Chapter 1: Introduction to Materials Science and Engineering

1-1 Define materials science and engineering (MSE).

Solution:

Materials science and engineering (MSE) is an interdisciplinary field that studies and manipulates the composition and structure of materials across length scales to control materials properties through synthesis and processing.

1-2 What is the importance of the engineering tetrahedron for materials engineers?

Solution:

Structure, properties and performance all depend on the route in which a material is processed. We cannot predict the end properties for a material until we have specified a process to produce the component. Using the same material, but changing the way it is processed will result in different structure, properties and performance of that material. This is applicable to all material systems.

1-3 Define the following terms:
(a) composition;
(b) structure;
(c) synthesis;
(d) processing; and
(e) microstructure.

Solution:

(a) The chemical make-up of a material.

(b) The arrangement of atoms, seen at different levels of detail.

(c) How materials are made from naturally occurring or man-made chemicals.

(d) How materials are shaped into useful components.

(e) The structure of an object at the microscopic scale.

1-4 Explain the difference between the terms materials science and materials engineering.

Solution:

Materials scientists work on understanding underlying relationships between the synthesis and processing, structure, and properties of materials. Materials engineers focus on how to translate or transform materials into useful devices or structures.

1-5 The myriad materials in the world primarily fall into four basic categories; what are they? What are materials called that have one or more different types of material fabricated into one component? Give one example.

Solution:

Metals, polymers and ceramics. The addition of one or more of these to a single system is called a composite. An example of a composite material is fiberglass.

1-6 What are some of the materials and mechanical properties of metals and alloys?

Solution:

Metals and alloys have good electrical and thermal conductivity, high strength, ductility and formability, and high stiffness.

1-7 What is a ceramic, and what are some of the properties that you expect from a ceramic?

Solution:

Ceramics tend to have very high compressive strengths, but behave in a brittle (glass-like) manner. They have very high melting temperatures. Poor thermal conductivity and electrical conductivity make ceramics behave as an insulator instead of a conductor.

1-8 Make comparisons between thermoplastics and thermosetting polymers (a) on the basis of mechanical characteristics upon heating, and (b) according to possible molecular structures.

Solution:

Thermoplastics tend to soften with elevated temperature exposure with gradually decreasing viscosity. Thermosetting polymers do not soften with elevated temperature exposure; instead they will remain hard and will degrade, possibly charring with prolonged exposure.

Thermoplastics consist of long chain molecular arrangements of covalently bonded carbon atoms with various side groups. Thermosetting polymers tend to be a complex 3-D arrangement usually deviating from the clearly defined long-chain molecular arrangement.

1-9 Give three examples of composites that can be fabricated.

Solution:

Metal matrix composites (MMC) – A metal matrix reinforced with a ceramic material in the form of particles, whiskers or fibers. Example: Cobalt alloy reinforced with tungsten-carbide particulates.

Polymer matrix composites (PMC) – A polymer matrix reinforced with a ceramic material in the form of whiskers or fibers. Example: Kevlar or fiberglass.

Ceramic matrix composites (CMC) – A ceramic matrix reinforced with ceramic or metallic material in the form of whiskers or fibers. Example: Carbon fibers in an alumina (Al_2O_3) matrix.

1-10 For each of the following classes of materials, give two *specific* examples that are a regular part of your life:
(a) metals;
(b) ceramics;
(c) polymers; and
(d) semiconductors.

Specify the object that each material is found in and explain why the material is used in each specific application. *Hint:* One example answer for part (a) would be that aluminum is a metal used in the base of some pots and pans for even heat distribution. It is also a lightweight metal that makes it useful in kitchen cookware. Note that in this partial answer to part (a), a specific metal is described for a specific application.

Solution:

(a) Aluminum was described in the problem statement. Stainless steel is used for flatware. It is easily formed and has good corrosion resistance, strength, and hardness.

(b) Two specific examples of polymers are polystyrene and polytetrafluoroethylene also known as Teflon. Styrofoam is polystyrene rigid foam insulation that is used for cups that keep hot drinks warm. Teflon is used as a coating on the inside of kitchen cookware such as frying pans because it prevents food from sticking to the pan while cooking.

(c) Two examples of semiconductors are silicon doped with phosphorus (*n*–type) and silicon doped with boron (*p*–type). Both types of impurities convert silicon from a poor into a useful conductor. Both *n* and *p*–type semiconductors are contained in the semiconductor device called a diode, so that at the junction between both types, current is able to flow. A diode blocks current in one direction while allowing current flow in the other direction. A device that uses batteries, e.g. a remote control or a calculator, often contains a diode that protects the device if the batteries are inserted backward. The diode blocks the current from leaving the battery if it is reversed, protecting the sensitive electronics in the device. Another semiconductor is the compound semiconductor $Al_xGa_{1-x}As$, which is used in lasers.

(d) Ceramics are compounds that contain metallic and nonmetallic elements. Two specific examples are tungsten carbide and magnesia. Tungsten carbide is often bonded with cobalt and/or nickel. Tungsten carbide is used mainly in tips for metal cutting tools (knives can be made with this) because of its good wear resistant characteristics. Magnesia is a heat resistant ceramic that is used in liners for ovens. Magnesia can resist high temperatures but is susceptible to thermal stress cracking.

1-11 Describe the enabling materials property of each of the following and why it is so:
(a) steel for I-beams in skyscrapers;
(b) a cobalt chrome molybdenum alloy for hip implants;
(c) polycarbonate for eyeglass lenses; and
(d) bronze for artistic castings.

Solution:

(a) Steel for I-beams in skyscrapers must be strong in order to bear large mechanical loads.

(b) A cobalt chrome molybdenum alloy for hip implants must be biocompatible, meaning that it must not degrade when inserted into the body nor be toxic or otherwise dangerous.

(c) Polycarbonate for eyeglass lenses must be transparent and impact-resistant.

(d) Bronze can be melted and poured into molds to be shaped. It is also fairly corrosion resistant (which is important for outdoor sculptures). Over long periods of time when subjected to an outdoor environment, bronze will develop an oxide known as a patina. The patina protects the bronze from further corrosion.

1-12 Describe the enabling materials property of each of the following and why it is so:
(a) aluminum for airplane bodies;
(b) polyurethane for teeth aligners (invisible braces);
(c) steel for the ball bearings in a bicycle's wheel hub;
(d) polyethylene terephthalate for water bottles; and
(e) glass for wine bottles.

Solution:

(a) Aluminum has a high strength to weight ratio. Thus it has the strength needed to withstand the forces imposed on an airframe, but keeps the weight of the airplane low compared to other metals. The lighter the airplane body, the less force it takes to lift the plane into the air. This results in less fuel being used and a reduction in operating costs. Aluminum also has good corrosion resistance.

(b) Polyurethane for teeth aligners must be highly formable and transparent. Since teeth aligners are worn during the day, a transparent material is desirable to make them less conspicuous. A unique set of teeth aligners must be produced for each individual, and so the polyurethane must be easily molded. Computer software is used to produce computer models of a person's teeth during various stages of the correction process. A rapid prototyping tool is used to create physical models of the person's teeth at each stage. A sheet of polyurethane is then heated and formed onto the models to produce the teeth aligners.

(c) Ball bearings in a bicycle's wheel hub reduce friction between metal surfaces. Therefore, steel is used because it has high strength and hardness.

(d) Polyethylene terephthalate is easily formed by a blow molding process and is recyclable, critical properties for mass-produced water bottles.

(e) Glass has high chemical resistance; thus, glass bottles are used to preserve the taste of the wine contained in them.

1-13 What properties should an engineer consider for a total knee replacement of a deteriorated knee joint with an artificial prosthesis when selecting the materials for this application?

Solution:

Properties that should be considered are those relating to strength (fatigue, tensile and compressive) since the knee sustains static, dynamic and cyclic loads. Hardness will promote wear resistance. Modulus of elasticity similar to that of the human bone otherwise other problems will occur. Chemical stability in regards to corrosion resistance and cellular toxicity to prevent negative reactions to the material selected. The material needs to have the ability to bond with the residual bone material and have longevity in order to avoid frequent replacement.

1-14 Write one paragraph about why single-crystal silicon is currently the material of choice for microelectronics applications. Write a second paragraph about potential alternatives to single-crystal silicon for solar cell applications. Provide a list of the references or websites that you used. You must use at least three references.

Solution:

Answers will vary.

1-15 Coiled springs should be very strong and stiff. Silicon nitride (Si_3N_4) is a strong, stiff material. Would you select this material for a spring? Explain.

Solution:

Springs are intended to resist high elastic forces, where only the atomic bonds are stretched when the force is applied. The silicon nitride would satisfy this requirement; however, we would like to also have good resistance to impact and at least some ductility (in case the spring is overloaded) to ensure that the spring will not fail catastrophically. We also would like to be sure that all springs will perform satisfactorily. Ceramic materials such as silicon nitride have virtually no ductility, poor impact properties, and often are difficult to manufacture without introducing at least some small flaws that cause failure even for relatively low forces. The silicon nitride is NOT recommended.

1-16 Temperature indicators are sometimes produced from a coiled metal strip that uncoils a specific amount when the temperature increases. How does this work; from what kind of material would the indicator be made; and what are the important properties that the material in the indicator must possess?

Solution:

Bimetallic materials are produced by bonding two materials having different coefficients of thermal expansion to one another, forming a laminar composite. When the temperature changes, one of the materials will expand or contract more than the other material. This difference in expansion or contraction causes the bimetallic material to change shape; if the original shape is that of a coil, then the device will coil or uncoil, depending on the direction of the temperature change. In order for the material to perform well, the two materials must have very different coefficients of thermal expansion and should have high enough moduli of elasticity so that no permanent deformation of the material occurs.

1-17 What is the purpose of the classification for functional materials?

Solution:

It specifically categorizes the types of materials used with specific applications. For instance, aerospace materials use lightweight materials such as aluminum alloys or carbon-composites for flight applications instead of using heavy materials such as stainless steel.

1-18 Explain the difference between crystalline and amorphous materials. Give an example of each that you use in your daily life.

Solution:

Crystalline materials have long-range order arrangement of its atoms while amorphous materials have short-range order. One example of a crystalline material is metal and an example of an amorphous material is glass.

1-19 If you were given a material and were asked to determine whether it is crystalline or amorphous, how would you determine it?

Solution:

Crystalline materials can be delineated from amorphous materials using diffraction techniques. Crystalline materials will produce diffraction patterns while amorphous materials will not.

1-20 List six materials performance problems that may lead to failure of components.

Solution:

Excessive deformation (overload), fracture, wear, corrosion, fatigue and creep.

1-21 Steel is often coated with a thin layer of zinc if it is to be used outside. What characteristics do you think the zinc provides to this coated, or galvanized, steel? What precautions should be considered in producing this product? How will the recyclability of the product be affected?

Solution:

The zinc provides corrosion resistance to the iron in two ways. If the iron is completely coated with zinc, the zinc provides a barrier between the iron and the surrounding environment, therefore protecting the underlying iron. If the zinc coating is scratched to expose the iron, the zinc continues to protect the iron because the zinc corrodes preferentially to the iron (see Chapter 23). To be effective, the zinc should bond well to the iron so that it does not permit reactions to occur at the interface with the iron and so that the zinc remains intact during any forming of the galvanized material. When the material is recycled, the zinc will be lost by oxidation and vaporization, often producing a "zinc dust" that may pose an environmental hazard. Special equipment may be required to collect and either recycle or dispose of the zinc dust.

1-22 The relationship between structure and materials properties can be influenced by the service conditions (environmental conditions). Name two engineering disasters that have had tragic results and why they happened.

Solution:

Answers will vary. Two sample answers:

The Titanic sank when it hit an iceberg. Hull plate and rivets of the ship were made of the strongest material to use at that time, but at room temperature. The material failed due to its anisotropy and temperature sensitivity for when it was exposed to the frigid waters during its voyage, behaved like glass (brittle).

The Space Shuttle Challenger tragic flight when the rocket boosters exploded due to the solid rocket booster (SRB) O-ring failure. The freezing temperatures of that morning had the O-rings behave like glass and the vibrations during lift-off cracked the O-rings and the boosters exploded.

1-23 What is the difference between physical and mechanical properties? List three examples for each one.

Solution:

Physical properties are the properties of a material as it is found in nature such as density, thermal conductivity, electrical conductivity, luster, color, corrosion resistance, oxidation resistance, coefficient of thermal expansion (CTE) and magnetic permeability.

Mechanical properties are properties that can be tested for such as strength (fatigue, impact, tensile, yield), ductility, stiffness, creep rupture, toughness and hardness.

1-24 The type of jet engine used on most large commercial aircraft is called a turbofan jet engine because it has a large wheel at the front of the engine that propels air rearward. Most of this air bypasses the engine, but bypass air significantly increases thrust and efficiency of these engines. Some engine manufacturers are now using carbon fiber-epoxy composites rather than traditional aluminum blades.
(a) What materials properties do you think an engineer must consider when selecting a material for this application? Be as specific as possible.
(b) What benefits do you think carbon fiber epoxy composites have compared to aluminum alloys? What limitations or possible downsides could there be to using a carbon fiber epoxy composite?

Solution:

(a) Properties that should be considered include the following: Tensile strength, impact toughness, fracture toughness, modulus of elasticity and resistance to ultraviolet radiation, which is a deteriorative property for polymers.

(b) Potential benefits include significant weight reduction and greater stiffness over aluminum. The downsides include increase cost and most likely lower fracture toughness.

1-25 You are an engineer working for a manufacturer of land-based gas turbines. These turbines are similar to jet engines, but they are used on land to provide power for electricity generation and gas compression pipeline applications. Suppose that you would like to apply a ceramic-based thermal barrier coating to the turbine blades in the first-stage turbine to increase the operating temperature and efficiency of the engine.
(a) What difficulties might engineers experience in trying to design a ceramic coating that will be applied to a super alloy metal blade?
(b) What properties should be taken into consideration when choosing a suitable ceramic material for a coating? Be as thorough as possible.

Solution:

(a) Difficulties include a suitable method to apply and bond the ceramic to the metal blades. Coefficients of thermal expansion (CTE) for metals and ceramics differ greatly which would result in spallation of the ceramic coating.

(b) Properties to be considered should be coefficient of thermal expansion (CTE), thermal conductivity, specific heat, melting temperature, impact toughness and deteriorative properties.

1-26 We would like to produce a transparent canopy for an aircraft. If we were to use a traditional window glass canopy, rocks or birds might cause it to shatter. Design a material that would minimize damage or at least keep the canopy from breaking into pieces.

Solution:

We might sandwich a thin sheet of a transparent polymer between two layers of the glass. This approach, used for windshields of automobiles, will prevent the “safety” glass from completely disintegrating when it fails, with the polymer holding the broken pieces of glass together until the canopy can be replaced.

Another approach might be to use a transparent, “glassy” polymer material such as polycarbonate. Some polymers have reasonably good impact properties and may resist failure. The polymers can also be toughened to resist impact by introducing tiny globules of a rubber, or elastomer, into the polymer; these globules improve the energy-absorbing ability of the composite polymer, while being too small to interfere with the optical properties of the material.

1-27 You would like to design an aircraft that can be flown by human power nonstop for a distance of 30 km. What types of material properties would you recommend? What materials might be appropriate?

Solution:

Such an aircraft must possess enough strength and stiffness to resist its own weight, the weight of the human “power source,” and any aerodynamic forces imposed on it. On the other hand, it must be as light as possible to ensure that the human can generate enough work to operate the aircraft. Composite materials, particularly those based on a polymer matrix, might comprise the bulk of the aircraft. The polymers have a light weight (with densities of less than half that of aluminum) and can be strengthened by introducing strong, stiff fibers made of glass, carbon, or other polymers. Composites, having the strength and stiffness of steel, but with only a fraction of the weight, can be produced in this manner.

1-28 You would like to place a three-foot diameter microsatellite into orbit. The satellite will contain delicate electronic equipment that will send and receive radio signals from earth. Design the outer shell within which the electronic equipment is contained. What properties will be required, and what kind of materials might be considered?

Solution:

The shell of the microsatellite must satisfy several criteria. The material should have a low density, minimizing the satellite weight so that it can be lifted economically into its orbit; the material must be strong, hard, and impact resistant in order to ensure that any “space dust” that might strike the satellite does not penetrate and damage the electronic equipment; the material must be transparent to the radio signals that provide communication between the satellite and earth; and the material must provide some thermal insulation to ensure that solar heating does not damage the electronics.

One approach might be to use a composite shell of several materials. The outside surface might be a very thin reflective metal coating that would help reflect solar heat.

The main body of the shell might be a light weight fiber-reinforced composite that would provide impact resistance (preventing penetration by dust particles) but would be transparent to radio signals.

1-29 What properties should the head of a carpenter's hammer possess? How would you manufacture a hammer head?

Solution:

The head for a carpenter's hammer is produced by forging, a metal working process; a simple steel shape is heated and formed in several steps while hot into the required shape. The head is then heat treated to produce the required mechanical and physical properties.

The striking face and claws of the hammer should be hard—the metal should not dent or deform when driving or removing nails. These portions must also possess some impact resistance, particularly so that chips do not flake off the striking face and cause injuries.

1-30 You would like to select a material for the electrical contacts in an electrical switching device that opens and closes frequently and forcefully. What properties should the contact material possess? What type of material might you recommend? Would Al_2O_3 be a good choice? Explain.

Solution:

The material must have a high electrical conductivity to ensure that no electrical heating or arcing occurs when the switch is closed. High purity (and therefore very soft) metals such as copper, aluminum, silver, or gold provide the high conductivity. The device must also have good wear resistance, requiring that the material be hard. Most hard, wear resistant materials have poor electrical conductivity.

One solution to this problem is to produce a particulate composite material composed of hard ceramic particles embedded in a continuous matrix of the electrical conductor. For example, silicon carbide particles could be introduced into pure aluminum; the silicon carbide particles provide wear resistance while aluminum provides conductivity. Other examples of these materials are described in Chapter 17.

Al_2O_3 by itself would not be a good choice—alumina is a ceramic material and is an electrical insulator; however, alumina particles dispersed into a copper matrix might provide wear resistance to the composite.

1-31 Aluminum has a density of 2.7 g/cm^3. Suppose you would like to produce a composite material based on aluminum having a density of 1.5 g/cm^3. Design a material that would have this density. Would introducing beads of polyethylene, with a density of 0.95 g/cm^3, into the aluminum be a likely possibility? Explain.

Solution:

In order to produce an aluminum-matrix composite material with a density of 1.5 g/cm^3, we would need to select a material having a density considerably less than 1.5 g/cm^3. While polyethylene's density would make it a possibility, the polyethylene has a very low melting point compared to aluminum; this would make it very difficult to introduce the polyethylene into a solid aluminum matrix—processes such as casting or powder metallurgy would destroy the polyethylene. Therefore polyethylene would NOT be a likely possibility.

One approach, however, might be to introduce *hollow* glass beads. Although ceramic glasses have densities comparable to that of aluminum, a hollow bead will have a very low density. The glass also has a high melting temperature and could be introduced into liquid aluminum for processing as a casting.

1-32 You would like to be able to identify different materials without resorting to chemical analysis or lengthy testing procedures. Describe some possible testing and sorting techniques you might be able to use based on the physical properties of materials.

Solution:

Some typical methods might include: measuring the density of the material (may help in separating metal groups such as aluminum, copper, steel, magnesium, etc.), determining the electrical conductivity of the material (may help in separating ceramics and polymers from metallic alloys), measuring the hardness of the material (perhaps even just using a file), and determining whether the material is magnetic or nonmagnetic (may help separate iron from other metallic alloys).

1-33 You would like to be able to physically separate different materials in a scrap recycling plant. Describe some possible methods that might be used to separate materials such as polymers, aluminum alloys, and steels from one another.

Solution:

Steels can be magnetically separated from the other materials; steel (or carbon-containing iron alloys) are ferromagnetic and will be attracted by magnets. Density differences could be used—polymers have a density near that of water; the specific gravity of aluminum alloys is around 2.7; that of steels is between 7.5 and 8. Electrical conductivity measurements could be used—polymers are insulators while aluminum has a particularly high electrical conductivity.

1-34 Some pistons for automobile engines might be produced from a composite material containing small, hard silicon carbide particles in an aluminum alloy matrix. Explain what benefits each material in the composite may provide to the overall part. What problems might the different properties of the two materials cause in producing the part?

Solution:

Aluminum provides good heat transfer due to its high thermal conductivity. It has good ductility and toughness, reasonably good strength, and is easy to cast and process. The silicon carbide, a ceramic, is hard and strong, providing good wear resistance, and also has a high melting temperature. It provides good strength to the aluminum, even at elevated temperatures. There may be problems, however, producing the material—for example, the silicon carbide may not be uniformly distributed in the aluminum matrix if the pistons are produced by casting. We need to ensure good bonding between the particles and the aluminum—the surface chemistry must therefore be understood. Differences in expansion and contraction with temperature changes may cause debonding and even cracking in the composite.

1-35 Investigate the origins and applications for a material that has been invented or discovered since you were born *or* investigate the development of a product or technology that has been invented since you were born that was made possible by the use of a novel material. Write one paragraph about this material or product. Provide a list of the references or websites that you used. You must use at least three references.

Solution:

Answers will vary.