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ORIGINAL ARTICLE

Fabrication of PCD micro cutting tool and experimental investigation on machining of copper grating

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Abstract This paper presents an investigation on machining of copper grating. Ultra-hard polycrystalline diamond (PCD) micro cutting tools were designed and machined, especially focused on fabricating micro channel arrays characterized by excellent quality with high efficiency. Micro cutting experiments of copper grating were carried out using the self-developed PCD micro tools, and the effect of width of cut, feed per tooth, and spindle speed on dimensional accuracy and burr formation was investigated. Additionally, optimum combination of processing parameters was obtained. As a result, a complete copper grating with superior dimensional accuracy and minimum top burrs was machined by employing the self-developed micro cutting tools under the optimal parameters.

Keywords Micro cutting · Copper grating · PCD micro tool · Dimensional accuracy · Burr formation

1 Introduction

Miniaturization technology has been developed rapidly among a large number of industrial fields, such as aerospace, biomedical, optical engineering, and information technology in recent years [1, 2]. This phenomenon creates increasing demand for micro components with higher reliability, more complex structure features, and better performances. Micro structures play a critical role in the behavior of engineering parts within a range of areas, attributed to their excellent performances, for instance, optical, tribological, lubricative, and information-storing properties [3]. And, the quality of the machined micro parts has a particularly prominent effect on these aforementioned performances.

Micro electro discharge machining (EDM), micro laser beam machining, and micro cutting are common methods utilized to manufacture micro parts. However, EDM is widely known of poor machined quality [4], and laser beam machining shows inefficiency due to the low material removal rate. The advantages of micro cutting in contrast with other micro fabrication techniques are fewer material restrictions, better quality, and the ability to manufacture intricate three-dimensional features or free-form surfaces [5–7]. These aforementioned merits of micro cutting make it such an important area in manufacturing of micro parts that a large amount of research has been devoted to.

Micro tool technology is one of the most critical aspects to the successful application of micro cutting, whereas fabrication of micro tools is a challenging task [8–10]. Therefore, design and fabrication of micro cutting tools are decisive to the development of micro cutting. Cheng et al. [11] summarized the limitations of the existing micro milling tools and introduced design criteria for micro tools. A new polycrystalline diamond (PCD) micro end-milling tool with a diameter of 0.5 mm was designed and fabricated based on the criteria. Fang et al. [12] conducted a systematic study of different tool geometries and concluded that D-type end-mills are more suitable for micro machining. Using six-axis wire-cut EDM, a single-edged micro milling tool was designed and manufactured by Nakamoto et al. [13]. On the same topic of tool study, Zhan et al. [14] optimized the grinding process of PCD micro tool; a quadrilateral PCD micro milling tool with a

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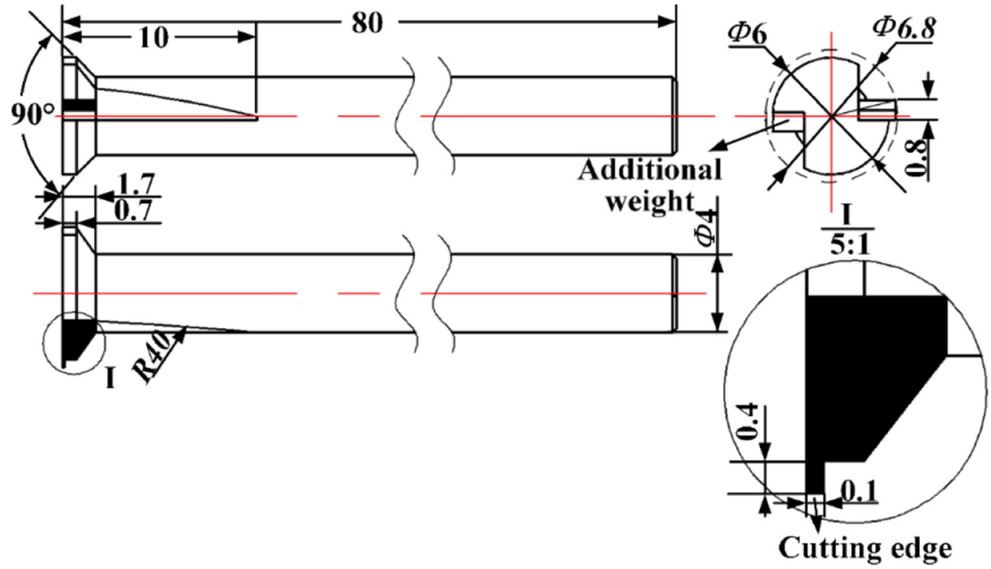


Fig. 1 Structure of the self-developed micro cutting tool

diameter of 80 μm was machined and evaluated by micro grooving. In addition, a micro milling tool with a single edge was developed by Fleischer et al. [15]; they conducted stability analysis of three different geometries utilizing finite element model (FEM) simulation and concluded that semi-circular shape is better as compared with trapezium. A resulting tool with a diameter down to 30 μm was fabricated by EDM. High-precision PCD end mills were fabricated by Zhang et al. [16], and cutting performance of the tools was examined by manufacturing micro dimples and micro grooves on tungsten carbide mold substrates.

Finding appropriate strategies to ensure dimensional features and the quality of micro parts is such a challenging issue in micro cutting that many researchers have performed theoretical and experimental analysis to figure it out [17, 18]. Li et al. [19] explored the challenges in micro milling of thin ribs with high aspect ratios using FEM models and experimentations. They successfully obtained thin ribs 15 μm in width and that have an aspect ratio of over 50 with good form and excellent quality. To control the deformation and ensure dimension quality of the thin-walled structures, Kou et al. [20] employed a low-melting-point alloy as an auxiliary support to balance the axial force of the cutter and improve the stiffness of the workpiece. The novel method was verified by manufacturing a beryllium bronze alloy with 15 μm thick. Suitable combination of processing parameters also has an influential effect on quality of the machined micro parts. Filiz et al. [21] performed an experimental investigation of micro cutting of pure copper and found suitable parameters for decreasing burr formation. Associated with the study of the same topic, Vazquez et al. [22] conducted experiments on aluminum and copper under various machining conditions. They studied the characteristic of micro milling to generate micro channels and observed better results through the evaluation of dimensions, shape, and burr formation. With respect to the influence of material micro structure on the quality of the machined parts, Wu et al. [23] studied micro slot milling

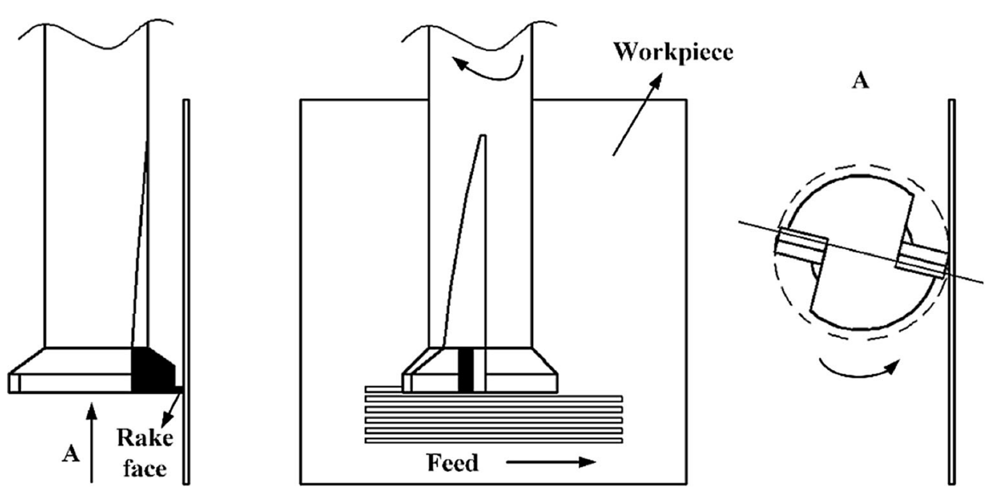


Fig. 2 The schematic diagram of the cutting model

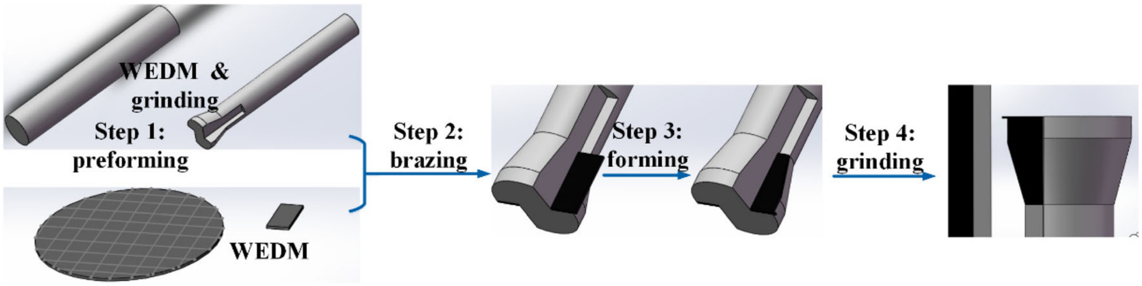


Fig. 3 The scheme of manufacturing procedure

on oxygen-free copper. They drew a conclusion that both crystallographic orientation and grain size have a significant influence on burr formation, and consequently, minimum burrs could be obtained when fine grain material and sharp cutting edge reached an appropriate combination.

In general, micro channel arrays typically feature considerable material removal amount, and therefore, higher efficiency is more favorable. In this paper, micro cutting tools with sharp and high wear resistance cutting edge were fabricated. A set of micro cutting experiments of copper grating were conducted. The effect of width of cut, feed per tooth, and spindle speed on dimensional precision and burr formation was investigated. In addition, a comparative research was conducted with a PCD end-milling tool.

2 Fabrication of the micro cutting tool

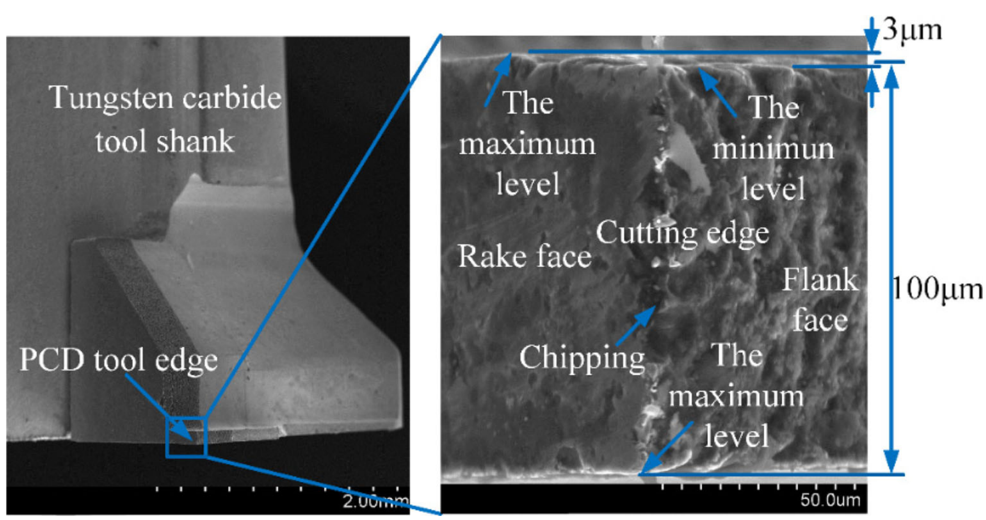
2.1 Design of the micro cutting tool

The micro cutting tool proposed in this paper was aimed at improving both time efficiency and quality of the machined micro channel arrays. It is well known that diamond flying cutting is characterized by high machining efficiency and high quality of the machined surface [24, 25]. The self-developed micro cutting tool stemmed from the combination of diamond flying cutting tool and sawing blade, and it was focused especially on generating micro channels with high efficiency. Similar to diamond flying cutting tool, the self-developed micro cutting tool had only a single edge which could effectively avoid deflection compared with multiple edges. Moreover, an additional weight was added to the counter of the cutting edge to keep dynamic balance. The micro tool has a cutting edge of specific width, which is capable of machining micro channels characterized by the same width as the edge.

Design illustration of the micro cutting tool is given in Fig. 1, and the rake face is parallel to the horizontal plane and 0.8 mm higher than the center line. The eccentric edge structure is designed to achieve the principle of single edge. The rake and the relief angles are 0° and 2°, respectively. Additionally, the design of tool neck with variable cross section is intended to avert unnecessary contact between the cutting tool and the workpiece. Cutting model of the developed tools is presented in Fig. 2, and it is proper to adopt this cutting mode; only in this way can the rake face contact the workpiece first. Otherwise, the first contact is experienced on the flank face which is relatively vulnerable and, consequently, resulting in severe wear or even breakage of the tool.

Since the design philosophy mainly aimed at machining micro channels characterized by the same width as the cutting edge, it is of great significance to maintain original edge

Fig. 4 Close-up image of cutting edge



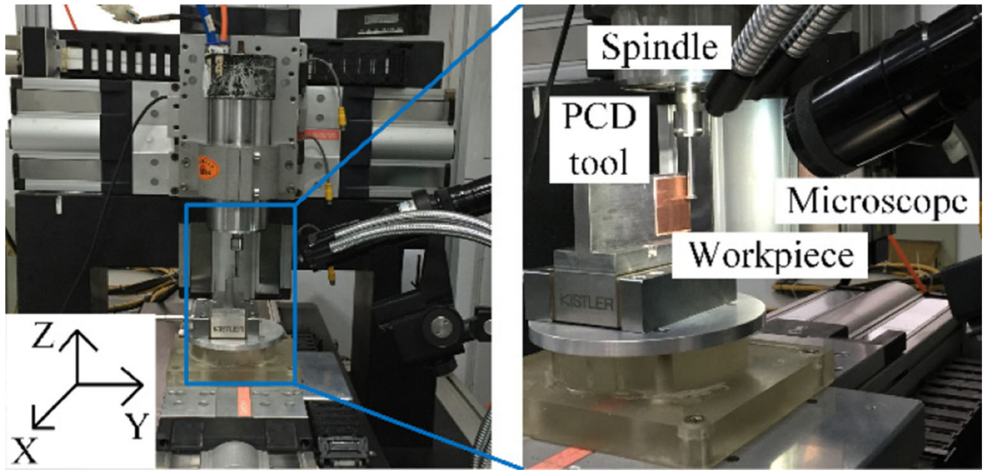


Fig. 5 Setup of micro cutting experiments

geometry. PCD was utilized to manufacture the tool edge due to its superior performance, for instance, high hardness, excellent abrasion property, very small friction coefficient, and high binding phase intensity of polycrystalline structure. As the micro cutting tool has a relatively long overhanging than conventional micro end mills, tungsten carbide with high elastic modulus was applied to manufacture tool shank for the purpose of ensuring stiffness and, therefore, reducing deflection of the micro tools.

2.2 Machining of the micro cutting tool

The general procedure for fabrication of the micro cutting tools included four steps as follows: preforming, brazing, forming, and sharpening of the cutting edge, as seen in Fig. 3.

First, the tool shank made of tungsten carbide and the PCD compact was preprocessed, respectively. The tool shank was machined into specific geometry by wire-cut electrical discharge machining (WEDM); furthermore, grinding method was employed in finish machining. And, the PCD compact was machined into small tablets by WEDM. Then, the tool shank and the PCD tablet were brazed together by means of high-frequency inductive welding technology, and an additional weight was added to the counter of the cutting edge in the same way. In the forming stage, a single edge with specific geometry was generated by a WEDM technique. A precision grinder was used in the last procedure to sharpen the cutting edge, as grinding can deliver a high accuracy of the tool shape and sharp cutting edges. It is sensible to sharpen the major edge of the tool only, namely, just grinding the rake and the flank face with respect to improving efficiency and making it much easier to grind.

Micro cutting tools were fabricated successfully, and Fig. 4 exhibits the scanning electron microscope (SEM) photograph of one micro tool with a valid edge width of 100 μm. It is illustrated from the picture that the micro cutting tool features good surface quality and a sharp edge generally. Moreover, it can be seen in the picture that there is a little chipping on the cutting edge where materials were removed unexpectedly due to the vibration of the grinder. And, it is also presented in the figure that there is some

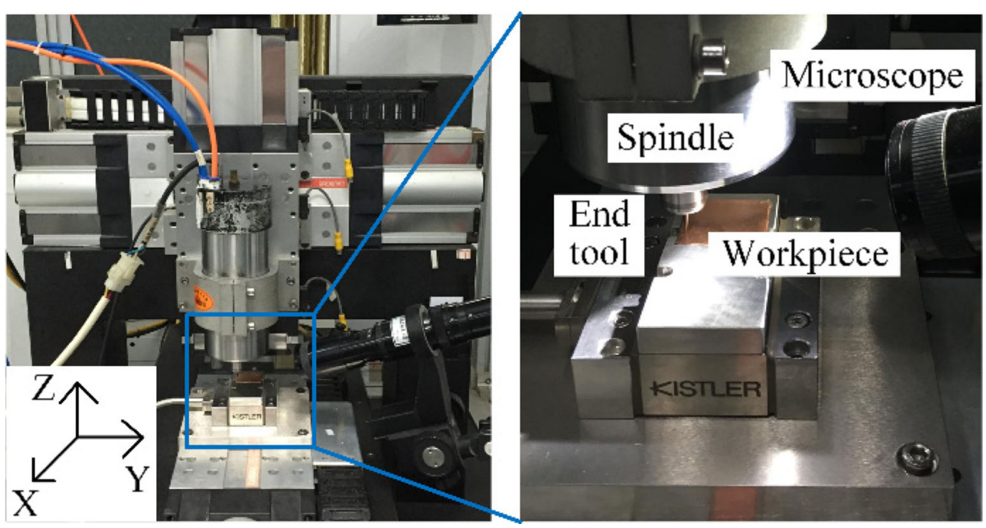


Fig. 6 Experimental setup of the micro end milling

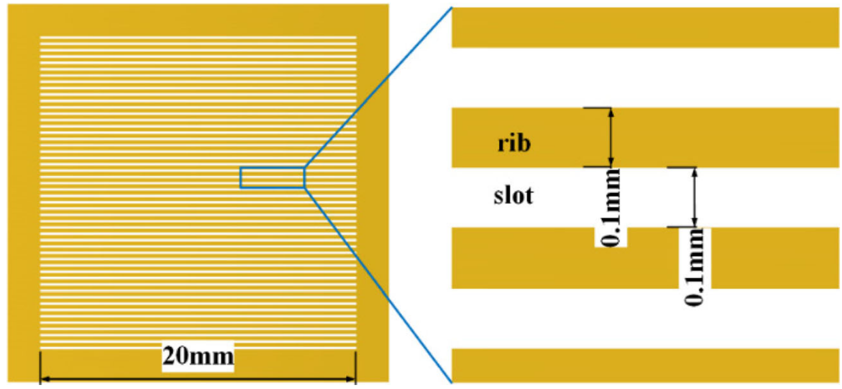


Fig. 7 The schematic diagram of the copper grating design

difference between two sides of the edge, as one side is smoother and the maximum level is experienced at the location of the cutting edge, while another features a maximum level about 3 μm greater than the minimum level, making the maximum level not on the cutting edge.

3 Experimental procedure

3.1 Experimental setup

A self-developed machine tool was employed in the experiments, as illustrated in Fig. 5. It is a multipurpose machine with three axes, and X and Y stages are driven by linear motors. Z stage is equipped with a high-speed air bearing spindle, and it is driven by a brushless direct-drive torque motor. Furthermore, it has a maximum speed not in excess of 120,000 rpm. The stroke of each linear axis (*X*, *Y*, *Z*) is 150, 150, and 100 mm, respectively. The positioning accuracy of the machine tool is ±0.1 μm, with a resolution of 100 nm.

The aforementioned cutting tools (see Fig. 4) were employed in the experiments. Copper features a thickness of 0.1 mm and is chosen as the workpiece material because it is the material broadly used for optical components. A thin slice of copper was pasted on the T-shaped holder, which is mounted on the machine table. An experimental setup of micro cutting is shown as Fig. 5. To give a better comparison of the developed PCD micro cutting tools and PCD end mills, a comparative study was conducted. Experimental setup of the micro end milling is shown as Fig. 6. Prior to the experiments, a dial indicator was used to inspect the flatness of the copper sheet. The copper grating is designed for a type of X-ray space telescope, and the schematic diagram of the detail design is illustrated in Fig. 7. For each test, a micro slot 20 mm long and 0.1 mm wide was cut along the X direction. The PCD micro cutting tool was directly clamped on the air bearing spindle with an overhanging of 35 mm. The micro cutting process was monitored with a long-distance microscope.

Single-factor experiments are designed to evaluate the cutting feasibility and performance of the self-developed micro tools. The feed per tooth (f_z) was varied from 1.5 to 7.5 μm/tooth at intervals of 1.5 μm/tooth, at a constant width of cut of 10 μm and spindle speed of 20,000 rpm. To investigate the effect of width of cut (a_w), the width of cut was studied by varying its value at 4, 7, 10, and 13 μm, respectively, and fixing the spindle speed at 20, 000 rmp and feed per tooth at 6 μm. The spindle speed (n) was varied at 16,000; 20,000; and 24,000 rpm, respectively, at a constant width of cut of 10 μm and feed per tooth of 6 μm. The full experimental parameters are listed in Table 1. Three micro slots were produced by utilizing repeatedly each set of parameters. End milling experiments were conducted under the optimal parameters ($f_z = 4$ μm/tooth, $a_p = 4$ μm, $n = 20{,}000$ rpm) obtained through previous investigations. All experiments were performed under dry machining conditions.

Table 1 Cutting parameters

Width of cut a_w (μm)	4 7 10 13
Feed per tooth f_z (μm/tooth)	1.5 3 4.5 6 7.5
Spindle speed n (rpm)	16,000; 20,000; 24,000

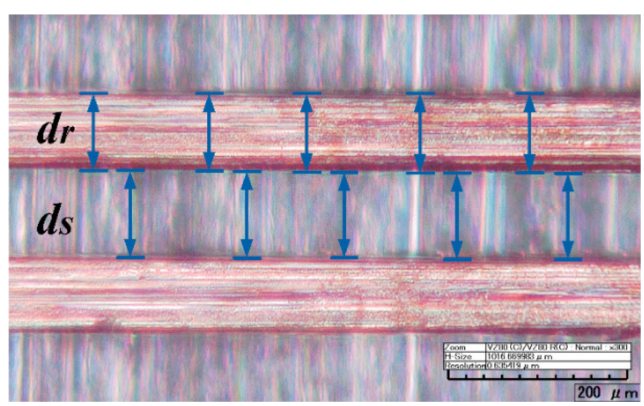


Fig. 8 Measurement locations for the widths of micro slots and ribs

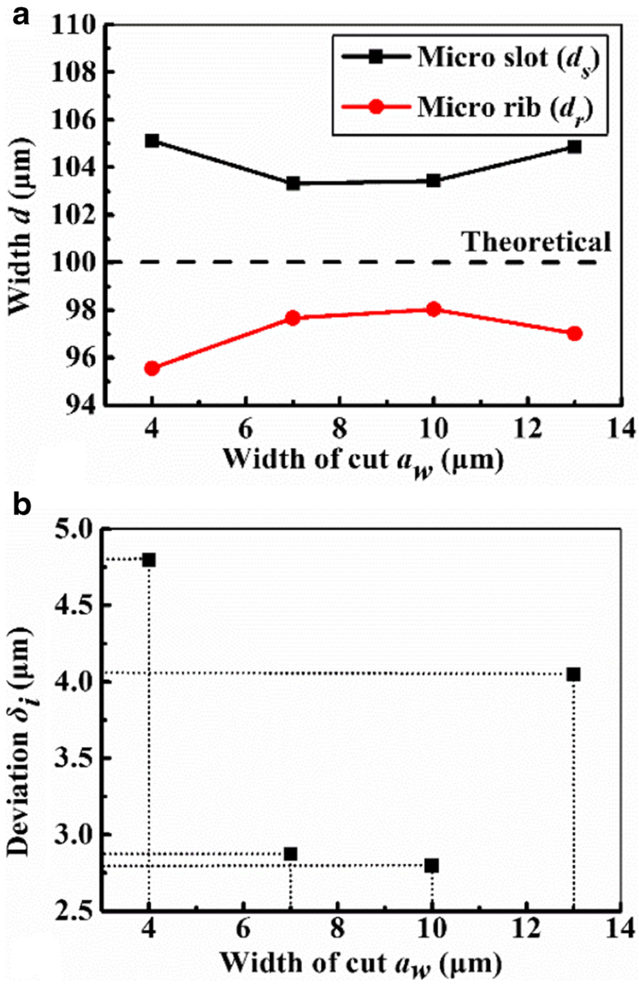


Fig. 9 Effect of width of cut on dimensional accuracy

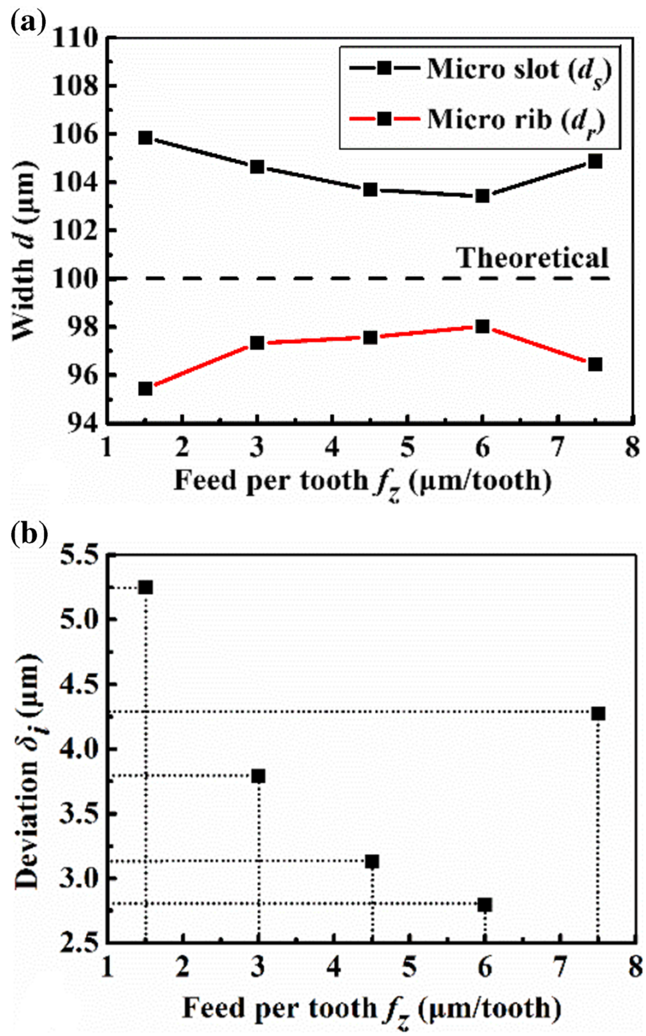


Fig. 10 Effect of feed per tooth on dimensional accuracy

3.2 Dimension and burr height measurement

Dimensional measurements of copper grating were performed with an optical microscope Leica DVM 5000. To reduce the uncertainty of the measurement, five measurements were conducted on different positions of each micro slot and rib, respectively. The results of width used for analysis are the average values of these measurements. The widths of micro slot and rib are represented by d_s and d_r, respectively, and the measurement locations are shown as Fig. 8.

Burrs in micro machining can be classified as bottom, top, entrance, and exit burrs according to their positions [26]. The measurement of burr is a challenging task for burr research, and there is no standard specification for evaluating burr quantities. In this paper, top burrs were studied since they were the overwhelming majority and considered to be the most difficult to remove. Burr height was selected as the assessment metric of burr formation, and it was inspected by SEM of type Hitachi S-3400N. Burrs across each slot were measured and averaged respectively, since obvious difference of the burrs on the corresponding sides was observed in earlier research. The height of top burrs formed at two sides of the slot is represented by b_1 and b_2, respectively. Five measurements were taken from different locations where burr height is uniform on each side of the slots.

4 Results and discussion

To give a better understanding on the relationship of feed per tooth (f_z), width of cut (a_w), and spindle speed (n) to dimensional precision and burr formation, the results of experiments are summarized.

4.1 Effect of cutting parameters on dimensional precision

Widths of micro slots and ribs are measured metrics that can be used to analyze the dimensional accuracy of copper grating. To give a more direct comparison of the dimensional results, a comprehensive deviation δ_i was introduced:

$$\delta_i = \sqrt{\frac{(d_s - d_i)^2 + (d_r - d_i)^2}{2}} \quad (1)$$

where δ_i is the comprehensive deviation of width, $d_i = 100$ μm is the desired width of micro slot and rib, and d_s and d_r represent the obtained widths of micro slot and rib, respectively.

Figures 9, 10, and 11 exhibit the relations of width of cut, feed per tooth, and spindle speed to dimensional accuracy. It can be observed from Figs. 9a, 10a, and 11a that the width of micro slot is always slightly larger than the ideal value of 100 μm, while the width of micro rib is a little smaller. These results are independent from width of cut, feed per tooth, and spindle speed. According to [27], the possible effect of tool wear is rather slight that can be ignored for the cutting distance in this study. The main reason for this characteristic of dimension is the tool edge structure as illustrated in Fig. 4. Since on one side of the cutting edge, the maximum level is not on the edge, when performing deeper cutting, the highest point may cut the machined sidewall again (henceforth referred to as "secondary cutting"), and consequently, the slot width is larger than the ideal value. Another possible reason is the run-out of the spindle, as there is always spindle run-out, predestinating the width of micro slot larger than that of cutting edge.

Figure 9 demonstrates the effect of width of cut on dimensional accuracy. It can be observed from Fig. 9a that the tendency is toward smaller slot width and larger rib width with increase in width of cut. However, when the width of cut is larger than 10 μm, there is an opposite tendency. The values of both widths most approaching to the target of 100 μm occur at width of cut of 10 μm, followed by that at width of cut of 7 μm. It can be seen from Fig. 9b that the comprehensive deviation δ_i reaches a minimum level when the width of cut is 10 μm. It should be noted that the relative difference between the effect of width of cut of 7 μm and 10 μm on dimensional deviation is on rather a low level. The increase of width of cut means fewer tool passes, i.e., less contact between the workpiece and the tool, in turn decreasing the unexpected secondary cutting, and consequently, the width of micro slot and micro rib tends to be closer to the ideal value of 100 μm. When adopting larger width of cut, the material removal per pass increases so that larger cutting force is needed. Since the copper sheet features weak rigidity, it will be experienced severe deformation when encountering larger forces. It is responsible for the observation that the dimensional accuracy at width of cut of 7 and 10 μm is better than that at the width of cut of 13 μm.

Feed per tooth is essential for undeformed chip thickness and, thus, the determining factor for ploughing effect. It is of great importance to analyze the effect of feed per tooth on micro machining process. Figure 10 depicts the influence of feed per tooth on dimensional accuracy. It is illustrated in Fig. 10 that both the widths of micro slots and ribs are the

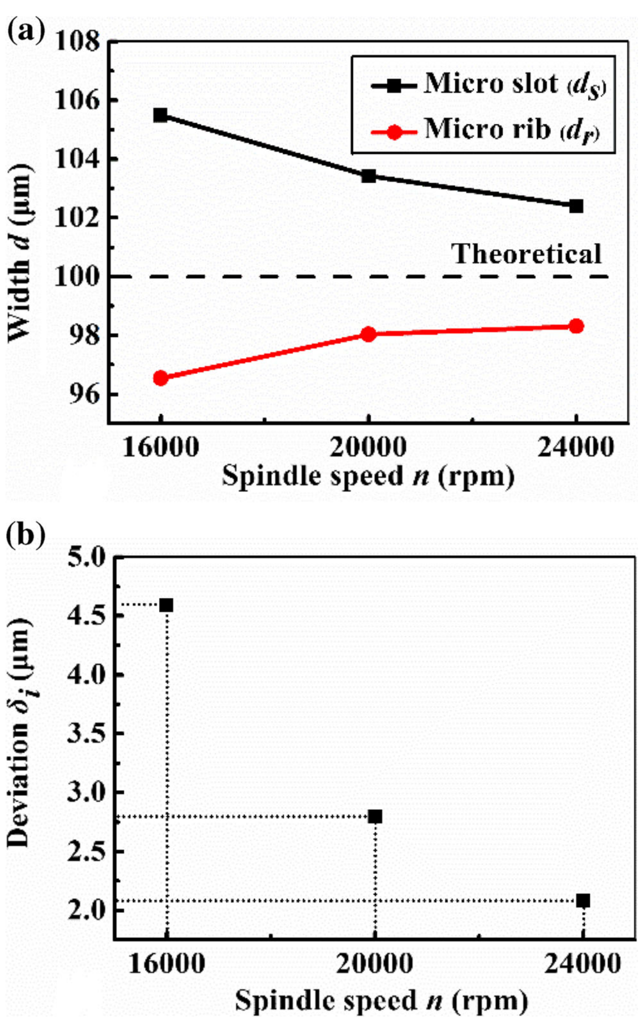


Fig. 11 Effect of spindle speed on dimensional accuracy

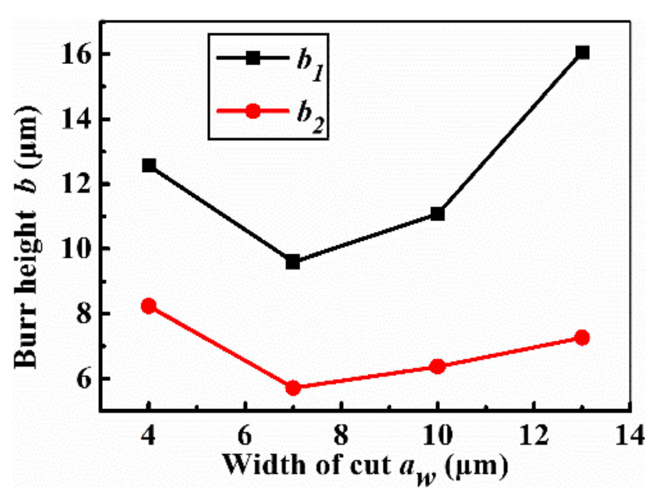


Fig. 12 Influence of width of cut on top burr formation

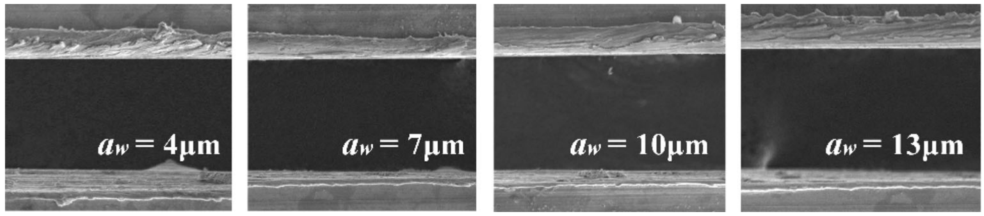


Fig. 13 SEM pictures of top burrs formed at various widths of cut

most approaching to the target of 100 μm when the feed per tooth is 6 μm/tooth, and the minimum comprehensive deviation of the dimension also occurs at feed per tooth of 6 μm/tooth. The micro cutting tool with a single edge is prone to instability, since there is always either one cutting edge in contact with the workpiece or no contact with the workpiece, which induces periodic variation of the cutting force. When the feed per tooth is smaller than 6 μm/tooth, ploughing is the dominant mechanism, and the worse dimensional accuracy may be one of the aspects of the famous size effect phenomenon arising from ploughing. When the feed per tooth is greater than 6 μm/tooth, the effect of feed per tooth becomes more similar to that of conventional cutting, and cutting forces increase with the increase of feed per tooth, which induces more deformation of the ribs and makes the dimensional accuracy worse.

Figure 11 demonstrates the effect of spindle speed on dimensional accuracy of the copper grating. It is clearly indicated in Fig. 11 that there is a beneficial influence on the width of micro slots and micro ribs as spindle speed is increased, and the spindle speed of 24,000 rpm is recommendable for the control of dimensional feature. As greater spindle speed means greater cutting speed, it can be stated that in the analyzed range, relatively high cutting speed is more favorable.

4.2 Effect of cutting parameters on burr formation

In micro cutting process, burr formation has a significant influence on workpiece quality; particularly, top burrs of the micro slots greatly affect the optical performance of the grating, such as diffraction and reflection efficiency. The suppression of burr formation in cutting miniature components is very important for the purpose of avoiding burr removal post-processing [28].

It is illustrated in Figs. 12, 14, and 15 that top burr height b_1 is always higher than b_2. And, it is interesting to note that these observations could be found regardless of the variation of width of cut, feed per tooth, and spindle speed. The tool structure shown in Fig. 4 is also the most reasonable explanation for this phenomenon. As the tool edge structure causes more unnecessary secondary cutting, it also introduces more burr accumulation simultaneously.

Burr height at various widths of cut is plotted in Fig. 12. The width of cut has a strong effect on top burr height b_1 of the copper grating, while the effect on top burr height b_2 is on such a low level that can be ignored especially when the width of cut is larger than 7 μm. The tendency is toward higher burr height with increase in width of cut when the width of cut is greater than 7 μm. While the width of cut is smaller than 7 μm, the burr height decreases with increase in width of cut. The minimum burr height is observed at width of cut of 7 μm. One potential explanation for this correlation is that more tool passes introduce more contact between the tool and the workpiece, and therefore, more top burrs are accumulated at both sides of the channel (see Fig. 13). It is clearly presented in Fig. 13 that there are more top burrs accumulated and even scrolled at width of cut of 4 μm compared with that at width of cut of 7 μm. With further increase in width of cut, the material removal in once pass of the tool increases so that higher top burrs are produced. That is why burr height increases with the increase of width of cut when the width of cut is larger than 7 μm.

Burr formation as a function of feed per tooth f_z is summarized in Fig. 14. Top burrs first show reduction in height with the increase of feed per tooth, and with further increase in feed per tooth, burr height tends to increase. It is revealed from the figure that top burr height b_2 reaches a minimum level at feed per tooth of 6 μm/tooth, followed successively by $f_z = 4.5$ μm/tooth. Notably, the top burr height b_1 changed rather slightly when the feed per tooth ranged from 3 to 6 μm/tooth. Thus, it can be concluded that the smallest top burr height was

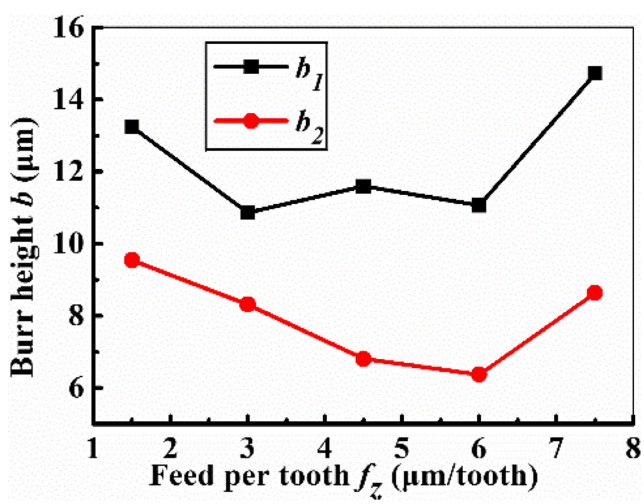


Fig. 14 Influence of feed per tooth on top burr formation

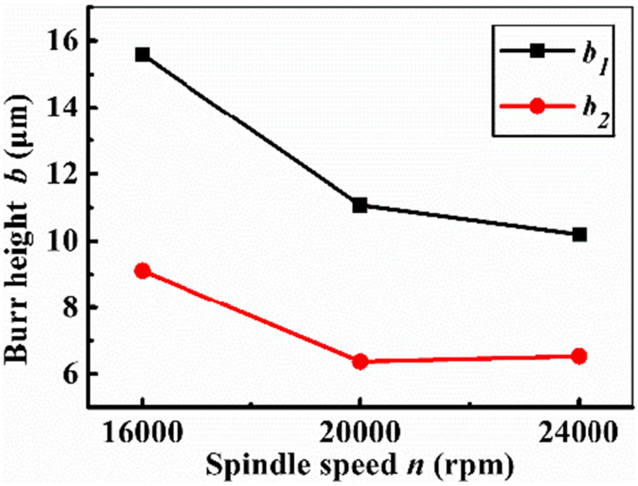


Fig. 15 Influence of spindle speed on top burr formation

experienced at feed per tooth of 6 μm/tooth. The different changing trend of top burr height b_1 and b_2 at feed per tooth from 3 to 6 μm/tooth can be well explained by the secondary cutting caused by the tool structure. To avoid the influence of the unnecessary secondary cutting, this study only took account of top burr height b_2 when analyzing the effect of feed per tooth on burr formation. When the feed per tooth is of the same order as the tool edge radius, the effective rake angle may become negative. Size effect resulting from a small ratio of feed per tooth to the tool edge radius will be a dominant factor for the material removal mechanism in micro cutting [29]. Ploughing will occur, predominated by this ratio, and will eventually affect burr formation. When the feed per tooth is much less than 6 μm/tooth, ploughing is dominant in the cutting mechanism. The extruded materials accumulated at both sides of the channel, producing a considerable burr formation. When the feed per tooth is around 6 μm/tooth, whole chip formation was observed, the burrs were the accumulation of the uncut chip, and thus, burr height tends to increase when the feed per tooth is larger than 6 μm/tooth.

The changing trend of top burr height with the variation of spindle speed is illustrated in Fig. 15. It is obviously exhibited in the picture that top burr heights b_1 and b_2 show the similar tendency, and the optimal results of burrs on both sides occur at the spindle speed of 24,000 rpm. This finding is in accord with the conclusion drawn in [27]; for diamond tools, comparatively high cutting speeds help to reduce burr formation, although more experimental data are needed further to verify this observation.

Generally, good dimensional precision normally corresponds to small top burr height, which makes cutting parameter optimization less complex. It can be concluded from the results above that it is judicious to select width of cut of 7 μm, feed per tooth of 6 μm, and spindle speed of 24,000 rpm with respect to obtaining optimal dimensional accuracy and minimum burr formation. As an example, a designed grating of copper with 20 mm in width and length of 20 mm, as exhibited in Fig. 16, was fabricated with the self-developed micro cutting tools by utilizing the optimized processing parameters. It is illustrated in the close-up picture in Fig. 16 that the copper grating is characterized by a good dimensional precision and excellent quality with only a few top burrs. In fact, the grating features an average micro rib width of 99.07 μm, micro slot width of 101.25 μm, and average top burr height b_1 of 6.23 μm and top burr height b_2 of 3.54 μm.

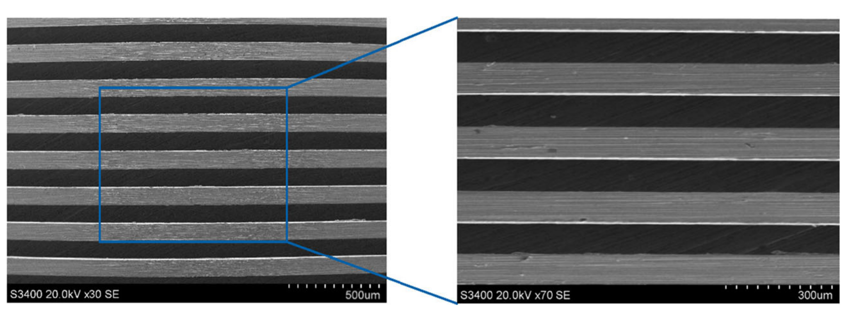
Additionally, the self-developed PCD micro cutting tool has a larger material removal rate than the PCD micro end-milling tool employed in the comparative study, and the quality of the grating machined by the self-developed tools is also much better than that machined by end milling as shown in Fig. 17. In other words, the self-developed micro cutting tool is more efficient and has the ability to machine micro parts with better quality as compared with the previous PCD end mills.

5 Conclusions and outlook

In this work, an investigation was conducted on micro cutting of copper grating. The following specific conclusions have been drawn from this study:

- PCD micro cutting tools with sharp and high wear resistance cutting edge were designed and fabricated. They are capable of efficiently generating micro channel arrays with high quality.

Fig. 16 Close-up of the copper grating



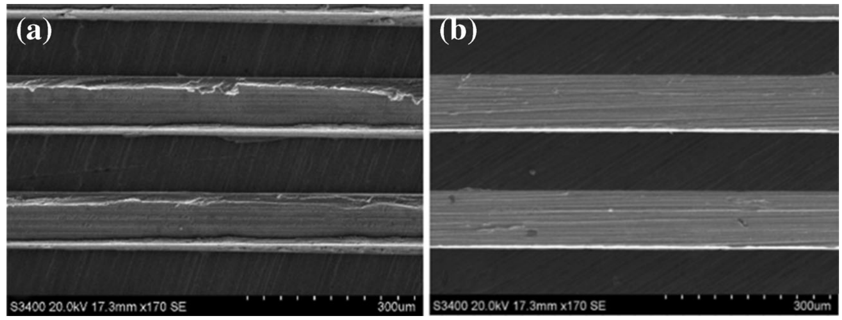


Fig. 17 The copper grating machined by **a** a previous PCD micro end-milling tool and **b** the self-developed PCD micro cutting tool

- The effect of parameters on dimensional accuracy and burr formation was investigated. A medium level of width of cut and relatively high feed per tooth and spindle speed are favorable with regard to achieving accurate dimension and minimum burr formation, whereas the relations of width of cut, feed per tooth, spindle speed to dimensional accuracy, and burr formation are not simply linear due to the possible influence of ploughing effect, tool structure, and run-out of the spindle.
- A complete copper grating was machined successfully, and it is characterized by excellent dimensional accuracy and has only a few top burrs on both sides of the micro slots.

The micro cutting tools proposed in this paper will be optimized in further research. Another future effort will be directed toward micro channel arrays of other materials, such as difficult-to-process material titanium-based alloys, tungsten, and ceramics.

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