Paper:

Water Repellency Control of Oxygen-Free Copper Surface by Diamond-Cut Micro Grooves

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Improving water repellency of a metal surface is required in a wide range of industrial applications. In this study, the water repellency control of an oxygen-free copper surface was attempted by generating micro V grooves on the surface by using ultraprecision cutting technology. The results showed that the maximum contact angle of a water drop on a micro V-grooved surface could be as high as approximately twice that of a flat surface. The contact angle depended strongly on the direction, depth, pitch of the grooves, and burr formation at the edges of the micro grooves. A method for controlling burr formation was proposed.

Keywords: ultraprecision cutting, water repellency, micro-structured surface, micro groove

1. Introduction

The demand for water-repellent surfaces has increased significantly in recent years. By improving the water repellency of a surface, it is harder for water and dirt to stick to the surface. For this reason, water-repellent surfaces are expected to have a wide range of applications for many industrial products. For example, by using water-repellent surfaces in a heat exchanger, the efficiency of thermal exchange and the service life of the exchanger can be greatly improved.

Many previous studies have been conducted on increasing water repellency by modifying a solid surface. A typical method for improving water repellency is surface coating with water-repellent materials [1–3]. However, surface coatings have disadvantages, such as low strength and low durability. Chemical etching is another method for improving surface water repellency by generating micro grooves or micro textures on a solid surface (typically a silicon wafer). A grooved or textured surface is water-repellent because air penetrates into the micro grooves or textures under a water droplet. However, etching a metal surface is challenging because of the low controllability of groove geometry and accuracy. In addition, masks are normally required in etching processes, which increases production costs [4].

In this study, the control of water repellency of an oxygen-free copper surface was attempted by creating micro V grooves on the surface by ultraprecision cutting using a single-crystal diamond tool. The effects of the direction, pitch, and depth of the grooves on the water repellency of the surface were experimentally investigated, and the optimal range of groove geometry was found.

2. Relationship Between Surface Shape and Wettability

It is known that the water repellency, or wettability, of a solid surface varies with the microscopic shape of the surface. If the surface has gentle irregularities, the following equation is satisfied, as was reported very early on by Wenzel [5].

$$\cos\theta_w = r\cos\theta \quad \text{(1)}$$

In the above equation, θ_w is the contact angle when the solid surface has gentle irregularities, θ represents the contact angle on a flat surface, and r is the ratio between the actual area of a surface and the apparent area if considering the surface as flat. This state of wetting is called the Wenzel state (**Fig. 1(a)**).

If a solid surface has sharp irregularities, however, water repellency will be improved. This is because air enters the gap between the water droplet and the solid surface. As formulated by Cassie et al. [6], when a surface is composed of two substances, 1 and 2, the following equation is satisfied.

$$\cos\theta_c = A_1\cos\theta_1 + A_2\cos\theta_2 \quad \text{(2)}$$

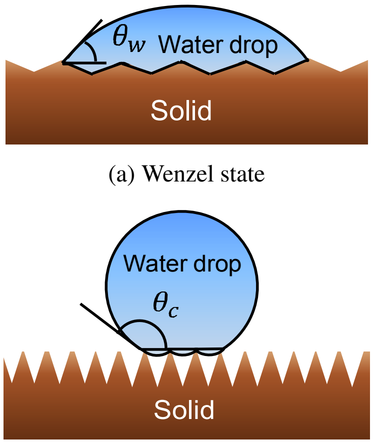
In the above equation, θ_c is the contact angle, and A_1 and A_2 are the area percentages of substances 1 and 2 of the total surface area ($A_1 + A_2 = 1$). θ_1 and θ_2 are the contact angles with the flat surfaces of substances 1 and 2. In this study, substances 1 and 2 are oxygen-free copper and air, respectively. Thus, $\theta_2 = 180°$.

Accordingly, the following equation is satisfied.

$$\cos\theta_c = A_1(1+\cos\theta_1) - 1 \quad \text{(3)}$$

This state is called the Cassie–Baxter state (**Fig. 1(b)**).

In previous studies, the water repellency of textured or grooved non-metal materials, such as plastic and silicon [7–20], has been investigated. However, for metal



(a) Wenzel state

(b) Cassie–Baxter state

Fig. 1. Wetting states of a surface with irregularities.

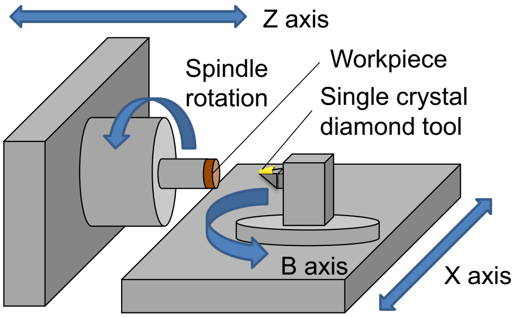


Fig. 2. Schematic of the experimental setup for groove cutting.

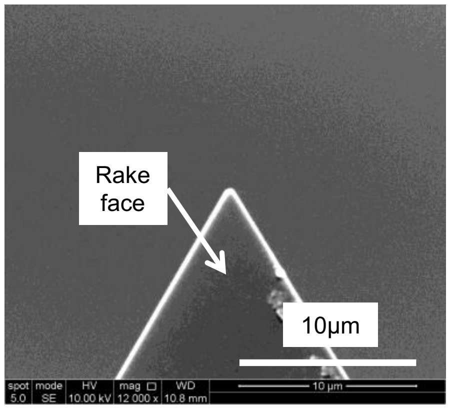
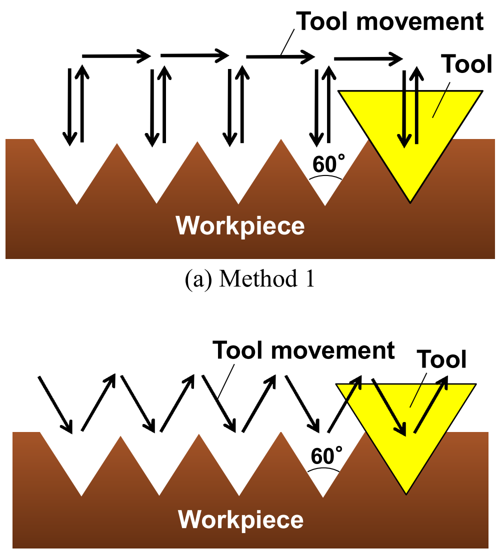


Fig. 3. SEM image of the tip of a single-crystal diamond cutting tool for cutting micro V grooves.



(a) Method 1

(b) Method 2

Fig. 4. Models of two micro groove cutting methods.

materials, such as oxygen-free copper, the relationship between groove shape and surface water repellency has not been clarified. The boundary condition between the Wenzel state and the Cassie–Baxter state has not been found yet [4, 21].

3. Materials and Methods

A 3-axis simultaneous control ultraprecision machine tool, ASP-15, produced by Nachi-Fujikoshi Corp. was used for groove cutting experiments. The schematic of the machine is shown in **Fig. 2**. Oxygen-free copper was used as the workpiece material. The workpiece was rotated by the spindle at a constant rate of 2,000 rpm. The workpiece was face-cut by a round nosed single-crystal diamond tool (nose radius of 0.5 mm) for flattening the surface. Then, a single-crystal diamond tool in the shape of a V (included angle of 60°), as shown in **Fig. 3**, was used to cut micro V grooves. The rake angle of the V tool was 0°, and the relief angle was 4°. Kerosene mist was used as a coolant.

Two methods were used for cutting micro grooves, as schematically shown in **Fig. 4**. In **Fig. 4(a)**, the tool is fed perpendicularly to the workpiece surface, and then removed from the workpiece along the same trajectory in the reverse direction after a groove is finished. In **Fig. 4(b)**, the tool is fed at angle of 60° to the workpiece surface, and then removed from the workpiece at the same angle, but from the other side of the groove. The chip formation mechanisms are different in these two methods; thus, the burr formation behavior during micro groove cutting will also be different.

To evaluate water repellency, a contact angle meter DM 500 (Kyowa Interface Science Co., Ltd) was used, and droplets of distilled water were evaluated. The surface samples were ultrasonically cleaned in anhydrous ethanol 2 hours before testing. A 5-μl water droplet was dripped on the sample surface, a picture of the water droplet was taken from the side directions using a CCD camera, and the contact angle of the water droplet was measured. Five measurements were performed under each condition, and the average value of the contact angle of the five measurements was obtained. The contact angle measurement was done from two side directions, namely, the parallel direction and the perpendicular direction to the grooves.

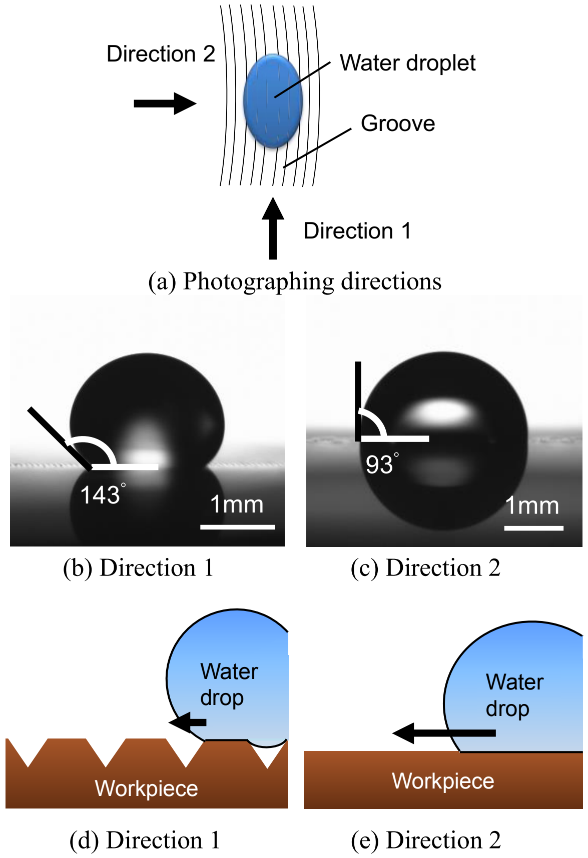


Fig. 5. Relationship between the measurement directions and the contact angles of water droplets, showing anisotropy in water repellency.

4. Results and Discussion

4.1. Effects of Groove Direction on Water Repellency

Figure 5(a) shows a schematic of a water droplet on a micro-grooved surface. The shape of the droplet is not round, but ellipsoidal. **Figs. 5(b)** and **(c)** are micrographs of water droplets observed along the parallel direction (Direction 1) and the perpendicular direction (Direction 2) to the grooves, respectively. The contact angle along Direction 1 is obviously larger than that along Direction 2. The anisotropic phenomenon of surface wettability is presumed to be caused by the difference in the expansion behavior of the water droplet. As shown in **Fig. 5(d)**, in Direction 1, the water droplet expansion is suppressed by the discontinuity of the surface, while in Direction 2, the surface is flat and nothing prevents the expansion of the water droplet allowing it to spread easily, as shown in **Fig. 5(e)**.

4.2. Effects of Groove Depth on Water Repellency

Micro grooves were cut at a constant depth (17 μm), while changing the groove pitch from 25 μm to 505 μm. **Fig. 6** shows micrographs of water droplets observed along Direction 1 and Direction 2 for different groove pitches. **Fig. 7** shows a plot of the contact angle versus

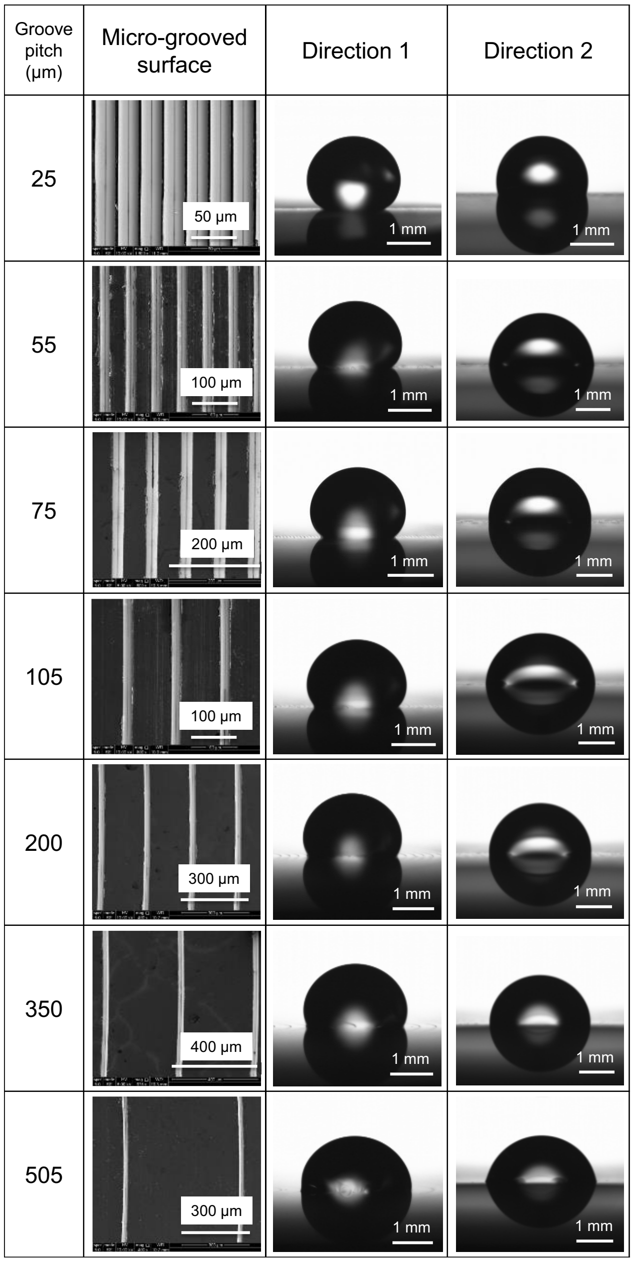


Fig. 6. Micrographs of V grooves cut at different pitches and water droplets on the grooved surfaces.

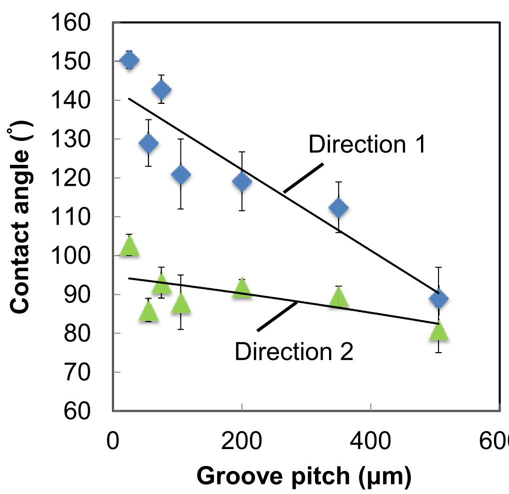


Fig. 7. Change in contact angle with the pitch of grooves.

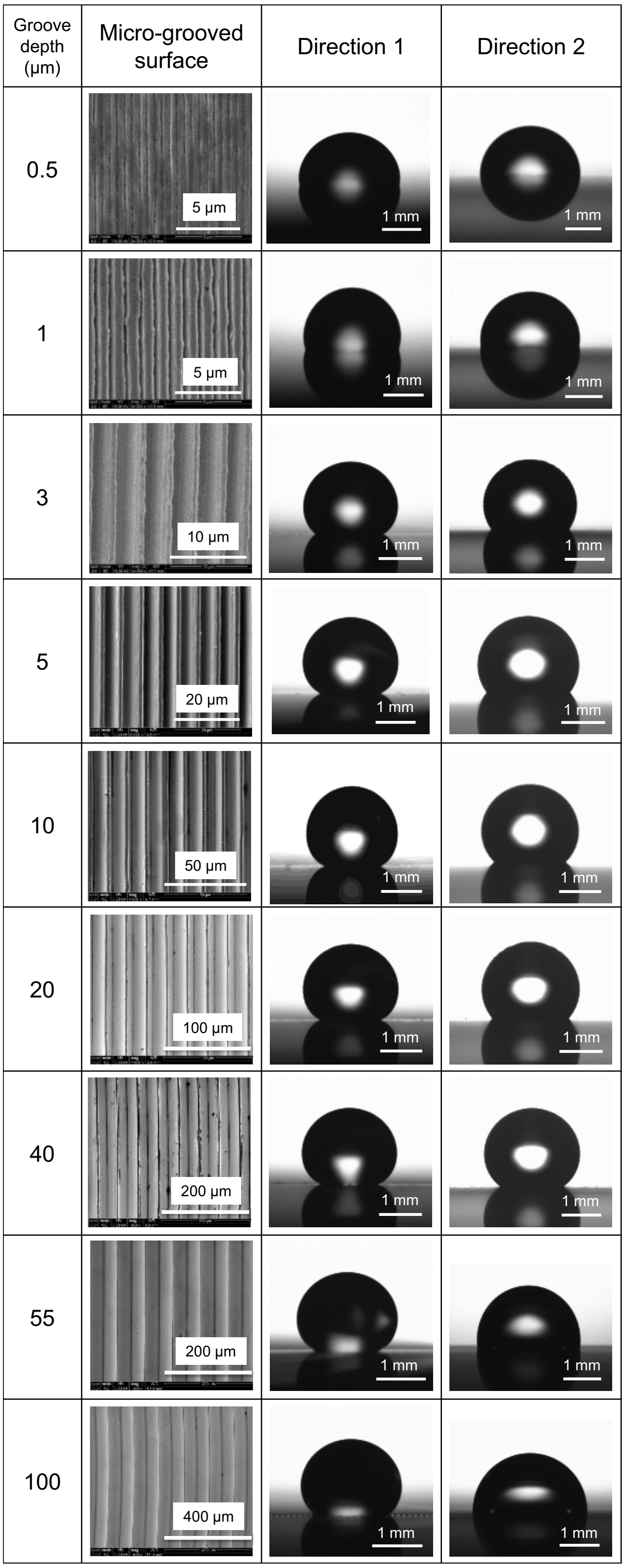


Fig. 8. Micrographs of continuous V grooves cut at different depths and water droplets on the grooved surfaces.

the pitch of grooves. As the groove pitch increases, the contact angle decreases for either Direction 1 or 2. As the groove pitch increases, the number of grooves in a certain surface area decreases. Therefore, the area of contact between the water and the oxygen-free copper increases,

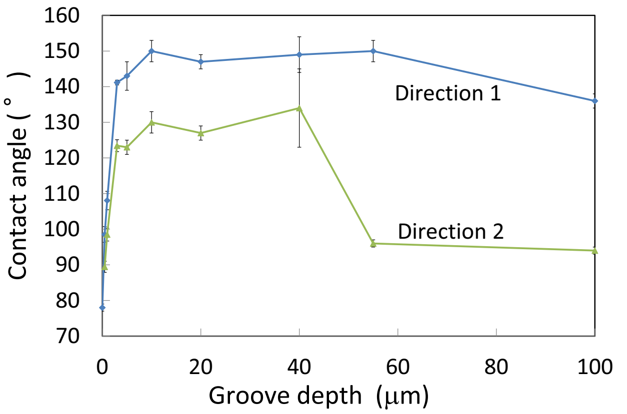


Fig. 9. Change of contact angle with groove depth.

which causes the decrease in contact angle, as can be seen from Eq. (3).

Next, continuous grooves were cut by changing both their widths and the depths. **Fig. 8** shows micrographs of micro grooves cut at various depths, and the water droplets on the grooved surfaces. The change of contact angle with the depth of the grooves is plotted in **Fig. 9**. The contact angle increases significantly as the groove depth increases from 0.5 to 3 μm and increase gradually until 40 μm. Further increases in groove depth over 40 μm cause a decrease of the contact angle.

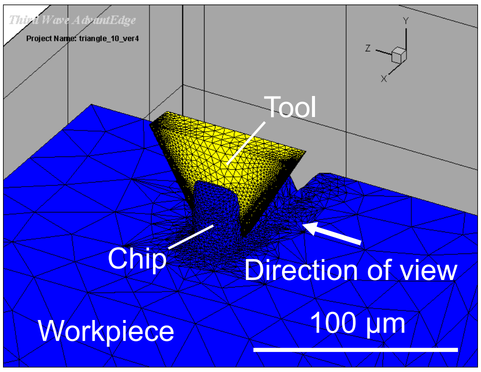
The results in **Fig. 9** indicate that the depth of continuous grooves should be set within a range from 10 μm to 40 μm in order to improve the water repellency of an oxygen-free copper surface.

4.3. Effects of Cutting Conditions on Burr Formation

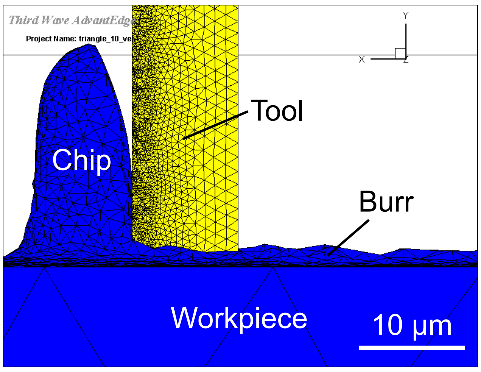
Burrs on the edges of micro grooves might influence the water repellency, but the burr formation mechanism in the cutting of micro V grooves has not been clarified [22]. To investigate the relationship between burr formation and cutting conditions, a finite element method (FEM) simulation program AdvantEdge, produced by Third Wave Systems, was used to simulate the cutting process. **Fig. 10(a)** shows an FEM analysis results for cutting a V groove at a depth of cut of 10 μm. The tool shape used in the simulation was the same as that in the cutting experiments.

Figure 10(b) shows the side view of the same results as shown in **Fig. 10(a)**. From the side view, it can be seen that the maximum height of the burr is 2.2 μm. **Fig. 10(c)** shows the results for the depth of cut of 3 μm. In this case, the maximum height of the burr is 0.8 μm, about one third of that in **Fig. 10(b)**. These results indicate that the size of the burr depends strongly on the depth of cut and that burr formation can be suppressed by using a smaller depth of cut.

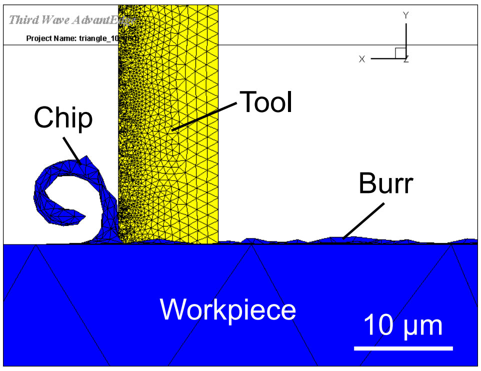
Burr formation also depends on the groove cutting method. **Fig. 11** schematically shows the burr formation behaviors in groove cutting Method 1, shown in **Fig. 4(a)**. Due to the squeezing effects of the cutting tool, significant side burrs will be generated at the groove edges.



(a) Overall view (depth of cut 10 μm)

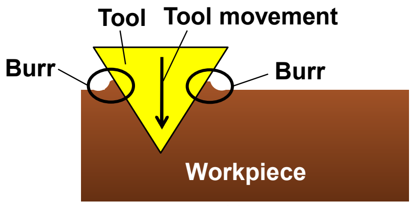


(b) Side view (depth of cut 10 μm)

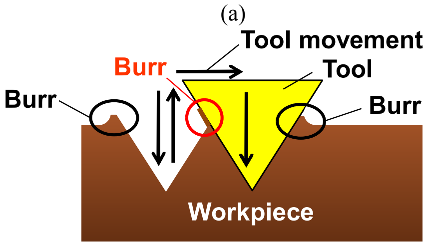


(c) Side view (depth of cut 3 μm)

Fig. 10. Comparison of burr size at different depths of cut in FEM simulation of micro groove cutting.



(a)



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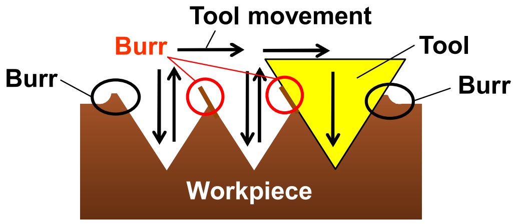
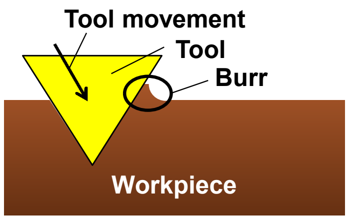
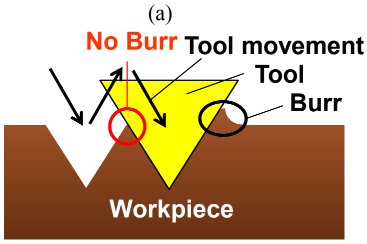


(c)

Fig. 11. Schematic of burr formation behavior in groove cutting Method 1, shown in **Fig. 4(a)**.



(a)



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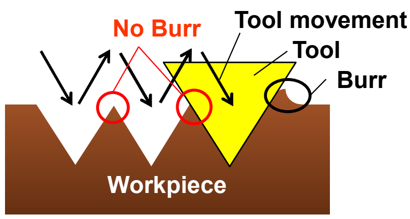


(c)

Fig. 12. Schematic of burr formation behavior in groove cutting Method 2, shown in **Fig. 4(b)**.

These burrs cannot be removed by a subsequent tool pass. **Fig. 12** shows the burr formation behaviors in groove cutting Method 2, shown in **Fig. 4(b)**. In this case, the burrs formed at the groove edge can be removed by a subsequent tool pass, so that no side burrs remain at the groove edges.

4.4. Effects of Burr Formation on Water Repellency

In order to investigate the effects of burrs on water repellency, micro-grooving tests were performed by using Methods 1 and 2 at different depths of cut, 3 μm and 10 μm, respectively. **Fig. 13** shows micrographs of groove cross-sections and water droplets on the surfaces grooved under the different conditions. Results A and C are obtained by Method 1, and results B and D are obtained by Method 2. The depths of the grooves are 3 μm in A and B and 10 μm in C and D.

By comparing the groove cross-sections, it is clear that burr formation is significant in A and C, but insignificant

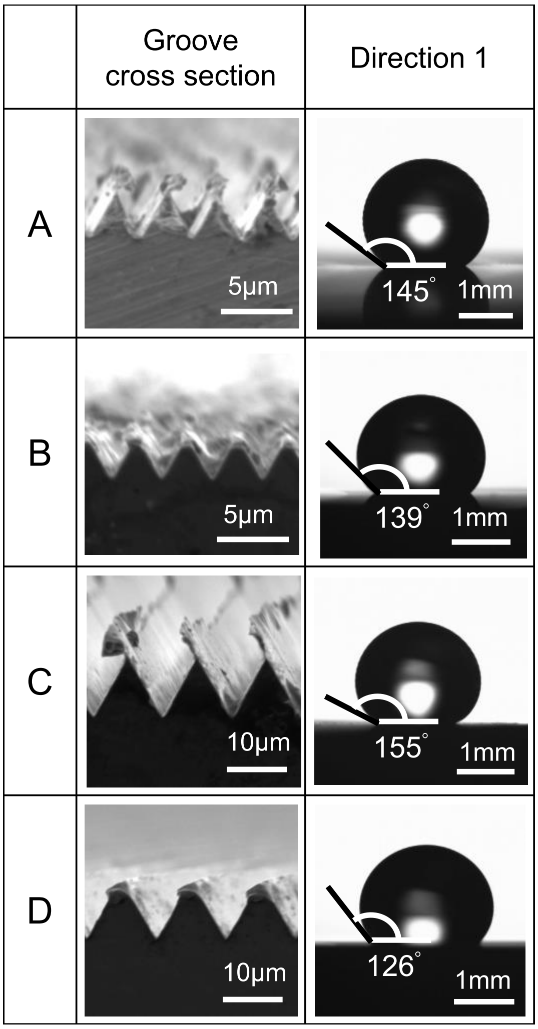
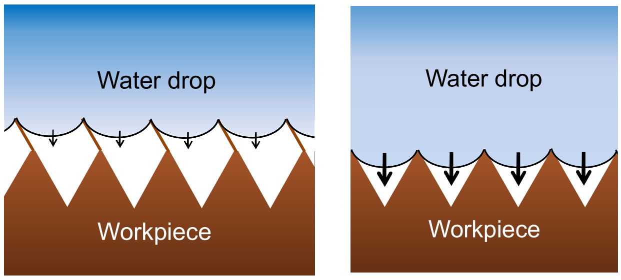


Fig. 13. Micrographs of groove cross-sections and water droplets for different methods of groove cutting, showing the difference in burr formation.



(a) With burrs (b) Without burrs

Fig. 14. Schematic of the change in water repellency caused by burr formation.

in B and D. Among the four conditions, A corresponds to the largest burr formation. These results agree well with those in Section 4.3, indicating that burr formation increases with depth of cut and that Method 2 is effective to suppress burr formation during groove cutting.

In **Fig. 13**, it is also evident that the contact angle of the water droplet increases with burr size. That is to say, burrs can improve water repellency to some extent. It is known that if water enters the micro grooves, the contact angle decreases because of the increase in contact area of the surface and the water droplet [7]. Therefore, burr formation might be able to prevent the water droplet from entering the groove, as schematically shown in **Fig. 14**. By effectively controlling the burr formation, the water repellency of the surface might be further improved.

5. Conclusions

Micro V grooves of various pitch and depth were cut on oxygen-free copper surfaces, and the change in water repellency was investigated. The conclusions can be summarized as follows.

1. Water repellency shows anisotropy. The contact angle of a water drop is higher in the perpendicular direction to the grooves than that in the parallel direction.

2. At a constant groove depth, water repellency decreases as the groove pitch increases.

3. For continuously cut grooves, the contact angle increases sharply with the groove depth when the depth is smaller than 3 μm and decreases when the depth is larger than 40 μm. To improve water repellency, the groove depth should be set from 10 μm to 40 μm.

4. Water repellency may be improved by burr formation. The size of a burr is controllable by using various methods and conditions for groove cutting.

As future work, micro grooves having other kinds of cross-sectional shapes, such as arcs, squares, and sinusoids, will be cut on metal surfaces, and their water repellency will be investigated.

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- Japan Society for Abrasive Technology (JSAT)
- Japan Society for Applied Physics (JSAP)
- American Society for Precision Engineering (ASPE)
- European Society for Precision Engineering and Nanotechnology (euspen)
- International Academy for Production Engineering (CIRP)