Springer

KSME

Journal of Mechanical Science and Technology 24 (11) (2010) 2261~2268
www.springerlink.com/content/1738-494x
DOI 10.1007/s12206-010-0804-7

Design and development of PCD micro straight edge end mills for micro/nano machining of hard and brittle materials [†]

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(Manuscript Received September 22, 2009; Revised June 4, 2010; Accepted July 12, 2010)

Abstract

One of the biggest challenges for mechanical micro/nano milling is the design and fabrication of high precision and high efficiency micro milling tools. Commercially available micro milling tools are either too expensive (around several hundred US dollars) or simply made from downsizing of macro milling tools, which is sometimes not appropriate for the specific micro/nano milling requirements. So the design and fabrication of custom micro milling tools are necessary. In this paper, a micro straight edge endmill (SEE) is designed. Static and dynamic FEM analyses have been done for the SEEs with different rake angles trying to identify their stiffness and natural frequencies. By wire electrical discharge machining (WEDM), the SEEs made of polycrystalline diamond (PCD) with three different rake angles have been fabricated. The evaluation milling on tungsten carbide (WC) and silicon wafer have processed on a nano milling center. Experimental results show the SEEs have a good ability to simultaneously micro/nano milling of both the side and bottom surfaces with submicron surface roughness, and the SEE has high accuracy for large aspect ratio thin wall machining. The milling experiments on silicon wafer have successfully demonstrated that ductile mode machining was achieved and the coolant played an important role in silicon wafer milling.

Keywords: Micro end mill; Micro/nano milling; PCD; WC; Silicon wafer

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1. Introduction

Micro/nano machining is requisite by the tendency of high accuracy and miniaturization of components used for electromechanical instruments, aerospace equipments and medical devices, etc. Among mechanical micro/nano machining processes, micro/nano milling is the most flexible one to create three dimension (3D) features for applications such as micro-electro-mechanical systems (MEMS) and the die/moulds for very high accuracy glass products. They are usually accomplished by two basic groups of micromachining processes: mask based and tool based (mechanical micromachining). The mask based technology has the limitations of fabricating 3D structures [1, 2] and mechanical micro engineering is an easy and cheap way to fabricate microstructures [3]. For this mechanical micromachining, the fabrication of hard molds has typically been done by grinding with micro diamond wheels [4, 5]. However, the three dimensional shape of the recent micro glass products is getting more sophisticated and axis asymmetric. Thus, its mold is difficult or almost impossible to be fabricated by using simple grinding wheels. These shapes require three-dimensional micro/nano machining using end milling technologies.

One of the most important aspects for micro/nano milling is micro milling tools. The reason is that inappropriate tool design and fabrication will result in the long tool fabrication time and high cost due to the complicated tool fabrication processes, and even worse it reduces the geometrical accuracy of fabricated tools, subsequently with these tools, it is difficult to achieve acceptable micro machining accuracies and surface qualities. There are two main categories of micro end mills. One is micro ball end mill and another is the straight or helical edged end mill. This paper focuses on the design and development of straight edge end mills. Many studies have been performed to fabricate or optimize the geometry of the micro machining tools [6-13]. But the following drawbacks or limitations exist in these designed micro end mills. Micro/nano milling needs high spindle speed usually more than 100,000 rpm. So the asymmetrical micro tool geometries in [6, 7] may cause tool chatters and affect the final machining accuracy. Dimensions of micro/nano milling objects are usually on the micron level, which needs higher micro tool stiffness to

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[†] This paper was recommended for publication in revised form by Associate Editor Dae-Eun Kim

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achieve the high finished geometrical accuracy. But the downsizing of the macro helical end mills in [8] may cause the tool stiffness problems. The spindles used in micro/nano milling machines are usually air turbine spindles, which allow smaller cutting forces. The extra contact between the micro end mills [9, 10, 11, 12] and the workpieces may cause the spindle stop or the cutting conditions are not uniform resulting in a bad surface finish.

The SEE series micro straight edge end mills are designed and developed in this paper trying to avoid the possible problems as mentioned above. The SEE has a simply two-edged symmetrical geometry, which can be fabricated by only three (linear) and half (rotational) CNC WEDM axes. Axial rake angle equals radial clearance angle, which makes the fabricating of the bottom cutting edges easily and accurately. By changing the rake angles, a series of SEEs can be achieved for different machining purposes.

Static and dynamic FEM analyses of the developed SEEs have been done for the stiffness and frequency verifications. Micro/nano milling on WC show the SEEs can achieve a high machining quality for both the side face (P-V=0.143 μm, Ra=0.015 μm) and bottom face (P-V=0.075μm, Ra=0.006 μm), which is especially useful for micro channel machining. A large aspect ratio thin wall with the thickness of 5μm and height of 100μm has been successfully machined, which show the high geometrical accuracy can be achieved by the designed SEE with the rake angle of -70° (in short, SEE-70). Also the ductile mode machining of silicon wafer has been demonstrated by the developed SEE-70.

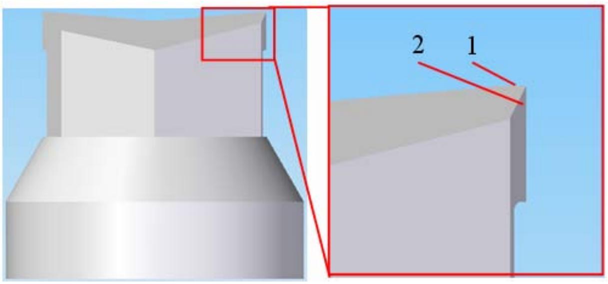
2. Geometry design of SEE

2.1 Analysis of available micro end mills

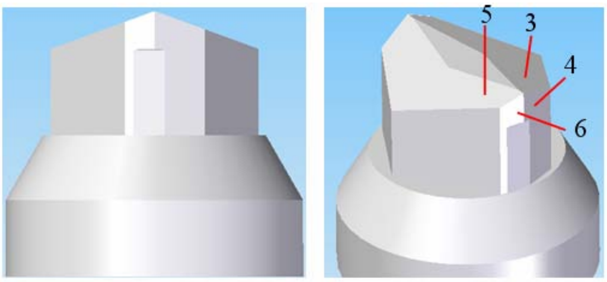
Previously, two-flute end mills and hexagonal end mills have been successfully designed and developed for the bottom and side surface machining of thin walls or grooves, respectively [14]. But they cannot simultaneously machine the bottom and side surfaces individually. The machining time becomes longer due to the tool change among milling processes. For example, using the nano milling center AZ150 [14], the tool change procedure is as follows: spindle stops from 120,000 rpm→tool change → spindle rotates to 120,000 rpm → tool measurement by two laser systems. The standard total tool change time is more than 30 minutes. Considering the machining cost and efficiency, the authors try to design and develop a kind of micro end mills which can simultaneously machine the bottom and side surfaces with the same level surface roughness as that of separately machining.

2.2 Geometry design

The geometry of designed SEE is shown in Fig. 1. The SEE has a symmetrical geometry. It has the same axial and radial rake angles and the axial rake angle equals to the axial clearance angle, which makes the machining of the bottom cutting edges simpler. Faces other than the rake and clearance faces are mainly designed for avoiding unnecessary contact between the peripheral or bottom and the workpiece being machined. The simple geometry can be easily machined by three and half CNC WEDM axis motions. Various negative rake angles can be easily assigned to the SEE for different application purposes.



(a) Front view (b) Detailed view



(c) Side view (d) Isometric view

Fig. 1. SEE-70 (Straight Edge Endmill has the negative 70° rake angle). (1) Bottom cutting edge; (2) Side cutting edge; (3) Axial rake face; (4) Radial rake face; (5) Axial clearance face; (6) Radial clearance face.

3. FEM analysis

In order to make the contrast, two-flute end mill, hexagonal end mill [14] and the designed SEEs with negative 45°, 60° and 70° are analyzed by the FEM software Abaqus. The PCD blank used in the research is shown in Fig. 2, where the PCD material is bonded to WC material. The material properties are shown in Table 1. In the FEM model, the WC and PCD material properties are assigned to the two portions respectively. The length of the micro tools outside the spindle for our applications is around 12 mm. In the following FEM simulations, the total tool length is 12 mm and the end surface is constrained or driven imitating the spindle.

For micro/nano ductile mode machining of brittle materials, the axial depth of cut and the feedrate are on the submicron level. The machining forces are usually smaller than 0.3N [16]. Forces (F_X=0.3N, F_Y=0.3N) are applied to the tip of the cutting edge as shown in Fig. 3. The mesh type is explicit 3D Stress C3D4. In order to save simulation time, the end mills with larger radius of 0.45 mm are simulated.

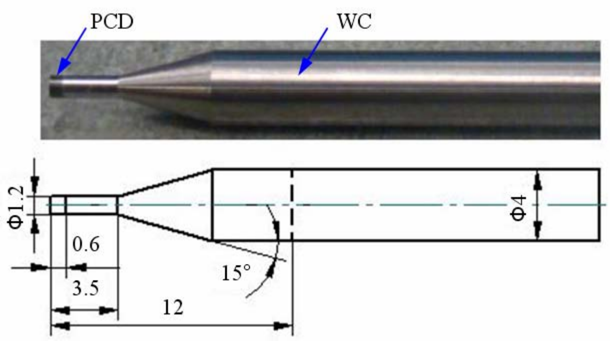


Fig. 2. PCD blank.

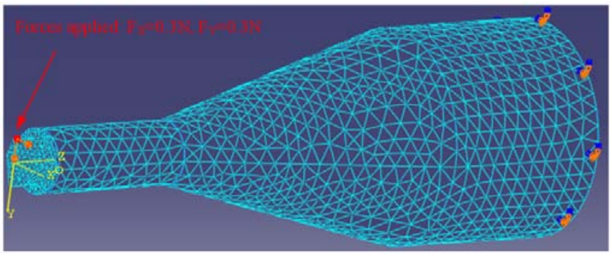


Fig. 3. Load assigning and meshing (C3D4).

3.1 Static analysis

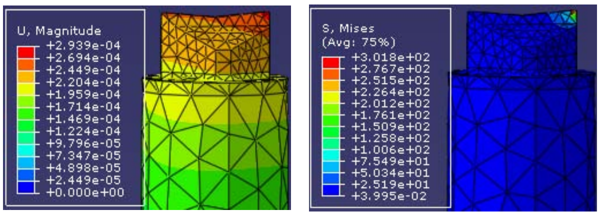
The static stiffness analysis is first processed. Fig. 4 shows the simulation results. Maximum deformation of the SEEs become smaller with the decrease of the rake angles, namely the SEE-70 has the highest stiffness. The SEE-70 also has a higher stiffness than the two-flute end mill and the hexagonal end mill. All mises stresses are lower than the transverse rapture strength. The two-flute end mill undertakes the lowest mises stress, and then the SEE-70. From the finished workpiece geometrical accuracy point of view, the SEE-70 is the best one among these micro end mills.

3.2 Modal analysis

Table 2 shows the minimum frequency in the modal analyses of the SEE-70and corresponding minimum spindle speed of all the micro end mills used in this paper. The frequency is mainly decided by the PCD blank geometry. In our case, the spindle speed of the nano milling center is fixed to 120,000rpm, which is far from the minimum spindle speed. Thus, these micro end mills do not have resonant vibrations under the fixed spindle speed.

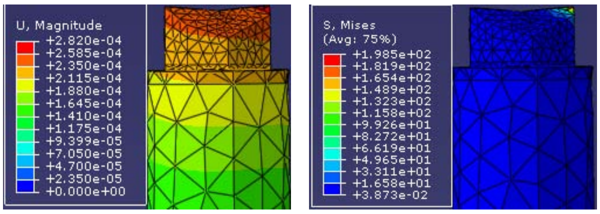
3.3 Dynamic analysis

Then the dynamics analysis simulating the deformation of the cutting edge is processed under the fixed spindle rotational speed of 120,000 rpm. The forces are applied to the same place as in the static analysis and the directions follow the nodal rotation. Considering the simplified simulation model, the amplitude changes with the rotation of the cutter and reaches the highest value when the cutter rotation angle equals 90°, as shown in Fig. 5(a). The deformations of the cutting edge are shown in Fig. 5(b), (c), (d), (e) and (f).



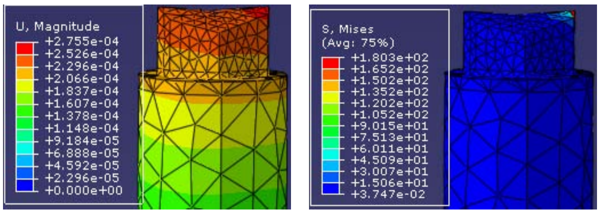
(a1) SEE-45
(max. deform.=0.2939 μm)

(a2) SEE-45
(max. stress=0.3018 GPa)



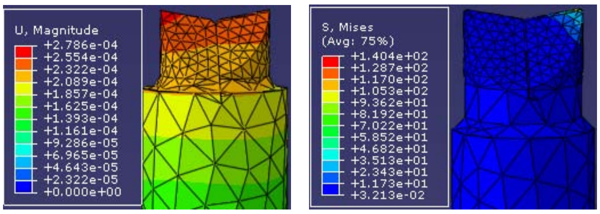
(b1) SEE-60
(max. deform.=0.2820 μm)

(b2) SEE-60
(max. Stress=0.1985 GPa)



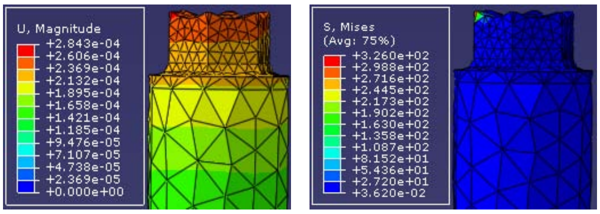
(c1) SEE-70
(max. deform.=0.2755 μm)

(c2) SEE-70
(max. Stress=0.1803 GPa)



(d1) Two-flute
(max. deform.=0.2786 μm)

(d2) Two-flute
(max. Stress=0.1404 GPa)

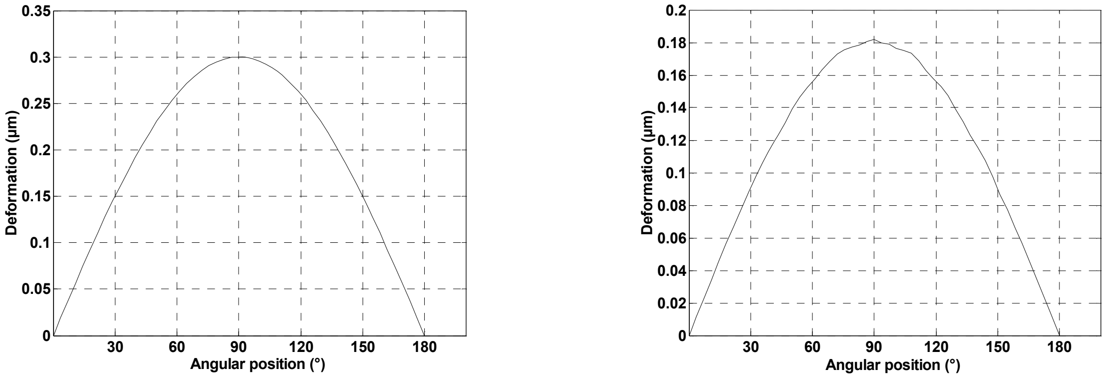


(e1) Hexagonal
(max. deform.=0.2843 μm)

(e2) Hexagonal
(max. Stress=0.3260 GPa)

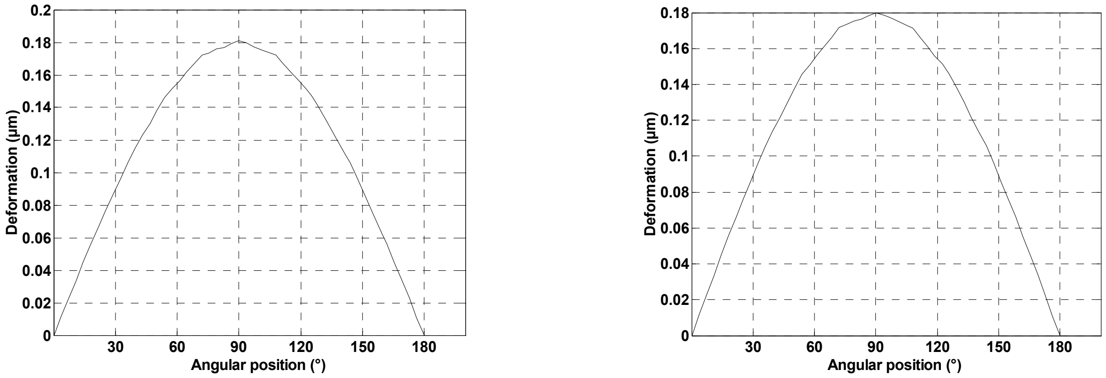
Fig. 4. Static FEM analysis.

The maximum deformation of the cutting edge has almost the same tendency as that of the static. The SEE with the -70° rake angle has the similar dynamic stiffness as the two-flute end mill.



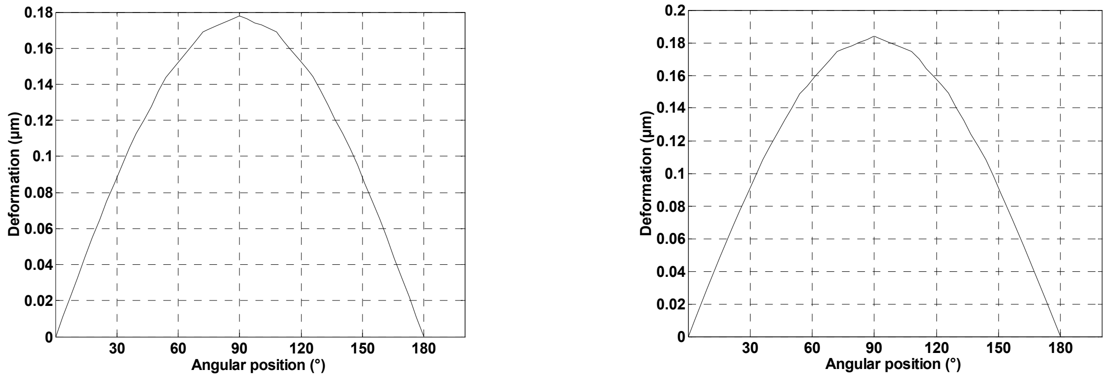
(a) Loads applied (max. 0.3N)

(b) SEE-45 (max. 0.18195 μm)



SEE-60 (max. 0.18095 μm)

SEE-70 (max. 0.17995 μm)



Two-flute (max. 0.17795 μm)

Hexagonal (max. 0.18395 μm)

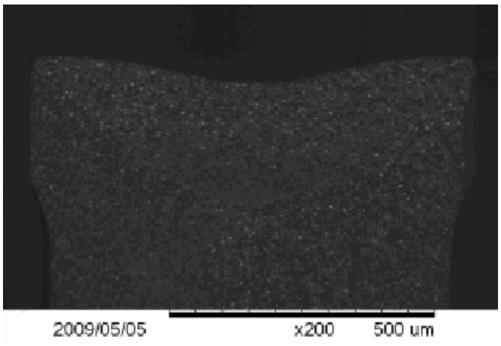
Fig. 5. Loads applied and dynamic deformations.

4. Experimental evaluation

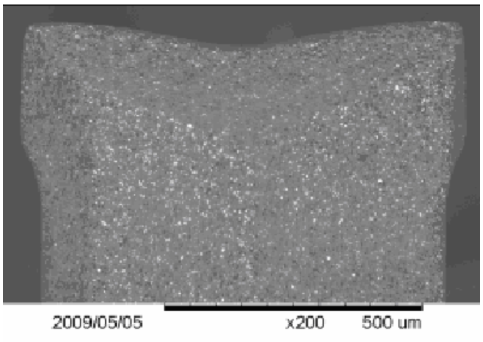
Experimental evaluations are processed on hard and brittle materials of WC and silicon wafer. The properties of WC are that Young's modulus is 570.0 GPa, fracture toughness is 8.3 $\text{MPam}^{1/2}$, hardness is 17.29 GPa [14] and the properties of silicon wafer <1 0 0> are that shear modulus is 75.5 GPa, torsion modulus is 39.7 GPa, Young's modulus is 130 GPa, Poison ratio is 0.27, surface micro-hardness is 1150 Kg/mm^2, and density is 2.329 g/cm^3. In order to compare the SEEs with different angles, the first step is to compare the SEEs with rake angles of -45°, -60° and -70°. The second step is to compare side and bottom surface machining capabilities and efficiencies between the SEE identified in the first step and the two-flute and hexagonal end mills, separately. The third step is to test the machining accuracy of the SEE identified by large aspect ratio thin wall machining. At last, the silicon wafer machining capabilities of the SEE are tested.

4.1 SEE fabrications

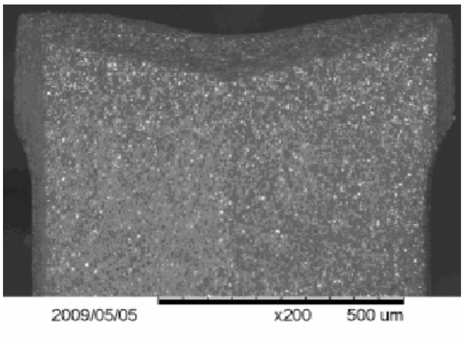
The six-axis WEDM machine ASX350L [15] with a Φ0.1 mm electrode wire has been used to fabricate the micro end mills for the following experiments. Total ten passes were



(a) SEE-45 (radius=0.45578 mm)



(b) SEE-60 (radius=0.45687 mm)



(c) SEE-70 (radius=0.45461 mm)

Fig. 6. Fabricated PCD SEEs.

used from rough to finish machining of the micro end mills. The finish WEDM conditions are shown in Table 3.

Fig. 6 shows the fabricated SEEs, whose nominal radius is 0.45 mm and the measured radius by the Blum laser measurement system is also shown in Fig. 6.

4.2 Comparison experiments for various SEEs

The nano milling center AZ150 was used for the following experiments [14]. The SEEs with rake angles of -45°, -60° and -70° are used to cut the WC while the tool engagement during machining is 100% as shown in Fig. 7. The machining parameters are that axial depth (Ad) of cut is 1μm and flood coolant. The finished surface roughness, tool radius wear and length wear are shown in Fig. 8. For all the SEEs, surface roughness changes smoothly and slowly when the feedrate is lower than 0.2 μm/tooth. When the feedrate is higher than 0.2 μm/tooth, surface roughness sharply becomes poor. Fig. 9 shows the brittle material removal while the feedrate is higher than 0.2 μm/tooth. The possible reason for the surface roughness is that 0.2 μm/tooth is the critical feedrate for ductile mode machining of WC material by the SEEs. Under the feedrate 0.2 μm/tooth while Ad=1 μm, ductile mode machining of the WC can be realized. The tool radius wear of SEE-45 is higher than that of SEE-60 and SEE-70. The tool length wear of SEE-45 and SEE-60 are higher than that of SEE-70. The possible reason for the serious tool wear is that the higher

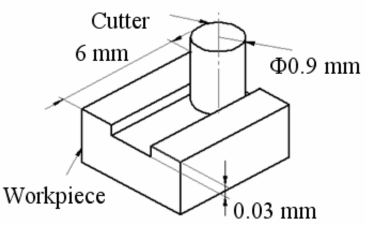
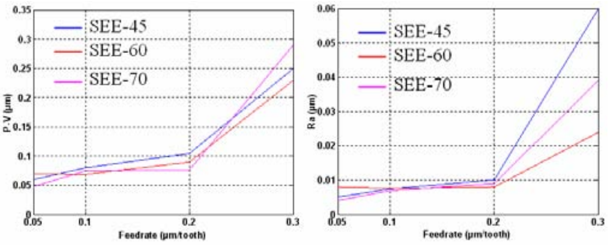
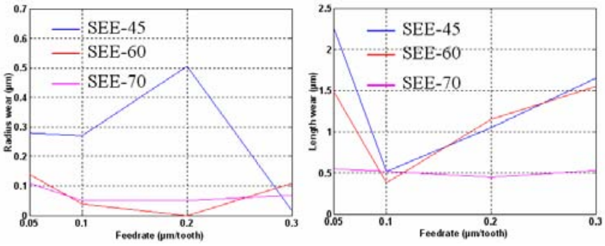


Fig. 7. Single slot machining.



(a) P-V vs. feedrate (b) R_a vs. feedrate



(c) Radius wear vs. feedrate (d) Length wear vs. feedrate

Fig. 8. Comparison experiments of SEEs with different rake angles on WC.

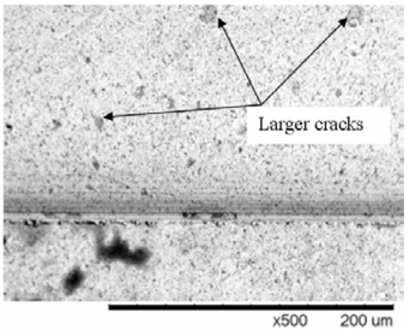
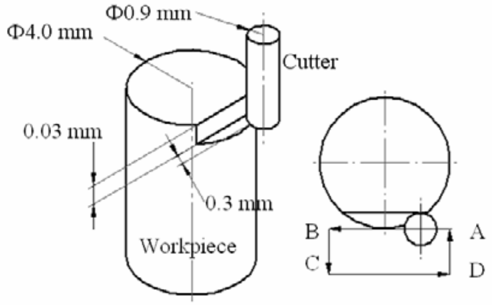
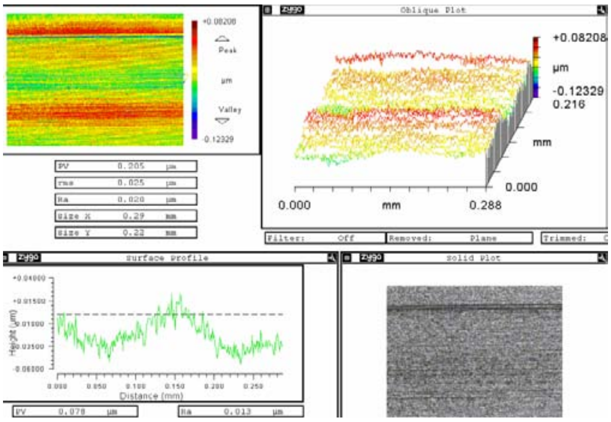


Fig. 9. Brittle material removal (Ad=1 um, feedrate=0.3 um/tooth).



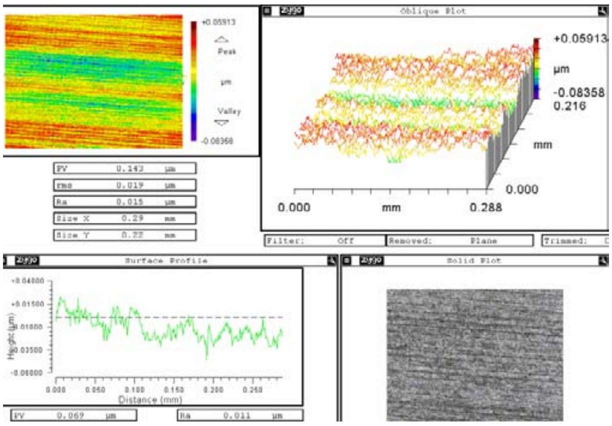
(a) Isometric view (b) Top view and process

Fig. 10. Side surface machining diagram.



PV 0.205 µm
rms 0.025 µm
Ra 0.020 µm
Size X 0.29 mm
Size Y 0.22 mm
Filter: Off
Removed: Plane
PV 0.078 µm
Ra 0.013 µm

(a) Hexagonal end mill (Ry=0.205 µm, Ra=0.020 µm)



PV 0.143 µm
rms 0.019 µm
Ra 0.015 µm
Size X 0.29 mm
Size Y 0.22 mm
Filter: Off
Removed: Plane
PV 0.069 µm
Ra 0.011 µm

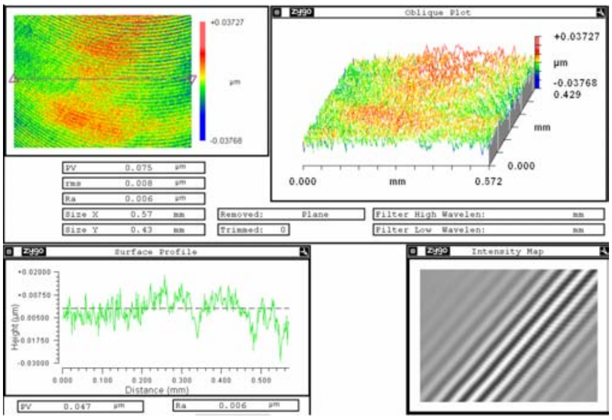
(b) SEE-70 (Ry =0.143 µm, Ra=0.015 µm)

Fig. 11. Comparison of side surface machining on WC.

maximum stress bearing as shown in Fig. 4. So in the following experiments, the SEE-70 was used due to its higher stiffness and tool wear resistance capabilities.

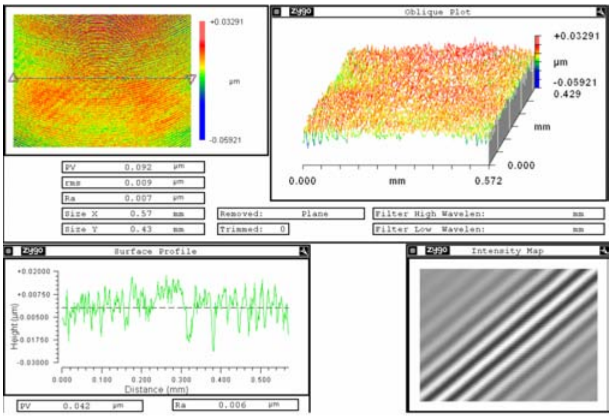
4.3 Side and bottom surface machining

The comparison side surface machining experiments were done between SEE-70 and the hexagonal end mill with the radius of 0.45 mm. The machining strategy is shown in Fig. 10 and machining parameters are Ad=1 µm, feedrate=0.1 µm/tooth. In axial direction, the side surface is machined layer by layer following the cutter path of A→B→C→D. Surface roughness of the side surfaces by the two micro end mills are shown in Fig. 11, where the SEE-70 achieved a higher surface roughness for side face machining than that of hexagonal end mill. The surface roughness P-V is larger than 0.1 µm and Ra is larger than 0.01 µm for both micro end mills. The main possible reason is that the positioning errors have been introduced into the side face machining while the tool moves from B to C or from D to A.*



PV 0.075 µm
rms 0.008 µm
Ra 0.006 µm
Size X 0.57 mm
Size Y 0.43 mm
Removed: Plane
Trimmed: 0
Filter High Wavelen: mm
Filter Low Wavelen: mm
PV 0.047 µm
Ra 0.006 µm

(a) Two-flute end mill (Ry=0.092 µm, Ra=0.007 µm)



PV 0.092 µm
rms 0.009 µm
Ra 0.007 µm
Size X 0.57 mm
Size Y 0.43 mm
Removed: Plane
Trimmed: 0
Filter High Wavelen: mm
Filter Low Wavelen: mm
PV 0.042 µm
Ra 0.006 µm

(b) SEE-70 (Ry =0.075 µm, Ra=0.006 µm)

Fig. 12. Comparison of bottom surface machining on WC.

The comparison bottom surface machining experiments were done between SEE-70 and the two-flute end mill with the radius of 0.45 mm. The machining strategy is shown in Fig. 8 and machining parameters are Ad=1 µm, feedrate=0.1 µm/tooth and flood coolant. Surface roughness of the bottom surfaces by the two micro end mills are shown in Fig. 12, where the SEE-70 achieved a little higher surface roughness for bottom face machining than that of two-flute end mill.

4.4 Large aspect ratio thin wall machining

A thin wall with the width of 5 µm and height of 100 µm was machined by the SEE-70 as shown in Fig. 13. The ma-

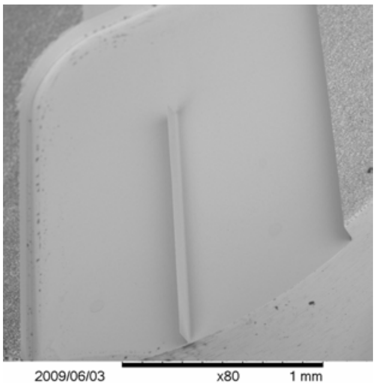
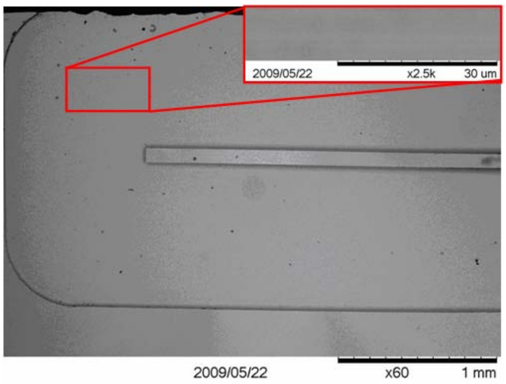
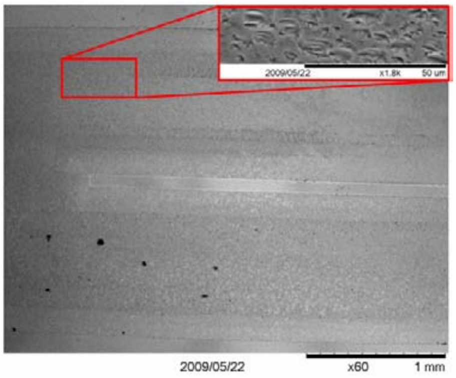


Fig. 13. High aspect ratio thin wall machining on WC.

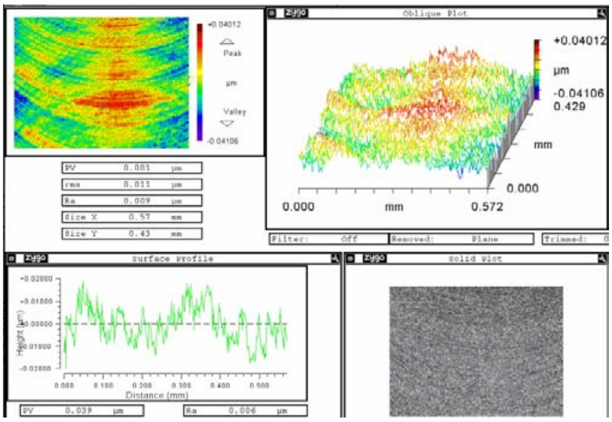


(a) With flood coolant



(b) Dry machining

Fig. 14. Silicon wafer machining by SEE-70.

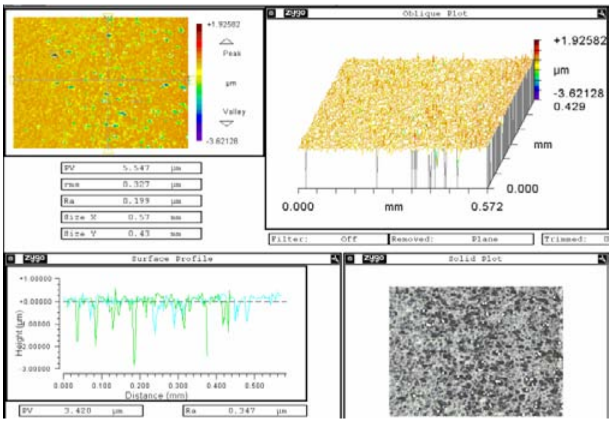


PV 0.081 µm
rms 0.011 µm
Ra 0.009 µm
Size X 0.57 mm
Size Y 0.43 mm

Filter: Off
Removed: Plane
Trimmed:

PV 0.039 µm
Ra 0.006 µm

(a) Surface roughness under flood coolant



PV 5.547 µm
rms 0.327 µm
Ra 0.199 µm
Size X 0.57 mm
Size Y 0.43 mm

Filter: Off
Removed: Plane
Trimmed:

PV 3.420 µm
Ra 0.347 µm

(b) Surface roughness under dry cutting

Fig. 15. Surface roughness of the silicon wafer.

chining parameters are Ad=0.1 µm, feedrate=0.05 µm/tooth and flood coolant. The bottom surface roughness P-V=0.085 µm and Ra=0.009 µm.

4.5 Silicon wafer machining

Silicon wafer machining has been done under flood coolant (density of 0.86 g/cm^3 and kinematic viscosity of 7.59 mm^2/s) and dry conditions with the same machining parameters Ad=1 µm, feedrate=0.05 µm/tooth by SEE-70 as shown in Fig. 14. As shown in Fig. 15, the surface roughness for (a) is P-V=0.081 µm and Ra=0.009 µm, and for (b) is P-V=5.547 µm and Ra=0.199 µm. Judged by the SEM pictures and surface roughness, ductile mode machining has been achieved in Fig. 14(a), and Fig. 14(b) shows a brittle material removal process. The coolant plays a very important role in silicon wafer milling by the SEE-70. In [17], a commercial two flute carbide diamond-coated end mill tool was used and ductile mode machining can only be achieved under the Ad=0.3 µm and feedrate=0.002 µm/tooth for silicon end milling. Compared to the Ad=0.1 µm, feedrate=0.05 µm/tooth used in this paper by the newly designed micro end mill SEE-70, the machining efficiency has been improved to more than 8 times.

5. Conclusions

Micro milling tool is one of the most important aspects affecting the successful applications of micro/nano milling. However, the limited versatility of micro end mills and high prices of commercially available micro end mills constraint the development of micro end milling technologies. Considering the multi-process machining capabilities for simultaneous side and bottom face machining, a new straight edge end mill SEE has been developed and evaluated in this paper with the following are conclusions:

- The developed SEEs with smaller rake angles have better stiffness and lower tool wear rate based on the FEM simulations and experimental tests.
- SEE-70 has good capabilities for simultaneous side and bottom surface machining on the hard and brittle material WC. It achieved higher surface roughness than that of previously successfully designed hexagonal and two-flute end mills.
- SEE-70 has a higher machining accuracy and a thin wall with large aspect ratio of 1:20 has been successfully machined on WC material.
- SEE-70 has 8 times higher machining efficiency for ductile machining of brittle material silicon than the previously researches.
- Coolant plays a very important role in ductile machining of silicon wafer by SEE-70.

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