

PHYSICAL PROPERTIES OF MATERIALS

- Volumetric and Melting Properties
- Thermal Properties
- Mass Diffusion
- Electrical Properties
- Electrochemical Processes

Physical Properties Defined

Properties that define the behavior of materials in response to physical forces other than mechanical

- **Components in a product must do more than simply withstand mechanical stresses**
- They must conduct electricity (or prevent conduction), allow heat to transfer (or allow its escape), transmit light (or block transmission), and satisfy many other functions
- Includes: volumetric, thermal, electrical, and electrochemical properties

Physical Properties in Manufacturing

- Important in manufacturing because they often influence process performance
- Examples:
 - In machining, **thermal properties** of the work material determine the cutting temperature, which affects how long tool can be used before failure
 - In microelectronics, **electrical properties** of silicon and how these properties can be altered by chemical and physical processes is the basis of semiconductor manufacturing

Volumetric and Melting Properties

Properties related to the volume of solids and how the properties are affected by temperature

- Includes:
 - Density
 - Thermal expansion
 - Melting point

Density Defined

Weight per unit volume

- Typical units are g/cm^3 (lb/in^3)
- Determined by atomic number and other factors such as atomic radius, and atomic packing

Specific gravity = density of a material relative to density of water and is a ratio with no units

Why Density is Important

Important consideration in material selection for a given application, but it is generally not the only property of interest

- Strength is also important, and the two properties are often related in a *strength-to-weight ratio*, which is tensile strength divided by its density
 - Useful ratio in comparing materials for structural applications in aircraft, automobiles, and other products where weight and energy are of concern

Thermal Expansion

- Density of a material is a function of temperature
 - In general, density decreases with increasing temperature
 - Volume per unit weight increases with increasing temperature
 - Thermal expansion is the name for this effect of temperature on density
 - Measured by *coefficient of thermal expansion* α

Coefficient of Thermal Expansion

Change in length per degree of temperature, such as mm/mm/°C (in/in/°F)

- Length ratio rather than volume ratio because this is easier to measure and apply

Change in length for a given temperature change is:

$$L_2 - L_1 = \alpha L_1 (T_2 - T_1)$$

where α = coefficient of thermal expansion; L_1 and L_2 are lengths corresponding respectively to temperatures T_1 and T_2

Thermal Expansion in Manufacturing

- Thermal expansion is used in *shrink fit* and *expansion fit* assemblies
 - Part is heated to increase size or cooled to decrease size to permit insertion into another part
 - When part returns to ambient temperature, a tightly-fitted assembly is obtained
- Thermal expansion can be a problem in *heat treatment* and *welding* due to thermal stresses that develop in material during these processes

Melting Characteristics for Elements

Melting point T_m of a pure element = temperature at which it transforms from solid to liquid state

- The reverse transformation occurs at the same temperature and is called the *freezing point*

Heat of fusion = heat energy required at T_m to accomplish transformation from solid to liquid

Melting of Metal Alloys

- Unlike pure metals, most alloys do not have a single melting point
- Instead, melting begins at a temperature called the *solidus* and continues as temperature increases until converting completely to liquid at a temperature called the *liquidus*
 - Between the two temperatures, the alloy is a mixture of solid and molten metals
 - Exception: *eutectic alloys* melt (and freeze) at a single temperature

Melting of Noncrystalline Materials

- In noncrystalline materials (glasses), a gradual transition from solid to liquid states occurs
- The solid material gradually softens as temperature increases, finally becoming liquid at the melting point
- During softening, the material has a consistency of increasing plasticity (increasingly like a fluid) as it gets closer to the melting point

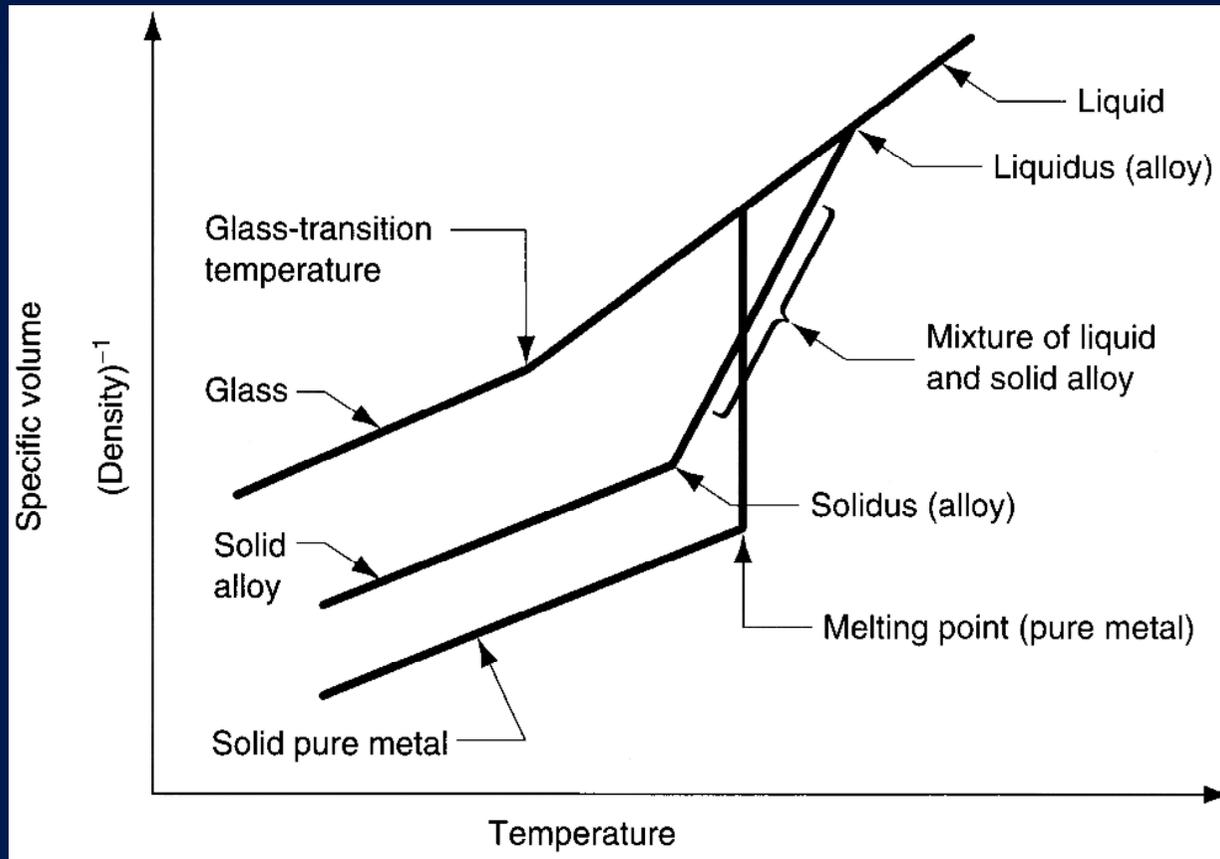


Figure 4.1 - Changes in volume per unit weight (1/density) as a function of temperature for a hypothetical pure metal, alloy, and glass; all exhibiting similar thermal expansion and melting characteristics

Importance of Melting in Manufacturing

- *Metal casting* - the metal is melted and then poured into a mold cavity
 - Metals with lower melting points are generally easier to cast
- *Plastic molding* - melting characteristics of polymers are important in nearly all polymer shaping processes
- *Sintering of powdered metals* - sintering does not melt the material, but temperatures must approach the melting point in order to achieve the required bonding of powders

Thermal Properties

- Thermal expansion, melting, and heat of fusion are thermal properties because temperature determines the thermal energy level of the atoms, leading to the changes in materials
- Additional thermal properties:
 - Specific heat
 - Thermal conductivity
 - These properties relate to the storage and flow of heat within a substance

Specific Heat

The quantity of heat energy required to increase the temperature of a unit mass of material by one degree

To determine the energy to heat a certain weight of metal to a given elevated temperature:

$$H = C W (T_2 - T_1)$$

where H = amount of heat energy; C = specific heat of the material; W = its weight; and $(T_2 - T_1)$ = change in temperature

Volumetric Specific Heat

The quantity of heat energy required to raise the temperature of a unit volume of material by one degree

- Density ρ multiplied by specific heat C
- *Volumetric specific heat* = ρC

Thermal Conductivity

Thermal conduction - transfer of thermal energy within a material from molecule to molecule by purely thermal motions; no transfer of mass

Thermal conductivity of a material = capability to transfer heat through itself by this physical mechanism

- Measured by *coefficient of thermal conductivity k*.
Units: J/s mm °C (Btu/in hr °F)
- Coefficient of thermal conductivity is generally high in metals, low in ceramics and plastics

Thermal Diffusivity

The ratio of thermal conductivity to volumetric specific heat is frequently encountered in heat transfer analysis

$$K = \frac{k}{\rho C}$$

Thermal Properties in Manufacturing

- Important in manufacturing because heat generation is common in so many processes
 - In some cases, heat is the energy that accomplishes the process
 - Examples: heat treating, sintering of powder metals and ceramics
 - In other cases, heat is generated as a result of the process
 - Examples: cold forming and machining of metals

Mass Diffusion

Movement of atoms or molecules within a material or across a boundary between two materials in contact

- Because of thermal agitation of the atoms in a material (solid, liquid, or gas), atoms are continuously moving about
 - In liquids and gases, where the level of thermal agitation is high, it is a free-roaming movement
 - In metals, atomic motion is facilitated by vacancies and other imperfections in the crystal structure

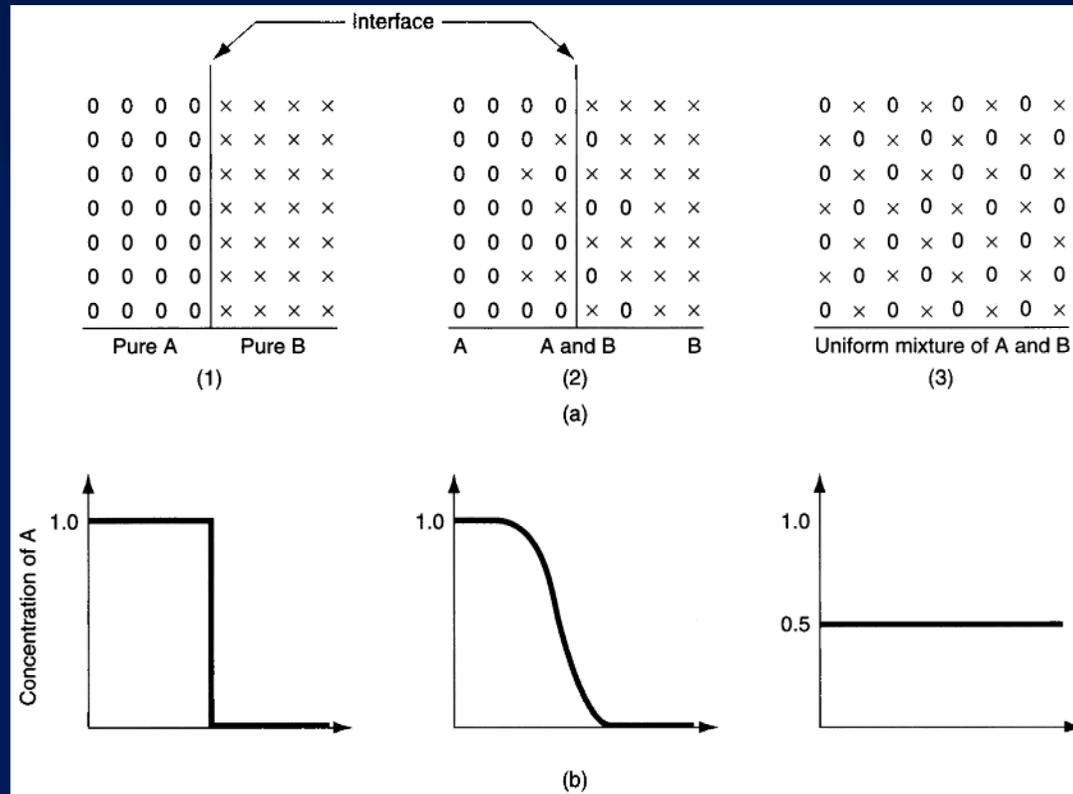


Figure 4.2 - Mass diffusion: (a) model of atoms in two solid blocks in contact: (1) when two pieces are first brought together, each has its own compositions; (2) after time, an exchange of atoms occurs; and (3) eventually, a uniform concentration occurs. The concentration gradient dc/dx for metal A is plotted in (b).

Mass Diffusion in Manufacturing

- Surface hardening treatments based on diffusion include *carburizing* and *nitriding*
- *Diffusion welding* - used to join two components by pressing them together and allowing diffusion to occur across boundary to create a permanent bond
- Diffusion is also used in *electronics manufacturing* to alter the surface chemistry of a semiconductor chip in very localized regions to create circuit details

Electrical Properties

- Engineering materials exhibit a great variation in their capability to conduct electricity
- Flow of electrical current involves movement of *charge carriers* - infinitesimally small particles possessing an electrical charge
 - In solids, these charge carriers are electrons
 - In a liquid solution, charge carriers are positive and negative ions

Electrical Properties

- Movement of charge carriers is driven by the presence of electric voltage
- And resisted by the inherent characteristics of the material, such as atomic structure and bonding between atoms and molecules

Ohm's law: $I = \frac{E}{R}$

where I = current, A, E = voltage, V, and R = electrical resistance, Ω

Electrical Resistance

Resistance in a uniform section of material (e.g., a wire) depends on its length L , cross-sectional area A , and resistivity of the material r

$$R = r \frac{L}{A} \quad \text{or} \quad r = R \frac{A}{L}$$

where resistivity r has units of $\Omega\text{-m}^2/\text{m}$ or $\Omega\text{-m}$ ($\Omega\text{-in.}$)

Resistivity

Property that defines a material's capability to resist current flow

- Resistivity is not a constant; it varies, as do so many other properties, with temperature
- For metals, resistivity increases with temperature

Conductivity

Often more convenient to consider a material as conducting electrical current rather than resisting its flow

Conductivity of a material is simply the reciprocal of resistivity:

$$\text{Electrical conductivity} = \frac{1}{r}$$

where conductivity has units of $(\Omega\text{-m})^{-1}$ $((\Omega\text{-in})^{-1})$

Engineering Materials and Electrical Properties

- Metals are the best *conductors* of electricity, because of their metallic bonding
- Most ceramics and polymers, whose electrons are tightly bound by covalent and/or ionic bonding, are poor conductors
- Many of these materials are used as *insulators* because they possess high resistivities

Semiconductors

A material whose resistivity lies between insulators and conductors

- Most common semiconductor material is *silicon*, largely because of its abundance in nature, relative low cost, and ease of processing
- What makes semiconductors unique is the capacity to significantly alter conductivities in their surface chemistries in very localized areas to fabricate integrated circuits

Electrical Properties in Manufacturing

- *Electric discharge machining* - uses electrical energy in the form of sparks to remove material from metals
- The important welding processes, such as *arc welding* and *resistance spot welding*, use electrical energy to melt the joint metal
- Capacity to alter electrical properties of semiconductor materials is the basis for *microelectronics manufacturing*

Electrochemistry

Field of science concerned with the relationship between electricity and chemical changes, and with the conversion of electrical and chemical energy

- In a water solution, molecules of an acid, base, or salt are dissociated into positively and negatively charged ions
- Ions are the charge carriers in the solution - they allow electric current to be conducted, playing the same role that electrons play in metallic conduction

Terms in Electrochemical Processes

- *Electrolyte* - the ionized solution
- *Electrodes* – where current enters and leaves the solution in electrolytic conduction
 - *Anode* - positive electrode
 - *Cathode* - negative electrode
- The whole arrangement is called an *electrolytic cell*

Electrolysis

The name given to these chemical changes occurring in the solution

- At each electrode, chemical reaction occurs, such as:
 - Deposition or dissolution of material
 - Decomposition of gas from the solution

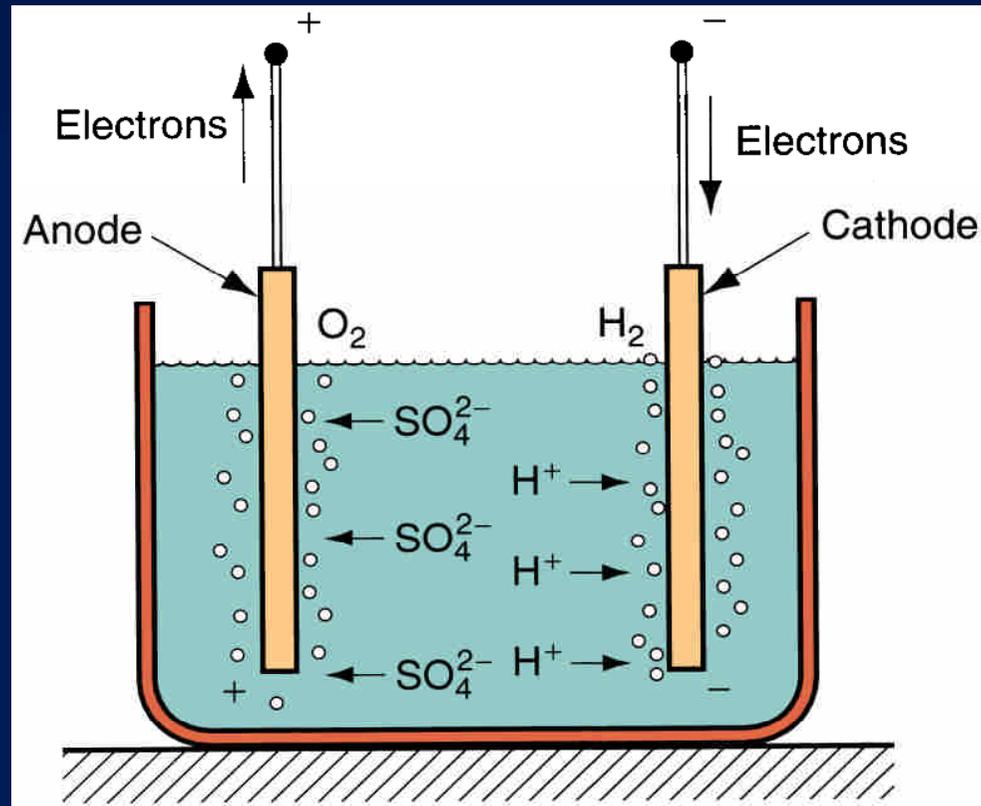


Figure 4.3 – Example of electrolysis: decomposition of water
Dilute sulfuric acid (H_2SO_4) = electrolyte
Platinum and carbon (both chemically inert) = electrodes

Chemical Reactions in Decomposition of Water

- The electrolyte dissociates into the ions H^+ and SO_4^-
- H^+ ions are attracted to negatively charged cathode; upon reaching it they acquire an electron and combine into molecules of hydrogen gas



Chemical Reactions in Decomposition of Water

- The SO_4^- ions are attracted to the anode, transferring electrons to it to form additional sulfuric acid and liberate oxygen



- The product H_2SO_4 is dissociated into ions of H^+ and SO_4^- again and so the process continues

Electrolysis in Manufacturing Processes

- *Electroplating* - an operation that adds a thin coating of one metal (e.g., chromium) to the surface of a second metal (e.g., steel) for decorative or other purposes
- *Electrochemical machining* - a process in which material is removed from the surface of a metal part
- Production of hydrogen and oxygen gases