Combined lubrication of surface texturing and copper covering for broaching tool

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Abstract
Broaching is widely used in the aerospace field owing to its high efficiency and heavy load. However, heavy-load cutting causes intense squeezing and friction in the tool-chip contact area, resulting in a lack of lubrication. Therefore, three textures (i.e., micro-pit, stripe, mesh) are prepared on the rake face of broaching tool with a laser processing technique to improve cutting performance. Afterward, textures are covered with copper using the reciprocating rotational friction to enhance the wettability and heat dissipation capacity of the broaching tool. Experiments approve that striped textures covered with copper reduce the cutting force by 14.6% and the cutting temperature decreases from 90.13 to 76.9 °C, compared with non-textured cutting teeth. Obtained results indicate that the wettability of cutting fluid on the tool surface is significantly improved due to the capillary force of micro-pores generated by the copper covering, especially in the direction to the cutting edge. Furthermore, the copper debris absorbs heat quickly in the cutting areas and is subsequently taken away by chips and cutting fluids, thereby reducing the cutting temperature.

Keywords Textured tool · Copper covering · Chip thickness · Curling radius · Broaching

1 Introduction
Broaching tool has multiple rows of teeth for roughing, semi-finishing, and finishing, respectively, and is frequently used in mass production owing to high efficiency [1]. However, due to the heavy load, strong friction, and extrusion occur between tool and workpiece during the cutting process, reducing the service life of tool as well as the surface quality and machining accuracy of the workpiece [2]. To modify the frictional aspect at the tool-chip interface, cutting fluid [3] and surface texture technology [4] are introduced to augment cutting performance. However, broaching is a closely teethed cutting process, and the cutting fluid cannot be sprayed directly onto the surface of contact area between tool and workpiece, resulting in an insufficient lubrication at the defined area. Therefore, texture has received much attention owing to its ability to reduce contact area and store cutting fluid.

In recent years, research has been carried out for methods of fabricating different textures on diverse tool surfaces using various processing technologies. Koshy and Tovey [5] used electrical discharge machining (EDM) to generate an isotropic texture on the rake face of turning tool with a view to improving lubricant penetration and retention. Results showed that the existence of textures improved the friction state of tool-chip interface. Niketh and Samuel [6] created dimpled textures on the flute and margin side of drill tool using a laser micromachining technique. Experimental results proved that textures of the drill tool were able to reduce frictional force in the cutting area for Ti-6Al-4 V machining. Zhou et al. [7] used a laser to prepare a micro-groove texture on the rake face of milling tool and conducted experiments under two different coolant conditions. The texture enhanced the physical lubrication film formed on the tool-chip interface and improved the lubrication effect. Ahmed et al. [8] fabricated different textures on the rake face of the cutting tool by a femtosecond laser and, afterward, made performance tests for turning machining of AISI 304. Results revealed that maximum reductions in cutting force, feed force, and coefficient of friction were 58%, 100%, and 24%, respectively, for the square textured tool. Ge et al. [9] prepared textures in different groove widths on the rake face
of turning tool by a femtosecond laser and revealed that textures enhanced the penetration of cutting fluid, improving the lubrication of tool-chip interface and significantly reducing the cutting force compared to non-textured tools. Moreover, an in situ hot-press sintering technology was used to prepare ceramic tools with different morphological parameters in order to explore the best size and cutting parameters of microstructure morphology [10]. The wire spark erosion machining technology was used to prepare textures on the rake face of turning tool [11]. Both results showed that the textured tool effectively reduces the cutting force, temperature, and wear.

In summary, proper surface texture can reduce the friction of tool-chip interface, and the cutting fluid is stored to form micro-pool lubrication, which in turn leads to a reduction in cutting force and temperature. Above-mentioned processing methods have their benefits and drawbacks in terms of flexibility, accuracy, and processing speed. In particular, the laser processing technology is frequently used because of its wide acceptability and high efficiency.

Although textured tools perform well in reducing cutting force and temperature, the wearing between tool and material still affects tool life. Hence, surface coating and solid lubrication are usually introduced with textured tools. Textures enhance the bonding strength between coatings and textured surfaces; textures in different scales significantly affect the specific surface area and wettability of the substrate [12]. Obikawa et al. [13] fabricated four types of micro-surface textures on the rake face of cemented carbide turning tool by a photolithography and covered surfaces of textured tools with a diamond-like carbon (DLC). Results indicated that textured tool with coating effectively improved the lubrication conditions for machining aluminum alloy A6061-T6. Enomoto and Sugihara [14] proposed a new type of micro/nano-combined micro-groove tool, on which DLC was deposited by an arc ion plating. They found that the DLC coating significantly improved the anti-adhesion and lubrication properties of the textured surface in aluminum alloy milling experiments [15]. Meng et al. [16] reported a plasma-assisted laser machining approach to producing texture, and TiAlN was deposited on the textured tool by a cathode arc evaporation technique. Results exhibited an obvious reduction in cutting force compared to the conventional covered tool used in a dry cutting of the stainless steel. To improve the tribological property, the texture filled with a solid lubrication has also been demonstrated [17]. Deng et al. [18] used a femtosecond laser to prepare nano-scale texture on the rake face close to the main cutting edge of WC/TiC/Co carbide tools, and these textured tools were then deposited with WS₂ solid lubricant coatings. The deposition of a lubricating film on the textured surface was shown to be effective in improving cutting performance in a dry cutting. Voevodin and Zabinski [19] created 10–20-μm dimples on the surface of TiCN coatings by the laser texturing technique, and afterward, the MoS₂ was filled in the dimples. The performance of textured film in terms of wear and friction exceeded that of
MoS₂ have outstanding self-lubricating properties through lubricants. They reported that elliptical textured tools with MoS₂ have outstanding self-lubricating properties through the dry cutting test of carbon steel.

In the above literatures, the coatings on textured tools are made by expensive materials, such as DLC, TiAlN, WS₂, and MoS₂, and their preparations are also complex. This hinders the widespread use of multi-tooth-coated textured tools in broaching tools. In this paper, laser processing technology is used to prepare three types of textures on the broaching tool. Copper with low hardness and excellent thermal conductivity has been chosen as the covering material for textures. The copper covering is prepared by a reciprocating rotational movement between the broaching tool and the copper bar, which has a reasonable cost. Comparative experiments are carried out on a horizontal internal broaching machine under MQL condition. The performance of textured tool with copper covering is evaluated based on cutting force, chip thickness, and curling radius of the chip. The cutting mechanism using various textures with copper covering on broaching for cutting steel 1045 is also investigated.

## 2 Experimental details

### 2.1 Broaching tests

As shown in Fig. 1, the experimental workpiece is made of steel 1045 (AISI). The size of the workpiece is 90 mm in outer diameter (OD), 41 mm in inner diameter (ID), and 5 mm in thickness (δₘ). There is a hole with a diameter of 1.8 mm and 3 mm away from the initial cutting position of the workpiece (h). The experimental system consists of broaching machine, force transducer, thermocouple, data acquisition instrument, and atomization system. A horizontal internal broaching machine (Changer LG612Ya-800) is used in this experiment; parameters are given in Table 1.

The force transducer is for acquiring broaching force, composed of four pressure sensors (CTY-204) having one amplifier with a maximum output voltage of 10 V, a maximum load of 2 t, and a frequency response of 50 Hz. Data acquisition instrument (INV3018CT) with a sample software (CIONV DASP V10) is applied to make sampling of data with a sampling frequency of 1 kHz. The thermocouple (OMEGA: 5TC-GG-K-20~36) with a range of 0 ~ 180 °C is chosen to measure the cutting temperature. It is glued to the hole with a diameter of 1.8 mm on the workpiece through a silver silicone grease (QM850). The thermal conductivity of silver silicone grease is >4.15 W/(m·K) and a working temperature range of 30 ~ 280 °C. Data are collected through the temperature collector (YET-640) with a resolution of 0.01 °C and a sampling frequency of 2 times per second. Based on the previous work [21], the cutting fluid with 10 wt% castor oil and 1.5 wt% surfactants when added with a linear alkylbenzene sulfonate, the lowest broaching force is obtained, and therefore, the composition is selected as a cutting fluid for the experiment. An atomization nozzle with a working gas pressure of 7 bar is applied to deliver cutting fluids into the cutting tool. A ramp angle of θ=15° with a distance of l₉=50 mm is used for the atomization nozzle to achieve the best lubrication and cooling.

Cutting tools under four working conditions are investigated in broaching processing. Figure 2 depicts the preparation process of tool surface in this test; the processing scheme of this broaching test is listed in details in Table 2.

For the first test, the tool’s surface is not processed, and its surface is uneven on the microscopic scale, as exhibited in Fig. 2a. Afterward, the surface of non-textured tool is covered with copper for the second test. The texture is fabricated on the tool surface as shown in Fig. 2b and is used for the third test. For the last test, the surface of textured tool is covered with copper, forming a new flat surface as illustrated in Fig. 2c.

### Table 1 Broaching machine and machining parameters

| Parameter                        | Value   |
|----------------------------------|---------|
| Rated broaching force            | 20 KN   |
| Maximum broaching stroke         | 800 mm  |
| Broaching speed                  | 80 mm/s |
| Diameter of the master cylinder  | Ø80 mm ×45 mm |
| Oil pressure                     | 6 MPa   |

### Table 2 Processing plan for broaching test

| Testing order number | Tool textures | Covered copper | Cooling condition |
|----------------------|--------------|----------------|-------------------|
| 1                    | Non-texture  | No             | MQL               |
| 2                    | Yes          | MQL            |                   |
| 3                    | Texture      | No             | MQL               |
| 4                    | Yes          | MQL            |                   |

![Fig. 2 Preparation process of tool surface: a) initial surface and b) textured surface and c) textured surface with copper](image-url)
2.2 Preparation of textured tools

The broaching tool is made from steel HSS-6542 with a length of 600 mm, a width of 16 mm, a front height of 35.1 mm, and a gear height of 36.75 mm as illustrated in Fig. 3a. The broaching tool has fifty cutting teeth in total, divided into six parts as demonstrated in Fig. 3b. The first four parts (I–IV) are for roughing with the same feed per tooth of 0.04 μm, the fifth part is for semi-finishing with a feed per tooth of 0.01 μm, and the sixth part is for finishing without the feed per tooth. Each tooth retains a rake angle of 12°, a clearance angle of 6°, and a pitch of 6 mm. Rake faces of every ten teeth have the same texture prepared by a laser-marking machine (Han’s Laser H20); parameters are listed in Table 3. The first ten teeth in part I of the broaching tool have no texture (denoted as NT). The micro-pitted surfaces are prepared on the cutting teeth in part II (characterized as PT); the cutting teeth in part III are striped textures (designated as ST); and meshed surfaces are fabricated on part IV teeth (denoted as MT).

On account of the actual condition of this experiment and the research by Obikawa et al. [13], the dimension of textures is designed as shown in Fig. 3c, the surface size \( a \) is 0.1 mm, and the texture spacing \( b \) is 0.25 mm. The depth of texture is 0.06 mm under a consistent processing parameter. It is worth mentioning that the surface was treated preliminarily with 2000-mesh sandpaper and 5000-mesh sandpaper after the laser processing. Finally, the processed textured tool is rinsed with an absolute ethanol. The photomicrograph is taken with 500 times magnification using a high-speed digital camera (Type: KEYENCE VW-9000). The photomicrographs of three-dimensional morphology of different textures are shown in Fig. 3d.

| Parameter          | Value |
|--------------------|-------|
| Power               | 12 W  |
| Spot diameter      | 50 μm |
| Frequency           | 60 kHz|
| Processing times    | 10    |
| Repeat accuracy     | ± 0.003 mm |

2.3 Covering process

The process of covering copper on the rake face of broaching tool is illustrated in Fig. 4. The material of copper bar used in this experiment is made of red copper C11000; main components and properties are listed in Table 4.

![Fig. 3 Broaching tool: a schematic diagram of broaching tool, b distribution of textures on cutting teeth, c different textures, and d surface topography of textures](image-url)
An automatic equipment is developed for covering the copper as demonstrated in Fig. 4a. The broaching tool with different textures is clamped on the fixture of sliding Table 1; the feed movement of sliding Table 1 is along the $x$-direction. A copper bar is fastened with a DC motor rotor through a flexible coupling and the DC motor is fixed on the sliding Table 2. To cover the copper on the rake face of cutting teeth more evenly, the copper bar rotates while making reciprocating movements with the sliding Table 2 in the $y$-direction as demonstrated in Fig. 4b. The P direction in Fig. 4b is shown in Fig. 4c, which depicts the position of textures on the rake face of broaching tool. Since the rake face of broaching tool is located in a concave narrow space, it is difficult to directly observe its surface topography. Several $10 \times 10 \times 5$ specimens (HSS-6542) have been selected to be processed under the same working conditions which are used to characterize the copper-covering surface. After the copper is evenly added in grooves of the texture, the SEM with a magnification of 350 times. Among them, the presence of fewer copper debris at the intersection of meshed texture is due to the lack of support here and the copper debris cannot be retained stably. EDS diagrams of Fig. 5a2–c2 show the distribution of copper content on the surface of material treated by the copper bar. It can be concluded from Fig. 5 that the reciprocating rotation of copper bar on the textured surface can effectively cover the specimen surface with copper.

The cutting teeth with micro-pitted texture, striped texture, meshed texture, and non-texture are denoted as PT-C, ST-C, MT-C, and NT-C after copper covering, respectively. Detailed processing parameters of the device for covering copper are given in Table 5.

### 3 Results

Results are discussed in terms of cutting force, chip thickness, and curling radius of the chip. A broaching tool without texture is used as a reference for comparison purposes. As mentioned earlier, repeatability is guaranteed for each experiment.

#### Table 4 Main components and properties of red copper C11000

| Component | Cu + Ag | Bi | Sb | As | Fe | Pb | S | Others |
|-----------|---------|----|----|----|----|----|---|--------|
| %         | %       | %  | %  | %  | %  | %  | % | %      |
| Tensile strength | ≥ 295 MPa | ≥ 65 HRF | Elongation | ≥ 3% |
Cutting force

In order to ensure the reliability of experimental data, each set of tests is carried out five times. The test is firstly performed using the broaching tool without textures; this test is used as a reference for subsequent research. To maintain the same working condition for cutting teeth, textures are prepared on the same broaching tool; afterward, copper is covered on the textured tool. The effect of different textures and copper on the cutting performance of broaching tool is investigated as follows. To ensure consistent working conditions for each broaching test, copper is covered by the equipment each time. The maximum cutting force of each tooth is chosen based on broaching test data; the average value of maximum cutting force corresponding to each texture is then calculated.

As shown in Fig. 6, after the textures are fabricated, the cutting force (blue bar) decreases dramatically compared with that of the non-textured broaching tool. The cutting force of ST (III) has the most significantly reduced value, which amounted to 86.7 N (7.6%). The cutting force of PT (II) is reduced by 60.4 N (5.4%). The cutting force of MT (IV) has a minor reduction, equivalent to 32.6 N (2.8%).

After covering the copper on the rake face of the broaching tool, the downward trend of cutting force exhibits some changes compared with that of the textured tool. The most significant reduction in the cutting force can be ascribed to MT-C, which is 80.2 N (7.2%). The cutting force for ST-C is decreased by 72.7 N (7%), followed by PT-C, whose cutting force is reduced by 52.5 N (5%). The minor reduction in cutting force is for NT-C, representing 44.4 N (3.9%).

According to the above analysis, the cutting force of tool with copper is compared with that of the non-textured tool. The cutting force of ST-C decreases by 14.1%; minor differences in reducing cutting forces between PT-C and MT-C exist, reduced by 10% and 9.8%, respectively.

### Table 5 Processing parameters of the device for covering copper

| Unit             | Parameter          | Value   |
|------------------|--------------------|---------|
| Sliding Table 1  | Linear speed (x)   | 50 mm/s |
|                  | Stroke             | 300 mm  |
| Sliding Table 2  | Linear speed (y)   | 50 mm/s |
|                  | Stroke             | 100 mm  |
| DC motor         | Rotational speed   | 100 rpm |
| Single tooth     | Process time       | 3 min   |
3.2 Chip thickness

Chips in three parts of the broaching tool are collected after broaching. The middle section of the chip (stable cutting area) is selected as the research object. Photos are taken using the high-speed digital camera at a magnification of 1000 times, as shown in Fig. 7. The average of five measurements at equal intervals is calculated as follows:

\[
d = \frac{(d_1 + d_2 + d_3 + d_4 + d_5)}{5}
\]

where \(d\) is the average value of chip thickness and \(d_1\)–\(d_5\) are measured values of the chip thickness at five positions, respectively.

The variation in chip thickness under different working conditions is described in Fig. 8. NT generates the largest chip thickness, which equals to 90.2 \(\mu m\). The smallest chip thickness 64.1 \(\mu m\) is produced by ST. The chip thickness of PT is 77.6 \(\mu m\), which is smaller than that of MT (i.e., 86.7 \(\mu m\)).

When the copper-covering teeth are used for testing, the variation in chip thickness differs from the textured tool without copper. The smallest chip thickness 57.2 \(\mu m\) comes from ST-C. The thickest chip obtained by NT-C is 80.1 \(\mu m\). Chip thicknesses of PT-C and MT-C are almost similar; they are 72.1 \(\mu m\) and 72.2 \(\mu m\), respectively.

3.3 Curling radius of chip

Photomicrographs of the chip are taken using a high-speed digital camera at a magnification of 20 times as displayed in Fig. 9. The curling radius of a chip on three different positions is measured to accurately describe the influence of various working conditions. A rectangular coordinate system is established. The initial point \(A\) and the highest point \(B\) of the chip pass through the \(x\)-axis and \(y\)-axis, respectively, and the cut-in part of the chip is perpendicular to the \(x\)-axis. The chip and the coordinate system intersect at three points \(B\), \(C\), and \(D\), respectively; \(p_1\), \(p_2\), and \(p_3\) denote tangents on these three points. The origin of coordinates is the center of circle 1 (\(O_1\)), and \(O_1B\) is the radius. The center of circle 2 (\(O_2\)) is on a line perpendicular to \(p_2\), and circle 2 is circumscribed to circle 1. Similarly, circle 3 is circumscribed to circle 2, and the center of circle 3 (\(O_3\)) lies on a line perpendicular to \(p_3\).

The curling radius of chips on three positions under each working condition is measured and demonstrated in Fig. 10. As shown in Fig. 10a, lengths of \(O_1B\), \(O_2C\), and \(O_3D\) reflect the influence of different textures on the curling radius with consistent changing trends. The smallest curling radius of the chip occurs in ST; NT has the largest curling radius of the chip. Lengths of the curling radius of the chip are sorted from large to undersized as NT, MT, PT, and ST. It proves that textures on the tool surface reduce the curling radius of
the chip. The curling radius of chips using the tool covered with copper is illustrated in Fig. 10b. The largest curling radius of the chip is obtained by NT-C, followed by PT-C, MT-C, and ST-C. The data mentioned above show that the curling radius of chips is reduced because of the copper covering, which is enhanced more for the meshed texture.

3.4 Temperature of workpiece

Cutting temperature not only affects the quality of machined workpieces but also affects the service life of the tool. The temperature of broaching tool in the cutting area is extremely difficult to estimate. Therefore, the temperature of workpiece near the cutting area is taken as the research object. The thermocouple has been chosen to measure the cutting temperature at 28 °C in the natural environment.

The variation of workpiece temperature under four cutting conditions is shown in Fig. 11. The non-textured tool generates the largest peak temperature during the cutting processing with a value of 90.13 °C. After covering copper on the surface of the non-textured tool, the peak temperature reduces by 6.4%, resulting in a value of 84.36 °C. Afterward, the peak temperature of textured tool is 81.69 °C; a decrease of 9.4% is obtained when compared with non-textured tools. The peak temperature of textured tool covered with copper is the lowest at 76.9 °C, which is 14.7% lower than that of the non-textured tool. Therefore, it can be concluded that textured tool with copper significantly reduces the cutting temperature during the cutting processing.

4 Discussions

4.1 Mechanism of the texture

In the metal cutting process, chips are formed by the extrusion and shearing of the tool. Bai et al. [22] proved that the contact and friction of the tool-chip interface directly affect the deformation of the material, cutting temperature, the surface quality of workpiece, and cutting force. Based on the research of Hwang [23], the contact area between chip
and tool is divided into bonding zone $l_1$ and slip zone $l_2$. The forming of chip in the cutting process is demonstrated in Fig. 12.

Fang [24] reported that the frictional force and positive pressure on the tool-chip interface are the main sources of cutting force during the cutting process. The relationship between them can be given according to Shaw [25] as

$$F_f = F_N \tan \beta$$

where $F_f$ is the frictional force, $F_N$ is positive pressure, and $\beta$ is the frictional angle.

Textures on the tool surface do not significantly change the positive pressure. Therefore, $F_N$ is regarded as a fixed value in this condition and will not be discussed. $F_f$ mainly comes from the shearing of materials and lubricants [26] and can be expressed by

$$F_f = \tau_s A_s + \tau_l A_l$$

where $\tau_s$ is the shear yield stress of material, $A_s$ is the bonding area of tool-chip interface, $\tau_l$ is the shear strength of lubricant, and $A_l$ is the penetration area of lubricant.

Compared with non-textured cutting teeth, the $A_s$ of textured cutting teeth is significantly reduced. $F_f$ in turn decreases according to Eq. (3), and $\beta$ also becomes lower according to Eq. (2).

According to the research of Lee and Shaffer [27], the shear angle $\phi$ is given by

$$\phi = \frac{\pi}{4} - \beta + \gamma_0$$

where $\gamma_0$ is the rake angle of the cutting tooth which is a fixed value. To investigate the deformation of chip, the following relation is introduced [25]:

$$\xi = \frac{a_0}{\delta} = \frac{MN \cdot \cos(\bar{\phi} - \gamma_0)}{MN \cdot \sin \bar{\phi}} = \frac{\cos(\bar{\phi} - \gamma_0)}{\sin \bar{\phi}}$$

where $\xi$ is the chip deformation coefficient, $a_0$ is the deformed chip thickness (actual measured value), $\delta$ is the undeformed chip thickness, and $MN$ is the shear band. According to the above equations, the relationship between $a_0$ and $A_s$ is finally deduced.

The mechanism of different textures in the cutting process is illustrated in Fig. 13, where the area ratios $S$ for each surface are calculated based on the following relation:

$$S = \frac{A_{\text{texture}}}{A_{\text{unit}}}$$

where $A_{\text{texture}}$ is the area of texture per unit area and $A_{\text{unit}}$ is the unit area; values of $S$ for mesh, stripe, and micro-pit textures are calculated as 64%, 40%, and 12.6%, respectively.

In the bonding zone, interface materials bond to each other due to higher stress as shown in Fig. 13a. Figure 13b, c demonstrate that the value of $S$ on ST is greater than that of PT. An increase in $S$ reduces the area of bonding zone, thereby reducing the cutting force. As exhibited in Fig. 13d, the maximum value of $S$ happens to be imposed on MT when the workpiece material is easily pressed into grooves of the meshed texture due to the lack of support. This results in a significant increase in the bonding zone and the cutting force. Therefore, the cutting force of MT does not decrease with an increase in $S$.

The actual shear band is a convex curved surface as demonstrated in Fig. 14. The shear angle $\phi_1$ at the bottom layer of chip is greater than the shear angle $\phi_2$ at the upper layer. Based on Eq. (5), the larger the $\phi$ is, the smaller the $\xi$ will be. According to the literature [25], the relationship between the speed of chip and $\xi$ can be calculated as
where $v_c$ is the speed of the chip and $v$ is the cutting speed. In fact, $v$ is considered a constant during the cutting process; therefore, $v_c$ is inversely proportional to $\xi$. The cutting speed at the bottom of chip equals the upper layer ($v_1 = v_2$). A speed vector triangle can be drawn according to the sliding direction and shear angles of the chip on the bottom and upper layers. Among them, $v_{s1}$ and $v_{s2}$ are parallel to tangents of the shear plane, adhering to bottom and upper layers, respectively. The flow speed of bottom metal of the chip is greater than that of the upper layer ($v_{c1} > v_{c2}$), causing the chip to curl upward. The curling radius of chip is inconsistent in different parts of the broaching tool. One possible reason is that textures on the tool surface reduce $\xi$ such that the relative flow speed between bottom and upper metals of the chip is different. The curling radius of chip is compatible with the changing trend of cutting force discussed earlier.

\begin{equation}
\begin{aligned}
v_{c} &= \frac{\sin \phi}{\cos(\varphi - \gamma)} \\
v &= \frac{v}{\xi}
\end{aligned}
\end{equation}

4.2 Influence of copper covering on cutting performance

Chips are in close contact with the tool’s rake face during the cutting process, especially at the bonding area ($l_1$) as depicted in Fig. 15a. The existence of texture on the tool surface allows the cutting fluid to be stored, and hence, a lubricating oil film is formed in the cutting area as displayed in Fig. 15b. Because of a lower hardness, copper is used as the solid lubricant for the textured tool surface. The low-hardness copper forms a solid lubricating film without causing scratches and wearing on the tool surface as demonstrated in Fig. 15c. After covering copper in the groove of textures, there are gaps between chip and tool surface due to the support of copper debris. The existence of these gaps assists the cutting fluid to penetrate more into the slit of tool tip. Therefore, copper covering reduces the bonding area between chip and tool and increases the thickness of lubricating film, leading to a reduction in the cutting force.

To further investigate the influence of textures and copper covering on the wetting performance of tool, six sets of surfaces are prepared on the specimen of steel HSS-6542. The spacing and size are the same as the textures fabricated on cutting tooth; three sets of textured surface are covered with copper using the same method of reciprocating rotational friction. As shown in Fig. 16, the contact angle ($\alpha$) of the cutting fluid on each specimen is measured by contact angle meter (TYPE: POWER EACH JC2000D1). The droplet volume for each wettability test is 5 μL. The contact angle is evaluated when the droplet falls on the specimen for 8 s (namely, the steady state). Moreover, a high-speed camera is used to take a snapshot of the droplet.

Textures on the tool surface store the cutting fluid and generate micro-pool lubrication. However, according to the Cassie and Baxter model [28], the presence of texture generates an air cushion in the groove of tool surface, thereby
reducing the wettability of cutting fluid at the tool-chip interface. As exhibited in Fig. 16, the slightest contact angle 53° occurs on the specimen without any consistency, which means that the cutting fluid has an affinity for the material surface. The biggest contact angle takes place on the striped texture, which is 66.5°. Its length along the longitudinal direction of texture is also the largest, i.e., 4565 μm. This is due to the fact that grooves formed by the striped surface hinder the horizontal spreading of cutting fluid and the longitudinal grooves have a drainage effect as a channel to make the cutting fluid spread quickly. Longitudinal lengths of micro-pitted and meshed textures are almost similar, which are 3206 μm and 3405 μm, respectively, and much smaller than those of striped textures. Since the cutting fluid on the striped texture flows faster in the longitudinal direction, the tool surface is wetted rapidly during the cutting process. Therefore, the lubrication of tool-chip interface is greatly improved.

After textures are processed by the copper bar, grooves of the texture are covered by tiny copper debris. According to Wenzel’s model [29], the specimen surface is generally flat, and the specimen grooves are filled with liquid. It can be seen from Fig. 16 that contact angles and longitudinal lengths of all textures with copper covering are improved. Remarkably, the contact angle of meshed surface is reduced from 54° to 16.5°, while its longitudinal length is increased by 501 μm (from 3405 to 3906 μm). Since the copper in the groove of textures forms many loose micro-pores, the generated capillary force makes droplets spread rapidly on the surface. The lubrication condition of machining is enhanced as the surface wettability improved and the cutting force is reduced accordingly. Therefore, the cutting force of MT-C is significantly reduced, and the striped texture still has a good performance in the longitudinal spreading.

As illustrated in Fig. 17a, the tool surface has a wavy surface profile with an unevenness in the microscopic view. As a soft metal, copper fills the dimples on the tool surface during the rotating frictional process and blunts the prominent convex peaks. It reduces the shear force and friction generated by the relative movement of material and tool. This is also the reason for reducing the cutting force for non-textured cutting teeth after being covered with copper.

Figure 17b indicates that a large amount of copper debris acts as a solid lubricant in the cutting area. The relative violent friction between chip and tool generates large
amounts of heat because of the heavy load in broaching. The copper debris in the cutting area quickly absorbs heat owing to its excellent thermal conductivity. Some copper debris with a high temperature adheres to the chips and is taken away with the flow of chips. The rest is either washed away by the cutting fluid or squeezed into the textured groove. Textures increase the superficial area of tool and heat dissipation rises accordingly. Consequently, copper debris accelerates the heat transfer efficiency in the groove and lowers the temperature of tool surface. A decrease in temperature makes difficulties for the workpiece material to be accumulated and bonded at the tooltip; thereby, the shear force generated by material bonding is reduced and so is the cutting force. Moreover, the copper covering changes the frictional force of tool-chip interface and affects the frictional and shear angles when chips are generated.

5 Conclusion

The research outcome of this paper can be summarized as follows:

• Textures on the tool surface decrease the contact area of tool-chip interface and reduce the cutting force. The striped texture has an excellent spread-ability in the longitudinal direction, and therefore, the cutting force of tool with a striped texture is the smallest.

• Textured tool decreases the chip thickness, curling radius, and friction of the tool surface. This is due to a reduction in the chip deformation coefficient and an increase in the shear angle.

• Convex peaks on the tool surface are passivated during the reciprocating rotation of copper bar; thereby, the shearing force caused by convex peaks on the surface of tool and chips is reduced. Simultaneously, copper debris is filled in the textures as the solid lubricant and decreases the cutting force.

• A large number of micro-pores are generated in the groove of copper-coated textures. The capillary force formed by these micro-pores improves the wettability of tool surface. In addition, copper debris with a high temperature sticks to chips and is removed from the tool surface with the chip slide.

Author contribution All authors have contributed significantly to the work in the order provided.

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Declarations

Ethics approval and consent to participate This manuscript follows the guidelines of the Committee on Publication Ethics (COPE) and involves no studies on human or animal subjects.

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