## Module-15

# Thermal properties

# Contents

# Introduction

- Engineering materials are important in everyday life because of their versatile structural properties.
- Other than these properties, they do play an important role because of their physical properties.
- Prime physical properties of materials include: electrical properties; thermal properties; magnetic properties; and optical properties.
- The thermal properties of engineering materials are diverse, and so are their uses in different applications.

# Heat capacity

- A solid material’s potential energy is stored as its heat energy.
- Temperature of a solid is a measure its potential energy.
- External energy required to increase temperature of a solid mass is known as the material’s *heat capacity*. it is defined as its ability to absorb heat energy.

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

- 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.

# Specific heat

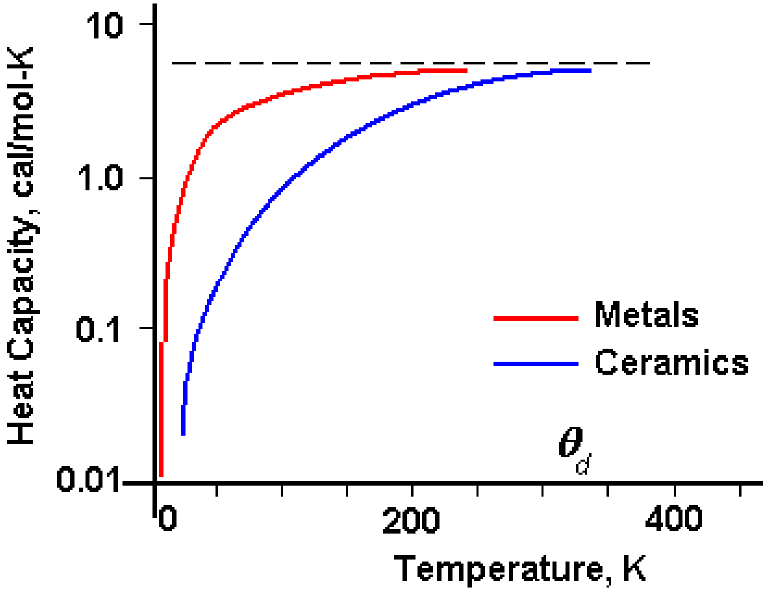
- For comparison of different materials, heat capacity has been rationalized.
- *Specific heat* is heat capacity per unit mass. It has units as J/kg-K *or* Cal/kg-K.
- With increase of heat energy, dimensional changes may occur. Hence, two heat capacities are usually defined.
- Heat capacity at constant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

# Heat capacity

- 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.



# Thermal expansion

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

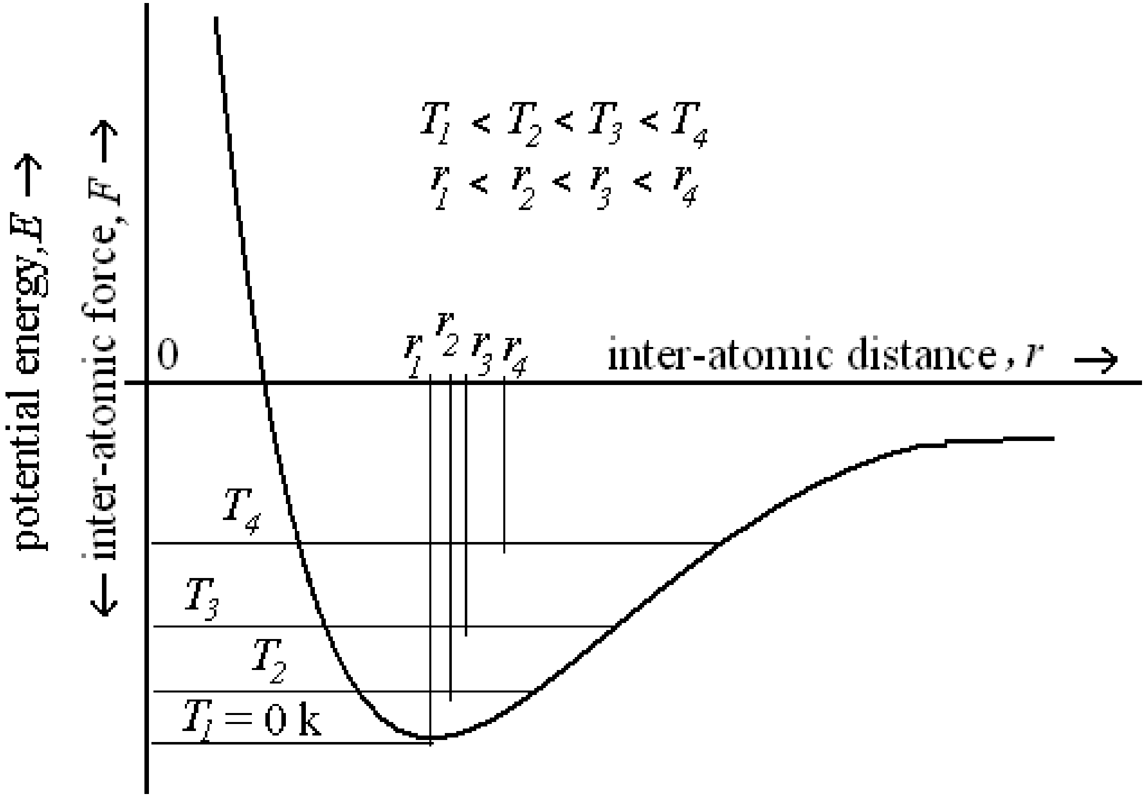
$$\alpha = \frac{l_f - l_0}{l_0(T_f - T_0)} = \frac{\Delta l}{l_0 \Delta T} = \frac{\varepsilon}{\Delta T}$$

- $\alpha$ has units as $(^\circ C)^{-1}$.
- $\alpha$ values:

| | |
|---|---|
| for metals | $5\text{-}25 \times 10^{-6}$ |
| for ceramics | $0.5\text{-}15 \times 10^{-6}$ |
| for polymers | $50\text{-}400 \times 10^{-6}$ |

# Thermal expansion (contd…)

- Changes in dimensions with temperature are due to change in inter-atomic distance, rather than increase in vibrational amplitude.



# 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.

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

- 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; phase transformations.

# Thermal shock (contd…)

- 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.
- Heat energy transported through a body with thermal conductivity $k$ is

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

- It is a microstructure sensitive property.
- It has units as W/m.K.
- 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, vibratioanl (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 ($5.5 \times 10^{-9}$ cal.ohm/sec.$K^2$)

- As different contributions to conduction varies with temperature, the above relation is valid to a limited extension for many metals.

# Mechanisms - Thermal conductivity (contd…)

- 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*.

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

- 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.