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Thermal modulation of the water-induced surface ordering effect for tunable machining performance in copper micro-cutting

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Abstract
The water-induced surface ordering (WISO) effect, *i.e.*, water molecules ordering the surface atoms of copper, has been shown to dramatically reduce the cutting force in micro-cutting of copper. However, its modulation beyond a simple "on-off" state remains unexplored. In this study, experiments are designed to investigate the regulation of WISO by qualitatively controlling the quantity of surface-bound water molecules via thermal means. Orthogonal micro-cutting was conducted on polycrystalline copper under varying depths of cut (doc) and surface temperatures. The experiments reveal that the cutting force reduction ratio (CFRR), defined as the percentage reduction of cutting force in the region with H_2O compared to that without, demonstrates distinct consistency across doc and thermal sensitivity. Specifically, while cutting forces rise with increasing doc, the CFRR stabilizes at 40%-44% within the range of 15 µm–30 µm doc, which confirms that the effectiveness of WISO remains stable within a specific range of doc. In contrast, as surface temperature increases from 20 °C to 80 °C, the CFRR decreases from 70.72% to 57.67%. Since the increase in actual doc caused by thermal expansion plays a negligible role in the CFRR, this decay is mainly attributed to the thermally induced reduction of effective surface-bound water molecules. This is also demonstrated by the reduced difference in surface roughness Sa between regions with and without H_2O at higher surface temperatures, as the Sa in regions with H_2O remains lower than in regions without H_2O. Furthermore, chip morphology changes from short, thick shapes in regions without H_2O to long, thin ones in regions with H_2O. Ultimately, this study reveals that the quantity of surface-bound water molecules is a crucial factor influencing the WISO effect, and modulating it through thermal means shows potential for controlling the machining performance in copper micro-cutting.

Keywords: Water-induced surface ordering; Micro-cutting; Temperature; Copper; Cutting force

1. Introduction

The micro-cutting of metals presents significant challenges to machining performance, particularly in terms of cutting force, surface roughness, and energy consumption, especially for ductile metals such as copper and aluminum, due to their high ductility [1-5]. To address these issues, recent research has focused on the surface effect, which offers a clean and sustainable approach, such as the Rehbinder effect [6, 7]. The Rehbinder effect is defined as the reduction in strength of solids due to the adsorption of surface-active media (SAM), which is widely utilized in the micro-cutting of metals and has recently become a topic of significant research interest. It has been demonstrated that several types of SAM, including ink, glue, carbon tetrachloride, deep eutectic solvents, and water, can affect certain metals, such as iron, nickel alloys, copper, and aluminum alloys, which can significantly reduce the cutting force, improve the surface roughness and change the chip morphology [5, 6, 8-11]. In particular, the water-induced surface ordering (WISO) effect, *i.e.*, water molecules ordering the surface atoms of Cu, has been shown to dramatically improve machining performance in micro-cutting of copper by reducing both the surface energy and fracture toughness of Cu [6].

However, despite the proven effect of WISO, most existing studies have predominantly treated this phenomenon as a binary "on-off" state, simply comparing SAM-coated conditions against non-SAM-coated conditions. The tunability of this effect and the governing factors that modulate its intensity to meet varying processing requirements remain unexplored. Since the WISO effect is triggered by water bound to the surface of Cu, the quantity of surface-bound water molecules is considered the key factor in the WISO effect. Theoretically, elevated temperatures increase the kinetic energy of the water molecules' thermal motion enough to overcome the intermolecular forces, causing them to escape from the liquid surface [12]. Previous research has indicated that below 100 °C, water interacts with copper mainly through physical adsorption, which is highly reversible. As the temperature increases, the quantity of surface-bound water molecules and molecular coverage on flat Cu surfaces decreases, driven by the thermodynamic tendency for thermal desorption [13-15]. Thus, thermal means could be used to control the quantity of surface-bound water molecules during micro-cutting qualitatively, thereby offering a pathway to regulate the WISO intensity during micro-cutting. However, no studies have been conducted to validate this hypothesis.

Therefore, this paper aims to address the aforementioned research gaps in modulating the WISO effect for tunable machining performance in copper micro-cutting. Experiments were designed to investigate the regulation of WISO by qualitatively controlling the quantity of surface-bound water molecules via thermal means, *i.e.*, changing the surface temperature during cutting. Meanwhile, a series of experiments with varying depth of cut (doc) was conducted to investigate the consistency across doc of the effect and to exclude the impact of thermal expansion on the actual doc. The cutting forces, the surface roughness of the machined surfaces, and the chip morphology were observed and analyzed. This study presents a new perspective on understanding the WISO effect, offering a viable method to modulate the cutting force in copper micro-cutting.

2. Experimental Setup

Figure 1(a) illustrates the orthogonal cutting (grooving) process on Cu. The workpiece material used in this study was polycrystalline copper, with dimensions of either (10 × 10 × 10) mm or (15 × 15 × 10) mm. The experiment was conducted on a NanoTech 350FG ultraprecision machining center (UPM), and the experiment setup is shown in Figure 1(b). The Cu workpiece was mounted on the spindle of UPM via an aluminum fixture. The Cu workpiece was trimmed by a single-crystal diamond (SCD) cutter with a 0.509 mm nose radius and a 10° rake angle without using flushing coolant, to minimize the influence of initial surface morphology. After trimming, distilled water was applied to the upper half of the Cu workpiece using a cotton swab at room temperature (~22 ℃). When the water was uniformly coated on the target region, the Cu workpiece was placed in air for 10 min, ensuring the macroscopic evaporation of the bulk liquid water. Subsequently, grooving experiments were conducted using an SCD cutter with a 0.828 mm nose radius and a 0° rake angle, which was placed on a Kistler dynamometer for force measurement with a sampling frequency of 2000 Hz. The cutting parameters for trimming and grooving are listed in Table 1.

Table 1. The parameters for the trimming and grooving process.

Parameter	Trimming	Grooving
Spindle speed/ $r\cdot min^{-1}$	2000	0
Depth of cut / μm	5	1 - 30
Feed rate/ $mm\cdot min^{-1}$	1.5	50
Surface temperature/ ℃	20	20 - 100

For the experiment of grooving at different surface temperatures, an infrared lamp was integrated into the experimental setup to modulate the workpiece surface temperature. Two K-type thermocouples were attached at different positions on the surface of the Cu workpiece, and a TASI TA611B thermometer was used to monitor the surface temperature in real time to cross-check the accuracy of the Cu surface temperature measurement, as shown in Figure 1(c).

After grooving, the chips were collected and observed via a JEOL JSM-5600 scanning electron microscope (SEM). The surface roughness Sa of the groove was measured using an Olympus OLS 5100 laser confocal microscope with an S-filter of 2.5 μm and an L-filter of 250 μm, in accordance with the ISO 25178 standard. The actual doc of the groove was measured using a Taylor Hobson TalySurf Series 2 phase grating interferometer (PGI).

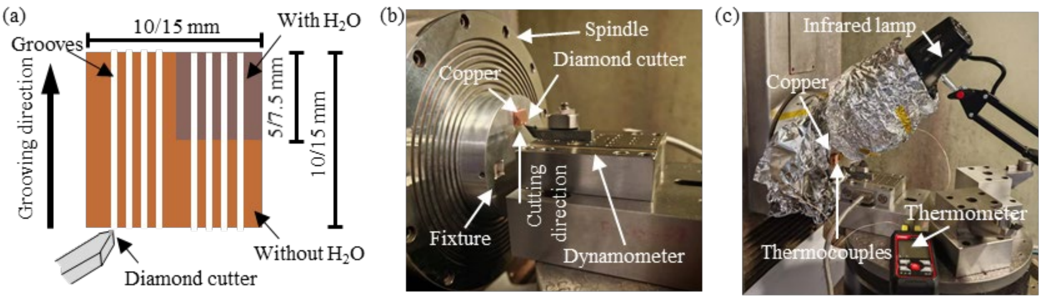

Figure 1. Experimental procedures and equipment. (a) Experimental schematic diagram. (b) Experimental equipment. (c) Infrared heating and temperature measurement device.

3. Results and Discussion

3.1. The influence of depth of cut

The study investigated the influence of different doc, conducted over a range of 2.5 μm, 5 μm, 10 μm, 15 μm, 20 μm, 25 μm, and 30 μm. Figure 2(a) illustrates a typical variation in cutting force with a 15 μm doc, showing that the average maximum cutting force decreases sharply from 9.07 N ± 0.34 N in the region without H_2O to 5.06 N ± 0.18 N in the region with H_2O. To better demonstrate this change in cutting force, the cutting force reduction ratio (CFRR), defined as the percentage reduction in cutting force in the region with H_2O compared to that without it, as shown in Equation (1), was calculated.

$$Cutting\ force\ reduction\ ratio = \left(1 - \frac{Cutting\ force\ in\ the\ region\ with\ H_2O}{Cutting\ force\ in\ the\ region\ without\ H_2O}\right) \times 100\% \quad (1)$$

Figure 2(b) displays the cutting force and CFRR for different doc. For 2.5 μm and 5 μm doc, the cutting force in the region with H_2O was higher than that in the region without H_2O, resulting in a negative CFRR. As the doc increases, the cutting force in both regions increases accordingly, while the CFRR rises and stabilizes at 40%–44% for 15 μm–30 μm doc. It indicates that the effect of WISOs remains consistent within a specific range of doc and demonstrates distinct consistency across doc.

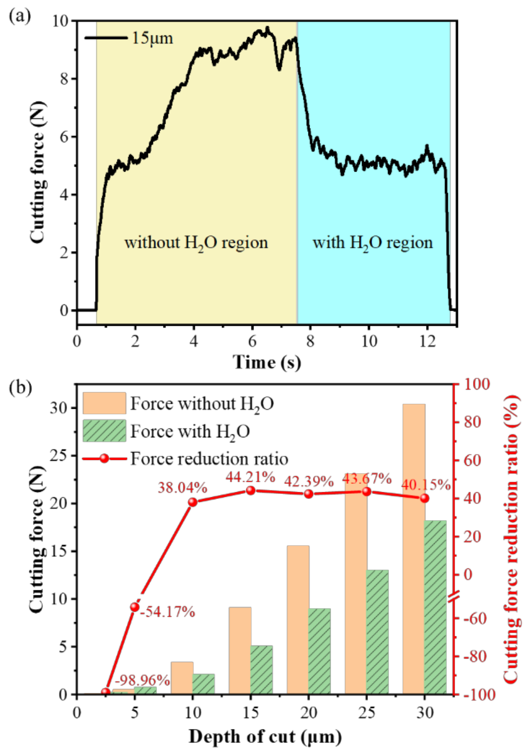

Figure 2. Cutting force and force reduction ratio at different depths of cut. (a) Typical variation of cutting force with a 15 μm depth of cut. (b) Cutting force and force reduction ratio with different depths of cut.

3.2. The influence of surface temperature

The study investigated the influence of surface temperature from 20 °C to 100 °C. Figure 3(a) illustrates a typical variation in cutting force at 20 °C, showing that the average maximum cutting force decreases sharply from 19.62 N ± 0.88 N in the region without H_2O to 5.74 N ± 0.30 N in the region with H_2O, with the CFRR of 70.72% ± 2.01%.

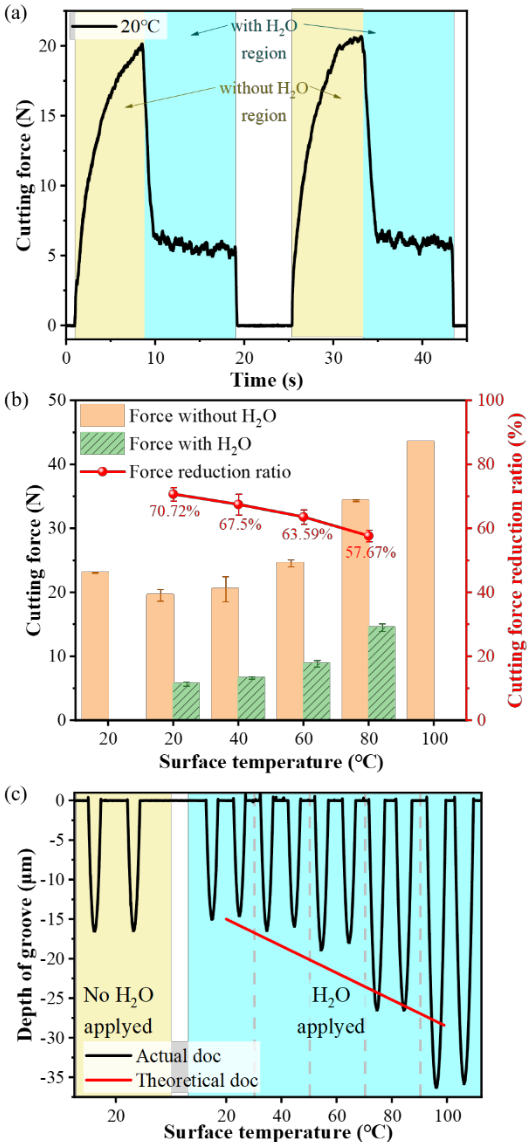

Figure 3. Cutting force and force reduction ratio at different surface temperatures during cutting. (a) Typical variation of cutting force at 20 °C during cutting. (b) Cutting force and force reduction ratio at different surface temperatures during cutting. (c) The measured groove profile after cutting and the theoretical groove depth considering thermal expansion at different surface temperatures.

However, as illustrated in Figure 3(b), the cutting force in both regions increases with rising surface temperature during cutting, while the CFRR exhibits a decreasing trend, from 70.72% at 20 °C to 57.67% at 80 °C. Regarding the condition with a surface temperature of 100 °C, the fixture mounted on the spindle exhibited displacement during the cutting process due to the elevated temperature. This resulted in the grooving process failing to traverse the surface of the Cu workpiece as intended fully. Therefore, only the cutting forces in the initial region without H_2O were thoroughly documented and analyzed, whereas those in the H_2O region could not be precisely determined.

The increase in cutting force is due to the thermal expansion of the Cu workpiece as the temperature increases, leading to a larger actual doc. This is evidenced by measuring the depth of the grooves after cutting via the PGI, as shown in Figure 3(c). Figure 3(c) presents that the actual groove depth is similar to the doc, considering thermal expansion at different surface temperatures (red line). However, the experiment of varying doc has demonstrated that the effect of WISO remains consistent within a specific range of doc, which contains the actual doc under different surface temperatures during cutting. Consequently, the change in the actual doc plays a negligible role in the CFRR, and the decay of the CFRR is attributed to the increasing surface temperature during cutting. Research indicates that below 100 °C, water interacts with copper mainly through physical adsorption, forming an oriented water dipole layer. This process is highly reversible, so increasing temperature decreases the quantity of surface-bound water molecules and molecular coverage on flat Cu surfaces, driven by the thermodynamic tendency for thermal desorption [1, 6, 13-15]. The primary reason for the decrease in CFRR may be the reduction in surface-bound water molecules resulting from the increase in surface temperature. Therefore, the quantity of surface-bound water molecules is a crucial factor influencing the WISO effect, and the temperature changes are just one method to influence this parameter.

This is also evident from the surface roughness Sa between water-coated and uncoated regions at various surface temperatures, as shown in Figure 4. The Sa in both regions increases slightly with higher surface temperature during cutting. Notably, although the surface roughness in regions with H_2O remains lower than in those without H_2O, the difference between the two decreases. This confirms the weakening of the WISO effect at higher surface temperatures due to thermal desorption.

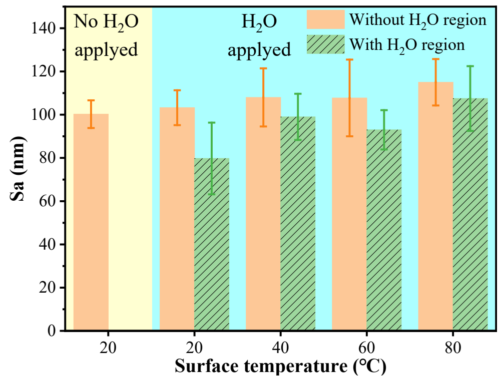

Figure 4. Surface roughness of grooves at different surface temperatures during cutting.

The cutting chips presented in Figure 5 exhibit significant changes in chip morphology with and without H_2O applied before cutting. The chip without H_2O applied is thick, whereas the chip with H_2O is thin, and there are no significant differences in chip morphology at different surface temperatures during cutting, as shown in Figure 5(a)-(c). Magnified views of the chip show that the chip morphology changes from a folded structure in the region without H_2O to a regular layered structure in the region with H_2O, similar to previous studies [1, 6, 13-15]. The reduction in surface energy and strength of solids results in alterations to the surface properties of Cu, which transform the material deformation pattern during micro-cutting, accompanied by an increase in shear angle and a decrease in cutting resistance. Nevertheless, the substantial CFRR, the lower surface roughness in the region with H_2O, and the observed changes in the chip all indicate that WISO enhances machining performance in copper micro-cutting.

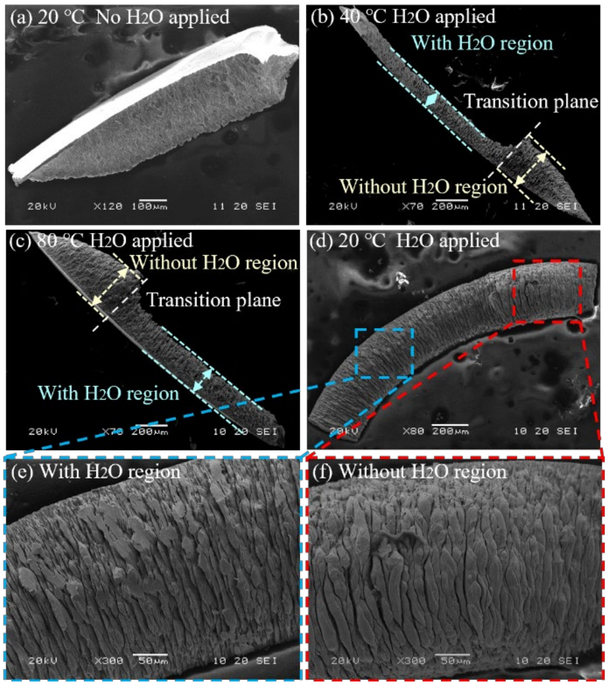

Figure 5. Chip morphology at different surface temperatures during cutting. (a)-(c) Chip morphology of grooves during cutting at 20 °C without H_2O applied, and at 40 °C and 80 °C with H_2O applied, respectively. (d)-(f) Chip morphology and magnified views of a groove during cutting at 20 °C with H_2O applied, respectively.

4. Conclusion

In this study, the regulation of WISO is achieved by qualitatively controlling the quantity of surface-bound water molecules via thermal means. The stable CFRR within the range of 15 μm–30 μm confirms that the effectiveness of WISO remains stable within a specific range of doc. Consequently, the increase in actual doc caused by thermal expansion plays a negligible role in the CFRR of cutting under varying surface temperatures. The CFRR decreases from 70.72% to 57.67% as the surface temperature increases from 20 °C to 80 °C, primarily due to the thermally induced reduction of effective surface-bound water molecules. This is also evident in the surface roughness of grooves at varying surface temperatures during cutting. The difference in surface roughness between regions with and without H_2O decreases, thereby confirming the weakening of the WISO effect at higher surface temperatures. Nevertheless, the surface roughness in regions with H_2O remains lower than in those without H_2O. Furthermore, an analysis of chip morphology reveals a transition from short, thick shapes in regions without H_2O to long, thin shapes in regions with H_2O. The substantial CFRR, the lower surface roughness in the region with H_2O, and the observed changes in the chip all indicate that WISO enhances machining performance in copper micro-cutting. Future work should aim to generalize these findings by investigating the WISO mechanism on a broader range of workpiece materials and exploring alternative modulation strategies beyond thermal control to further advance the capability of surface-active media in precision manufacturing.

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