Paper

High-output micro-trochoid pump fabricated by a surface treatment technique

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We developed a technique that prevents the leakage of the liquid from a channel and applied it to micro-trochoid pump. When a minute texture is formed on the interior wall of a channel and is coated by a low-surface-energy material that is much thinner than the texture, the wettability of the surface can be greatly reduced. This technique is effective in sealing liquid in a channel. And it can seal the water at a pressure difference of 18.1 kPa in a gap of 5 μm. This seal can then be used in high-output micro-trochoid pump.

Keywords: surface treatment, wettability, fluid seal, micropump, trochoid pump, microfactory

1. Introduction

Microfluid operation devices such as micropumps and microvalves have been developed by many research organizations. These devices are aimed at the miniaturization of analysis apparatus that is widely used for medical or environmental applications (1). Also, in the micromachine project under the Ministry of Trade and Industry, it is specified that high-output microfluid operation devices, such as devices that supply the processing liquid of a micro part, should be reduced in size.

We have already developed a high-output turn-drive-type micro-trochoid oil pump (2)(3). Following on this previous work, the current work developed a surface-treated fluid seal and processing used to seal fluid with a viscosity lower than the oil. And we applied this technique to a micro-trochoid pump.

2. Microfluid operation devices for a microfactory

The microfactory is an ultra-small production factory where microparts are processed and assembled (4). The trial microfactory system under development processes and assembles a micro gear train on a desktop. The electrolysis processing, plating, etching, and washing of the microparts are done in the processing unit of the system. Various processing liquids are therefore used in this unit.

In the basic construction of the microfactory trial system, a microfluid operation device must ensure a processing liquid tub does not interfere with other devices, so the size of the devices must be ϕ 10×30 mm or less. The capacity of the processing liquid tub is 20 to 30 mL. The flow rate of the processing liquid was therefore selected to be over 10 mL/min. The microfactory trial system is a desktop construction. So the lifting power of the processing liquid should be equivalent to 1 m; in other words, the maximum pressure should be 10 kPa. The pH of the processing liquid was selected to be between 1 and 10.

The ideal flow rate Q_{th} of the turn-drive-type micropump used in this study and the leakage quantity ΔQ from the high-pressure region to the low-pressure region are expressed as follows (5).

$$Q_{th} = V \cdot n / 60 \qquad (1)$$

$$\Delta Q = C_{sv} (V \cdot \Delta p / 2\pi \mu) \qquad (2)$$

Here Q_{th} is an ideal flow rate (m^3/s), V is a displacement in every turn of the rotor (m^3), n is a revolution (1/min), ΔQ is a leakage quantity (m^3/s), C_{sv} is a leakage coefficient, Δp is a pressure difference (Pa), and μ is a viscosity of the working fluid (Pa・s). An actual flow rate Q is ideal flow rate Q_{th} minus leakage quantity ΔQ, and it decreases as ΔQ increases. According to Eq. (2), ΔQ increases when the viscosity of operation fluid becomes smaller. So the actual flow rate decreases. On the other hand, a leakage coefficient C_{sv} is influenced by the structure and processing precision of the pump. Therefore, the performance of the pump improves when C_{sv} is smaller. It is possible to make C_{sv} small by using a mechanical seal, but the structure of the micropump becomes more complex and it becomes difficult to manufacture a micropump. So we investigated the possibility of making C_{sv} small by using surface treatment. Leakage of fluid from the opening in a channel was kept low, by using fluorocarbon film to adjust the wettability of fluid on the interior wall of a channel. Microfluid operation devices have been developed by many research organizations, but none of them have tried to seal fluid by modifying surface state of the interior wall of a channel. However, our novel surface treatment can seal fluid with a high pressure in a high-output micro-trochoid pump.

3. Development of surface treatment seal technology

3.1 Low-surface-energy treatment technology Earlier, we developed a surface treatment technique that decreases the wettability of a solid surface (6). This technique is based on the fact that the wettability of a solid depends on the free energy and roughness of a solid surface (7). In this technique, a texture of a specified size is formed on the surface of a solid and is coated by using a material with a low surface-free energy. This technique makes it possible to increase a contact angle. Here, a contact angle θ (a parameter used to evaluate the wettability of an interface between the liquid and the solid) is defined as the angle between the line on the solid surface and the line tangent to the liquid surface at the point where the solid, gas, and liquid come in contact with one another and with the free surface. Using Young's equation, we can calculate a contact angle θ of the surface or the interfacial tension of the solid, gas, and liquid as follows (7).

$$\cos\theta = (\gamma_S - \gamma_i) / \gamma_L \quad \cdots\cdots\cdots\cdots\cdots \quad (3)$$

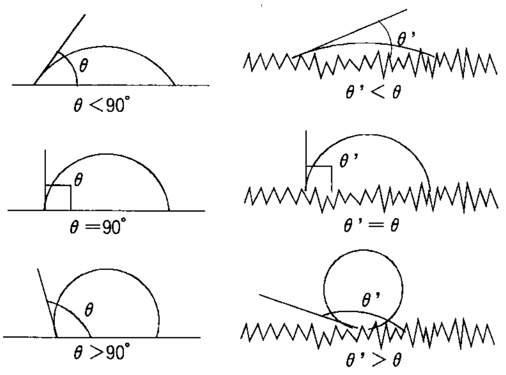
Here, γ_S is a surface tension of a solid, γ_i is a interfacial tension between the solid and the liquid, and γ_L is a surface tension of the liquid. The wettability of a solid on a textured surface, however, is different from that on a flat surface, and an apparent contact angle θ' is calculated by using Wenzel's equation:

$$r \cdot (\gamma_S - \gamma_i) = \gamma_L \cdot \cos\theta'. \quad \cdots\cdots\cdots\cdots \quad (4)$$

Here, r is a roughness factor defined as the surface-area ratio of the textured solid surface to the flat solid surface(7). From Eqs. (3) and (4), we get the following equation:

$$r \cdot \cos\theta = \cos\theta'. \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (5)$$

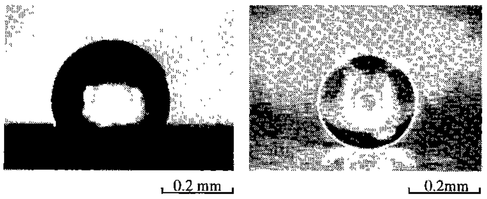
Since $r>1$, Eq (5) gives the apparent contact angle, which is shown in Fig. 1.



(a) flat surface (b) textured surface

Fig. 1 Variation diagram of wettability of a flat and textured surfaces

Figure 2(a) is a photograph of a drop of water on a flat metal surface coated by a fluorocarbon compound, which is a low-surface-energy material. The contact angle is 115° . When the metal surface is textured and coated with the same low-surface-energy material, the drop of water forms the shape as shown in Fig. 2(b). The contact angle is 171° , so it is difficult to wet the surface with water. On the other hand, the contact angle of water on low-surface-energy materials such as polytetrafluoroethylene (PTFE) is about 115° . The terminal base (-CF3) of a fluorocarbon compound is one of the materials with the lowest surface free energy. The arrangement of the base (-CF3) therefore greatly influences the wettability of a liquid.



(a) flat surface
(contact angle: 115°)

(b) textured surface
(contact angle: 171°)

Fig. 2 A drop of water on a surface treated with a low-surface-energy material

The surface treatment process is composed of two steps. The first step is a texturing process. For texturing a metal, especially aluminum, a hydrolysis reaction was used. Aluminum reacts only in boiled water and forms a so-called boehmite structure (AlOOH). Figure 3 shows the boehmite structure of aluminum. A great number of ultra-small protrusions like a needle are formed on the surface of the aluminum. This structure is suitable for our surface treatment. For a material other than aluminum, etching process can be used for texturing. For example, dry-etching of Si gives a textured surface.

The second step is a coating process with a low-surface-energy material. The textured material was dipped in a dispersion liquid of a fluorocarbon compound and baked at a temperature of 150-200℃.

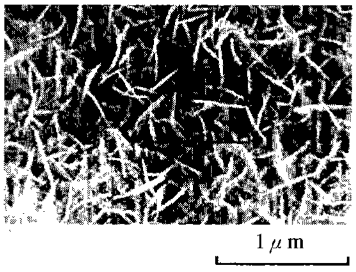


Fig. 3 A textured surface of aluminum

3.2 Applying surface treatment to a fluid seal The surface treatment technique was applied to the seal of a turn-drive-type microfluid operation device (micro-trochoid pump). There is a problem that in a micropump, the fluid leaks from a high-pressure area to a low-pressure area. There is also a problem that the fluid flows through the gap between the shaft and the casing. To solve these problems, we tried to stop the liquid from leaking by treating the surface of the shaft, the rotor, and the casing.

We used an ideal model to analyze the effects of the surface-treated seal. Figure 4 shows a cross-section of the interface of the gas and liquid in the thin tube to which our surface treatment was applied. The bold lines show where the surface treatment was applied. The liquid was sealed at boundary (K), which is between the treated surface and the untreated surface. The balance between the pressure difference and the surface tension of the liquid at boundary (K) is expressed as follows.

$$\Delta P = -4\ \gamma_L \cdot \cos\theta \ / \ d \cdots\cdots\cdots\cdots\cdots \quad (6)$$

Here, γ_L is a surface tension, θ is a contact angle of the liquid, ΔP is a pressure difference between the gas and the liquid, and d is a tube diameter.

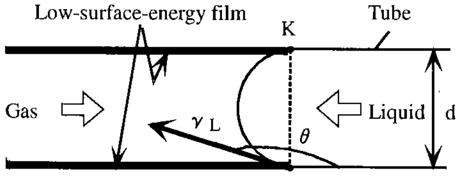


Fig. 4 Model of liquid sealing

The range of conditions under which it is possible to seal the liquid can be obtained from Eq. (6). Figure 5 shows the contact angle vs. the tube diameter. That is, when the pressure difference between the gas and the liquid ΔP is 10 kPa, and the surface tension of water is 72 mN/m, the relationship between the contact angle θ and the tube diameter d is given by Eq. (6). When the low-surface-energy material: tetrafluoroethylene (the contact angle of water is about 115°) was used, it was possible to seal the tube with the diameter of about 10 μm. When the contact angle was 171° , it was possible to seal the tube with the diameter of about 27 μm.

Figure 6 shows the experimental setup used to evaluate the seal. We used thin tubes in our theoretical analysis. However, because the seal area of a micropump has a channel with a depth considerably smaller than the width, we evaluated the effectiveness of the seal by making a shallow groove in the wafer-like test piece to create a microchannel. The pressure difference between the gas and the liquid was estimated by measuring height H of the water level when it moved up and down the water tank.

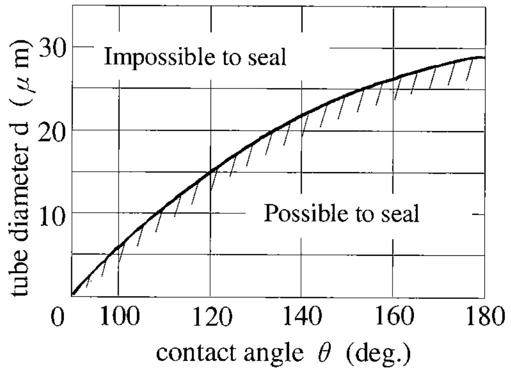


Fig. 5 Seal performance of water

(γ_L = 72 mN/m; ΔP = 10 kPa)

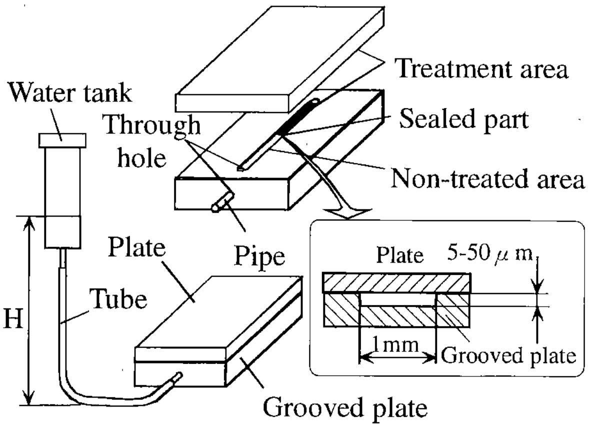


Fig. 6 Experimental setup used to evaluate the seal

The balance between the pressure difference and the surface tension of the liquid at the seal in a rectangular groove is given by;

$$\Delta P \cdot w \cdot t = -2\,(w+t) \cdot \gamma_L \cdot \cos\theta \ \cdots\cdots \quad (7)$$

Here, w is a width and t is a depth of the channel (rectangular groove). In the experimental setup, the section part of the channel had a depth of 5 μm to 50 μm and a width of 1 mm. The channel width was so much larger than the channel depth that Eq. (7) could be approximated as follows.

$$\Delta P = -2\,\gamma_L \cdot \cos\theta \ / \ t \ \cdots\cdots\cdots\cdots\cdots \quad (8)$$

The measured pressure difference vs. the channel depth is shown in Fig. 7 along with the theoretically estimated pressure difference estimated by using Eq. (8). For the contact angle of 171° and the depth of 5 μm, the measured ΔP was 18.1 kPa while the estimated ΔP was 28.4 kPa. According to Eq. (8), this result corresponds to the contact angle of 128° of the sealed part. We suppose this discrepancy is due to disorder of boundary between the treatment area and the non-treated area. Treatment process of test piece has a limitation of forming the restricted treatment area.

It was concluded that it was possible to seal the water when the pressure difference is 18.1 kPa in the surface-treated gap of the depth of 5 μ m in despite of the limitation of treatment process.

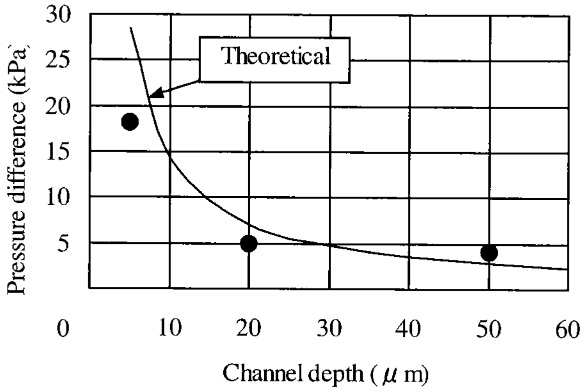


Fig. 7 Measured pressure difference vs. channel depth

4. Experimental production of a surface-treated sealed micro-trochoid pump

We produced some experimental turn-drive-type micro-trochoid pumps that use surface-treated seals. Figure 8 shows the cross-sectional structure of the trial micropump. Trochoid pump is a kind of gear pump. The volume enclosed by rotors, casing, and flange varies by turning rotors and pumps fluid up. The external dimensions of the main body of the micropump are $\phi 7 \times 7.5$ mm, the outside diameter of the outer rotor is $\phi 5$ mm, and the seal gap between the shaft and the casing is 5 μ m or less. The thickness of a low-surface-energy treatment layer is about 1 μ m.

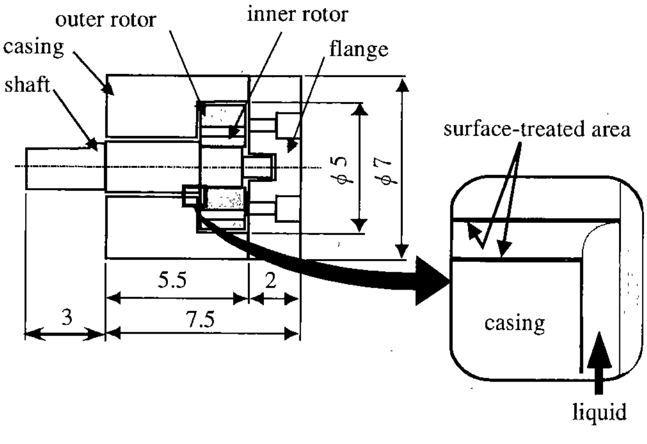


Fig. 8 Cross-sectional structure of the trial micro-trochoid pump

Figure 9 shows an experimental microfluid operation device with a micro-trochoid pump and three miniature valves. The physical size of the device is 20×20×30 mm. This device has a function of selecting and driving the liquid on demands. The micro-trochoid pump were repeatedly machined, by using a high-precision machining (for example, an electro-discharge machining) and measured. After machining, each part was treated with a low-surface-energy material. Then the pump and valves were assembled by hand. Adhesives were used to connect the parts.

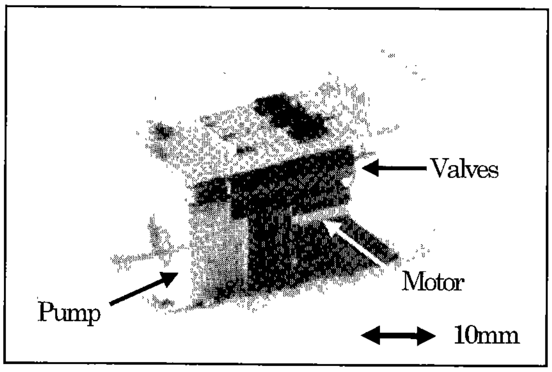


Fig. 9 Experimental microfluid operation device with the micro-trochoid pump

The micro-trochoid pump was connected to the DC core-less motor (maximum output of 0.2 W) with the diameter of 10 mm, and the output characteristics were evaluated by using water as the operation fluid. The micro-trochoid pump was driven at different pressures and flow rates were measured with a messcylinder.

The dependency of flow rates of three sets of trial devices (model 1 to 3) on the pressure difference is shown in Fig. 10. The pressure difference was measured by means of the water head. The maximum flow rate was 40 mL/min or higher. When the surfaces of the shaft and casing were not treated, the fluid leaked out of the pumps. And even when the pumps were operated at a pressure difference of 10 kPa, no water leaked from the pumps, thus confirming that the surface treatment seals work.

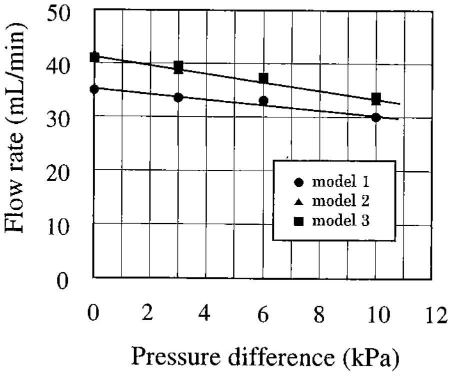


Fig. 10 Dependency of flow rates of the trial devices on pressure difference

5. Summary

Low-surface-energy material was used to surface treatment of the seal of the micro-trochoid pump, and the main results of this treatment are summarized below.

1) When boundary is formed in the channel between the area treated with the low-surface-energy material and the non-treated area, the liquid cannot enter into the treated area. It is therefore possible to seal the liquid in boundary.

2) It is experimentally verified to be able to seal water at a pressure difference of about 18.1 kPa in a channel with a rectangular section of 1-mm width and 5-μm depth by using our surface treatment technique.

3) We made experimental turn-drive-type microfluid operation devices containing micro-trochoid pumps using surface-treated seals, and these provide a high-output operation: a flow rate of 40 mL/min or higher at a pressure difference of 10 kPa.

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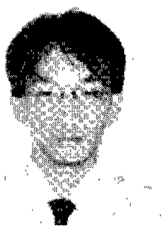

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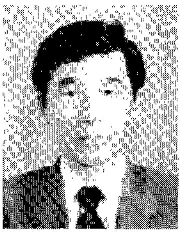

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