Chapter 7: Designing and Machining

The shape of the living body is formed and maintained by self-healing and by regeneration, on the base of proliferation of cells *in vivo*. In this chapter, we learn the basic designing and machining including the design of the artificial organs to be applied to the living body.

7.1 Designing

7.1.1 Specifications

In organism, information is retained as a gene in the nucleotide sequence of **deoxyribonucleic acid (DNA)** in the nucleus of the cell. Cells, tissues and organs are formed with proteins synthesized according to the sequence information of the base. The organism adapts to repetitive selection by the surrounding circumstances.

Cells form a tissue as a group of cells with repeating division. **Division** and **proliferation** is controlled by various factors. A cell starts division, stops division, or dies in the interaction with the surrounding cells. For example, a cell stops division, when the cell is surrounded by the neighboring cells. A cell makes apoptosis, when the division number exceeds a certain value. When the control changes, the organization of cells changes. **Cancer** might occur in the similar process.

The behavior of the cell depends on the several factors: the cycle of cell **mitosis**, the number of division, the number of neighboring cells (coordination number) (**Fig. 7.1**) [45]. The relation between factors can be discussed by simulation of formation of the colony of cells.

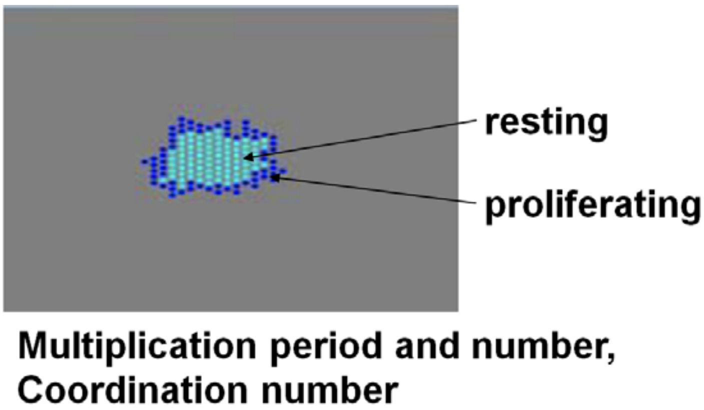

Fig. 7.1: Simulation of cell colony.

The **design** of the machine, on the other hand, is expressed by the **specification**. Functionality and materials are described in the specification. Let us see the case of "a pump to send the liquid". The energy source is selected according to the flow rate and the pressure head. The material is selected according to the type of liquid (cf. corrosive liquid) and the environmental conditions (cf. temperature). The diameter of the connecting line is adjusted to the predetermined size.

The conventional products are available for designing machines. **Japanese Industrial Standards** (JIS), and **International Standards** by **International Organization for Standardization** (ISO) are used for the reference. For example, standardized screws of size, shape and strength are used as the element of the machine.

There are various types in the pump (**Fig. 7.2**). The piston bellows type of pump controls the flow rate by the stroke volume and the beats (Fig. 7.2 (a)). In the centrifugal type of pump, the shape of the impeller is selected in conjunction with the rotational speed of the impeller (Fig. 7.2 (b)). The screw-type of pump controls the flow rate by the rotational speed of the screw (Fig. 7.2 (c), Fig. 6.16 and (b)). The roller pump (see 6.2.3) controls the flow rate by the peripheral speed and the diameter of the tube. In Fig. 7.2, tubes of the inner diameter of 15 mm are connected at the inlet and the outlet.

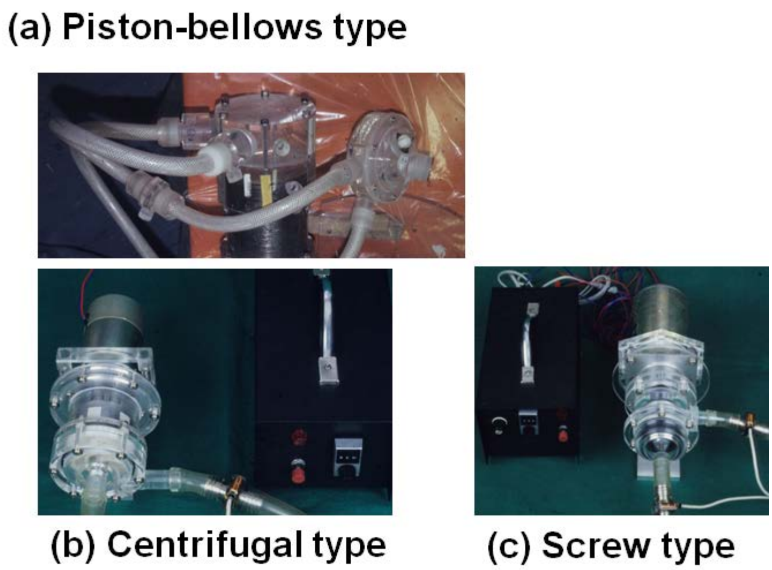

Fig. 7.2: Types of artificial heart.

The **artificial heart** pumps the blood. Pumps are classified into two types: the **positive displacement types** (piston bellows-type, screw-type, etc.) and the **turbo types** (centrifugal type, etc.). The cyclic variation of the rotational speed of the impeller (or the screw) in the turbo type can generate pulsatile flow. The density of the blood is close to that of the water. The viscosity of the blood is several times higher than that of the water. Since the blood includes electrolyte, the blood is classified in corrosive liquids. The **thrombus** formation and the destruction of blood cells should be inhibited.

The **washout effect** may inhibit the growth of clot at the wall shear rate higher than 500 s^{-1} [25]. In the pulsatile flow, the clot growth in the **stagnation** area may be inhibited by keeping the period shorter than 2 seconds, while the wall shear rate is lower than 100 s^{-1} [29]. The erythrocytes destruction decreases at the shear rate periodically below 300 s^{-1} [15] (see Fig. 4.42).

The machine might be used not only for the application limited to the initial design, but also for the application beyond the initial strength limit. To keep the margin of the strength, the design should include several times of the multiplied coefficient called "the **safety factor**". The safety factor would become as small as possible to promote downsizing.

In vivo, homeostasis is maintained by balance between antagonized actions in the range between thresholds. Regeneration and self-repairing maintain the function of the entire system beyond the **threshold**. For example, when the blood vessel is broken, the agent contained in blood or in the vessel walls (platelets and blood coagulation factors) are activated to close the fracture surface, and to repair the vessel wall (see Fig. 6.18 (b)).

7.1.2 Draft

The contents of the design are expressed in the **draft**. The intent of the design should be communicated by the drawings. In the drawings, three-dimensional design is projected onto a two dimensional plane.

The **third angle projection method** is commonly used in the drawings. It consists of a front view, a plan view, and a side view. The front view shows the representative aspects of the solid. A plan view is placed above the front view, as viewed from the top. A side view is placed at the right side of the front view, as viewed from the right (**Fig. 7.3**).

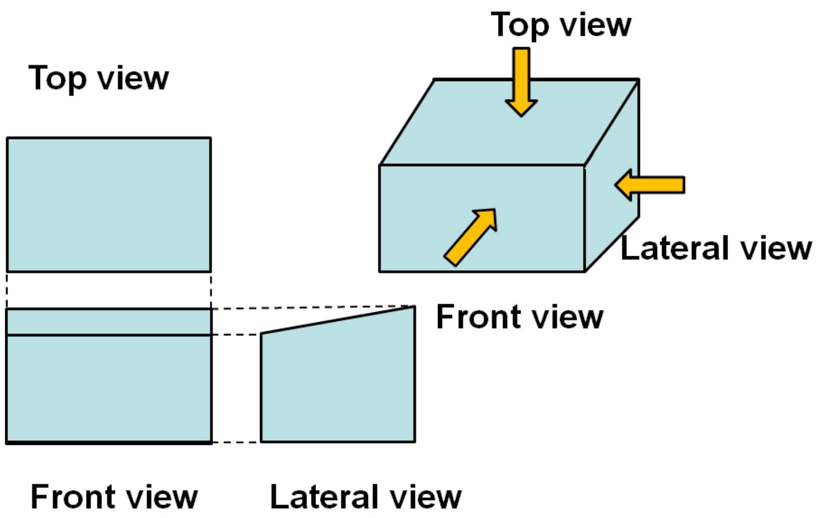

Fig. 7.3: Third angle projection method.

The drawings are drawn with lines. Each type of line has information (**Fig. 7.4**). “Solid line” shows the outline. “Dashed line” shows the symmetry line. “Thin line” introduces the dimension. “Two-dot chain line” is used for hidden lines. Hatching shows the cross section.

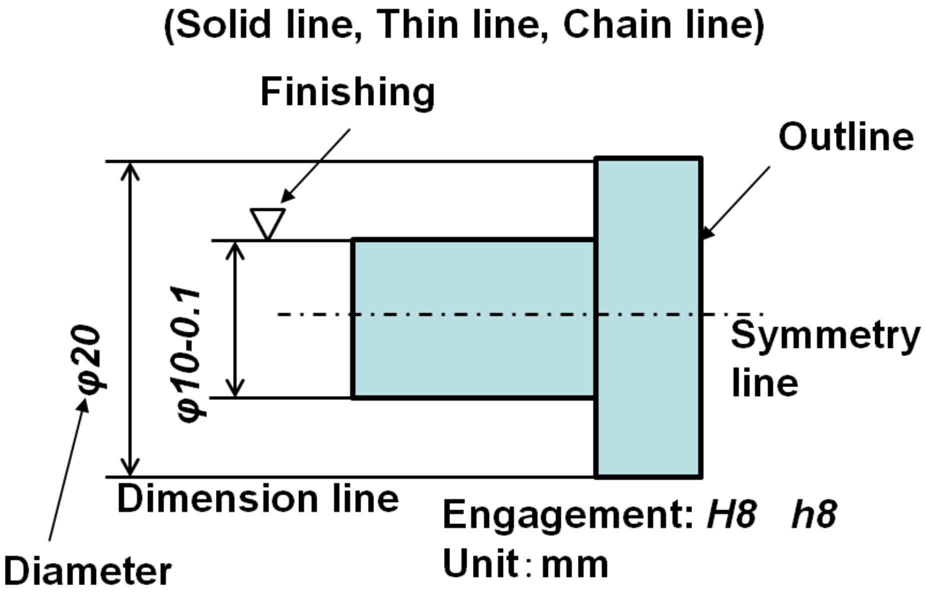

Fig.7.4: Drawing.

The unit of mm is used for the dimension. Several symbols are used in the drawing: *Φ* for the diameter, *R* for the radius, ∠ for the angle, and ∟ or ⊥ for the right angle.

When the dimensional accuracy is required, the notation is used as follows. The range of dimension is displayed. When there is a direction of the range, + or − is displayed with the number. When the dimension has **engagement**, the symbol of *H* is used with the corresponding dimension. For example, the surfaces are processed to fit each other between the bearing and the shaft.

For the accuracy of the finished surface, ▽ symbol is used as ▽, ▽▽, or ▽▽▽. The larger of the number of ▽ shows the smaller surface roughness (see 7.1.3). For fitting symbol, the combination of letters and numbers is used to show the relative dimension, such as “H8 and h8” to the corresponding dimension.

7.1.3 Surface roughness

Minute irregularity of the surface is measured as "**roughness**." The roughness is measured by several methods: tracing the surface with a tip of the needle attached to the lever (**Fig. 7.5**), or using the reflection of light at the surface.

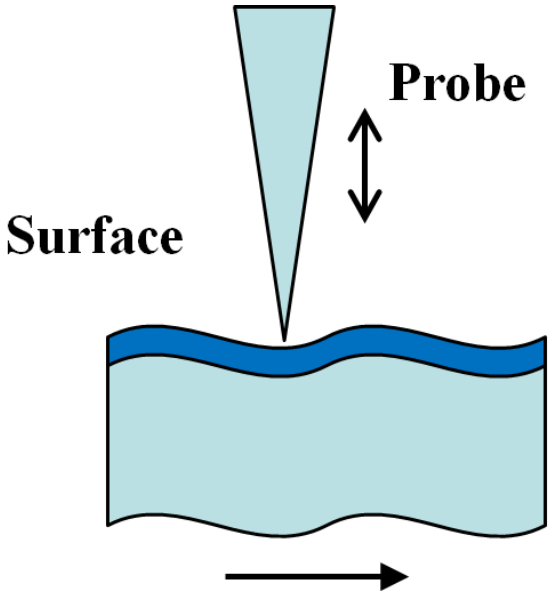

Fig. 7.5: Measurement of roughness.

Most of the finished surface has unevenness at the order of micrometers. The unevenness of a large cycle is called "**waviness**". The surface can be finished with smaller roughness by polishing with the smaller diameter of the abrasive grains.

The roughness is displayed by several parameters: the **arithmetic average roughness** *Ra* (**Fig. 7.6**), the **maximum height** *Ry* (between the peak and the valley) (**Fig. 7.7**), the **ten-point average roughness** *Rz* (**Fig. 7.8**), and the **root mean square roughness** *Rs*. Data of height at the surface are often displayed by the scale enlarged against that of distance to emphasize the surface irregularities. The unevenness along the selected line segment on the surface is displayed in the two-dimensional way in Figs. 7.5-7.7.

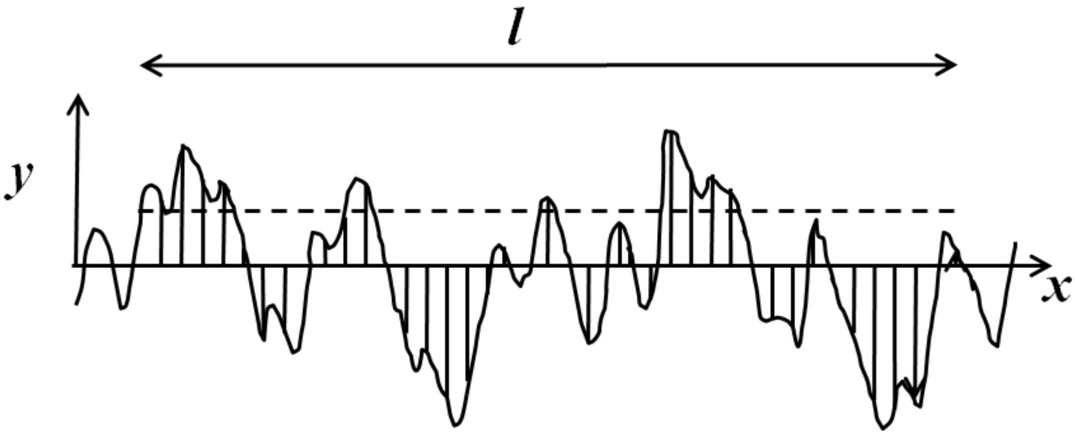

Fig. 7.6: Arithmetic average roughness: *Ra*.

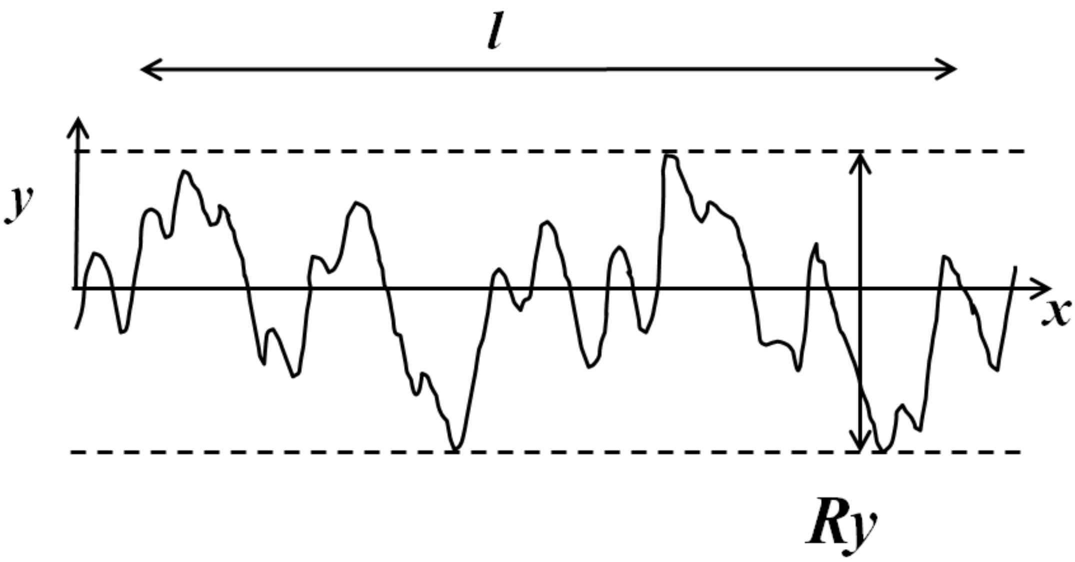

Fig. 7.7: Maximum height: *Ry*.

The arithmetic average roughness *Ra* is calculated as the mean value of the deviation from the averaged surface of the unevenness at the sampled line segment *l*.

$$R_a = \frac{1}{l}\int_0^l |y(x)|\, dx \tag{7.1}$$

The ten-point average roughness *Rz* at the sampled line *l* is calculated as the average value of the difference from the summit to the bottom. The data of the height of the summit and the depth of the valley from the mean plane are used. The sum of the five absolute values of the height (from the maximum to the fifth) and five absolute values of the depth (from the maximum to the fifth) is divided by five.

$$R_z = \frac{|y_1 + y_2 + y_3 + y_4 + y_5| + |y_6 + y_7 + y_8 + y_9 + y_{10}|}{5} \tag{7.2}$$

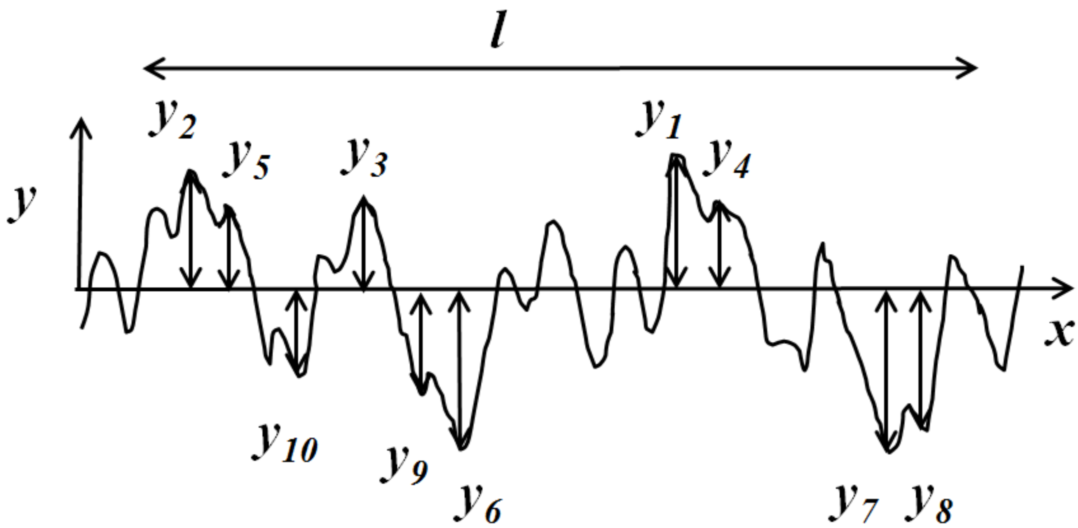

Fig. 7.8: 10-point average roughness: *Rz*.

The mean square roughness (*Rs*) is the root of the average of the squares of deviations (*y*) from the mean surface.

$$R_s = \sqrt{\frac{1}{l}\int_0^l \{y(x)\}^2\, dx} \tag{7.3}$$

Relationship between the roughness of the surface and the wavelength of the light determines the optical properties such as reflection and refraction. The gap between the summit and the valley less than the wavelength of visible light (approximately 1 μm) makes a mirror.

The diameter of the human cells is the order of micrometers. Unevenness of micrometer order at the surface scaffold affects the behavior of the cell.

7.2 Machining

7.2.1 Type of machining

Cells form tissues, organs, and an individual by **mitosis**, **proliferation**, **differentiation**, and **orientation** (see Fig. 4.33). Living body is exposed to the magnetic, the electrical and the mechanical fields. The behavior of the cells is modified by the magnetic [32-34], electrical [35], and mechanical [14, 16, 27] stimulations.

Magnetic, electric, and mechanical fields affect the orientation of the cell. When electrical pulses are applied on cells, the behavior of the cell changes (**Fig. 7.9**): adhesion of cells to the scaffold is controlled, and subsequent differentiation and proliferation of cells are promoted by control of the density of cells [35]. The results of the research would be applied to the tissue technology in the field of regenerative medicine.

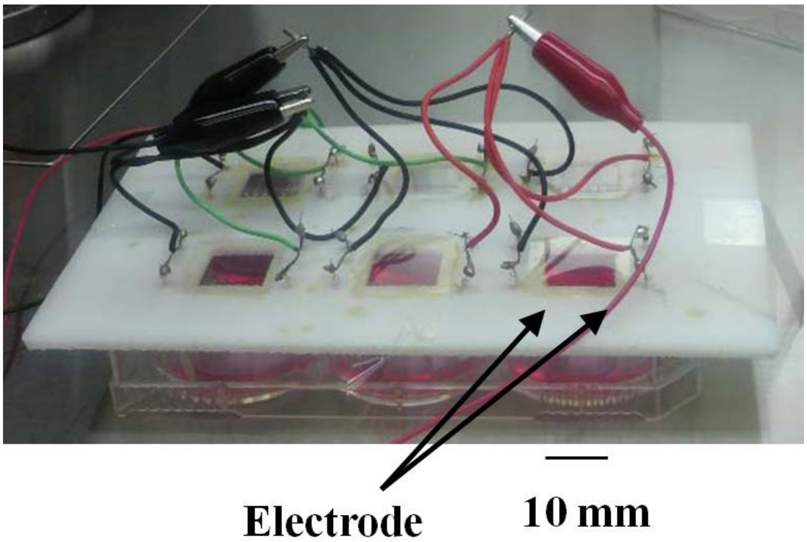

Fig. 7.9: Cell culture with electric stimulation.

At the machine, each part is manufactured by the **machining**. Deformation and destruction of the material is applied in the machining. The machining is categorized into **cutting**, **grinding**, **polishing**, **extrusion**, **melting**, **molding**, **welding**, and **pressure bonding**.

The machine tool includes the **drilling machine**, the **turning machine**, the **milling machine**, the **planar**, and **NC (numerical controlled) machine tool**.

At the spinning, the melted material is squeezed from the die, and cooled. The solvent around the thread is vaporized, or the thread is coagulated in a solvent. At the **electro spinning**, the charged material is jetted to form thin threads by the high voltage. The process is applied to make the scaffold of the cell culture.

At a surgical operation, a part of a living body is cut. Because a rotary saw might catch the soft tissue around the bone, a reciprocating saw is applied to the cutting of the bone (**Fig. 7.10**). The idea comes from the difference in deformation of the workpiece. The bone of the lesser compliance is selectively cut by the reciprocating saw.

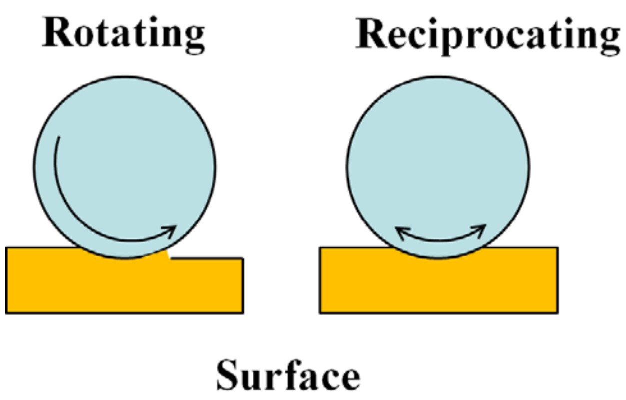

Fig. 7.10: Saw-tooth.

It is not easy to define the machining position *in vivo*. Tomographic imaging techniques such as MRI help positioning. The technology is applied to a three-dimensional display of the end position of the surgical tool, or to recognition of the character of the tissue. Several novel systems are introduced for the training and the planning of surgery.

The image display during surgery is also implemented. The online image helps to confirm the position and to guide the direction during the surgery. The system shows the operative field to multiple surgeons for the surgical training.

The image periodically fluctuates with the respiratory movement of the lung and with the beating movement of the heart. The technique to compensate the position synchronized with the periodic movement realizes the still image. The contrivance assists the vision of the operator.

7.2.2 Finishing and biological reaction

A virgin surface is formed in the material at **cutting** by the blade. The chip side of the blade is called “**rake face**”. The finished surface side of the blade is called "**flank**" (**Fig. 7.11**). Friction between the rake face and the chips affects the cutting force. Friction phenomena at the flank affect the finish of the machined surface. The lubrication by cutting fluids reduces the cutting force, and improves the finish of the surface by stabilizing the cutting conditions. Some lubrications use the chemical reaction at the virgin surface of the cutting. The cutting fluid also has the cooling effect.

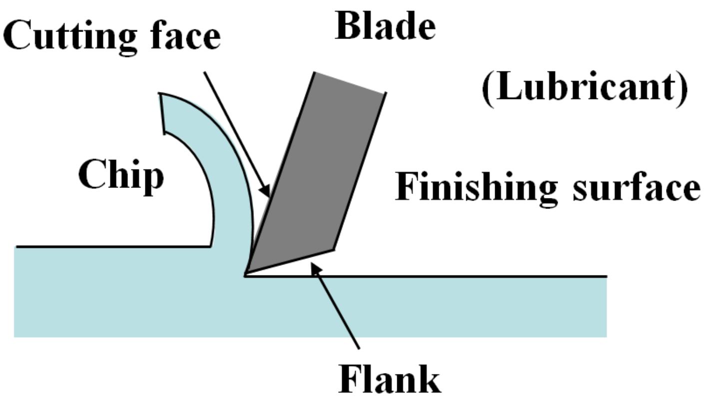

Fig.7.11: Cutting.

In **polishing**, the unevenness of the surface is grinded by the mechanism of abrasive wear.

The machining method is selected according to the finishing accuracy. Structural changes in the vicinity of the material surface at the machining change the mechanical properties near the surface. The plastic deformation at the surface causes “**work hardening”**. "**Quenching**", and "**annealing**" are applied to change the property of the material. Because the surface property of the material is easily varied by machining, temperature should be controlled during the machining.

In the processing using a mold, the **mold release agent** is applied to remove the product from the mold. At the processing of material to be implanted *in vivo*, it is necessary to pay attention to reaction of the living body with the residual release agents besides the original material.

The material of synthetic polymer includes **monomer**. The synthetic polymer has the distribution of molecular weight, because of variations at the degree of polymerization. The component of the small molecular weight (the small dimensions) can dissolved from the bulk material, and has higher reactivity with living body (**Fig. 7.12**). Through dissolution in the physiological fluid, the component may show the toxicity and may cause inflammatory reactions.

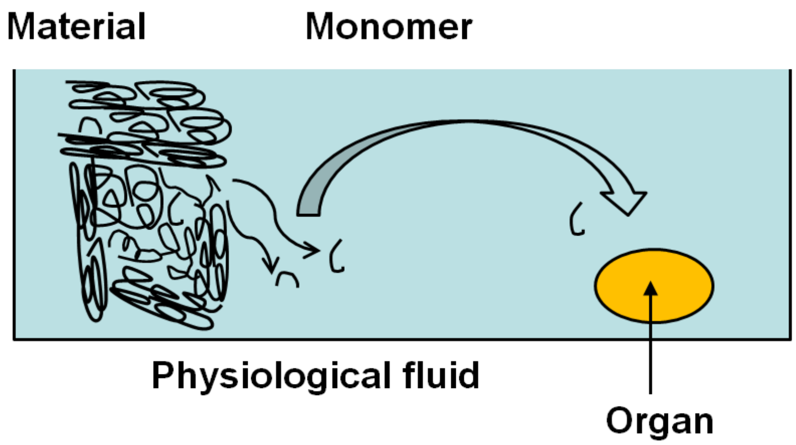

Fig. 7.12: Synthetic polymer in organ.

7.2.3 Assembly

Every part is not formed before assembly *in vivo*. Every adjacent part is formed relatively each other. Several portions incorporate complementarity-redundant variations, which allow modification adapted to the circumstances. While maintaining the diversity, the organism adapts to the surrounding environment.

The damaged vessel wall is clogged and repaired *in vivo* by several steps: adsorption of platelets, and clot formation. Elements for repair are contained in the vessel wall and in the blood (see Fig. 6.18). Does the fluid supply network system contain elements for the repair in the system itself? The blood clotting process also plays roll at the adhesive function between tissues.

The materials of the machine are connected by several ways: chemical reaction, crimping at high pressure, and welding at high temperature. At the prosthetic valve, rupture of the weld between the strut and the valve seat had occurred. Without welding, the durability was improved by cutting from one piece of material.

Fine droplets of the ink are arranged in the ink jet printer. The principle may be applied for the alignment of cells in three dimensions.

A photocurable resin is hardened in a liquid. Through the process, the solid can be formed along the trajectory of the optical path. The technique is called **photolithography**, and is applied to a **micro machining** [48, 49] (**Fig. 7.13**). The technique is suitable to form a model of a micro capillary, which has an internal diameter of 5 μm (**Fig. 7.14**). The technique can be applied to build complex structures in three dimensions by stacking the layers.

In conventional surgical operations, threads have been used for the suture, and the stitches have been removed after fixation of the tissue. When the biodegradable thread is applied, the stitches need not to be removed after operation.

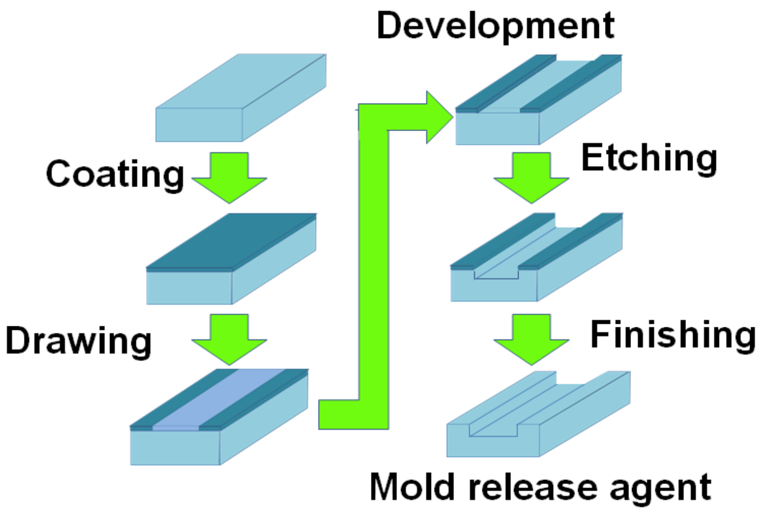

Fig. 7.13: Photolithography.

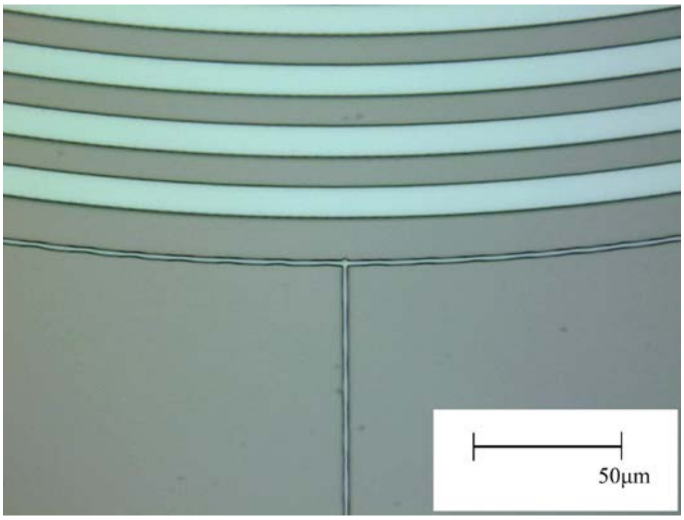

Fig. 7.14: Micro channel.

Questions

Q 7.1: Create a specification of a pump for the left ventricle of human adult.

Q 7.2: Draw cross section of the connector including symmetry axis shown in Fig. 7.15.

Q 7.3: List representative value of surface roughness, and explain each definition of roughness.

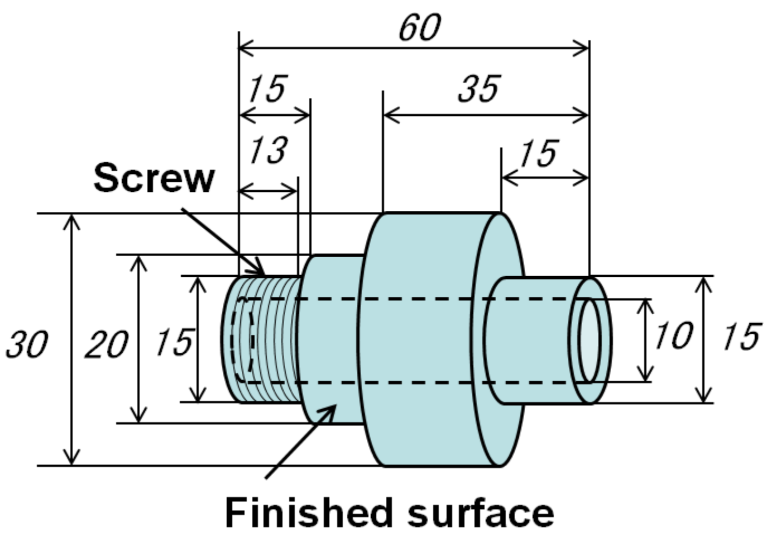

Fig. 7.15: Connector.