Classification Of Engineering Materials, And Their Properties:

1] Material classification:

There are different ways of classifying materials. One way is to describe five groups or families (Table 1-1):

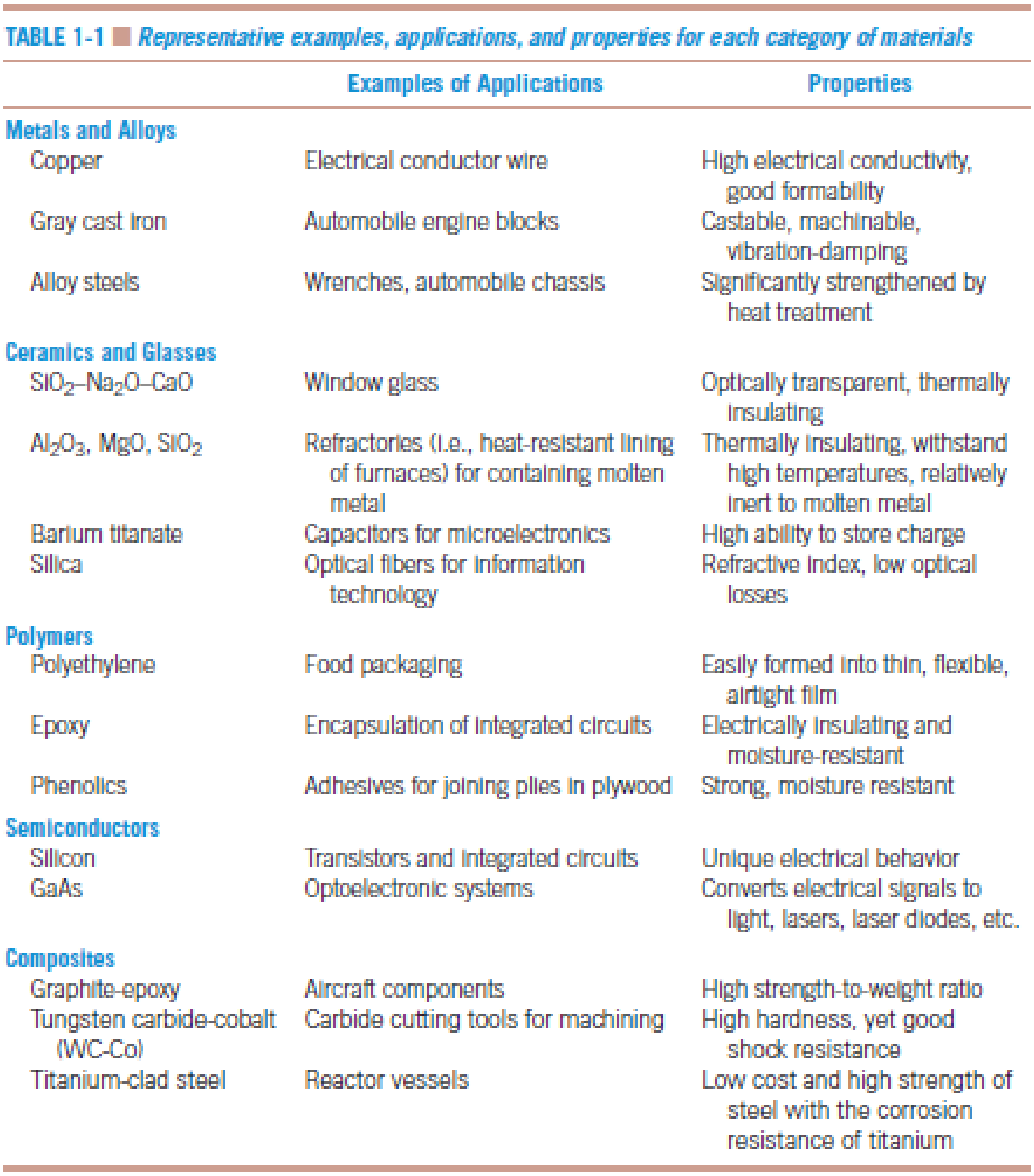


TABLE 1-1 ■ *Representative examples, applications, and properties for each category of materials*

	Examples of Applications	Properties
Metals and Alloys		
Copper	Electrical conductor wire	High electrical conductivity, good formability
Gray cast iron	Automobile engine blocks	Castable, machinable, vibration-damping
Alloy steels	Wrenches, automobile chassis	Significantly strengthened by heat treatment
Ceramics and Glasses		
SiO_2–Na_2O–CaO	Window glass	Optically transparent, thermally insulating
Al_2O_3, MgO, SiO_2	Refractories (i.e., heat-resistant lining of furnaces) for containing molten metal	Thermally insulating, withstand high temperatures, relatively inert to molten metal
Barium titanate	Capacitors for microelectronics	High ability to store charge
Silica	Optical fibers for information technology	Refractive index, low optical losses
Polymers		
Polyethylene	Food packaging	Easily formed into thin, flexible, airtight film
Epoxy	Encapsulation of integrated circuits	Electrically insulating and moisture-resistant
Phenolics	Adhesives for joining plies in plywood	Strong, moisture resistant
Semiconductors		
Silicon	Transistors and integrated circuits	Unique electrical behavior
GaAs	Optoelectronic systems	Converts electrical signals to light, lasers, laser diodes, etc.
Composites		
Graphite-epoxy	Aircraft components	High strength-to-weight ratio
Tungsten carbide-cobalt (WC-Co)	Carbide cutting tools for machining	High hardness, yet good shock resistance
Titanium-clad steel	Reactor vessels	Low cost and high strength of steel with the corrosion resistance of titanium

1. **Metals and alloys**;
2. **Ceramics**, **glasses**, and **glass-ceramics**;
3. **Polymers** (plastics);
4. **Semiconductors**
5. **Composite materials**

1- Metals and Alloys:

Metals and alloys include steels, aluminum, magnesium, zinc, cast iron, titanium, copper, and nickel. An alloy is a metal that contains additions of one or more metals or non-metals. In general, metals have good electrical and thermal conductivity. Metals and alloys have relatively high strength, high stiffness, ductility or formability, and shock resistance. They are particularly useful for structural or load-bearing applications. Although pure metals are occasionally used, alloys provide improvement in a particular desirable property or permit better combinations of properties.

2- **Ceramics:**

Ceramics can be defined as inorganic crystalline materials. Beach sand and rocks are examples of naturally occurring ceramics. Advanced ceramics are materials made by refining naturally occurring ceramics and other special processes. Advanced ceramics are used in substrates that house computer chips, sensors and capacitors, wireless communications, inductors, and electrical insulation. Some ceramics are used as barrier coatings to protect metallic substrates in turbine engines. Ceramics are also used in such consumer products as paints, and tires, and for industrial applications such as the tiles for the space shuttle.

Traditional ceramics are used to make bricks, tableware, toilets, bathroom sinks, refractories (heat-resistant material), and abrasives. In general, due to the presence of porosity (small holes), ceramics do not conduct heat well; they must be heated to very high temperatures before melting. Ceramics are strong and hard, but also very brittle. We normally prepare fine powders of ceramics and convert these into different shapes. New processing techniques make ceramics sufficiently resistant to fracture that they can be used in load-bearing applications, such as impellers in turbine engines. Ceramics have exceptional strength under compression.

Can you believe that an entire fire truck can be supported using four ceramic coffee cups?

3- Glasses and Glass-Ceramics:

Glass is an amorphous material, often, but not always, derived from a molten liquid. The term “amorphous” refers to materials that do not have a regular, periodic arrangement of atoms. The fiber optics industry is founded on optical fibers based on high purity silica glass. Glasses are also used in houses, cars, computer and television screens, and hundreds of other applications. Glasses can be thermally treated (tempered) to make them stronger. Forming glasses and nucleating (forming) small crystals within them by a special thermal process creates materials that are known as glass-ceramics. Zerodur™ is an example of a glass-ceramic material that is used to make the mirror substrates for large telescopes (e.g., the Chandra and Hubble telescopes). Glasses and glass-ceramics are usually processed by melting and casting.

4- Polymers:

Polymers are typically organic materials. They are produced using a process known as **polymerization.** Polymeric materials include rubber (elastomers) and many types of adhesives. Polymers typically are good electrical and thermal insulators although there are exceptions such as the semiconducting polymers. Although they have lower strength, polymers have a very good **strength-to-weight ratio.** They are typically not suitable for use at high temperatures. Many polymers have very good resistance to corrosive chemicals. Polymers have thousands of applications ranging from bulletproof vests, compact disks (CDs), ropes, and liquid crystal displays (LCDs) to clothes and coffee cups. **Thermoplastic** polymers, in which the long molecular chains are not rigidly connected, have good ductility and formability; **thermosetting** polymers are stronger but more brittle because the molecular chains are tightly linked (Figure 2-1). Polymers are used in many applications, including electronic devices. Thermoplastics are made by shaping their molten form. Thermosets are typically cast into molds. **Plastics** contain additives that enhance the properties of polymers.

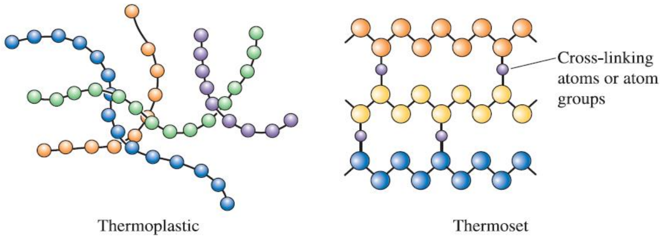


Figure 2-1 Polymerization occurs when small molecules, represented by the circles, combine to produce larger molecules, or polymers. The polymer molecules can have a structure that consists of many chains that are entangled but not connected (thermoplastics) or can form three-dimensional networks in which chains are cross-linked (thermosets)

5- **Semiconductors:**

Silicon, germanium, and gallium arsenide-based semiconductors such as those used in computers and electronics are part of a broader class of materials known as electronic materials. The electrical conductivity of semiconducting materials is between that of ceramic insulators and metallic conductors. In some semiconductors, the level of conductivity can be controlled to enable electronic devices such as transistors, diodes, etc., that are used to build integrated circuits. In many applications, we need large single crystals of semiconductors. These are grown from molten materials. Often, thin films of semiconducting materials are also made using specialized processes.

6- **Composite Materials:**

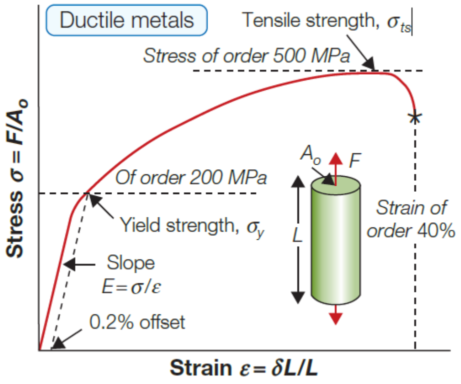
The main idea in developing composites is to blend the properties of different materials. These are formed from two or more materials, producing properties not found in any single material. Concrete, plywood, and fiberglass are examples of composite materials. Fiberglass is made by dispersing glass fibers in a polymer matrix. The glass fibers make the polymer stiffer, without significantly increasing its density. With composites, we can produce lightweight, strong, ductile, temperature-resistant materials or we can produce hard, yet shock-resistant, cutting tools that would otherwise shatter. Advanced aircraft and aerospace vehicles rely heavily on composites such as carbon fiber-reinforced polymers (Figure 2-2). Sports equipment such as bicycles, golf clubs, tennis rackets, and the like also make use of different kinds of composite materials that are light and stiff.

Figure 2-2 The X-wing for advanced helicopters relies on a material composed of a carbon fiber reinforced polymer. (Courtesy of Sikorsky Aircraft Division – United Technologies Corporation.)

2] Material properties:

So what are these properties? Some, like density (mass per unit volume) and price (the cost per unit volume or weight) are familiar enough, but others are not, and getting them straight is essential. Think first of those that have to do with carrying load safely—the *mechanical properties.*

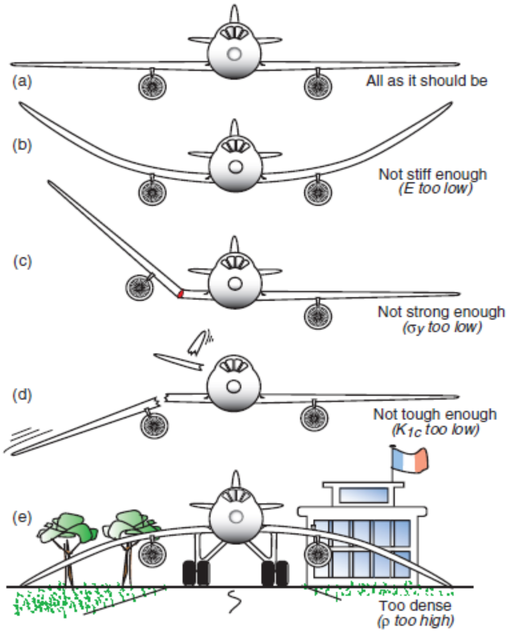
1- Mechanical properties



The stress-strain curve for a metal, showing the modulus, E, the 0.2% yield strength, σ_y, and the ultimate strength, σ_{ts}.

A steel ruler is easy to bend *elastically*—'elastic' means that it springs back when released. Its elastic stiffness (here, resistance to bending) is set partly by its shape—thin strips are easy to bend—and partly by a property of the steel itself: their elastic moduli, E. Materials with high E, like steel, are intrinsically stiff; those with low *E*, like polyethylene, are not. The steel ruler bends elastically, but if it is a good one, it is hard to give it a permanent bend. Permanent deformation has to do with *strength*, not stiffness. The ease with which a ruler can be permanently bent depends, again, on its shape and on a different property of the steel—its *yield strength*, *σ*y. Materials with large *σ*y, like titanium alloys, are hard to deform permanently even though their stiffness, coming from *E*, may not be high; those with low *σ*y, like lead, can be deformed with ease. When metals deform, they generally get stronger (this is called 'work hardening'), but there is an ultimate limit, called the *tensile strength*, *σ*ts, beyond which the material fails (the amount it stretches before it breaks is called the *ductility*). So far so good. One more. If the ruler were made not of steel but of glass or of PMMA (Plexiglas, Perspex), as transparent rulers are, it is not possible to bend it permanently at all. The ruler will fracture suddenly, without warning, before it acquires a permanent bend. We think of materials that break in this way as brittle, and materials that do not as tough. There is no permanent deformation here, so σy is not the right property. The resistance of materials to cracking and fracture is measured instead by the fracture toughness, K1c. Steels are tough—well, most are (steels can be made brittle)—they have a high K1c. Glass epitomizes brittleness; it has a very low K1c. Figure 1.2(d) suggests consequences of inadequate fracture and toughness. We started with the material property density, mass per unit volume, symbol ρ. Density, in a ruler, is irrelevant. But for almost anything that moves, weight carries a fuel penalty, modest for automobiles, greater for trucks and trains, greater still for aircraft, and enormous in space vehicles. Minimizing weight has much to do with clever design is equally to choice of material. Aluminum has a low density, lead a high one. If our little aircraft were made of lead, it would never get off the ground at all (Figure 1.2(e)).These is not the only mechanical properties, but they are the most important ones.

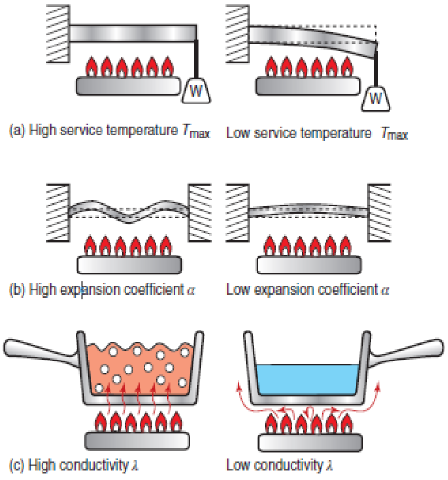
Figure 2-3



2- Thermal properties

The properties of a material change with temperature, usually for the worse. Its strength falls, it starts to ‘creep’ (to sag slowly over time), and it may oxidize, degrade or decompose (Figure 2.4). This means that there is a limiting temperature called the *maximum service temperature*, *T*max, above which its use is impractical. Stainless steel has a high *T*max—it can be used up to 800°C; most polymers have a low *T*max and are seldom used above 150°C.

Figure 2-4

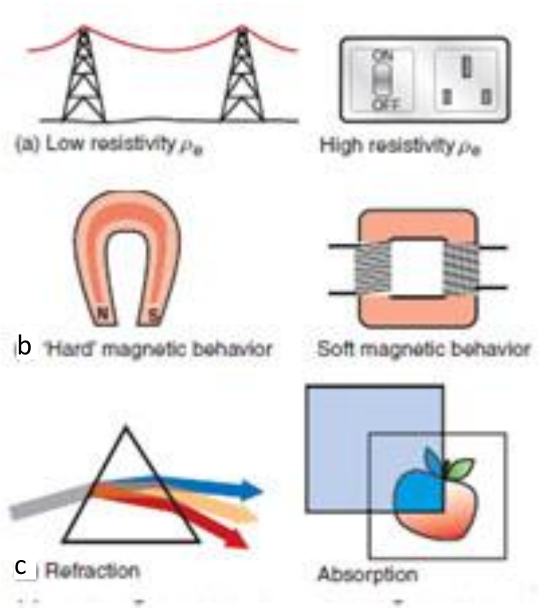


Most materials expand when they are heated, but by differing amounts depending on their thermal expansion coefficient, *α*. The expansion is small, but its consequences can be large. If, for instance, a rod is constrained, as in Figure 2.4(b), and then heated, expansion forces the rod against the constraints, causing it to buckle. Railroad track buckles in this way if provision is not made to cope with it. Some materials—metals, for instance—feel cold; others—like woods—feel warm. This feel has to do with two thermal properties of the material: *thermal conductivity* and *heat capacity*. The first, thermal conductivity, *λ*, measures the rate at which heat flows through the material when one side is hot and the other cold. Materials with high *λ* are what you want if you wish to conduct heat from one place to another, as in cooking pans, radiators and heat exchangers; Figure 2.4(c) suggests consequences of high and low *λ* for the cooking vessel. But low *λ* is useful too—low *λ* materials insulate homes, reduce the energy consumption of refrigerators and freezers, and enable space vehicles to re-enter the earth's atmosphere. These applications have to do with long-time, steady, heat flow. When time is limited, that other property—*heat capacity*, Cp—matters. It measures the Amount of heat that it takes to make the temperature of material rise by a given amount. High heat capacity materials—copper, for instance—require a lot of heat to change their temperature; low heat capacity materials, like polymer foams, take much less

3- Electrical, magnetic and optical properties

We start with electrical conduction and insulation (Figure 2.5(a)). Without electrical conduction we would lack the easy access to light, heat, power, control and communication that—today—we take for granted. Metals conduct well—copper and aluminum are the best of those that are affordable. But conduction is not always a good thing. Fuse boxes, switch casings, all require insulators. Here the property we want is *resistivity*, *ρ*e, the inverse of electrical conductivity *κ*e. Most plastics and glass have high resistivity (Figure 2.5(a))—they are used as insulators—though, by special treatment, they can be made to conduct a little. Electricity and magnetism are closely linked. Electric currents induce magnetic fields; a moving magnet induces, in any nearby conductor, an electric current. The response of most materials to magnetic fields is too small to be of practical value. But a few—called ferromagnets have the capacity to trap a magnetic field permanently. These are called 'hard' magnetic materials because, once magnetized, they are hard to demagnetize. They are used as permanent magnets in headphones, motors and dynamos. Here the key property is the *remanence*, a measure of the intensity of the retained magnetism.

Figure 2-5

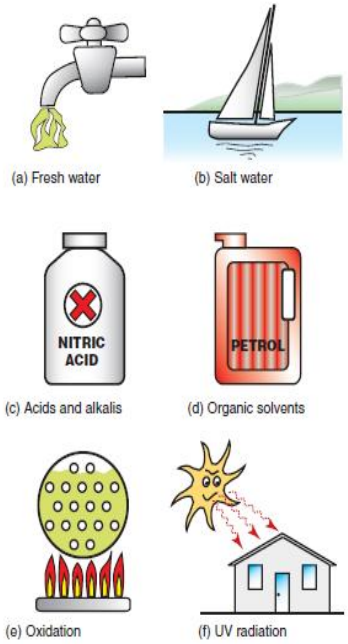


A few others—‘soft Magnet materials—are easy to’ magnetize and demagnetize. They are the materials of transformer cores. They have the capacity to conduct a magnetic field, but not retain it permanently (Figure 2.5(b)). For these a key property is the *saturation magnetization*, which measures how large a field the material can conduct. Materials respond to light as well as to electricity and magnetism—hardly surprising, since light itself is an electromagnetic wave. Materials that are opaque *reflect* light; those that are transparent *refract* it, and some have the ability to *absorb* some wavelengths (colors) while allowing others to pass freely (Figure 2.5(c)).

4- Chemical properties

Products often have to function in hostile environments, exposed to corrosive fluids, to hot gases or to radiation. Damp air is corrosive, so is water; the sweat of your hand is particularly corrosive, and of course there are far more aggressive environments than these. If the product is to survive for its design life it must be made of materials—or at least coated with materials—that can tolerate the surroundings in which they operate. Figure 2.6 illustrates some of the commonest of these: fresh and salt water, acids and alkalis, organic solvents, oxidizing flames and ultraviolet radiation. We regard the intrinsic resistance of a material to each of these as material properties, measured on a scale of 1 (very poor) to 5 (very good).

Figure 2-6



(a) Fresh water (b) Salt water

(c) Acids and alkalis (d) Organic solvents

(e) Oxidation (f) UV radiation

Chemical properties: resistance to water, acids, alkalis, organic solvents, oxidation and radiation.