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Fabrication of PCD Mechanical Planarization Tools by using µ-Wire Electrical Discharge Machining

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Abstract

Fabrication of micro components made from difficult-to-cut materials require the use of micro cutting tools which can withstand the harsh conditions during machining. Polycrystalline diamond micro tools, produced using micro wire electro discharge machining, have been used to machine silicon. In this study, fabrication of PCD planarization tools having micro-pyramid lattice structure is considered. A tungsten wire with 30 µm diameter was used, which makes it possible to obtain very precise micro-features by employing extremely low discharge energies. The performance of the tools is investigated through micro scale grinding of silicon and appropriate machining parameters which resulted in ductile regime machining of silicon are determined.

Keywords: Electrical Discharge Machining; Polycrystalline Diamond; Micro Cutting Tool; Ductile Mode Machining; Micro Grinding

1. Introduction

Brittle materials such as different grades of ceramics, carbides, glasses, single crystal materials, PVD hard-coatings or semiconductor materials have found widespread applications in micro electro mechanical systems (MEMS), medical devices, micro-fluidics systems, electronics, aeronautics, optics, semiconductor and molding industries because of their excellent and desirable engineering properties such as high hardness, high wear and corrosion resistance, thermal stability and etc. [1-5].

Abrasive processes are the most commonly used process for machining these hard and brittle materials. However, due to their nondeterministic nature, high wear rates and self-sharpening, it is more difficult to machine high precision parts by abrasive processes [1, 2]. Ductile mode machining as a deterministic process can be a promising solution to have an acceptable surface quality while maintaining the contouring and form accuracy of the machined parts. The idea of ductile mode machining comes from the fact that brittleness is a scale dependent material characteristics, which means that all brittle materials can show some ductility when the scale of deformation becomes small enough. It was confirmed by Bifano et al. [6] that in brittle materials, as depth of cut decreases to a critical value known as critical depth of cut, a transition in deformation regime from brittle to ductile occurs. This transition has been described in terms of material removal energy, and it has been shown that for machining depth of cuts lower that critical depth of cut, plastic flow is energetically favorable material removal mechanism. Blackley and Scattergood [7] proposed a relation for the critical chip thickness at the point of transition, where the critical chip thickness and surface damage depth is related to tool feed, tool nose radius and location of ductile to brittle transition. Material removal energy has been used by Blake and Scattergood [8] to present the concept of ductile to brittle transition. They mentioned that the ratio between energy of plastic flow and energy of brittle fracture is proportional to the undeformed chip thickness. The J-integral approach based on elastic-plastic fracture mechanics has been used by Ueda et al. [9] to analyze material removal mechanisms during micro cutting of ceramics. Using finite element method, they obtained J-integral values along several contours around the tip of the crack formed ahead of the cutting tool. The

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calculated J-integral values are compared to the critical value of J, which is a property of the material being cut. For J values greater than critical J values, material removal considered to be of brittle. Recently, molecular dynamics simulations have been used to study the mechanism of material removal in ductile mode. Using MD simulations, Xiao and Zhang [10] studied atomic scale details of ductile deformation in the machining of silicon carbide, where the occurrence of phase transformation has been observed during cutting process.

Ductile regime machining has been experimented on different brittle materials. Included in this paper are few examples of the application of ductile mode machining in processing of different brittle materials. Engineered diamond wheels with defined and semi-defined diamond grain patterns has been developed by Heinzel and Rickens [2] and used for deterministic notch grinding of optical glass BK7. A minimum areal arithmetic mean height of Sa= 20 nm has been obtained. Zhang et al.[3] investigated the influence of microstructure and brittleness of RB-SiC/Si and WC/Co carbides in ultra-precision grinding. They obtained a surface roughness of 20 nm for SiC/Si under brittle material removal mode and 5 nm for WC/Co under ductile removal mode. Recently, Aurich et al. [5] conducted micro-grinding of mono-crystalline silicon [1 0 0] using their developed Nano Grinding Center by means of on-machine fabricated galvanic coated ultra-small micro pencil grinding tools with a diameter between 4-40 µm. They obtained a surface roughness of 25 nm on silicon using 40 µm micro grinding tools.

Recently, polycrystalline diamond (PCD) is accepted as an excellent super hard tool material for machining of hard and brittle materials, especially at micro-scale, and several processing framework were developed for its fabrication, including liquid phase solvent-catalyst assisted sintering, encapsulation in refractory metal containers (normally tantalum), incorporation of a WC-Co substrates and diamond powder treatment prior to high-pressure/high temperature sintering [11]. Among these frameworks, infiltration from WC-Co substrates provides some advantages for tool fabrication purposes because the WC-Co gave a surface which could be readily joined to other materials.

Owing to its high hardness and strength, PCD is extremely difficult to be machined by mechanical methods, especially for feature sizes smaller than 100 µm [12]. Very low G-ratio (the ratio of the volume of material removed from PCD to the volume of material removed from the grinding wheel) is the characteristics of PCD grinding. EDM-based techniques can be considered as an alternative machining method for processing PCDs. The presence of cobalt as a PCD matrix, not only imparts in a significant degree to PCD toughness, but also makes it electro-discharge machinable. However, machining of PCD is still a challenging task for researchers and practicing engineers. In an attempt for better machining of PCD, Yan et al. [13] developed a new pulse generator for µ-WEDM of PCD. They achieved a minimum surface roughness of Ra=0.6 µm in a PCD of 2 µm grain size. Chen and Jiang [5] fabricated a boron doped PCD tool having double sided negative back rake angle of -60º fabricated using WEDM process. They conducted force controlled grinding-milling of quartz glass. A critical depth of cut of 1 µm is determined experimentally and they obtained surface roughness of 25 nm. On-machine fabrication of PCD micro tools by block-EDM method has been done by Parveen et al.[14], and are used for machining three glass materials (BK7, Lithosil and N-SF14). A minimum average surface roughness of 12.79 nm is achieved on BK7.

In macro-scale grinding of optical glasses, it has been shown that grinding wheels with well-defined grain patterns known as engineered grinding tools (EGT) usually have advantages over randomly structured (stochastic) grinding wheels in terms of material removal predictability, lower grinding forces and power, and workpiece surface integrity [15]. Therefore, in this study attempts have been made to fabricate micro-engineered planarization grinding tools, where an array of cutting edges in the form of pyramids have been produced on a PCD using µ-WEDM process. The performance of the fabricated planarization tools has been analyzed in terms of tool wear and workpiece surface quality. Fabricated mechanical planarization tools can be used as pre-processing tools before doing any precision machining operations on silicon or other brittle materials, because it is normally difficult to perfectly align the silicon surface with respect to the machine table. Knowing the fact that ductile mode machining is very sensitive to depth of cut variations, removing workpiece inclinations and misalignment arising from fixturing of the workpiece seems to be necessary. In addition to their applications for pre-processing, these tools can also be used to remove subsurface damage layers produced during precision machining of brittle materials. In these cases, process efficiency can be improved by first performing machining at a higher material removal rate which may induce some subsurface damages. These subsurface damages can be removed in a subsequent post-processing step by performing ductile mode machining via developed mechanical planarization tools. In this study micro-grinding experiments are done on silicon as a working material.

2. Fabrication of PCD Mechanical Planarization Tools

In this study mechanical planarization tools has been designed and fabricated using µ-WEDM process. Sodick AP250L high precision WEDM machine is used for machining micro-pyramids on Sumitomo DA150 grade PCD rods with 5 µm grain size and 10-15% cobalt content was used. PCD rods of 2 mm diameter are mounted on the indexer of the WEDM machine as depicted in Figure 1. The concentricity between PCD rod and rotational axis of the indexer is controlled using Mahr Federal Electronic lever type gauge (EHE 2056) with a sapphire ball tip of 1.6 mm, connected to a Mahr Millimar C 1208 display with linearity of – 0.1% over full range of ±0.250 mm. Concentricity within ±1 µm is obtained by fine adjustments. Open contour cutting with open nozzle positions is done in the form of cross cut (one cut at 0º and the other cut after 90º rotation).

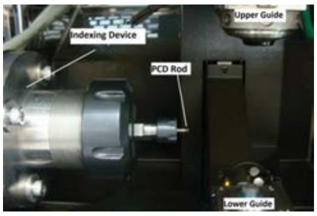

Fig. 1. Tool Fabrication Setup

Figure 2 schematically illustrates the tool fabrication process. µ-WEDM of the PCD is conducted by using 30 µm tungsten wire (TWS-30, 3330 N/mm^2 tensile strength).

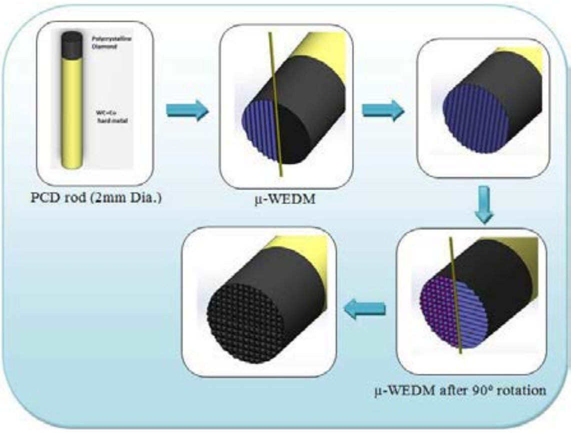

Fig. 2. Tool Fabrication Steps

Table 1 illustrates the EDM parameters used in this study. One rough cutting and one finish cutting operations are done. Total cutting perimeter was 5.98 mm and 4.87 mm for coarse patterned and fine patterned tools, respectively. The feed rate has been varied by servo controller between 0.1 mm/min and 0.85 mm/min which resulted in a total cutting time of 20 min for coarse patterned tool and 17 min for fine patterned tool.

Table 1. µ-WEDM parameters used for tool fabrication (*Encrypted code of the machine tool manufacturer.)

Parameters	Roughing	Finishing
Pulse On Time*	000	000
Pulse Off Time*	005	008
Reference Voltage (V)	+ 170.0	+120.0
Supply Voltage (V)	5.0	2.0
IP (Peak Current)*	0012	0006
Capacitance	0	0
Wire Speed (m/min)	3	5
Inverter Frequency* (Hz)	020	012
Flushing (l/min)	2	2

EDMfluid 108 MP-S is used as a dielectric fluid with the specifications given in Table 2. The use of oil as a dielectric fluid eliminates electrolysis and minimizes kerf, recast layer and micro-cracking. This can be attributed to the lower cooling rate of oil compared to water.

Table 2. EDMfluid 108 MP-S specifications

Viscosity 20º C	Flash Point (ASTM D 93)	Distillation Interval	Density
3.0 (cSt)	≥ 108 (º C)	6(º C)	0.767(kg/l)

Array of micro-pyramids with an apex angle of 60º are machined on a PCD-WC rod. Depending on the spacing between pyramids, their height and base area, coarse patterned or fine pattern planarization tools can be fabricated. Figure 3 and 4 illustrate examples of fine patterned and coarse patterned planarization tools, respectively.

Mechanism of material removal in PCD is different than metallic materials. Discharge energy and the grain size of the PCD are two surface roughness controlling parameters in electrical discharge machining of PCD.

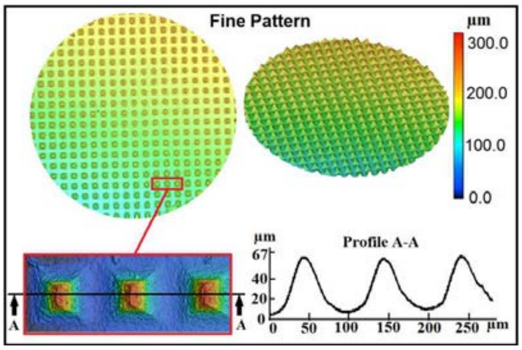

Fig. 3. Fine patterned planarization tool.

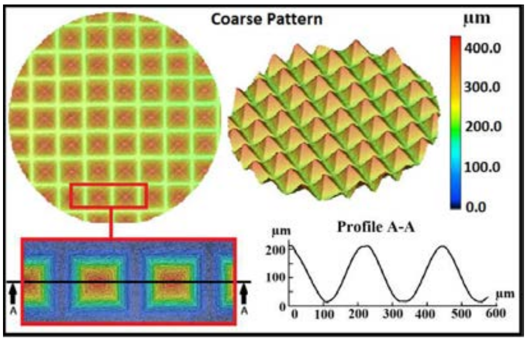

Fig. 4. Coarse patterned planarization tool.

At high energy discharges the dominant material removal mechanism of PCD is believed to be the melting of binder (normally Cobalt or Nickel) and falling off of diamond grains. This can be considered as the main reason why the craters on PCD tools are not like shallow bowl as can be observed in tungsten carbide tools [16]. However, when machining PCD at low discharge energies, gradual removal of diamond grains can occur as a result of microstructural changes through graphitization and thermo-mechanical reactions without falling off of diamond grains [12, 17]. In this study, low discharge energies are used to avoid wire breakage, which makes it possible to obtain a lower surface roughness on PCD. Figure 5 illustrates a PCD surface obtained by machining under the conditions of Table 1. An average roughness of Ra=0.12 µm is achieved on PCD which is quite low compared to the value of Ra=0.6 µm reported by Yan et al. [13].

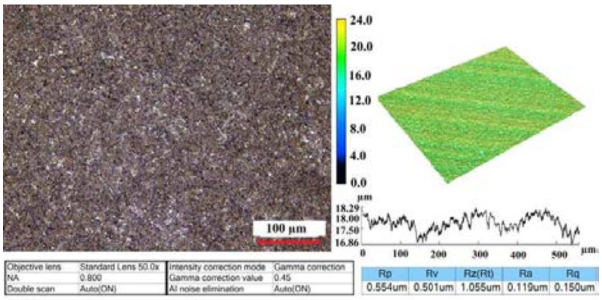

Fig. 5. PCD surface machined at low discharge energies.

The fabricated planarization tools have been used for micro-grinding of silicon wafers which will be discussed in detail in the next section. It has been observed that some silicon material accumulated and clogged at the center of the tool (where the cutting velocity is zero). The accumulated material is shown in Figure 6(a). In this case, due to the contact between the center of the tool and the machined surface, squeezing and rubbing of the silicon chips to the machined surface resulted poor surface quality and brittle fracturing has been observed as shown in Figure 6(b). The surface finish is deteriorated at the middle of the tool path, while in outer sections a good surface roughness is achieved.

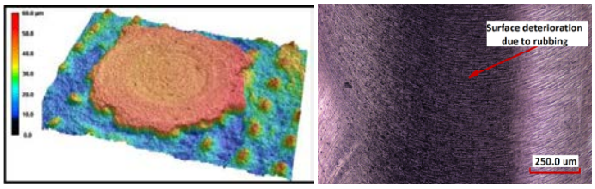

Fig. 6. (a) Accumulation and clogging of silicon at the center of the cutting tool, (b) Surface deterioration due to the rubbing of clogged silicon material.

To overcome this problem a clearance was created at the middle of the tool by producing a hole at the centre. Therefore, an additional µ-EDM hole drilling step is added to the process of tool fabrication as depicted in Figure 7.

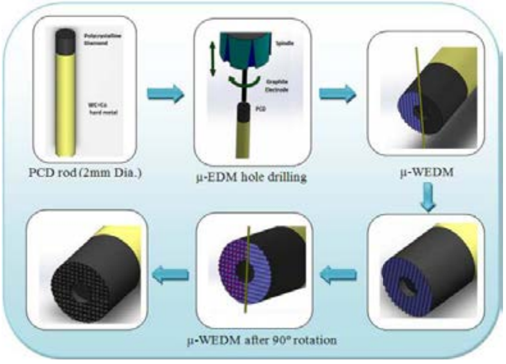

Fig.7. µ-EDM hole drilling of PCD tools.

Micro-EDM hole drilling were carried out using a graphite electrode of 500µm diameter in a hybrid micro-machine tool (MIKROTOOLS- DT-110). The machine has a resolution of 100 nm. Table 3. shows the µ-EDM parameters. A 3D close up view of the planarization tool with a hole at the centre is depicted in Figure 8.

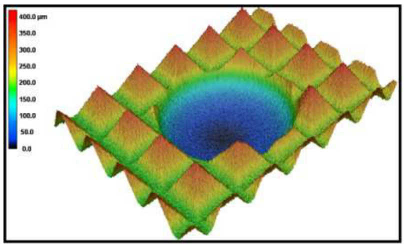

Fig.8. 3D close-up view of the hole drilled PCD tool.

Table 3. µ-EDM hole drilling parameters

Spindle Speed	Capacitance	Voltage
1000 (RPM)	400 (nF)	100 (V)

3. Micro-grinding Experiments

In this study the performance of the fabricated PCD mechanical planarization tools are tested by doing micro-grinding experiments on silicon. Micro-grinding experiments were carried out in MIKROTOOLS- DT-110 as depicted in Figure 9. All experiments were performed at a spindle speed of 2000 RPM.

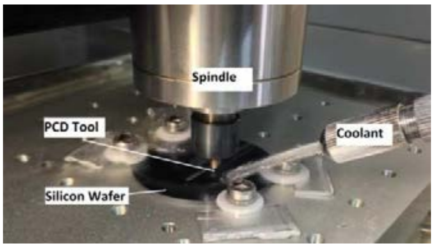

Fig.9. Micro-grinding experimental setup

The performance of both fine patterned and coarse patterned tools are tested at various axial depth of cut and feed per revolutions. Table 4 shows the experimental conditions used for micro-grinding experiments. After each experiments 3D laser topography of the machined surface is obtained by using 3D laser scanning microscope (Keyence VK-X100).

Table 4. Silicon micro-grinding experimental conditions

Exp. #	Feed per revolution [µm]	Axial depth of cut [µm]	Machining Mode (Fine P.)	Machining Mode (Coarse P.)
1	1	1	Brittle	Brittle
2	1	0.5	Ductile	Brittle
3	3	0.5	Transition	Brittle
4	3	0.2	Ductile	Ductile

5	3	0.1	Ductile	Ductile
6	6	0.1	Ductile	Ductile
7	6	0.2	Ductile	Ductile
8	10	0.1	Ductile	Ductile
9	10	0.2	Ductile	Transition
10	15	0.1	Transition	Brittle
11	15	0.2	Brittle	Brittle

Three different cutting regimes can be distinguished by analysing machined surfaces; ductile mode machined surface, brittle mode machined surface and a transition surface. In ductile mode machining a nanometre surface roughness is achieved by removing material through plastic deformations rather than brittle fractures. Figure 10 illustrates silicon chips produced as a result of ductile mode machining of silicon. In brittle mode machining, material is removed by brittle fractures and a completely damaged surface will be achieved. The transition mode cutting regime is a combination of brittle fractures and ductile material removal. These three different cutting regimes are shown in Figure 11. The mode of machining for micro-grinding experiments is given in Table 4.

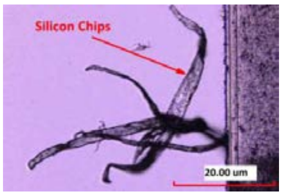

Fig.10. Chips produced as a result of ductile mode machining of silicon

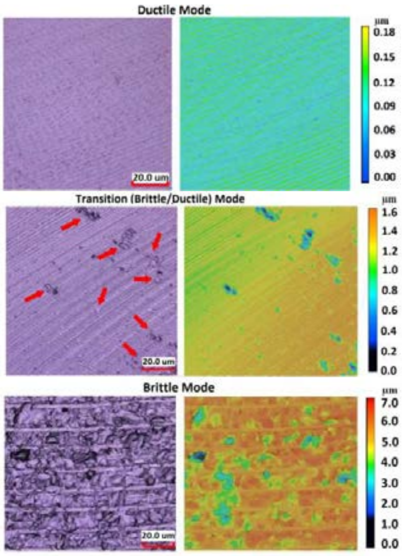

Fig.11. Different cutting regimes when machining silicon using different machining parameters

For the experimental conditions of Table 4, areal surface roughness parameter (Sa: arithmetic mean height) is measured using a 3D laser scanning microscope. The results of measurements for experimental cases which resulted in a ductile mode machining are shown in Figure 12. For transition mode machining the value of 'Sa' varies between 0.12 µm and 0.18 µm, while for brittle mode machining 'Sa' values goes up to 2 µm.

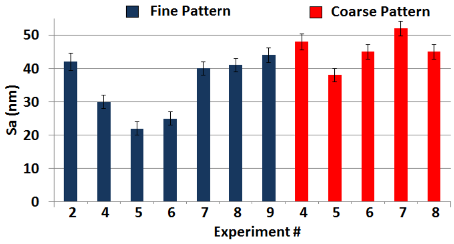

Fig.12. Measured Sa values for ductile mode machined silicon surfaces under different experimental conditions.

Figure 13. illustrates a machining of 10mm×10mm area using a fine patterned planarization tool on silicon. In this case two different radial immersions have been used. Surface of Figure 12 (a) has been machined with 70% radial immersion, while surface in Figure 12 (b) is machined with 5% radial immersion. It has been observed that radial immersion of 70% resulted in an arithmetic mean roughness of Sa=25 nm, while 5% radial immersion resulted in a surface with a roughness of 0.15 µm. The reason for obtaining such a poor surface quality can be attributed to the excessive rubbing and increased friction between the cutting tool and workpiece surface at low radial immersions, which causes excessive tool wear.

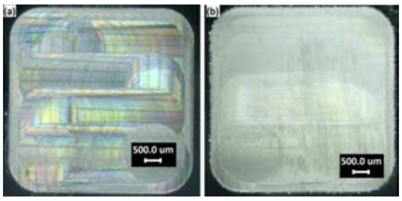

Fig.13. Machining of 10 mm×10 mm area using a fine patterned planarization tool at (a) 70% radial Immersion (b) 5% radial immersion

The mechanical planarization tools have also been examined for removing a damaged layer of the silicon. For this purpose, a surface which was produced as a result of brittle mode machining was selected and re-machined under the conditions of already obtained ductile mode machining. Figure 14 illustrates the improvement in the surface after post-processing. After long term cutting operations under the conditions of Table 4, 3D topography of the cutting tools has been obtained. For coarse patterned PCD tool only wear flats has been observed, but for fine patterned tools especially at higher feed and depth of cut values the breakage of the edges has been observed as depicted in Figure 15. It has also been observed that coarse patterned PCD planarization tools have a longer tool life compare to the fine patterned tools especially at larger feed and depth of cut values. This can be mainly due to smaller localized stresses of the coarse patterned tools because of their larger base area.

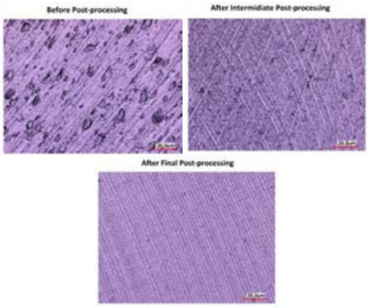

Fig.14. Post-processing using mechanical planarization tools to remove subsurface damage layer

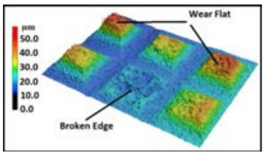

Fig.15. Wear and breakage of the edges of fine patterned PCD tool

4. Conclusion

In this study, µ-WEDM process is successfully implemented for machining micron size pyramids on PCD to manufacture mechanical planarization tools for ductile mode machining of silicon. Following conclusions can be drawn from the results of this study:

1. For tools without any clearance at the center, problem of silicon material accumulation has been observed which had an adverse effect on the quality of the machined surfaces. µ-EDM hole drilling has been introduced as an appropriate solution to overcome this problem.
2. Both fine patterned and coarse patterned PCD tools fabricated by a combination of µ-WEDM and µ-EDM hole drilling, showed a good performance in ductile mode machining of silicon, when appropriate machining parameters are used.
3. Fabricated tools have been employed successfully as a post-processing tool to remove subsurface damage layer of silicon.
4. Tools with fine patterns can be employed in a wider range of machining parameters in terms of feed per revolution and depth of cut; however tool life issues must be taken into consideration when choosing machining parameters. On the other hand, while coarse patterned tools have narrower machining parameter selection domain, they have a longer tool life.
5. Progress of wear flat and breakage of pyramids are identified as tool life issues of fine patterned tools, while for coarse patterned tools under machining conditions of this study the only observable tool life issue was the wear flat and no pyramid breakage is observed.

Acknowledgements

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