Materials Science and Engineering

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By

Sanjeev Singh Yadav, Rajat Dhiman
and Rupendra M. Anklekar

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This book is dedicated to
Material Scientists

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SALIENT FEATURES OF THE BOOK

1. The significance of the subject and its contents is highlighted by correlating them with practical applications that make readers realize the importance of the subject.

2. All concepts and explanations are supported with relevant schematic diagrams and well-designed figures for better clarity and easy understanding.

3. The explanation of the contents and presentation of the subject are easy to understand.

4. Self-study materials, such as objective questions for self assessment, are compiled for each chapter.

5. Unit-wise conceptual, theoretical questions and practical numerical problems (short and comprehensive) are given for students' self-evaluation.

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PREFACE

Identifying suitable materials has always played a critical role in human progress since prehistoric times in terms of the development of new civilizations throughout the world till the present day. Materials science and engineering have gained significance lately as an essential branch since they are directly related to different engineering branches and other fields like medicine, forensic science, archaeology, sports, entertainment, and so on, and are thus very useful to society in day-to-day life. The state of the technology that we see today has all been possible mainly due to the advances in materials development in various sectors like agriculture, transportation, energy, telecommunication, construction, aerospace, computers, education, and many others that have significantly impacted the lives of everyone in our society.

The properties of materials play a pivotal role in the choice of correct materials for any specific applications; therefore, an in-depth knowledge of materials becomes very much necessary to develop better, lighter, stronger, and more durable materials. This is only possible by understanding the building blocks of materials in terms of the atomic arrangement and crystal structure of different materials. Various defects like vacancies, dislocations, stacking faults, and precipitates influence the properties of materials. The knowledge of physical metallurgy, like phase diagrams, phase transformations, diffusion processes, heat treatment processes, and various strengthening mechanisms, enables one to explain the materials' behavior precisely and, if required, alter the properties of the materials for any given application. In addition, the knowledge and understanding of the nature of failures and different failure mechanisms like fracture, fatigue, creep, and corrosion mechanisms help expedite research and development activities for improving the properties of materials and processes for various applications in other fields.

The proposed book covers all the aspects mentioned above to prepare strong materials science fundamentals that are important for advanced material design and development. The first chapter of this book highlights the significance of understanding materials science and its introduction. Chapter 2 deals with the different types of crystal structures and defects. The various deformation and strengthening mechanisms of materials are discussed in detail in Chapter 3. The significance and role of Gibbs free energy in evolution in the phase diagrams and some commonly used phase diagrams relevant to metallurgy and materials are explained in Chapter 4. Nucleation and growth phenomena are discussed in Chapter 5. Chapter 6 discusses heat treatment's role in improving materials' properties. The basic understanding of the various failure mechanisms of materials is discussed in Chapter 7. Finally, Chapter 8 introduces the world of advanced materials to the readers.

Although several books on Materials Science and Engineering are available in the market, the proposed book highlights the subjects' significance by correlating them with practical applications that make readers realize the importance of the subjects. Some salient features are as follows:

- The significance of the subject and its contents is highlighted by correlating them with practical applications that make readers realize the importance of the subject.
- The explanation of the contents and presentation of the subject is easy to understand.
- All concepts and explanations are supported with relevant schematic diagrams and well-designed figures for better clarity and easy understanding.
- Unit-wise conceptual, theoretical questions and practical numerical problems (short and comprehensive) are given for students' self-evaluation.
- Self-study materials, such as objective questions for self assessment, are compiled for each chapter.

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R. Dhiman
R. M. Anklekar

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1	Dr. Shivani Gupta (Chapter 1)	Assistant Professor at MIT World Peace University, Pune, India.
2	Mr. Nitin Patel (Chapter 2)	SRF, Indian Institute of Technology, Delhi, India.
3	Dr. Ruchita Patel (Chpaters 3, 5, & 8)	Post Graduate Researcher (PGR) at Bournemouth University, UK.
4	Dr. Digvijay Bhosale (Chapters 4, 5 & 8)	Assistant Professor at D.Y. Patel College of Institute of Technology Pune, India.
5	Mr. Himanshu Markanday (Chapter 6)	SRF, Indian Institute of Technology, Ropar, India.
6	Mr. Atul Kumar Choudhary (Chapter 7)	SRF, Indian Institute of Technology, Bhilai, India.

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CHAPTER 1

INTRODUCTION

1.1 Introduction to Engineering Materials

The selection of appropriate materials plays a vital role in ensuring optimal quality, performance, durability, and other essential criteria across various walks of our society. It is possible to prevent engineering disasters by having in-depth knowledge about the structure, properties, and utilization of diverse materials to prevent engineering catastrophic failures. Numerous instances of engineering disasters have resulted in a significant loss of life, injuries and heavy property loss due to material failure during operational scenarios. Some of the typical failures encountered in real-life situations have been described below.

Titanic Sinking

The Titanic, constructed in the early 1900s, was a monumental achievement in passenger ship engineering that started its maiden voyage on April 10, 1912, from the Port of Southampton, England, to New York City, United States of America. The ship was well equipped with the latest state-of-the-art safety features using novel design and technology, such as sealing off the watertight compartments in the lower section of the ship in case of an accident leading to a puncture in the hull. Being equipped with cutting-edge safety features, the company operating the passenger steamship further marketed its services by boasting the Titanic as an unsinkable ship. However, tragedy struck just four days into its journey when the Titanic collided with an iceberg in the North Atlantic Ocean during the early morning hours. The forceful impact of the iceberg fractured the wrought iron rivets and punched holes in the steel plates comprising the ship hull. Consequently, six compartments in the lower deck rapidly filled with water, leading to the rapid catastrophe of the vessel on April 15, 1912, within a mere two hours after the accident (see Fig. 1-1).

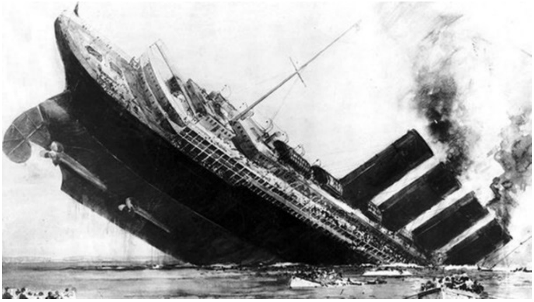

Fig. 1-1 A photograph showing the Titanic sinking incident. (Picture Courtesy: USA Today)

The Titanic disaster was one of the worst accidents ever recorded in history, claiming the lives of over 1500 individuals out of the 2240 passengers and crew on board. The root cause of the Titanic's failure was a brittle fracture that resulted when three critical factors converged: extremely low temperature, high impact loading due to high speed, and significant sulfur content in the hull steel. This caused such a catastrophic disaster of unprecedented magnitude. The concepts of materials science and engineering have been fruitfully applied to the Titanic incident throwing light on the root cause for the new type of brittle fracture mechanism, and this knowledge was successfully utilized for the development of double-sided hulls, enabling the implementation of effective preventive measures.

Comet Plane Accident

The de Havilland Comet, the world's first commercial air jetliner, was developed and produced by a British company that went into operation in 1952. This feat was a crowning achievement for the further advancement of the company's aviation superiority in the world. However, within the span of one year, the aircraft experienced three tragic accidents (Fig. 1-2) caused by the crashing of the planes during the flights, and the company was forced to carry out detailed research investigations into the primary root causes for the failures in all these related accidents.

The primary cause was identified as resulting from the metal fatigue phenomenon caused by repeated pressurization and depressurization of the

Fig. 1-2 Comet Plane Disaster Accident (Picture Courtesy: Josep Ayants)

aircraft cabin and also due to an overstressing of the airframe as a result of severe weather conditions during the flight in case of one incident. Another major factor for the metal fatigue was the stress caused in the supports of the windows by using a faulty riveting process instead of adopting the standard glueing process specified in the original design specifications. Thus, in this incident also, the basic concepts of materials engineering were found to be of great value and were effectively utilized to overcome the problems faced in the aircraft design for safe and reliable air transport in the sky at very high speeds.

Eschede Train Disaster, 1998

The Eschede train accident occurred on June 3, 1998, when the Inter-City Express (ICE) highspeed train travelling from Munich to Hamburg at a speed of 200 km/h collided with an overhead bridge near the Eschede village after more than a dozen train cars got derailed (Fig. 1-3) violently

Fig. 1-3 The Eschede train disaster

killing more than a hundred people and causing around the same number of injuries. The root cause for this failure was a single damaged train wheel that had developed cracks that led to its disintegration just before passing over the switch tracks, thereby resulting in a heavy collision with the bridge supports after the derailment. This heavy impact of the train slamming the bridge and the additional impact of the rear engine at high speed with the cars destroyed the main supports resulting in the collapse of the bridge.

After carrying out detailed investigations, it was clear that the wheel design was flawed, and sufficient validation testing was not done before starting the commercial train services. In addition, a rubber damping ring used to reduce the vibrations present during cruising and placed between the tire and wheel body led to increased fatigue susceptibility in material, causing this catastrophic accident. Thus, after this train accident, the basic concepts of materials engineering, including failure mechanisms, were found to be valuable and utilized effectively to eliminate the problems encountered in the high-speed train design for safe and reliable transport.

1.2 Historical Background

Materials have always played a vital role in society since prehistoric times and are often considered an integral part of our society. This role is no less relevant in modern times, be it in agriculture, transportation, communication, energy, construction, pharmaceuticals, textiles, entertainment, sports, and other domestic and industrial sectors. It will be no exaggeration to say that the type of materials chosen for specific applications in our everyday lives has been critical for overall performance and markedly influences the quality of life to a large extent.

The earliest humans had knowledge of only a minimal number of naturally occurring materials such as stone, wood, clay, bones, horns, etc. However, as civilizations and societies developed with time, humans discovered new material processes and techniques for making newer materials and modifying existing ones with properties superior to those of naturally existing materials. This development led to new materials like clay and different metals. With further development of these materials processes and techniques, it was discovered that the properties of these newly discovered materials could be modified and improved to a great extent by the addition of other substances and employing other processes.

Only recently have scientists and engineers come to understand the close relationships between the composition and the structure of materials and their properties. Using new science techniques, tens of thousands of different materials have been developed with tailor-made properties, including specific material characteristics, to meet the advanced technological needs of our complex modern society. These materials can be broadly classified into the following main classes: metals, glasses, ceramics, plastics, and composites.

The research and development of suitable materials for their easy accessibility and availability is a crucial element that has always been intimately associated with the development of many advanced technologies and their applications to help provide a comfortable life in the present society. To illustrate an example, the mass use of automobiles would not have been possible without the development of steel specifically made inexpensively and available in plenty. Likewise, advancement in the aerospace industry would not be possible without designing lightweight aluminum and titanium alloys. Another illustration of our contemporary era would be the state-of-the-art sophisticated electronic devices that rely on components made from materials having properties intermediate between metals and ceramics called semiconductors. The earliest prehistoric times, called the Stone Age, were when humans lived before societies were even developed, and stone tools were primarily employed for hunting animals for food and self-defence against threats from wild animals or enemies. Much later came the Bronze Age, followed by the Iron Age when it was discovered that copper metal, along with tin, was used to produce bronze which is very hard and has excellent properties for making tools, and later, the discovery of a process to make iron when man learned the art of producing much higher temperatures required for extracting iron from the ore which was an ideal material for making tools and weapons with better properties. The characteristic feature of each of these periods was that it had developed more advanced techniques and technology than used in the earlier period. Therefore, the names employed are based on the materials used for making the tools. These ages of material science are discussed below.

Stone Age

The Stone Age refers to the prehistoric period starting as early as about 2.6 million years ago and all the way lasting till 3300 BC. In this period, humans used tools and weapons made primarily from stone and other organic materials such as wood, bone and horn. It may be clearly understood that stone was the primary material used for making tools in the Stone Age. However, other materials, such as clay, also made significant progress.

There were other materials used, such as wood, bones and horns. However, at the end of the Stone Age, there was the advent and development of bronze metallurgy to make improved and sophisticated tools and weapons that paved the way for effectively reducing the use of stone tools and finally making them almost obsolete, and new materials and technology flourished.

Bronze Age

The Bronze Age was the period that followed the Stone Age and preceded the Iron Age, where tools and weapons were made from bronze alloys rather than stone. The Bronze Age lasted approximately 3300 BC to 1200 BC and ended when bronze was replaced by iron and steel for making tools and weapons. It became possible to produce more sophisticated tools and objects from bronze as compared to stone tools. Also, the first swords were produced from bronze by the moulding process and later on worked into different shapes, which was more convenient than working with stone tools.

To briefly illustrate the progress of metallurgy, historically, human beings started making objects from noble metals such as gold, silver and copper around 10,000 years ago. As these metals were found to be very soft, so they were primarily used for making jewellery, and decorative items, including pots and pans, for cooking rather than for producing tools. Nevertheless, around 3300 BC, a new discovery in metallurgy showed that adding other elements to copper metal, specifically tin made it much harder and stronger. Therefore, this property was taken advantage of and used for making tools. This alloy of copper and tin, called bronze, was found more suitable for making much stronger and more durable tools than before using pure metal.

Iron Age

The Iron Age has been characterized as that period in human history when people across vast regions of Europe, Asia and some parts of Africa started making tools and weapons from iron and steel to take advantage of higher strengths and better durability. This period lasted from around 1200 BC to 400 BC and immediately followed the Bronze Age. The ancient civilizations and societies that produced strong steel had a competitive edge over earlier civilizations, where people used bronze weapons. The widespread production of iron-based objects started in Europe and Asia around 1000 BC and focused on manufacturing weapons such as swords, shields, spears, armours and so on from steel. Early metallurgists discovered that the minimal addition of carbon to iron increases the strength of materials.

Industrial Age

The Industrial revolution started around 1760 with the advent of the steam engine and lasted till 1840, resulting in unprecedented rapid industrialization and economic growth. The industrial revolution was made possible mainly because of the introduction of a new material called coke, a carbonaceous material produced by heating coal in the absence of air. This new coke served multiple functions and was primarily used for manufacturing pig iron in the blast furnace. Coke significantly lowered the production costs for steel manufacturing by enabling scaling up operations to drastically increase the production volumes of iron and steel. It should be noted that the quality of life and economic prosperity that we see at present in modem society would not have been possible without the role played by this key material despite knowing fully well our current environmental concerns regarding high levels of carbon sources and air pollution.

Technology Age

The Technology Age started with the development of semiconductor devices in the last 70 years or so. A tiny-sized chip-like device made from a semiconducting material popularly called the silicon chip has been the most significant invention of our modern times. It is primarily because of its unique properties, like possessing electrical resistance, which makes it an intermediate between metals and ceramics. Computers were invented before the silicon chip (microchip), but the advancement of this electronic device made the modern computer era possible. The ability to create miniaturized circuit boards from a semiconductor material has enabled vast advancements in speeds and accuracy in present computers, thus transforming them from the earlier huge room-sized devices to machines that can fit on a desk or even be placed on one’s lap as in the case of a laptop.

1.3 Classification of Engineering Materials

Engineering materials can be broadly classified into three main categories: metals, ceramics and polymers. This classification is primarily based on chemical composition and atomic structure, and most materials fall into these three broad categories. Additional materials are somewhat intermediates or combinations of the abovementioned material types, and we can further group them into three different classes of materials: composites, semiconductors, and biomaterials. A brief description of all the above material types along with essential characteristics, is highlighted below.

Metals and Alloys

Metals and alloys are inorganic materials generally comprised of metals or combinations of different metals and usually contain a large number of delocalized electrons and exhibit metallic bonding, which is a type of chemical bonding resulting from the electrostatic attraction between the conduction band electrons and positively charged metal ions. Metals exhibit many good properties that make them very useful as engineering materials. For example, most metallic materials show good metallic luster on polishing and are not transparent to visible light. Metals are also extremely good conductors of heat and electricity and can be easily plastically deformed by hammering and pulling, for instance.

Ceramics

Ceramics are inorganic compounds comprising either non-metals or metals and non-metals, generally exhibiting ionic and covalent bonds. Ceramic materials are mostly non-metallic in nature and often found to be crystalline oxides, carbides, nitrides, and borides. Ceramics are generally very brittle, much harder, and stronger in compression but weak in tension and shear loading concerning their mechanical behavior. Most ceramics are poor conductors of heat and electricity and exhibit higher resistance to high temperatures and harsh environments as compared to metals and polymers.

Polymers

Polymers are organic compounds based on carbon and generally contain hydrogen, oxygen, and other non-metallic elements like nitrogen and sulfur. Polymers represent a distinct class of engineering materials that can be further classified into four main categories: thermoplastics, thermosets, elastomers, and synthetic fibers. They are commonly found in various consumer products used daily and include familiar plastics, rubbers, adhesives, paints, coatings, insulators, fibers, and other materials. They typically have low densities, high molecular weights, and large molecular structures. Polymers are held together primarily by covalent bonds and hence show extreme flexibility.

Composites

Composites, by their very definition, consist of two or more different combinations of metallic, ceramic, and polymeric materials. Composites are primarily designed to display a combination of the best properties of each of the different materials used. A typical example will be fiberglass reinforced plastic (FRP) composite in which glass fibers are embedded within a polymeric matrix to produce much stronger and tougher materials for various engineering applications. FRP composite material acquires high tensile strength from its glass fibers and ductility and flexibility from the polymer matrix.

Semiconductors

Semiconductors can be considered as another distinct class of materials that possesses an electrical conductivity which is intermediate between that of conductors (primarily metals) and insulators (mostly ceramics). These materials can be pure elements, for example, silicon or germanium, and compounds such as gallium arsenide or cadmium selenide. The electrical properties of these materials are highly sensitive to the deliberate addition of minute concentrations of impurity atoms, generally called dopants, to modify the charge carriers inside these materials to engineer the required electrical characteristics for various electronic applications. Semiconductors have totally revolutionized the electronics and computer industry over the past few decades with the invention of integrated circuits, drastically changing the world in many ways.

Biomaterials

Biomaterials are substances that have been engineered to interact with biological systems, mostly for medical applications. These can be employed for therapeutic use, such as to treat, augment, repair, or replace a tissue function of the body, or for diagnostic use. Biomaterials, a special class of materials, have only about fifty years of history. These materials are implanted into the human body to meet specific functions. They are also used in components implanted into the human body to replace diseased or damaged body parts. Therefore, these materials should be stable and inert and not produce toxic substances. Also, they should be compatible with body tissues, i.e., they must not cause adverse biological reactions.

1.4 Applications of Engineering Materials

In this modern scientific age, human life has been made easy and comfortable with the help of many technologies developed earlier and many more under continuous development. The research and development of suitable materials is the key factor for the easy availability of engineering materials for enabling critical technologies in the modern world. Thus, at present, engineering materials play a crucial role in developing modern advanced technologies, including commercial success, as the performance of many of these engineering products is largely governed by the right choice of materials used to manufacture the product for specific applications.

Biomedical Applications

Biomaterials in metallic form are mainly used to support and replace various components of the skeleton, heart, teeth, and other organs of the human body. Some of the typical examples where these biomaterials find applications are in artificial bone joints, heart valves, bone plates, spinal fixators, and dental implants. These metal-based biomaterials show intrinsically greater tensile strength, fatigue strength or endurance strength, and fracture toughness as compared to polymeric and ceramic materials. 316L stainless steels, cobalt alloys, commercially pure titanium, and Ti-6Al-4V alloys are the most widely used biomaterials based on metals for implants and devices. These materials are most ideally suitable for biomedical applications due to their excellent mechanical properties and may even be left inside the body for a prolonged period mainly due to their relatively high corrosion resistance, which results in a very small release of harmful toxins when exposed to fluids of the body.

Medical implants are highly engineered products that have to function with the highest reliability in the human body, which is the working environment. In principle, ideally, this is possible mainly due to the biochemical and biomechanical properties of these implants and products, which make them compatible with the autogenous tissues they are used in, with no adverse effects. The implants need to be regulated to ensure safety and effectiveness during their use. Some critical properties, such as biocompatibility, bio-adhesion, bio-functionality, corrosion resistance, etc., decide the choice of materials for designing a medical implant.

Aerospace Applications

The most commonly used engineering materials for aerospace applications in commercial airframe structures are aluminum alloys, titanium alloys, high-strength steels, and composites, which generally account for more than 90% of the total weight of aerospace structures. Aluminum alloys have dominated the aerospace industry for more than 60 years as they have been used in almost all parts from the fuselage to main engine components, mainly cause they are lightweight and inexpensive. In fact, as much as 70% of an aircraft by weight was made of aluminum alloys while other new materials, such as composites, titanium alloys, graphite, and fiberglass, were used in significantly smaller quantities, typically in the range of 3-7%. However, times have changed now, and a typical jet aircraft manufactured today consists of less than 20% aluminum metal by weight.

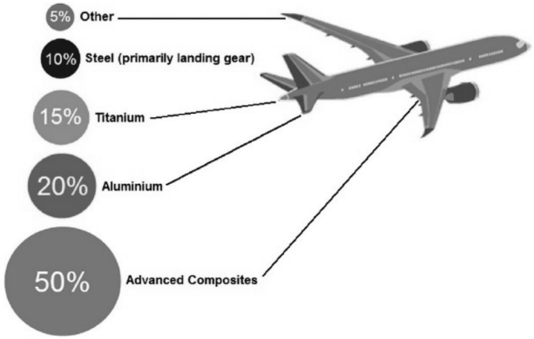

Fig. 1-4 Typical use of different materials for aerospace applications

At present, much lighter-weight carbon fiber-reinforced polymer (CFRP) composites and honeycomb materials are widely used to fabricate most of the non-critical paneling structures and aesthetic interiors of airplanes. Fig. 1-4 shows the typical use of different materials in percentage for aerospace applications. However, there is a big push for lower weight and higher temperature resistance materials for having better fuel efficiency for the engine parts and critical components, thereby researching to develop new or previously impractical-to-machine metals into the aerospace material basket.

Satellite Applications

Fig. 1-5 Polar satellite launch vehicle. (Picture Courtesy: ISRO)

For building a spacecraft and satellite carriers like PSLV (see Fig. 1-5), the correct choice of materials and optimal design to accommodate any limitations of material properties constitute the 12 most important factors to be considered. The key factor for the design of the space shuttle systems is to overcome many material challenges, such as reducing the weight of the structure and components by developing lighter and stronger materials ability to operate in the space environment, that is, withstand extreme conditions of temperature, pressure, gravity, infra-red and solar radiation and other variables encountered in space, and preferably to make them reusable for multiple missions. These constraints have driven many innovative materials solutions, and some of these innovative pathfinders have been used in industry. For example, large composite payload bay doors, non-destructive testing for the evaluation of materials, the super lightweight tank, and the basic understanding of hydrogen effects on materials, just to name a few. In addition to these above advancements, there are many innovations in materials engineering, flight testing and flight analysis, and manufacturing processes that have taken place. However, materials innovations seem to be at the top for overcoming the launching, landing, and low-Earth orbit operational challenges in many instances, including environmental ones, both in space and on the Earth.

Electrical Applications

The field of electrical engineering heavily depends on metallurgy and materials engineering for the availability of suitable materials such as conductors (silver, copper, gold, aluminum), insulators (paper, plastic, Teflon, rubber, mica, glass, porcelain, ceramic), magnetic materials (alnico, ferrites) and various construction materials (copper, iron, silicon steel) for the manufacturing of electrical machines and equipment. It is important to have good knowledge of the properties and applications of these materials for proper design and fabrication of electrical machines as the performance of electrical equipment is dependent to a great extent on the type and quality of materials used for each specific equipment and application. To design an electrical equipment for meeting good performance, it is mandatory to have a thorough knowledge of all the factors governing the quality of engineering materials for the successful launching of the product in the market.

Electronics Applications

Different engineering materials such as metals, ceramics, semiconductors, polymers or plastics, various raw materials, and chemicals are widely used in different forms such as metalized film conductors, dielectric films, and both active and passive electronic components and devices along with a host of materials such as solders, solder masks, flux cleaners and so on used for various manufacturing processes for making core components used in different electronic devices and related applications. Some of the typical components such as memories, displays, and LEDs are used in daily electronic gadgets like mobile phones, computers, laptops, tablets, GPS devices, LED bulbs, TVs, and monitors and for a variety of other electronic applications (Fig. 1-6). The continuous ongoing research efforts focused on improving the fundamental understanding of electronic properties of various materials at different length scales have made all these advances possible. This has also been complemented by the concurrent advances in processing and fabrication technologies, particularly in thin film and nanostructure processing to make electronic devices and applications.

Mechanical and Structural Applications

Fig. 1-6 Electron appliances. (Picture Courtesy: LG)

Generally, the main purpose of structural materials is to transmit or support a force. Structural materials can be metallic, ceramic, polymeric, and composite. Structural materials can be used in various areas such as transportation (Fighter aircraft, trains and automobiles), construction (skyscrapers, buildings and roads), mechanical machinery components (common workshop machines, compressor, pump), energy production systems (turbine blades, boiler pipeline) and other smaller structures such as those used in electronic industries.

1.5 Properties of Engineering Materials

The different properties of various engineering materials directly influence the applications of the materials used in different industries for a variety of applications. For example, the mechanical strength and the ability of a material to be formed into a suitable shape directly affect the formability of mechanical components. So, it becomes very important to understand the mechanical and other properties of various materials before finalizing the material for any product or specific engineering application. The following typical list of the mechanical properties of a material is important for many engineering applications, as described below.