Material Science

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Chapter 15. Thermal properties

- Physical property of a solid body related to application of heat energy is defined as a thermal property.
- Thermal properties explain the response of a material to the application of heat
- Important thermal properties are
    - Heat capacity
    - Thermal expansion
    - Thermal conductivity
    - Thermal stresses

Heat capacity

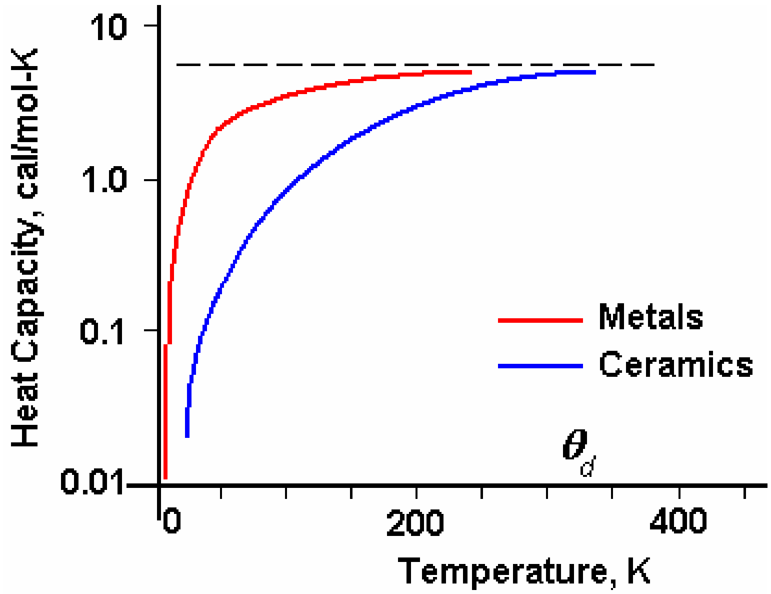
- A solid material's potential energy is stored as its heat energy.
- Temperature of a solid is a measure its potential energy.
- Heat capacity is a property that is indicative of a material's ability to absorb heat from the external surroundings
- It is defined as the amount of energy required to produce a unit temperature rise.
- Mathematically, it is expressed as:

$$C = \frac{dQ}{dT}$$

- Where *dQ* is the energy required to produce a temperature change equal to *dT*.
- Heat capacity has units as J/mol-K *or* Cal/mol-K.
- Heat capacity is not an intrinsic property i.e. It changes with material volume/mass.
- At low temperatures, vibrational heat contribution of heat capacity varies with temperature as follows:

$$C_v = AT^3$$

- The above relation is not valid above a specific temperature known as *Debye temperature*. The saturation value is approximately equal to 3R.



Specific heat

- For comparison of different materials, heat capacity has been rationalized.
- Specific heat is heat capacity per unit mass. It has units as J/kg-K *or* Cal/kg-K.
- With increase of heat energy, dimensional changes may occur. Hence, two heat capacities are usually defined.
- Heat capacity at constant pressure, *Cp*, is always higher than heat capacity at constant volume, *Cv*.
- *Cp* is ONLY marginally higher than *Cv*.
- Heat is absorbed through different mechanisms: lattice vibrations and electronic contribution.

Thermal expansion

- Increase in temperature may cause dimensional changes.
- Linear *coefficient of thermal expansion* (*α)* defined as the change in the dimensions of the material per unit length.

$$\alpha = \frac{l_f - l_0}{l_0(T_f - T_0)} = \frac{\Delta l}{l_0 \Delta T} = \frac{\varepsilon}{\Delta T}$$

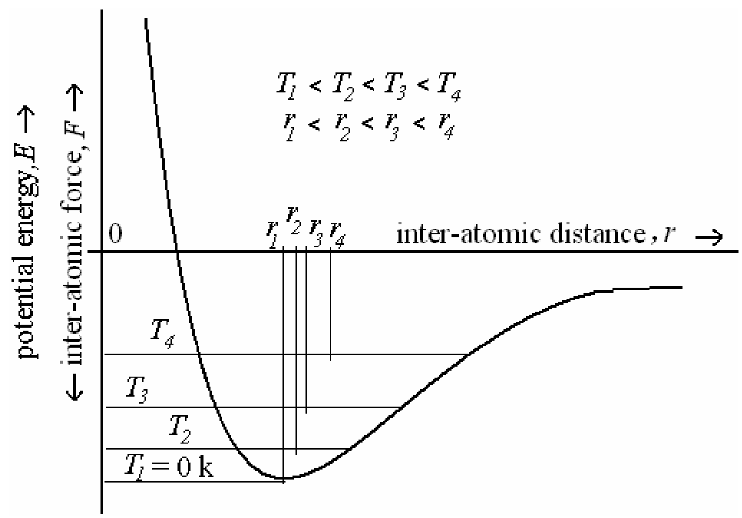
- T_0 and T_f are the initial and final temperatures (in K)
- l_0 and l_f are the initial and final dimensions of the material and
- ε is the strain.
- α has units as (˚C)-1.
- α values:
  - for metals 5-25x10^{-6}
  - for ceramics 0.5-15x10^{-6}

- for polymers 50-400x10^{-6}

- A volume coefficient of thermal expansion, α_v (=3α) is used to describe the volume change with temperature.

$$\alpha_v = \frac{\Delta v}{v_0 \Delta T}$$

- Where Δv and vo are the volume change and the original volume.
- An instrument known as dilatometer is used to measure the thermal expansion coefficient.
- At microscopic level, because of asymetric nature of the potential energy trough, changes in dimensions with temperature are due to change in inter-atomic distance, rather than increase in vibrational amplitude.



- If a very deep energy trough caused by strong atomic bonding is characteristic of the material, the atoms separate to a lesser and the material has low linear coefficient of thermal expansion. This relationship also suggests that materials having a high melting temperature – also due to strong atomic bonds – have low thermal expansion coefficients.

Thermal shock

- If the dimensional changes in a material are not uniform, that may lead to fracture of brittle materials like ceramics. It is known as thermal shock.
- The capacity of a material to withstand thermal shock is defined as *thermal shock resistance*, TRS.

$$TSR \cong \frac{\sigma_f k}{E\alpha}$$

- where σ_f – fracture strength.
- Thermal shock behavior is affected by several factors:
  - thermal expansion coefficient – a low value is desired;
  - thermal conductivity – a high value is desired;
  - elastic modulus – low value is desired;
  - fracture strength – high value is desired
- Thermal shock may be prevented by altering external conditions to the degree that cooling or heating rates are reduced and temperature gradients across the material are minimized.
- Thermal shock is usually not a problem in most metals because metals normally have sufficient ductility to permit deformation rather than fracture.
- However, it is more of a problem in ceramics and glass materials. It is often necessary to remove thermal stresses in ceramics to improve their mechanical strength. This is usually accomplished by an annealing treatment.

Thermal conductivity

- *Thermal conductivity* is ability of a material to transport heat energy through it from high temperature region to low temperature region.
- The heat energy, Q, transported across a plane of area A in presence of a temperature gradient $\Delta T/\Delta l$ is given by

$$Q = kA\frac{\Delta T}{\Delta l}$$

- where k is the thermal conductivity of the material.
- It has units as W/m.K.
- It is a microstructure sensitive property.
- Its value range
  - for metals 20-400
  - for ceramics 2-50
  - for polymers order of 0.3

Mechanisms - Thermal conductivity

- Heat is transported in two ways – electronic contribution, vibrational (phonon) contribution.
- In metals, electronic contribution is very high. Thus metals have higher thermal conductivities. It is same as electrical conduction. Both conductivities are related through Wiedemann-Franz law:

$$\frac{k}{\sigma T} = L$$

- where L – Lorentz constant (5.5x10-9 cal.ohm/sec.K2)
- As different contributions to conduction vary with temperature, the above relation is valid to a limited extension for many metals.

- With increase in temperature, both number of carrier electrons and contribution of lattice vibrations increase. Thus thermal conductivity of a metal is expected to increase.
- However, because of greater lattice vibrations, electron mobility decreases.
- The combined effect of these factors leads to very different behavior for different metals.
- Eg.: thermal conductivity of iron initially decreases then increases slightly; thermal conductivity decreases with increase in temperature for aluminium; while it increases for platinum

Thermal stresses

- Stresses due to change in temperature or due to temperature gradient are termed as *thermal stresses*($\sigma_{thermal}$).

$$\sigma_{thermal} = \alpha E \Delta T$$

- Thermal stresses in a constrained body will be of compressive nature if it is heated, and vice versa.
- Engineering materials can be tailored using multi-phase constituents so that the overall material can show a zero thermal expansion coefficient.
  - Eg.: Zerodur – a glass-ceramic material that consists of 70-80% crystalline quartz, and the remaining as glassy phase.
  - Sodium-zirconium-phosphate (NZP) have a near-zero thermal expansion coefficient.

<u>Multiple Choice Questions' Bank</u>:

1. Find the wrong statement: Specific heat of a material ______________.

(a) Constant for a material (b) Heat capacity per unit mass
(c) Extrinsic property (d) Has units as J/kg-K.

2. Heat capacity has units as

(a) J/kg.K (b) J/mol.K (c) J.ohm/sec.K^2 (d) W/m.K

3. Units for thermal conductivity

(a) J/kg.K (b) J/mol.K (c) J.ohm/sec.K^2 (d) W/m.K

4. Lorentz constant has units as

(a) J/kg.K (b) J/mol.K (c) J.ohm/sec.K^2 (d) W/m.K

5. Thermal expansion of a material has units as

(a) J/kg-K (b) J/mol-K (c) J.ohm/sec.K^2 (d) 1/°C

6. Polymers have thermal conductivities in the range of

(a) < 1 (b) 1-10 (c) 10-100 (d) >100

7. Polymers have thermal expansion coefficients in the range of _____x10^{-6}.

(a) 0.5-15 (b) 5-25 (c) 25-50 (d) 50-400

8. Coefficient of thermal expansion for ceramics is the range of _______x10^{-6}.

(a) 0.5-15 (b) 5-25 (c) 25-50 (d) 50-400

9. Metals have thermal conductivities in the range of

(a) < 1 (b) 1-5 (c) 5-25 (d) 20-400

10. Heat capacity of most materials is approximately equal to ________.

(a) R (b) 2R (c) 3R (d) R/2

11. With increase in temperature, thermal conductivity of a metal _____________.

(a) Increases (b) Decreases (c) Either (d) All, depending on metal.

12. Thermal conductivity in polymers increases with ________.

(a) Increase in crystallinity (b) Decrease in crystallinity (c) Either (d) None

Answers:

1. c
2. b
3. d
4. c
5. d
6. a
7. d
8. a
9. d
10. c
11. d
12. a