Study on shaping spherical Poly Crystalline Diamond tool by Micro-electro-Discharge Machining and micro-grinding with the tool

Takeshi Masaki*, Tsunemoto Kuriyagawa, Jiwang Yan and Nobuhito Yoshihara

Department of Nanomechanics,
Graduate School of Engineering,
Tohoku University, Aoba 6-6-01,
Aramaki, Aoba-ku, Sendai 980-8579, Japan
E-mail: masaki-giken@ric.hi-ho.ne.jp
E-mail: tkuri@cc.mech.tohoku.ac.jp
E-mail: yanjw@pm.mech.tohoku.ac.jp
E-mail: yoshihara@pm.mec.tohoku.ac.jp
*Corresponding author

Abstract: Micro-electro-Discharge Machining (Micro-EDM) for shaping of a spherical tool made of Poly Crystalline Diamond (PCD) has been developed for the purpose of enabling a grinding process of a micro-free form surface on hard and brittle materials. Using this spherical PCD tool as a grinding tool, the surface roughness of a minute flat plane (90×70 µm), which was ground into tungsten carbide, has 28 nm Rz and 5 nm Ra. This paper describes the capabilities of spherical PCD tool grinding with the following results.

Keywords: micromachining; Microelectro-Discharge Machining; Micro-EDM; Poly Crystalline Diamond; PCD; microgrinding.

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Biographical notes: Takeshi Masaki is now the President of MASAKI GIKEN, and also a PhD candidate of Department of Nanomechanics, Tohoku University. He had been working as a Researcher for Matsushita Electric Industry Co. Ltd. for 26 years. His research interest is the microshape processing based on the micro-EDM.

Tsunemoto Kuriyagawa is a Professor of Nano-Precision Mechanical Fabrication Laboratory, Tohoku University. He is studying a Nano-Precision Mechanical Machining, M^4 processes (Micro/Meso Mechanical Manufacturing) and a powder jet machining.

Jiwang Yan is an Associate Professor in the Department of Nanomechanics, Tohoku University. His research interests include ultraprecision machining of optical and optoelectronic materials, design and fabrication of nanostructural surfaces, micro/nanomachining mechanics, laser processing of materials, and tooling technology using diamond and diamond-related materials.

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Nobuhito Yoshihara is an Assistant Professor in the Department of Nanomechanics at Tohoku University. He Graduated from the same University with BE (1999), ME (2001) and PhD (2004). His research interests include ultraprecision grinding.

1 Introduction

Minute devices that have three-dimensional shapes and which require high precision are needed in a variety of industries. Micro-EDM had been developed as a processing method to accomplish this. Micro-EDM has been used for the boring of 20–100 μm diameter micronozzles for inkjet printer heads (Masaki et al., 1990). The micro-EDM technology is also being used for shaping mechanical devices of submillimetre size in the medical industry as well as other industries (Takahata and Gianchandani, 2004).

Conversely, nanometre order roughness and shape precision are in demand for optical production, and new micromachining methods are needed for materials such as glass and ceramics for many biomedical fields and applications (Li and Gianchandani, 2006).

The materials which can be processed by micro-EDM are limited to materials having electrical conductivity. In addition, the result of a micro-EDM surface is a construct of piled up craters that have a 0.2 μm Rz minimum roughness value.

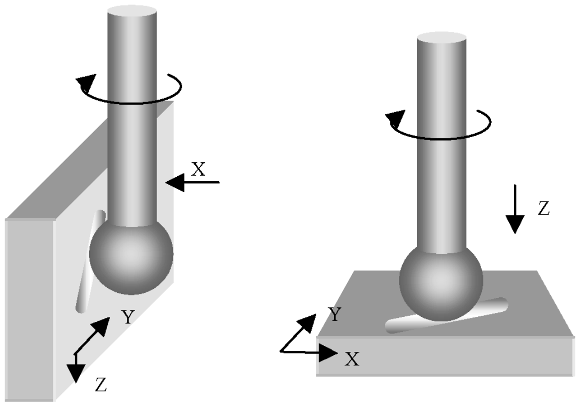
The development of a new microshaping process and technique is necessary. Microgrinding, using a PCD which is shaped by micro-EDM, is presented here. Micro-PCD tool grinding is applied as a highly precise finishing process of super minute shapes, used for dies of optical devices, and orders of nanometres of surface roughness have been achieved (Wada et al., 2002). Research studies using the micro-PCD tool grinding on glass material have been reported (Morgan et al., 2004). The PCD tool shapes that were used in that report were simple shapes like a cylinder, a sharpened cone, and a thin disk-type wheel for exclusive processing of a cylindrical surface, V grooves, and straight grooves, respectively (Wada and Masaki, 2005).

In this study, in order to accomplish the microshape grinding of micro-free form surfaces, the processing and shaping of a submillimetre size PCD spherical tool have been developed. The capabilities of the grinding process using the spherical PCD tool was carried out, and the evaluation of the surface roughness of the processed surface of tungsten carbide was conducted. Tungsten carbide is a widely used material for dies and also as a tool material. Silicon and alumina ceramic, which are hard and brittle materials, were processed and also evaluated. The accuracy of the shape is not discussed by this report because it depends greatly on the machine's precision.

2 Micro-free form shaping technology using a spherical tool

On a conventional machining centre, a ball end mill is used to process the milling of a variety of complex shapes. A ball end mill has a normal hemisphere and therefore a machine which has four or five axis control is necessary to realise the high degree of free form shaping possibilities. In the case of the micro-EDM-machined spherical PCD tool, there are innumerable cutting edges uniformly located along its entire surface. The tool shape can be machined closer to a full sphere than a hemisphere without limitations, except holding the shape, and thereby a larger surface area can be used for processing. Figure 1 shows the two types of machining using the spherical PCD tool, in the *XY* plane and the *YZ* plane. The combination of these two and a slant plane are also possible. There is a limit to the speed of the cutting edge while grinding in the *XY* plane, but there is no limit to the depth of cut. Grinding in the *YZ* plane can be processed utilising the maximum speed of the cutting edge, but there is a limitation to depth due to the shape of the tool. In both planes the formed surface is a replication of the tool path. This microgrinding process is the combination of an arc envelope grinding method and a parallel grinding method when shaping a free form surface. This report focuses on the surface roughness generated by both grinding methods in *YZ* plane.

Figure 1 Tool location of microgrinding process with spherical PCD tool



3 Processing equipment

In this study, the microgrinding and EDM machine (GM703 made by SmalTec International) is used for shaping the spherical PCD tools and also to perform the microgrinding processes (Mraz et al., 2007). This processing equipment has a micro-EDM function with an advanced pulse discharge current as short as 5 ns, achieved by the optimisation of the insulation. The PC-based numerical motion control has a 10 nm step resolution in the *X*- and *Y*-axes and 100 nm step resolution in the *Z*-axis. This equipment achieves highly precise positioning by the use of a fully closed-loop system combining AC servo motors and linear scales.

The PCD tool is held at the end of the mandrel, and the mandrel can be rotated by a belt on the ceramic V-bearing using a DC servo motor. The maximum rotation speed of the mandrel is 7500 rpm. By utilising the simple belt-type holding and driving system of the mandrel, a high level of precision is easily accomplished while replacing the mandrel onto the machine. Therefore, the tool can be inspected for dimensions and the aspects of the surface before and after processing, providing for a good analysis.

4 Micro-EDM-machined PCD surface and forming a spherical shape

4.1 Evaluation of the aspect property of the micro-EDM-machined PCD surface

The micro-EDM-machined surface roughness can be controlled by the discharge energy of one pulse of electro discharge. The PCD has conductivity through the cobalt-binding material. The fine particles of diamond in the PCD material sublimates with electro discharge. The following experiment was conducted for the evaluation of the aspect properties of the PCD surface provided by the micro-EDM as compared to tungsten carbide tooling, and to analyse the surface properties for use as a grinding tool. Using a 50 µm diameter tungsten electrode, a shallow groove was machined with three values of the discharge energy settings listed in Table 1. The PCD (Sumitomo Electric Industries made Sumi-diamond DA200, average particle size 0.5 micron) and the tungsten carbide (ultrafine particles NM10 JIS Z10 equivalency made by Hitachi Tools) are observed and compared relevant to surface finish. Figure 2 is an optical microscope image showing the comparison of each of the three processed surfaces. The average crater size value is an average of ten sample craters formed by a one shot of electrical discharge as it relates to the electrical discharge energy applied. The diameter of a crater is proportional to the electric discharge energy applied. Using larger discharge energy, the crater diameters on the PCD material are smaller than on tungsten carbide. The following differences are observed. The crater on tungsten carbide, formed by a single-pulse electro discharge, is the shape that resembles a shallow bowl, and the surface is generated by piled up craters. In contrast, with PCD, and larger electro discharge energy, there is no clear crater shape. The form of the cavity is created in depth without the expansion in surface direction. Figure 3 is an illustration showing the difference of the formation mechanism of a single pulse electro discharge between the two materials of tungsten carbide and PCD. An arc occurs with breakdown between the electrode and the work piece. In tungsten carbide, the portion which was not flushed away solidifies again as a shallow bowl-shaped crater on the surface. On the other hand, with PCD, only the part which sublimated becomes a cavity without melting. It is thought that the fine diamond particles which were not removed around the cavities edge, and are dotted along the surface, work like cutting edges. In other words the cutting edges have enough strength, same as PCD itself and therefore it is thought that this is the reason for the small abrasion reported here.

Table 1 Micro-EDM conditions

Conditions	*1*	*2*	*3*
Voltage (Volts)	80	110	110
Capacitance (pF)	10	470	3300
Dielectric	IDEMITU Daphne cut HL-25		

Figure 2 Micro-EDM surface observation comparison on PCD and tungsten carbide

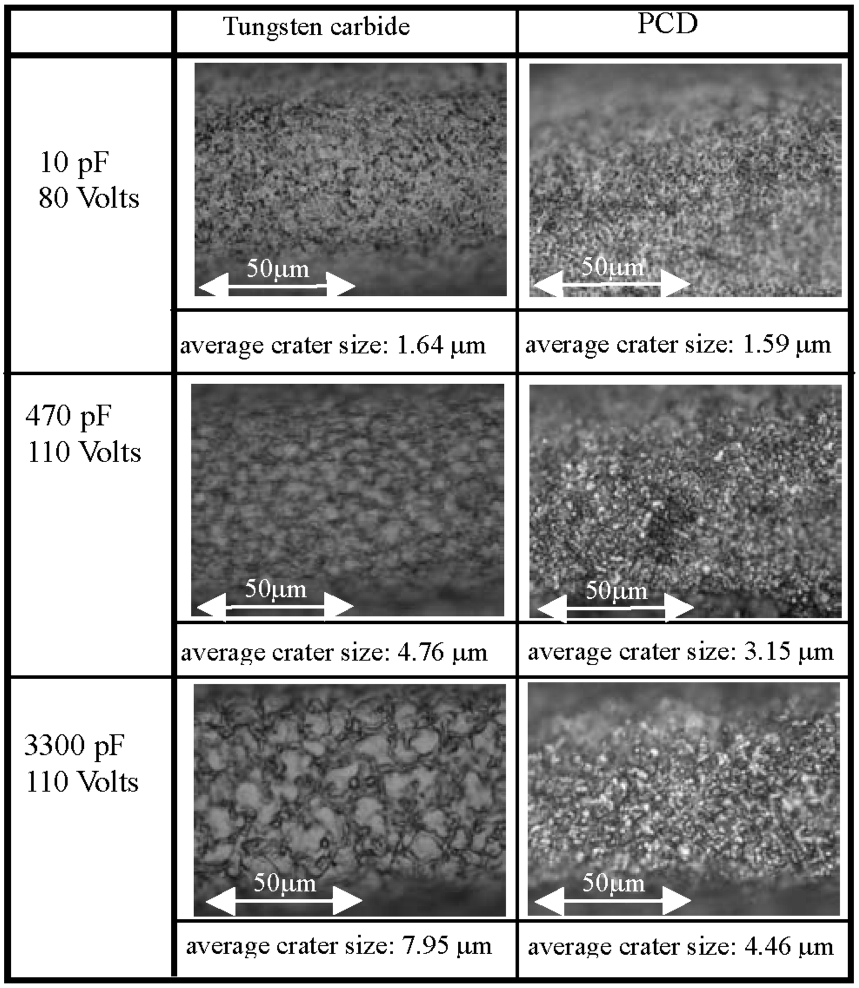
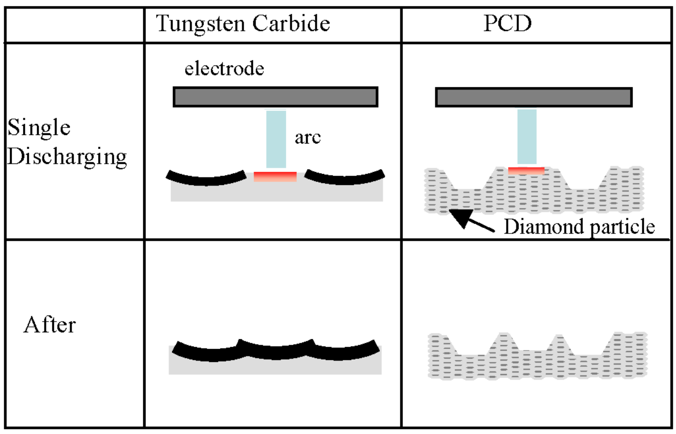


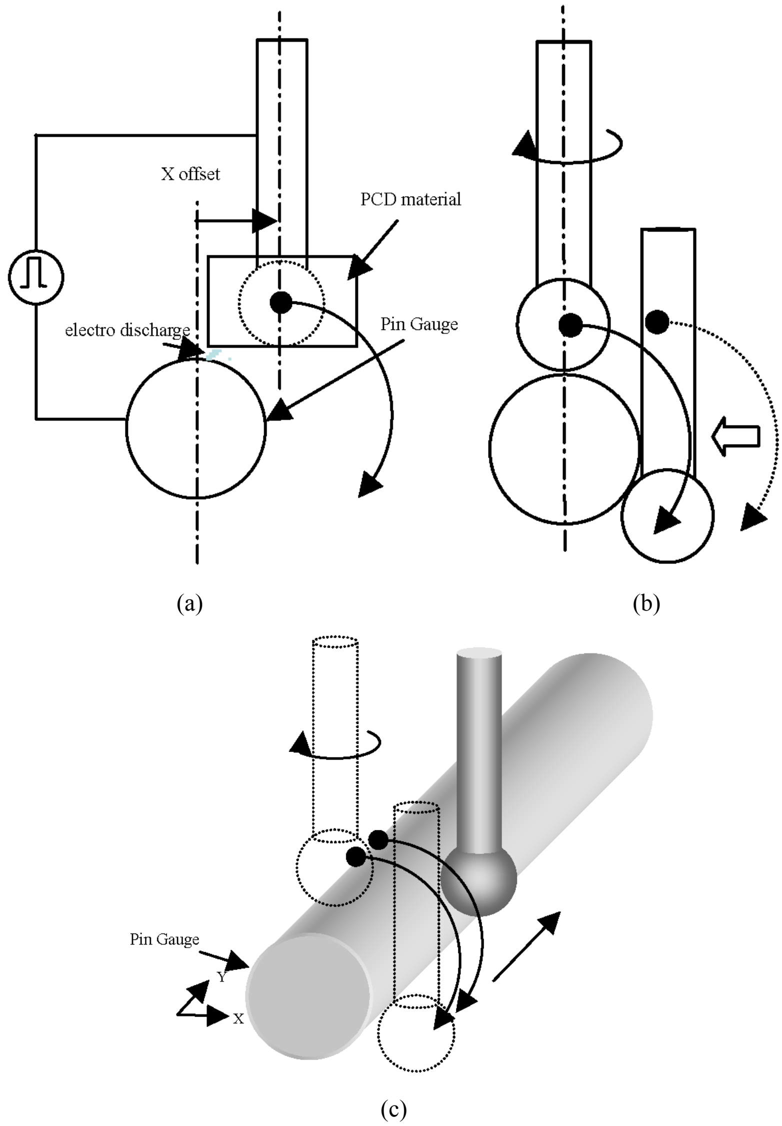
Figure 3 EDM process comparison between PCD and tungsten carbide



4.2 The shaping method of the spherical PCD

The Wire Electro Discharge Grinding (WEDG) (Masuzawa et al., 1985) can be used for the shaping of a minute cylindrical electrode. The shaping of the spherical PCD by the WEDG is possible, but the diameter precision of the wire which is used is approximately ±1 micron, and it is thought that it is extremely difficult to make the shape of a precision spherical tool for use during microshape grinding requiring high precision, using this process. Therefore a pin gauge made of tungsten carbide, that has a precisely controlled diameter and straightness, is used as a tool electrode for this study. Figure 4 is an illustration of the shaping procedure of the spherical PCD tool using the pin gauge.

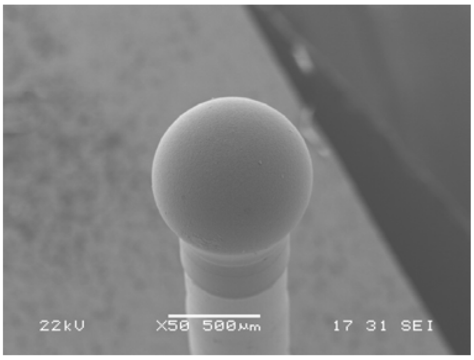
Figure 4 Procedure of shaping a spherical PCD tool: (a) start tool path with *X* offset; (b) final tool path and (c) repetitive shaping to compensate electrode wear



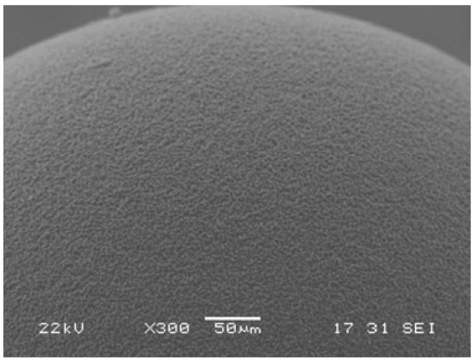
A process using reverse polarity micro-EDM is used for shaping the spherical PCD tool. With the PCD material rotating, the machining path follows a cylindrical shape along the pin gauge. With this motion the PCD tool becomes a spherical shape. Figure 4(a) shows the original tool shape and tool path with the *X* offset. The *X* offset value is reduced in successive steps. The final tool path is defined by the radius of the pin gauge and the resulting spherical shape is shown in Figure 4(b). This process is repeated moving in a positive *Y*-axis direction, added with the X movement, compensates for the pin-gauge wear. This process is considered completed when there is no discharge detected between the PCD and the pin gauge.

The SEM images of the micro-EDM-shaped spherical PCD is shown in Figure 5. The Micro-EDM conditions used during shaping were capacitance 3300 pF and voltage 110 V. The pin gauge used had a 1 mm diameter. The spherical diameter of the PCD tool was 840 µm. The entire spherical surface is shaped with uniform aspect properties. The remaining surface appears to be a web following the process as described in Section 4.1, and therefore the remaining surface is covered with innumerable cutting edges uniformly distributed along the surface. The difference comes from the fact that electrical discharge occurs between both electrode as a cylinder and the sphere. The discharge point is small so the particles which are produced by the discharge do not stay between the electrode and the sphere and this allows the discharge to occur uniformly.

Figure 5 SEM image of micro-EDM-shaped PCD spherical tool

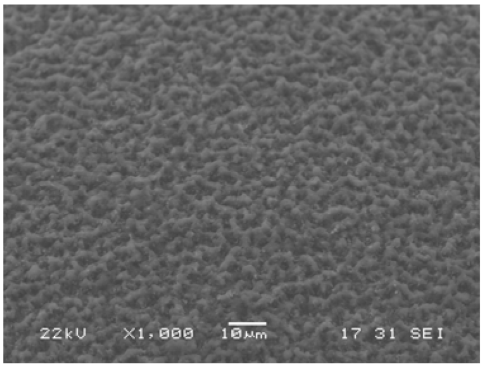


(a)



(b)

Figure 5 SEM image of micro-EDM-shaped PCD spherical tool (continued)



(c)

5 Microgrinding with the spherical PCD tool

5.1 Point processing

Figure 6 shows the procedure of the simple point process to evaluate the replication of an aspect property of the tool. The spherical PCD tool was moved in the *X* direction around 10 µm after it was positioned in the *YZ* plane. One of the PCD tools (tool A) was shaped with the EDM conditions of 10 pF/80 V to a diameter of 610 µm, the other tool (tool B) was shaped with EDM conditions of 3330 pF/110 V to a diameter of 650 µm. The work piece material used was Tungsten Carbide (ultrafine particles NM10 JIS Z10 equivalency made by Hitachi Tool). The tool rotation was 3000 rpm and the dielectric oil (Idemitsu Kosan Dafney cut HL-25) was used as the processing liquid as a function of the equipment.

Figure 6 Procedure to point the spherical PCD tool

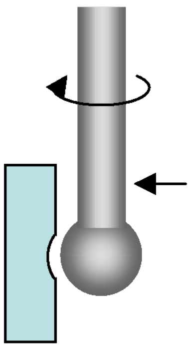
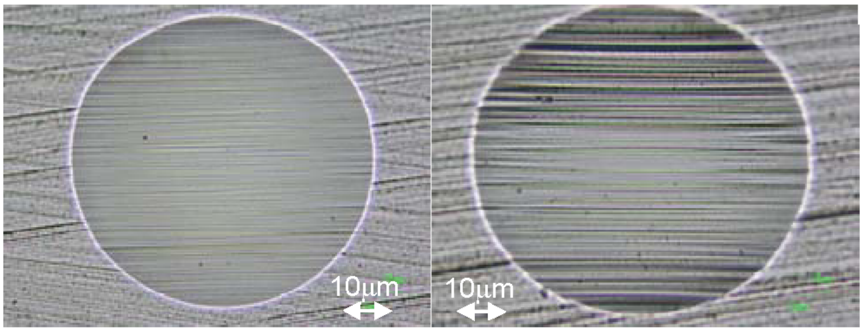


Figure 7 shows an optical microscope image of the result, Figure 7(a) of tool A and Figure 7(b) of tool B. The cutting marks were generated in the rotational direction of the spherical tool, and the roughness is better with tool A, which was shaped by the lower discharge energy. It is observed that the surface roughness of the centre area is better when compared with the circumference, and this is visible in Figure 7(b). The centre area was ground by the largest portion of the diameter of the spherical PCD tool which has the most number of cutting edges, and therefore the surface roughness was averaged to be smoother. The machined area, when using a spherical PCD tool of 650 µm diameter into a plane of 1 µm cutting depth, would be around 50 µm diameter. It is expected when generating a flat plane, with a good surface roughness, the curved surface of the cutting edge at high latitudes on the spherical PCD tool, contributes in generating a rougher surface.

The following experiments in Sections 5.2, 5.3 and 6.3 use tool B which was shaped using the larger discharge energy.

Figure 7 Optical microscope images of pointed shapes formed by PCD spherical tool (material: tungsten carbide): (a) 10 pF, 80 Volts and (b) 3300 pF, 110 Volts



(a) (b)

5.2 *Forming a flat plane and a microcylindrical surface*

In order to confirm the expectation of the surface roughness stated in Section 5.1, a basic processing experiment of forming a microsurface with the spherical PCD tool was conducted. The forming of a small flat plane and a microconcave cylindrical surface with radius of 4 mm was ground on the same tungsten carbide. Figure 8 shows the procedure of this test grinding. The tool path was orientated in the *Z*-axis direction which was perpendicular to the rotational direction to avoid the surface aspect of the result in Section 5.1, and then repetitively stepped in the *Y*-axis direction. During the rough forming pass the cutting feed step along *X*-axis was 2 µm for each increment and the *Y*-axis feed step was 100 µm, and during the final cutting pass the feed steps were 2 µm and 1 µm for the *X* and the *Y* directions, respectively. The feed rate of the tool and the rotation speed during the final cut pass were set at 1 mm/s and 3000 rpm, respectively.

With Figure 9, it is observed that the ground surface has a mirror finish. Figure 10(a) and (b) are SEM images and (c) and (d) are the surface roughness of a flat plane of the machined area. The area that was evaluated for surface roughness was measured to be 90×70 µm (measured by Zygo NewView10 equipment with a 40X object lens).

The surface generated by the arc envelope grinding process has roughness of 5 nm Ra and 28 nm in PV (equivalent to Rz). It is confirmed that an aspect is formed in the cutting surface, and is a visible mark created in the direction of tool rotation shown in Figure 10(b), but the granular unevenness characteristics of tungsten carbide is identified to be rougher.

Figure 8 Procedure of shaping a flat and cylindrical surface using a spherical PCD tool

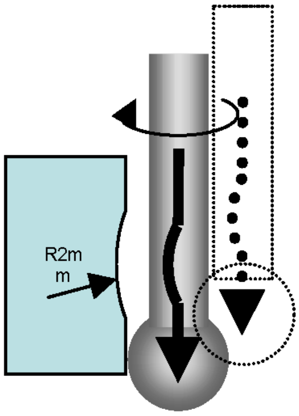


Figure 9 Optical microscope image of shaped flat and cylindrical surface on tungsten carbide

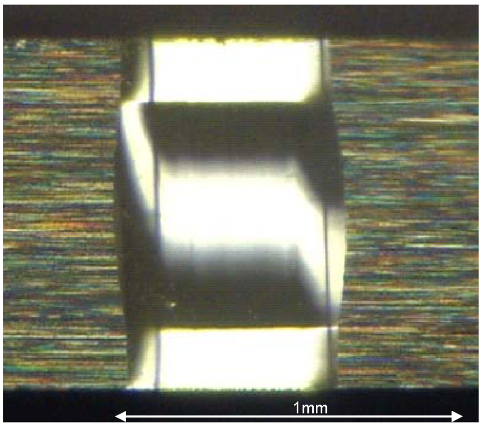
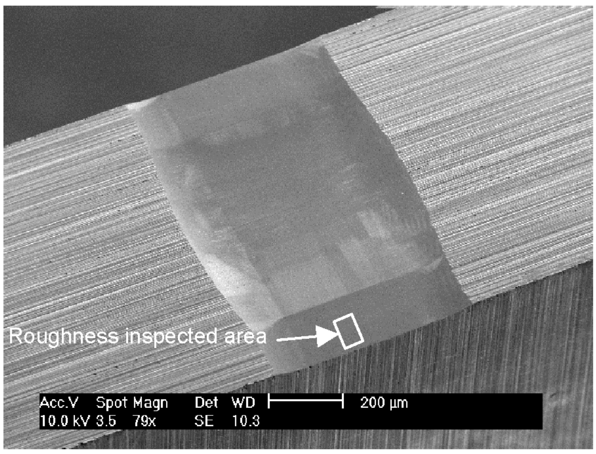
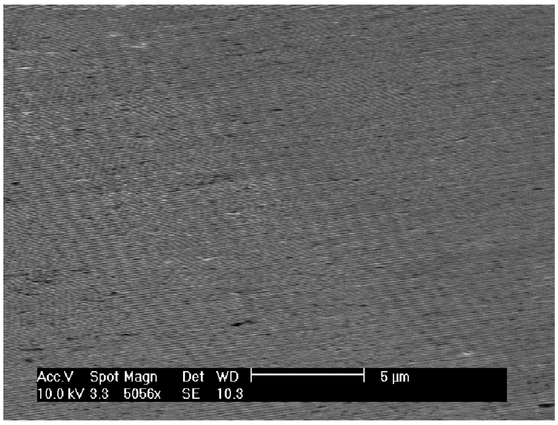


Figure 10 SEM images of machined area and also surface and roughness data

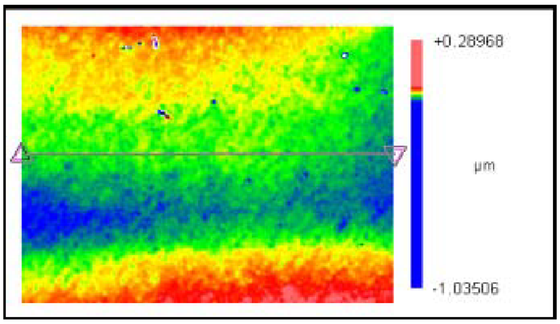


(a)

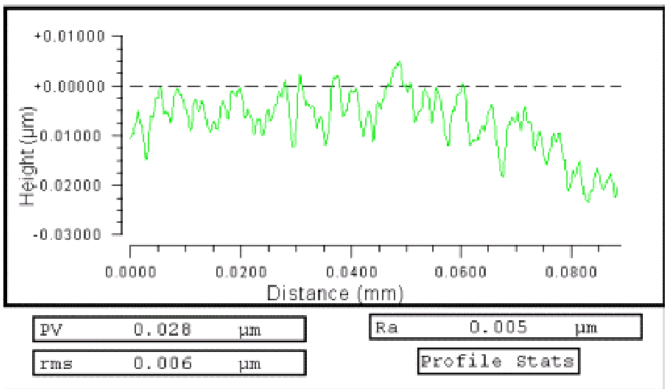
Figure 10 SEM images of machined area and also surface and roughness data (continued)



(b)



(c)



(d)

5.3 *Forming of a convex spherical surface (SR1 mm)*

The procedure of forming a convex spherical surface, which has a spherical radius of 1 mm, is shown in Figure 11. The form was shaped by moving the spherical PCD tool in a circular path in the *YZ* plane with a cutting feed direction in the *X* plane. The material was a tungsten carbide, same as above. The diameter of the final convex spherical-shaped surface was 0.5 mm, and the circumference portion was only the roughing processing. The roughing processing step in radial direction was 20 µm and the cutting unit in the *X*-axis was 2 µm per step. The finishing step in radial direction was 2 µm. During both roughing and finishing process, the tool rotation was 4000 rpm and the tool feed rate was 2 mm/min. Figure 12 is an image from an optical microscope. Figure 13 is an SEM image of the machined results. Figure 14 is an image from an optical microscope of the machined centre area. It is observed that generally the surface has a mirror like finish. Observing the vertical domain, from top to bottom, in Figure 15, the tool marks of the finishing process are visible as a transfer of the radial direction, but in the horizontal domain, no tool marks are observed and the grain structure of tungsten carbide is clearly visible.

The radial marks are suspected to be caused as defined here. During this processing the cutting area is a small point since both the work piece and the tool are convex shaped. When the tool rotation is parallel to the tool travel the resulting surface reveals the tool marks at the point of contact from each path step. Conversely, when the tool rotation is perpendicular to the tool travel the resulting surface does not show any tool marks, since the small points of contact overlap. Optimisation of the feed step size and the tool path will reduce the tool mark.

Figure 11 Procedure of shaping a convex spherical surface

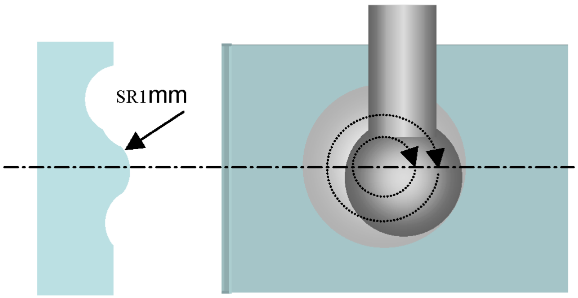


Figure 12 Optical microscope image of a shaped convex spherical surface on tungsten carbide

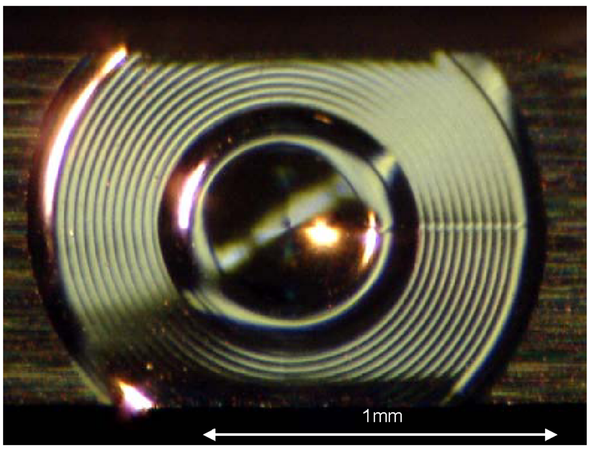


Figure 13 SEM image of a shaped convex spherical surface

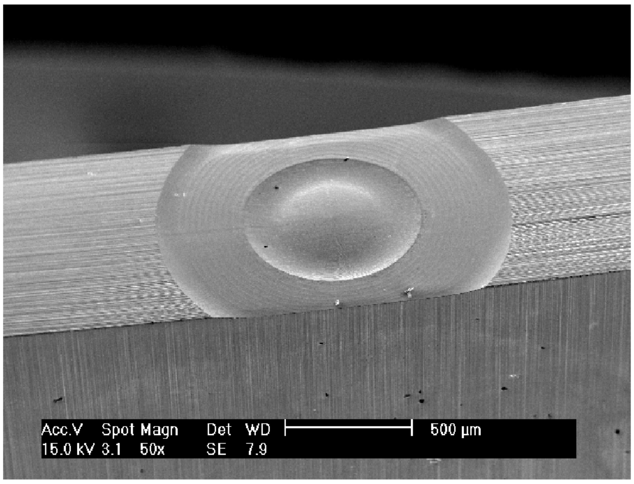


Figure 14 Optical microscope image of a shaped convex spherical surface on tungsten carbide

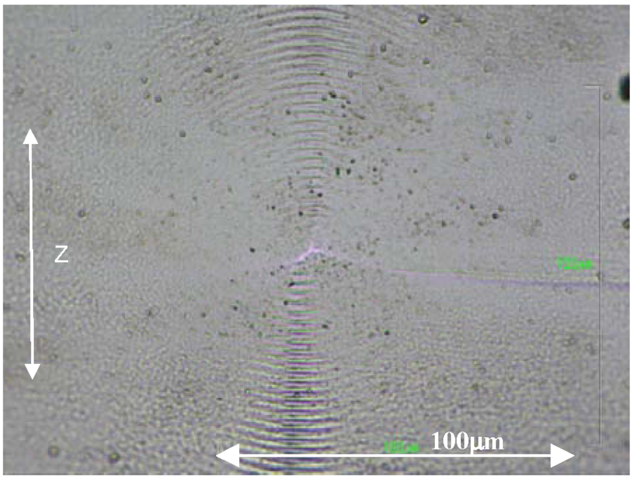
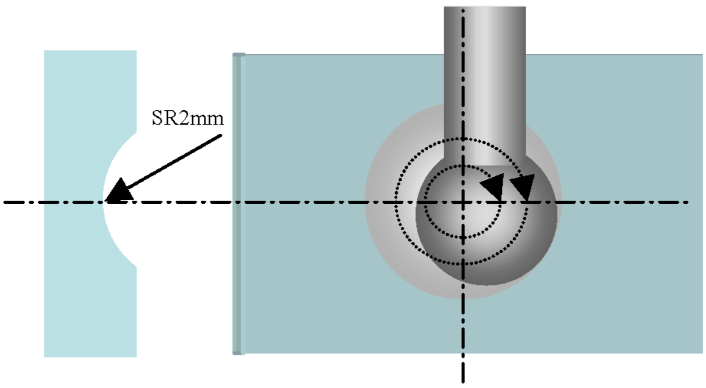


Figure 15 Procedure of shaping a concave spherical surface



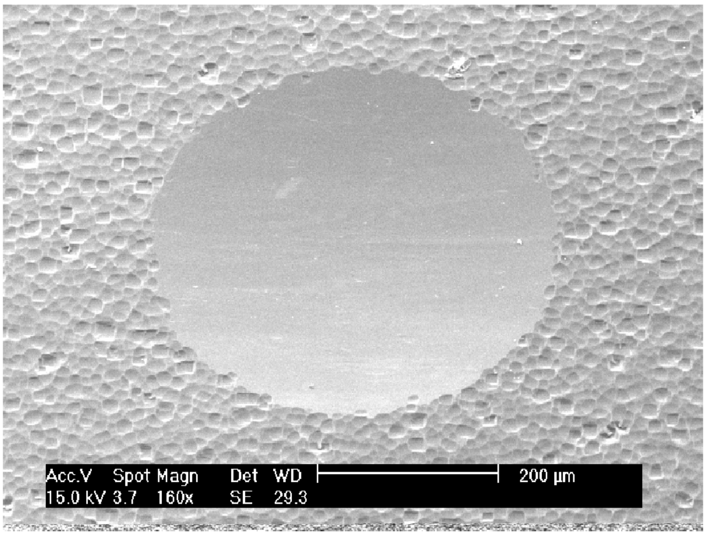
6 Applications

It is feasible to apply this spherical PCD tool-grinding method to hard brittle materials. Following are the results of grinding on silicon and alumina ceramics as examples.

6.1 Concave spherical surfacing on silicon

The procedure of creating a concave spherical surface, which has a spherical radius of 2 mm and a diameter of 400 μm is shown in Figure 15. Silicon wafer material was used. The processing conditions of rough cutting and finishing were same as in Section 5.3, except the feed rate was changed to 4 mm/min. PCD tool A was used which was shaped with the EDM conditions of 10 pF/80 V. Figure 16 shows an SEM image of the machined results. The whole plane is formed with a uniform minute tool mark. A correct roughness measurement was not possible because it was insignificant, and the domain was a curved surface. The process is very similar with Section 5.3 but there is no singular domain because the work shape is concave. The cutting area is around 53 μm at a depth of 1 μm so that the tool mark by the step feed are eliminated and a uniform surface is generated.

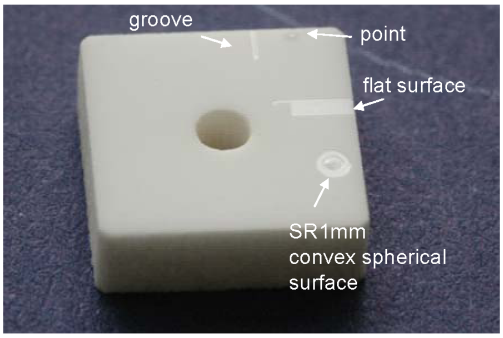
Figure 16 SEM image of a concave spherical surface shaped on silicon



6.2 Processing of alumina ceramics

Figure 17 is an image of PCD-ground micro shapes on alumina ceramic. All of a variety of microshapes were processed using the spherical PCD tool on alumina as an example of machining of ceramic materials. All of the features were successfully shaped as on the tungsten carbide, a single point, a single groove, a flat plane with overlapping grooves, and a microconvex spherical surface SR 1 mm same as in Section 5.3. The aspect property of the machined surfaces was not measured because of the porous surface of alumina.

Figure 17 Optical microscope image of PCD-ground microscope on alumina ceramic



7 Tool abrasion

The abrasion value of the spherical PCD tool, after its use for the above-stated processing, was too small to measure with available optical microscope.

8 Conclusions

- By observing the surface of the micro-EDM-shaped PCD tool surface, it is thought that the material which was sublimated becomes a cavity in the PCD tool and the fine diamond particles which were not sublimated around the cavities edge, and are dotted along the surface, work like cutting edges.
- Using a pin gauge to shape a spherical PCD tool performs well as a tool electrode for making a uniform cutting edge on the complete spherical tool surface.
- In forming a flat plane, using the spherical PCD tool on Tungsten Carbide, the surface roughness was measured to be 5 nm in Ra and 28 nm in Rz.
- The capability to shape a microconcave cylindrical surface and a microconvex spherical surface using a spherical PCD tool are confirmed with good surface roughness on tungsten carbide, silicon and alumina ceramic.
- It is observed that when the tool rotation is parallel to the tool travel, the resulting surface reveals the tool marks at the point of contact from each path step. Conversely, when the tool rotation is perpendicular to the tool travel the resulting surface does not show any tool marks, since the small points of contact overlap.

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