Int J Adv Manuf Technol (2012) 61:101–115
DOI 10.1007/s00170-011-3688-5

ORIGINAL ARTICLE

Fabrication of different geometry cutting tools and their effect on the vertical micro-grinding of BK7 glass

Asma Perveen · Wong Yoke San · Mustafizur Rahman

Received: 6 October 2010 / Accepted: 4 October 2011 / Published online: 26 October 2011

Abstract With the demand for microstructures of not only with diversified shape but also of reduced dimension on glass, fabrication of polycrystalline diamond (PCD) tool/ microelectrodes with different shape has become important. However, to date, fabrication of different shapes in single setup is not possible and also needs special indexing attachment. To solve this problem, in this study, a specially designed block containing three v-slots of 60°, 90°, and 120° has been designed and fabricated using wire cut. Thereafter with the help of block electro-discharge machining method and using this specially designed block, different shapes of microelectrodes with symmetrical and non-symmetrical section has been fabricated. This study also investigates the feasibility of using these different geometry PCD tool for micro-grinding of BK7 glass. In this context, a relative study on the micro-grinding performance of four different geometry tools (circular, D-shaped, triangular, and square) has been carried out. It has been observed that among the different shaped tools, D-shaped tool experienced lowest cutting force along *x*- and *y*-axes where as triangular tool faced lowest force along *z*-axis, and highest cutting forces were found to be experienced by square tool. Average and maximum roughness of machined surface was found to be improved from circular to others tool except triangular one. But, it was also observed that side surface started to deteriorate from circular to other tool due to edge wear. In case of tool wear, square and triangular tool experienced more wear than circular and D-shaped tool due to their frequent edge blunting or rounding effect. Finally, among four different geometry tools, D-shaped tool was considered to provide better performance in terms of the achieved surface finish, tool wear, and cutting force analysis.

Keywords Micro-grinding · PCD tool · On-machine tool fabrication · Block micro-EDM process · BK7 glass

A. Perveen (✉) · W. Y. San · M. Rahman
Department of Mechanical Engineering,
National University of Singapore,
10 Kent Ridge Crescents,
Singapore 119260, Singapore
e-mail: perveen.asma@gmail.com

1 Introduction

The demand for fabricated glass has been increasingly rising to generate diversified functionalities on optical devices, micro-molds and micro-fluidics devices due to their attractive features like high strength, wear resistance, and good chemical stability [1, 2].

For certain applications, like DNA micro-arrays, glass component with micro-features are typically produced by photolithography and etching process that is time consuming and may involve hazardous chemical. Hence, it would be a better idea to produce these glass micro-features by mechanical processes [2]. Literature review shows that many researchers have studied glass machining process which involves single-point diamond turning tool [3, 4], conventional grinding wheel [5–12], and milling cutter [13–15]. However, the hardness and brittleness of glass makes these mechanically micro-machining processes problematic due to damage resulting to brittle fracture, cutting force-induced tool deflection or breakage, and tool wear [16]. On the other hand, micro-tools made of polycrystalline diamond (PCD) meet up this challenge for micro-machining of hard and brittle materials. PCD tool containing micrometer-sized diamond grains is manufactured by sintering under high temperature and pressure with metallic cobalt. The cobalt fills the interstices between the diamond particles [17, 18]. Besides this, sintered tungsten carbide, which is next to diamond in hardness, is often used to produce these tools components in tool manufacturing industries. These two materials are very popular due to their high hardness and low wear characteristics. Moreover, PCD has added advantage of possessing small diamond grain where each grain acts as one cutting edge. As a result, abrasive material like glass can be micro-machined by these diamond cutting edges.

Due to heavy industrial demand of three-dimensional complex micro-shapes, fabrication of different shape tool has got importance in addition to commercial ones. Generally, it has two purposes; on-machine fabrication minimizes clamping error and freedom of desired shape and size of tool. Several methods are available to meet these requirements. Among these methods, focused ion beam, mechanical diamond grinding, and diamond turning have been most extensively used [19]. However, the fabrication of such tools by diamond grinding gives rise to difficulties, associated with high cost of diamond wheel due to large consumption of diamond. Besides this, diamond grinding is characterized by significant mechanical and thermal impact on the work piece resulting in the formation of split and flaw [20]. As a result, conventional tool fabrication processes including grinding and turning which apply large force to work piece cannot be applied due to low strength of small-sized tool [21]. In addition to this, focused ion beam is problematic as it has Gaussian distribution that causes material removal at the axis of beam rather than around the periphery [22]. On the other hand, whereas the efficiency of traditional cutting processes is limited by the mechanical properties of the processed material and the complexities of work piece geometry, electro-discharge machining is not subjected to such restrains. Electro-discharge machining(EDM), now a day is extensively and successfully applied for difficult-to-cut material [20]. Concerted research efforts have been directed towards the development of fabrication technologies for microelectrodes using micro-EDM. Among all these methods, wire electro-discharge grinding (WEDG) method, mesh method, EDM block method, LIGA, and other micromechanical machining method are commonly practiced. The block EDM method has been extensively used due to its lower investment cost and easy setup. More importantly, it makes possible on-machine fabrication of electrode, which reduces electrode installation cost and error [23]. In addition to this, with micro-EDM technology, there is no direct contact between electrode and work piece, thus eliminating mechanical stress, chatter, and vibration problems [24]. The Block EDM process for fabricating different geometry of tungsten electrodes has been investigated first by Ravi et al. [23]. The authors used special indexing attachment for fabricating different shaped tool. However, conical-shaped tool cannot be fabricated even by using this special indexing attachment. On the other hand, using the specially designed block proposed in this paper makes it possible to fabricate all useful shapes of grinding tools. The machining of different shapes of grinding tool by micro-EDM has been possible due to different angle of the blocks which overcome the limitations of the indexing attachment used in a previous study. We believe that this is a significant contribution and this type of process has never been approached by researchers before, as known from literature.

In addition, Morgan et al. [16, 25] has fabricated the PCD and tungsten carbide tool combining the process of the wire EDG and micro-EDM. The study involved only the preliminary test of micro-grinding of soda lime and ultralow expansion glass and micro-drilling of conductive material using fabricated tools. However, the authors have not conducted micro-grinding on different varieties of glass materials. More importantly, they have not focused on micro-grinding of BK7 glass, which is a widely used commercial glass. Moreover, the authors have not focused on the detail investigation of cutting forces, surface roughness, and tool wear. On the other hand, our study has focused on these important aspects of micro-grinding and presented a complete study including design, fabrication, and experimentation.

Jiwang et al. [26] studied the fabrication of end-mill tools by wire EDM process where the tool material was tungsten carbide. The objective was to machine rectangular groove on nickel-plated steel and to investigate the effect of tool geometry on the burr formation and tool wear. Our study is different from this study as we have used the fabricated tools for micro-grinding of glass and studied the cutting forces, tool wear, and surface finish. Shun et al. [27] also investigated the feasibility of fabricating different shaped PCD tool using combined wire EDM and precision co-deposition method. The objective was to use those fabricated tools for grinding of ZrO2 ceramics. A similar study by Jung et al. reported same technique of combined EDM and co-deposition to fabricate the spherical tool for grinding nickel alloy mould [28]. In addition, several researchers have used micro-EDM and micro-grinding hybrid process for fabricating simple-shaped grinding tool for machining different materials. Masaki et al. has applied micro-EDM technique for fabricating spherical tool for grinding concave spherical surface on silicon [29]. Egashira et al. fabricated micro-drilling tool of D-shape using WEDG for making micro-hole on silicon wafer [21]. Wada et al. also fabricated PCD micro-grinder using WEDG for micro-grinding of tungsten material [30]. Our study is different from those studies, as our study mainly focused on the design of a special block by which we can fabricate different geometry grinding tools for micro-grinding of glass. In addition, our study compared the performance of those tools with different geometry by analyzing cutting forces, tool wear, and machined surface roughness. Again, Fang et al. has investigated the effect of tool geometry using FEM analysis to understand the tool life [31]. Torres et al. has compared the performance of diamond-coated micro-tool with that of uncoated tool on an aluminum work piece. The diamond tool has been fabricated by the chemical vapor deposition of diamond film on tungsten carbide tool. Tool with mono-crystalline coating seems to perform better than fine-grained diamond-coated tool [32]. Similar work has been conducted by Smith et al., where diamond-coated fibers produced by the chemical vapor deposition on grinding wheel work as abrasive grains [33]. Although, these studies also involved the tool fabrication processes, they are different from our study of fabrication of different geometry tools using specially designed block. The major advantage of using on-machine-fabricated tool is that it can reduce the run out error, which is very critical for micron-sized tool. Moreover, our study includes the tool geometry effect on the cutting forces, surface roughness, and tool wear during micro-grinding process, which allows the selection of optimum grinding parameters and tool geometry for grinding of BK7 glass.

In our previous work, we have used block EDM method only for shaping circular tool using simple tungsten block [34]. Different geometry tool has not been tried and was not possible with that tungsten block even. Therefore, in this study, modification of block EDM method for fabrication of electrodes of various useful shapes in existing single-machine setup has been chosen and with those on-machine-fabricated electrodes, micro-features of different types can be nicely fabricated on glass. Although numerous researches have been conducted on grinding of glasses and silica using commercially available diamond grinding wheels [5–7], the application of this newly developed on machined fabricated PCD micro-tool has not yet been studied extensively. A number of issues remain to be solved before the usage of this on-machine-fabricated PCD micro-tool as a micro-grinder will become a well accepted process for glass machining, especially in industries. Moreover, extensive researches on the selection of optimum tool geometry for improved surface finish, reduced cutting forces, and less wear particularly in the case of this newly developed PCD micro-tools seems to be still scarce.

Hence, this paper intends to investigate the possibility of on-machine fabrication of PCD tools of different geometry using modified block EDM process for glass micro-grinding. Moreover, the effect of tool geometry on cutting forces, achieved surface finish, and tool wear during the micro-grinding of BK7 glass has also been studied.

2 Experimental setup and methodology

2.1 Machine tool

A multi-purpose miniature machine tool that has been developed for high-precision micro-machining at the National University of Singapore is used for conducting the block EDM on PCD tool material and micro-grinding of glass with this on-machine-fabricated tool as well. The capability of this machine can be extended from micro-EDM to micro-turning, micro-grinding, micro-milling and micro-ECM. The maximum travel range of the machine is 210 (x)×110 (y)×110 mm (z) with the resolution of 0.1 μm in x-, y-, and z-directions, respectively. In addition, each axis has optical linear scale with the resolution of 0.1 μm, and full closed feedback control ensures the accuracy of sub-micron. Figure 1 gives schematic diagram of experimental setup with multi-purpose miniature machine tool.

2.2 Materials

The work piece material used in this study is Bk7 glass. The work piece was fabricated and ground to 10.0 mm thickness with a length of 25 mm and width of 25 mm. Commercially available polycrystalline diamond tool containing 0.5 micron grain size is used as micro-grinder after shaping. Diamond grains are exposed after conducting block EDM that acts as a hard and tough cutting edge for micro-machining. The sacrificial electrode material for PCD shaping used in here was pure tungsten (99.9% W) block of a length of 4.5 cm, width 1.3 cm, and height 0.5 cm with negative polarity. The dielectric fluid used in this study is EDM oil having relatively high flash point, high auto-ignition temperature, low viscosity, and high dielectric strength. The EDM oil has served both the purpose of dielectric during PCD tool fabrication and coolant during glass micro-grinding. The important properties of the sacrificial W block and EDM 3 oil are presented in Tables 1 and 2, respectively.

2.3 Methodology

For the fabrication of different geometry tool, specially prepared fixture was used. The block containing three v-slots was manufactured by wire EDM. Prior to using PCD tools for micro-grinding, the tool was first fabricated with a two-step process using block micro-block EDM and scanning micro-EDM with a polished flat surface. The use of a specially designed conductive block as a tool electrode and the PCD rod as a work piece in block micro-EDM has been identified as a useful approach for producing microelectrodes of different shapes due to its low investment cost and quick setup rather than WEDG [35]. A tungsten block of higher wear resistance was used for this specially designed block fabrication, which

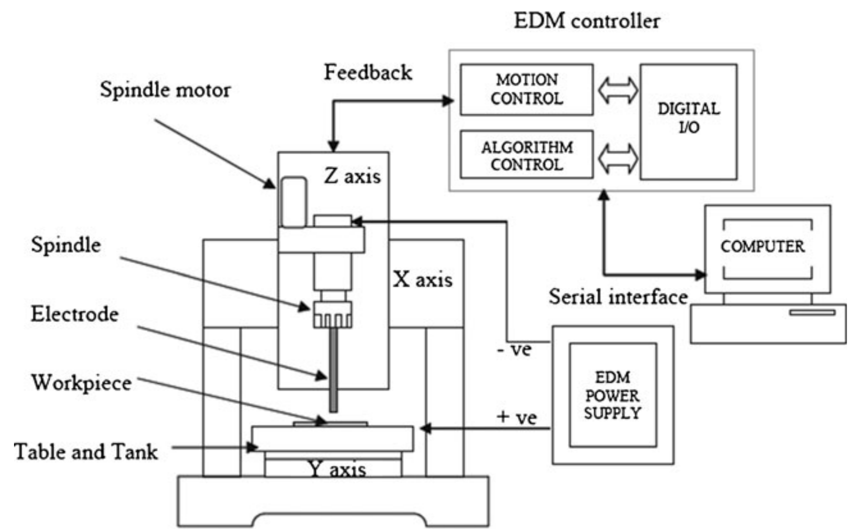

Fig. 1 Schematic diagram of the setup with multi-purpose miniature machine tool

is used for PCD tool fabrication later on. During the tool fabrication process, the tool was set in positive polarity and the tungsten block was used as negative polarity. When a voltage is applied between the rod and block, an intermittent spark occurs between the inter-electrodes gap. Subsequently, the spark caused a rise in the surface temperature of both the block and the rod to a point where the temperature exceeded the melting point of the materials. Consequently, a small amount of material is removed from both the electrodes and flushed away from the machine zone using side flushing. In this process, varying capacitance and voltage can control surface roughness. Side surface of tool was prepared using 1,000 pF and 100 V, for bottom surface 100 v and 100 pF was used. After the fabrication of PCD tool with desired shape and surface finish using micro-EDM, the tool was used for glass grinding on the same machine without changing the tool from collet. During glass micro-grinding, the specimen was mounted on top of a three-component force dynamometer (KISTLER type 9345) fixed on the machine table. The dynamometer was connected to a charge amplifier (KISTLER type 5007) from which the output voltage signals were fed into a digital data recorder and the signals were recorded at a sampling frequency of 180 kHz. Thereafter, average diameter and length of the microelectrodes were measured and examined using Keyence optical microscope and SEM. Figure 2a shows the photograph of the setup representing glass micro-grinding with micro-EDM of PCD tool. The schematic diagram of the setup for glass micro-grinding is illustrated in Fig. 2b.

2.4 Fabrication of fixture

For the fabrication of square, circular, D-shaped, triangular, and conical-shaped tool of 60°, 90° and 120, a fixture was manufactured which made possible the fabrication of all these shapes in single setup. For this purpose, Makino conventional horizontal wire EDM machine was used, the ultra-high accuracy UPJ-2 automatically threads and machines with wire as small as 0.00078 in. (0.02 mm) in diameter. Wire EDM conditions were automatically fixed by the wire material and diameter and work piece material and thickness. In this case, brass wire of 200 μm in diameter and work piece material of W (3-mm cut thickness) was used. Angles of these V-shapes were determined to be 60°, 90°, and 120°, respectively. Fabricated block shown in Figs. 3 and 4 illustrates the schematic of this fixture along with the tool for fabricating triangular, conical, and square microelectrodes.

3 Results and discussion

3.1 Fabrication of microelectrode

Microelectrodes of symmetrical and non-symmetrical sections can be fabricated using this specially designed block. Unlike conventional EDM machining, it is critical to carry out micro-machining in EDM system with a few machining passes, as a high volume of material removal in a single

Table 1 Properties of the sacrificial electrode material

Material composition (wt.%)	Density (g/cm^3)	Melting point (°C)	Relative conductivity (to silver)	Specific resistance (μΩ)	Thermal expansion coefficient (K^{-1})
99.9% W	19.3	3,370	14.0	56.5	4.6×10^{-6}

Table 2 Properties of the dielectric fluid and/or coolant

Material	Volumetric mass at 15°C (kg/m^3)	Viscosity at 20°C (mm^2/s)	Flash point Pensky–Martens (°C/°F)	Auto-ignition temperature (°F)	Aromatics content (wt.%)	Distillation range (IBP/FBP (°C))
EDM oil 3	813	7.0	134/259	470	0.01	277/322

step may lead to electrode breakage, especially when required electrode size is of micron level.

The block EDM technique has been used for fabricating symmetrical electrode using indexing attachment with transistor type circuit and with tungsten tool electrode [23]. The authors suggested setting the micro-machining in *z*-direction rather than *y*-direction to reduce the machining contact area and electrode breakage. The basic of block micro-EDM will be the same here in this study, and the only change is to use one fixture of desired shape. Figure 4 shows the methodology of fabricating microelectrodes with different shapes and cross sections. As demonstrated in Fig. 4a, for making the triangular-shaped tool, the rod electrode was feed downward from CD edge to the required feed length in *z*-direction along the face of triangular slot without tool rotation. Few passes were required to remove the material to have desired electrode shape. From a mechanical drawing, the number of passes was calculated for the required dimension tool and dimension of tool was checked using camera during machining. Voltage and capacitance was set at 110 V and 1,000 pF during machining. As higher energy caused larger crater size and lower energy lengthen the machining time, we have selected some intermediate energy level for tool preparation [36]. Once one face of the triangle was prepared, and then next DE edge of triangular slot was used to fabricate another face. Finally, BF edge was used to get the third face of triangular tool. Thus, using this method, fabrication of equilateral triangle and triangle with others angles tools are possible also.

Next for making conical tool, three slots of 60°, 90°, and 120° were already cut in the tungsten block. For conical tool, the same block was tilted to 90°. Slope of these triangular slots were used to fabricate different angle conical tool. In Fig. 4b, PCD rod with rotation was feed along the slop in *z*-direction. After one pass was finished, tool was moved along *y*-axis to have fresh place of cut and then next pass along *z*-axis started. Hence, in this way,

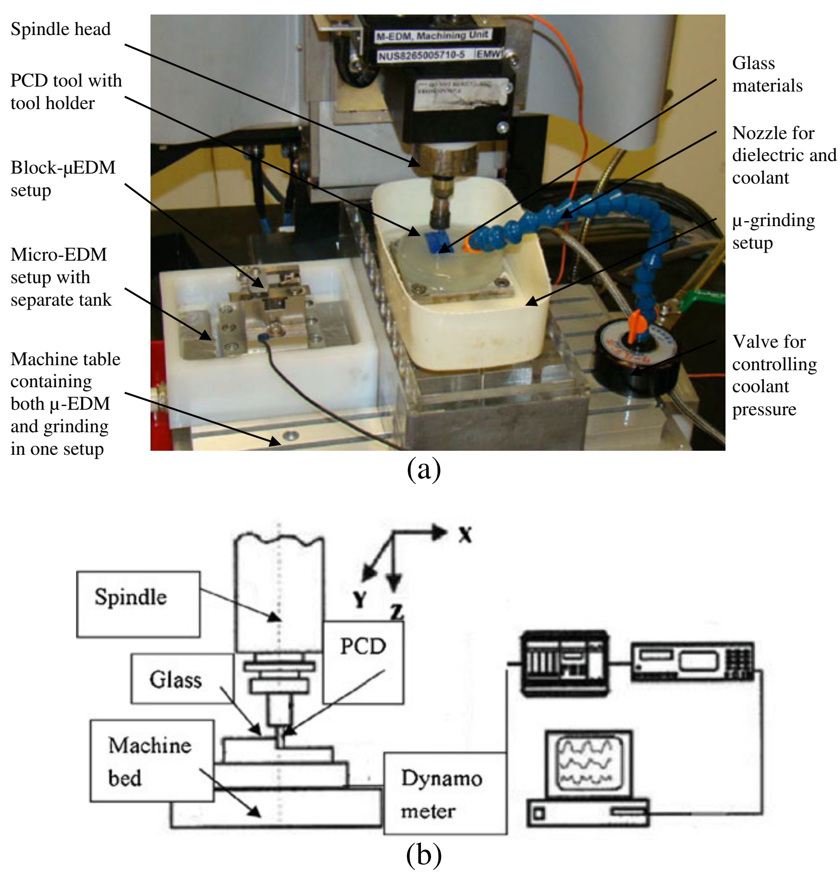

Fig. 2 **a** Photograph of the setup with micro-EDM and micro-grinding arrangement on the same table, **b** schematic setup for glass grinding

Fig. 3 Specifically designed block

conical tools of three different angles were possible to fabricate. In addition to this, AB, EH, BF, and FG edge of the same block were used to fabricate square tool without tool rotation. Moreover, any of the edges like AB or AD can be used to fabricate circular tool with tool rotation. When tool was given feed along *z*-direction without rotation, D-shaped tool was possible to fabricate. Thus, using this same block, it is possible to fabricate triangular, square, conical, circular, and D-shaped tools. Figure 5 shows the fabricated tools using this specifically designed block.

3.2 Comparison on micro-grinding performance of different shape tool on BK7 glass

3.2.1 Comparison of cutting forces

Brittle material like glass is very problematic to mechanically micro-machine due to damage resulting from material removal by brittle fracture, cutting force-induced tool deflection or breakage, and tool wear. The forces arise from micro-machining processes need important consideration as it can affect the material removal rate, surface finish, and dimension of the microstructure. The following section will present a comparative analysis of cutting forces generated along all three axes during micro-grinding of BK7, glass using on-machine-fabricated four different shaped PCD tool. The cutting conditions (depth of cut= 5 μm, feed rate=10 μm/min, and spindle speed= 2,000 rpm) remain same for all experiments. Figures 6a–c, 7a–c, 8a–c, and 9a–c, showed the cutting force behavior for the above mentioned tools.

With the change of cutting tool shape, how the cutting force along three axes has changed can be seen from Fig. 6, 7, 8 and 9. From the cutting force vs. time curves, it has been found that cutting force for D-shaped tool is prominently different from other tools. Discontinuous cutting was observed for D-shaped tool (throughout the whole cycle it does not remove material, when the D-shape is on the opposite to feed direction, it does not remove any material at that time), which results zero point force in curve. Due to its shape, chip removal becomes easier in case of D-shaped tool. Hence, the main effect is the improved flushing of chips due to the notch in one side. On the other hand, square tool cut with two or three edges at the same time and triangular tool cut using one or two cutting edges at the same time. In fact, these three and four edges of triangular and square tool work like single-point cutting tool. So cutting process become intermittent for these two tools. In addition, circular tool exhibited continuous material cutting using its periphery consisted of diamond grains. All of the force curves are sinusoidal

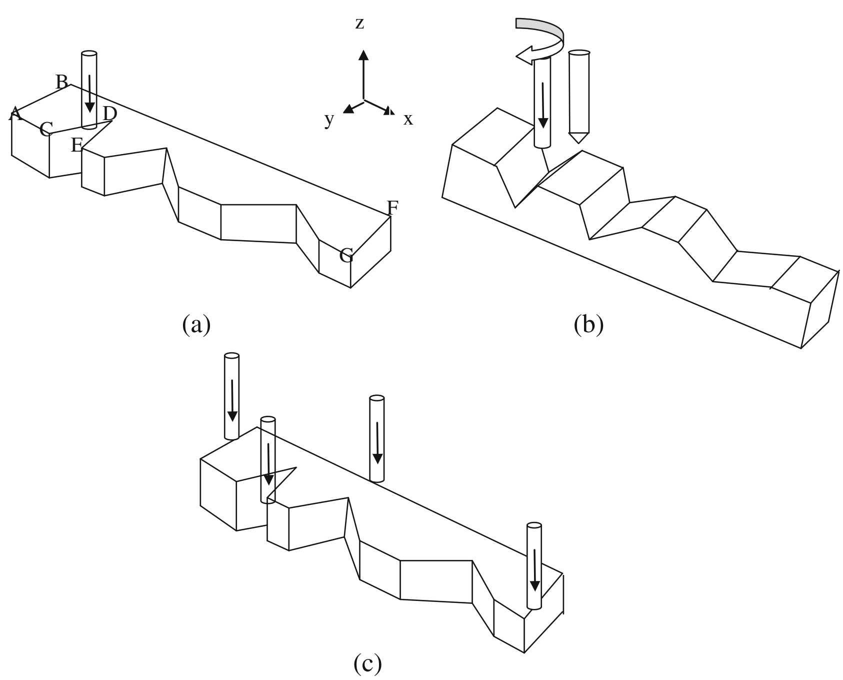

Fig. 4 Schematic diagram: **a** before machining PCD rod along with fixture prepared by wire EDM for triangular microelectrode, **b** same fixture in different orientation for conical microelectrode preparation, and **c** fixture orientation for square and D-shaped tool

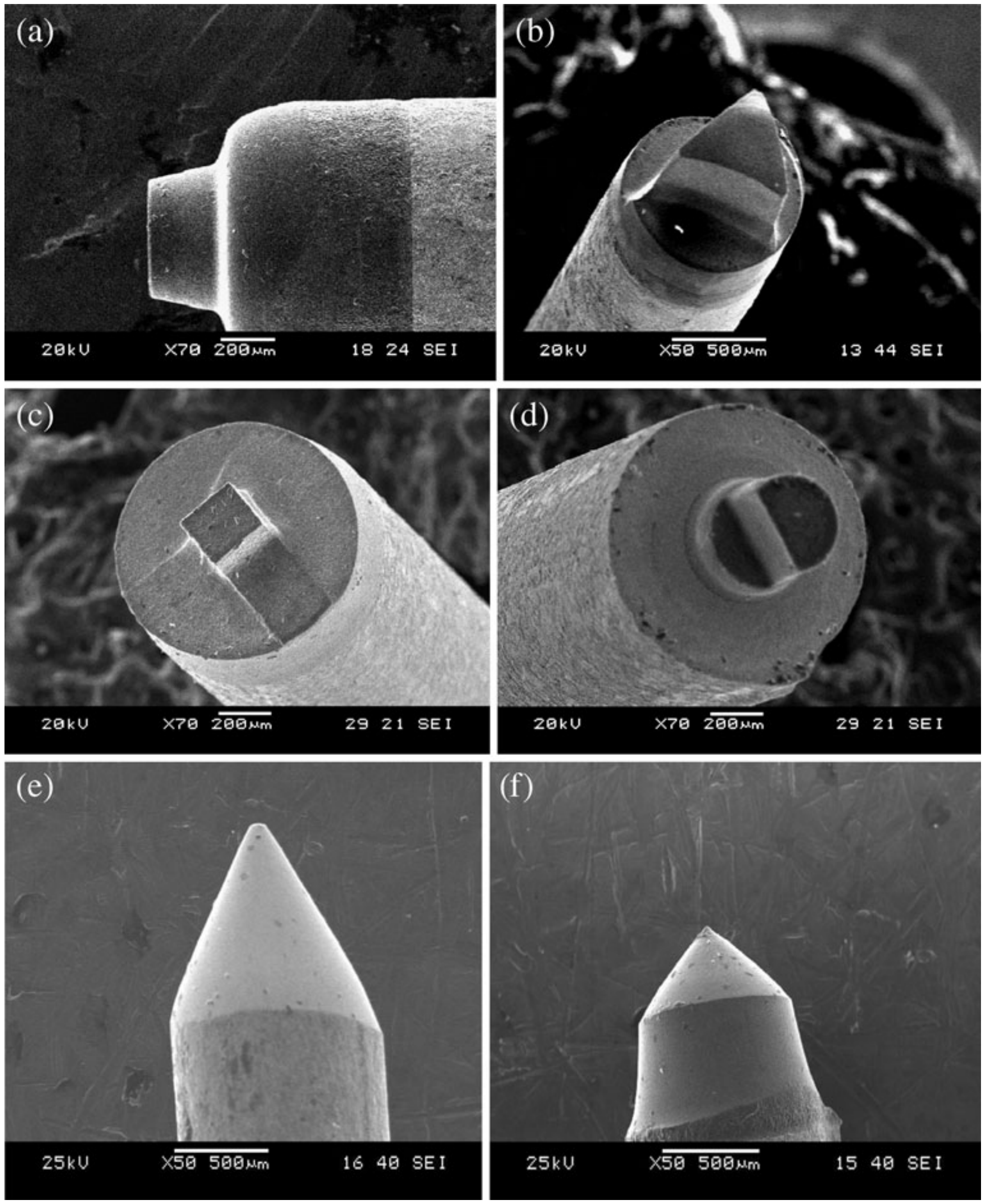

Fig. 5 **a** Circular tool, **b** triangular tool, **c** square tool, **d** D-shaped tool, **e** conical tool of 60°, and **f** conical tool of 90°

though they have some difference in their pattern, due to different geometry of tool. For example, circular tool cutting force curve, every cyclic pattern consists of small cycle due to the stochastic nature of cutting using infinite numbers of diamond cutting edge. That is why lots of peaks are observed on the curve. In fact, rake angle is changing from 0° at side surface to 90° at middle of the surface for circular tool but there is no clearance for chip removal. When the tool becomes machined to D-shape, force pattern becomes so sharp still possessing some peak. For D-shaped tool, rake angle is varying like circular one, but clearance area for chip removal has been facilitated due to its shape. In case of square tool, crown-like sinusoidal force curve along axes with lots of peak has been found. Along with material removal by the edge, side surface can sweep the chip away from the machined area.

Figure 10a–c shows average force data for same cutting condition for different shape tools. Error bar indicates the minimum and maximum force experienced by these tools. From average force data, it was found that average forces along three axes for square tool were higher than other shaped tools. To the contrary, D-shaped tool experienced lower force in all axes compared with others. In addition, force experienced by circular tool along *z*- and *x*-axes was also comparatively higher than other tools but a little smaller than square tool. For the same cutting conditions, force along *z*-axis showed decreasing tendency from circular tool to D-shaped tool, up to triangular tool and then increases again for square shape. On the other hand, force along *x*- and *y*-axes showed decreasing trend from circular to D-shaped tool and then increasing tendency from triangular to square tool. Higher cutting force along *z*-axis resulted in the more

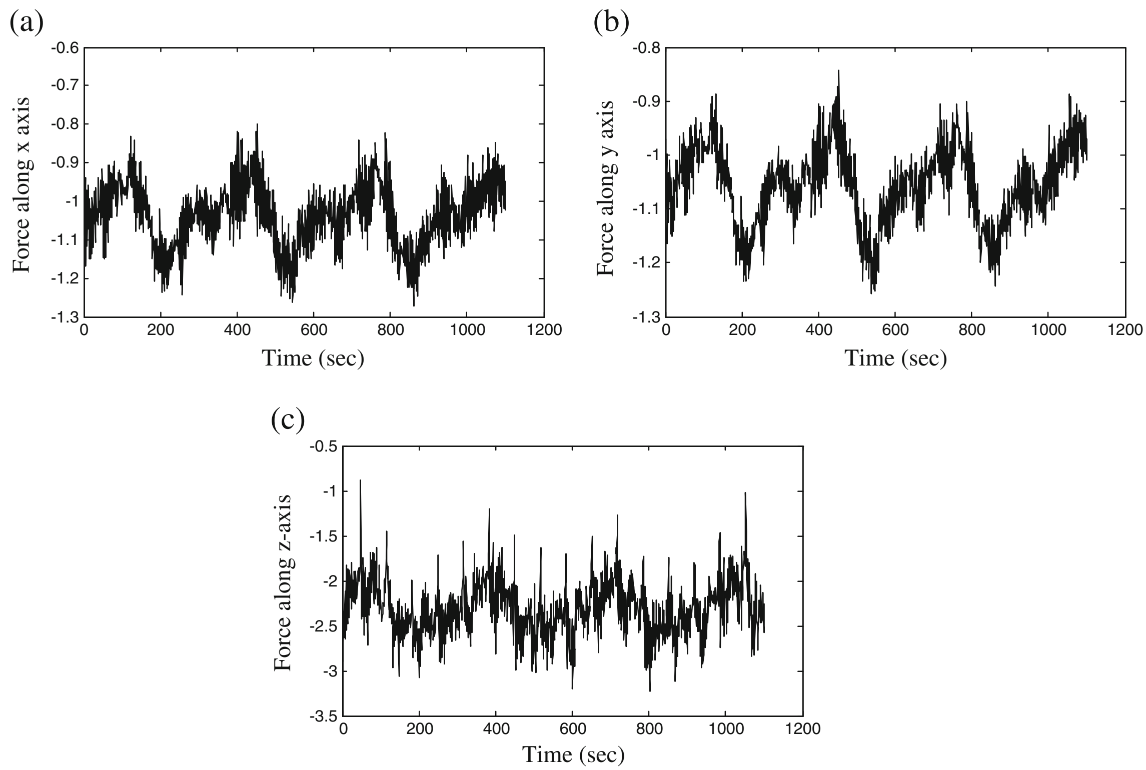

Fig. 6 Cutting force along (**a**) *x*-, **b** *y*-, and **c** *z*-axes for circular tool

bending effect for square tool than other tools. While observing force variation, e.g., maximum and minimum force, it was found that circular and D-shaped tool experienced variation higher than rest of the two tools. This

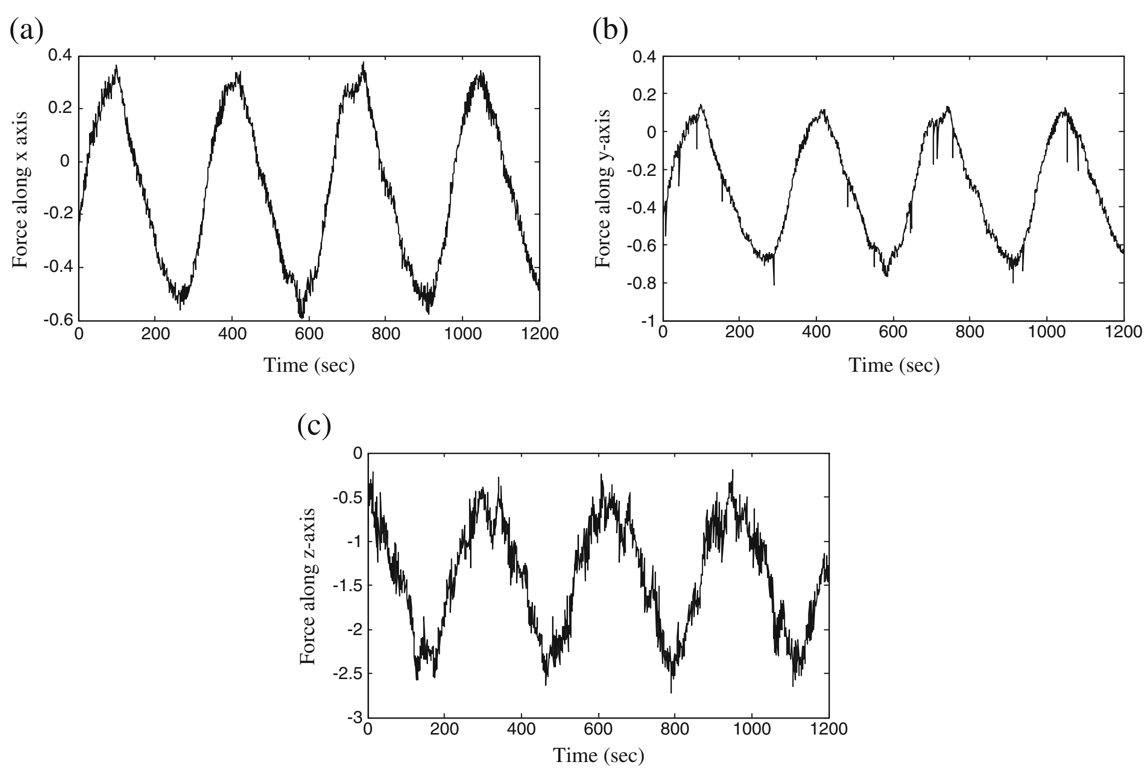

Fig. 7 Cutting force along **a** *x*-, **b** *y*-, and **c** *z*-axes for D-shaped tool

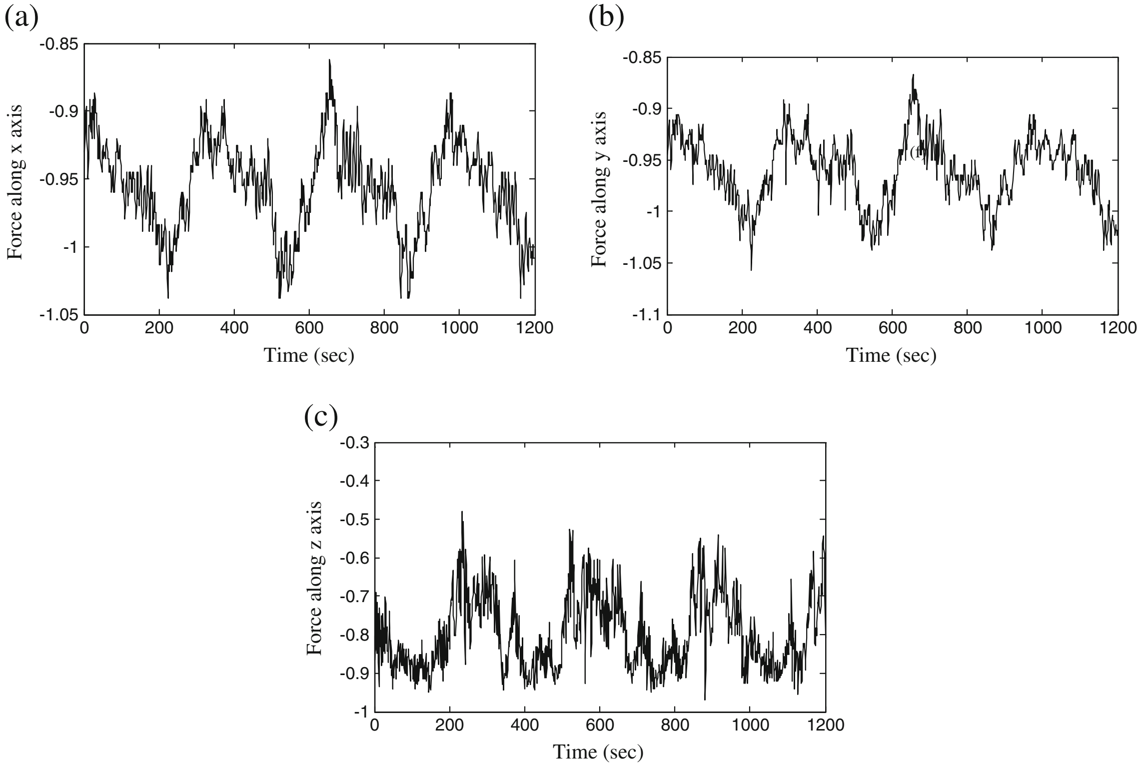

Fig. 8 Cutting force along **a** *x*-, **b** *y*-, and **c** *z*-axes for triangular tool

is probably due to the stochastic nature of cutting in case of circular and D-shaped tool. Triangular and square tool has defined geometry and therefore they only cut with their three or four edges. At the same time in case of triangular or

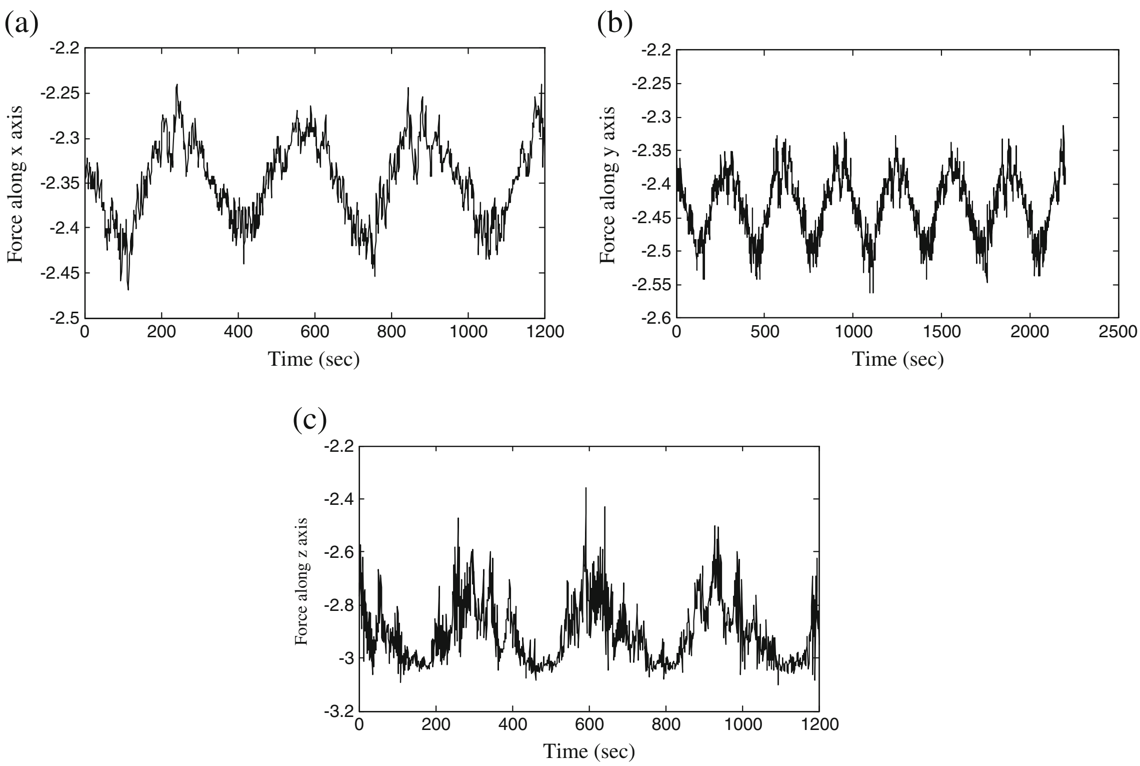

Fig. 9 Cutting force along **a** *x*-, **b** *y*-, and **c** *z*-axes for square tool

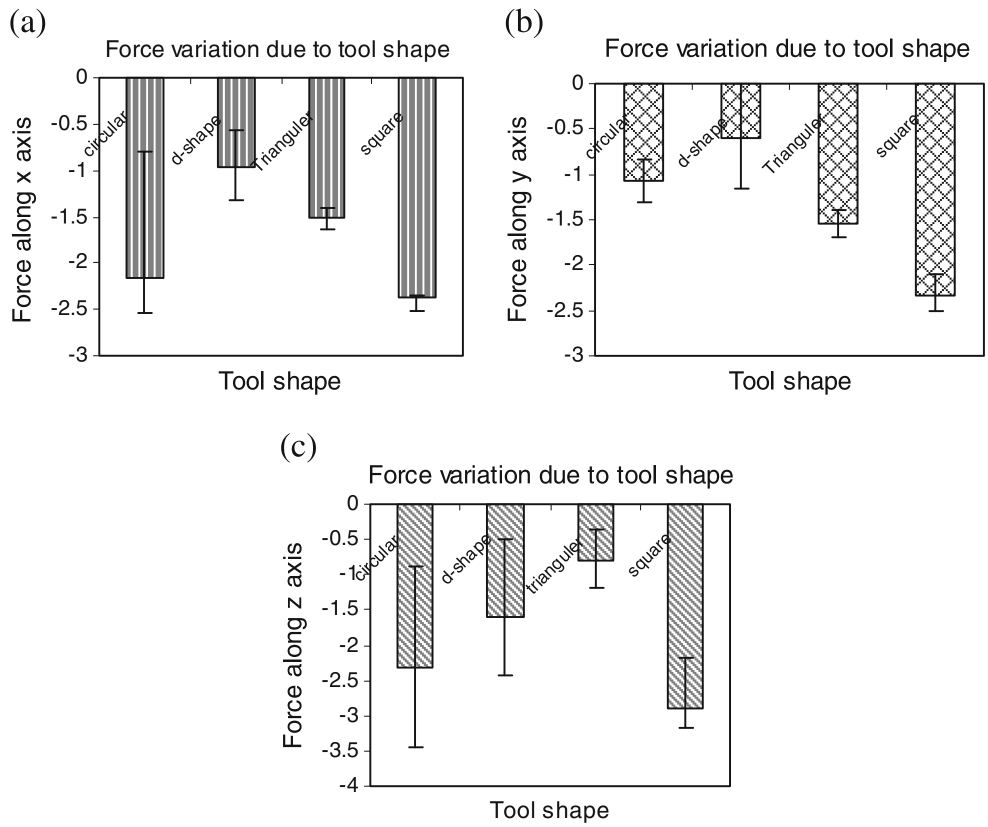

Fig. 10 Average, minimum, and maximum cutting force **a** along *x*-, **b** *y*-, and **c** *z*-axes for different geometry tool

square tool, two or three edges are taking part in the cutting process. These edges consist of diamond grains, which stand in straight line along the edge. Moreover, chip removal is easier for these tools compared to circular tool. Hence, chip loading on these tools will be comparatively less than circular tool. As a result, variation of force for square and triangular is less than others. On the other hand, circular and D-shaped tool surface consist of non-countable diamond grains. Circular tool removes material from the surface continuously whereas, D-shaped tool removes material during half cycle. Hence, chip removal is also easier for D-shaped tool. Even that due to stochastic nature of cutting, variation of force is higher for these two tools.

3.2.2 Comparison of surface roughness

Surface roughness is a measure of texture of a surface. It is quantified by the vertical deviations of a real surface from its ideal form. If these deviations are large, the surface is rough; if they are small the surface is smooth. Surface roughness of the machined surface was measured using Atomic Force Microscopy (AFM), Taylor Hobson Profilometer. In addition, optical image of machined surface using different shape tool was also taken to compare the cutting mode (ductile or brittle). Surface roughness has been improved much using D-shape, triangular, and square tools rather than circular. Figure 11 shows a comparison of 3D surface topography of the machined surface using different shaped PCD tool. From AFM images of machined surface, it is clearly seen that how the surface has experienced transition with the change of the cutting edge shape. It has been observed that, except circular PCD tool, the surfaces generated by other tools are comparatively smoother. Surface machined by circular tool contains small particles throughout the whole area, which are absent on the surface machined by other tools. These small particles may be the small portion of chips removed during machining. Except circular tool, all the tools have some clearance space which facilities easy chips removal. Chips removed by the circular tool have the higher chance of being paste on the machined surface again due to continuous cutting. Hence, this might be due to easy chip removal for other tools rather than circular one, although the entire surfaces still have some scattered sudden peak here and there. Moreover, these peaks are prominent for the all the tool except circular one. During machining, materials adjacent to the tool edge are immediately compressed and displaced upward form the bulk work pieces. As the tool is further advanced, more material along the cutting path is displaced on the tool edge with a change in direction according to the degree of curve radius. Therefore, these high peaks are becoming noticeable in case of square triangular and D-shaped tool [37].

A comparison of average surface roughness and maximum roughness values of machined surface are shown in

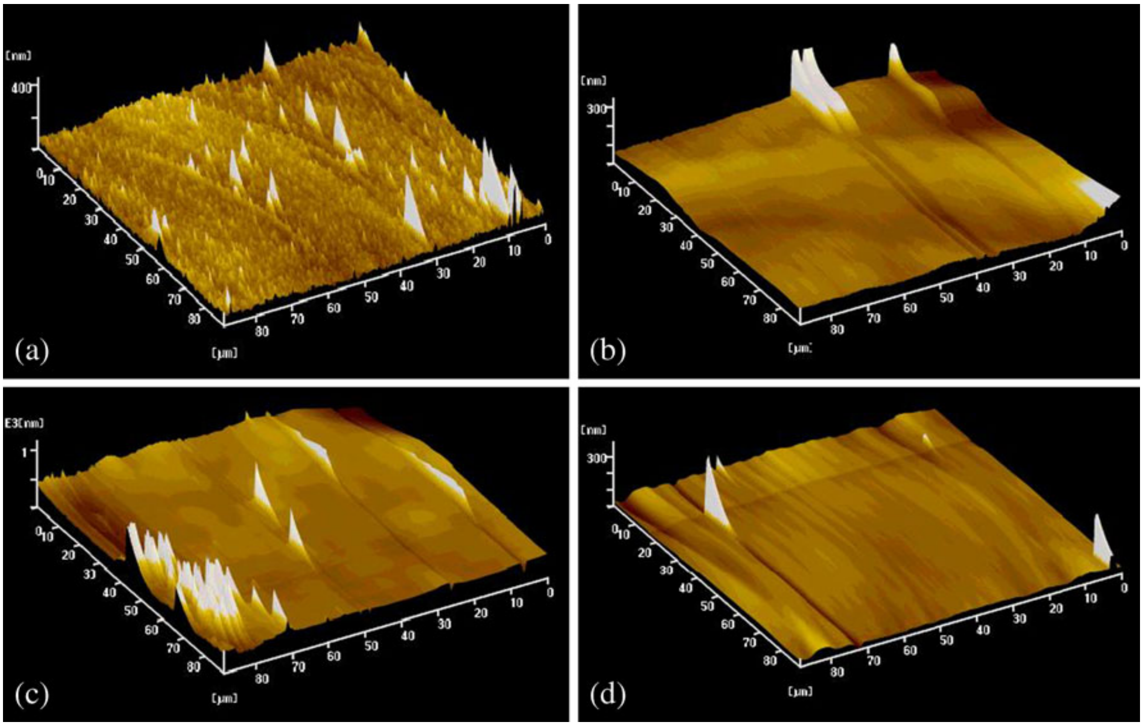

Fig. 11 AFM image of machined surface using **a** circular, **b** D-shaped, **c** triangular, and **d** square tool

Fig. 12. It was found that average roughness of the machined surface has been improved a little form circular tool to D-shaped and square tools. Surface machined by a triangular tool has higher average and maximum roughness than the rest. The reason behind this higher roughness is the sudden peak density, which is higher in case of surface machined by a triangular tool.

Figure 13 shows the optical images of ground surface for different tool geometry. From optical images, it was observed that ductile mode cutting was dominant for all four different type tools. It was found from the optical images that all four tools produced ground surface with nano-level roughness. Some grinding marks were also present on the surface as well. Magnified image of the side of the grooves were also presented in Fig. 14. For surface ground by a circular tool, side wall seemed reasonably straight even in higher magnification. For a D-shaped tool, the edge of the micro-slots deteriorates at some position. Side flow of a glass material has been found. The edge of the micro-slot machined by a triangular tool was found to be worst among all. Usually, material around the cutting edge was subjected to high pressure which causes the material to flow to the side. The similar phenomenon can be observed in case of machining with blunt tool edge, which tries to remove more material from the side surface than a sharp edged tool. Comparatively larger radius of curvatures at the edge of the slots are the typical proof of the phenomenon. In addition, the edge surface machined by a square tool also had some waviness as well but with lower curvature than that of a triangular tool. Moreover, this side surface phenomenon was not present throughout the whole groove rather it appeared suddenly on the machined grooves. Among all the surfaces, the ground surface with triangular-shaped PCD tool suffered more rounding at the edge of the micro-slots, thus providing inferior surface finish at the side wall of the slots. Brittle and amorphous properties of glass material can also contribute to this side flow behavior [38].

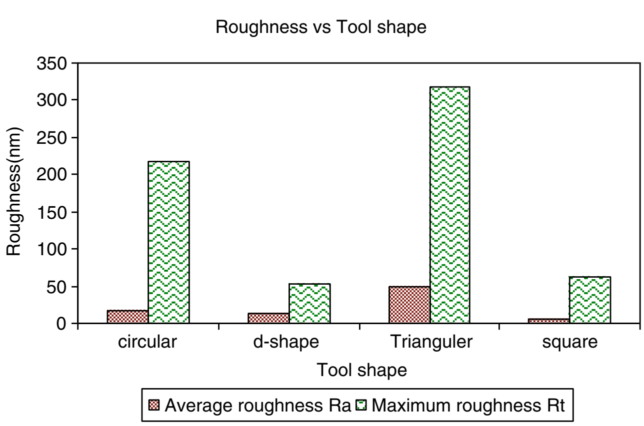

Fig. 12 Surface roughness value for different tool

3.2.3 Comparison of tool wears

Figure 15 shows a comparison of different shaped PCD tool surface after grinding micro-slots in the glass material. From

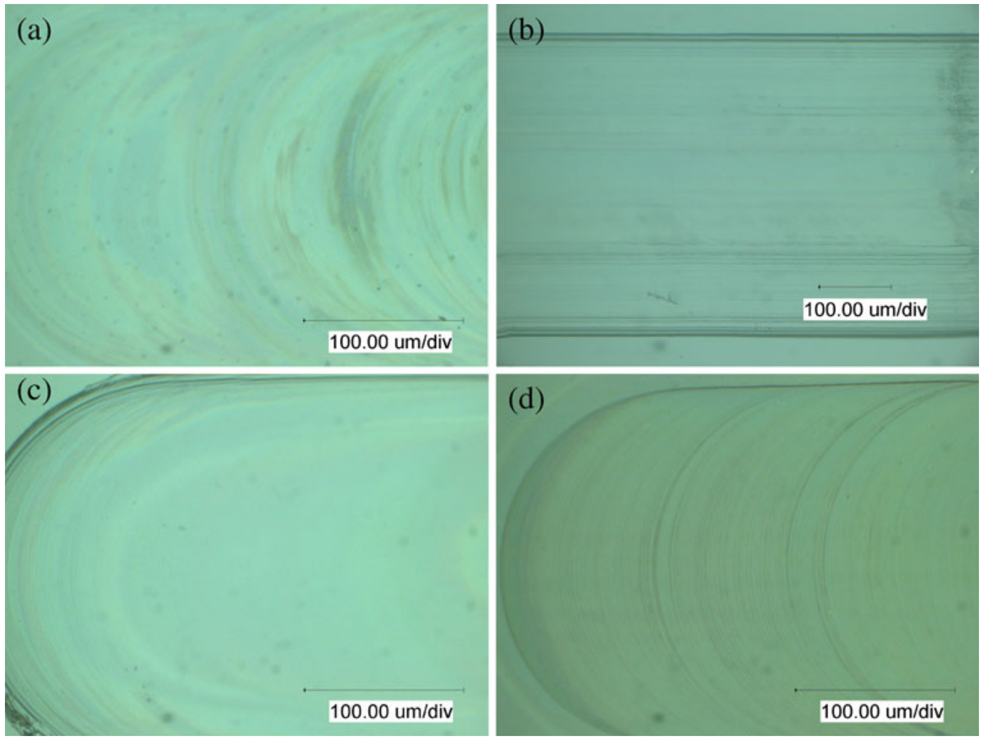

Fig. 13 Optical image of ground surface by **a** circular, **b** D-shaped, **c** triangular, and **d** square tool

the SEM picture of tools in Fig. 15 after machining, it was found that all four-shaped tools except the circular one had the tendency of wearing more. This was basically due to the sharp edge of the tool which suffered more wear and became rounded. When circular tool experienced wear or re-sharpening, it became smaller in diameter but still become round. Hence, a worn-out circular tool did not affect the machining performance significantly. On the other hand, when the edges of a square or triangular tool experienced wear, wear is usually non-uniform as all the four or three edges cannot wear out at the same rate. For the shaped tool, it was found that edge rounding or pull out of grain was the

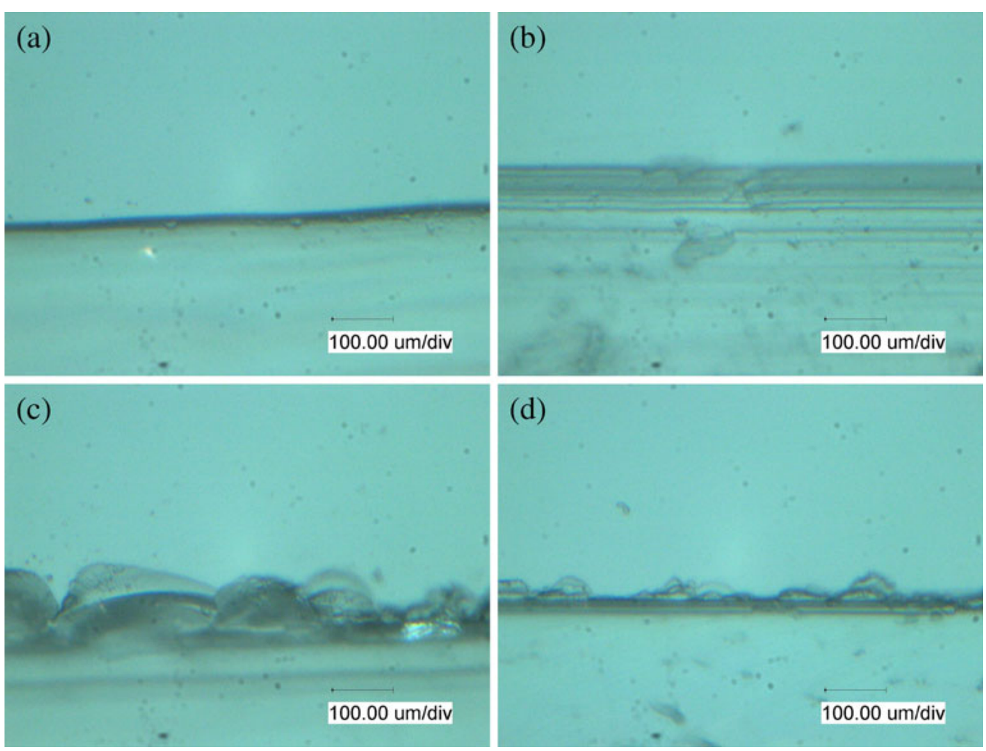

Fig. 14 Optical image of side surface of ground groove by **a** circular, **b** D-shaped, **c** triangular, and **d** square tool

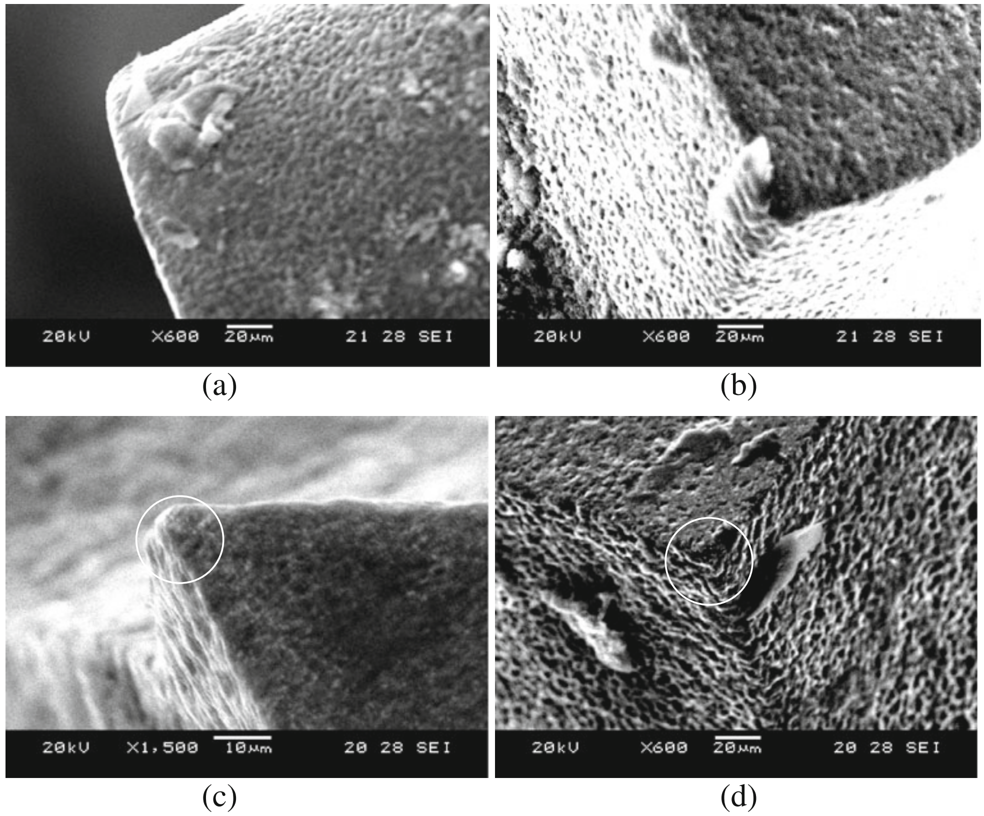

Fig. 15 SEM image of tool after machining **a** circular, **b** D-shaped, **c** triangular, and **d** square tool

main wear mechanism. At the same time, machining condition varied form a sharp edge to round edge. In contrast to conventional sharp edge cutting model, chip shearing in micro-machining occurs along the rounded tool edge. Therefore, this large edge radius affects the magnitude of ploughing and shearing forces. Higher plastic deformation resulted from larger cutting edge radius. As a result, surface roughness as well as cutting force kept changing with this wears of square and triangular tools [39].

4 Conclusions

In this study, a new fabrication technique for different geometry tools has been proposed using specially designed block along with a comparative analysis on the micro-machining performance of four different geometry PCD tools: circular, D-shaped, triangular, and square on BK7 glass. In addition, the effect of tool geometry on the cutting forces surface roughness and tool wear were investigated during the glass micro-machining. The following conclusions can be drawn from this experimental investigation:

- With the aim of fabricating different shaped tool in a single setup, a specially designed block containing three ‘v-slots’ has been designed and fabricated using wire cut. With the concept of block micro-EDM and using this specifically designed block, microelectrodes of conical, triangular, square or rectangular, circular, and D-shaped tool have been fabricated. Using this specifically designed block has been established to be a feasible method for the fabrication of microelectrodes of few tens of micrometers.
- D-shaped tool experienced lowest cutting force along *x*- and *y*-axes, whereas triangular tool has experienced lowest force along *z*-axes. Both square and circular tools had generated quite high cutting forces along *z*- and *x*-axes during micro-grinding, though along all axes square tool had experienced highest cutting force. Comparatively lower cutting force along the *y*-axis has been observed for triangular tool than square one.
- For the groove machined by micro-grinding using PCD tool, surface roughness showed considerable change from circular tool to others. Small particles, which were present on the surface machined by circular tool, was almost absence in case of surface machined by other tools. Lowest average surface roughness has been achieved using square tool and little higher in case of D-shaped tool. Higher peak density on the surface machined by a triangular tool resulted in higher average and maximum surface roughness. Moreover, side wall of a machined groove using D-shaped tool was much

better than a square or triangular tool, whereas the circular tool demonstrated the best result in this case.

- Square and triangular tools experienced more wear compared to circular and D-shaped tools due to the tendency of tool edge blunting
- Finally, D-shaped tool demonstrated better performances among all the tools in terms of cutting force, roughness value, side surface, and wear rate due to its geometry, which enhances the chip removal process from the machined surface.

References

1. Yin S, Ohmori H, Uehara Y, Shimizu T, Lin W (2004) Micro V-groove grinding technique of large germanium immersion grating element for mid-infrared spectrograph. jsme int j c-mech sy 47 (1):59–65
2. Khan Malek C, Robert L, Boy J-J, Blind P (2007) Deep microstructuring in glass for microfluidic applications. Microsyst Technol 13(5):447–453. doi:10.1007/s00542-006-0185-0
3. Nakasuji T, Kodera S, Hara S, Matsunaga H, Ikawa N, Shimada S (1990) Diamond turning of brittle materials for optical components. CIRP Ann-Manuf Techn 39(1):89–92
4. Fang FZ, Chen LJ (2000) Ultra-precision cutting for ZKN7 glass. CIRP Ann-Manuf Techn 49(1):17–20
5. Takahashi T, Funkenbusch PD (2000) Micromechanics of diamond composite tools during grinding of glass. Mater Sci Eng, A 285(1–2):69–79
6. Gao GF, Zhao B, Xiang DH, Kong QH (2009) Research on the surface characteristics in ultrasonic grinding nano-zirconia ceramics. J Mater Process Technol 209(1):32–37
7. Sun X, Stephenson DJ, Ohnishi O, Baldwin A (2006) An investigation into parallel and cross grinding of BK7 glass. Precis Eng 30(2):145–153
8. Luo SY, Tsai YY, Chen CH (2006) Studies on cut-off grinding of BK7 optical glass using thin diamond wheels. J Mater Process Technol 173(3):321–329
9. Agarwal S, Rao PV (2008) Experimental investigation of surface/subsurface damage formation and material removal mechanisms in SiC grinding. Int J Mach Tool Manuf 48 (6):698–710
10. Sinhoff V, König W (1998) Generative precision grinding of optical glass. CIRP Ann-Manuf Techn 47(1):253–258
11. Suratwala T, Wong L, Miller P, Feit MD, Menapace J, Steele R, Davis P, Walmer D (2006) Sub-surface mechanical damage distributions during grinding of fused silica. J Non-Cryst Solids 352(52–54):5601–5617
12. Zhao Q, Liang Y, Stephenson D, Corbett J (2007) Surface and subsurface integrity in diamond grinding of optical glasses on Tetraform 'C'. Int J Mach Tool Manuf 47(14):2091–2097
13. Matsumura T, Hiramatsu T, Shirakashi T (2005) A study on cutting force in the milling process of glass. J Manuf Processes 7:102–108
14. Cai MB, Li XP, Rahman M (2007) Study of the mechanism of nanoscale ductile mode cutting of silicon using molecular dynamics simulation. Int J Mach Tool Manu 47(1):75–80
15. Matsumura T, Ono T (2008) Cutting process of glass with inclined ball end mill. J Mater Process Technol 200(1–3):356–363
16. Morgan CJ, Vallance RR, Marsh ER (2004) Micro machining glass with polycrystalline diamond tools shaped by micro electro discharge machining. J Micromech Microeng 14(12):1687–1692. doi:10.1088/0960-1317/14/12/013
17. Kozak J, Rajurkar KP, Wang SZ (1994) Material removal in wire EDM of PCD blanks. J Eng Ind 116(3):363
18. Liu YH, Guo YF, Liu JC (1997) Electric discharge milling of polycrystalline diamond. Proc IMechE Part B: J Eng Manuf B 211 (8):643–647. doi:10.1243/0954405981516580
19. Nakazawa H (1994) Principles of precision engineering. Oxford Science, Oxford University Press
20. Mamalis AG, Grabchenko AI, Magazeev MG, Krukova NV, Prohàszká J, Vaxevanidis NM (2004) Two-stage electro-discharge machining fabricating superhard cutting tools. J Mater Process Technol 146(3):318–325
21. Egashira K, Mizutani K (2002) Micro-drilling of monocrystalline silicon using a cutting tool. Precis Eng 26(3):263–268
22. Friedrich CR, Coane PJ, Vasile MJ (1997) Micromilling development and applications for microfabrication. Microelectron Eng 35 (1–4):367–372
23. Ravi N, Huang H (2002) Fabrication of symmetrical section microfeatures using the electro-discharge machining block electrode method. J Micromech Microeng 12(6):905
24. Hung J-C, Lin J-K, Yan B-H, Liu H-S, Ho P-H (2006) Using a helical micro-tool in micro-EDM combined with ultrasonic vibration for micro-hole machining. J Micromech Microeng 16 (12):2705
25. Morgan CJ, Vallance RR, Marsh ER (2007) Micro-machining and micro-grinding with tools fabricated by micro electro-discharge machining. Int J Nanomanuf 1(2):242–258
26. Yan J, Uchida K, Yoshihara N, Kuriyagawa T (2009) Fabrication of micro end mills by wire EDM and some micro cutting tests. J Micromech Microeng 19(2):025004
27. Chen S-T, Lai Y-C, Liu C-C (2008) Fabrication of a miniature diamond grinding tool using a hybrid process of micro-EDM and co-deposition. J Micromech Microeng 18(5):055005
28. Hung J-C, Lien S-C, Li J-K, Huan F-Y, Yan B-H (2008) Fabrication of a micro-spherical tool in EDM combined with Ni-diamond co-deposition. J Micromech Microeng 18 (4):045010
29. Masaki T, Kuriyagawa T, Yan J, Yoshihara N (2008) Study on shaping spherical poly crystalline diamond tool by micro-electro-discharge machining and micro-grinding with the tool. I J Surf Se 1(4):344–359
30. Wada T, Masaki T, Davis DW (2002) Development of micro grinding process using micro EDM trued diamond tools. In: Proc Ann Meeting of the American Society for Precision Engineering
31. Fang FZ, Wu H, Liu XD, Liu YC, Ng ST (2003) Tool geometry study in micromachining. J Micromech Microeng 13(5):726
32. Torres CD, Heaney PJ, Sumant AV, Hamilton MA, Carpick RW, Pfefferkorn FE (2009) Analyzing the performance of diamond-coated micro end mills. Int J Mach Tool Manuf 49 (7–8):599–612
33. Smith NP, Smith DJ, Pearce TRA, Ashfold MNR (2003) The ductile grinding of glass using diamond fibres oriented radially in a grinding wheel. Proc IMechE Part B: J Eng Manuf 217(3):387–396. doi:10.1243/095440503321590541
34. Perveen A, Jahan MP, Rahman M, Wong YS (2011) A study on microgrinding of brittle and difficult-to-cut glasses using on-machine fabricated poly crystalline diamond (PCD) tool. J Mater Process Technol (in press)
35. Jahan MP, Rahman M, Wong YS, Lee F (2009) On-machine fabrication of high-aspect-ratio micro-electrodes and application in vibration-assisted micro-electrodischarge drilling of tungsten carbide. Proc IMechE Part B: J Eng Manuf 224 (5):795–814

36. Perveen A, Jahan MP, Wong YS, Rahman M (2011) Cutting force analysis of on machine fabricated PCD tool during glass micro-grinding. Ad Mater Res 264–265:1085–1090
37. Woon KS (2009) Modeling of the tool edge radius effect on the mechanics of micromachining. Dissertation, National University of Singapore
38. Liu K, Melkote SN (2006) Effect of plastic side flow on surface roughness in micro-turning process. Int J Mach Tool Manuf 46 (14):1778–1785
39. Kim J-D, Kim DS (1995) Theoretical analysis of micro-cutting characteristics in ultra-precision machining. J Mater Process Technol 49(3–4):387–398