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Characteristics of machined surface controlled by cutting tools and conditions in machining of brittle material

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Abstract: One of the ultra-precision machining methods was adapted for brittle material as well as soft material by using multi-arrayed diamond tips and high speed spindle. Conventional machining method is too hard to control surface roughness and surface texture against brittle material because the particles of grinding tools are irregular size and material can be fragile. Therefore, we were able to design tool paths and machine controlled pattern on surface by multi-arrayed diamond tips with uniform size made in MEMS fabrication and high speed spindle, and the maximum speed was about 3×10^5 r/min. We defined several parameters that can affect the machining surface. Those were multi-array of diamond tips ($n\times n$), speed of air spindle and feeding rate. The surface roughness and surface texture can be controlled by those parameters for micro machining.

Key words: brittle material; surface roughness; surface texture; multi-arrayed tips; micro machining

1 Introduction

Higher value-added industries in fields, such as information transfer, medical devices and aerospace engineering, have been developing rapidly for several years. These industries require products that are smaller with more functionality, which has resulted in more active research of machining. Micro machining technology has been investigated to improve machining conditions and develop miniaturized tools. The results have resulted in new commercialized products[1]. Being able to directly machine optical surfaces for both infrared and visual applications has made ultra-precision cutting technology of the most widely used optical fabrication technologies of the last two decades[2−3]. Brittle materials, such as glass, silicon and quartz, are widely used in electronic and optical industries due to their unique electronic, chemical and physical characteristics. In order to utilize these materials in nano technology, ultra fine structures should be fabrication on the surface of these materials, which constitute many mechanisms, such as electronic circuits, optical devices and chemical reactors[4−5]. Nano/micro structures of brittle materials can be fabricated by MEMS. This process is advantageous advantageous for mass production which requires hug and expensive facilities and generates industrial emission. We propose a new machining method to produce nano/micro structures on the surface of brittle materials. Polishing and high-speed machining can be used to improve the productivity and accuracy of mechanical machining. High-speed machining improves the surface roughness by increasing the cutting speed and removing more material[6], and polishing using minute particles on a wheel improves the accuracy of the machined workpieces. However, obtaining a high-quality surface is difficult when machining brittle materials example wafer due to the irregular size and array of particles on the grinding wheels.

A new machining method that uses a multi-arrayed diamond tip and high-speed air turbine spindle can be operated at 2×10^5 r/min to obtain a uniform pattern and surface roughness on machining brittle materials as well as soft materials such as brass and aluminum. The goals of this study are to understand the machined pattern obtained using a given diamond-tipped array ($n\times n$), investigate the change in the surface roughness as a function of the cutting speed and establish the machining conditions required to obtain a nanoscale surface quality.

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2 Theory and components of machining system

2.1 Polishing method using uniform multi-arrayed tool

Conventional polishing tools consist of irregular particles and resin. When a workpiece is machined using particles with irregular shapes and sizes, the surface roughness depends on the average size of the particles. In order to control surface roughness, the size of the tool must be changed or the same position must be machined repeatedly. In our proposed machining methods, the particles on the machining tool are uniform in shape and size and located in the same orientation, so that we can prescribe the tool path and control the surface roughness. Our polishing tool is shown in Fig.1, and the prescribed tool path and SEM image of the machined surface are shown in Fig.2.

Eq.(1) is used to determine tool path of trochoidal move. Trochoid is the word created by de Roberval for the curve described by a fixed point as a circle rolls along a straight line. f_c is displacements of tool center, which is F/n each rotation moved.

$$f_c = \frac{F}{n} \cdot \frac{\varphi}{2\pi} \tag{1}$$

Where F is feeding speed and n is spindle speed. Displacement of x and y of tool path can be written as Eq.(2). We can calculate turning radius and removal volume. Therefore, we can control surface pattern and quality.

$$\Delta x = \gamma \sin\varphi + \frac{F}{2\pi n}\varphi \tag{2}$$

$$\Delta y = \gamma(1 - \cos\varphi) \tag{3}$$

Where F is feeding speed, min/mm; n is counts of tool rotation; φ is tool rotation angle; r is radius of tool.

2.2 Fabrication of multi-arrayed tips

The tool tips were made from a diamond compound because diamond has ideal properties for machining applications, a high stiffness and good heat transfer in machining tool materials. Microtools for polishing must be fabricated on microscale levels, and machining diamond directly is difficult due to its high stiffness, we produced a silicon mold using MEMS fabrication and then applied chemical vapor deposition(CVD) to deposit

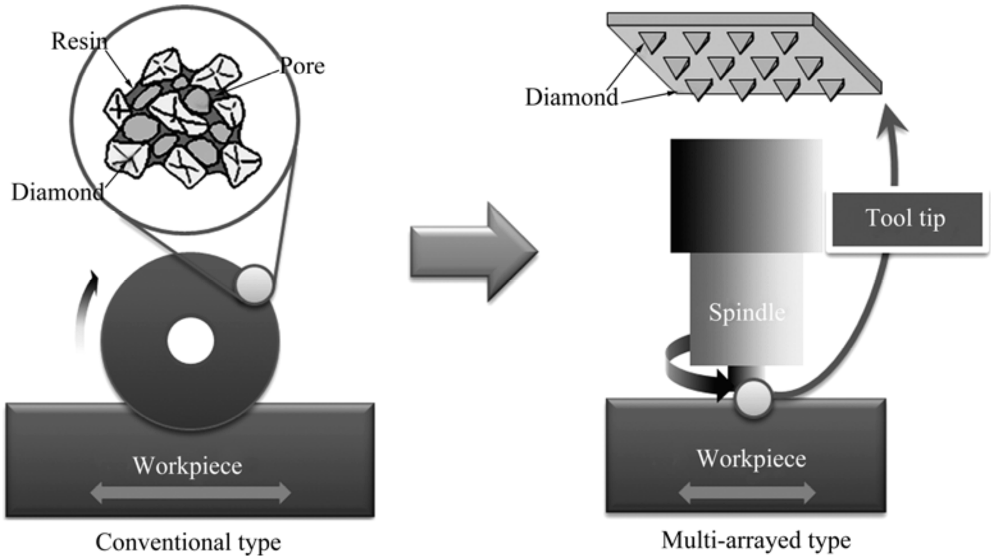

Fig.1 Schematic diagram of new machining method for polishing process

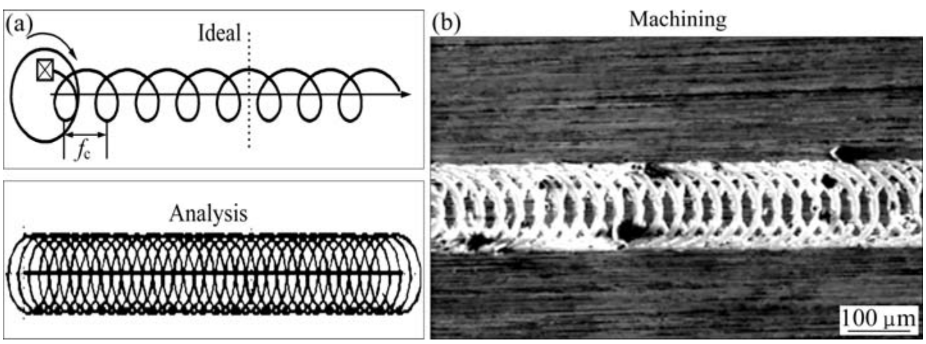

Fig.2 Tool path (a) and SEM image (b) of machined surface

synthetic diamond in the mold. The resultant diamond tip was pyramidal with four leading edges. The process was used to manufacture the diamond tips, as shown in Fig.3.

The size of multi-arrayed tip manufactured in this study was 100 μm×100 μm×60 μm, and the radius of leading edge was below 1 μm. The distance between each pyramid was about 50 μm and the distance of leading edges was 150 μm. Fig.4 shows SEM images of multi-arrayed tips.

2.3 Design and manufacture of high-speed spindle

A high-speed air turbine spindle was manufactured to turn the multi-arrayed diamond tips. The detailed spindle structure is shown in Fig.5. A bucket turbine without blades was used to reduce the mass unbalance and evaluate critical speeds. We used a shape-memory alloy(SMA) to clamp the rotating tools, resulting in a simplified structure with less mass. We measured the spindle speed pursuant to the air pressure using a laser diode(LD) and photo-sensor diode(PSD). The properties of the spindle are shown in Fig.6.

3 Experimental

3.1 Equipment

The machining system consisted of an air spindle, a multi-arrayed diamond-tipped tool, and a 3 degree of freedom(DOF) transfer system, as shown in Fig.7.

3.2 Machining condition

The machining conditions are listed in Table 1. The

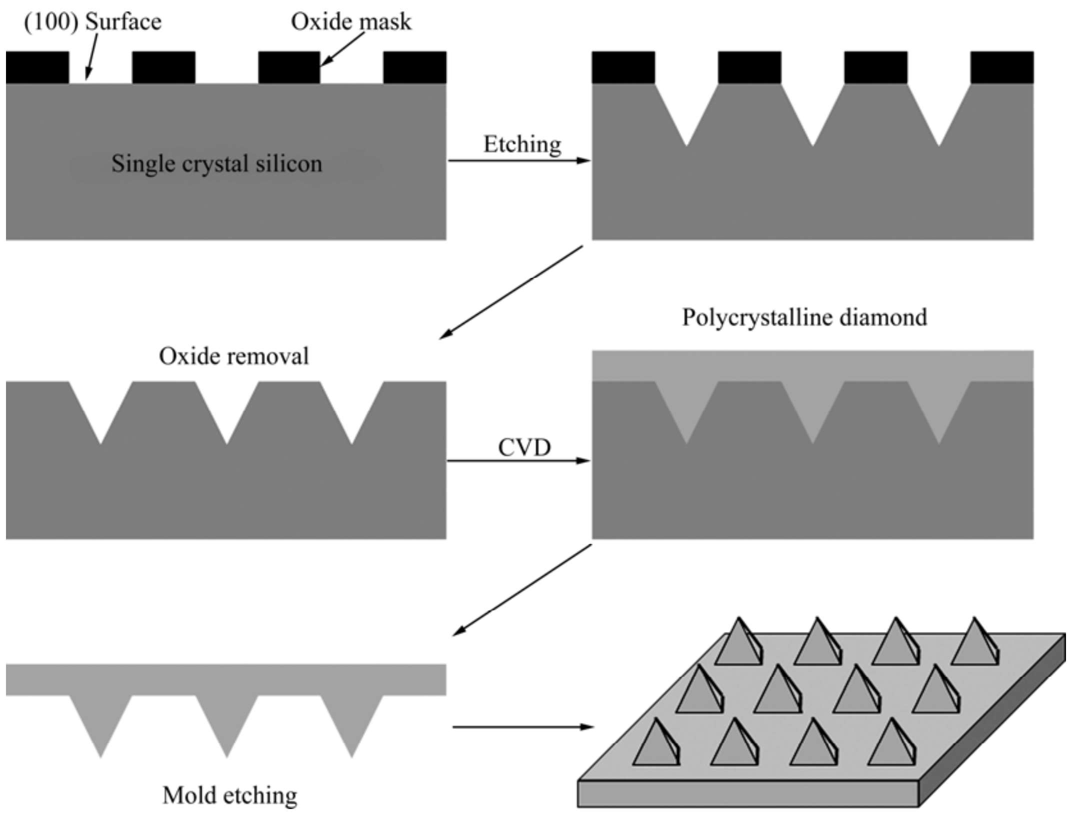

Fig.3 Fabrication of diamond tips

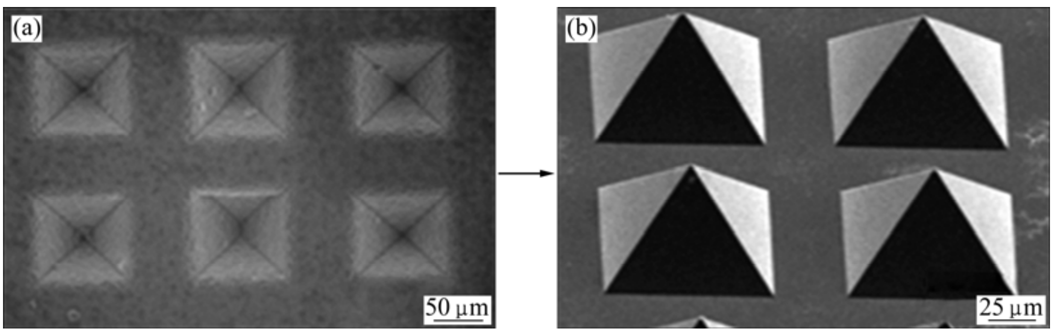

Fig.4 SEM images of multi-arrayed tips

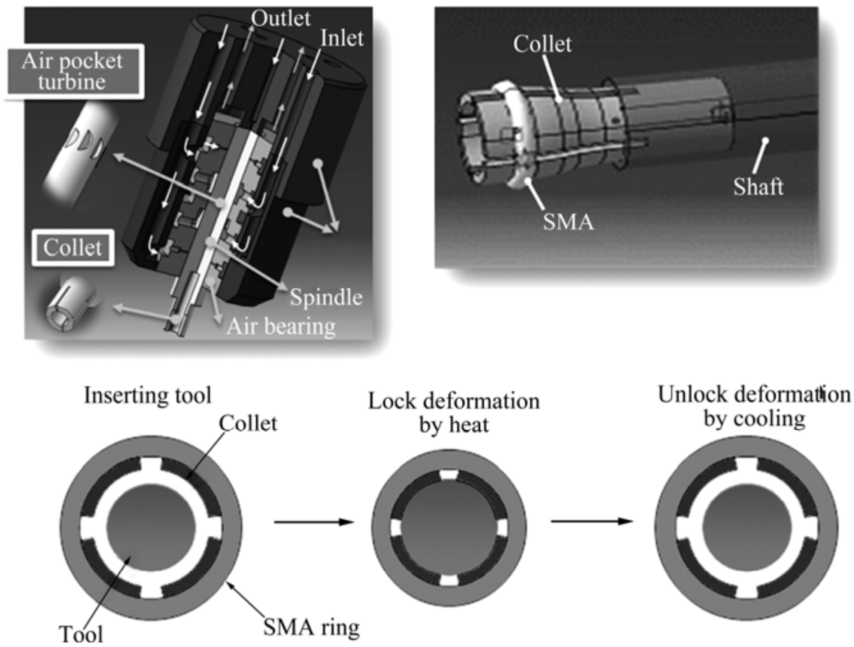

Fig.5 High-speed spindle and SMA for tool clamping

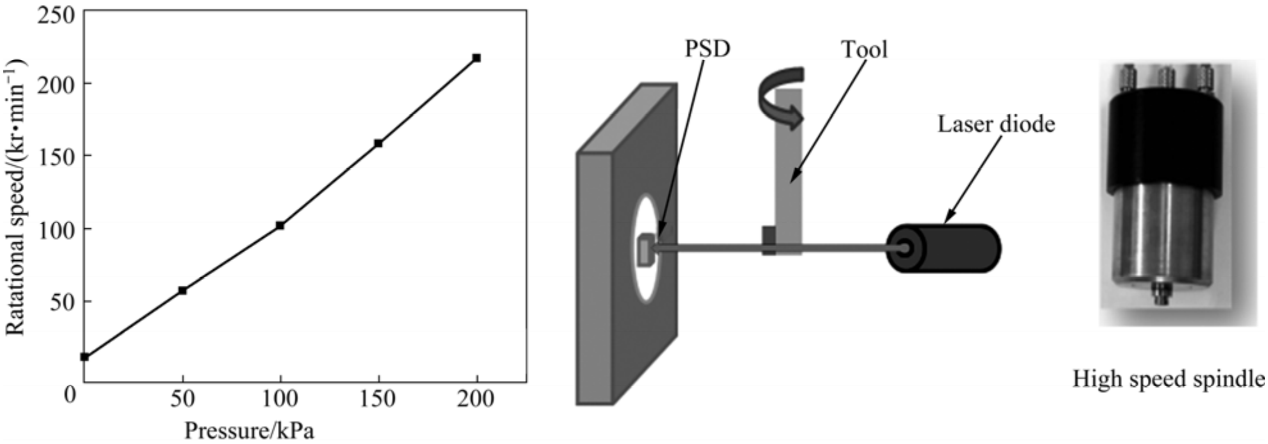

Fig.6 Properties of spindle

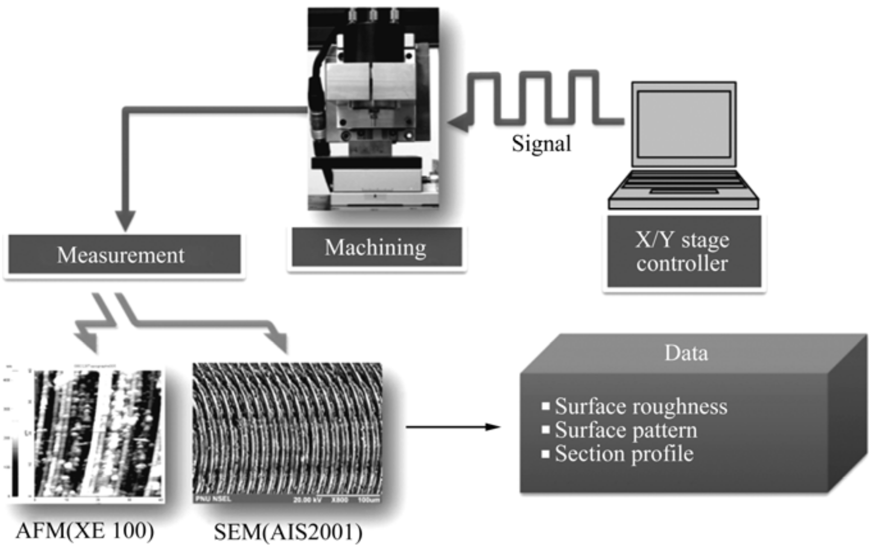

Fig.7 Equipment setup

parameters are the tip array, cutting speed and feed speed. Two types of arrays were considered for the tip: one with a 3×3 patterns and the other with a 10×10 patterns. The parameters affecting the overall work piece were surface roughness and the roughness pattern.

3.3 Machined materials

We tested brass and aluminum alloy. They are soft materials that are difficult to machine because of their low stiffness values. The mechanical properties of the materials are listed in Table 2.

Table 1 Machining conditions

Array	Feed speed/ $(mm\cdot min^{-1})$	Cutting speed/$(r\cdot min^{-1})$	Material
	60		Brass
3×3	12	1×10^5	
	240		Al
	480		
10×10	720	2×10^5	Wafer(Si)
	960		

Table 2 Mechanical properties of machined materials

Material	Element	Vicker hardness, HV	Elastic modulus/GPa	Poisson's ratio/%
Brass	(Cu: Zn)	90	103	0.32
Al alloy	(Al: Zn)	175	69	0.33
Wafer	(Si, 111)	1167	186.5	0.28

4 Results and discussion

4.1 Effect of tip array on machined surface pattern

We machined a brass sample using the two different multi-arrayed tips. The machining conditions were rotational speed of 2×10^5 r/min and feed speed of 120 mm/min. Fig.8 shows SEM images of materials with different surface roughness. Fig.9 shows the surface roughness (*R*a) and section profiles and corresponding tip array. The groove patterns were machined more clearly with smaller burrs when the 10×10 array was used rather than the 3×3 array. The surface roughness were 82 nm for the 3×3 array and 69 nm for the 10×10 array. Thus, the larger array produced a higher surface quality because more mass was removed due to the tool overlap.

4.2 Effect of cutting speed on machined surface pattern

Fig.10 shows the SEM images of materials with different surface roughness. Fig.11 shows the machined groove pattern images and profiles obtained using different cutting speeds. Fewer burrs and a closer groove

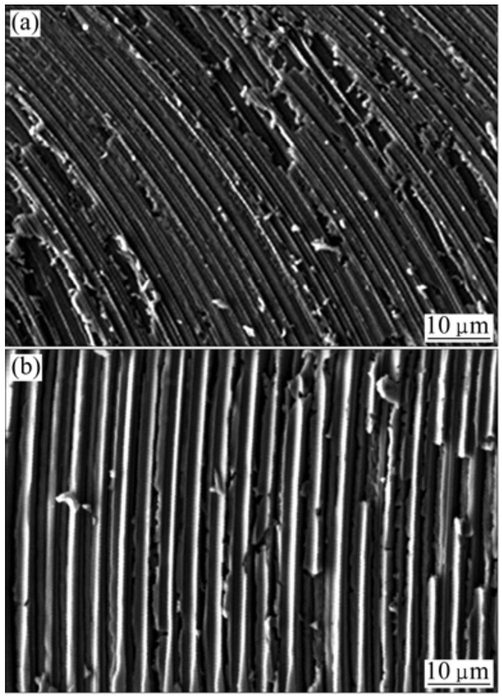

Fig.8 SEM images of materials with different surface roughness (a) 69 nm; (b) 82 nm

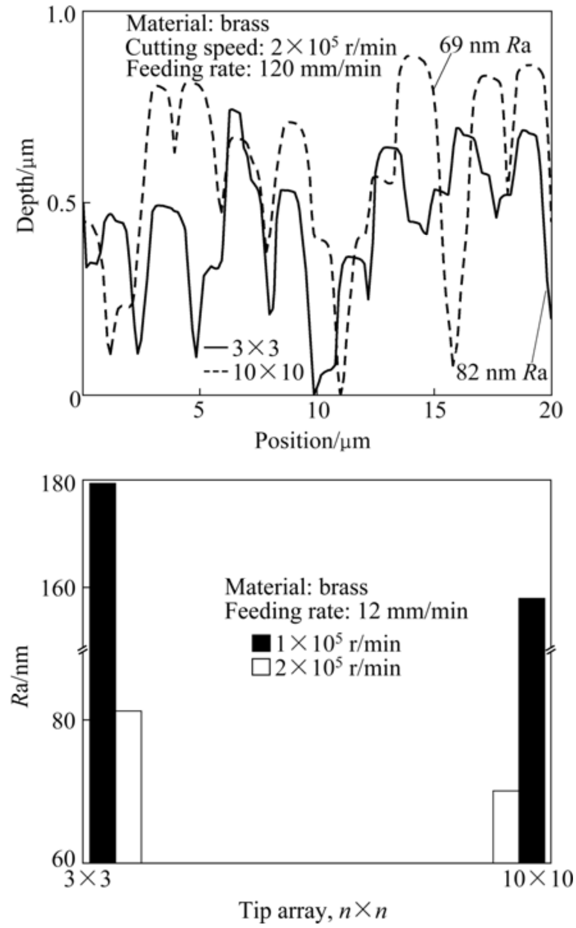

Fig.9 Surface roughness and section profiles and corresponding tip array

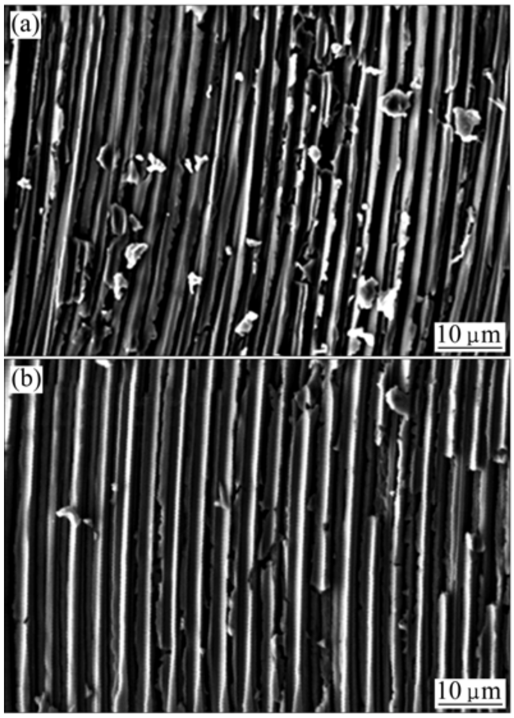

Fig.10 SEM images of materials with different surface roughness: (a) 69 nm; (b) 157 nm

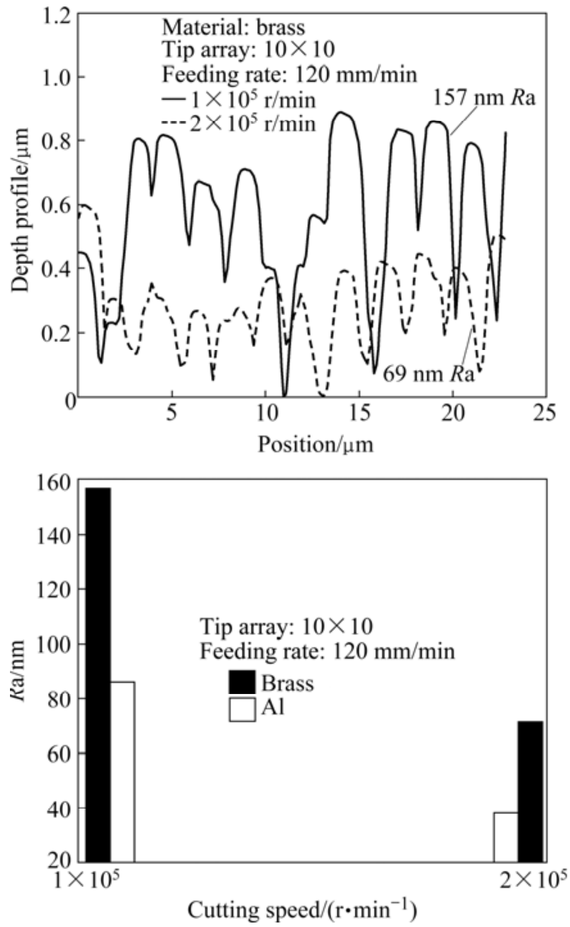

Fig.11 Effect of cutting speed on machined surface roughness

pattern were obtained when we machined brass at cutting speed of 2×10^5 r/min. The tool overlap increases with the cutting speed, and the surface roughness is almost twice larger at the slower cutting speed.

4.3 Effect of feed speed on machined surface pattern

We also examined the influence of the feed speed to determine whether nano scale machining was feasible to using our proposed method. The feed speed was set to 60, 240, 720, and 960 mm/min. The tip array and spindle speed were maintained at tip array of 10×10 and acting speed of 2×10^5 r/min, respectively. Fig.12 shows SEM images of materials with different surface roughness. Fig.13 shows the effect of feed speed on machined surface pattern. The surface roughness is 35 nm when the feed speed is 60 mm/min. This set of conditions produce the cleanest surface and slower feeding speeds produce narrower surface patterns due to the repeated overlapping tool path.

We can determine the optimum condition of machining materials with multi arrayed tip. Fig.14 shows the optimum machining conditions at feed speed below 240 mm/min and spindle of 10×10 tip array speed of 2×10^5 r/min. Especially, surface roughness under 50 nm is able to obtain, when machining condition should be set to under 400 mm/min of feeding speed.

Finally, we machine brittle material under the optimum machining condition. Fig.15 shows SEM image and depth profile of machined Si wafer. Unlike soft materials, few burrs were generated and clean edge of the tool path was obtained without crack. Fig.16 shows the atomic force microscope (AFM) images of surface

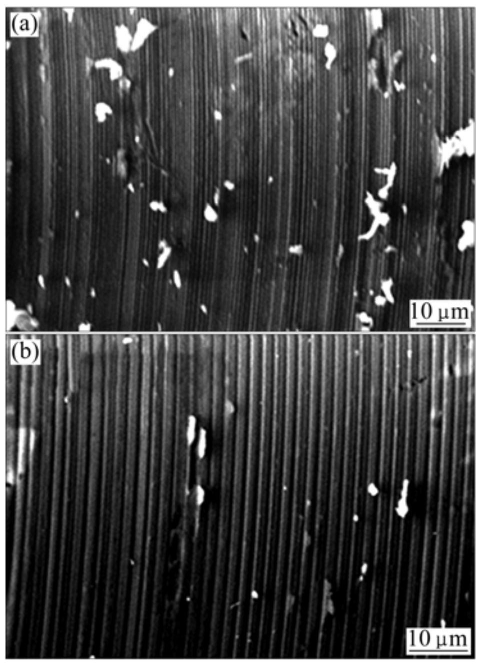

Fig.12 SEM images of materials with different surface roughness: (a) 87 mm; (b) 135 mm

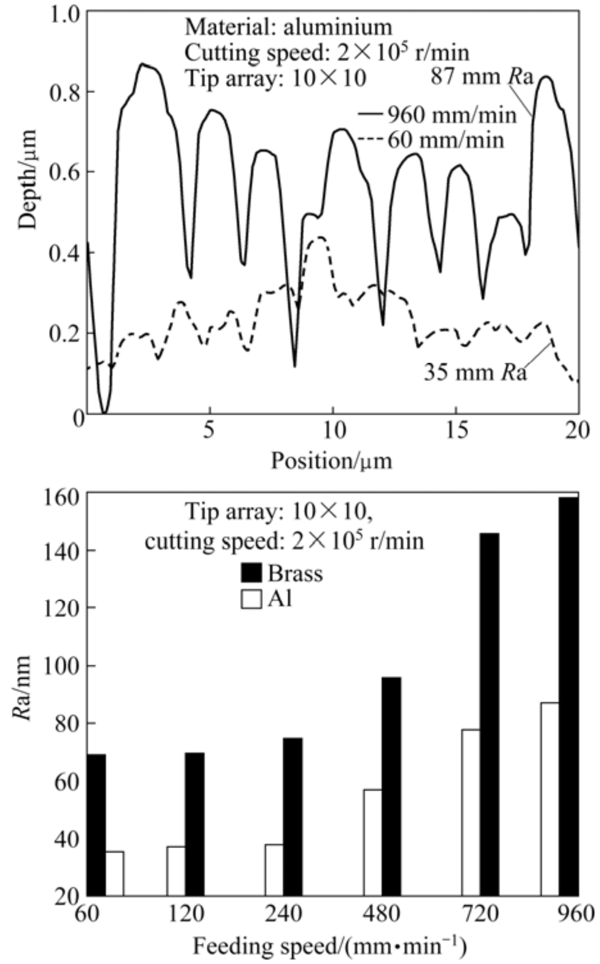

Fig.13 Effect of feed speed on machined surface roughness

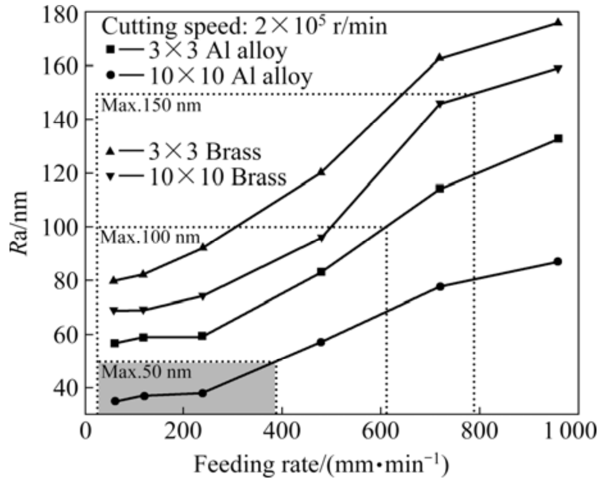

Fig.14 Optimum machining conditions for high quality surface

roughness of materials. However, center surface of groove is broken and torn out locally due to high normal force about 50 mN.

5 Conclusions

1) We can control the surface topology and prescribe the required tool path if a tool with uniformly sized and equally spaced particles is used to machine several materials that have different mechanical properties.

2) Especially, surface roughness under 50 nm is able to obtain, when the machining condition should be set to under 400 mm/min of feeding speed.

3) A good surface roughness of aluminum and brass obtained are less than 40 nm and 70 nm, respectively. In the case of wafer, the highest surface roughness value, about 97 nm, is presented in the same machined conditions due to high normal force. The clean surface with generation of low burr and no crack in the edge of tool path is obtained. The brittle material can be machined to obtain a polished surface directly, but the load conditions required to obtain the same quality are dependent on the material.

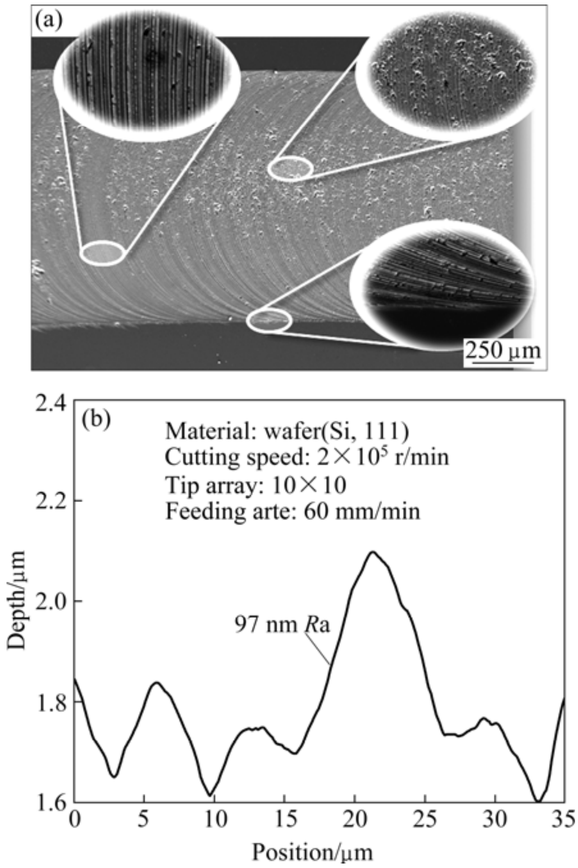

Fig.15 SEM image (a) and depth profile (b) of machined Si wafer

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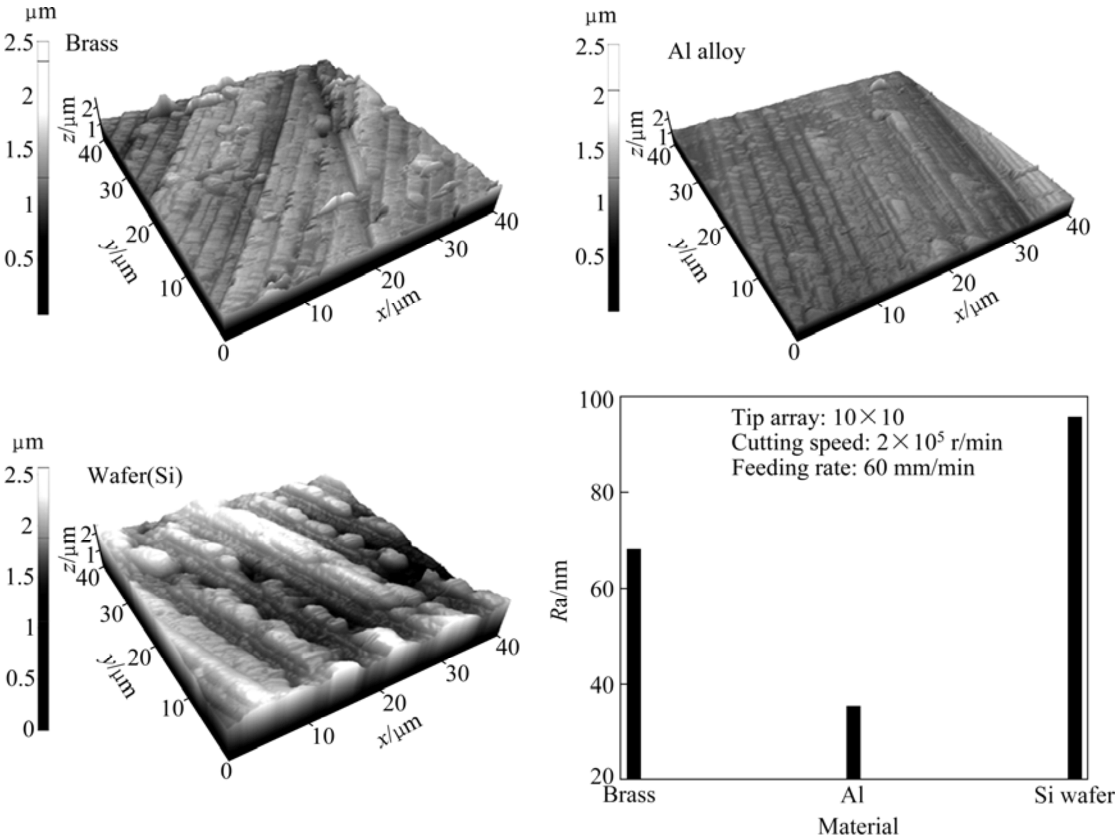

Fig.16 Comparison of surface roughness of each material

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