Int J Adv Manuf Technol (2017) 90:1165–1176
DOI 10.1007/s00170-016-9413-7

ORIGINAL ARTICLE

Fast generation of micro structured surface by applying PCD tools in micro turning

Jianguo Zhang[1] · **Quansong Li**[1] · **Hui Zhang**[1] · **Qinglong Cui**[1] · **Tao Cui**[1] · **Cheng Ge**[1] · **Zhen Sun**[1] · **Defu Zhang**[1]

Received: 13 January 2016 / Accepted: 29 August 2016 / Published online: 19 September 2016

Abstract This paper studies the fast generation of micro structured surface by means of micro polycrystalline diamond (PCD) tools, which are manufactured by applying the wire cut electrical discharge machining (WEDM). Firstly, the fabrication of micro PCD tools is introduced in the WEDM process. Furthermore, by applying the micro cutting tools, the micro structures are directly fabricated on the alumina workpiece with just a simple micro turning process, which verifies the feasibility of the proposed microfabrication method. Following that, the tool wear in the micro turning process is also investigated. Although there is no considerable tool shape deterioration and tool edge damage, the adhesion of the workpiece material to the cutting edge is observed, which may cause the increase of cutting forces and the decrease of the machining accuracy. As following, a series of fundamental micro turning tests are conducted, and the influence of cutting conditions on the machined structure quality is investigated in detail. Finally, it is proposed that the micro/nano structures can also provide the self-cleaning properties due to the low surface energy. The proposed microfabrication process is expected to become a potential method for the fast generation of micro structured surface in the future.

Keywords Micro structured surface · Micro PCD tool · WEDM · Micro turning

✉ Jianguo Zhang
zhangjg@ciomp.ac.cn

1 Engineering Research Center of Extreme Precision Optics, State Key Laboratory of Applied Optics, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, No. 3888, East of Nanhu Road, Changchun 130033, China

1 Introduction

Structured surfaces with sophisticated micro/nano structures can provide advanced and useful functions. Structured surfaces have been increasingly demanded in various applications, such as optics [1–3], solar energy technology [4, 5], bioengineering [6–8], self-cleaning [9, 10], advanced manufacturing [11–13], and so on [14, 15]. To promote widespread use of the functional structured surfaces in the practical industries, the manufacturing technology of miro/nano structures is absolutely essential. When the feature size is downscaled into micrometer or nanometer level, those fabrications may become extremely challenging. To overcome this problem, numerous methods for the micro/nano structure fabrication have been proposed so far. As the diamond machining has a large dimension span in the micro/nano structure fabrication, which is flexible and capable for many different designs. Ultra-precision diamond cutting is superior to produce ultra-precision and sophisticated structures in the feature size of several to hundreds micrometers practically. It also has many advantages of high geometrical accuracy, good surface quality, and high machining efficiency. Commercial diamond cutting machines are generally available for machining axisymmetric or free-form optical surfaces [16–18], and hence, quickly popularizes among the related industries. Recently, the micro diamond cutting is one of the most important machining technologies for fabricating the complex micro structures. For example, the micro diamond milling is frequently utilized for fabrication of the simple micro grooves and micro dimples [19]. A high-speed spindle with a hydrostatic bearing is generally utilized, and specially designed micro milling tool made of diamond is mounted. Although a series of micro V-shaped, trapezoid-shaped, R-shaped, and square grooves are successfully fabricated with high machining accuracy, the micro milling process expresses the shortages of low machining efficiency and difficult tool setting. Among a series of diamond cutting techniques, the micro diamond turning process is hoped as one of the simple and efficient methods for the fast generation of micro/nano structures. The tool setting is simple, and the arbitrary designed geometries of micro tools can be directlly transferred to the workpiece material with high machining accuracy. Moreover, combination of the micro diamond turning and the fast tool servo (FTS) technology possibly enables the highly efficient fabrication of complex micro/nano structures in a variety of applications [16, 20, 21].

It is well known that the single crystal diamond (SCD) tool is usually applied to the ultra-precision diamond machining process, which can be obtain both the sharp cutting edges and the high hardness. However, its cleavage feature and anisotropy of mechanical properties to SCD tool often cause practical problems in particular applications [22]. For example, Chen et al. [23] reported that the chipping of SCD tool usually occurs when fabricating the diffraction optics. Zhang et al. [24] considered that the SCD tool damage is due to the accumulation of small-scale chippings of the tool cutting edge. Although the fine tool sharpness can be obtained in SCD tool, the tool damage or breakage occurs easily. On the other hand, the hardness of PCD material is nearly close to that of SCD. Although the cutting edge is not sharp in the commercial PCD tool due to the relatively large size of the diamond grain, the PCD tool can also be successfully applied to the untra-precision machining process. With the development of the micro PCD milling tool, micro Fresnel molds and micro dimple lens are successfully fabricated on the tungsten carbide [25, 26]. With the assistant of ultrasonic vibration turning, the precision machinability of tungsten carbide and hardened steel is confirmed by using PCD tools [27, 28]. Moreover, the feasibility of precision machining of glass and ZrO_2 is also verified by applying the micro PCD grinding tools [29, 30]. Recently, a novel nano-polycrystalline diamond, which has the nano size diamond grains (10–50 nm) bonded directly to form a dense structure without any binder materials, was developed by Sumitomo Electric Industries, Ltd. [22, 31]. Due to the extremely high hardness, high wear resistance, no anisotropic mechanical properties, no cleavage feature, and high thermal stability, the nano-polycrystalline diamond is one of the excellent potential materials for precise cutting tool manufacture in the future. Moreover, the cost of PCD is much lower as compared with the SCD, which makes the PCD tool more suitable in the precision industrial applications. In order to obtain the fast generation of micro structures, the micro turning process equipped with the micro PCD tool was investigated in this paper.

In order to perform the micro turning process, the fabrication of micro cutting tool is an important issue. In recent years, the micro grinding, focused ion beam (FIB) milling, and micro electrical discharge machining (EDM) are applied to the fabrication of micro cutting tools [26, 29, 32, 33]. Compared with the micro grinding process, the macroscopic mechanical force is very small in the FIB and EDM process, which does not cause the workpiece deformation. As compared with the EDM process, FIB milling has the disadvantages of low removal rate, time-consuming nature, and high cost. Recently, the wire electrical discharge machining (WEDM) is considered as one of the effective methods for the micro tool processing. By precisely controlling the relative movement between the wire guider and the tool, various complex micro structures can be fabricated as the micro tool cutting edges. Fleischer et al. [34] manufactured a micro end milling tool with 100 μm diameter using the WEDM process, confirming that the WEDM has an advantage of acceptable machining time and tolerable costs. Yan et al. [35] fabricated a micro end milling tool on tungsten carbide by WEDM process, and a series of micro rectangular grooves were fabricated on nickel-plated steel. Zhang et al. [36] also fabricated a series of micro square grooves on the cemented carbide cutting tool edge by applying WEDM process and successfully applied it to the fast generation of micro square structures in turning process. Zhang et al. [26] fabricated a micro hemispherical PCD end milling tool by applying WEDM, and the micro dimples on tungsten carbide were successfully fabricated. Gao et al. [37] fabricated the PCD micro milling tool by WEDM process, and the roughing and finishing optimal parameter values were investigated. The excellent feasibility of micro PCD tool processing was experimentally confirmed by applying the WEDM process. Nowadays, a series of novel methods are also proposed to improve the machined profile accuracy in WEDM process. For example, in order to enhance the profile machining accuracy, Werner [38] proposed an online feedback measurement method, Wang et al. [39] proposed a axial electrolyte flow method, and Sarkara et al. [40] proposed a wire lag model in WEDM process. With the increase of machining accuracy, WEDM becomes more and more suitable for the fabrication of micro PCD tools.

In this paper, a method for the fast generation of micro structures is introduced in turning process by applying the micro PCD tools, which are fabricated in WEDM process. Firstly, the micro machining process is introduced. The target micro structures are fabricated on the PCD as the tool cutting edge, and then the envelop of the cutting edge is directly transferred into the workpiece in the turning process. The efficiency of the micro structure fabrication can be increased efficiently by applying the proposed method. Following that, the fabrications of micro PCD tools are introduced in detail by applying the WEDM process. In order to improve the accuracy of the fabricated tool shape, the motion path of the cutting wire, the sparking gap, and the discharging energy are considered. Then, the edge radius of the fabricated micro tools is measured by applying a surface profiler, which is helpful to determine the minimum depth of cut in the micro turning process. After that, the micro PCD tools are equipped to an ultra-precision turning machine tool, and the feasibility of fast generation of micro structures is experimentally verified. Following that, a series of fundamental micro turning tests are conducted in order to investigate the influence of cutting conditions on the machined structure quality. Finally, it is proposed that the optical elements with the micro/nano structures may provide both the advanced optical and the self-cleaning properties.

2 Target structure fabrication on PCD material in WEDM process

Commercial PCD tool inserts (Grade D10, SANDVIK Co., Ltd) were used as the workpiece material for the micro tool fabrication in the WEDM process. The micro cutting tools were designed with a clearance angle of 5° and a rake angle of 0°. In the WEDM process, the cutting wire is made of CuZn37 coated with special layer, which is fabricated by Agie Charmilles Co., Ltd. The radius of the cutting wire is 50 μm. Figure 1 shows the experimental setup for fabricating the micro PCD turning tools. A precision WEDM machine named Agie Charmilles CUT3000 is used, which has a positioning resolution of 0.1 μm in each axes. The lower guide head is fixed in the present WEDM machine system. With adjusting the position of upper guide head under *x*-axis and *y*-axis controlling, the designed clearance angle can be obtained when fabricating the micro cutting tool. In order to obtain the designed rake angle, the tool position can be modulated in the *x*-*z* plane by positioning the tool jig, as shown in Fig. 1. The tool jig is mounted on a movable table which can move in the horizontal plane under *u*-axis and *v*-axis controlling. The designed geometric profiles of the micro cutting tool can be successfully fabricated by positioning the *u*-axis and *v*-axis.

The micro PCD tools with the simple profiles, i.e., the triangular shape and the square shape, are fabricated by applying the WEDM process. In order to improve the accuracy of the fabricated tool shape, the motion path of the cutting wire, the sparking gap, and the discharging energy are considered in the WEDM process. Figure 2 shows the micro tools fabricated by applying the WEDM process. The tool geometries were examined by using an optical microscope. A designed intersection angle of 105° is fabricated on the micro triangular tool.

Following that, the edge radius of the micro cutting tools is measured by applying a surface profiler (Taylor Hobson PGI 1250S). In advance of the measurement, the tool is cleaned with acetone carefully. Subsequently, the tool edge is vertically placed beneath the probe, as shown in Fig.3a. Figure 3b shows a measurement result of the tool cutting edge. A stylus with a radius of 2 μm is used in the measurement. Based on the measured profile which is the motion path of the stylus center position, the actual measured profile can be obtained in Fig.3b. Hence, the edge radius r_e of the fabricated micro tools can be calculated as about 4.5 μm, which is between the 1.8 μm reported by Zhang et al. [26] and 6.7 μm reported by Gao et al. [37] when fabricating the micro PCD tools in WEDM process.

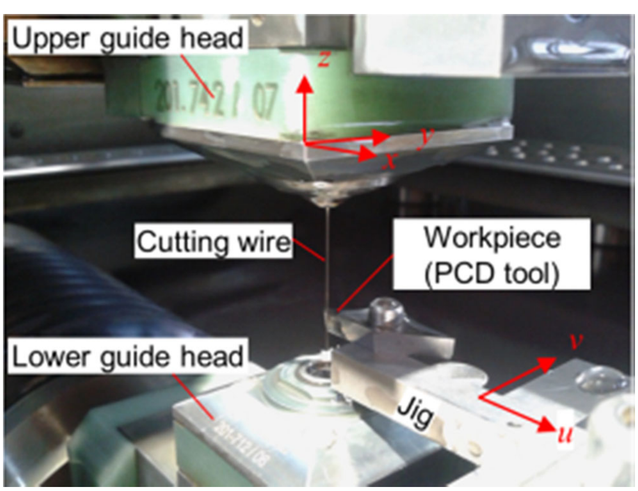


Fig. 1 Experimental setup for the fabrication of micro cutting tool

3 Fast generation of micro structures by applying the micro PCD tools

3.1 Experimental setup

In order to verify the feasibility of micro structure fabrication, a series of turning process are carried out by applying the fabricated micro PCD tools. The designed micro structures are fabricated on the aluminum alloy (Al6061), which is adopted as the workpiece material in the present research. The experimental setup is shown in Fig. 4. A precision machine tool Microturn 1000 V made by Hembrug Machine Tool Corp. is used for the target structure fabrication. A positioning resolution of linear axes is 10 nm. The workpiece with a diameter of 100 mm is fixed to the top surface of B-axis, and the rotation velocity is set to be 5 rpm. The maximum nominal cutting speed is calculated as about 1.5 m/min. The tool is set to be along the Z-axis direction, and the rake face of the cutting tool is vertical to the cutting direction. With the designed depth of cut, a simple face turning process is carried out by just controlling the motion of X-axis.

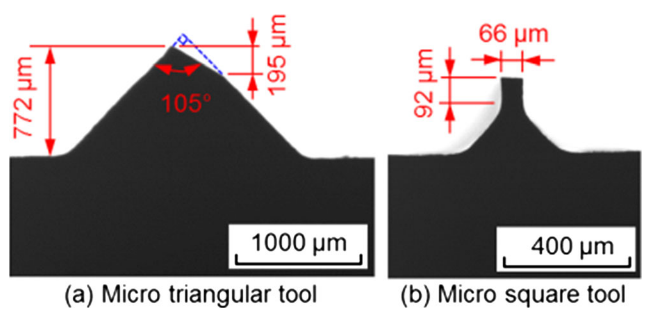


Fig. 2 **a**, **b** Micro tools fabricated by applying WEDM process

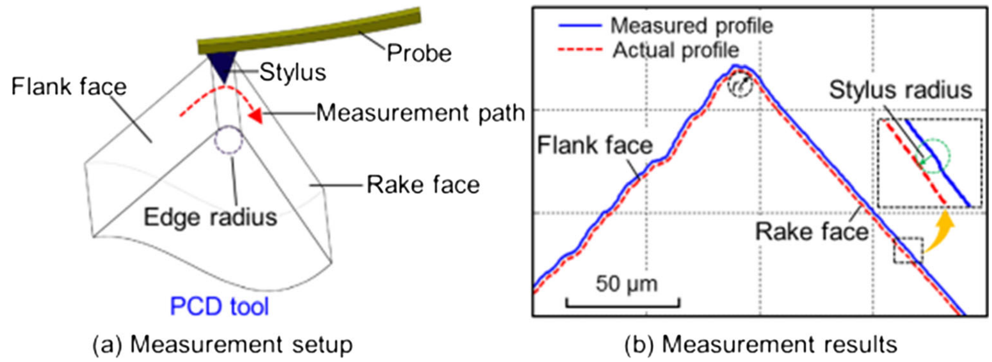


Fig. 3 **a** Measurement setup and **b** results in obtaining the tool edge radius

3.2 Feasibility of micro structure fabrications

In advance of the micro fabrication process, a flat surface with a surface roughness of Rz 25 nm is prepared on the workpiece material by applying a SCD tool. As following, the fabricated micro triangular tool in Fig. 2a is applied to the fabrication of micro triangular structures in turning process. In the micro turning process, the minimum uncut chip thickness (MUCT) should be considered in order to improve the machining accuracy. Malekian et al. [41] clarified that the MUCT in micro machining of aluminum Al6061 is about $0.23r_e$, where r_e is the edge radius of cutting tool. Below the MUCT, the cutting process is dominated by a plowing process, which is a type of plastic deformation of the workpiece material without chip formation. The plowing process causes the increase of edge force and the deterioration of finished surface quality, i.e., burr generation and plastic recovery of workpiece material. It should be noted that the uncut chip thickness is the same as the depth of cut in this present research. Moreover, the edge radius r_e of the fabricated micro tools was measured as about 4.5 μm as shown in Fig. 3b. Hence, the MUCT should be adopted as larger than 0.9 μm based on the Malekian's research results. In the present research, a much larger depth of cut is applied to the micro turning process in order to decrease the plowing process. Table 1 shows the experimental conditions, including details for subset conditions A and B in which cutting speed, feed, and depth of cut were varied. Figure 5 shows an optical photograph and a measured profile of the fabricated triangular structures under conditions subset A. The sharp edges on the top surface can be successfully obtained. The average pitch value is measured as 40.2 μm, and the measured structure height is about 16.5 μm.

It should be noted that the profile along the feed direction in Fig. 5b is measured by applying the aforementioned surface profiler (Taylor Hobson PGI 1250S). The stylus radius of 2 μm should be considered in analyzing the measurement results. Because of this nature, in terms of the curvature, there is no restriction in measuring the convex structures. On the other hand, for concave structures measurement in the present research, the curvature restriction needs to be taken into account. If the machined corner radius r_2 is larger than the stylus radius r, as shown in Fig. 6, the measured corner radius r_1 is calculated as $r_1 = r_2 - r$. As the measured corner radius r_1 is 2.9 μm as shown in Fig. 5b, the actual machined corner radius r_2 is about 4.9 μm in considering the stylus radius r of 2 μm. The value of the machined corner radius is similar as the measured edge radius of the micro cutting tool in Fig. 3b.

Figure 7 shows an optical photograph and a measured profile of the fabricated triangular structures under conditions

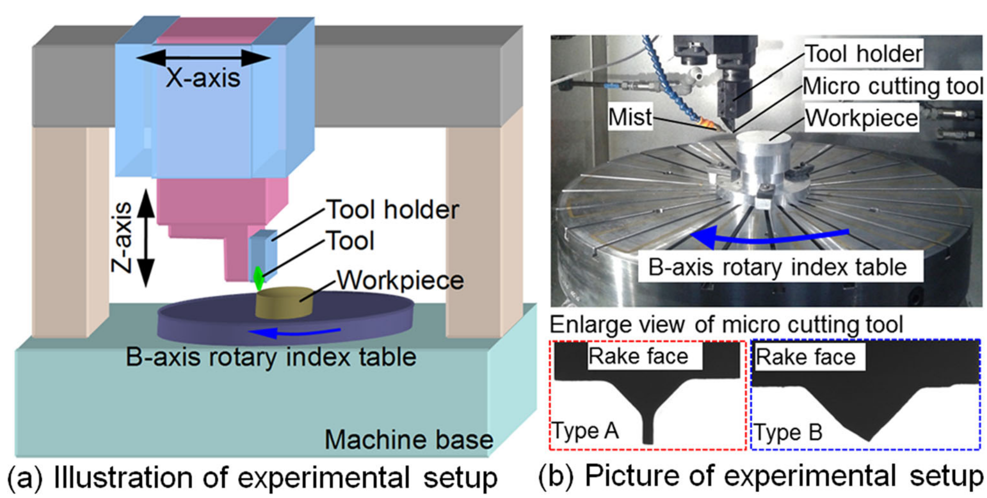


Fig. 4 **a** Illustration and **b** picture of experimental setup for micro structure fabrication in turning process

Table 1 Experimental conditions for micro triangular structures fabrication

Conditions		A	B
Cutting conditions	Cutting speed [mm/min]	265–415	640–825
	Depth of cut [μm]	20	125
	Feed [μm/r]	40	400
Tool	Rake angle [degree]	0	
	Clearance angle [degree]	5	
Workpiece	Aluminum alloy	Al6061	

subset B. With a large depth of cut of 125 μm and a large feed value of 400 μm, the triangular grooves can also be successfully fabricated by applying the micro triangular tool. It is experimentally verified that the strength of micro tool is enough with a large material removal ratio. It is advantageous to improve the micro machining efficiency.

As following, the tool wear was also investigated. Figure 8 shows the tool cutting edges after the micro turning process in the fabrication of triangular structures and grooves. Although the adhesion of the workpiece material can be observed on the rake face of the tool, the tool geometries in the cutting regime keep stable. It shows that the clear tool cutting edges and the sharp corner of the cutting tool can be obtained in Fig. 8b with no considerable tool wear.

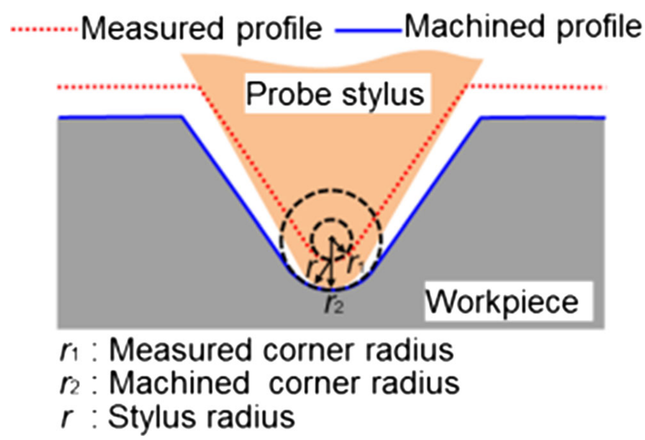


Fig. 6 Relationship between the measured profile and the actual machined profile

As following, the feasibility of micro square structures fabrication is also investigated by applying the micro square tool as shown in Fig. 2b. The experimental conditions are summarized in Table 2.

Figure 9 shows an optical photograph and a part of measured profile of the fabricated square structures. The average pitch value is almost equal to the designed value of 120 μm because of the stable feed value of the precision turning

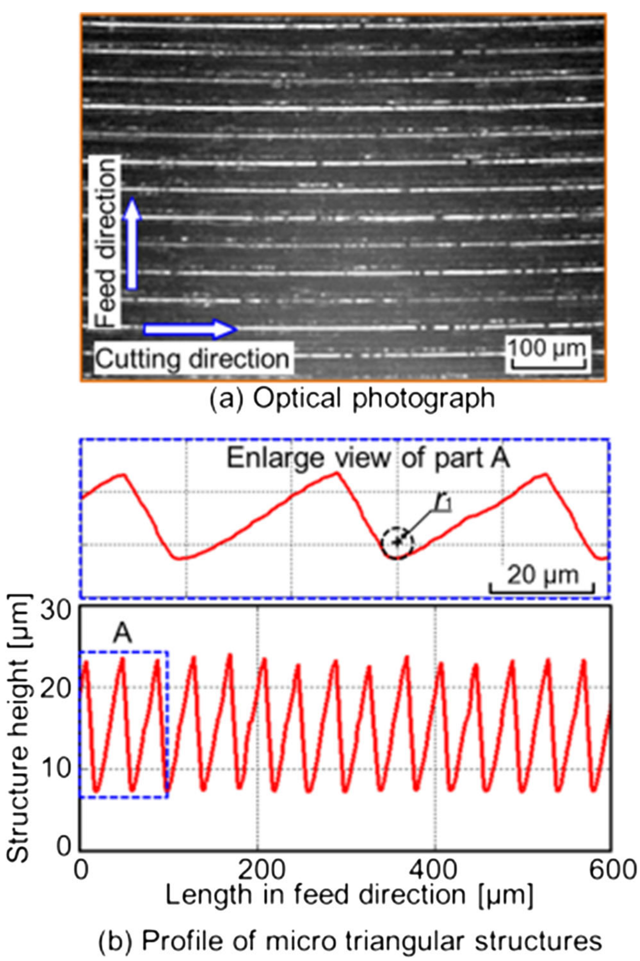


Fig. 5 **a** Optical photograph and **b** a feed direction profile of the fabricated micro triangular structures

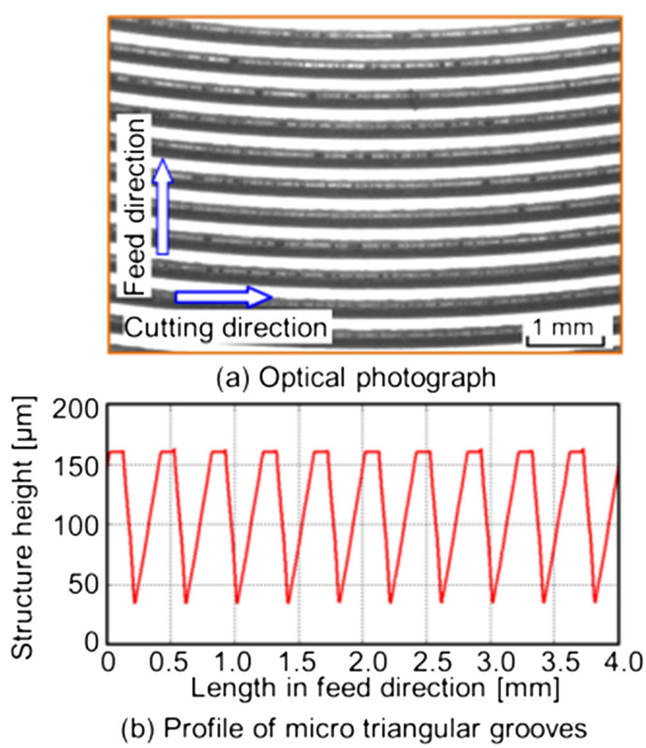
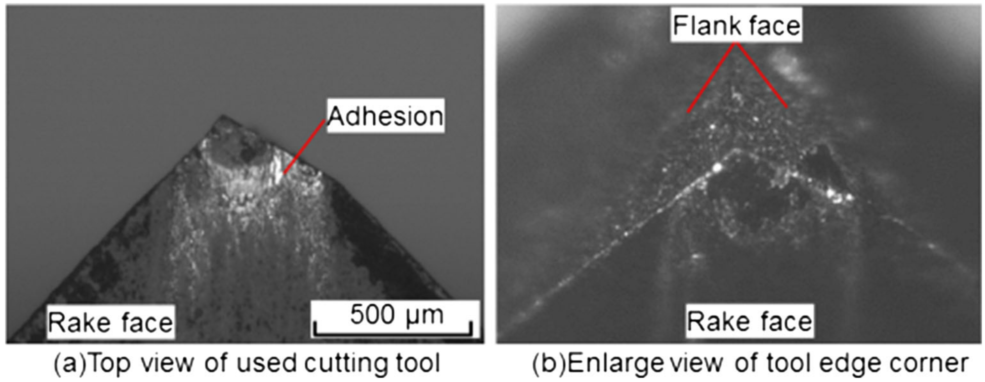


Fig. 7 **a** Optical photograph and **b** a feed direction profile of the fabricated micro triangular grooves

Fig. 8 **a**, **b** Optical images of the micro triangular tool after turning process



machine tool. The measured structure height is about 56.2 μm, which is a little smaller than the designed value of 60 μm.

As following, the tool wear was also investigated. Figure 10 shows the tool cutting edges after the micro turning process in the fabrication of square structures. Although the sharp corner of the tool cutting edges can keep stable, the adhesion of the workpiece material to the cutting edges becomes serious. This phenomenon increases the edge radius of the cutting tool, which causes the increase of edge force and cutting forces. The motion of workpiece material being pushed may be huge at the bottom of the cutting edge. This pushing process may also cause the burr generation in micro machining of the square groove. Moreover, it was observed that the designed square structures are changed into the trapezoidal structures because of the elastic/plastic deformation of the workpiece material under the large cutting forces, as shown in Fig. 9. In the future, the micro tools equipped with the elliptical vibration cutting process [42–44] may be a potential method to reduce the cutting forces and the adhesion in the micro turning process, which is advantageous to improve the machining accuracy in the micro/nano structure fabrications.

3.3 Influence of cutting parameters on the machined micro structure quality

As known, the cutting parameters have a significant influence on the machined structure quality in the micro machining process. As introduced in Fig. 9, the burrs are generated on the edge of the micro square structures, which causes the decreasing of the machining accuracy in the micro structure fabrication process. Hence, it is necessary to indicate the appropriate cutting conditions to accurately and efficiently fabricate the micro structures in this research. As following, a series of micro square grooves are fabricated by applying the micro square tools in the turning process. In order to indicate the variation of the cutting forces, a dynamometer is adopted in the micro turning. The experimental setup is shown in Fig. 11. A groove with the width of 10 mm and the depth of 1 mm was fabricated on the top surface of the workpiece, which is advantageous to monitoring the cutting forces in each turning cycle.

At first, the influence of depth of cut on the machined structure quality is investigated in an empirical manner.

Table 2 Experimental conditions for micro square structures fabrication

Cutting conditions	Cutting speed [mm/min]	1570–825
	Depth of cut [μm]	60
	Feed [μm/r]	120
Tool	Rake angle [degree]	0
	Clearance angle [degree]	5
Workpiece	Aluminum alloy	Al6061

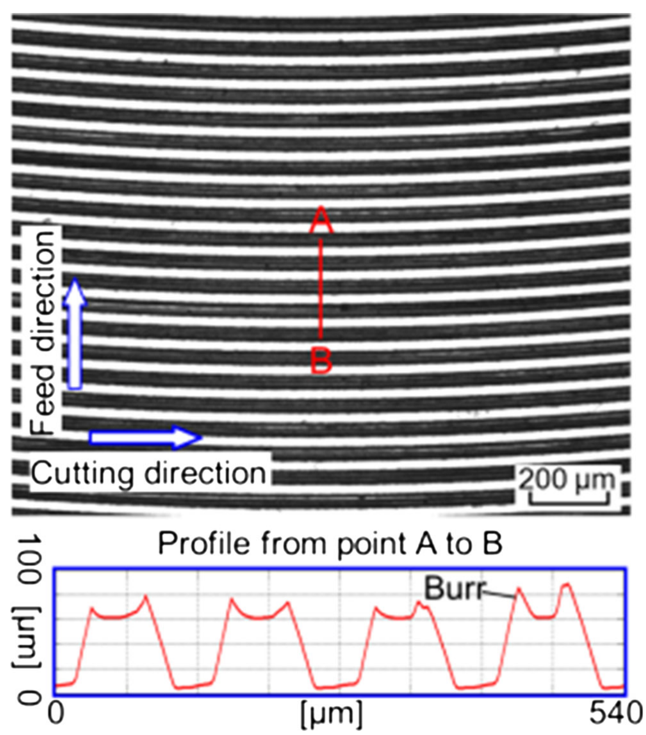


Fig. 9 Optical photograph and a feed direction profile of the fabricated micro square grooves

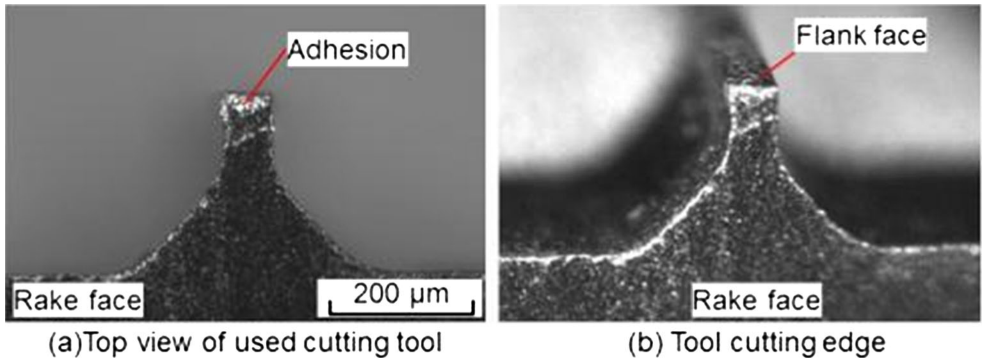


Fig. 10 **a**, **b** Optical images of the micro square tool after turning process

Asakura and Yan [45] clarified that the size of the burr depends strongly on the depth of cut, and the burr formation can be suppressed with a smaller depth of cut. Figure 12 demonstrates the micro square structures fabricated with the different depth of cut in the present experiments. The pitch value of the neighboring square grooves is 300 μm. The cutting speed is adopted as an almost stable value of 1.57 m/min, and a similar micro square tool as shown in Fig. 2b is utilized.

Surface quality of the fabricated micro structures changes depending on the depth of cut in the proposed micro turning process. As shown in Fig. 12, inconspicuous burrs are generated with the depth of cut not larger than 10 μm. In contrast, the burrs are obviously generated on the edge of the micro grooves with the depth of cut larger than 15 μm. With the increase of the depth of cut, the plastic deformation ability of the workpiece material becomes larger, which results in the serious burr generation in the present investigations. Based on the abovementioned experiments, a depth of cut less than or equal to 10 μm should be adopted in order to accurately fabricate the micro structures. Moreover, the variation of cutting forces, i.e., principal forces and thrust forces, is also investigated with the increase of the depth of cut. As shown in Fig. 13, both the principal forces and the thrust forces become larger as increasing the depth of cut from 0 to 20 μm. At the small depth of cut, the thrust force in the micro turning is dominant due to the existence of the cutting edge radius as introduced in Fig. 3. The radius of cutting edge is about 4.5 μm, which cannot be ignored as comparing with the adopted depth of cut. In case of a small depth of cut compared to the tool edge radius, some workpiece material is deformed, uncut, underneath the tool in the micro turning process. The force associated with this phenomenon is defined as the plowing force. The arc cutting edge generally initiates the plowing process, where the large thrust force generates due to the contact of flank face to workpiece. For example, the principal force is smaller than the thrust force at the small depth of cut of 5 and 10 μm, as shown in Fig. 13d. On the other hand, the chip formation process becomes dominant at a large depth of cut in the micro turning process. The workpiece material is mainly removed by the rake face of the cutting tool with the shear deformation. As shown in Fig. 13d, the principal force becomes larger than the thrust force with increasing the depth of cut to 20 μm. At the depth of cut of 10 μm, the principal force is almost equal to the thrust force, and the chip formation process plays an important role in the material removal process.

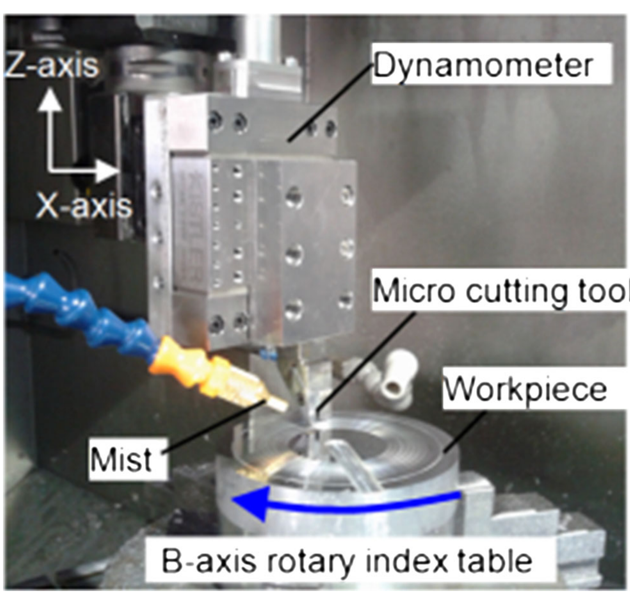


Fig. 11 Micro turning process with the cutting forces detecting

Moreover, the influence of cutting speed on the machined structure quality was also investigated. Based on the abovementioned micro turning results, a depth of cut of 10 μm was adopted in the following experiments. The pitch value of the neighboring square grooves is 300 μm, and a micro square tool as shown in Fig. 2b is utilized. The cutting speed v is changed from 1.57 m/min to the maximum value of 15.7 m/min. The top surfaces of the fabricated micro square grooves are measured by applying an optical microscope, as shown in Fig. 14.

All of the fabricated micro square grooves almost have the same surface quality. Inconspicuous burrs are measured at the side edge of the square grooves, and strong relationship between the cutting speed and the machined structure quality

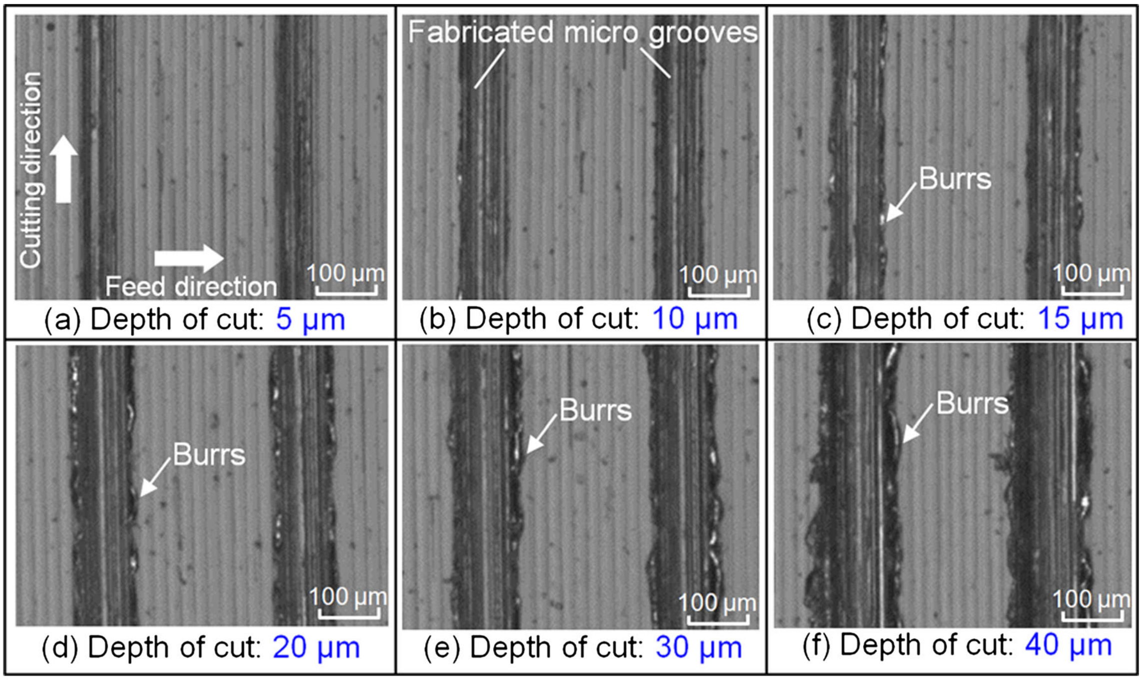


Fig. 12 **a**–**f** Micro square grooves fabricated with the different depth of cut

cannot be found. Furthermore, the variation of cutting forces with the different cutting speed is also investigated, as shown in Fig. 15. Although the different cutting speed is adopted, the cutting forces keep the stable average values, i.e., the thrust force of 3.4 N and the principal force of 2.7 N. In the proposed micro turning process, the edge force (for plowing) on the tool flank face and the shear force (for chip formation) on the tool rake face have little relationship with the cutting speed. In order to improve the machining efficiency, a larger cutting speed of 15.71 m/min can be adopted in the micro square structure fabrication process. About 3 min was taken for the micro square grooves fabrication on the workpiece with a diameter of 100 mm. The pitch value of the square grooves is 300 μm, and with a depth of cut of 10 μm.

Furthermore, as introduced in Fig. 10, the adhesion of the workpiece material to the cutting edges becomes serious in fabricating the micro square structures. Hence, the influence of cutting distance on the cutting forces variation is also experimentally certified. A depth of cut of 10 μm and a constant cutting speed of 1.57 m/min were adopted in the following experimental investigations. Figure 16 shows the variation of measured cutting forces with the increase of the cutting

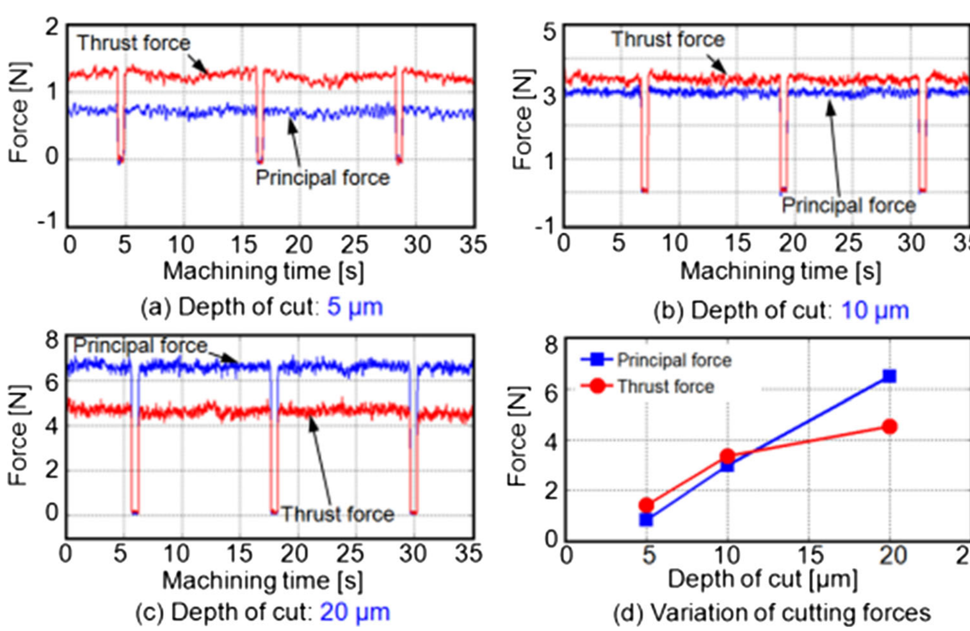


Fig. 13 **a**–**c** Cutting forces at different depths of cut and **d** the variation of cutting forces with the increase of the depth of cut

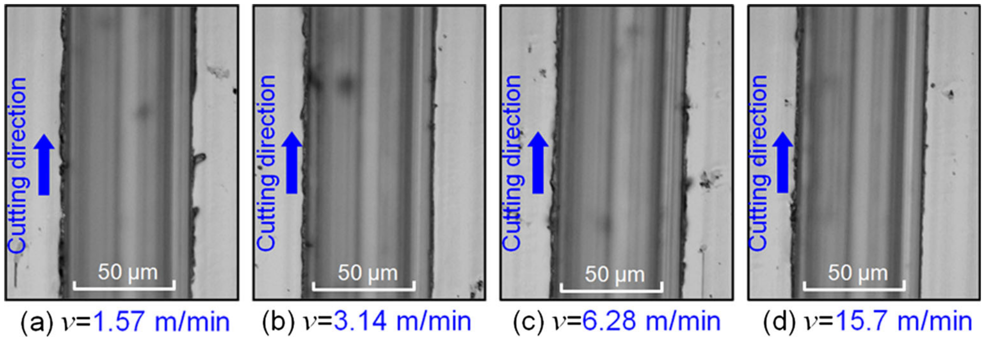


Fig. 14 a–d Effect of the cutting speed on the machining quality of micro structures

distance. Although no obvious tool wear was measured after the experiment, the adhesion of the workpiece material to the cutting edges occurs. At the cutting distance of about 100 m, both the principal force and the thrust force increase as compared with those values at the beginning of cutting of 0.6 m. However, the increase ratio of the thrust force is a little larger than that of the principal force. It is assumed that the adhesion of the workpiece material to the cutting edge becomes serious with the increasing of the cutting distance. This phenomenon may increase the edge radius of the cutting tool and cause the increase of edge forces and cutting forces. Hence, a novel micro turning method with the reduction of the cutting forces and the adhesion should be applied to the proposed micro structure fabrication process in the future.

3.4 Application of the textured surface

Furthermore, it is well known that the applications of micro structured surfaces have been widespread in recent years. The textured surface with micro/nano structures can also provide hydrophobic function because of its low surface energy [46, 47]. Different types of micro structures, e.g., shallow cavities and micro grooves, can be applied as hydrophobic surfaces as reported by Bico et al. [9]. For example, Fig. 17 shows the shapes of water drop (1 μL) on the flat surface and the textured surface with the micro triangular structures in Fig. 5.

Surface hydrophobicity is often characterized by the water contact angle. For the flat surface, the water droplet tends to be a spherical shape due to its minimal energy state [48]. For the textured surface with the micro triangular structures fabricated in the present research, the water drop tends to be compressed in the feed direction, which indicated that a larger contact angle can be obtained. The image of the water droplet was taken from the side direction with a digital camera, and the contact angle of the water droplet can be measured. Figure 18a shows a schematic of a water droplet on the flat surface. The contact angle is almost isotropic, and with a value of 32°. Figure 18b shows the water droplet observed along the parallel direction (direction 1) and the perpendicular direction (direction 2) as indicated in Fig. 12. The contact angle is measured as 105° and 73°, respectively, which are both larger than the value of 32° obtained on the flat surface. Moreover, the water droplet is ellipsoidal due to the different expansion behavior of the water droplet on the micro grooved surface [45].

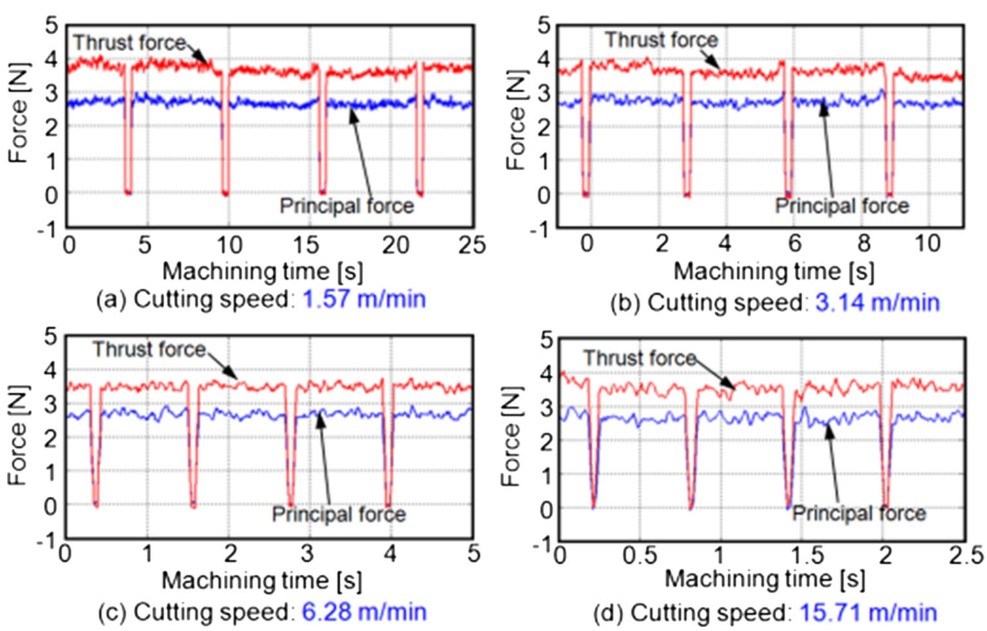


Fig. 15 a–d Variation of cutting forces with the increase of the cutting speed

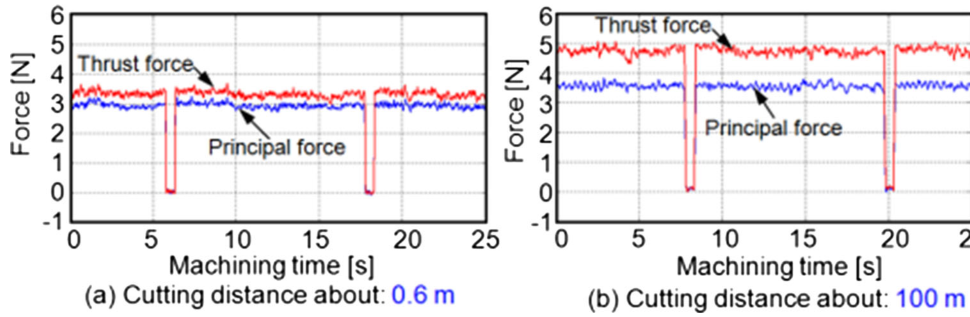


Fig. 16 **a**, **b** Variation of cutting forces with the increase of the cutting distance

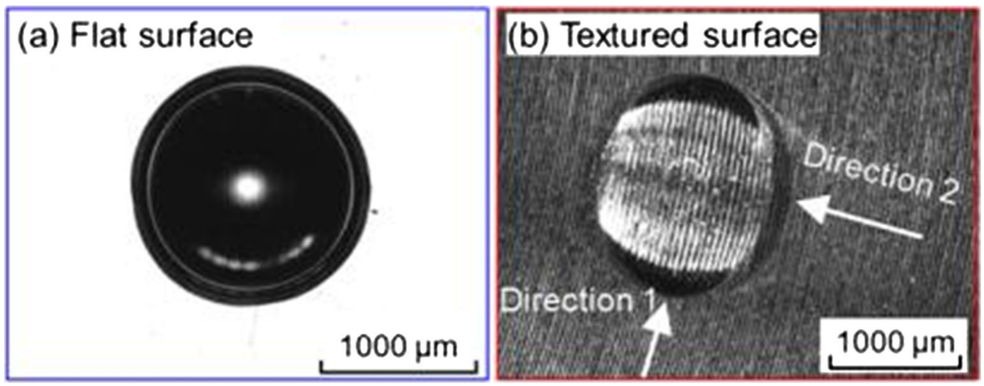


Fig. 17 Top view of water drops on **a** flat and **b** textured surfaces

This phenomenon is helpful to facilitate the water drop to roll off the textured surface. For example, with the combination of optical micro structure and the hydrophobic function, the fabricated optical elements can be applied to some special environments with both optical and self-cleaning properties. It allows dirt and water to simply wash off and decreases the cost by nonuse of cleaning chemicals.

4 Conclusion

Based on the experimental study, it is confirmed that practical fast generation of micro structured surface is feasible by means of the micro PCD tools fabricated in the WEDM process. Firstly, the fabrications of micro PCD tools are introduced in detail by applying the WEDM process. And then, the edge radius of the fabricated micro tools is measured as 4.5 μm. After that, the micro PCD tools are equipped to an ultra-precision turning machine tool, and the feasibility of fast generation of micro structures is experimentally verified. The triangular structures with a pitch value of 40.2 μm, and a structure height of 16.5 μm was successfully fabricated. With the increase of material removal ratio, the triangular grooves with a large depth of cut of 125 μm can be successfully fabricated by applying the fabricated micro triangular tool. It is experimentally verified that the strength of micro tool is enough with a large material removal ratio. After the experimental verifications, no considerable tool wear is observed. Following that, the fabricated micro square tool is applied to the fabrication of micro square structures. Due to the adhesion of the workpiece material to the cutting edge, the edge force is seriously increased which causes the machining accuracy deterioration because of the elastic/plastic deformation of the workpiece material under the large cutting forces. As following, the influence of cutting conditions on the machined micro structures quality is investigated. A depth of cut

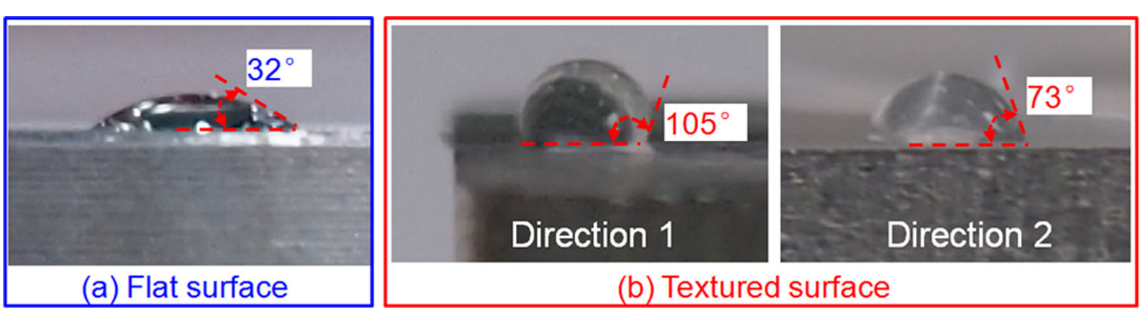


Fig. 18 Contact angle measured on **a** the flat surface and **b** the textured surface

of smaller than 10 μm and a large cutting speed of about 15.71 m/min are advantageous to reduce the burr generation and improve the machining efficiency. Finally, it is proposed that the optical elements with the micro/nano structures maybe can provide both advanced optical and self-cleaning properties, which is helpful to promote the applications of the optical elements in some special environments.

Acknowledgments We acknowledge Agie Charmilles Co., Ltd., Hembrug Machine Tool Co., Ltd., and SANDVIK Co., Ltd. for their experimental support. We thank the National Basic Research Program of China (Grant No. 2009ZX02005) and the National Natural Science Foundation of China (Grant No. 61504142) for the financial support.

References

1. Shieh HPD, Huang YP, Chien KW (2004) Micro-optics components for liquid crystal displays applications. In Proceedings of the 24th International Display Research Conference, Daegu, Korea. 56–58
2. Schumann M, Bückmann T, Gruhler N, Wegener M, Pernice W (2014) Hybrid 2D-3D optical devices for integrated optics by direct laser writing. Light: Sci Appl 3:e175. doi:10.1038/lsa.2014.56
3. Sun YL, Dong WF, Niu LG, Jiang T, Liu DX, Zhang L, Wang YS, Chen QD, Kim DP, Sun HB (2014) Protein-based soft micro-optics fabricated by femtosecond laser direct writing. Light: Sci Appl 3: e129. doi:10.1038/lsa.2014.10
4. Xie WT, Dai YJ, Wang RZ, Sumathy K (2011) Concentrated solar energy applications using Fresnel lenses: a review. Renew Sust Energ Rev 15:2588–2606
5. Yang J, Luo FF, Kao TS, Li X, Ho GW, Teng JH, Luo XG, Hong MH (2014) Design and fabrication of broadband ultralow reflectivity black Si surfaces by laser micro/nano processing. Light: Sci Appl 3:e185. doi:10.1038/lsa.2014.66
6. Miyoshi H, Adachi T, Ju J, Lee SM, Cho DJ, Ko JS, Uchida G, Yamagata Y (2012) Characteristics of motility-based filtering of adherent cells on microgrooved surfaces. Biomaterials 33:395–401
7. Lewis PR, McCutchen CW (1959) Experimental evidence for weeping lubrication in mammalian joints. Nature 184:1285
8. Henry S, McAllister DV, Allen MG, Prausnitz MR (1998) Microfabricated micro-needles: a novel approach to transdermal drug delivery. J Pharm Sci 87:922–925
9. Bico J, Marzolin C, Quéré D (1999) Pearl drops. Europhys Lett 47: 220–226
10. Callies M, Chen Y, Marty F, Pepin A, Quere D (2005) Microfabricated textured surfaces for super-hydrophobicity investigations. Microelectronics. Engineering 78-79:100–105
11. Gao W, Dejima S, Kiyono S (2005) A dual-mode surface encoder for position measurement. Sensors Actuators A 117:95–102
12. Gao W, Kimura A (2007) A three-axis displacement sensor with nanometric resolution. CIRP Ann Manuf Technol 56:529–532
13. RM W, Li HF, Zheng ZR, Liu X (2011) Freeform lens arrays for off-axis illumination in an optical lithography system. Appl Opt 50: 725–732
14. Evans CJ, Bryan JB (1999) Structured", "textured" or "engineered" surfaces. CIRP Ann Manuf Technol 48:541–556
15. Vaezi M, Seitz H, Yang SF (2013) A review on 3D micro-additive manufacturing technologies. Int J Adv Manuf Technol 67:1721–1754
16. Fang FZ, Zhang XD, Weckenmann A, Zhang GX, Evans C (2013) Manufacturing and measurement of freeform optics. CIRP Ann Manuf Technol 62:823–846
17. Brinksmeier E, Gläbe R, Schonemann L (2012) Review on diamond-machining processes for the generation of functional surface structures. CIRP J Manuf Sci Technol 5:1–7
18. Zhu ZW, To S (2015) Adaptive tool servo diamond turning for enhancing machining efficiency and surface quality of freeform optics. Opt Express 23: 20234–20248
19. Sawada K, Kawai T, Takeuchi Y, Sata T (2000) Development of ultraprecision micro grooving (manufacture of V-shaped groove), JSME international journal. Series C: mechanical systems. Mach Elements Manuf 43:170–176
20. Zhang X, Liu Q, Zhou XQ, Lin C (2015) Determining issues in optimal turning of micro-structured functional surfaces. Int J Adv Manuf Technol 81:387–396
21. DP Y, Gan SW, Wong YS, Hong GS, Rahman M, Yao J (2012) Optimized tool path generation for fast tool servo diamond turning of micro-structured surfaces. Int J Adv Manuf Technol 63:1137–1152
22. Sumiya H, Harano K (2012) Distinctive mechanical properties of nano-polycrystalline diamond synthesized by direct conversion sintering under HPHT. Diam Relat Mater 24:44–48
23. Chen YL, Cai YD, Shimizu Y, Ito S, Gao W, BF J (2016) On-machine measurement of microtool wear and cutting edge chipping by using a diamond edge artifact. Precis Eng 43:462–467
24. Zhang JG, Suzuki N, Wang YL, Shamoto E (2014) Fundamental investigation of ultra-precision ductile machining of tungsten carbide by applying elliptical vibration cutting with single crystal diamond. J Mater Process Technol 214:2644–2659
25. Suzuki H, Moriwaki T, Yamamoto Y, Goto Y (2007) Precision cutting of aspherical ceramic molds with micro PCD milling tool. CIRP Ann Manuf Technol 56:131–134
26. Zhang ZY, Peng HM, Yan JW (2013) Micro-cutting characteristics of EDM fabricated high-precision polycrystalline diamond tools. Int J Mach Tools Manuf 65:99–106
27. Nath C, Rahman M, Neo KS (2009) Machinability study of tungsten carbide using PCD tools under ultrasonic elliptical vibration cutting. Int J Mach Tools Manuf 49:1089–1095
28. Zhang XQ, Kumar AS, Rahman M, Nath C, Liu K (2011) Experimental study on ultrasonic elliptical vibration cutting of hardened steel using PCD tools. J Mater Process Technol 211: 1701–1709
29. Perveen A, San WY, Rahman M (2012) Fabrication of different geometry cutting tools and their effect on the vertical micro-grinding of BK7 glass. Int J Adv Manuf Technol 61:101–115
30. Chen ST, Lai YC, Liu CC (2008) Fabrication of a miniature diamond grinding tool using a hybrid process of micro-EDM and co-deposition. J Micromech Microeng 18:055005
31. Harano K, Satoh T, Sumiya H (2012) Cutting performance of nano-polycrystalline diamond. Diam Relat Mater 24:78–82
32. Morgan CJ, Vallance RR, Marsh ER (2004) Micro machining glass with polycrystalline diamond tools shaped by micro electro discharge machining. J Micromech Microeng 14:1687–1692
33. ZW X, Fang FZ, Zhang SJ, Zhang XD, XT H, YQ F, Li L (2010) Fabrication of micro DOE using micro tools shaped with focused ion beam. Opt Express 18:8025–8032
34. Fleischer J, Masuzawa T, Schmidt J, Knoll M (2004) New applications for micro-EDM. J Mater Process Technol 149:246–249
35. Yan JW, Uchida K, Yoshihara N, Kuriyagawa T (2009) Fabrication of micro end mills by wire EDM and some micro cutting tests. J Micromech Microeng 19:025004
36. Zhang JG, Li QS, Zhang H, Sui YX, Yang HJ (2015) Investigation of micro square structure fabrication by applying textured cutting tool in WEDM. Micromachines 6:1427–1434
37. Gao C, Zhan Z, Wang S, He N, Li L (2013) Research on WEDM process optimization for PCD micro milling tool. Procedia CIRP 6: 209–214

38. Werner A (2015) Method for enhanced accuracy in machining curvilinear profiles on wire-cut electrical discharge machines. Precis Eng 44:75–80
39. Wang SH, Zeng YB, Liu Y, Zhu D (2011) Micro wire electrochemical machining with an axial electrolyte flow. Int J Adv Manuf Technol 63:25–32
40. Sarkara S, Sekhb M, Mitraa S, Bhattacharyya B (2011) A novel method of determination of wire lag for enhanced profile accuracy in WEDM. Precis Eng 35:339–347
41. Malekian M, Mostofa MG, Park SS, Jun MBG (2012) Modeling of minimum uncut chip thickness in micro machining of aluminum. J Mater Process Technol 212:553–559
42. Shamoto E, Moriwaki T (1994) Study on elliptical vibration cutting. CIRP Ann Manuf Technol 43:35–38
43. Ma CX, Shamoto E, Moriwaki T, Zhang YH, Wang LJ (2005) Suppression of burrs in turning with ultrasonic elliptical vibration cutting. Int J Mach Tools Manuf 45:1295–1300
44. Kim GD, Loh BG (2010) Machining of micro-channels and pyramid patterns using elliptical vibration cutting. Int J Adv Manuf Technol 49:961–968
45. Asakura K, Yan JW (2015) Water repellency control of oxygen-free copper surface by diamond-cut micro grooves. Int J Autom Technol 9:396–402
46. Bhushan B, Jung YC, Koch K (2009) Micro-, nano- and hierarchical structures for superhydrophobicity, self-cleaning and low adhesion. Phil Trans R Soc A 367:1631–1672
47. Lu Y, Guo P, Pei PC, Ehmann KF (2015) Experimental studies of wettability control on cylindrical surfaces by elliptical vibration texturing. Int J Adv Manuf Technol 76:1807–1817
48. Guo P, Lu Y, Ehmann KF, Cao J (2014) Generation of hierarchical micro-structures for anisotropic wetting by elliptical vibration cutting. CIRP Ann Manuf Technol 63:553–556