University of Al-Mustaqbal
College of Science
Department of Medical Physics

Medical Physics

Lecture 6: Mechanical Properties

Third stage

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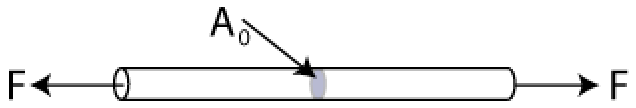
Mechanical Properties

The mechanical properties of a material are those properties that involve a reaction to an applied load. The mechanical properties of metals determine the range of usefulness of a material and establish the service life that can be expected. Mechanical properties are also used to help classify and identify material. The most common properties considered are strength, ductility, hardness, impact resistance, and fracture toughness.

Stress

The term stress (s) is used to express the loading in terms of force applied to a certain cross-sectional area of an object. From the perspective of loading, stress is the applied force or system of forces that tends to deform a body. From the perspective of what is happening within a material, stress is the internal distribution of forces within a body that balance and react to the loads applied to it. The stress distribution may or may not be uniform, depending on the nature of the loading condition. For example, a bar loaded in pure tension will essentially have a uniform tensile stress distribution. However, a bar loaded in bending will have a stress distribution that changes with distance perpendicular to the normal axis.



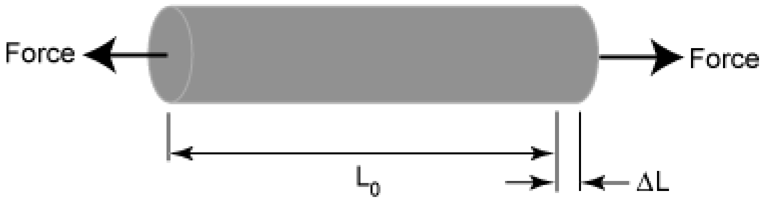
$$\text{Stress, } \sigma = \frac{\text{Force}}{\text{Cross-Sectional Area}} = \frac{F}{A_0}$$

Equation 1

Figure (1)

Strain (ε)

Strain is the response of a system to an applied stress. When a material is loaded with a force, it produces a stress, which then causes a material to deform. Engineering strain is defined as the amount of deformation in the direction of the applied force divided by the initial length of the material.



$$\text{Strain} = \frac{\text{Elongation}}{\text{Orininal Length}} = \frac{\Delta L}{L_0}$$ Equation 2

Figure (2)

If the stress is small, the material may only strain a small amount and the material will return to its original size after the stress is released. This is called elastic deformation, because like elastic it returns to its unstressed state. Elastic deformation only occurs in a material when stresses are lower than a critical stress called the yield strength. If a material is loaded beyond it elastic limit, the material will remain in a deformed condition after the load is removed. This is called plastic deformation.

Stress–Strain behavior

The degree to which a structure deforms or strains depends on the magnitude of an imposed stress. For most metals that are stressed in tension and at relatively low levels, stress and strain are proportional to each other through the relationship

$$6 = E\varepsilon$$ Equation 3

This is known as Hooke's law, and the constant of proportionality *E* (GPa) is the **modulus of elasticity,** or *Young's modulus*. For most typical metals the magnitude of this modulus ranges between 45 GPa, for magnesium, and 407 GPa, for tungsten.

Deformation in which stress and strain are proportional is called **elastic deformation;** a plot of stress versus strain results in a linear relationship, as shown in Figure 3. The slope of this linear segment corresponds to the modulus of elasticity *E*. This modulus may be thought of as stiffness, or a material's resistance to elastic deformation. The greater the modulus, the stiffer the material, or the smaller the elastic strain that results from the application of a given stress. The modulus is an important design parameter used for computing elastic deflections.

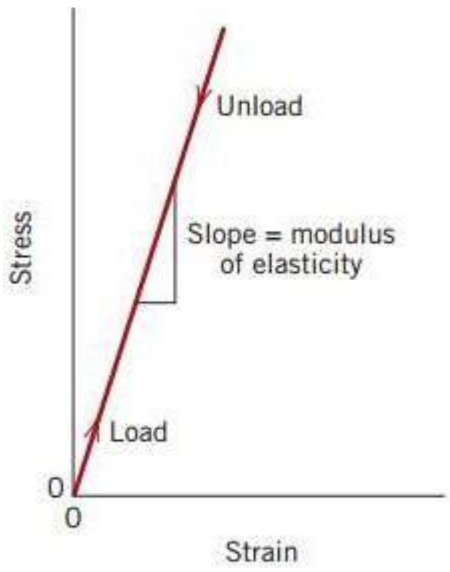


Figure 3, Schematic stress–strain diagram showing linear elastic deformation for loading and unloading cycles.

Elastic deformation is nonpermanent, which means that when the applied load is released, the piece returns to its original shape.

Poisson's ratio (*v*):

The ratio of the proportional decrease in a lateral measurement to the proportional increase in length in a sample of material that is elastically stretched and is defined as the ratio of the lateral and axial strains, or

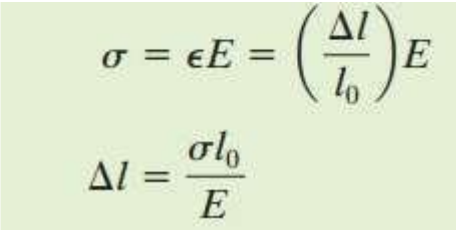
$$\nu = -\frac{\epsilon_x}{\epsilon_z} = -\frac{\epsilon_y}{\epsilon_z}$$

Elongation (Elastic) Computation

Example/ A piece of copper originally 305 mm (12 in.) long is pulled in tension with a stress of 276 MPa. If the deformation is entirely elastic, what will be the resultant elongation?

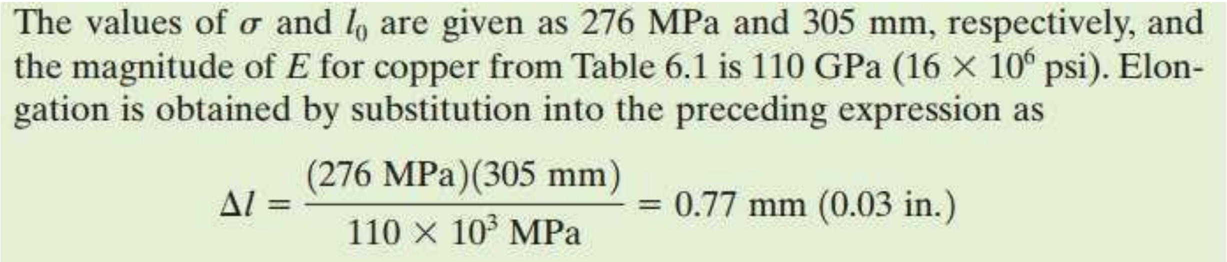
Solution:

Because the deformation is elastic, strain is dependent on stress according to equation 3 Furthermore, the elongation l is related to the original length l_0 through Equation 2. Combining these two expressions and solving for Δl yields.



$$\sigma = \epsilon E = \left(\frac{\Delta l}{l_0}\right)E$$

$$\Delta l = \frac{\sigma l_0}{E}$$



The values of σ and l_0 are given as 276 MPa and 305 mm, respectively, and the magnitude of E for copper from Table 6.1 is 110 GPa (16×10^6 psi). Elongation is obtained by substitution into the preceding expression as

$$\Delta l = \frac{(276\ \text{MPa})(305\ \text{mm})}{110 \times 10^3\ \text{MPa}} = 0.77\ \text{mm}\ (0.03\ \text{in.})$$

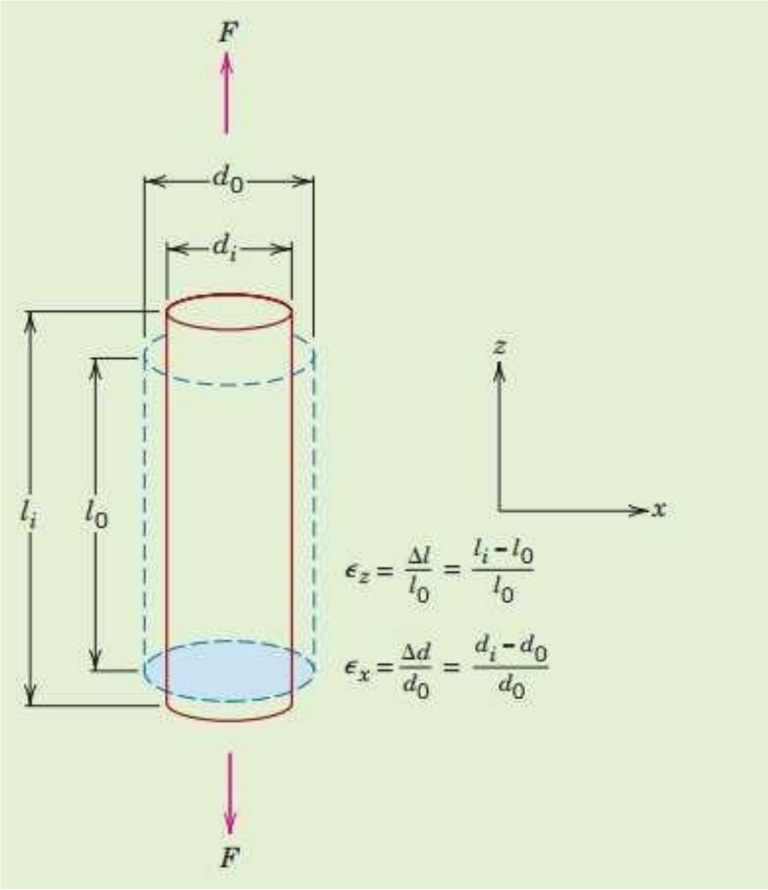
Computation of Load to Produce Specified Diameter Change

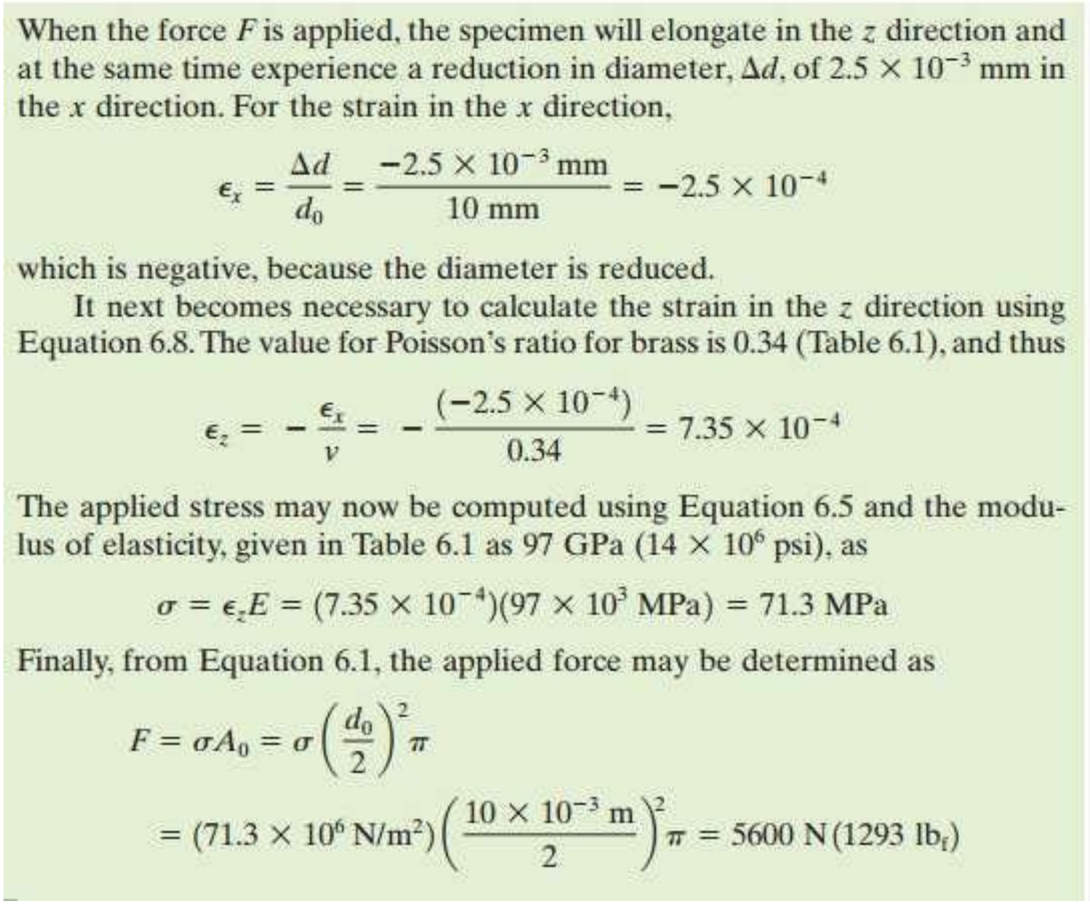
Example

A tensile stress is to be applied along the long axis of a cylindrical brass rod that has a diameter of 10 mm (0.4 in.). Determine the magnitude of the load required to produce a 2.5×10^{-3} mm (104 in.) change in diameter if the deformation is entirely elastic.

Solution:

This deformation situation is represented in the accompanying drawing.





When the force F is applied, the specimen will elongate in the z direction and at the same time experience a reduction in diameter, Δd, of 2.5×10^{-3} mm in the x direction. For the strain in the x direction,

$$\epsilon_x = \frac{\Delta d}{d_0} = \frac{-2.5 \times 10^{-3}\ \text{mm}}{10\ \text{mm}} = -2.5 \times 10^{-4}$$

which is negative, because the diameter is reduced.

It next becomes necessary to calculate the strain in the z direction using Equation 6.8. The value for Poisson's ratio for brass is 0.34 (Table 6.1), and thus

$$\epsilon_z = -\frac{\epsilon_x}{\nu} = -\frac{(-2.5 \times 10^{-4})}{0.34} = 7.35 \times 10^{-4}$$

The applied stress may now be computed using Equation 6.5 and the modulus of elasticity, given in Table 6.1 as 97 GPa (14×10^6 psi), as

$$\sigma = \epsilon_z E = (7.35 \times 10^{-4})(97 \times 10^3\ \text{MPa}) = 71.3\ \text{MPa}$$

Finally, from Equation 6.1, the applied force may be determined as

$$F = \sigma A_0 = \sigma \left(\frac{d_0}{2}\right)^2 \pi$$

$$= (71.3 \times 10^6\ \text{N/m}^2)\left(\frac{10 \times 10^{-3}\ \text{m}}{2}\right)^2 \pi = 5600\ \text{N}\,(1293\ \text{lb}_\text{f})$$

Plastic Deformation

For most metallic materials, elastic deformation persists only to strains of about 0.005. As the material is deformed beyond this point, the stress is no longer proportional to strain (Hooke's law, Equation 3, ceases to be valid), and permanent, nonrecoverable, or plastic deformation occurs. Figure 4 plots schematically the tensile stress–strain behavior into the plastic region for a typical metal. The transition from elastic to plastic is a gradual one for most metals; some curvature results at the onset of plastic deformation, which increases more rapidly with rising stress.

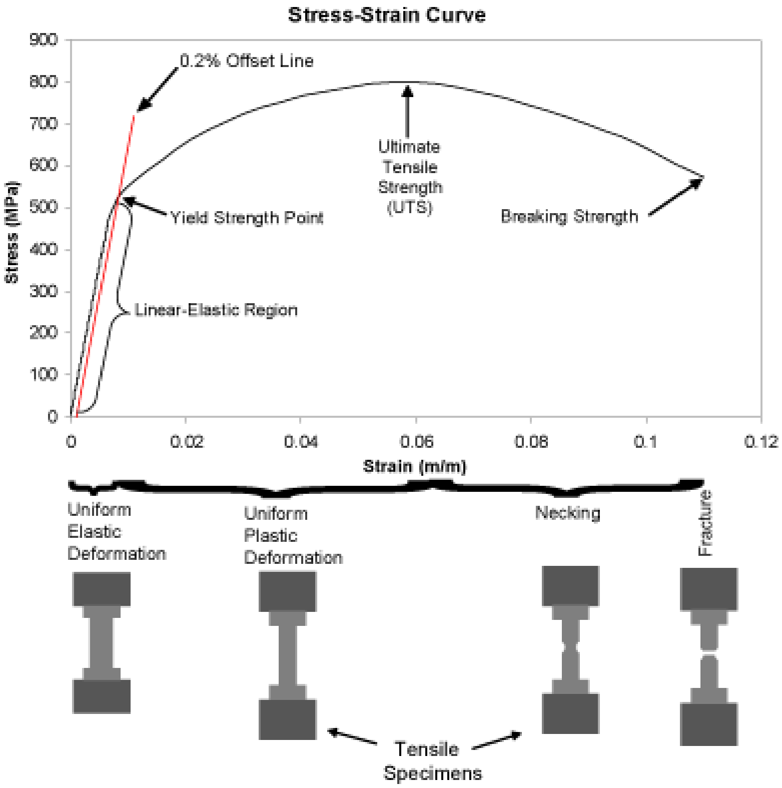


Figure 4

Yield Strength

The yield point is the point on a stress–strain curve that indicates the limit of elastic behavior and the beginning of plastic behavior. Yield strength or yield stress is the material property defined as the stress at which a material begins to deform plastically whereas yield point is the point where nonlinear (elastic + plastic) deformation begins. Prior to the yield point the material will deform elastically and will return to its original shape when the applied stress is removed. Once the yield point is passed, some fraction of the deformation will be permanent and non-reversible.

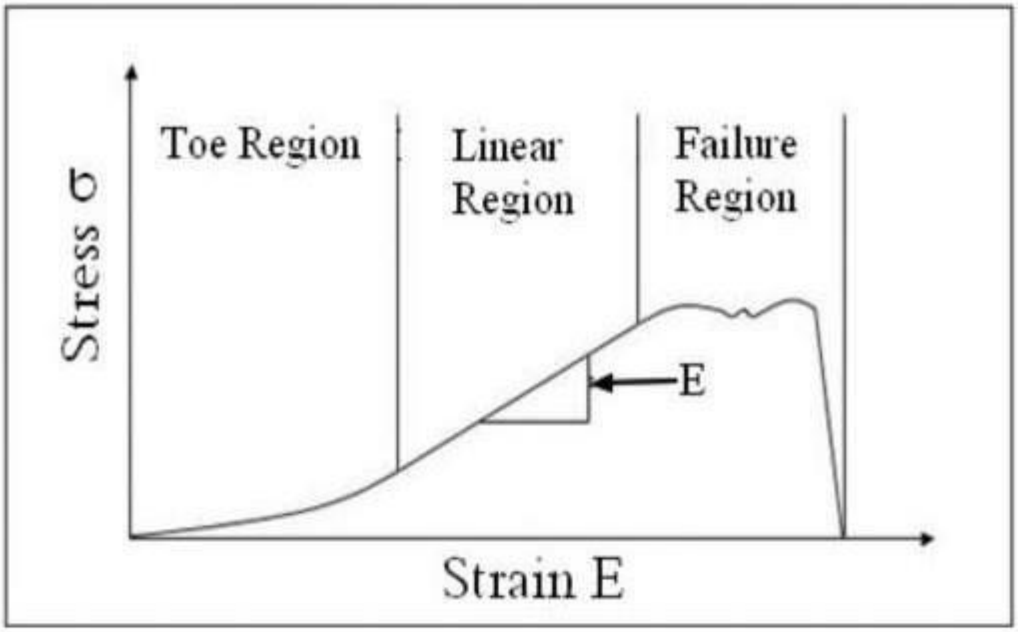
Ultimate tensile strength (UTS)

Ultimate tensile strength is measured by the maximum stress that a material can withstand while being stretched or pulled before breaking.

Biological Soft Tissue Materials

The assumptions made for the traditional materials are not valid when testing biological soft tissue samples. These materials are, in general, nonhomogeneous due to the orientation of their collagen and elastin fibers. Hence, care must be taken when collecting samples and positioning them in testing system to ensure the directions are consistent with the intended analysis.

Biological tissues exhibit large deformation before failure, therefore, any transducer used to measure strain will need to accommodate the large movement. Due to the un-crimping of collagen fibers and elasticity of elastin, the initial portion of a biological sample stress-strain curve has a high deformation/low force characteristics known as the toe region. In short, unlike traditional materials, this region is non-linear. A linear region is typically identified after the toe region and is used for the determination of E.

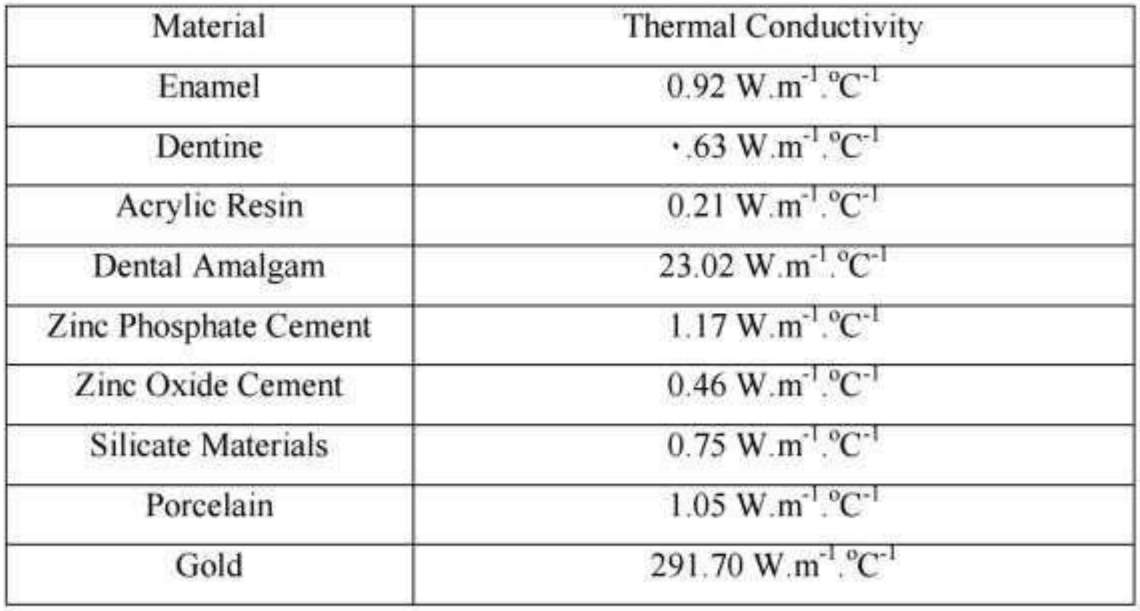


Stress-Strain Curve of Biological Soft Tissue Material

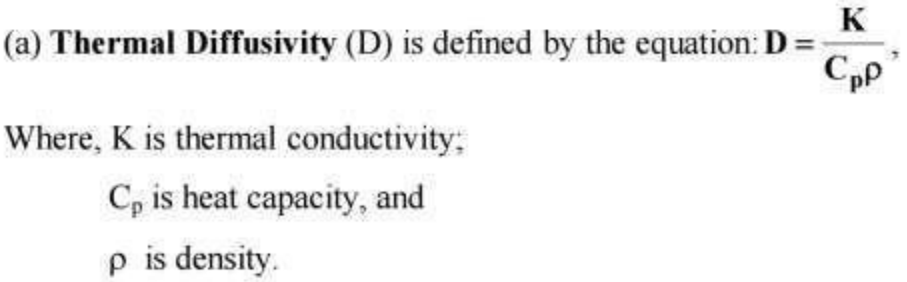
The mechanical properties of biological tissues are strain or loading rate dependent due to these tissues, visco-elastic nature. For example, biological tissues typically become stiffer with increasing strain rate (see figure below).

Thermal Properties:

Wide temperature fluctuations occur in the oral cavity due to the ingestion of hot or cold food and drink. Thermal Conductivity is the rate of heat flow per unit temperature gradient. Thus, good conductors have high values of conductivity.



Material	Thermal Conductivity
Enamel	0.92 $W.m^{-1}.^{o}C^{-1}$
Dentine	•.63 $W.m^{-1}.^{o}C^{-1}$
Acrylic Resin	0.21 $W.m^{-1}.^{o}C^{-1}$
Dental Amalgam	23.02 $W.m^{-1}.^{o}C^{-1}$
Zinc Phosphate Cement	1.17 $W.m^{-1}.^{o}C^{-1}$
Zinc Oxide Cement	0.46 $W.m^{-1}.^{o}C^{-1}$
Silicate Materials	0.75 $W.m^{-1}.^{o}C^{-1}$
Porcelain	1.05 $W.m^{-1}.^{o}C^{-1}$
Gold	291.70 $W.m^{-1}.^{o}C^{-1}$



(a) **Thermal Diffusivity** (D) is defined by the equation: $\mathbf{D} = \frac{\mathbf{K}}{\mathbf{C_p \rho}}$,

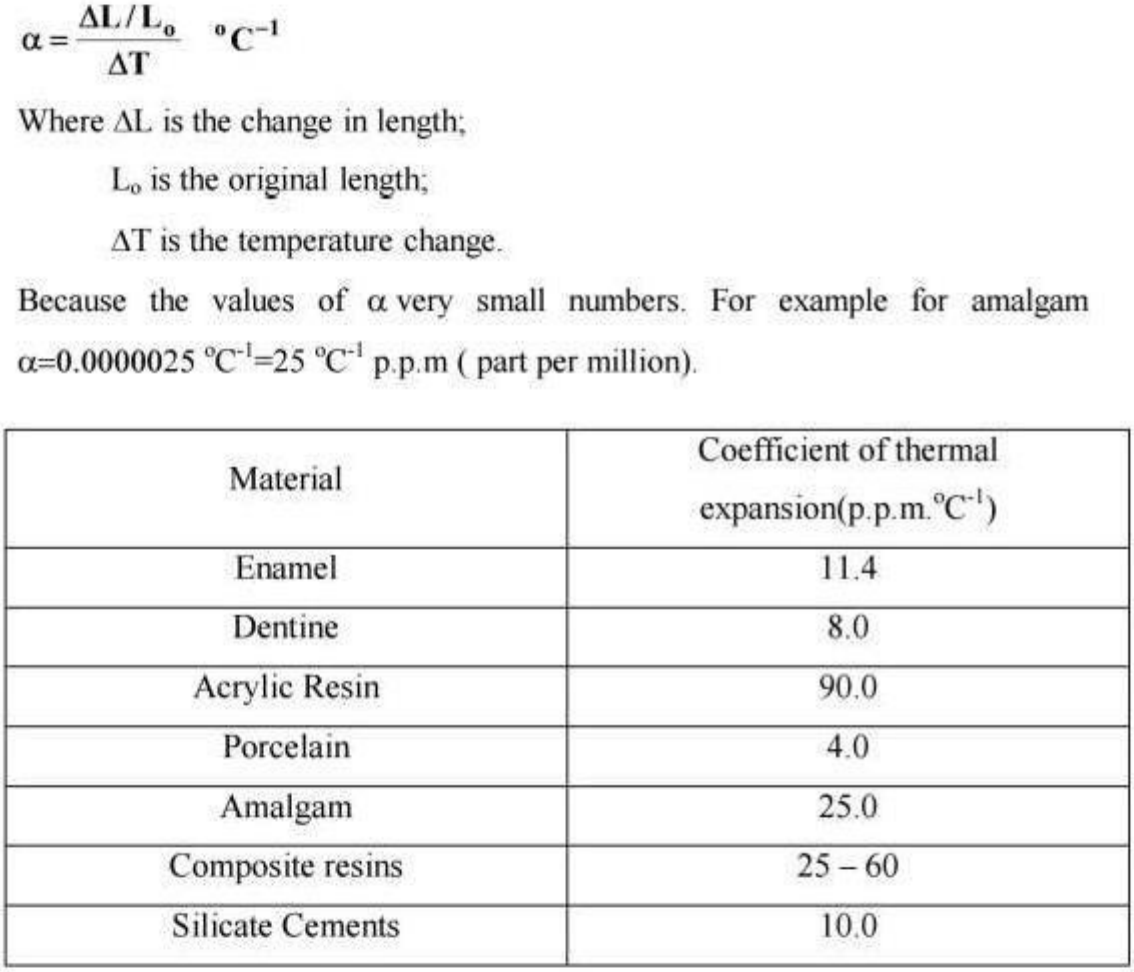
Where, K is thermal conductivity;

C_p is heat capacity, and

ρ is density.

Measurements of thermal diffusivity are often made by embedding a thermocouple in a specimen of material and plunging the specimen into hot or cold liquid. If the temperature, recorded by the thermocouple, rapidly reaches that of the liquid, this indicates a high value of diffusivity. A slow response indicates a lower value of diffusivity is preferred. In many circumstances, a low value of diffusivity is preferred. There are occasions on which a high value is beneficial. For example, a denture base material, ideally, should have a high value of thermal diffusivity in order that the patient retains a satisfactory response to hot and cold stimuli in the mouth.

Coefficient of Thermal Expansion is defined as the fractional increase in length of a body for each degree centigrade increase in temperature.



$$\alpha = \frac{\Delta L / L_o}{\Delta T} \quad {}^{o}C^{-1}$$

Where ΔL is the change in length;

L_o is the original length;

ΔT is the temperature change.

Because the values of α very small numbers. For example for amalgam α=0.0000025 $^{o}C^{-1}$=25 $^{o}C^{-1}$ p.p.m (part per million).

Material	Coefficient of thermal expansion(p.p.m.$^{o}C^{-1}$)
Enamel	11.4
Dentine	8.0
Acrylic Resin	90.0
Porcelain	4.0
Amalgam	25.0
Composite resins	25 – 60
Silicate Cements	10.0

This property is particularly important for filling materials. For filling materials, the most ideal combination of properties would be low value of diffusivity combined with (a) similar to that for tooth substance.

MCQ

1) Mechanical properties of materials are those that:

A) Describe chemical reactions
B) Describe optical behavior
C) Involve a reaction to an applied load
D) Describe thermal color changes

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2) Stress (σ) is defined as:

A) Force multiplied by area
B) Force divided by cross-sectional area
C) Change in length divided by area
D) Length divided by force

3) Engineering strain (ε) is:

A) Final length ÷ original length
B) Change in length ÷ original length
C) Force ÷ original length
D) Stress × original length

4) When a material returns to its original shape after removal of load, the deformation is called:

A) Plastic deformation
B) Fracture
C) Elastic deformation
D) Yielding

5) The coefficient of thermal expansion is defined as:

A) Heat flow per unit temperature gradient
B) Fractional increase in length per degree Celsius
C) Resistance to heat transfer
D) Maximum temperature before melting