

## MATERIALS ENGINEERING

### 3.1 Materials Engineering

Material engineers improve the road you travel on, the coal used to fuel a factory, and the sidewalk in your neighborhood. Through their study of asphalt and bituminous materials, roads and sidewalks last longer and fuels, like coal, are more energy efficient.

New materials have been among the greatest achievements of every age and they have been central to the growth, prosperity, security, and quality of life of humans since the beginning of history. It is always new materials that open the door to new technologies, whether they are in civil, chemical, construction, nuclear, aeronautical, agricultural, mechanical, biomedical or electrical engineering.

Materials scientists and engineers continue to be at the forefront of all of these and many other areas of science, too. Materials science and engineering influences our lives each time we buy or use a new device, machine, or structure. (You can read more about the impact of this exciting field in our list of suggested readings.) The definition of the academic field of Materials Science & Engineering stems from a realization concerning the every application of materials: it is the properties of the material that give it value. A material may be chosen for its strength, its electrical properties, resistance to heat or corrosion, or a host of other reasons; but they all relate to properties.

Experience shows that all of the useful properties of a material are intimately related to its structure, at all levels, including which atoms are present, how the atoms are joined, and how groups of atoms are arranged throughout the material. Most importantly, we learn how this structure, and the resulting properties, are controlled by the processing of the material.

Finally materials must perform their tasks in an economical and societally responsible manner. Understanding the relationships between properties, structure, processing and performance makes the Materials Engineer the master of the engineering universe.

It is an important part of forensic engineering (the investigation of materials, products, structures or components that fail or do not operate or function as intended, causing personal injury or damage to property) and failure analysis, the

latter being the key to understanding, for example, the cause of various aviation accidents. Many of the most pressing scientific problems that are faced today are due to the limitations of the materials that are available and, as a result, breakthroughs in this field are likely to have a significant impact on the future of technology.

### **What Materials Engineers Do**

Materials engineers develop, process, and test materials used to create a range of products, from computer chips and aircraft wings to golf clubs and snow skis. They work with metals, ceramics, plastics, composites, and other substances to create new materials that meet certain mechanical, electrical, and chemical requirements.

### **Work Environment**

Materials engineers generally work in offices where they have access to computers and design equipment. Others work in supervisory roles either in a factory or in research and development laboratories. Materials engineers typically work full time and may work overtime hours when necessary.

### **How to Become a Materials Engineer**

Materials engineers must have a bachelor's degree in materials science or engineering, or a related field. Employers also value practical experience.

Therefore, cooperative engineering programs, which provide college credit for structured job experience, are valuable as well.

### **Pay**

The median annual wage for materials engineers was \$85,150 in May 2012.

### **History**

The material of choice of a given era is often a defining point. Phrases such as Stone Age, Bronze Age, Iron Age, and Steel Age are great examples. Originally deriving from the manufacture of ceramics and its putative derivative metallurgy,

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

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

### **3.2 Fundamentals**

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

The basis of materials science involves studying the structure of materials, and relating them to their properties. Once a materials scientist knows about this structure-property correlation, he/she can then go on to study the relative performance of a material in a certain application. The major determinants of the structure of a material and thus of its properties are its constituent chemical elements and the way in which it has been processed into its final form. These characteristics, taken together and related through the laws of thermodynamics and kinetics, govern a material's microstructure, and thus its properties.

## Structure

As mentioned above, structure is one of the most important components of the field of materials science. Materials science examines the structure of materials from the atomic scale, all the way up to the macro scale. Characterization is the way materials scientists examine the structure of a material. This involves techniques such as diffraction with x-rays, electrons, or neutrons, and various forms of spectroscopy and chemical analysis such as Raman spectroscopy, energy-dispersive spectroscopy (EDS), chromatography, thermal analysis, electron microscope analysis, etc. Structure is studied at various levels, as detailed below.

### *Atomistic structure*

This deals with the atoms of the materials, and how they are arranged to give molecules, crystals, etc. Much of the electrical, magnetic and chemical properties of materials arise from this level of structure. The length scales involved are in angstroms (0.1 nm). The way in which the atoms and molecules are bonded and arranged is fundamental to studying the properties and behavior of any material.

### *Nanostructure*

Nanostructure deals with objects and structures that are in the 1—100 nm range.<sup>[5]</sup> In many materials, atoms or molecules agglomerate together to form objects at the nanoscale. This leads to many interesting electrical, magnetic, optical and mechanical properties.

In describing nanostructures it is necessary to differentiate between the number of dimensions on the nanoscale. Nanotextured surfaces have **one dimension** on the nanoscale, i.e., only the thickness of the surface of an object is between 0.1 and 100 nm. Nanotubes have **two dimensions** on the nanoscale, i.e., the diameter of the tube is between 0.1 and 100 nm; its length could be much greater. Finally, spherical nanoparticles have **three dimensions** on the nanoscale, i.e., the particle is between 0.1 and 100 nm in each spatial dimension. The terms nanoparticles and ultrafine particles (UFP) often are used synonymously although UFP can reach into the micrometre range. The term 'nanostructure' is often used when referring to magnetic technology. Nanoscale structure in biology is often called ultrastructure.

Materials whose atoms/molecules form constituents in the nanoscale (i.e., they form nanostructure) are called nanomaterials. Nanomaterials are subject of intense research in the materials science community due to the unique properties that they exhibit.

### ***Microstructure***

Microstructure is defined as the structure of a prepared surface or thin foil of material as revealed by a microscope above 25× magnification. It deals with objects in from 100 nm to few cm. The microstructure of a material (which can be broadly classified into metallic, polymeric, ceramic and composite) can strongly influence physical properties such as strength, toughness, ductility, hardness, corrosion resistance, high/low temperature behavior, wear resistance, and so on. Most of the traditional materials (such as metals and ceramics) are microstructured.

The manufacture of a perfect crystal of a material is physically impossible. For example, a crystalline material will contain defects such as precipitates, grain boundaries (Hall–Petch relationship), interstitial atoms, vacancies or substitutional atoms. The microstructure of materials reveals these defects, so that they can be studied.

### ***Macrostructure***

Macrostructure is the appearance of a material in the scale millimeters to meters—it is the structure of the material as seen with the naked eye.

### **Crystallography**

Crystallography is the science that examines the arrangement of atoms in crystalline solids. Crystallography is a useful tool for materials scientists. In single crystals, the effects of the crystalline arrangement of atoms is often easy to see macroscopically, because the natural shapes of crystals reflect the atomic structure. In addition, physical properties are often controlled by crystalline defects. The understanding of crystal structures is an important prerequisite for understanding crystallographic defects. Mostly, materials do not occur as a single crystal, but in poly-crystalline form (i.e., as an aggregate of small crystals with different orientations). Because of this, the powder diffraction method, which uses diffraction patterns of polycrystalline samples with a large number of crystals, plays an important role in structural determination. Most materials have a crystalline structure. But, there are some important materials that do not exhibit regular crystal structure. Polymers display varying degrees of crystallinity, and many are completely non-crystalline. Glass as, some ceramics, and many natural materials are amorphous, not possessing any long-range order in their atomic arrangements. The study of polymers combines elements of chemical and statistical thermodynamics to give thermodynamic, as well as mechanical, descriptions of physical properties.

## **Bonding**

To obtain a full understanding of the material structure and how it relates to its properties, the materials scientist must study how the different atoms, ions and molecules are arranged and bonded to each other. This involves the study and use of quantum chemistry or quantum physics. Solid-state physics, solid state chemistry and physical chemistry are also involved in the study of bonding and structure.

**Properties** Materials exhibit a myriad of properties. The important properties of materials are as follows:

- Mechanical properties
- Chemical Properties
- Electrical Properties
- Thermal Properties
- Optical Properties
- Magnetic Properties

The properties of a materials determine its usability and hence its engineering application.

## **Synthesis and processing**

Synthesis and processing involves the creation of a material with the desired micro/nanostructure. From an engineering standpoint, a material cannot be used in industry if no economical manufacturing method for it has been developed. Thus, the processing of materials is very important to the field of materials science.

Different materials require different processing/synthesis techniques. For example, the processing of metals has historically been very important and is studied under the branch of materials science known as physical metallurgy. Also, chemical and physical techniques are also used to synthesis other materials such as polymers, ceramics, thin films, etc. Currently, new techniques are being developed to synthesize nanomaterials such as graphene.

## **Thermodynamics**

Thermodynamics is concerned with heat and temperature and their relation to energy and work. It defines macroscopic variables, such as internal energy, entropy, and pressure, that partly describe a body of matter or radiation. It states

that the behavior of those variables is subject to general constraints, that are common to all materials, not the peculiar properties of particular materials. These general constraints are expressed in the four laws of thermodynamics.

Thermodynamics describes the bulk behavior of the body, not the microscopic behaviors of the very large numbers of its microscopic constituents, such as molecules. The behavior of these microscopic particles is described by, and the laws of thermodynamics are derived from, statistical mechanics.

The study of thermodynamics is fundamental to materials science. It forms the foundation to treat general phenomena in materials science and engineering, including chemical reactions, magnetism, polarizability, and elasticity. It also helps in the understanding of phase diagrams and phase equilibrium.

### **Kinetics**

Kinetics is the study of the rates at which systems that are out of equilibrium change under the influence of various forces. When applied to materials science, it deals with how a material changes with time (moves from non-equilibrium to equilibrium state) due to application of a certain field—it details the rate of various processes evolving in materials including shape, size, composition and structure. Diffusion is important in the study of kinetics as this is the most common mechanism by which materials undergo change.

Kinetics is essential in processing of materials because, among other things, it details how the microstructure changes with application of heat.