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Biomaterials



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قسم الفيزياء الطبية
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BIOMATERIALS

المحاضرة الثالثة

CHARACTERIZATION OF MATERIALS —1

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The characterization of materials is an important step to be taken before utilizing the materials for any purpose. Depending on the purpose one can subject the material to mechanical, thermal, chemical, optical, electrical, and other characterizations to make sure that the material under consideration can function without failure for the life of the final product.

1. MECHANICAL PROPERTIES

Among the most important properties for the application of materials in medicine and dentistry are the mechanical properties. We will study the fundamental mechanical properties that will be used in later.

1.1. Stress-Strain Behavior

For a material that undergoes a mechanical deformation, the stress is defined as a force per unit area, which is usually expressed in Newton's per square meter (Pascal, Pa)

$$\text{Stress } (\sigma) = \frac{\text{force}}{\text{cross-sectional area}} \quad \frac{N}{m^2}$$

A load (or force) can be applied upon a material in tension, compression, and shear or any combination of these forces (or stresses). Tensile stresses are generated in response to loads (forces) that pull an object apart (Figure 1a), while compressive stresses squeeze it together (Figure 1b). Shear stresses resist loads that deform or separate by sliding layers of molecules past each other on one or more planes (Figure -1c). The shear stresses can also be found in uniaxial tension or compression since the applied stress produces the maximum shear stress on planes at 45° to the direction of loading (Figure 1d).

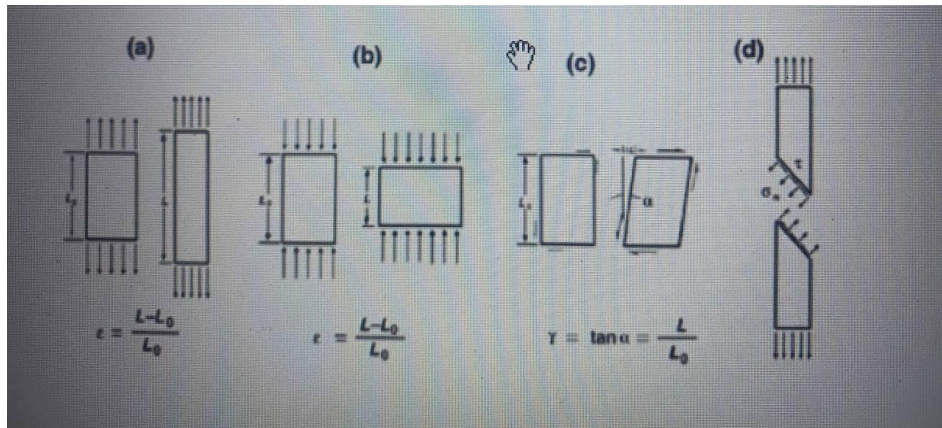


Figure 1. Three different modes of deformation: (a) tension, (b) compression, (c) shear, and (d) shear in tension.

The deformation of an object in response to an applied load is called strain;

Strain (α) = (deformed length - original length) / original length (m/m)

It is also possible to denote strain by the stretch ratio, i.e., deformed length/original length. The deformations associated with different types of stresses are called tensile, compressive, and shear strain (Figure 1).

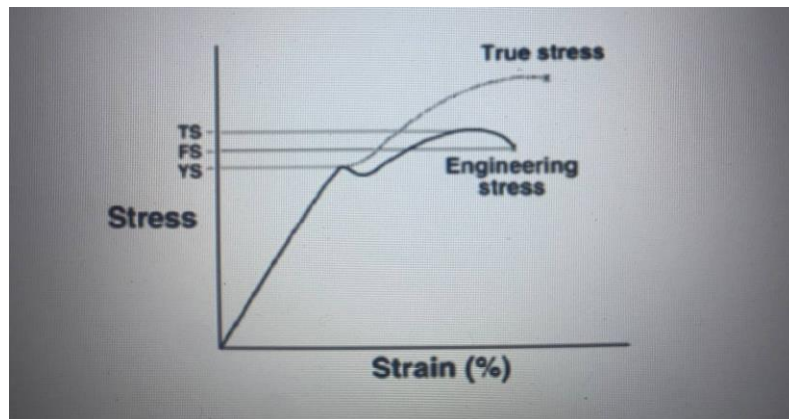


Figure 2. Stress-strain behavior of an idealized material.

If the stress-strain behavior is plotted on a graph, a curve that represents a continuous response of the material toward the imposed force can be obtained, as shown in Figure 2. The stress-strain curve of a solid sometimes can be demarcated by the yield point (σ_y , or YP) into elastic and plastic regions. In the elastic region, the strain ϵ increases in direct proportion to the applied stress σ (Hooke's law):

$$\sigma = E \epsilon$$

$$\text{stress} = (\text{initial slope}) \times (\text{strain}).$$

The slope (E) or proportionality constant of the tensile/compressive stress strain curve is called Young's modulus or the modulus of elasticity. It is the value of the increment of stress over the increment of strain. The stiffer a material is, the higher the value of E and the more difficult it is to deform. Similar analysis can be performed for deformation by shear, in which the shear modulus (G) is defined as the initial slope of the curve of shear stress versus shear strain. The unit for the modulus is the same as that of stress since strain is dimensionless. The shear modulus of an isotropic material is related to its Young's modulus by

$$E=2G (1+ \nu)$$

in which ν is the Poisson's ratio of the material. Poisson's ratio is defined as the negative ratio of the transverse strain to the longitudinal strain for tensile or compressive loading of a bar. Poisson's ratio is close to 1/3 for common stiff materials, and is slightly less than 1/2 for rubbery materials and for soft biological tissues. For example, stretch a rubber band by 10% of its original length and the cross-sectional dimensions will decrease by about 5%.

1.2. Mechanical Failure

1.2.a. Static failure

Mechanical failure usually occurs by fracture. The fracture of a material can be characterized by the amount of energy per unit volume required to produce the failure. The quantity is called toughness and can be expressed in terms of stress and strain:

$$\text{Toughness} = \int \sigma d\epsilon = \int \sigma dl/l$$

1.2.b. Dynamic fatigue failure

When a material is subjected to a constant or a repeated load below the fracture stress, it can fail after some time. This is called static or dynamic (cyclic) fatigue respectively, the effect of cyclic stresses (Figure3) is to initiate micro cracks at centers of stress concentration within the material or on the surface, resulting in the growth and propagation of cracks, leading to failure. The rate of crack growth can be plotted in a log-log scale versus time. The most significant portion of the curve is the crack propagation stage, which can be estimated as follows:

$$da/dN = A(\Delta K)^m$$

where a , N , and ΔK are the crack length, number of cycles, and range of stress intensity factor.

$$\Delta K = A\sigma \sqrt{\pi a}$$

and m are the intercept and slope of the linear portion of the curve. This is called the Paris equation.

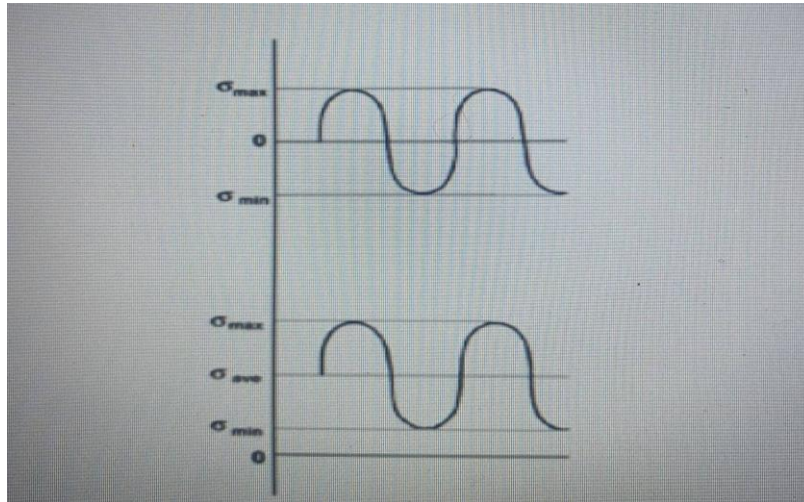


Figure 3, Cyclic stresses. σ_{max} and σ_{min} are the maximum and minimum values of the cyclic stresses, The range of stresses $\Delta\sigma = \sigma_{max} - \sigma_{min}$ and average stress $\sigma_{ave} = (\sigma_{max} + \sigma_{min})/2$. The top curve is fluctuating, and the bottom curve is for reversed cyclic loading.

1.2.c. Friction and wear failure

Wear properties of an implant material are important, especially for various joint replacements. Wear cannot be discussed without some understanding of friction between two materials. When two solid materials contact, they touch only at the tips of their highest asperities (microscopic protuberances). Therefore, the real contact area is much smaller than the apparent surface area. It is found that the true area of contact increases with applied load (P) for ductile materials. Ductile materials can be pressure welded due to the formation of plastic junctions, the plastic junctions are the main source of an adhesive friction when two materials are sliding over each other with or without a lubricating film.

1.3. Viscoelasticity

1.3.a. Viscoelastic material behavior

Viscoelastic materials are those for which the relationship between stress and strain depends on time. In such materials the stiffness will depend on the rate of application of the load. In addition, mechanical energy is dissipated by conversion to heat in the deformation of viscoelastic materials. All materials exhibit some viscoelastic response. In metals such as steel or aluminum at room temperature, as well as in quartz, the response at small deformation is almost purely elastic, Metals can behave plastically at large deformation, but ideally plastic deformation is independent of time. Also, plastic deformation occurs only if a threshold stress is exceeded. By contrast, materials such as synthetic polymers, wood, and human tissue display significant viscoelastic effects, and these effects occur at small or large stress.

1.3.b. Characterization of viscoelastic materials

1.3.c. Prediction of the response

1.3.d. Mechanical models

1.3.e. Behavior of viscoelastic materials

1.3.f. Applications

There are a variety of consequences of viscoelastic behaviors that influence the application of viscoelastic materials. For example, in those applications for which a steady-state stress is applied, the creep behavior is of greatest importance. The expected service life of implant materials may be very long; consequently, attention to the long-term creep behavior is in order.

2. THERMAL PROPERTIES

The most familiar thermal properties are the melting and freezing (solidification) temperatures. These are phase transformations that occur at specific temperatures, these transformation temperatures depend on the bond energy, e.g., the higher the bonding strength, the higher the melting temperature. If the material is made of different elements or compounds, then it may have a range of melting or solidification temperatures, that is, the liquid coexists with solid over a range of temperatures, unlike a pure material.

The thermal energy spent on converting one gram of material from solid to liquid is called the heat of fusion. The unit is Joules per gram, where one Joule is equivalent to one Newton meter. The heat of fusion is closely related to the melting temperature (T)

The thermal energy spent on changing the temperature of a material by 1°C per unit mass is called specific heat. Traditionally, water is usually chosen as a standard substance, and 1calorie is the heat required to raise 1 gram of water from 15 to 16°C, but now the standard unit of energy including energy associated with heat is the Joule. Thus, the specific heat is in units of J/g. (1 calorie is equivalent to 4.187 J. The calorie used to represent food or metabolic energy is actually a kilocalorie, or 1000 calories.)

The change in length ΔL for a unit length (, per unit temperature is called the linear coefficient of expansion (α), which can be expressed as

$$\alpha = \frac{\Delta L}{L_0 \Delta T}$$

The thermal expansion may depend on the direction in a single crystal or composite, and it may depend on temperature. If the material is homogeneous and isotropic, then the volumetric thermal expansion coefficient (V_{exp}) can be approximated:

$$V_{exp} = 3\alpha$$

3. PHASE DIAGRAMS

When two or more metallic elements are melted and cooled they form an intermetallic compound or a solid solution or, more commonly, a mixture thereof. Such combinations are called "alloys." The alloys can exist as either a single phase or a blend of multiple phases depending on temperature and composition. A phase is defined as a physically homogeneous part of a material system. Thus, a liquid and gas are both single phase, but there can be more than one phase for a solid, such as fee iron and bee iron, depending on pressure and temperature. Among multiphase metals, steels are iron-based alloys containing various amounts of a carbide (usually Fe_3C) phase. In this case, the carbon atoms occupy the interstitial sites of the iron atoms, this is called an interstitial solid solution. Most metal atoms are too large to exist in the interstitial sites. If the two metal atoms are roughly the same size, have the same bonding tendencies, and tend to crystallize in the same types of crystal structure, then a substitutional solid solution may form. This structure is composed of a random mixture of two different atoms, as shown in Figure 4. Unless the elements are very similar in properties, such a solution will exhibit a limited solubility, i.e., as more substitutional atoms are added into the matrix, the lattice will be more and more distorted until phase separation occurs at the solubility limit. In some systems, such as Cu-Ni, as shown in Figure, complete solid solubility exists.

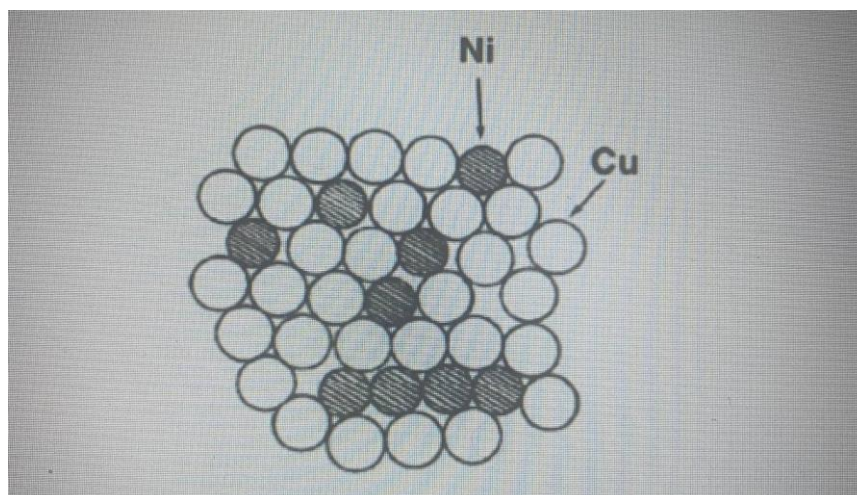


Figure 4. Substitutional solid solution of a Cu-Ni system.

The phase diagram is constructed first by preparing known compositions of Cu-Ni, and then melting and cooling them under thermal equilibrium. During the cooling cycle one has to determine at what temperatures the first solid phase (α) appears and all of the liquid disappears. These points will determine the liquids and solidus line in the phase diagram. From this phase diagram one can determine the types of phase and amount of each element present for a given composition and temperature. Thus, if we cool a 40 w/o Ni-60 w/o Cu liquid solution,

Temperature (°C)	Phase (relative amount)	Composition of each phase
above 1270	liquid (all)	40 Ni – 60 Cu
1250	liquid (63%) α (37%)	33 Ni – 67 Cu 52 Ni – 48 Cu
1220	liquid (5%) α (95%)	26 Ni – 74 Cu 43 Ni – 57 Cu
below 1210	α (all)	40 Ni – 60 Cu

The relative amount of each phase present at a given temperature and composition is determined by the lever rule after making a horizontal isothermal (tie) line at the temperature of interest. Let C_l and C_a be the composition of element A (Ni) and B (Cu) in the two-phase region met by the tie line (say 1240 °C) with the same composition given above (40 w/o Ni = C_l): then the amount of liquid (L) phase can be calculated as follows:

$$\frac{L}{a + L} = \frac{C_l - C_A}{C_l - C_a} = \frac{52 - 40}{52 - 33} = \frac{12}{19} = 0.63$$

Example 1

Copper and silver metal are mixed thoroughly in powder form, in proportions 80 w/o Cu and 20 w/o Ag and heated to well above the melting temperature of the alloy. The liquid metal is then cooled and allowed to reach thermodynamic equilibrium. Give the composition of each phase and the relative amount of each phase:

- At 1,000°C.
- At 780°C.
- At 700°C.

Answer

- a. At 1,000°C, all liquid (80 w/o Cu + 20 w/o Ag)
 b. At 780°C. β (92 w/o Cu + 8 w/o Ag) 81 w/o.

L (28.1 w/o Cu + 71.9 w/o Ag) 19 w/o.

$$\frac{\beta}{\beta + L} = \frac{28.1 - 80}{28.1 - 92} = 0.81$$

- c. At 700°C, α (6 w/o Cu + 94 w/o Ag): 15 w/o.

b (93 w/o Cu + 7 w/o Ag); 85 w/o,

$$\frac{\alpha}{\alpha + \beta} = \frac{93 - 80}{93 - 6} = \frac{13}{87} = 0.15$$

4. STRENGTHENING BY HEAT TREATMENTS*4.1. Metals*

One of the strengthening processes is precipitation (or age) hardening of alloys by heat treatments. This is accomplished by rapidly cooling (quenching) a solid solution of decreasing solubility. If quenching is done properly, there will not be enough time for the second phase (B) to form. Hence, a quasi-thermal equilibrium exists, but depending on the amount of thermal energy (related to temperature) and time, the second phase (B) will form (precipitation). If the B phase particles are small and uniformly dispersed throughout the matrix, their presence can increase the strength greatly. It is important that they be dispersed within a grain as well as at grain boundaries, so that the dislocations can be impeded during the deformation process, as in the case of cold-working.

4.2. ceramics and glasses

As mentioned earlier, ceramics and glasses are hard and brittle due to their non-yielding character during deformation, which in turn is due to their bonding characteristics. Because of this brittleness they are subject to stress concentration effect at the microcracks present in the material when in tensile deformation