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MATERIAL SCIENCE & ENGINEERING

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Material Science & Engineering

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ACKNOWLEDGEMENT

“There are a limited number of books on material science and engineering; therefore, this book has been designed to simplify the knowledge of materials. This book also covers the areas of basic fundamentals of materials science and engineering. The course focuses on material structures, properties, fabrication methods, corrosion, thermal processing, and material testing mostly of metals and alloys. The new fabrication method of powder metallurgy is introduced to students to cater to the fabrications of devices, and sensors for Industry 4.0 technology.

We are thankful to our contributors for their cooperation and support of this book project. We also thank the families for their support and encouragement throughout this project”

CONTENT

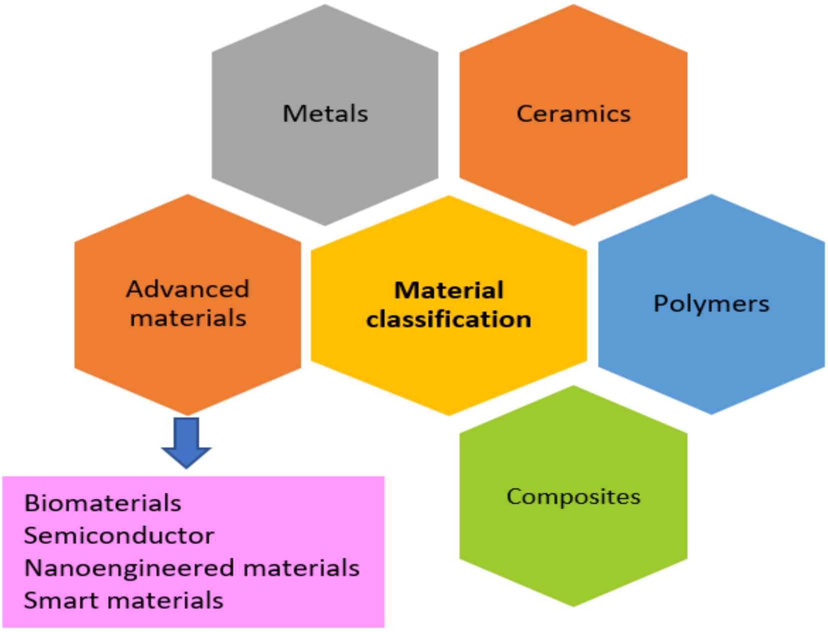
PREFACE

The primary objective is to present the basic fundamentals of materials science and engineering on a level appropriate for the Polytechnics series. A second objective is to present the material in a logical order, from the simple to the more complex. This book was written based on the latest syllabus content of DJJ30113 Material Science and Engineering.

This book introduces the material structure and interatomic bonding, mechanical properties of metal and failure, phase diagram and etc. Each chapter is accompanied by notes and questions for the final examination and some simple activities that can be carried out during the lecture. This book should help them in their attempt to achieve their goal.

CHAPTER 1:

INTRODUCTION TO MATERIAL SCIENCE AND ENGINEERING



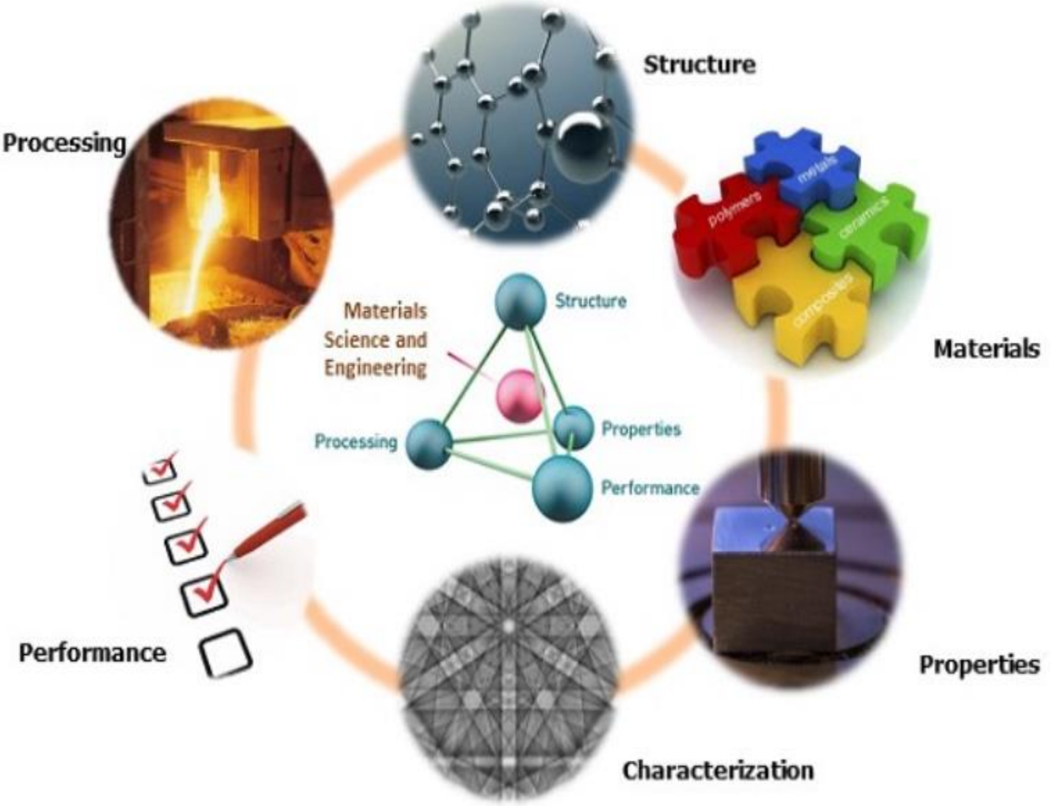
SYNOPSIS

This topic introduces materials science and engineering which explains further about material classification such as metals, ceramics, polymers, composites, and advanced materials.

LEARNING OUTCOMES

Upon completion of this course, students should be able to: -

1.1 Explain the fundamental of material science and engineering1.2 Classify the materials
- 1.2.1 Metals
- 1.2.2 Ceramics
- 1.2.3 Polymers
- 1.2.4 Composites
- 1.2.5 Advanced materials
  - 1.2.5 .1 Semiconductors
  - 1.2.5 .2 Biomaterials
  - 1.2.5 .3 Nanomaterials
  - 1.2.5 .4 Smart materials



1.1 FUNDAMENTALS OF MATERIAL SCIENCE AND ENGINEERING

What is material science and engineering? To make any engineered device, structure or product, you need the right materials. Materials science teaches us what things are made of and why they behave as they do. Materials engineering shows us how to apply knowledge to make better things and to make things better. Materials science and engineering drive innovation in both research and industry in everything from aerospace to medicine. It is fundamental to all other science and engineering disciplines.

As materials scientists and engineers, we integrate chemistry, physics, mathematics, and biology with engineering to address global challenges relevant to technology, society, and the environment. The study of materials covers all materials, both natural and synthetic. Materials Science and Engineering is the field that deals with the science of making, characterizing, and testing all types of materials.

The development of many technologies that make our existence so comfortable has been intimately associated with the accessibility of suitable materials. An advancement in understanding a material type is often the forerunner to the stepwise progression of technology. For example, automobiles would not have been possible without the availability of inexpensive steel or some other comparable substitute. In our contemporary era, sophisticated electronic devices rely on components that are made from what are called semiconducting materials.

In addition to structure and properties, two important components are involved in the science and engineering of materials, namely, processing and performance. With regard to the relationships of these four components, the structure of a material will depend on how it is processed. Furthermore, a material's performance will be a function of its properties. Thus, the interrelationship between processing, structure, properties, and performance is presented in the schematic illustration in Figure 1.1.

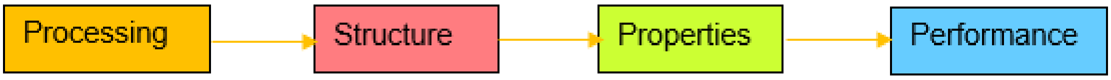


Figure 1.1: The four components of the discipline of materials science and engineering and their interrelationship

Why is the material important? Material means choice, application, contribution, and innovation. Figure 1. 2 and Figure 1.3 present examples of material issues.

Why study materials?

- To be able to select a material for a given use based on consideration of cost and performance.
- To understand the limits of materials and the change of their properties with use.
- To be able to create a new material that will have some desirable properties.
- All engineering disciplines need to know about materials. Even the most immaterial like software or system.

Figure 1.2: Air crash

Figure 1.3: Train crash

1.2 CLASSIFICATION OF MATERIALS

Common engineering materials that fall within the scope of material science and engineering can be classified into the following groups:

(i) Metals (ferrous and non-ferrous)

(ii) Ceramics

(iii) Polymers

(iv) Composites

(v) Advanced materials

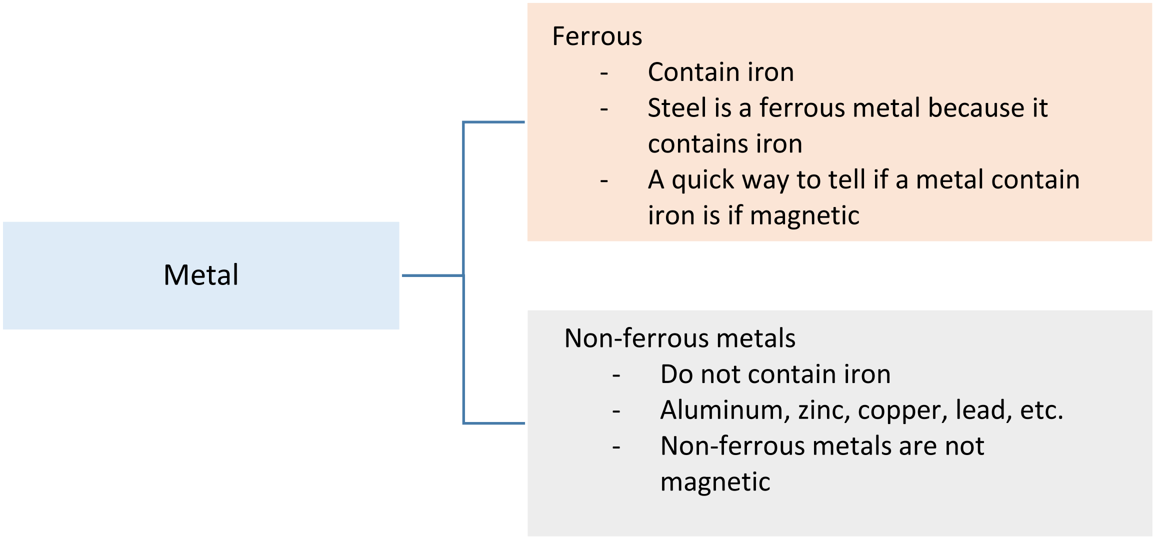
- Semiconductors
- Biomaterials
- Nanomaterials
- Smart materials

1.2.1 Metals

Metals can be divided into two main groups as presented in Figure 1.4.

i. **Ferrous metals** are those which contain iron. Pure Iron is of little use as an engineering material because it is too soft and ductile.

ii. **Non-ferrous metals** are those which contain no iron.



Ferrous
- Contain iron
- Steel is a ferrous metal because it contains iron
- A quick way to tell if a metal contain iron is if magnetic

Non-ferrous metals
- Do not contain iron
- Aluminum, zinc, copper, lead, etc.
- Non-ferrous metals are not magnetic

Figure 1.4: Classification of metals

Metals can also be classified as pure metals or alloys:

- Pure metals are made up of one element
- Alloys are two or more pure metals mixed together

1.2.2 Ceramics

Ceramics are compounds between metallic and non-metallic elements; they are most frequently oxides, nitrides, and carbides. In other words, ceramic is an inorganic non-metallic solid made up of either metal or non-metal compounds that have been shaped and then hardened by heating to high temperatures. Generally, they are hard, corrosion-resistant, and brittle. Products made from ceramic such as clay, bricks, tiles, glass, and cement, as shown in Figure 1.5.

Figure 1.5: Products made from ceramic

1.2.3 Polymers

Polymers are constructed from relatively small molecular fragments known as monomers that are joined together. Polymers, which consist of repeating units in them called “mers”. Mers shares electrons to form very large molecules - usually of carbon and some other elements like oxygen, hydrogen, nitrogen, chlorine, and other nonmetallic elements. There are two types of polymers namely natural and synthetic. Natural polymers occur in nature and can be extracted. They are often water-based. Examples of naturally occurring polymers are silk, wool, DNA, cellulose, and proteins. Whereas synthetic polymers are derived from petroleum oil, and made by scientists and engineers. Examples of synthetic polymers include nylon, polyethylene, polyester, Teflon, and epoxy. Different polymers have a number of unique physical and chemical properties, due to which they find usage in everyday life. Figure 1.6 presents the different types of polymers.

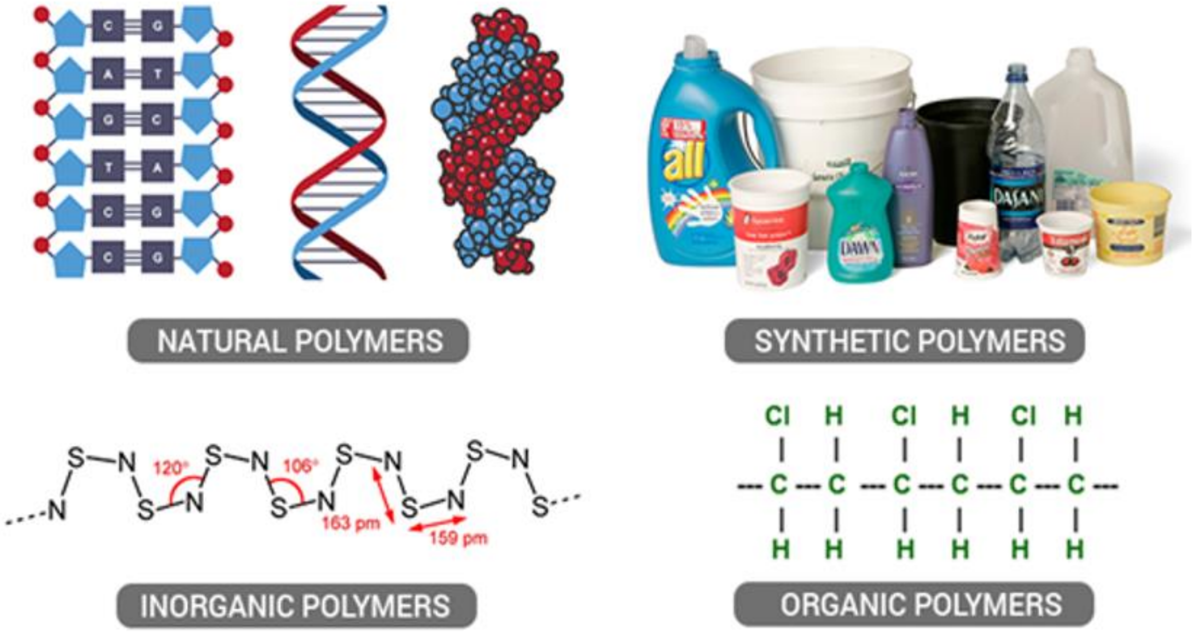


Figure 1.6: Different types of polymers

There are three principal classes of polymers namely thermosetting, thermoplastics, and elastomers:

i. **Thermosetting** - A thermosetting polymer is a permanent setting polymer as it gets hardened and sets during the moulding process and cannot be softened again. It is stiff and not easy to recycle. Some common uses for thermosetting plastics across various industries and sectors include gas and water pipelines, automotive parts, medical equipment, construction machinery parts, signage, storage boxes, electrical plugs and casings, kitchen appliances, and toys. Figure 1.7 shows an example of thermosetting plastic.

Figure 1.7: Thermosetting plastic

ii. **Thermoplastics** - Thermoplastics are polymers that can be softened through heating before being processed and then left to cool and harden. Once cooled, they show no changes in chemical properties. It is soft and easy to be recycled. Common examples of thermoplastics include acrylic, polyester, polypropylene, polystyrene, nylon, and Teflon. Polyethylene is probably the most commonly thermoplastic and is used to make shampoo bottles, plastic grocery bags, and bullet-proof vests. Figure 1.8 shows an example of thermoplastic in daily life.

Figure 1.8: Example of thermoplastic in daily life

iii. **Elastomers -** Elastomers are elastic materials that regain their original shape if they are distorted. They have the unique ability to elastically deform by extremely large amounts without permanent damage to their shape. Some common elastomers are rubber as shown in Figure 1.9.

Figure 1.9: Elastomeric materials

The key difference between polymers and plastics is that plastic is a specific type of polymer. Plastics are comprised of a long chain of polymers, whereas polymers are composed of smaller, uniform molecules.

1.2.4 Composites

A composite material is a combination of two materials with different physical and chemical properties. When they are combined, they create a material that is specialized to do a certain job, for instance to become stronger, lighter, or resistant to electricity. They can also improve strength and stiffness. The reason for their use over traditional materials is that they improve the properties of their base materials and are applicable in many situations. For example, a material that compresses well could be combined with a material that stretches well to form a compressible and stretchable composite.

The design goal of a composite is to achieve a combination of properties that is not displayed by any single material, and also to incorporate the best characteristics of each of the component materials. The phases are processed separately and then bonded together to achieve properties superior to the constituents. One of the most common and familiar composites is fiberglass, in which small glass fibers are embedded within a polymeric material (normally an epoxy or polyester). The glass fibers are relatively strong and stiff (but also brittle), whereas the polymer is ductile (but also weak and flexible). Thus, the resulting fiberglass is relatively stiff, strong, flexible, and ductile. Today, fiberglass profiles are used in a wide range of industry sectors including building, aircraft, boats, automobiles, bathtubs and enclosures, swimming pools, hot tubs, septic tanks, water tanks, roofing, pipes, cladding, orthopedic casts, surfboards, and external door skins. Figure 1.10 presents the application of the composites.

Figure 1.10: The application of the composites

1.2.5 Advanced Materials

Advanced Materials are materials that are specifically engineered to exhibit novel or enhanced properties that confer superior performance relative to conventional materials. Advanced Materials offer major improvements in a wide variety of different fields, such as in aerospace, transport, building, and health care. They facilitate recycling, lowering the carbon footprint and energy demand as well as limiting the need for raw materials. Examples of technologically advanced materials dealt with in the course are semiconductors, biomaterials, nanomaterials, and smart materials.

1.2.5.1 Semiconductors

Semiconductors are materials that have a conductivity between conductors (generally metals) and non-conductors or insulators (such as most ceramics). Semiconductors are created by adding impurities to the element. The conductance or inductance of the element depends on the type and intensity of the added impurities. Semiconductors can be pure elements, such as silicon or germanium, or compounds such as gallium arsenide or cadmium selenide. Silicon is used in electronic circuit fabrication and gallium arsenide is used in solar cells, laser diodes, etc. Semiconductors are an essential component of electronic devices, enabling advances in communications, computing, healthcare, military systems, transportation, clean energy, and countless other applications. Many digital consumer products in everyday life such as mobile phones/smartphones, digital cameras, televisions, washing machines, refrigerators, and LED bulbs also use semiconductors. Figure 1.11 presents the semiconductor devices and applications.

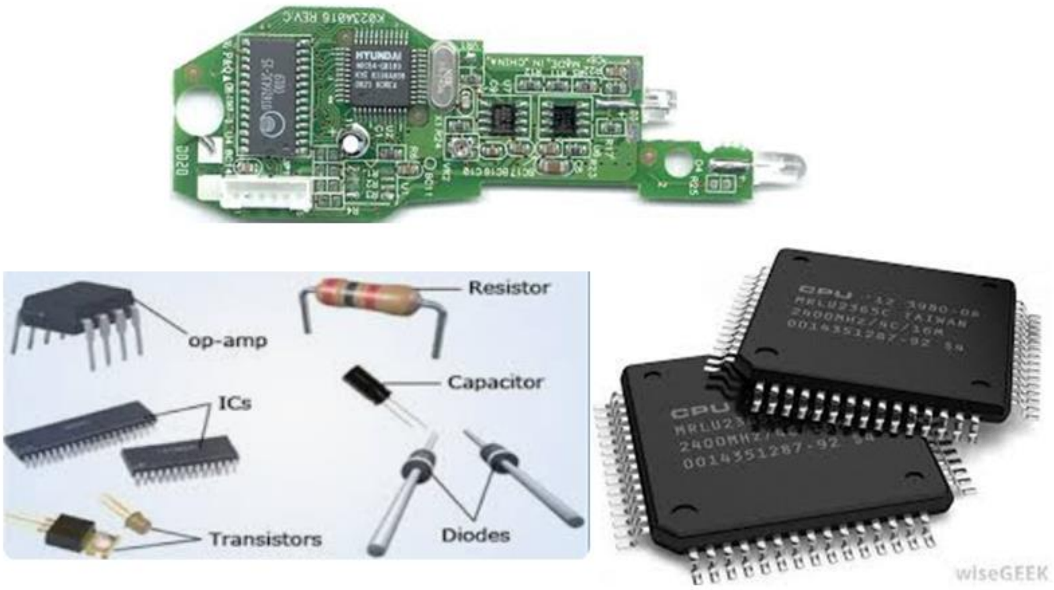


Figure 1.11 The semiconductor devices and applications

1.2.5.2 Biomaterials

A biomaterial is any substance that has been engineered to interact with biological systems for a medical purpose - either a therapeutic (treat, augment, repair or replace a tissue function of the body) or a diagnostic one. They are often used and/or adapted for a medical application, and thus comprise the whole or part of a living structure or biomedical device which performs, augments, or replaces a natural function. Biomaterials must not produce toxic substances and must be compatible with body tissues (i.e., these materials must not cause adverse biological reactions).

Doctors, researchers, and bioengineers use biomaterials for a broad range of applications such as medical implants, including heart valves, stents, and grafts; artificial joints, ligaments, bone plates, joint replacement, and tendons; hearing loss implants; dental implants; and devices that stimulate nerves. The example application of the biomaterials is presented in Figure 1.12.

Figure 1.12 The application of biomaterials

1.2.5.3 Nanomaterials

Nanomaterial is defined as a material with any external dimension in the nanoscale or having an internal structure or surface structure in the nanoscale. Nanomaterials research takes a materials science-based approach to nanotechnology, leveraging advances in materials metrology and synthesis which have been developed in support of microfabrication research. Nanomaterials can occur naturally, be created as the by-products of combustion reactions, or be produced purposefully through engineering to perform a specialized function. These materials can have different physical and chemical properties to their bulk-form counterparts.

They have unique physical and chemical features which give them improved properties such as greater reactivity, strength, electrical characteristics, and functionality. These benefits have resulted in nanomaterials being incorporated into a wide range of consumer products. The properties of nanomaterials, particularly their size, offer various different advantages compared to the bulk-form of the materials, and their versatility in terms of the ability to tailor them for specific requirements accentuates their usefulness. An additional advantage is their high porosity, which again increases demand for their use in a multitude of industries.

In the energy sector, the use of nanomaterials is advantageous in that they can make the existing methods of generating energy - such as solar panels - more efficient and cost-effective, as well as opening up new ways in which to both harness and store energy.

Nanomaterials are also set to introduce a number of advantages in the electronics and computing industry. Their use will permit an increase in the accuracy of the construction of electronic circuits on an atomic level, assisting in the development of numerous electronic products. Figure 1.13 shows some applications of nanomaterials.

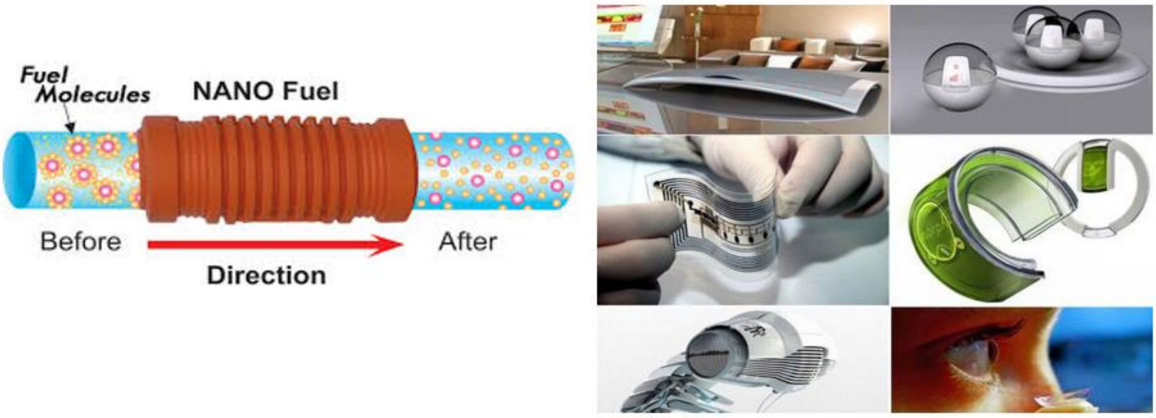


Figure 1.13 Some applications of nanomaterials

1.2.5.4 Smart materials

Smart or intelligent materials form a group of new and state-of-the-art materials now being developed that will have a significant influence on many technologies. The adjective “smart” implies that these materials are able to sense changes in their environments and then respond to these changes in predetermined manners. In addition, the concept of smart materials is being extended to rather sophisticated systems that consist of both smart and traditional materials.

Smart materials have intrinsic and extrinsic capabilities, first, to respond to stimuli and environmental changes and, second, to activate their functions according to these changes. External stimuli, such as stress, moisture, electric or magnetic fields, light, temperature, pH, or chemical compounds. Whereas the response consists of motion or change in optical properties, modulus, surface tension, and piezoelectricity. The components of smart materials are:

i. Sensor - detects an input signal
ii. Actuator - performs a responsive and adaptive function

Currently, piezoelectric, magnetostrictive and ferroelectric materials, optical fibers, electrorheological and magnetorheological fluids, shape memory alloys, and shape memory polymers can be considered smart materials. In general, smart materials and structure comprise a smart system as shown in Figure 1.14.

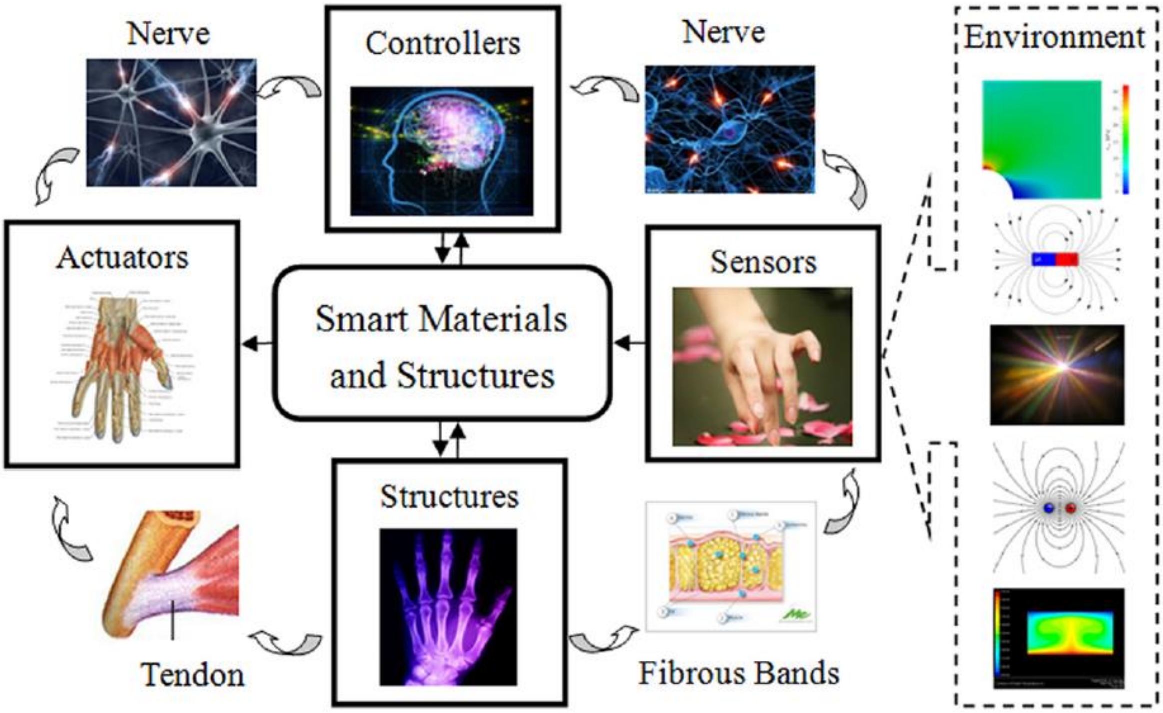


Figure 1.14: Smart materials and structures

DISCUSSION QUESTIONS

QUESTION 1

Advanced materials are materials that are utilized in high technology applications. These advanced materials are typically traditional materials whose properties have been enhanced and developed into high performance materials.

a. Write FOUR (4) types of advanced materials.

b. Discuss the applications for each type of advanced material as stated in (a).

ANSWER 1

a. i. Biomaterials
  ii. Semiconductor
  iii. Nano engineered materials
  iv. Smart materials

b. **Biomaterials**: Materials that interact with biological system / tissue. Examples: Bone plates, Joint replacement, heart valves

Semiconductor: Materials with conductive or resistive properties depend on voltage supply. Example: Transistor, microchip, solar cell, LED display

Nano engineered materials: Materials manufactures at nanoscale. Example: nanowires, nanotubes, nanofibers

Smart materials: Materials that react with certain stimuli. Examples: smart glass, dental braces, thermochromic baby spoon

QUESTION 2

Continuous research and development in material science accelerate the advancement of modern technology. To fulfill the requirement of advanced and modern technology, give and relate FOUR (4) types of materials to be used in medical, electronic, smart sensor, and cosmetic industries.

ANSWER 2

i. **Biomaterials –** implanted into the human body for replacement of diseased or damaged body parts.

ii. **Semiconductors –** have electrical properties that are intermediate between the electrical conductors and insulators.

iii. **Nano engineered materials –** the nano prefix denotes that the dimensions of these structural entities are on the order of a nanometer (10-9 m).

iv. **Smart materials –** materials that are able to sense changes in their environments and then respond to these changes in predetermined manners.

PAST YEARS' QUESTIONS:

1) Define biomaterial and list THREE (3) applications of biomaterial. [5 marks]

2) Define polymer and list THREE (3) applications of polymer. [5 marks]

3) Discuss the application for THREE (3) types of advanced materials. [6 marks]

4) State FIVE (5) properties of ceramic. [5 marks]

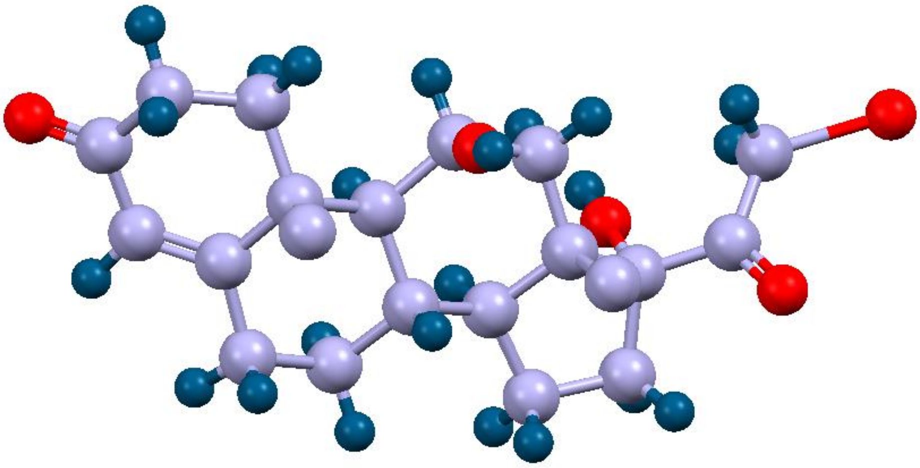
5) List THREE (3) classes of materials in material science and engineering with TWO (2) examples for each. [9 marks]

6) State THREE (3) applications of biomaterials in industry. [3 marks]

7) Material Science is a field of science that emphasizes studies of relationships between the microstructure, synthesis and processing, and properties of materials. Sketch a suitable chart to show the classification of materials. [7 marks]

CHAPTER 2:

MATERIAL STRUCTURE AND INTERATOMIC BONDING



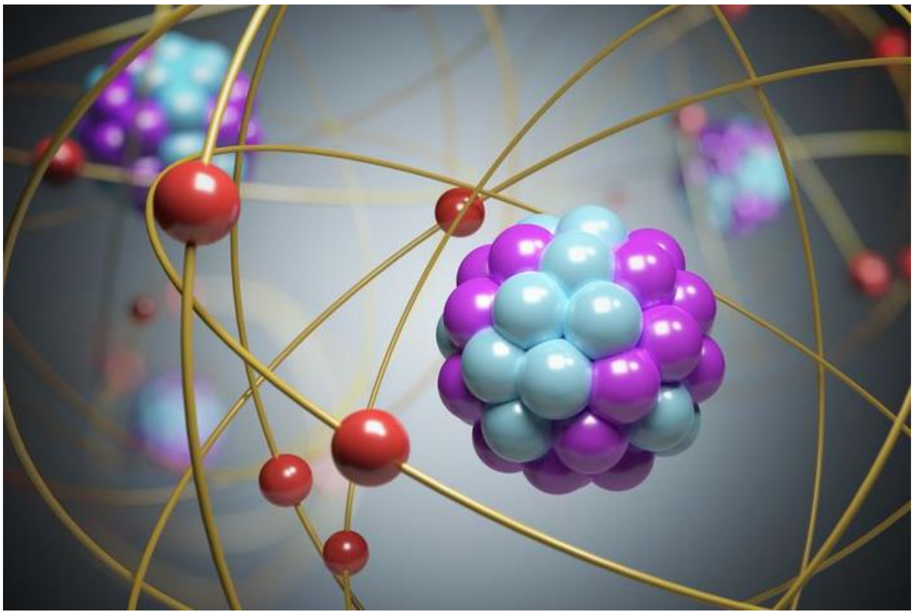
SYNOPSIS

This topic explains the concepts of material structure and bonding, the physical structure of atoms, and crystal structure. In addition, the topic also covers the interpretation of the periodic table.

LEARNING OUTCOMES

Upon completion of this course, students should be able to: -

2.1 Explain the fundamental of atomic structure
  2.1.1 Terminology
    a. Atom
    b. Element
    c. Compound
    d. Mixture
2.2 Interpret the Periodic Table
2.3 Draw the atomic bonding in solids
  2.3.1 Covalent
  2.3.2 Ionic
  2.3.3 Metallic
2.4 Construct the metallic crystal structures
  2.4.1 Fundamental concepts
  2.4.2 Unit cells
  2.4.3 Metallic crystal structures
    2.4.3.1 Simple cubic
    2.4.3.2 Body-centered cubic
    2.4.3.3 Face-centered cubic
    2.4.3.4 Hexagonal close-packed



2.1 FUNDAMENTAL OF ATOMIC STRUCTURE

Why is it important to understand atomic structure? By learning about atomic structure, we can find out how atoms combine and form many compounds. By learning about atomic structure, we can find out how atoms collide. All material things are made of the atom, and all atoms are made of the same three basic particles consisting of protons, neutrons, and electrons.

2.1.1 Terminology

a) Atom

An atom is the basic unit of an element formed for all materials whether in solid, liquid, or gas. It is the smallest particle of an element and has the same chemical properties of the element. Particles that make up an atom as presented in Figure 2.1.

Protons : positive (+) charge
Neutrons : no charge
Electrons : negative (-) charge
Protons + neutrons define the nucleus of an atom

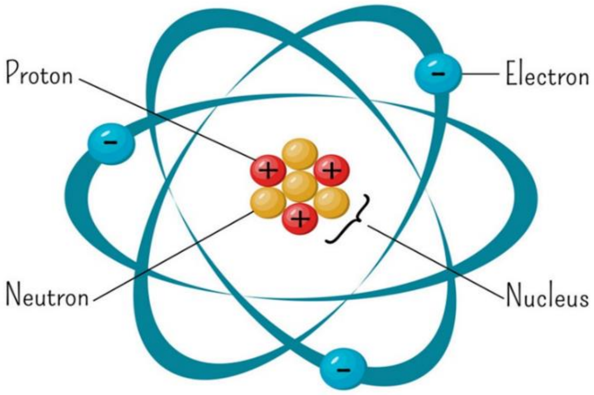


Figure 2.1: Atomic structure

b) Element

Element is a substance composed of a single kind of atom. It contains one or more of the same type of atom, which is cannot be broken down into another substance by chemical or physical means. Examples of elements are Copper (Cu), Platinum (Pt), Helium (He), Oxygen (O_2), and Hydrogen (H_2) as illustrated in Figure 2.2.

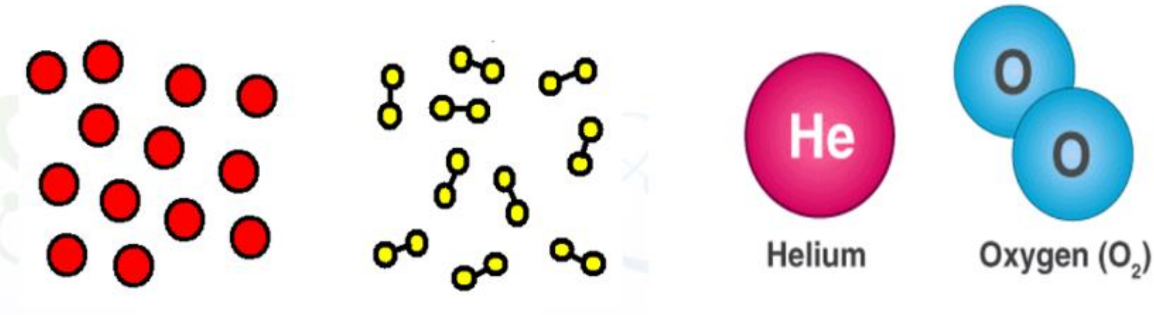


Figure 2.2: Elements contain only one kind of atom

c) Compound

Compounds are chemical substances consisting of two or more different types of elements that are chemically bonded together in a fixed ratio. When the elements combine, some individual property of the elements is lost and the newly formed compound has new properties. Example of compounds includes water (H_2O), HCl (hydrochloride), carbon dioxide (C_2O), and Hydrogen Peroxide (H_2O_2) as illustrated in Figure 2.3.

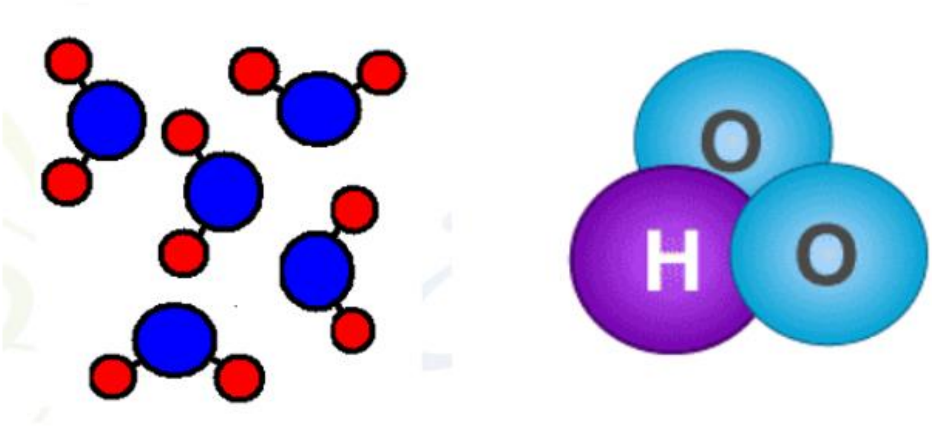


Figure 2.3: Compounds contain two or more kinds of atoms

d) Mixture

The mixture is composed of one or more pure substances in varying compositions, that are mixed together but not chemically bonded. That means each substance keeps its identity, and it can be separated by physical means as well. An example of a mixture is an alloy made when two or more metals are mixed together. Other examples are sand and water, water and salt, oil and water, and sand and sugar as illustrated in Figure 2.4.

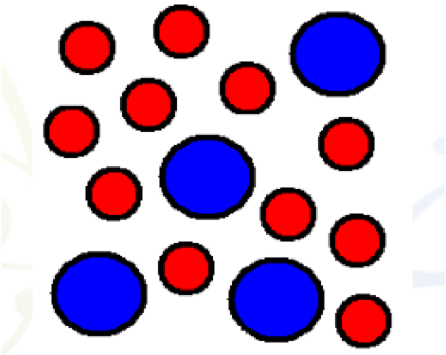


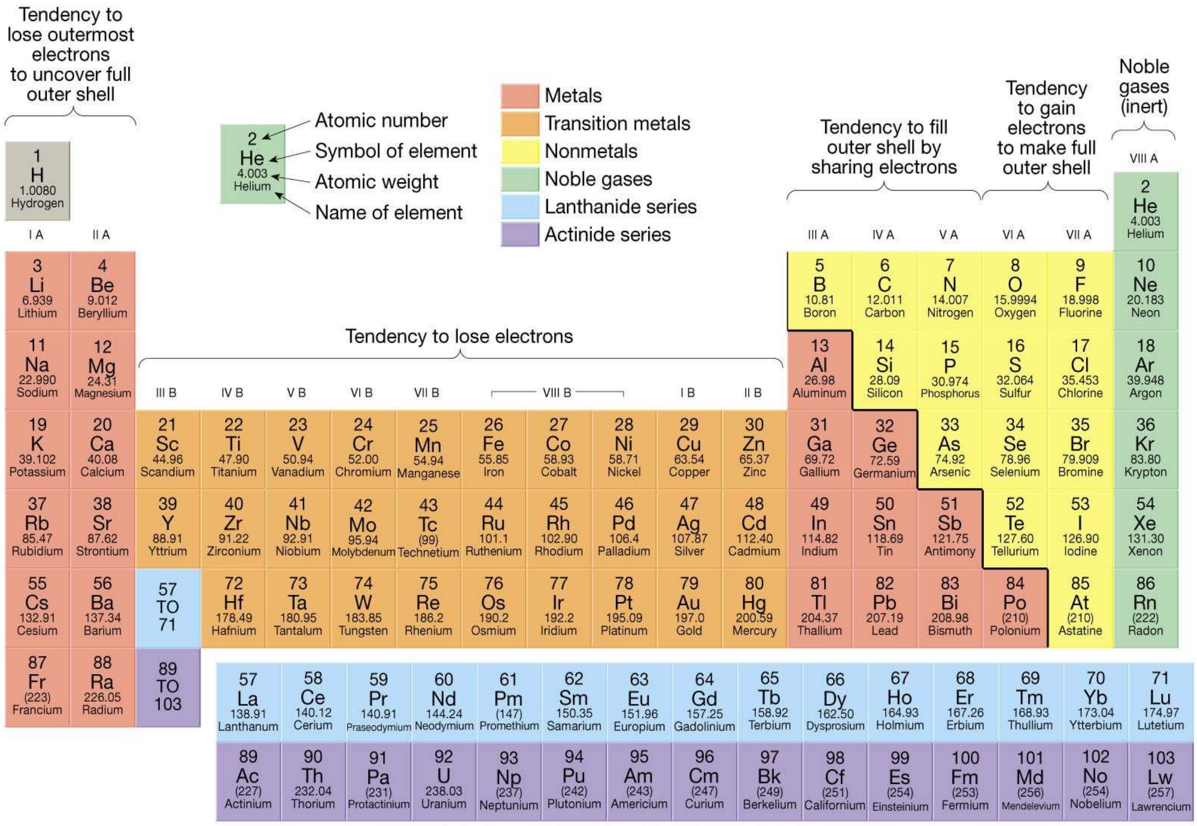
Figure 2.4: Illustration of mixture

2.2 THE PERIODIC TABLE

The periodic table is a tabular array of chemical elements organized by atomic number, from the element with the lowest atomic number, hydrogen, to the element with the highest atomic number, oganesson. The chemical elements are the basic substances that make up all matter. Each chemical element has a particular feature called its atomic number. The groups of the periodic table are displayed as vertical columns numbered from 1 to 18. The elements in a group have very similar chemical properties, which arise from the number of valence electrons present, that is the number of electrons in the outermost shell of an atom.

For example, the elements in the first column (the alkali metals) are all metals that usually carry a 1+ charge in reactions, react vigorously with water, and combine readily with nonmetals. Elements in the same row as one other are known as periods and they share the same highest unexcited electron energy level. The periodic table is presented in Figure 2.5.

The majority of chemical elements are metals. Metals tend to be shiny (metallic luster), hard, conductive, and capable of forming alloys. Nonmetals tend to be soft, coloured, insulators, and capable of forming compounds with metals. Metalloids display properties intermediate between those of metals and nonmetals. Toward the right side of the periodic table, the metals transition into nonmetals. There is a rough staircase pattern, starting at boron and going through silicon, germanium, arsenic, antimony, tellurium, and polonium that identified the metalloids. However, chemists increasingly categorize other elements as metalloids, including carbon, phosphorus, gallium, and others.



I A	II A	III B	IV B	V B	VI B	VII B	VIII B	VIII B	VIII B	I B	II B	III A	IV A	V A	VI A	VII A	VIII A
1 H 1.0080 Hydrogen																	2 He 4.003 Helium
3 Li 6.939 Lithium	4 Be 9.012 Beryllium											5 B 10.81 Boron	6 C 12.011 Carbon	7 N 14.007 Nitrogen	8 O 15.9994 Oxygen	9 F 18.998 Fluorine	10 Ne 20.183 Neon
11 Na 22.990 Sodium	12 Mg 24.31 Magnesium											13 Al 26.98 Aluminum	14 Si 28.09 Silicon	15 P 30.974 Phosphorus	16 S 32.064 Sulfur	17 Cl 35.453 Chlorine	18 Ar 39.948 Argon
19 K 39.102 Potassium	20 Ca 40.08 Calcium	21 Sc 44.96 Scandium	22 Ti 47.90 Titanium	23 V 50.94 Vanadium	24 Cr 52.00 Chromium	25 Mn 54.94 Manganese	26 Fe 55.85 Iron	27 Co 58.93 Cobalt	28 Ni 58.71 Nickel	29 Cu 63.54 Copper	30 Zn 65.37 Zinc	31 Ga 69.72 Gallium	32 Ge 72.59 Germanium	33 As 74.92 Arsenic	34 Se 78.96 Selenium	35 Br 79.909 Bromine	36 Kr 83.80 Krypton
37 Rb 85.47 Rubidium	38 Sr 87.62 Strontium	39 Y 88.91 Yttrium	40 Zr 91.22 Zirconium	41 Nb 92.91 Niobium	42 Mo 95.94 Molybdenum	43 Tc (99) Technetium	44 Ru 101.1 Ruthenium	45 Rh 102.90 Rhodium	46 Pd 106.4 Palladium	47 Ag 107.87 Silver	48 Cd 112.40 Cadmium	49 In 114.82 Indium	50 Sn 118.69 Tin	51 Sb 121.75 Antimony	52 Te 127.60 Tellurium	53 I 126.90 Iodine	54 Xe 131.30 Xenon
55 Cs 132.91 Cesium	56 Ba 137.34 Barium	57 TO 71	72 Hf 178.49 Hafnium	73 Ta 180.95 Tantalum	74 W 183.85 Tungsten	75 Re 186.2 Rhenium	76 Os 190.2 Osmium	77 Ir 192.2 Iridium	78 Pt 195.09 Platinum	79 Au 197.0 Gold	80 Hg 200.59 Mercury	81 Tl 204.37 Thallium	82 Pb 207.19 Lead	83 Bi 208.98 Bismuth	84 Po (210) Polonium	85 At (210) Astatine	86 Rn (222) Radon
87 Fr (223) Francium	88 Ra 226.05 Radium	89 TO 103															
			57 La 138.91 Lanthanum	58 Ce 140.12 Cerium	59 Pr 140.91 Praseodymium	60 Nd 144.24 Neodymium	61 Pm (147) Promethium	62 Sm 150.35 Samarium	63 Eu 151.96 Europium	64 Gd 157.25 Gadolinium	65 Tb 158.92 Terbium	66 Dy 162.50 Dysprosium	67 Ho 164.93 Holmium	68 Er 167.26 Erbium	69 Tm 168.93 Thullium	70 Yb 173.04 Ytterbium	71 Lu 174.97 Lutetium
			89 Ac (227) Actinium	90 Th 232.04 Thorium	91 Pa (231) Protactinium	92 U 238.03 Uranium	93 Np (237) Neptunium	94 Pu (242) Plutonium	95 Am (243) Americium	96 Cm (247) Curium	97 Bk (249) Berkelium	98 Cf (251) Californium	99 Es (254) Einsteinium	100 Fm (253) Fermium	101 Md (256) Mendelevium	102 No (254) Nobelium	103 Lw (257) Lawrencium

🟥	Metals
🟧	Transition metals
🟨	Nonmetals
🟩	Noble gases
🟦	Lanthanide series
🟪	Actinide series

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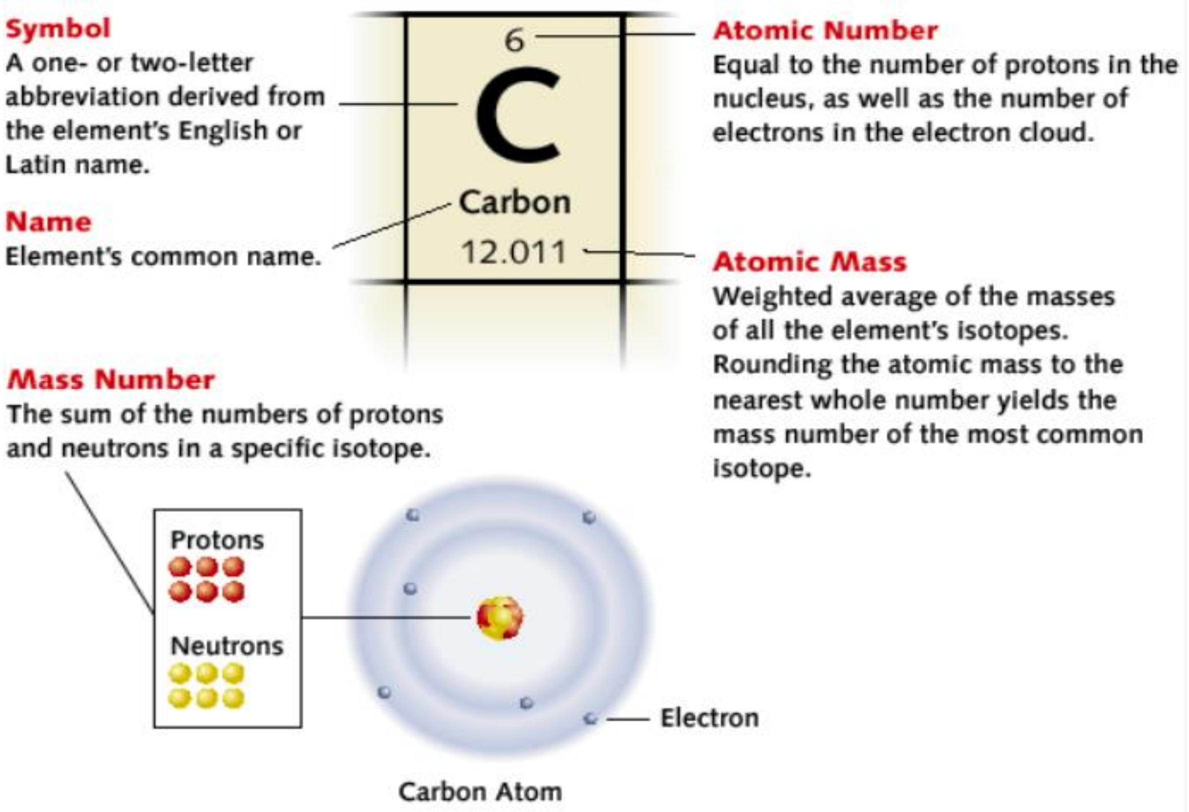
Figure 2.5: Periodic table of the elements

How do you read the periodic table?

On the periodic table, elements are listed in order of increasing atomic number.

- ♣ The horizontal rows of elements on the periodic table are called periods.
- ♣ The vertical columns are called groups or families.
- ♣ Elements in the same row are in the same period. This means they have similar physical properties, such as how well they bend or conduct electricity.
- ♣ Elements in the same column are in the same group. This means they react with other elements in similar ways.

Figure 2.6 shows a close-up look at the carbon square from the periodic table and Figure 2.7 represents the importance of the periodic table.



Symbol
A one- or two-letter abbreviation derived from the element's English or Latin name.

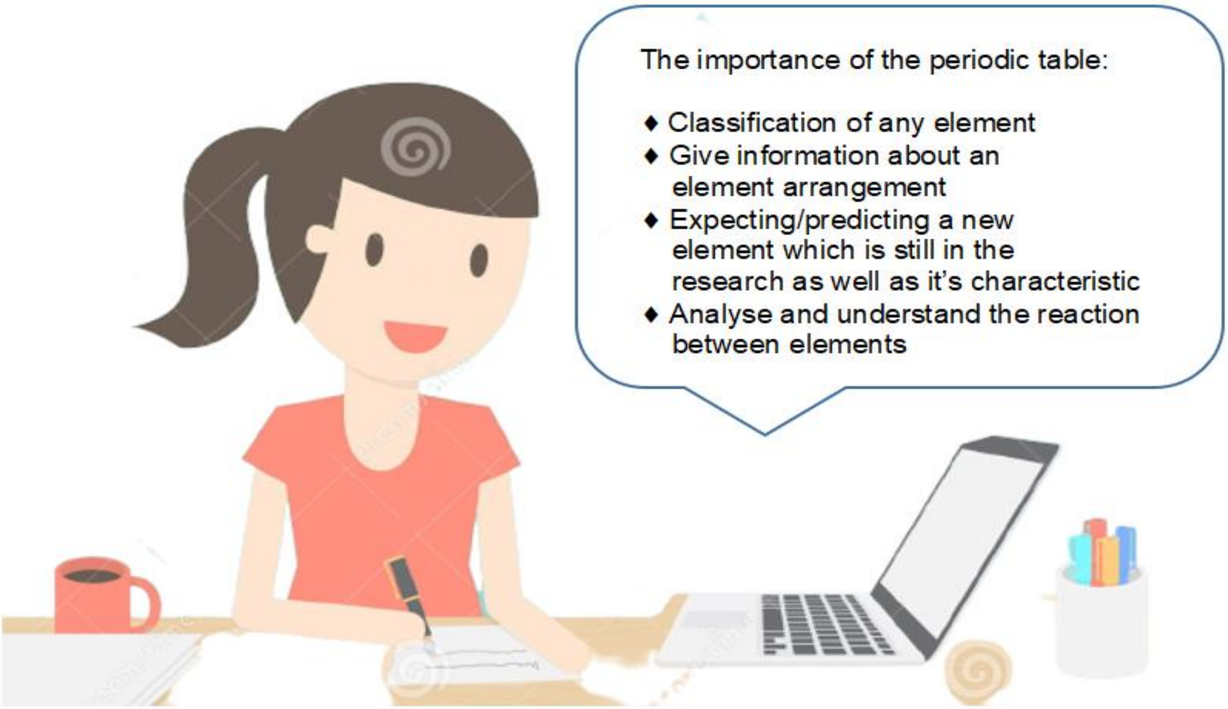
Name
Element's common name.

Atomic Number
Equal to the number of protons in the nucleus, as well as the number of electrons in the electron cloud.

Atomic Mass
Weighted average of the masses of all the element's isotopes. Rounding the atomic mass to the nearest whole number yields the mass number of the most common isotope.

Mass Number
The sum of the numbers of protons and neutrons in a specific isotope.

Figure 2.6: Understanding the periodic table



The importance of the periodic table:

- Classification of any element
- Give information about an element arrangement
- Expecting/predicting a new element which is still in the research as well as it's characteristic
- Analyse and understand the reaction between elements

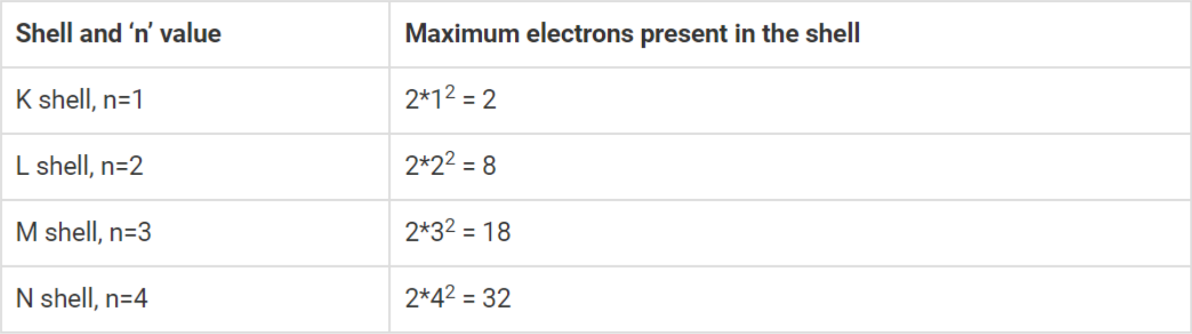
Figure 2.7: The importance of the periodic table

Electron Configuration

Electron configurations describe where electrons are located around the nucleus of an atom. As we learned earlier, each neutral atom has a number of electrons equal to its number of protons. What we will do now is place those electrons into an arrangement around the nucleus that indicates their energy and the shape of the orbital in which they are located.

The first shell (closest to the nucleus) can hold two electrons. The second shell can hold 8 electrons. The third shell can hold 32 electrons. Within the shells, electrons are further grouped into subshells of four different types, identified as s, p, d, and f in order of increasing energy. The maximum number of electrons that can be accommodated in a shell is based on the principal quantum number (n). It is represented by the formula 2n2, where ‘n’ is the shell number. The shells, values of n, and the total number of electrons that can be accommodated are tabulated in Table 2.1 below.

Table 2.1: Maximum electrons present in the shell



Shell and ‘n’ value	Maximum electrons present in the shell
K shell, n=1	$2*1^2 = 2$
L shell, n=2	$2*2^2 = 8$
M shell, n=3	$2*3^2 = 18$
N shell, n=4	$2*4^2 = 32$

For example, calcium has 20 electrons so its electron configuration is 2,8,8,2 as illustrated in Figure 2.8.

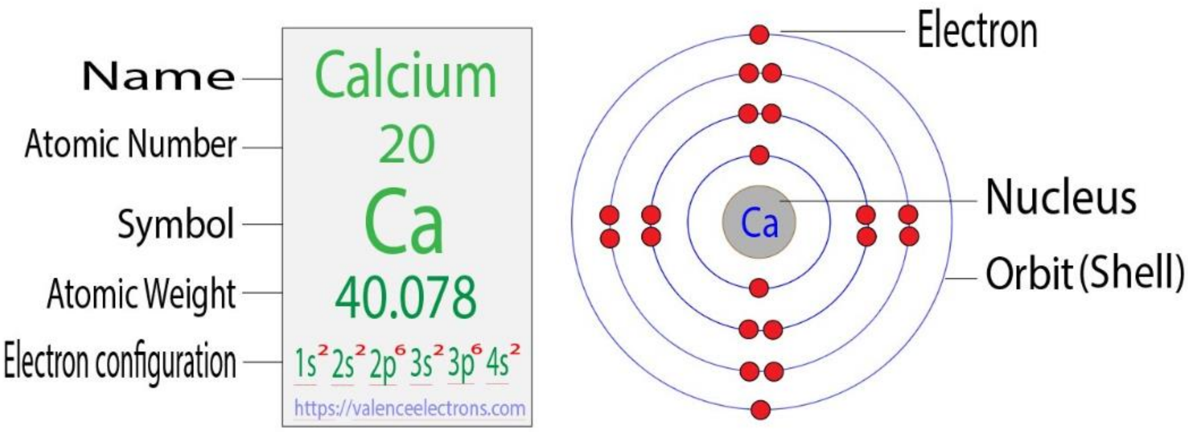


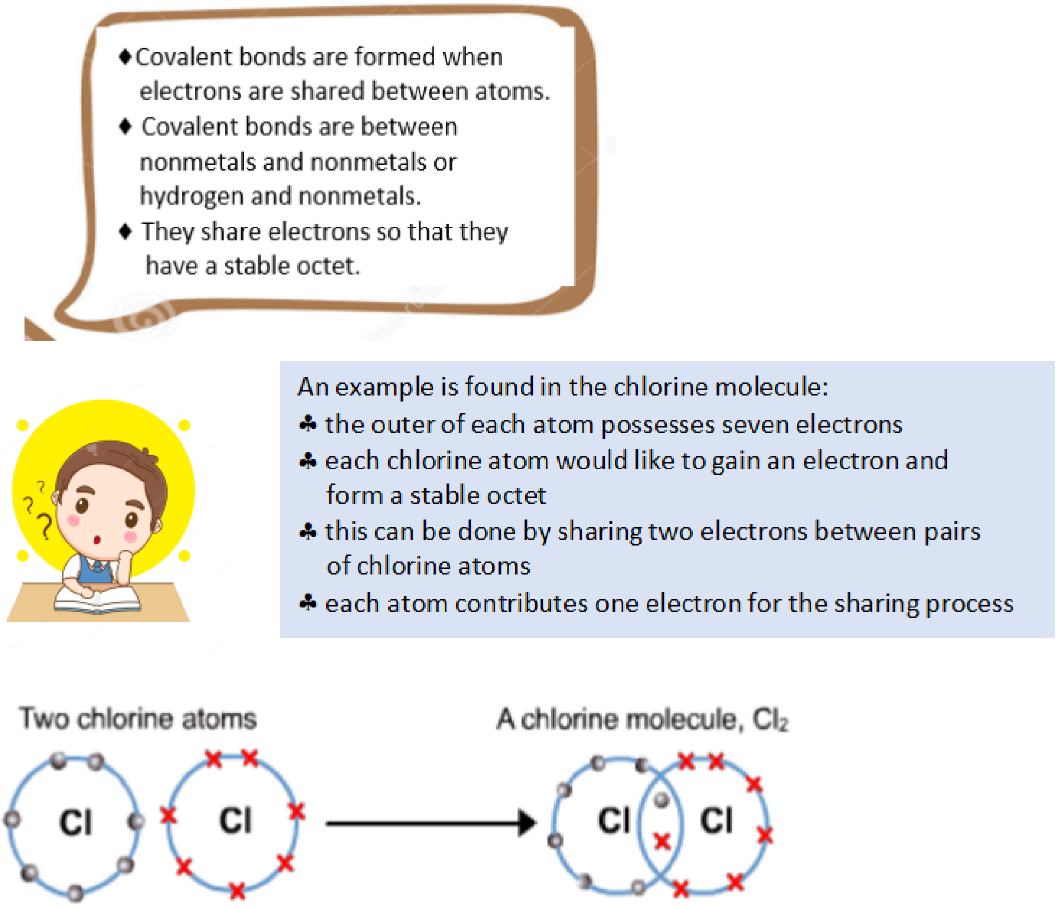
Figure 2.8: Electron configuration for calcium

2.3 ATOMIC BONDING

All materials are made up of atoms. These atoms are held together by forces called interatomic bonds. The bonds act like springs, linking each atom to its neighbour. Atomic bonding is chemical bonding. Chemical bonding is the physical process that is responsible for the interactions between atoms and molecules. Atomic bonds have two types of bonds; primary and secondary bonds, and primary bonds have three types of bonds, covalent, ionic, and metallic. The secondary bonds are also subsections of bonds, and are considered the weaker elements.

2.3.1 Covalent bonding

Atoms like to share their electrons and this causes their outer shell to be complete. A covalent bond is produced by the sharing of atoms and electrons. This produces a strong covalent bond. Two atoms that are covalently bonded will each contribute at least one electron to the bond, and the shared electrons may be considered to belong to both atoms. The covalent bond for the chlorine molecule is illustrated in Figure 2.9.



♦ Covalent bonds are formed when electrons are shared between atoms.
♦ Covalent bonds are between nonmetals and nonmetals or hydrogen and nonmetals.
♦ They share electrons so that they have a stable octet.

An example is found in the chlorine molecule:
♣ the outer of each atom possesses seven electrons
♣ each chlorine atom would like to gain an electron and form a stable octet
♣ this can be done by sharing two electrons between pairs of chlorine atoms
♣ each atom contributes one electron for the sharing process

Figure 2.9: Covalent bonds schematic illustration

Another example of covalent bonding is schematically illustrated in Figure 2.10 for a molecule of methane (CH_4). The carbon atom (C 6) has four valence electrons, whereas each of the four hydrogen atoms (H 1) has a single valence electron. Each hydrogen atom can acquire a helium electron configuration (He 2) (two 1s valence electrons) when the carbon atom shares with it one electron. The carbon now has four additional shared electrons, one from each hydrogen, for a total of eight valence electrons, and the electron structure of neon (Ne 10). The covalent bond is directional; that is, it is between specific atoms and may exist only in the direction between one atom and another that participates in electron sharing.

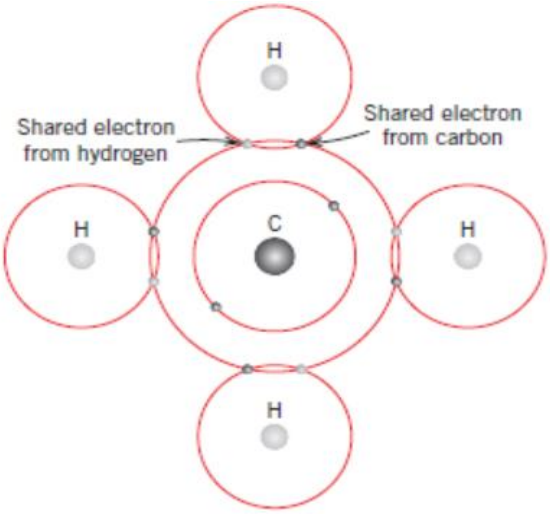


Figure 2.10: Schematic representation of covalent bonding in a molecule of methane (CH_4)

2.3.2 Ionic bonding

Ionic bonds are formed between two or more atoms by the transfer of one or more electrons between atoms. When an ionic bond is formed, electrons are transferred from one chemical unit to another. Charged ions are produced as a consequence. Anions are negatively charged atoms that gain electrons as a consequence of the creation of ionic bonds. Cations are positively charged atoms that have lost electrons during the creation of ionic bonds. It is always found in compounds that are composed of both metallic and nonmetallic elements.

Metal ions act as cations most of the time, whereas nonmetal ions act as anions due to their electrical configuration. Atoms of a metallic element easily give up their valence electrons to the nonmetallic atoms. In the process all the atoms acquire stable or inert gas configurations and, in addition, an electrical charge that is, they become ions. The electrovalence of the atoms determines the strength of the ionic connection that is further determined by the atoms' electronic structure.

Ionic bonds example includes natrium chloride (NaCl), lithium bromide (LiBr), potassium chloride (KCl), lithium oxide (Li_2O), etc. Figure 2.10 shows the diagram of ionic bonding in natrium chloride (NaCl). Natrium holds an atomic number of 11 and an electron configuration of 2,8,1. Thus, it has one electron more than the nearest stable noble gas electronic configuration, Neon. As a result, natrium tends to lose one electron from its outermost shell and obtain a stable electron configuration, resulting in a natrium cation (Na+). Chlorine holds an atomic number of 17 and an electronic configuration of 2,8,7. It has one lower electron than the closest stable noble gas electrical configuration - Argon. As a result, chlorine tends to gain one electron to achieve a stable electronic configuration, resulting in the formation of the chloride anion (Cl−). Another example of the ionic bonds is magnesium chloride as illustrated in Figure 2.11.

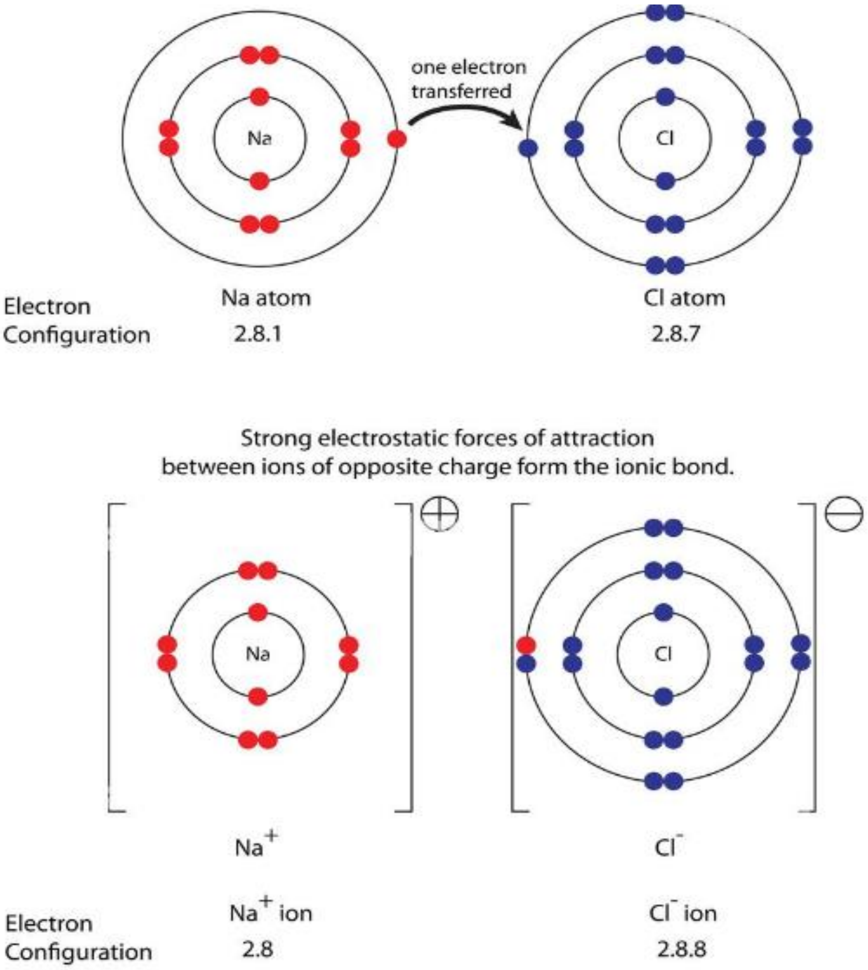
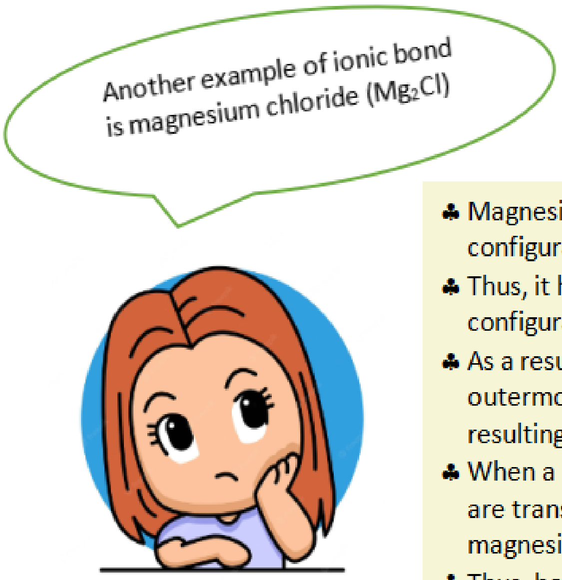


Figure 2.11: Ionic bonding in natrium chloride



- Magnesium holds an atomic number of 12, and its electron configuration is 2,8,2.
- Thus, it has two more electrons than the closest stable electronic configuration of a noble gas, Neon.
- As a result, magnesium tends to lose two electrons from its outermost shell and obtains a stable electron configuration, resulting in magnesium cation (Mg2+).
- When a magnesium atom joins two chlorine atoms, two electrons are transferred from the magnesium to the chlorine, resulting in a magnesium chloride molecule.
- Thus, both atoms have a stable octet electron configuration.

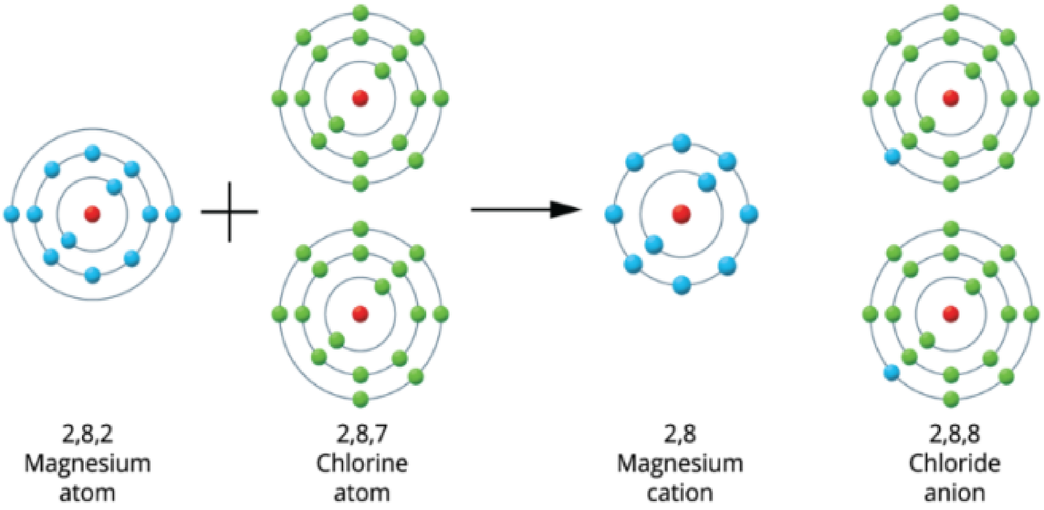


Figure 2.12: Diagram to show ionic bonding in magnesium chloride

2.3.3 Metallic bonding

Metallic bonding is a type of chemical bonding that arises from the electrostatic attractive force between conduction electrons (in the form of an electron cloud of delocalized electrons) and positively charged metal ions. In metallic bonding, many atoms share the same electron. Individual atoms give up their valence electrons and the delocalized electrons are free to move and interact with all the positively charged ions in the structure as illustrated in Figure 2.13. Metallic bonding, is especially common in minerals involving transition metals. Gold, silver, and copper are examples of minerals with metallic bonds. Because valence electrons move easily throughout the structure, metallically bonded compounds are good conductors of heat and electricity.

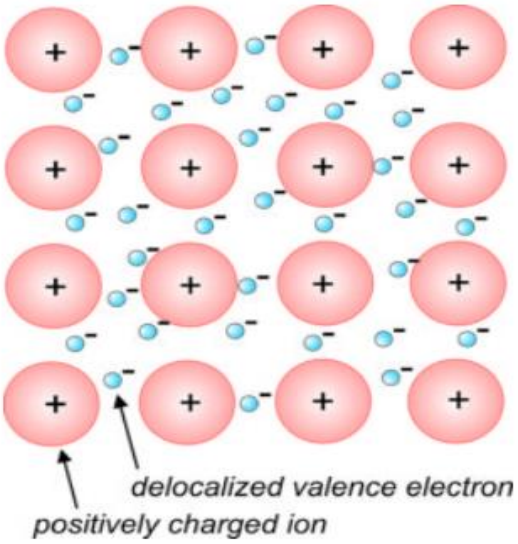


Figure 2.13: Metallic bonding of metal element

Metallic bonds are formed when the charge is spread over a larger distance as compared to the size of single atoms in solids. Mostly, in the periodic table, left elements form metallic bonds, for example, zinc and copper. Because metals are solid, their atoms are tightly packed in a regular arrangement. They are so close to each other so valence electrons can be moved away from their atoms. A "sea" of free, delocalized electrons is formed surrounding a lattice of positively charged metal ions. These ions are held by strong attractive forces to mobile electrons; in this way, metallic bonds are formed as shown in Figure 2.14.

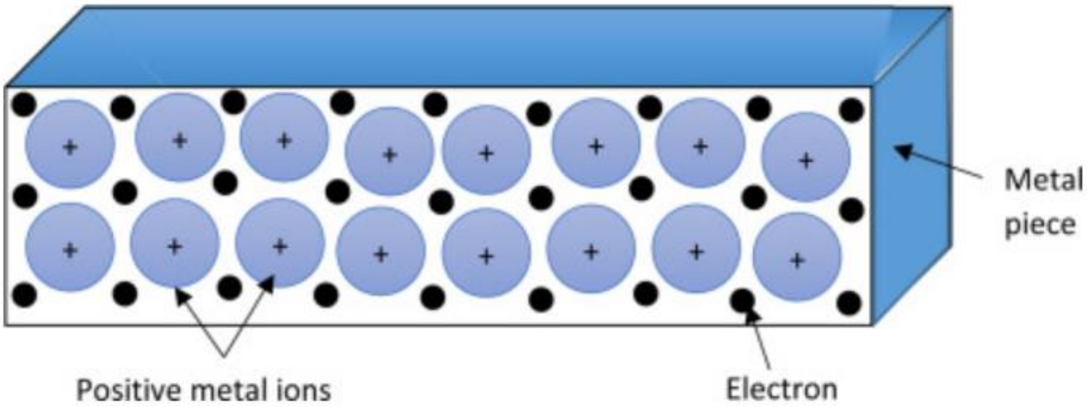


Figure 2.14: Schematic illustration of metallic bonds

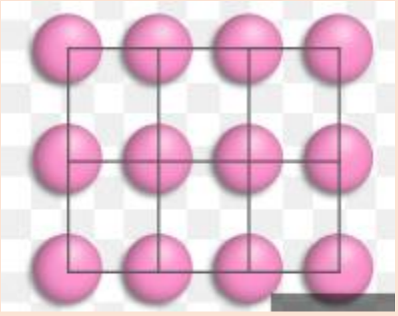
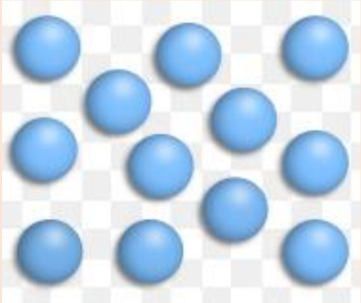
The properties of metals that are a consequence of metallic bonding include malleability, ductility, high melting, and boiling point.

2.4 CRYSTAL STRUCTURE OF MATERIALS

2.4.1 Fundamental concepts

Metal crystal structure and specific metal properties are determined by metallic bonding force, holding together the atoms of metal. Each of the atoms of the metal contributes its valence electrons to the crystal lattice, forming an electron cloud or electron 'gas', surrounding positive metal ions. A crystalline solid in which the atoms are held together by metallic bonds. Metallic crystals are found in some interstitial compounds as well as in metals and alloys. There are two main forms of solid substance, characterizing different atoms arrangement in their microstructures, consisting of crystalline structures and non-crystalline structures (amorphous structures) as tabulated in Table 2.2.

Table 2.2: The differences between crystalline and amorphous structures

Crystalline structures	**Amorphous structures**
Crystalline solids have regularly repeated units	Amorphous solids do not contain repeating units
Have highly ordered three-dimensional arrangement of particles	They have no fixed geometrical shapes
They are highly rigid solids	They are less rigid solids
Have sharp melting and boiling points	Do not have a sharp melting point
Crystalline structures are perfectly symmetrical	They have no symmetry among their molecules
Examples: Copper sulphide (CuSO4), NiSO4, diamond, graphite, NaCl, sugar	Examples: Waxes, glass, plastic, rubber
	

2.4.2 Metallic crystal structures

A crystal structure is a unique arrangement of atoms or molecules in a crystalline liquid or solid. A crystal structure is composed of a pattern, a set of atoms arranged in a particular way, and a lattice exhibiting long-range order and symmetry. Above the melting point, metals are liquids, and their atoms are randomly arranged and relatively free to move. However, when cooled below their melting point, metals rearrange to form ordered, crystalline structures. Patterns are located upon the points of a lattice, which is an array of points repeating periodically in three dimensions.

The points can be thought of as forming identical tiny boxes, called unit cells, that fill the space of the lattice as presented in Figure 2.15. The lengths of the edges of a unit cell and the angles between them are called the lattice parameters. The symmetry properties of the crystal are embodied in its space group. A crystal's structure and symmetry play a role in determining many of its physical properties, such as cleavage, electronic band structure, and optical transparency. The common crystal structure found in metals are simple cubic (SC), body centered cubic (BCC), face centered cubic (FCC), and hexagonal close packed (HCP).

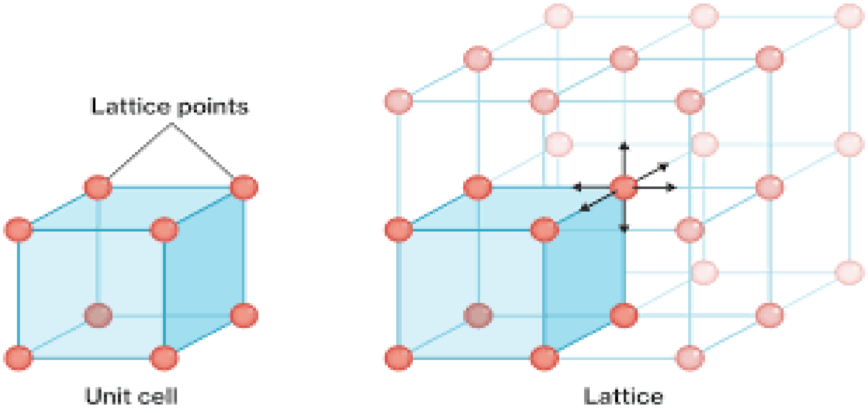


Figure 2.15: Diagram of the unit cell and lattice

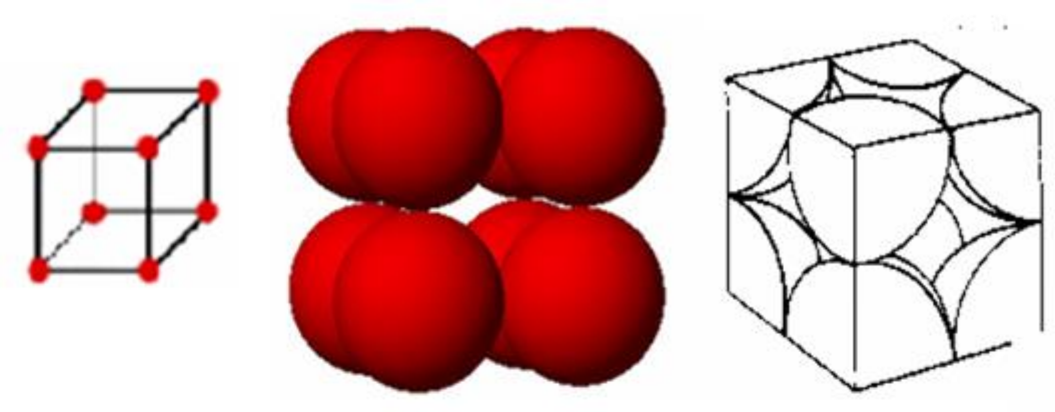
2.4.3.1 Simple cubic

- In the simple cubic structure, there is only one lattice point at each corner of the cube-shaped unit cell. They mark the position of either a single atom, or the same group of atoms, known as the motif, which is repeated across the lattice.

- The simple cubic (SC) unit cell can be imagined as a cube with an atom on each corner. This unit cell is the simplest for people to understand, although it rarely occurs in nature due to its low packing.

- A unit cell with an atomic packing arrangement in which eight identical atoms are located at the corners of an imaginary cube.

- Contains only one atom per unit cell as presented in Figure 2.16. Polonium (Po) and natrium chloride (salt) are reported to crystallize in the simple cubic structure.



No of atoms:
8 corner atom x 1/8 = 1 atom
Total atom = <u>1 atom</u>

Figure 2.16: Simple cubic structure

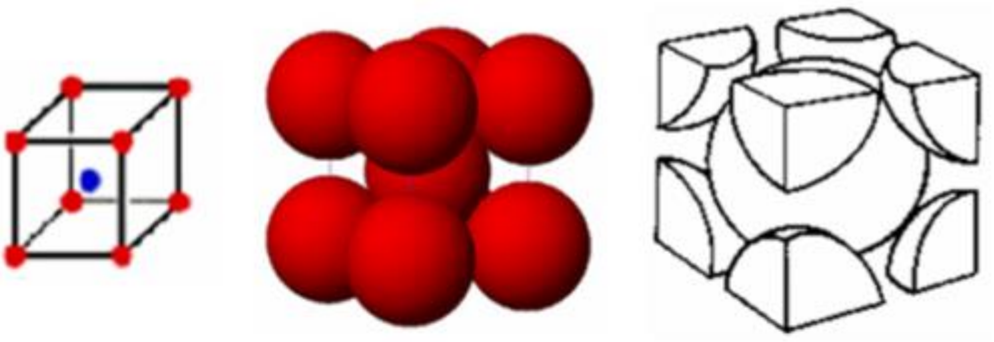
2.4.3.2 Body Centered Cubic (BCC)

- 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. Each of the corner atoms is the corner of another cube so the corner atoms are shared among eight unit cells.

- The BCC unit cell consists of a net total of two atoms, the one in the center and eight eighths from the corners.

- The packing efficiency and the nearest neighbour interaction are slightly higher than for the simple structure, so it is more common in nature.

- Prominent metallic solids with this structure are Iron (Fe), Chromium (Cr), Molybdenum (Mo), and Tungsten (W). Figure 2.17 presents the diagram body centered cubic.



No of atoms:
8 corner atom x 1/8 = 1 atom
1 centre atom = 1 atom
Total atom = <u>2 atoms</u>

Figure 2.17: Body centered cubic structure

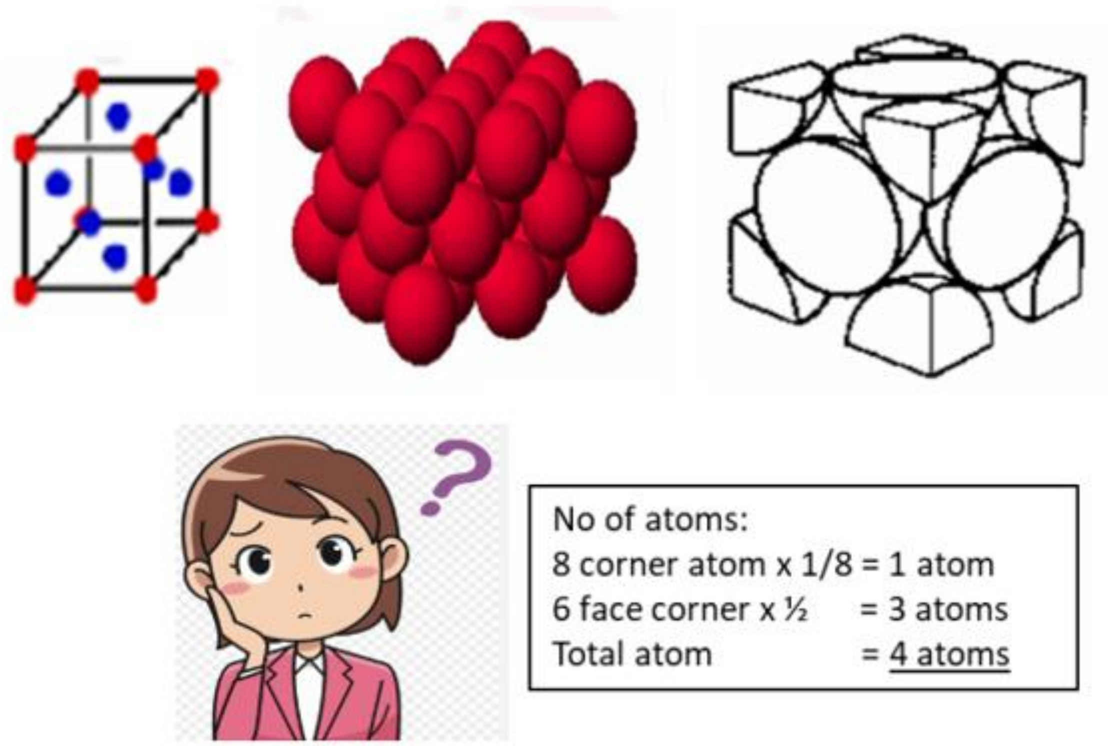
2.4.3.3 Face Centered Cubic (FCC)

- In this crystal structure, there are eight lattice points at each corner, as in the simple cubic, but there is an additional lattice point at the centre of each face of the cube.

- Atoms are arranged at the corners and center of each cube face of the cell. Atoms are assumed to touch along face diagonals, 4 atoms in one unit cell.

- This structure is very common for metallic elements as it maximizes the packing efficiency and has the highest number of nearest neighbours, increasing its stability.

- Metals with the FCC structure include aluminum, copper, nickel, gamma iron, gold, and silver. Figure 2.18 illustrated the face centered cubic structure.



No of atoms:
8 corner atom x 1/8 = 1 atom
6 face corner x ½ = 3 atoms
Total atom = 4 atoms

Figure 2.18: Face centered cubic structure

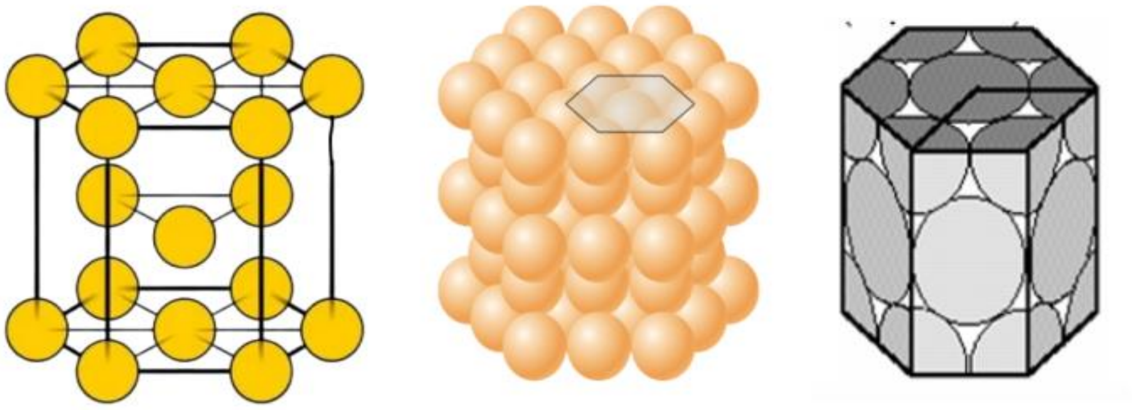
2.4.3.4 Hexagonal Close Packed (HCP)

- The Hexagonal Close-Packed crystal structure is one of the most common ways for atoms to arrange themselves in metals.

- The HCP crystal structure is based on the Bravais lattice of the same name, with 1 atom per lattice point at each corner of the hexagonal prism, and 3 inside the prism. HCP has 6 atoms per unit cell. The diagram of HCP is presented in Figure 2.19.

- HCP is one of the most stable crystal structures and has the highest packing density.

- Since HCP is one of the most common crystal structures, there are many materials to choose from such as cadmium, titanium, zinc, scandium, cobalt, zirconium, cadmium, gadolinium, terbium, etc.



No of atoms:
12 corner atom x 1/6 = 2 atoms
2 centre atom x ½ = 1 atom
3 centre atom = 3 atoms
Total atom = 6 atoms

Figure 2.19: The diagram of Hexagonal Close-Packed crystal structure

DISCUSSION QUESTIONS

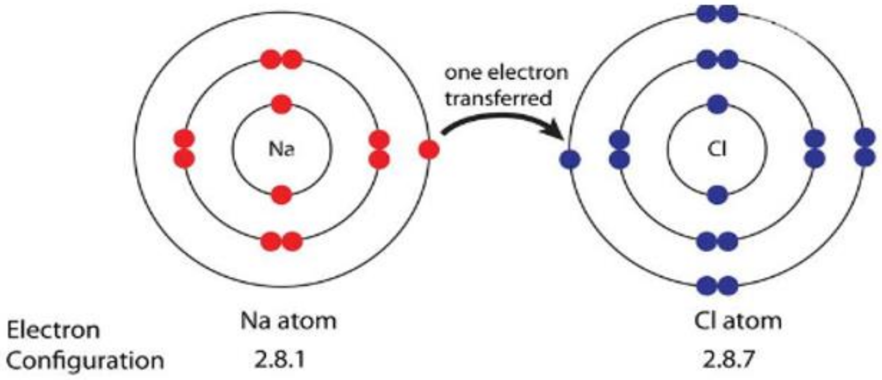
QUESTION 1

Atomic bonding is a chemical bonding for the interactions between atoms and molecules. With the aid of a suitable diagram, explain the ionic bonding.

ANSWER 1

Ionic bonds are formed between two or more atoms by the transfer of one or more electrons between atoms. When an ionic bond is formed, electrons are transferred from one chemical unit to another. It is always found in compounds that are composed of metallic and nonmetallic elements.

Example: NaCl



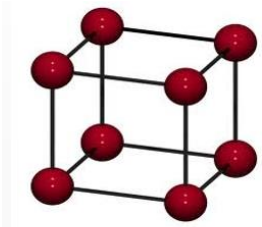
QUESTION 2

A crystal structure is composed of a unit cell which is a set of atoms are arranged in a particular way. Draw THREE (3) metallic crystal structure and indicate the amount of atom in each cell unit.

ANSWER 2

* Choose any 3 crystal structures

Simple Cubic (SC)

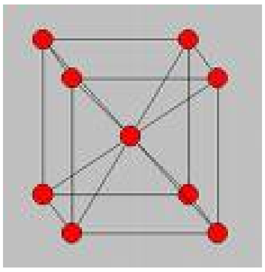


Number of atom

8 atoms at corners X 1/8 = 1atom

Total = 1 atom

Body centred Cubic (BCC)

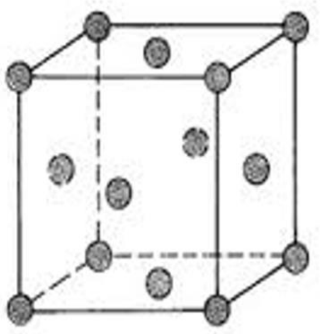


Number of Atom

8 atom at corners X 1/8=1 atom

1 atom at center = 1 atom

Face Centered Cubic (FCC)



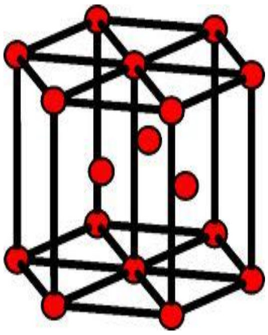
Number of Atom

8 atom at corners X 1/8= 1 atom

6 atom at face X 1/2 = 3 atom

Total = 4 atom

Hexagonal Closed Packed (HCP)



Number of Atom

12 atom at corners X 1/6 = 2 atom

2 atom at face X 1/2 = 1 atom

3 atom at center = 3 atom

Total = 6 atom

PAST YEARS QUESTIONS

1) List THREE (3) types of atomic bonding and define ONE (1) type of atomic bonding only. [5 marks]

2) Sketch and state the numbers of atoms for each of the structures below:
   i. Face center cubic (FCC)
   ii. Body center cubic (BCC)
   iii. Hexagonal close packed (HCP)
   iv. Simple cube

[8 marks]

3) Define the following terms:
   i. Atom
   ii. Element
   iii. Mixture

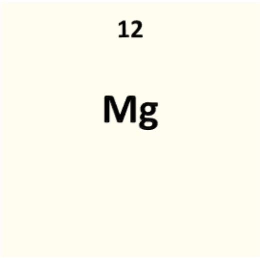
[6 marks]

4) Explain FIVE (5) characteristics of the Periodic Table. [10 marks]

5) Solid materials can be broadly classified as crystalline and non-crystalline solids. Most metals are crystalline while ceramics and polymers may be either crystalline or non-crystalline.
   i. Compare between crystalline solids and non-crystalline solids. [4 marks]
   ii. With the aid of a diagram, explain the simple cubic and body centered cubic structures. [4 marks]

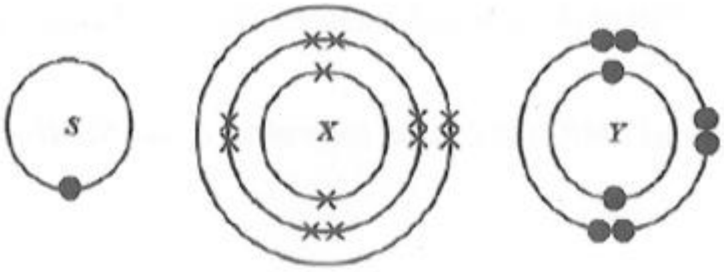
6) Explain the ionic bonding for Natrium Chloride with aid of a diagram. [10 marks]

7) The diagram below shows an atom in the element periodic table. With reference to the diagram, explain the meaning of the numbers and the symbols it represents. [9 marks]



   i. 12
   ii. 24.31
   iii. Mg
   iv. 2:8:2
   v. Sketch the electron configuration for the atom

8) Figure below shows the electron arrangement of elements S, X, and Y.



i. Sketch a diagram showing how a chemical bond is made between X and Y. [2 marks]

ii. Assign the type of expected atomic bonding between X and Y. [2 marks]

iii. Sketch a diagram of how an atomic bonding is formed between S and Y. [4 marks]

iv. Assign the type of expected atomic bonding between S and Y. [2 marks]

9) Choose TWO (2) structures of the metallic crystal and elaborate the amount of atom in each cell unit. [4 marks]

CHAPTER 3

MECHANICAL PROPERTIES OF METALS AND FAILURE

SYNOPSIS

This topic describes the concepts of stress-strain and discuss the elastic and plastic deformation from the stress-strain curve.

LEARNING OUTCOMES

3.1 Construct the concepts of stress-strain
- 3.1.1 Tension
- 3.1.2 Compression
- 3.1.3 Shear and torsional test

3.2 Describe the elastic and plastic deformation from the stress-strain curve
- 3.2.1 Stress-strain behavior for elastic deformation
- 3.2.2 Tensile properties for plastic deformation
  - 3.2.2.1 Yielding and yield strength
  - 3.2.2.2 Tensile strength
  - 3.2.2.3 Ductility
  - 3.2.2.4 Resilience
  - 3.2.2.5 Toughness
  - 3.2.2.6 Brittleness

3.3 Analyze the failure in engineering materials
- 3.3.1 Fundamentals of fracture
  - 3.3.1.1 Ductile fracture
  - 3.3.1.2 Brittle fracture
- 3.3.2 Fatigue
- 3.3.3 Creep

3.0 MECHANICAL PROPERTIES OF METALS

The mechanical properties of materials are ascertained by performing carefully designed laboratory experiments that replicate as nearly as possible the service conditions. Consequently, it is imperative that there be some consistency in the manner in which test are conducted, and in the interpretation of their results. The consistency is accomplished by using standardized testing techniques such as American Society for Testing and Materials (ASTM), British Standard Institution (BS) or Japanese Industrial Standard (JIS).

Many materials, when in service, are subjected to forces or loads. It is necessary to know the characteristics of the material and to design the member from which it is made such that any resulting deformation will not be excessive and fracture will not occur.

3.1 CONCEPTS OF STRESS-STRAIN

If a load is static or changes relatively slowly with time and is applied uniformly over a cross section or surface of a member, the mechanical behaviour may be ascertained by a simple stress-strain test; these are most commonly conducted for metals at room temperature. There are three principal loads applied, namely tension, compression and shear.

3.1.1 Tension

In general, tensile test is a measurement of the ability of a material to withstand forces that tend to pull it apart and to what extent the material stretches before breaking (figure 3.1). A specimen is deformed (figure 3.2), usually to fracture with a gradually increasing tensile load that is applied uniaxially along the long axis of a specimen. Figure 3.3 shows schematic illustration of how a tensile load produces an elongation.

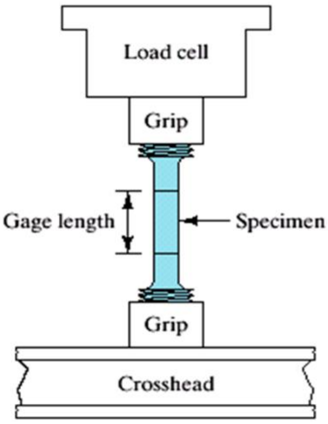


Figure 3.1 Tensile tests.

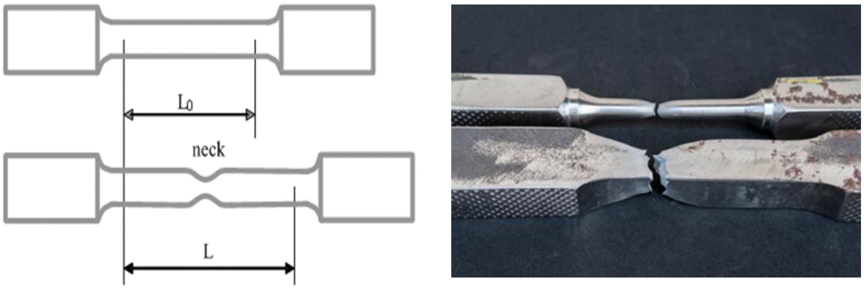


Figure 3.2 Standard tensile test specimen

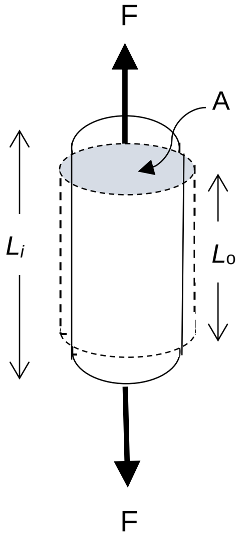


Figure 3.3 Tensile load; dashed lines represent the shape before deformation; solid lines after deformation.

Stress, σ is a measure of the internal resistance of a material to an externally applied load. Its defined by the relationship;

$$\boxed{\sigma = \frac{F}{A}} \qquad \text{………………… (i)}$$

which, F = Force applied perpendicular to the specimen cross section, newton (N)

A = original cross-sectional area before any load applied (m^2)

σ = Stress (Pa or N/m^2)

Strain, ε is not a measure of force but is a measure of the deformation produced by the influence of stress. Strain is dimensionless.

$$\boxed{\varepsilon = \frac{L_i - L_o}{L_o} = \frac{\Delta L}{L_o}} \qquad \text{………………..(ii)}$$

which, L_o = original length

L_i = instantaneous length

3.1.2 Compression

A compression test is conducted in manner similar to the tensile test, except that the force is compressive and specimen contracts along the direction of the stress. Equation (i) and (ii) are utilized to compute compressive stress and strain, respectively. By convention, a compressive force is taken to be negative. Since L_o is greater than L_i, compressive strain also negative (figure 3.4).

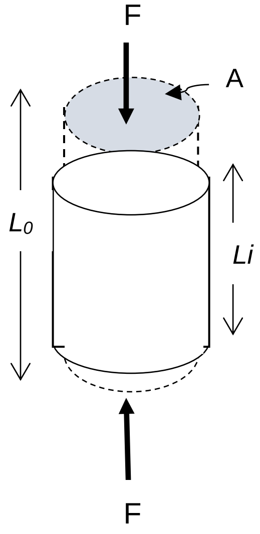


Figure 3.4 Compressive load; dashed lines represent the shape before deformation; solid lines after deformation.

3.1.3 Shear and torsional test

Shear stress is a measure of the internal resistance of a material to an externally applied shear load.

The shear stress is defined as:

$$\boxed{\tau = \frac{F}{A}}$$

which, F = Force/ load imposed parallel to the upper and lower faces in newton (N)

A = area (m^2)

τ = Stress (Pa or N/m^2)

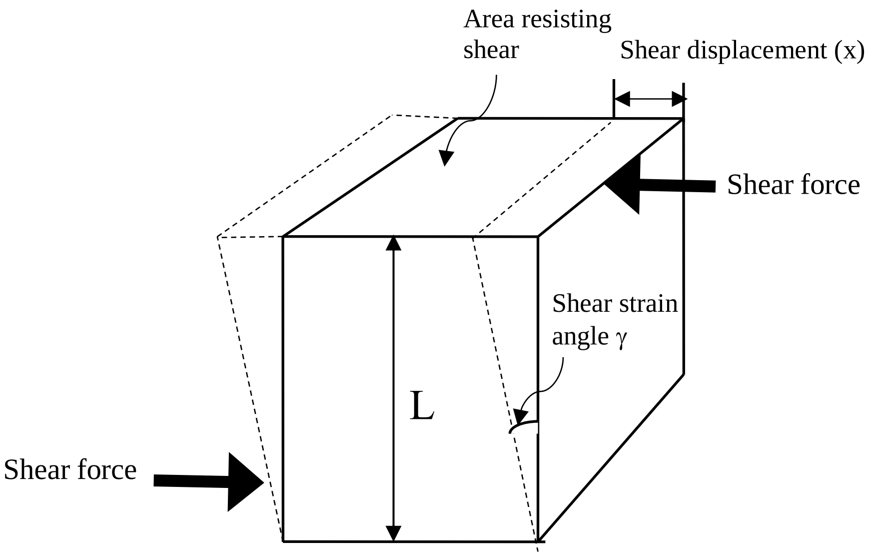


Figure 3.5 Shear strain γ, dashed lines represent the shape after deformation.

The shear strain, γ is defined as the tangent of the strain angle θ, as indicated in figure 3.5. This is measured in radians.

$$\boxed{\gamma = \frac{\text{shear displacement}}{\text{width}} = \frac{x}{L}}$$

Torsion is a moment that twists or deforms a member about its longitudinal axis. Under torsion, every section of the shaft is subjected to shear stress. By observation, if the angle of rotation is small, length of the shaft and its radius remain unchanged. Torsional tests are normally performed on cylindrical solid shafts or tubes. A shear stress t is a function of the applied torque T, whereas shear strain g is related to the angle of twist, ϕ in figure 3.6.

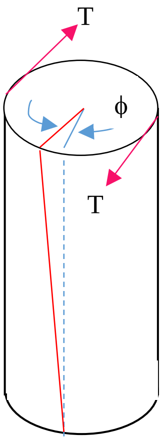


Figure 3.6 Torsional deformation

3.2 ELASTIC AND PLASTIC DEFORMATION

When a sufficient load is applied to a metal or other structural material, it will cause the material to change shape. This change in shape is called deformation. A temporary shape change that is self-reversing after the force is removed, so that the object returns to its original shape, is called elastic deformation. Elastic deformation is a change in shape of a material at low stress that is recoverable after the stress is removed. This type of deformation involves stretching of the bonds, but the atoms do not slip past each other. When the stress is sufficient to permanently deform the metal, it is called plastic deformation. Plastic deformation involves the breaking of a limited number of atomic bonds by the movement of dislocations. Atoms are permanently displaced and take up new positions. It involved the breaking of bonds with original atom neighbours and then reforming bonds with new neighbours, upon removal of the stress they do not return to their original positions.

3.2.1 Stress-strain behavior for elastic deformation

Hooke’s Law defines that when a material is loaded, within its elastic limit, the stress is proportional to the strain (equation iii).

$$\boxed{\sigma = E\varepsilon} \qquad \text{……………………. (iii)}$$

where, E is the modulus of elasticity, or Young’s modulus (GPa or psi). The value of E of materials, in everyday use, are given in Table 3.1.

Table 3.1: Values of Modulus of elasticity (E)

Material	Modulus of elasticity (E) GPa or GN/m^2
Steel	200-220
Wrought iron	190-200
Cast iron	100-160
Copper	90-110
Brass	80-90
Aluminium	60-80
Timber	10

Deformation in which stress and strain are proportional is called elastic deformation; a plot of stress versus strain results in a linear relationship. The slope of this linear segment corresponds to the modulus of elasticity, E. This modulus may be thought of as stiffness, or a material's resistance to elastic deformation. The greater the modulus, the stiffer the material, or the smaller the elastic strain that results from the application of a given stress. Elastic deformation is a change in shape of a material at low stress that is recoverable after the stress is removed. This type of deformation involves stretching of the bonds, but the atoms do not slip past each other. Elastic deformation is no permanent, which means that when the applied load is released, the piece returns to its original shape. Figure 3.7 is shown in the stress–strain plot, application of the load corresponds to moving from the origin up and upon release of the load, the line is traversed in the opposite direction, back to the origin.

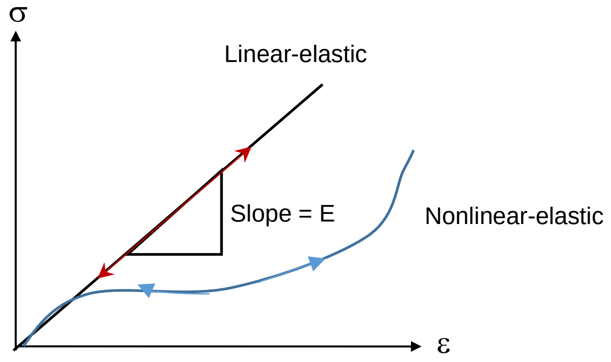


Figure 3.7 Elastic deformation

3.2.2 Tensile properties for plastic deformation

Plastic deformation occurs when the stress is sufficient to deform a permanent change in shape. It involves the breaking of a limited number of atomic bonds by the movement of dislocation. However, the movement of dislocations allows atoms in crystal planes to slip past one another at a much lower stress level. Since the energy required to move is lowest along the densest planes of atoms, dislocations have a preferred direction of travel within a grain of the material. This results in slip that occurs along parallel planes within the grain. These parallel slip planes group together to form slip bands, which can be seen with an optical microscope.

3.2.2.1 Yielding and yield strength

Yield stress is the stress level at the point where the material begins to have permanent deformation, where the material no longer returns to its original shape and size after the release of the applied stress. Figure 3.8 show the point at which the material transforms from elastic to plastic is known as the yield point (P). The magnitude of the stress at which the transition from elastic to plastic occurs is known as the yield strength. Yield strength is a constant that represents the maximum limit of elastic behaviour.

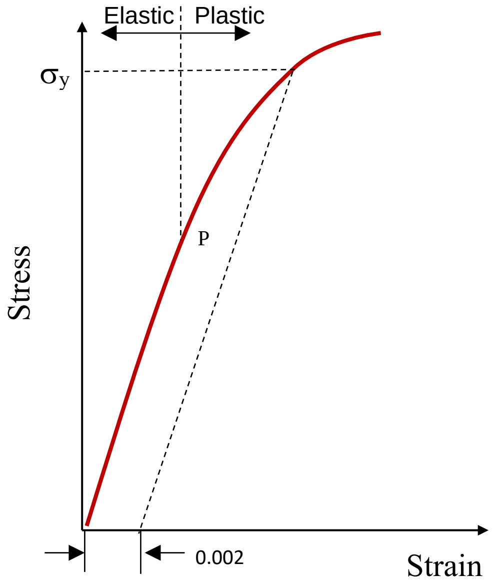


Figure 3.8 Yielding (Adapted from Fig. 6.10 (a), Callister 9e)

3.2.2.2 Tensile strength

The tensile strength is the stress at the maximum on the engineering stress–strain curve (Figure 3.9). This corresponds to the maximum stress that can be sustained by a structure in tension; if this stress is applied and maintained, a fracture will result. All deformation to this point is uniform throughout the narrow region of the tensile specimen.

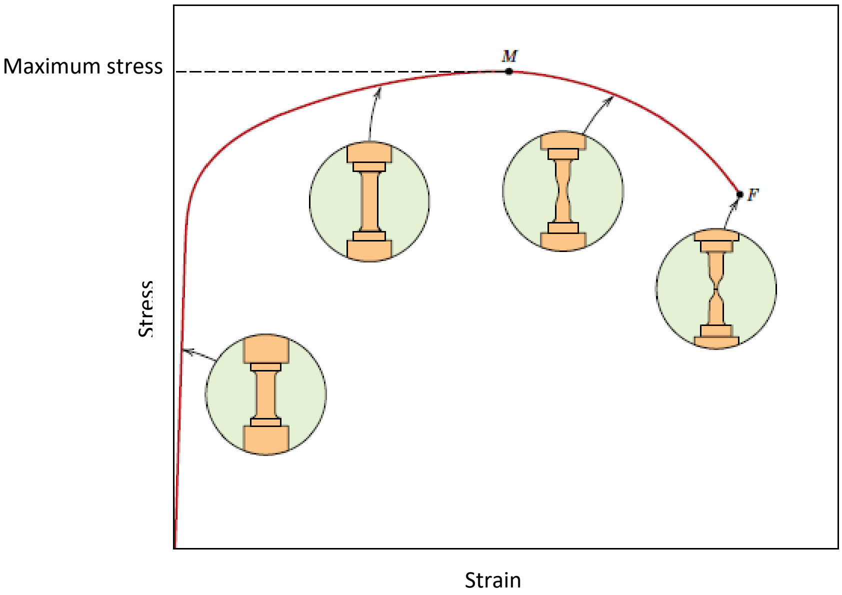


Figure 3.9 Maximum stress (Adapted from Fig. 6.11, Callister 9e).

3.2.2.3 Ductility

Ductility is the ability of a material to be in sustaining plastic deformation under tensile stress before failure. Ductility is often categorized by the ability of the material to get stretched into a wire by pulling or drawing. This mechanical property is also an aspect of the plasticity of material and is temperature dependent. With the rise of temperature, the ductility of material increases. The tensile stress–strain behaviors for both ductile and brittle metals are schematically illustrated in Figure 3.10. Figure 3.11 shows the percent elongation and the reduction in area in tension are often used as empirical measures of ductility.

Ductility as percent elongation;

$$\boxed{\%\ E = \left(\frac{L_f - L_o}{L_o}\right) \times 100\%}$$

Ductility as percent reduction in area;

$$\boxed{\%\ AR = \left(\frac{A_o - A_f}{A_o}\right) \times 100\%}$$

Where, L_O = original length

L_f = fracture length

A_o = original cross-sectional area

A_f = cross-sectional area at the point of fracture

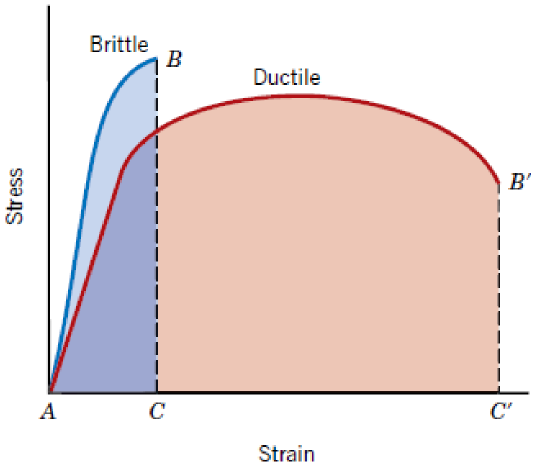


Figure 3.10 Tensile-strain behaviour for brittle and ductile metal

(Adapter from Fig.6.13, Callister 9e)

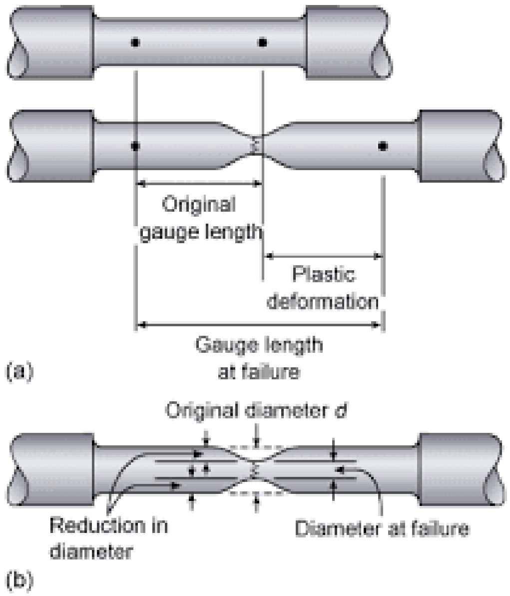


Figure 3.11 Measurements after the tensile test are used to calculate (a) the % elongation and (b) the % reduction of area

3.2.2.4 Resilience

Resilience is the ability of a material to absorb energy when it is deformed elastically, and release that energy upon unloading. Resilience is quantified with the modulus of resilience, Ur, which is the strain energy per unit volume required to stress a material from an unloaded state up to the point of yielding. As shown in Figure 3.12, this is simply the area under the curve to the yield point. Again, note how the yield point is determined from the 0.2% offset in metals. Assuming a linear elastic region up to the yield point (which we know is an approximation in most situations), the modulus of resilience can be found from the yield strength, σ_y, and modulus of elasticity, E:

$$\boxed{U_r = \frac{1}{2}\sigma_y\varepsilon_y = \frac{\sigma_y^2}{2E}}$$

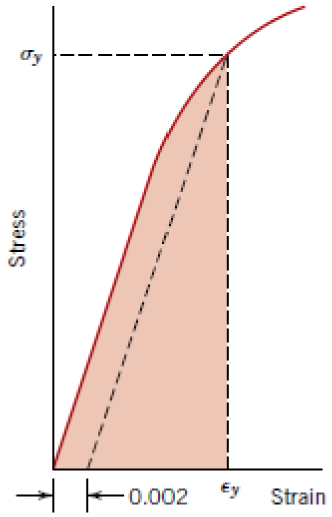


Figure 3.12 Resilience (corresponding to the shaded area)
(Adapter from Fig.6.15, Callister 9e)

3.2.2.5 Toughness

Toughness as indicated in Figure 3.13, is the area under the stress–strain curve up to the point of fracture. Thus, it is both a measure of a material's strength and ability to deform plastically. A material with low strength and high ductility may possess more toughness than one with high strength and low ductility. This is an important design consideration in many applications. The continued use of metals in automobile manufacturing (for frames and other structural components) is the result, in part, of safety considerations. There are certainly stronger materials than aluminium, less dense materials than steel, and less costly materials than either, but the combination of properties, including the ability to absorb energy during impact, is what keeps metals attractive for these applications

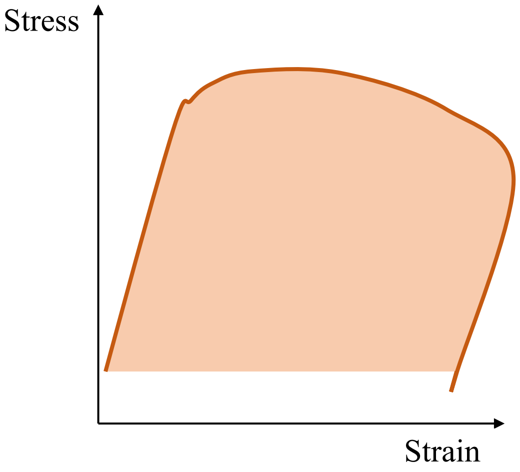


Figure 3.13 Toughness (corresponding to the shaded area)

3.2.2.6 Brittleness

Brittleness indicates how easily it breaks when under force or load. When a brittle material is subjected to stress is observed much less energy and results in fractures without significant stress. Brittleness is converse to the ductility of the material. Brittleness of the material is temperature depended. Some metals which are ductile at normal temperatures become brittle at low temperatures.

3.3 ANALYZE THE FAILURE IN ENGINEERING MATERIALS

The purpose of failure analysis is to identify the most basic reason for failure. Hopefully with the intent of eliminating it and finding ways to prevent it from happening again.

3.3.1 Fundamentals of fracture

Fracture is a form of failure, and is defined as the separation or fragmentation of a solid body into two or more parts under the action of stress. A fracture that occurs over a very short time period and under simple loading conditions (static i.e. constant or slowly changing) is considered here. Fracture under complex condition, for example alternating stress, is considered in later sections. The process of fracture can be considered to be made up of two components, crack initiation followed by crack propagation. For metals, two fracture modes are possible: ductile and brittle. Fracture also can occur from fatigue and creep.

3.3.1.1 Ductile fracture

Ductile fracture in tension occurs after appreciable plastic deformation. It occurs by a slow tearing of the metal with the expenditure of considerable energy. It can be said that ductile fracture in tension is usually preceded by a localized reduction in cross-sectional area, called necking. The failure it goes through three stages: (1) after the onset of necking, cavities form in the necked region, typically at inclusions at second-phase particles; (2) the cavities grow; further growth causes them to coalesce; this results in the formation of a crack that grows outward in a direction perpendicular to the application of stress; and (3) the final failure involves rapid crack propagation at about 45° to the tensile axis. This angle represents the direction of maximum shear stress that causes shear slip in the final stage. During the shear slip, crack propagates at a rapid speed around the outer perimeter of neck leaving one surface in form of cup, and the other in form of cone. Thus, it is known as cup-and-cone fracture (figure 3.13). In this central interior region has an irregular and fibrous appearance, which signifies plastic deformation. Different progressive stages of ductile fracture are shown in figure 3.14.

Figure 3.13 Cup-and-cone fracture

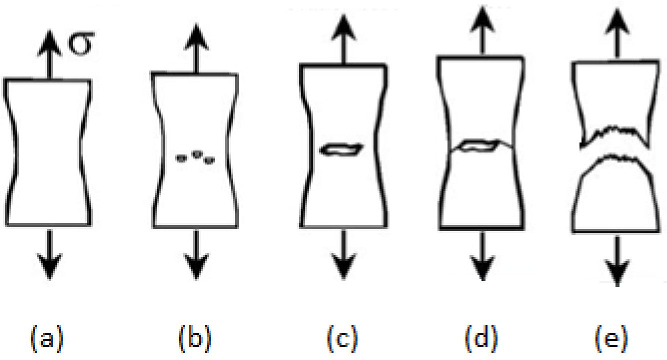


Figure 3.14 Stages of ductile tensile fracture (a) necking, (b) void nucleation, (c) void growth and linkage, (d) shearing at the surface, and (e) fracture

3.3.1.2 Brittle fracture

Brittle fracture occurs often at unpredictable levels of stress, by rapid crack propagation. The direction of crack propagation is very nearly perpendicular to the direction of applied tensile stress. This crack propagation corresponds to successive and repeated breaking to atomic bonds along specific crystallographic planes, and hence called cleavage fracture (figure 3.15). This fracture is also said to be transgranular because crack propagates through grains (figure 3.16). Thus, it has a grainy or faceted texture. Most brittle fractures occur in a trans granular manner. However, brittle fracture can occur in intergranular manner i.e. crack propagates along grain boundaries. This happens only if grain boundaries contain a brittle film or if the grain-boundary region has been embrittled by the segregation of detrimental elements.

Figure 3.15 Brittle fracture

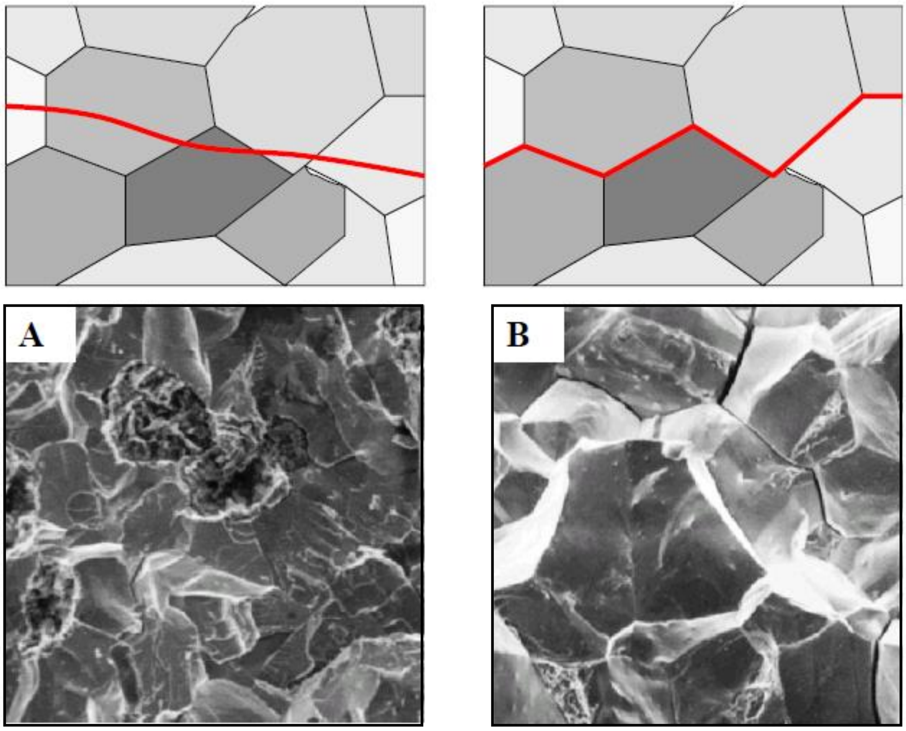


Figure 3.16 (a) Transgranular fracture and (b) Intergranular fracture

3.3.2 Fatigue

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

A typical fatigue-fracture surface looks like the one shown in figure 3.17. The fatigue crack nucleates at the stress concentration. Generally, the fatigue fracture surface is perpendicular to the direction of an applied stress. A fatigue failure can be recognized from the appearance of the fracture surface, which shows a smooth and polished surface that corresponds to the slow growth of crack, when the crack faces smoothen out by constant rubbing against each other and a rough/granular region corresponds to the stage of fast growth, after critical conditions is attained where member has failed in a ductile manner when cross section was no longer able to carry the applied load. The region of a fracture surface that formed during the crack propagation step may result in a characteristic pattern of concentric rings spread over the smooth region of the fracture surface, known as beach marks or striations, radiating outward from the point of initiation of the failure, as shown in figure 3.17.

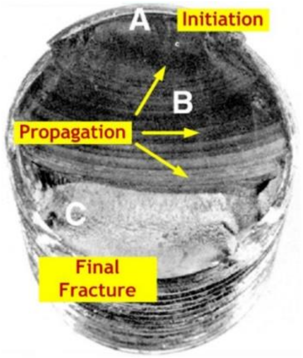


Figure 3.17 Fatigue fracture

3.3.3 Creep

Many engineering components are exposed to high temperature for a long period of time. Changes within the component due to this (at constant stress) is called creep. Creep test is carried out at high temperature. A creep curve is a plot of elongation of a tensile specimen versus time, for a given temperature and under constant stress. Test are carried out for a period of a few days to many years. The test can be carried out on Universal Testing Machine with special attachments. Figure 3.18 shown a typical creep curve of strain versus time at constant stress and constant elevated temperature.

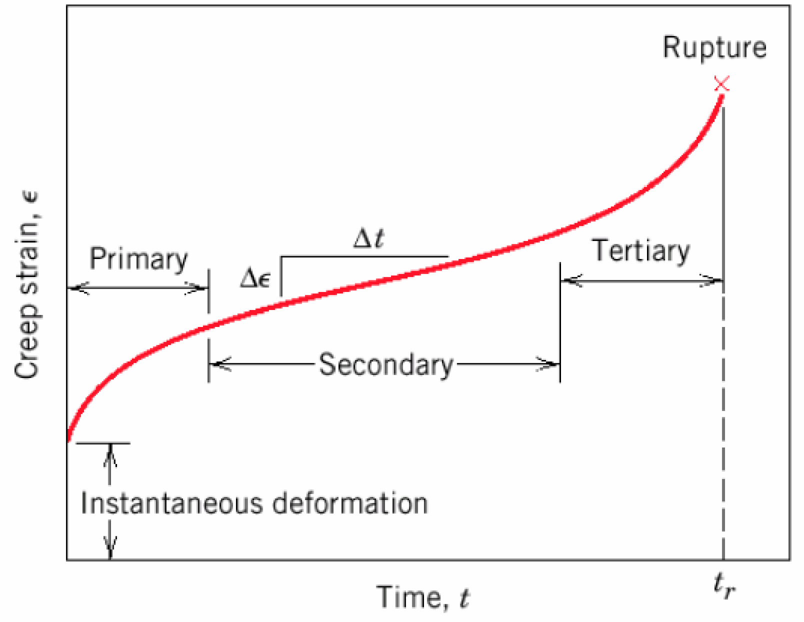


Figure 3.18 Typical creep curve.

DISCUSSION QUESTIONS

QUESTION 1

Define brittleness and ductility

ANSWER

i. Brittleness: Tendency of a material to fracture or fail upon the application of a relatively small amount of force, impact or shock
ii. Ductility: The property that enables a material to stretch, bends or twist without cracking or breaking.

QUESTION 2

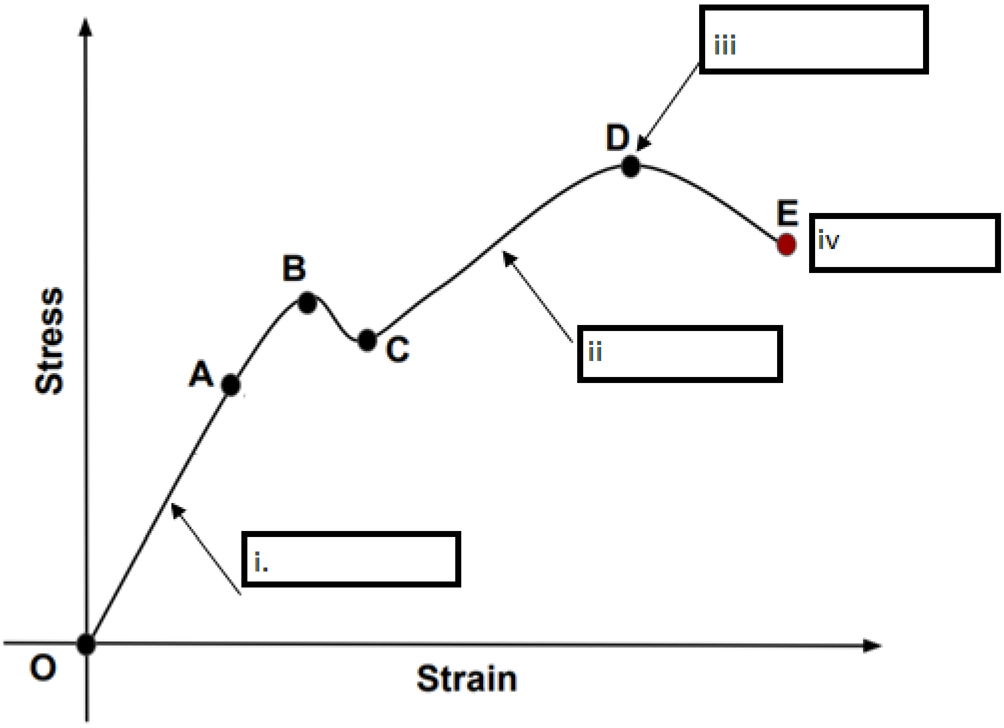
Explain the differences between resilience and toughness in material properties.

ANSWER

Resilience	Toughness
Resilience is defined as the ability of the solid material to absorb energy when it is elastically deformed.	Toughness is defined as the ability of the solid material to absorb energy until fracture occurs.
Modulus of resilience is the indication of resilience property of solid material. By definition, modulus of resilience is the energy, per unit volume, required to deform a particular solid material up to its elastic limit under tensile testing.	Modulus of toughness is the indication of toughness property of solid material. By definition, modulus of toughness is the energy, per unit volume, required for breaking a particular solid material under tensile testing.
Modulus of resilience is the area below engineering stress-strain curve up to elastic point.	Modulus of toughness is the total area below engineering stress-strain curve.
Value of modulus of resilience is smaller.	Value of modulus of toughness is much larger than modulus of resilience.
Resilience is important property to consider when high elastic deformation is desired, such as in springs.	Toughness is important consideration for metal forming processes (forging, bending, sheet metal operations, etc.).

PAST YEARS QUESTIONS

1) State **FOUR (4)** types of stress. [4 marks]
2) Figure below shows a stress-strain diagram. Fill in the blank with suitable regions or point.



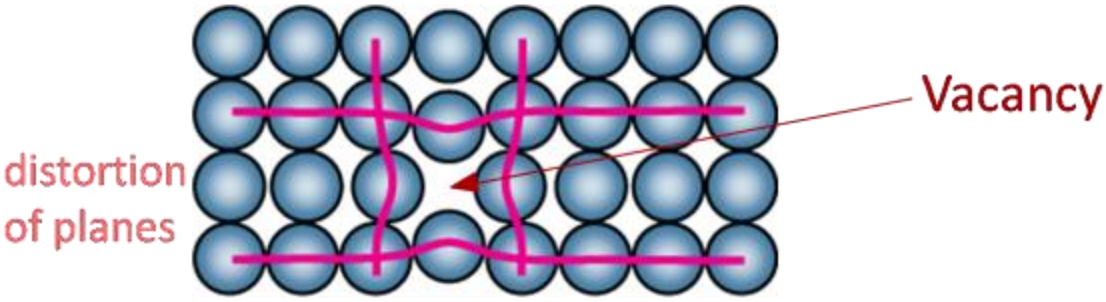
[4 marks]

3) List **FOUR (4)** types of material properties and state **ONE (1)** importance of materials properties for engineers. [4 marks]
4) List **THREE (3)** types of material failure. Then, briefly describe any **ONE (1)** of those three failures. [3 marks]
5) Creep is one of the factors of material failure. Explain the creep curve with the aid of graph strain versus time. [5 marks]
6) State the mechanical properties below;
    - i. Toughness
    - ii. Brittleness
    - iii. Ductility
    - iv. Elasticity
    - v. Strength

[5 marks]

CHAPTER 4

IMPERFECTIONS IN SOLIDS AND PHASE DIAGRAM



SYNOPSIS

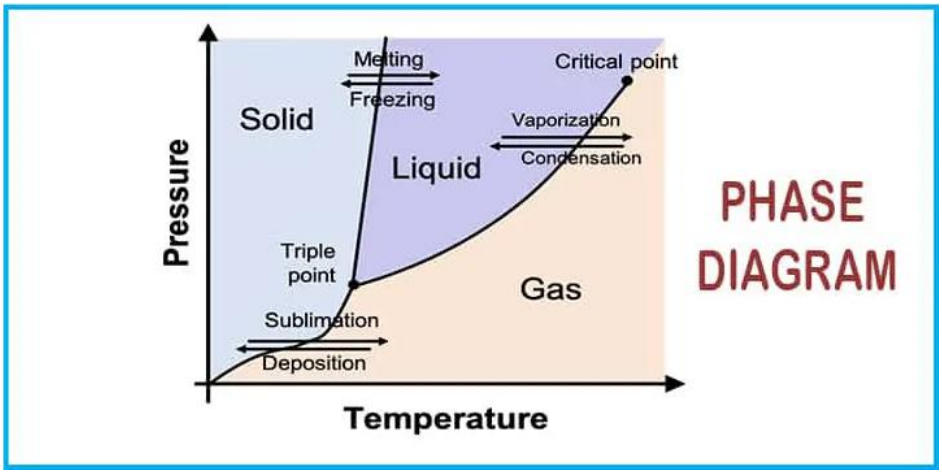
This topic explains solid solution and equilibrium phase for ferrous-carbon.

LEARNING OUTCOMES

4.1 Explain the impurities in solids
4.1.1 Terminology in solid solutions
4.1.2 Solid solutions
4.1.3 Substitutional solid solution
4.1.4 Interstitial solid solution

4.2 Define concepts in phase diagram
4.2.1 Solubility limits and phase equilibrium
4.2.2 Binary isomorphous systems
4.2.3 Interpretation of phase diagrams
4.2.4 Development of microstructure in isomorphous alloys

4.3 Examine the iron-carbon phase diagram
4.3.1 Iron-iron carbide (Fe-Fe3C) phase diagram
4.3.2 Development of microstructure in iron-carbon alloys
4.3.3 The influence of other alloying elements



4.1 THE IMPURITIES IN SOLIDS

4.1.1 Terminology in solid solutions

1. Solid solution is a solid–state solution of one or more solutes in a solvent
2. Solvent - substance in which the solute is dissolved
3. Solute - substance which is dissolved in a solvent
4. Solution - a homogenous mixture of two or more substances (Figure 4.1)

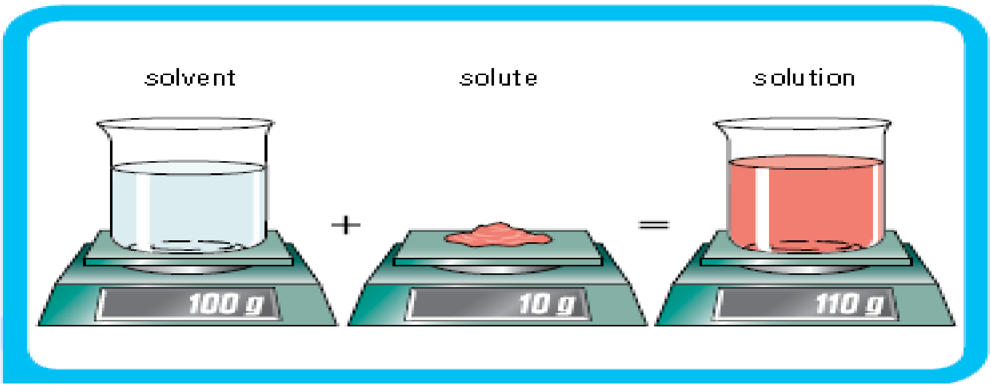


Figure 4.1 Solvent, solute, and solution

4.1.2 Solid solutions

In other words, when homogeneous mixtures of two or more kinds of atoms (of metals) occur in the solid state, they are known as **solid solutions.**

For example:

1. Much of the steel used in construction, for example, is actually a solid solution of iron and carbon. The carbon atoms, which fit neatly within the iron's crystal lattice, add strength to its structure.
2. Brass is a solid solution of copper (64%) and zinc (36%). In this case copper atoms are solvent atoms whereas zinc atoms are solute atoms.

Characteristic of solid solution

- Form when solute atoms are added to the host material
- Crystal structure is maintained
- No new structure formed
- Compositionally homogeneous

Types of solid solution

When two metals are mixed together they form an alloy if one metal is soluble in the other one in solid state. Therefore, an alloy is a solid solution of two or more metals. They are two types of solid solution:

a. Substitutional solid solution
b. Interstitial solid solution

4.1.3 Substitutional solid solution

Atoms of the parent metal (or solvent metal) are replaced or substituted by atoms of the alloying metal (solute metal) as shown in Figure 4.2.

In this case, the atoms of the two metal in the alloy, are almost similar size.

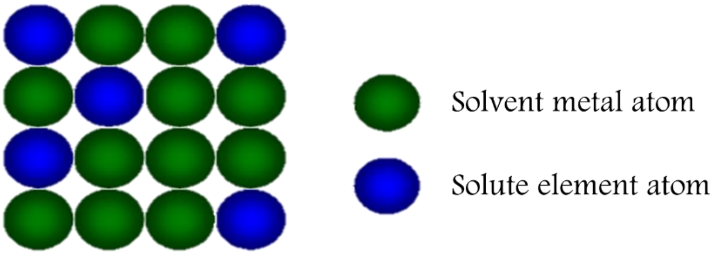


Figure 4.2 Substitutional solid solution

There are two types of substitutional solid solution:

- Disordered/randomly arrange: atomic particles (solute) take place of the main atoms (solvent) at random and haphazard arrangement.
- Ordered/Properly arrange: Atomic particles take place of the main atoms (solvent) and their arrangements are in order.

Figure 4.3 shown types of substitutional solid solution.

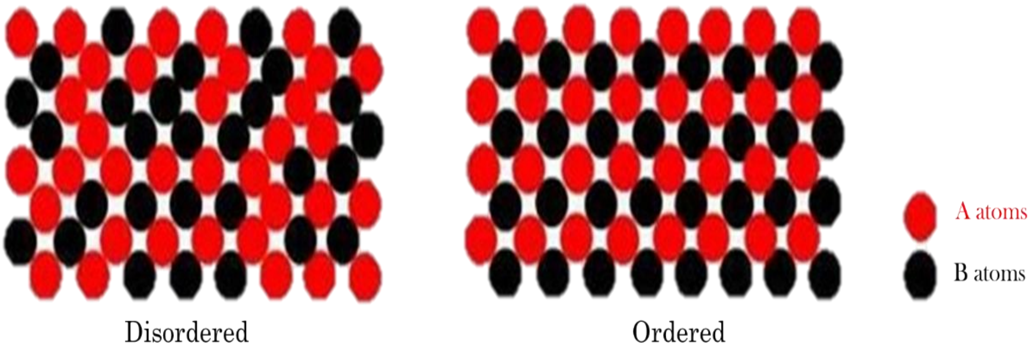


Figure 4.3 Types of substitutional solid solution

4.1.4 Interstitial solid solution

The atoms of the parent or solvent metal are bigger than the atoms of the alloying or solute metal. In this case, the smaller atoms fit in between the larger atoms (Figure 4.4).

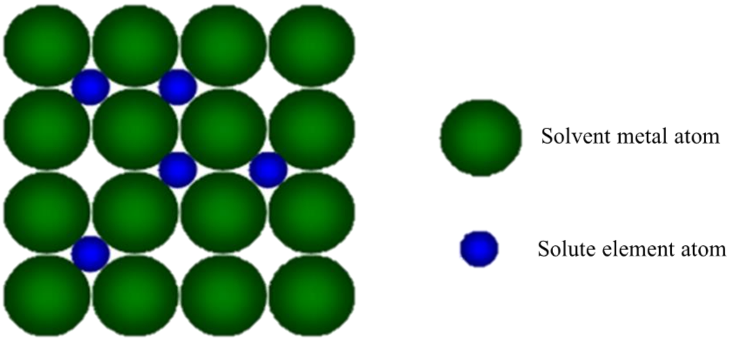


Figure 4.4 Interstitial solid solution

4.2 CONCEPT OF PHASE DIAGRAM

4.2.1 Solubility limits and phase equilibrium

a. Equilibrium may be defined as a state of balance of stability.
b. Phase is a portion of a system that has uniform physical and chemical characteristics.
c. Phase diagram is a graphical representation of the physical states of a substance under different conditions of temperature and pressure.
d. A typical phase diagram has pressure on the y-axis and temperature on the x-axis.
e. Solubility Limit: Maximum concentration for which only a single-phase solution exists.
f. Typically, a phase diagram, displays the phases (solid, liquid, and gas) of a substance graphically as shown figure 4.5.

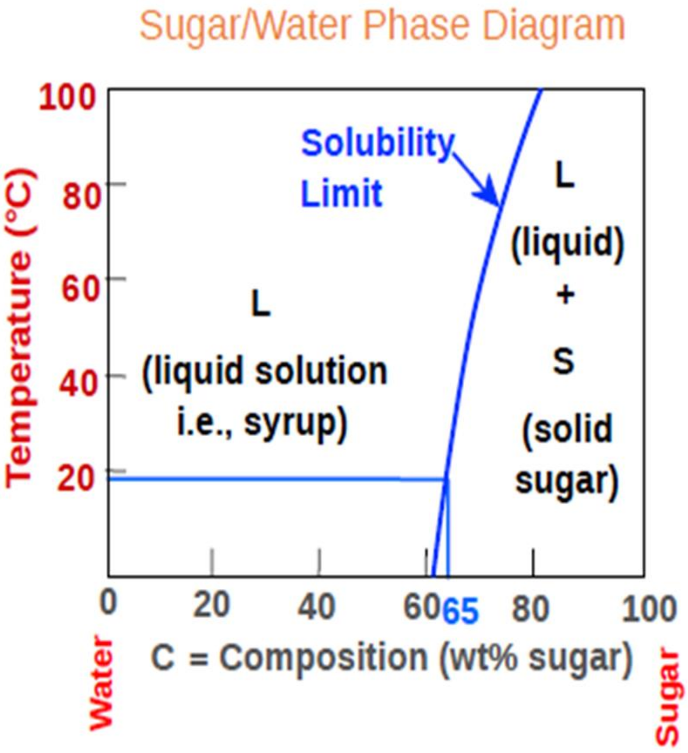


Figure 4.5 Sugar/water phase diagram

4.2.2 Binary isomorphous systems

a. A binary alloy contains two components; however, a ternary alloy contains three components.
b. A mixture of two metals is called binary alloy. In binary metallic systems, the two elements are completely soluble in each other in both liquid and solid states.
c. This very simple case is one complete liquid and solid solubility, an isomorphous system. The example is the Cu-Ni alloy.
d. 3 contributing factors of this complete solubility occurs because (1) both Cu and Ni have the same crystal structure (FCC), (2) the atomic radii of Cu & Ni nearly identical, (3) Both Cu & Ni have similar electronegativity and valence.
e. At temperature below 1080 °C, Cu and Ni are mutually soluble in each other in the solid state for all compositions
f. The Cu-Ni system is termed isomorphous because of this complete liquid and solid solubility of the two components

The figure 4.6 shows Cu-Ni Binary alloy phase diagram.

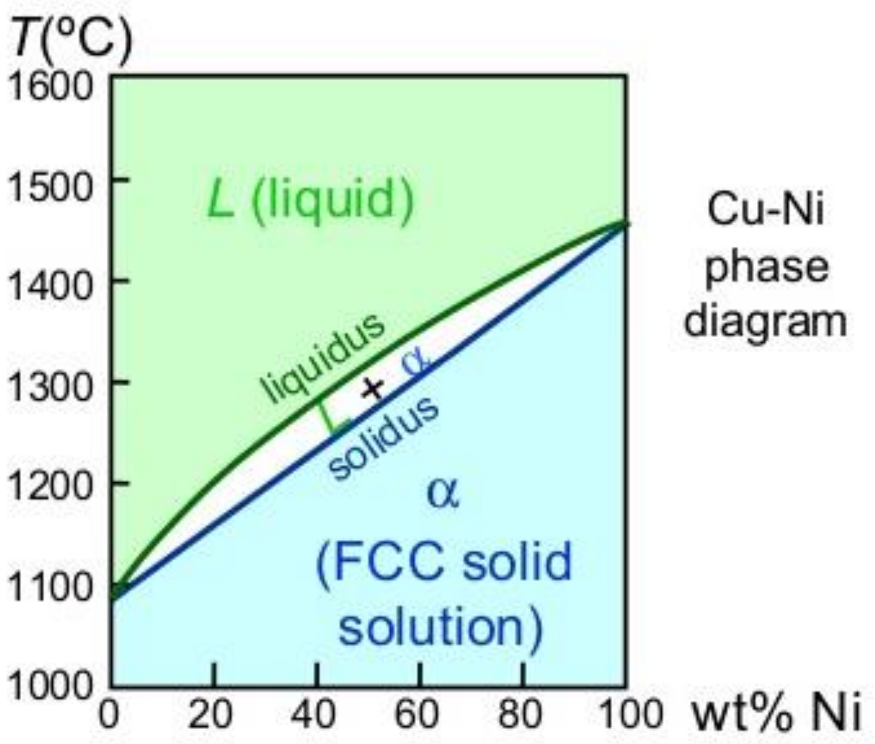


Figure 4.6 Cu-Ni Binary alloy phase diagram

4.2.3 Interpretation of phase diagrams

The temperature is plotted on y-axis and the composition of the alloy is on the x-axis. The pressure is assumed to be constant. The left edge of the phase diagram represents pure copper (Cu= 100%, Ni =0%) while the right edge represents pure nickel (Cu= 0%, Ni= 100%). Both edges indicate the melting points of copper and nickel respectively. For all other points than these two edges, the system is a mixture of copper and nickel. The composition of the alloy could be in the percentage of weight, atomic, or mole fraction. Figure 4.7 shows Cu-Ni Binary alloy phase diagram.

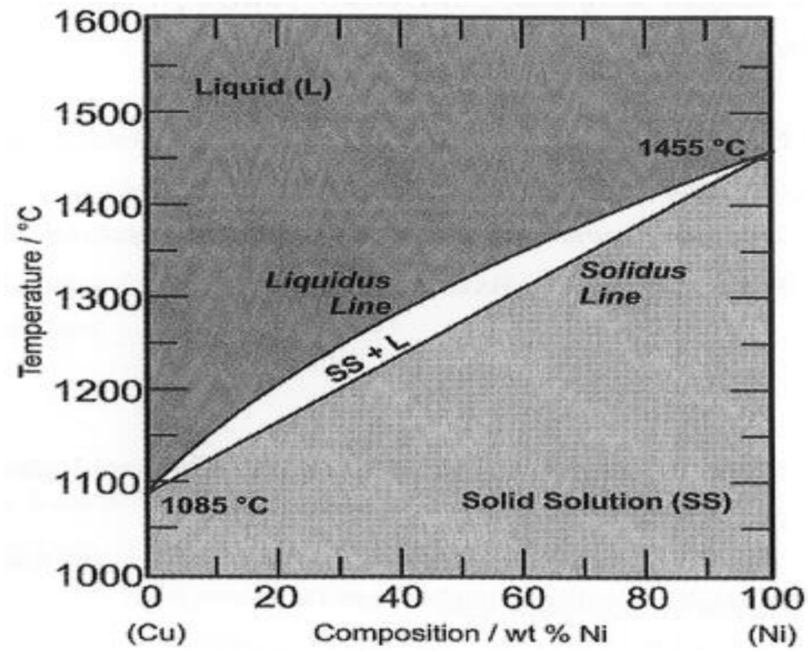


Figure 4.7 Cu-Ni Binary alloy phase diagram

For a given temperature and composition we can use phase diagram to determine:

- The phases that are present
- Compositions of the phases
- The relative fractions of the phases

The phase is separated by the lines called phase boundaries. There are two phase boundaries in this phase diagram:

- Liquidus: separating the liquid phase region (L) from the two-phase region (L+ɑ̣).
- Solidus: separating the two phase religion (L+ ɑ̣) from the single phase solid region (a).

There are three different phases appear in the copper-nickel phase diagram:

- Liquid phase (L) : homogeneous liquid solution consists copper and nickel.
- Two phases (L+ ɑ̣) : Liquid solution mixed with a (FCC solid solution of copper and nickel).
- Solid phase (ɑ̣) : ɑ̣ phase of FCC substitutional solid solution consists both copper and nickel.

4.2.4 Development of microstructure in isomorphous alloys

Fast (non-equilibrium) cooling

Compositional changes require diffusion in solid and liquid phases. Diffusion in the solid state is very slow. The new layers that solidify on top of the existing grains have the equilibrium composition at that temperature but once they are solid their composition does not change. Formation of layered (cored) grains and the invalidity of the tie-line method to determine the composition of the solid phase. Upon heating grain boundaries will melt first. This can lead to premature mechanical failure. Figure 4.8 shows the schematic representation of the development of microstructure during nonequilibrium of a 35wt% Ni-65 wt% Cu alloy.

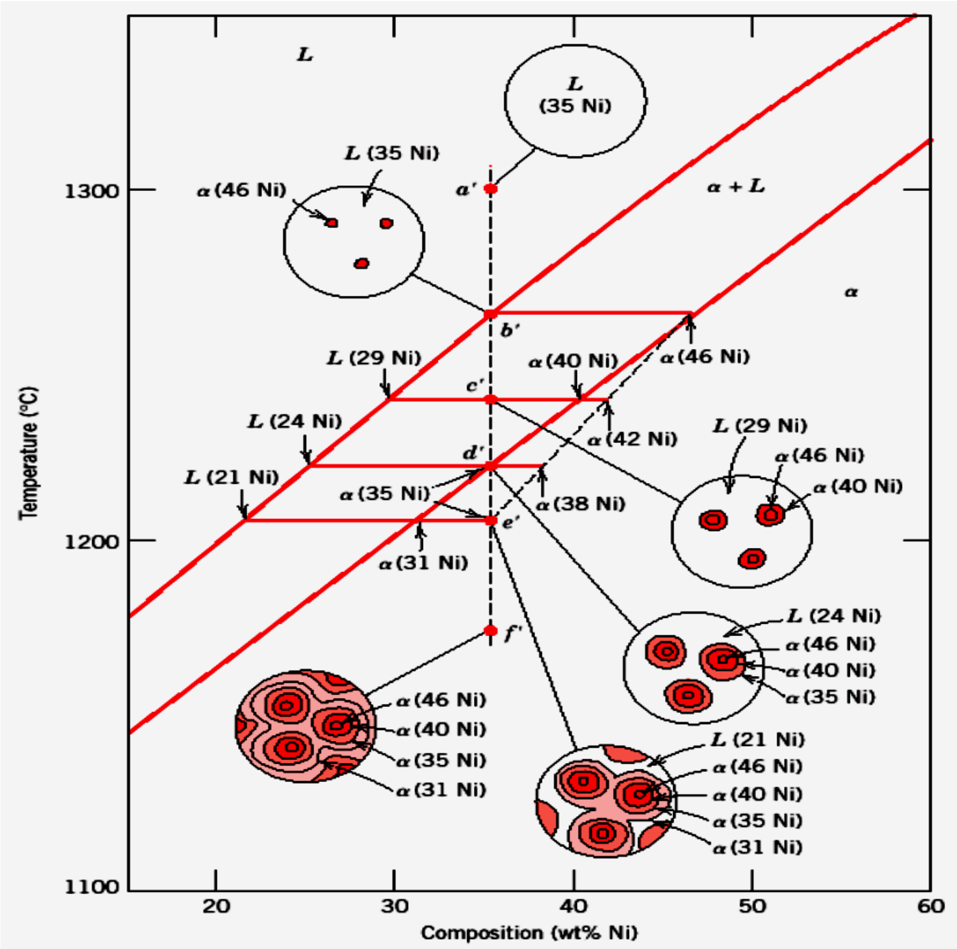


Figure 4.8 Schematic representation of the development of microstructure during nonequilibrium of a 35wt% Ni-65 wt% Cu alloy.

4.3 THE IRON-CARBON PHASE DIAGRAM

4.3.1 Iron-iron carbide (Fe-Fe3C) phase diagram

In their simplest form, steels are alloys of Iron (Fe) and Carbon (C). The Fe-C phase diagram is a fairly complex one, but we will only consider the steel part of the diagram, up to around 7% carbon. Figure 4.9 shows the iron carbide phase diagram.

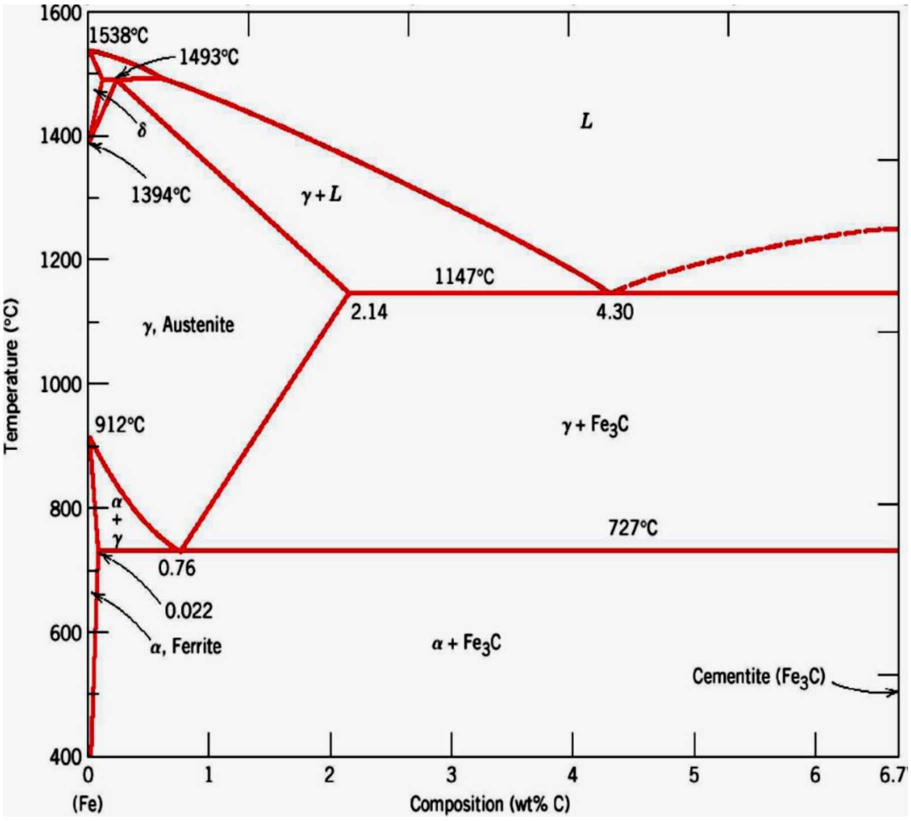


Figure 4.9 The iron carbide phase diagram

4.3.2 Development of microstructure in iron-carbon alloys

Several of the various microstructures that maybe produced in steel alloys and their relationships to the iron - iron carbon phase diagram is now discussed, and it is shown that the microstructure that develops depends on both the carbon content and heat treatment. This discussion is confined to very slow cooling of steel alloys, in which equilibrium is continuously maintained. Consider, for example, an alloy of eutectoid composition (0.76 wt% C) as it is cooled from a temperature within the γ phase region, say, 800 ℃ - that is, beginning at point a. No changes will occur until the eutectoid temperature (727 ℃) is reached. Upon crossing this temperature to point b, the austenite transforms according to equation.

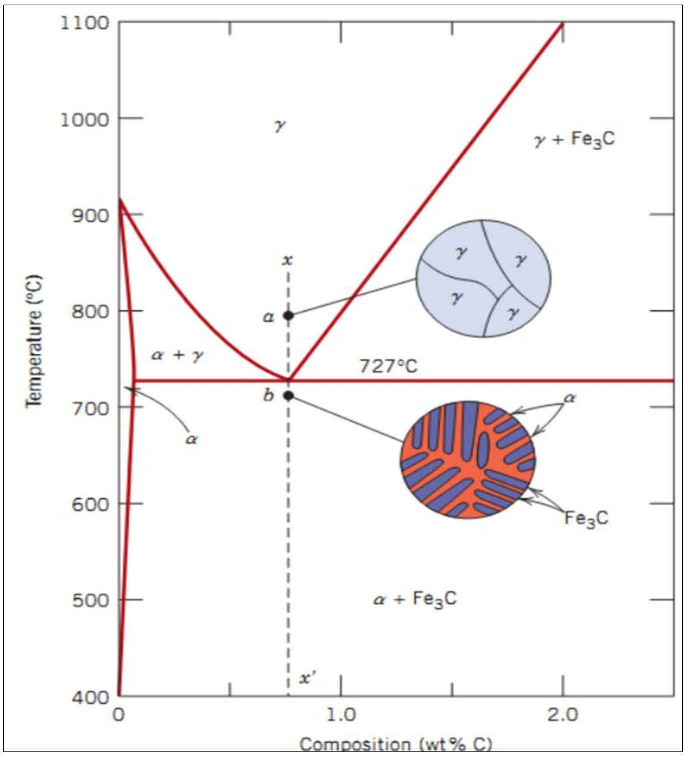


Figure 4.10 Schematic representation of the microstructures for an iron-carbon alloy of eutectoid composition (0.76 wt% C) above and below the eutectoid temperature.

The microstructure for this eutectoid steel that is slowly cooled through the eutectoid temperature consists of alternating layers or lamellae of the two phases (α and Fe3C) that form simultaneously during the transformation. Figure 4.10 shows a schematic representation of the microstructures for an iron-carbon alloy of eutectoid composition (0.76 wt% C) above and below the eutectoid temperature. This microstructure, represented at point b, is called Pearlite. The thick light layers are the ferrite phase, and the cementite phase appears as thin lamellae most of which appear dark.

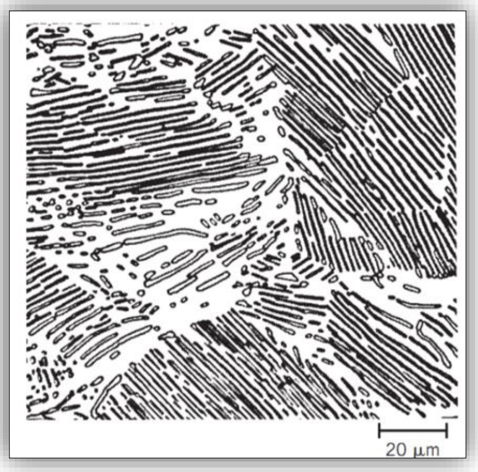


Figure 4.11 Photomicrograph of a eutectoid steel showing the pearlite microstructure

Microstructures for iron–iron carbide alloys other than the eutectoid composition are now explored; these are analogous to the fourth case described in the eutectic system. Consider a composition C0 to the left of the eutectoid, between 0.022 and 0.76 wt % C; this is termed a hypoeutectoid (less than eutectoid) alloy. At about 875℃, point c, the microstructure will consist entirely of grains of the γ phase in cooling to point d, about 775℃, which is within the α + γ phase region, both these phases will coexist as in the schematic microstructure. Most of the small α particles will form along the original γ grain boundaries. Figure 4.11 shows the photomicrograph of a eutectoid steel showing the pearlite microstructure.

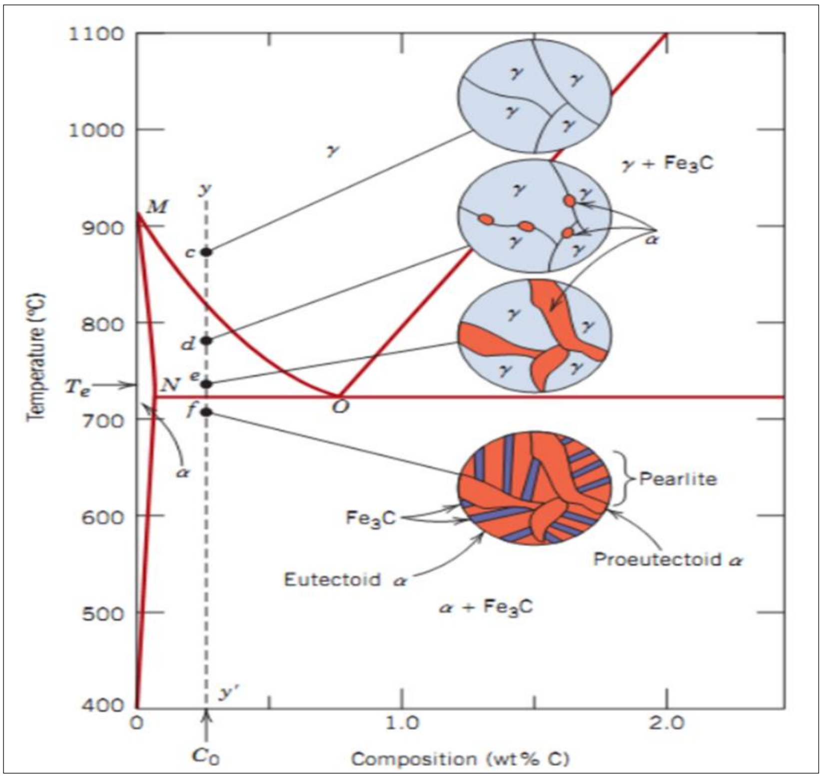


Figure 4.12 Schematic representation of the microstructures for an iron-carbon alloy of hypo eutectoid composition.

The compositions of both α and γ phases may be determined using the appropriate tie line; these compositions correspond, respectively, to about 0.020 and 0.40 wt.% C.

Cooling from point d to e, just above the eutectoid but still in the α+γ region, will produce an increased fraction of the α phase and a microstructure similar to that also shown: the α particles will have grown larger (Figure 4.12).

As the temperature is lowered just below the eutectoid, to point f, all the γ phase that was present at temperature Te (and having the eutectoid composition) will transform to Pearlite, according to the reaction in Eutectoid Equation.

The ferrite that is present in the Pearlite is called eutectoid ferrite, whereas the other, that formed above Te, is termed Proeutectoid (meaning “pre – or before eutectoid”) ferrite.

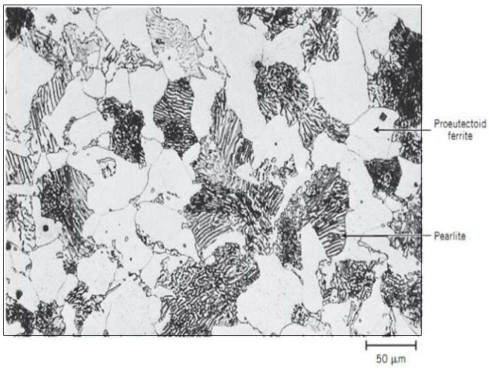


Figure 4.13 Photomicrograph of a 0.38% C steel having a microstructure consisting of pearlite and proeutectoid ferrite.

Analogous transformations and microstructures result for hypereutectoid alloys, those containing between 0.76 wt.% C and 2.14 wt.% C, which are cooled from temperatures within the γ phase field. Consider an alloy of composition C1. At point g only the γ phase will be present with a composition of C1. Upon cooling into the α+Fe3C phase field - say, to point h – the cementite phase will begin to form along the initial γ grain boundaries. This cementite is called proeutectoid cementite that which forms before the eutectoid reaction. Figure 4.13 shown photomicrograph of a 0.38% C steel having a microstructure consisting of pearlite and proeutectoid ferrite.

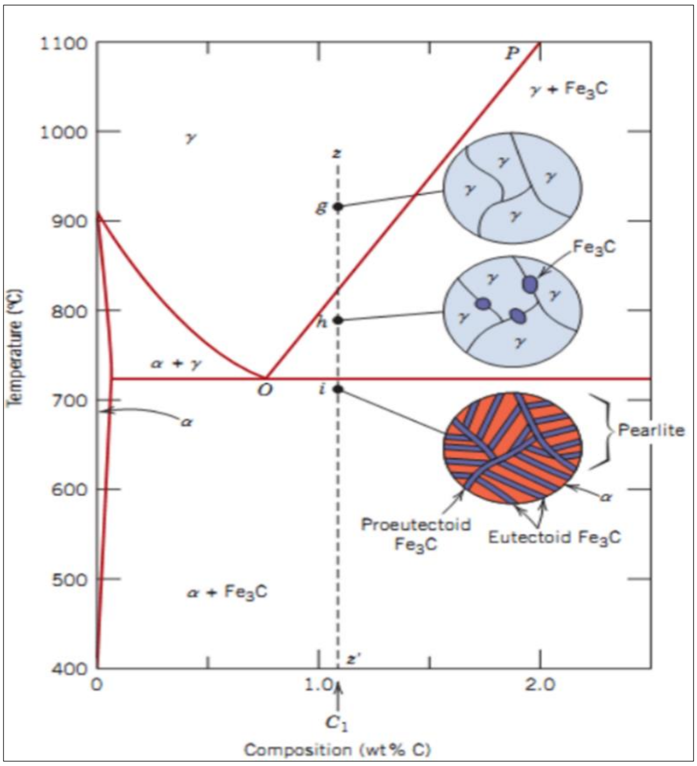


Figure 4.14 Schematic representation of the microstructures for an iron-carbon alloy of hyper eutectoid composition.

The cementite composition remains constant (6.70 wt% C) as the temperature changes. However, the composition of the austenite phase will move along line PO toward the eutectoid. As the temperature is lowered through the eutectoid to point i, all remaining austenite of eutectoid composition is converted into Pearlite; thus, the resulting microstructure consists of Pearlite and proeutectoid cementite as micro constituents. Figure 4.14 shows a schematic representation of the microstructures for an iron-carbon alloy of hyper eutectoid composition.

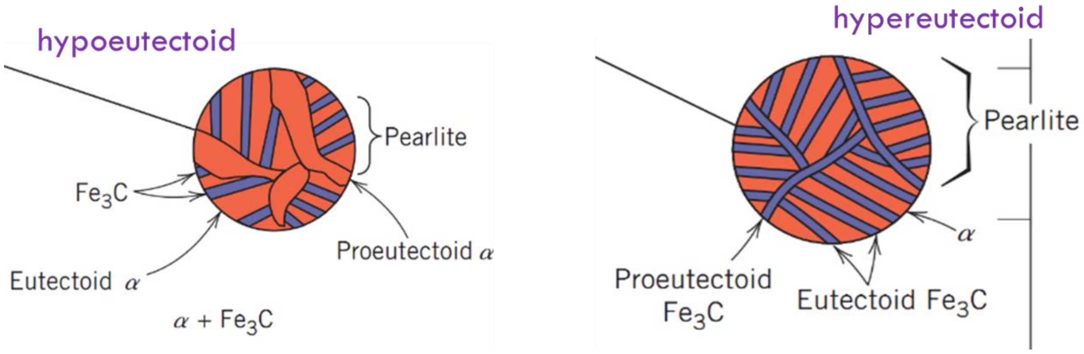


Figure 4.15 Schematic representation of the microstructures for an iron-carbon alloy of hypo eutectoid hyper eutectoid composition.

Because it has much the same appearance as proeutectoid ferrite, there is some difficulty in distinguishing between hypoeutectoid and hypereutectoid steels on the basis of microstructure (Figure 4.16).

Figure 4.16 Photomicrograph of a 1.4 wt.% C steel having a microstructure consisting of a white proeutectoid cementite network surrounding the pearlite colonies.

IRON CARBON PHASE DIAGRAM DEFINITION

Ferrite

Ferrite or alpha iron (α-Fe) is a weak solid solution of carbon in body centered cubic iron. The maximum solubility of carbon is 0.03% at 723°C and dropped at room temperature. Ferrite is a ductile material, soft and have low strength (Figure 4.17).

Figure 4.17 Photomicrograph of ferrite

Pearlite

Pearlite is lamellar (or layer) structure between ferrite and cementite which eutectoid composition is 0.83%C and 99.17% Fe (Figure 4.18).

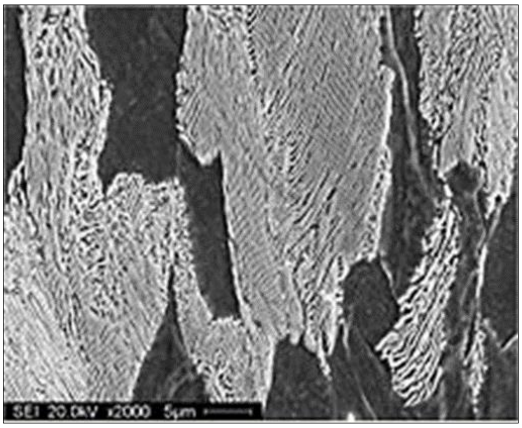


Figure 4.18 Photomicrograph of pearlite

Austenite

Austenite, also known as gamma phase iron, is a solid solution of carbon in the face-centered cube and the solubility of iron is quite high compared to ferrite (Figure 4.19). The maximum solubility of carbon is 1.7% at 1130°C and this is the maximum solubility limit for plain carbon steels. Nevertheless, solubility of carbon in excess of 1.4% is rare in practice.

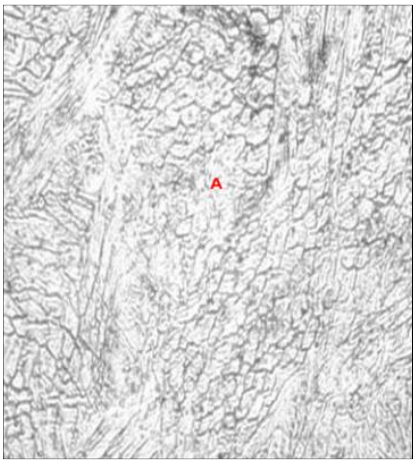


Figure 4.19 Photomicrograph of austenite

Cementite

Cementite, also known as iron carbide, is a chemical compound of iron and carbon, with the formula Fe3C (or Fe2C: Fe). By weight, it is 6.67% carbon and 93.3% iron. It is a hard, brittle material (Figure 4.20).

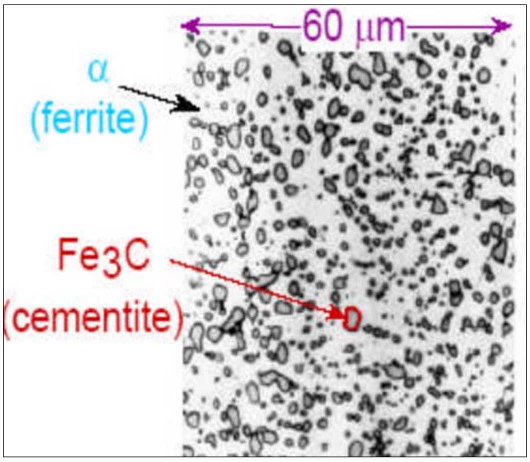


Figure 4.20 Photomicrograph of cementite

4.3.3 The influence of other alloying elements

Manganese

Slightly increases the strength of ferrite, and also increases the hardness penetration of steel in the quench by decreasing the critical quenching speed.

Chromium

Has a tendency to increase hardness penetration, toughness of steel, as well as the wear resistance.

Silicon

Increases tensile and yield strength, hardness, forge ability and magnetic permeability.

Nickel

Increases strength and hardness without sacrificing ductility and toughness. It also increases resistance to corrosion and scaling at elevated temperatures when introduced in suitable quantities in high-chromium (stainless) steels.

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

Increases strength, wear resistance, hardness and toughness. Tungsten steels have superior hot-working and greater cutting efficiency at elevated temperatures.

Copper

The addition of copper in amounts of 0.2 to 0.5 percent primarily improves steels 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 behaviour 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.

Cobalt

Increases strength and hardness and permits higher quenching temperatures and increases the red hardness of high speed steel. It also intensifies the individual effects of other major elements in more complex steels.

Columbium

Used as stabilizing elements in stainless steels. Each has a high affinity for carbon and forms carbides, which are uniformly dispersed throughout the steel. Thus, localized precipitation of carbides at grain boundaries is prevented.

Phosphorus

Increases strength and hardness and improves machinability. However, it adds marked brittleness or cold-shortness to steel.

Sulphur

Improves machinability in free-cutting steels, but without sufficient manganese it produces brittleness at red heat. It decreases weldability, impact toughness and ductility.

Tantalum

Used as stabilizing elements in stainless steels. Each has a high affinity for carbon and forms carbides, which are uniformly dispersed throughout the steel. Thus, localized precipitation of carbides at grain boundaries is prevented.

DISCUSSION QUESTIONS

QUESTION 1

A solid solution is a uniform mixture of two crystalline solids that share a common crystal lattice.

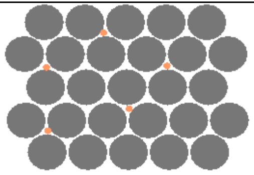
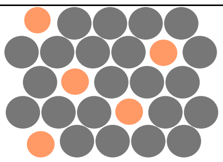
(i) Write TWO (2) types of solid solution

ANSWER

- Interstitial solid solution
- Substitutional solid solution

(ii) Examine the differences between TWO (2) types of the solid solution mentioned above.

ANSWER

Interstitial Solid Solution	Substitutional Solid Solution
The atoms of the parent or solvent metal are bigger than the atoms of the alloying or solute metal. In this case, the smaller atoms fit in between the larger atoms.	Atoms of the parent metal (or solvent metal) are replaced or substituted by atoms of the alloying metal (solute metal).
 e.g., Cu in Ni	 e.g., C in Fe

QUESTION 2

Based on the Cu-Ni phase Diagram in Figure 1, answer the following question:

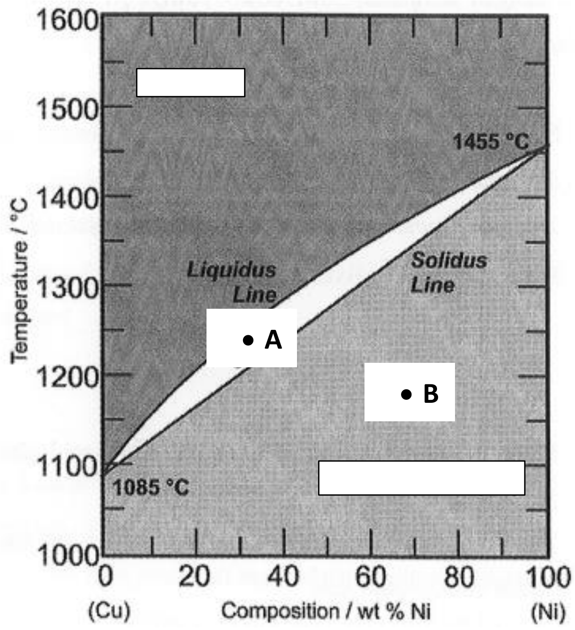


Figure 1

i. Show the type of phases present in A and B. [2 marks]

ii. Show the composition of those phases in A and B. [2 marks]

iii. For an alloy of composition 50wt% Ni-50wt% Cu, show the phase of those phases at 1150°C, 1300°C and 1450°C. [3 marks]

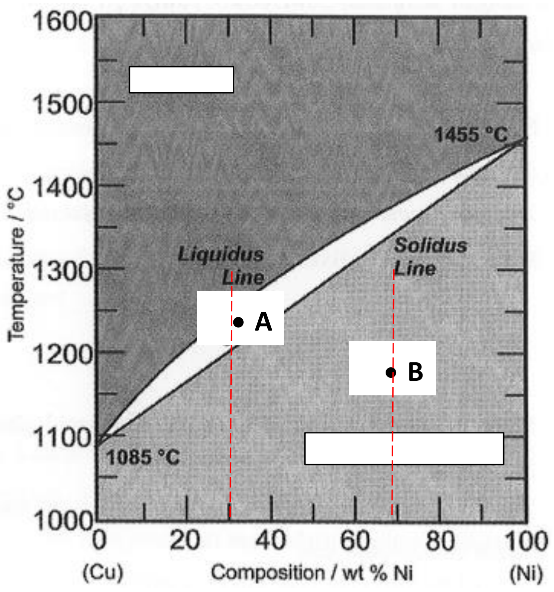
ANSWER

i. The type of phases presents in A & B

Phases for A: Solid solution + Liquid

Phases for B: Solid Solution

ii. The composition of those phases A and B



The composition phases A:30wt%Ni-70wt%Cu

The composition phases B:70wt%Ni-30wt%Cu

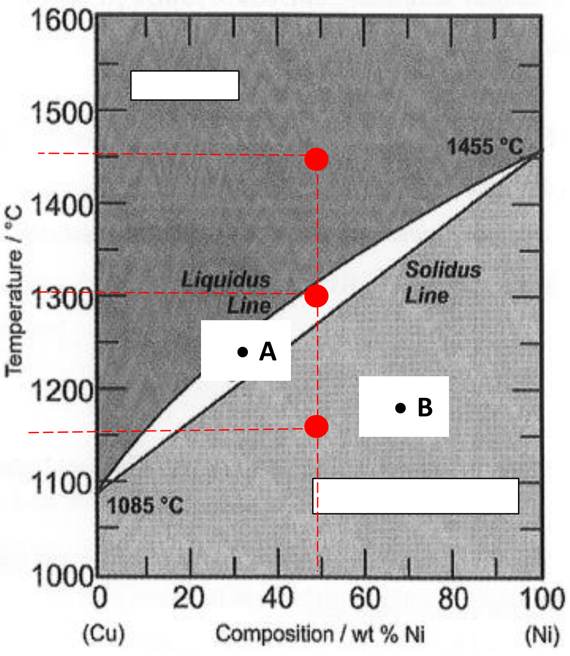
iii. For an alloy of composition 50wt% Ni-50wt% Cu, the phase of those phases at 1150°C, 1300°C and 1450°C.

Phases at

1150°C: Solid Solution

1300°C: Solid Solution + Liquid

1450°C: Liquid



PAST YEARS QUESTIONS

1. With the aid of a diagram, explain the atomic arrangement of the Substitutional and Interstitial Solid Solution

2. Figure 1 below shows the Copper-Nickel phase diagram;

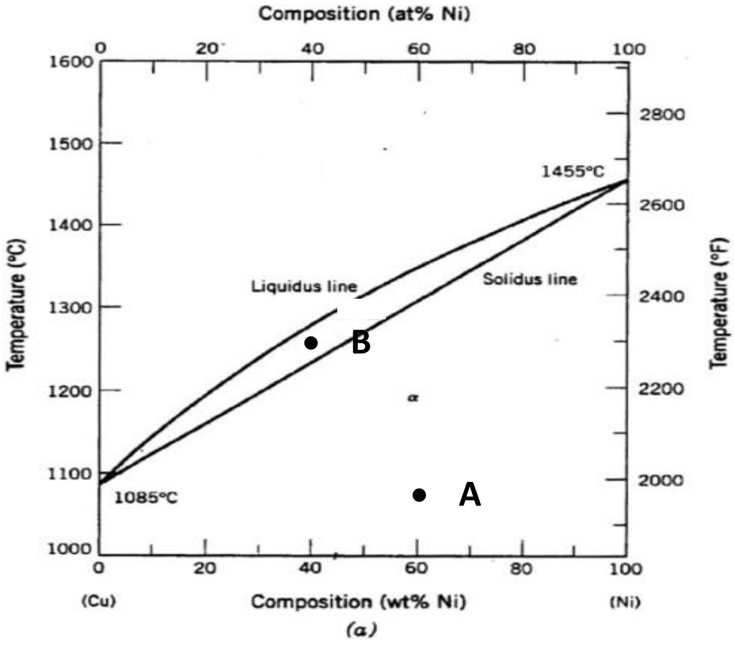


Figure 1

a. Write down THREE (3) information that can be obtained from equilibrium phase diagram [3 marks]

b. Show the temperature for liquidus phase at 30% Ni -70% Cu by sketching a phase diagram. [3 marks]

c. Assign the compositions of the solid and liquid phases at 1300°C in a phase diagram. [3 marks]

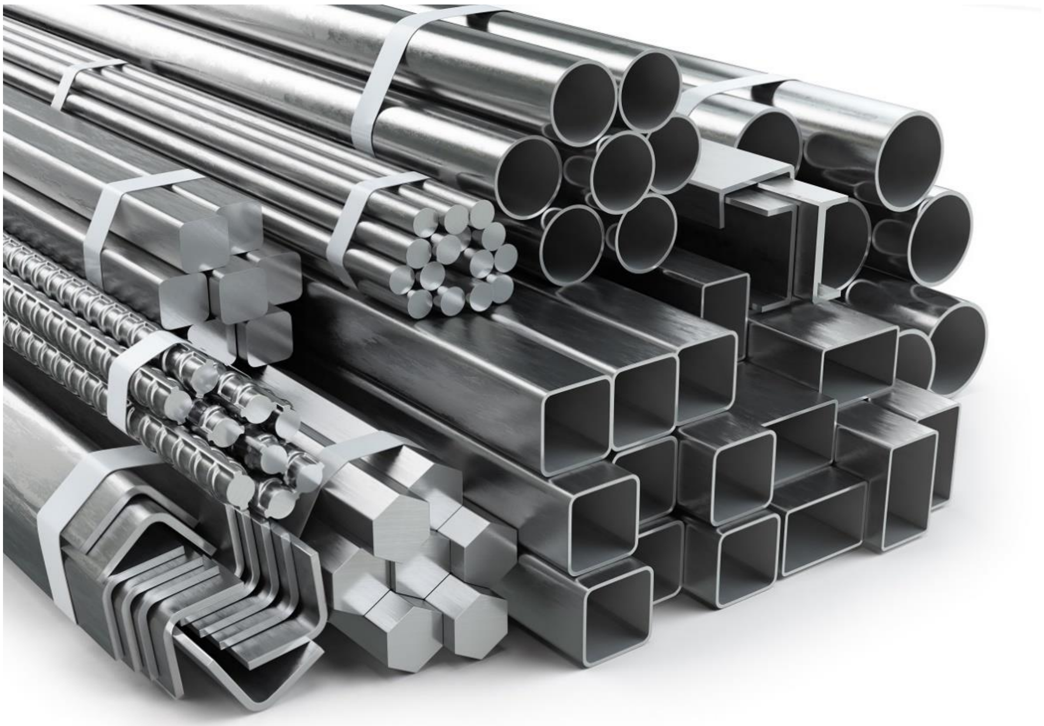
d. Interpret the type of phases present in A and B [2 marks]

e. Interpret the composition of those phases present in A and B [2 marks]

f. For an alloy of composition 60 wt% Ni-40 wt% Cu, show phase of the phases at 1100°C and 1300°C. [2 marks]

CHAPTER 5

APPLICATION & TYPES OF METAL ALLOYS



SYNOPSIS

This topic describes the characteristics and application of ferrous alloys and nonferrous alloys.

LEARNING OUTCOMES

Applications and Types of Metal Alloys

5.1 Explain the ferrous alloys and its application
  - a. Steels
  - b. Cast irons

5.2 Acquire the common types of non-ferrous alloys and its application
  - a. Copper and its alloys
  - b. Aluminium and its alloys
  - c. Magnesium and its alloys
  - d. Titanium and its alloys
  - e. Others non-ferrous alloys
    - i. Refractory metals
    - ii. Nickel
    - iii. Zirconium

5.1 EXPLAIN THE FERROUS ALLOYS AND ITS APPLICATION

Definition

A ferrous metal is any metal that is primarily composed of iron and has magnetic properties. A ferrous metal is known for its hardness, durability and tensile strength. Some common ferrous metals include:

- Alloy steel
- Carbon steel
- Cast iron
- Wrought iron

Non-ferrous metal is a metal does not contain iron, not magnetic, more corrosion resistance, more malleable than ferrous metals, and is much lighter and have a higher resistance to rust and corrosion.

Non-ferrous metals include aluminum, copper, lead, zinc and tin, as well as precious metals like gold and silver and etc. Comparison between ferrous and non-ferrous metal is tabulated in Table 5.1.

Table 5.1 Comparison ferrous and non-ferrous metal

Ferrous metal	**Non-Ferrous metal**
Contains any amount of iron as its basic form	Does not contains any amount of iron in its basic form
Possess magnetic property and makes them prone to corrosion	They do not possess magnetic property, but resist corrosion: much better than ferrous metals
They have a high tensile strength since they carry a high amount of strain	They have very low tensile strength
Ability for oxidation, known as corrosion	Lighter weight, higher melting points, basically resistant to corrosion
Typically used when the magnetic attraction of iron may be disadvantages	Ideal for electronic & electrical applications
Ex: iron, steel, cast iron, alloy steel	Example: Aluminum, copper, titanium

a. Steels

Steel is an alloy of iron and carbon in which the carbon content ranges up to 2 percent. If it has a higher carbon content, the material is defined as cast iron. By far the most widely used material for building the world's infrastructure and industries, it is used to fabricate everything from sewing needles to oil tankers. In addition, the tools required to build and manufacture such articles are also made of steel.

Most common steels are classified according to the carbon concentration of other alloying elements' low, medium and high carbon types. Subclasses also exist according to the concentration of other alloying elements such as plain carbon steel and alloy steels.

Low Carbon Steel

- Low carbon steel or mild steel
- Containing carbon below 0.3% responds to heat treatment as an improvement in the ductility is concerned but has no effect in respect of its strength properties.

Properties:

- Relatively soft and weak
- Outstanding ductility
- Outstanding toughness
- Machinable and weldable
- Least expensive

Application

- rivet, wire, nails, nut, bolts, boiler-plates, ship-plates, reinforcing bar, pipelines, etc

Medium Carbon Steel

- Have between 0.3 and 0.6% carbon.
- Special Advantages
- Balance ductility and strength
- Good wear resistance
- Good toughness and ductility. Enough carbon to be quenched to form martensite and bainite (if the section size is small)

- A good balance of properties can be found.
- Extremely popular and have numerous applications.
- Fair formability
- Responds to heat treatment but is often used in the natural condition.

Application

- lead screws, gears, worms, spindles, shafts, and machine parts, crankshafts, gears, mandrels, tool shanks, and heat-treated machine parts.

High Carbon Steels

- Carbon contain: 0.60 wt.% - 1.4 wt.%
- Offer better responses to heat treatment and longer service life than medium carbon steel and extremely strong yet more brittle.
- Properties:
- high hardness
- high strength
- good wear resistance low ductility

Applications:

- punches for metal, rock drills, shear blades, rivet sets, High strength wires and many hand tools.

High Alloy Steel

Stainless Steel

- The corrosion resistance of stainless steels is due to their high chromium contents, at least 11% chromium.
- Chromium or nickel forms an oxide layer which protects the underlying steel alloy from corroding

Properties:

- Highly resistant to corrosion (rusting) in a variety of environments.
- Moderate ductility and formability.

Applications:

- Springs, knives, automotive exhaust components, pressure vessels etc.

b. Cast irons

Cast irons are a class of ferrous alloys with carbon contents in the range of 1.8% to 4.5% in addition, to other alloying elements (Silicon, Manganese, Sulphur etc). While the pig iron that forms the basis for cast iron is being melted, scrap iron and steel are often thrown into the mix.

Types of cast irons:

i. Grey cast iron
ii. White Cast Iron
iii. Nodular Cast Iron
iv. Malleable Cast Iron

Grey cast iron (Figure 5.1)

- Slow cooling rate
- Shows a grey surface on the fracture
- Large amounts of carbon in the form of graphite flakes
- Carbon contains 2-4%

Properties

- Higher Silicon content
- Easy to machine
- Have good wear resistance
- High compressive strength
- Application: gearboxes, base plates, bearing brackets

Figure 5.1: Photomicrograph of Grey iron: the dark graphite flakes are embedded in an -ferrite matrix

White Cast Iron (Figure 5.2)

- Rapid cooling rate
- Shows a white fractured surface
- Carbon contains 1.8-3.6%
- Lower Silicon content

It contains large amounts of iron carbide causing:

- Hard
- White in colour
- Wear resistance
- Tough to machine

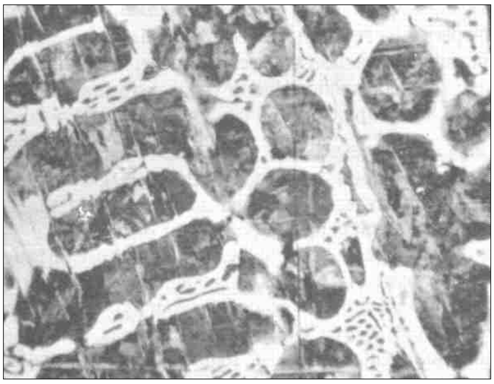


Figure 5.2 Photomicrograph of white cast iron

Malleable Cast Iron

Malleable cast iron (Figure 5.3) is produced from white cast iron (Figure 5.4), which is made from hot liquid iron with certain chemical components. It is formed when white cast iron is heated to around 1000◦ C and then left to cool very slowly. Compared with grey cast iron, malleable cast iron has better strength and ductility, especially better impact resistance in low temperatures. Application: Automotive parts and tractor

Are divided into two type:

- White malleable Cast iron
- Black Malleable Cast Iron

White malleable cast iron produced: -

- White cast iron wrapped in a container with an iron ore
- It is slowly heated to a temperature between 950-1000 C

- It is left for 4-5 days before being slowly cooled
- Carbon with nodular shapes/spheres is formed (Figure 5.3)

Black malleable cast iron produced:

- White cast iron wrapped in a container with a sand/slag
- It is slowly heated to a temperature between 950◦C-1000◦C
- It is left for 4-5 days before being slowly cooled
- Carbon with a rosettes shape is formed (Figure 5.4).

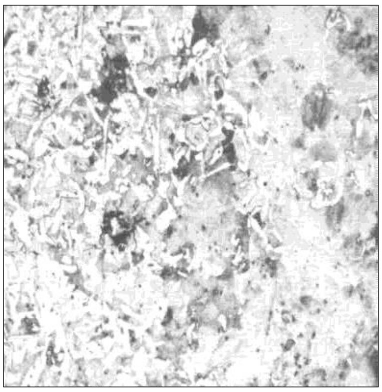


Figure 5.3 Photomicrograph of malleable cast iron

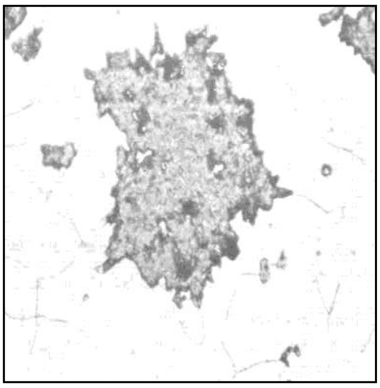


Figure 5.4 Photomicrograph of white cast iron

Nodular Cast Iron/Ductile Iron

- Containing large amounts of carbon in the form of graphite nodules (spheres) instead of flakes as in the case of grey cast iron. Figure 5.5 shows the photomicrograph of nodular cast iron.

Properties:

- Has a strength much higher than grey cast iron and close to steel
- High in toughness and ductility
- Can be welded and machined

- Graphite balls formed from solidified or chilled processes, not from heat treatment process as grey cast iron

Application:

- automotive parts (piston, crankshafts, gears),
- dies (punch dies, sheet metal dies)

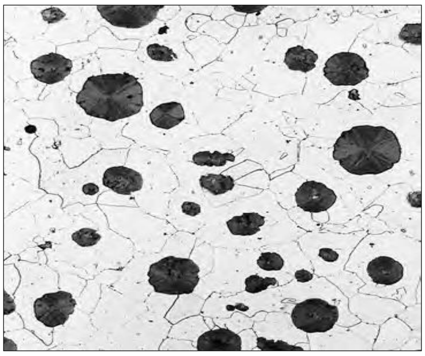


Figure 5.5 Photomicrograph of nodular cast iron

5.2 NON-FERROUS ALLOYS AND ITS APPLICATION

COPPER & ITS ALLOY

Copper (Cu)

- atomic weight 63.546
- is soft, malleable and ductile metal
- high thermal and electrical conductivity.

The mechanical and corrosion resistance properties – improved by alloying.

- Copper alloys have electrical and mechanical properties, corrosion resistance, thermal conductivity and wear resistance.

Application are electronic components, springs and heat exchanger.

Most copper alloys:

Brass

- Brass is an alloy of copper and zinc (Cu & Zn)
- Brass is a low-friction, soft, non-ferrous metal that is easily drilled, machined, sawed, and punched. It is an excellent choice for applications in which corrosion resistance is important.

Application:

- costume jewellery, automotive radiators, musical instrument, electronic packaging, coin, etc.

Most copper alloys:

- Bronze – is an alloy of copper and stanum (Cu & Sn)
- Strong than brass, high corrosion resistance.

Application:

- bearing, gears, spring, clutch disks, etc.

Figure 5.6 represents the differences between brass and bronze.

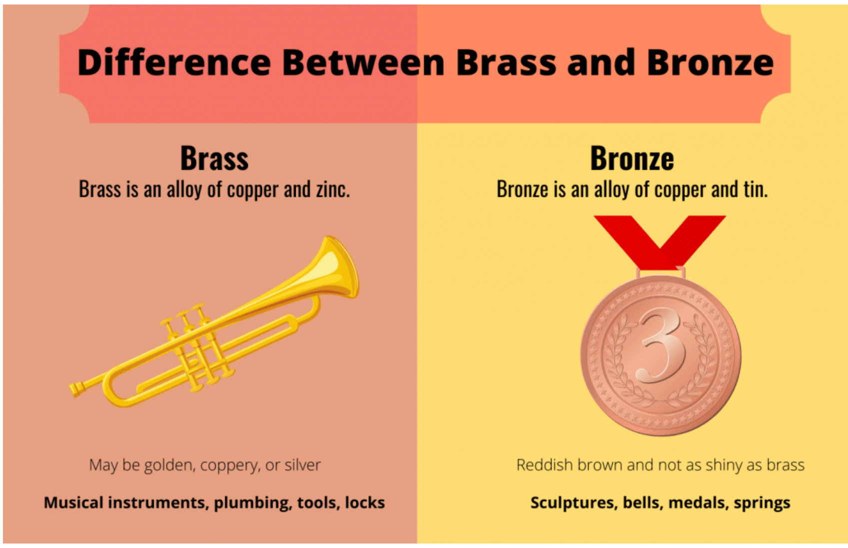


Figure 5.6 Difference between brass and bronze

ALUMINIUM & ITS ALLOYS

Properties:

- high electrical & thermal conductivities
- good corrosion resistance
- high ductility
- low density (refer Periodic Table)
- Limitation – low melting temperature (660°C); restrict the maximum temperature at which it can be used.
- Alloying – enhanced the mechanical strength of pure Aluminium
- Elements: Cu, Mg, Si, Mn and Zn

Application of Aluminum alloys

- Aluminum alloys are widely used for aeronautical applications because of their high strength weight ratio.
- For automobiles for reducing the weight of the vehicle thus reducing fuel consumption.
- For applications such as, electrical conductors including overhead transmission lines.
- House hold and consumer items such as utensils.
- Marine application.
- Used in making windows, doors and roofs of factories.
- Sports equipment.

TITANIUM AND ITS ALLOYS

Properties:

- High strength-to-weight ratio
- Like SS, Titanium Oxide is formed on the surface, preventing corrosion.
- Titanium and Titanium alloy are resistant to nitric acid, which is very corrosive. Hence, it is used in this kind of process environment.
- However, an inert atmosphere is required for welding Titanium and Titanium Alloys.
- It starts losing its strength above 400°C
- Titanium is also used as a clade material with carbon steel to reduce the cost of equipment. Figure 5.7 represents the biomedical applications of titanium and its alloy.

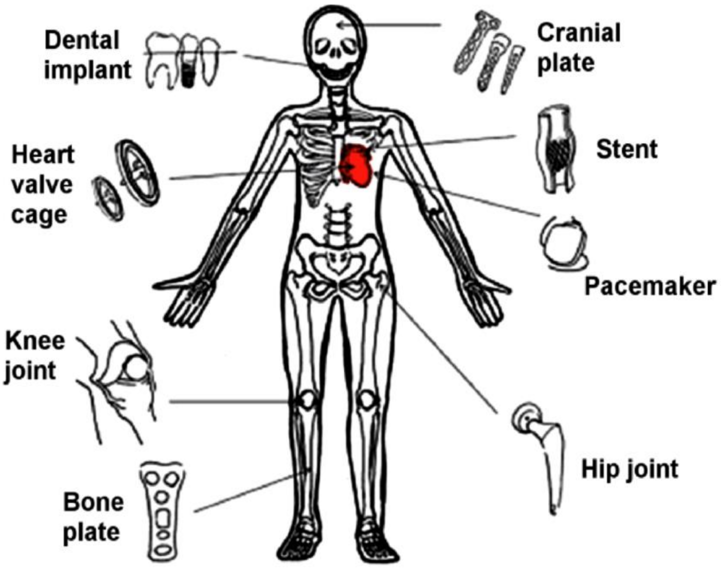


Figure 5.7 Biomedical applications of titanium and its alloy

OTHERS NON-FERROUS ALLOYS

REFRACTORY METALS

Refractory metals are a group of metallic elements that are highly resistant to heat and wear, melting point higher than 3600 ^{o}F (2,000 ^{o}C).

Due to their high melting points and hardness, the refractory metals are most often processed in powder form and never fabricated by casting.

- Tungsten (W),
- Molybdenum (Mo),
- Niobium (Nb),
- Tantalum (Ta),
- Rhenium (Re).

A few of the most common applications from refractory metals include wire filaments, tools, chemical vessels within corrosive atmospheres, casting moulds. With their very high melting point, refractory metals are highly stable

They are strong under extremely high temperatures and are innately hard, making these metals perfect for drilling and cutting tools. Also, these metals are highly resistant to factors like thermal shock. This means that they will not experience cracking, expansion or stress when cooled and heated repeatedly.

NICKEL

Nickel is a chemical element with the symbol (Ni) and atomic number 28 (Figure 5.8). Nickel is a silvery-white metal that is used mainly to make stainless steel and other alloys stronger and better able to withstand extreme temperatures and corrosive environments (Figure 5.9).

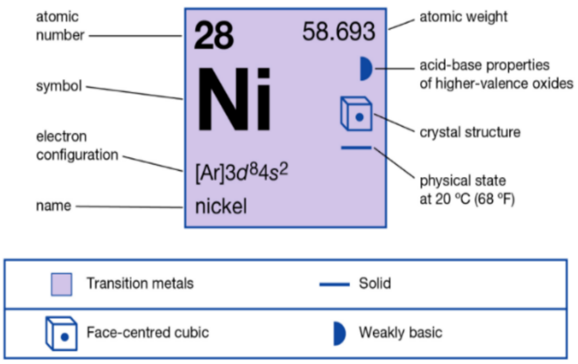


Figure 5.8 Chemical Element of Nickel

Nickel in jet engines: Nickel alloys are used in the turbine blades and other parts of jet engines where temperature can reach 2700 °F and pressures can reach 40 atm. Illustration from NASA.gov.

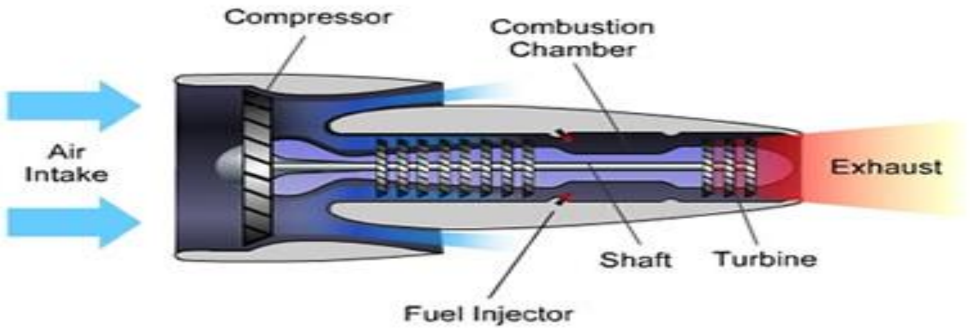


Figure 5.9 Application Nickel in Jet Engines.

ZIRCONIUM

Zirconium is a chemical element with the symbol Zr and atomic number 40. The name zirconium is taken from the name of the mineral zircon, the most important source of zirconium (Figure 5.10). Zirconium is a silver-gray transition metal, a type of element that is malleable and ductile and easily forms stable compounds. It is also highly resistant to corrosion. Zirconium and its alloys have been used for centuries in a wide variety of ways. It is commonly used in corrosive environments. Zirconium is a corrosion resistant metal that is used in high performance pumps and valves. Since it also does not easily absorb neutrons, zirconium is widely used in nuclear reactors. The nuclear power industry uses nearly 90% of the zirconium produced each year, which must be nearly free of hafnium. Zirconium is also used as an alloying agent in steel, to make some types of surgical equipment, and as a getter, a material that combines with and removes trace gases from vacuum tubes.

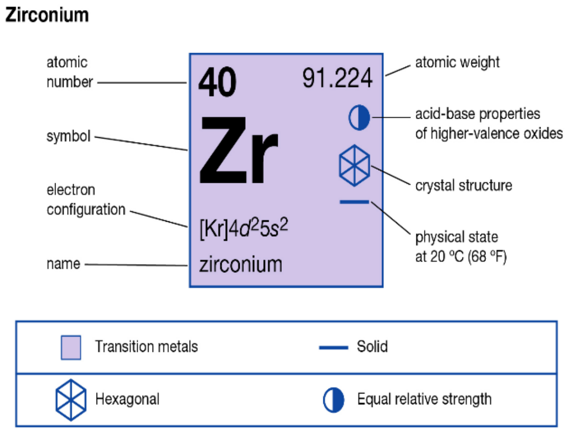


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Figure 5.10 Chemical Element of Zirconium

DISCUSSION QUESTIONS

QUESTION 1

Discuss how black malleable cast iron is produced and sketch the microstructure diagram.

[6 marks]

ANSWER

Black malleable cast iron produced:

White cast iron wrapped in a container with a sand/slag

It is slowly heated to a temperature between

950-1000 °C.

It is left for 4-5 days before slowly cooled.

Carbon with rosettes shape is formed.

QUESTION 2

Explain 3 categories of Plain Carbon Steel [9 Marks]

ANSWER

i. Low Carbon Steel

Carbon content in steel is less than 0.3%. Used to make flat-rolled sheets or steel strips that are utilized to create ships, wire products, car bodies, domestic appliances, tin plates. Generally, are used for fabrication and panelling purposes. Cheaper, but they cannot be altered by heat treatment. [3 marks]

ii. Medium Carbon Steel

Carbon content in steel between 0.3-0.8%. Heat treated to have a good balance of ductility and strength. Typically used in large parts, forgings, machined components, shafts, gear and crankshaft. [3 marks]

iii. High Carbon Steel.

Carbon content between 0.8-2.0%. Offer better responses to heat treatment and longer service life than medium carbon steel and extremely strong yet more brittle. Used to make cutting, molds, springs, cable fasteners, and railway wheels. [3 marks]

QUESTION 3

(a) Compare the differences between Grey Cast Iron and White Cast Iron.

ANSWER

Grey Cast Iron	White Cast Iron
Slow cooling rate Shows grey surface on the fracture	Rapid cooling rate Shows a white fractured surface
Higher Silicon content Easy to machine Have good wear resistance High compressive strength	Hard White in colour Wear resistance Tough to machine

PAST YEARS QUESTIONS

1) List **THREE (3)** types of non-ferrous metals. State **ONE (1)** characteristic and **ONE (1)** application of aluminum and aluminum alloys that are widely used in industry. [7 marks]

2) What are the differences between ferrous and non-ferrous metals [3 marks]

3) Define non-ferrous metals and list THREE (3) example of non-ferrous metals. [5 marks]

CHAPTER 6

FABRICATION OF METALS

SYNOPSIS

This topic explains the fabrication of metal works which focuses on hot and cold works, forming operation and casting process.

LEARNING OUTCOMES

6.1 Explain the forming operations

a. Hot working and cold working
b. Forging
c. Rolling
d. Extrusion
e. Drawing

6.2 Elaborate the casting processes

a. Sand casting
b. Die casting
c. Investment casting/Lost wax casting

6.3 Investigate the miscellaneous techniques in fabrication of metals

a. Powder metallurgy
b. Welding

6.4 Perform the heat treatment of steel

a. Heating, soaking and cooling stages in heat treatment cycle
b. Annealing
c. Normalizing
d. Quenching

6.5 Report the outcomes of the heat treatment of steels

a. Effect to the mechanical characteristics

6.1 THE FORMING OPERATIONS

Forming is a mechanical process used in manufacturing industries wherein materials (mostly metals) undergo plastic deformations and acquire required shapes and sizes by application of suitable stresses such as compression, shear and tension.

a. Hot working and cold working

Hot Working - refers to processes where metals that is heated above their recrystallization temperature.

Example: Forging, Hot Rolling and Extrusion

Cold Working - is defined as a plastic deformation process that occurs below recrystallization temperature or room temperature.

Example:

> Rolling	> Spinning
> Drawing	> Extruding
> Pressing	> Heading

b. Forging

Forging is a primary method for working metals into useful shapes. In the forging process, the metal is hammered or pressed into a desired shape. There are two major types of forging methods: hammer and press forging. Figure 6.1 and Figure 6.2 presents the forging process and product of forging process respectively.

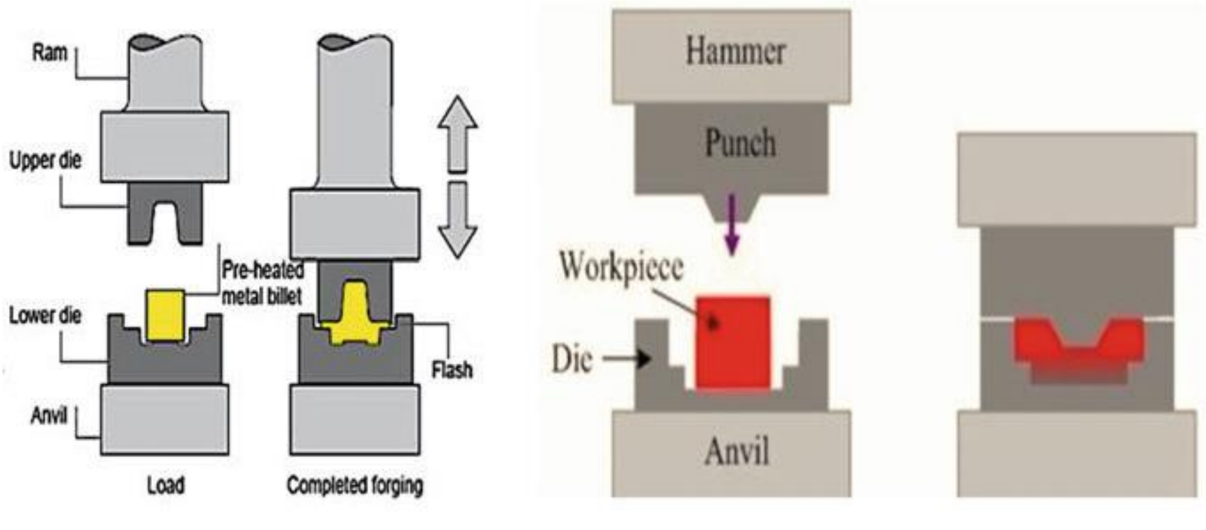


Figure 6.1 Forging Process

Figure 6.2 Products of forging Process

c. Hot Rolling

Hot Rolling is a metalworking process in which metal is heated above the recrystallization temperature to plastically deform it in the working or rolling operation.

This process is used to create shapes with the desired geometrical dimensions and material properties while maintaining the same volume of metal. Figure 6.3 and Figure 6.4 presents metal rolling process and hot rolling process respectively.

Application

Hot rolling is used mainly to produce sheet metal or simple cross sections, such as rail tracks.

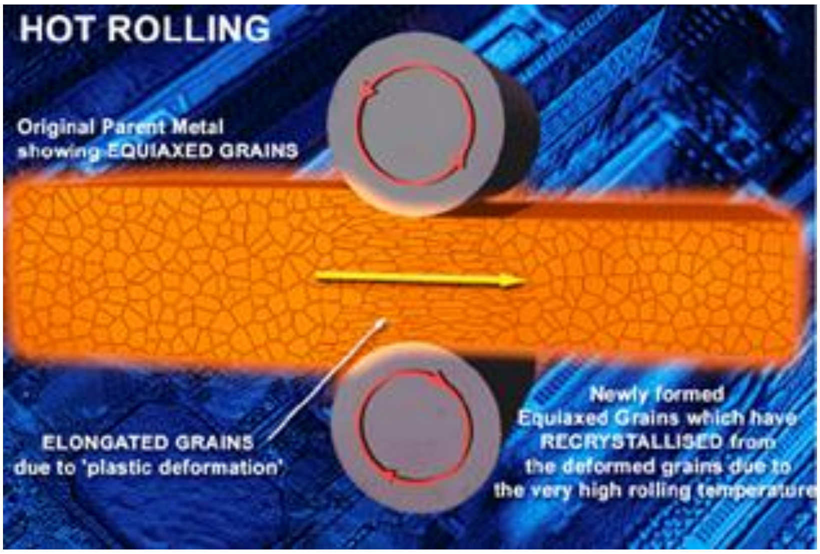


Figure 6.3: Metal Rolling Process

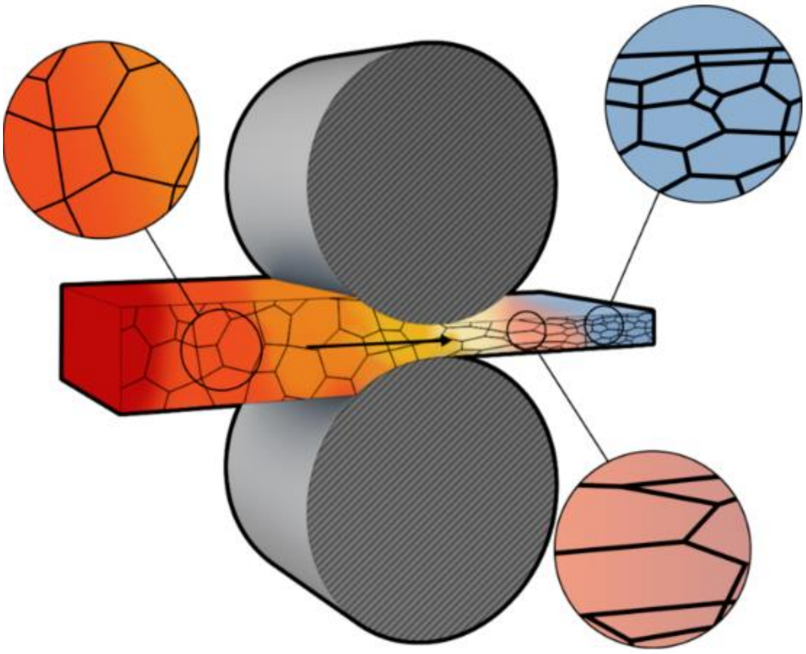


Figure 6.4: Hot Rolling Process

Cold Rolling

Cold rolling is a process by which the sheet metal or strip stock is introduced between rollers and then compressed and squeezed as shown in Figure 6.5. Figure 6.6 presents the different roller for cold rolling process. The amount of strain introduced determines the hardness and other material properties of the finished product.

The advantages of cold rolling are good dimensional accuracy and surface finish.

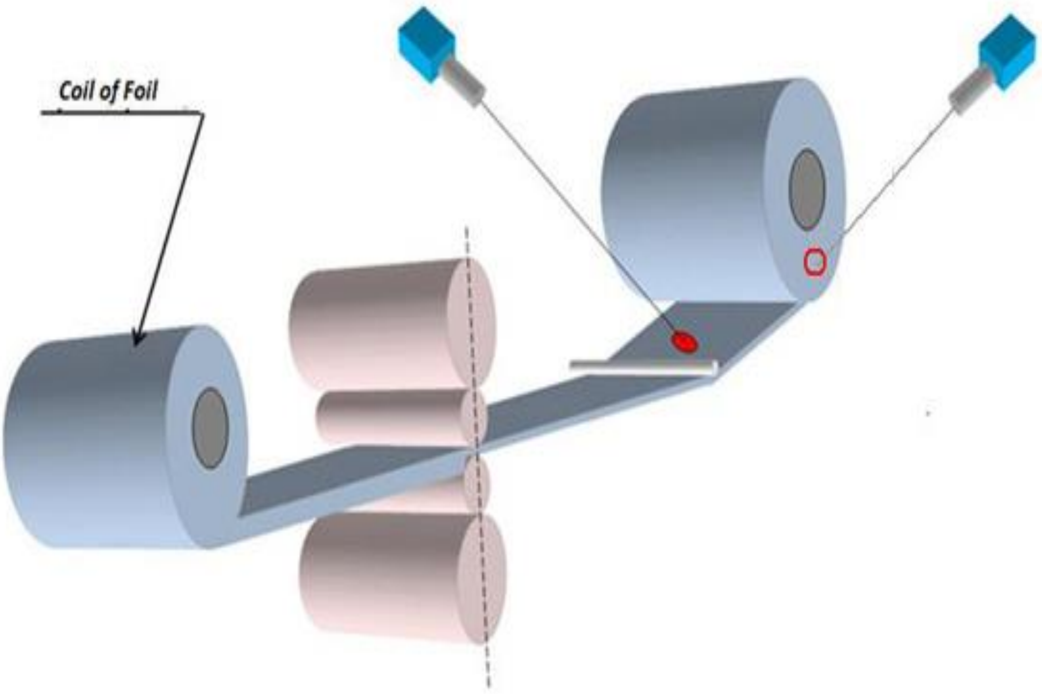


Figure 6.5 Cold Rolling Process

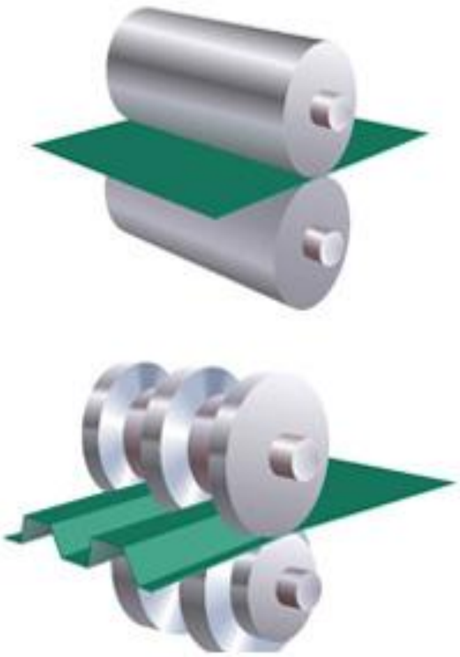


Figure 6.7 Different roller for cold rolling process

d. Extrusion

A bar or metal is forced from an enclosed cavity via a die orifice by a compressive force applied by a ram. During extrusion, the metal of a billet in the container of an extrusion press is forced by a ram through a die so that the metal is continuously deformed. Figure 6.8 and Figure 6.9 present the extrusion process and product of the extrusion process respectively.

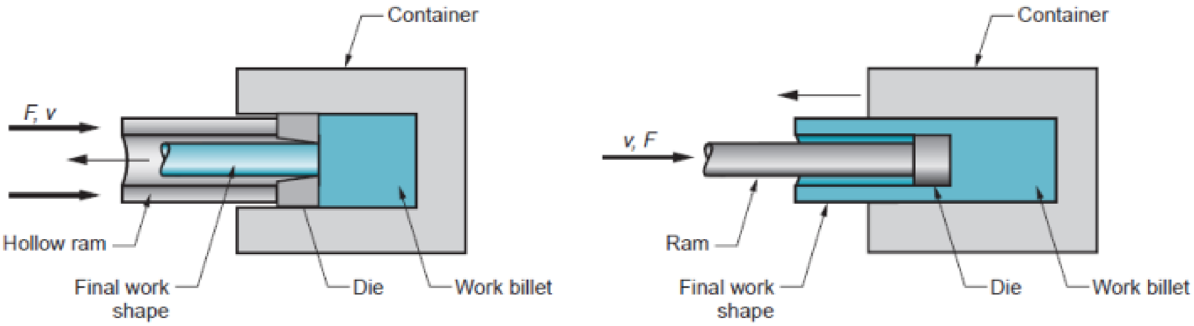


Figure 6.8 Extrusion Process

Figure 6.9 Products of the extrusion process

e. Drawing

Wire drawing process is quite simple in concept. As the wire is pulled through the die, its volume remains the same, so as the diameter decreases, the length increases. The wire is prepared by shrinking the beginning of it, by hammering, filling, rolling & swaging, so that it will fit through the die; the wire is then pulled through the die. Figure 6.10 shows the wire drawing process.

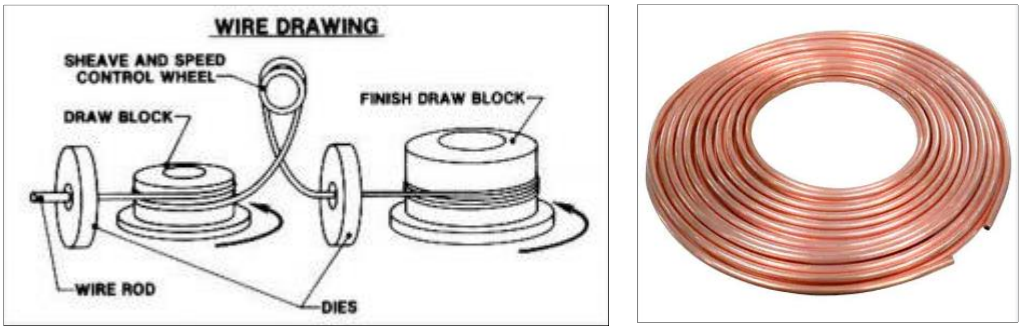


Figure 6.10 Wire drawing process

Tube Drawing

Process to size tube by shrinking a large diameter tube into a smaller one, by drawing the tube through a die. Drawing is a process which uses tensile forces to stretch metal. Figure 6.11 is an examples of tube drawing operations, with and without internal mandrel. Note that a variety of diameters and wall thickness can be produced from the same initial tube stock (which had been made by other processes).

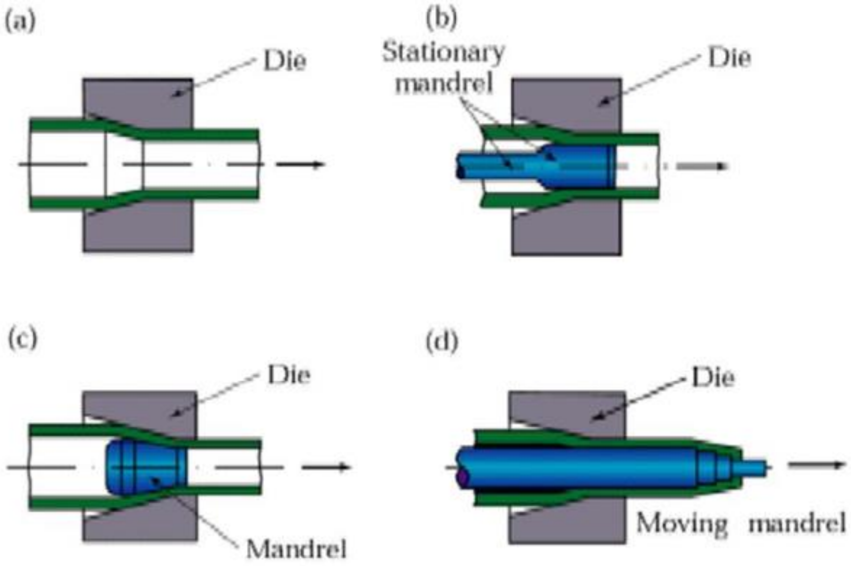


Figure 6.11 Tube drawing operations

Produces:

high quality tubing with precise dimensions

good surface finish

suitable for both large and small scale production

6.2 THE CASTING PROCESSES

Definition of casting-process by which a liquid material is usually poured into a mold which contains a hollow cavity of the desired shape, and then allowed solidifying. Used for making complex shapes that would be difficult to make by other methods.

Types of casting

1. Sand casting
2. Lost wax casting/investment casting
3. Pressure die casting
4. Gravity (permanent mold) and shell

a. Sand casting processes

Step 1

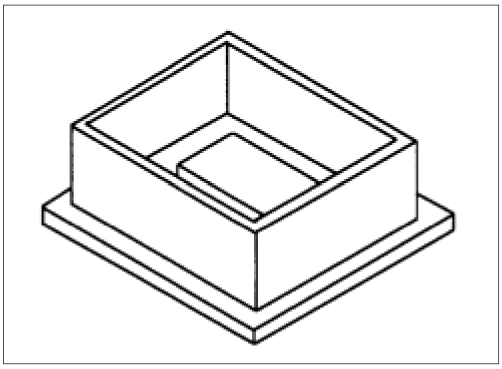


Figure 6.12 Drag ready for sand

The drag (lower molding box) in an upside-down position and a clean plate. Ensure the floor is also flatted

Step 2

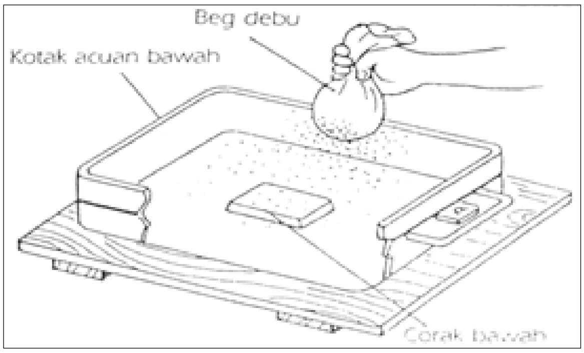


Figure 6.13 The parting powder scattered over the pattern and the plate

Lower part of the split pattern is placed in the drag.

The parting powder scattered over the pattern and the plate

Step 3

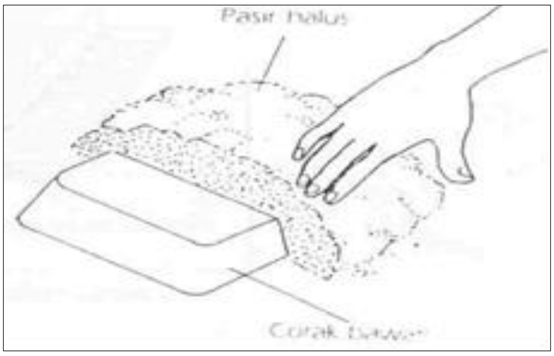


Figure 6.14 The fine sand is then pressed to the pattern

Finer sand gain from the sieving process is place around and over the pattern for 3 cm of thickness.

By pressing with the fingers, the fine sand is then pressed to the pattern and around it compacted.

Ensure that the pattern is still while the sand is compacted.

Step 4

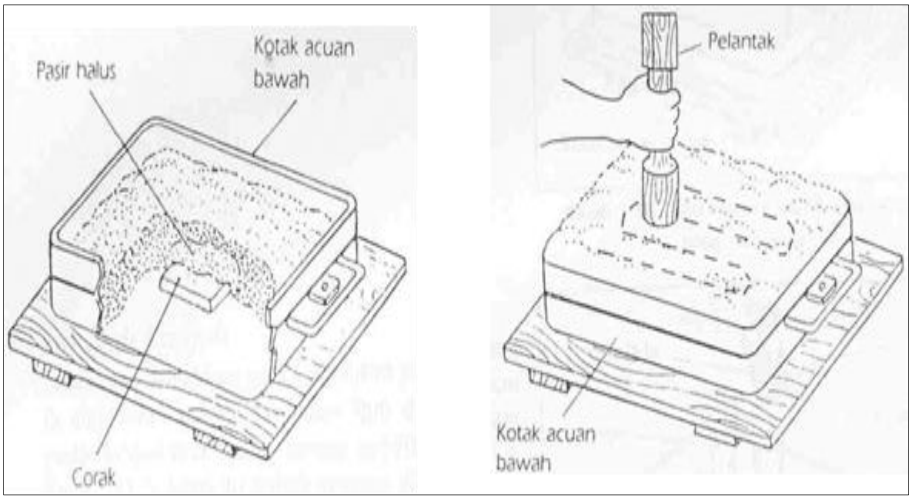


Figure 6.15 The molding box

Then add the rest of the sand for ¾ into the molding box. Use a rammer to compact the sand with a slow stroke. Add more sand over the molding box and com press it with harder stroke. Continue/repeat this process until getting compacted sand over the molding box.

Step 5

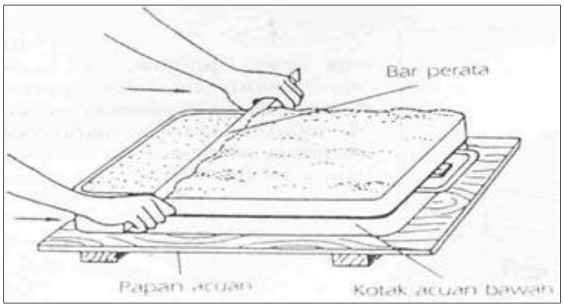
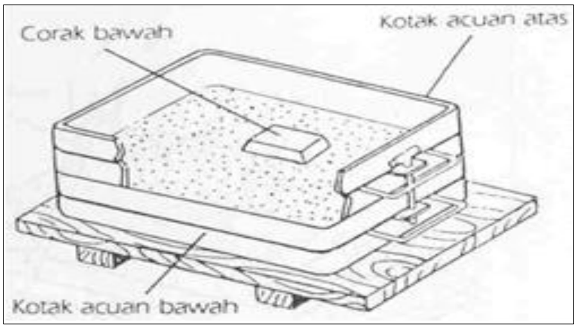


Figure 6.16 flatten the surface of the compressed sand

By using a strip bar, stripped/flatten the surface of the compressed sand.
The bar is pulled from a corner to another by moving it to the right and left

Step 6



Find the drag so that the pattern would be on the top, then placed the cope on the drag.
Lock both cope and drag together.
Figure 6.17 Placed the cope on the drag

Step 7

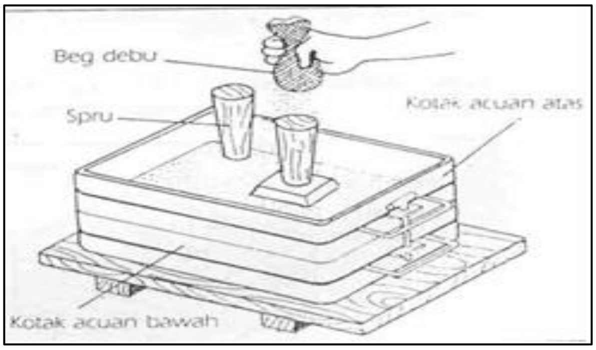


Figure 6.18 parting powder over the pattern, sprues, and the sand surface in the drag.

The upper slip pattern is placed on top of the lower pattern in the drag then placed the sprues (runner and riser) are in suitable positions.

Shattered the parting powder over the pattern, sprues, and the sand surface in the drag.

Step 8

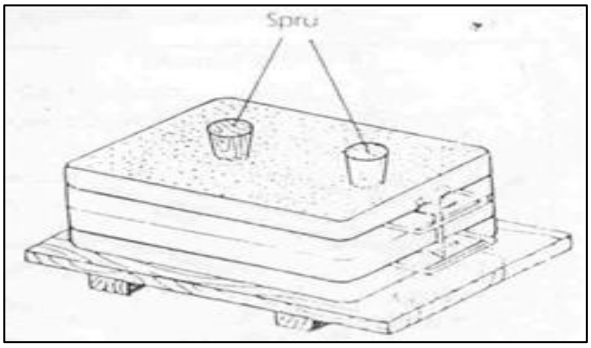


Figure 6.18 The molding box

Sieve the sand in the molding box to gain 3 cm of the finer sand around and over the pattern.

Compress the sand with fingers.

Add and ram the sand same us the fourth step

Step 9

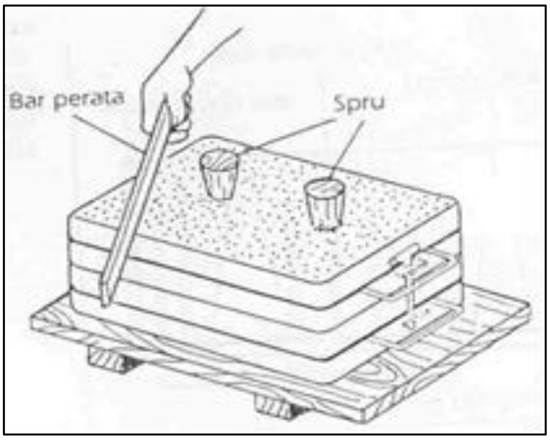


Figure 6.19 Flatten the surface

Use a strip to striped / flatten the surface of the sand in the cope.

Use a ladle to strip the sand surface around the sprues.

Step 10

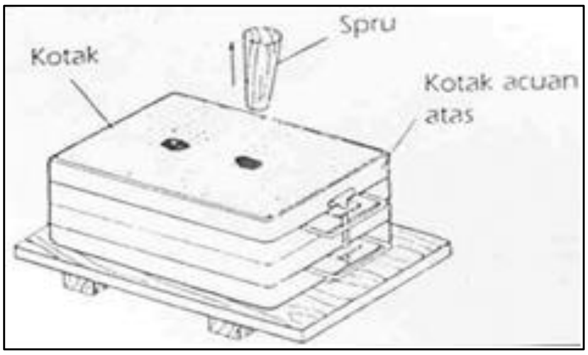


Figure 6.20 Twist the sprues

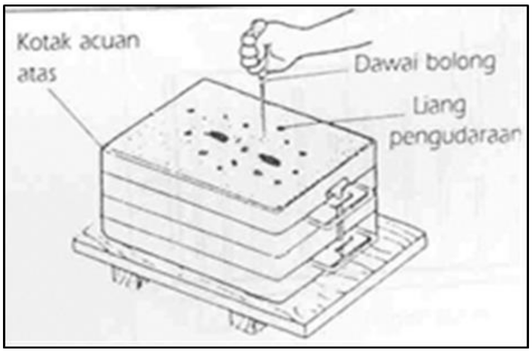


Figure 6.21 Ventilation rod to make ventilation holes

Twist the sprues, then pull it out slowly. Use a ventilation rod to make ventilation holes at the sand mould surface.

Step 11

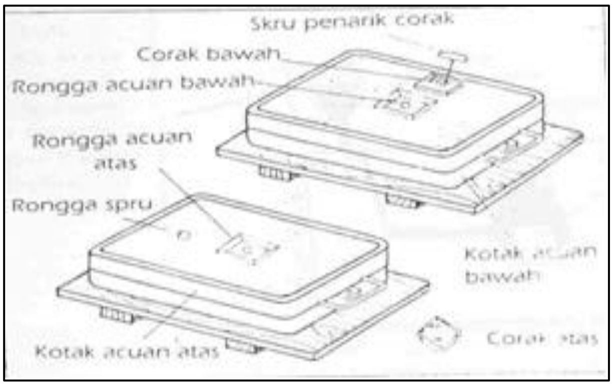


Figure 6.22 Separate both boxes (cope and drag)

Separate both boxes (cope and drag) and flip it to retrieve the slip pattern.

Before retrieve the pattern, knock it slowly so that the sand surface is loosen.

Use draw pins to retrieve both pattern sides from the mould. The cavity will be formed after retrieve the pattern.

The cavity will formed retrieve the pattern.

Step 12

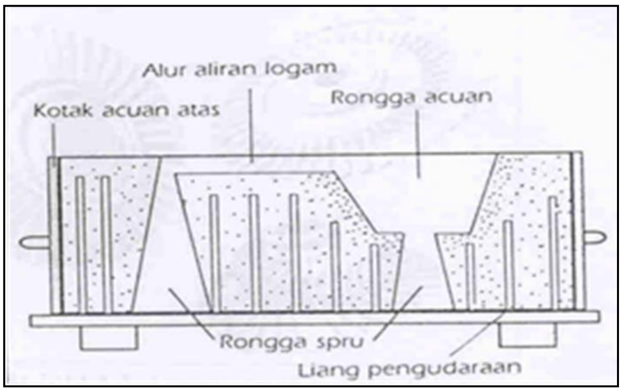


Figure 6.23 Chanel for molten metal flow

Chanel for molten metal flow creates using gate cutter and squire

The channel should connect the sprue cavities and the mould cavity

The channel function as a guide for the molten metal to flow to the mould cavity through sprue cavities

Step 13

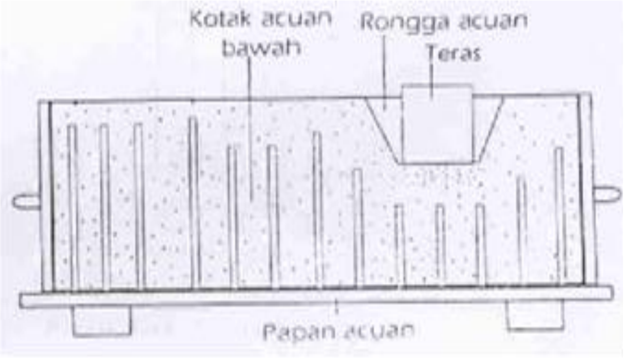


Figure 6.24 Core will be place in the lower cavity mould

Figure 6.25 Core

Core will be place in the lower cavity mould then the upper moulding box (cope) will be placed back to its position (on top of drag

Step 14

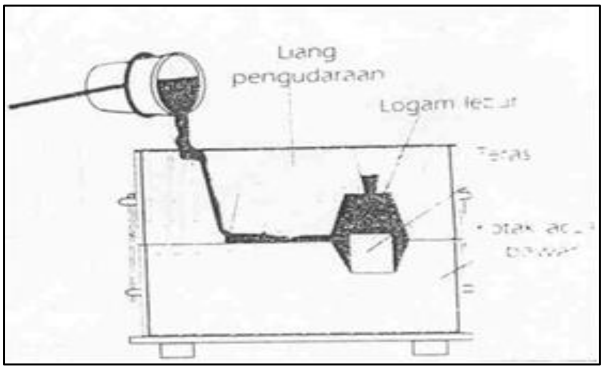


Figure 6.26 The molten metal poured into the basin

Using moulding trowel, a basin for pouring the molten metal into are made on the surface of the cope beside a sprue cavity called the runner.
The ready for pouring molten metal brought closer to the furnace.
The molten metal poured into the basin, flowing through the runner and straight to the cavity
After the molten metal solidify the product can be retrieve by breaking the mould.

Advantages:

- Low capital investment means that short production runs are viable;
- Use of sand cores allows fairly complex shapes to be cast;
- Large components can be produced;

- Suitable for small branch production (small production rates)
- No skilled operators needed

Disadvantages:

- The process has a high unit cost, as it is labor intensive and time consuming
- The sand mold leaves bad surface finish, due to sand indentation and oxidizing medium, which often requires further processing;
- Cannot make thin sections.
- Not suitable for mass production, often used to produce few numbers of products compared with other casting processes which produce thousands and millions.
- Dangerous operation, may cause harmful injuries etc.

b. Die casting

Die casting is a metal casting process that is characterized by forcing molten metal under high pressure into a mold cavity. The mold cavity is created using two hardened tool steel dies which have been machined into shape and work similarly to an injection mould during the process. Figure 6.27 presents the product of die casting.

Most die castings are made from non-ferrous metals, specifically zinc, copper, aluminium, magnesium, lead, pewter, and tin-based alloys. Depending on the type of metal being cast, a hot- or cold-chamber machine is used.

The type of mould used is permanent mould made by metal and consists of two parts: fixed part and moveable part, the mould also has air ventilations to expel the air trapped in the mould when the casting process occurs.

Figure 6.27 Product of die casting

Advantages of die casting:

- Excellent dimensional accuracy
- Smooth cast surfaces
- Thinner walls can be cast as compared to sand and permanent mould casting
- Minimum surface treatment prior to plating
- Reduces or eliminates secondary machining operations.
- Rapid production rates.

Disadvantages:

- The process is limited to high-fluidity metals. Increased scrap rates can be caused by fluidity failure, and scrap costs in die casting are high.
- Die casting involves a large number of parts, so questions of repeatability are particularly important.
- Expensive machinery and dies
- In the standard die casting process the final casting will have a small amount of porosity.

c. Investment casting/Lost wax casting

1. "Lost wax casting" is a manufacturing method named after its process, fire a wax pattern coated with ceramic shell to melt out the wax, then pour molten metal inside the ceramic shell.
2. In industrial uses, the modern process is called investment casting.
3. An ancient practice, the process today varies from foundry to foundry, but the steps which are usually used in casting small bronze sculptures in a modern bronze foundry are generally quite standardized.

The step of lost wax casting is shown in Figure 6.28.

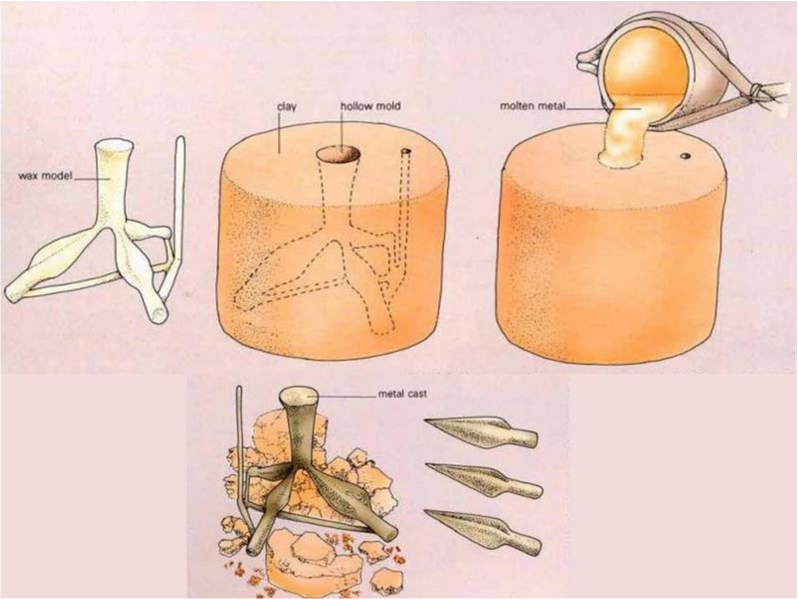


Figure 6.28 Step for lost wax casting

Step 1

Lost wax casting pattern made by wax.

Type of wax used for this casting: paraffin, bee wax, acrawax, and resin(dammar).

The wax pattern then dipped into concentrated material heat resistance coating to gain smoother surface for inside wall of the mould.

Step 2

The wax pattern coated with heat resistance material then put into metal mould box or a flacks.

Molten material is inserted into the mould box.

Then molten material consists of harden material and silica sand.

Figure shows how a pattern posted in the mould and the molten material poured into the box.

Step 3

The wax pattern then heated in a furnace between 100°C to 200 °C.

The wax will be melt and flow out or lost to form a cavity in the mould.

Step 4

The mould will be retrieved from the furnace and flipped upside down. The molten metal will be poured into the cavity.

When it is solidify, the casting product can be retrieved.

Investment Casting

1. Create a wax pattern
2. Sprue the wax pattern
3. Invest the wax pattern
4. Eliminate the wax pattern by burning it (inside the furnace or in hot water). This will create a mould.
5. Force molten metal into the mould - casting.
6. Clean the cast.
7. Remove sprue from the cast
8. Finish and polish the casting on the die.

Example product of investment casting is presented in Figure 6.29.

Figure 6.29 Product of investment casting

Advantages

Lost wax casting is suitable for manufacturing thin wall parts, three dimensional parts.

Security parts that require high strength.

It also features beautiful casting surface with fine metallic structure.

6.3 INVESTIGATE THE MISCELLANEOUS TECHNIQUES IN FABRICATION OF METALS

a. Powder metallurgy

Powder metallurgy is used for manufacturing products or articles from powdered metals by placing these powders in molds and are compacting the same using heavy compressive force. Figure 6.30 shows the powder metallurgy process.

Typical examples of such article or products are grinding wheels, filament wire, magnets, welding rods, tungsten carbide cutting tools, self-lubricating bearing electrical contacts and turbine blades having high temperature strength.

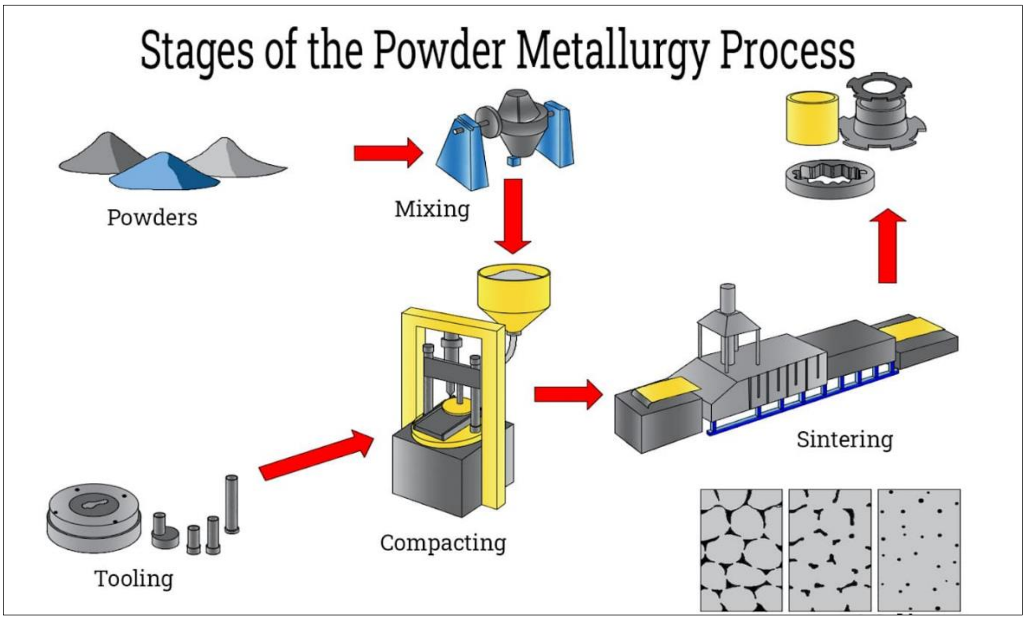


Figure 6.30 Powder metallurgy process

b. Welding

Welding is a fabrication process whereby two or more parts are fused together by means of heat, pressure or both forming a join as the parts cool?

Welding is usually used on metals and thermoplastics but can also be used on wood. The completed welded joint may be referred to as a weldment.

Types of Welding

- Arc Welding
- Gas Welding

Arc Welding

- These processes use a welding power supply to create and maintain an electric arc between an electrode and the base material to melt metals at the welding point.
- They can use either direct current (DC) or alternating current (AC), and consumable or non-consumable electrodes.

Common types of arc welding are:

- Shielded Metal Arc Welding (SMAW),
- Gas Metal Arc Welding (GMAW),
- Gas Tungsten Arc Welding (GTAW) &
- Submerged Arc Welding (SAW).

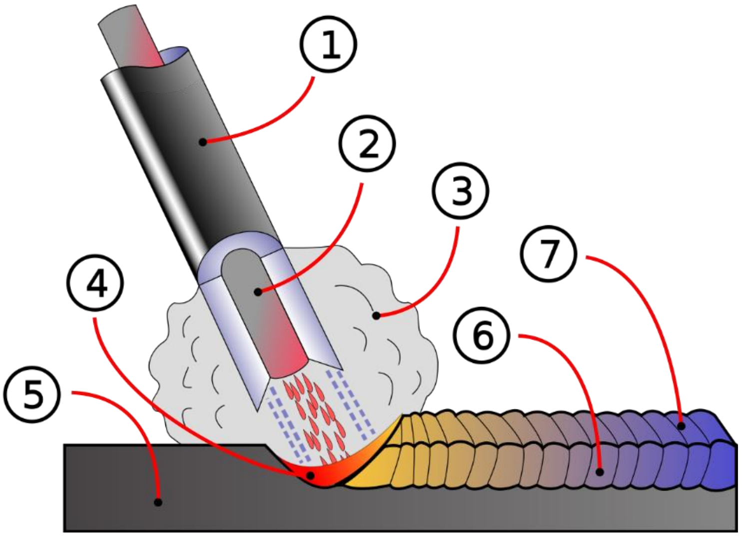


Figure 6.31 Arc and weld area

Gas Welding

The most common gas welding process is oxyfuel welding, also known as oxyacetylene welding. It is one of the oldest and most versatile welding processes, but in recent years it has become less popular in industrial applications. It is still widely used for welding pipes and tubes, as well as repair work.Types of gas welding:

Resistance Welding-Spot Welding, Seam Welding

Figure 6.32 Spot welder

6.4 HEAT TREATMENT OF STEEL

Steel often requires heat treatment to obtain improved properties, increase hardness or strength, or to neutralise negative effects resulting from previous manufacturing processes remove internal stresses generated by fabrication processes. Heat treating of steel is the process of heating and cooling of carbon steel to change the steel's physical and mechanical properties without changing the original shape and size.

Definition

A process of heating the metal to a certain temperature level, followed by a process cooling with a certain rate.

a. Heating, soaking and cooling stages in heat treatment cycle

Stages of Heat Treatment

Stage 1 – Heating the metal slowly to ensure a uniform temperature.

Stage 2 - Soaking (holding) the metal at a given temperature for a given period of time,

Stage 3 – Cooling the metal to room temperature.

b. Annealing

Annealing treatment is heating the steel over the upper critical temperature and then cooling slowly. Slow cooling is generally achieved on a closed furnace by switching off the supply.

c. Normalizing

The purpose of anneal heat treating may involve one or more of the following aims:

- To soften the steel and to improve machinability.
- To relieve internal stresses induced by some previous treatment (rolling, forging, uneven cooling).
- To remove coarseness of grain.
- The treatment is applied to forgings, cold-worked sheets and wire, and castings.
- Normalising is similar to annealing except that the rate of cooling is faster, the metal being allowed to cool in still air. Draughts may cause it to cool too quickly.

Normalising is used to:

- To refine the grain structure and to create a more homogeneous austenite when a steel is to be reheated for quench hardening or full annealing.
- To encourage reduced grain segregation in castings and forgings and provide a more uniform structure.
- To provide moderate hardening.
- To improve the machine ability.

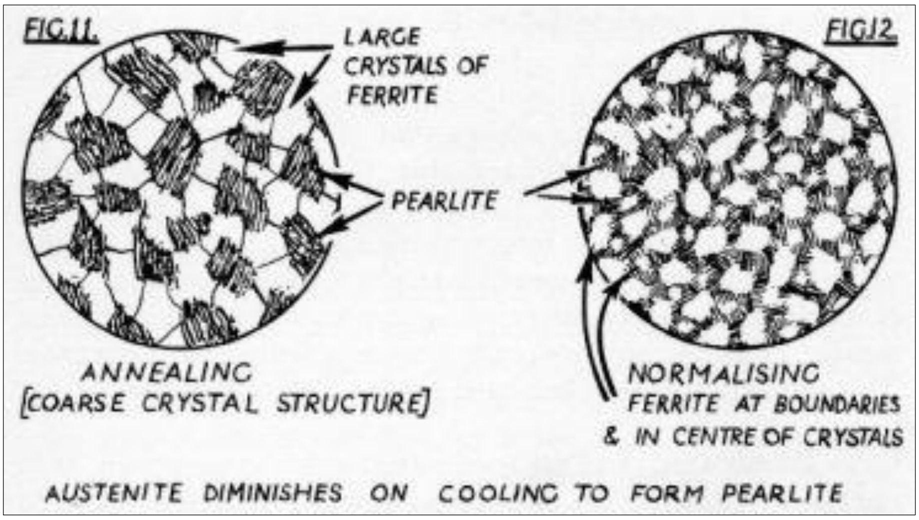


Figure 6.3 Microstructure of annealing and normalising

d. Quenching

- Rapid cooling from a high temperature by immersion in a liquid bath of oil or water. Molten salts may also be used.
- Purpose - To increase hardness, strength and wear resistance

Quenching Media

There are a number of fluids used for quenching steels listed below in order of quenching severity:

1. Brine (Salt water) – faster cooling rate
2. Water – moderate cooling rate
3. Oil – slowest cooling rate
4. Liquid Nitrogen – used in automatic furnace, can be very fast cooling

6.5 Effect Heat treatment of steel is designed to;

- Harden
- Strengthen
- Soften
- Improve machinability
- Improve formability
- Improve dimensional stability
- Relieve internal stresses.
- Give more resistant to impact
- Give more ductile

DISCUSSION QUESTIONS

QUESTION 1

Heat treatment process is the most important process in a metal fabrication process.
Define heat treatment process. (3 marks)
State the purpose of conducting heat treatment process into steel. (2 marks)
List four types of heat treatment process of steel. (4 marks)

QUESTION 2

A steel knife required a heat treatment process in order to maintain sharp cutting edge. Explain the heat treatment process involved.

ANSWER
Quenching
Quenching is a process of heating the metal up to 30-50C above its upper critical temperature, held for a considerable time and quenched (cooled suddenly) in a suitable cooling medium.
Rapid cooling from a high temperature by immersion in a liquid bath of oil or water.
The purpose of quenching are to increase hardness, strength and wear resistance especially to cutting tool edge in order to cut other metals or materials.

Discuss FIVE (5) differences between hot work and cold work.

ANSWER

Hot work	**Cold work**
Temperature above the recrystallization temperature	Temperature below the recrystallization temperature
The deformation and recovery takes place simultaneously	No appreciable recovery takes place during deformation
Doesn’t produce internal stress in metal	Produce internal stress in metal
Doesn’t effect hardness, tensile, fatigue in metal	Improve hardness, tensile, fatigue in metal
Improve toughness, impact strength & ductility	Reduce toughness, impact strength and ductility

Doesn’t produce good surface finish on metal	Produce good surface finish on metal
Cost cheaper	Expensive

PAST YEAR QUESTION

1. Describe hot work and give THREE advantages of hot work. (5 marks) Jun17
2. With aid of diagram, explain the drawing process that use to produce steel wire. (8 marks) Dis 16
3. Give 2 types of forming operation. (2 marks) Jun15
4. Sketch and explain Hot Rolling Process. (10 marks) Jun16

CHAPTER 7

CORROSION OF METALS

SYNOPSIS

This topic explains the electrochemical corrosion phenomenon includes the differences between the types of corrosion phenomenon includes the differences between the types of corrosion and their remedial action to metal alloys.

LEARNING OUTCOMES

7.1 Demonstrate the electrochemical considerations
    7.1.1 Electrochemical reactions
    7.1.2 Electrochemical cell
    7.1.3 Passivity
    7.1.4 Oxidation

7.2 Examine the forms of corrosion in metals
    7.2.1 Uniform attack
    7.2.2 Galvanic
    7.2.3 Crevice
    7.2.4 Pitting
    7.2.5 Intergranular
    7.2.6 Stress corrosion cracking

7.3 Correlate the forms of corrosion with the prevention methods
Inhibitors
    7.3.1 Design changes
    7.3.2 Coatings
    7.3.3 Cathodic protect

7.0 DEFINITION

Corrosion is a process of reduction of the metal that can be applied to cases that can not be used again.This occurs when the metal is damaged, change the look and the material is reduced after the occurrence of chemical reactions

Corrosion is defined as the destructive and unintentional degradation of a material caused by its environment; it is electrochemical and ordinarily begins at the surface.
For metals almost all environments can cause corrosion to some degree, since the corroded state is the more stable state

A common type of corrosion is rust, which is found on iron and steel structures. In this type of corrosion, the iron is reacting with oxygen to form iron oxide compounds.

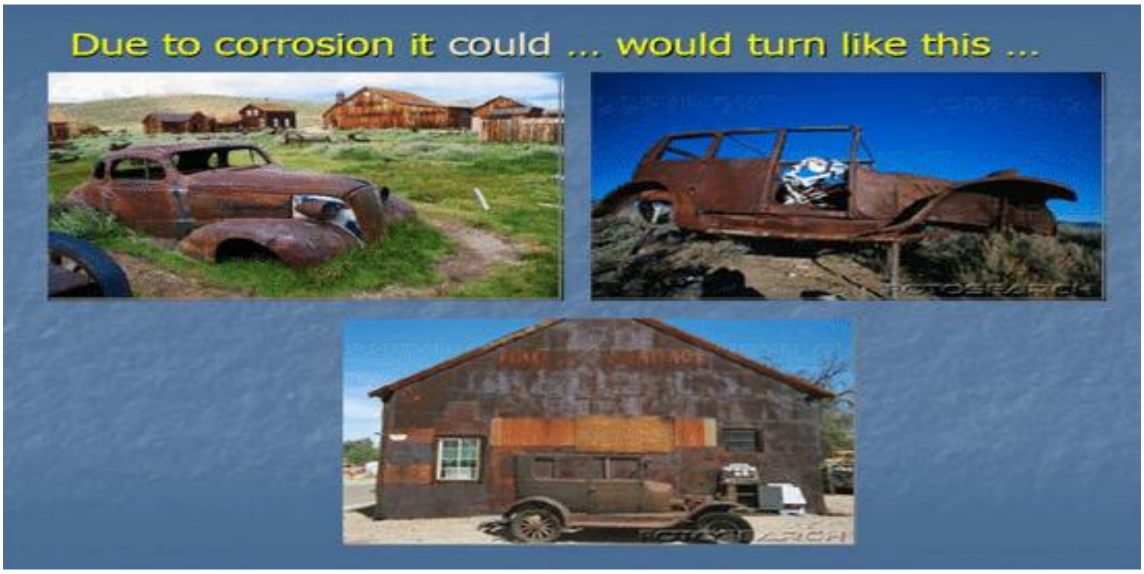


Figure 7.1: Example due to corrosion

7.1 ELECTROCHEMICAL REACTIONS

Corrosion is also known as wet corrosion occurs at ordinary temperatures (room temperature) in a presence of moisture or electrolyte.

Corrosion involves the position of a metal in the electrochemical series, which cause damage to metal slowly but effectively.

In this process the metal will be transformed into ions or chemical compounds, and with the help of an electrolyte, it becomes a solution to the electrical current of the ion + ve and-ve.

This is caused by the movement of ions + ve and-ve ions between the two metals are different potentials.

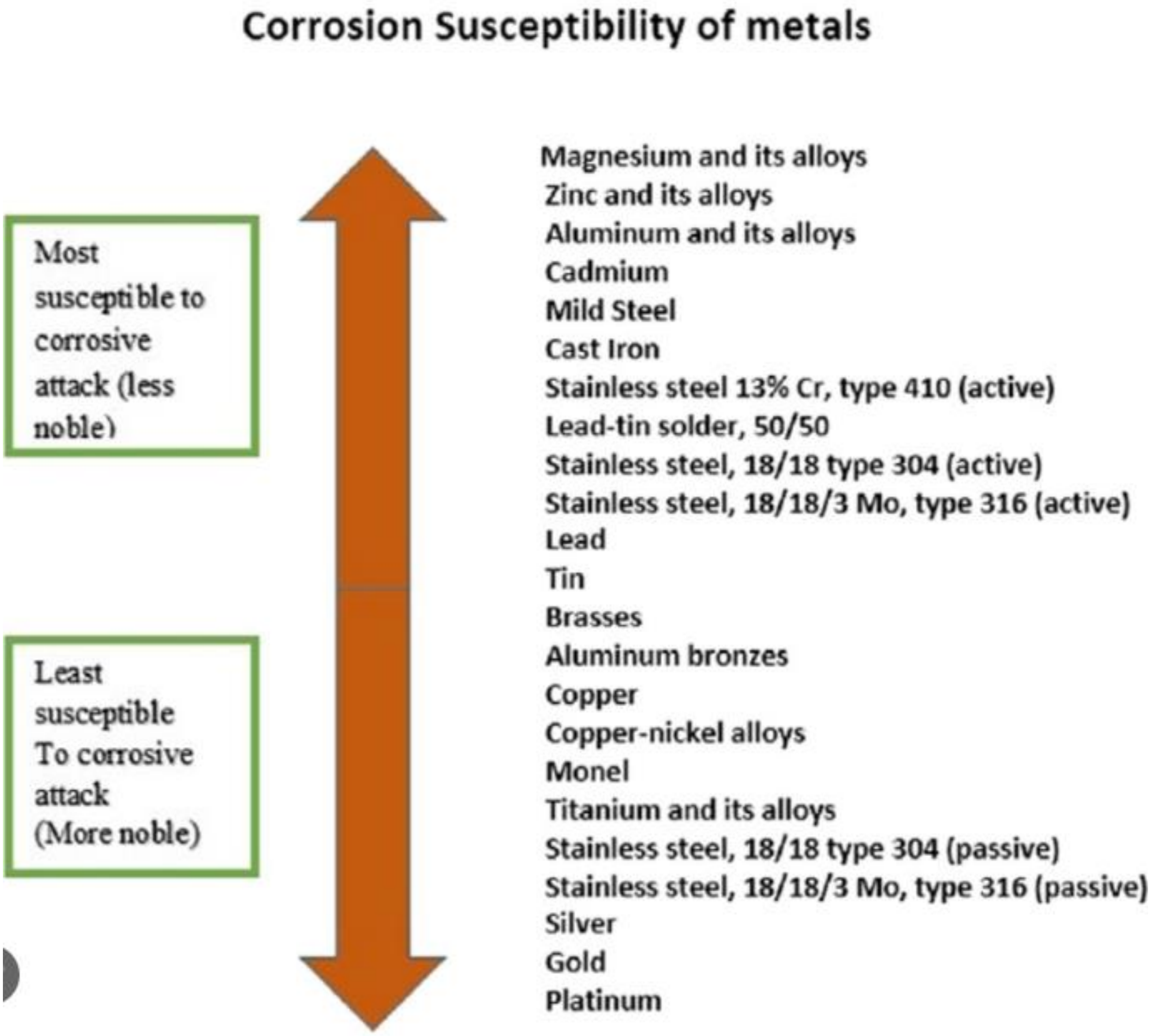


Figure7.2 : Galvanic series

Galvanic Series

Galvanic Series indicates the metal which is more anodic and cathodic relative. For example, metallic nickel with aluminum, nickel is more cathodic than aluminum.

Electrochemical Corrosion

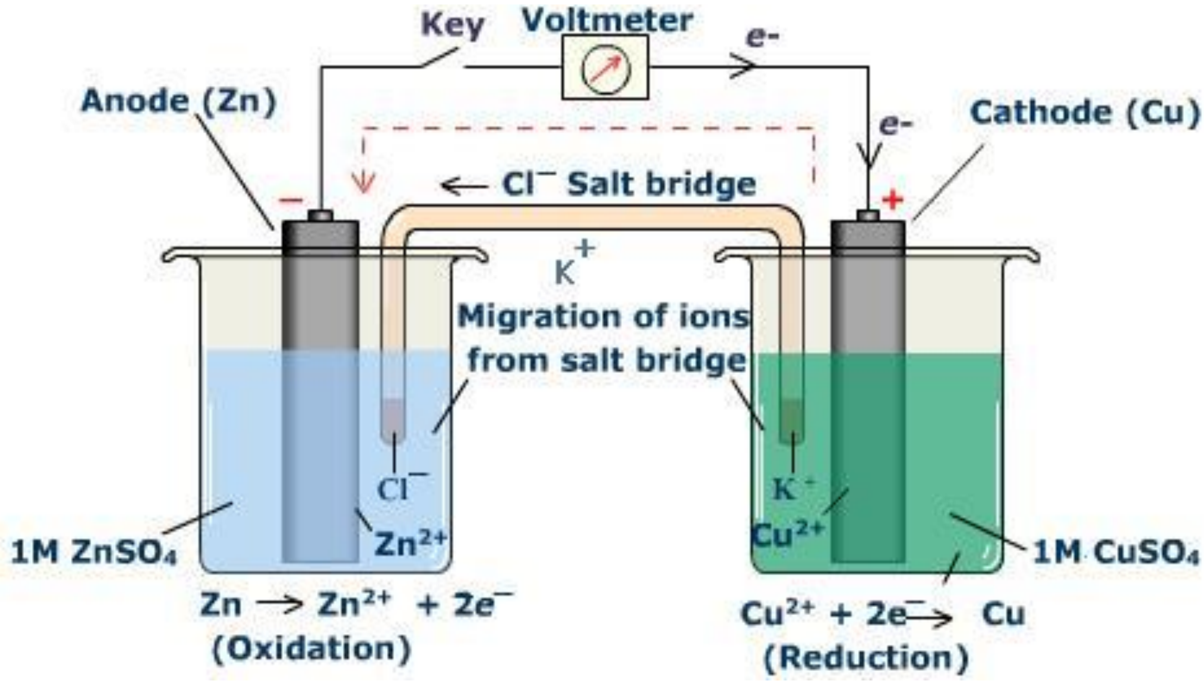


Figure 7.3 : Electrochemical Corrosion

An example is when connected to copper and zinc immersed in electrolyte materials such as salt water, acid or alkaline.

In this process the metal will turn into ions or chemical compound and with the help of electrolyte, it becomes a solution to a current of electrically namely ion + ve and-ve.

This is caused by the movement of ions + ve and-ve ions between the two metals are different potentials.

If there are two types of metal in the electrolyte the more anodic material will corrode in electrochemical process.

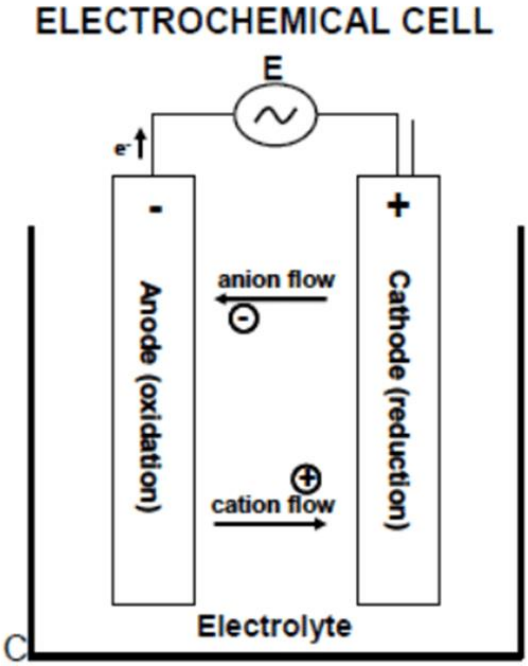
7.1.2 Electrochemical Cell

An electrochemical cell is a device that can generate electrical energy from the chemical reactions occurring in it, or use the electrical energy supplied to it to facilitate chemical reactions in it.

These devices are capable of converting chemical energy into electrical energy, or vice versa.
A common example of an electrochemical cell is a standard 1.5-volt cell which is used to power many electrical appliances such as TV remotes and clocks.

Electrochemical cell:
The devices used for converting chemical energy to electrical energy & electrical energy into chemical energy are known as electrochemical cells they contain two electrodes in contact with an electrolyte, they are mainly of two types:-

- Galvanic cells
- Electrolytic cell



Anode: Oxidation reaction site (negative)Cathode: Reduction reaction site (positive)E: Cell Potential or Cell EMF

Figure 7.4: electrochemical cell

1) Galvanic cells:
It is an electrochemical cell in which the free energy of chemical reaction is converted into electrical energy i.e. electricity is produced from a spontaneous chemical reaction.

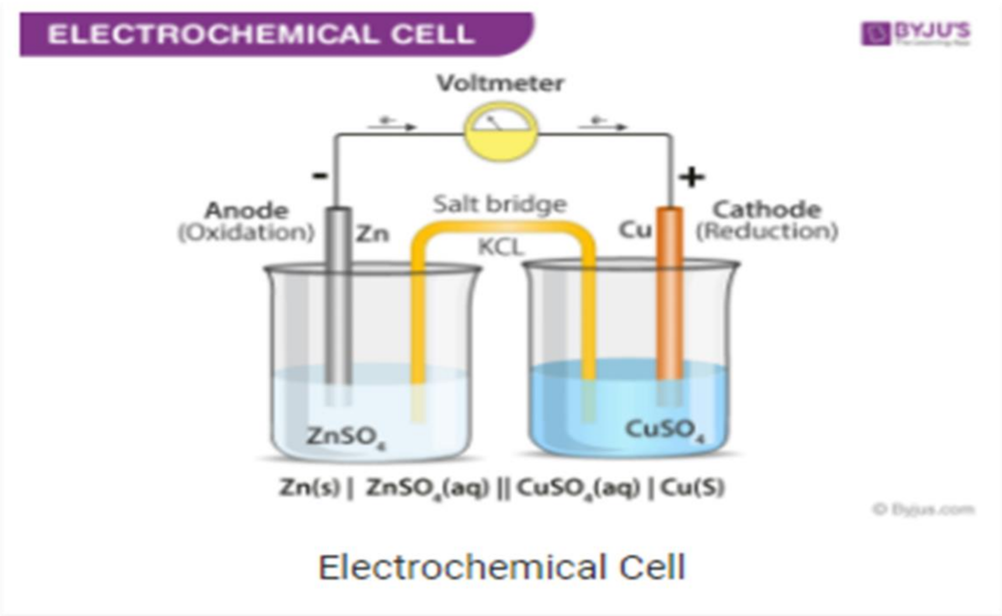
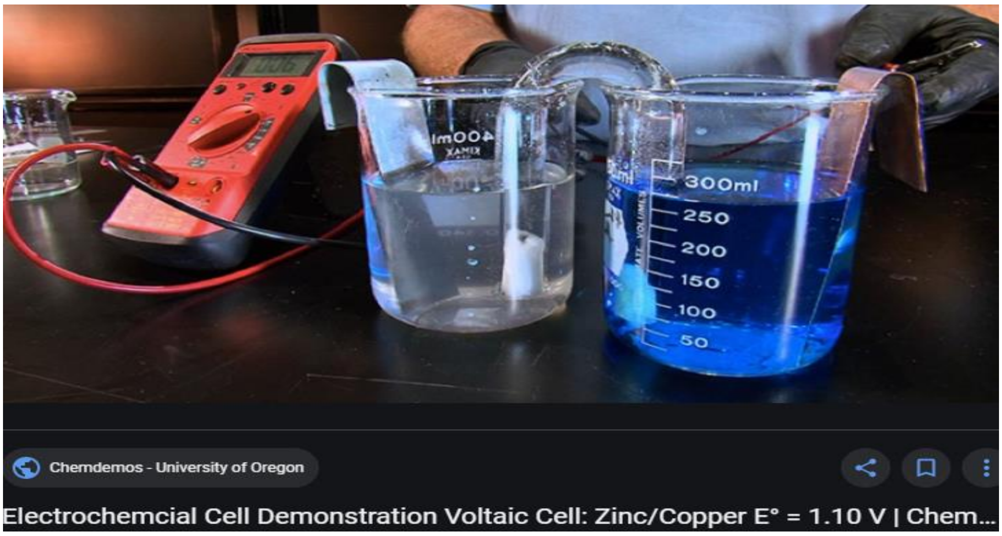


Figure 7.5 Electrochemical cell for Copper and Zinc



Electrochemcial Cell Demonstration Voltaic Cell: Zinc/Copper E° = 1.10 V | Chem...

Figure 7.6 Electrochemical cell for Copper and Zinc Process

A variety of standard sizes of primary cells. From left:4.5V multicell battery, D, C, AA, AAA, AAAA, A23, 9V multicell battery, *(top)* LR44, *(bottom)* CR2032

Figure 7.7 sample of primary cell

Figure 7.8 Sample of electrochemical Cell

2) Electrolytic cell: It is an electrochemical cell in which external electrical energy is used to carry out a non-spontaneous
3) chemical reaction.

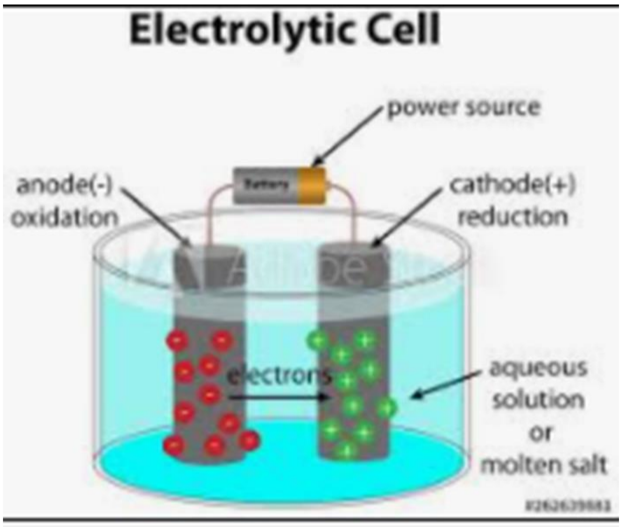


Figure 7.9 Elecrolytic Cell

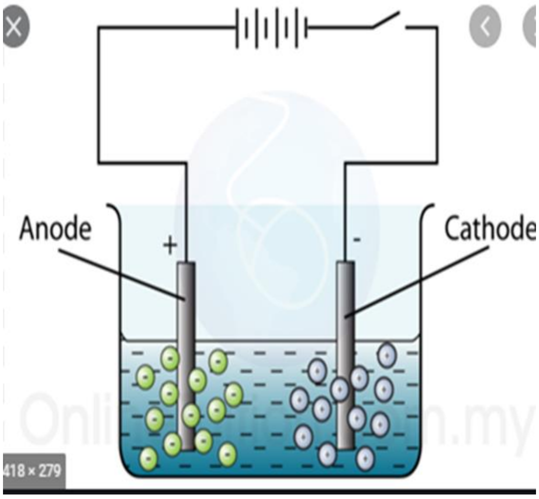


Figure 7.10 Elecrolytic Cell

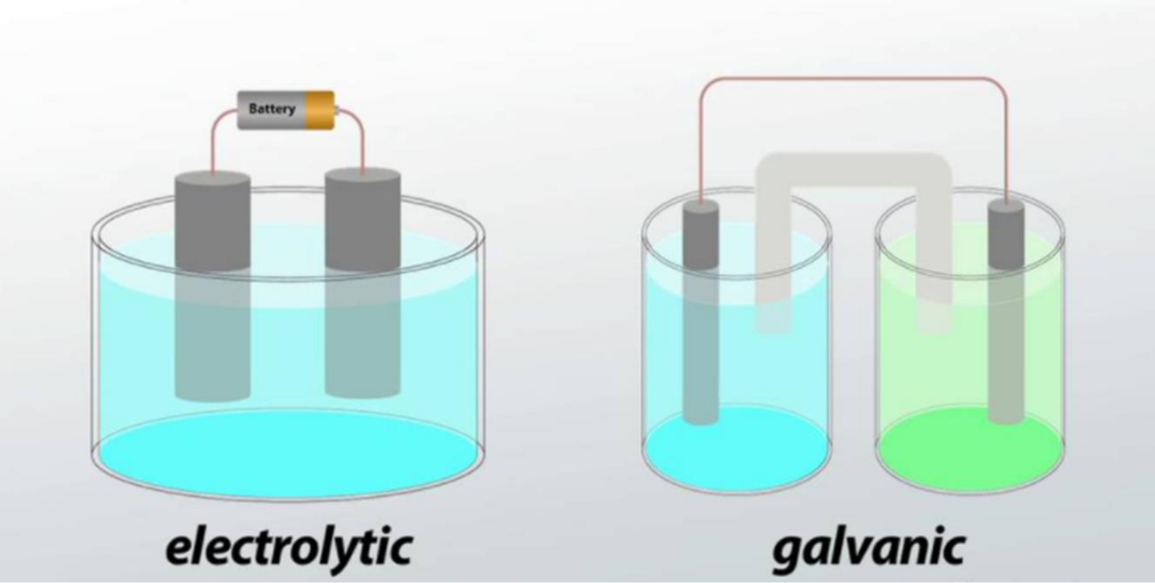
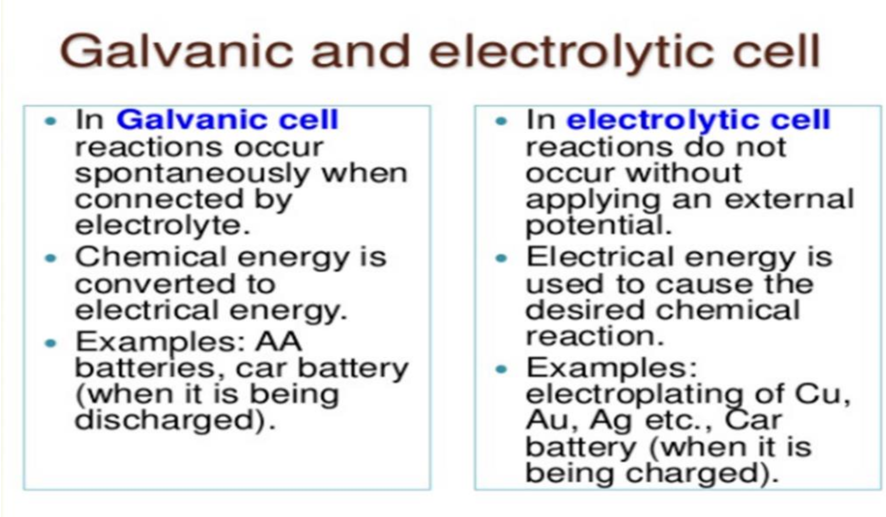


Figure 7.11 Elecrolytic Cell and Galvanic Cell



Galvanic and electrolytic cell

- In **Galvanic cell** reactions occur spontaneously when connected by electrolyte.
- Chemical energy is converted to electrical energy.
- Examples: AA batteries, car battery (when it is being discharged).

- In **electrolytic cell** reactions do not occur without applying an external potential.
- Electrical energy is used to cause the desired chemical reaction.
- Examples: electroplating of Cu, Au, Ag etc., Car battery (when it is being charged).

Figure 7.12 Comparison between Elecrolytic Cell and Galvanic Cell

7.1.3 Passivity

Passivity refers to a corrosion preventative mechanism whereby an oxidation layer forms a continuous film on a metal's surface that prevents further corrosion. Passivity is the loss of electrochemical reactivity, thereby decreasing the corrosion rate of the metal.

Passivation results in a barrier of passive film between the metal and the electrolyte. The barrier film can be crystalline or amorphous, and can be made of either insulator, such as aluminum, titanium, or tantalum, or made of semiconductors, such as iron or nickel.

Passivation is used on many different engineering alloys, such as stainless steel, nickel-based alloys, and aluminum-based alloys.

Some normally active metals and alloys, under particular environmental conditions, lose their chemical reactivity and become extremely inert.

This phenomenon, termed passivity, is displayed by chromium, iron, nickel, titanium, and many of their alloys. It is felt that this passive behavior results from the formation of a highly adherent and very thin oxide film on the metal surface, which serves as a protective barrier to further corrosion.

Stainless steels are highly resistant to corrosion in a rather wide variety of atmospheres as a result of passivation

They contain at least 11% chromium that, as a solid-solution alloying element in iron, minimizes the formation of rust; instead, a protective surface film forms in oxidizing atmospheres.

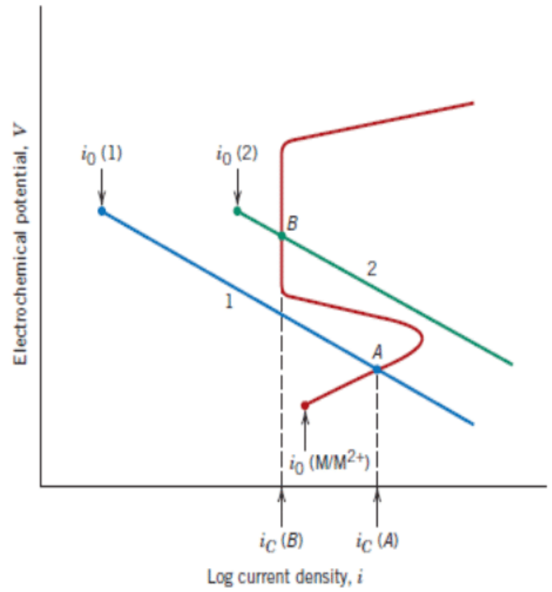


Figure 7.13 Passivation

QUESTION

With the aid of diagram. Discuss the electrochemical cell.

ANSWER

An electrochemical cell is a device that can generate electrical energy from the chemical reactions occurring in it, or use the electrical energy supplied to it to facilitate chemical reactions in it.

These devices are capable of converting chemical energy into electrical energy, or vice versa. A common example of an electrochemical cell is a standard 1.5-volt cell which is used to power many electrical appliances such as TV remotes and clocks.

7.2 FORMS OF CORROSION IN METALS

7.2.1 Uniform attack corrosion

Results from uniform penetration over the surface.

This type of attack is mostly found where a metal is in contact with an acid, a humid atmosphere or in a solution

Example: Rust on steel structure or the green patina on a copper roof are examples of uniform corrosion

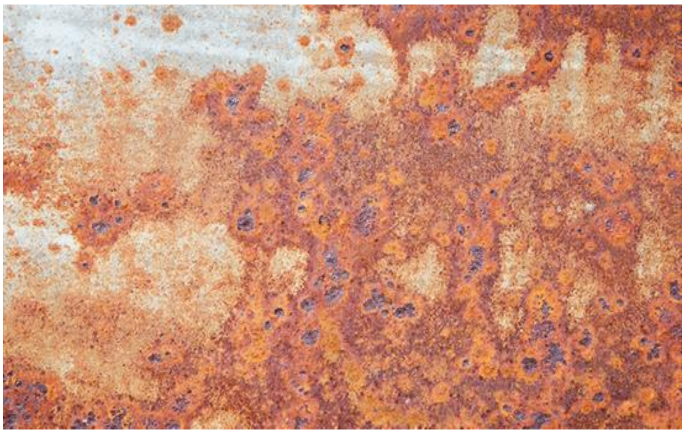


Figure 7.14 Uniform attack corrosion

7.2.2 Galvanic Corrosion

Galvanic corrosion occurs when two metals or alloys having different compositions are electrically coupled while exposed to an electrolyte

The less noble or more reactive metal in the particular environment will experience corrosion; the more inert metal, the cathode, will be protected from corrosion.

For example, steel screws corrode when in contact with brass in a marine environment; or if copper and steel tubing are joined in a domestic water heater, the steel will corrode in the vicinity of the junction.

Photograph showing galvanic corrosion around the inlet of a single-cycle bilge pump that is found on fishing vessels. Corrosion occurred between a magnesium shell that was cast around a steel core.

Figure 7.15 Galvanic Corrosion

7.2.3 Crevice Corrosion

Electrochemical corrosion may also occur as a consequence of concentration differences of ions or dissolved gases in the electrolyte solution, and between two regions of the same metal piece.

For such a concentration cell, corrosion occurs in the locale that has the lower concentration.

A good example of this type of corrosion occurs in crevices and recesses or under deposits of dirt or corrosion products where the solution becomes stagnant and there is localized depletion of dissolved oxygen

Corrosion preferentially occurring at these positions is called crevice corrosion.

Figure 7.16 Crevice Corrosion

On this plate, which was immersed in seawater, crevice corrosion has occurred at the regions that were covered by washers

Pitting Corrosion is the localized corrosion of a metal surface confined to a point or small area, that takes the form of cavities

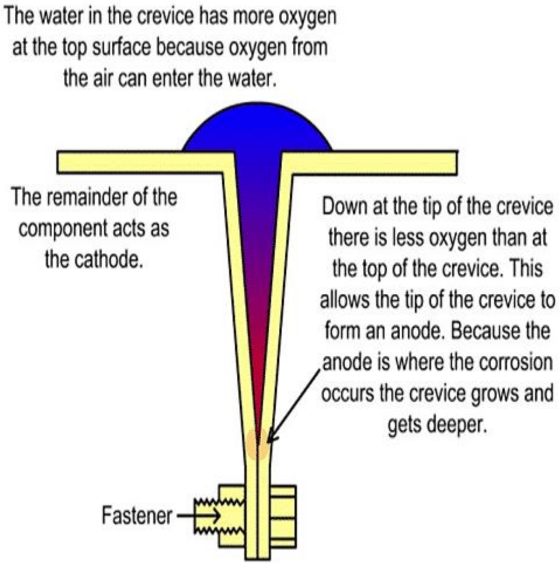


Figure 7.17 Crevice Corrosion

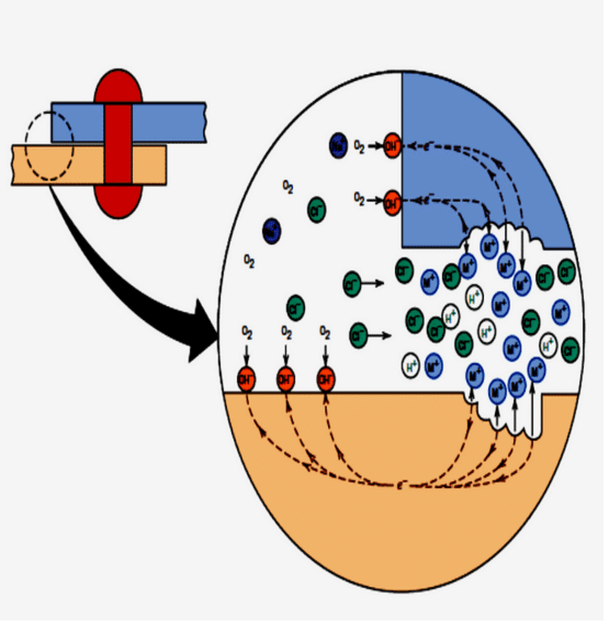


Figure 7.18 Schematic illustration of the mechanism of crevice corrosion between two riveted sheets.

7.2.4 Pitting Corrosion

Is a form of extremely localized corrosion that leads to the random creation of small holes in metal.

The driving power for pitting corrosion is the depassivation of a small area, which becomes anodic (oxidation reaction) while an unknown but potentially vast area becomes cathodic (reduction reaction), leading to very localized galvanic corrosion.

The corrosion penetrates the mass of the metal, with a limited diffusion of ions.

Another term arises, pitting factor, which is defined as the ratio of the depth of the deepest pit (resulting due to corrosion) to the average penetration, which can be calculated based on the weight loss

Figure 7.19 Pitting Corrosion

Severe pitting corrosion problems caused by chloride ions on a truss beam of the Nandu River Iron Bridge (Hainan Province, China) leading to the complete rupture of a metallic element.

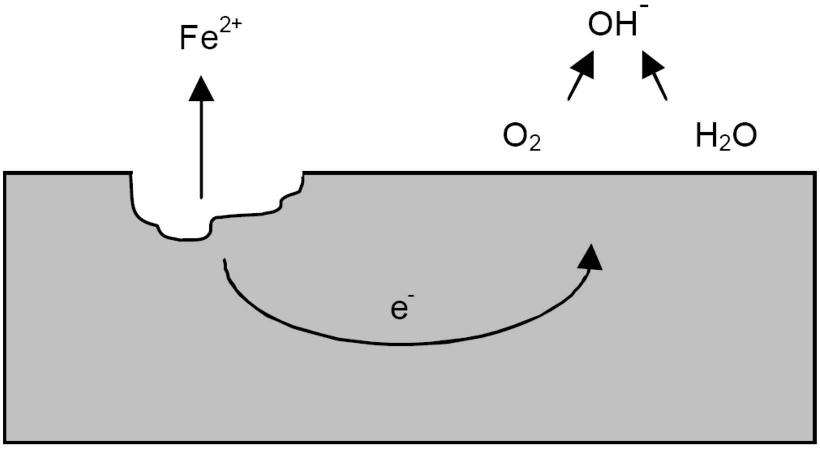


Figure 7.20 Schematic diagram showing the mechanism of localized corrosion with anodic zone (Fe oxidized into Fe2+ inside the pit) and cathodic zone (O2 reduced into OH−elsewhere outside the pit) developing on a metal

7.2.4 Intergranular Corrosion

As the name suggests, intergranular corrosion occurs preferentially along grain boundaries for some alloys and in specific environments.

The net result is that a macroscopic specimen disintegrates along its grain boundaries.

It is believed that this heat treatment permits the formation of small precipitate particles of chromium carbide (Cr23C6) by reaction between the chromium and carbon in the stainless steel.

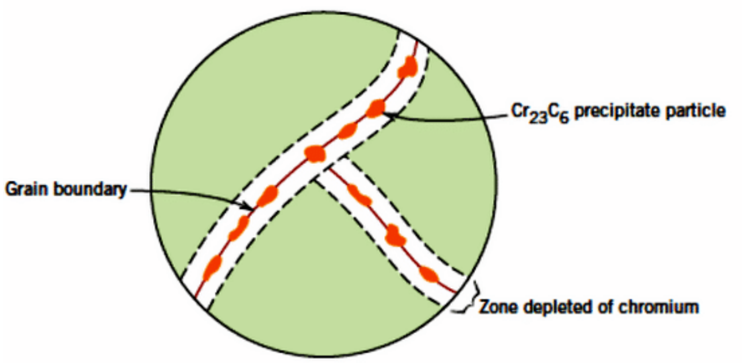


Figure 7.21 Intergranlar Corrosion

Figure 7.22 Intergranular Corrosion

7.2.5 Stress corrosion cracking

Stress corrosion, sometimes termed stress corrosion cracking, results from the combined action of an applied tensile stress and a corrosive environment; both influences are necessary. In fact, some materials that are virtually inert in a particular corrosive medium become susceptible to this form of corrosion when stress is applied.

Small cracks form and then propagate in a direction perpendicular to the stress, with the result that failure may eventually occur.

Failure behavior is characteristic of that for a brittle material, even though the metal alloy is intrinsically ductile.

Figure 7.23 Impingement failure of an elbow that was part of a steam condensate line.

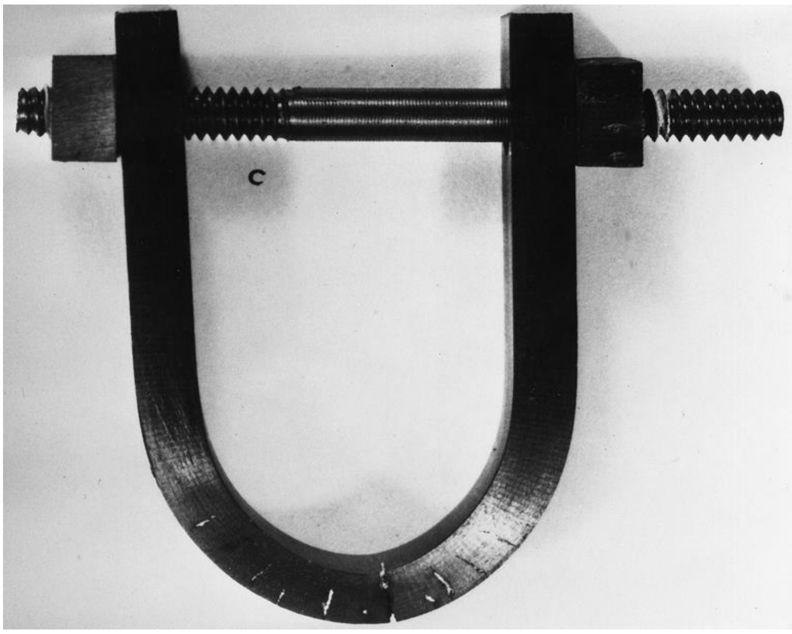


Figure 7.24The following photo shows the pitting corrosion of SAF2304 duplex stainless steel exposed to 3.5% NaCl solution.

7.3 CORRELATE THE FORMS OF CORROSION WITH THE PREVENTION METHODS

7.3.1 Inhibitors

Inhibitors are chemicals that react with the surface of a material decreasing the material's corrosion rate, or interact with the operating environment to reduce its corrosivity. The corrosion inhibitors are added to the environment to decrease corrosion of metals.

Example of inhibitors

- Chromate, Phosphates & Silicates protect iron and Steel in aq solution.
- Organic sulphide and Amines protect iron and Steel in acidic solution.
- Copper sulphate protects S.S in hot diluted solution of H2SO4.

Figure 7.25 Example of vapor inhibitors

7.3.2 Design changes

The design of a structure is as equally important as the choice of materials of construction since it can greatly reduce the time and cost associated with corrosion maintenance and repair.

The proper design of equipment or tools made up of metals and alloys must consider mechanical and strength requirements along with corrosion resistance.
The most common rule for design is avoiding heterogeneity. It is very important to make all conditions as uniform as possible throughout the entire system.

Corrosion frequently happens in dead spaces or crevices and it is highly recommended to eliminate or minimize these areas while designing.

All the components and structures should be designed by keeping its expected service life, otherwise premature collapse of the component or structure is the inevitable and large sum of money should be spent for its repair or replacement

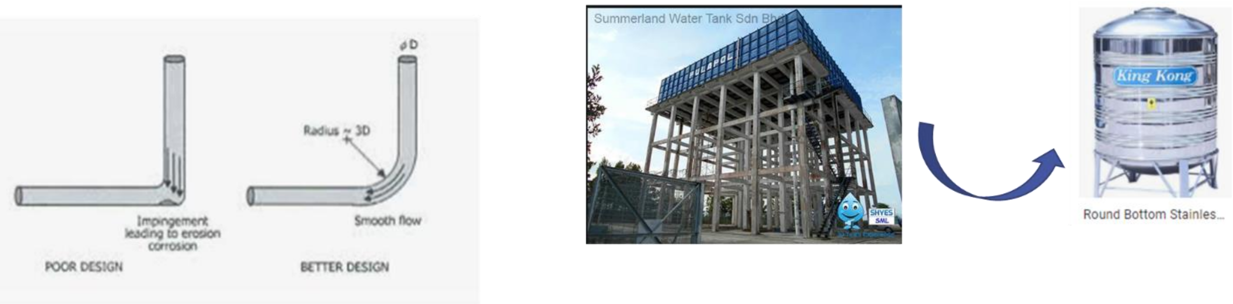


Figure 7.26 Example of design changes

The interrelation of various materials within a material system that can influence the corrosion process

The configuration of the material system as it affects the presence and conditions of a corrodent

Avoid sharp bend in piping system where the flow will occur.

Designing simple attachable system or changeable component if predicted it is easier to break or fail in the service.

The functioning of the operating system as it influences the generation and distribution of stress, erosion, and wear
Active corrosion prevention systems that can only be incorporated into the system design.

7.3.2 Coatings

There are two types of coating:
Metal Coating: Sacrificial Coating & Noble Coating

Noble Coating

In nobel plating, the coating is nobel in nature to the base metal. This type of coating will not protect the base metal if there are holes in the coating. This is because the base metal will be the anode.

Examples of this type of coating are Cu, Ni, Cr.
Non-Metal Coating: Organic & non Organic

Sacrificial Coating

While in the sacrificial coating, the base metal is protected at the expense of the coating metal that acts as an anode. Unlike the nobel coating, this method still protects the base metal even though there are holes in it.

An example of this coating method is roof plating made of steel with a layer of zinc. Zinc acts as a barrier layer of corrosion elements from hitting the steel roof.

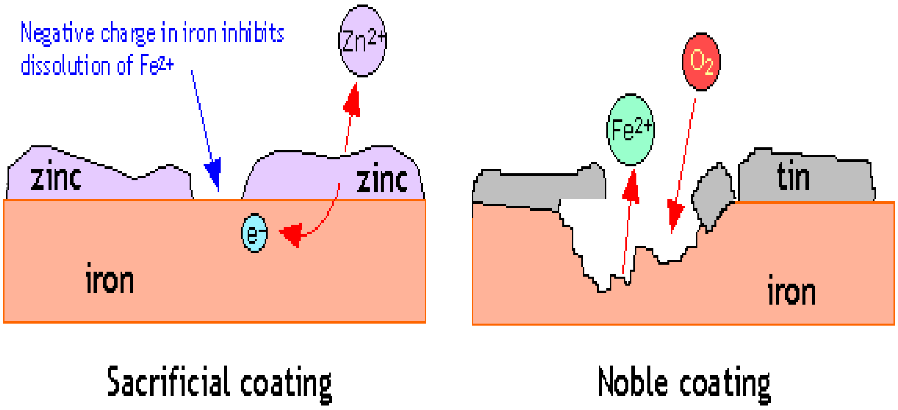


Figure 7.27 Sacrificial Coating and Noble Coating

Non Metal Coating

Examples of organic coatings are paint, tar, oil and varnish. While the inorganic coating is enamel.

Figure 7.28 Example of enamel

Plastic and oil are among the two main non-metallic materials used as coating materials

Figure 7.29 Plactic Coating

7.3.3 Cathodic protection

It is based on the galvanic action between the metals of the anode and cathode suspended in the solution.The metals to be protected is made a cathode.

Electrons are supplied, there by dissolution of metal is suppressed.

It can be achieved by:

- Sacrificial anode method
- Impressed emf method

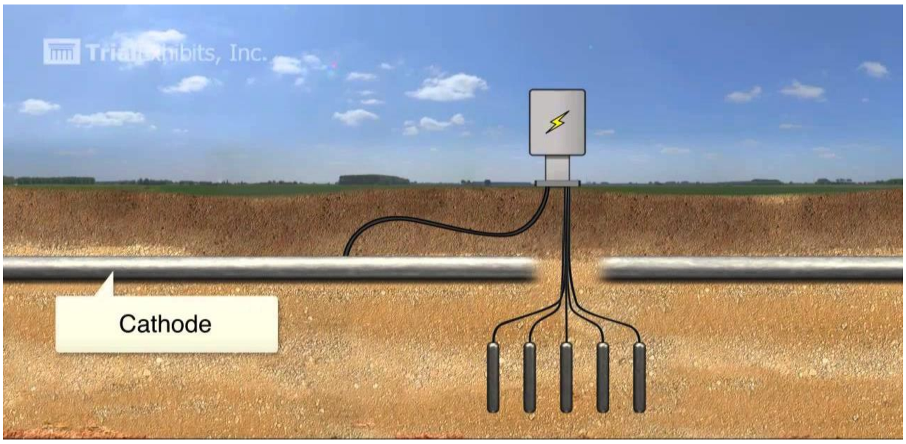


Figure 7.30 Cathodic protection for piping system

A more sophisticated strategy is to maintain a continual negative electrical charge on a metal, so that its dissolution as positive ions is inhibited.

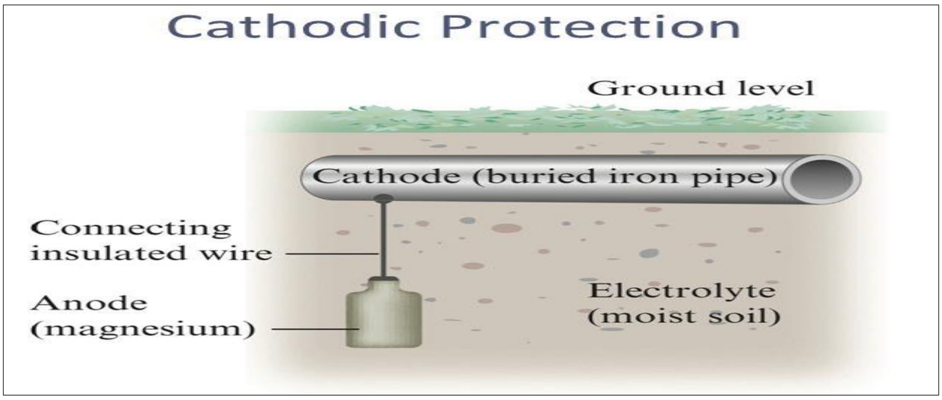


Figure 7.31 Cathodic protection for piping system

The source of electrons can be an external direct current power supply (commonly used to protect oil pipelines and other buried structures), or it can be the corrosion of another, more active metal such as a piece of zinc or aluminum buried in the ground nearby, as is shown in the illustration of the buried propane storage tank below.

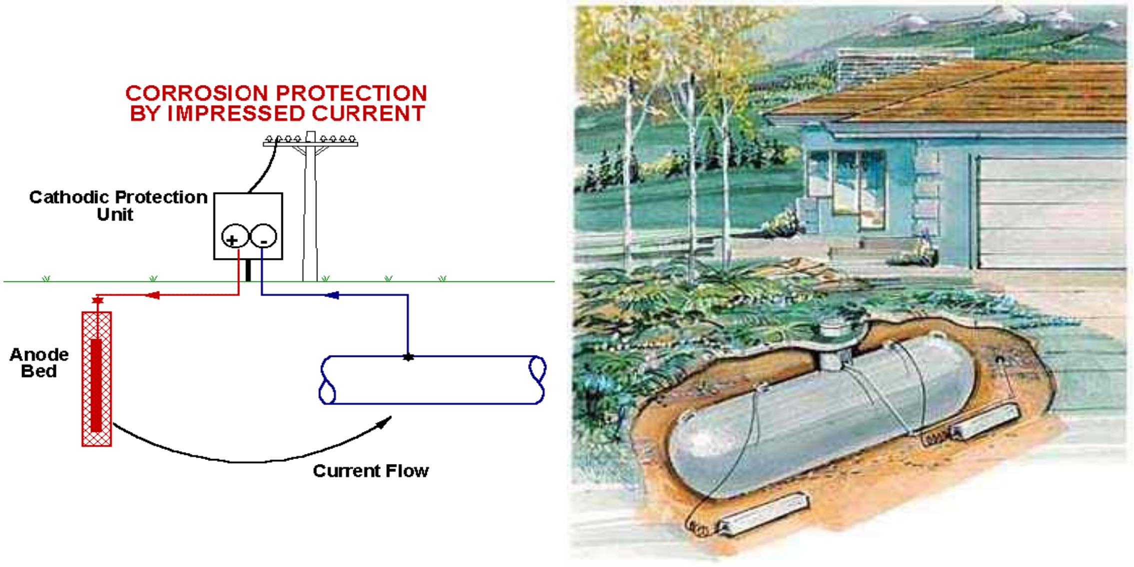


Figure 7.32 Cathodic Protection

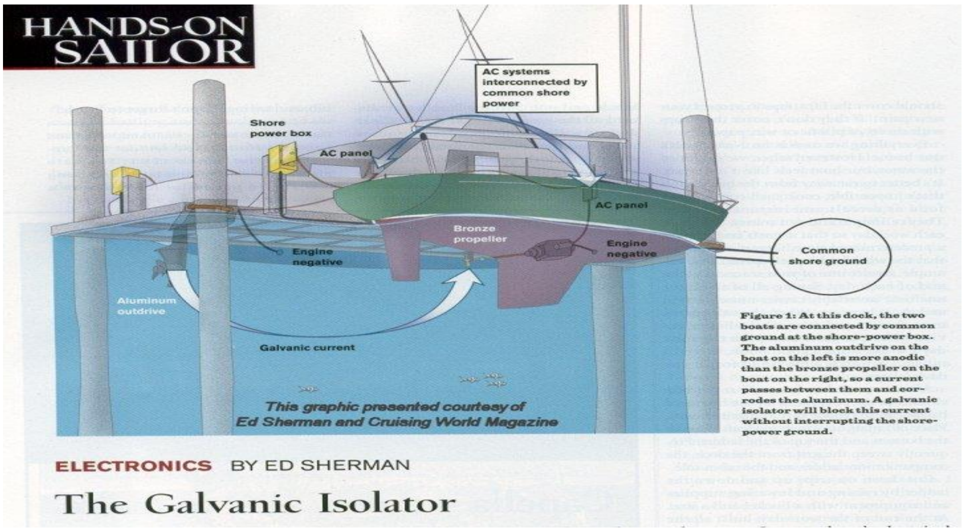


Figure 1: At this dock, the two boats are connected by common ground at the shore-power box. The aluminum outdrive on the boat on the left is more anodic than the bronze propeller on the boat on the right, so a current passes between them and corrodes the aluminum. A galvanic isolator will block this current without interrupting the shore-power ground.

This graphic presented courtesy of Ed Sherman and Cruising World Magazine

ELECTRONICS BY ED SHERMAN

The Galvanic Isolator

Figure 7.33 Example of the hull

This protection means that the material that needs to be protected from corrosion is converted into a cathode due to the anode metal undergoing corrosion. The hull is usually made of steel and the propellant is made of bronze.

Steel is anodic while its propellant is cathodic and both are in seawater which is an electrolyte material. The hull will corrode due to its anodic properties, so to overcome this problem a material that is more anodic than bronze and steel is used as a corrosion resistor namely zinc metal.

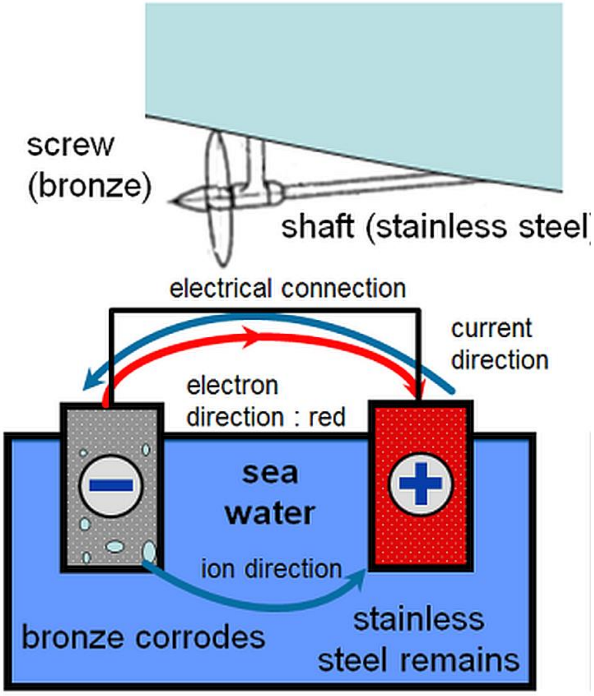


Figure 7.34 Cathodic Protection for boat

Zinc sheets are placed on the hull so that during the process of electrochemical corrosion occurs only zinc is corroded because it is the most anodic.These zinc sheets need to be replaced from time to time due to wear due to corrosion as in the diagram

Application of Cathodic Protection:

- Underground tanks
- Condenser water boxes
- Structures eg. Bridges
- Evaporators
- Valves, Piping and other metal surfaces submerged in a liquids or constructed underground.

DISCUSSION QUESTIONS

QUESTION 1

Explain two anti corrosion measures for steel jetty piles. (10 marks)-Dis16

ANSWER 1

Inorganic coating

Unprotected jetty steel piles with concrete jackets are expose to corroding environment such as sea water and weathering.

The outer surface of jetty piles are coating with high density polyethylene (HDPE) jacket to protect against weathering and mechanical damage.

Polymer coating are used to seal out oxygen and water effectively, stopping corrosion on steel surfaces.

The system forms an anti-corrosion barrier by displacing water and forming a moisture-resistant bond. The systems also prevent spalling and corrosion of steel reinforcement in concrete piles.

(choose other methods of corrosion prevention such as cathodic protection or inhibitors)

QUESTION 2

State FIVE (5) types of corrosion

ANSWER 2

i. Galvanic
ii. Stress and Fretting
iii. Oxidation
iv. Pitting
v. Uniform surface
vi. Intergranular

QUESTION 3

(b) Discuss FOUR (4) corrosion prevention methods

ANSWER 3

i. Design changes

The design of a structure is as equally important as the choice of materials for construction since it can greatly reduce the time and cost associated with corrosion maintenance and repair

ii. Inhibitors

Inhibitors are chemicals that react with the surface of a material decreasing the material's corrosion rate or interacting with the operating environment to reduce its corrosivity. The corrosion inhibitors are added to the environment to decrease the corrosion of metals.

iii. Coatings

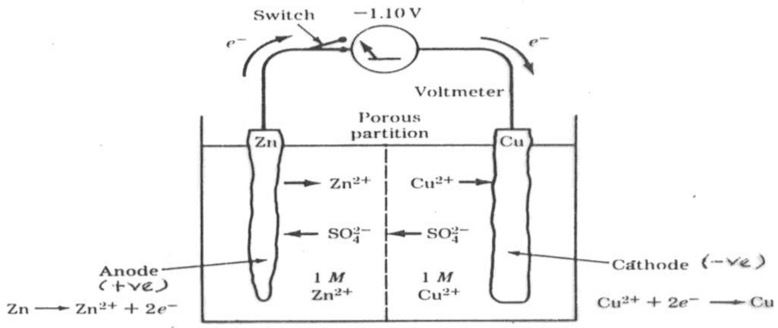
Non-metallic coatings and linings can be applied on steel and other materials of construction in order to combat corrosion

iv. Cathodic protection

- It is based on the galvanic action between the metals of the anode and cathode suspended in the solution.

PAST YEAR QUESTION:

1) Explain the basic principle in electrochemical corrosion.
   Diagram: Galvanic corrosion



[6 marks]

CHAPTER 8

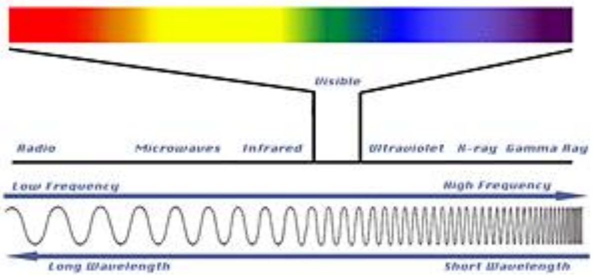
MATERIAL TESTING

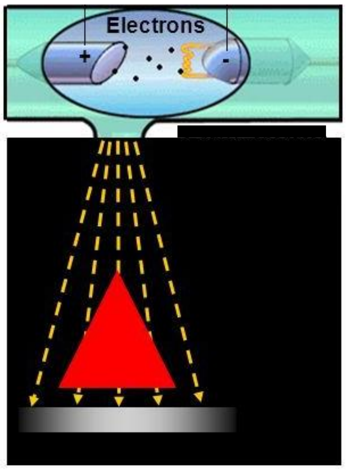
SYNOPSIS

This topic provides an understanding on the materials testing. It also explains the principles of destructive tests and non-destructive tests.

LEARNING OUTCOMES

8.1 Explain the purposes of materials testing
8.2 Define the principles of destructive tests
    a. Hardness tests
        i. Rockwell
        ii. Vickers microhardness
    b. Impact tests
        i. Izod
        ii. Charpy
8.3 Attain the principles of non-destructive tests
    a. Dye penetrant test
    b. Magnetic particle test
    c. Ultrasonic test
    d. Radiographic test





8.1 MATERIALS TESTING

Materials testing is the measurement of the properties and behaviour of materials like metals, ceramics, or polymers under different circumstances. The information so gathered can be used to describe whether a material is suitable for usage in a variety of applications, such as machinery, packaging, or building or aircraft construction.

The purpose of material testing:

1. To determine the quality of material
2. To determine the mechanical properties
3. To detect flaw in a product
4. To evaluate the performance of certain conditions of service

There are two types of tests for the materials:

i. Destructive Testing
ii. Non-Destructive Testing

Table 8.1 Differences between Destructive Testing and Non-Destructive Testing

Destructive Testing	Non-Destructive Testing
Used for finding out the properties of the material	Used for finding out defects of materials
Load is applied on the material	Load is not applied on the material
Due to load applications, material gets damaged	No load application so no material damage
Special equipment's are required	No requirement of special equipment's
Expensive	Non-expensive
Skill is required	Less skill
Examples: tensile test, compression test, hardness, impact test, torsion test creep test, shear and bending test, fatigue test	Examples: Dye penetrate test, ultrasonic, radiography, particle testing, magnetic particle testing

8.2 PRINCIPLES OF DESTRUCTIVE TESTS

Destructive testing involves applying different loads and causing the material to fail. In order to determine a material's mechanical properties, such as tensile strength, yield strength, hardness, impact toughness, elongation, etc., destructive testing is utilised.

a. Hardness tests

Hardness is the ability to withstand indentation or scratches.

i. Rockwell

Rockwell hardness measurements is automated and very simple to use; hardness is read directly, and each measurement requires only a few seconds. This apparatus also permits a variation in the time of load application. The Rockwell hardness test method consists of indenting the test material with a diamond cone or hardened steel ball indenter (figure 8.1). Figure 8.2 shows the Rockwell test determines the hardness by measuring the depth of penetration of an indenter under a large load compared to the penetration made by a preload.

(a) (b)

Figure 8.1 (a) Diamond cone and (b) hardened steel ball indenter

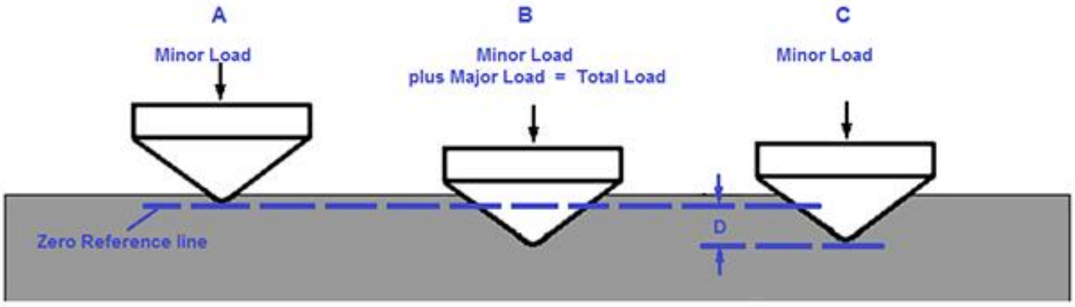
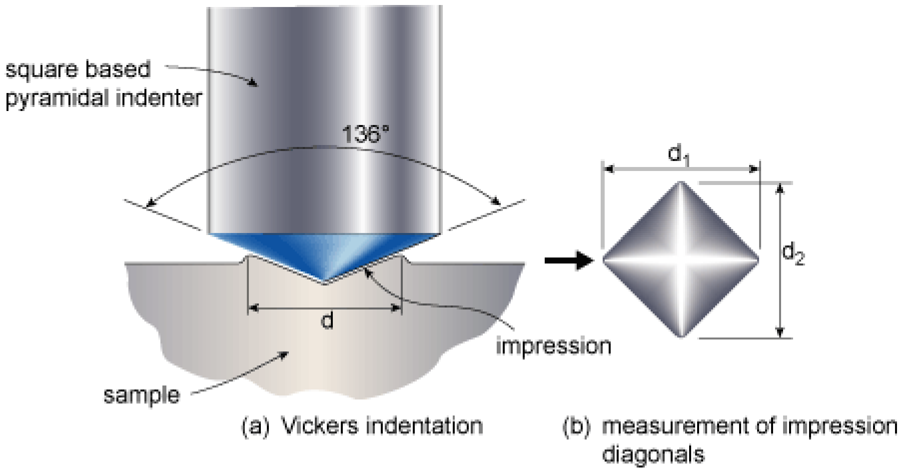


Figure 8.2 Applied load in Rockwell hardness test

ii. **Vickers microhardness**

The Vickers Hardness test method consists of indenting the test material with a diamond indenter (figure 8.3). Applied loads are much smaller than for the Rockwell and Brinell tests, ranging between 1 and 1000g. Table 8.2 shows example of Vickers hardness.



8.3 Vickers hardness test

Vickers hardness value (HV) measured as follows:

HV = load / indentation surface area (kg/mm2)

$HV = F / (d^2 / 2) \sin \frac{1}{2} (136^\circ)$

$HV = 2F \sin 68^\circ / d^2$

$HV = 1.854F / d^2$

Table 8.2 Example of Vickers Hardness

MATERIAL	VALUE
316L Stainless Steel	140HV30
347L Stainless Steel	180HV30
Carbon Steel	55-120HV5
Iron	30-80HV5

b. Impact tests

Impact tests are designed to measure the resistance to failure of a material to a suddenly applied force such as collision, falling object or instantaneous blow. The test measures the impact energy or the ability of material to absorb energy prior to fracture. The most common methods of measuring impact energy are Izod Test and Charpy Test. It is widely applied in industry, since it is easy to prepare and conduct and results can be obtained quickly and cheaply. Today it is utilized in many industries for testing materials, for example the construction of pressure vessels and bridges to determine how storms will affect the materials used.

i. Izod

The Izod test for determining toughness, or the tendency of a material to resist breaking on been subjected to sudden shock. The Izod test involves striking a suitable test piece with a striker, mounted at the end of a pendulum. Figure 8.4 shows the test sample is clamped vertically with the notch facing striker. The striker swings downwards impacting the test piece at the bottom of its swing.

ii. Charpy

The Charpy impact test also known as the Charpy V-notch test, is a standardized high strain-rate test which determines the amount of energy absorbed by a material during fracture. This absorbed energy is a measure of a given material’s notch toughness. In a Charpy test, a simple is laid horizontally on two supports against an anvil. The sample is notched in the centre and the notch side is positioned away from the pendulum. When the pendulum swings through the gap in the anvil, it impacts the centre of the sample with a radiused hammer. The energy to break is measured and reported in the same way with the Izod test.

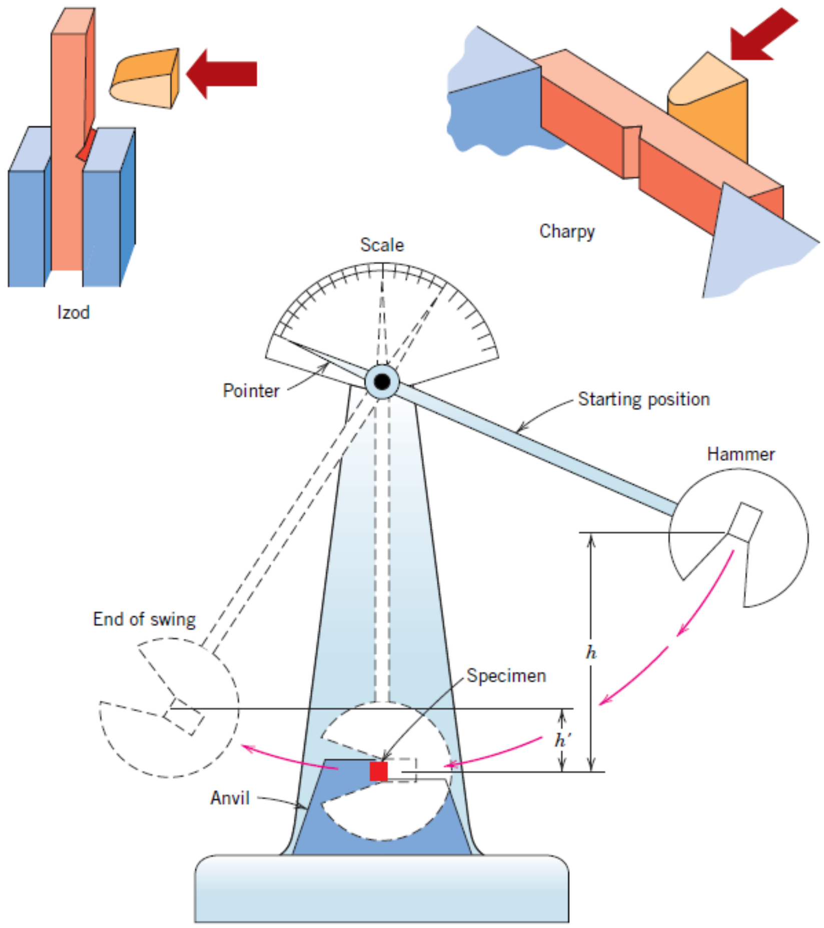


Figure 8.4 Impact Testing Apparatus (Addapted from Fig.8.12, Callister 9e)

8.3 NON-DESTRUCTIVE TESTS (NDT)

Non-destructive testing (NDT) is the process of inspecting materials for defects without causing damage to the test subject. As an industrial test technique, NDT offers a low-cost way to test while preserving the object's suitability for its intended use.

a. Dye penetrant test

The dye penetrant solvent removable method is most popular because it is low cost and very versatile. It typically comes in three aerosol cans such as cleaner, penetrant, and developer (figure 8.5). Table 8.3 are several advantages and disadvantages to using liquid penetrant examination.

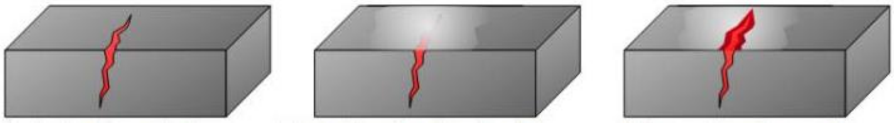
Figure 8.5 Dye penetrant solvent removable aerosol cans

Table 8.3 Advantaged and disadvantages for

Advantages	Disadvantages
High sensitivity to small surface discontinuities	Examiner must have direct access to surface being examined
Easy inspection of parts with complex shapes	Materials with porous surfaces cannot be examined using this process
Quick and inexpensive inspection of large areas and large volumes of parts/materials	Only clean, smooth surfaces can be inspected. (Rust, dirt, paint, oil and grease must be removed.)
Few material limitations (metallic and non-metallic, magnetic and nonmagnetic, and conductive and nonconductive can all be inspected)	Metal smearing from power wire brushing, shot blasting, or grit blasting must be removed prior to liquid penetrant examination.
A visual representation of the flaw is indicated directly on the part surface	Detects flaws only open to the surface
Aerosol spray cans make the process portable, convenient, and inexpensive	Surface finish and roughness can affect examination sensitivity. (It may be necessary to grind surfaces before PT.) Fumes can be hazardous and flammable without proper ventilation
Indications can reveal relative size, shape, and depth of the flaw	Post cleaning of parts and material is required, especially if welding is to be performed
It is easy and requires minimal amount of training	Proper handling and disposal of chemicals is required

The basic idea behind liquid penetrant testing is that the liquid penetrant is drawn into the surface-breaking crack by capillary action, and excess surface penetrant is then removed (figure 8.6). It is possible to find cracks that are 150 nanometres wide. Since the indicators created are much wider than the actual fault, they are simpler to see.

1)contaminated workpiece 2) cleaning the workpiece 3) applying the flaw detection ink



4) rising the workpiece 5) applying the dye developer 6) inspecting the crack

Figure 8.6 Dye penetrant testing for flaws

b. Magnetic particle test

One of the most often used NDT techniques is magnetic particle testing since it can be applied quickly, is very simple, and does not require as careful surface preparation of the component as some other techniques do. This technique looks for component faults using magnetic fields and tiny magnetic particles. Only that the component being inspected be made of a ferromagnetic material, such as iron, nickel, cobalt, or certain of their alloys, is necessary in terms of inspect ability.

Castings, forgings, and weldments are just a few of the product shapes that can be inspected using this technique. Magnetic particle inspection is used in a wide range of industries, including the structural steel, automotive, petrochemical, power generation, and aerospace sectors. Another area where magnetic particle inspection may be employed is underwater inspection, where items like offshore infrastructure and underwater pipelines can be tested.

The primary advantages and disadvantages when compared to other NDT methods are:

Advantages

- High sensitivity (small discontinuities can be detected).
- Indications are produced directly on the surface of the part and constitute a visual

- representation of the flaw.
- Minimal surface preparation (no need for paint removal)
- Portable (small portable equipment & materials available in spray cans)
- Low cost (materials and associated equipment are relatively inexpensive)

Disadvantages

- Only surface and near surface defects can be detected.
- Only applicable to ferromagnetic materials.
- Relatively small area can be inspected at a time.
- Only materials with a relatively nonporous surface can be inspected.
- The inspector must have direct access to the surface being inspected.

Basic Principles

In theory, magnetic particle testing has a relatively simple concept. It can be considered as a combination of two non-destructive testing methods: magnetic flux leakage testing and visual testing. For the case of a bar magnet, the magnetic field is in and around the magnet. Any place that a magnetic line of force exits or enters the magnet is called a “pole” (figure 8.7 shows magnetic lines of force exit the magnet from north pole and enter from the south pole).

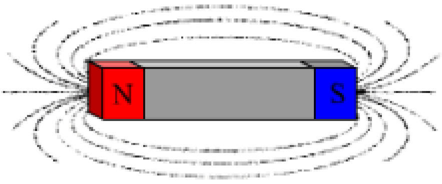


Figure 8.7 Magnet bar

When a bar magnet is broken in the centre of its length, two complete bar magnets with magnetic poles on each end of each piece will result. If the magnet is just cracked but not broken completely in two, a north and south pole will form at each edge of the crack. The magnetic field exits the north pole and re-enters at the south pole. The magnetic field spreads out when it encounters the small air gap created by the crack because the air cannot support as much magnetic field per unit volume as the magnet can. When the field spreads out, it appears to leak out of the material and, thus is called a flux leakage field (figure 8.8).

If iron particles are sprinkled on a cracked magnet, the particles will be attracted to and cluster not only at the poles at the ends of the magnet, but also at the poles at the edges of the crack.

This cluster of particles is much easier to see than the actual crack and this is the basis for magnetic particle inspection.

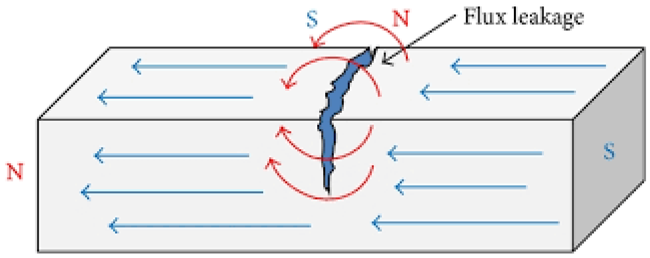


Figure 8.8 Flux leakage field

The first step in a magnetic particle testing is to magnetize the component that is to be inspected. If any defects on or near the surface are present, the defects will create a leakage field. After the component has been magnetized, iron particles, either in a dry or wet suspended form, are applied to the surface of the magnetized part. The particles will be attracted and cluster at the flux leakage fields, thus forming a visible indication that the inspector can detect.

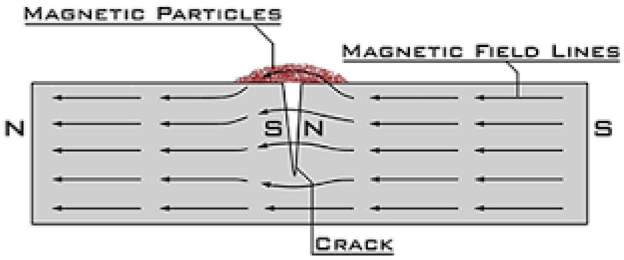


Figure 8.9 Magnetic particle testing

c. Ultrasonic test

Ultrasonic technology is widely utilised in engineering applications (such as flaw detection/evaluation, dimensional measurements, material characterization, etc.) as well as in the medical sector (such as sonography, therapeutic ultrasound, etc.). Ultrasonic testing (UT) used high frequency sound waves (usually between 0.5 and 15 MHz) to perform inspections and take measurements.

The primary advantages and disadvantages when compared to other NDT methods are:

Advantages

- It is sensitive to both surface and subsurface discontinuities.
- The depth of penetration for flaw detection or measurement is superior to other
- NDT methods.
- Only single-sided access is needed when the pulse-echo technique is used.
- It is highly accurate in determining the reflector position and estimating its size
- and shape.
- Minimal part preparation is required.
- It provides instantaneous results.
- Detailed images can be produced with automated systems.
- It is non-hazardous to operators or nearby personnel and does not affect the
- material being tested.
- It has other uses, such as thickness measurement, in addition to flaw detection.
- Its equipment can be highly portable or highly automated.

Disadvantages

- Surface must be accessible to transmit ultrasound.
- Skill and training are more extensive than with some other methods.
- It normally requires a coupling medium to promote the transfer of sound energy
- into the test specimen.
- Materials that are rough, irregular in shape, very small, exceptionally thin or not
- homogeneous are difficult to inspect.
- Cast iron and other coarse-grained materials are difficult to inspect due to low
- sound transmission and high signal noise.
- Linear defects oriented parallel to the sound beam may go undetected.
- Reference standards are required for both equipment calibration and the
- characterization of flaws.

Basic Principles

The pulser/receiver, transducer, and display device are among the various functional components that make up a conventional pulse-echo UT inspection system. An electronic device that can generate high voltage electrical pulses is known as a pulser or receiver. The transducer produces high frequency ultrasonic energy under the control of the pulser. Waves made of sound energy go through the materials after being introduced. A portion of the energy is reflected back from the fault surface when there is a break in the wave path (like a crack). The transducer converts the reflected wave signal into an electrical signal, which is then shown on a screen. The signal's travel time can be calculated from its velocity to determine how far it travelled. From the signal, information about the reflector location, size, orientation and other features can sometimes be gained.

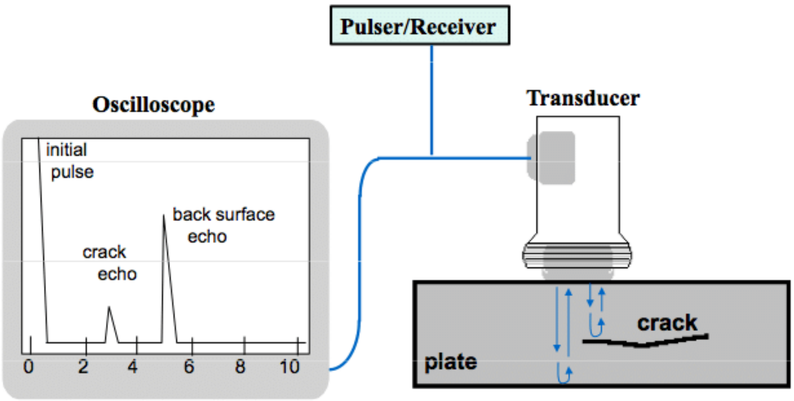


Figure 8.10 UT inspection system

d. Radiographic test

Radiography is used in a very wide range of applications including medicine, engineering, forensics, security, etc. In NDT, radiography is one of the most important and widely used methods. Radiographic testing (RT) offers a number of advantages over other NDT methods, however, one of its major disadvantages is the health risk associated with the radiation.

In general, RT is method of inspecting materials for hidden flaws by using the ability of short wavelength electromagnetic radiation (high energy photons) to penetrate various materials. The intensity of the radiation that penetrates and passes through the material is either captured by a radiation sensitive film (Film Radiography) or by a planer array of radiation sensitive sensors (Real-time Radiography). Film radiography is the oldest approach, yet it is still the most widely used in NDT. The primary advantages and disadvantages as compared to other NDT methods are:

Advantages

- Both surface and internal discontinuities can be detected.
- Significant variations in composition can be detected.
- It has a very few material limitations.
- Can be used for inspecting hidden areas (direct access to surface is not required)
- Very minimal or no part preparation is required.
- Permanent test record is obtained.
- Good portability especially for gamma-ray sources.

Disadvantages

- Hazardous to operators and other nearby personnel.
- High degree of skill and experience is required for exposure and interpretation.
- The equipment is relatively expensive (especially for x-ray sources).
- The process is generally slow.
- Highly directional (sensitive to flaw orientation).
- Depth of discontinuity is not indicated.
- It requires a two-sided access to the component.

Basic Principles

In radiographic testing, the part to be inspected is placed between the radiation source and a piece of radiation sensitive film. The radiation source can either be an X-ray machine or a radioactive source (Ir-192, Co-60, or in rare cases Cs-137). The part will stop some of the radiation where thicker and more dense areas will stop more of the radiation. The radiation that passes through the part will expose the film and forms a shadowgraph of the part. The film darkness (density) will vary with the amount of radiation reaching the film through the test object where darker areas indicate more exposure (higher radiation intensity) and lighter areas indicate less exposure (lower radiation intensity). This variation in the darkness of the picture can be used to determine the thickness or composition of the material and would also reveal the presence of defects or discontinuities within the material.

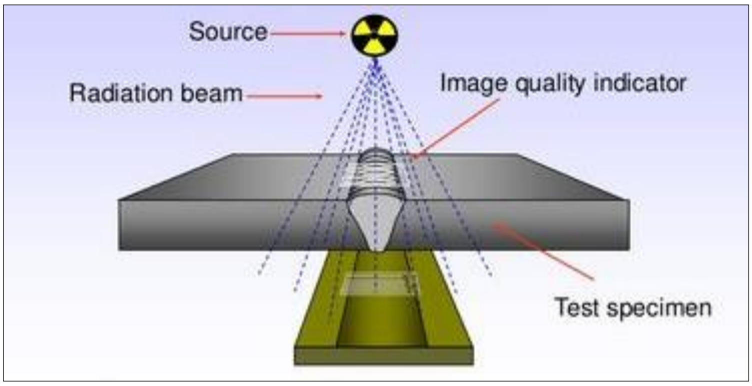


Figure 8.11 Radiographic testing

DISCUSSION QUESTIONS

QUESTION 1

(a) Non-destructive testing is one of the methods in material testing

i) Write THREE (3) types of Non-destructive test [3marks]

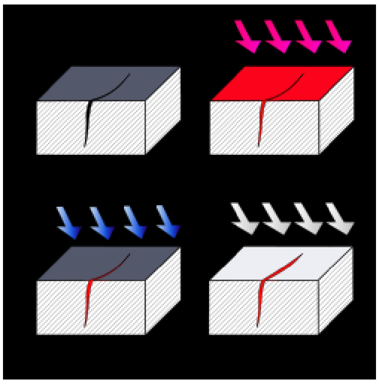
Answer

i. Dye penetrant inspection
ii. Magnetic particle inspection
iii. Ultrasonic inspection
iv. Radiographic inspection

ii) Sketch diagram of ONE (1) type of non-destructive testing that has been mentioned above with a brief explanation. [9marks]

ANSWER 1

Dye penetrant inspection



1. Section of material with a surface-breaking crack that is not visible to the naked eye.
2. Penetrant is applied to the surface
3. Excess penetrant is removed.
4. Developer is applied, rendering the crack visible.
5. Section of material with a surface-breaking crack that is not visible to the naked eye

PAST YEARS' QUESTIONS:

1) Explain Procedures of dye penetrant test. [10 marks] Jun 17 & Jun 16
2) Illustrate Vickers Hardness Test with a suitable sketch. [9 marks] Jun 17
3) An impact test is done to determine material toughness or impact strength in the presence of a flaw or notch of a material. with the aid of a diagram, explain about the Izod Test and Charphy test in material testing. [10 marks] Dis16
4) Ultrasonic testing is used to locate surface and subsurface defects in many materials including metals, plastics and wood. Explain about the principle of Ultrasonic Testing of materials and state 3 advantages of the test. [9 marks] Dis16
5) Rockwell hardness Test conducted with aim to determine the level of hardness of a substance. With the aid of diagrams, explain clearly the principle of the test conducted. [10 marks] Jun 16

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