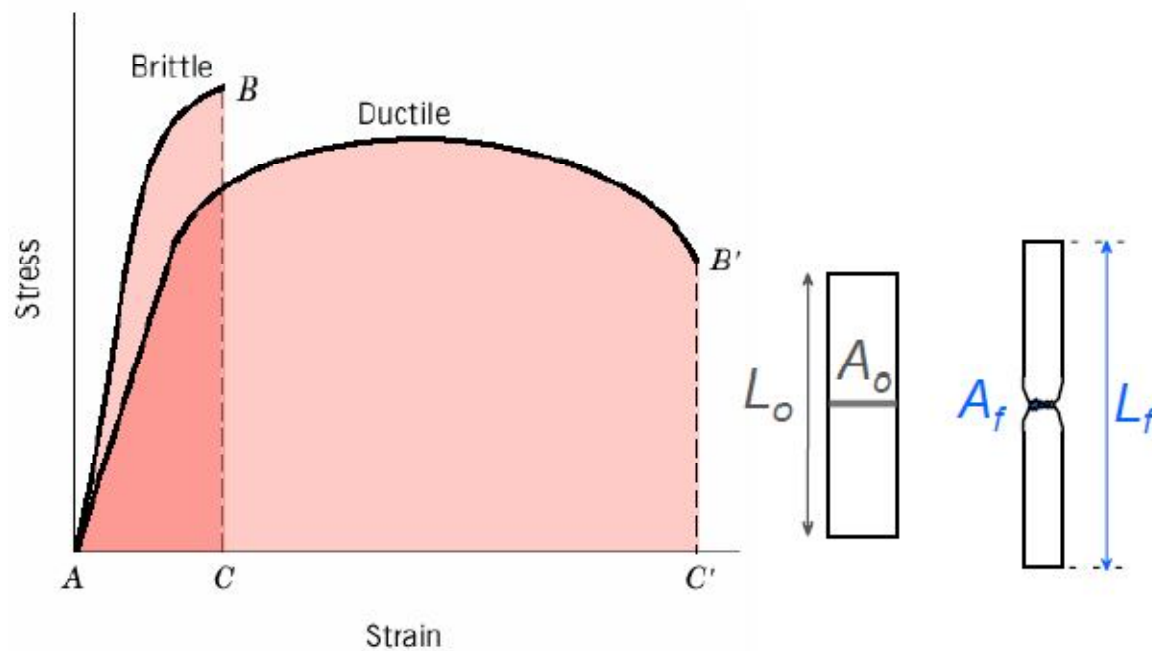
Parameter	Ductile fracture	Brittle fracture
Strain energy required	Higher	Lower
Stress, during cracking	Increasing	Constant
Crack propagation	Slow	Fast
Warning sign	Plastic deformation	None
Deformation	Extensive	Little
Necking	Yes	No
Fractured surface	Rough and dull	Smooth and bright
Type of materials	Most metals (not too cold)	Ceramics, Glasses, Ice

Ductile brittle transition

Ductile to brittle transition occurs in materials when the temperature is dropped below a *transition temperature*. Alloying usually increases the ductile-brittle

transition temperature, for ceramics, this type of transition occurs at much higher temperatures than for metals.

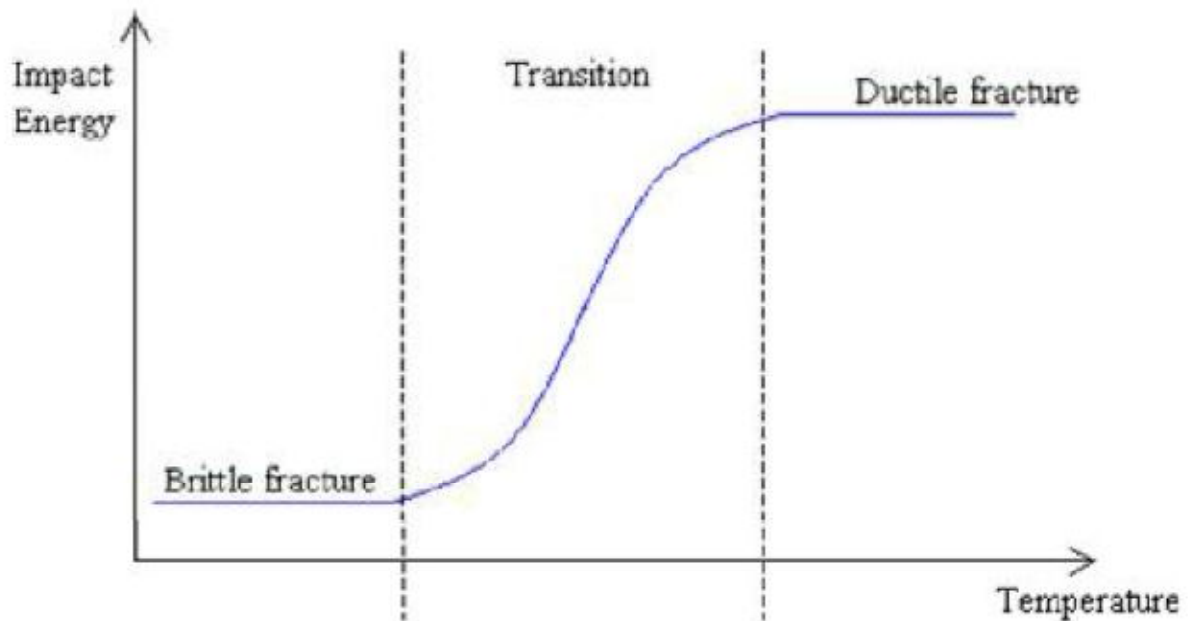
The notched-bar impact test can be used to determine whether or not a material experiences a ductile-to-brittle transition as the temperature is decreased. In such a transition, at higher temperatures the impact energy is relatively large since the fracture is ductile. As the temperature is lowered, the impact energy drops over a narrow temperature range as the fracture becomes more brittle.



The transition can also be observed from the fracture surfaces, which appear fibrous or dull for totally ductile fracture, and granular and shiny for totally brittle fracture. Over the ductile-to brittle transition features of both types will exist.

While for pure materials the transition may occur very suddenly at a particular temperature, for many materials the transition occurs over a range of temperatures. This causes difficulties when trying to define a single transition temperature and no specific criterion has been established.

The ductile-brittle transition is exhibited in bcc metals, such as low carbon steel, which become brittle at low temperature or at very high strain rates. Fcc metals, however, generally remain ductile at low temperatures.



Fatigue:

Fatigue is the catastrophic failure due to dynamic (fluctuating) stresses. It can happen in bridges, airplanes, machine components, etc. The characteristics are: • long period of cyclic strain

- the most usual (90%) of metallic failures (happens also in ceramics and polymers)
- is brittle-like even in ductile metals, with little plastic deformation
- it occurs in stages involving the initiation and propagation of cracks.

Cyclic Stresses

These are characterized by *maximum*, *minimum* and *mean stress*, *the stress amplitude*, and the *stress ratio*.

Crack Initiation and Propagation

Stages is fatigue failure:

- I. crack initiation at high stress points (stress raisers)
- II. propagation (incremental in each cycle)

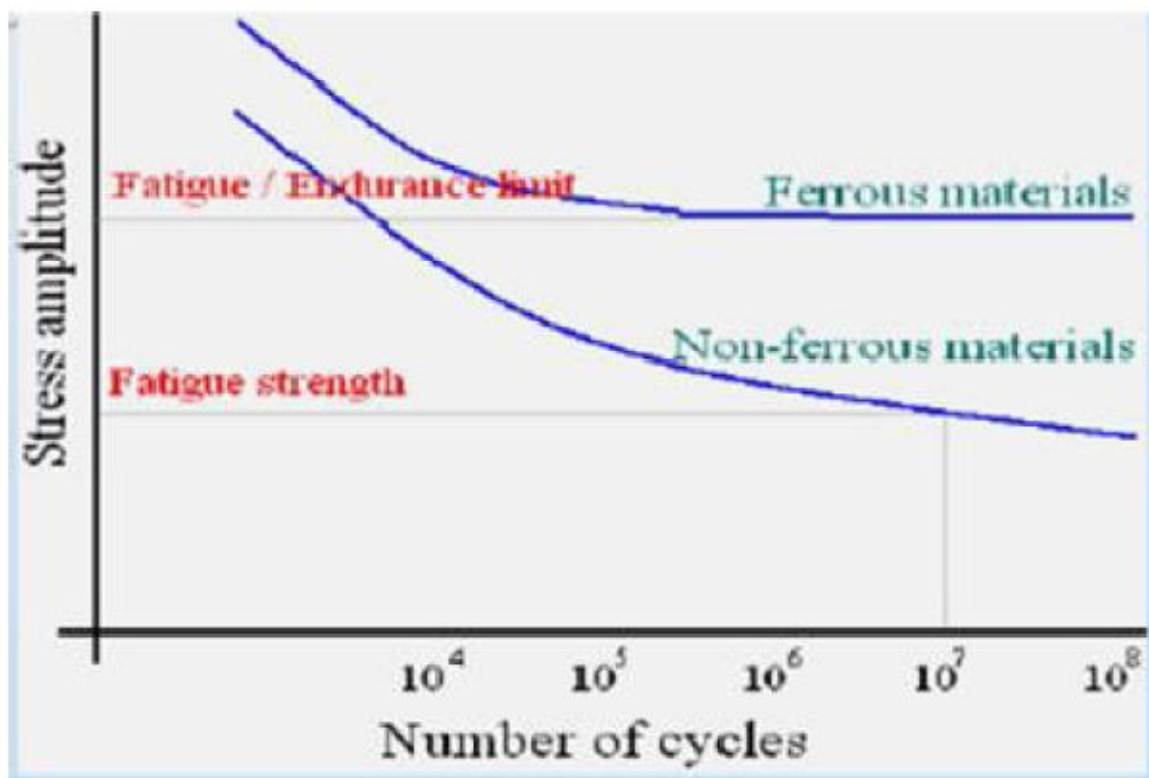
III. final failure by fracture

Stage I - propagation

- slow
- along crystallographic planes of high shear stress
- flat and featureless fatigue surface

Stage II - propagation

Crack propagates by repetitive plastic blunting and sharpening of the crack tip.



Creep

Creep is the time-varying plastic deformation of a material stressed at high temperatures.

Examples: turbine blades, steam generators. Keys are the time dependence of the strain and the high temperature.

The Creep Curve

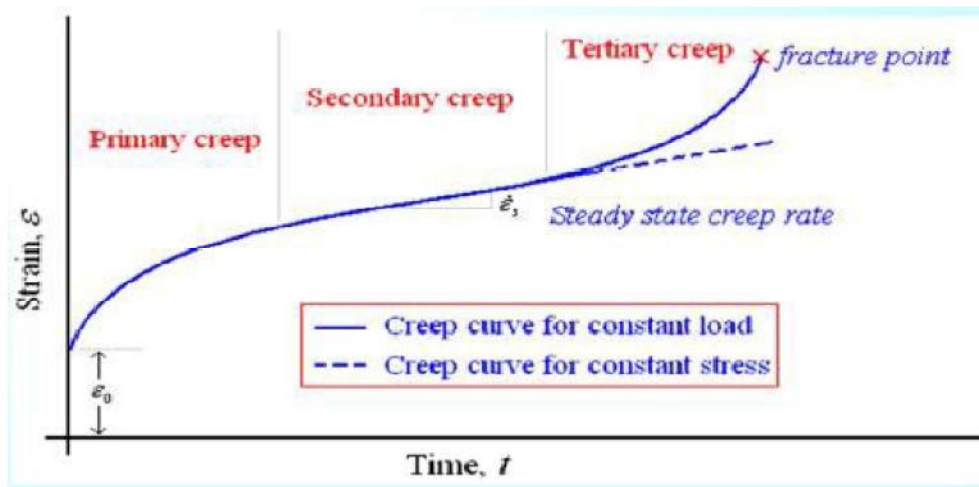
Creep in metals is defined as time dependent plastic deformation at constant stress (or load) and temperature. The form of a typical creep curve of strain versus time is in Figure. The slope of this curve is the **creep rate** $d\varepsilon / dt$. The curve may show the instantaneous elastic and plastic strain that occurs as the load is applied, followed by the plastic strain which occurs over time. Three stages to the creep curve may be identified:

Primary creep: in which the creep resistance increases with strain leading to a decreasing creep strain rate.

Secondary (Steady State) creep: in which there is a balance between work hardening and recovery processes, leading to a minimum constant creep rate.

Tertiary creep: in which there is an accelerating creep rate due to the accumulating damage, which leads to creep rupture, and which may only be seen at high temperatures and stresses and in constant load machines.

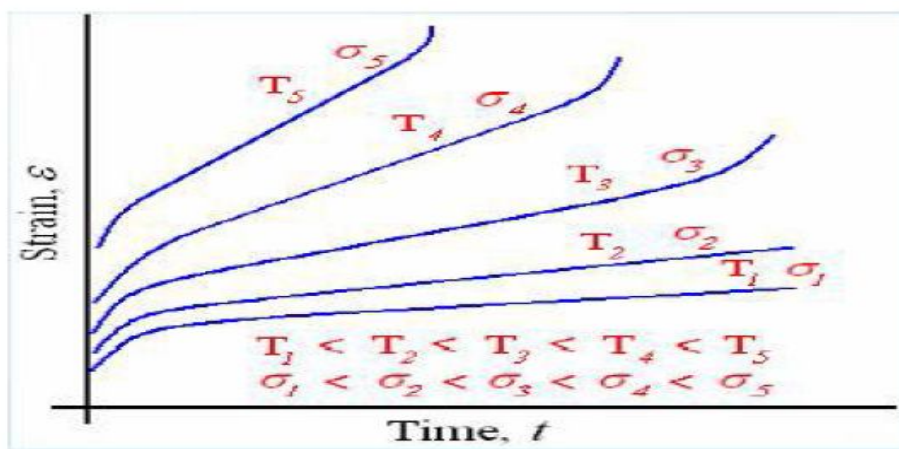
The minimum secondary creep rate is of most interest to design engineers, since failure avoidance is required and in this region some predictability is possible. In the USA two Standards are commonly used: (i) The stress to produce a creep rate of 0.0001% per hour (1% in 10,000 hours). (ii) The stress to produce a creep rate of 0.00001% per hour (1% in 100,000 hours or approximately 11.5 years). The first requirement would be typical of that for gas turbine blades, while the second for steam turbines. Constant load machines simulate real engineering situations more accurately, but as the specimen extends its cross section area reduces, leading to a rising stress. Machines designed to reduce the load to compensate for the reduced area and maintain constant stress may produce an extended steady state region.



Stress and Temperature Effects

Both temperature and the level of the applied stress influence the creep characteristics. The results of creep rupture tests are most commonly presented as the logarithm of stress versus the logarithm of rupture lifetime. Creep becomes more pronounced at higher temperatures. There is essentially no creep at temperatures below 40% of the melting point. Creep increases at higher applied stresses. The behavior can be characterized by the following expression, where K , n and Q_c are constants for a given material:

$$d\varepsilon/dt = K \sigma^n \exp(-Q_c/RT)$$



Impact Fracture:

Impact fractures can best be described as a flute or strip of material that was cleanly sheared from a projectile point. The most common type of impact fracture starts at the tip of a point and runs down one blade edge possibly reaching the shoulder of a point. Some points were reworked into a useable point after having been damaged by an impact fracture. Normalized tests, like the

Charpy and Izod tests measure the *impact energy* required to fracture a notched specimen with a hammer mounted on a pendulum. The energy is measured by the change in potential energy (height) of the pendulum. This energy is called ***notch toughness***.

Non-Destructive testing (NDT)

NDT is the method of detection and measurement of properties or condition of materials, structures, machines without damaging or destroying their operational capabilities. Examples of

NDT are: **magnetic dust method, penetrating liquid method, ultrasonic test and radiography**. All NDTs are used to detect various types of flaws on the surface of material or internal inclusions of impurities and these techniques are also very useful during preventive maintenance and repair. There are few techniques which do not require any special apparatus and are quite simple to handle and only a moderate skill being required. Some of the applications of

NDTs are detecting: (i) surface cracks (ii) material composition (iii) internal inclusions (iv) internal voids and discontinuities and (v) condition of internal stresses.

Ultrasonic Test

High frequency ultrasonic (sound) waves are applied to the test piece by a Piezoelectric crystal. If the test piece is free from cracks, or flawless, then it reflects ultrasonic waves without distortion. If there are any flaws in the specimen, the time taken by the ultrasonic waves will be less as the reflection of these waves will be from flaw points and not from the bottom of the specimen. Cathode ray

oscilloscope (CRO) is used to receive the sound signals, whose time base circuit is connected to it. Knowing the time interval between the transmission of the sound pulse and the reception of the echo signal, we can calculate the depth of the crack. This test is a very fast method of inspection and often used to test aerospace components and automobiles. This test is generally used to detect internal cracks like shrinkage cavities, hot tears, zones of corrosion and non-metallic inclusions.

Liquid-Penetration test

This test is employed for detection of small defects which are very small to detect with the naked eye. This test is used to detect surface cracks or flaws in non-ferrous metals. This test employs a visible colour contrast dye penetrant technique for the detection of open surface flaws in metallic and non-metallic objects. The penetrants are applied by spraying over the surface of material to be inspected. The excess penetrant is then washed or cleaned. Absorbent powder is then applied to absorb the penetrants in the cracks, voids which reveals the flaws. This test reveals flaws such as shrinkage cracks, porosity, fatigue cracks, grinding cracks, forging cracks, seams, heat treatment cracks and leaks etc., on castings, weldings, machined parts, cutting tools, pipes and tubes. If the fluorescent penetrant is used, the developed surface must be examined under ultra violet light to see the presence of defects. This technique is used for non-porous and nonabsorbent materials. Care may be taken to clean the surface so that it is free from dust, scale, etc. to have better results. Penetrants are highly toxic and flammable and hence proper precautions should be taken both during use and of storage of penetrants.

Microstructural Exam

Microstructure is defined as the structure of a prepared surface or thin foil of material as revealed by a microscope above 25× magnification. The microstructure of a material can strongly influence physical properties such as strength, toughness, ductility, hardness, corrosion resistance, high/low temperature behavior, wear resistance, and so on, which in turn govern the application of these materials in industrial practice.

a) Sectioning and cutting

The areas of interest forming the metallography specimens need to be sectioned for ease of handling. Depending on the type of material, the sectioning operation can be done by using abrasive cutter (for metal and metallic composite), diamond wafer cutter (ceramics, electronics and minerals) or thin sectioning with a microtome (plastics). In order not to damage the specimen, proper cutting requires the correct selection of abrasive cutting wheel, proper cutting speed & cutting load and the use of coolant.

b) Mounting

The mounting operation accomplishes three important functions:

1. To protect the specimen edge and maintain the integrity of materials surface features.
2. Fill voids in porous materials.
3. Improves handling of irregular shaped samples.

Samples for microstructure evaluation are typically encapsulated in a plastic mount for handling during sample preparation. Large sample or samples for macrostructure evaluation can be prepared without mounting.

The metallography specimen mounting is done by encapsulating the specimen into:

1. A compression/hot mounting compound (thermosets – e.g. phenolics, epoxies or thermoplastics – e.g. acrylics)
2. A castable resin/cold mounting (e.g. acrylics resins, epoxy resins and polyester resins)

c) Grinding

Grinding is required to ensure the surface is flat & parallel and to reduce the damage created during sectioning. Grinding is accomplished by decreasing the abrasive grit size sequentially to obtain the required fine surface finish prior to polishing. It is important to note that the final appearance of the prepared surface is dependent on the machine parameters such as grinding/polishing pressure, relative velocity distribution and the direction of grinding/polishing.

d) Polishing

For microstructure examination a mirror/reflective finish is needed whereas a finely ground finish is adequate for macrostructure evaluation. Polishing can be divided into two main steps:

1. Rough polishing

The purpose is to remove the damage produced during grinding. Proper polishing will maintain the specimen flatness and retain all inclusions or secondary phases by eliminating the previous damage and maintaining the specimen integrity.

2. Fine polishing

The purpose is to remove only surface damage.

e) Etching

Etchants are specially formulated for the specific material and evaluation objectives. Etching alters the micro structural features based on composition; stress or crystal structure and it will develop the surface topology, which can be visible in the microscope. Typically, chemical etching involve immersing the polished surface in the prepared chemical solution for a specified time (usually seconds) followed by rinsing the etched specimen under running tap water and drying.

f) Microscopic Analysis

For microscopic analysis, a reflective surface is required. The analysis can be done by using a metallurgy microscope.

UNIT-3 CORROSION & HEAT TREATMENT OF METALS AND ALLOYS

Types of corrosion – effect of corrosion on mechanical properties – stress corrosion cracking – corrosion resistance materials used for space vehicles heat treatment of carbon steels – aluminium alloys, magnesium alloys and titanium alloys – effect of alloying treatment, heat resistance alloys – tool and die steels, magnetic alloys

CORROSION

Corrosion is the deterioration of materials by chemical interaction with their environment. The term corrosion is sometimes also applied to the degradation of plastics, concrete and wood, but generally refers to metals. The most widely used metal is iron (usually as steel) and the following discussion is mainly related to its corrosion.

THE CONSEQUENCES OF CORROSION

The consequences of corrosion are many and varied and the effects of these on the safe, reliable and efficient operation of equipment or structures are often more serious than the simple loss of a mass of metal. Failures of various kinds and the need for expensive replacements may occur even though the amount of metal destroyed is quite small. Some of the major harmful effects of corrosion can be summarised as follows:

1. Reduction of metal thickness leading to loss of mechanical strength and structural failure or breakdown. When the metal is lost in localised zones so as to give a crack-like structure, very considerable weakening may result from quite a small amount of metal loss.
2. Hazards or injuries to people arising from structural failure or breakdown (e.g. bridges, cars, aircraft).
3. Loss of time in availability of profile-making industrial equipment.
4. Reduced value of goods due to deterioration of appearance.
5. Contamination of fluids in vessels and pipes (e.g. beer goes cloudy when small quantities of heavy metals are released by corrosion).
6. Perforation of vessels and pipes allowing escape of their contents and possible harm to the surroundings. For example a leaky domestic radiator can

cause expensive damage to carpets and decorations, while corrosive sea water may enter the boilers of a powerstation if the condenser tubes perforate.

7. Loss of technically important surface properties of a metallic component. These could include frictional and bearing properties, ease of fluid flow over a pipe surface, electrical conductivity of contacts, surface reflectivity or heat transfer across a surface.
8. Mechanical damage to valves, pumps, etc, or blockage of pipes by solid corrosion products.
9. Added complexity and expense of equipment which needs to be designed to withstand a certain amount of corrosion, and to allow corroded components to be conveniently replaced.

CLASSIFICATION OF CORROSION:

General Corrosion:	Localized Corrosion:	Metallurgically Influenced Corrosion:	Mechanically Assisted Degradation:	Environmentally Induced Cracking:
Corrosive attack dominated by uniform thinning <ul style="list-style-type: none"> • Atmospheric corrosion • Galvanic corrosion • Stray-current corrosion • General biological corrosion • Molten salt corrosion • Corrosion in liquid metals • High – temperature corrosion 	High rates of metal penetration at specific sites <ul style="list-style-type: none"> • Crevice corrosion • Filiform corrosion • Pitting corrosion • Localized biological corrosion 	Affected by alloy chemistry & heat treatment <ul style="list-style-type: none"> • Intergranular corrosion • Dealloying corrosion 	Corrosion with a mechanical component <ul style="list-style-type: none"> • Erosion corrosion • Fretting corrosion • Cavitation and water drop impingement • Corrosion fatigue 	Cracking produced by corrosion, in the presence of stress. <ul style="list-style-type: none"> • Stress – Corrosion Cracking (SCC) • Hydrogen Damage • Liquid metal embrittlement • Solid metal induced embrittlement

CORROSION PREVENTION

By retarding either the anodic or cathodic reactions the rate of corrosion can be reduced. This can be achieved in several ways:

1. Conditioning the Metal

This can be sub-divided into two main groups:

(a) Coating the metal, in order to interpose a corrosion resistant coating between metal and environment. The coating may consist of:

- I. another metal, e.g. zinc or tin coatings on steel,
- II. a protective coating derived from the metal itself, e.g. aluminium oxide on “anodised” aluminium,

III. organic coatings, such as resins, plastics, paints, enamel, oils and greases.

The action of protective coatings is often more complex than simply providing a barrier between metal and environment. Paints may contain a corrosion inhibitor zinc coating in iron or steel confers cathodic protection.

(b) Alloying the metal to produce a more corrosion resistant alloy, e.g. stainless steel, in which ordinary steel is alloyed with chromium and nickel. Stainless steel is protected by an invisibly thin, naturally formed film of chromium sesquioxide Cr_2O_3 .

2. Conditioning the Corrosive Environment

(a) Removal of Oxygen

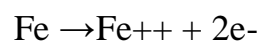
By the removal of oxygen from water systems in the pH range 6.5-8.5 one of the components required for corrosion would be absent. The removal of oxygen could be achieved by the use of strong reducing agents e.g. sulphite.

However, for open evaporative cooling systems this approach to corrosion prevention is not practical since fresh oxygen from the atmosphere will have continual access.

(b) Corrosion Inhibitors

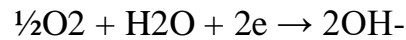
A corrosion inhibitor is a chemical additive, which, when added to a corrosive aqueous environment, reduces the rate of metal wastage. It can function in one of the following ways:

- (i) anodic inhibitors – as the name implies an anodic inhibitor interferes with the anodic process.



If an anodic inhibitor is not present at a concentration level sufficient to block off all the anodic sites, localised attack such as pitting corrosion can become a serious problem due to the oxidising nature of the inhibitor which raises the metal potential and encourages the anodic reaction (equation 1). Anodic inhibitors are thus classified as “dangerous inhibitors”. Other examples of anodic inhibitors include orthophosphate, nitrite, ferricyanide and silicates.

(ii) cathodic inhibitors – the major cathodic reaction in cooling systems is the reduction of oxygen.



There are other cathodic reactions and additives that suppress these reactions called cathodic inhibitors. They function by reducing the available area for the cathodic reaction. This is often achieved by precipitating an insoluble species onto the cathodic sites. Zinc ions are used as cathodic inhibitors because of the precipitation of $\text{Zn}(\text{OH})_2$ at cathodic sites as a consequence of the localised high pH. Cathodic inhibitors are classed as safe because they do

not cause localised corrosion.

(iii) adsorption type corrosion inhibitors – many organic inhibitors work by an adsorption mechanism. The resultant film of chemisorbed inhibitor is then responsible for protection either by physically blocking the surface from the corrosion environment or by retarding the electrochemical processes. The main functional groups capable of forming chemisorbed bonds with metal surfaces are amino ($-\text{NH}_2$), carboxyl ($-\text{COOH}$), and phosphonate ($-\text{PO}_3\text{H}_2$) although other functional groups or atoms can form co-ordinate bonds with metal surfaces.

(iv) mixed inhibitors – because of the danger of pitting when using anodic inhibitors alone, it became common practice to incorporate a cathodic inhibitor into formulated performance was obtained by a combination of inhibitors than from the sum of the individual performances. This observation is generally referred to a ‘synergism’ and demonstrates the synergistic action which exists between zinc and chromate ions.

3. Electrochemical Control

Since corrosion is an electrochemical process its progress may be studied by measuring the changes which occur in metal potential with time or with applied electrical currents. Conversely, the rate of corrosion reactions may be controlled by passing anodic or cathodic currents into the metal. If, for example, electrons are passed into the metal and reach the metal/electrolyte interface (a cathodic current) the anodic reaction will be stifled while the cathodic reaction rate increases. This

process is called cathodic protection and can only be applied if there is a suitable conducting medium such as earth or water through which a current can flow to the metal to be protected. In most soils or natural waters corrosion of steel is prevented if the potential of the metal surface is lowered by 300 or 400 mV. Cathodic protection may be achieved by using a DC power supply (impressed current) or by obtaining electrons from the anodic dissolution of a metal low in the galvanic series such as aluminium, zinc or magnesium (sacrificial anodes). Similar protection is obtained when steel is coated with a layer of zinc. Even at scratches or cut edges where some bare metal is exposed the zinc is able to pass protective current through the thin layer of surface moisture.

In certain chemical environments it is sometimes possible to achieve anodic protection, passing a current which takes electrons out of the metal and raises its potential. Initially this stimulates anodic corrosion, but in favourable circumstances this will be followed by the formation of a protective oxidised passive surface film.

Stress corrosion cracking

Stress corrosion cracking is cracking due to a process involving conjoint corrosion and straining of a metal due to residual or applied stresses

Corrosion can take many forms; the form that concerns us here is the interaction of corrosion and mechanical stress to produce a failure by cracking. This type of failure is known as stress corrosion cracking, often abbreviated to SCC

SCC is an insidious form of corrosion; it produces a marked loss of mechanical strength with little metal loss; the damage is not obvious to casual inspection and the stress corrosion cracks can trigger mechanical fast fracture and catastrophic failure of components and structures.

SCC is not an inevitable process, and for most metals in most environments it will not occur. We can therefore identify specific combinations of metal and environment that are subject to the problem. Unfortunately, of course, as time goes by we identify more and more such combinations, especially as engineers strive to use materials more efficiently by increasing working stresses and using less expensive materials.

Heat Treatment

Heat Treatment is the controlled heating and cooling of metals to alter their physical and mechanical properties without changing the product shape. Heat treatment is sometimes done inadvertently due to manufacturing processes that either heat or cool the metal such as welding or forming. Heat Treatment is often associated with increasing the strength of material, but it can also be used to alter certain manufacturability objectives such as improve machining, improve formability, restore ductility after a cold working operation. Thus it is a very enabling manufacturing process that can not only help other manufacturing process, but can also improve product performance by increasing strength or other desirable characteristics.

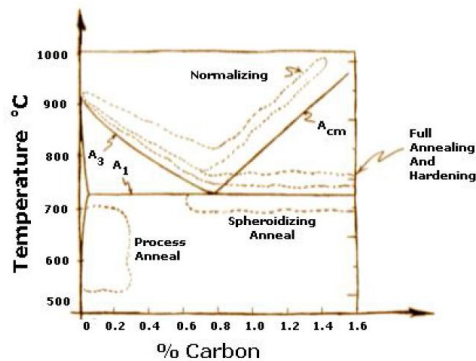
Steels are particularly suitable for heat treatment, since they respond well to heat treatment and the commercial use of steels exceeds that of any other material. Steels are heat treated for one of the following reasons:

1. Softening
2. Hardening
3. Material modification

Softening: Softening is done to reduce strength or hardness, remove residual stresses, improve toughness, restore ductility, refine grain size or change the electromagnetic properties of the steel. Restoring ductility or removing residual stresses is a necessary operation when a large amount of cold working is to be performed, such as in a cold-rolling operation or wire drawing. Annealing — full Process, spheroidizing, normalizing and tempering austempering, martempering are the principal ways by which steel is softened.

Hardening: Hardening of steels is done to increase the strength and wear properties. One of the pre-requisites for hardening is sufficient carbon and alloy content. If there is sufficient Carbon content then the steel can be directly hardened. Otherwise the surface of the part has to be Carbon enriched using some diffusion treatment hardening techniques.

Material Modification: Heat treatment is used to modify properties of materials in addition to hardening and softening. These processes modify the behavior of the steels in a beneficial manner to maximize service life, e.g., stress relieving, or strength properties, e.g., cryogenic treatment, or some other desirable properties



HEAT TREATMENT PROCESS

Full annealing is the process of slowly raising the temperature about 50 °C (90 °F) above the Austenitic temperature line A₃ or line A_{cm} in the case of Hypoeutectoid steels (steels with <0.77% Carbon) and 50 °C (90 °F) into the Austenite-Cementite region in the case of Hypereutectoid steels (steels with > 0.77% Carbon).

It is held at this temperature for sufficient time for all the material to transform into Austenite or Austenite-Cementite as the case may be. It is then slowly cooled at the rate of about 20 °C/hr (36°F/hr) in a furnace to about 50 °C (90 °F) into the Ferrite-Cementite range. At this point, it can be cooled in room temperature air with natural convection. The grain structure has coarse Pearlite with ferrite or Cementite (depending on whether hypo or hyper eutectoid). The steel becomes soft and ductile.

Normalizing is the process of raising the temperature to over 60 °C (108 °F), above line A₃ or line A_{cm} fully into the Austenite range. It is held at this temperature to fully convert the structure into Austenite, and then removed from the furnace and cooled at room temperature under natural convection. This results in a grain structure of fine Pearlite with excess of Ferrite or Cementite.

The resulting material is soft; the degree of softness depends on the actual ambient conditions of cooling. This process is considerably cheaper than full annealing since there is not the added cost of controlled furnace cooling.

Process Annealing is used to treat work-hardened parts made out of low-Carbon steels (< 0.25% Carbon). This allows the parts to be soft enough to undergo further cold working without fracturing. Process annealing is done by raising the temperature to just below the Ferrite-Austenite region, line A₁ on the diagram. This

temperature is about 727 °C (1341 °F) so heating it to about 700 °C (1292 °F) should suffice. This is held long enough to allow recrystallization of the ferrite phase, and then cooled in still air. Since the material stays in the same phase throughout the process, the only change that occurs is the size, shape and distribution of the grain structure. This process is cheaper than either full annealing or normalizing since the material is not heated to a very high temperature or cooled in a furnace.

Stress Relief Anneal is used to reduce residual stresses in large castings, welded parts and cold formed parts. Such parts tend to have stresses due to thermal cycling or work hardening. Parts are heated to temperatures of up to 600 - 650 °C (1112 - 1202 °F), and held for an extended time (about 1 hour or more) and then slowly cooled in still air.

Tempering is a process done subsequent to quench hardening. Quench-hardened parts are often too brittle. This brittleness is caused by a predominance of Martensite. This brittleness is removed by tempering. Tempering results in a desired combination of hardness, ductility, toughness, strength, and structural stability. Tempering is not to be confused with tempering on rolled stock—these tempers are an indication of the degree of cold work performed.

The mechanism of tempering depends on the steel and the tempering temperature. The prevalent Martensite is a somewhat unstable structure. When heated, the Carbon atoms diffuse from Martensite to form a carbide precipitate and the concurrent formation of Ferrite and Cementite, which is the stable form. Tool steels for example, lose about 2 to 4 points of hardness on the

Rockwell C scale. Even though a little strength is sacrificed, toughness (as measured by impact strength) is increased substantially. Springs and such parts need to be much tougher — these are tempered to a much lower hardness.

Tempering is done immediately after quench hardening. When the steel cools to about 40 °C (104 °F) after quenching, it is ready to be tempered. The part is reheated to a temperature of 150 to 400 °C (302 to 752 °F). In this region a softer and tougher structure Troostite is formed.

Alternatively, the steel can be heated to a temperature of 400 to 700 °C (752 to 1292 °F) that results in a softer structure known as Sorbite. This has less strength than Troostite but more ductility and toughness. The heating for tempering is best done by immersing the parts in oil, for tempering up to 350 °C (662 °F) and then heating the oil with the parts to the appropriate temperature. Heating in a bath also ensures that the entire part has the same temperature and will undergo the same tempering. For temperatures above 350 °C (662 °F) it is best to use a bath of nitrate salts. The salt baths can be heated up to 625 °C (1157 °F). Regardless of the bath, gradual heating is important to avoid cracking the steel. After reaching the desired temperature, the parts are held at that temperature for about 2 hours, then removed from the bath and cooled in still air.

Hardening

Hardness is a function of the Carbon content of the steel. Hardening of a steel requires a change in structure from the body-centered cubic structure found at room temperature to the face-centered cubic structure found in the Austenitic region. The steel is heated to Austenitic region. When suddenly quenched, the Martensite is formed. This is a very strong and brittle structure. When slowly quenched it would form Austenite and Pearlite which is a partly hard and partly soft structure. When the cooling rate is extremely slow then it would be mostly Pearlite which is extremely soft.

Usually when hot steel is quenched, most of the cooling happens at the surface, as does the hardening. This propagates into the depth of the material. Alloying helps in the hardening and by determining the right alloy one can achieve the desired properties for the particular application.



AUSTENITE



MARTENSITE



CEMENTITE



PEARLITE
COARSE



PEARLITE
FINE

ALUMINIUM ALLOYS

- WROUGHT ALUMINIUM ALLOYS
 - Al-Zn-Mg-Cu superalloys and high-strength alloys
 - Long-life aluminium alloys
 - High-workable weldable corrosion-resistant aluminium alloys
 - Al-Li alloys with lowered density
 - Heat-resistant alloys
 - SiAl-type laminates

CASTABLE ALUMINIUM ALLOYS

- High strength castable aluminium alloys
- Castable heat-resistant aluminium alloys
- Weldable corrosion-resistant aluminium alloys

TITANIUM ALLOYS

- WROUGHT TITANIUM ALLOYS
 - Heat-resistant titanium alloys for GTE components
 - Structural titanium alloys
 - High strength structural titanium alloys
 - Intermetallic titanium alloys
- CASTABLE TITANIUM ALLOYS

- **MAGNESIUM ALLOYS**

- **WROUGHT MAGNESIUM ALLOYS**

- Medium-strength alloys
 - High-strength alloys
 - Granulated alloys
 - Heat-resistant alloy
 - Ultra-light alloys (alloys with lowered density)

- **CASTABLE MAGNESIUM ALLOYS**

- Mg–Zn–Zr High-strength alloys
 - Mg–Al–Zn corrosion-resistant alloys
 - Mg–REM–Zr heat-resistant alloys
 - Antiburining-on adding materials

Magnetic alloys and intermetallics are metallic materials capable of producing a constant magnetic field for a prolonged period of time. There are only a limited number of chemical elements that can produce alloys with permanent magnetic properties at ambient temperature; Fe, Ni, Co and rare earth metals are the most important ones.

1. Samarium-Cobalt Alloys
2. Aluminium-Nickel-Cobalt Alloys
3. Neodymium-Iron-Boron Alloys

Effects of Alloying Elements in Steel

Alloying elements are added to effect changes in the properties of steels. The basis of this section is to cover some of the different alloying elements added to the basic system of iron and carbon, and what they do to change the properties or effectiveness of steel.

Carbon

As I've already stated, the presence of carbon in iron is necessary to make steel. Carbon is essential to the formation of cementite (as well as other carbides), and to the formation of pearlite, spheroidite, bainite, and iron-carbon martensite, with martensite being the hardest of the micro-structures, and the structure sought after

by knifemakers. The hardness of steel (or more accurately, the hardenability) is increased by the addition of more carbon, up to about 0.65 percent. Wear resistance can be increased in amounts up to about 1.5 percent. Beyond this amount, increases of carbon reduce toughness and increase brittleness. The steels of interest to knifemakers generally contain between 0.5 and 1.5 percent carbon. They are described as follows:

- Low Carbon: Under 0.4 percent
- Medium Carbon: 0.4 - 0.6 percent
- High Carbon: 0.7 - 1.5 percent

Carbon is the single most important alloying element in steel.

Chromium

As with manganese, chromium has a tendency to increase hardness penetration. This element has many interesting effects on steel. When 5 percent chromium or more is used in conjunction with manganese, the critical quenching speed is reduced to the point that the steel becomes air hardening. Chromium can also increase the toughness of steel, as well as the wear resistance. Probably one of the most well known effects of chromium on steel is the tendency to resist staining and corrosion. Steels with 14 percent or more chromium are referred to as stainless steels. A more accurate term would be stain resistant. Stainless tool steels will in fact darken and rust, just not as readily as the non-stainless varieties. Steels with chromium also have higher critical temperatures in heat treatment.

Nickel

Nickel increases the strength of ferrite, therefore increasing the strength of the steel. It is used in low alloy steels to increase toughness and hardenability. Nickel also tends to help reduce distortion and cracking during the quenching phase of heat treatment.

Molybdenum

Molybdenum increases the hardness penetration of steel, slows the critical quenching speed, and increases high temperature tensile strength.

Vanadium

Vanadium helps control grain growth during heat treatment. By inhibiting grain growth it helps increase the toughness and strength of the steel.

Tungsten

Used in small amounts, tungsten combines with the free carbides in steel during heat treatment, to produce high wear resistance with little or no loss of toughness. High amounts combined with chromium gives steel a property known as red hardness. This means that the steel will not lose its working hardness at high temperatures. An example of this would be tools designed to cut hard materials at high speeds, where the friction between the tool and the material would generate high temperatures.

Copper

The addition of copper in amounts of 0.2 to 0.5 percent primarily improves steel's resistance to atmospheric corrosion. It should be noted that with respect to knife steels, copper has a detrimental effect to surface quality and to hot-working behavior due to migration into the grain boundaries of the steel.

Niobium

In low carbon alloy steels Niobium lowers the transition temperature and aids in a fine grain structure. Niobium retards tempering and can decrease the hardenability of steel because it forms very stable carbides. This can mean a reduction in the amount of carbon dissolved into the austenite during heat treating.

Boron

Boron can significantly increase the hardenability of steel without loss of ductility. Its effectiveness is most noticeable at lower carbon levels. The addition of boron is usually in very small amounts ranging from 0.0005 to 0.003 percent.

Titanium

This element, when used in conjunction with Boron, increases the effectiveness of the

Boron in the hardenability of steel.

UNIT-4 CERAMICS AND COMPOSITES

Introduction – powder metallurgy - modern ceramic materials – cermets - cutting tools – glass ceramic – production of semi fabricated forms - plastics and rubber – carbon/carbon composites, fabrication processes involved in metal matrix composites - shape memory alloys – applications in aerospace vehicle design, open and close mould processes.

Ceramic materials

An inorganic compound consisting of a metal (or semi-metal) and one or more nonmetals

Important examples: –Silica - silicon dioxide (SiO_2), the main ingredient in most glass products

–Alumina - aluminum oxide (Al_2O_3), used in various applications from abrasives to artificial bones –More complex compounds such as hydrous aluminum silicate ($\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$), the main ingredient in most clay products

Ceramic materials are inorganic, non-metallic materials made from compounds of a metal and a non metal. Ceramic materials may be crystalline or partly crystalline. They are formed by the action of heat and subsequent cooling. Clay was one of the earliest materials used to produce ceramics, as pottery, but many different ceramic materials are now used in domestic, industrial and building products. Ceramic materials tend to be strong, stiff, brittle, chemically inert, and non-conductors of heat and electricity, but their properties vary widely. For example, porcelain is widely used to make electrical insulators, but some ceramic compounds are superconductors.

A ceramic material may be defined as any inorganic crystalline material, compounded of a metal and a non-metal. It is solid and inert. Ceramic materials are brittle, hard, and strong in compression, weak in shearing and tension. They withstand chemical erosion that occurs in an acidic or caustic environment. In many cases withstanding erosion from the acid and bases applied to it. Ceramics generally can withstand very high temperatures such as temperatures that range from $1,000\text{ }^\circ\text{C}$ to $1,600\text{ }^\circ\text{C}$. Exceptions include inorganic materials that do not have oxygen such as silicon carbide. Glass by definition is not a ceramic because it is an amorphous solid (non-crystalline). However, glass involves several steps of the ceramic process and its mechanical properties behave similarly to ceramic materials.

Traditional ceramic raw materials include clay minerals such as kaolinite, more recent materials include aluminium oxide, more commonly known as alumina. The modern ceramic materials, which are classified as advanced ceramics, include silicon carbide and tungsten carbide. Both are valued for their abrasion resistance, and hence find use in applications such as the wear plates of crushing equipment in mining operations. Advanced ceramics are also used in the medicine, electrical and electronics industries.

IMPORTANT PROPERTIES

Ceramics can withstand high temperatures, are good thermal insulators, and do not expand greatly when heated. This makes them excellent thermal barriers, for applications that range from lining industrial furnaces to covering the space shuttle to protect it from high reentry temperatures.

Glasses are transparent, amorphous ceramics that are widely used in windows, lenses, and many other familiar applications. Light can induce an electrical response in some ceramics, called photoconductivity. Fiber optic cable is rapidly replacing copper for communications, as optical fibers can carry more information for longer distances with less interference and signal loss than traditional copper wires.

Ceramics are strong, hard, and durable. This makes them attractive structural materials. The one significant drawback is their brittleness, but this problem is being addressed by the development of new materials such as composites

Ceramics vary in electrical properties from excellent insulators to superconductors. Thus, they are used in a wide range of applications. Some are capacitors, others semiconductors in electronic devices. Piezoelectric materials can convert mechanical pressure into an electrical signal and are especially useful for sensors. There is now a strong research effort to discover new high T_c superconductors and to develop possible applications.

The processing of crystalline ceramics follows the basic steps that have been used for ages to make clay products. The materials are selected, prepared, formed into a desired shape, and sintered at high temperatures. Glasses are processed by pouring in a molten state, working into shape while hot, and then cooling. New methods such as chemical vapor deposition and sol-gel processing are presently being developed.

The diversity in their properties stems from their bonding and structure.

CLASSIFICATION

Ceramic materials can be divided into two classes: crystalline and amorphous (non-crystalline). In crystalline materials, a lattice point is occupied either by atoms or ions depending on the bonding mechanism. These atoms (or ions) are arranged in a regularly repeating pattern in three dimensions (i.e., they have long-range order). In contrast, in amorphous materials, the atoms exhibit only short-range order. Some ceramic materials, like silicon dioxide (SiO₂), can exist in either form. A crystalline form of SiO₂ results when this material is slowly cooled from a temperature ($T > T_{mp}$ @ 1723 °C). Rapid cooling favors non-crystalline formation since time is not allowed for ordered arrangements to form.

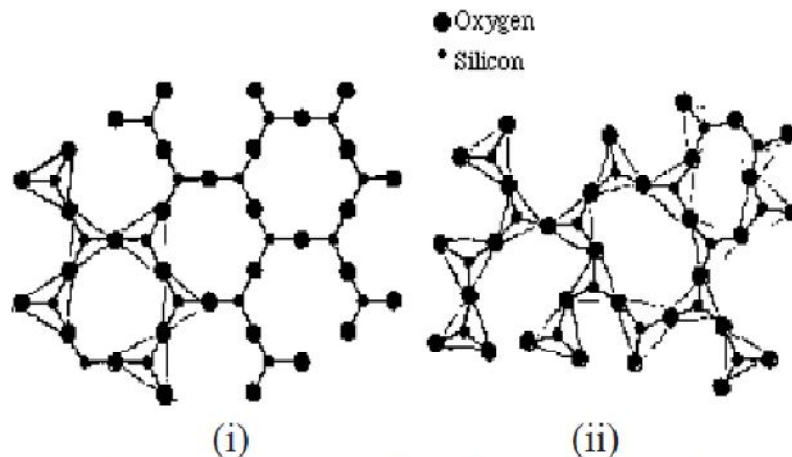


Figure 1: Comparison of physical structures of
 (i) crystalline silicon dioxide (regular pattern) and
 (ii) amorphous silicon dioxide (random pattern)

Properties of Ceramic Materials

- High hardness, electrical and thermal insulating, chemical stability, and high melting temperatures
- Brittle, virtually no ductility - can cause problems in both processing and performance of ceramic products
- Some ceramics are translucent, window glass (based on silica) being the clearest example

Ceramic materials developed synthetically over the last several decades

- The term also refers to improvements in processing techniques that provide greater control over structures and properties of ceramic materials
- In general, new ceramics are based on compounds other than variations of aluminum silicate, which form most of the traditional ceramic materials
- New ceramics are usually simpler chemically than traditional ceramics; for example, oxides, carbides, nitrides, and borides

Oxide Ceramics

- Most important oxide new ceramic is alumina
- Although also included as a traditional ceramic, alumina is today produced synthetically from bauxite, using an electric furnace method
- Through control of particle size and impurities, refinements in processing methods, and blending with small amounts of other ceramic ingredients, strength and toughness of alumina are improved substantially compared to its natural counterpart
- Alumina also has good hot hardness, low thermal conductivity, and good corrosion resistance

Products of Oxide Ceramics

- Abrasives (grinding wheel grit)
- Bioceramics (artificial bones and teeth)
- Electrical insulators and electronic components
- Refractory brick
- Cutting tool inserts
- Spark plug barrels
- Engineering components

Carbides

- Silicon carbide (SiC), tungsten carbide (WC), titanium carbide (TiC), tantalum carbide (TaC), and chromium carbide (Cr₃C₂)
- Although SiC is a man-made ceramic, its production methods were developed a century ago, and it is generally included in traditional ceramics group
- WC, TiC, and TaC are valued for their hardness and wear resistance in cutting tools and other applications requiring these properties
- WC, TiC, and TaC must be combined with a metallic binder such as cobalt or nickel in order to fabricate a useful solid product

Nitrides

- The important nitride ceramics are silicon nitride (Si₃N₄), boron nitride (BN), and titanium nitride (TiN)
- Properties: hard, brittle, high melting temperatures, usually electrically insulating, TiN being an exception

Applications:

- Silicon nitride: components for gas turbines, rocket engines, and melting crucibles
- Boron nitride and titanium nitride: cutting tool material and coatings

Glass

- A state of matter as well as a type of ceramic
- As a state of matter, the term refers to an amorphous (non-crystalline) structure of a solid material

The glassy state occurs in a material when insufficient time is allowed during cooling from the molten state for the crystalline structure to form

- As a type of ceramic, glass is an inorganic, nonmetallic compound (or mixture of compounds) that cools to a rigid condition without crystallizing
- Silica is the main component in glass products, usually comprising 50% to 75% of total chemistry
- It naturally transforms into a glassy state upon cooling from the liquid, whereas most ceramics crystallize upon solidification

Other Ingredients in Glass

- Sodium oxide (Na₂O), calcium oxide (CaO), aluminum oxide (Al₂O₃), magnesium oxide (MgO), potassium oxide (K₂O), lead oxide (PbO), and boron oxide (B₂O₃)

Functions:

- Act as flux (promoting fusion) during heating
- Increase fluidity in molten glass for processing
- Improve chemical resistance against attack by acids, basic substances, or water
- Add color to the glass
- Alter index of refraction for optical applications

Glass-Ceramics

A ceramic material produced by conversion of glass into a polycrystalline structure through heat treatment

- Proportion of crystalline phase range = 90% to 98%, remainder being unconverted vitreous material
- Grain size - usually between 0.1 - 1.0 μm (4 and 40μ-in), significantly smaller than the grain size of conventional ceramics
- This fine crystal structure makes glass-ceramics much stronger than the glasses from which they are derived
- Also, due to their crystal structure, glass-ceramics are opaque (usually grey or white) rather than clear

Processing of Glass Ceramics

- Heating and forming operations used in glass working create product shape
- Product is cooled and then reheated to cause a dense network of crystal nuclei to form throughout
 - High density of nucleation sites inhibits grain growth, leading to fine grain size
- Nucleation results from small amounts of nucleating agents in the glass composition, such as TiO₂, P₂O₅, and ZrO₂
- Once nucleation is started, heat treatment is continued at a higher temperature to cause growth of crystalline phases

Advantages of Glass-Ceramics

- Efficiency of processing in the glassy state
- Close dimensional control over final product shape
- Good mechanical and physical properties
 - High strength (stronger than glass)
 - Absence of porosity; low thermal expansion
 - High resistance to thermal shock
- Applications:
 - Cooking ware
 - Heat exchangers
 - Missile radomes

CERMET

A cermet is a composite material composed of ceramic (cer) and metal (met) materials.

A cermet is ideally designed to have the optimal properties of both a ceramic, such as high temperature resistance and hardness, and those of a metal, such as the ability to undergo plastic deformation. The metal is used as a binder for an oxide, boride, or carbide. Generally, the metallic elements used are nickel, molybdenum, and cobalt. Depending on the physical structure of the material, cermets can also be metal matrix composites, but cermets are usually less than 20% metal by volume.

Cermets are used in the manufacture of resistors (especially potentiometers), capacitors, and other electronic components which may experience high temperature.

Cermets are used instead of tungsten carbide in saws and other brazed tools due to their superior wear and corrosion properties. Titanium nitride (TiN), titanium carbonitride (TiCN), titanium carbide (TiC) and similar can be brazed like tungsten carbide if properly prepared however they require special handling during grinding.

Cermets are used in situations where neither metals nor ceramics alone would be ideal. For example, metal is not capable of resisting the heat produced in space rockets and airplane engines, although it is highly versatile. On the other hand, ceramics are excellent at withstanding extremely high temperatures. Additionally, ceramics are more resistant to chemical attacks and oxidation, which could lead to corrosion damage.

Therefore, industries that require materials with great strength and flexibility as well as resistance to high temperature often use cermets. In addition to benefits already mentioned, cermets also have high resistance to plastic deformation and impressive toughness.

Cermets play a vital role in the electronics industry because they can be applied in electrical components. Electronic elements may get very hot, so they must act like ceramics, but they also have to act as conductors of electricity. The most ideal applications of cermets are in vacuum tubes and resistors. Another application is in machine tools. For instance, a great number of drilling, boring, milling, turning and cutting tools are made of cermets.

Cermet's ability to reduce friction wear is highly notable. It can reduce friction in equipment parts as it behaves like a metal-ceramic conditioner in order to prevent corrosion and wear in machine parts

Cermet is a cutting tool material composed mainly of TiC (Titanium Carbide) and TiN (Titanium Nitride). Cutting performance is also in the mid-range of ceramic's and carbide's. The advantages

of this material grade are high-quality and excellent surface finishes can be achieved with elevated cutting speeds. Cermets provide extended tool life.

Features

High quality surface finish

The main components, TiC and TiN, have good BUE resistance as they have low affinity with work materials. Thus, machining with cermets brings high quality surface finish over extended periods of time.

High speed cutting

The main components, TiC and TiN, are more resistant to wear and oxidation at high temperature than WC (tungsten carbide), which is the main component of carbide tools. Because of excellent wear and oxidation resistance, cermet grades are less reactive with work materials and make stable high speed machining possible.

PLASTICS

Plastic is material consisting of any of a wide range of synthetic or semi-synthetic organic compounds that are malleable and so can be molded into solid objects.

Plasticity is the general property of all materials which can deform irreversibly without breaking but, in the class of moldable polymers, this occurs to such a degree that their actual name derives from this specific ability.

Plastics are typically organic polymers of high molecular mass and often contain other substances. They are usually synthetic, most commonly derived from petrochemicals, however, an array of variants are made from renewable materials such as polylactic acid from corn or cellulosic from cotton linters.

Natural plastics - these are naturally occurring materials that can be said to be plastics because they can be shaped and moulded by heat. An example of this is amber, which is a form of fossilised pine tree resin and is often used in jewellery manufacture.

Semi synthetic plastics - these are made from naturally occurring materials that have been modified or changed but mixing other materials with them. An example of this is cellulose acetate, which is a reaction of cellulose fibre and acetic acid and is used to make cinema film.

Synthetic plastics - these are materials that are derived from breaking down, or 'cracking' carbon based materials, usually crude oil, coal or gas, so that their molecular structure changes. This is generally done in petrochemical refineries under heat and pressure, and is the first of the manufacturing processes that is required to produce most of our present day, commonly occurring plastics.

Synthetic and semi synthetic plastics can be further divided into two other categories. These two categories are defined by the ways in which different plastics react when heated.

Thermoplastics - these are plastics that can be softened and formed using heat, and when cool, will take up the shape that they have been formed into.

But if heat is reapplied they will soften again. Examples of thermoplastics are acrylic and styrene, probably the most common plastics found in school workshops.

Thermosetting plastics - these are plastics that soften when heated, and can be moulded when soft, and when cool they will set into the moulded shape. But if heat is reapplied they will not soften again, they are permanently in the shape that they have been moulded into. Why this happens we will look at later. Examples of thermosetting plastics are polyester resins used in glass reinforced plastics work, and melamine formaldehyde used in the manufacture of Formica for kitchen work surfaces.

'Polymers' is a general term for all plastic materials and means that they are organic, carbon based compounds whose molecules are linked together in long chain patterns. Later on in this book we will look more closely at the molecular structure of plastics so that we can understand how we can make this work to our advantage when designing and making things. When we talk about plastics in general we will call them polymers, and when we talk about specific plastic materials we will give them their real names, such as nylon or polythene.

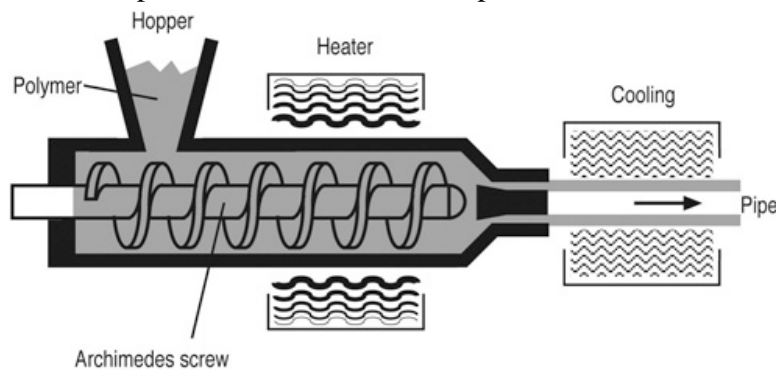
Plastics Processing

Because of the properties of polymers it is possible to mould them and change their shape using a number of different repetitious manufacturing processes.

The most important of these are extrusion, injection moulding, blow moulding, vacuum forming, extrusion blow moulding, rotational moulding, calendaring, foaming and compression moulding.

Extrusion.

Extrusion is a process that can be compared to squeezing toothpaste out of a tube. Thermoplastic granules are forced through a heated barrel and the fused polymer is then squeezed through a die that is the profile of the extruded component.

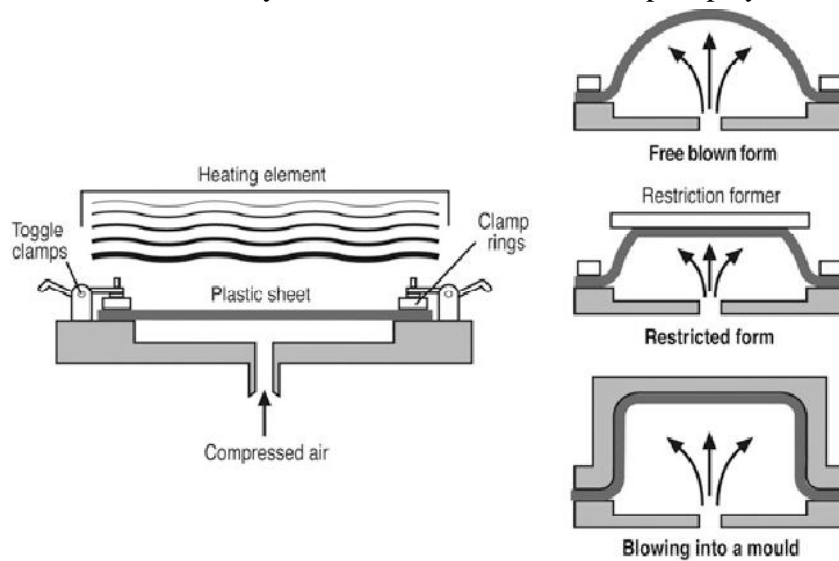


Extruding a pipe

The extrusion is cooled by water or air as it leaves the die and is finally cut to the required length. The shape of the die can be varied from a simple hole with a centrally supported core to produce tubes such as pipes, to very complex sections for curtain tracks or hollow window frames.

Blow moulding.

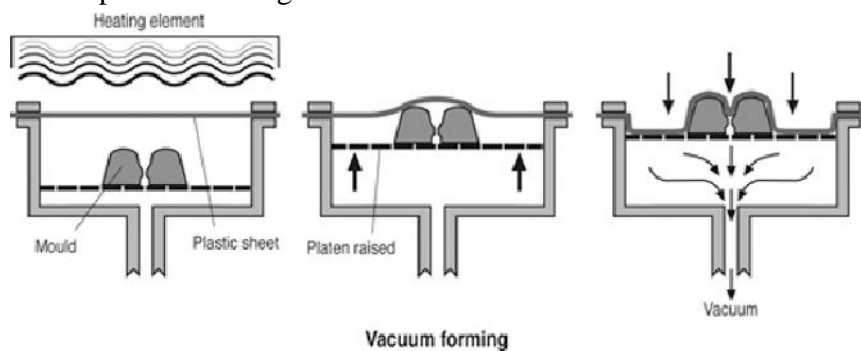
Blow moulding is a simple process where compressed air is introduced underneath a warmed sheet of thermoplastic material forcing the material into a mould cavity, or allowing it to expand freely into the shape of a hemisphere. It is a good way of forming large domes, which when made out of clear acrylic sheet are often used in shop displays.



Vacuum forming.

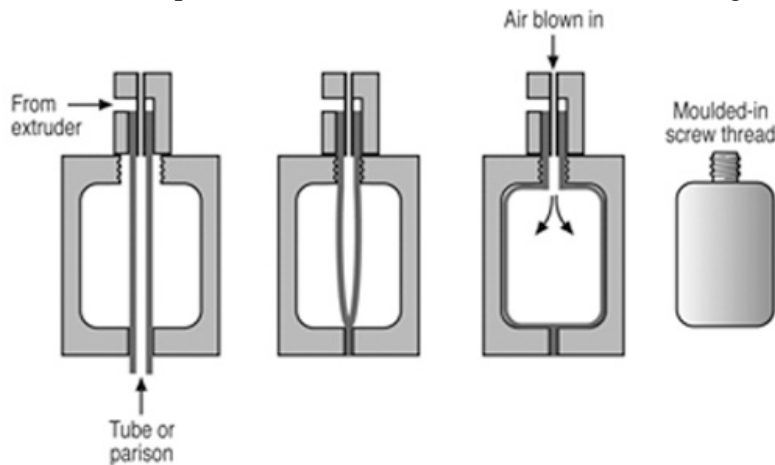
This is a very common manufacturing process used, for example, to make a range of plastics packaging. Think of the boxes sandwiches come in, or the inner in a chocolate box, or your acrylic bath. It is really the opposite of blow moulding. Instead of the warmed plastic sheet being forced into a mould by air pressure, in vacuum forming the air is drawn out from under the softened plastic sheet, so it is forced over or into a mould by atmospheric pressure.

Vacuum forming is a very common and effective way of producing complex shapes in thermoplastic sheeting.



Extrusion blow moulding.

This is a combination of extrusion and blow moulding and is often used where the article to be made has a narrow neck, such as a bottle. The plastic material is first extruded as a tube shape into an open die. The die is then closed to seal the ends of the tube and air is blown in forcing the plastic tube to take up the shape of the die cavity. As the material is extruded first and then blow moulded, the process is known as extrusion blow moulding.

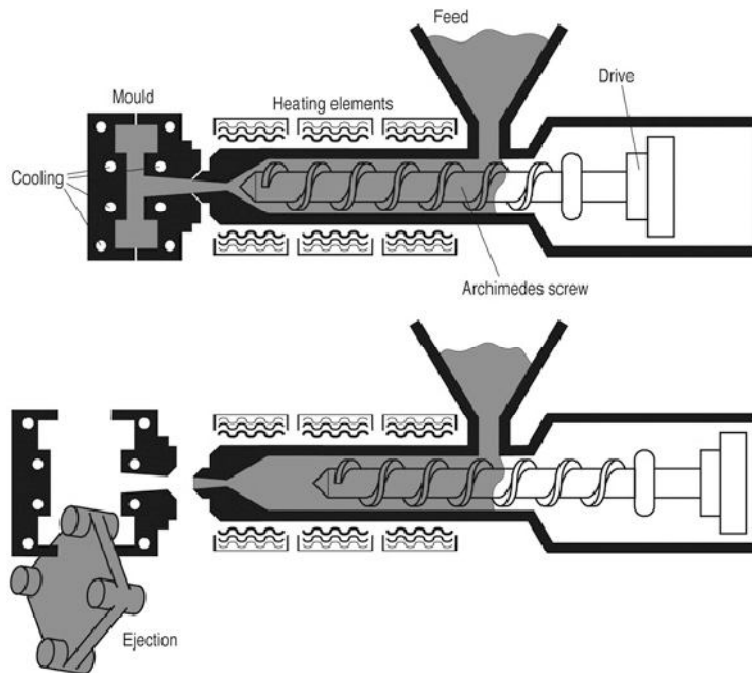


Extrusion blow moulding

Injection Moulding.

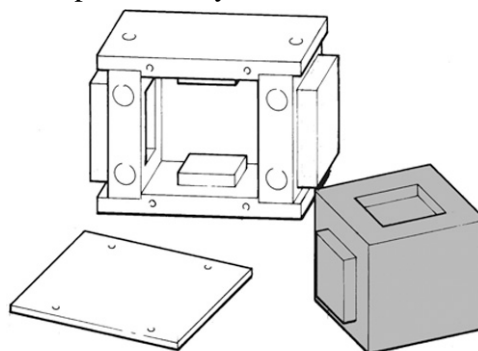
This process is one of the most common of all plastics manufacturing processes. The polymer, in granule form, is heated until fused and forced into a closed mould. Because of the viscous (thick, syrupy) nature of the fused polymer, very high pressures are needed to make it flow, which means that the machine and mould have to be very strong to withstand the forces involved.

A typical industrial injection moulding machine uses a screw to force the granules along a heated barrel, and when the granules become fused the screw is used as a plunger to force the polymer into the mould. The moulds are usually made from high-grade steel to withstand the forces involved and must also be highly polished to produce a very good finish on the product, as any scratches will show up in the moulded plastic surface. Because of the ability of the plastic to show even the smallest of marks very fine detail can be cut into the surface of the mould, for example in the form of trade marks, lettering or textures.



Rotational Moulding.

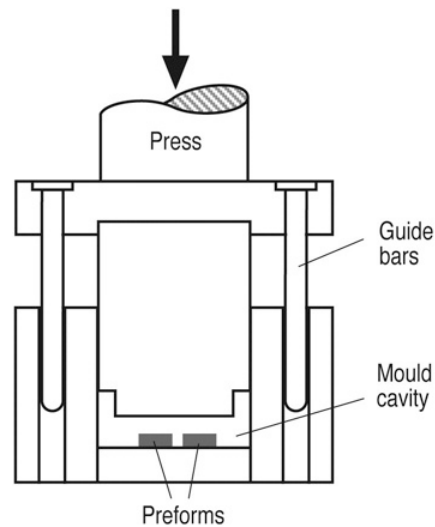
Rotational moulding is used to produce hollow thermoplastic products such as drums, storage tanks and litterbins. A carefully calculated amount of plastic is placed in a closed mould that is heated in an oven and rotated slowly around both a vertical and horizontal axes. The plastic material fuses and sticks to the hot mould surface, building up the required thickness. The mould is then gradually cooled by air or water while still rotating. The mould is opened, the finished product removed and the mould reloaded and closed for the next cycle. The time it takes to make one of the product is known as the product's cycle time.



Compression moulding.

Compression moulding is one of the oldest manufacturing technologies associated with plastics and was used in 1854, for example, by Samuel Peck to make picture frames from shellac mixed with wood flour. The process is almost always used with thermosetting plastics. A carefully weighed amount of thermosetting polymer is placed into a preheated lower mould cavity. The mould is then closed by the placing of the upper half and subjected to further heat, and pressure

provided by a press, often of several hundred tons capacity. The pressure and heat causes polymerisation and the flow of the plasticized material within the mould.



Compression moulding

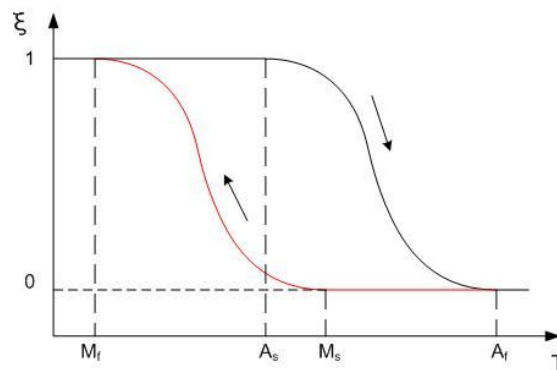
Raw thermoplastic materials containing fillers may be compressed whilst cold into small blocks of predetermined weight called preforms. Using preforms in compression moulds saves having to weigh out powdered material each time the mould is filled and decreases the cycle time, as the preforms may be preheated.

A development of compression moulding is transfer moulding. In this process the thermosetting polymer is first loaded into a heating chamber above the mould cavity and allowed to polymerise. It is then squeezed through channels into the mould cavity by the action of a powerful press. Transfer moulding is used when complex mouldings are required and the polymer needs to flow quickly around the mould cavity. Many plastic articles have metal parts included within them during the moulding process. These metal parts are called inserts, and may, for example, be in the form of captive nuts used in conjunction with bolts to hold other parts of the final product assembly. The inserts are placed in recesses in the lower mould either by hand or by using loading jigs before the polymer is introduced into the mould. Compression and transfer moulding are manufacturing techniques that lend themselves to the inclusion of moulded inserts. When inserts are used the technique is often termed insert moulding.

SHAPE MEMORY ALLOYS

A shape memory alloy (SMA, smart metal, memory metal, memory alloy, muscle wire, smart alloy) is an alloy that "remembers" its original, cold-forged shape: returning the pre-deformed shape by heating. This material is a lightweight, solid-state alternative to conventional actuators such as hydraulic, pneumatic, and motor-based systems. Shape memory alloys have applications in industries including medical and aerospace.

The three main types of shape memory alloys are the copper-zinc aluminium-nickel, copper-aluminium-nickel, and nickel-titanium (NiTi) alloys but SMA's can also be created by alloying zinc, copper, gold, and iron. NiTi alloys are generally more expensive and change from austenite to martensite upon cooling; M_f is the temperature at which the transition to Martensite is finished during cooling. Accordingly, during heating A_s and A_f are the temperatures at which the transformation from Martensite to Austenite starts and finishes. Repeated use of the shape memory effect may lead to a shift of the characteristic transformation temperatures (this effect is known as functional fatigue, as it is closely related with a change of microstructural and functional properties of the material)



In this figure, $\xi(T)$ represents the martensite fraction. The difference between the heating transition and the cooling transition gives rise to the hysteresis effect where some of the mechanical energy is lost in the process. The shape of the curve depends on the material properties of the shape memory alloy, such as the alloying and work hardening

One way memory effect

- When a shape memory alloy is in its cold state (below A_s), the metal can be bent or stretched and will hold this shape until heated above the transition temperature.
- Upon heating, the shape changes to its original.
- When the metal cools again, it will remain in the hot shape until deformed again.
- In this case, cooling from high temperature does not cause macroscopic shape change.

Two way memory effect

- This is the effect that the material remembers two shapes: one at high temp and the other at low temperature.
- These metals show shape memory effect during both cooling and heating.
- The metal can be trained to leave some reminders of the deformed low temp condition in the high temp phases.
- Above a certain temp, the metal loses the 2 way memory effect. This is called “amnesia”

Aircraft

Boeing, General Electric Aircraft Engines, Goodrich Corporation, NASA, and All Nippon Airways developed the Variable Geometry Chevron using shape memory alloy that reduces aircraft's engine noise.

Robotics

There have also been limited studies on using these materials in robotics (such as "Roboterfrau Lara"), as they make it possible to create very light robots. Weak points of the technology are energy inefficiency, slow response times, and large hysteresis.

Medicine

Shape memory alloys are applied in medicine, for example, as fixation devices for osteotomies in orthopaedic surgery, in dental braces to exert constant tooth-moving forces on the teeth and in stent grafts where it gives the ability to adapt to the shape of certain blood vessels when exposed to body temperature.

Alloys of metals having the memory effect at different temperatures and at different percentages of its solid solution contents:

- Ag-Cd 44/49 at.% Cd
- Au-Cd 46.5/50 at.% Cd
- Cu-Al-Ni 14/14.5 wt.% Al and 3/4.5 wt.% Ni
- Cu-Sn approx. 15 at.% Sn
- Cu-Zn 38.5/41.5 wt.% Zn
- Cu-Zn-X (X = Si, Al, Sn)
- Fe-Pt approx. 25 at.% Pt
- Mn-Cu 5/35 at.% Cu

Two or more chemically distinct materials combined to have improved properties

- Natural/synthetic
- Wood is a natural composite of cellulose fiber and lignin.

Cellulose provides strength and the lignin is the "glue" that bonds and stabilizes the fiber.

Bamboo is a wood with hollow cylindrical shape which results in a very light yet stiff structure.

Composite fishing poles and golf club shafts copy this design.

A composite material consists of two phases:

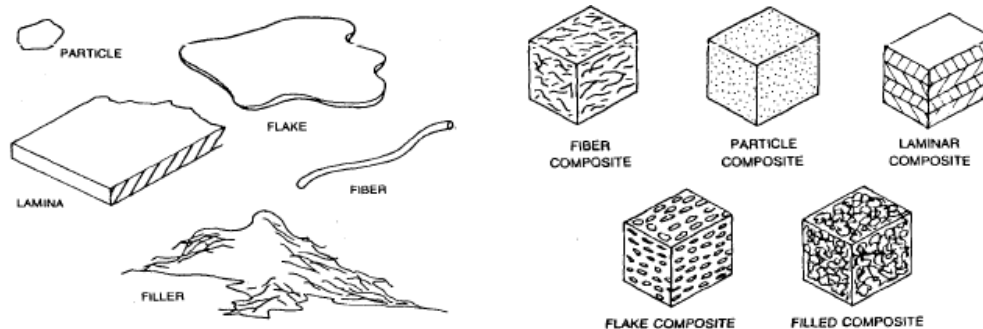
Primary

- Forms the matrix within which the secondary phase is imbedded
- Any of three basic material types: polymers, metals, or ceramics

Secondary

- Referred to as the imbedded phase or called the reinforcing agent
- Serves to strengthen the composite (fibers, particles, etc.)
- Can be one of the three basic materials or an element such as carbon or boron

There are five basic types of composite materials: Fiber, particle, flake, laminar or layered and filled composites.



Classification of composite material

Metal Matrix Composites (MMCs)

- Mixtures of ceramics and metals, such as cemented carbides and other cermets
- Aluminum or magnesium reinforced by strong, high stiffness fibers

Ceramic Matrix Composites (CMCs)

- Least common composite matrix
- Aluminum oxide and silicon carbide are materials that can be imbedded with fibers for improved properties, especially in high temperature applications

Polymer Matrix Composites (PMCs)

- Thermosetting resins are the most widely used polymers in PMCs.
- Epoxy and polyester are commonly mixed with fiber reinforcement

Matrix material serves several functions in the composite

- Provides the bulk form of the part or product
- Holds the imbedded phase in place
- Shares the load with the secondary phase

The reinforcing phase

- The imbedded phase is most commonly one of the following shapes:
 - Fibers, particles, flakes
- Orientation of fibers:
 - One-dimensional: maximum strength and stiffness are obtained in the direction of the fiber
 - Planar: in the form of two-dimensional woven fabric
 - Random or three-dimensional: the composite material tends to possess isotropic properties

Types of phases

Currently, the most common fibers used in composites are glass, graphite (carbon), boron and Kevlar 49.

- Glass – most widely used fiber in polymer composites called glass fiber-reinforced plastic (GFRP)
- E-glass – strong and low cost, but modulus is less than other (500,000 psi)
- S-glass – highest tensile strength of all fiber materials (650,000 psi). UTS~ 5 X steel ; r ~ 1/3 x steel
- Carbon/Graphite –Graphite has a tensile strength three to five times stronger than steel and has a density that is one-fourth that of steel.
- Boron – Very high elastic modulus, but its high cost limits its application to aerospace components
- Ceramics – Silicon carbide (SiC) and aluminum oxide (Al₂O₃) are the main fiber materials among ceramics. Both have high elastic moduli and can be used to strengthen low-density, low- modulus metals such as aluminum and magnesium
- Metal – Steel filaments, used as reinforcing fiber in plastics

Manufacturing of composites

1. Open Mold Processes- some of the original FRP manual procedures for laying resins and fibers onto forms
2. Closed Mold Processes- much the same as those used in plastic molding
3. Filament Winding- continuous filaments are dipped in Manufacturing of composites liquid resin and wrapped around a rotating mandrel, producing a rigid, hollow, cylindrical shape
4. Pultrusion Processes- similar to extrusion only adapted to include continuous fiber reinforcement
5. Other PMC Shaping Processes

Open Mold Processes

Family of FRP shaping processes that use a single positive or negative mold surface to produce laminated FRP structures

- The starting materials (resins, fibers, mats, and woven rovings) are applied to the mold in layers, building up to the desired thickness
- This is followed by curing and part removal
- Common resins are unsaturated polyesters and epoxies, using fiberglass as the reinforcement

Open Mold FRP Processes

1. Hand lay-up
2. Spray-up
3. Vacuum Bagging – uses hand-lay-up, uses atmospheric pressure to compact laminate.
4. Automated tape-laying machines the differences are in the methods of applying the laminations to the mold, alternative curing techniques, and other differences

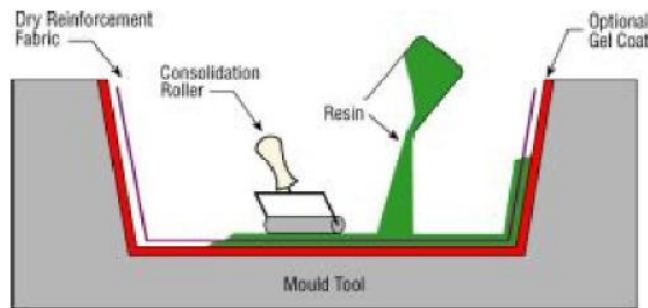
Hand Lay-Up Method

Open mold shaping method in which successive layers of resin and reinforcement are manually applied to an open mold to build the laminated FRP composite structure

- Labor-intensive
- Finished molding must usually be trimmed with a powersaw to size outside edges
- Oldest open mold method for FRP laminates, dating to the 1940s when it was first used for boat hulls

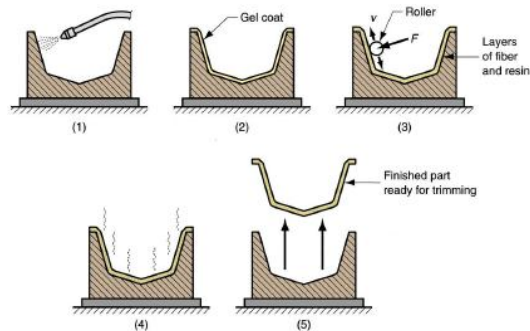
Hand Lay-up

Hand lay-up, or contact molding, is the oldest and simplest way of making fiberglass-resin composites. Applications are standard wind turbine blades, boats, etc.)



Hand lay-up:

- (1) mold is treated with mold release agent;
- (2) thin gel coat (resin) is applied, to the outside surface of molding;
- (3) when gel coat has partially set, layers of resin and fiber are applied, the fiber is in the form of mat or cloth; each layer is rolled to impregnate the fiber with resin and remove air;
- (4) part is cured;
- (5) fully hardened part is removed from mold.



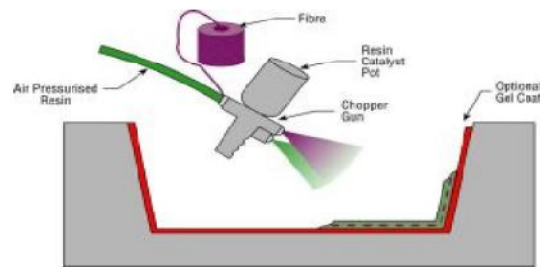
- Generally large in size but low in production quantity -not economical for high production
- Applications:
 - Boat hulls
 - Swimming pools
 - Large container tanks
 - Movie and stage props
 - Other formed sheets

Spray-Up Method

Liquid resin and chopped fibers are sprayed onto an open mold to build successive FRP laminations

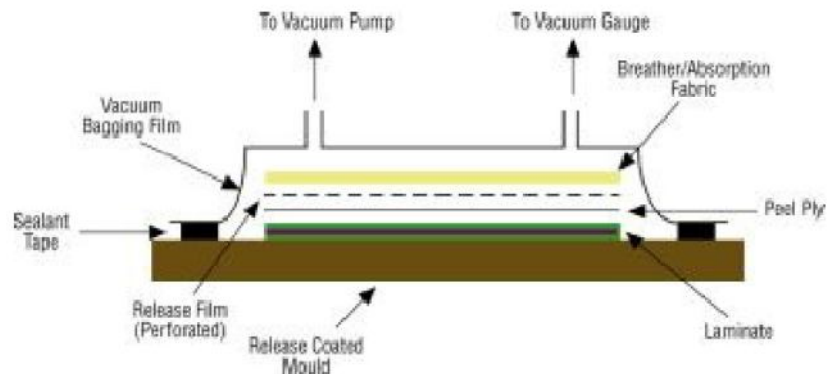
- Attempt to mechanize application of resin-fiber layers and reduce lay-up time
- Alternative for step (3) in the hand lay-up procedure

In Spray-up process, chopped fibers and resins are sprayed simultaneously into or onto the mold. Applications are lightly loaded structural panels, e.g. caravan bodies, truck fairings, bathtubs, small boats, etc.



Vacuum-Bag Molding

The vacuum-bag process was developed for making a variety of components, including relatively large parts with complex shapes. Applications are large cruising boats, race car components, etc.

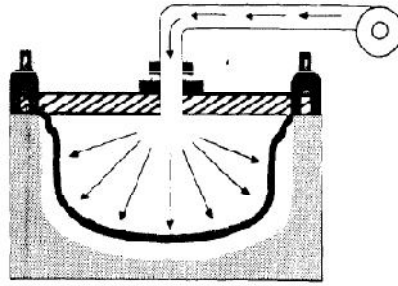


Use atmospheric pressure to suck air from under vacuum bag, to compact composite layers down and make a high quality laminate

Layers from bottom include: mold, mold release, composite, peel-ply, breather cloth, vacuum bag, also need vacuum valve, sealing tape.

Pressure-Bag Molding

Pressure-bag process is virtually a mirror image of vacuum-bag molding. Applications are sonar domes, antenna housings, aircraft fairings, etc.



Curing in Open Mold Processes

- Curing is required of all thermosetting resins used in FRP laminated composites
- Curing cross-links the polymer, transforming it from its liquid or highly plastic condition into a hardened product
- Three principal process parameters in curing:
 - Time
 - Temperature
 - Pressure

Curing at Room Temperature

- Curing normally occurs at room temperature for the TS resins used in hand lay-up and spray-up procedures
 - Moldings made by these processes are often large (e.g., boat hulls), and heating would be difficult due to product size
 - In some cases, days are required before room temperature curing is sufficiently complete to remove the part

Closed Mold Processes

- Performed in molds consisting of two sections that open and close each molding cycle
- Tooling cost is more than twice the cost of a comparable open mold due to the more complex equipment required in these processes
- Advantages of a closed mold are: (1) good finish on all part surfaces, (2) higher production rates, (3) closer control over tolerances, and (4) more complex three-dimensional shapes are possible

Classification of Closed Mold Processes

Three classes based on their counterparts in conventional plastic molding:

1. Compression molding
2. Transfer molding
3. Injection molding

The terminology is often different when polymer matrix composites are molded

Compression Molding PM Processes

A charge is placed in lower mold section, and the sections are brought together under pressure, causing charge to take the shape of the cavity

- Mold halves are heated to cure TS polymer
 - When molding is sufficiently cured, the mold is opened and part is removed
- Several shaping processes for PMCs based on compression molding
 - The differences are mostly in the form of the starting materials

Injection Molding PMC Processes

- Injection molding is noted for low cost production of plastic parts in large quantities
- Although most closely associated with thermoplastics, the process can also be adapted to thermosets
- Processes of interest in the context of PMCs:
 - Conventional injection molding
 - Reinforced reaction injection molding

Conventional Injection Molding

- Used for both TP and TS type FRPs
- Virtually all TPs can be reinforced with fibers
- Chopped fibers must be used
 - Continuous fibers would be reduced by the action of the rotating screw in the barrel
- During injection into the mold cavity, fibers tend to become aligned as they pass the nozzle
 - Part designers can sometimes exploit this feature to optimize directional properties in the part

UNIT-5 HIGH TEMPERATURE MATERIALS CHARACTERIZATION

Classification, production and characteristics – methods and testing – determination of mechanical and thermal properties of materials at elevated temperatures – application of these materials in thermal protection systems of aerospace vehicles – super alloys – high temperature material characterization.

HIGH TEMPERATURE MATERIALS

Materials operating in service at elevated temperatures are relevant to many processing and productive industries and hence provide an illuminating example of the desirability for materials research to be carried out with a broad view of the ultimate applications of the product, rather than in concentrating on the satisfaction of a single requirement. Nevertheless in the final stages of development of a material the detailed requirements of each potential application must be considered. Close cooperation is therefore demanded between, on the one hand a research organisation with a wide understanding of the basic sciences involved and the production and application problems arising in materials technology, and on the other hand the designers and development engineering engaged in individual industries.

The extent of interest in high-temperature materials can be appreciated by considering the main fields in which they are used.

High temperature materials application in various industries as follows

High-temperature steam turbines

Oil- or coal-fired steam turbines provide the majority of power generation in the world, using maximum steam temperatures close to 600°C. In the steam-raising plant certain components reach higher temperatures and may be subject to severe erosive and corrosive attack; critical components are super heater tubes and tube supports. Piping and valves conveying steam from boilers to turbines are highly stressed and may also suffer steam erosion. In the turbines the casings and casing bolts are highly stressed due to the steam pressure, while the rotors, blades and nozzles have imposed stresses due to centrifugal forces, gas pressure and thermal changes.

Nuclear reactors

In all types of nuclear reactor high-temperature material problems arise with the fuel cans due to stressing by fuel expansion and to corrosion by the coolant. The majority of nuclear reactors at present operating, whether water cooled or gas cooled with carbon dioxide, generate steam at relatively modest temperatures in the range 300-400°C

Aircraft and Space Vehicles

The aircraft gas turbine provide the main stimulus for the development of modern superalloys, the term used to describe materials resistant to creep and fracture at temperatures in the range 700-1100°C. The alloys were originally required specifically for stator and rotor blades to resist the high centrifugal or thermal stresses imposed on the blades, but with progressive increase in the severity of operating conditions similar alloys are now used for other gas-turbine components including discs, combustion chambers, casings and tail pipes. The aircraft gas turbine is likely to remain the primary application of the most advanced superalloys or competitive high-temperature materials.

The rocket motor for space travel has led to severe problems in high-temperature materials technology. The high temperature and velocity of the exhaust gas generates high thermal stresses and erosive action; refractory metals, particularly tungsten, and special forms of graphite have been used to resist these satisfactorily, even though the required life may be restricted to a few minutes. Similar problems arise with re-entry vehicles on account of aerodynamic heating, and these have led to the development of special refractory ablative tiles or coatings.

Marine

Merchant shipping mainly relies on the diesel engine in which a number of critical components are subjected to severe mechanical or thermal stresses and corrosive attack at high temperatures. The highest temperature (about 800°C) is reached in pre-combustion chambers, but closely similar temperatures may be reached in exhaust valves, associated with high mechanical stress.

Chemical Industry

A wide range of chemical for the conversion of feedstock, from the oil industry or elsewhere, into required products, involve treatment at elevated temperatures and often at high pressures. The systems consist of the reactor tubes, which typically are 12-15 m long and 100 mm bore with a wall thickness about 20 mm, which are connected by smaller bore "pigtail" pipes to a header and hence to transfer piping. Welding is an essential operation in the construction of such plant. The operating temperatures of the equipment may rise to 950-1050°C.

TYPES OF HIGH-TEMPERATURE ALLOYS

The metallic materials used for high-temperature purposes range from the simplest plain carbon steels to the scarce and expensive metals of the platinum group, but they can be categorized into a few distinctive groups based on composition and structure. Typical compositions of representative alloys of the main groups are given in Table I and the principal characteristics of the structure and properties are indicated in the following sections.

Table I. Typical Compositions of Selected High-Temperature Alloys

Alloy Type	Commercial Name	Cast or Wrought	Composition												
			Fe	Ni	Co	Cr	W	Mo	Nb	Ti	Al	C	Others		
Austenitic Cast Iron	Ni-Resist	C	Bal.	20	-	5	-	-	-	-	-	-	3	2 Si	
Ferritic Steel	FV 448	W	Bal.	1	-	11	-	0.7	0.4	-	-	-	0.1	0.05 N	
Austenitic Steel	AISI 321	W	Bal.	10	-	18	-	-	-	0.4	-	-	0.05	-	
	HK40	C	Bal.	21	-	25	-	-	-	-	-	-	0.4	0.05 N	
Nickel-chromium Alloys	Alloy 800	W	46	32	-	20	-	-	-	0.3	0.3	0.04	0.04	0.3 Cu	
	Nichrome V	W	-	78	-	20	-	-	-	-	-	-	0.04	2 Si	
Iron-based Superalloy	N 155	W	Bal.	20	20	21	2.5	3	1	-	-	-	0.15	0.15 N	
Nickel-based Superalloy	Nimonic 90	N	-	Bal.	18	20	-	-	-	2.5	1.5	0.1	0.1	B, Zr	
	IN 100	C	-	Bal.	15	10	-	3	-	5	5	0.2	0.2	B, Zr	
Cobalt-based Superalloy	HA 188	W	1.5	22	40	22	14	-	-	-	-	0.1	0.08 La	-	
Cobalt-based Wear-resistant Alloy	UmCo 50	C	22	-	50	28	-	-	-	-	-	-	0.1	-	
Refractory Metal	TZM	W	-	-	-	-	-	-	Bal.	-	0.5	-	-	0.08 Zr	
Platinum-Rhodium	-	W	-	-	-	-	-	-	-	-	-	-	-	80Pt,20Rh	

Irons and Steels

Cast irons

Conventional cast iron has been used for many years for grates and burners of combustion stoves, but progressive internal oxidation following the path of the graphite flakes leads to growth and distortion. This can be overcome by the use of austenitic cast irons containing nickel at levels up to 20 or even 25 per cent together with chromium and silicon, and these materials find application in combustion and heat-treatment equipment where stresses are not high but corrosive and erosive conditions are severe. They are serviceable at temperatures up to about 750°C.

Ferrite steels

Plain carbon and low-alloy steels are serviceable at moderate stresses at temperatures up to about 500°C but scaling due to oxidation limits their life at higher temperatures and the strength, in terms of creep resistance, falls steeply at temperatures above 400°C. The scaling resistance is improved by additions of chromium, usually in the order of 12 per cent, and strength by carefully balanced additions of molybdenum, niobium, vanadium, etc., so that there are many proprietary steels offering high strength and serviceability at temperatures up to about 600°C. Such steels are used for critical components, such as blades, in steam turbines.

Austenitic steels

These steels contain levels of nickel and chromium which are sufficient to stabilise the face-centred-cubic or austenitic structure at normal temperatures and to confer high corrosion resistance and, in general, good ductility. They range in basic composition from the simple 18 chromium, 8 nickel alloy normally used in the wrought form for a variety of corrosion-resistant applications, to 20 chromium, 35 nickel alloys used for moderately-stressed components in power plant. Many varieties of this broad class of alloy are commercially available with additions of molybdenum, manganese, titanium, niobium, etc. and with carbon up to about 0.5 per cent, to confer particular characteristics of strength or corrosion resistance. Most are used as wrought products but certain compositions are particularly chosen for use as castings.

Nickel-chromium Alloys

There is no structural difference between the basic austenitic steels referred to above and the high nickel alloys containing up to 80 per cent nickel with smaller contents of iron. Such alloys, typified by 60Ni, 24Fe, 16Cr; 76Ni, 8Fe, 16Cr and 80Ni, 20Cr, are widely in use, for their oxidation resistance at high temperatures, as electric heating elements and furnace parts and depending on the details of composition may be serviceable up to 1150°C.

Superalloys

This term has been adopted for alloys specifications developed to have high strength at temperatures in the range 700-1100°C. The alloys may be based on iron, nickel or cobalt, and normally require 15-20 percent chromium to ensure satisfactory oxidation or corrosion resistance. The high strength is developed by the precipitation or dispersion of fine particles throughout the matrix, usually by additions of titanium, aluminium or carbide-forming elements.

Iron-based superalloys

These alloys are developments of austenitic steels with nickel contents in the range 20-40 per cent, chromium contents usually 15-20 percent and sometimes with additions of cobalt. The strengthening precipitate is mainly the intermetallic compound γ' formed from additions of titanium and aluminium, but strength may also be conferred by carbides or nitrides of niobium or vanadium.

Nickel - based superalloys

The addition of small proportions of titanium and aluminium to the 80Ni-20Cr oxidation-resistant alloy produced the first of the now large family of nickel - base superalloys. The strengthening precipitate is the intermetallic compound $\text{Ni}_3(\text{Ti}, \text{Al})$ termed γ' , while the fracture resistance is promoted by grain-boundary precipitates of carbides. In the many alloys now in this group additions of cobalt, molybdenum or tungsten may be made to the matrix, while smaller additions of niobium, zirconium, boron and other elements control and modify the character of the precipitates. Such alloys provide the most advanced superalloys required for the rotor blades of gas turbines, while other alloys of the family are adopted for other gas - turbine components and for highly stressed applications in many engineering fields. Most may be used as wrought components but the most highly developed are used in the vacuum -- cast form.

Cobalt-based superalloys

Hardening by γ' precipitation has not been applied successfully to cobalt-base alloys, but carbide precipitations using stable carbide formers such as niobium, tantalum and vanadium can give attractive high-temperature strength, and this, combined with their ready castability, has caused the alloys to be used in many applications in gas-turbine technology. Cobalt-base alloys are also prominent in the field of corrosion- and wear-resistant high-temperature materials. In these the corrosion resistance is conferred by chromium contents in the range 20-30 per cent and wear resistance is developed by large proportions of carbides formed from additions of molybdenum, tungsten or niobium with carbon contents up to about 2 per cent. These alloys are mostly used in the cast form, either as shaped castings or as weld-deposited coatings on other materials, and find applications as furnace parts in the metallurgical industry and as protective coatings on valve seats in internal combustion engines and various parts of steam turbines subject to steam erosion.

Refractory Metals

The metals with melting points above 1800°C have, as would be expected, high strength at elevated temperatures, but the commoner refractory metals, viz. molybdenum, tungsten, niobium, tantalum and vanadium all form volatile oxides, so that they cannot be used for long-time service in oxidising atmospheres without a protective coating. No alloying elements have been found to form a self-protective scale so that high-temperature applications of these metals have been restricted to short-time (e.g. rocket nozzles) or non-oxidising atmospheres (e.g. lamp filaments, vacuum furnace elements, etc.). Alloys based on these metals have mainly involved the addition of small proportions of reactive elements or dispersed oxides to act as grain-growth restrictions or to maintain ductility.

Other Metals

The metals of the platinum group and alloys formed from them, in spite of their scarcity and high cost, are important high-temperature materials used for thermocouple wires, glass-melting and working equipment, crystal-growing crucibles, aircraft spark plugs etc. Other metals with high melting points, e.g. chromium, titanium, are important alloying constituents, but their high reactivity inhibits their use as a matrix for useful high-temperature alloys.

METAL AND ALLOY PRODUCTION AND USAGE

The problems arising in the use of metallic materials in high-temperature engineering range throughout the full range of the science and technology of metallurgy, from the mining and extraction of the virgin metals from their ores to the study and investigation of components in service and the analysis of failures. In all these areas there is scope for research and development action aimed at improving the serviceability or economics of the products.

Mining, Extraction and Refining

The provision of adequate supplies of the constituent elements of an alloy in a suitable form and of satisfactory purity is an essential first step. Since the natural occurrence of the element in the ore deposits is often at a low level (less than 1 per cent) and at regions of difficult access in politically unstable or antagonistic countries, problems of transport, energy availability, manpower and economic balance arise, and may play an essential role in the selection of the most suitable procedure.

The major steps in the recovery process are:

(a) Mining: the deposits may be near the earth's surface and recoverable by open quarrying, or in deep mines; they may be soft, so that they can be dealt with by mechanical shovels or drags, or hard, needing explosives to break up the rock.

(b) Beneficiation: to separate the desired ore from the unwanted gangue or waste rock, methods vary from hand-picking to sophisticated magnetic or grind the ore to a fine particle size, and for flotation methods, to treat with surface active agents to select the ore from the gangue.

(c) Roasting and reduction: depending on the composition of the ore it may need roasting to convert to oxide, for example by expulsion of sulphur dioxide. The oxide is then reduced to crude metal by thermal treatment using carbon or hydrogen as the reducing agent.

Alternative processes now being more widely used are hydrometallurgical in character and involve the solution of the ore in chemical reagents and the reprecipitation of selected compounds of the required metal, which then provides the feed material for subsequent reduction.

(d) Refining: the crude metal will normally contain appreciable quantities of other elements and, particularly for the manufacture of high-temperature alloys, these may be deleterious to the properties of the final alloys. Refining is therefore necessary and may be carried out by processes such as chemical solution and reprecipitation, electrolytic deposition, vaporization, etc. While the processes may be generalised in character the details must be specifically developed for the metal in question.

In addition to the supply of primary metal by the processes outlined above, significant contributions to the current industrial demands are made by recycling used materials - so-called secondary metal. For most materials secondary metal is used for lower-grade products in which some contamination can be tolerated, but with the possible future reduction or exhaustion of primary supplies and the consequent increasing costs, the need for improved recycling procedures is apparent. The system currently used for the precious metals provides a basis for extension to other metals as the economic or supply situations justify it.

The process of recovery of metals from their ores and the provision of them at the site of application is highly energy intensive and consequently very careful study of the energy consumption at all stages, including transport, is necessary to ensure the most economical process.

Development of Alloy Composition

Most current high-temperature alloys have been developed by essentially empirical methods over a period of years, but parallel studies of a basic scientific nature have provided guidance as to the effects of composition and structure on mechanical properties. Studies of the mechanisms of creep and fatigue in pure metals and single- and multi-phase alloys, have all contributed to an understanding of the way in which composition affects properties, and have enabled the alloy developers to improve their products by the adjustment of contents of the major constituents, by the elimination of injurious contaminants, and by the addition of trace elements having a beneficial effect on structure (e.g. boron and zirconium in the effects on grain-boundary

structures and of yttrium on protective scale formation). Continuing research of this nature is therefore essential to support and stimulate metallurgical developments of all types.

Alloying and Consolidation

The primary metals may be supplied in a variety of forms ranging from cast pigs to powder and either as nominally pure metals or as intermediate alloys (e.g. ferro-alloys for the production of alloy steels or iron-based alloys). The conversion of these to the required alloy composition usually involves remelting under carefully controlled conditions to minimize contamination by unwanted elements. High-temperature alloys are conventionally, and still to a large extent, melted in electric arc or induction furnaces open to the atmosphere but under a cover of a protective slag. The slag is chosen to minimize atmospheric pick-up (both oxygen and nitrogen) and also aids in the removal from the melt of unwanted low-melting-point elements. For the more advanced superalloys, however, air melting is inadequate, and improved techniques have been adopted. First, electro-slag refining, in which an air-melted alloy is cast in the form of suitable ingot electrodes and then remelted by electric arc under a complete cover of reactive slag; further refining takes place in the molten pool and progressive solidification gives an improved structure to the ingot, aiding subsequent hot working. Second, vacuum refining or complete vacuum remelting, usually by induction methods, enables atmospheric contamination to be eliminated and reduces the content of unwanted volatile constituents. It has been established that even very low contents of some elements (e.g. lead, silver, bismuth) measured in a few parts per million are detrimental to high-temperature properties of advanced superalloys.

The molten alloy, adjusted to the required composition, may be cast into ingots for subsequent hot working or into bars for remelting for castings, but, particularly for larger components such as rotor discs for gas turbines, the ingot structure may be too segregated and coarse grained for satisfactory forging or to give uniform properties. The alloy may therefore be blown by inert gas to produce an alloy powder for subsequent consolidation. The powder may be pressed to form in shaped dies as in conventional powder metallurgical techniques, but for critical components in advanced high-temperature alloys is more likely to be hot isostatically pressed. This involves enclosing the powder in an evacuated metal container and hot pressing using an inert gas as the pressure medium. A very uniform fine-grained compact is thereby obtained, suitable for further hot working. An additional advantage of the powder route to consolidated materials is that dispersion-strengthened alloys are readily produced. In such materials finely dispersed stable non-metallic compounds, usually oxides, are incorporated to the extent of a few per cent by volume, and provide additional strength at temperature higher than those at which intermetallic compounds are effective.

Working with material

The consolidated material in the form of cast ingot or pressed powder compact is now required to be shaped to be an intermediate form from which the final component is to be machined. Hot-

working processes are normally used and these serve to break down the coarse grain size and segregated structure of the ingot, thus improving the uniformity of properties of the material. Hot working may be by hammer or press forging, extrusion or hot-rolling, and the conditions of temperature, deformation rate, lubrication, etc., need to be separately developed for each particular material and for the form of product required. Some products such as sheet, tube and wire require further stages of cold working which again require careful development to ensure that a satisfactory and consistent material is obtained.

The more advanced high-temperature materials are not workable even at temperatures close to their melting points, and hence must be cast to form. Precision casting by developments of the lost-wax technique are used, and to avoid atmospheric contamination may be carried out entirely in vacuum. Improvements in pattern production, moulding, melting and pouring techniques all contribute to advancement of this art in high-temperature materials technologies and may be expected to be applicable to other metallic materials.

Machining

The conversion of intermediate forms to the required final shape of component involves machining of the material. The hardness, and in general rapid work-hardening characteristics of high-temperature alloys, make this often a difficult process and although conventional high-speed steels and sintered carbide tools are widely used, alternative methods are being sought and brought into use. Spark machining and electrochemical methods are already established and other high-energy methods, such as the use of lasers, electron beams and ultrasonics are of interest. Continuing research on this topic can yield benefits to many fields of engineering production.

Heat Treatment

The properties of high-temperature alloys are critically dependent on the metallurgical structure developed by controlled heat treatments, which may be carried out before or after machining to final form. The treatments often need to be effected in controlled atmospheres or environments to avoid detrimental surface reactions, or to produce surface layers with improved mechanical or corrosion-resistant characteristics. Heat treatments may also be designed to minimise internal stresses or, in special component shapes to develop favorable stresses to combat the initiation of fatigue failures. The study of heat treatment and its association with controlled mechanical deformation is a fruitful field of investigation for all metallic materials.

Joining

Particularly for larger complex installations such as boilers and petrochemical plant, the individual components must be joined together either by dismantable mechanical joints or by permanent or semi-permanent methods. Welding is the most widely used permanent joining method and for the less ductile of the high-temperature materials difficulties arise due to cracking in the weld metal itself or in the heat-affected zone alongside the joint. The choice of

welding method and of the consumable materials -electrodes or filler wires- depends critically on the parent alloy and the dimensions of the parts to be joined, as well as on their location and mobility. Much research is in progress on the welding problems associated with high-temperature materials and should continue, particularly on the high-energy-input processes such as electron beam welding and laser welding. The higher strength high-temperature alloys are not weldable even in quite thin sections, and semi-permanent joints made by brazing, or perhaps diffusion bonding, are possible alternatives. Brazing alloys with melting points in the range 900-1200°C have been developed specifically for use with high-temperature alloys, the most familiar of which are the gold-nickel alloys or those based on palladium alloys. Improvement in these alloys and in the techniques of their use, as applied to the superalloys and the refractory metals, could lead to benefits in other engineering fields.

For all types of joint data are required relating the mechanical strength of the joint to that of the parent material at the temperatures and stress levels of interest.

Protection

The search for high strength at elevated temperatures has eventually led to alloys which have inadequate inherent resistance to environmental corrosion at the service temperature and hence to the need to develop protective coatings.

Specifications and Testing

In order to ensure the reliability and consistency of materials used for engineering purposes it is necessary that specifications should be established for the benefit of producer and user. These may be individually arranged between the two parties or established by industrial, national or international bodies. The specifications normally define the composition of the material and the type and limits of specific property tests required. The formulation of specifications should be in the hands of both engineers and material scientists, so that all factors of importance are taken into account.

Similar considerations apply to the preparation of design codes which define the way in which material property data are used in engineering design. Such codes are of especial relevance in high - temperature engineering where interpolation or extrapolation of property data in terms of time or temperature is often necessary. The various attempts being made to correlate creep and fatigue data by mechanistic or phenomenological methods are aimed at giving greater confidence in these procedures. The acceptance of materials in their part-processed form and as finished components rests on testing to specification requirements and to such proof testing and non-destructive testing as is feasible. The latter field, embracing radiography by X-rays or γ -rays, ultrasonics inspection and various electrical and magnetic tests is a progressive field of research the results of which are generally applicable to all materials.

Failure Investigations

Inevitably from time to time failure occur in service and much can be learnt by careful scientific study of these. Material faults may be diagnosed or design faults identified, and steps then taken to remedy the shortcomings. In the same area of study are the attempts being made to assess the remaining life of high-temperature components after a period of service, for this would enable the safe life of plant to be extended without risk of early failure. Recovery treatments by thermo-mechanical processing are also possible, and indeed are already partly in use, particularly for aero-engine gas-turbine blades.

REFRACTORIES AND CERAMICS FOR HIGH-TEMPERATURE SERVICE

Conventional Refractories

Non-metallic materials have a long history of usage in high-temperature technology, mainly as thermal insulating and containment materials for such purposes as metal-melting crucibles, hearths and linings for pottery kilns and for industrial furnaces of all types. For such applications strength is an important factor but is not the primary requirement, since failure usually results from thermal cracking due to temperature changes, or from reaction with the contained material. The high-tonnage refractory materials of this type are mainly mixed oxides or silicates and the commercial materials have been developed to balance performance against cost. For more critical applications pure single oxides are increasingly used, alumina, zirconia, magnesia and beryllia being the commonest, since these generally have higher melting points than the mixed oxides.

Advanced Ceramics

Non-metallic materials other than oxides have become of increasing importance in high-temperature technology in recent years. Silicon carbide, long known as an abrasive and also for many years as a high-temperature electrical furnace element, is finding increasing use in a variety of advanced refractory applications, particularly in the self-bonded or reaction-bonded form. The high strength and low density of this material make it a strong candidate for certain aero-space components. Similarly silicon nitride provides competitive levels of strength and hot-corrosion resistance. Both these materials are formed from cheap and abundant elements so that there are no problems of availability, and the cost of components made from them will depend on energy costs and the level of commercial demand. Many other non-metallic materials, elemental or compound, are being examined in the light of their possible merits as high-temperature materials, and these include oxides, carbides, nitrides, borides and silicides, predominantly of the higher-melting-point refractory metals, but also of the more reactive metals such as aluminium, magnesium and calcium which can form compounds of high thermal stability. In the same class of advanced non-metallic refractory materials must be included carbon. Although its oxidation resistance is generally poor, so that it can only be used at high temperatures in a protective atmosphere or vacuum, it can be obtained in a range of crystalline or vitreous

forms, depending on the production process adopted, so that its extremely high melting point can be exploited.

Production and Consolidation Processes

The constituent compounds of ceramic materials are derived either from naturally occurring deposits of suitable precursors, which may be purified by conventional chemical means and then thermally decomposed to yield the oxide, or by high-temperature exothermic reactions between the elements to be combined or between selected compounds of them, often gaseous, e.g. ammonia to produce nitrides. The required compounds are usually obtained in the form of powders or crystals, which may need milling to refine the grain size, and they must then be consolidated. This is the step that offers considerable scope for the development of special methods appropriate to individual materials. The common methods include slip casting, cold pressing or paste extrusion, all followed by sintering; hot pressing; hot isostatic pressing; activated or reaction sintering; fusion casting; and deposition by chemical vapours or by pyrolytic decomposition. In most all these processes the effect of particle size of the powders, and of the presence of small proportions of impurities or added compounds, may have critical effects on the properties of the resultant material.

The shaping of ceramic or refractory materials to the required form presents considerable difficulties since many of them, and certainly the more advanced fully-densified materials, can only be machined by the use of diamond tools. The tendency, therefore, is to employ the materials in relatively simple forms which can be produced directly by the consolidation process, or to machine in the "green" or partly-sintered condition, with allowance for shrinkage in final sintering to be within acceptable limits. Research on consolidation and processes and their effects on shrinkage and resultant mechanical and physical properties are hence of major relevance in the application of these materials.

Mechanical, Physical and Chemical Properties

Ceramic materials are essentially brittle in character and their mechanical properties cannot be directly compared with those of ductile metal alloys, since different testing procedures are adopted. Bend tests normally take the place of tensile tests and the fracture stress is reported on a statistical basis since the results are more scattered due to the influence of minor flaws. Nevertheless measurements of bend strength against temperature and of time to fracture against bending stress provide a suitable basis for the comparison of different high-temperature ceramics and for the assessment of their temperatures of serviceability. These data need to be supplemented by determinations of impact strength and thermal shock resistance, which properties, in general, are much lower than those for metals. Application of recent developments in fracture mechanics should improve the confidence with which these brittle materials can be used.

The physical and chemical properties of ceramic materials are required for design guidance, with particular attention being paid to the influence of environmental attack on fracture characteristics. Surface changes may promote or inhibit crack propagation.

Testing

Procedures for inspection and testing, and analysis of service failures must be developed and applied in exactly the same manner already referred to for metallic materials.

AE 8007
AIRCRAFT MATERIALS



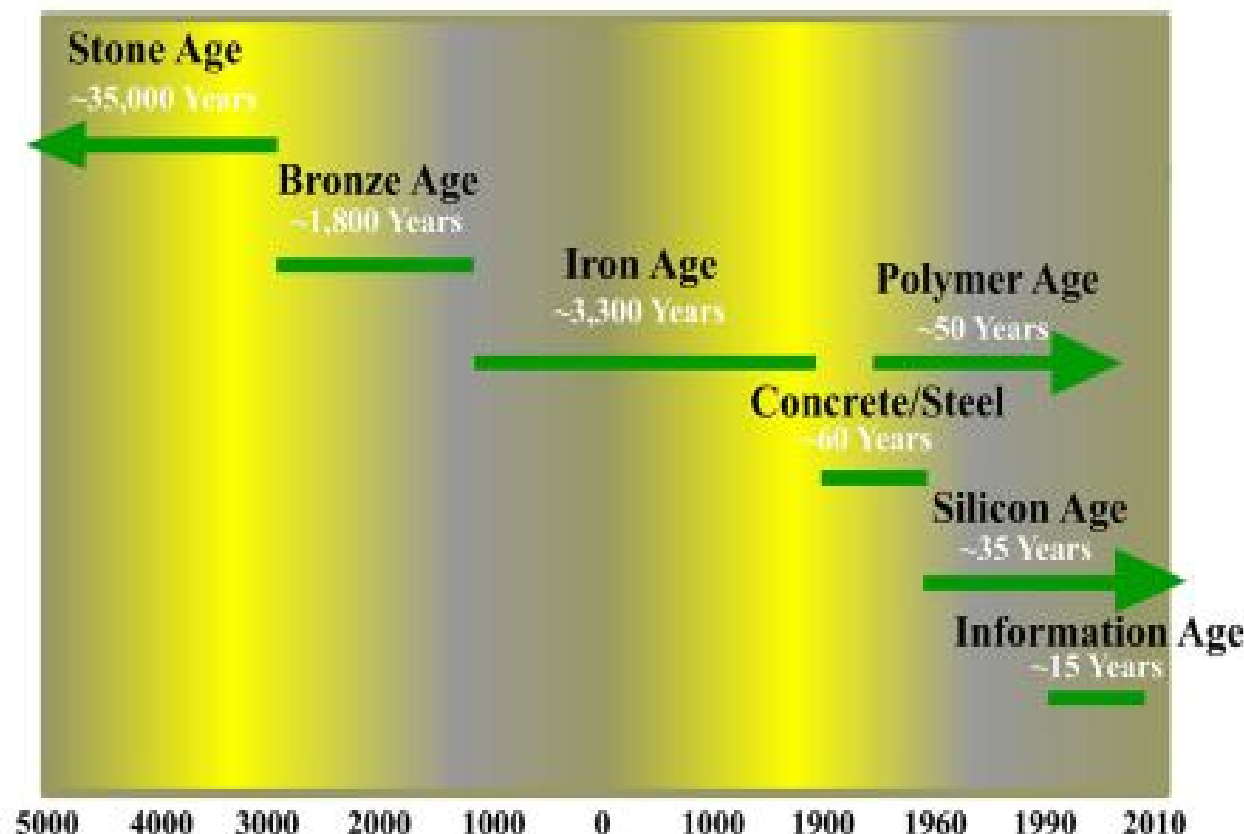
UNIT -1

Materials in day to day life



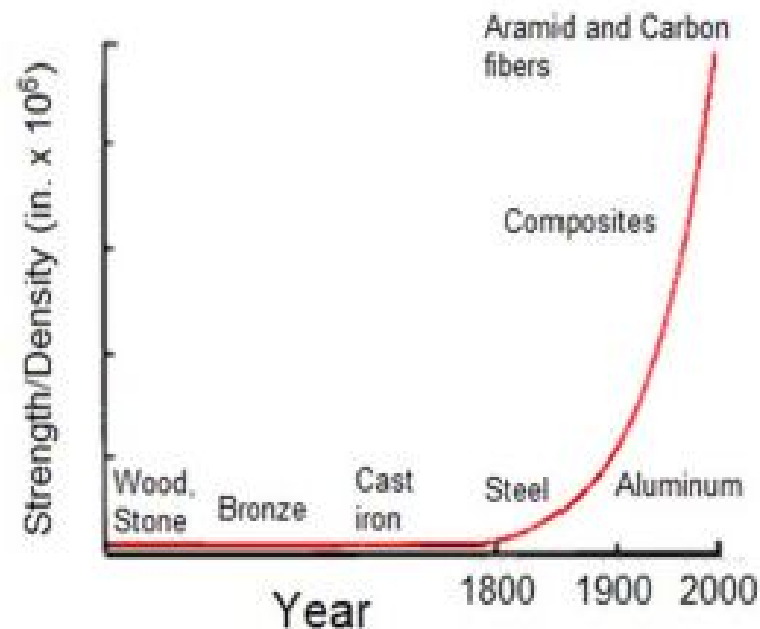
Materials: The Milestones of Progress

- Development and advancement of Human societies- closely related with materials
- Civilizations have been named based on the level of their materials development – Stone age, Bronze age etc.



Quest for newer materials:

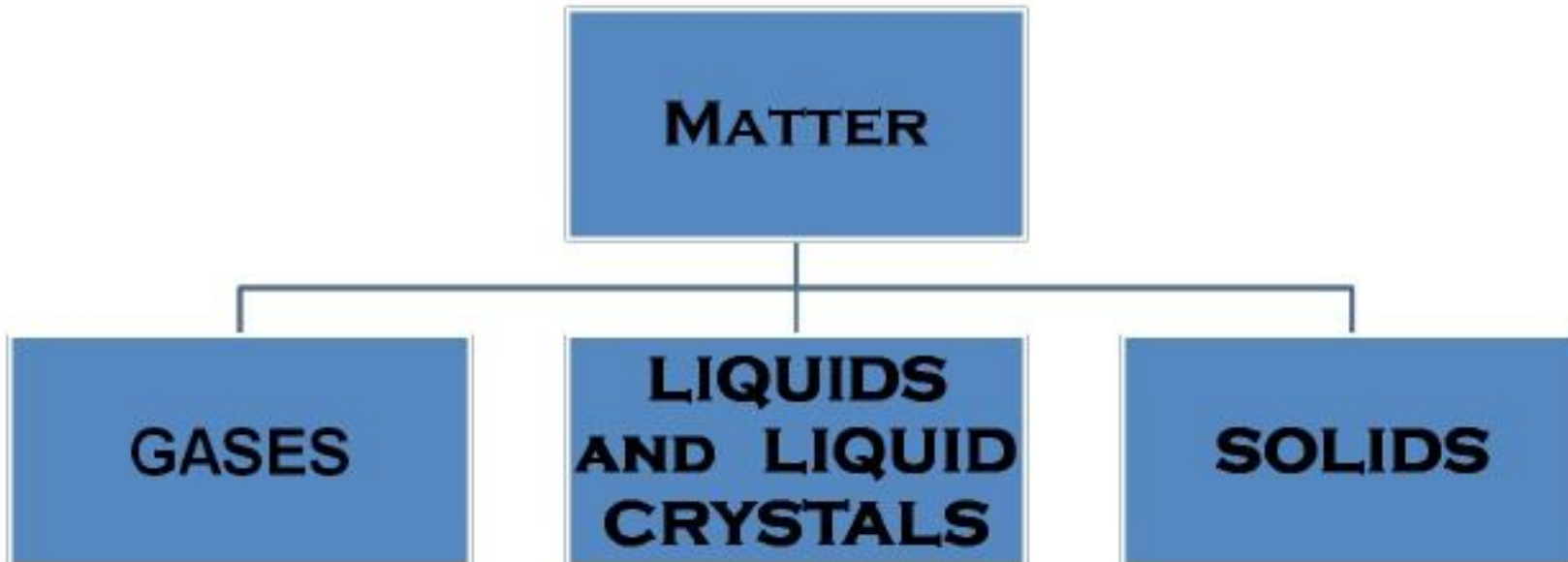
The driving force for the progress- stone age to IT age



Quest for more advanced materials to meet the growing needs as the civilization progressed.

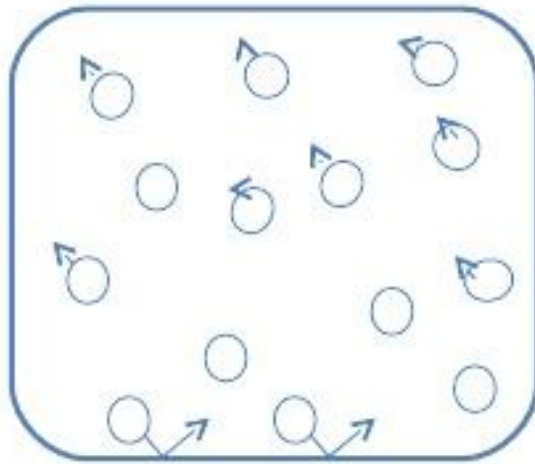
A look at the history of materials chronologically clearly reveals this

MATTER



Gases

- Gases have atoms or molecules that do not bond to one another in a range of pressure, temperature and volume.
- These molecules haven't any particular order and move freely within a container.

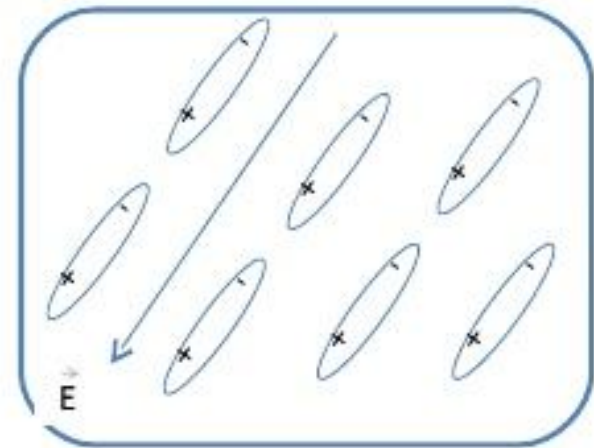


Crystal Structure

Liquids and Liquid Crystals

- Similar to gases, liquids haven't any atomic/molecular order and they assume the shape of the containers.
- Applying low levels of thermal energy can easily break the existing weak bonds.

Liquid crystals have mobile molecules, but a type of long range order can exist; the molecules have a permanent dipole. Applying an electric field rotates the dipole and establishes order within the collection of molecules.



Types of Solids

- Solids can be divided into two groups based on the arrangement of the atoms. These are
 - Crystalline
 - Amorphous

SOLID MATERIALS

CRYSTALLINE

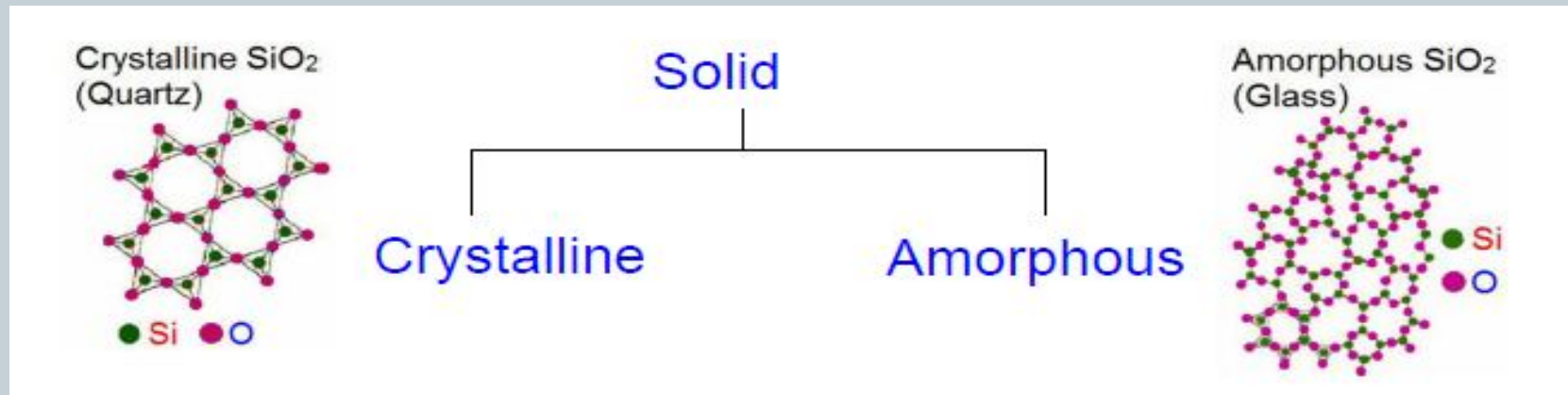
POLYCRYSTALLINE

**AMORPHOUS
(NON-CRYSTALLINE)**

Single Crystal



Atomic arrangement



Crystalline – periodic arrangement of atoms: definite repetitive pattern

Non-crystalline or **Amorphous** – random arrangement of atoms.

Types of Solids

- In a Crystalline solid, atoms are arranged in an orderly manner. The atoms are having long range order.
 - Example : Iron, Copper and other metals, NaCl etc.
- In an Amorphous solid, atoms are not present in an orderly manner. They are haphazardly arranged.
 - Example : Glass

Crystals

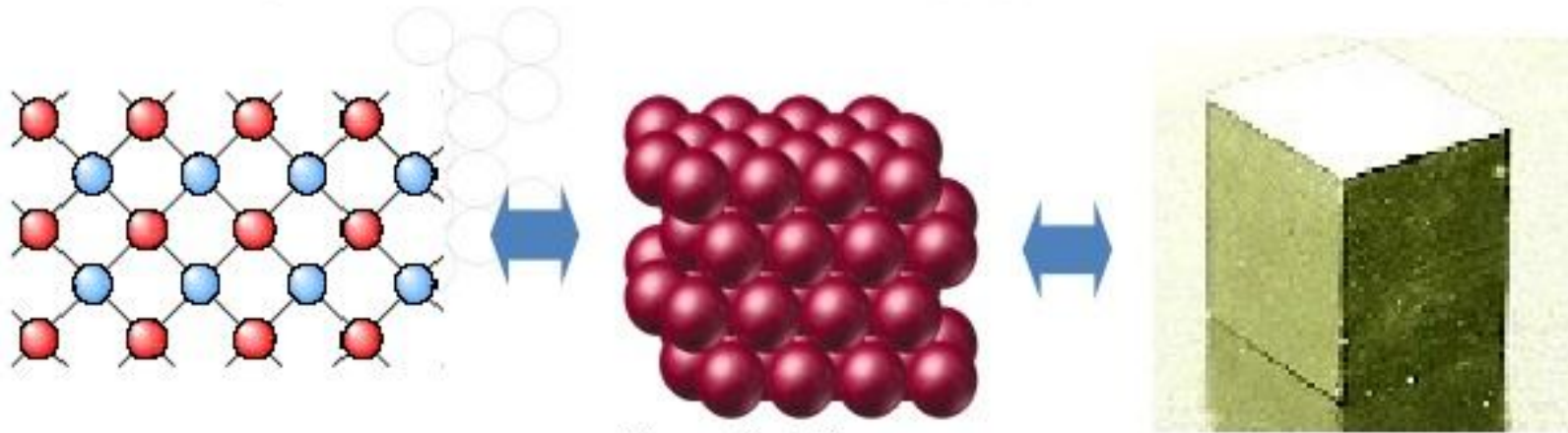
- Solids consist of atoms or molecules **executing thermal motion** about an equilibrium position **fixed at a point** in space.
- Solids can take the form of crystalline, polycrystalline, or amorphous materials.
- Solids (at a given temperature, pressure, and volume) **have stronger bonds** between molecules and atoms than liquids.
- Solids **require more energy** to **break the bonds**.

Some Definitions

- ❑ **Crystalline material** is a material comprised of one or many crystals. In each crystal, atoms or ions show a long-range periodic arrangement.
- ❑ **Single crystal** is a crystalline material that is made of only one crystal (there are no grain boundaries).
- ❑ **Grains** are the crystals in a polycrystalline material.
- ❑ **Polycrystalline material** is a material comprised of many crystals (as opposed to a single-crystal material that has only one crystal).
- ❑ **Grain boundaries** are regions between grains of a polycrystalline material.

Crystalline Solid

- Crystalline Solid is the solid form of a substance in which the **atoms or molecules** are arranged in a definite, repeating pattern in three dimension.
- Single crystals, ideally **have a high degree of order**, or regular geometric periodicity, throughout the **entire volume of the material**.

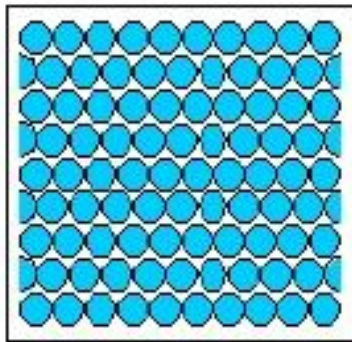


(a) Crystalline solid

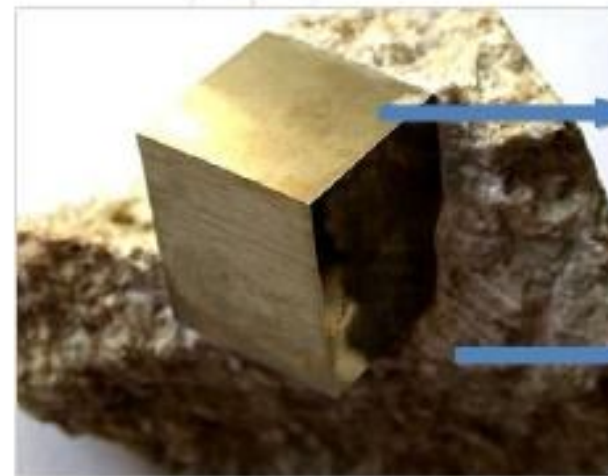
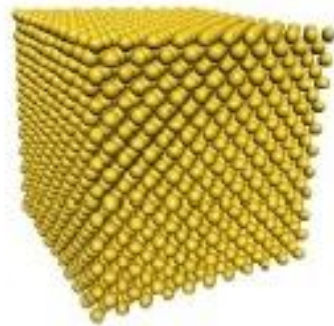
Crystal Structure

Crystalline Solid

- Single crystal has an atomic structure that repeats periodically across its whole volume. Even at infinite length scales, each atom is related to every other equivalent atom in the structure by translational symmetry



Single Crystal

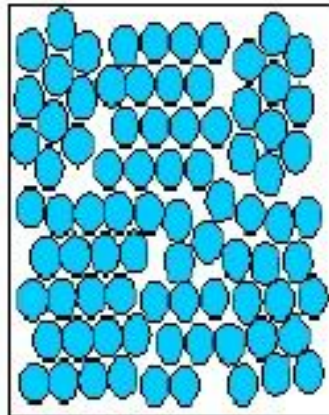


Single Pyrite
Crystal

Amorphous
Solid

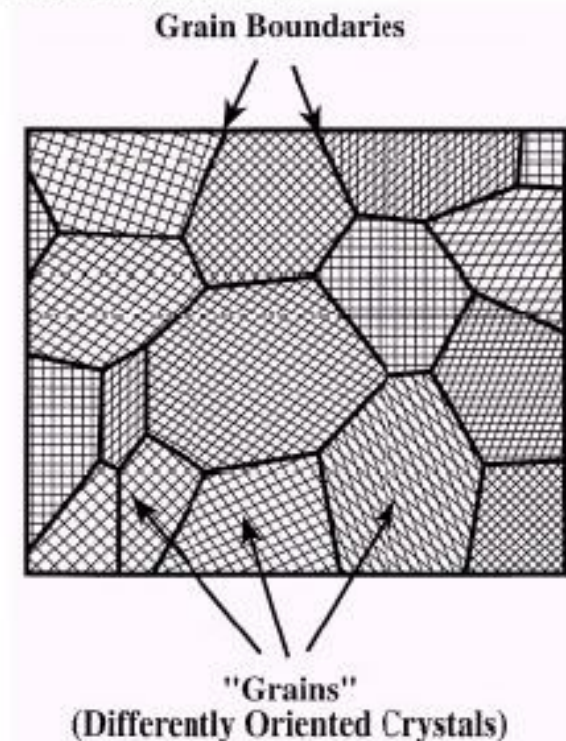
Polycrystalline Solid

- Polycrystal is a material made up of an aggregate of *many small single crystals* (also called crystallites or grains).
- Polycrystalline material **have a high degree of order over many atomic or molecular dimensions.**



Polycrystalline
Pyrite form
(Grain)

Crystal Structure



- These *ordered regions*, or single crystal regions, **vary in size and orientation** wrt **one another**.
- These regions are called as *grains (domain)* and are separated from one another by *grain boundaries*. The **atomic order** can vary from **one domain to the next**.
- The grains are usually *100 nm - 100 microns in diameter*.
- Polycrystals with grains that are <10 nm in diameter are called **nanocrystalline**

Atomic structure



- An atom consists of a nucleus composed of protons and neutrons and electrons which encircle the nucleus.
- Protons and electrons have same and opposite charge of $1.6 \times 10^{-19} \text{ C}$.
- Atomic number (Z) = Number protons = number of electrons.
- Atomic mass (A) = proton mass + neutron mass.
- Isotopes are the same element having different atomic masses. Number of protons in isotopes remains same while number of neutrons varies.

Atomic Bonding



- The mechanisms of bonding between the atoms are based on the foregoing discussion on electrostatic interatomic interaction.
- The types of bond and bond strength are determined by the electronic structures of the atoms involved.
- The valence electrons take part in bonding. The atoms involved acquire, loose or share valence electrons to achieve

Primary Bonds

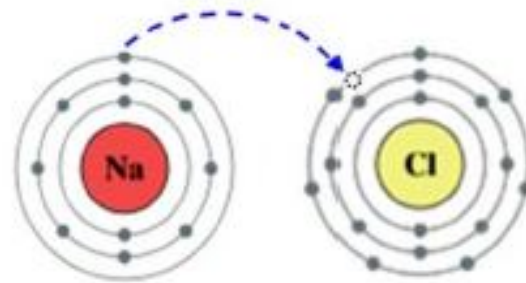


Three types primary bonds are found in solids

- Ionic
 - Covalent
 - Metallic
- Majority of the engineering materials consist of one of these bonds. Many properties of the materials depend on the specific kind of bond and the bond energy.

Ionic Bond

Ionic bonds are generally found in compounds composed of metal and non-metal and arise out of electrostatic attraction between oppositely charged atoms (ions).

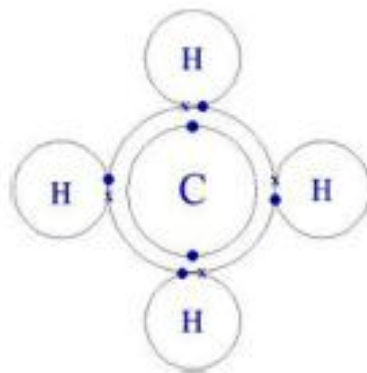


Number of electron in outer shell is 1 in Na and 7 in Cl .
Therefore, Na will tend to reject one electron to get stable configuration of Ne and Cl will accept one electron to obtain Ar configuration. The columbic attraction between Na^+ and Cl^- ions thus formed will make an ionic bond to produce NaCl. Some other examples are CaF_2 , CsCl , MgO , Al_2O_3 .

Covalent Bond

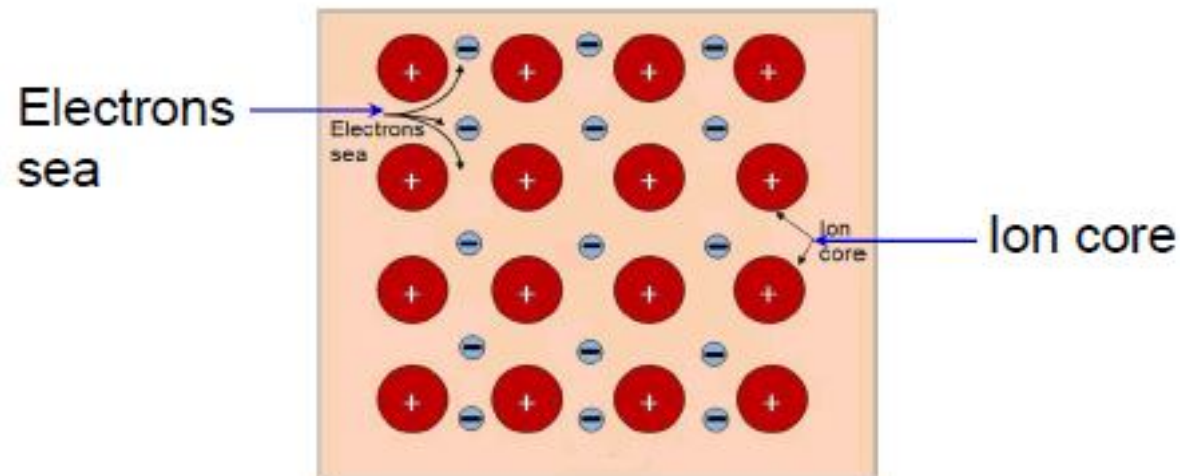
In this type of bonding, atoms share their valence electrons to get a stable configuration.

❖ Methane (CH_4): Four hydrogen atoms share their valence electrons with one carbon atom and the carbon atom in turn shares one valence electron with each of the four hydrogen atoms. In the process both H and C atoms get stable configuration and form a covalent bond.



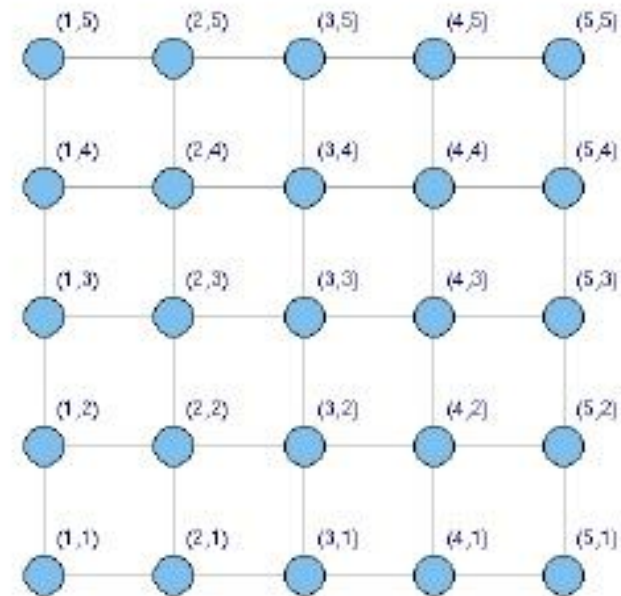
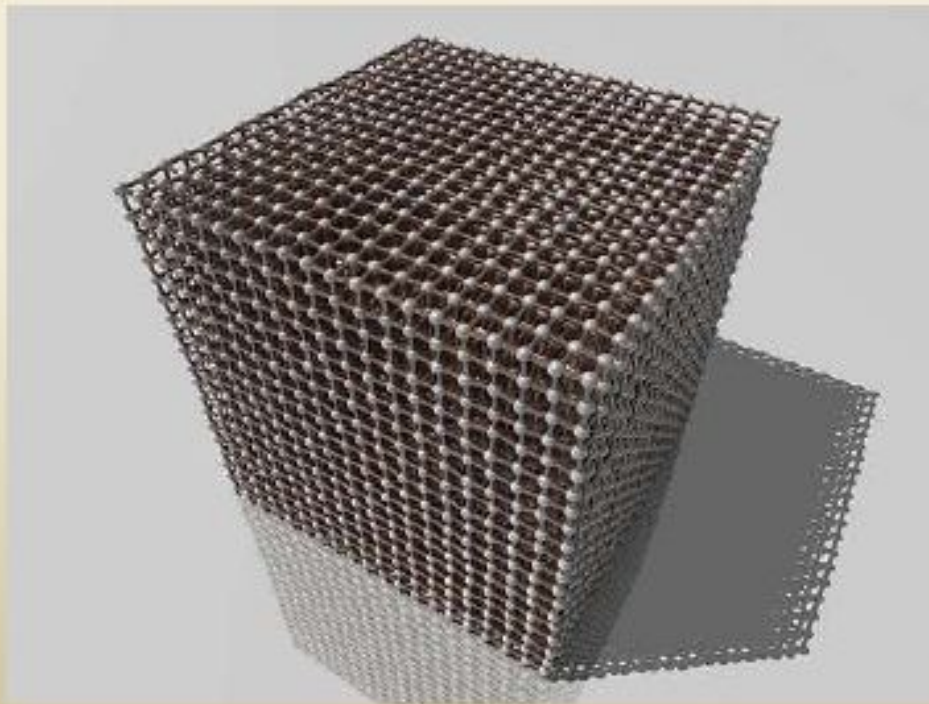
Metallic Bond

In metals the valence electrons are not really bound to one particular atom, instead they form a sea or cloud of valence electrons which are shared by all the atoms. The remaining electrons and the nuclei form what is called the ion core which is positively charged. The metallic bond arises out of the columbic attraction between these two oppositely charged species – the electron cloud and the ion cores.



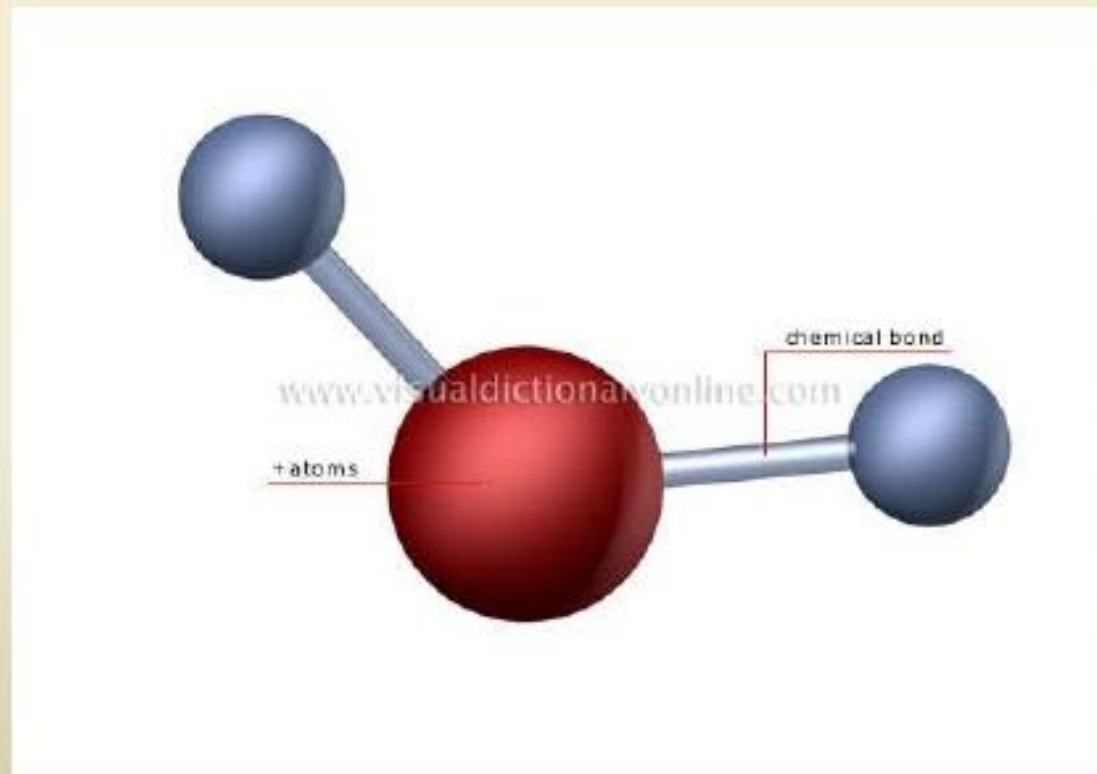
Lattice

- Regular , periodical arrangements of points in three dimension.
- Lattice point : The points which presents in the lattice



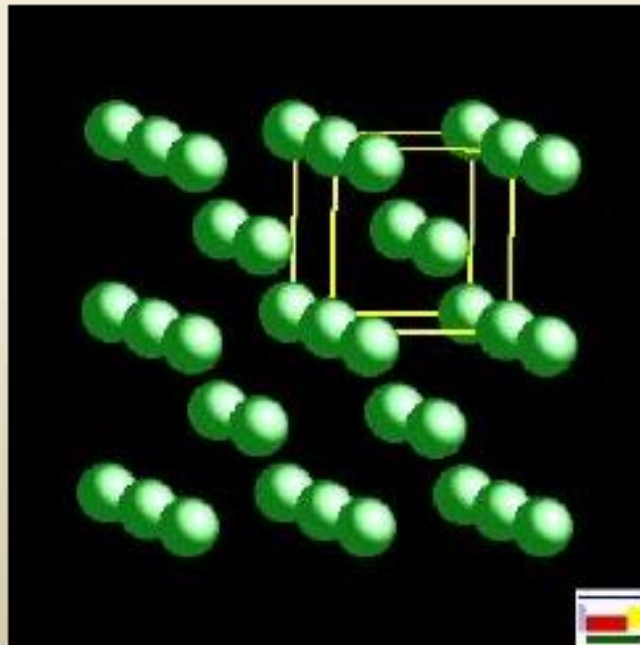
Basis

- Group of atom is called as basis



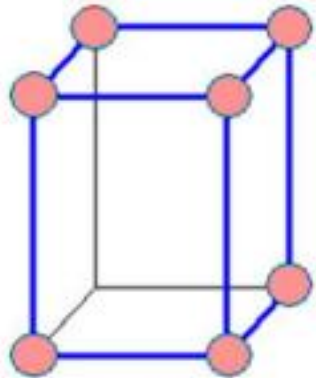
Crystal structure

- Lattice + basis = crystal structure
- Crystal structure is obtained by arranging the basis in each and every lattice point

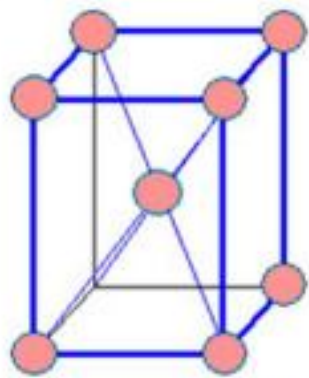


Crystal Systems

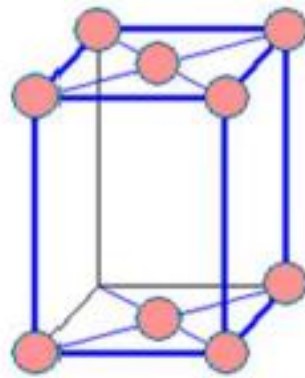
Orthorhombic: $a \neq b \neq c$, $\alpha = \beta = \gamma = 90^\circ$



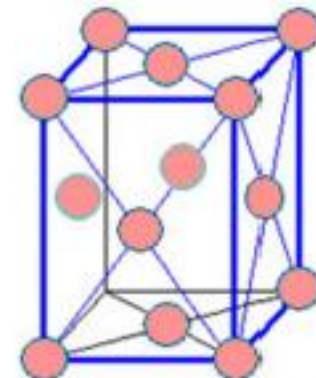
Simple



Body-centered

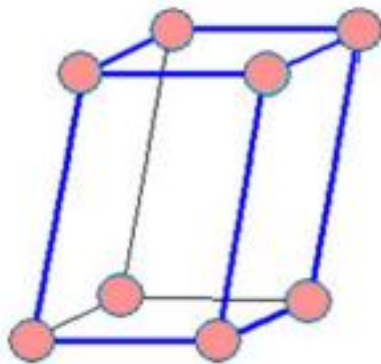


Base-centered

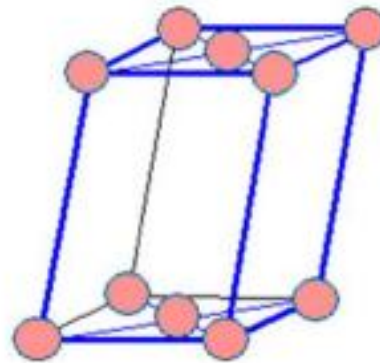


Face-centered

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



Simple
monoclinic

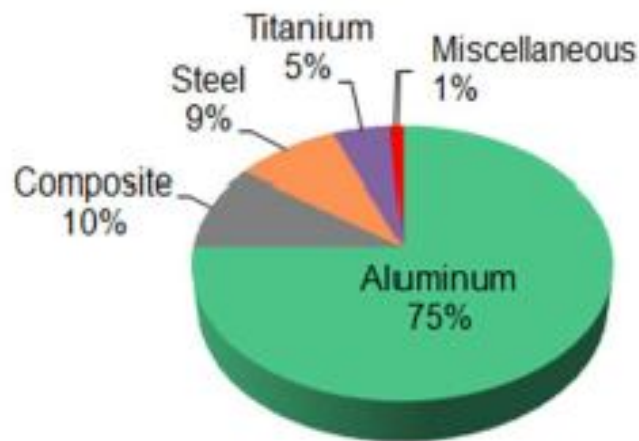


Base-centered
monoclinic

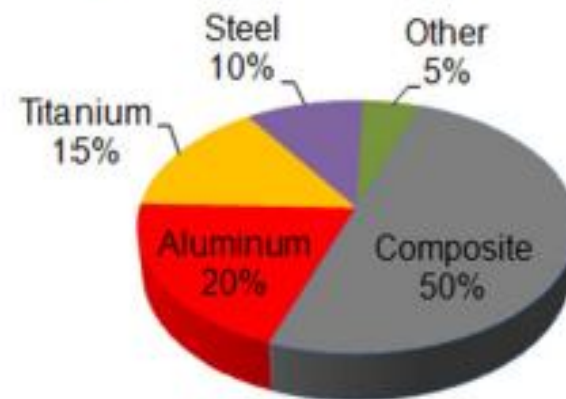
Invention of Aeroplane

- ❑ From Wright Brothers' invention in 1902 To today's Aircraft
- ❑ Materials played a very important role in this case also
- ❑ Use of advanced materials - Stronger, lighter and better aerodynamic design, greater speed.
- ❑ Boeing 777, for example, used 75% aluminum whereas half of the materials used in the advanced version 787 is fiber reinforced composite.

Total materials used by weight



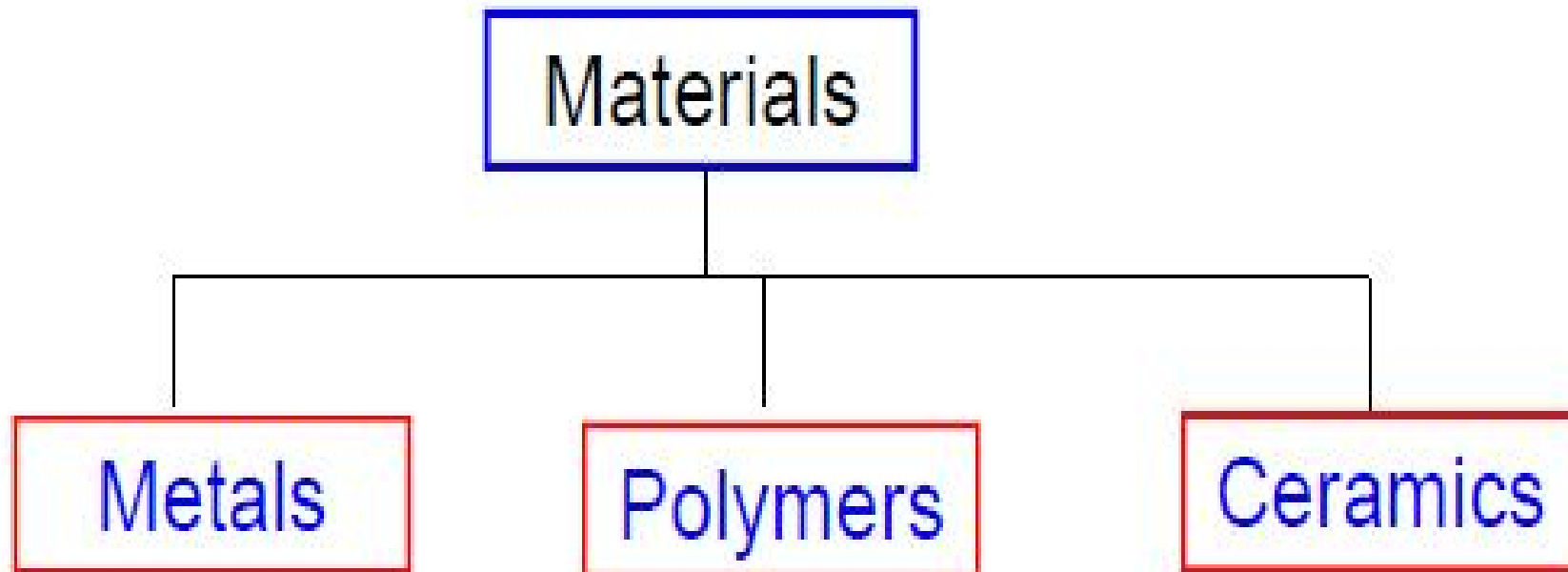
Boeing 777



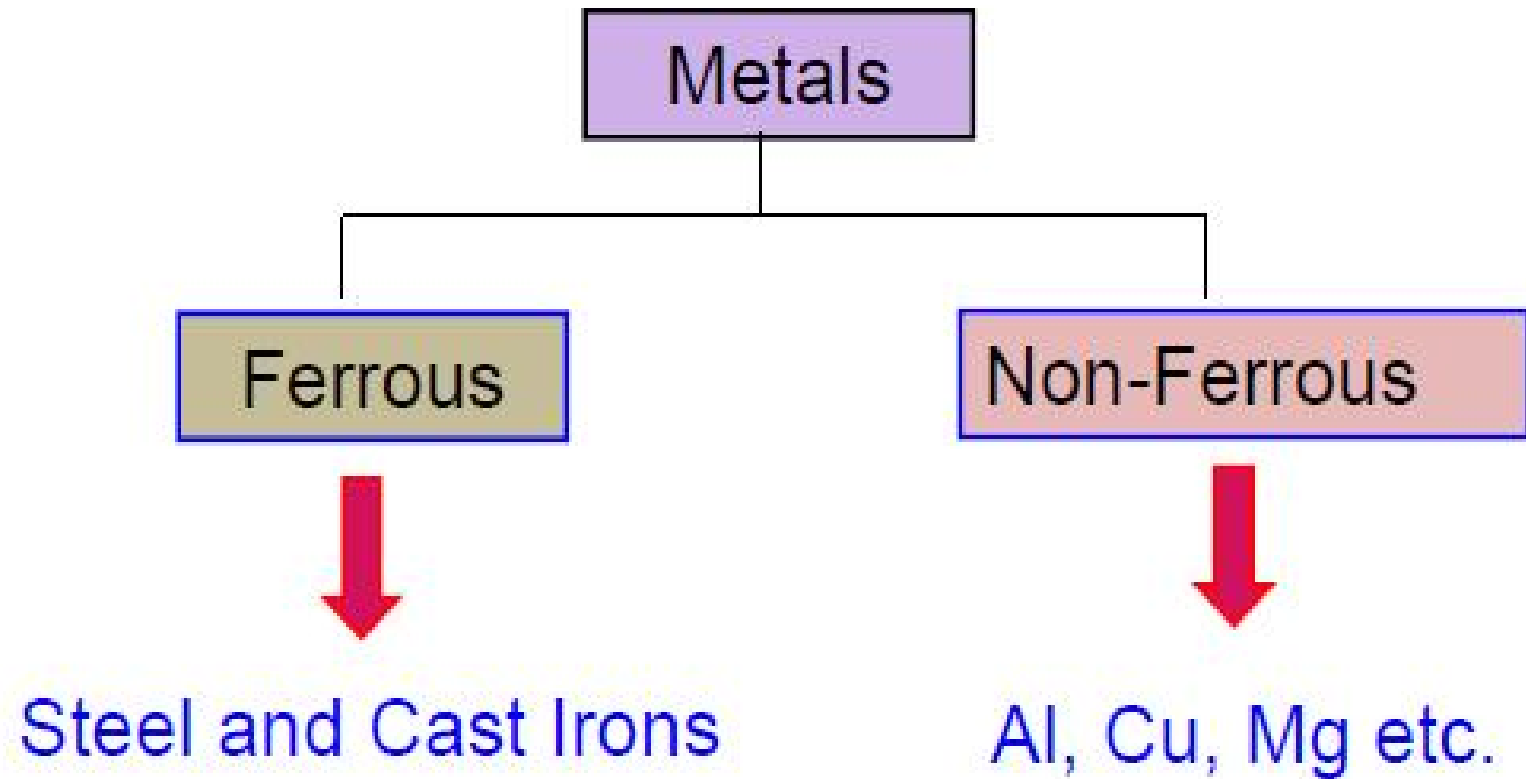
Boeing 787

(Source: Boeing)

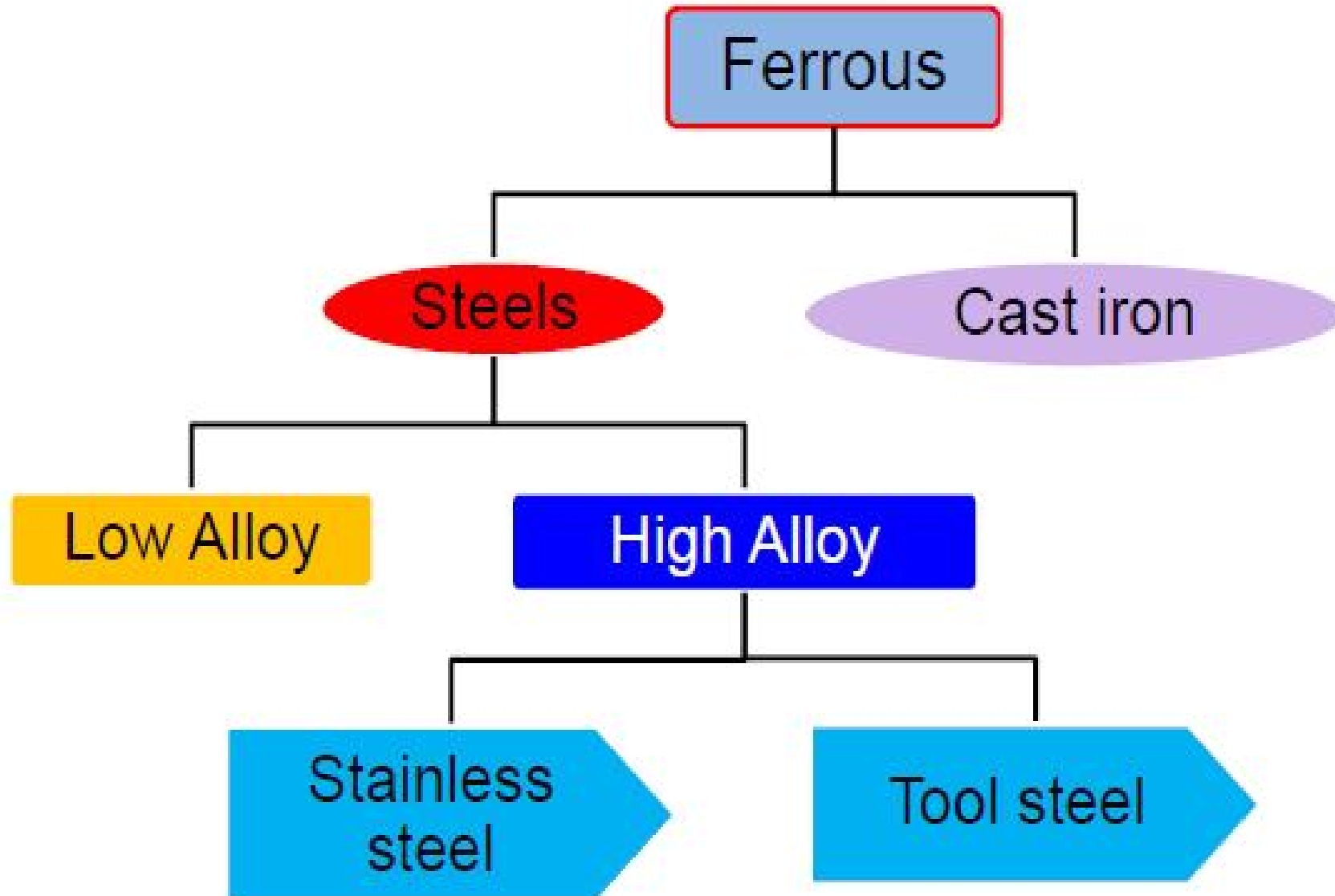
Classification of Materials



Metals

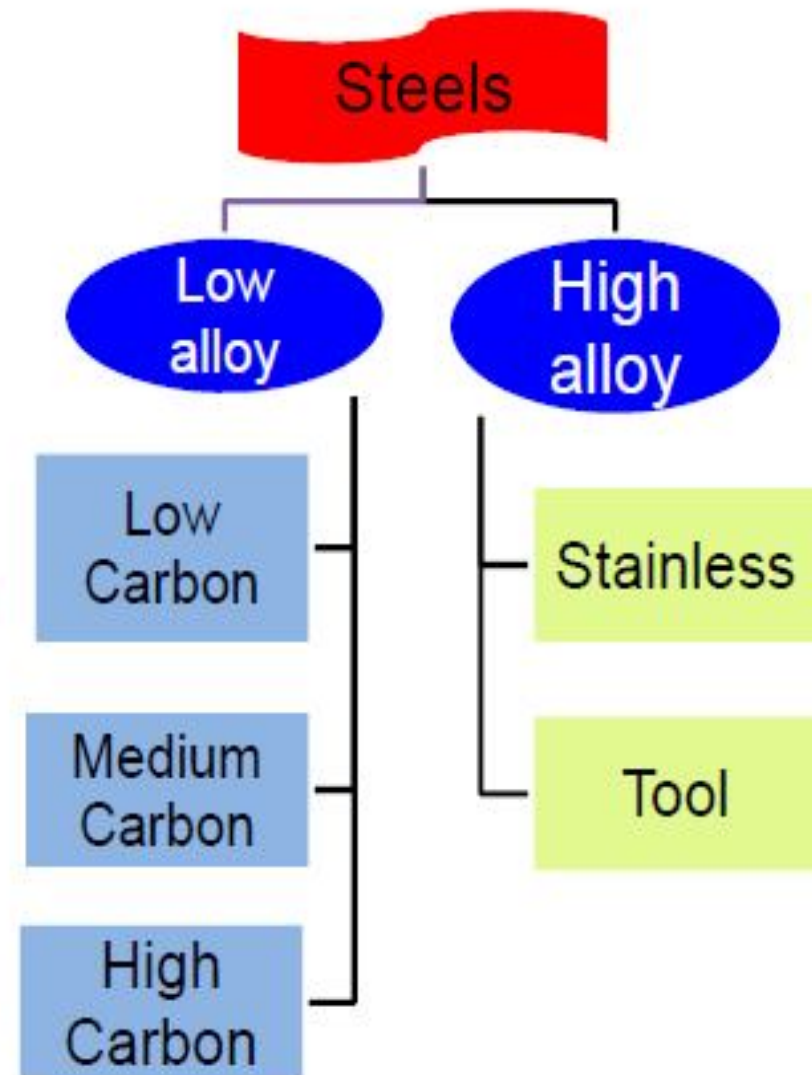


Ferrous Materials



Ferrous Materials - Steels

- Steels - alloys of iron-carbon. May contain other alloying elements.
- Several grades are available.
- Low Alloy (<10 wt%)
 - Low Carbon (<0.25 wt% C)
 - Medium Carbon (0.25 to 0.60 wt%)
 - High Carbon (0.6 to 1.4 wt%)
- High Alloy
 - Stainless Steel (> 11 wt% Cr)
 - Tool Steel



Nonferrous Metals

• Cu Alloys

Brass: Cu-Zn alloy.
Corrosion resistant. Used in costume jewelry, coins

Bronze : Cu – with Sn, Al, Si, Ni

Cu-Be:
precipitation hardened
(bushings, landing gear)

• Ti Alloys

relatively low ρ : 4.5 g/cc
reactive at high T 's
space and biomedical application

• Al Alloys

-low ρ : 2.7 g/cm³
-Cu, Mg, Si, Mn, Zn additions
-solid solution or precipitation strengthened (structural aircraft parts & packaging)

• Mg Alloys

-very low ρ : 1.7g/cm³
-ignites easily
-aircraft, missiles

• Refractory metals

-high melting T 's
-Nb, Mo, W, Ta

Nonferrous

Noble metals
- Ag, Au, Pt
oxidation/corrosion resistant

Effect of High Temperature on Metals: Alloys developed for successful use at high temperatures must cope with the following effects:

- (i) Lower strength.
- (ii) Greater atomic and dislocation mobility, assisting dislocation climb and diffusion.
- (iii) Higher equilibrium concentration of vacancies.
- (iv) New deformation mechanisms, such as new slip systems or grain boundary sliding.
- (v) Recrystallisation and grain growth.
- (vi) Age hardened alloys will overage by particle coarsening and lose strength.
- (vii) Oxidation and intergranular penetration.

creep



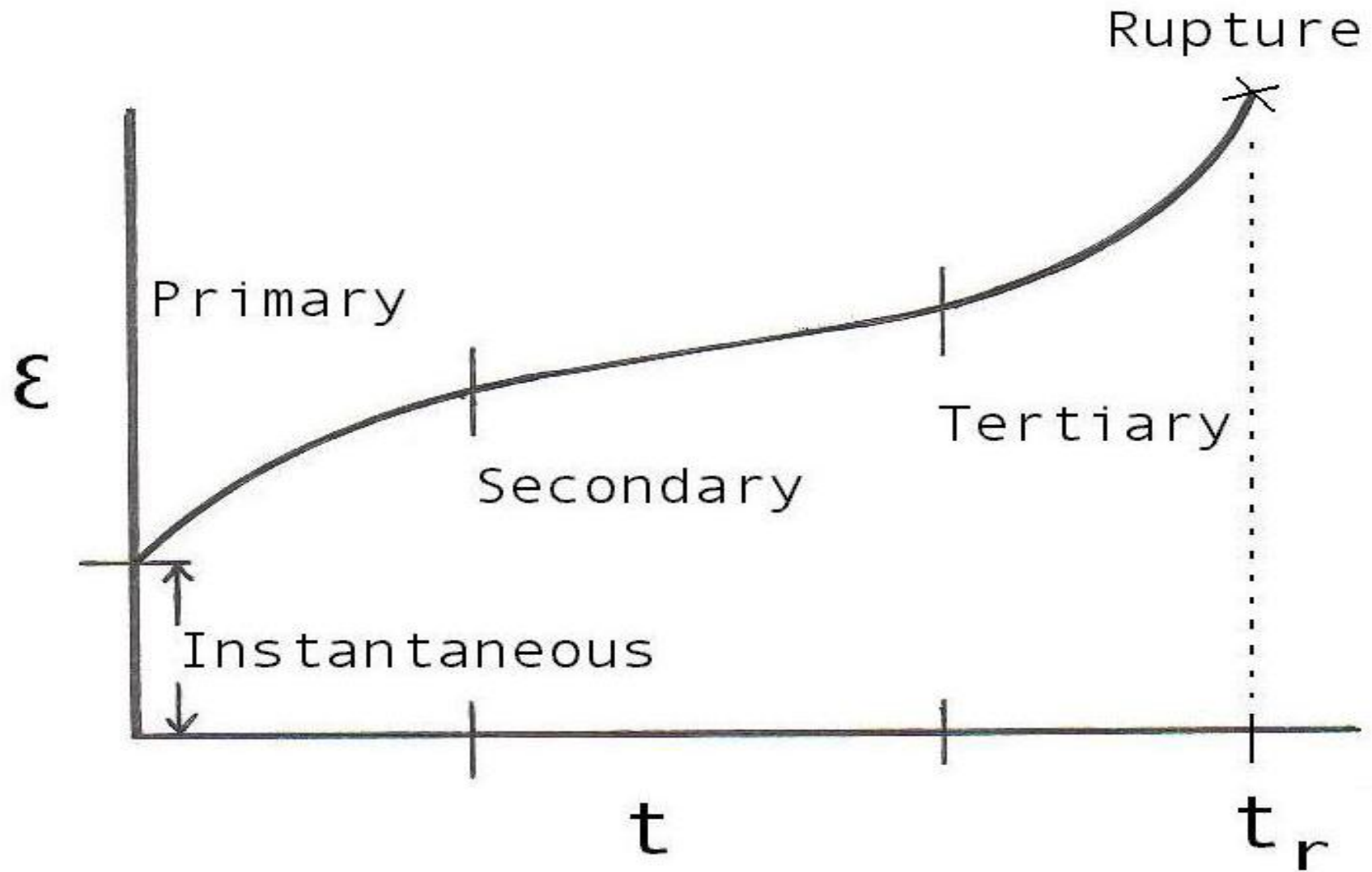
- Creep is the tendency of a solid material to slowly move or deform permanently under the influence of stresses. It occurs as a result of long term exposure to levels of stress that are below the yield strength of the material. Creep is more severe in materials that are subjected to heat for long periods, and near the melting point. Creep always increases with temperature

creep



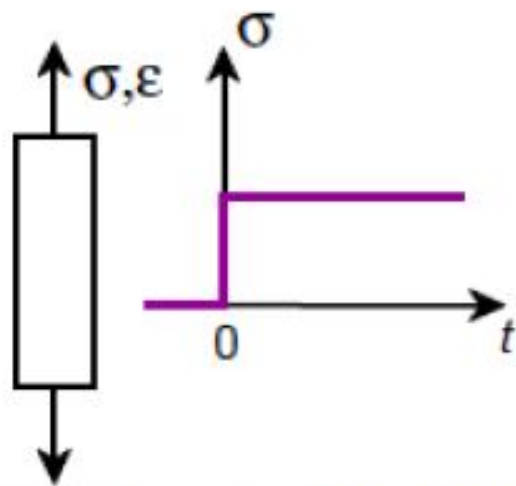
- The rate of this deformation is a function of the material properties, exposure time, exposure temperature and the applied structural load. Depending on the magnitude of the applied stress and its duration, the deformation may become so large that a component can no longer perform its function—for example creep of a turbine blade will cause the blade to contact the casing, resulting in the failure of the blade.

creep curve



Creep

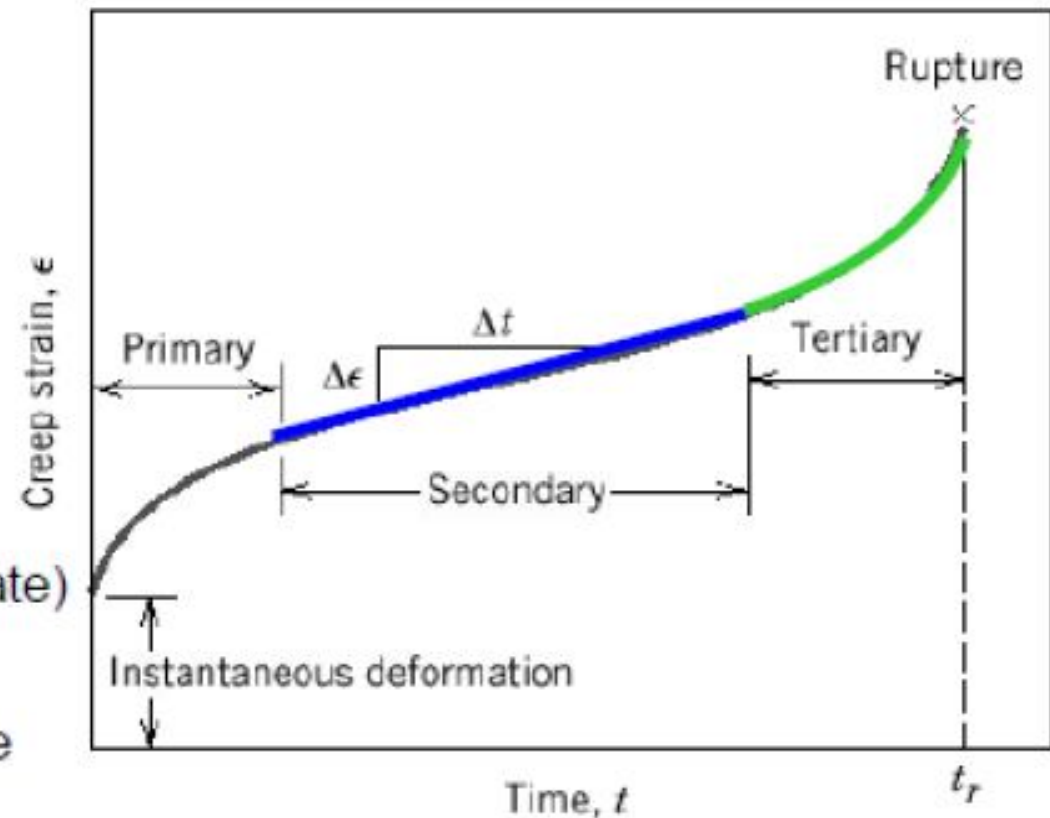
- Time dependent high temperature deformation under load.



Primary Creep: slope (creep rate) decreases with time.

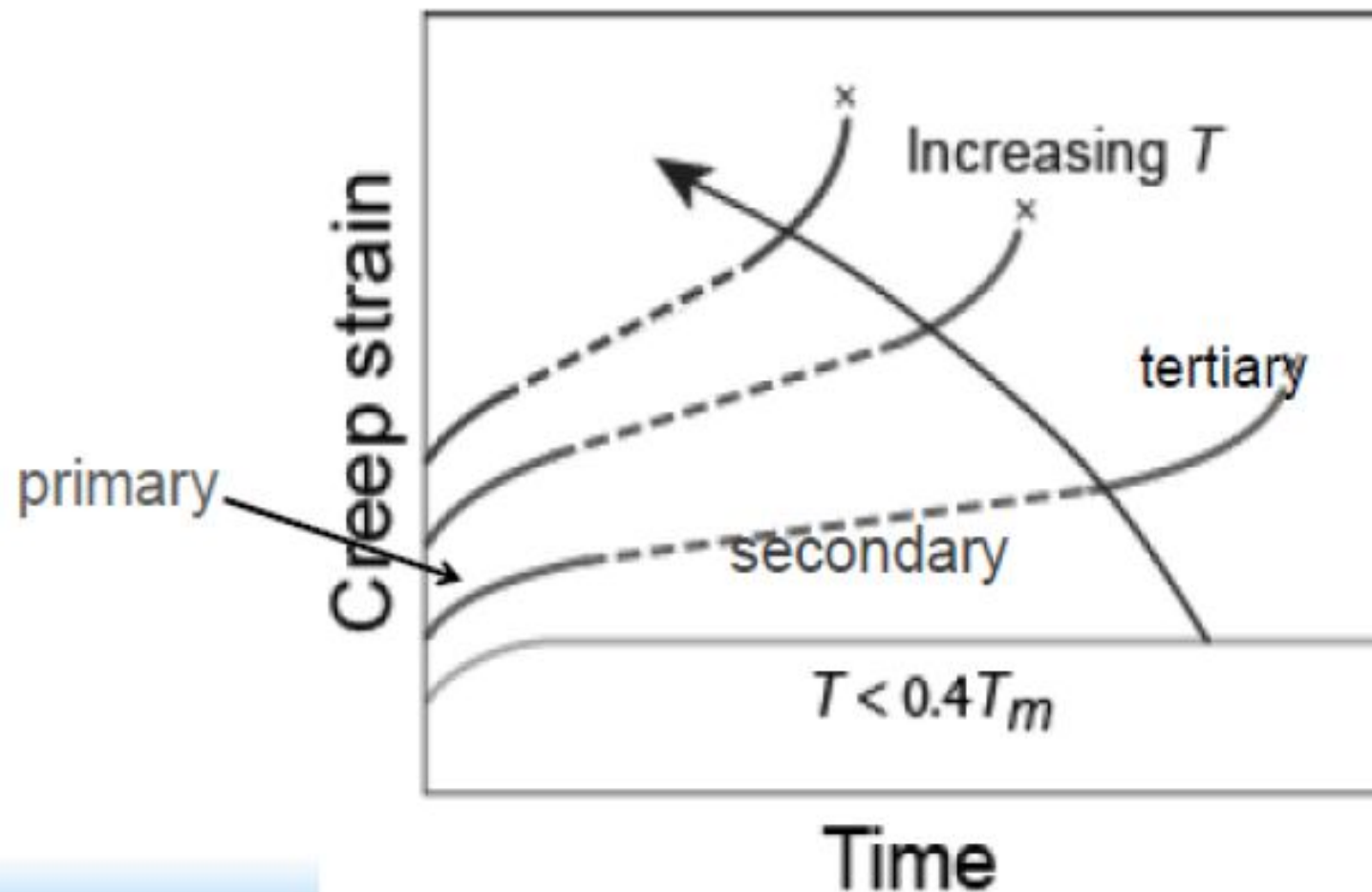
Secondary Creep: steady-state i.e., constant slope.

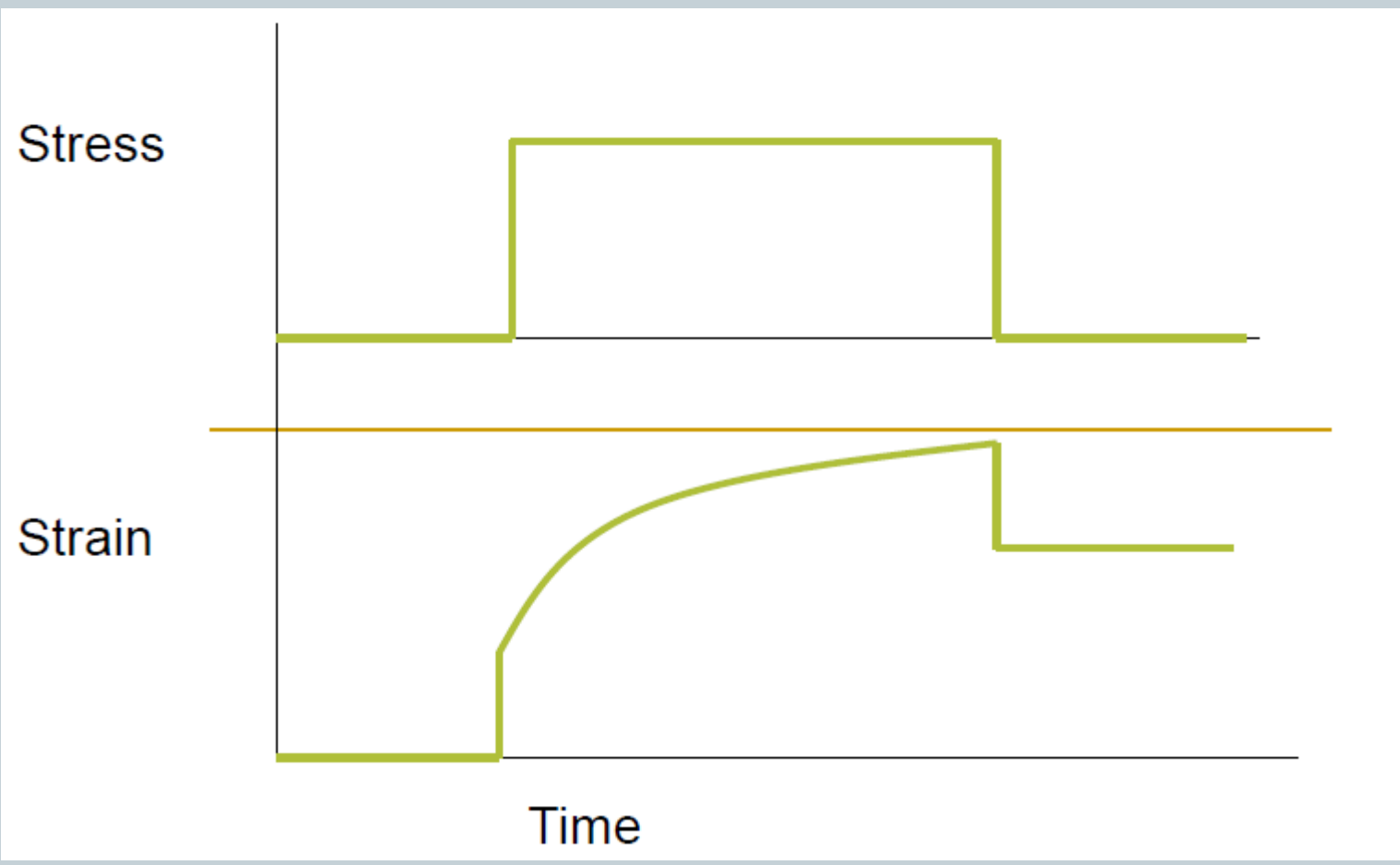
Tertiary Creep: slope (creep rate) increases with time, i.e. acceleration of rate.



Creep

- Occurs at elevated temperature, $T > 0.4 T_m$





Mechanisms of Creep in metals



- **Mechanisms of Creep in metals:** There are three basic mechanisms that can contribute to creep in metals, namely:
 - (i) Dislocation slip and climb.
 - (ii) Grain boundary sliding.
 - (iii) Diffusional flow.

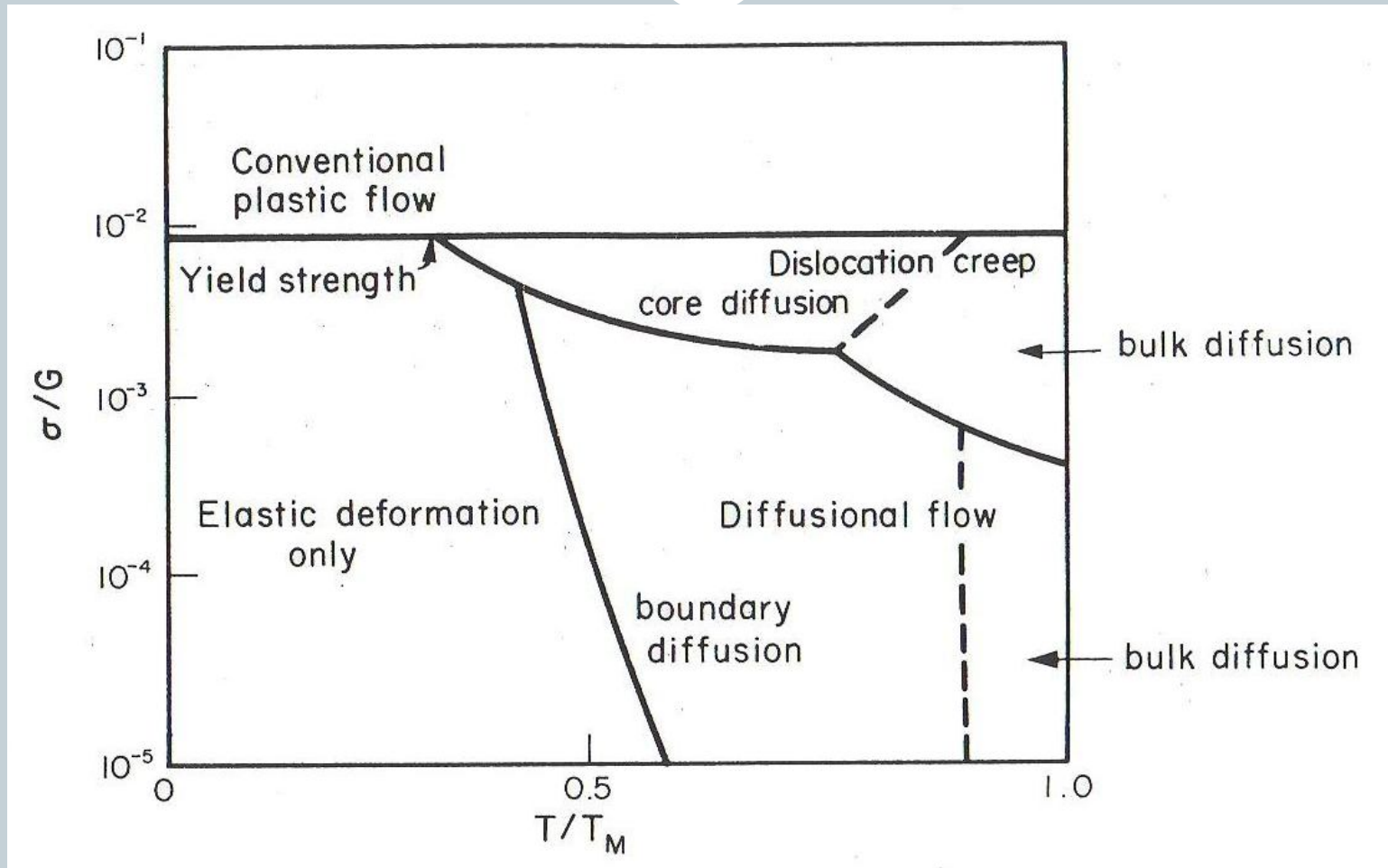


Mechanisms of creep

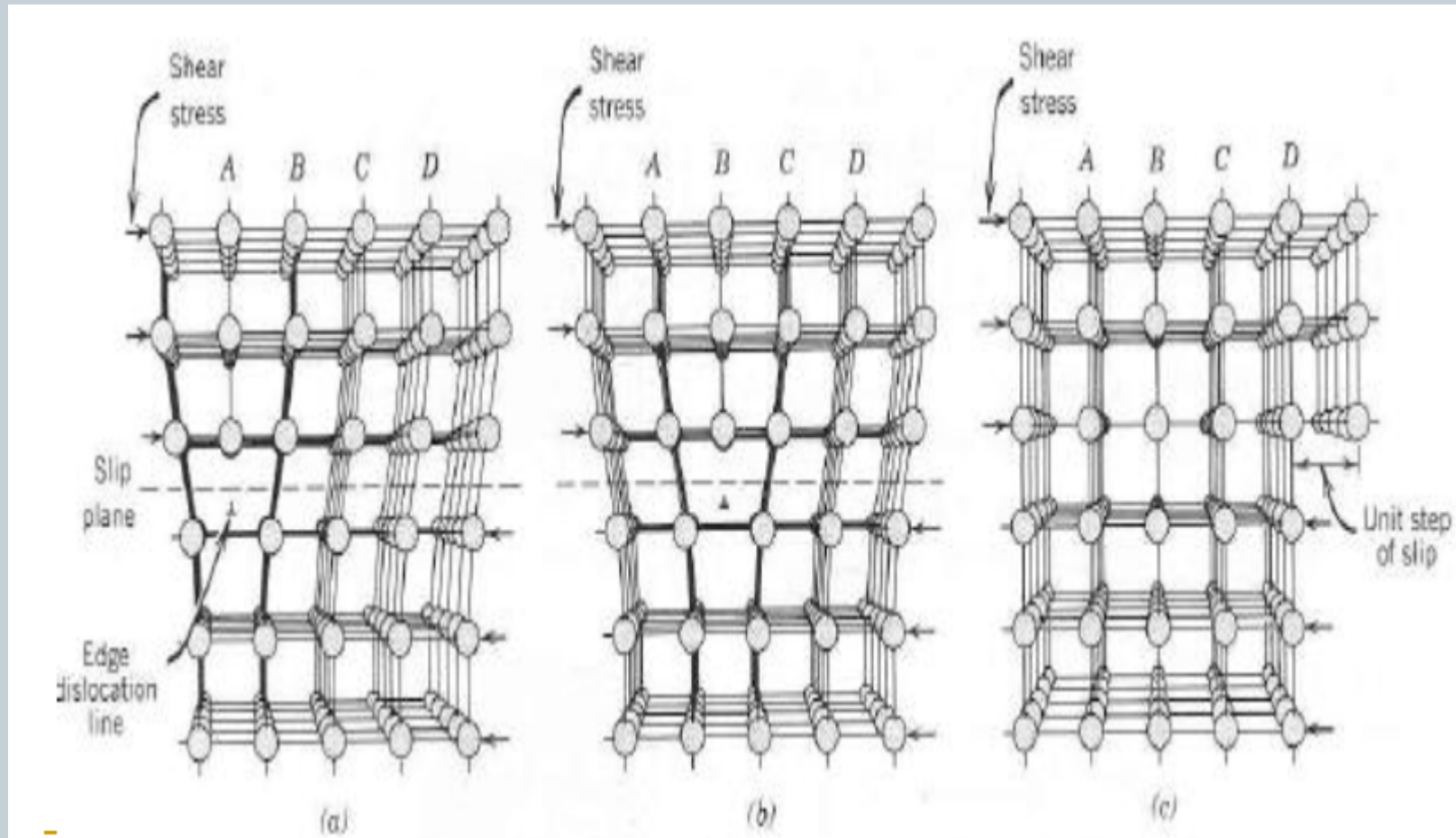
The mechanism of creep depends on temperature and stress. The various methods are:

- Thermally activated glide - e.g., via cross-slip
- Climb assisted glide - here the climb is an enabling mechanism, allowing dislocations to get around obstacles
- Climb - here the strain is actually accomplished by climb
- Grain boundary diffusion

Mechanisms of Creep



slip of an edge dislocation



Grain Boundary sliding



Grain Boundary sliding: The onset of tertiary creep is a sign that structural damage has occurred in an alloy. Rounded and wedge shaped voids are seen mainly at the grain boundaries and when these coalesce creep rupture occurs. The mechanism of void formation involves grain boundary sliding which occurs under the action of shear stresses acting on the boundaries.



Dislocation creep

At high stresses (relative to the shear modulus), creep is controlled by the movement of dislocations. When a stress is applied to a material, plastic deformation occurs due to the movement of dislocations in the slip plane.

Materials contain a variety of defects, for example solute atoms, that act as obstacles to dislocation motion.

examples



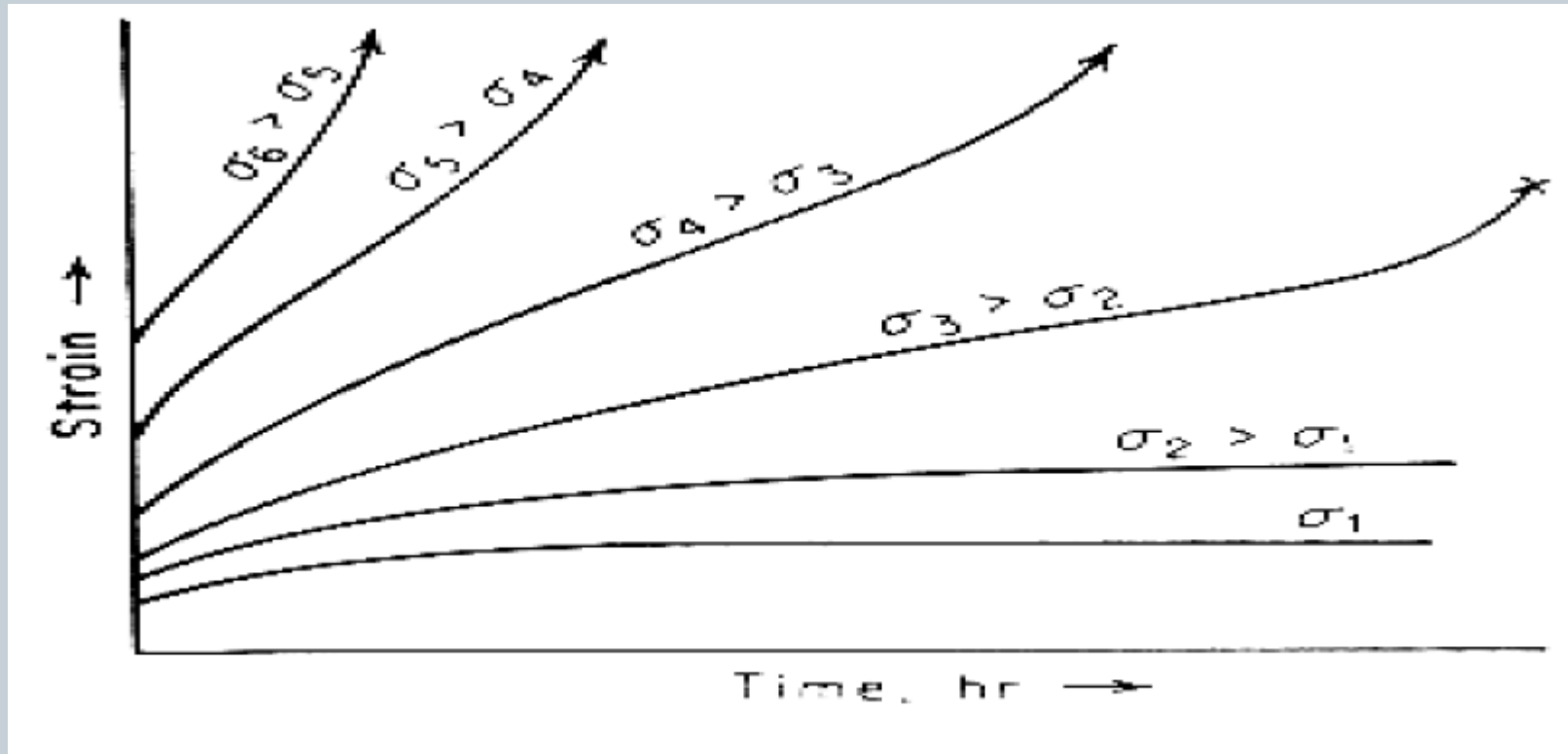
- An example of an application involving creep deformation is the design of tungsten lightbulb filaments. Sagging of the filament coil between its supports increases with time due to creep deformation caused by the weight of the filament itself. If too much deformation occurs, the adjacent turns of the coil touch one another, causing an electrical short and local overheating, which quickly leads to failure of the filament

examples



- **Other examples**
- Though mostly due to the reduced yield stress at higher temperatures, the Collapse of the World Trade Center was due in part to creep from increased temperature operation.
- The creep rate of hot pressure-loaded components in a nuclear reactor at power can be a significant design-constraint, since the creep rate is enhanced by the flux of energetic particles.
- Creep was blamed for the Big Dig tunnel ceiling collapse in Boston, Massachusetts that occurred in July 2006

Effect of stress on creep curves at constant temperature



UNIT -II

MECHANICAL BEHAVIOUR OF MATERIALS

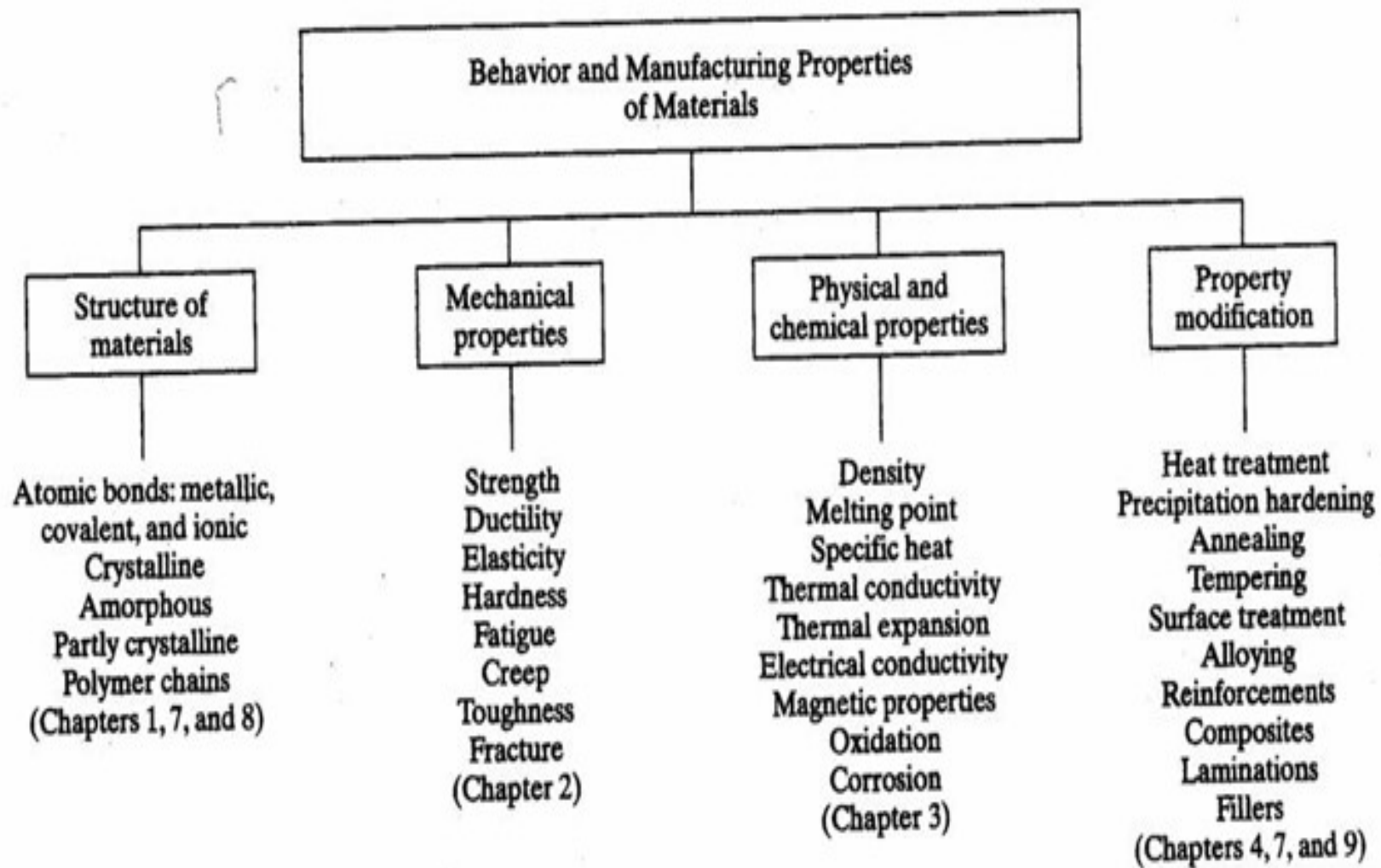
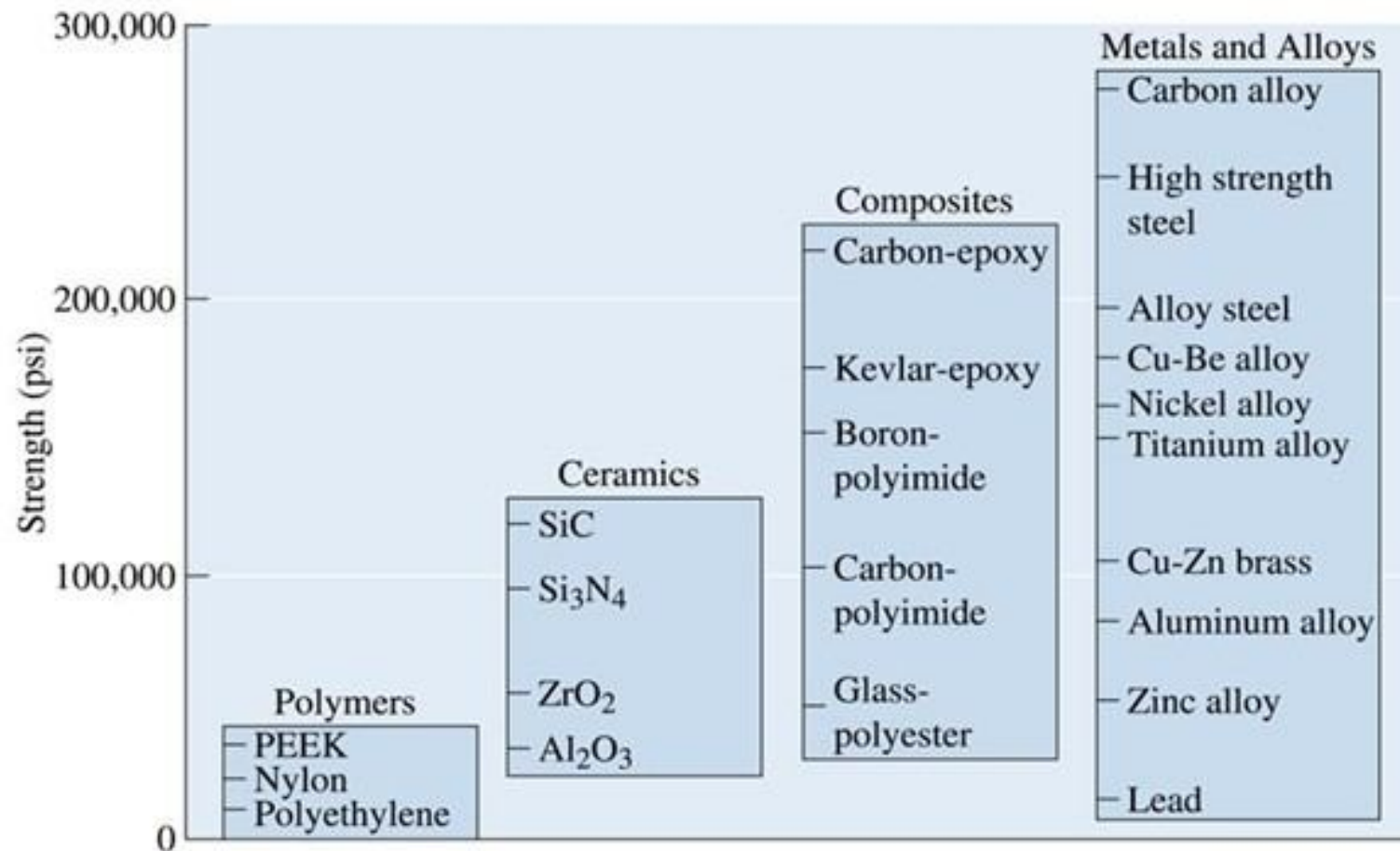
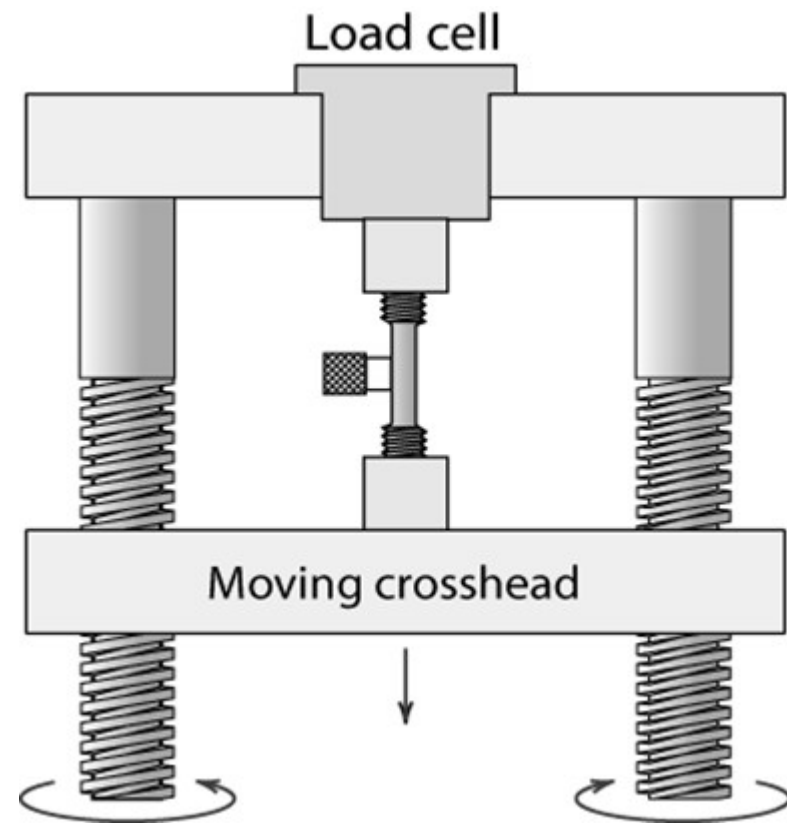
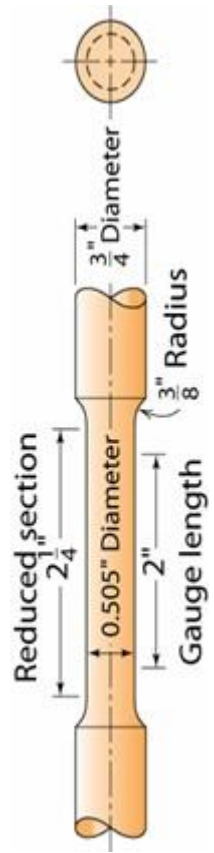


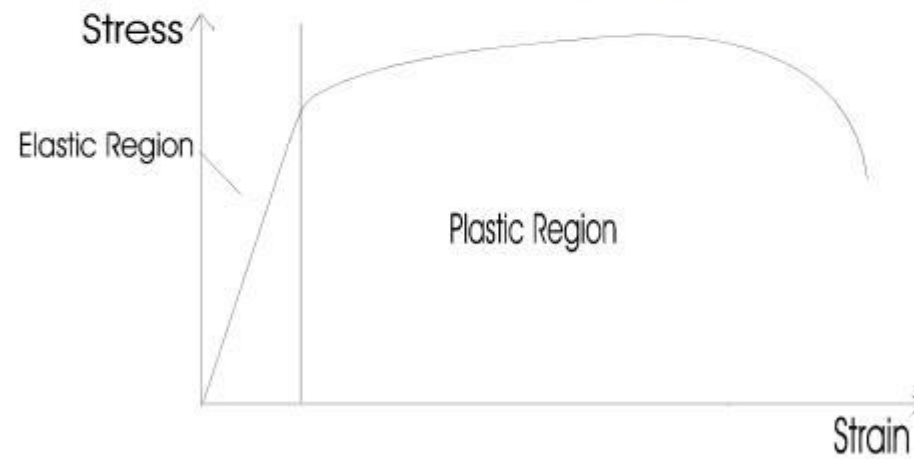
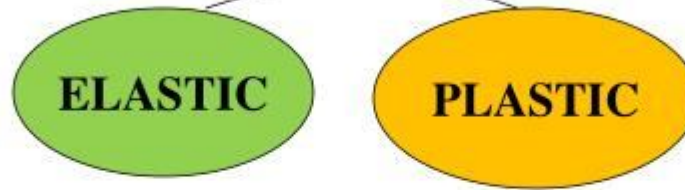
FIGURE I.3 An outline of the behavior and the manufacturing properties of materials described in Part I.

Strength of various materials





The Engineering Stress - Strain curve Divided into 2 regions



STRESS STRAIN CURVE SHOWS ELASTICITY AND PLASTICITY FOR MATERIALS:

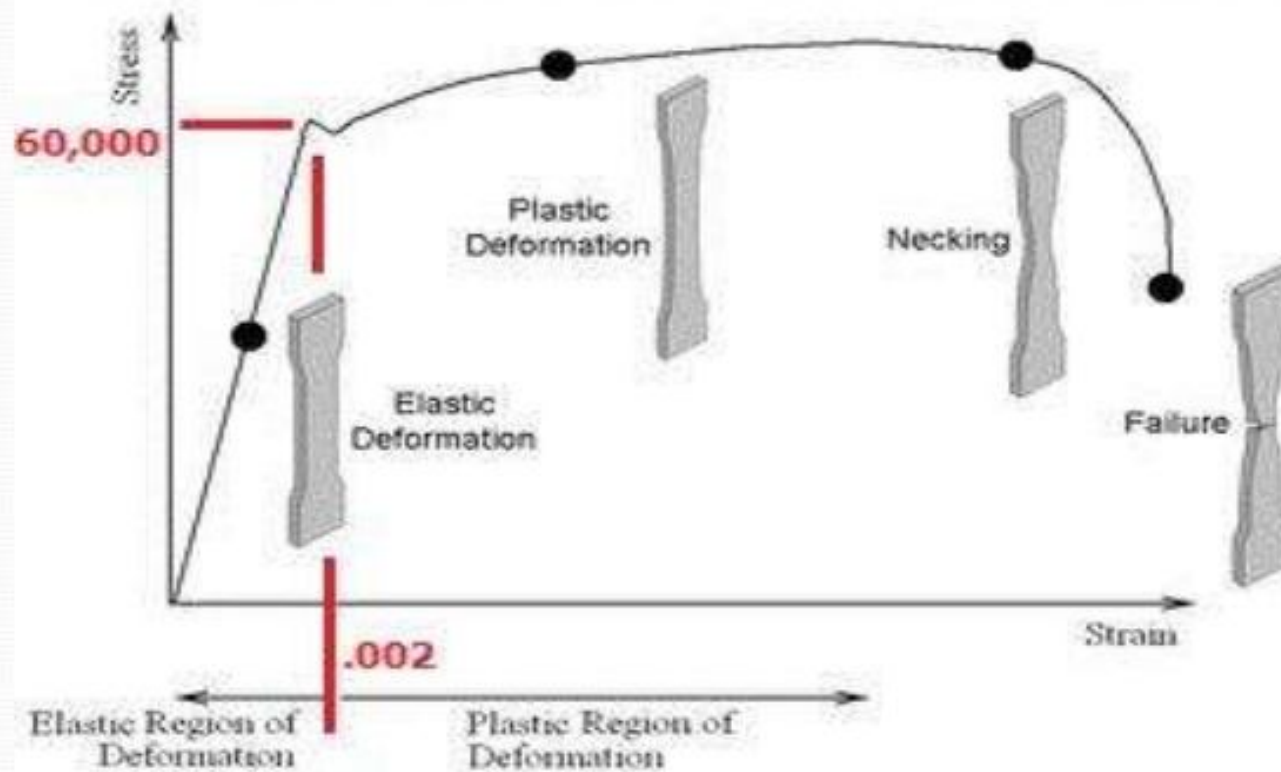
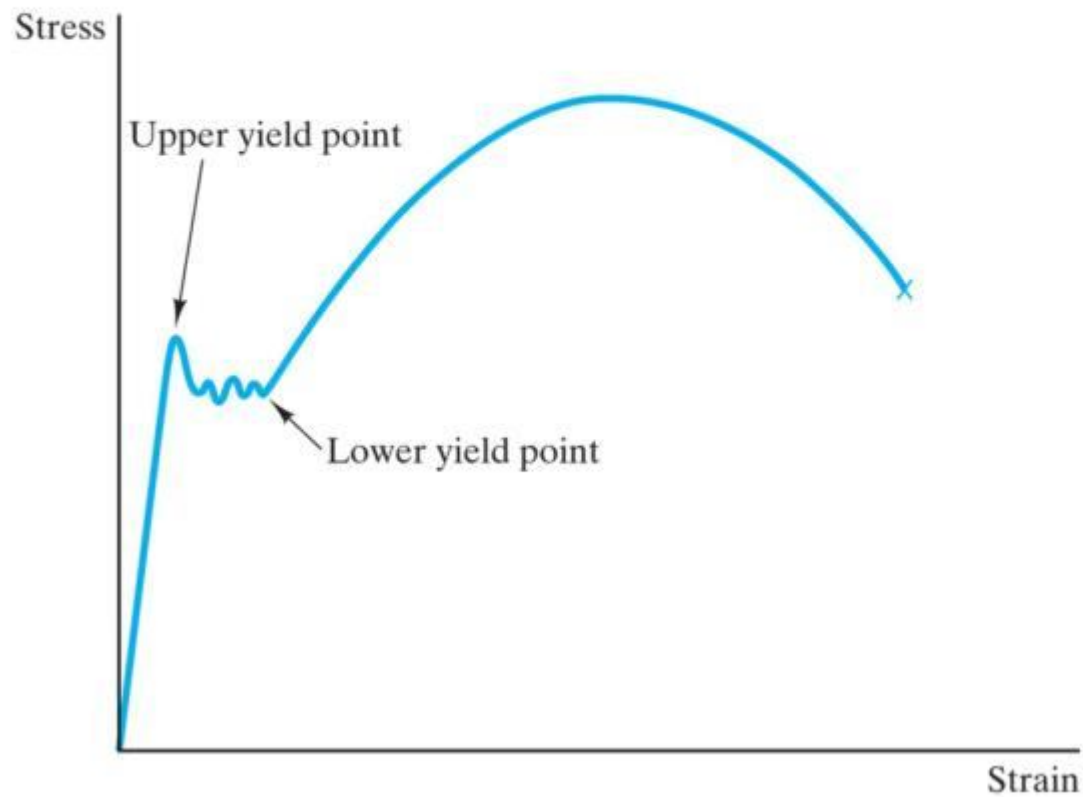
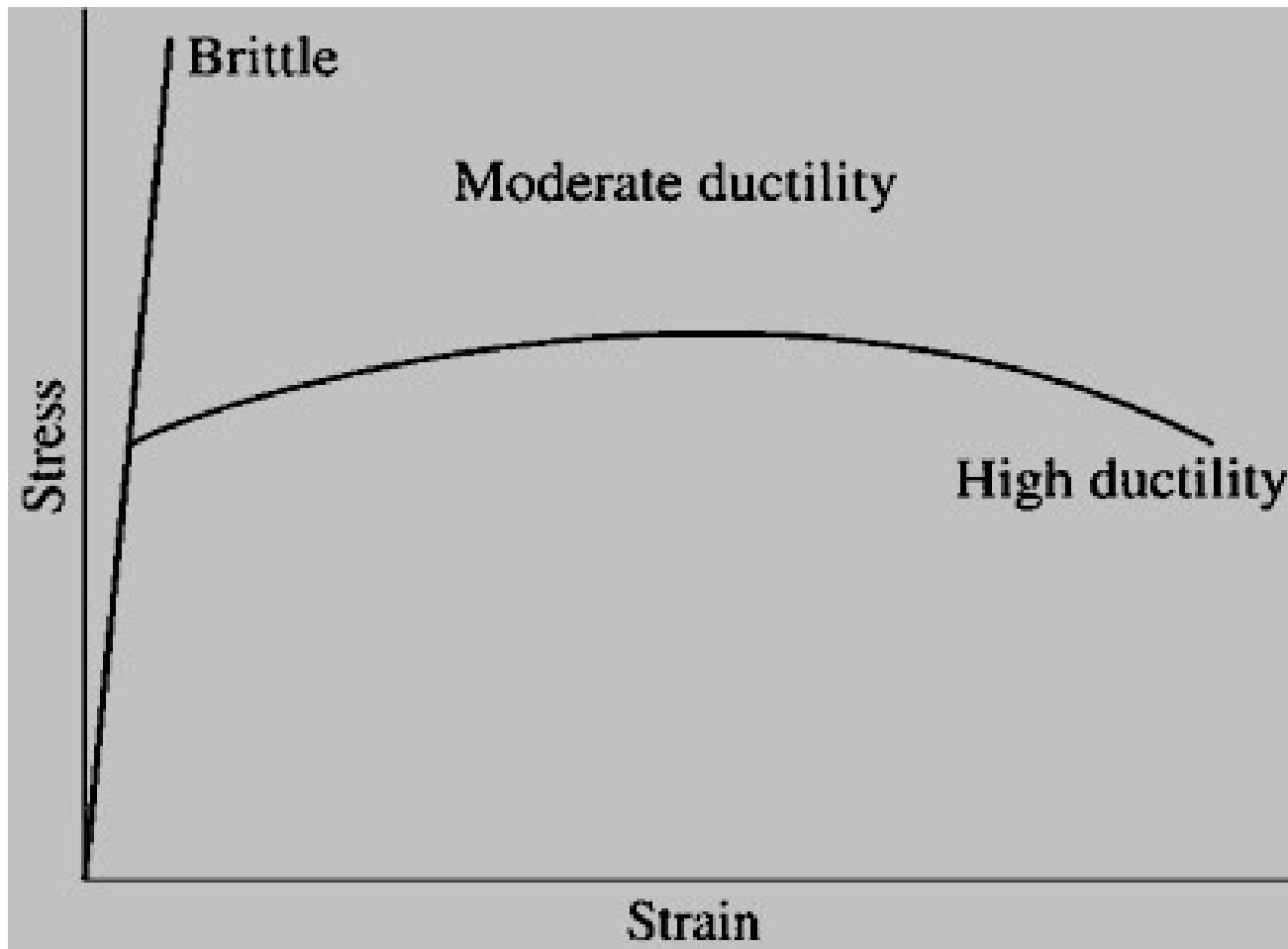


Figure 6.10 For a low-carbon steel, the stress-versus-strain curve includes both an upper and lower yield point.





Work hardening

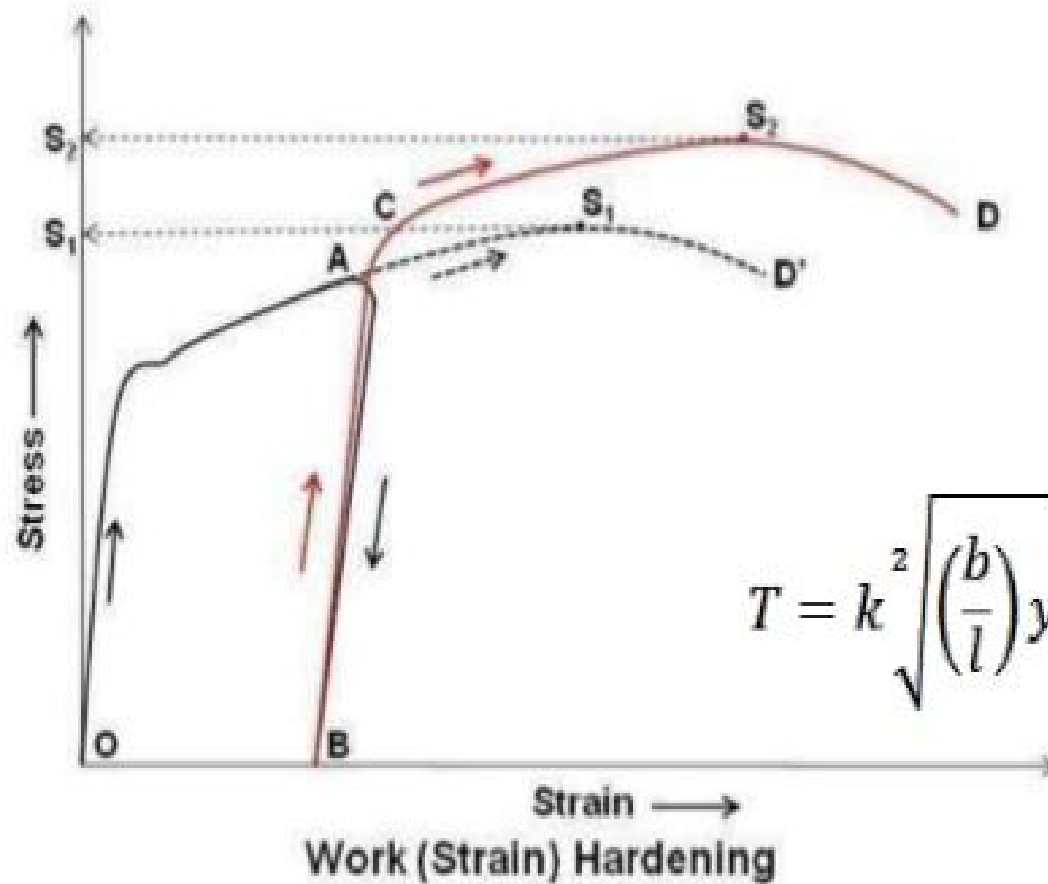
- ▣ *Work hardening is the strengthening of a metal by plastic deformation.*
- ▣ *This strengthening occurs because of dislocation movements and dislocation generation within the crystal structure of the material.*
- ▣ *Work hardening also known as Strain Hardening Or Cold Hardening.*

- ▣ *Work or Strain hardening is very commonly employed both on pure metals and on alloys , as a means of improving the useful mechanical properties such as strength and hardness.*
- ▣ *Work hardening however , reduce ductility and plasticity .*

Principle of work hardening

- ▣ *When loaded , the strain increase with stress and the curve reaches the point A in the plastic range.*
- ▣ *If at this stage , the specimen is unloaded , the strain does not recover along the original path AO , but moves along AB .*

STRAIN HARDENING



ADVANTAGES

- ⑩ No heating required.
- ⑩ Better surface finish.
- ⑩ Superior dimensional control.
- ⑩ Better reproducibility and interchange ability.
- ⑩ Directional properties can be imparted into the metal.
- ⑩ Contamination problems are minimized.



DISADVANTAGES

- ⑩ Greater forces are required.
- ⑩ Heavier and more powerful equipment and stronger tooling are required.
- ⑩ Metal is less ductile.
- ⑩ Intermediate anneals may be required to compensate for loss of ductility that accompanies strain hardening.
- ⑩ Undesirable residual stress may be produced.



bauschinger effect

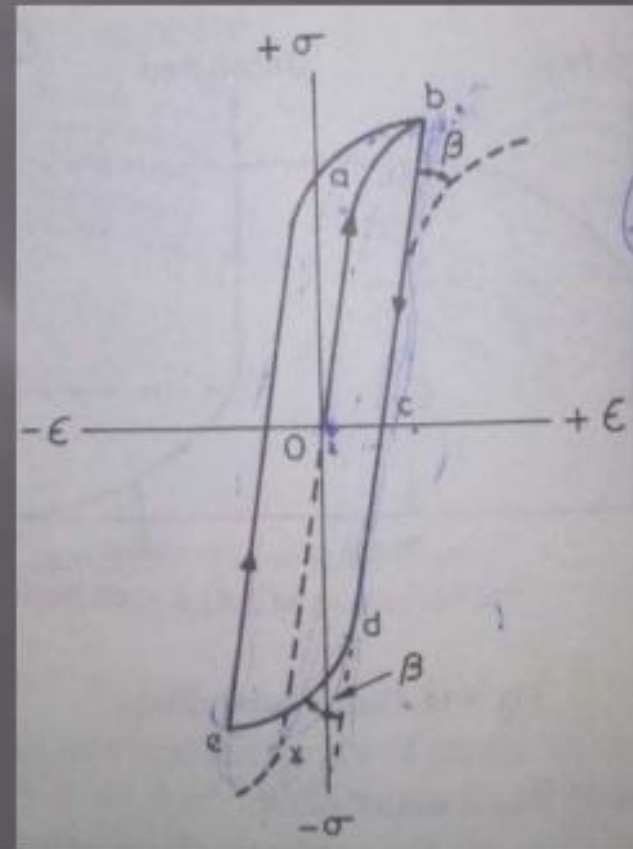
- *The Bauschinger effect was discovered by Ohann Bauschinger in 1886.*
- *Bauschinger effect is a phenomenon in plastic flow.*
- *In most materials plastic deformation in one direction will affect subsequent response in another direction.*

- ▣ *The phenomenon by which plastic deformation of a metal increases the yield strength in the direction of plastic flow and decreases the yield strength in the opposite direction*

STRESS STRAIN GRAPH

- Let the material has the yield stress in tension as 'a' and the same in compression as 'x'.

If a new specimen of the same material is loaded in tension past the tensile yield stress to 'b' along the path 'oab' and then it is unloaded, it will follow the path 'bc'. If now, the specimen is subjected to reverse stress i.e. the compressive stress, the plastic flow will begin at the stress corresponding to point 'd' which is apparently lower than the original compressive yield stress

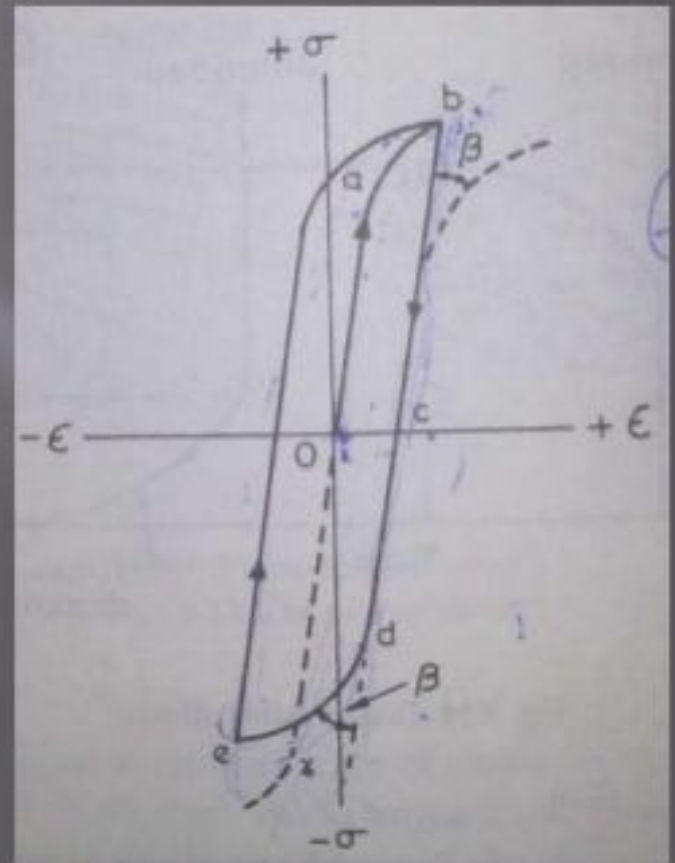


of the material, corresponding to point 'x'.

- Thus while the yield stress in tension was increased by strain hardening from 'a to b' the yield stress in compression is decreased from 'x' to 'd'. This is BAUSCHINGER EFFECT.
- Bauschinger effect is reversible, i.e. the specimen originally been stressed plastically in compression, the yield stress in tension would have been decreased.
- The Bauschinger strain B , helps describing the Bauschinger effect.
- B is the difference between strain and compression curve at a given stress

STRESS STRAIN CURVE

- Let the material has a yield stress in tension as 'a' and the same in compression as 'x'. If a new specimen of same material is loaded, it will follow the path 'bc'. If now specimen is subjected to reverse stress i.e, the compressive stress, the plastic flow at the stress corresponding to the point 'd' which is apparently lower than the original compressive yield stress of the material, corresponding



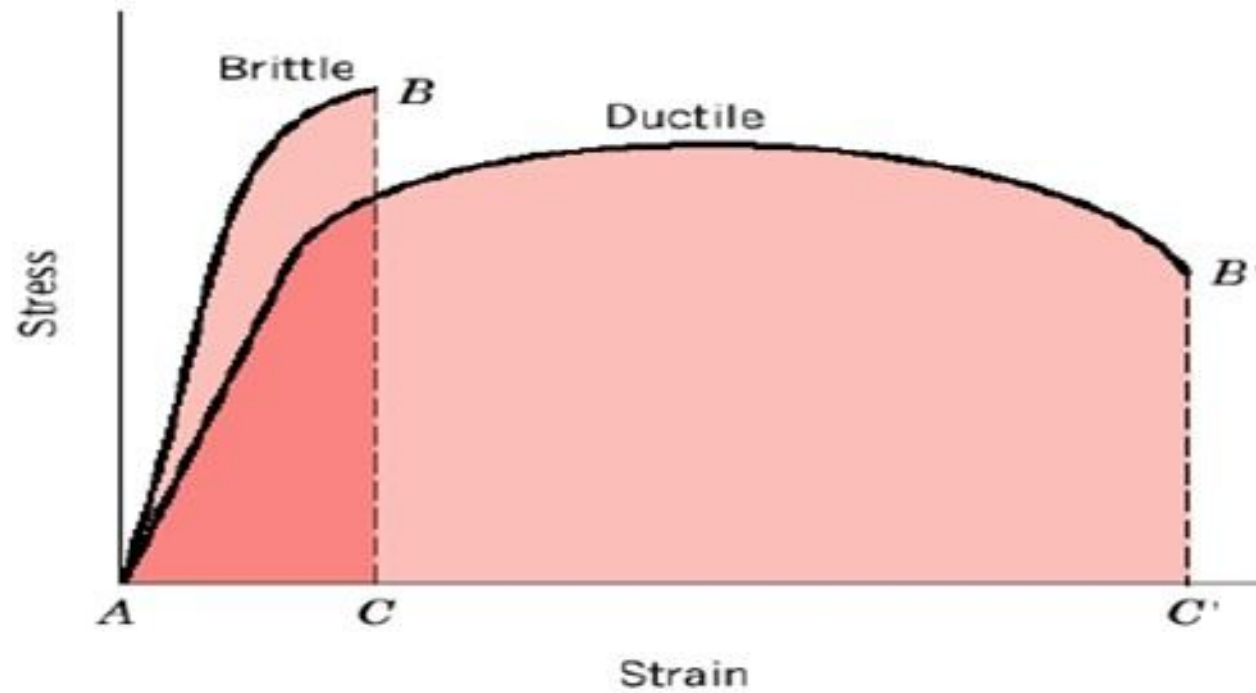
CONCLUSION FROM BAUSCHINGER EFFECT

- Metal forming operations result in situations exposing the metal workpiece to stresses of reversed sign. The Bauschinger effect contributes to work softening of the workpiece, for example in straightening of drawn bars or rolled sheets, where rollers subject the workpiece to alternate bending stresses, thereby reducing the yield strength and enabling greater cold drawability of the workpiece

S.No.	Cold working	Hot working
1	It is done at a temperature below the recrystallization temperature.	Hot working is done at a temperature above recrystallization temperature.
2.	It is done below recrystallization temperature so it is accomplished by strain hardening.	Hardening due to plastic deformation is completely eliminated.
3.	Cold working decreases mechanical properties of metal like elongation, reduction of area and impact values.	It increases mechanical properties.
4.	Crystallization does not take place.	Crystallization takes place.
5.	Material is not uniform after this working.	Material is uniform thought.
6.	There is more risk of cracks.	There is less risk of cracks.
7.	Cold working increases ultimate tensile strength, yield point hardness and fatigue strength but decreases resistance to corrosion.	In hot working, ultimate tensile strength, yield point, corrosion resistance are unaffected.

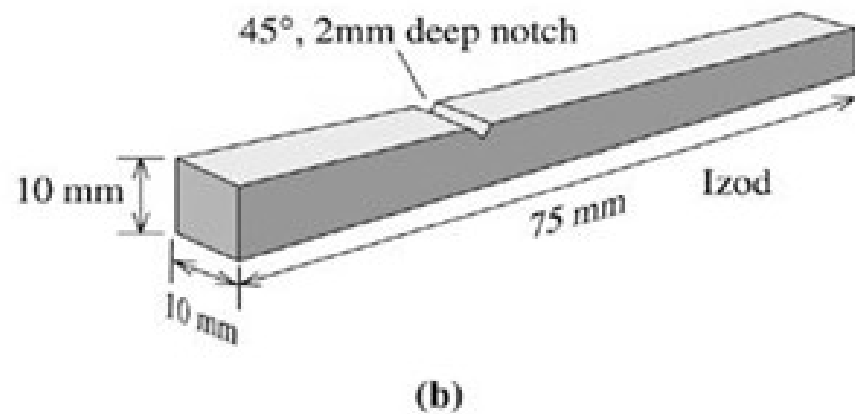
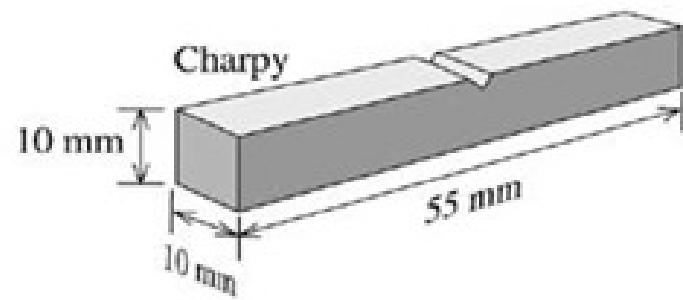
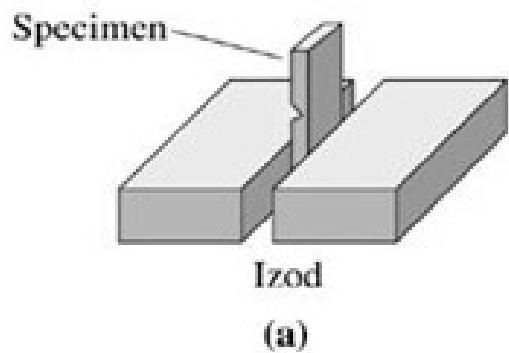
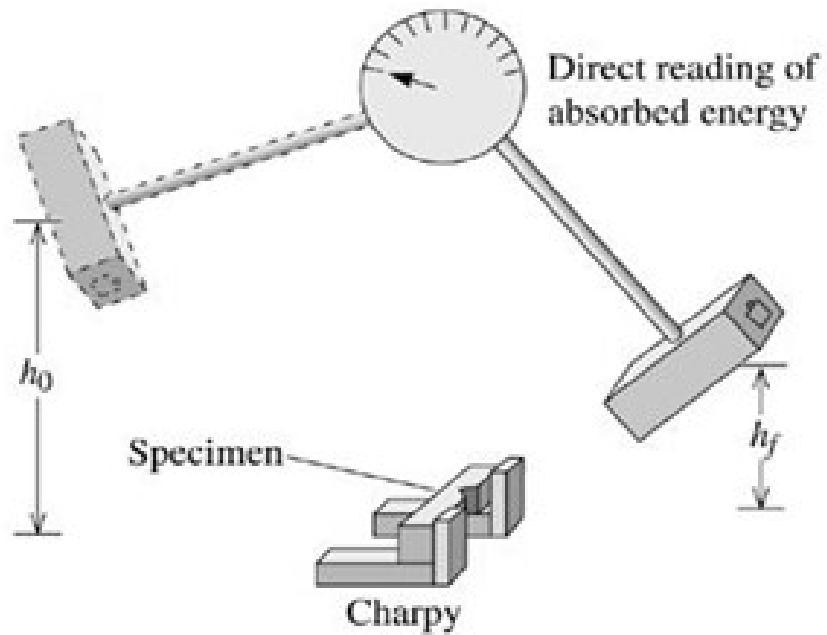


Toughness



Toughness = the ability to absorb energy up to fracture = the total area under the strain-stress curve up to fracture

Units: the energy per unit volume, e.g. J/m^3



What is NDT?

- **Nondestructive testing** or **non-destructive testing (NDT)** is a wide group of analysis techniques used in science and technology industry to evaluate the properties of a material, component or system without causing damage.
- The terms **nondestructive examination (NDE)**, **nondestructive inspection (NDI)**, and **nondestructive evaluation (NDE)** are also commonly used to describe this technology.

- Because NDT does not permanently alter the article being inspected, it is a highly valuable technique that can save both money and time in product evaluation, troubleshooting, and research. The six most frequently used NDT methods are [eddy-current](#), [magnetic-particle](#), [dye/liquid penetrant](#), [radiographic](#), [ultrasonic](#), and [visual testing](#)

- ❖ NDT does not directly measure mechanical properties but they are used **to locate defects or flaws in the component.**
- ❖ Flaws reduce useful life of component resulting in **premature failure** even with a sound design and proper selection of materials.
- ❖ To obtain high level of **reliability** , defect should be absent or at minimum level.
- ❖ NDT is carried out **periodically.**
- ❖ **Replacement of component** before its premature failure to avoid dangerous results.

DIFFERENT NDT METHODS

1. DYE PENETRATION TEST
2. SONIC TEST
3. ULTRASONIC TEST
4. MAGNETIC PARTICLE TEST
5. RADIOGRAPHY TEST
6. EDDY CURRENT TEST

1.Dye Penetrant Inspection

- ❖ Invisible cracks, porosity and other defects on the surface of components easily detected by this technique.
- ❖ Components may be ferrous, nonferrous, plastic, glass or ceramic.
- ❖ Procedure:-
 1. Cleaning of surface.(Grease, oil, any other material).
 2. Drying of surface.

3. Applying dye-penetrant on clean and dry surface.
It is allowed to penetrate in surface flaws.
 - i) Liquid Soluble Penetrant
 - ii) Fluroscent
4. Removing excess penetrant by soft or clean cotton.
5. Applying developer on surface. This pulls out dye from flaws and flaws are revealed by colour of dye. Instead of developer, fine developing powder or talc powder can be sprinkled on the surface.



1 Crack filled with dirt



2 Ideally cleaned



3 Application of penetrant



4 Intermediate cleaning



5 Application of developer



6 Crack indication



Advantages of Dye Penetrant Inspection

- This test can be applied to almost any type of metals, nonmetals, magnetic or non magnetic type.
- Simple to utilize and control.
- Results of test can be interpreted fastly.
- Cost of test is very less as it does not require any instrument or electronic display units.
- Sensitivity is greater than that of magnetic particle testing.

Disadvantages of Dye Penetrant Inspection

- Cleaning of components is must before and after testing to avoid rusting
- Misleading results may be obtained in case of components with surface films and coatings
- Only surface defects can be detected
- Test is not applicable for powder metallurgical components

2.Sonic Inspection

- ❖ Sound is created in the component and from quality of sound ,presence of defect is judged.
- ❖ e.g. C.I. piece gives a dull sound as compared to steel piece if dropped from certain height on the floor.
- ❖ e.g. Cups, saucer, earthen pots ,coconuts.

3.Ultrasonic Test/inspection

Principle-

1. Measure of time required by ultrasonic vibrations to penetrate material of interest , reflect from opposite side or from internal discontinuity and return to point from where first introduced.
2. Behaviour of waves through cycle with regard to time is recorded on CRO screen.
3. By observing this presence of defect and their location can be detected.

Two types of Ultrasonic testing method-

- i)Pulse –echo method
- ii) Transmission Method

4.Magnetic Particle (Magnaflux) Inspection

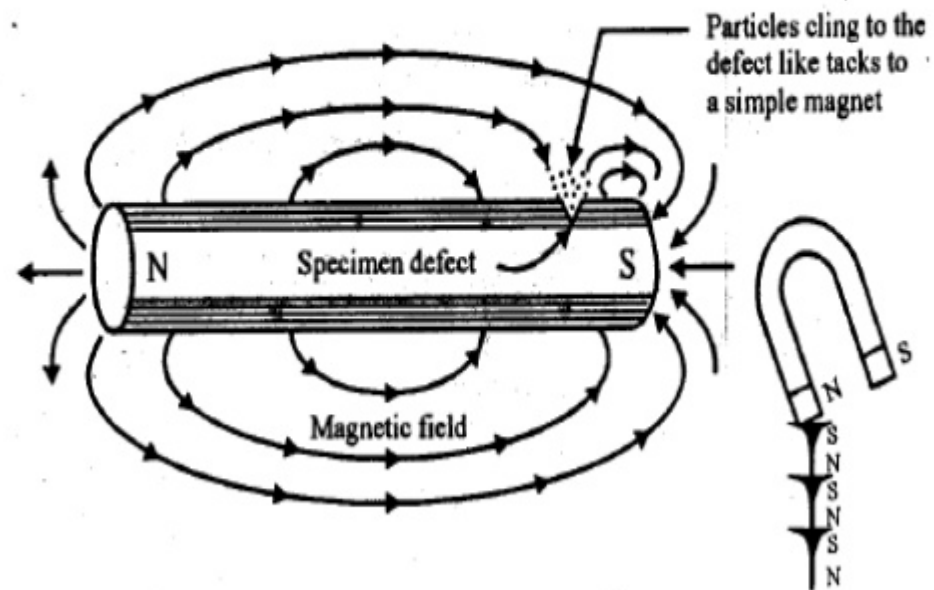
- It is used to detect various kinds of flaws in ferromagnetic components such as weldings, castings, forgings of iron and steel.
- Component to be inspected for flaws is magnetized.
- In dry method of inspection special fine ferromagnetic powder is applied on surface .

- This test is a very fast method of inspection and often used to test aerospace components and automobile parts.
- This test is generally used to detect internal cracks like shrinkage cavities, hot tears, zones of corrosion and non-metallic inclusions

Magnaflux Test Procedure:-

1. Cleaning Surface
2. Magnetization
3. Application of ferromagnetic Powder
4. Observation and Inspection
5. Demagnetization

Magnetic Particle /Magnaflux Inspection



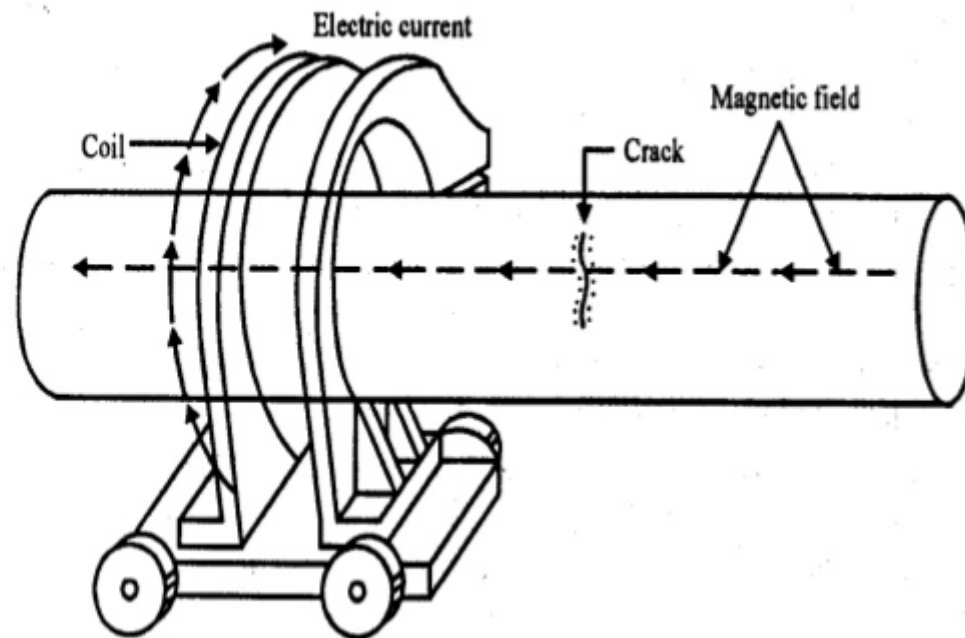


Fig. 4.2 : Longitudinal method of magnetization.

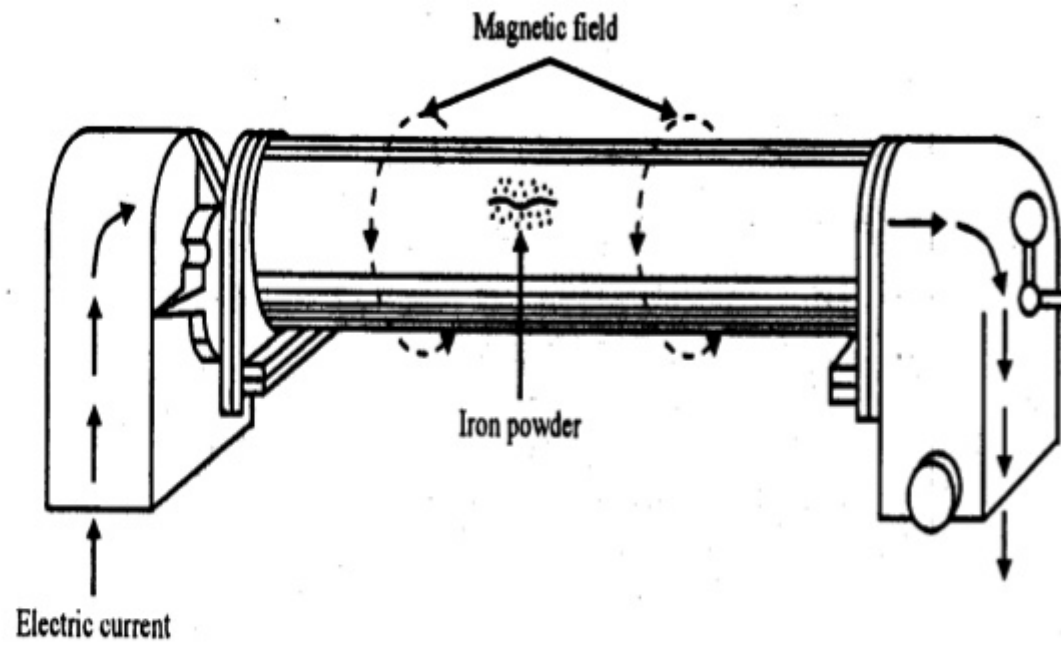


Fig. 4.3 : Circular method of magnetization.

Advantages of Magnaflux Test

- Sub-surface cracks can be easily detected
- Almost any shaped and sized component can be tested for defects
- Instruments are portable and easy to handle
- Highly sensitive method to detect small and shallow surface cracks

Disadvantages of Magnaflux Test

- Method is applicable only to ferromagnetic materials
- Surface plating or thin paint coating affect the sensitivity of the test
- After testing, demagnetization is a must
- Local heating and sparking is possible during test hence proper care must be taken

5. Radiography Test

- NDT method that utilizes x-rays or gamma radiation to detect discontinuities in materials, and to present their images on recording medium.
- This includes X-rays, gamma rays and radio-isotopes. This method is used to check internal cracks, defects in materials which are made by casting, welding, forging.
- Nowadays, radiography techniques are finding more extensive applications in the field of physical metallurgy and in the treatment of various diseases.

- Rays are absorbed by the materials through which they are passed in the proportion of their density. The rays, after passing through the components, show a picture on a fluorescent screen or on a photographic plate.
- The cracks, blow holes and cavities appear lighter, whereas inclusions of impurities appear darker than the metal component.
- Developed photographic film show lighter and darker areas to represent the radiograph of defects in the component.

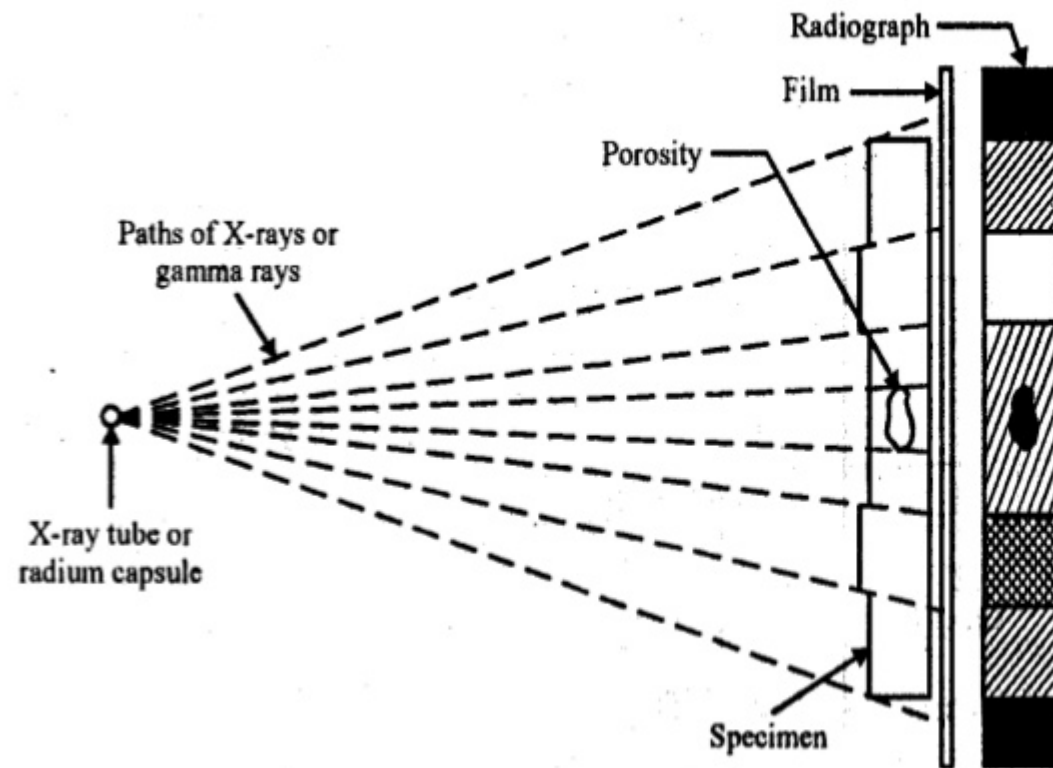
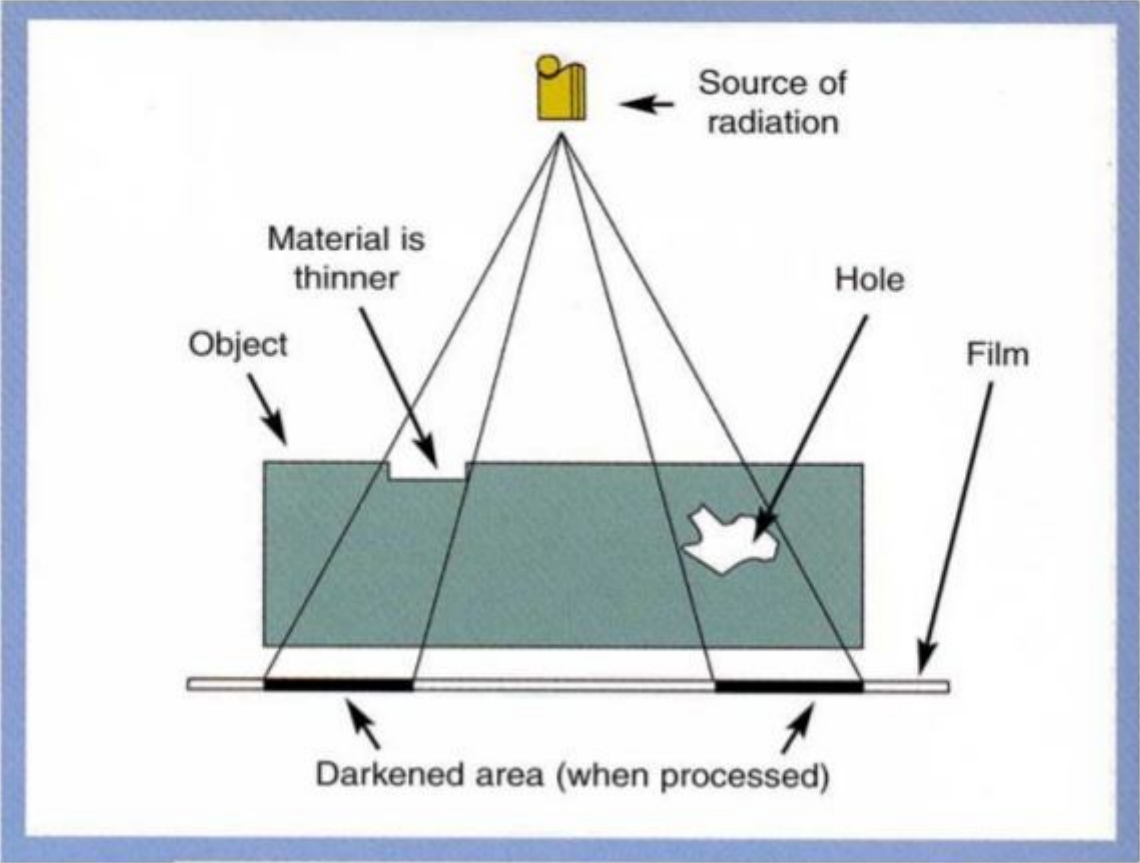


Fig. 4.7 : Production of radiograph.



6.Eddy Current Testing

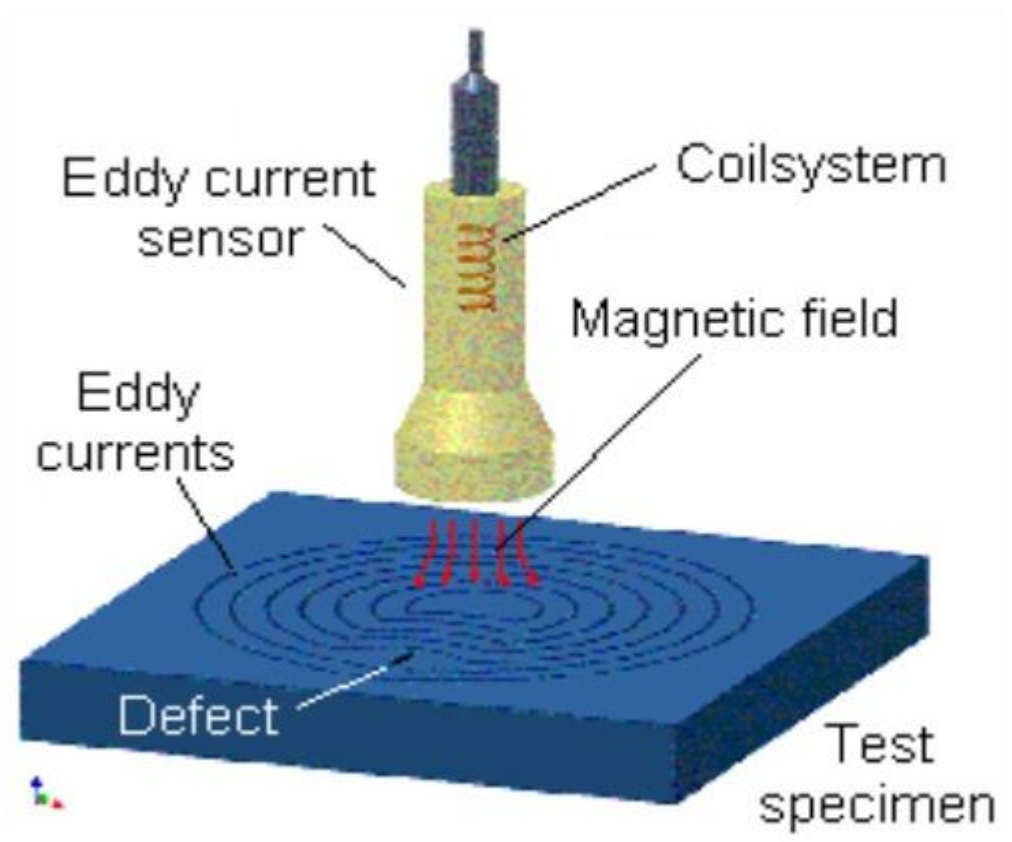
- ❖ Basic Principle:- When coil carrying alternating current is brought near metallic specimen, eddy currents are developed in specimen due to electromagnetic induction.
- ❖ Magnitude of induced EMI depend on –
 - i) Magnitude and frequency of alternating current flowing in coil.
 - ii) Electrical conductivity of specimen.
 - iii) Magnetic permeability of specimen.

iv) Shape of specimen.

v) Relative positions of coil and specimen.

vi) Microstructure and hardness of Specimen.

vii) Amount and type of defects in the specimen.

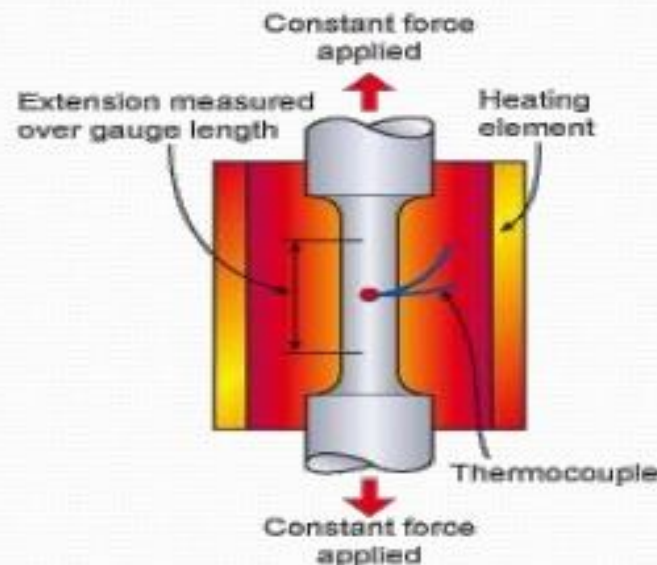


Applications of NDT

- NDT is commonly used in forensic engineering, mechanical engineering, petroleum engineering, electrical engineering, civil engineering, systems engineering, aeronautical engineering, medicine, and art.
- Innovations in the field of nondestructive testing have had a profound impact on medical imaging, including on echocardiography, medical ultrasonography, and digital radiography.

CREEP:

- The slow and progressive deformation of a material with time at constant stress is called creep.
- Depending on temperature, stresses even below the elastic limit can cause some permanent deformation.
- It is most generally defined as time-dependent strain occurring under stress.

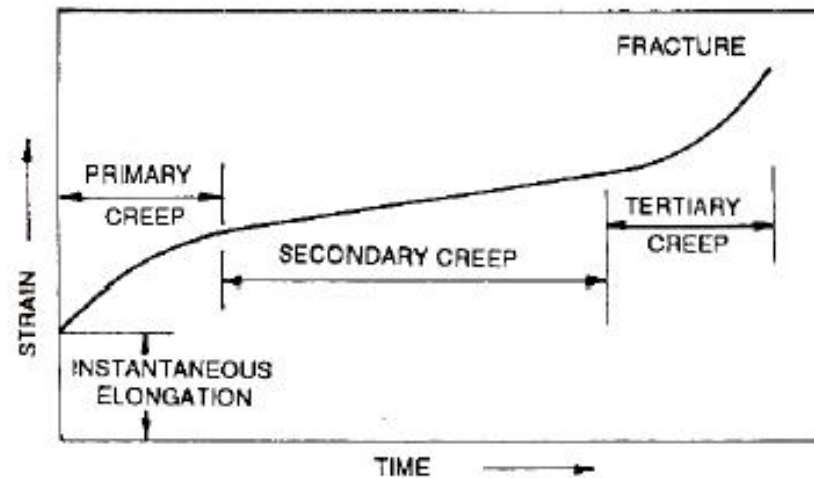


- The creep is defined as the property of a material by virtue of which it deforms continuously under a steady load.
- Creep is the slow plastic deformation of materials under the application of a constant load even for stressed below the yield strength of the material.
- Usually creep occurs at high temperatures.
- Creep is an important property for designing I.C. engines, jet engines, boilers and turbines. Iron, nickel, copper and their alloys exhibited this property at elevated temperature.
- But zin, tin, lead and their alloys shows creep at room temperature.
- In metals creep is a plastic deformation caused by slip occurring along crystallographic directions in the individual crystals together with some deformation of the grain boundary materials.

The creep curve usually consists of three \ stages of creep.

Primary Stage:

- In this stage the creep rate decreases with time, the effect of work hardening is more than that of recovery processes. The primary stage is of great interest to the designer since it forms an early part of the total extension reached in a given time and may affect clearness provided between components of a machine.



Secondary Stage:

In this stage, the creep rate is a minimum and is constant with time. The work hardening and recovery processes are exactly balanced. It is the important property of the curve which is used to estimate the service life of the alloy.

Tertiary Stage:

- In this stage, the creep rate increases with time until fracture occurs. Tertiary creep can occur due to necking of the specimen and other processes that ultimately result in failure.
- The “Creep Limit” is the stress at which a material can be formed by a definite magnitude during a given time at a given temperature. The calculation of creep limit includes the temperature, the deformation and the time in which this deformation appears.

Creep are classified based on temperature

- Logarithmic Creep
- Recovery Creep
- Diffusion Creep
- At low temperature the creep rate decreases with time and the logarithmic creep curve is obtained.
- At high temperature, the influence of work hardening is weakened and there is a possibility of mechanical recovery. As a result, the creep rate does not decrease and the recovery creep curve is obtained.
- At very high temperature, the creep is primarily influenced by diffusion and load applied has little effect. This creep is termed as diffusion creep or plastic creep.

Factors affecting Creep

Heat Treatment

- Creep resistance of steel is affected by heat treatment.
- At temperatures of 300°C or higher maximum creep resistance is usually produced. But the quacking and drawing decreases the creep resistance.

Grain size

- The major factor in creep is grain size.
- Normally large grained materials exhibit better creep resistance than fine grained one based on the temperature.
- At temperatures below the lowest temperature of recrystallisation, a fine grained structure possesses the greater resistance whereas at temperature above this point a large grained structure possesses the greater resistance and we must select it for high temperature applications.

Factors affecting Creep

Strain Hardening

- Strain hardening of steel increases its creep resistance.
- Particularly below the equicohesive temperature at which the fracture changes from intra crystalline to inter-crystalline strain hardening increases the creep resistance and hence there is no measurable creep. So the second stage of creep curve is almost horizontal.
- At temperature above the equicohesive temperature yield rate exceeds the strain hardening rate and creep will proceed even under low stresses.

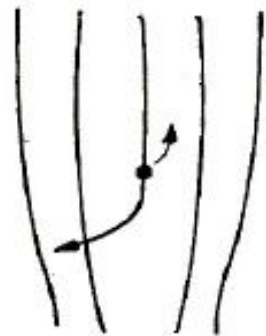
Alloying additions

- At temperatures, below the lowest temperatures of recrystallation the creep resistance of steel may be improved by the ferrite forming elements like nickel, cobalt and manganese or by the carbide forming elements like chromium molybdenum, tungsten and vanadium.

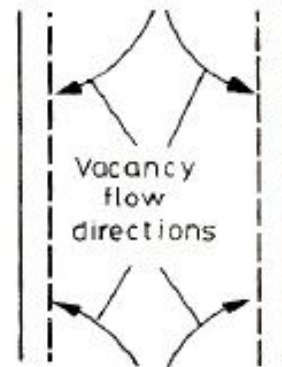
Mechanism of Creep

Some mechanisms that play vital roles during the creep process are:

- Dislocation climb
- Vacancy Diffusion
- Grain boundary sliding



(a)



(b)



(c)

Mechanism of Creep

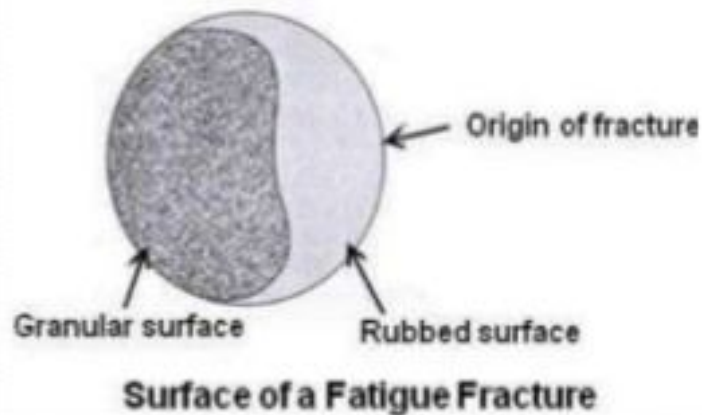
- ◆ At high temperature, the appreciable atomic movement causes the dislocation to climb up or down.
- ◆ By a simple climb of edge dislocation the diffusion rate of vacancies may produce a motion in response to the applied stress.
- ◆ Thus edge dislocations are piled up by the obstacles in the glide plane and the rate of creep is governed by the rate of escape of dislocation.
- ◆ Another mechanism of creep is called diffusion of vacancies.
- ◆ In this mechanism, the diffusion of vacancies controls the creep rate but does not involve the climb of edge dislocations.
- ◆ It depends on the migration of vacancies from one side of a grain to another. In response to the applied stress, the vacancies move from surfaces of the specimen transverse to the stress axis

Mechanism of Creep

- The third mechanism of creep is sliding of grain boundaries.
- It means sliding of neighboring grains with respect to the boundary that separates them.
- Grain boundaries become soft at low temperature as compared to individual grains.
- Grain boundaries play a major role in the creep of polycrystals at high temperatures as they slide past each other or create vacancies.
- At high temperature, ductile metals begin to lose their ability to strain – harden and become viscous to facilitate the sliding of grain boundaries.
- As the temperature increases the grain boundaries facilitate the deformation process by sliding, whereas at low temperature, they increase the yield strength by stopping the dislocations.

FATIGUE:

- This phenomenon leads to fracture under repeated or fluctuating stress.
- Fatigue fractures are progressive beginning as minute cracks and grow under the action of fluctuating stress.
- Many components of high speed aero and turbine engines are of this type.



Fatigue

Fatigue is caused by repeated application of stress to the metal. It is the failure of a material by fracture when subjected to a cyclic stress.

Fatigue is distinguished by three main features.

- i) Loss of strength
- ii) Loss of ductility
- iii) Increased uncertainty in strength and service life

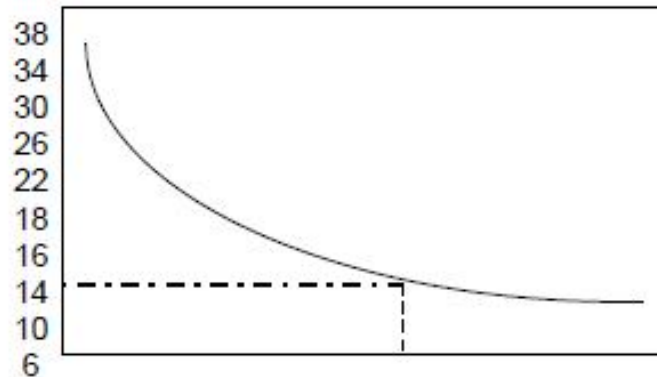
Fatigue

- ✦ Fatigue is an important form of behaviour in all materials including metals, plastics, rubber and concrete.
- ✦ All rotating machine parts are subjected to alternating stresses.
- ✦ Example: aircraft wings are subjected to repeated loads, oil and gas pipes are often subjected to static loads but the dynamic effect of temperature variation will cause fatigue.
- ✦ There are many other situations where fatigue failure will be very harmful.
- ✦ Because of the difficulty of recognizing fatigue conditions, fatigue failure comprises a large percentage of the failures occurring in engineering.
- ✦ To avoid stress concentrations, rough surfaces and tensile residual stresses, fatigue specimens must be carefully prepared.

Fatigue

The S-N Curve

- A very useful way to visual the failure for a specific material is with the S-N curve.
- The “S-N” means stress verse cycles to failure, which when plotted using the stress amplitude on the vertical axis and the number of cycle to failure on the horizontal axis.
- An important characteristic to this plot as seen is the “**fatigue limit**”.



Fatigue

- ✦ The point at which the curve flattens out is termed as fatigue limit and is well below the normal yield stress.
- ✦ The significance of the fatigue limit is that if the material is loaded below this stress, then it will not fail, regardless of the number of times it is loaded.
- ✦ Materials such as aluminium, copper and magnesium do not show a fatigue limit; therefore they will fail at any stress and number of cycles.
- ✦ Other important terms are fatigue strength and fatigue life.
- ✦ The fatigue strength can be defined as the stress that produces failure in a given number of cycles usually 10^7 .
- ✦ The fatigue life can be defined as the number of cycles required for a material to fail at a certain stress.

Factors affecting fatigue properties

Surface finish:

- Scratches dents identification marks can act as stress raisers and so reduce the fatigue properties.
- Electro-plating produces tensile residual stresses and have a detrimental effect on the fatigue properties.

Temperature:

- As a consequence of oxidation or corrosion of the metal surface increasing, increase in temperature can lead to a reduction in fatigue properties.

Factors affecting fatigue properties

Residual stresses:

- ✦ Residual stresses are produced by fabrication and finishing processes.
- ✦ Residual stresses on the surface of the material will improve the fatigue properties.

Heat treatment:

- ✦ Hardening and heat treatments reduce the surface compressive stresses; as a result the fatigue properties of the materials are getting affected.

Stress concentrations:

- ✦ These are caused by sudden changes in cross section holes or sharp corners can more easily lead to fatigue failure. Even a small hole lowers fatigue-limit by 30%.

Fracture

Fracture: separation of a body into pieces due to stress, at temperatures below the melting point.

Steps in fracture:

- crack formation
- crack propagation

Depending on the ability of material to undergo plastic deformation before the fracture two fracture modes can be defined - **ductile or brittle**

- **Ductile fracture** - most metals (not too cold):
 - Extensive plastic deformation ahead of crack
 - Crack is “stable”: resists further extension unless applied stress is increased
- **Brittle fracture** - ceramics, ice, cold metals:
 - Relatively little plastic deformation
 - Crack is “unstable”: propagates rapidly without increase in applied stress

Ductile fracture is preferred in most applications

Types of fracture in metals

- *The concept of material strength and fractures has long been studied to overcome failures.*
- *The introduction of malleable irons during the revolution of material construction led to the perception of brittle and ductile fractures as well as fatigue failure in metals.*

Failure in metallic materials can be divided into two main categories;

Ductile failure

Ductile fracture involves a large amount of plastic deformation and can be detected beforehand.

Brittle failure

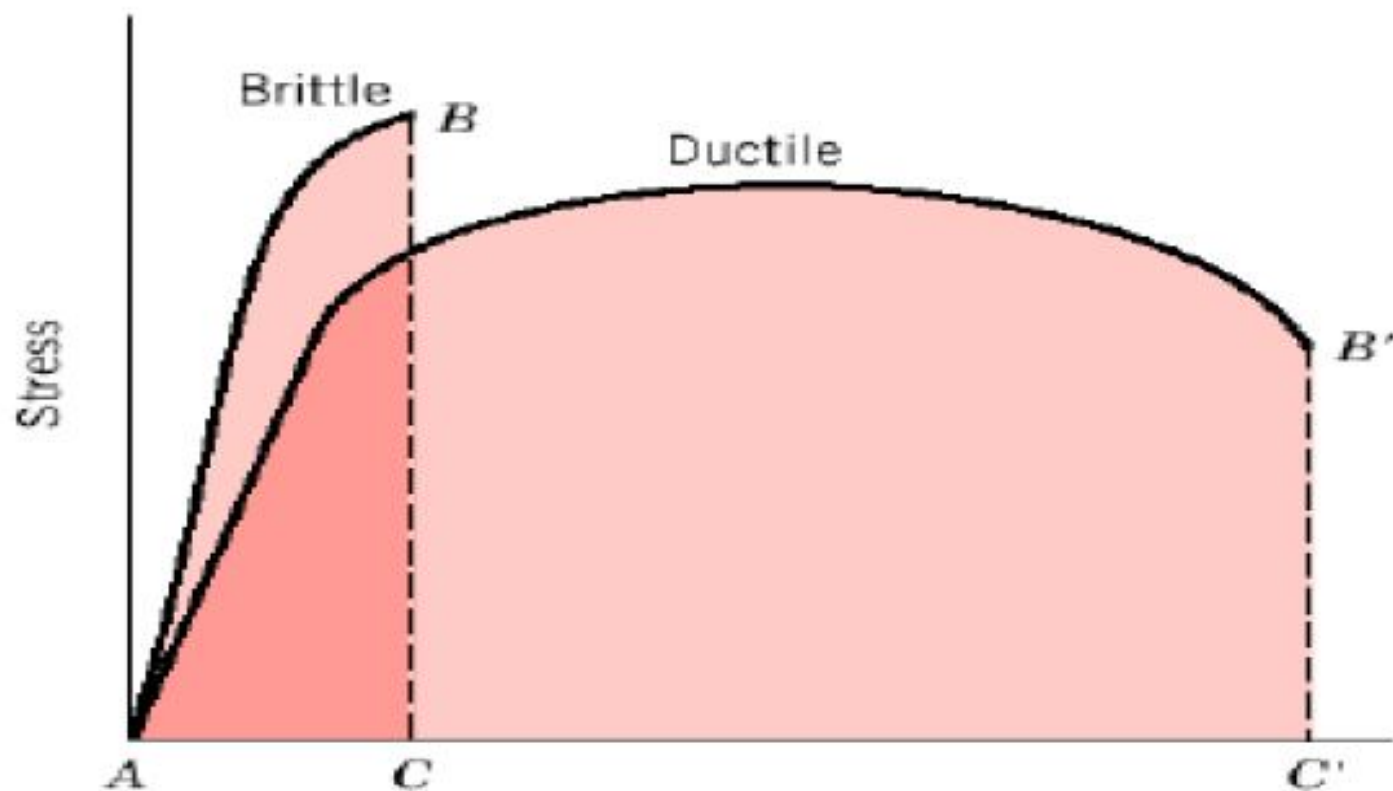
Brittle fracture is more catastrophic and has been intensively studied.

Theories of brittle fracture

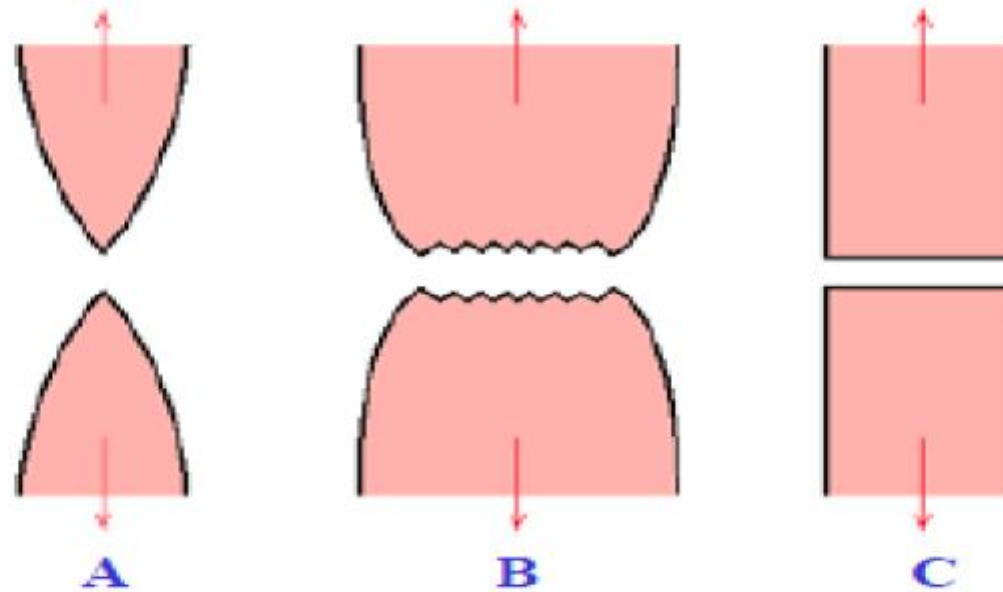


Brittle vs. Ductile Fracture

- **Ductile materials** - extensive plastic deformation and energy absorption (“toughness”) before fracture
- **Brittle materials** - little plastic deformation and low energy absorption before fracture

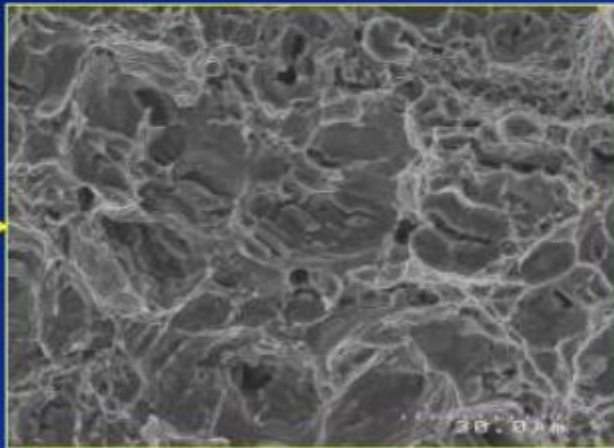


Brittle vs. Ductile Fracture

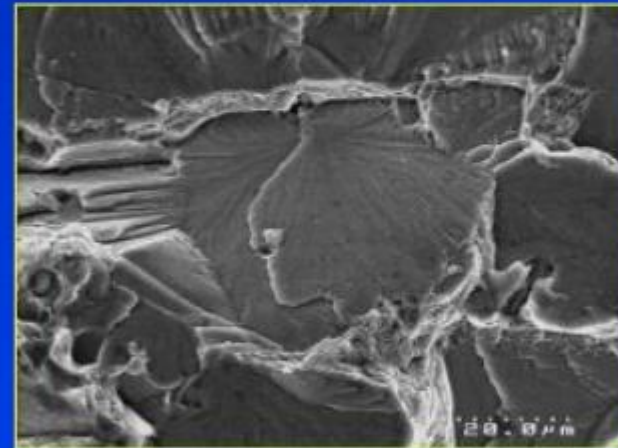


- A. **Very ductile**, soft metals (e.g. Pb, Au) at room temperature, other metals, polymers, glasses at high temperature.
- B. **Moderately ductile fracture**, typical for ductile metals
- C. **Brittle fracture**, cold metals, ceramics.

Failure modes



- **High energy** is absorbed by microvoid coalescence during ductile failure (high energy fracture mode)



- **Low energy** is absorbed during transgranular cleavage fracture (low energy fracture mode)

Brittle Fracture (Limited Dislocation Mobility)

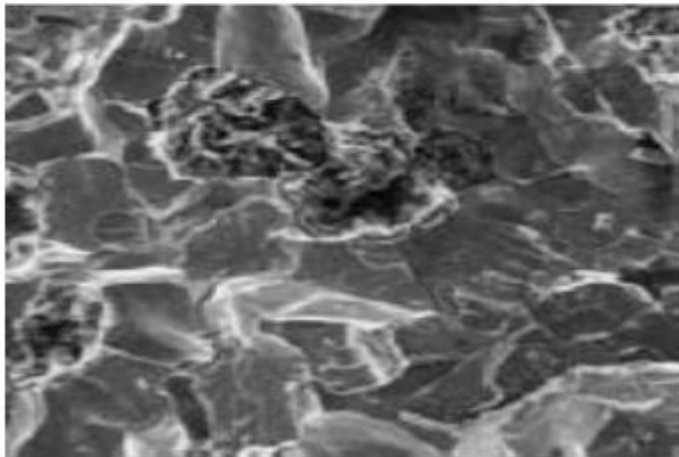
- No appreciable plastic deformation
- Crack propagation is very fast
- Crack propagates nearly perpendicular to the direction of the applied stress
- Crack often propagates by **cleavage** - breaking of atomic bonds along specific crystallographic planes (**cleavage planes**).



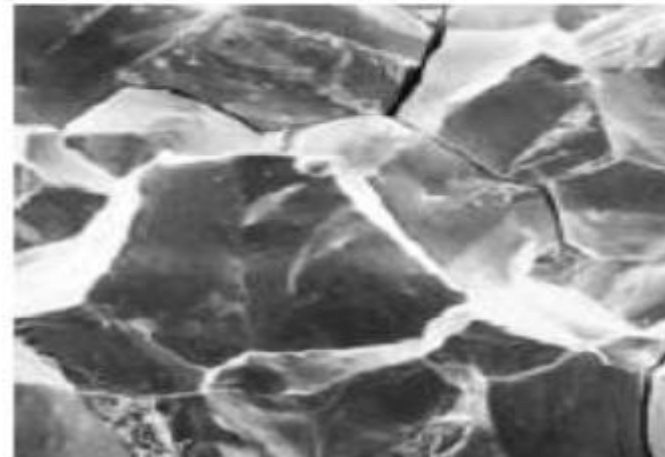
Brittle fracture in a mild steel

Brittle Fracture

- A. **Transgranular fracture:** Fracture cracks pass through grains. Fracture surface have faceted texture because of different orientation of cleavage planes in grains.
- B. **Intergranular fracture:** Fracture crack propagation is along grain boundaries (grain boundaries are weakened or embrittled by impurities segregation etc.)



A



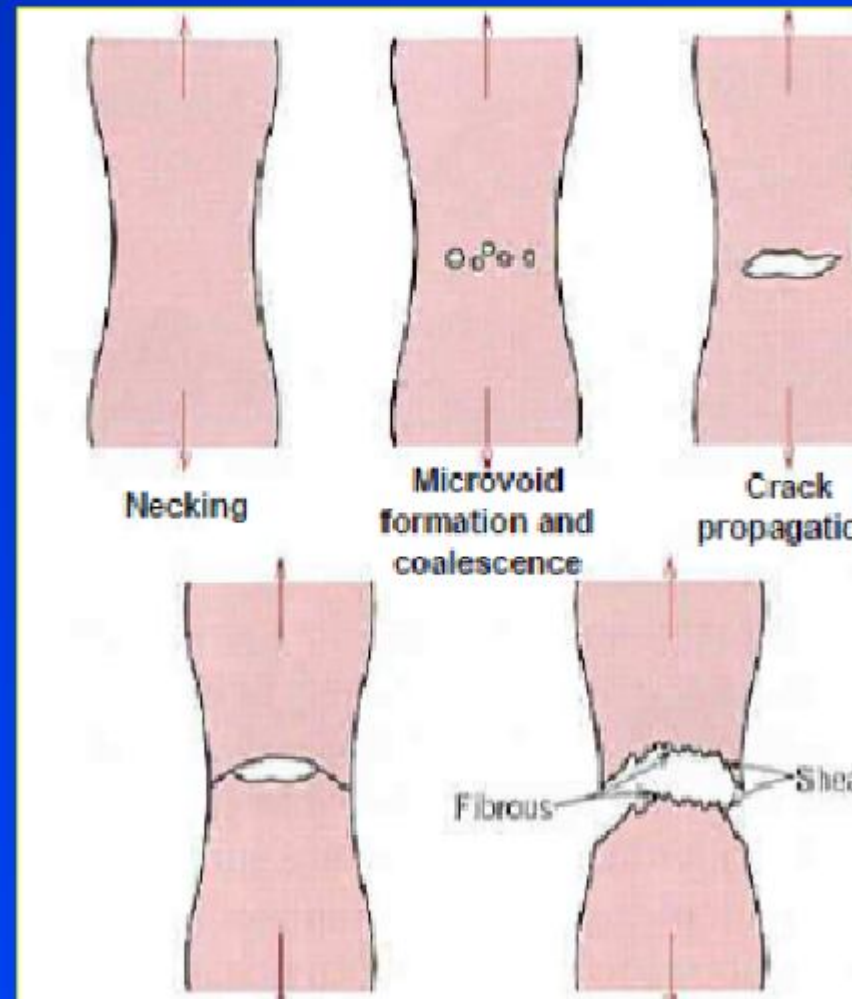
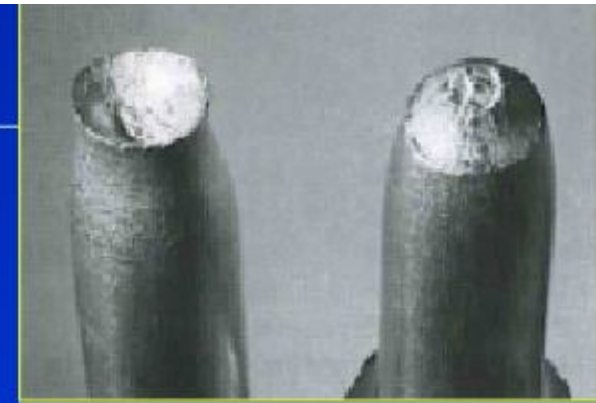
B

Ductile Fracture

Ductile fracture is a much less serious problem in engineering materials since failure can be detected beforehand due to observable **plastic deformation** prior to failure.

Under uniaxial tensile force, after necking, **microvoids** form and coalesce to form crack, which then propagates in the direction normal to the tensile axis.

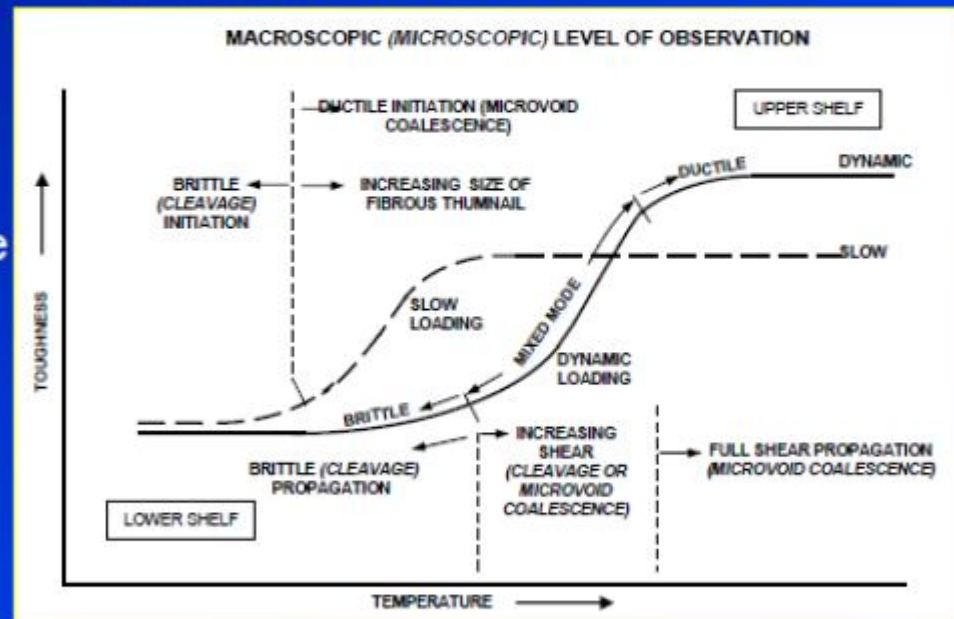
The crack then rapidly propagates through the periphery along the shear plane at 45° , leaving the **cup and cone fracture**.



Ductile to brittle transition behaviour

BCC structure metals experience **ductile-to-brittle transition behaviour** when subjected to decreasing temperature, resulting from a strong yield stress dependent on temperature.

- **BCC** metals possess **limited slip systems** available at low temperature, **minimising the plastic deformation** during the fracture process.
- **Increasing temperature** allows more slip systems to operate, yielding **general plastic deformation** to occur prior to failure.



Low temperature



Brittle cleavage fracture

High temperature



Ductile fracture

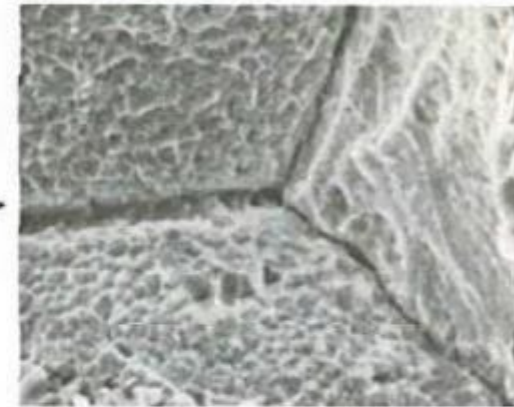


Intergranular fracture

- **Intergranular failure** is a moderate to low energy brittle fracture mode resulting from **grain boundary separation** or segregation of embrittling particles or precipitates.

- **Embrittling grain boundary particles** are weakly bonded with the matrix, → high free energy and unstable, which leads to **preferential crack propagation path**.

Intergranular fracture with microvoid coalescence



Intergranular fracture without microvoid coalescence



Intergranular fracture with and without

Factors affecting modes of fracture

Metallurgical aspect

Temperature

**State of stresses
(notch effect)**

Strain rate

Loading condition

Brittle fracture

Large grained materials
with GB particles.

Low temperature

Triaxial state of
stresses (notch effect)

High strain rate

Ductile fracture

Fine grained material
without GB particles.

High temperature

Absence of the notch

Low strain rate

Hydrostatic pressure
(suppress crack initiation)

UNIT III

CORROSION & HEAT TREATMENT OF METALS AND ALLOYS

CORROSION

- **Corrosion is the deterioration of a metal as a result of chemical reactions between it and the surrounding environment.**
- **It is an oxidation process. It causes loss of metal.**
- **The responsible factors for the corrosion of a metal are the composition of the metal, the environmental chemicals, temperature and the design.**
- **Corrosion comes in many different forms and can be classified by the cause of the chemical deterioration of a metal.**

Example: Formation of rust on the surface of iron



Formation of green film on the surface of copper

FORMS OF CORROSION

- **Uniform or General attack**
- **Galvanic or Two-metal**
- **Crevice**
- **Pitting**
- **Intergranular**
- **Selective leaching or Parting**
- **Erosion corrosion**
- **Stress corrosion**
- **Hydrogen damage**

1. Uniform Corrosion

- This corrosion is also called General Corrosion.
 - Effect produced by most direct chemical attacks.
 - This is common form of corrosion.
 - This type of corrosion is first seen as a general dulling of the surface and, if allowed to continue; the surface becomes rough.
-

How to prevent uniform corrosion?

Uniform corrosion or general corrosion can be prevented through a number of methods:

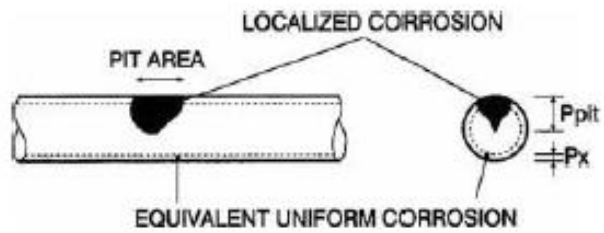
- Use thicker materials for corrosion allowance
- Use paints or metallic coatings such as plating, galvanizing or anodizing
- Use Corrosion inhibitors or modifying the environment

Images

Thickness is reduced uniformly



Uniform Corrosion



2. Galvanic Corrosion

- Also called as “dissimilar metal corrosion”
- Takes place when two metals are in physical contact with each other and are immersed in a conducting fluid.
- Corrosion damage induced when two dissimilar materials are coupled in a corrosive electrolyte.

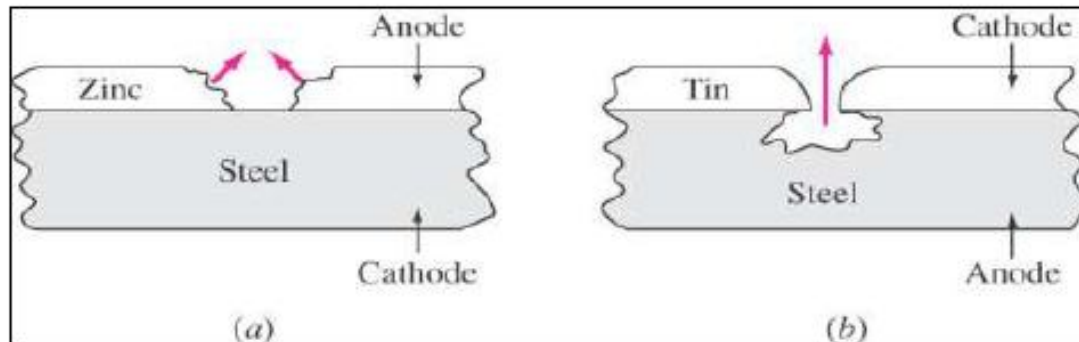
Examples

- Plate and screw of different electrical potentials due to differences in processing
- Multiple component implant using different metals for each component
- Copper and steel tubing are joined in a domestic water heater, the steel will corrode in the vicinity of the junction

The relative nobility of a material can be predicted by measuring its corrosion potential. The well known galvanic series lists the relative nobility of certain materials in sea water. A small anode/cathode area ratio is highly undesirable. In this case, the galvanic current is concentrated onto a small anodic area. Rapid thickness loss of the dissolving anode tends to occur under these conditions. Galvanic corrosion problems should be solved by designing to avoid these problems in the first place.



Galvanic corrosion between Steel and Brass.



Galvanic corrosion between stainless steel screw and Aluminium.

Prevention of Galvanic Corrosion

- **Select metals/alloys as close together as possible in the galvanic series.**
- **Avoid unfavorable area effect of a small anode and large cathode.**
- **Insulate dissimilar metals wherever practical.**
- **Apply coatings with caution. Paint the cathode (or both) and keep the coatings in good repair on the anode.**
- **Avoid threaded joints for materials far apart in the galvanic series.**

3. Differential Aeration Corrosion

- This type of corrosion takes place when a metal is unevenly exposed to different oxygen/air concentrations.
- The part which is exposed to less oxygen undergoes corrosion.

Examples

➤ **Drop Corrosion:**

It takes place when a drop of electrolyte is in contact

with the metal surface. The metal surface covered by

is in contact with lesser amount of air than the uncovered metal surface. Thus, metal covered by drop becomes anodic and corroded whereas the

Waterline Corrosion

- Waterline corrosion is a case of differential aeration corrosion, more prevalent in cases such as ocean going ships, water storage steel tanks, etc., in which a portion of the metal is always under water. The waterline corrosion takes place due to the formation of differential oxygen concentration cells. The part of the metal below the water line is exposed only to dissolved oxygen while the part above the water is exposed to higher oxygen concentration of the atmosphere. Thus, part of the metal below the water acts as anode and undergoes corrosion and part above the waterline is free from corrosion. A distinct brown line is formed just below the water line due to the deposition

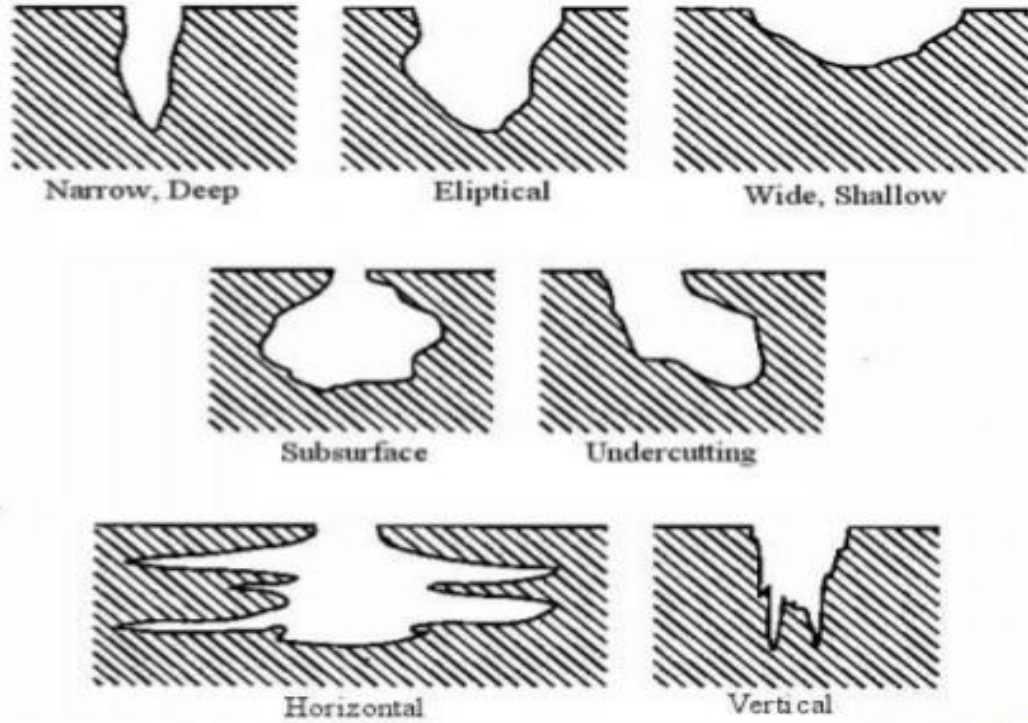
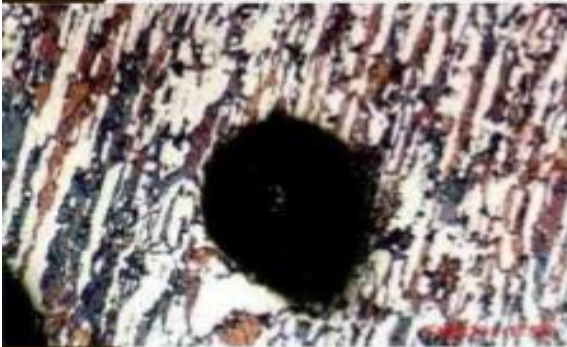


4. Pitting Corrosion

- ❑ Pitting corrosion is a localized form of corrosive attack that produces holes or small pits in a metal.
- ❑ the bulk of the surface remains unattacked.
- ❑ Pitting is often found in situations where resistance against general corrosion is conferred by passive surface films.

4. Pitting Corrosion (cont...)

- Localized pitting attack is found where these passive films have broken down.
- Pitting attack induced by microbial activity, such as sulfate reducing bacteria (SRB) also deserves special mention.



ASTM-G46 has a standard visual chart for rating of pitting corrosion

Pitting Corrosion (Images)



Corrosion Pits are the primary source of leaks in **water handling systems**



Prevention of pitting corrosion

- **Proper selection of materials with known resistance to the service environment**
- **Control pH, chloride concentration and temperature**
- **Cathodic protection and/or Anodic Protection**
- **Use higher alloys (ASTM G48) for increased resistance to pitting corrosion**

5. Stress Corrosion

- This type of corrosion is observed in fabricated articles which are subjected to various mechanical operations
- Here mechanical operations refers Bending, Hammering and annealing.
- This corrosion is usually unpredictable in nature.

Mechanism

- **Stress corrosion cracking results from the conjoint action of three components:**
 - (1) **a susceptible material**
 - (2) **a specific chemical species (environment)**
 - (3) **tensile stress**
- **For example, copper and its alloys are susceptible to ammonia compounds, mild steels are susceptible to alkalis and stainless steels are susceptible to chlorides.**
- **There is no unified mechanism for stress corrosion cracking in the literature.**

- Various models have been proposed which include the following:
- **Adsorption model:** specific chemical species adsorbs on the crack surface and lowers the fracture stress.
- **Film rupture model:** stress ruptures the passive film locally and sets up an active-passive cell. Newly formed passive film is ruptured again under stress and the cycle continues until failure.
- **Pre-existing active path model:** Pre-existing path such as grain boundaries where intermetallics and compounds are formed.
- **Embrittlement model:** Hydrogen embrittlement is a major mechanism of SCC for steels and other alloys such as titanium. Hydrogen atoms diffuse to the crack tip and embrittle the metal.

Examples

- Season Cracking
- Caustic embrittlement of mild steel



Prevention of stress corrosion cracking

- **Avoid the chemical species that causes SCC.**
- **Control of hardness and stress level (residual or load).**
- **Introduce compressive stress by shot-peening for example.**
- **Use of materials known not to crack in the specified environment.**
- **Control operating temperature and/or the electrochemical potential of the alloy.**

6. Corrosion Fatigue

- Corrosion Fatigue is a special case of stress corrosion caused by the combined effects of cyclic stress and corrosion.
- Control of corrosion fatigue can be accomplished by either lowering the cyclic stress or by corrosion control.

Images

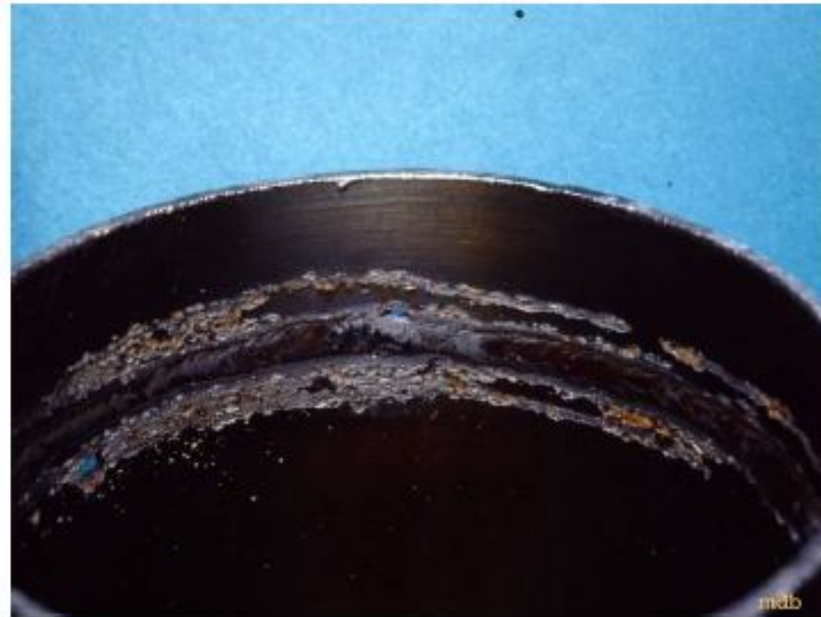
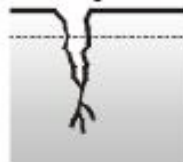
A. SCC or Fatigue Cracks
nucleate at pits



B. SCC Cracks are
highly branched



C. Corrosion
fatigue cracks
have little
branching



7. Crevice Corrosion

- ❑ Crevice corrosion is a localized form of corrosion usually associated with a stagnant solution on the micro-environmental level.
- ❑ Such stagnant microenvironments tend to occur in crevices (shielded areas) such as those formed under gaskets, washers, insulation material, fastener heads, surface deposits, disbanded coatings, threads, lap joints and clamps.

Crevice Corrosion (cont..)

- ❑ Occurs under gaskets, rivets and bolts, between valve disks and seats.
- ❑ Well-known examples of such geometries including flanges, gaskets, disbonded linings/coatings, fasteners, lap joints and surface deposits.

Crevice Corrosion (Images)



Prevention of Crevice Corrosion

- **Use welded butt joints instead of riveted or bolted joints in new equipment**
- **Eliminate crevices in existing lap joints by continuous welding or soldering**
- **Avoid creating stagnant conditions and ensure complete drainage in vessels**
- **Use solid, non-absorbent gaskets such as Teflon**
- **Use higher alloys (ASTM G48) for increased resistance to crevice corrosion**

8. Intergranular Corrosion

- ❑ Intergranular corrosion refers to preferential (localized) corrosion along grain boundaries.
- ❑ **or** immediately adjacent to grain boundaries, while the bulk of the grains remain largely unaffected.
- ❑ This form of corrosion is usually associated with chemical segregation effects (impurities have a tendency to be enriched at grain boundaries) or specific phases precipitated on the grain boundaries.

Intergranular Corrosion (cont...)

- ❑ This selective dissolution may lead to the dislodgement of grains.
- ❑ Intergranular corrosion in sensitized stainless steels and exfoliation in aluminum alloys represent industrially significant examples of this form of damage.

Intergranular Corrosion (Images)

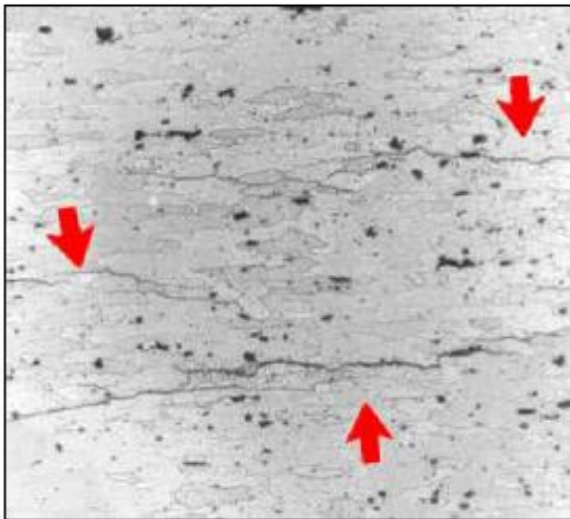


FIG. Intergranular corrosion of a failed aircraft component made of 7075-T6 aluminum (*picture width = 500 mm*)

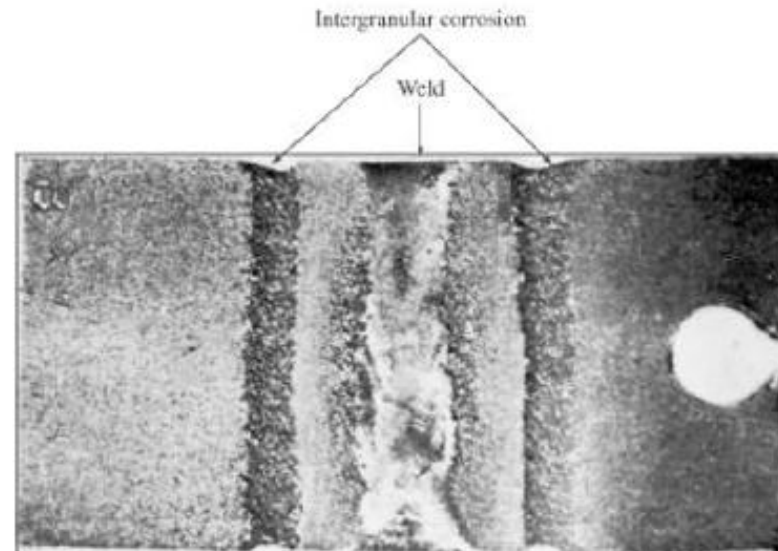


Fig. Severe problem in the welding of stainless steels, when it is termed **weld decay**.

Prevention of intergranular corrosion

- **Use low carbon (e.g. 304L, 316L) grade of stainless steels**
- **Use stabilized grades alloyed with titanium (for example type 321) or niobium (for example type 347). Titanium and niobium are strong carbide- formers. They react with the carbon to form the corresponding carbides thereby preventing chromium depletion.**
- **Use post-weld heat treatment.**

9. Microbiological Corrosion

- Caused by microbes like bacteria, algae fungi etc
- These microbes can be aerobic or anaerobic
- Aerobic bacteria decrease the concentration of oxygen in the medium in contact with metal surface.
- The main product of corrosion in anaerobic corrosion is iron sulphide

Microbiological Corrosion



10. Filiform Corrosion

- ❑ Occurs under painted or plated surfaces when moisture permeates the coating.
- ❑ Filiform corrosion is also known as "underfilm Corrosion" or "filamentary corrosion".
- ❑ Filiform corrosion can be visually recognized without using a microscopy

Prevention methods for Filiform Corrosion

- Filiform Corrosion can be prevented with the following methods:
 - control the relative humidity
 - use brittle coatings

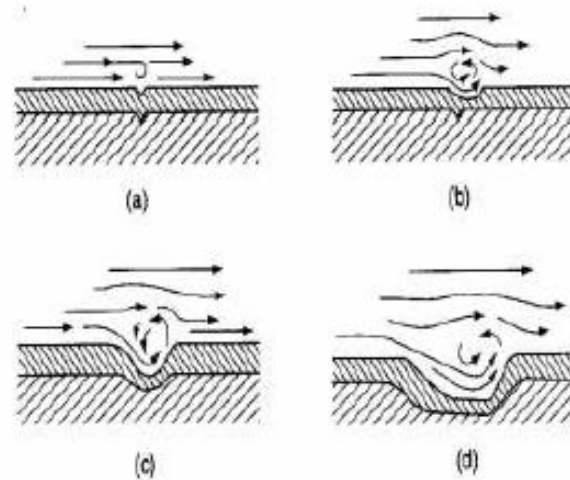
11. Erosion Corrosion

- It is the result of relative movement between the corrosive fluid and metal surface
- All types of equipments exposed to moving fluids are subjected to erosion corrosion.
- Surface chemistry can play a role in erosion corrosion due to mechanochemical effects.

Erosion Corrosion Examples

- Ship propellers
- Hydraulic turbines
- Pump impellers
- Diesel engine cylinder

Erosion Corrosion snaps



Prevention of Erosion Corrosion

- **Streamline the piping to reduce turbulence**
- **Control fluid velocity**
- **Using more resistant materials**
- **Using corrosion inhibitors or cathodic protection to minimize erosion corrosion**

14. Fretting Corrosion

- Fretting refers to wear and sometimes corrosion damage at the asperities of contact surfaces
- This corrosion occurs at the interface between contacting, highly loaded metal surfaces when subjected to slight vibratory motions is known as fretting corrosion.

Fretting Corrosion (cont..)

- This corrosion is most common in bearing surfaces in machinery.
- The most common type of fretting is caused by vibration.
- The protective film on the metal surfaces is removed by the rubbing action and exposes fresh, active metal to the corrosive action of the atmosphere.

Fretting Corrosion Images



Example of Fretting Corrosion





Introduction

. Heat Treatment

- *Heat Treatment process is a series of operations involving the **Heating and Cooling** of metals in the solid state.*
- *Its purpose is to change a mechanical property or combination of mechanical properties so that the metal will be more useful, serviceable, and safe for definite purpose.*
- *By heat treating, a metal can be made harder, stronger, and more resistant to impact, heat treatment can also make a metal softer and more ductile.*

- *No one heat-treating operation can produce all of these characteristics. In fact, some properties are often improved at the expense of others. In being hardened, for example, a metal may become brittle.*



Types of Heat Treatment

1. **Annealing**
2. **Normalizing**
3. **Quenching or Hardening**
4. **Tempering**
5. **Surface Hardening**
6. **Case Hardening**
7. **Austempering**
8. **Marquenching**
9. **Ausforming**



1. Annealing

- **Annealing** is the process for softening materials or to bring about required changes in properties, such as machinability, mechanical or electrical properties, or dimensional stability.
- The annealing process consists of heating the steel to or near the critical temperature (temperature at which crystalline phase change occurs) to make it suitable for fabrication.
- A material can be annealed by heating it to a specific temperature and then letting the material slowly cool to room temperature in an oven.



2. Normalizing

- It is a type of heat treatment applicable to ferrous metals only.*
- It differs from annealing in that the metal is heated to a higher temperature and then removed from the furnace for air cooling.*
- The purpose of normalizing is to remove the internal stresses induced by heat treating, welding, casting, forging, forming, or machining.*



3. Quenching or Hardening

- It is done to increase the strength and wear properties. One of the pre-requisites for hardening is sufficient carbon and alloy content.*
- To harden by quenching, a metal (usually steel or cast iron) must be heated into the austenitic crystal phase and then quickly cooled.*
- Depending on the alloy and other considerations (such as concern for maximum hardness vs. cracking and distortion), cooling may be done with forced air or other gas (such as nitrogen), oil , polymer dissolved in water, or brine.*

4. Case Hardening

- *Case Hardening is the process of hardening the surface of a metal, often a low carbon steel, by infusing elements into the material's surface, forming a thin layer of a harder alloy.*
- *Case hardening improves the wear resistance of machine parts without affecting the tough interior of the parts.*





5. Austempering

- **Austempering** is heat treatment that is applied to ferrous metals, most notably steel and ductile iron.
- In steel it produces a bainite microstructure whereas in cast irons it produces a structure of acicular ferrite and high carbon, stabilized austenite known as ausferrite.
- It is primarily used to improve mechanical properties or reduce / eliminate distortion.



6. Tempering

- *Tempering is carried out by preheating previously quenched or normalized steel to a temperature below the critical range, holding, and then cooling to obtain the desired mechanical properties.*
- *Tempering is used to reduce the brittleness of quenched steel.*
- *The temperature chosen for the tempering process directly impacts the hardness of the work piece . The higher the temperature in the tempering process, the lower the hardness.*

WHAT IS ALLOY?

- ❖ Alloy is the metal made by the combination of two or more metals or elements combined to attain certain chemical or mechanical properties

A BRIEF HISTORY OF ALLOYS

- ❖ Historically, the earliest alloys created by man was brass, a simple alloy of copper and zinc known to be in use from as early as 3000 BC
- ❖ King Croesus of Lydia during the years 560-546 BC desired and developed the first official government coinage system using a naturally occurring alloy of gold and silver, known as Electrum

ALLOY STEEL

- ❖ Alloy steel is basically mixture of Iron and Carbon and other trace elements (Silicon Manganese Sulphur etc)
- ❖ Carbon %age in steel is about 0.12 - 2%

ALLOYING ELEMENTS IN STEEL

- ❖ Carbon
- ❖ Chromium
- ❖ Silicon
- ❖ Manganese
- ❖ Nickel
- ❖ Vanadium
- ❖ Molybdenum
- ❖ Tungsten
- ❖ Aluminum
- ❖ Titanium
- ❖ Boron

CARBON

- ❖ **Percentage range 0.12 - 2%**
- ❖ **Increases hardness**
- ❖ **Increases Strength**

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.

CHROMIUM

- ❖ **Percentage range** **0.5 - 18%**
- ❖ **Increases hardenability of steel (0.5-2%)**
- ❖ **Provides Corrosion Resistance (4-18%)**

Chromium is added to the steel to increase resistance to oxidation. This resistance increases as more chromium is added. 'Stainless Steel' has approximately 18% chromium and a very marked degree of general corrosion resistance when compared with steels with a lower percentage of chromium. When added to low alloy steels, chromium can increase the response to heat treatment, thus improving hardenability and strength.

CHROMIUM PROTECTION

Chromium oxide blocks corrosion



SILICON

- ❖ **Percentage Range** **0.2 – 2%**
- ❖ **Increases Strength (0.2 – 0.7%)**
- ❖ **Spring Steels (0.7 – 2%)**
- ❖ **Improve Magnetic Properties (Higher Percentages)**

This metalloid improves strength, elasticity, acid resistance and results in larger grain sizes, thereby, leading to greater magnetic permeability. Because silicon is used in a deoxidizing agent in the production of steel, it is almost always found in some percentage in all grades of steel.

SILICON USE



The addition of 2% silicon changes the behavior of the steel drastically for use in a katana. This spring steel is most commonly seen in application on fencing foils where it needs to withstand a high degree of bend and still be able to return to center.

MANGANESE

- ❖ **Percentage Range 0.25 – 1%**
- ❖ **When combined with Sulfur Improves Brittleness (0.25-0.40%)**
- ❖ **Increases Hardenability (>1%)**

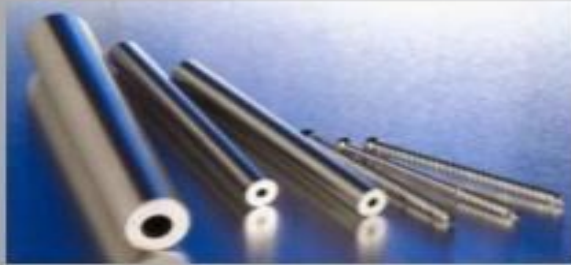
Increases strength at high temperatures by eliminating the formation of iron sulfides. Manganese also improves hardenability, ductility and wear resistance. Like nickel, manganese is an austenite forming element and can be used in the AISI 200 Series of Austenitic stainless steels as a substitute for nickel.

NICKEL

- ❖ **Percentage Range** 2 - 20%
- ❖ **Provide Toughness (2-5%)**
- ❖ **Provides Corrosion Resistance (12-20%)**

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

NICKEL APPLICATIONS



Nickel stainless steel alloy



Environmental Protection Agency (EPA) eliminates a stronger and thicker corrosion-resistant.

VANADIUM

- ❖ Percentage Range 0 - 0.15%
- ❖ Stable Carbides-Increase Strength While Retaining Ductility
- ❖ Promotes fine grain structure (FGS)

vanadium can produce stable carbides that increase strength at high temperatures. By promoting a fine grain structure, ductility can be retained.

VANADIUM USE



high carbon high chromium die steel with added carbon and vanadium for abrasion resisting qualities.



The first large-scale industrial use of vanadium in steels was found in the chassis of the Ford Model T, inspired by French race cars. (1927)

MOLYBDENUM

- ❖ **Percentage Range** 0.2-5%
- ❖ **Stable Carbides**
- ❖ **Inhibits Grain Growth**

Found in small quantities in stainless steels, molybdenum increases hardenability and strength, particularly at high temperatures. Often used in chromium-nickel austenitic steels, molybdenum protects against pitting corrosion caused by chlorides and sulfur chemicals.

TUNGSTEN

- ❖ **Percentage Range**
- ❖ **Hardness at high temperatures**

Produces stable carbides and refines grain size so as to increase hardness, particularly at high temperatures

TUNGSTEN USES



Many high speed steels - those used in cutting and machining tools like saw blades - contain around 18 percent tungsten.

Tungsten-steel alloys are also used in the production of rocket engine nozzles, which must have high heat resistant properties.

ALUMINUM

- ❖ Percentage Range 0.95 – 1.30%
- ❖ Increase ductility in steel alloys
- ❖ commonly used in draw quality steels.
- ❖ Helps in removing the dissolved oxygen from the liquid steel. This process is known as killing.

TITANIUM

- ❖ Percentage Range
- ❖ Improves Strength
- ❖ Reduces martensitic hardness in chromium steels

Improves both strength and corrosion resistance while limiting austenite grain size. At 0.25-0.60 percent titanium content, carbon combines with the titanium, allowing chromium to remain at grain boundaries and resist oxidization.

TITANIUM USE



EOS has expanded its metal materials portfolio with EOS titanium Ti64ELI and EOS stainless steel 316L.

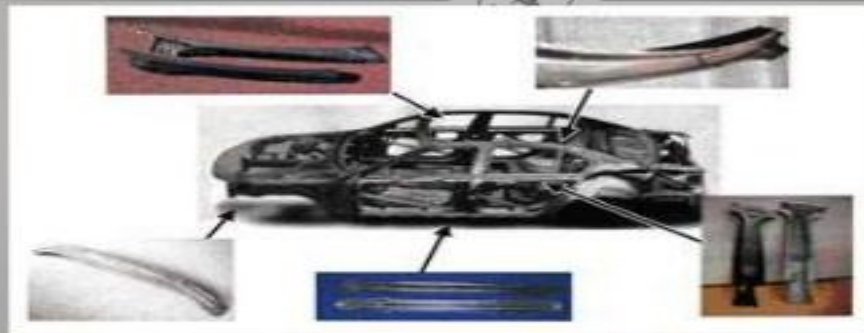
EOS titanium Ti64ELI is a light metal alloy that is corrosion resistant and bio-compatible

BORON

- ❖ **Percentage range** **0.001-0.003%**
- ❖ **Powerful hardenability agent**

A hardenability agent that improves deformability and machinability. Boron is added to fully killed steel and only needs to be added in very small quantities to have a hardening affect. Additions of boron are most effective in low carbon steels.

BORON USE



Hot-stamping boron-alloyed steels for
automotive parts

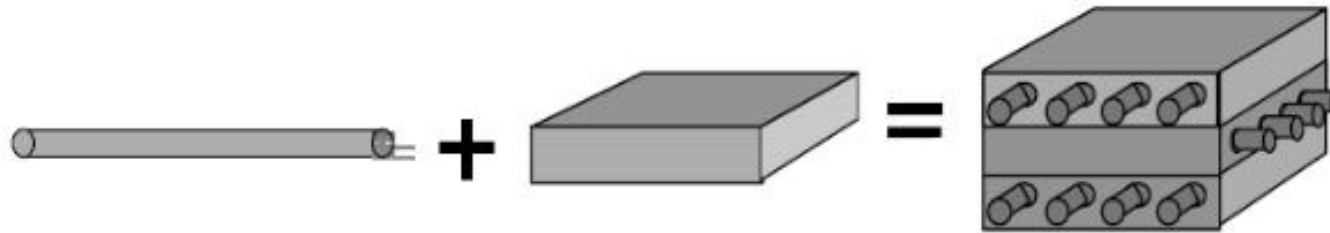
UNIT 4

CERAMICS AND COMPOSITES

Definition

- A broad definition of composite is: Two or more chemically distinct materials which when combined have improved properties over the individual materials.
- The constituents retain their identities in the composite; that is, they do not dissolve or otherwise merge completely into each other, although they act in concert.

Composition of Composites



Fiber/Filament Reinforcement

- High strength
- High stiffness
- Low density

Matrix

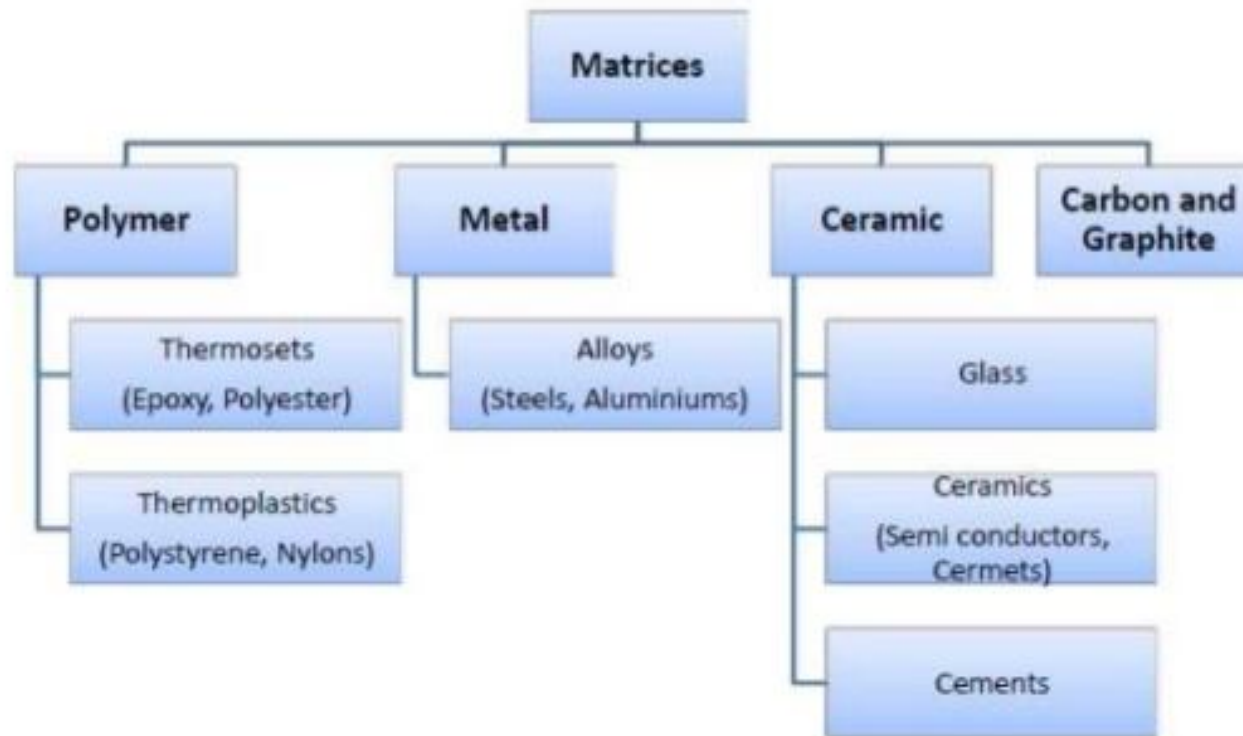
- Good shear properties
- Low density

Composite

- High strength
- High stiffness
- Good shear properties
- Low density

CLASSIFICATION OF COMPOSITE MATERIALS

The composites are classified as mainly two constituents are matrix and a reinforcement



METAL MATRIX COMPOSITE (MMCs)

- ❖ Metal matrix composites are High strength, fracture toughness and stiffness are offered by metal matrices than those offered by their polymer counterparts. They can withstand elevated temperature in corrosive environment than polymer composites.
- ❖ MMCs are widely used in engineering applications where the operating temperature lies in between 250 °C to 750 °C.
- ❖ Matrix materials: Steel, Aluminum, Titanium, Copper, Magnesium and Super alloys.

CERAMIC MATRIX COMPOSITE (CMCs)

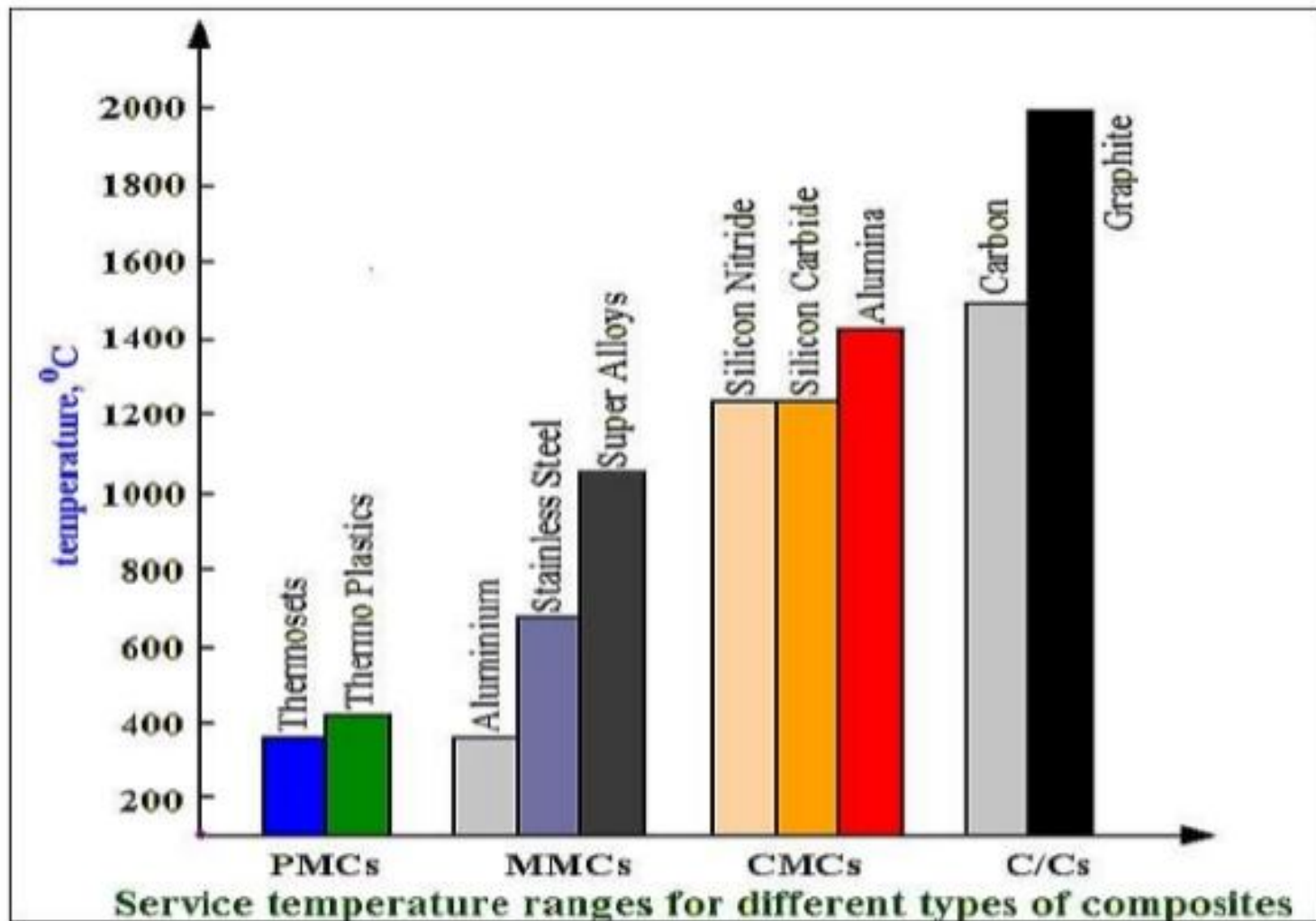
- Ceramics can be described as solid materials which exhibit very strong ionic bonding in general and in few cases covalent bonding. High melting points, good corrosion resistance, stability at elevated temperatures and high compressive strength
- CMCs are widely used in engineering applications where the operating temperature lies in between 800°C to 1650°C

CARBON/CARBON MATRIX COMPOSITE

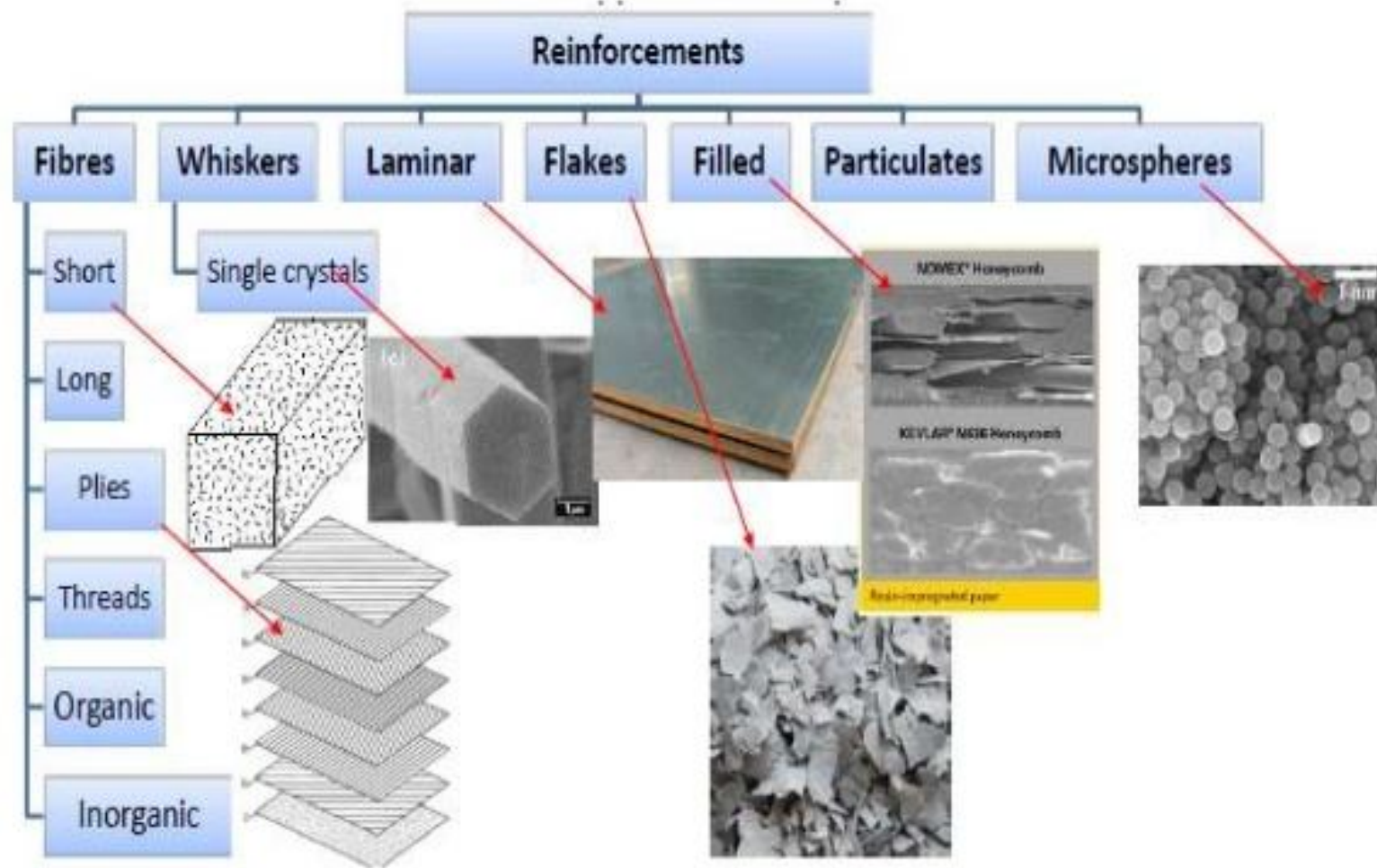
- C/Cs are developed specifically for parts that must operate in extreme temperature ranges. Composed of a carbon matrix reinforced with carbon yarn fabric, 3-D woven fabric, 3-D braiding, etc.
- C/C composites meet applications ranging from rockets to aerospace because of their ability to maintain and even increase their structural properties at extreme temperatures.

Advantages:

- Extremely high temperature resistance (1930°C – 2760°C).
- Strength actually increases at higher temperatures (up to 1930°C).
- High strength and stiffness.
- Good resistance to thermal shock.



CLASSIFICATION OF COMPOSITE MATERIALS

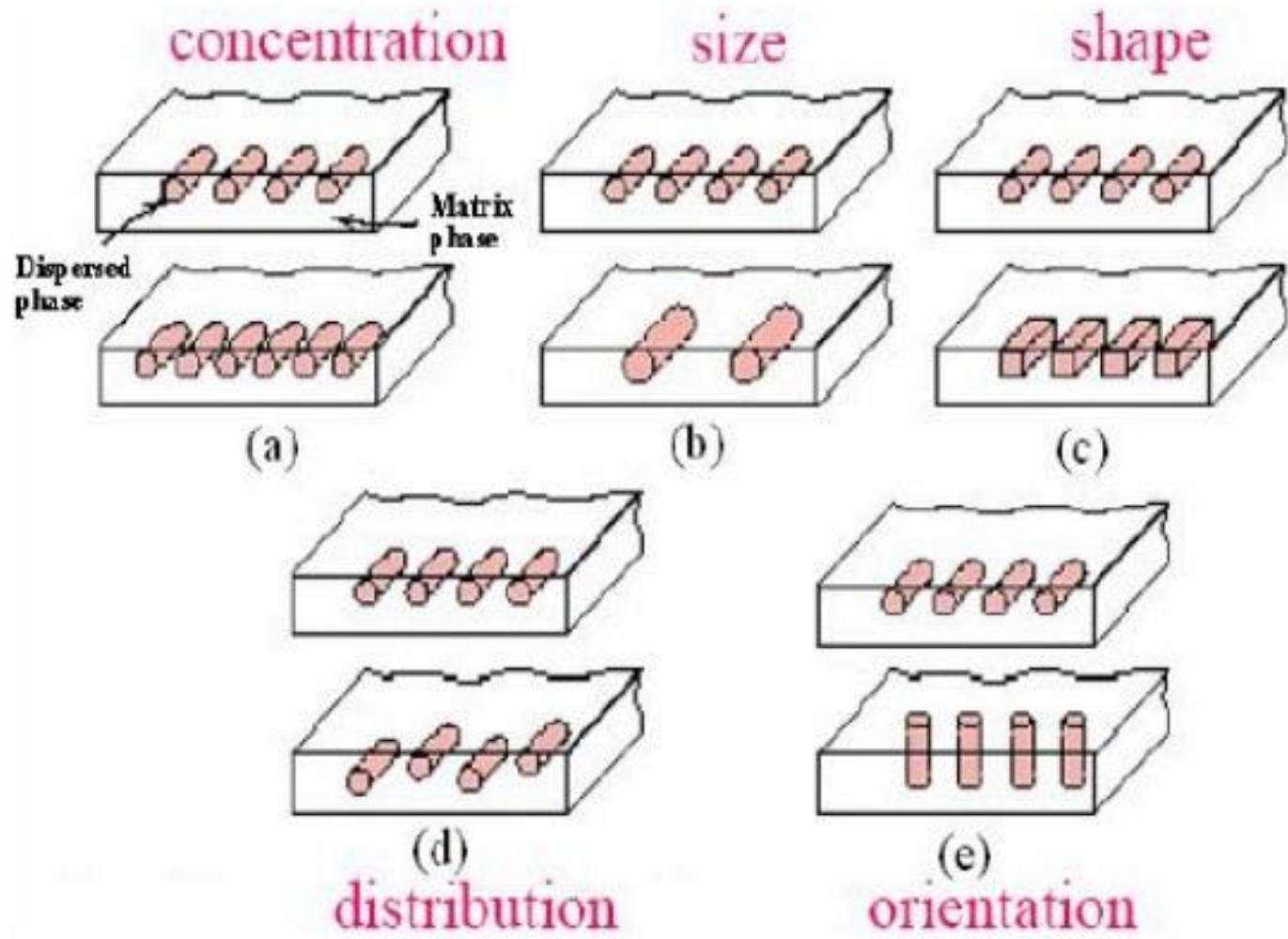


Factors in Creating Composites

Matrix material

Reinforcement material

- *Concentration*
- *Size*
- *Shape*
- *Distribution*
- *Orientation*



Applications

1. Aircraft and aerospace applications
2. Automotive applications
3. Marine applications
4. Sporting industries
5. Biomaterials
6. Industrial applications

Common MMCs and Applications

TABLE 9.3

Metal-Matrix Composite Materials and Applications

Fiber	Matrix	Applications
Graphite	Aluminum	Satellite, missile, and helicopter structures
	Magnesium	Space and satellite structures
	Lead	Storage-battery plates
	Copper	Electrical contacts and bearings
Boron	Aluminum	Compressor blades and structural supports
	Magnesium	Antenna structures
	Titanium	Jet-engine fan blades
Alumina	Aluminum	Superconductor restraints in fission power reactors
	Lead	Storage-battery plates
Silicon carbide	Magnesium	Helicopter transmission structures
	Aluminum, titanium	High-temperature structures
	Superalloy (cobalt-base)	High-temperature engine components
Molybdenum, tungsten	Superalloy	High-temperature engine components

Introduction

There are two general divisions of composites manufacturing processes:

- Open molding
- Closed molding

With open molding, the gel coat and laminate are exposed to the atmosphere during the fabrication process.

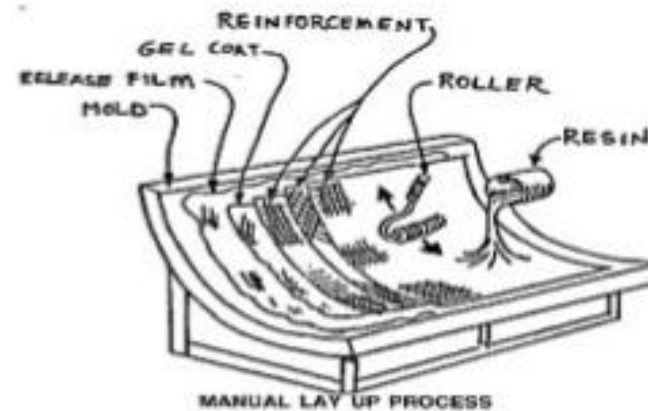
In closed molding, the composite is processed in a two-sided mold set, or within a vacuum bag.

There are a variety of processing methods within the open and closed molding categories:

- ◉ Open molding
 - Hand Lay-Up
 - Spray-up
 - Filament Winding
- ◉ Closed molding
 - Compression molding
 - Pultrusion
 - Vacuum Bag Molding
 - Vacuum Infusion Processing
 - Resin Transfer Molding (RTM)
 - Reinforced Reaction Injection Molding (RRIM)
 - Centrifugal Casting

Hand Lay-up

A Process wherein the application of resin and reinforcement is done by hand onto a suitable mould surface. The resulting laminate is allowed to cure in place without further treatment.



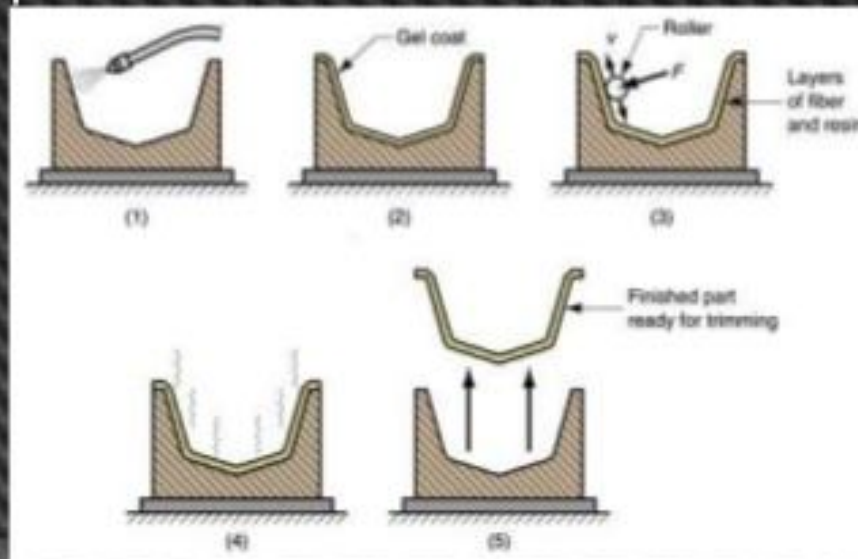
● Hand Lay-Up

Open mold shaping method in which successive layers of resin and reinforcement are manually applied to an open mold to build the laminated FRP composite structure.

Process Description - Gel coat is first applied to the mold using a spray gun for a high-quality surface. When the gel coat has cured sufficiently, roll stock fiberglass reinforcement is manually placed on the mold. The laminating resin is applied by pouring, brushing, spraying, or using a paint roller. FRP rollers, paint rollers, or squeegees are used to consolidate the laminate, thoroughly wetting the reinforcement, and removing entrapped air. Subsequent layers of fiberglass reinforcement are added to build laminate thickness.

Molds - Simple, single-cavity molds of fiberglass composites construction are generally used. Molds can range from very small to very large and are low cost in the spectrum of composites molds.

Major Advantages - Simplest method offering low-cost tooling, simple processing, and a wide range of part sizes. Design changes are readily made. There is a minimum investment in equipment. With skilled operators, good production rates and consistent quality are obtainable.



Spray Lay-up

- Glass fibers chopped up
- Resin, catalyst, & fibers sprayed onto a mold
- Cures at ambient temperature and atmospheric pressure

HOW LONG WILL IT TAKE ?
Before they say this one!

#1 Gun of choice in the **X-GUN**

Non-atomized choppers * Adhesive * Epoxy * Urethane * Granite coatings

PROVEN RELIABILITY

- * Multiple components
- * Designed for consistent high performance
- * Easy disassembly
- * 3.0 liter overall capacity (with optional parts or ability)
- * Longer gun length in the industry
- * Low pressure pneumatic controls
- * Ergonomically designed air trigger to reduce operator fatigue
- * Higher production
- * Less downtime

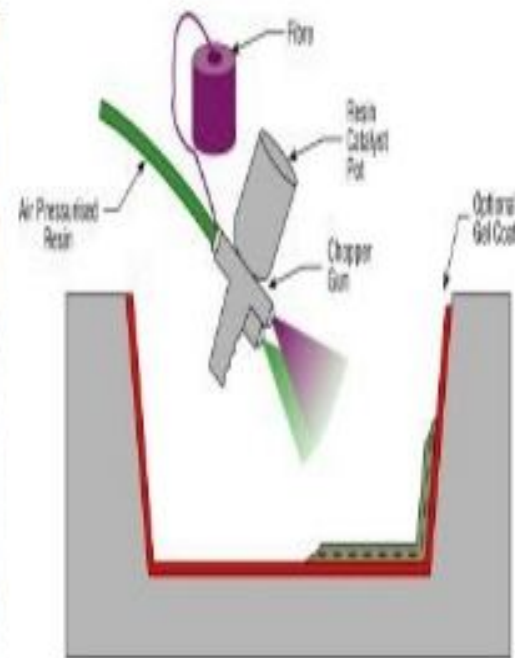
No needles * pneumatic cylinder extrudes resin from the open field valve (no need for additional)

Model: X-Gun gun, model number 1000

Leading edge technology in NON-ATOMIZED resin application

Z[®] GS MANUFACTURING

Phone: 949-442-7100 Fax: 949-442-6732
185 St. John Street Costa Mesa, CA 92627
Email: sales@gsmanufacturing.com



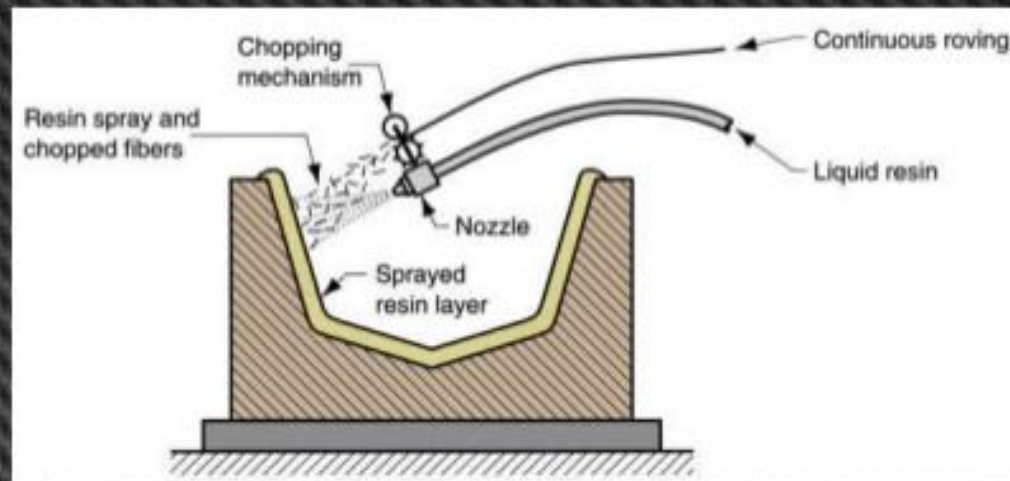
- Spray-Up (Chopping)

In the spray-up process the operator controls thickness and consistency, therefore the process is more operator dependent than hand lay-up.

Process Description - As with hand lay-up, gel coat is first applied to the mold prior to spray-up of the substrate laminate. Continuous strand glass roving and catalyzed resin are fed through a chopper gun, which deposits the resin-saturated "chop" on the mold. The laminate is then rolled thoroughly to saturate the glass strands and compact the chop. Additional layers of chop laminate are added as required for thickness. Roll stock reinforcements, such as woven roving or knitted fabrics, can be used in conjunction with the chopped laminates..

Molds - These are the same molds as in hand lay-up simple, single-cavity, molds of fiberglass composites construction. Molds can range from very small to very large and are low cost in the spectrum of composites molds.

Major Advantages - Simple, low-cost tooling, simple processing; portable equipment permits on-site fabrication; virtually no part size limitations. The process may be automated.



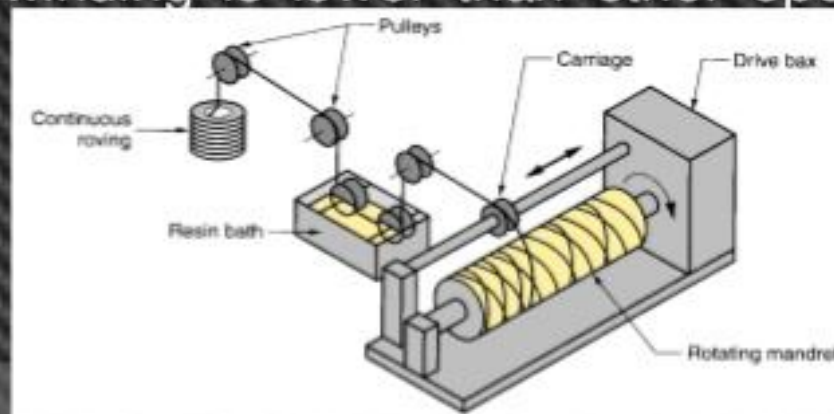
- ◉ Filament Winding

Filament winding is an automated open molding process that uses a rotating mandrel as the mold. The male mold configuration produces a finished inner surface and a laminate surface on the outside diameter of the product.

Process Description - Continuous strand roving is fed through a resin bath and wound onto a rotating mandrel. The filament is laid down in a predetermined geometric pattern to provide maximum strength in the directions required. When sufficient layers have been applied, the laminate is cured on the mandrel. The molded part is then stripped from the mandrel. Equipment is available for filament winding on a continuous basis and two axis winding for pressure cylinders. Filament winding can be combined with the chopping process and is known as the hoop chop process.

Molds - Mandrels of suitable size and shape, made of steel or aluminum form the inner surface of the hollow part. Some mandrels are collapsible to facilitate part removal.

Major Advantages - The process makes the high strength-to-weight ratio laminates and provides a high degree of control over uniformity and fiber orientation. The filament winding process can be used to make structures which are highly engineered and meet strict tolerances. Because filament winding is automated, the labor factor for filament winding is lower than other open molding processes.



- Compression Molding

Compression molding is a high-volume, high-pressure method suitable for molding complex, fiberglass-reinforced plastic parts on a rapid cycle time. Compression molding tooling consists of heated metal molds mounted in large presses.

Process Description - The mold set is mounted in a hydraulic or mechanical molding press. The molds are heated to 2500 to 4000 F. A weighed charge of molding compound is placed in the open mold. The two halves of the mold are closed and pressure is applied. Depending on thickness, size, and shape of the part, curing cycles range from less than a minute to about five minutes. The mold is opened and the finished part is removed.

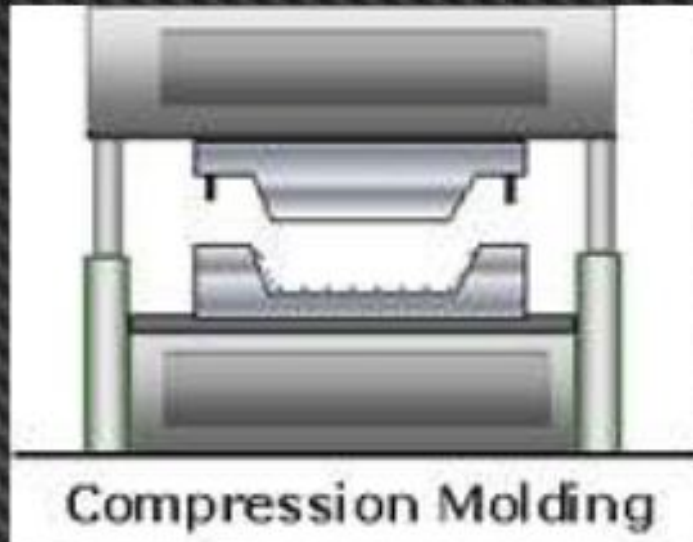
Molds - Tooling is usually machined steel or cast alloy molds that can be in either single or multiple-cavity configurations. Steel molds are hardened and sometimes chrome plated for enhanced durability. Mold materials include cast or forged steel, cast iron, and cast aluminum.

Major Advantages - Compression molding produces fast molding cycles and high part uniformity. The process can be automated. Good part design flexibility and features and attachments can be molded in. Good surface finishes are obtainable, contributing to lower part finishing cost. Subsequent trimming and machining operations are minimized in compression molding. Labor costs are low.

Products:

Typical parts include:

- Automobile components
- Appliance housings
- Structural components,
- Electrical components



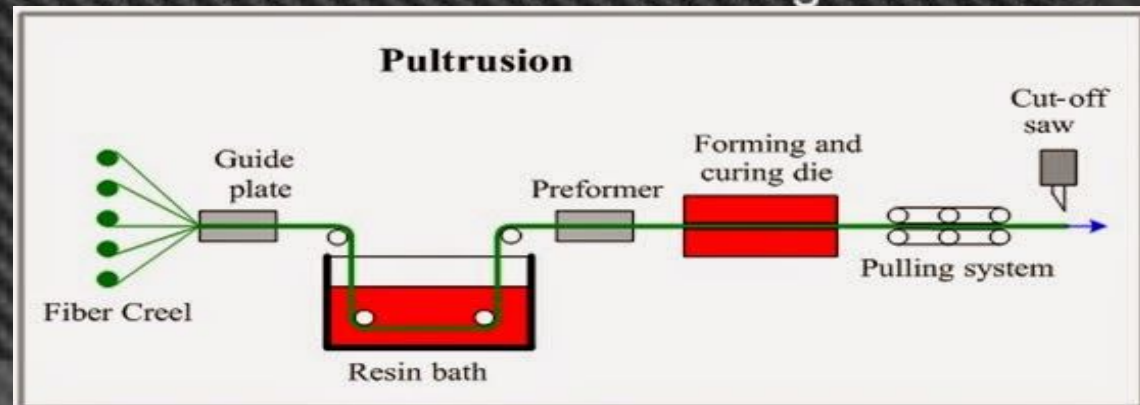
- Pultrusion

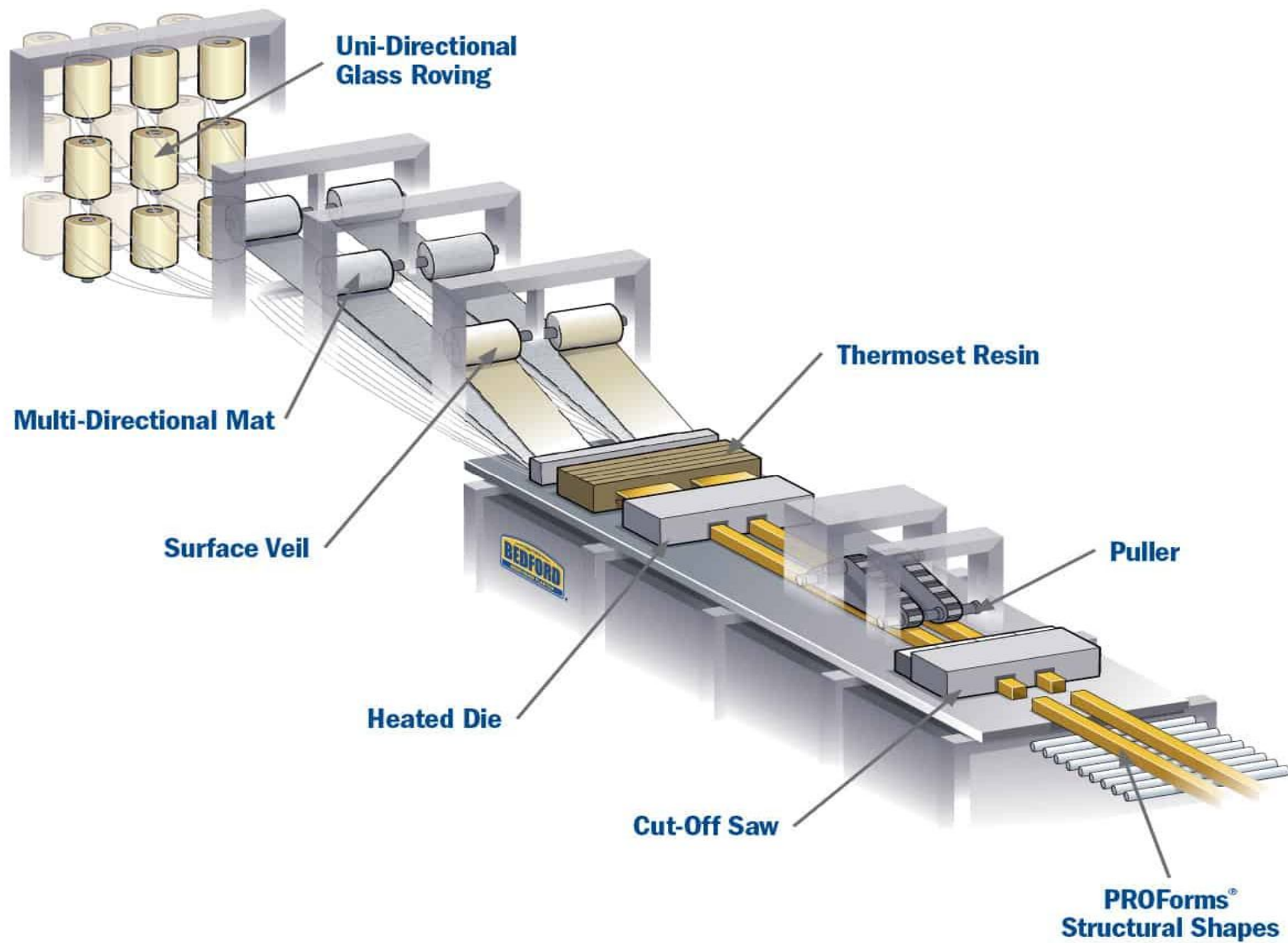
Pultrusion is a continuous process for the manufacture of products having a constant cross section, such as rod stock, beam etc.

Process Description - Continuous strand fiberglass roving, or surfacing veil is impregnated in a resin bath, then pulled (pul-trusion) through a steel die, by a powerful tractor mechanism. The steel die consolidates the saturated reinforcement, sets the shape of the stock, and controls the fiber/resin ratio. The die is heated to rapidly cure the resin. Many creels (balls) of roving are positioned on a rack, and a complex series of tensioning devices and roving guides direct the roving into the die.

Molds - Hardened steel dies are machined and include a preform area to do the initial shaping of the resin-saturated roving. The dies include heating which can be electric or hot oil. The latest pultrusion technology uses direct injection dies, in which the resin is introduced inside the die, rather than through an external resin bath.

Major Advantages - The process is a continuous operation that can be readily automated. It is adaptable to both simple and complex cross-sectional shapes. Very high strengths are possible due to the fiber loading and labor costs are low.





Vacuum Bag Molding

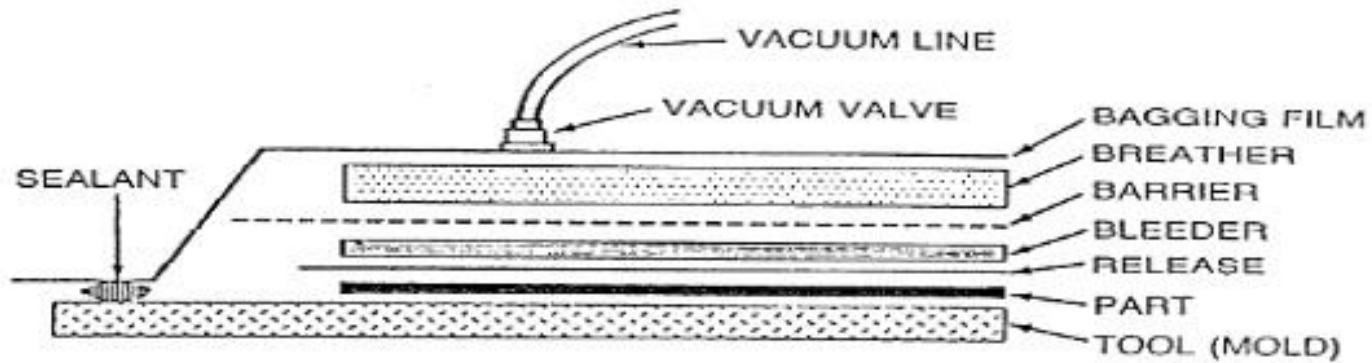
- ▮ Two-sided mold set.
- ▮ Shapes both surfaces of the panel.
- ▮ Lower side is a rigid mold
- ▮ Upper side is a flexible membrane or vacuum bag
- ▮ Bag made of silicone material or an extruded polymer film.
- ▮ Performed at either ambient or elevated temperature.
- ▮ Ambient atmospheric pressure acts upon the vacuum bag.
- ▮ Most economical way uses venturi vacuum and air compressor or a vacuum pump.

- Vacuum Bag Molding

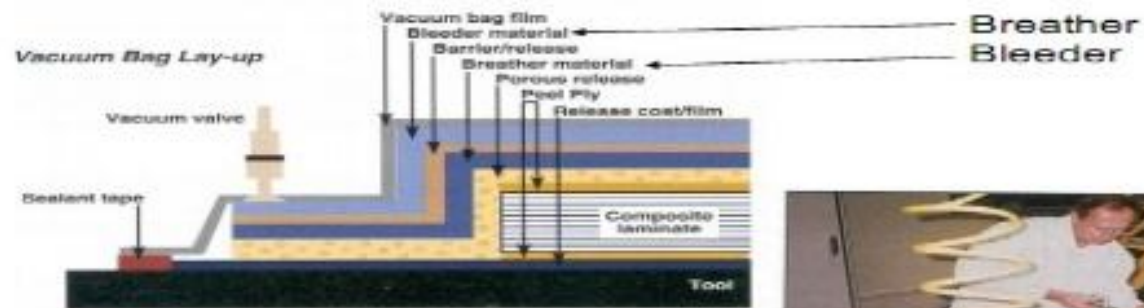
The mechanical properties of open-mold laminates can be improved with vacuum bagging. By reducing the pressure inside the vacuum bag, external atmospheric pressure exerts force on the bag. The pressure on the laminate removes entrapped air, excess resin, and compacts the laminate. A higher percentage of fiber reinforcement is the result.

Process Description - In the simplest form of vacuum bagging, a flexible film (PVA, nylon, mylar, or polyethylene) is placed over the wet lay-up, the edges sealed, and a vacuum drawn. Pulling a vacuum from within the bag uses atmospheric pressure to eliminate voids and force excess resin from the laminate. The addition of pressure further results in high fiber concentration and provides better adhesion between layers of sandwich construction.

Vacuum bag assembly



Vacuum bag



- Vacuum Infusion Processing

Vacuum infusion is a variation of vacuum bagging where the resin is introduced into the mold after the vacuum has pulled the bag down and compacted the laminate. The method is defined as having lower than atmospheric pressure in the mold cavity. The reinforcement and core material are laid-up dry in the mold. This is done by hand and provides the opportunity to precisely position the reinforcement. When the resin is pulled into the mold the laminate is already compacted; therefore, there is no room for excess resin. Very high resin to glass ratios are possible with vacuum infusion and the mechanical properties of the laminate are superior. Vacuum infusion is suitable to mold very large structures and is considered a low volume molding process.

Molds - Molds are similar to those used for conventional open-mold processes.

Major Advantages - Vacuum infusion can produce laminates with a uniform degree of consolidation, producing high strength, lightweight structures. This process uses the same low cost tooling as open molding and requires minimal equipment. Very large structures can be fabricated using this method. Vacuum infusion offers a substantial emissions reduction compared to either open molding or wet lay-up vacuum bagging.



- ◉ Resin Transfer Molding

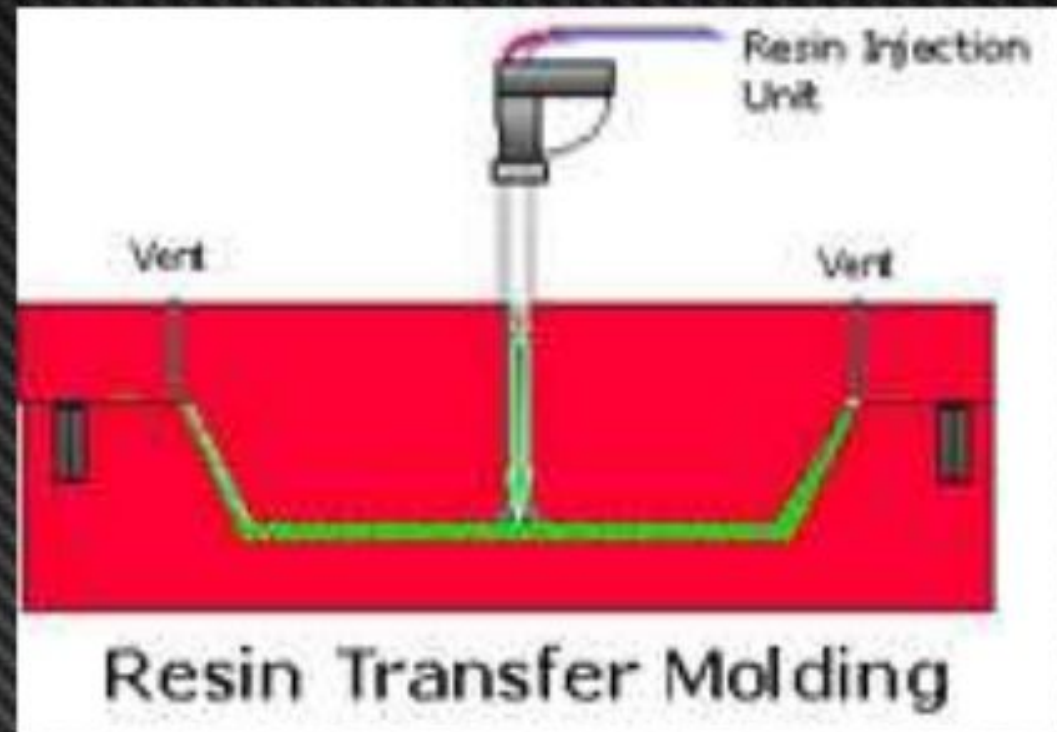
Resin transfer molding is an intermediate volume molding process for producing composites. The RTM process is to inject resin under pressure into a mold cavity. This process can be automated and is capable of producing rapid cycle times. Vacuum assist can be used to enhance resin flow in the mold cavity.

Process Description - The mold set is gel coated conventionally, if required. The reinforcement (and core material) is positioned in the mold and the mold is closed and clamped. The resin is injected under pressure, using mix/meter injection equipment, and the part is cured in the mold. The reinforcement can be either a preform or pattern cut roll from stock material. Preforms are reinforcement that is pre-formed in a separate process and can be quickly positioned in the mold.

RTM can be done at room temperature; however, heated molds are required to achieve fast cycle times and product consistency. Clamping can be accomplished with perimeter clamping or press clamping.

Molds - RTM can utilize either "hard" or "soft" tooling. Soft tooling would be either polyester or epoxy molds, while hard tooling may consist of cast machined aluminum, electroformed nickel shell, or machined steel molds.

Major Advantages - This closed molding process produces parts with two finished surfaces. By laying up reinforcement material dry inside the mold, any combination of materials and orientation can be used, including 3-D reinforcements. Part thickness is determined by the tool cavity. Fast cycle times can be achieved in temperature controlled tooling and the process can range from simple to highly automated.



Resin Transfer Molding

Definition

What is “Ceramic”?

- ❑ **Ceramic materials** are **inorganic, non-metallic materials and things made from them.**
- ❑ They may be crystalline or partly crystalline.
- ❑ They are formed by the action of **heat** and **subsequent cooling**.
- ❑ Most ceramics are compounds between **metallic** and **nonmetallic elements** for which the interatomic bonds are either totally ionic bond or predominantly ionic but having some covalent character.
- ❑ **Clay** was one of the earliest materials used to produce ceramics, but many different ceramic materials are now used in domestic, industrial and building products.
- ❑ A wide-ranging group of materials whose ingredients are **clays, sand and felspar.**
 - The term “*Ceramics*” comes from the Greek word *keramikos*, which means “**Burnt stuff** or **drinking vessel**”, indicating that desirable properties of these materials are normally achieved through a high-temperature heat treatment process called ***Firing***, but was later applied by the Greeks to ***all fired clay products***.

Ceramic Defined

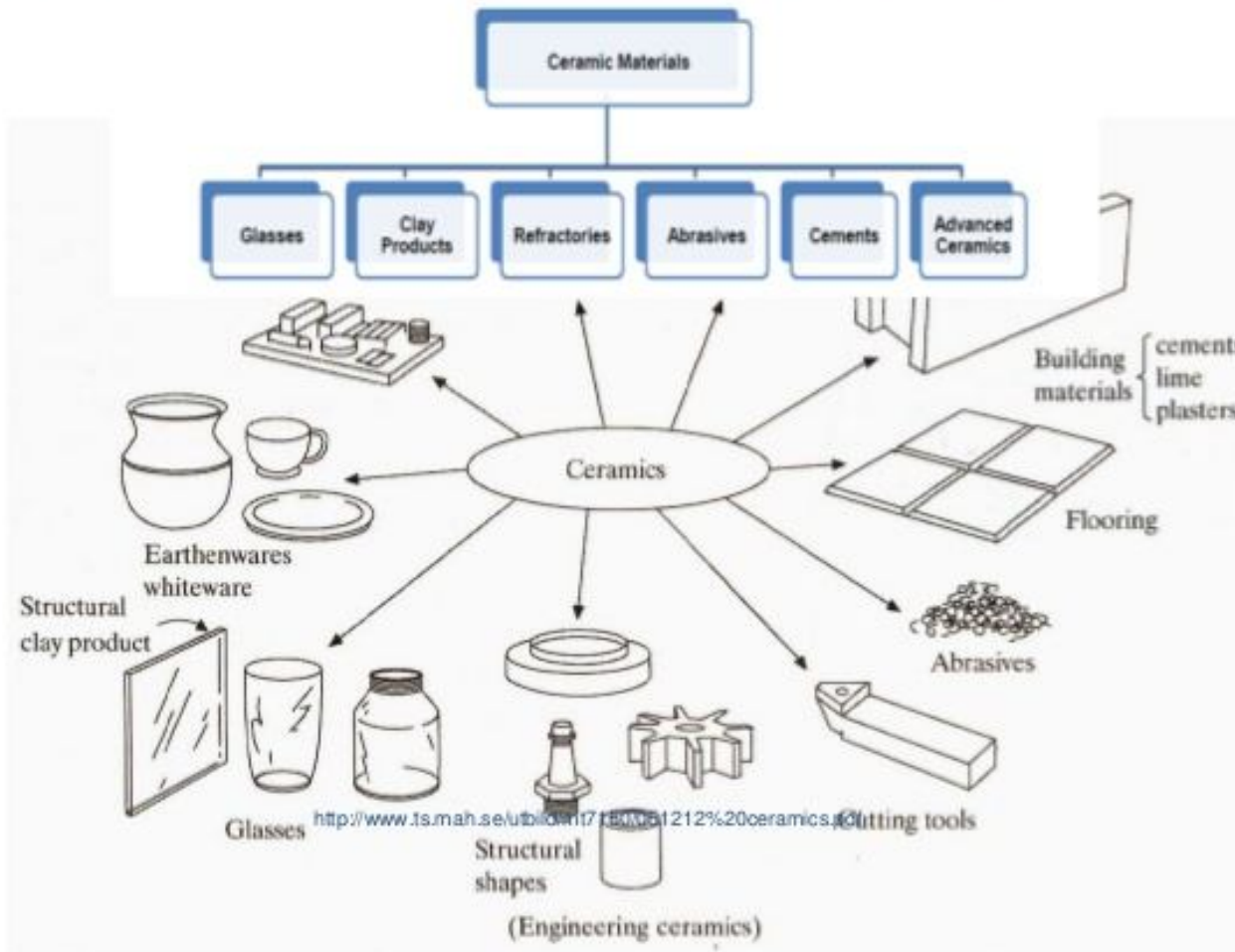
An inorganic compound consisting of a metal (or semi-metal) and one or more nonmetals

- Important examples:
 - *Silica* - silicon dioxide (SiO_2), the main ingredient in most glass products
 - *Alumina* - aluminum oxide (Al_2O_3), used in various applications from abrasives to artificial bones
 - More complex compounds such as hydrous aluminum silicate ($\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$), the main ingredient in most clay products

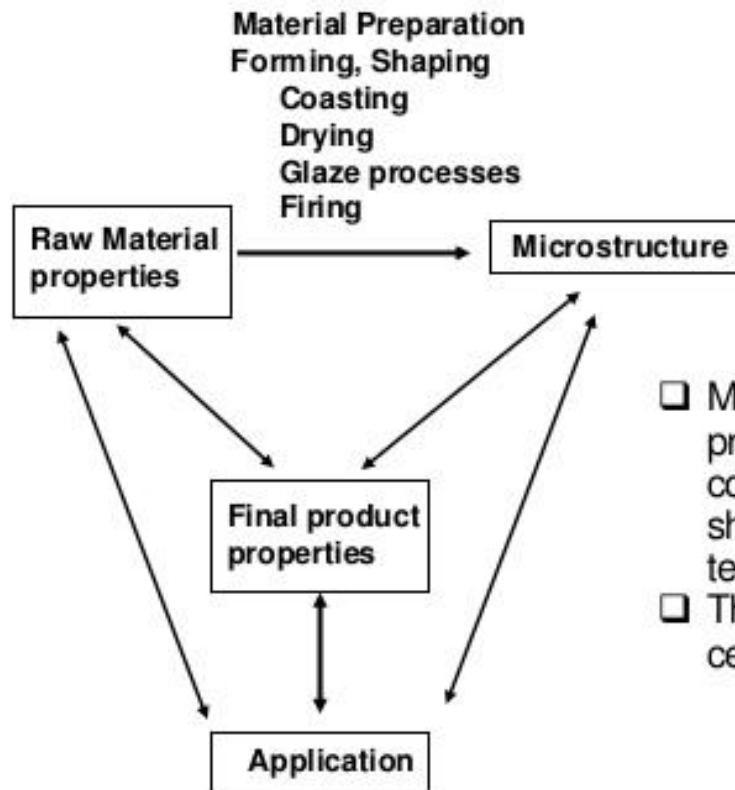
WHAT ARE CERAMICS?

- To be most frequently silicates, oxides, nitrides and carbides
- Typically insulative to the passage of electricity and heat
- More resistant to high temperatures and harsh environments than metals and polymers
- Hard but very brittle

SPECTRUM OF CERAMICS USES



FABRICATING AND PROCESSING OF CERAMICS



- ❑ Most traditional and technical ceramics product are manufactured by compacting powder or particles into shapes which are heated to high temperature.
- ❑ The basic steps in the processing of ceramics are:
 - Material Preparation
 - Forming & Casting
 - Thermal treatment by drying

Plastic

- This material is **man made** and is a by product of the **oil industry**.

- a synthetic material made from a wide range of organic polymers such as polyethylene, PVC, nylon, etc., that can be moulded into shape while soft, and then set into a rigid or slightly elastic form.



Plastics

```
graph TD; A[Plastics] --> B[Thermoplastics]; A --> C[Thermosetting]
```

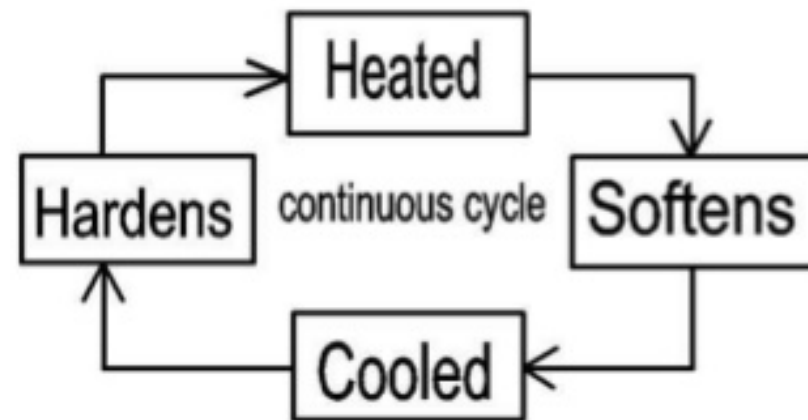
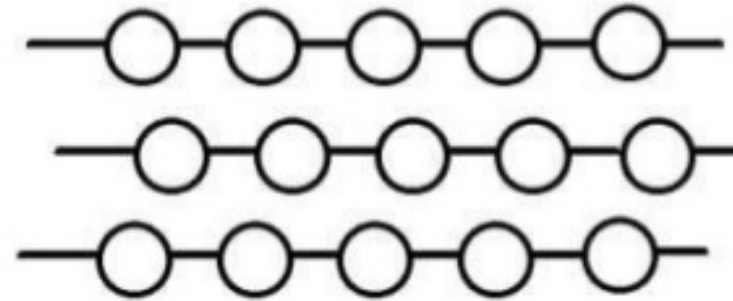
Thermoplastics

Thermosetting

Thermoplastics

- There are a wide range of thermoplastics, some that are rigid and some that are extremely flexible.
- The molecules of thermoplastics are in lines or **long chains** with very few entanglements. When heat is applied the molecules move apart, which increases the distance between them, causing them to become untangled. This allows them to become soft when heated so that they can be bent into all sorts of shapes.
- When they are left to cool the chains of molecules cool, take their former position and the plastic becomes stiff and hard again. The process of heating, shaping, reheating and reforming can be repeated many times.

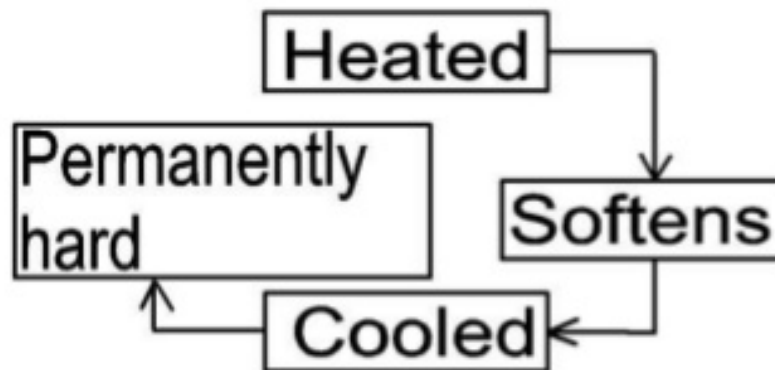
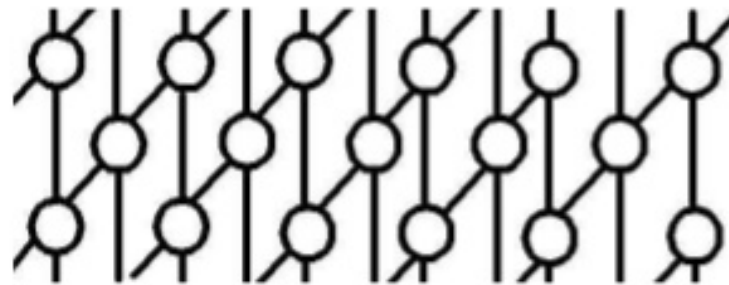
Long chain molecules



Thermosetting plastics

- The molecules of thermosetting plastics are heavily **cross-linked**. They form a **rigid molecular structure**.
- The molecules in thermoplastics sit **end-to-end and side-by-side**.
- Although they soften when heated the first time, which allows them to be shaped they become permanently stiff and solid and cannot be reshaped.
- Thermoplastics remain rigid and non-flexible even at high temperatures. **Polyester resin** and **urea formaldehyde** are examples of thermosetting plastics.

Cross-linked molecules



Rubber

- Natural rubber is obtained in the form of latex from rubber tree.
- It is a polymer that can stretch and shrink.
- Highly elastic.
- Used in tyres, footwears, conveyor belts , pipes etc.
- Shock absorber.
- Resistant to water has led to its use in rainwear, diving gear, and chemical and medicinal tubing, and as a lining for storage tanks, processing equipment and railroad tank cars.



UNIT 5

HIGH TEMPERATURE MATERIALS CHARACTERIZATION

Temperature – stress – strain-rate relation

Steady-state creep strain-rate:

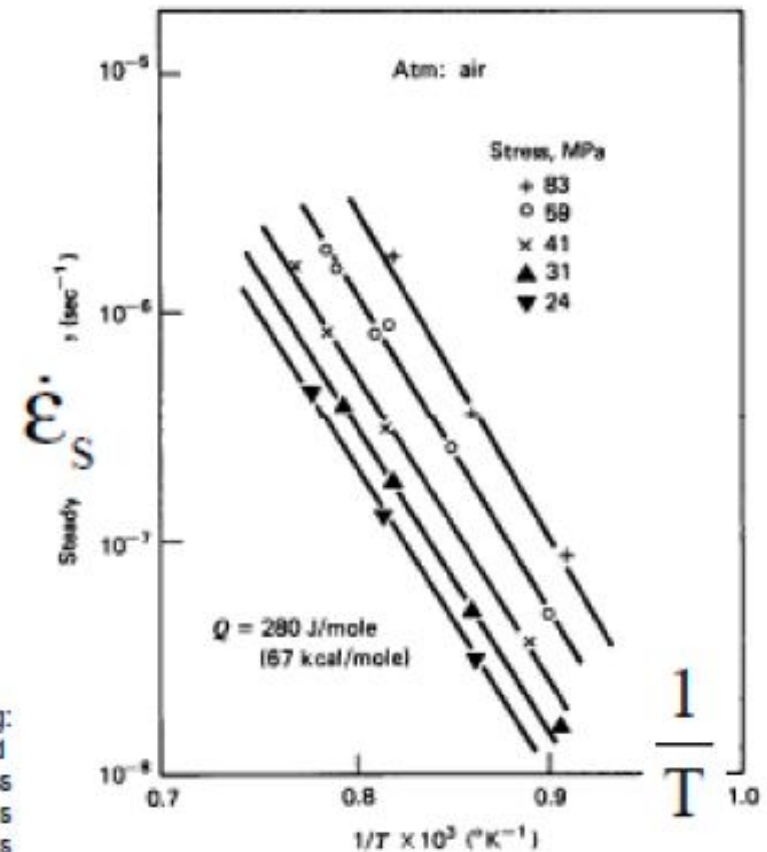
$$\dot{\epsilon}_s = f(T, \sigma, \epsilon, \text{metalurgical factors})$$

Creep strain:

$$\epsilon = t \exp\left(-\frac{Q}{RT}\right)$$

Creep strain-rate:

$$\dot{\epsilon} = \exp\left(-\frac{Q}{RT}\right)$$



Temperature – stress – strain-rate relation

Experimental data shows: $Q = f(T)$

For $0.5T_m < T < T_m$: self-diffusion a significant mechanism:

$$D = D_0 \exp\left(-\frac{Q_{SD}}{RT}\right)$$

The diagram shows the equation $D = D_0 \exp\left(-\frac{Q_{SD}}{RT}\right)$ with arrows pointing from labels to the corresponding terms in the equation:

- An arrow points from the label "Diffusivity" to the variable D .
- An arrow points from the label "Constant" to the variable D_0 .
- An arrow points from the label "Self-diffusion activation energy" to the variable Q_{SD} .
- An arrow points from the label "Gas constant" to the variable R .
- An arrow points from the label "Absolute temperature" to the variable T .

Temperature – stress – strain-rate relation

Current understanding:

$$T \sim T_m \text{ and } \sigma \text{ low: } \dot{\epsilon}_s \propto \sigma$$

Deformation mechanism: atomic diffusion

- migration of vacancies from tensile to compressive grain boundaries;
- atomic diffusion along grain boundaries

Temperature – stress – strain-rate relation

Current understanding:

$0.5T_m < T < T_m$ and σ medium/high:

$$\dot{\epsilon}_s \propto \sigma^{4-5} \quad (\text{power law creep})$$

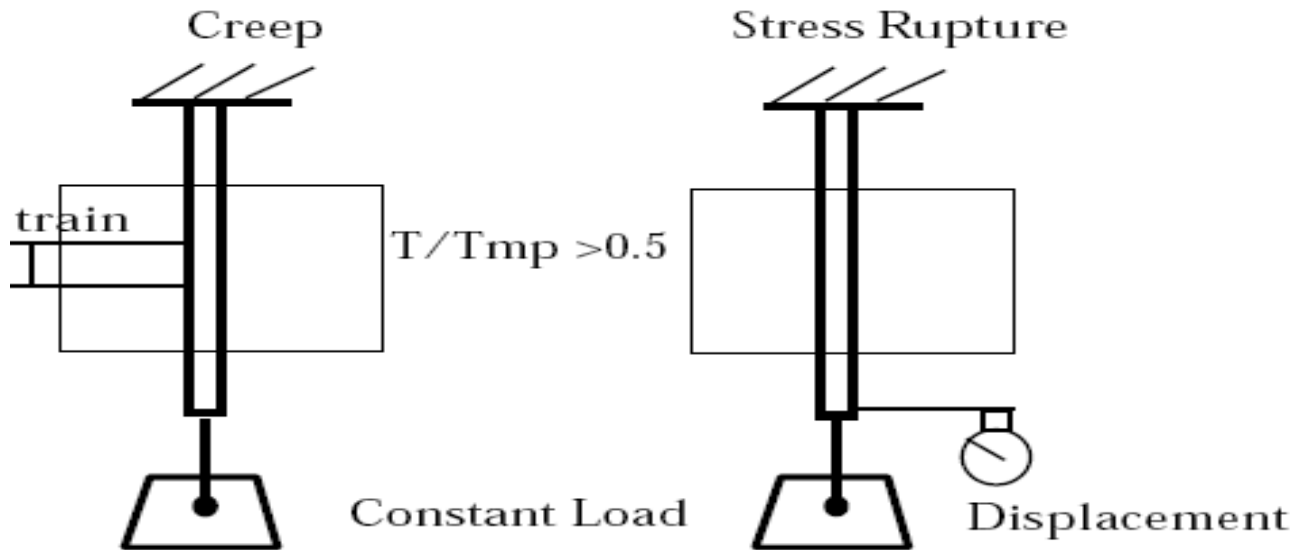
Deformation mechanisms:

- diffusion-controlled movement of dislocations
(dislocations climb away from barriers)
- grain boundary sliding

Stress Rupture Tests

- Determines the time necessary for material to result in failure under a overload.
- Useful in materials selection where dimensional tolerances are acceptable, but rupture cannot be tolerated.
- Generally performed at elevated temperatures.
- Smooth, notched, flat specimens or samples of any combination can be tested.

Creep VS Stress Rupture Test



- Low Loads
- Precision Strain Measurement ($\epsilon_f < 0.5\%$)
- Long term (2000-10,000 h)
- Expensive equipment

Emphasis on minimum strain rate at stress and temperature

- High Loads
- Gross Strain Measurement (ϵ_f up to 50%)
- Short term (<1000 h)
- Less expensive equipment

Emphasis on time to failure at stress and temperature

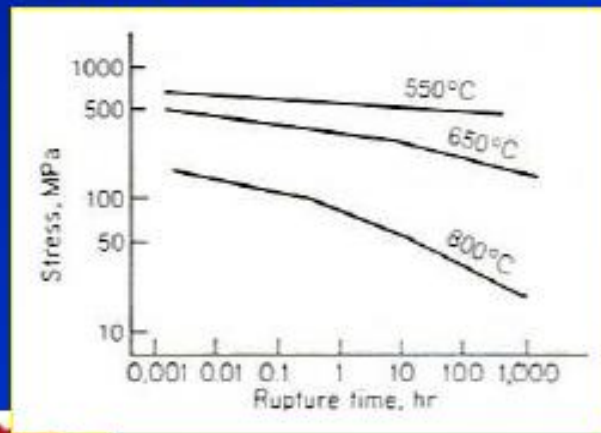
The stress rupture test

Creep test

Stress rupture test

<u>Load</u>	Low load	high load
<u>Creep rate</u>	minimum creep rate	high creep rate
<u>Test period</u>	2000-10000 h	1000 h
<u>Total strain</u>	0.5%	50%
<u>Strain gauge</u>	Good strain measuring devices	Simpler strain measuring devices

The **rupture test** is carried out in a similar manner to the **creep test** but at a **higher stress level** until the specimen fails and the **time at failure** is measured.



Stress rupture- time data on log-log scale

- **Rupture strength** and **failure time** are plotted, normally showing a **straight line**.
- **Changing of the slope** indicates **structural changes in the material**, i.e., transgranular → intergranular fracture, oxidation, recrystallisation, grain growth, spheroidization, precipitation.
- Direct application in **design**.

The Monkman–Grant relationship

The need to extrapolate the results of accelerated creep tests has been met by the development of several methods. We discuss one of these in some detail in Section 2.6. A simpler approach is the **Monkman–Grant relationship**, which states that for a given material in a certain range of stress and strain (Monkman and Grant, 1956)

$$\dot{\epsilon}_{\min} t_f = \text{constant} \quad (2.2)$$

where

$\dot{\epsilon}_{\min} = f(\sigma, T)$ is the minimum steady-state creep rate

$t_f = g(\sigma, T)$ is the time to fracture

and the constant characterizes the material.

Using the **Monkman–Grant relationship**, $\dot{\epsilon}_{\min}$ and t_f can be determined at a convenient stress and temperature; $\dot{\epsilon}_{\min}$ can be determined at the operating stress and temperature and hence t_f for the operating conditions may be calculated. The **relationship** (2.2) often holds true (Figure 2.8(a)) but in some cases it needs to be adapted to the form

$$(\dot{\epsilon}_{\min})^\beta t_f = \text{constant}; \quad \beta < 1 \quad (2.3)$$



AE8007 - AIRCRAFT MATERIALS
TWO MARKS WITH ANSWERS

UNIT-1- *ELEMENTS OF AEROSPACE MATERIALS*

1. Define solid.

A state of matter characterized by particles arranged such that their shape and volume are relatively stable. The constituents of a solid tend to be packed together much closer than the particles in a gas or liquid.

Examples: a brick, a piece of wood.

2. What is State of Matter?

One of the ways in which matter can interact with itself to form homogeneous phase. Examples: solid, liquids, gases, plasma.

3. Define plasma state of matter.

Plasma is not a common state of matter here on Earth, but may be the most common state of matter in the universe. Plasma consists of highly charged particles with extremely high kinetic energy. The noble gases (helium, neon, argon, krypton, xenon and radon) are often used to make glowing signs by using electricity to ionize them to the plasma state. Stars are essentially superheated balls of plasma.

4. What is Materials Science?

Materials Science is an interdisciplinary subject which is concerned with the study of materials as a whole like behavior of the material, production of the material, applications and study of all properties of the material along with its macro and microstructures.

5. Define atom.

An **atom** is the smallest constituent unit of ordinary matter that has the properties of a chemical element. Every solid, liquid, gas, and plasma is composed of neutral or ionized atoms. Every atom is composed of a nucleus and one or more electrons bound to the nucleus.

6. Define nucleus.

The nucleus is at the centre of the atom and made of one or more protons and typically a similar number of neutrons. Protons and neutrons are collectively known as *nucleons*.

7. What is atomic bonding?

The mechanisms of bonding between the atoms are based on electrostatic interatomic interaction.

8. What are the types of atomic bonding?

Atomic bonding can be broadly classified as

- i) Primary bonding
 - ✓ Ionic bond
 - ✓ Covalent bond
 - ✓ Metallic bond
- ii) Secondary bonding
 - ✓ Hydrogen bonding
 - ✓ Van der Waals Bonding

9. Explain ionic bonding?

In ionic bonding, electrons are completely transferred from one atom to another. In the process of either losing or gaining negatively charged electrons, the reacting atoms form ions. The oppositely charged ions are attracted to each other by electrostatic forces, which are the basis of the ionic bond.

10. Explain covalent bonding?

Covalent bonding occurs because the atoms in the compound have a similar tendency for electrons (generally to gain electrons). This most commonly occurs when two non-metals bond together. Because both of the nonmetals will want to

gain electrons, the elements involved will share electrons in an effort to fill their valence shells. A good example of a covalent bond is that which occurs between two hydrogen atoms.

11.Explain metallic bonding?

In metals, the atoms are ionized, losing some electrons from the valence band. Those electrons form a *electron sea*, which binds the charged nuclei in place, in a similar way that the electrons in between the H atoms in the H₂ molecule bind the protons.

12.What is crystal structure?

Crystallography or crystal structure is a unique arrangement of atoms, ions or molecules in a crystalline liquid or solid.. The basic principles of many materials characterization techniques such as X-ray diffraction (XRD), Transmission electron microscopy (TEM)

Lattice + basis = crystal structure

13.Define crystalline solid.

A crystal or crystalline solid is a solid material whose constituents, such as atoms, molecules or ions, are arranged in a highly ordered microscopic structure, forming a crystal lattice that extends in all directions.Periodic arrangement of atoms: definite repetitive pattern

14.Define polycrystalline solid.

Polycrystalline or multicrystalline materials, or polycrystals are solids that are composed of many crystallites of varying size and orientation. Crystallites are also referred to as grains. They are small or even microscopic crystals and form during the cooling of many materials.

15.Define Amorphous.

An amorphous or non-crystalline solid is a solid that lacks the long-range order characteristic of a crystal, the atoms and molecules are not organized in a definite lattice pattern. Such solids include glass, plastic, and gel.

16. Write the difference between crystalline solid and Amorphous.

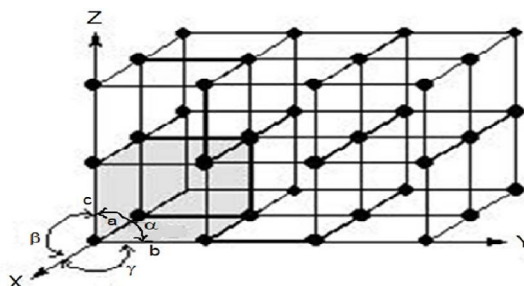
Crystalline solid	Amorphous
<ul style="list-style-type: none">✓ They have characteristic geometrical shape.✓ They have highly ordered three-dimensional arrangements of particles.✓ They are bounded by planes or faces✓ Planes of a crystal intersect at particular angles.✓ They have sharp melting and boiling points. <p>Ex: Copper Sulphate (CuSO_4), NiSO_4, Diamond, Graphite, NaCl, Sugar etc</p>	<ul style="list-style-type: none">✓ In these solids particles are randomly arranged in three dimensions.✓ They don't have sharp melting points.✓ Amorphous solids are formed due to sudden cooling of liquid.✓ Amorphous solids melt over a wide range of temperature <p>Ex: Coal, Coke, Glass, Plastic, rubber etc</p>

17. Define space lattice?

A space lattice can be defined as a three dimensional array of points, each of which has identical surroundings.

18. What is Bravais Lattice?

The unit vectors a , b and c is called lattice parameters. Based on their length equality or inequality and their orientation (the angles between them, α , β and γ) a total of 7 crystal systems can be defined. With the centering (face, base and body centering) added to these, 14 kinds of 3D lattices, known as **Bravais lattices**.



19. Define miller indices?

Vectors and atomic planes in a crystal lattice can be described by a three-value Miller index notation (lmn). The l , m , and n directional indices are separated by 90° , and are thus orthogonal.

20. What is Atomic packing factor?

Atomic packing factor (APF) or packing efficiency indicates how closely atoms are packed in a unit cell and is given by the ratio of volume of atoms in the unit cell and volume of the unit cell

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

21. What is Planer density?

Planar density (PD) refers to density of atomic packing on a particular plane.

$$\text{planer density} = \frac{\text{number of atoms on a plane}}{\text{Area of a plane}}$$

22. What is linear density?

Linear density (LD) is the number of atoms per unit length along a particular direction.

$$\text{Linear density} = \frac{\text{number of atoms on the direction vector}}{\text{length of the direction vector}}$$

UNIT-2 – MECHANICAL BEHAVIOUR OF MATERIALS

1. What is meant by hardness?

Degree to which a metal will resist cutting, abrasion, penetration, bending and stretching. The indicated hardness of metals will differ somewhat with the specific apparatus measuring hardness. (See Brinell Hardness, Rockwell Hardness, Vickers Hardness, Scleroscope Hardness) Tensile Strength also is an indication of hardness.

2. Define ductility and malleability of materials.

Ductility is the wire drawing capacity of the material by plastic deformation without fracture. Copper and platinum are highly ductile materials. Malleability is the sheet form ability of the material by hammering without fracture. Gold and aluminium are the highly malleable materials.

3. What is meant by strain hardening?

An increase in **hardness** and strength caused by **plastic deformation** at temperatures lower than the **recrystallization** range.

4. What are the factors affecting diffusion?

- ✓ Temperature : increases the rate of diffusion
- ✓ crystal structure : crystal with low packing factor increase the rate of diffusion
- ✓ Grain size : fine grain material has more diffusion rate
- ✓ Concentration : value of diffusion coefficient varies with concentration

5. Define Fracture?

Fracture is a process of breaking a solid into number of pieces as a result of stress. Fracture denotes the complete destruction of the material, resulting separation of a portion of the material body.

6. How does the yield strength vary with grain size?

The variation of yield strength σ_y with grain size is given by Hall-Petch relation

$$\sigma_y = \sigma_o + k_y d^{-1/2}$$

Where d is the average grain diameter, while σ_o and k_y are constants for a particular material. Fine grained material is harder and stronger than one that is coarse grained.

7. What are elastic and plastic materials?

Elastic materials can regain their original shape after removal of the deforming forces and within the elastic limit, the stress is proportional to strain and have high elastic modulus.

Example: Steel, Brasses, Gold. Plastic materials can undergo plastic deformation permanently in shape and size by the deforming forces up to the ultimate strength without any fracture.

Example: PVC, Polymers.

8. What are the uses of Vickers hardness test?

1. The material is tested without any destructions so its a nondestructive testing. After testing the material or product can be used or sold.
2. Only smaller loads are applied. That would not produce cracks or fractures inside the specimen.
3. Micro hardness of the surface hardened materials can be determined accurately.

9. What are creep and creep resistance?

Creep is the property of a material by which it deforms continuously under a steady load (yielding). The deformation during creep is nonrecoverable. The creep can produce fracture or rupture even though the applied stress is lower than the ultimate stress. So the creep in materials should be avoided, particularly at high temperatures.

Creep resistance is the property of the material by which the continuation of creep is stopped.

10. Define creep formation

It involves time-dependent deformation and high temperature creep cracking generally develops in an intercrystalline manner in components of engineering importance that fail over an extended time.

11. What are factors which affect creep resistant materials?

Creep is influenced by minor variations in metallurgical conditions. Some of these affecting variables are:

- ✓ Grain size
- ✓ Prior strain
- ✓ Formation of solid solutions and
- ✓ Precipitation and dispersion hardening

12. What is meant by diffusion process?

At low stress and high temperature atoms diffuse from sides to the top and bottom. The grain becomes longer as the applied stress does work. Atomic diffusion in one direction is same as vacancy diffusion in opposite direction.

13. Which types of materials are preferred for creep application?

A material which posses the following features to avoid creep formation and get creep resistant at high temperatures.

- ✓ Higher creep resistance is observed with metals having high melting point. Creep becomes significant above $0.4 T_m$.
- ✓ A coarse grain metal has high creep resistance than fine grained metals.
- ✓ Single crystals have excellent creep resistance because they have no grain boundary.

14. Name two metallurgical factors that affect creep rate.

- ✓ Work hardening
- ✓ Thermal Softening
- ✓ Grain boundary sliding
- ✓ Diffusion and cavitation

15. What are types of fracture?

Generally fracture can be divided into 2 types such

- ✓ Brittle fracture (eg. Cast iron)
- ✓ Ductile fracture (eg. Mild steel)

Further it can be classified,

Depends on the appearance as

-Shearing fracture and - Cleavage fracture.

Crystallographic nature as -Fibrous fracture and Granular fracture

16. Draw typical creep curve and mark the various stages.

1. Primary Or Transient Creep – **Strain or work hardening**
2. Secondary Or Steady State Or Recovery Creep- **Thermal Softening or Annealing**
3. Tertiary Creep – **Void Propagation and Grain boundary sliding**

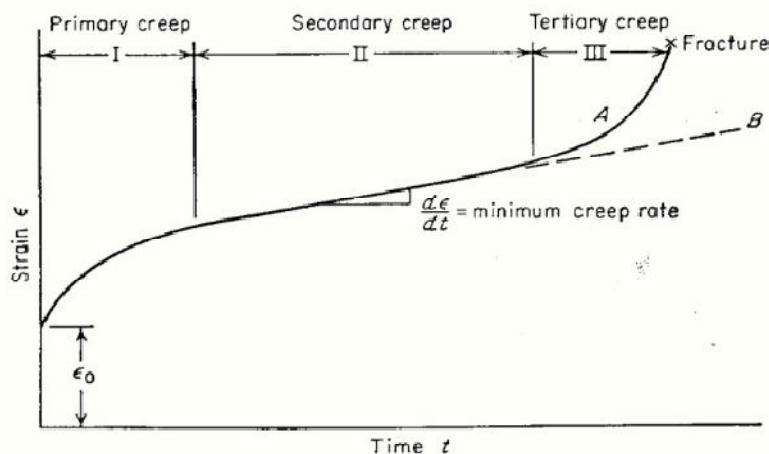


Figure 13-4 Typical creep curve showing the three steps of creep. Curve A, constant-load test; curve B, constant-stress test.

17. Write examples for Plastic Deformation/Yielding

Everyday Example:

Deforming a metal paper clip. If we only flex it a small amount- then it springs back to its original shape this is elastic deformation. If we twist enough to deform it permanently, this is plastic deformation. Elastic deformation is acceptable, plastic deformation is not.

Aircraft Examples:

Numerous airframes and propellers have been plastically deformed by hard landings. This often results in the scrapping of the aircraft.

UNIT-3 – CORROSION & HEAT TREATMENT OF METALS AND ALLOYS

1. What is Corrosion?

Corrosion is the deterioration of materials by chemical interaction with their environment. The term corrosion is sometimes also applied to the degradation of plastics, concrete and wood, but generally refers to metals. The most widely used metal is iron.

2. Define oxidation process.

Oxidation means the loss of electrons. The oxidation of a metal occurs when the metal loses one or more electrons, so that the atoms of the metal go from the neutral state and become a positively charge ion. This commonly results in the formation of a metal oxide (in the case of iron that is known as rust).

3. Define hot corrosion.

Hot corrosion is an high- temperature analog of aqueous atmospheric corrosion. A thin film deposit of fused salt on an alloy surface in a hot oxidizing gas causes accelerated corrosion kinetics.

4. What are the different stages of hot corrosion?

- ✓ Type -I hot CORROSION (Temp Range from 850-950°c)
- ✓ Type -II hot CORROSION (Temp Range from 650-800°c)

5. Define hot corrosion. What are the methods used for combat hot corrosion?

Hot corrosion is defined as an accelerated, often catastrophic surface attack super alloy by hot-gas path component. This is severe in the temperature range 750-1000°c and has affected A/C engines and industrial gas turbines.

There are three methods to combat hot corrosion such as

- ✓ Aluminide (diffusion) coatings
- ✓ Thermal barrier coatings
- ✓ Overlay coatings

6. Write any two methods to prevent corrosion.

- ✓ Control or removal of aggressive impurities.
- ✓ Development of new alloys with higher resistance to hot gas corrosion and greater mechanical properties.

✓ Development of protective surface coatings.

7. Define acidic fluxing in hot corrosion.

Acidic Fluxing: It defines dissolution, when a soluble metal M^{2+} and O^{2-} are produced from oxide. The acidic fluxing is generally associated with temperature range of 650°C to 800°C and it is termed as low temperature hot corrosion. Acidic fluxing takes place when the O^{2-} activity in the molten salt is markedly lowered, it leads to much more severe oxidation compared to basic fluxing.

8. Define basic fluxing in hot corrosion.

Basic fluxing: The term basic fluxing describes oxide dissolution, when O^{2-} reacts with the oxide to form a soluble MO^{2-} radical. It is generally associated with temperatures $> 900^\circ\text{C}$ and termed as high temperature hot corrosion. These results support a **basic fluxing** reaction, i.e. corrosive attack by forming a basic solute of the protective scale.



9. Name some oxidation resistance materials?

Conventionally **Aluminium, chromium and copper** materials are majorly used towards corrosion resistance. Some metals have naturally slow reaction kinetics, these include such metals as **zinc, magnesium, and cadmium**. While corrosion of these metals is continuous and ongoing, it happens at an acceptably slow rate. An extreme example is **graphite**, which releases large amounts of energy upon oxidation, but has such slow kinetics that it is effectively immune to electrochemical corrosion under normal conditions.

10. Define Pilling Bed worth theory.

The Pilling-Bedworth ratio, (P-B ratio) R , of a metal oxide is defined as the ratio of the volume of the metal oxide, which is produced by the reaction of metal and oxygen, to the consumed metal volume:

$$R \equiv \frac{V_{\text{metal oxide produced}}}{V_{\text{metal consumed}}} = \frac{Md}{amD}$$

M and D are the molecular weight and density of the metal oxide whose composition is $(\text{Metal})_a (\text{oxygen})_b$; m , and d are the atomic weight and density of the metal.

11. What are the Kinetic Laws of Oxidation?

- ✓ Parabolic rate law
- ✓ logarithmic rate law
- ✓ Linear rate law

12. What is meant by heat treatment? What are the different methods of heat treatment?

Heating and cooling a solid metal or alloy in such a way as to obtain desired conditions or properties is called heat treatment. There are different methods of strengthening and hardening by heat treatment. They are

- ✓ Age hardening (precipitation hardening)
- ✓ Annealing
- ✓ Normalizing
- ✓ Tempering and
- ✓ Case hardening

13. What is age hardening or precipitation hardening?

By uniformly dispersing extremely small particles within the original phase matrix the strength and hardness of metal alloys may be enhanced; this process of heat treatment is called precipitation hardening or age hardening.

14. What is overaging?

For some alloys, aging occurs spontaneously at room temperature over extended time periods. With increase of time the strength increases and after reaching a maximum a value, it finally diminishes. This type of reduction in yield strength and hardness that occurs after long time periods is known as overaging.

15. What is annealing and what is its purpose?

Annealing means heating the material to and holding at a suitable temperature and then cooling at a suitable rate. Annealing is for the purpose of

- ✓ Reducing hardness
- ✓ Improving machinability
- ✓ Facilitating cold working
- ✓ Producing a desired microstructure and
- ✓ Obtaining desired mechanical, physical and other properties.

16. Distinguish between hardening and annealing.

Hardening gives hardness to a material so that its yield strength, corrosion resistance, wear resistance and cutting ability are increased.

Annealing gives softness and ductility to the materials and also refines the grain size and removes the internal stresses.

17. What is normalizing?

Heating a ferrous alloy to a suitable temperature above the transformation range and then cooling in air to a temperature substantially below the transformation range is called normalizing.

18. What is high brass?

65% - A copper-zinc alloy containing 35% zinc. Possesses high tensile strength and is used for springs, screws, rivets, etc.

19. What is air hardening steel?

Alloy steel which may be hardened by cooling in air from a temperature above the transformation range. Such steels attain their martensitic structure without going through the quenching process. Additions of chromium, nickel, molybdenum and manganese are effective toward this end.

20. What is alloy steel?

Steel containing substantial quantities of elements other than carbon and the commonly accepted limited amounts of manganese, sulfur, silicon, and phosphorous. Addition of such alloying elements is usually for the purpose of increased hardness, strength or chemical resistance. The metals most commonly used for forming alloy steels are: nickel, chromium, silicon, manganese, tungsten, molybdenum and vanadium. "Low Alloy" steels are usually considered to be those containing a total of less than 5% of such added constituents.

21. Which steel is called as carbon steel?

Common or ordinary steel as contrasted with special or alloy steels, which contain other alloying metals in addition to the usual constituents of steel in their common percentages.

22. State the meaning of carburizing.

(Cementation) It is the process of adding carbon to the surface of iron-base alloys by absorption through heating the metal at a temperature below its

melting point in contact with carbonaceous solids, liquids or gasses. It is the oldest method of case hardening.

23. What is meant by decarburization?

It is the process of removing the carbon from the outer surface of iron or steel, usually by heating in an oxidizing or reducing atmosphere. Water vapor, oxygen and carbon dioxide are strong decarburizers. Reheating with adhering scale is also strongly decarburizing in action.

24. What is tempering?

Tempering is the process of re-heating the hardened steel to some temperature below its critical temperature in order to impart toughness and to reduce brittleness. This reduces the internal stresses developed during hardening.

25. What are low carbon steels? What are their applications?

Low carbon steels have 0.08% to 0.25% carbon. These are soft, ductile and easy to weld. These are used to make wires, rods and thin heats and boiler plates.

26. What are the effects of addition of boron, chromium and cobalt in steels?

Boron: increase the hardness

Chromium: improves wear and impact resistance and increases its strength.

Cobalt: increase its hardness, and residual magnetic induction.

27. What is an alloy?

An alloy is a mixture of two or more metals, or a mixture of metal and a non-metal, with the mixture exhibiting metallic properties.

28. Define eutectic reaction

A reaction wherein, upon cooling, one liquid phase transforms isothermally and reversibly into two new solid phases that are intimately mixed is called eutectic reaction.

29. Define eutectoid reaction

A reaction wherein, upon cooling, one solid phase transforms isothermally and reversibly into two new solid phases that are intimately mixed is called eutectoid reaction.

30. What is a hypereutectoid steel?

A steel having more than the eutectoid percentage of carbon.

31. What is a hypoeutectoid steel?

Steel with less than eutectoid percentage of carbon.

32. What do you understand by allotropy?

The possibility of existence of two or more different crystal structures for a substance (generally an elemental solid such as iron) is known as allotropy.

33. What is stainless steels and what are the possible classifications based on their microstructure?

The stainless steels are iron-chromium alloys with atleast 11 wt% of chromium. Addition of nickel and molybdenum enhances the corrosion resistance. Stainless steels are divided into three classes on the basis of the microstructure

- ✓ Martensitic stainless steels
- ✓ Ferritic stainless steels and
- ✓ Austenitic stainless steels

UNIT-4 – CERAMICS AND COMPOSITES

1. What are metallic glasses?

Metallic glasses have the properties of metals and glasses such that they have ductility, malleability and brittleness. Ferromagnetic metallic glasses are in the form of ribbons and are used as light weight magnetic cores having no losses and high energy products.

2. What is Ceramic materials?

Ceramic materials are complex chemical compounds containing both metallic and non metallic elements. Alumina (Al_2O_3) is a ceramic composed of both metallic aluminum and non metallic oxygen atoms. Ceramics are formed because of ionic or covalent bonding, hence are usually hard, brittle and have high melting point.

3. What is FRP?

Fibre-reinforced plastic (FRP) is a composite material made of a polymer matrix reinforced with fibers. The fibres are usually glass, carbon, aramid, or basalt. The polymer is usually an epoxy, vinylester or polyester thermosetting plastic, and phenol formaldehyde resins are used.

4. What are advantages of FRP?

- ✓ high strength to weight ratio
- ✓ high heat resistance
- ✓ low cost tooling
- ✓ high electrical conductivity

5. Mention few applications of fine ceramics.

- ✓ Piezoelectric ceramics are used as SAW devices.
- ✓ $Ti_2 Ba_2 Ca_2 Cu_3 O_3$ is a high T_c superconductor.
- ✓ Si C is used as a substrates and varistors.
- ✓ Ba Ti O₃ is used as a capacitor dielectric and ferroelectric energy converter.

6. Mention few biomaterials and their applications.

- a. Stainless steels (ASTMF – 138) have high tensile strength and high biocompatibility and are used as steel wires, plates and implant devices.
- b. Porous high density polyethylene is used in dental and cortical implants
- c. Ceramic implants (Al_2O_3 with some SiO_2 and alkali metal oxide) are used to make femoral head.

7. What are cermets?

Cermets are the composite materials having metallic and ceramic properties. Examples : iron, nickel and cobalt carbide ceramics.

Uses : Due to their higher hardness they are used as cutting tools and to shape the Refractories through machining.

8. What are intermetallic compounds?

Intermetallic compounds have combined properties of metal and nonmetals.

Example : Cu Zn alloy. It has ionic bond along with metallic bond. So that it behaves as insulator with high brittleness.

9. What are elastic and plastic materials?

Elastic materials can regain their original shape after removal of the deforming forces and within the elastic limit, the stress is proportional to strain and have high elastic modulus. Example: Steel, Brasses, Gold.

Plastic materials can undergo plastic deformation permanently in shape and size by the deforming forces up to the ultimate strength without any fracture.

Example: PVC, Polymers.

10. What are the applications of conducting polymers?

Conducting polymers are used to make transistors and diodes, large area light emitting device display and photoconductors. They also act as piezo and pyroelectric materials.

11. What is cementite?

A compound of **iron** and carbon known as “Iron Carbide,” which has the approximate chemical formula Fe_3C containing 6.69% of carbon. Hard and brittle, it is the hard constituents of cast iron, and the normal form in which **carbon** is present in steel. It is magnetizable, but not as readily as ferrite.

12. What is meant by cyaniding?

It is the process of Surface hardening of an iron-base alloy article or portion of it by heating at a suitable temperature in contact with a cyanide salt, followed by quenching.

13. What is mean by composites?

It is fiber reinforced composite materials which consists of fibers of high strength and modulus embedded in or bonded to a matrix with distinct Interfaces between them.

14. What is application of ceramic matrix?

CMS are finding increase application in high temperature areas where MMC and PMC cannot be used this is not to say that CMC are not attractive otherwise especially if you look at their high strength and modules and low density.

15. What are carbon carbon composites?

It is used carbon fibers in a carbon matrix .It is used in very high temperature environments of up to 60000F and are 20 times stronger and 30% lighter than graphite fibers.

16. What are applications of carbon carbon composites?

- ✓ Space shuttle nose cones,
- ✓ Aircraft Slakes,
- ✓ Mechanical fasteners.

17. Discuss the types of Open mould process.

- ✓ Spray layup,
- ✓ Hand layup,
- ✓ Filament winding,
- ✓ Sheet molding compound, Contact molding.

18. Write the Advantages of open mould process.

- ✓ Freedom to design,
- ✓ Easy to change design,
- ✓ Low mould and tooling cost,
- ✓ Tailored properties possible

19. Write the disadvantages of open mould process.

- ✓ Low to medium number of parts,
- ✓ Long cycles times per molding,
- ✓ Operator skill depended

20. Discuss the types of close mould process.

- ✓ Compression molding,
- ✓ Vacuum bag,
- ✓ Pressure bag ,
- ✓ Autoclave ,
- ✓ Injection molding
- ✓ Resin transfer

21. Discuss the types of glass fiber.

- E-Glass –E stands for electrical
- S-Glass –S stands for high silica content
High thermal expansion coefficient,
High fatigue strength
- C-Glass – C stands for Corrosion
Used in Chemical applications
Storage tanks
- R-Glass – R stands for Rigid
Structural applications
- D-Glass – D stands for Dielectric
Low dielectric constants
- A-Glass – A Stands for appearance
To improve surface appearance
For ornamental works
- E-CR Glass – E-CR stands for Electrical and corrosion resistance
- AR Glass – AR stands for Alkali resistance

UNIT-5 – HIGH TEMPERATURE MATERIALS

CHARACTERIZATION

1. What are the required properties of the materials for making thermocouples?

- ✓ The thermocouple material should have larger thermoelectric effect (i.e., produce more voltage or more cooling effect per unit rise of temperature.)
- ✓ It should have high melting point.

Example: Lead telluride semiconductor (where lead is the n type and tellurium is the p type semiconductor with 61.9% Pb + 38.1% Te). It has more thermoelectric generators to produce more electric power and thermoelectric refrigerators to produce more cooling effects.

2. What are the uses of high resistivity materials?

High resistivity materials are used

- ✓ In resistor applications
- ✓ As heating elements and
- ✓ In resistance thermometers

3. Define Super alloys. What are the properties of super alloys?

Super alloys, or high performance alloys, are alloys that exhibit excellent mechanical strength and creep resistance at high temperatures, good surface stability, and corrosion and oxidation resistance. They typically have an *austenitic face-centered cubic crystal structure* with a base alloying element of *nickel, cobalt, or nickel-iron*.

4. Why are super alloys preferred for high temperature application?

Super alloys, or high performance alloys, are alloys that exhibit excellent mechanical strength and creep resistance at high temperatures, good surface stability, and corrosion and oxidation resistance. The development of super alloys has primarily been driven by the *aerospace and power industries*.

5. Name a few examples for super alloys applicable for high temperature applications.

Examples of superalloys are Hastelloy, Inconel (e.g. IN100, IN600, IN713), Waspaloy, Rene alloys (e.g. Rene 41, Rene 80, Rene 95, Rene N5), Haynes alloys, Incoloy, MP98T, TMS alloys, and CMSX (e.g. CMSX-4) single crystal alloys.

6. What are Super alloys and their applications?

Super alloys are generally in three ways such as Nickel base, cobalt base and iron base super alloys. These superalloys are majorly available in many industries such Aerospace, Turbine blades and jet/rocket engines, Marine industry, Submarines, Chemical processing industry, Nuclear reactors, Heat exchanger tubing, Industrial gas Turbines.

7. What are the factors influencing functional life of components at elevated temp?

- ✓ Creep
- ✓ Corrosion
- ✓ High temperature fracture
- ✓ Thermo mechanical Fatigue
- ✓ Interaction of all above with each other
- ✓ Metallurgical ageing and metallurgical stability
- ✓ Micro structural changes

8. What are the problems associated with materials used at elevated temperature?

Generally a material subjected to high temperature reduces the strength of the material and failure mechanisms affecting the functional life of components are totally different. At high temperature the strength of material has strong dependence on time.

9. What materials are used for aerospace structures?

Aluminum	Very common, traditional aircraft material, light, strong, good corrosion resistance
Steel/Stainless Steel	Very high strength, for highly loaded components
Titanium	Roughly the strength of steel but 2/3 the weight
Magnesium	Similar to aluminum in properties but even lighter
Superalloys	Nickel based high temperature resistant alloys for use in engines
Ceramics	Combinations of metals and non-metals, strong but brittle, high temperature resistance
Plastics/Elastomers	Aircraft interiors, tires, sealants, adhesives
Composites	Rapid growth in use of complex engineered materials to replace much of the traditional materials

10. What are the failure modes of these materials?

- ✓ Fatigue
- ✓ Abrasion/ Wear
- ✓ Corrosion
- ✓ Thermal Shock
- ✓ Fracture
- ✓ Melting
- ✓ Impact
- ✓ Buckling
- ✓ Creep
- ✓ Plastic Deformation/ Yielding

11. What are the root causes of these failures?

Possible root causes:

- ✓ Misuse or abuse
- ✓ Assembly errors
- ✓ Processing/Manufacturing errors
- ✓ Improper material choice
- ✓ Non-optimized geometry design
- ✓ Improper maintenance
- ✓ Unforeseen operating conditions
- ✓ Inadequate quality control
- ✓ Inadequate environmental protection

12. Write the possible Percentage breakdown of types of failures.

- | | |
|------------------------------|-----|
| ✓ Fatigue | 55% |
| ✓ Corrosion | 16% |
| ✓ Overload | 14% |
| ✓ Stress Corrosion Cracking | 7% |
| ✓ Wear/ Abrasion | 6% |
| ✓ High Temperature Corrosion | 2% |

13. Define precipitation strengthening.

Precipitation hardening, also called **age 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 stainless steels. In super alloys, it is known to cause yield strength anomaly providing excellent high temperature strength.

14. Define TCP phases and its significance in super alloys.

In some alloys, if composition has not been carefully controlled, undesirable phases can form either during heat treatment or, more commonly, during service. These phases affect the creep resistance; fracture strength, premature cracking, and yield strength. These precipitates are known as TCP phases Topologically close-packed (TCP) type phases, which are plate-like or needle-like phases such as σ , and μ that may form for some compositions

and under certain conditions. These cause lowered rupture strength and ductility.

15. Explain why the single crystal turbine blades perform better than directionally solidified and coarse grained cast products.

Single crystal has the mechanical advantage of being able to operate at a much higher temperature than crystalline materials. Creep is a common cause of failure in turbine blades and is in fact the life limiting factor. When temperatures of a material under high stress are raised to a critical point, the creep rate quickly increases. The single crystal structure has the ability to withstand creep at higher temperatures than crystalline turbine blades due to the lack of grain boundaries present.

16. Name two chemical composition of super alloys.

Many **wrought nickel-base super alloys** contain 10 to 20% Cr, up to about 8% Al and Ti combined, 5 to 15% Co, and small amounts of boron, zirconium, magnesium, and carbon.

17. Define and list various TCP phases and explain whether they are beneficial or detrimental for high temperature properties.

The composition has to be carefully controlled in order to avoid topologically close packed (TCP) phases, for example γ phase, μ phase or Laves. These phases can be formed under certain conditions, usually during service. They are distinguished by their plate like or needle like shapes. Alloys containing transition metals, such as tantalum, niobium, chromium, tungsten or molybdenum, are the alloys the most vulnerable to the formation of TCP phases.



AE 8007 –AIRCRAFT MATERIALS

PART -B

1. Classify solid materials based upon their atomic / crystalline structure and give the examples (MAY/JUNE 2016)
2. Explain the X-ray diffraction technique and explain its role in the study of materials (MAY/JUNE 2016)
3. Explain the structure of solid materials
4. Explain the different types of point defects (NOV/DEC 2016)
5. Explain about the crystallography miller indices.
6. Derive and show that the packing efficiency of FCC crystal structure is more than BCC crystal structure (NOV/DEC 2016)
7. List the general requirements of materials used in aerospace applications. (NOV/DEC 2016)
8. With the help of neat stress – strain curve, contrast the mechanical behavior of brittle and ductile material in a tensile test (MAY/JUNE 2016)
9. Explain the bauchinger effect in the mechanical behavior of a material (MAY/JUNE 2016)
10. Explain the following (i) Bauchinger's effect, (ii) strain hardening (NOV/DEC 2016)
11. What are the typical elastic constant of the mechanical behavior of a material
12. Draw and explain the linear and non linear curve for ductile and brittle

13. Briefly explain the three steps of creep with a creep curve

14. What is super plasticity? Explain super plastic forming of aluminium alloys.

(MAY/JUNE 2016)

15. Describe different heat treatment processes available for aluminium alloys and state their respective purposes.

(MAY/JUNE 2016)

16. Write short note on the following topics

i. Corrosion and different types of corrosion

ii. Stress corrosion cracking

iii. Corrosion resistance materials used for air and space vehicles and their properties

(MAY/JUNE 2016)

17. Explain the various types of corrosion that occurs in metallic materials.

(NOV/DEC 2016)

18. Discuss the hardening and normalizing heat treatment processes that are applied to carbon steels.

(NOV/DEC 2016)

19. What are the effect of corrosion on mechanical properties of materials?

(NOV/DEC 2016)

20. Describe the shape memory effect and give examples of shape memory alloys

(MAY/JUNE 2016)

21. List a few examples of the use of metal matrix composite materials in air/space vehicles. Explain a fabrication process for a metal matrix composite part

(MAY/JUNE 2016)

22. What do you mean by composites and the classification of composites?

23. Explain the open mould process of composite materials

(MAY/JUNE 2016)

24. Explain the close mould process of composite materials

(MAY/JUNE 2016)

25. Explain the different types of alloying and effects alloy treatment

26. How is high temperature materials classified? And explain the methods of production.

(NOV/DEC 2016)

27. Discuss the various methods employed to determine the mechanical properties of materials at high temperature.

(NOV/DEC 2016)

28. Explain strengthening of cobalt-base super alloys.

29. Briefly explain the major phases of nickel-base alloys

30. Analyze how the processing parameters can influence the mechanical properties of super alloys at high temperatures.

31. Explain in detail about the factors influencing functional life of components at elevated temperatures.