Materials Science: An Introduction

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Spark…
The Change

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Materials by themselves do nothing; yet without materials man can do nothing.

Nature itself is a self-ordered structure which developed through time by the utilization of the same properties of atomic hierarchy that man presides over in his simple constructions.

Not only are we consuming materials more rapidly, but we are using an increasing diversity of materials.

A great new range of materials has opened up for the use of 20th-century man: refractory metals, light alloys, plastics, and synthetic fibers, for example.

Some of these do better, or cheaper, what the older ones did; others have combinations of properties that enable entirely new devices to be made or quite new effects to be achieved.

We now employ in industrial processes a majority of the ninety-two elements in the periodic table which are found in nature, whereas until a century ago, all but 20, if known at all, were curiosities of the chemistry laboratory.

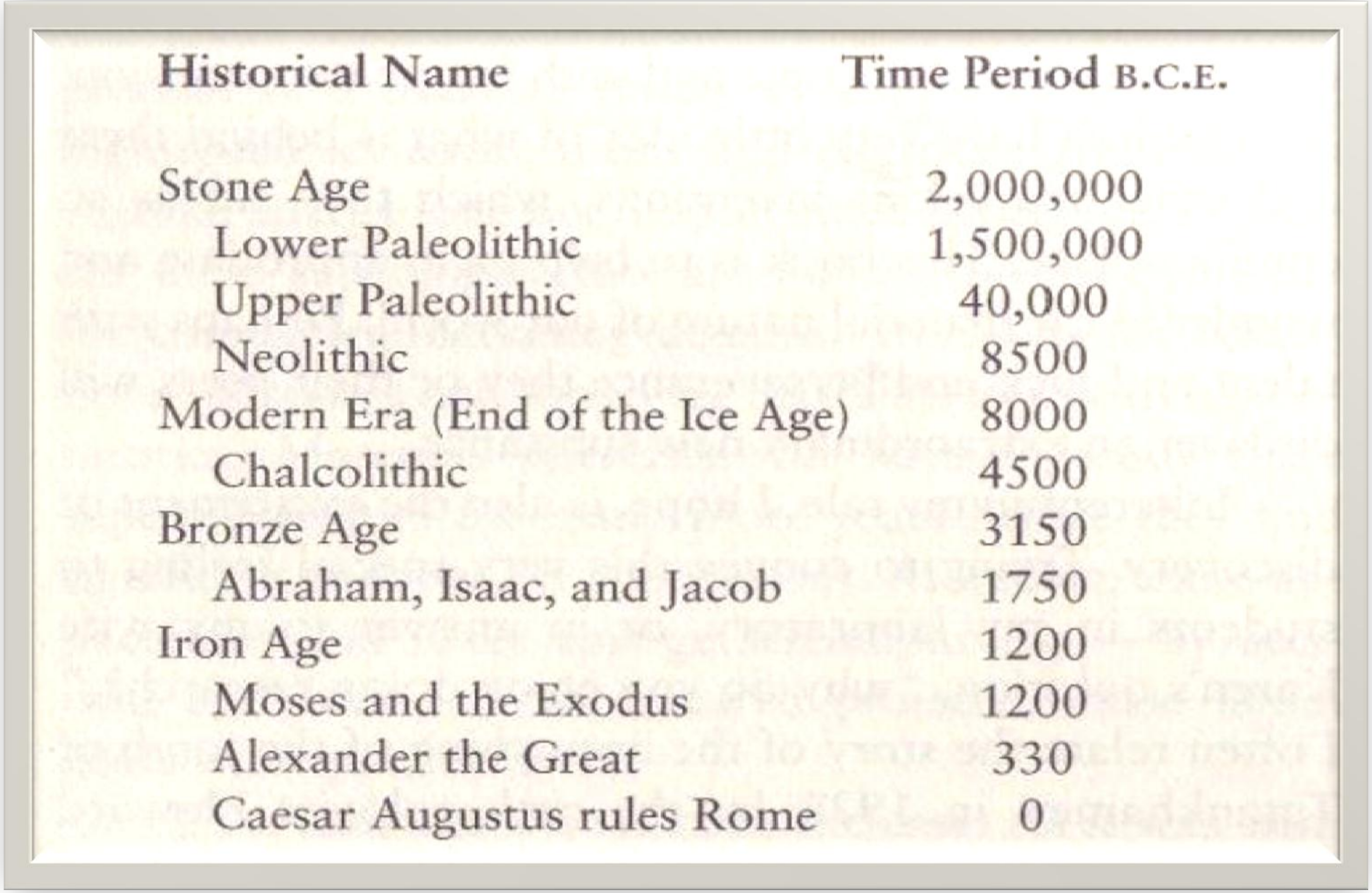
Not only are more of nature's elements being put into service, but completely new materials are being synthesized in the laboratory.

Materials have somewhat the quality of letters in the alphabet in that they can be used to compose many things larger than themselves;

- amber, gold jewelry, and iron ore inspired commerce and the discovery of many parts of the world;
- improvements in optical glass lies behind all the knowledge revealed by the microscope;
- conductors, insulators, and semiconductors were needed to construct new communication systems which today affect the thought, work, and play of everyone.
- Alloy steel permitted the development of the automobile;
- titanium the space program.

The transitions from, say, stone to bronze and from bronze to iron were revolutionary in impact, but they were relatively slow in terms of the time scale.

The changes in materials innovation and application within the last half century occur in a time span which is revolutionary rather than evolutionary.



Historical Name	Time Period B.C.E.
Stone Age	2,000,000
Lower Paleolithic	1,500,000
Upper Paleolithic	40,000
Neolithic	8500
Modern Era (End of the Ice Age)	8000
Chalcolithic	4500
Bronze Age	3150
Abraham, Isaac, and Jacob	1750
Iron Age	1200
Moses and the Exodus	1200
Alexander the Great	330
Caesar Augustus rules Rome	0

The Substance of civilization: Materials and Human History
by Stephen L Sass

Materials and civilisation

Stone age

(Before 5000 BC)

Copper age

(5000 - 3000 BC)

Bronze age

(3000 - 800 BC)

Iron age

(800 BC - 40 AD)

Plastic age ?

Types of materials

Metal

Ceramic

Polymer

Semiconductors

Biomaterials

Composites

Molecular materials

Materials Science and Engineering

- ✓ The word 'materials' here does not refer to all matter in the Universe.
- ✓ If this were so, it would include all the physical sciences and the life sciences- from astronomy to zoology!
- ✓ By including the word 'inanimate' in the definition, we can exclude the life sciences from our purview.
- ✓ Further, we can restrict the definition only to matter useful to mankind.
- ✓ Even here, the range is too broad for the purposes of the engineer. For example, we can list a large number of things useful to man, such as food, medicines, explosives, chemicals, water, steel, plastics and concrete, only some of which qualify as engineering materials.
- ✓ *We then have to be more specific and define materials as that part of inanimate matter, which is useful to the engineer in the practice of his profession.*
- ✓ In the currently understood sense of the term, **materials refer only to solid materials,** even though it is possible to quote a number of examples of liquid and gaseous materials such as sulphuric acid and steam, which are useful to the engineer

- The word '**science'** refers to the physical sciences, in particular to chemistry and physics. As we confine ourselves mainly to solids in materials science, the subject is related to solid state chemistry and solid state physics.
- The word '**engineering** indicates that the engineering usefulness of the matter under study is always kept in mind, irrespective of whether the basic laws of science can be applied rigorously or not.
- Where the basic laws cannot be applied, the materials engineer does not give up what is important to him from a practical point of view. He uses the best possible approximation, develops empirical rules, and extrapolates available information to unknown situations.
- In this respect, materials science and engineering draws heavily from the engineering sciences such as metallurgy, ceramics and polymer science.
- These in their own time, have grown out of their interaction with the basic sciences of chemistry and physics.

Classification of Engineering Materials

We can classify them in three broad groups according to their nature:

1) **Metals and alloys**

Metals are familiar objects with a characteristic appearance; they are capable of changing their shape permanently, and have good thermal and electrical conductivity.

An **alloy** is a combination of more than one metal.

Examples: Steels, aluminium, copper, silver, gold Brasses, bronzes, manganin, Ga invar G Superalloys Boron rare earth magnetic alloys

2) **Ceramics and glasses**

Nonmetallic inorganic substances, which are brittle and have good thermal and electrical insulating properties.

Examples: MgO, CdS, Al,O3, SiC, BaTiO3 Silica, soda-lime-glass, Concrete, cement, Ferrites and garnets Ceramic superconductors

3) **Organic polymers**

Relatively inert and light, and generally have a high degree of plasticity.

Examples: Plastics: PVC, PTFE, Polyethylene Fibres: terylene, nylon, cotton, Natural and synthetic rubbers Leather.

Other examples include materials which lie between two groups are:

Metal-reinforced plastics , Glass fibre-reinforced plastics ,

Si, Ge, GaAs, Boride –reinforced steel

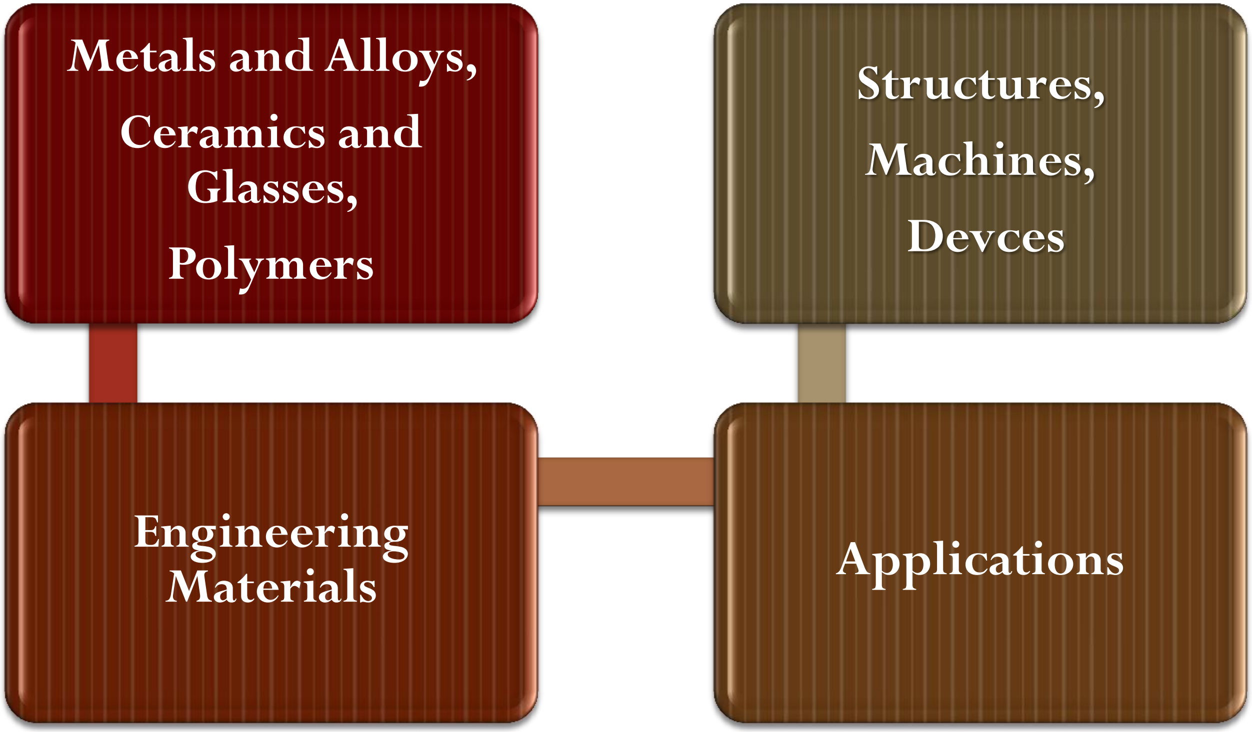
An alternative way of classifying materials is according to the three major areas in which they are used:

1) **Structures** (not to be confused with the internal structure of a material) refer to the objects without moving parts erected by engineers, such as a concrete dam, a steel melting furnace, a suspension bridge and an oil refinery tower.
2) **Machines** include lathes, steam and gas turbines, engines, electric motors and generators.
3) **Devices** are the most recent addition to engineering materials and refer to such innovations as a transistor, a photoelectric cell, piezoelectric pressure gauges, ceramic magnets and lasers.

Each category of applications, may include materials from all the three groups.

For example, an aircraft structure is built of aluminium alloys and plastics;
Steel melting furnace is built of refractory oxides and structural steel;
Safety helmets are made of glass-reinforced plastics.
Similarly, we have metal-oxide semiconductors.

The block diagram showing interplay between material groups and categories of applications



Metals and Alloys,
Ceramics and Glasses,
Polymers

Structures,
Machines,
Devces

Engineering Materials

Applications

Each category of engineering application requires materials from any or all of the three groups of materials.

Levels of Structure

- ➢ The internal structure of a material, simply called the structure, can be studied at various levels of observation.
- ➢ The magnification and resolution of the physical aid used are a measure of the level of observation.
- ➢ The higher the magnification, the finer is the level.
- ➢ The details that are disclosed at a certain level of observation are generally different from the details disclosed at some other level.

Depending on the level, we can classify the structure of materials as:

- Macrostructure
- Microstructure
- Substructure
- Crystal structure
- Electronic structure
- Nuclear structure.

Macrostructure

- examined with naked eye or under a low magnification.
- The internal symmetry of the atomic arrangements in a crystalline material may reflect in the external form of a crystal such as quartz.
- Large individual crystals of a crystalline material may be visible to the naked eye, as in a brass doorknob by the constant polishing and etching action of the human hand and sweat.

Microstructure

- generally refers to the structure as observed under the optical microscope.
- This microscope can magnify a structure up to about 1500 times linear, without loss of resolution of details of the structure.
- The limit of resolution of the human eye is about 0.1 mm (10^{-4}m), that is, the eye can distinguish two lines as separate lines, only when their distance of separation is more than 0.1 mm.
- The optical microscope can resolve details down to a limit of about 0.1 um (10^{-7} m).

Substructure

- Refers to the structure obtained by using a microscope with a much higher magnification and resolution than the optical microscope.
- In an ***electron microscope***, a magnification of 10,00,000 times linear is possible.
- By Virtue of the smaller wavelength of electrons as compared to visible light, the resolving power also increases correspondingly so that much finer details show up in the electron microscope.
- We can obtain a wealth of additional information on very fine particles or on crystal imperfections such as dislocations in a transmission electron microscope.
- Here, electrons pass through a thin foil of the specimen and the associated diffraction effects produce the image.
- The electron diffraction patterns obtained along with the photograph of the substructure greatly aid in understanding the processes taking place in materials on such a minute scale.

In a **scanning electron microscope**, an electron beam is scanned across the surface of the specimen, which must be conducting. Back scattered electrons at each point are collected and displayed at the same scanning rate on a cathode ray tube. The result is an image, much like a television image, of the surface features of the specimen. This image has a very great depth of field so that even a fractured surface without any polishing can be imaged. Magnifications range from 10 x to 50 000 x.

In the **electron probe microanalyzer**, a beam of electrons bombards the specimen surface. X-rays that have wavelengths characteristic of the elements in the specimen are emitted. Using suitable standards, elements present in the specimen can be identified and their concentration determined from the X-ray intensity. Thus this technique allows **microchemical analysis** on spots as small as 1 um.

Another modern microscope is the **field ion microscope**. It produces images of individual atoms and imperfections in atomic arrangements.

Crystal structure tells us the details of the atomic arrangement within a Crystal. It is usually sufficient to describe the arrangement of a few atoms within what is called a unit cell. The crystal consists of a very large number of unit cells forming regularly repeating patterns in space. The main technique employed for determining the crystal structure is the X-ray diffraction.

The **electronic structure** of a solid usually refers to the electrons in the outermost orbitals of individual atoms that constitute the solid. Spectroscopic techniques are very useful in determining the electronic structure.

Nuclear structure is studied by nuclear spectroscopic techniques such as nuclear magnetic resonance (NMR) and Mossbauer studies.

Structure-Property Relationships in Materials

Our knowledge of the internal structure of materials and how this structure correlates with the properties has rapidly advanced in recent decades.

So, it is more interesting and appropriate to study some of the key factors that determine the structure-property relationships, rather than go for a fully descriptive account of a large number of materials.

The levels of structure which are of the greatest interest in materials science and engineering are the microstructure, the substructure and the crystal structure.

The chemical, mechanical, electrical and magnetic properties are among the most important engineering properties.

We first develop the basic concepts pertaining to the levels of structure.

- ✓ These include concepts in equilibrium and kinetics, the geometry of crystals, the arrangement of atoms in the unit cell of crystalline materials, the substructural imperfections in crystals, and the microstructure of single phase and multi-phase materials.
- ✓ We then discuss how changes in the structure are brought about and how they can be controlled to the best possible advantage.

The gross composition of a material is important in determining its structure. Yet, for a given gross composition, radical changes in the structure and properties can be brought about by subtle changes in the concentration and distribution of minute quantities of impurities. The same may also be possible haw a thermal or a mechanical treatment that involves no change in the overall composition of the material.

Materials Science and Engineering deals more with this kind of changes rather than with the effect of gross composition on the properties.

CERAMICS

- ✓ A ceramic material is an inorganic, non-metallic, often crystalline oxide, nitride or carbide material.
- ✓ Some elements, such as carbon or silicon, may be considered ceramics.
- ✓ Ceramic materials are brittle, hard, strong in compression, and weak in shearing and tension.
- ✓ They withstand chemical erosion that occurs in other materials subjected to acidic or caustic environments.
- ✓ Ceramics generally can withstand very high temperatures, ranging from 1,000°C to 1,600°C.
- ✓ Glass is often not considered a ceramic because of its amorphous (noncrystalline) character. However, glassmaking involves several steps of the ceramic process, and its mechanical properties are similar to ceramic materials.

The term "ceramic" comes from the Greek word *keramikos,* which means "burnt stuff," indicating that desirable properties of these materials are normally achieved through a high-temperature heat treatment process called firing.

Traditional ceramic raw materials include:

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

A **ceramic** is any of the various hard, brittle, heat-resistant and corrosion-resistant materials made by shaping and then firing a nonmetallic mineral, such as clay, at a high temperature.
Examples: earthenware, porcelain, and brick.

- The earliest ceramics made by humans were pottery objects (i.e. *pots* or *vessels*) or figurines made from clay, either by itself or mixed with other materials like silica, hardened and sintered in fire.
- Later ceramics were glazed and fired to create smooth, colored surfaces, decreasing porosity through the use of glassy, amorphous ceramic coatings on top of the crystalline ceramic substrates.

Ceramics now include domestic, industrial and building products, as well as a wide range of ceramic art.
New ceramic materials were developed in the 20th century, for use in advanced ceramic engineering, such as in semiconductors.

History

- Human beings appear to have been making their own ceramics for at least 26,000 years, subjecting clay and silica to intense heat to fuse and form ceramic materials.
- The earliest known pottery was made by mixing animal products with clay, and baked in kilns at up to 800 °C. While actual pottery fragments have been found up to 19,000 years old, it was not until about ten thousand years later that regular pottery became common.
- An early people that spread across much of Europe is named after its use of pottery, the Corded Ware culture. These early Indo-European peoples decorated their pottery by wrapping it with rope while still wet. When the ceramics were fired, the rope burned off but left a decorative pattern of complex grooves in the surface.

The invention of the wheel eventually led to the production of smoother, more even pottery using the wheel-forming technique, like the pottery wheel.

Early ceramics were porous, absorbing water easily. It became useful for more items with the discovery of glazing techniques, coating pottery with silicon, bone ash, or other materials that could melt and reform into a glassy surface, making a vessel less pervious to water.

Properties ……………

The physical properties of any ceramic substance are a direct result of its crystalline structure and chemical composition.

Mechanical properties

Mechanical properties are important in structural and building materials as well as textile fabrics.

Ceramic materials are usually ionic or covalent bonded materials, and can be crystalline or amorphous. A material held together by either type of bond will tend to fracture before any plastic deformation takes place, which results in poor toughness in these materials.

Additionally, because these materials tend to be porous, the pores and other microscopic imperfections act as stress concentrators, decreasing the toughness further, and reducing the tensile strength. These combine to give catastrophic failures, as opposed to the more ductile failure modes of metals.

These materials do show plastic deformation. However, because of the rigid structure of the crystalline materials, there are very few available slip systems for dislocations to move, and so they deform very slowly. With the non-crystalline (glassy) materials, viscous flow is the dominant source of plastic deformation, and is also very slow. It is therefore neglected in many applications of ceramic materials.

Electrical properties

Some ceramics are semiconductors. Most of these are transition metal oxides that are II-VI semiconductors, such as zinc oxide.

GLASSES

The glasses are a familiar group of ceramics; containers, lenses, and fiberglass represent typical applications.

They are noncrystalline silicates containing other oxides, notably CaO, Na_2O, K_2O, and Al_2O_3, which influence the glass properties.

A typical soda–lime glass consists of approximately 70 wt% SiO_2, the balance being mainly Na_2O (soda) and CaO (lime).

Possibly the two prime assets of these materials are their optical transparency and the relative ease with which they may be fabricated.

GLASS–CERAMICS

Most inorganic glasses can be made to transform from a noncrystalline state to one that is crystalline by the proper high-temperature heat treatment. This process is called **crystallization,** and the product is a fine-grained polycrystalline material which is often called a **glass–ceramic.**

The formation of these small glass-ceramic grains is, in a sense, a phase transformation, which involves nucleation and growth stages.

As a consequence, the kinetics (i.e., the rate) of crystallization may be described using the same principles that were applied to phase transformations for metal systems.

A nucleating agent (frequently titanium dioxide) is often added to the glass to promote crystallization.The presence of a nucleating agent shifts the begin and end transformation curves to shorter times.

Properties and Applications of Glass–Ceramics

- Glass-ceramic materials have been designed to have relatively high mechanical strengths; low coefficients of thermal expansion (to avoid thermal shock); relatively high temperature capabilities; good dielectric properties (for electronic packaging applications); and good biological compatibility.
- Some glass–ceramics may be made optically transparent; others are opaque.
- Possibly the most attractive attribute of this class of materials is the ease with which they may be fabricated; conventional glass-forming techniques may be used conveniently in the mass production of nearly pore-free ware.
- Glass–ceramics are manufactured commercially under the trade names of Pyroceram™, Corningware™, Cercor™, and Vision™.
- The **most common uses for these materials** are as ovenware, tableware, oven windows, and rangetops—primarily because of their strength and excellent resistance to thermal shock. They also serve as electrical insulators and as substrates for printed circuit boards, and are used for architectural cladding, and for heat exchangers and regenerators.

POLYMERS

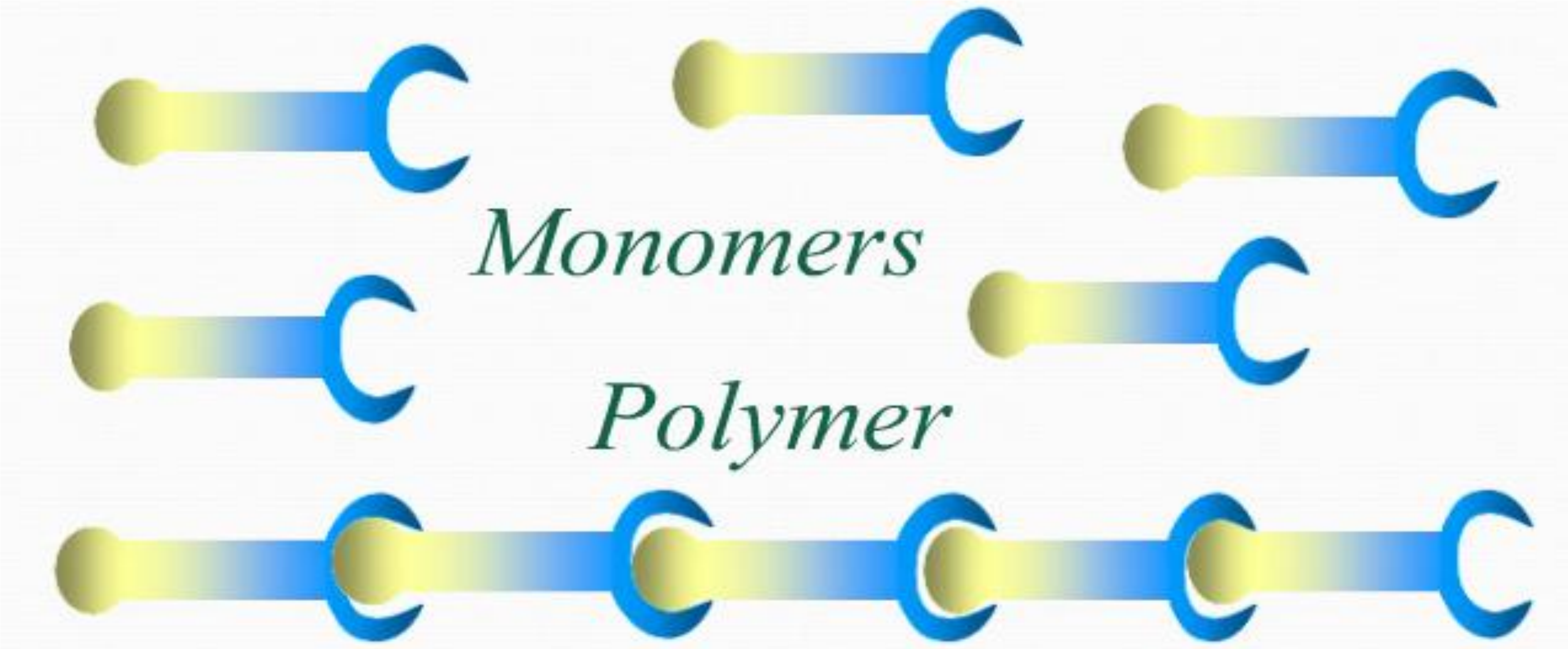
- The earliest synthetic polymer was developed in 1906, called Bakelite.
- The development of modern plastics started in 1920s using raw material extracted from coal and petroleum products (Ethylene). Ethylene is called a building block.
- Polymers are long-chain molecules and are formed by polymerization process, linking and cross linking a particular building block (***monomer***, a unit cell).
- The term polymer means many units repeated many times in a chainlike structure.
- Most monomers are organic materials, atoms are joined in covalent bonds (electron-sharing) with other atoms such as oxygen, nitrogen, hydrogen, sulfur, chlorine,….

Products from Bakelite

Polymer Building Blocks

- Hydrogen
- Carbon (key)
- Oxygen
- Nitrogen
- Fluorine
- Silicon
- Sulfur
- Chlorine

Monomer to Polymer



The word, polymer, implies that polymers are constructed from pieces (monomers) that can be easily connected into long chains (polymer).

Polymer Microstructure

- The word (poly)-(mer) means (many)-(parts) and refers to molecules consisting of many elementary units, called monomers (an unreacted small molecule capable of polymerizing).
- Monomers are structural repeating units of a polymer that are connected to each other by covalent bonds.
- Since monomer can mean anything that repeats along the chain, two types of monomers are important.
- **Chemical monomers** are the repeating unit that corresponds to the small molecules that were linked together to make the polymer chain.

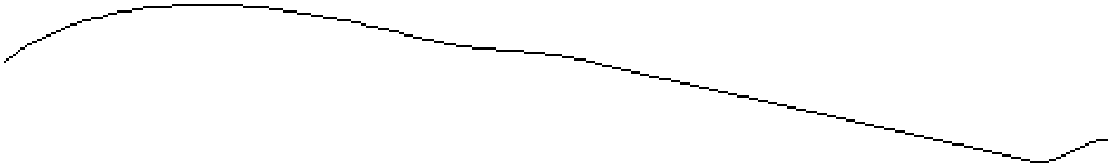
- **The entire structure of a polymer is generated during polymerization, the process by which elementary units (chemical monomers) are covalently bonded together.**
- **The number of monomers in a polymer molecule is called its degree of polymerization N**
- **The molar mass of a polymers is equal to its degree of polymerization N times the molar mass M_{mon} of its chemical monomer:**
  - $M = NM_{mon.}$
- **Repeat unit of the polymer is usually equivalent or nearly equivalent to the monomer, e.g. repeat unit of Ploy Vinyl Chloride (PVC) is - CH_2 CHCl- , its monomer is vinyl chloride $CH_2 = CHCl$**

- Polymers are used as dielectrics.
- The length of polymer chain is specified as the number of repeat unit in the chain and this is called the Degree of Polymerization (DP), i.e.,
- Degree of polymerization = length of polymer chain

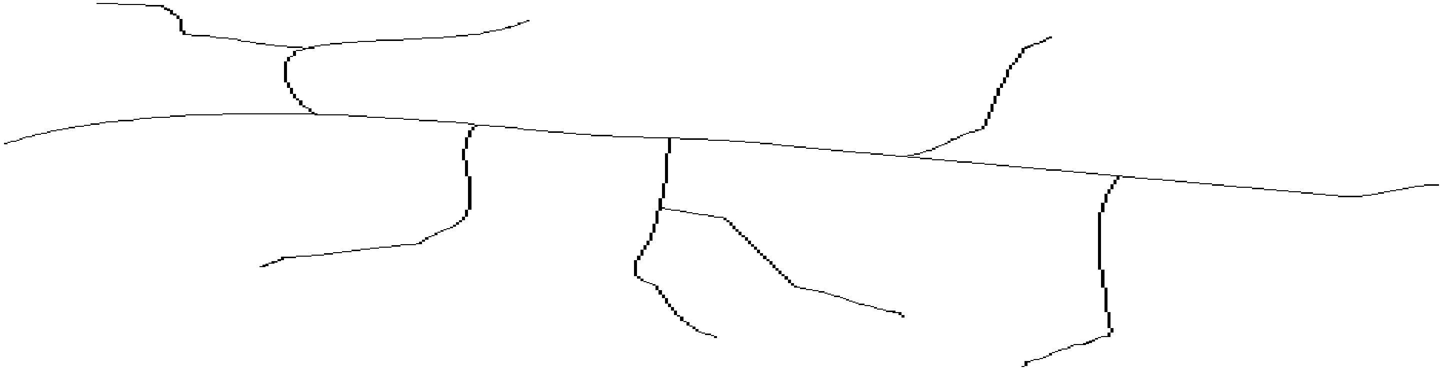
  = number of repeat units
- The molecular weight of a polymer is the product of the molecular weight of the repeat unit and the DP; e.g., the mole. Wt. of PVC having DP=1000 is 63 x 1000 = 63000.

- **Most high polymers useful for plastics, rubbers or fibres have monomer species are used to form the molecular weight between 10^4 & 10^6**
- **Polymers were first called anomalous because their properties were different from those of linear molecular weight compounds.**
- **If only one type of monomer is used to form the polymer, the resulting molecule is called homopolymer, whereas, when different monomer species are used to form the polymer, it is called copolymer.**
- **Polymers are also called tailor made materials.**
- **Polymer molecules are many times larger than those of ordinary substances**

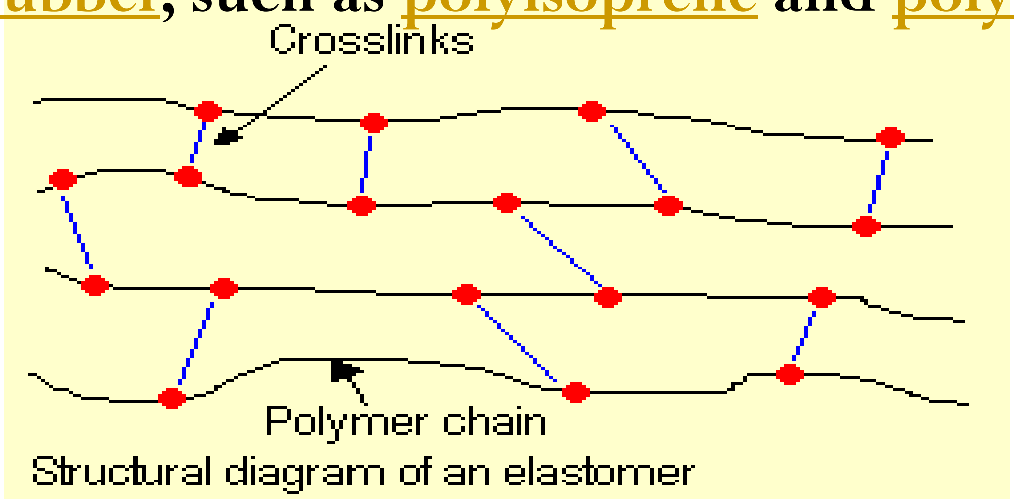
- If the repeat units are arranged in a single stranded structure, the molecule is said to be linear



- If the linear chain has side-chain appendages, where each molecule **is** still separate and discrete from its neighbours, the molecule is said to be nonlinear and referred to as branched polymer. **Sometimes there are chains attached to the backbone chain which are comparable in length to that backbone chain. This is called a *branched polymer*. Some polymers, like polyethylene, can be made in linear or branched versions.**



- **The branch chains have some strange habits. Sometimes, *both* ends of the branch chains are attached to the backbone chains of separate polymer molecules.**
- **If enough branch chains are attached to two polymer molecules, it can happen that *all* of the polymer backbone chains in a sample will be attached to each other in one giant network! When this happens, the sample is in fact one single molecule, a molecule large enough to pick up. Polymers like this are called crosslinked polymers.**
- **Many types of rubber, such as polyisoprene and polybutadiene, are crosslinked.**



The repeating units are joined in a 3-dimensional array

HYDROCARBONS

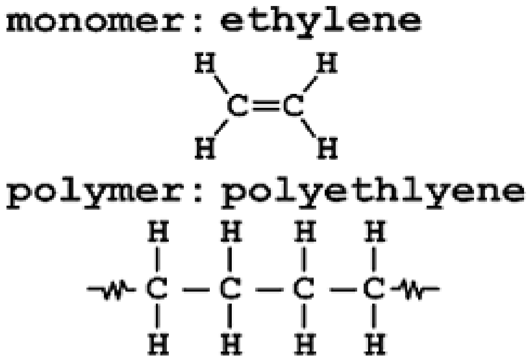
- A class of substances containing only the chemical elements carbon and hydrogen (C & H); e.g., $CH_{4,}$ C_2H_6.
- The molecular formula is C_nH_{2n+2}

There is a smooth change in the physical properties of the individual hydrocarbons as the chain length increases. Thus

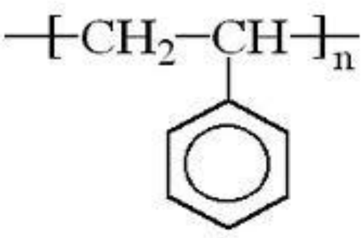
- $C_1 – C_4$ => Normal gases
- $C_5 – C_{12}$ => Volatile liquids (e.g. gasoline)
- $C_{13} – C_{18}$ => Higher boiling point liquids (e,g. aviation fuel, kerosene)
- $C_{19} – C_{38}$ => heavy oils and waxes
- C_{38} ------ => Waxes may have weak mechanical properties.
- If C > 100 to 1000 => polyethylene

HYDROCARBON POLYMERS

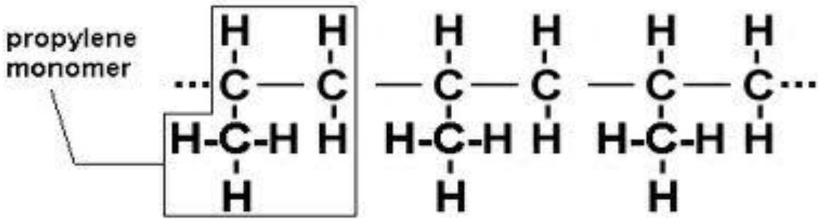
1. Polyethylene



2. Polystyrene (PS) Cheap moulded object, expanded with pentane to make plastic form, highly sensitive, hard



3. Polypropylene (PP): Polypropylene, also known as polypropene, is a thermoplastic polymer used in a wide variety of applications including packaging and labeling, textiles, stationery, plastic parts and reusable containers



COMPOSITES

- A composite is composed of two (or more) individual materials, viz., metals, ceramics, and polymers.
- 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.
- A large number of composite types exist that are represented by different combinations of metals, ceramics, and polymers.
- Furthermore, some naturally-occurring materials are also considered to be composites—for example, wood and bone.
- 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. In addition, it has a low density. Fiber glass is sometimes also termed a "glass fiber-reinforced polymer" composite, abbreviated "GFRP."

Another of these technologically important materials is the “carbon fiber reinforced polymer” (or “CFRP”) composite—carbon fibers that are embedded within a polymer. These materials are stiffer and stronger than the glass fiber-reinforced materials, yet they are more expensive.

The CFRP composites are used in some aircraft and aerospace applications, as well as high-tech sporting equipment (e.g., bicycles, golf clubs, tennis rackets, and skis/snowboards).

- A composite, is a multiphase material that is *artificially made,* as opposed to one that occurs or forms naturally.
- In addition, the constituent phases must be chemically dissimilar and separated by a distinct interface.
- Thus, most metallic alloys and many ceramics do not fit this definition because their multiple phases are formed as a consequence of natural phenomena.
- In designing composite materials, scientists and engineers ingeniously combine various metals, ceramics, and polymers to produce a new generation of extraordinary materials.
- Most composites have been created to improve combinations of mechanical characteristics such as stiffness, toughness, and ambient and high-temperature strength.

Many composite materials are composed of just two phases; one is termed the matrix, which is continuous and surrounds the other phase, often called the dispersed phase. The properties of composites are a function of the properties of the constituent phases, their relative amounts, and the geometry of the dispersed phase. "Dispersed phase geometry" in this context means the shape of the particles and the particle size, distribution, and orientation.

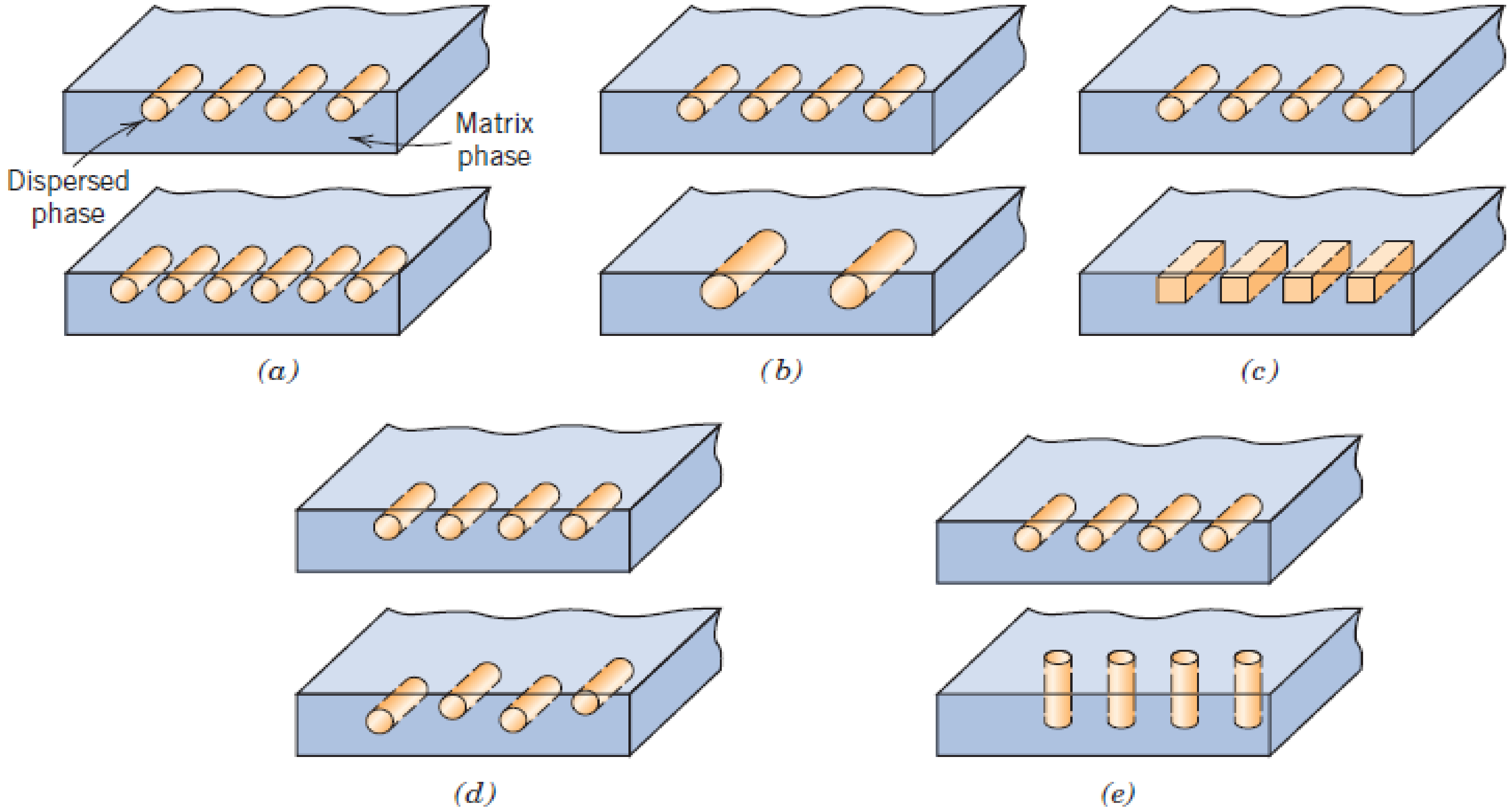
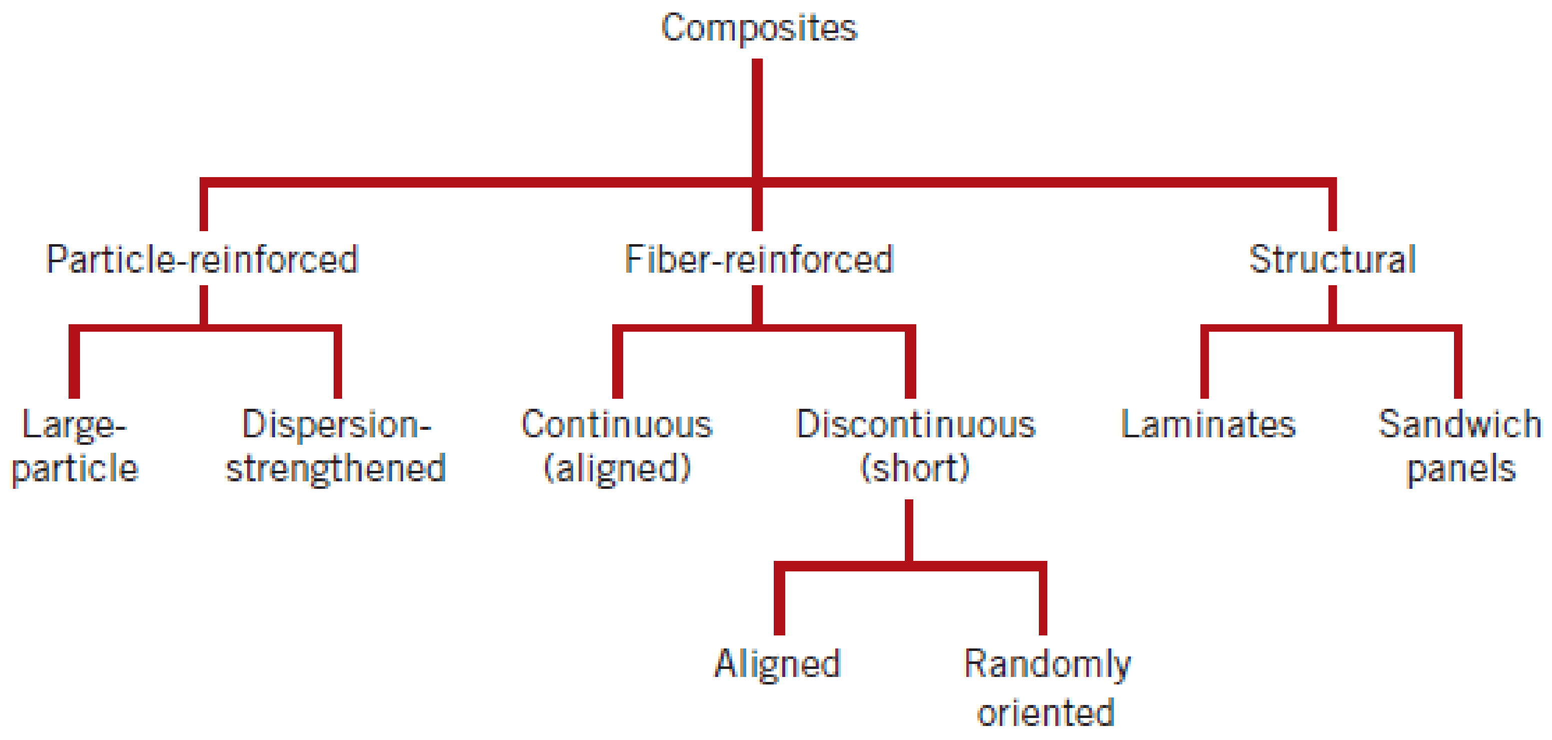


Figure. Schematic representations of the various geometrical and spatial characteristics of particles of the dispersed phase that may influence the properties of composites: (*a*) concentration, (*b*) size, (*c*) shape, (*d*) distribution, and (*e*) orientation.

Classification scheme for the various composite materials



Composites

Particle-reinforced

Large-particle

Dispersion-strengthened

Fiber-reinforced

Continuous (aligned)

Discontinuous (short)

Aligned

Randomly oriented

Structural

Laminates

Sandwich panels

Particle-Reinforced Composites

The dispersed phase for particle-reinforced composites is equiaxed (i.e., particle dimensions are approximately the same in all directions). The particulate phase is harder and stiffer than the matrix. These reinforcing particles tend to restrain movement of the matrix phase in the vicinity of each particle. In essence, the matrix transfers some of the applied stress to the particles, which bear a fraction of the load. The degree of reinforcement or improvement of mechanical behavior depends on strong bonding at the matrix–particle interface.

Examples: Cermet, Concrete, *Portland Cement Concrete, Reinforced Concrete*

Fiber-Reinforced Composites

The dispersed phase is in the form of a fiber. Design goals of **fiber-reinforced composites** often include high strength and/or stiffness on a weight basis. These characteristics are expressed in terms of **specific strength** and **specific modulus** parameters, which correspond, respectively, to the ratios of tensile strength to specific gravity and modulus of elasticity to specific gravity. Fiber-reinforced composites with exceptionally high specific strengths and moduli have been produced that utilize low-density fiber and matrix materials.

Structural Composites

A **structural composite** is normally composed of both homogeneous and composite materials, the properties of which depend not only on the properties of the constituent materials but also on the geometrical design of the various structural elements.

Laminar composite is composed of two-dimensional sheets or panels that have a preferred high-strength direction such as is found in wood and continuous and aligned fiber-reinforced plastics.

Sandwich panel consists of two **outer sheets, or faces**, that are separated by and adhesively bonded to a thicker **core**. The outer sheets are made of a relatively stiff and strong material, typically aluminum alloys, fiber-reinforced plastics, titanium, steel, or plywood; they impart high stiffness and strength to the structure, and must be thick enough to withstand tensile and compressive stresses that result from loading. The core material is lightweight, and normally has a low modulus of elasticity.

Semiconductors

Semiconductors have electrical properties that are intermediate between the electrical conductors (viz. metals and metal alloys) and insulators (viz. ceramics and polymers).

Furthermore, the electrical characteristics of these materials are extremely sensitive to the presence of minute concentrations of impurity atoms, for which the concentrations may be controlled over very small spatial regions.

Semiconductors have made possible the advent of integrated circuitry that has totally revolutionized the electronics and computer industries (not to mention our lives) over the past three decades.

HIGH T_C SUPERCONDUCTORS

The discovery of superconductivity aroused considerable interest in this field since the materials with no electrical resistance, and hence negligible het losses, could be exploited to fabricate powerful and economical devices, which consume very small amount of electrical energy.

However, due to requirement of very low temperature, it was not feasible to manufacture such devices. It is both difficult and expensive to attain the liquid helium temperature and maintain it for a long time.

Thus, tremendous efforts were made to develop the superconducting material having s high critical temperature as possible. A number of materials including various metals, alloys, intermetallic and interstitial compounds, and ceramics were employed.

Despite all these efforts, a T_C of maximum 23 K was achieved in 1977 in Nb_3Ge and intermetallic compound of niobium and Ge.

Thus, the scientist have given up the hope of producing superconducting devices to have a superconductor with the transition temperature equal to higher than 77 K, the liquid nitrogen temperature.

In 1986, Bednorz and Muller discovered a new class of oxide ceramic superconductors with critical temperature higher that 30K, which ushered a new era in the development of superconductivity. There are called high T_C superconductors.

The first group of such superconductors was $La_{2-x}M_xCuO_4$(M = Ba, Sr, Ca) with Tc ranging from 25 to 40 K and referred to as 214 system. This system possesses K_2NiF_4 structure with an orthorhombic distortion.

Another discovery took place with system having general formula $LnBa_2Cu_3O_{7-x}$(Ln = Y, Nd, Sm, Eu, Gd, Dy,Ho, Er, Tm, Yb) with x ~0.2. This is called 123 system with an orthorhombic structure.

In 1988, several other non rare-earth based copper oxide systems involving Bi and Tl were discovered which showed superconductivity between 60 K and 125 K

Properties of some selected superconductors in chronological order

Year	T_C (K)	Material	Class	Crystal Structure	Type	Hc (MAm^{-1})
1911	4.2	Hg	Metal	Tetragonal	I	0.033
1913	6.2	Pb	Metal	fcc	I	0.064
1930	9.25	Nb	Metal	bcc	II	0.164
1940	15	NbN	Interstitial compound	NaCI	II	12.2
1950	17	V_3Si	Intermetallic compound	β-tungsten (W_30)	II	12.4
1954	18	NbSn	Intermetallic compound	W_3O	II	18.5
1960	10	Nb-Ti	Alloy	bcc	II	11.9
1964	0.7	SrTiO	Ceramic	Perovskite	II	Small
1970	20.7	Nb_3 (Al, Ge)	Intermetallic compound	W_3O	II	34.0
1977	23	Nb_3Ge	Intermetallic compound	W_3O	II	29.6
1986	34	$La_{1.85}Ba_{0.15}CuO_4$	Ceramic	Tetragonal	II	43
1987	90	YBa2Cu3O7	Ceramic	Orthorhombic	II	111
1988	108	Bi cuprates	Ceramic	Orthorhombic	II	--
1988	125	Tl cuprates	Ceramic	Orthorhombic	II	--

Many of the properties of these conventional high-T_C, superconductors are identical to those of conventional low-T_C metallic superconductors. These include, for example, **the existence of energy gap over the entire Fermi surface below T_C and the Josephson tunnelling**.

These superconductors, however, possess **certain properties which do not match with those of conventional ones**. These are, for example, ***small isotope effect, small coherence lengths (a few lattice spacings) and unconventional temperature dependencies of normal state response functions***.

Also, the pressure is found to increase the transition temperature in high-T_C superconductors, whereas usually an opposite effect is observed in conventional superconductors.

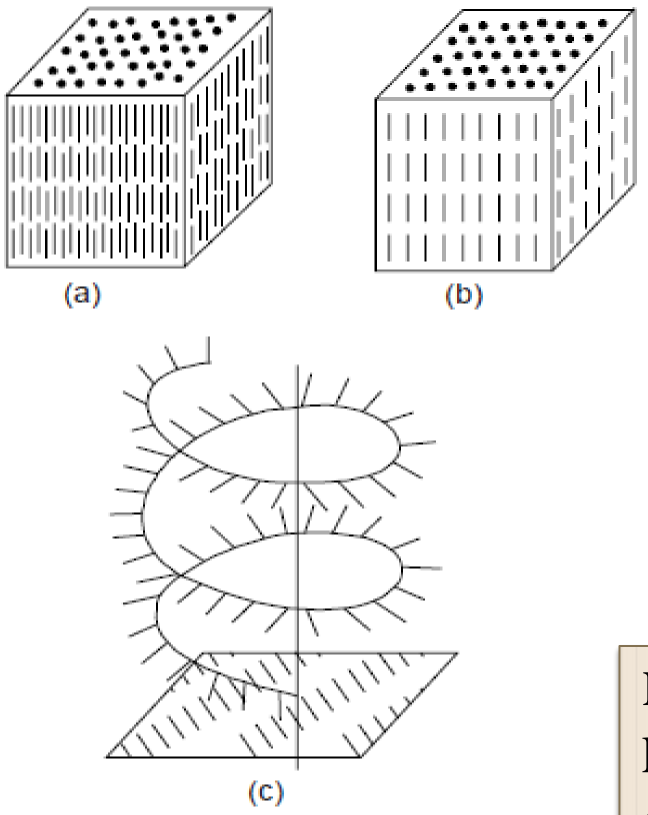
Thus there appears to be something essentially new in these high-T_C, superconductors which has not yet been clearly understood.

The identification of the possible conduction mechanism in the high-T_C, superconductors is perhaps the most challenging problem in condensed matter physics these days

LIQUID CRYSTALS

- These are liquids in which the molecular structure has a certain degree of order.
- Owing to the ordered arrangement of molecules, liquid crystals occupy an intermediate position between crystals and common liquids with disordered molecules.
- Liquid crystals are fluid as common liquids, but on the other hand, exhibit anisotropic properties as crystals.
- A large number of liquid crystals are known today; important among them are certain organic substances with molecules of an elongated form. On melting, these elongated molecules are arranged in a certain order by virtue of some pecularities in molecular interaction.
- ***The intermediate state of a liquid crystal with ordered structure is retained in the temperature interval from the melting point to a transition point at which the liquid crystal changes to isotropic liquid.***
- During this transition, thermal oscillations increase and the ordered molecular structure disappears completely, making the substance transparent. This is why, the upper temperature limit of the existence of a liquid crystal is called the *brightening point*.

From structure point of view, liquid crystals can be classified into three classes: *(i)* nematic *(ii)* smectic and *(iii)* cholesteric. These are shown in Fig. 3.58.



Structure of Liquid Crystals

- ✓ **In class I** (Fig. a), molecules are arranged into chains and the direction of preferable orientations of molecules is the optic axis of a liquid crystal.
- ✓ **In type II** (Fig. b), molecules form parallel layers which can be easily displaced relative to one another
- ✓ **In type III** (Fig. c), the structure is more complex, with molecules arranged on a spatial spiral.

Long molecules form parallel layers, with each layer having the structure of a liquid crystal of type-I. The direction of preferable orientation varies smoothly from one layer to another, thus forming a spiral of a definite pitch.

The structure of liquid crystals, is changed easily under the action of pressure, electric fields or heating.

The ability of type-I and type-III liquid crystals to change their optical properties under the action of electric fields and at temperature variations is widely utilized in instrument engineering.

A structural change in a liquid crystal caused by an external action is accompanied with displacements of molecules which take 1–10 ms; a still longer time, 20-200 ms, is required to restore their original state upon removal of the external action.

This pecularity of liquid crystals restricts their applications to low frequencies (not more than 2–5 kHz).

Type-I liquid crystals exhibit the electro-optical effect of dynamical light scattering. When an electric field of a sufficient intensity is applied, the original order of molecules is disturbed, molecules are stirred turbulently, and the substance becomes more transparent.

On heating, the spiral pitch increases in liquid crystals of type-III. This changes the conditions of light interference on the crystals, resulting in a different colour of reflected light.

- Liquid crystals are used in *colour indicators* and other colour devices. Colour pictures are obtained by mixing liquid crystals with certain pigments whose molecules are also of an elongated form.
- At a low field intensity, liquid crystal molecules are arranged perpendicular to the cell electrodes and cause pigment molecules to arrange in the same order. In this position of molecules, pigmenting is not observed. When, however, molecules are rotated by the field of a higher intensity, pigment molecules produce a certain colour image.
- The optical characteristics of liquid crystals are quite diverse, but the wavelength of reflected light changes on the average by 1–2 nm on heating per degree C.

Liquid crystals find use in

- ✓ clinical thermometers,
- ✓ temperature sensors for control of overheating of machine parts and units, and transducers of invisible infrared rays into visible light. In the last application, a liquid crystal absorbs infrared light and gets heated so that the colour of the reflected light is changed.
- ✓ Liquid crystals also find applications in **modulators, information displays: calculators, watches, etc., instruments of automobiles, devices for deviation of light flow, etc.**

Quasicrystal

Also called **quasi-periodic crystal**, matter formed atomically in a manner somewhere between the amorphous solids of glasses (special forms of metals and other minerals, as well as common glass) and the precise pattern of crystals.

Like crystals, quasicrystals contain an ordered structure, but the patterns are subtle and do not recur at precisely regular intervals.

Rather, quasicrystals appear to be formed from two different structures assembled in a nonrepeating array, the three-dimensional equivalent of a tile floor made from two shapes of tile and having an orientational order but no repetition.

Although when first discovered such structures surprised the scientific community, it now appears that quasicrystals rank among the most common structures in alloys of aluminum with such metals as iron, cobalt, or nickel. While no major commercial applications yet exploit properties of the quasicrystalline state directly, quasicrystals form in compounds noted for their high strength and light weight, suggesting potential applications in aerospace and other industries.

LUMINESCENCE

- The emission of light from a body from any cause other than high temperature is called luminescence.
- Luminescence can be stimulated by the incidence of light, bombardment of electrons or positive ions, passage of an electric current, chemical reaction, mechanical strain or heating,
- This radiation persists for times considerably longer than the periods of radiation in the optical range of the spectrum.
- If the ***emission of radiation occurs within 10^{-8} s of the incidence of the excitation***, the process is called **fluorescence**.
- If the ***luminescence persists for times greater than 10^{-8} s after the stimulating process has ceased to exist, it is called phosphorescence.*** *Phosphorescence may persist for time intervals ranging fro*

10^{-8} s is chosen because it is the order of the lifetime of an atomic state for an allowed transition in the visible spectrum.

Solids which convert other forms of energy into light energy with high efficiency are called phosphors. Today phosphors are very widely used in television screens, fluorescent lamps, cathode ray oscilloscopes, particle detectors and counters.

The ability for luminescence with high efficiency is acquired by the material when certain types of atoms called the activators, are present in the material.

Properties and applications of some of the luminescent materials

Host	**Activator**	**Wavelength of the absorption spectrum(Å)**	**Wavelength of the emission spectrum (Å)**	**Application**
ZnS	Ag	3410	--	Cathode ray tubes
ZnS	Cu	3410	6700	
Cds	Ag	5100	--	
Calcium	Sb	2537	4900	Phosphorescent

The sulphide phosphors like ZnS:Cu, ZnS:Ag, Cds:Ag are used in cathode ray tubes. In these materials the kinetic energy of the electrons is converted into light. The process occurs as follows. The energy given to the phosphor by the electrons in the cathode ray beam creates an electron-hole pair as shown in Fig. 15.9 for ZnS: Cu. The hole and electron begin to move in their respective bands.

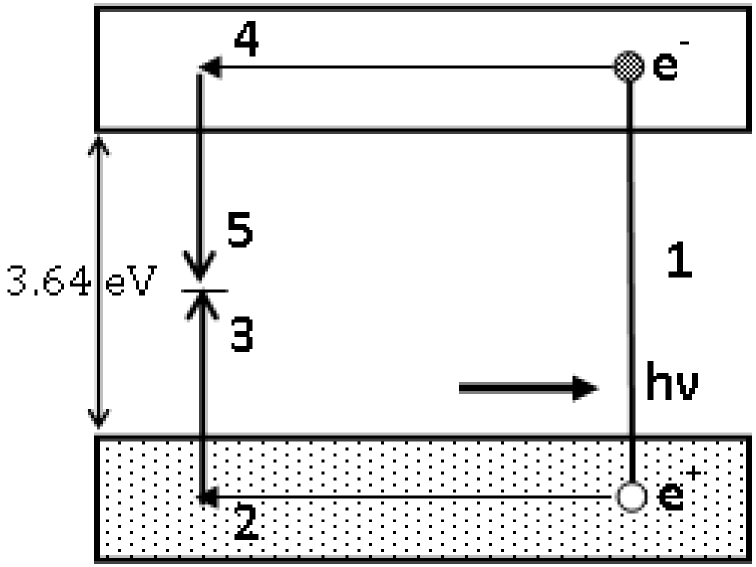


Figure: The emission of light in a sulphide phosphor like ZnS: Cu. (1) An electron impinging on the phosphor generates an electron-hole pair. (2) The hole wanders in the valence band and comes near the Cu^{1+} impurity atom. (3) The hole is captured and a photon of energy hν is emitted (4) The electron wanders in the conduction band. (5) Electron is captured by the impurity copper atoms. (introduction to Solid State Physics by C. Kittel, copyright 1956, second edition, Wiley Interscience Inc)

- Apart from activator based luminescent materials there are semiconductors which convert electrical energy into light directly. This phenomenon is called **electro-luminescence**.

There are two basic mechanisms for its occurrence.

- In some semiconducting crystals like CdS, SiC, Ge, Si, etc., when a current flows in the forward direction of a p-n junction, electrons from the n region are brought into the p region where they recombine with holes and give rise to visible radiation. In the second process impurity atoms are excited by electrons when a current is made to flow through them and give rise to photon emission while returning to the ground state. This type of excitation occurs in ZnS : Cu.

OPTOELECTRONICS (OR **OPTRONICS**)

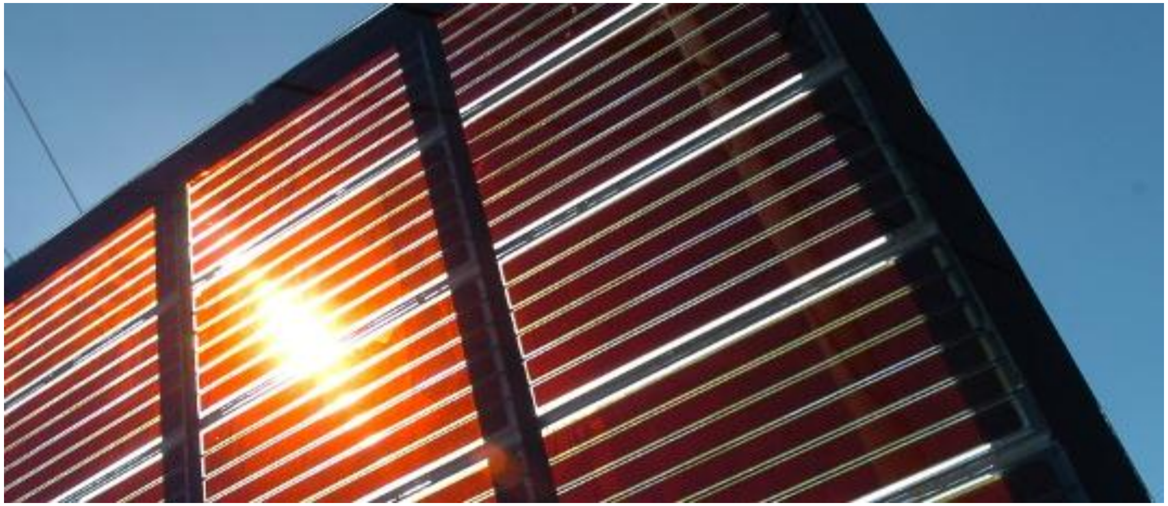
The study and application of electronic devices and ***systems that source, detect and control light, usually considered a sub-field of photonics***. In this context, *light* often includes invisible forms of radiation such as gamma rays, X-rays, ultraviolet and infrared, in addition to visible light.

- Optoelectronic devices are ***electrical-to-optical or optical-to-electrical transducers***, or instruments that use such devices in their operation.
- ***Electro-optics*** is often erroneously used as a synonym, but is a wider branch of physics that concerns all interactions between light and electric fields, whether or not they form part of an electronic device.
- Optoelectronics is based on the quantum mechanical effects of light on electronic materials, especially semiconductors, sometimes in the presence of electric fields

Optoelectronic materials have been known for nearly a century. In the late years, the interest in this material is attributed to the discovery of electroluminescence in molecular crystals and conducting polymers.

Optoelectronic materials at include:

1. **Dye-Sensitized Solar Cell (DSSC)**: Dye-sensitized solar cell (DSSCs) is low-cost solar cell belonging to the category of thin-film solar cells. It is based on a semiconductor formed between an electrolyte and a photo-sensitized anode. DSSC has many attractive features: it is easy to make use of conventional roll-printing techniques, and most of the materials used are low-cost



2. **Electrode:** An electrode is an electrical conductor for making contact with a non-metallic portion of a circuit. Electrodes are used to provide current through non-metallic object and to measure the electrical conductivity for many applications, such as fuel cells, EEG (for recording brain activity), electrophysiology techniques in biomedical research and so on.
3. **Flexible Printed Electronics:** Flexible print electronics combines the microelectronics, electronics assembly and printing industries. This technology makes it possible to print circuits, sensors, memories, batteries and displays onto thin, lightweight, flexible substrates.

4. **Organic Light Emitting Diode (OLED):** An organic light-emitting diode (OLED) is a light-emitting diode (LED) in which the emissive electroluminescent layer is a film of organic compound that emits light in response to an electric current. The layers are situated between two electrodes. OLEDs are used in manufacturing digital displays in devices such as television screens, computer monitors, mobile phones and PDAs.

5. **Organic Photovoltaic (OPV):** Organic photovoltaic (OPV) solar cells are designed to ***provide earth-rich and low-energy photovoltaic (PV) solutions***. This technology has the theoretical potential to provide electricity at low cost.
6. **Organic Thin-Film Transistor (OTFT):** Organic thin film transistor (OTFT) technology ***involves the use of organic semiconductor compounds***, particularly computer displays. These displays have high brightness, vivid colors, and are easy to read in most ambient lighting environments.
7. **Perovskite Solar Cells:** A perovskite solar cell is the solar cell that ***includes a perovskite structure compound***, in which a hybrid organic-inorganic lead or tin halide-based material is used as a light-harvesting active layer. Perovskite materials such as methylammonium halides are inexpensive to produce.

LIGHT EMITTING DIODE (LED)

- A light emitting diode is ***a solid state device which emits light when it is suitably activated.*** It is in fact a diode which emits light when it is forwardbiased when it is in reverse bias it does not conduct and hence does not emit light.
- When a p-n junction diode is forward biased, electrons move from the n-side to the p-side of the junction. In making this transition the electrons drop through the energy gap, E_g, that separates the two bands. This energy is given off in the form of light. In an ordinary rectifier diode this energy is released as heat. The wavelength of the radiated energy is given by

$$\lambda\,(\text{Å}) = 12380/E_g\,(\text{eV})$$

where E_g, is expressed in electron-volts and λ in Angstrom units.

For Si and Ge the energy gap, E_g, is 1.14 and 0.67 eV respectively. The emitted radiation has a wavelength of 10,620 Å for Si and 18,000 Å for Ge. These lie in the infrared region and are invisible to the eye.

Some LEDs and wavelengths of light emitted by them

Composition	Wavelength(Å)	Colour
GaAs:Zn	9000	infrared
GaAs: P	6600	red
GaP: N	5600	green
GaAsP: N	5900	yellow
GaAs: P	6100	amber

The LED differs from the conventional rectifying diodes in the following three distinct ways:

1. The maximum dc forward current is limited to about 100 mA.
2. The maximum reverse voltage is limited to about 5 V which is low compared to the ordinary rectifying diodes.
3. The forward voltage drop varies from 1.65 to 2.22 V depending on the type and colour of the LED.

LEDs are nowadays used in almost all instruments.

- ✓ They are used as general-purpose indicators, display devices, in entertainment electronics, etc.
- ✓ These have been developed in various shapes, sizes and colours to suit different requirements.
- ✓ On account of their attractive look, small requirement of space and long life, LEDs are fast replacing incandescent indicating lamps used earlier.