Chapter 3: Materials

Deformability and strength of each element of the living body is supporting a life activity. In this chapter, we learn the basics of materials engineering, while thinking about how to analyze the various parts of the body as material.

3.1 Deformation

3.1.1 Classification of deformation

If you hang a weight on a coil spring, the coil spring stretches. The stretch increases, as the weight increases. The increase of the length is proportional to the mass of the weight. If the weight is removed, the length of the spring returns to its original value (**Fig. 3.1**).

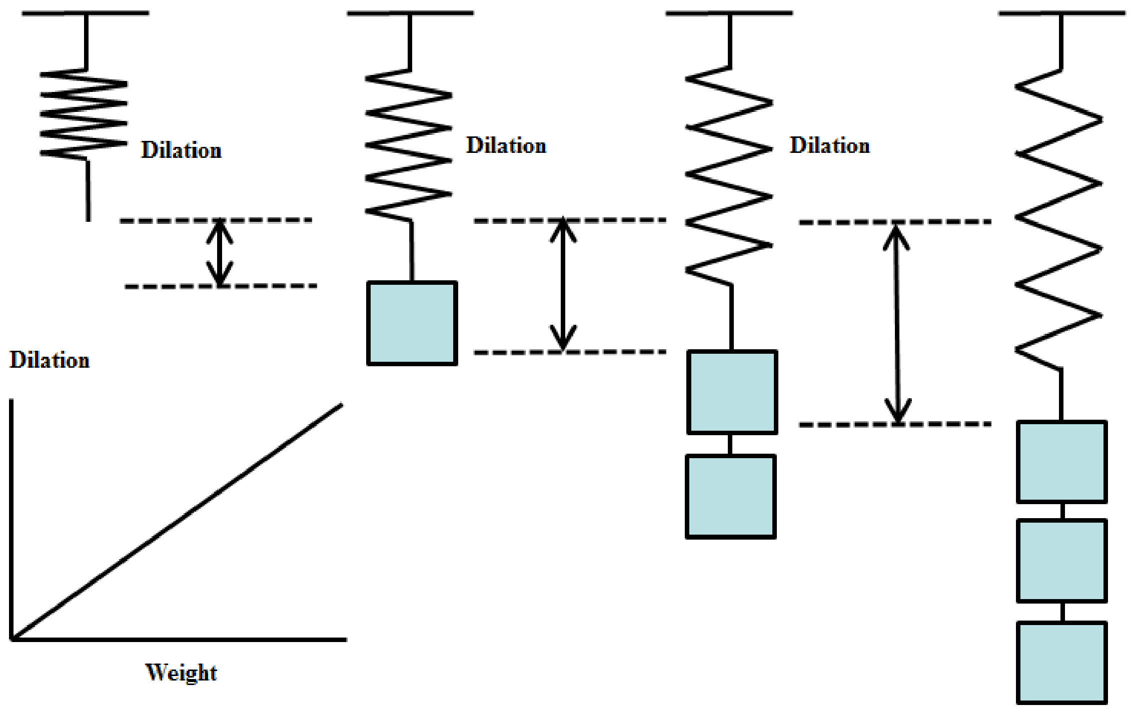


Fig. 3.1: Spring.

An object deforms, when it receives forces. The deformation is classified into extension, compression, bending, and torsion (**Fig. 3.2**). The direction of loading is classified into extension, compression, bending, and twisting. To compare the deformability, the deformation according to the internal pressure is measured in a pipe with a cavity, such as a blood vessel.

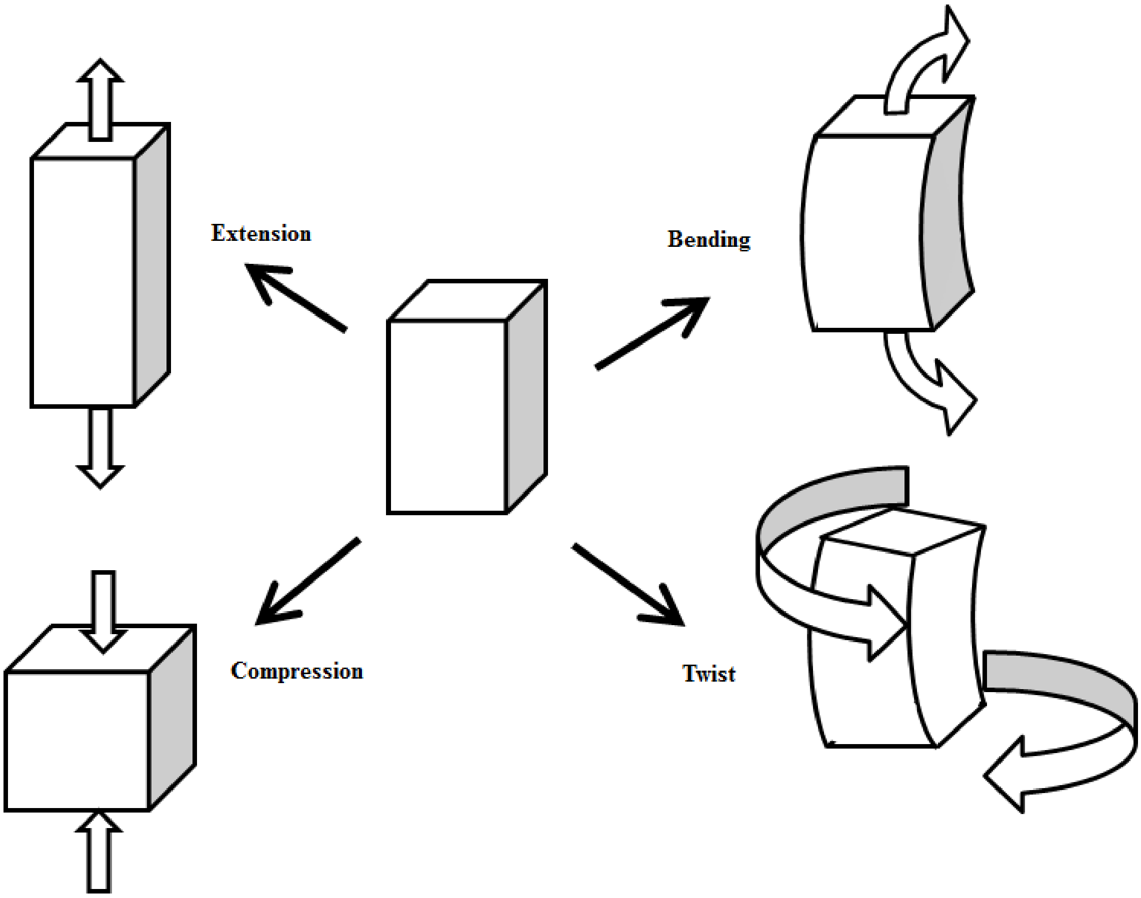


Fig. 3.2: Mode of deformation.

3.1.2 Cutting and fixation of specimen

An organism is composed of various elements. For example, a vessel wall of an artery consists of multiple layers of tissue. A layer of endothelial cells (**endothelium**) covers inner wall of a layer of smooth muscle. Each part of the biological tissue has

orientation: a cell, a group of cells, an extracellular matrix, and a group of extracellular matrices (**Fig. 3.3**).

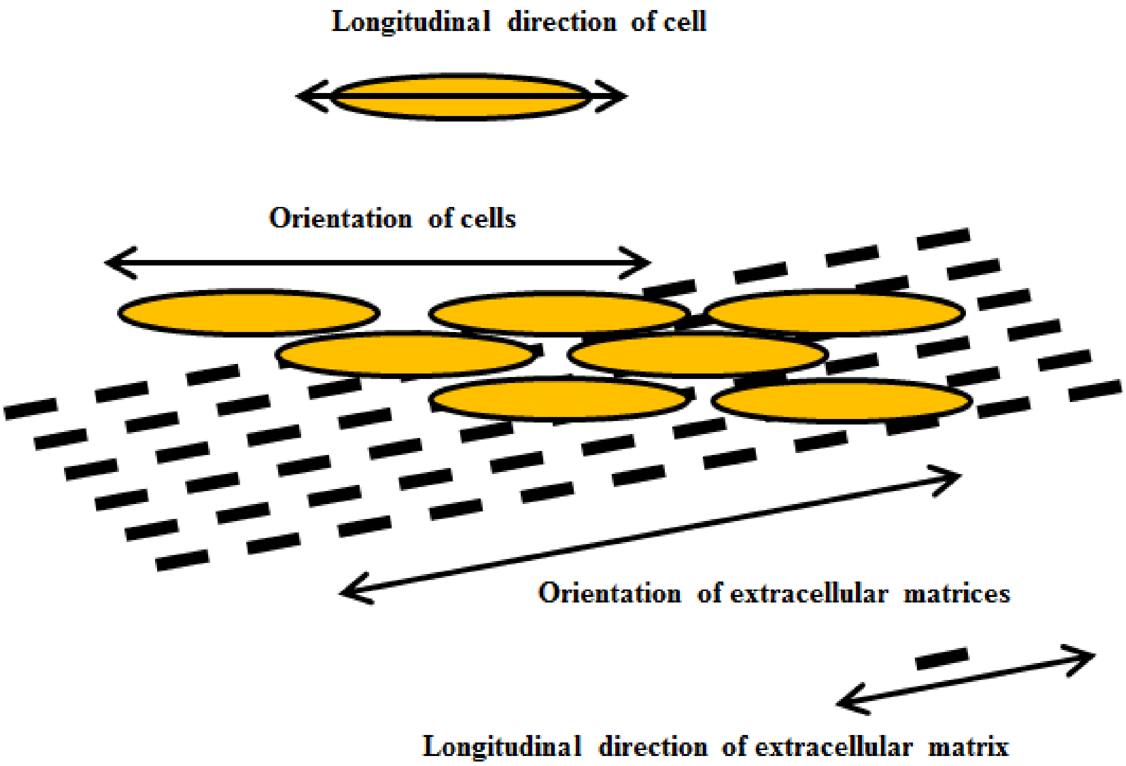


Fig. 3.3: Orientation of cells and matrices.

A part of objective material is cut for material testing. A part of a living body is handled as a **composite material** with an orientation. Apart from a non-directional uniform material, the structure and the direction of elements should be selected for a specimen.

The direction of load on the material is also selected: **tangential**, **radial**, or **longitudinal** direction in a tubular material (e.g. blood vessel wall) (**Fig. 3.4**). The direction should be defined according to the direction of the structure of biological materials: the cell, the cell-extracellular matrix or the tissue. It is important to cut out the specimen into a shape suitable for a direction to apply the load.

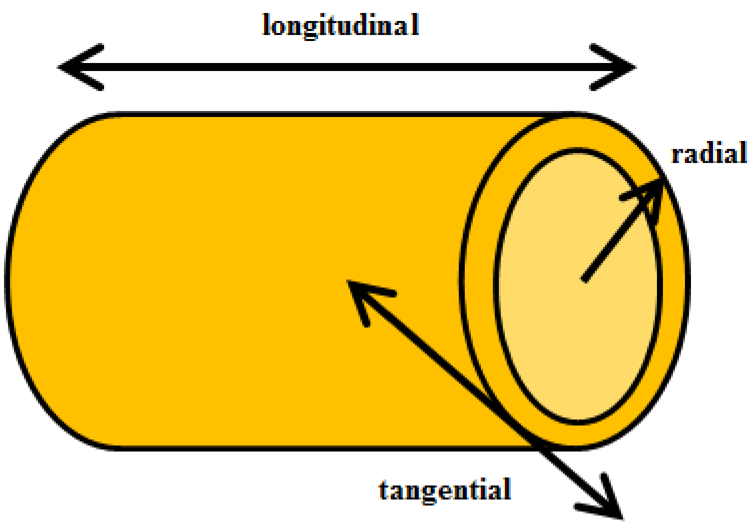


Fig. 3.4: Direction of forces at tube wall.

Several biological materials have large **compliance**. The special attention is necessary on the **chucking** of the specimen. The strong fixing force makes the local deformation of the fixed part, where destruction might occur. On the contrary, the weak fixation produces slip at fixation point.

The transmission of the force to the specimen should be examined carefully. In many cases, cells are cultured on the **scaffold**. When the scaffold deforms, the deformation of the cell depends on the adhesion between the cell and the scaffold (**Fig. 3.5**).

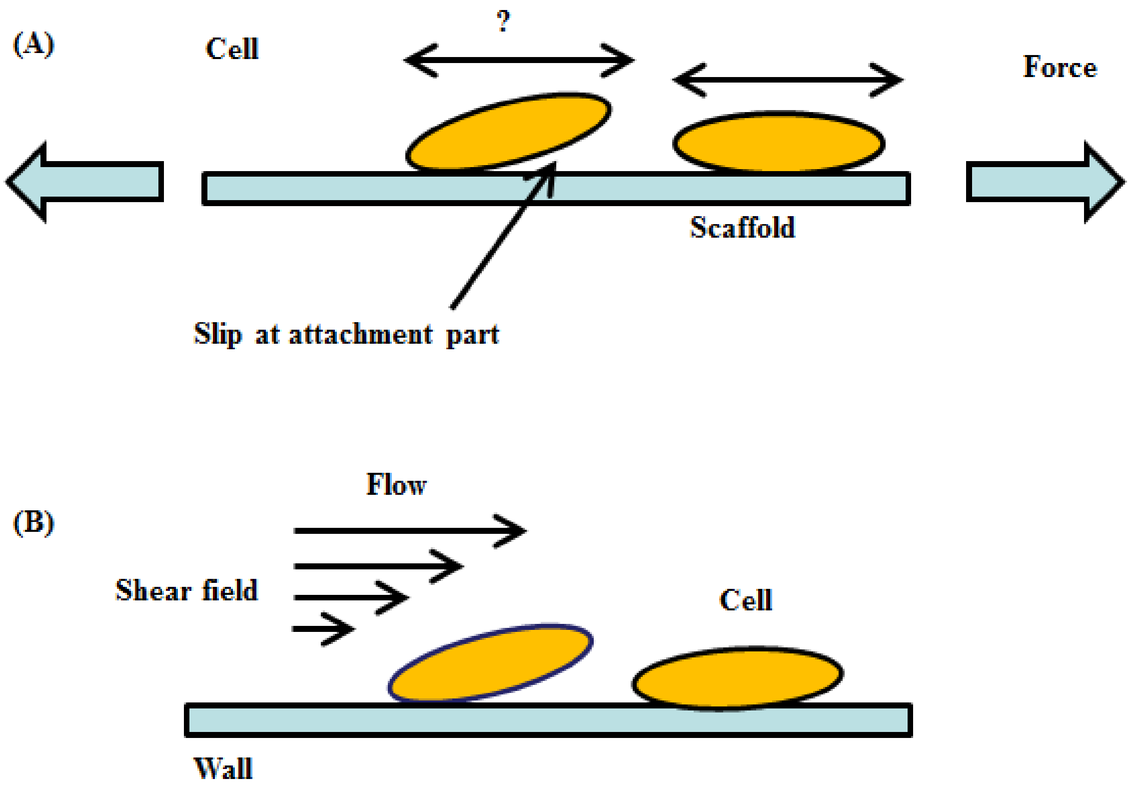


Fig. 3.5: Transmission of force.

If the cell adheres to the scaffold with every area, the deformation of the cell synchronizes with that of the scaffold. When the cell does not adhere to the scaffold with several areas, the deformation of the cell does not synchronize with that of the scaffold. The deformation depends on the combination of the adhesion portion. The cell may be sheared, even if the scaffold is pulled. When the slip occurs at the adhesion part, the deformation of the scaffold is not transmitted to the cell (Fig. 3.5(a)).

On the other hand, the shear stress can be transmitted to the cell in the fluid (Fig. 3.5(b)) [14]. By the shear stress in the fluid on the wall, the cell adhered on the wall deforms, migrates and peels off (see 4.2.5).

In a material of large compliance, the direction of deformation should be flexible. The equilibrium point is explored, while the force is applied (see 3.1.3).

A device with a large area of contact surface disperses the fixation pressure. The pneumatic pressure at the fixation device can control the fixation pressure (Fig. **3.6**(a)). The film-like or linear specimen is rolled around a cylindrical fixation device. The frictional force between the specimen and the cylinder disperses fixation force to avoid local concentration of fixation stress (Fig. 3.6(b)). The larger cross-sectional area of fixation part of the specimen is effective to increase the fixation force (Fig. 3.6(c)).

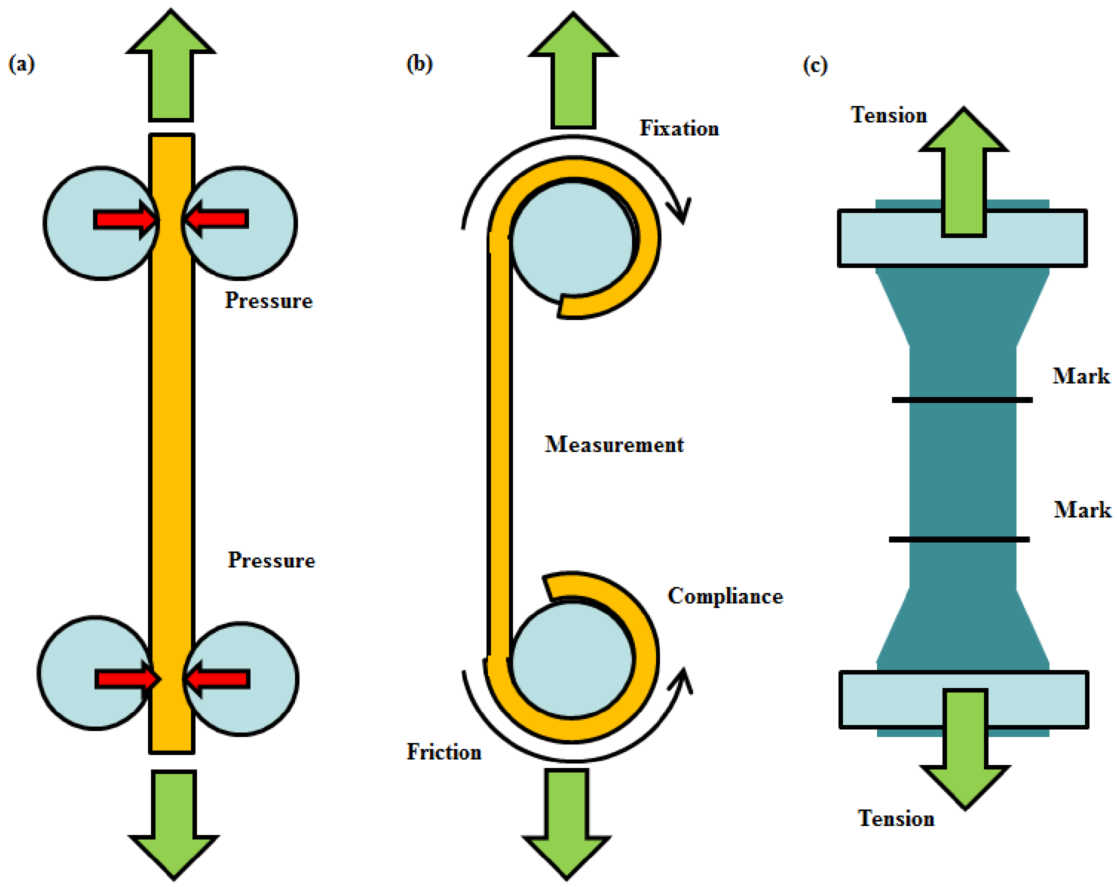


Fig. 3.6: Fixation.

3.1.3 Setting of origin and range of measurement

Because of the various state of each element in the composite specimen, the **origin** of the tensile test should carefully be determined. An initial load should be added at the origin, in order to apply load on every element in the specimen.

The **ligament** shows large deformation, when the load is small. The rate of increase of deformation decreases, as the increase of the load. The elastic modulus of the whole material might increase, as each element in the ligaments aligns to the direction of the load (**Fig 3.7**).

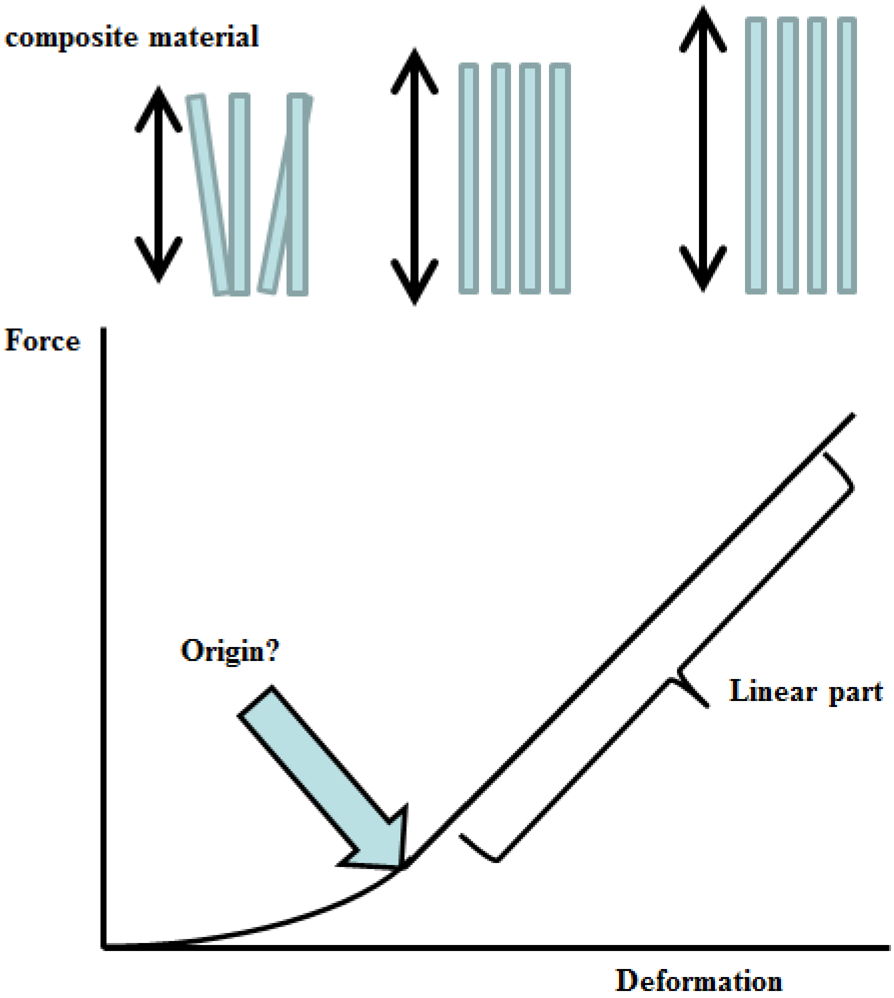


Fig. 3.7: Origin.

To escape from concentration of the deformation adjacent to the fixing portion, the part for measuring the deformation of the specimen is set at the distant portion from the fixed portion. At the measurement part, the uniformity of the deformability of the material had better been achieved: the uniform cross-sectional area of the specimen. The mark indicating the measurement position (Fig. 3.6(c)) is effective.

3.1.4 Stress-strain diagram

When a load is applied to the material, the deformation progresses with increase of the load. The thin material is easy to deform than a thick material. Instead of the force, the force per cross-sectional area is used to compare the deformability of the material. The force per cross-sectional area is called the "**stress**". The unit of the stress is Pa (Pascal), which is the same as that of the pressure.

The pressure is defined as the balanced force per unit area in the free flowing fluid; such as gas or liquid. The pressure is perpendicularly loaded on every plane. The stress, on the other hand, is defined as the force per unit area, and has a direction at an arbitrary plane (see 4.1.1). The stress (compression and tensile) perpendicular to the plane is called the "**normal stress**". The stress parallel to the plane is called the "**shear stress**" (**Fig. 3.8**).

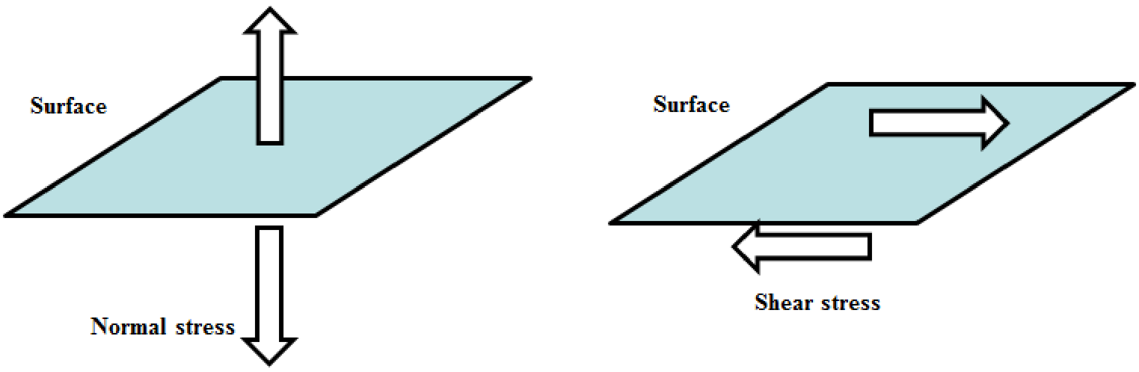


Fig. 3.8: Stress.

The larger material generates the larger deformation. The ratio of the deformed length Δx against the original length x is called "**strain**" ε.

$$\varepsilon = \Delta x / x \quad (3.1)$$

The strain is the ratio of the “length” and “length”. It is a dimensionless number. The term “strain” is conventionally used like a unit. In the deformation of the solid metal, “**micro-strain**” is used as 10^{-6}.

A material is not uniformly deformed in all directions. When the material is deformed in one direction, the deformation occurs also in the vertical direction. The ratio is expressed by “**Poisson's ratio**”. When the material is pulled in one direction, the ratio of “elongation at the parallel direction of the force application (strain Δx)” to “contraction at the vertical direction (strain Δy)” is Poisson's ratio κ.

$$\kappa = \Delta y / \Delta x \quad (3.2)$$

$\Delta y = -\Delta x$ in the uniform extension to every direction, which has the Poisson's ratio of $\kappa = -1$.

Consider about the following deformation: “the quadrangular prism with the height x at the side y of the bottom square”, while maintaining its volume, deforms to “the quadrangular prism with the height $x + \Delta x$ at the side $y - \Delta y$ of the bottom square” (**Fig. 3.9**).

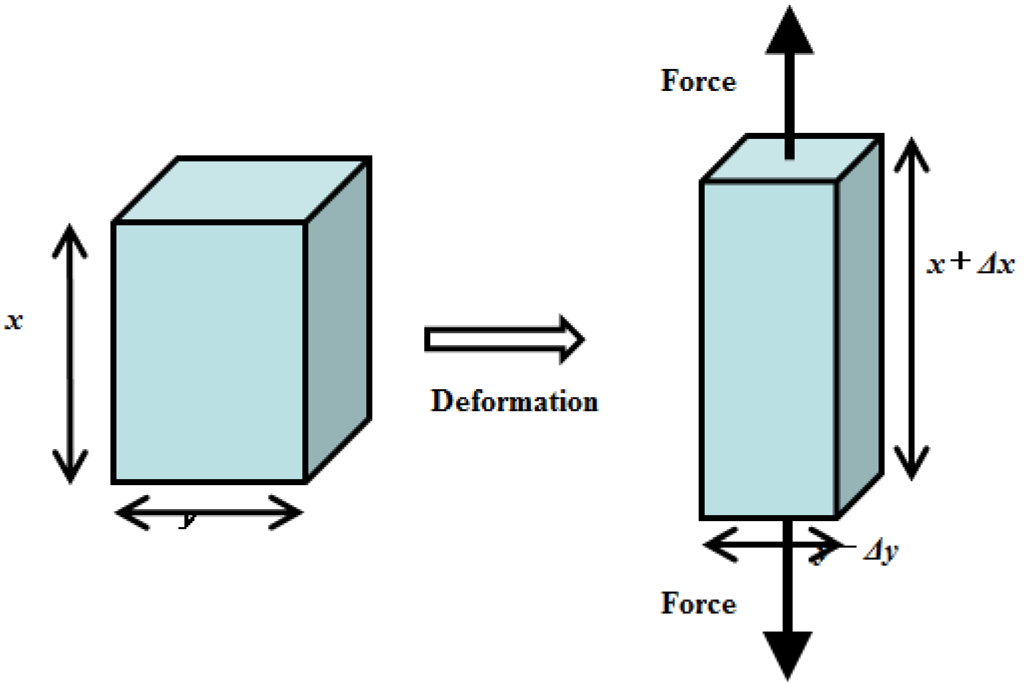


Fig. 3.9: Poisson's ratio.

$$(x+\Delta x)(y-\Delta y)^2=xy^2 \qquad (3.3)$$

If you expand the left-hand side of the equation,

$$\begin{aligned}&(x+\Delta x)(y^2-2\,y\,\Delta y+\Delta y^2)\\&=x\,y^2+y^2\Delta x-2\,x\,y\,\Delta y-2\,y\,\Delta x\,\Delta y+x\,\Delta y^2+\Delta x\,\Delta y^2\\&=x\,y^2\end{aligned} \qquad (3.4)$$

When Δx and Δy are minute amounts, the square term of Δx and Δy can be withdrawn.

$$y^2 \Delta x - 2xy \Delta y = 0 \tag{3.5}$$

Since x = y in the cube,

$$x^2 \Delta x - 2x^2 \Delta y = 0 \tag{3.6}$$

$$\Delta y / \Delta x = 1/2 \tag{3.7}$$

Poisson's ratio is 0.5, when the cube is deformed into a rectangular with maintaining its volume (Eq. 3.7). Poisson's ratio is usually smaller than 0.5 in the solid, because the volume increases slightly with the elongation.

In the solid, the tension in one direction usually causes the compressive strain in the perpendicular direction, and the shear strain in the oblique direction (**Fig. 3.10**).

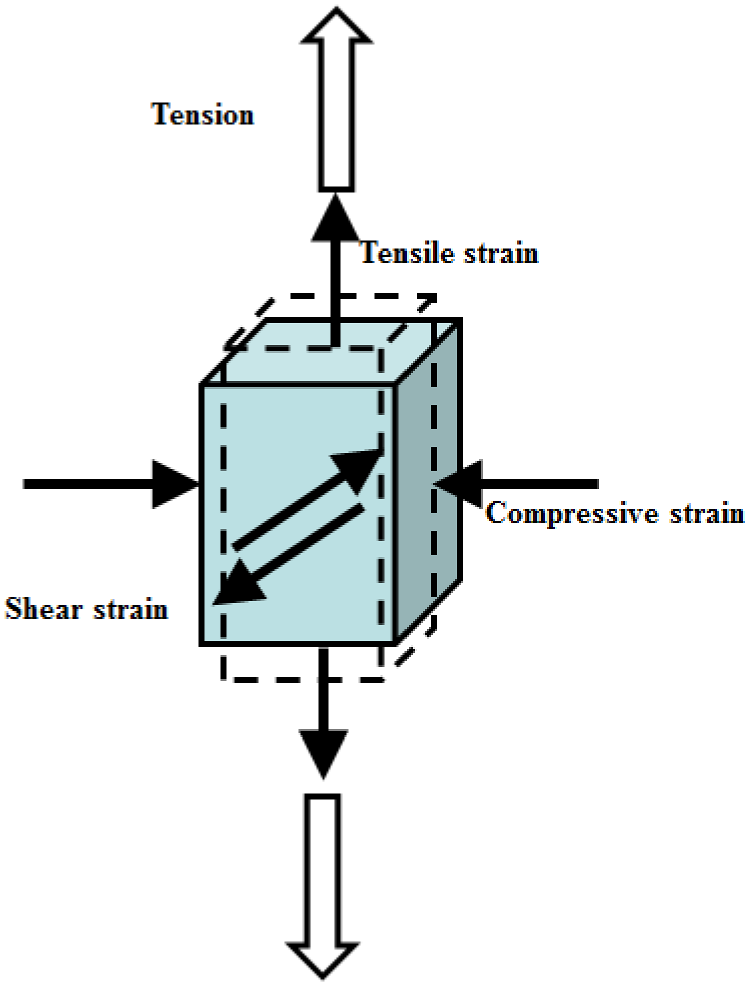


Fig. 3.10: Strains in tension.

A metal resistor, known as a **strain gauge,** is frequently used to measure the strain. The strain gauges has a direction at the resistor. Attention should be payed to the direction of the strain and the strain gauge.

The resistance of the strain gauge changes according to the strain. In other words, the electrical resistance changes according to the length and cross-sectional area of the metal resistor (**Fig. 3.11**). When the wire of resistance is pulled, both the increase of the length and the decrease of the cross-sectional area of the wire increases the electrical resistance. The change of the electrical resistance is detected by the bridge circuit (Fig.

2.11).

The graph representing the relationship between the strain (the horizontal axis) and the stress (the vertical axis) is called **stress-strain diagram** (**Fig. 3.12**). The cross-sectional area of the specimen changes with the deformation.

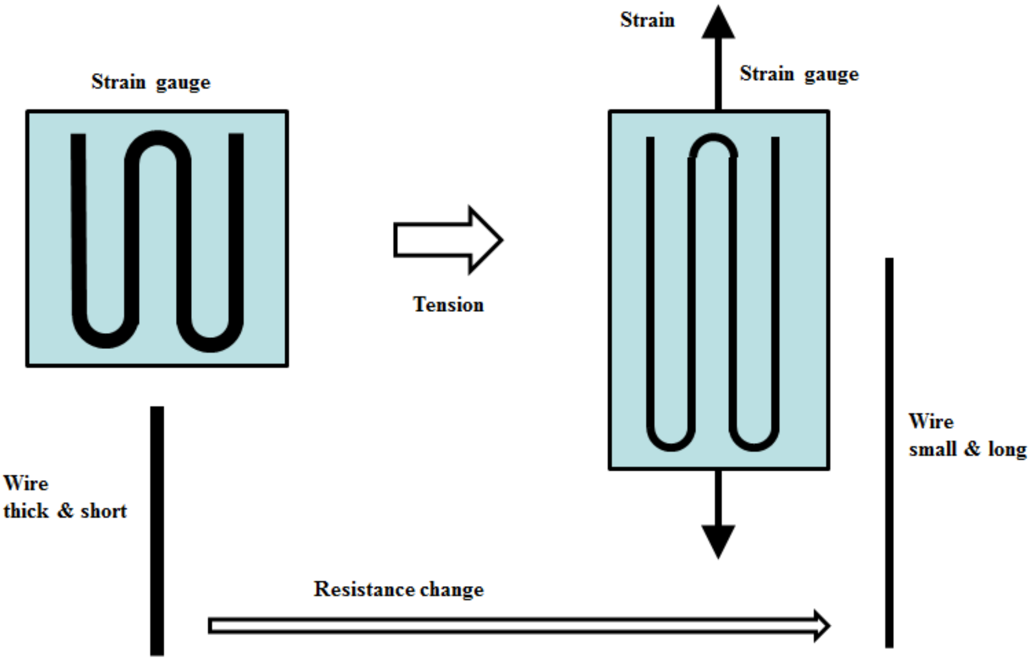


Fig. 3.11: Strain gauge.

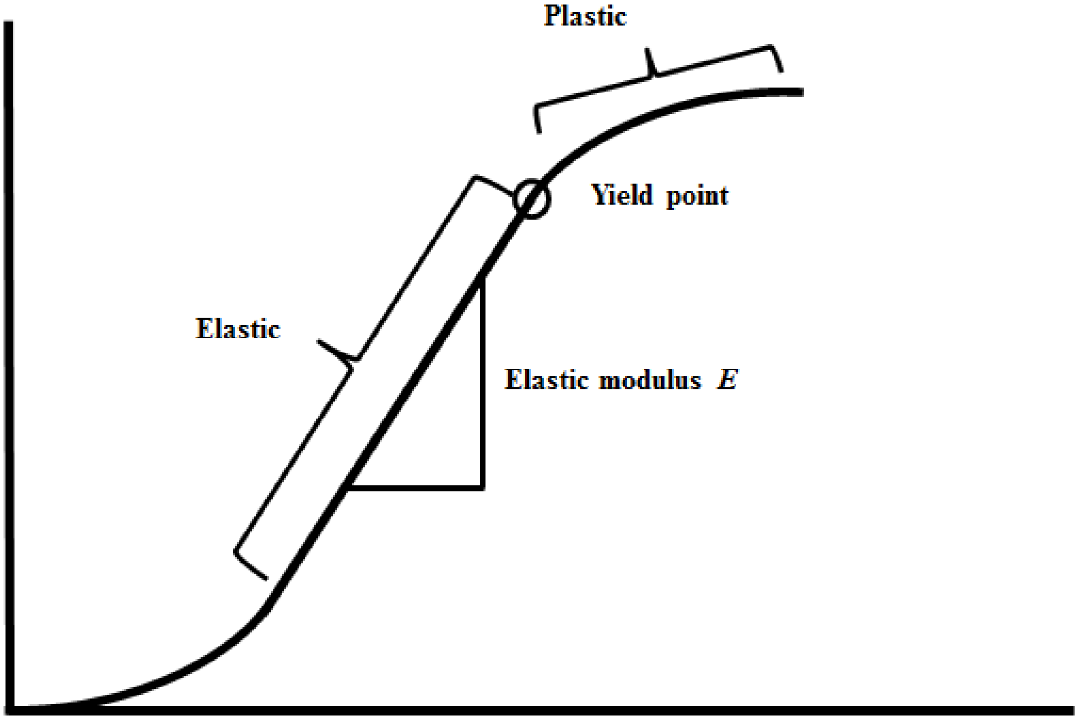


Fig. 3.12: Stress-strain diagram.

For example, when the length extends from x_0 to x_1 by a load F_1, the cross-sectional area of the vertical direction decreases from A_0 to A_1. The value τ_1 calculated by dividing the load F_1 by the cross-sectional area A_1 at the time of deformation is called the **true stress**. The value τ_0, on the other hand, calculated by dividing the load F_1 by the cross-sectional area A_0 before deformation, is called **nominal stress** (**Fig. 3.13**).

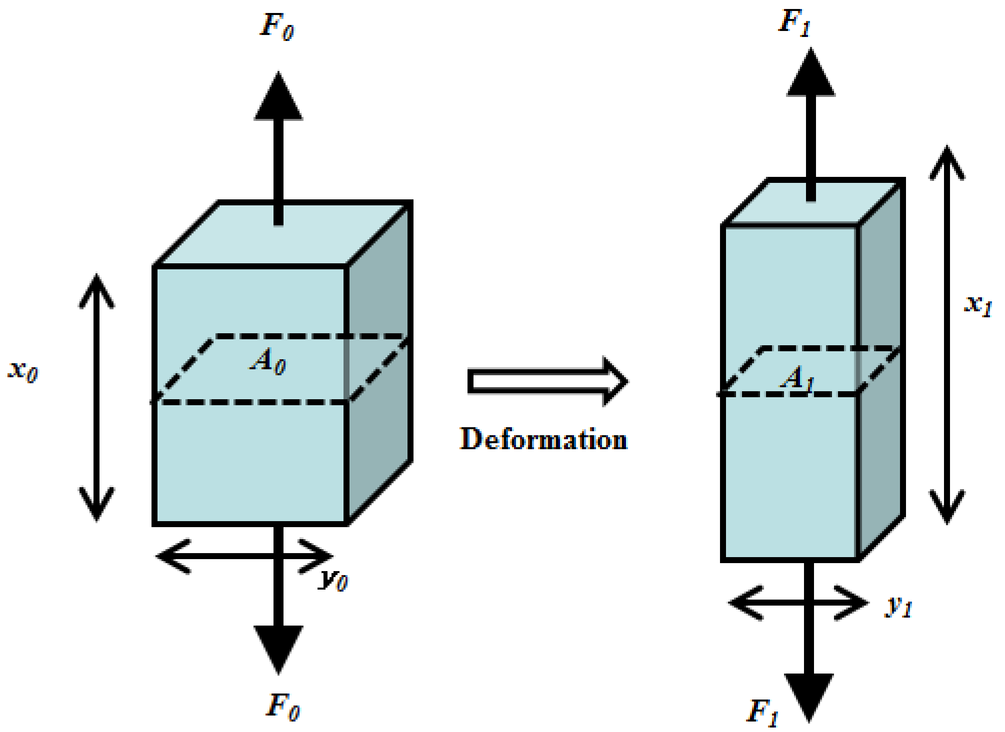


Fig. 3.13: True stress.

$$\tau_1 = F_1 / A_1 \tag{3.8}$$

$$\tau_0 = F_1 / A_0 \tag{3.9}$$

3.1.5 Elastic region and plastic region

The reversible deformation to its original shape after removal of the force is called the "**elastic deformation**". The ratio of "stress τ" and "strain ε" (τ / ε) is called **elastic modulus** *E* (Fig. 3.12). The unit of the elastic modulus is Pa, which is the same unit as stress. The stress is proportional to the strain at the idealized **Hookean elastic material**.

The reversible deformation region, where the shape returns to its original one after exclusion of the load, is called the **elastic region**. In the region, the relationship between the strain and the load is one-to-one correspondence. Elastic deformation is independent of the order of the load. In other words, it does not have the **hysteresis** effect.

In the elastic deformation model, the deformation rate does not affect the deformation. It is instantly deformed, when a load is applied. In the viscous flow model (see 4.1.2), on the other hand, the deformation depends on the deformation rate.

Beyond the elastic region, the deformation remains after exclusion of the load. The deformation is called **plastic deformation**, and the region is called the **plastic region**. The boundary between the elastic region and the plastic region is called **yield point** (Fig. 3.12).

The composite material may have several boundaries like a yield point. Most of the biological tissue has the **hysteresis** effect at deformation. The attention should be payed to the order of the deformation process at the biological tissue.

3.1.6 Sphere

At the hemisphere of radius r, "the product of the pressure difference ΔP (between the inner pressure and outer pressure across the sphere) and the area πr^2 of the cross-sectional circle of the sphere" balances with "the product of the circumference length $2\pi r$ of the cross-sectional circle of the sphere and the **surface tension** per unit length γ of circumference of the sphere" (Fig. **3.14**).

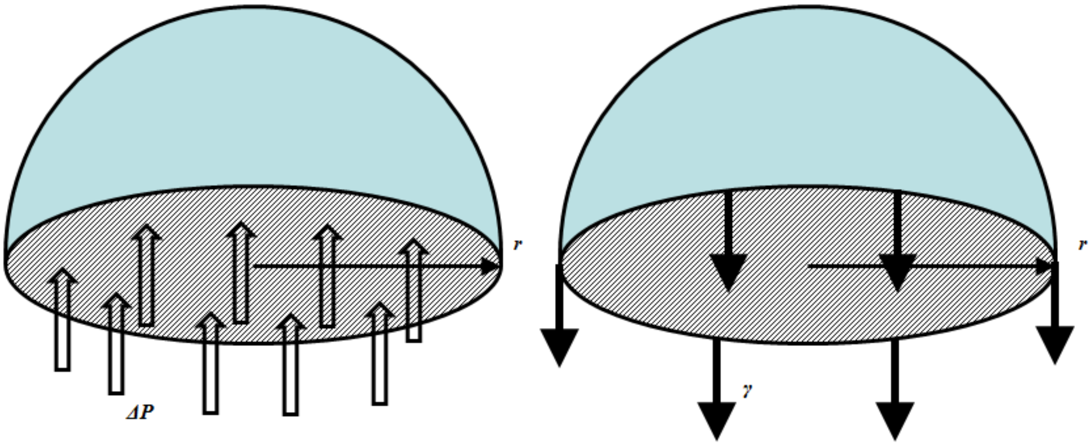


Fig. 3.14: Balance of forces in hemisphere.

$$\Delta P \pi r^2 = 2\pi r \gamma \qquad (3.10)$$

By transforming the equation (3.10),

$$\Delta P = 2\gamma / r \qquad (3.11)$$

The equation (3.10) is the expression of **Young-Laplace** at the droplet of the sphere. Unit of the surface tension γ is N m^{-1}. When an erythrocyte is aspirated by the capillary, the tension γ of the erythrocyte membrane can be estimated by the above equation with the radiuses of curvature r_1 and r_2 and with the ambient pressures P_1 and P_3 (**Fig. 3.15**).

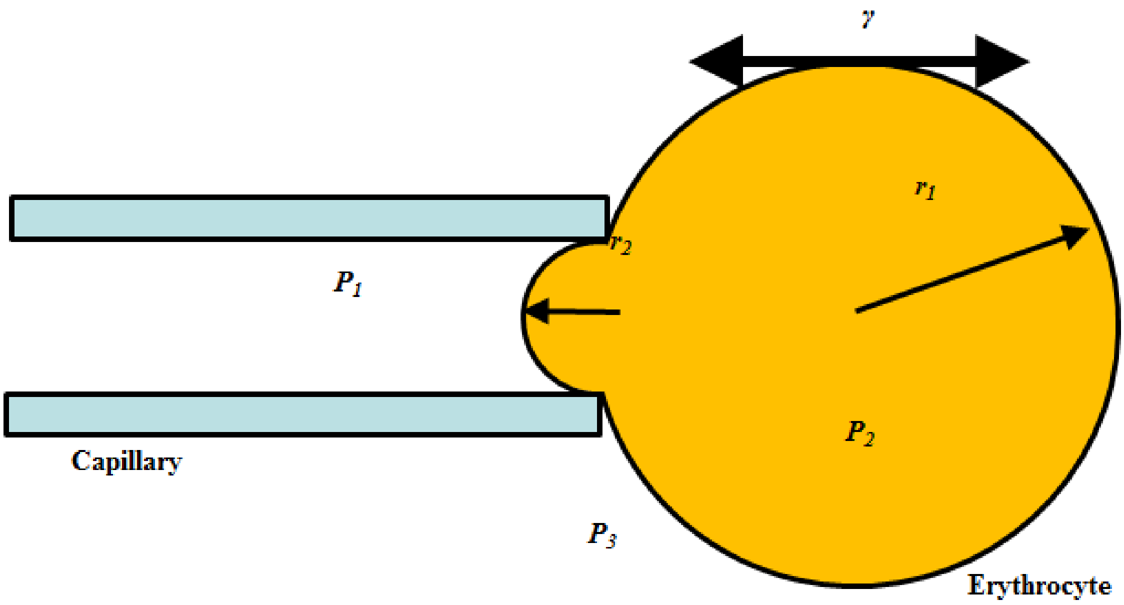


Fig. 3.15: Tensile force at membrane of erythrocyte.

To measure the deformation of the suspended particle in the liquid, the **counter rotating rheoscope** (see 4.2.4) is available. The deformation can be quantified by the ratio of the major axis and minor axis at the spheroid deformed from the sphere in the shear field (see 6.1.1).

3.1.7 Bending

The bending test is applied to measure the bending deformation of the material (**Fig. 3.16**). The graph, which displays the distribution of shearing force at the material, is called **shearing force diagram**. In the shear force diagram, the shear force of “downward on the left side of the cross section and upward on the right side of the cross section (counterclockwise)" is defined as positive. The graph, which displays the distribution of the bending moment at the material is called the **bending moment diagram**. In the bending moment diagram, the upward moment is defined as positive.

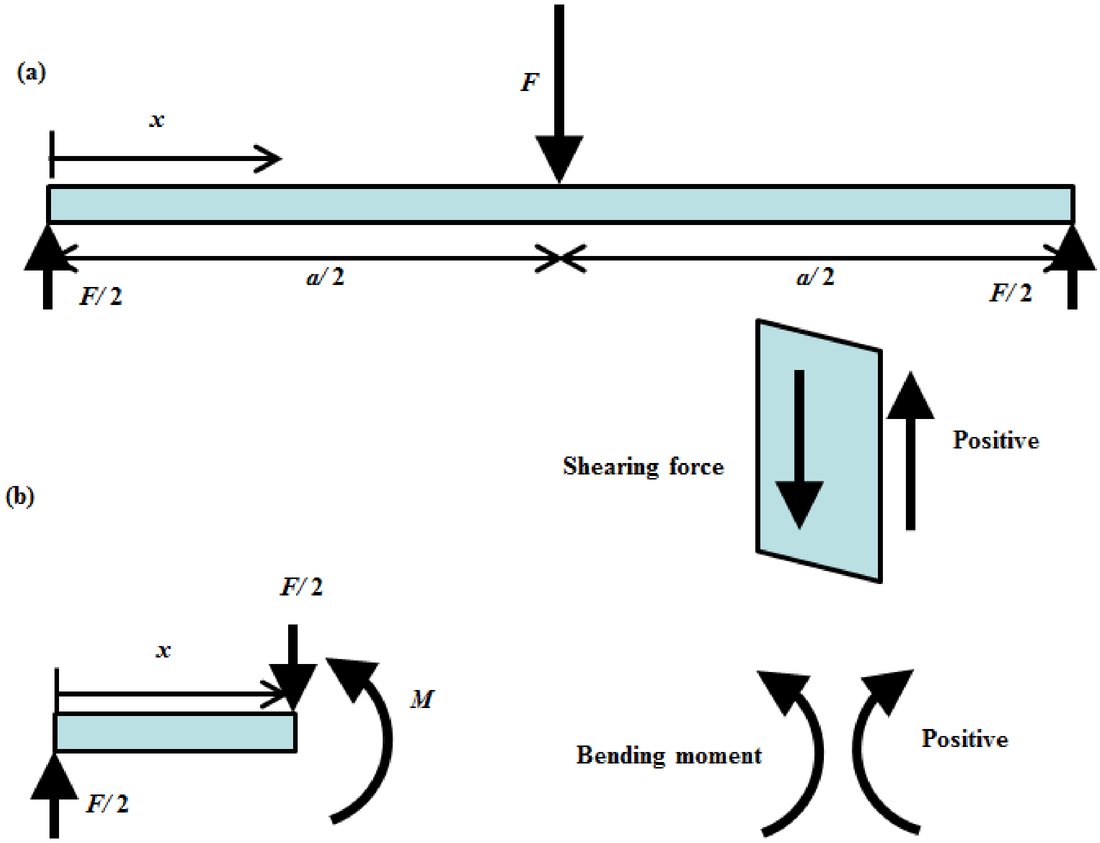


Fig. 3.16: Bending.

In Fig. 3.16, consider the shear force and the bending moment in the cross-section. The force *F* is applied to the vertical direction at the center of the straight horizontal beam of length *a*. The force applied at a point is called **concentrated load**. The forces applied with distribution, on the other hand, is called **distributed load**: the gravity due to the mass of the beam itself is taken into account.

In **Fig. 3.17** (a), the beam is supported by both ends of the **simple support**. The moment is not generated at the simple support, since the rotation is not fixed at the ends. At the **rigid support**, on the other hand, the moment *M* is generated, since the end cannot rotate (Fig. 3.17 (b)).

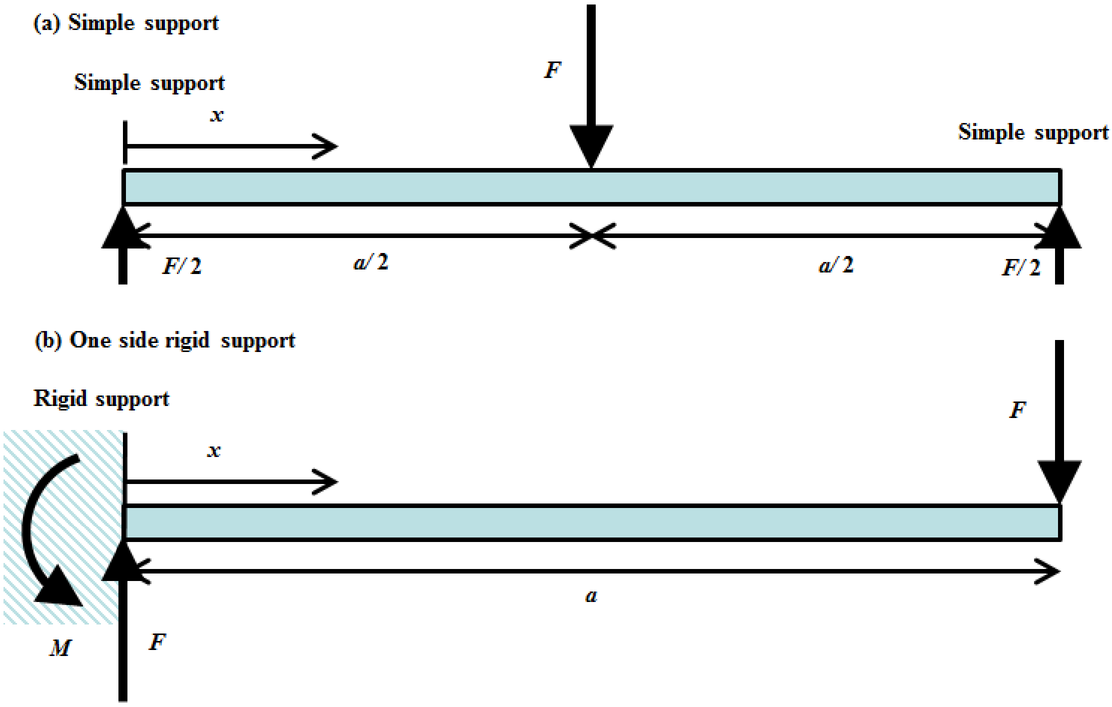


Fig. 3.17: Simple & rigid support.

The x-axis is defined along the beam (the length of a) from the left end to the right in Fig. 3.16(a). The upward force is defined as positive. Eq. 3.12 describes the balance of the forces F.

$$F/2+F/2-F=0 \tag{3.12}$$

The counter-clockwise moment is defined as positive in Fig. 3.16. Eq. 3.13 describes the balance of moment M around the left edge of the beam.

$$-(a/2)F+a(F/2)=0 \tag{3.13}$$

In Fig. 3.16 (b), the force $F/2$ downward at the position of x is necessary for the balance of the force at the parts of the beam: from the left end to the position x ($0 < x <$

a/2). The force F/2 upward at the position of x, on the other hand, is necessary for the balance of the force at the remaining right part of the beam: from the position x to the right end. Thus, shearing forces are generated in the cross-section at the position x of the beam: downward left and upward right (counterclockwise).

In Fig. 3.16 (b), the counterclockwise moment M at the position of x is necessary for the balance of the moment at the parts of the beam: from the left end to the position x ($0 < x < a/2$).

$$M - x (F / 2) = 0 \tag{3.14}$$

The clockwise moment M at the position of x, on the other hand, is necessary for the balance of the moment at the remaining right part of the beam: from the position x to the right end. Thus, the upward moment is generated in the cross-section at the position x of the beam.

At the **three-point bending test** in **Fig. 3.18**, estimate the bending moment and shearing force in the cross-section of the beam. A downward force F_1 is vertically applied at the center of the horizontal beam of length a. At the simple support, each end of the beam is supported by a vertical upward force $F_1/2$, respectively. At the left half of the cross-section of the beam, the shear force $+F_1/2$ is applied. At the right half of the cross-section of the beam, $-F_1/2$ is applied. The bending moment is $(a/2)(F_1/2)$ at the center of the beam, and decreases linearly toward zero at both ends.

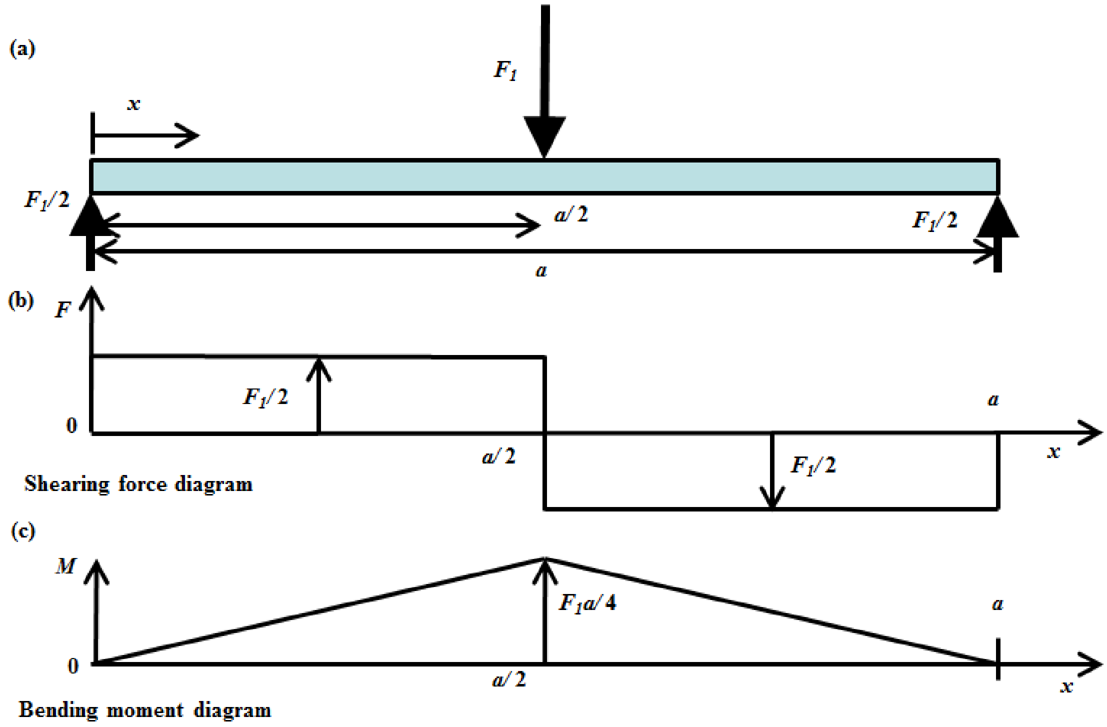


Fig. 3.18 Three-point bending test.

At the **four-point-bending test** in **Fig. 3.19**, the bending moment and the shear force in the cross-section are calculated as follows. The forces F_1 are applied vertically downward at the two points (a/3 and 2a/3 from the left) of the horizontal beam of the length a, respectively. The both sides of the simple support are supported by the vertical upward forces F_1, respectively. At the cross-section in the left part of one third of the beams, the shear force + F_1 is applied. At the cross-section in the right part of one third of the beams, the shear force −F_1 is applied. Bending moment is (a/3) F_1 at the central part of the beam between two points of application of the forces, and decreases linearly toward zero at both ends.

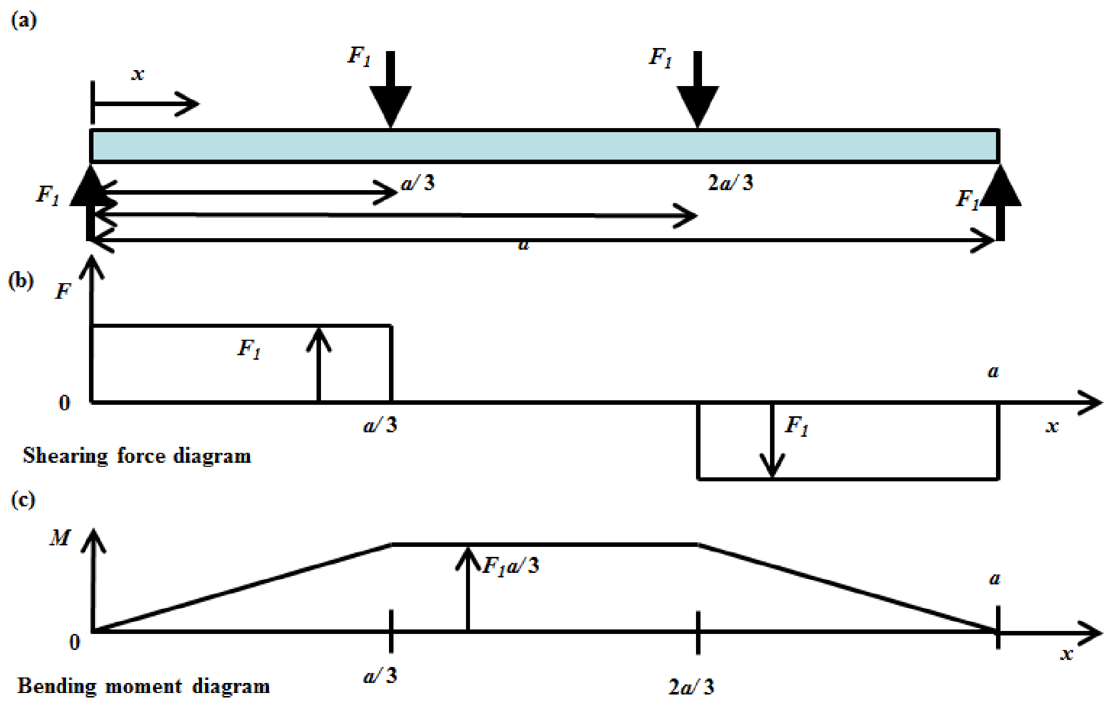


Fig. 3.19: Four-point bending test.

The 4-point bending has both the constant of the moment and zero of the shearing force between two points of application of the forces.

The bending deformation depends on the shape of the cross section of the beam, because the larger strain generates at the point farther from the center line (**Fig. 3.20**). The value calculated by integrating y^2 with respect to the very small area dA at the distance y from the z-axis is called the **moment of inertia of area** about the z-axis Iz.

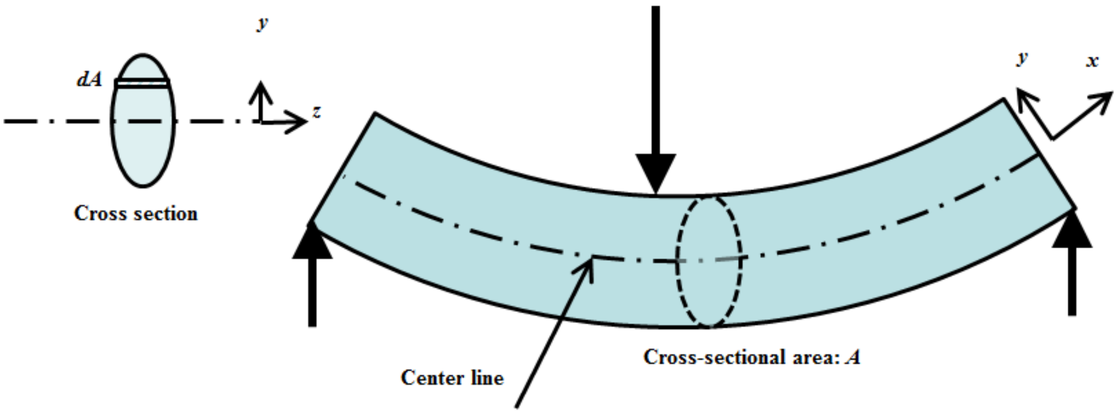


Fig. 3.20: Center line and strain.

$$Iz = \int y^2 \, dA \tag{3.15}$$

The moment of inertia of area represents the difficulty of bending deformation of the material.

3.2 Properties and Destruction of Material

3.2.1 Fatigue fracture

A material destroys, when it can no longer maintain the continuity as the deformation proceeds. The maximum strength before the fracture is referred to the “**strength**”. In some material, **maximum distortion** is used for the index of the strength before the destruction (**Fig. 3.21**).

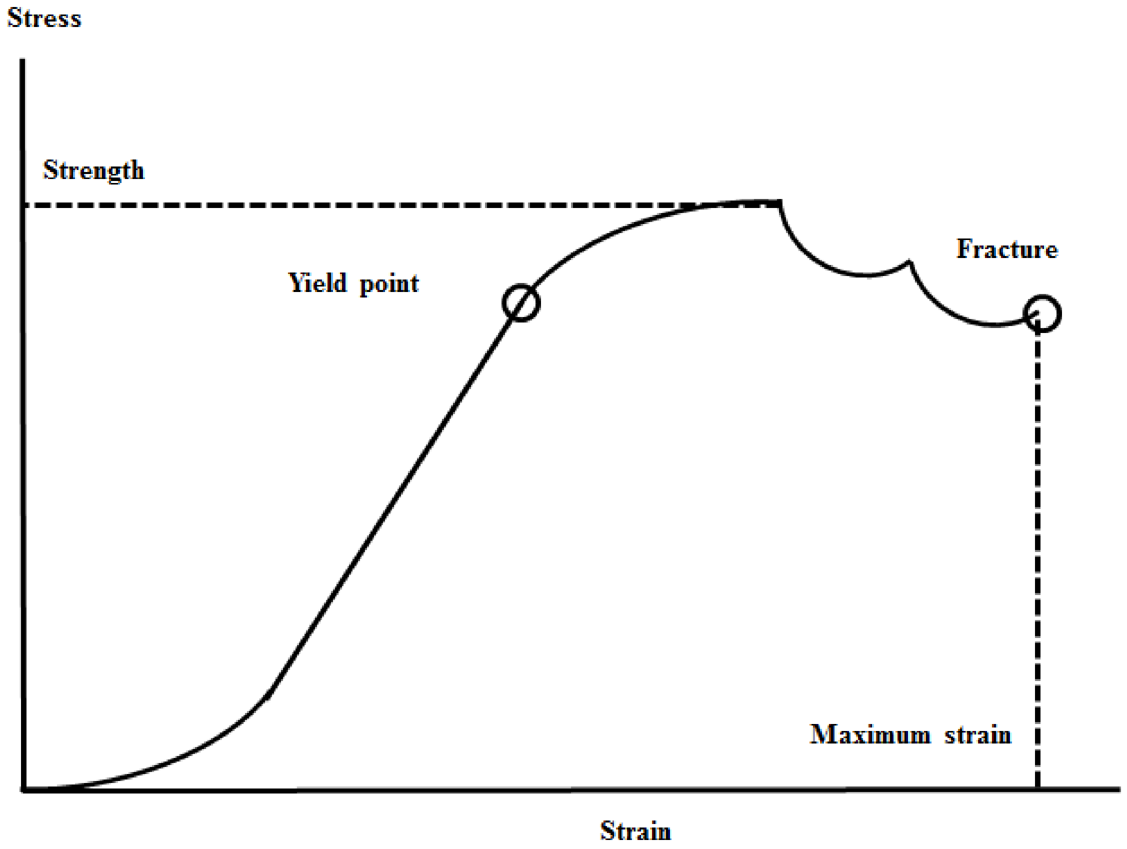


Fig. 3.21: Yield and fracture.

The deformation or the load, which does not lead to the fracture, leads to fracture by repetition in some cases. This fracture is called **fatigue fracture**. The applied way of cyclic loading can be classified into three types: extension, compression, and extension and compression (**Fig. 3.22**).

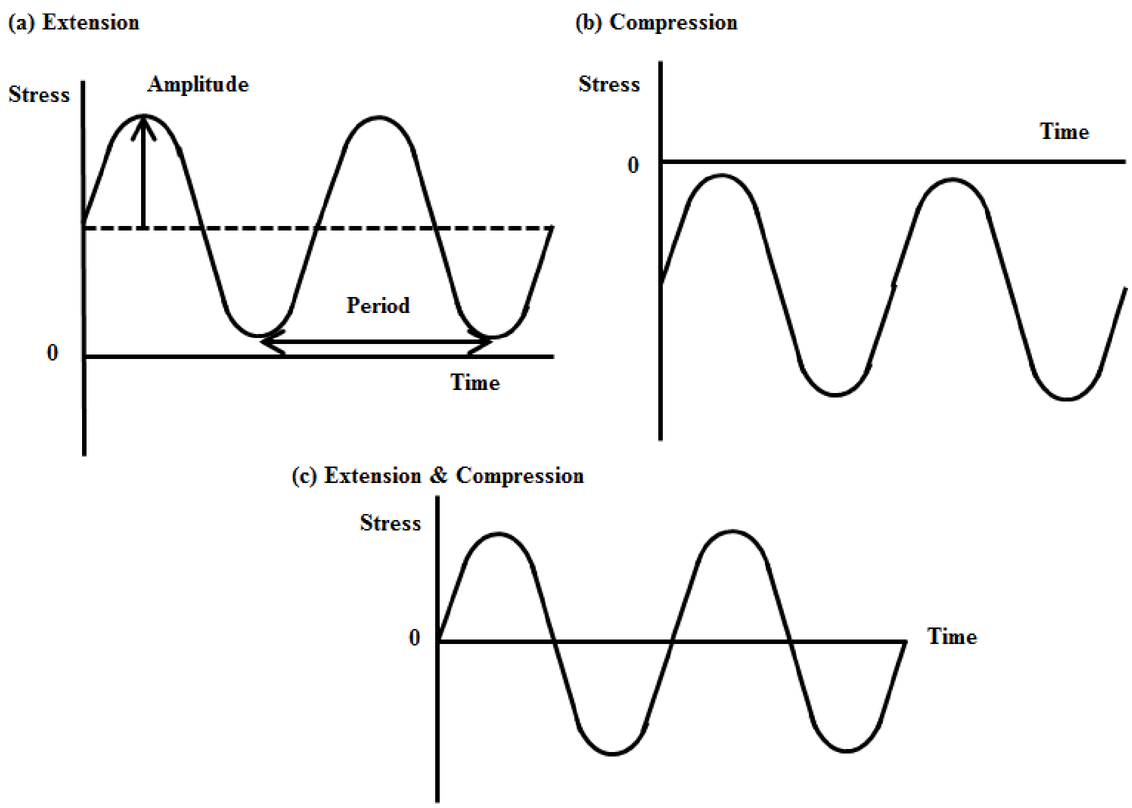


Fig. 3.22: Repetitive load.

The stripe pattern of the tracings is observed at the fracture surface of the fatigue fracture. The pattern is called **striation**. The unevenness pattern such as after tearing is observed, on the other hand, at the instantly fractured surface. The pattern is called **dimple** (**Fig. 3.23**). Observation of these patterns of the fracture surface is effective to determine the fracture mode of the metal material.

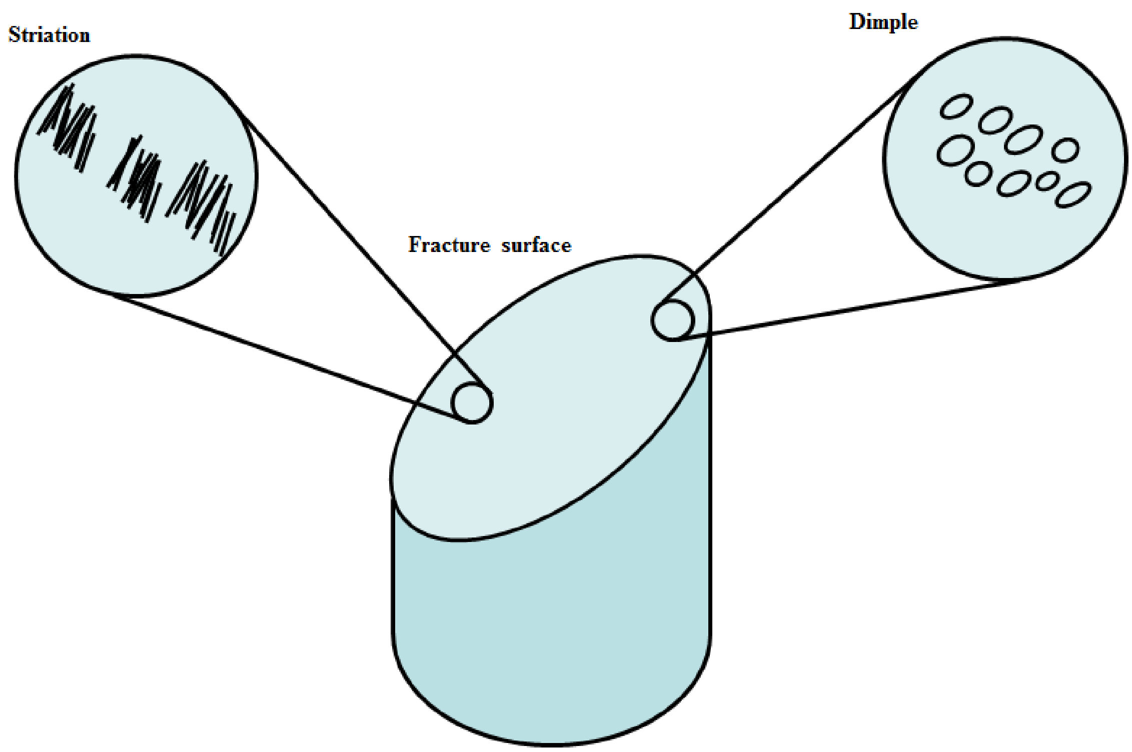


Fig. 3.23 Fracture surface.

The **stress amplitude** and the **number of cycles** are parameters at the fatigue fracture (**Fig. 3.24**). An erythrocyte has a large deformability, and is hard to break. The fatigue fracture of the erythrocyte occurs under the repeated deformation [15].

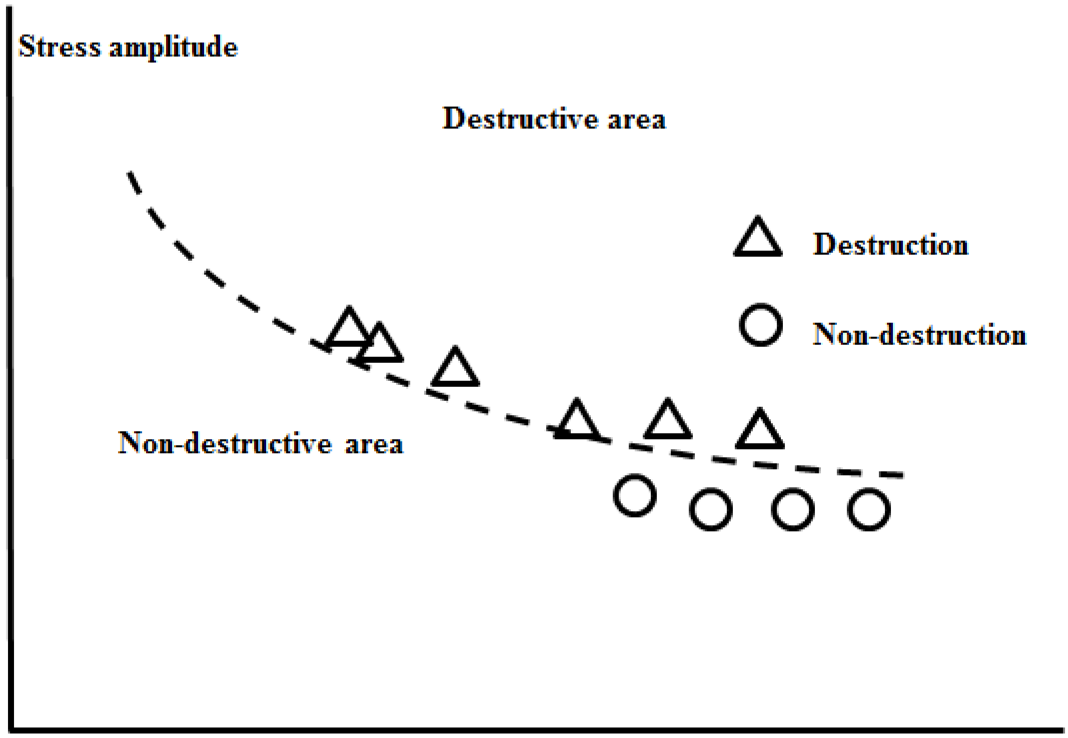


Fig. 3.24: Stress amplitude vs. number of cycles.

The biconcave of an **erythrocyte** deforms into an ellipsoid in response to shear stress in a shear flow (see 6.1.1). During the **tank tread motion** of the membrane, the membrane repeats deformation between the tensile and the compression according to the change of the curvature. When the shear rate increases, the speed of the tank tread motion increases. At the fatigue fracture of erythrocyte in the shear fluid, the product of "the shear rate" and "the exposure time to the shear field" corresponds to the number of repetitions of fatigue failure of the material (**Fig. 3.25**) [15].

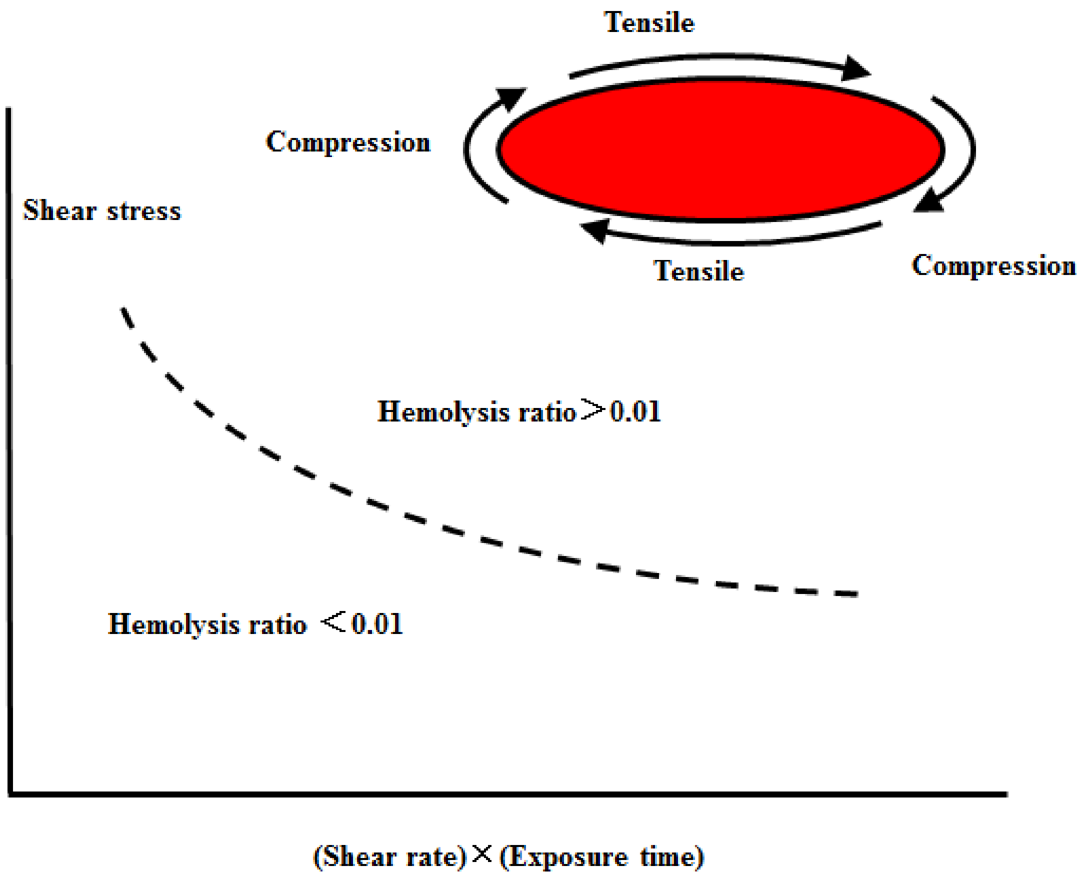


Fig. 3.25: Erythrocyte fatigue in flow.

In the erythrocyte, the fatigue failure at the membrane makes vibrating deformation of the erythrocyte in the shear flow, the contents of the erythrocytes come out to the outside (**Fig. 3.26**) [47]. The phenomenon, that the **hemoglobin** comes out to the outside of the erythrocyte, is called **hemolysis**. Hemoglobin is a protein, which transports oxygen.

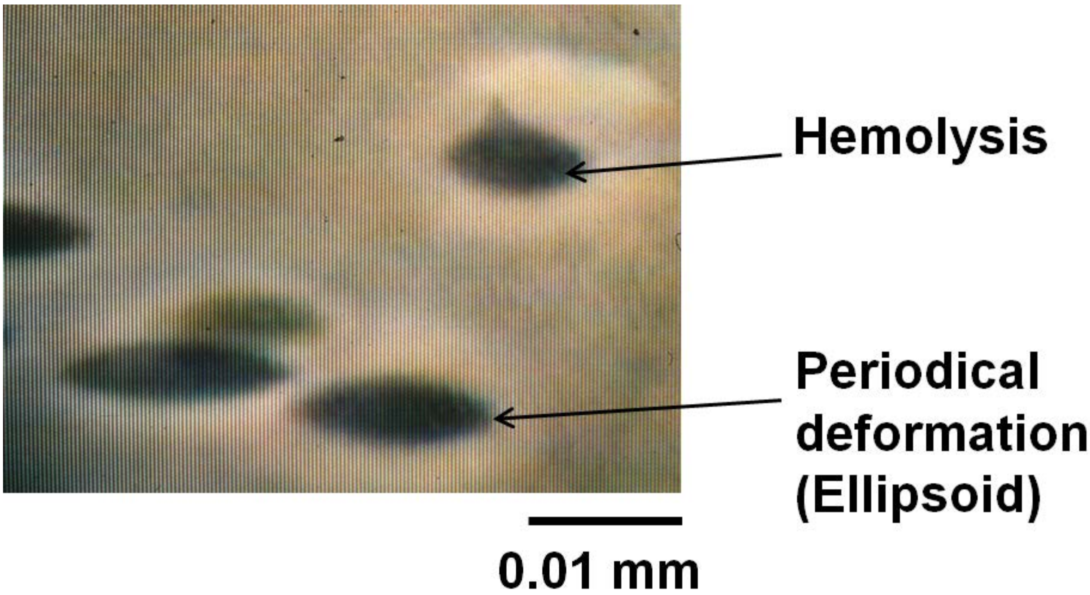


Fig. 3.26: Erythrocyte destruction.

Hemoglobin outside of the red blood cells adsorbs to the tissue, or is discharged to the outside the organization. The free hemoglobin cannot keep circulating in the blood circulation circuit, and the oxygen-carrying function is lost. Moreover, the erythrocyte with poor deformability is captured in the microcirculation system, and cannot keep circulating in the blood circulation circuit. The destruction of erythrocytes can be functionally evaluated by the ratio of hemoglobin released to the outside of erythrocytes (**hemolysis ratio**) [15].

3.2.2 Crystal and lattice defect

A substance consisted of regular atomic arrangement is called a **crystal**. The crystal is hard to be destroyed because of the strong interatomic force. A substance, of which the entire material is made of a single crystal, is called **monocrystal**.

The typical regular arrangements are the **face-centered cubic lattice** and

close-packed hexagonal lattice. The face-centered cubic lattice consists of the layers of the repeated pattern of ABCABCABC. The close-packed hexagonal lattice consists of the layers of the repeated pattern of ABABAB (**Fig. 3.27**).

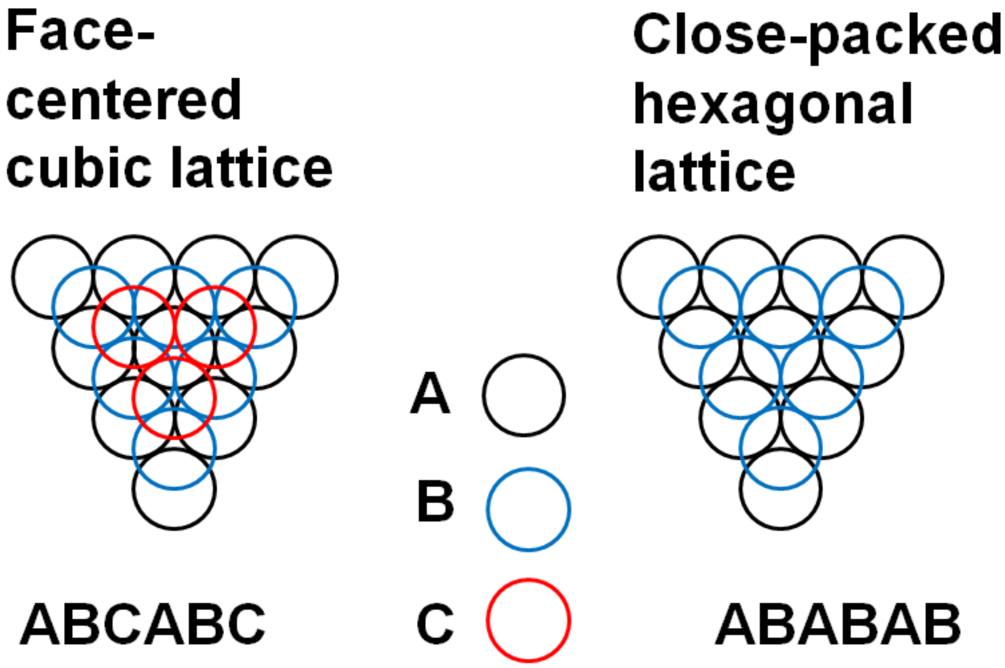


Fig. 3.27: Close-packed lattice.

The regularity of coordination of the atoms in the three-dimensional space defects at the surface, which has the open side of the neighbor (**Fig. 3.28**). The defect relates to the fracture initiated from the surface.

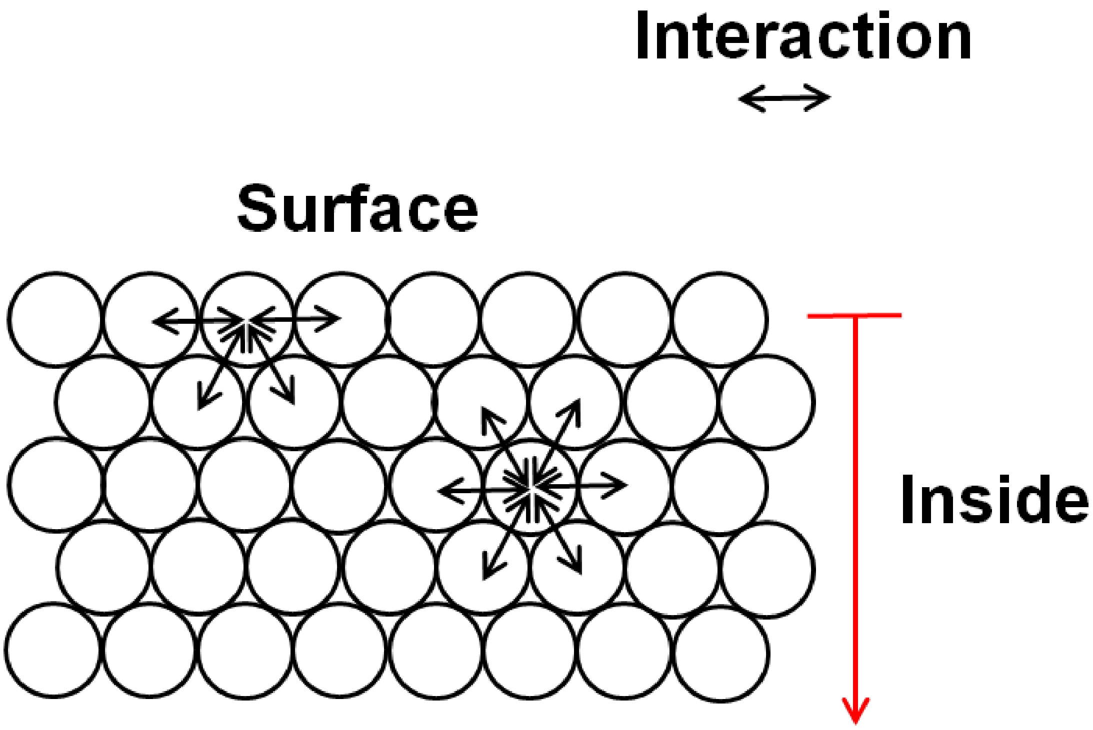


Fig. 3.28: Surface.

The material is usually an aggregation of single crystals, and is called **polycrystal**. The crystalline part in the polycrystal is called the **crystal grain** (**Fig. 3.29**). The binding force at the interface between the crystal grains is weaker than that in the crystal grain. The fracture occurs more frequently at the interface between the crystal grains than at the inside of the crystal grain.

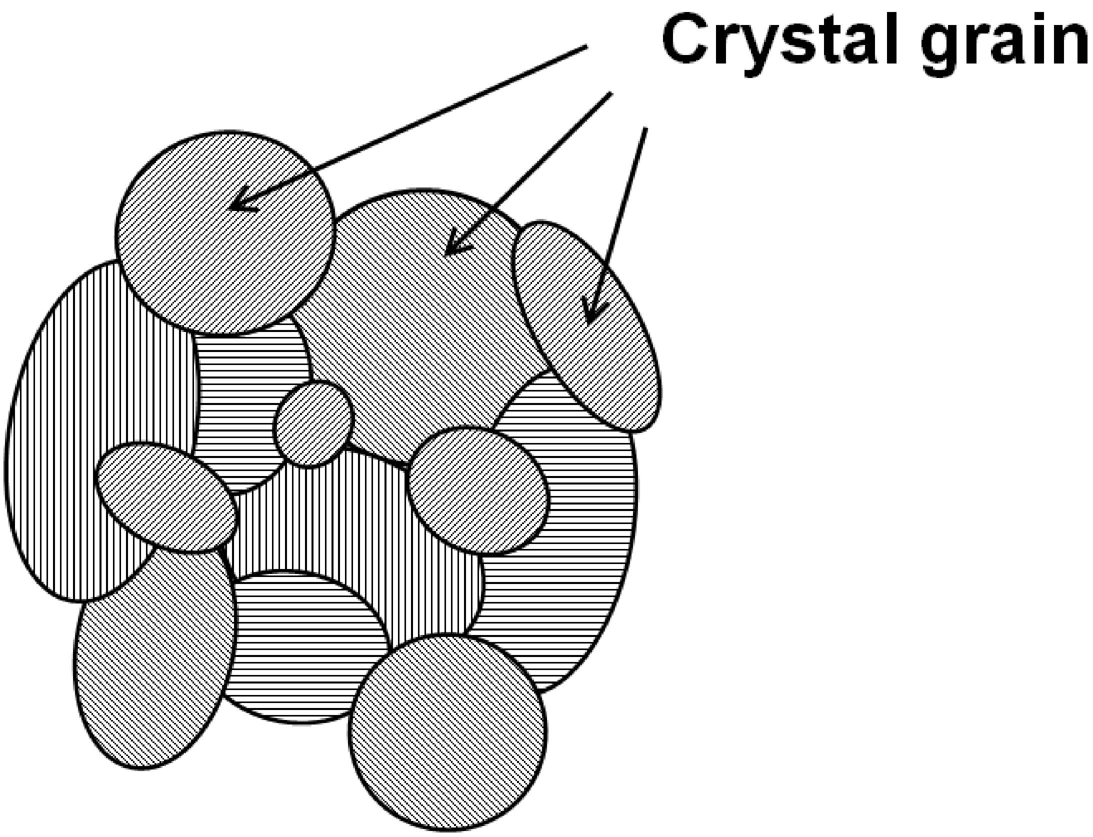


Fig. 3.29: Poly-crystal.

In crystals, the displacement of atoms from the regular position is called the **lattice defect** (**Fig. 3.30**). The defect, where the atomic arrangement is missing, is called the **vacancy**. The defect, where the position is shifted, is called the **dislocation**. The plastic deformation can be considered transfer phenomena of the lattice defects.

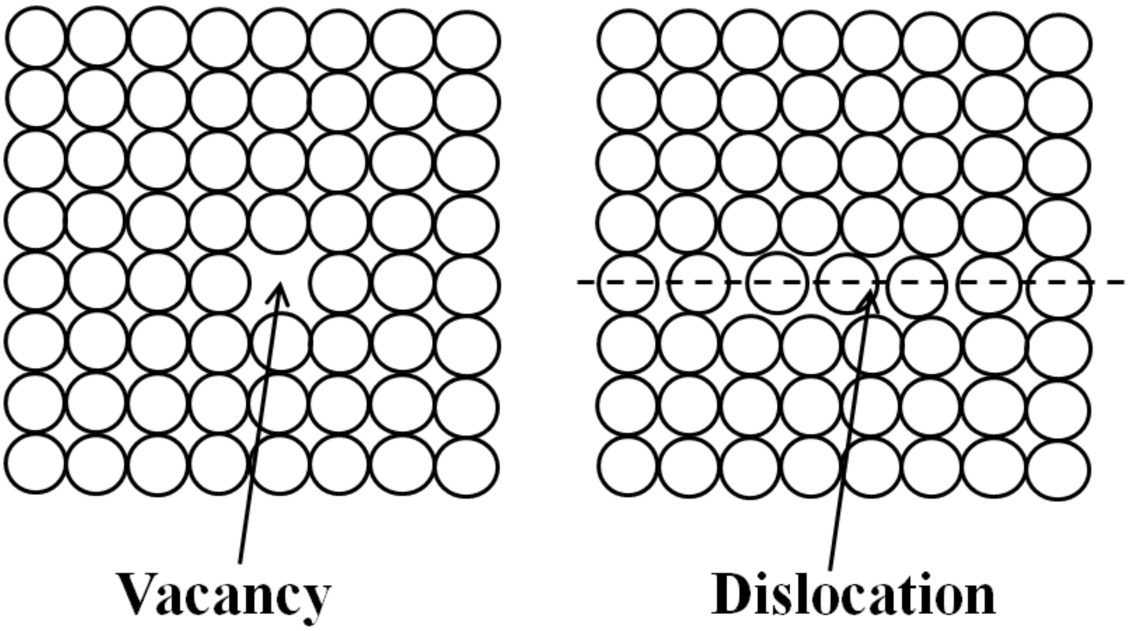


Fig. 3.30: Lattice defect.

Micro **cracks** generates at the point of low strength in the material: the interface between the crystal grains, and the lattice defect. The fracture starts at the crack. The distribution of cracks in the material should be examined to estimate the destruction of the material.

The crack inside of the material can be measured by the reflection of the sound wave (**non-destructive inspection**). The internal structure is measured by the ultrasound, X-rays, and MRI (**magnetic resonance imaging**) *in vivo*.

3.2.3 Stress concentration

When the loaded force and the deformation at the material are not uniform in the material, the distribution of stress is generated. A phenomenon of the partial increase of the stress is called the **stress concentration**. The stress concentration in the material is often generated, where the shape or the property of the material is discontinuous.

The stress concentration occurs at the surface of the small **curvature**. The smaller the curvature of the tip of the crack, the faster the crack progresses. Increase the radius of curvature of the crack tip decelerates the progress of cracks. A **notch** with the adjusted radius of curvature of the tip is provided at the observation position in the breaking strength test of materials (**Fig. 3.31**).

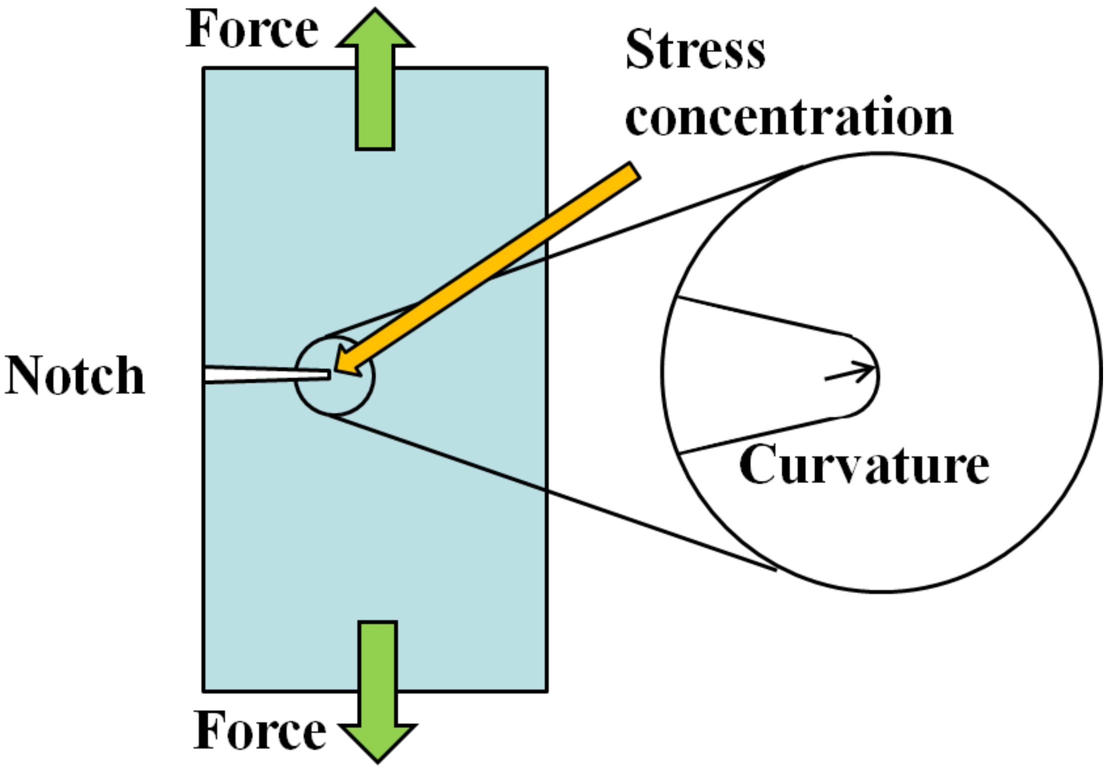


Fig. 3.31: Stress concentration.

The long axis of the cultured cell make orientation, when the repeated extension and contraction is applied to the scaffold. The shear stress by the flow affects the orientation and differentiation of cells. The parallel and perpendicular orientations of cells to the flow direction are observed (**Fig. 3.32**) [16]. The orientation might be adaptation of the cells to minimize the internal mechanical stress.

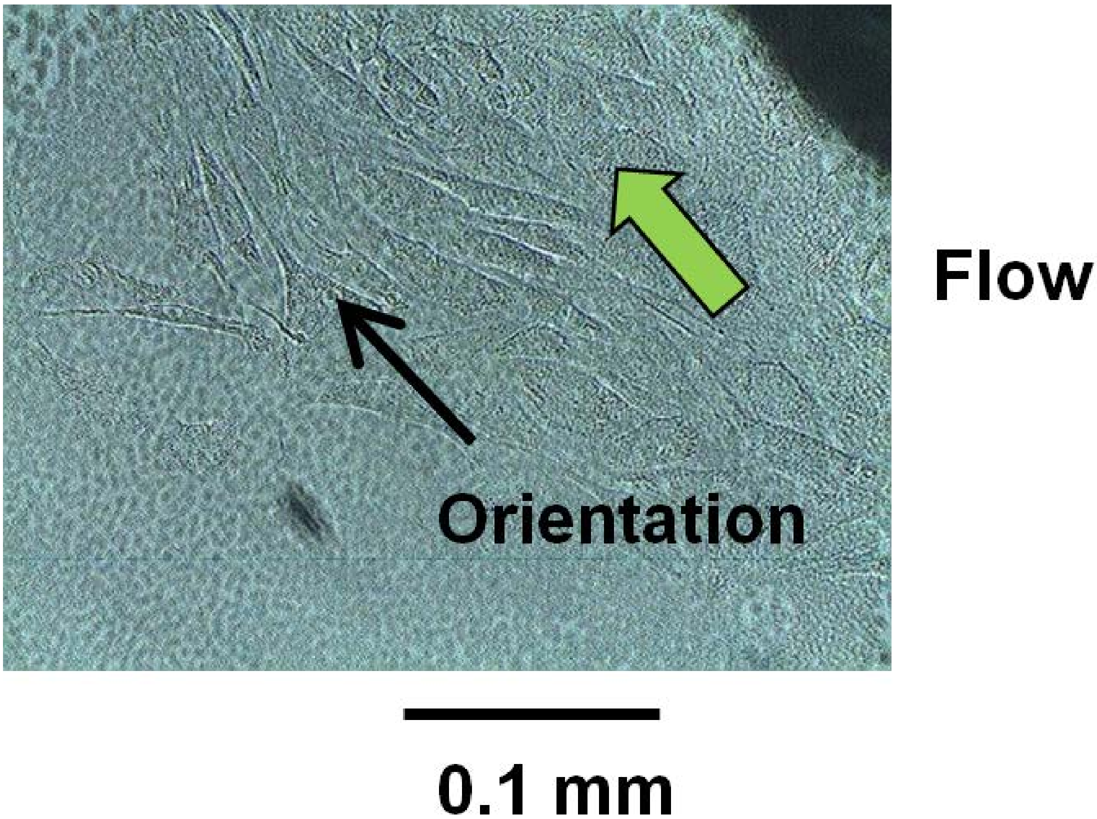


Fig. 3.32(a): Orientation of endothelial cells.

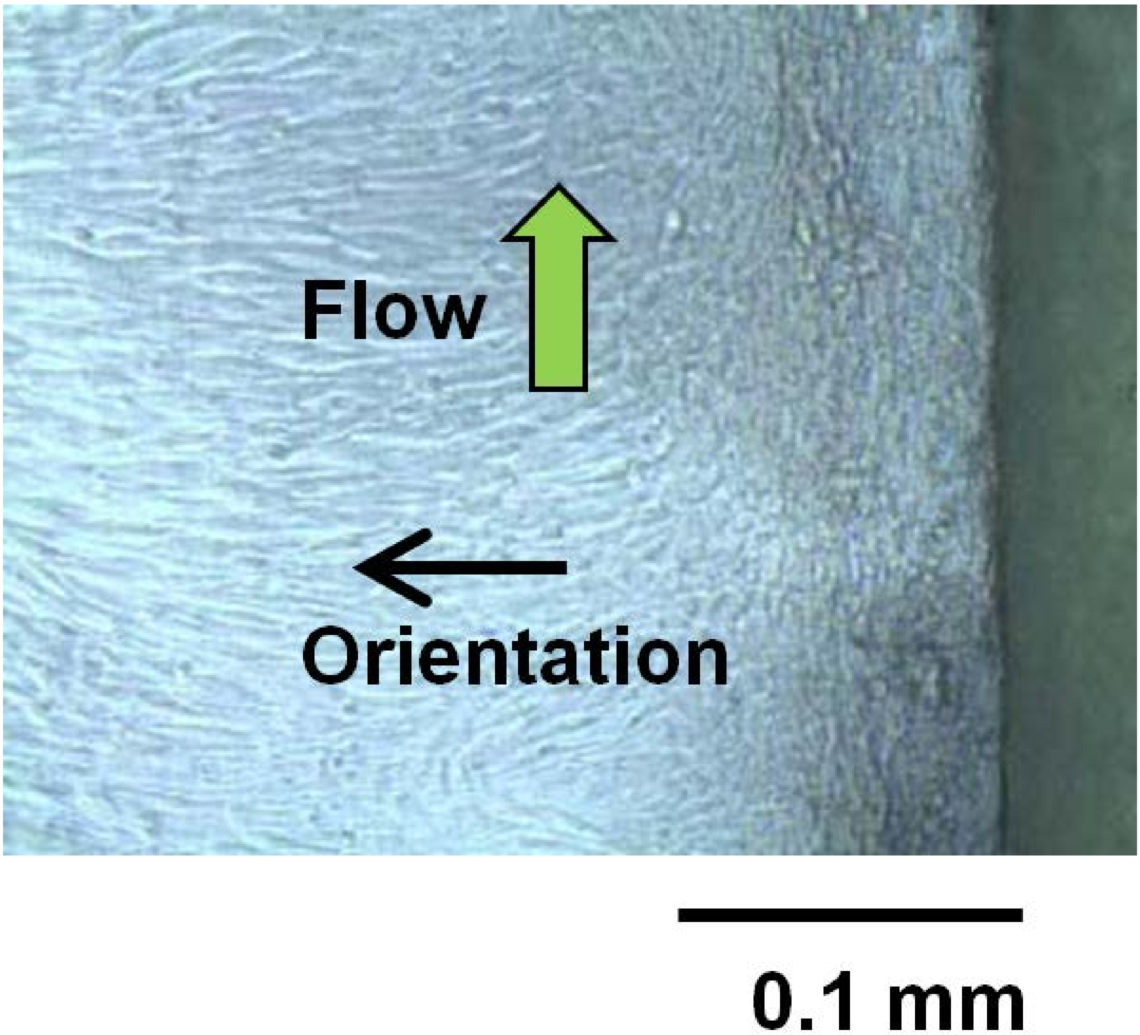


Fig. 3.32(b): Orientation of C2C12.

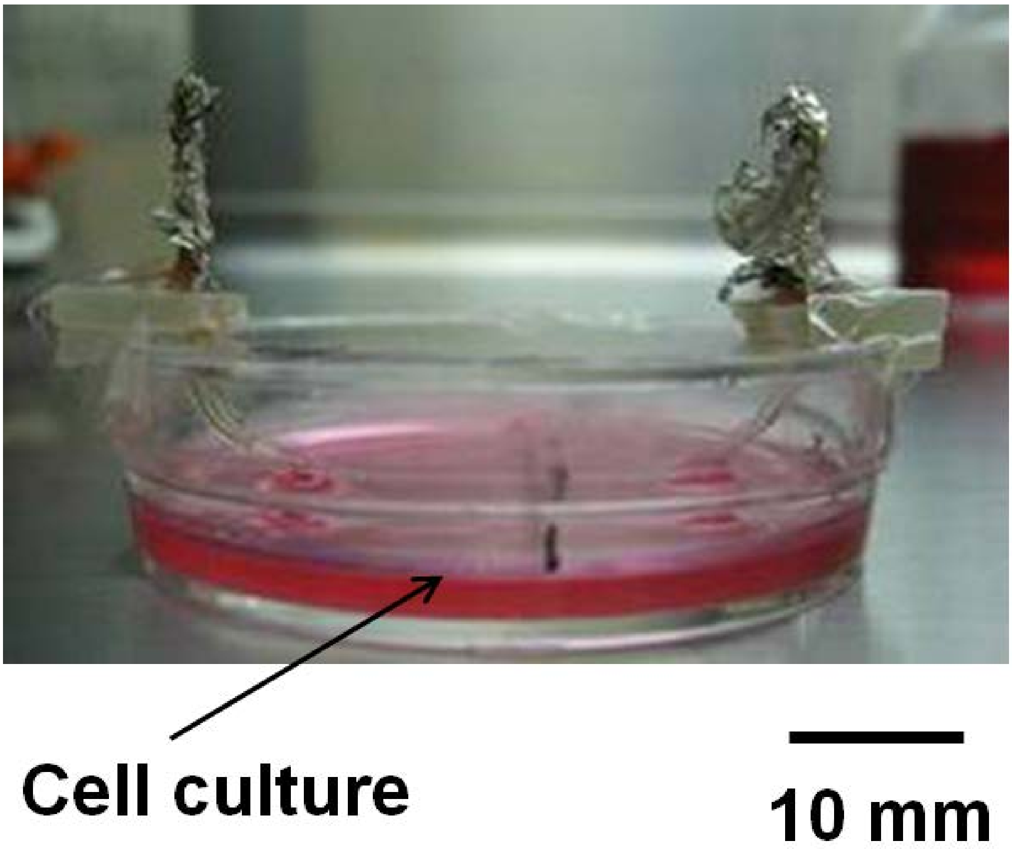


Fig. 3.33: Electrodes.

By the flow stimulation, myoblasts differentiate and fuse to myotubes. Myotubes contracts in synchronization with the pulse, when they are stimulated by electrical pulse with the electrode immersed in the culture medium (**Fig. 3.33**).

3.2.4 Composite material and environment

A material, which consists of various elements, is called **composite material**. The property of the composite material depends not only on the individual element, but also on the interaction between elements.

The biological tissue consists of cells and the extracellular matrix. The extracellular matrix has a large contribution to the deformation of the tissue.

The **cell membrane** is the partition between internal and external sides of the cell. The cell membrane consists of lipid bilayers supported by protein molecules. The membrane can be **resealed** after the fracture, even if the contents are released to the outside. The erythrocyte without contents is called **ghost**.

Without cutting out as a specimen, it is ideal for measurement to apply force to the targeted tissue *in situ*. A **laryngoscope** is a tool, which is used to assist passing the tube for the artificial respirator through the epiglottis. The pressure on the epiglottis, on the tongue, and on the cutting teeth applied by the laryngoscope can be measured with the pressure-sensitive paper pasted on the blade of the laryngoscope (**Fig. 3.34**) [17]. The limit pressure can be determined, to prevent damaging the tissue during intubation.

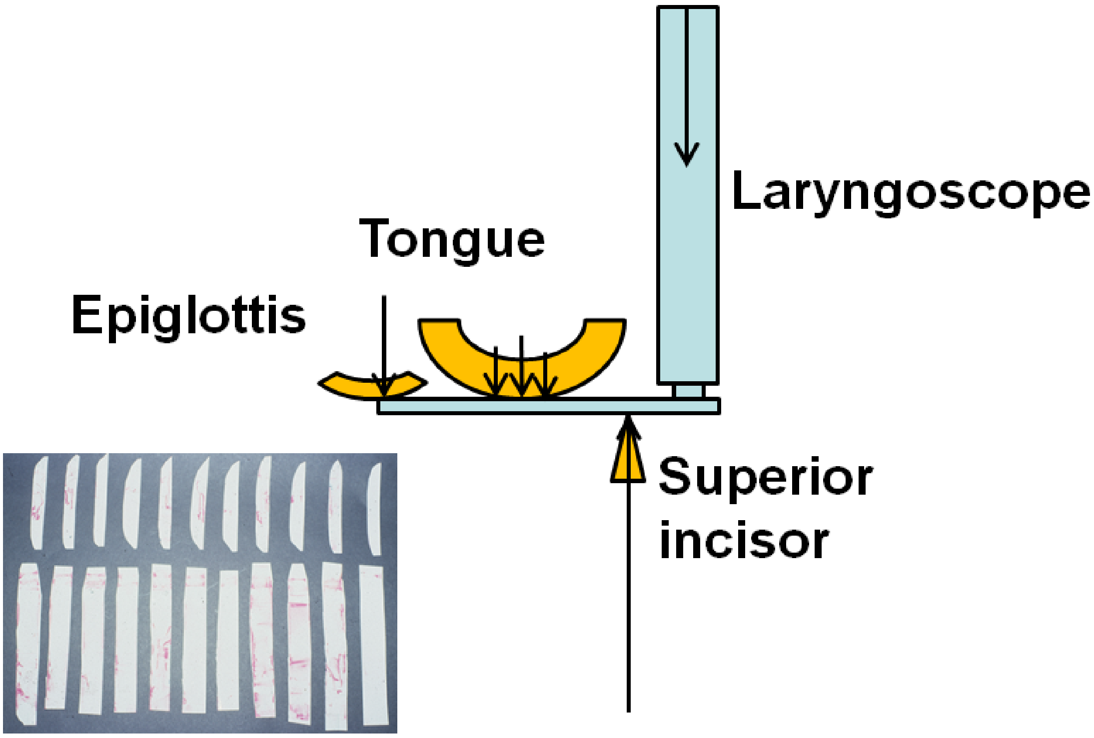
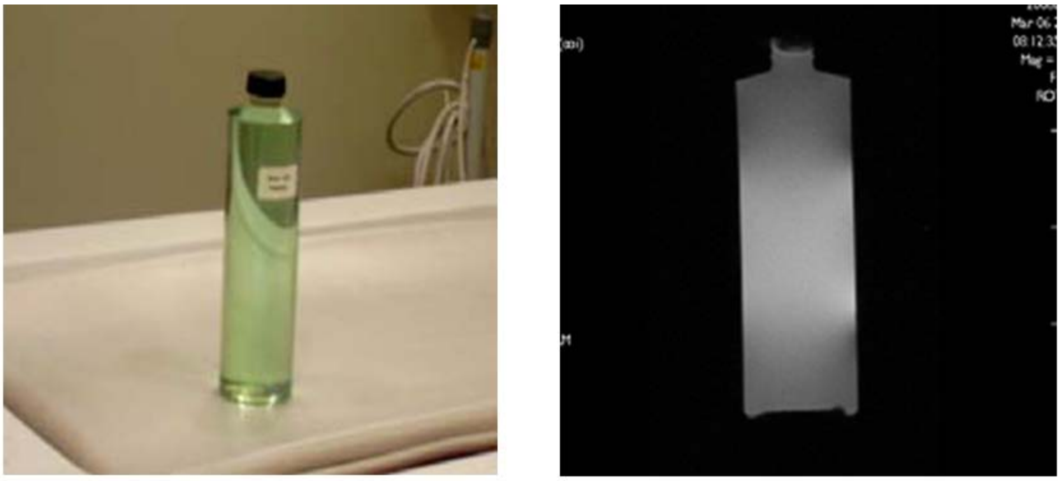


Fig. 3.34: Force applied on laryngoscope.

It is not usually easy to use a part of a living body or a whole living body for the measurement. The material, which imitates property of the living body, is called **phantom**.

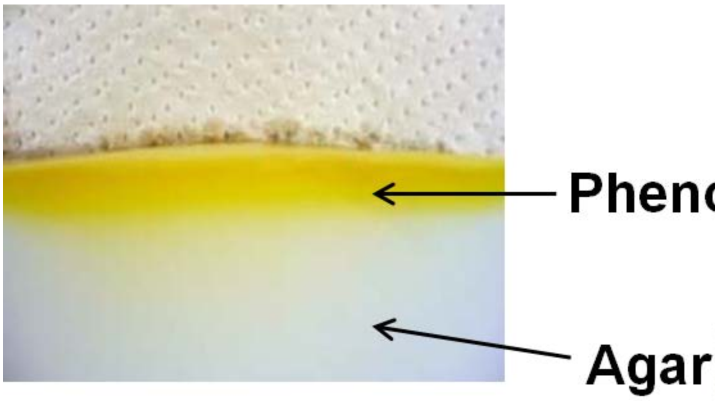
Several kinds of phantoms are available for the properties of a living body: mechanical property, electrical property, magnetic property, and thermal property. The bottle containing a copper sulfate solution is applied to test the homogeneity of the MRI image (**Fig. 3.35**) [18]. The agar is applied to measure the permeability (**Fig. 3.36**) [19].



(a) Copper sulfate aqueous solution

(b) MRI (magnetic resonance image)

Fig. 3.35: Phantom.



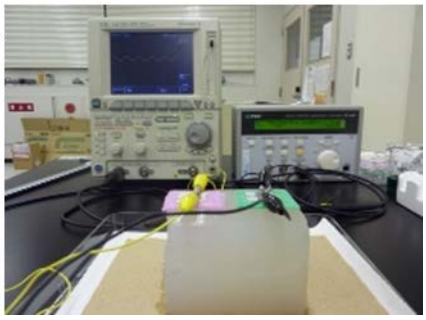


Fig. 3.36: Penetration of phenol-red into agar.

The property of the material is changed by the environment. The environment *in vivo* is as follows. The electrolyte solution containing polymers is filled *in vivo*. The body temperature is maintained, the carbon dioxide partial pressure is high, pH is not 7.0 (neutral). Several phenomena occur at the surface of the material *in vivo*: molecular adsorptions, and chemical reactions. By contact with the blood, several biological reactions occur at the surface: platelet adhesion, and the formation of clots (see 6.2.4).

Several materials are applied for implantation: **stainless steel**, titanium alloys, and ceramics. Stainless steel SUS316L used for the artificial joint includes C 0.03%, Cr 17%, Ni 12%, and Mo % to improve the corrosion resistance.

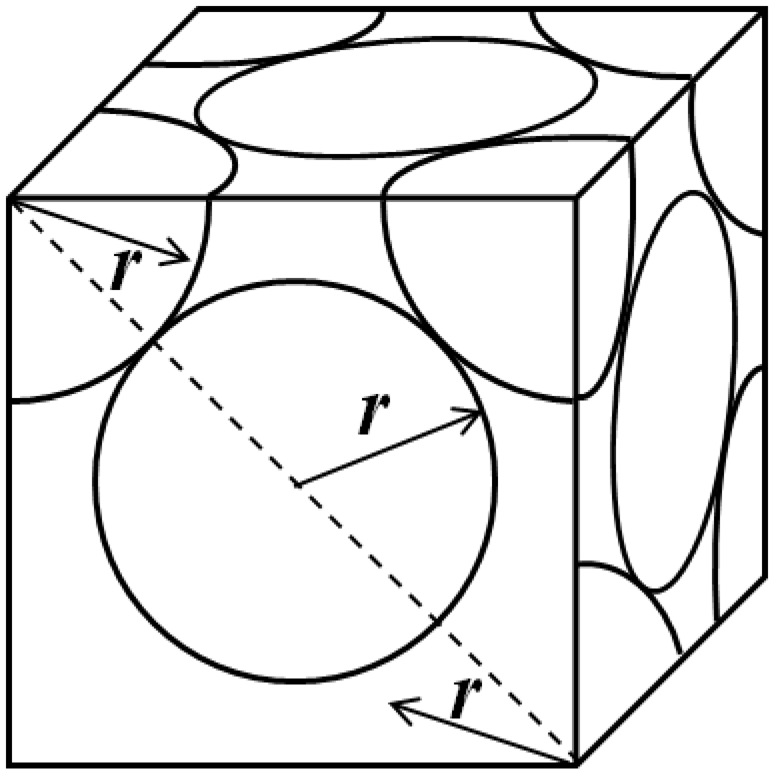
Questions

Q 3.1: List points to be devised, when you get and supply a test piece of the biological tissue for a tensile test.

Q 3.2: Estimate the number of repetitions of the opening and closing of the leaflets of the artificial valve in 10 years to think about the durability of the pivot.

Q 3.3: Find the filling rate, when rigid spheres are closely stacked without a gap in a sequence of the face-centered cubic lattice (**Fig. 3.37**).

Q 3.4: Describe ingenuity in the fracture test of materials, and features of the fracture surface.



Q. 3.3 Fig. 3.37: Face-centered cubic unit lattice.