Physical Properties of Materials

Manufacturing Materials, IE251
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PHYSICAL PROPERTIES OF MATERIALS

1. Volumetric and Melting Properties
2. Thermal Properties
3. Mass Diffusion

Physical Properties Defined

- Properties that define the behavior of materials in response to physical forces rather than mechanical
  - Include: volumetric, thermal, electrical, and electrochemical properties

- 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

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 affect tool life
  - **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

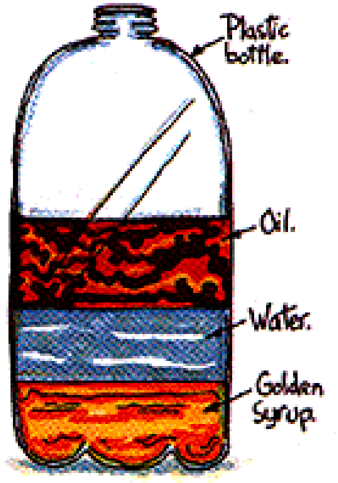
Volumetric and Melting Properties

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

- Includes:
  - Density
  - Thermal expansion
  - Melting point

Density and Specific Gravity Defined

Density = mass per unit volume



- Typical units are g/cm^3 (lb/in^3)
- Determined by atomic number, atomic radius, atomic packing, etc

Specific gravity = density of a material relative to density of water

(It 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 density
  - Useful ratio in comparing materials for structural applications in aircraft, automobiles, and other products where weight and energy are concerns (*light but strong materials are desirable*)

Thermal Expansion

- Density of a material is a function of temperature
  - In general, density decreases with increasing temperature

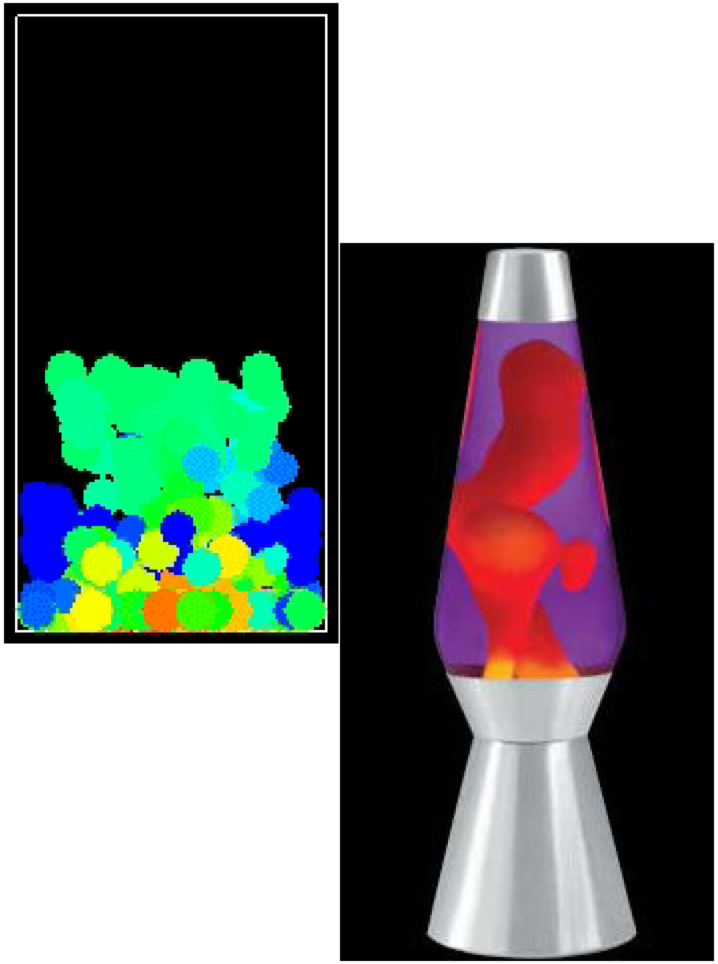
T ↗ Density ↘

  - Volume per unit weight (or volume per unit mass) increases with increasing temperature

T ↗ Volume per unit mass ↗

  - *Thermal expansion is the name for this effect of temperature on density*
  - Measured by *coefficient of thermal expansion* α

Example



Lava light: The "lava" in a Lava light doesn't mix with the liquid that surrounds it. When the light bulb in the lamp warms it up, the "lava" expands a little. When it expands, the "lava" stays the same weight but it takes up more space-so it's less dense.

When it's warm enough, the "lava" is less dense than the surrounding liquid, and so it rises up to the top to float. At the top of the lamp, it cools down, becomes more dense, and sinks once again.

This cycle repeats over and over as the "lava" warms up and rises, then cools down and sinks.

Coefficient of Thermal Expansion

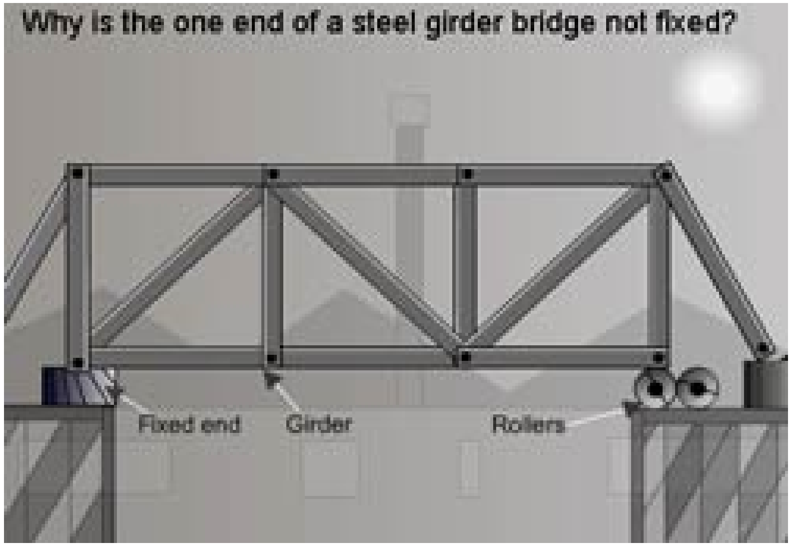
- Change in length per degree of temperature, such as mm/mm/°C (in/in/°F)
  - Length ratio rather than volume ratio because this is easier to measure and apply
  - Change in length for a given temperature change is:

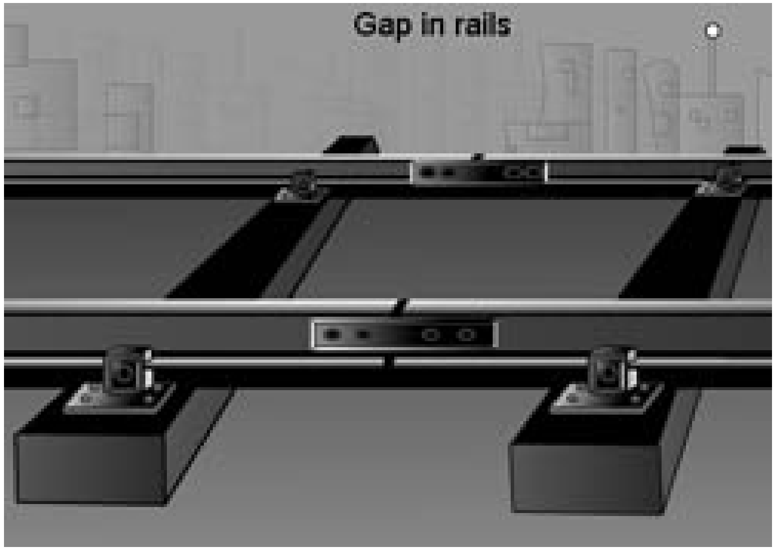
$$L_2 - L_1 = \alpha L_1 (T_2 - T_1)$$

where α = coefficient of thermal expansion (unit is 1/ °C);

L_1 is the length at temperatures T_1 and L_2 is the length at temperatures T_2

Examples





One end of a steel bridge is not fixed to provide for expansion

Gaps are provided between rails for expansion

Thermal Expansion in Manufacturing

- Thermal expansion is used in shrink fit and expansion fit assemblies
  - *Shrink fit: A tight interference fit between mating parts made by shrinking-on, that is, by heating the outer member to expand the bore for easy assembly and then cooling so that the outer member contracts.*

- 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
  - Eutectic: having the lowest melting point possible

Melting of Alloys: Solidus and Liquidus

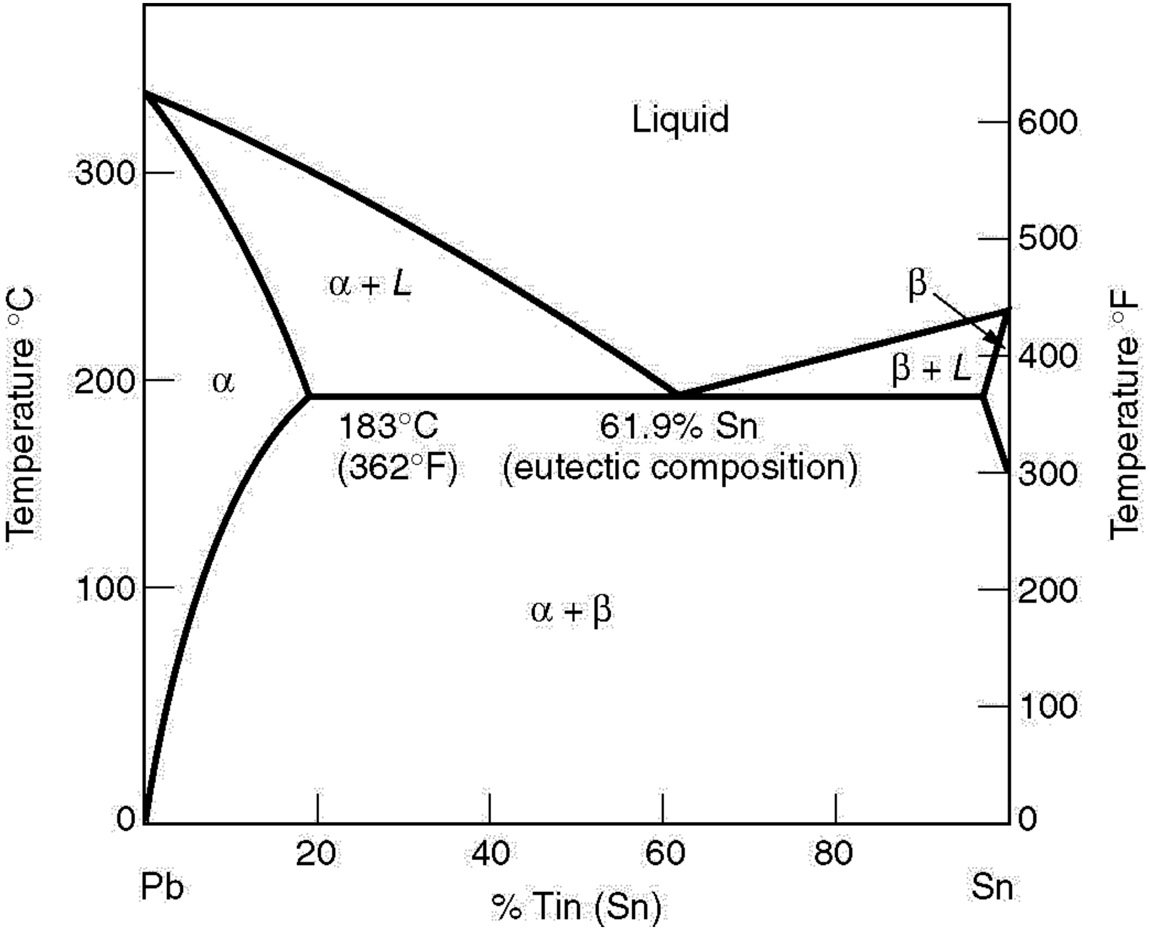
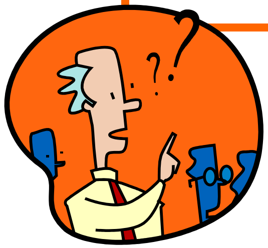


Figure 6.3 Phase diagram for the tin-lead alloy system.

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

glass has no melting point. Instead, it gets increasingly softer with increasing temperature, and its viscosity decreases with temperature.



Volume-to-Weight Changes

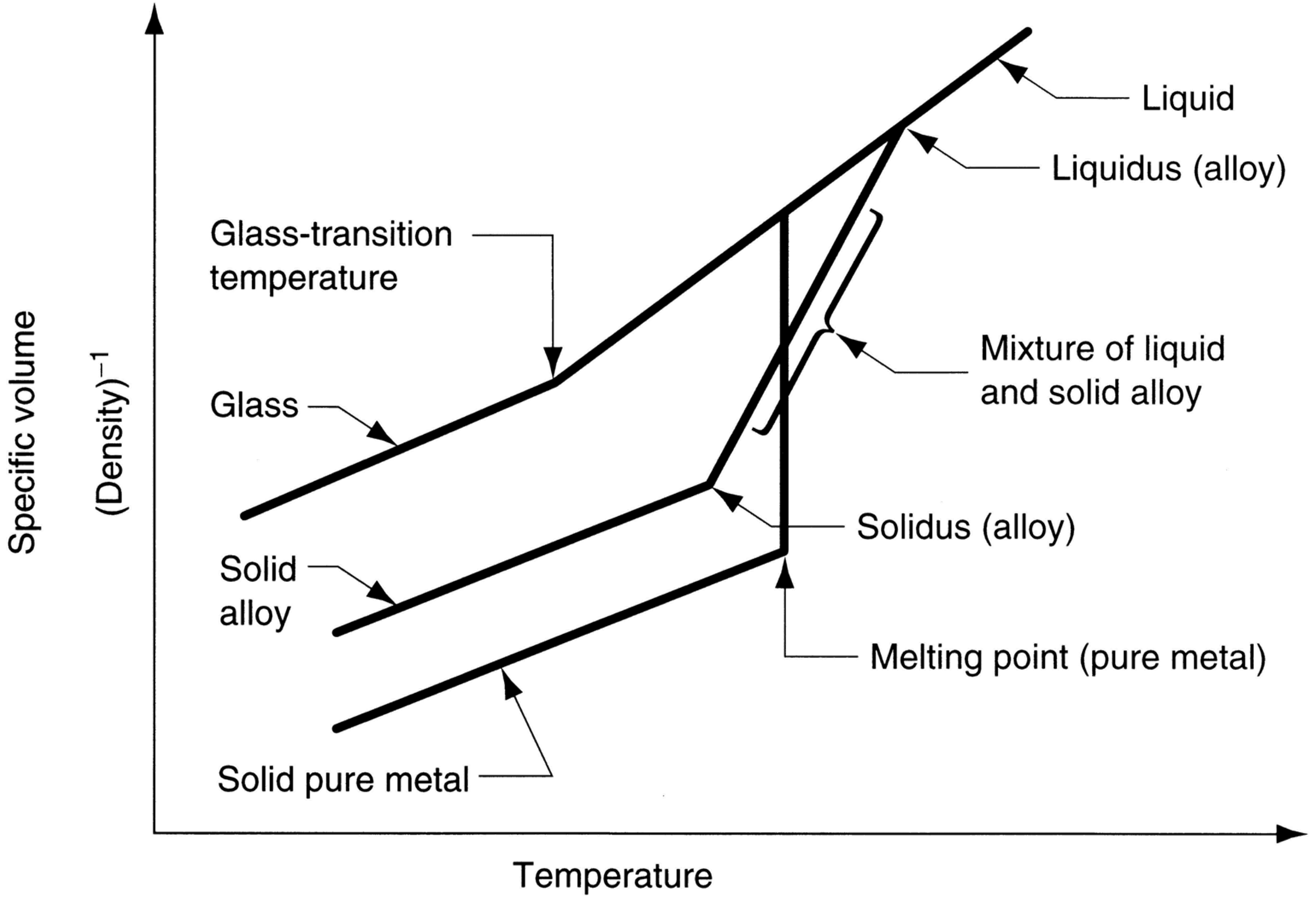


Figure 4.1 Changes in volume per unit weight (1/density) as a function of temperature for a hypothetical pure metal, alloy, and glass.

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 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

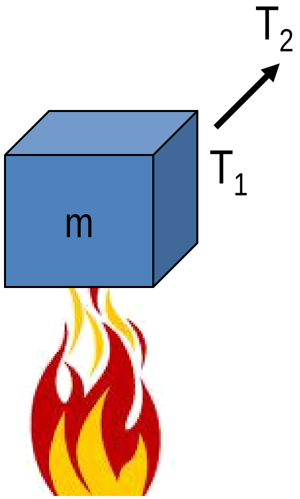
- Additional thermal properties:
  - Specific heat
  - Thermal conductivity
  - These properties relate to the storage and flow of heat within a substance

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 temperature:

$$\boxed{H = C\,m\,(T_2 - T_1)}$$



where H = amount of heat energy;

C = specific heat of the material;

m= its mass; and

$(T_2 - T_1)$ = change in temperature

Unit of C is J / kg. °C or BTU / lb. °F

(1 BTU / lb. °F = *4187* J / kg. °C)

BTU (British thermal unit)= 1055 J

Volumetric Specific Heat

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

- *Volumetric specific heat =* ρC

(Density ρ multiplied by specific heat C)

Its unit is J / $m^3.^oC$ or J / $mm^3.^oC$

Specific Heat Problem

1) What is the specific heat (in J/ Kg.C) of a substance that absorbs 2.5×10^3 joules of heat when a sample of 1.0×10^4 g of the substance increases in temperature from 10C to 70C?

$H = C\,m\,(T_2 - T_1)$

$C = H/\,m\,(T_2 - T_1) = (2.5 \times 10^3\ \text{J})/\ ((10\ \text{kg})\ (70-10)\text{C}))$

C = 4.167 J/ Kg C

Thermal Conductivity

Thermal conductivity of a material = capability to transfer heat through itself by the physical mechanism of thermal conduction

- Thermal conduction = transfer of thermal energy within a material from molecule to molecule by purely thermal motions; no transfer of mass
- Measure = *coefficient of thermal conductivity k*. Units: J / sec. mm. °C (Btu/ hr. in.°F)
- Coefficient of thermal conductivity is generally high in metals, low in ceramics and plastics

It is defined as the quantity of heat, *Q*, transmitted in time *t* through a thickness *L*, in a direction normal to a surface of area *A*, due to a temperature difference Δ*T*, under steady state conditions and when the heat transfer is dependent only on the temperature gradient.

$$k = \frac{Q}{t} \times \frac{L}{A \times \Delta T}$$

Thermal Diffusivity

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

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

the unit is mm²/sec

What is the difference between thermal conductivity and thermal diffusivity?

Thermal conductivity (k) is a property that determines HOW MUCH heat will flow in a material, while thermal diffusivity (K) determines HOW RAPIDLY heat will flow within it.

A homely example is to imagine holding a poker that is suddenly put into a fire. How hot you feel at the handle end is determined by the poker's thermal conductivity and how quickly you feel the heat is determined by its thermal diffusivity.

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

This section is just for your information

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

Mass Diffusion

concentration gradient or *dc / dx*

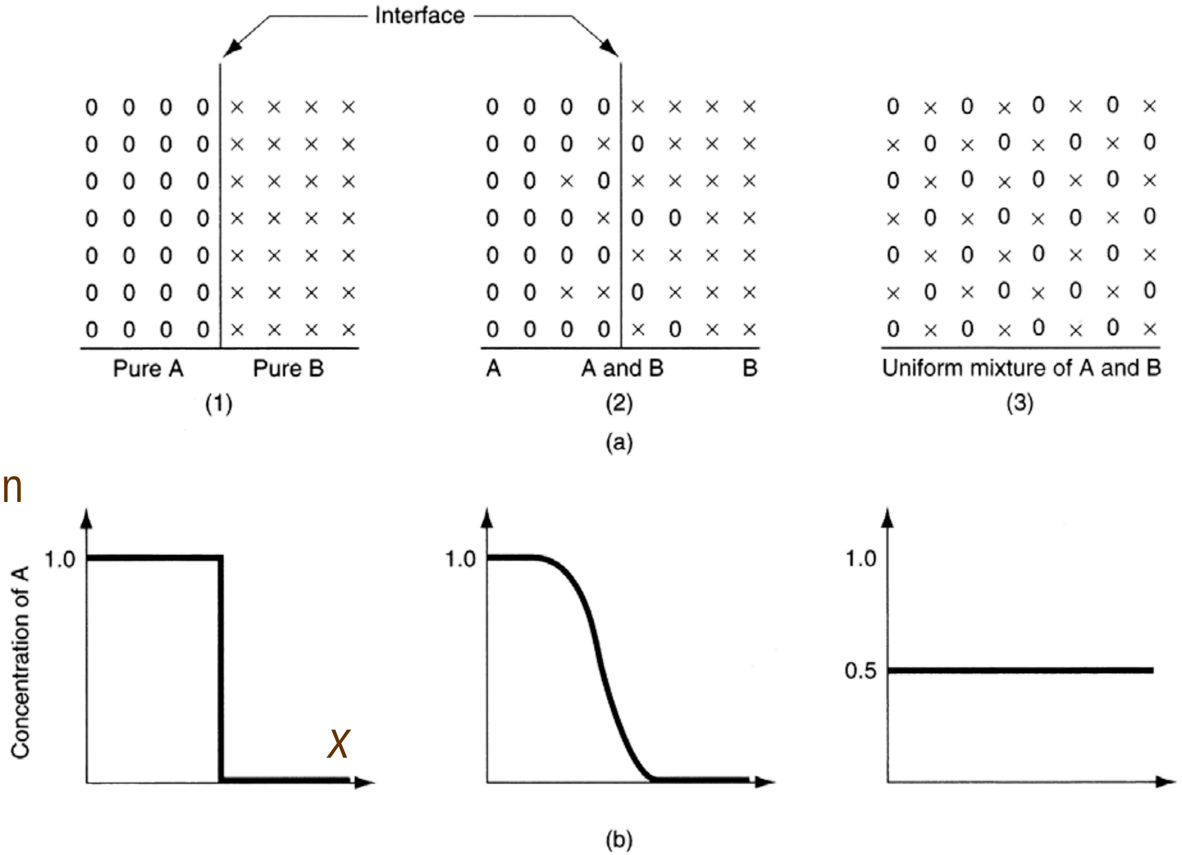


Figure 4.2 Mass diffusion: (a) **model of atoms in two solid blocks** in contact: (1) when two pieces are first brought together, each has its own compositions; (2) after time, an exchange of atoms occurs; and (3) eventually, a uniform concentration occurs. The concentration gradient *dc/dx* for metal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

Mass Diffusion in Manufacturing

- Surface hardening treatments based on diffusion include carburizing and nitriding
  - Carburizing = to combine with carbon
  - Nitriding= to case-harden (as steel) by causing the surface to absorb nitrogen

- 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