

Influence of tool deflection on micro channel pattern of 6:4 brass with rectangular tool

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Abstract: Machining experiment of micro channel structure with 6:4 brass was carried out by shaping process using a single crystal diamond tool. FEM simulation using solid cantilever beam model was analyzed. In result of experiment, tool deflection is observed as machining characteristics through result of experiments such as surface roughness, cutting force and burr formations. And the influence of tool deflection is experimentally proved.

Key words: tool deflection; single crystal diamond; high aspect ratio; micro channel pattern; surface roughness; cutting force; dynamic cutting force; burr formation; FEM simulation

1 Introduction

1.1 Micro channel pattern

Machining technology of micro channel pattern has been applied to various fields such as display and optical component. The functions of micro channel pattern on application component such as electromagnetic interference(EMI) filter for shielding electromagnetic field, privacy securing film for regulating view angle and wire grid polarization film for enhanced brightness are broadly used for IT industrials. And the research related to this field is gradually increased[1–2].

Fig.1(a) shows the shape of micro channel patterns. The patterns have the structural feature of high aspect ratio. And this aspect ratio is determined by the difference between upper and lower width (w_2 , w_3) for structure height (h). It is possible to make small size of pattern and to increase aspect ratio by adjusting the width of structure for fabricated tool shape. However, the way for increasing aspect ratio causes the instability of machining processing such as deformation or fracture of pattern and cutting tool. Therefore, it is necessary to apply step-by-step cutting method for pattern structure with high aspect ratio. Consequently, it is very important to find the optimal machining process including the maximum cutting depth in range of stabilized cutting conditions without any deformation and damage of the

cutting tool and pattern structure. And also in micro channel pattern, it is impossible to apply over-depth process in machining of other micro pattern such as prism and rectangular pattern. It is required to establish the optimal cutting condition to suppress deformation of structure and minimize burrs because micro burrs easily occur on upper surface[3–5].

Fig.1(b) shows the main dimensions of fabricated cutting tool. The shape of pattern in trapezoid or rectangle is determined by shape angle of cutting tool. The material of tool is a single crystal diamond. The width of tool is 80 μm , shape angle is 5.5° and relief angle is 3° . The effective length of the cutting tool is approximately 700 μm . Table 1 lists the specification of fabricated cutting tool. And its dimension is applied to the cantilever simulation model for FEM analysis of cutting tool.

1.2 Tool deflection due to machining in micro channel pattern

Tool deflection affects the limitation of machining characteristics on precision manufacturing due to a kind of vibration. The instability process occurs because the machining tool deflection is a abnormal cutting process that has influence on surface roughness and dimensional accuracy of workpiece, tool life and machine life[6–7]. Tool deflection related to vibration has been investigated in several studies for predicting the limit of stability on

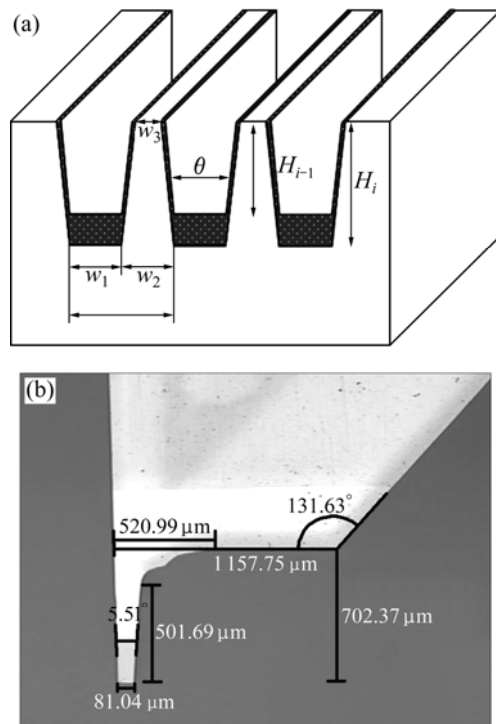


Fig.1 Shape of micro channel pattern and fabricated cutting tool: (a) Shape of micro channel pattern; (b) Single crystal diamond ($w=80\ \mu\text{m}$, $\theta=5.5^\circ$)

Table 1 Specification of fabricated cutting tool

Material	Shape	Relief angle
Single crystal diamond(SCD)	Rectangular type, Width=80 μm , $\theta=5.5^\circ$	3°

machining. The regenerative chatter is common in case of practical machining operation. Fig.2(a) shows the regeneration process that brings a kind of chatter on orthogonal metal cutting. In Fig.2(b), the relative displacement between workpiece and cutting tool generates deflection and vibration due to the interaction of cutting force that changes dynamic stiffness between two objects. The stability of cutting tool depends upon the interaction between the dynamic characteristics of the structure and the dynamic characteristics of the cutting process[6, 8]. In practical machining, the cutting force is fluctuated around an average value and relative deflection occurs between tool and workpiece[9]. The frequency of regenerative chatter is generated around the natural frequency of the machining system. The generative chatter has been generally analyzed with 1-D model of radial direction. However, the cutting tool with the feature of high aspect ratio has the lowest stiffness at the end part of tool tip[10]. Therefore, the serious weakness of dynamic stiffness characteristics in Y-axis of cutting direction in the cutting tool of the trapezoid or rectangular type that has the narrow width and sharp

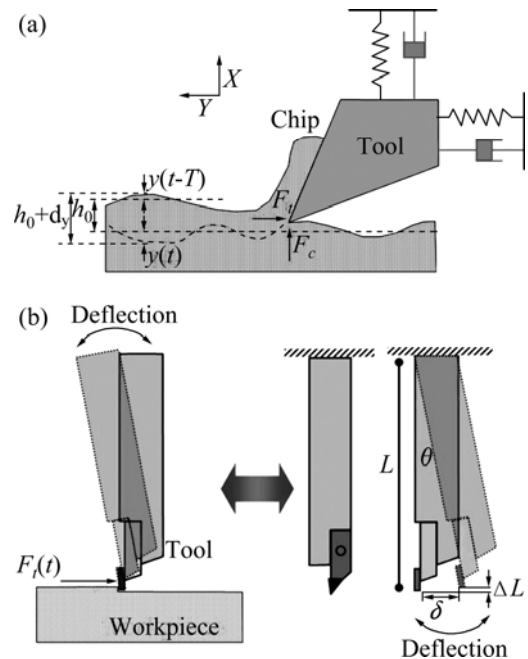


Fig.2 Generative process (a) and tool deflection on machining channel pattern (b)

shape angle with high aspect ratio must be considered.

The principal cutting force of Y-axis direction can be expressed as

$$F_t(t) = K_r K_s a_e [h_0 + y(t)(t-T) - Y] \quad (1)$$

where a_e is the effective width of cutter, K_s is the cutting force constant and K_r is the cutting force ratio.

Fig.2(b) shows that the relative displacement between cutting tool and workpiece produces the tool deflection of Y-axis direction in practical cutting process. It is assumed that the tool holder is rigidly supported by the tool without the deflection of machine and workpiece. And the cutting tool can be modeled as a solid cantilever beam with concentrated load at the end part of it.

1.3 FEM simulation of tool deflection

The FEM simulation of tool deflection simulation was carried out using the measured cutting force in case of practical machining. Table 2 shows the cutting conditions of FEM simulation. The cutting tool consists of shank, insert and tip. The contact conditions between parts of cutting tool are applied to be bonded with each other. The each part is automatically meshed. On constraint condition, the front and back surfaces of shank are fixed in all directions. Fig.3 shows the simulation modeling and simulation results of tool deflection by FEM. The total deflection of cutting tool is linearly increased by increasing cutting depth and most of tool deflections are observed at the end part of tip. In Fig.3(b), under cutting depth of 10 μm , the total deflection

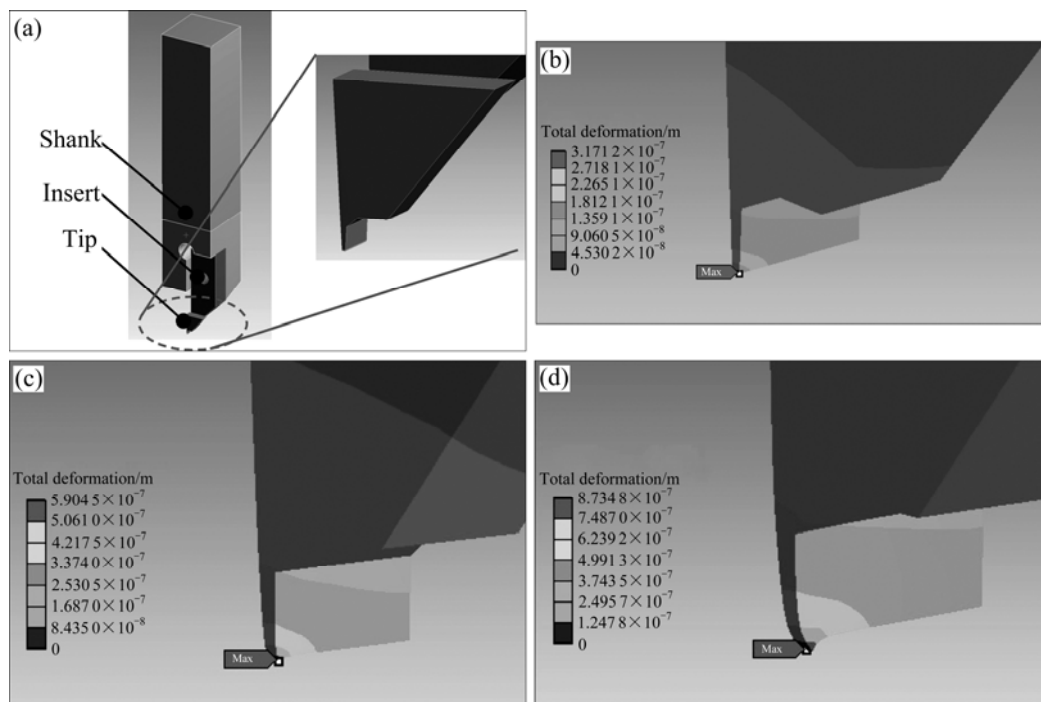


Fig.3 Simulation results of different cutting depths and total deflections of cutting tools: (a) Simulation modeling of tool deflection; (b) 10 μm , 320 nm; (c) 20 μm , 590 nm; (d) 20 μm , 870 nm

Table 2 Simulation conditions of tool deflection

Item	Condition
Material	Shank: structural steel, Insert: WC, Tip: single crystal diamond
Mesh	Auto mesh
Contact definition	Bonded contact
Constraint condition	Fix: front and behind surface of shank
Load condition	At loaded geometry 0.5, 1.1, 1.6, 2.2, 2.7, 3.4 N

of tool is 320 nm. In Fig.3(c), under condition of cutting depth of 20 μm , the total deflection of tool is 590 nm. In Fig.3(d), under condition of cutting depth of 30 μm , the total deflection of tool is 870 nm. This represents that the simplified cantilever model is very effective for predicting deflection of cutting tool. Later, additional simulation is needed to confirm the tool deflection under condition that tool relief angle, detailed contact condition and optimized mesh are considered.

2 Experimental setup

The machining system has three axes of driving system such as X -, Y - and Z -axis. Machining system is controlled by PMAC operation software. The air static pressure bearing in driving system can give the ability for the working table to be moved in X - and Y -axis with

5 nm of accuracy. Z -axis guide driven by linear motor has the positioning repeatability of 40 nm. Each cutting force of three axes can be measured in real time by dynamometer that is attached on the Z -axis. Fundamental machining experiment is carried out by shaping process with single crystal diamond with keeping increased cutting depth by 5 μm . If the pattern pitch is 150 μm , the line number of each cutting depth is 10. Table 3 shows the specification of fundamental machining conditions. The material of workpiece is 6:4 brass. Table 4 shows the properties of 6:4 brass workpiece. After machining experiment, cutting force, machined surface and burr formation are measured and analyzed for studying the

Table 3 Machining conditions of micro channel pattern

Item	Condition
Cutting tool	Width=80 μm ; $\theta=5.5^\circ$; Rectangular type: single crystal diamond
Cutting speed	1 200 mm/min
Cutting depth	5, 10, 15, 20, 25, 30, 35, 40 μm
Workpiece	6:4 brass

Table 4 Properties of 6:4 brass workpiece

Cutting tool	Tensile strength/MPa	Elongation/%	Hardness (HV)
6:4 brass	250	55	135.3

influence of tool deflection with increased cutting depth on machining.

3 Results and discussion

3.1 Cutting force analysis

The cutting forces and dynamic variation of cutting force in each axis are shown in Fig.4. When the cutting depth is increased, cutting force is increased with increasing dynamic variation of cutting force. In Fig.4(a), under cutting depth of 10 μm , the principle cutting force (F_y) is 1.1 N. In Fig.4(b), under condition of cutting depth of 20 μm , the cutting force is approximately 2.2 N. In Fig.4(c), under condition of cutting depth of 30 μm , the cutting force is approximately 3.4 N. The tool deflection due to the relative weak stiffness of cutting tool is varied by the parameters such as rake angle, clearance angle and instantaneous cutting direction, which influence the cutting force. The dynamic variation of cutting force is determined by considering the total force at any point during the motion of cutting tool, corresponding to the instantaneous values of the cutting depth, rake angle and

clearance angle, as shown in Fig.5[11–12].

The dynamic variation of cutting force that represents the tool deflection is increased with increasing cutting depth and its tendency is distinct in Y -axis direction with principle cutting force.

3.2 Machined surface analysis

The quality of the machined surface is mainly determined by the relative motion between the cutting tool edge and the workpiece. In practice, the tool path is deviated from the ideal tool path because the result of kinematic or dynamic factors due to the fact that the cutting process causes the motion errors and environmental disturbances of machining system. Fig.6 shows the results of machined surface. The burr formation of edge position on machined surface is proportional to cutting depth and its tendency is distinct above 20 μm in cutting depth. Its height has fluctuating values due to influence of tool deflection like the result of cutting force. The surface roughness values of bottom position are increased with increasing cutting depth, as shown Fig.7. In Fig.7(a), under cutting depth of 10 μm , surface roughness (R_a) is 2.0 nm and R_z is 28 nm. In

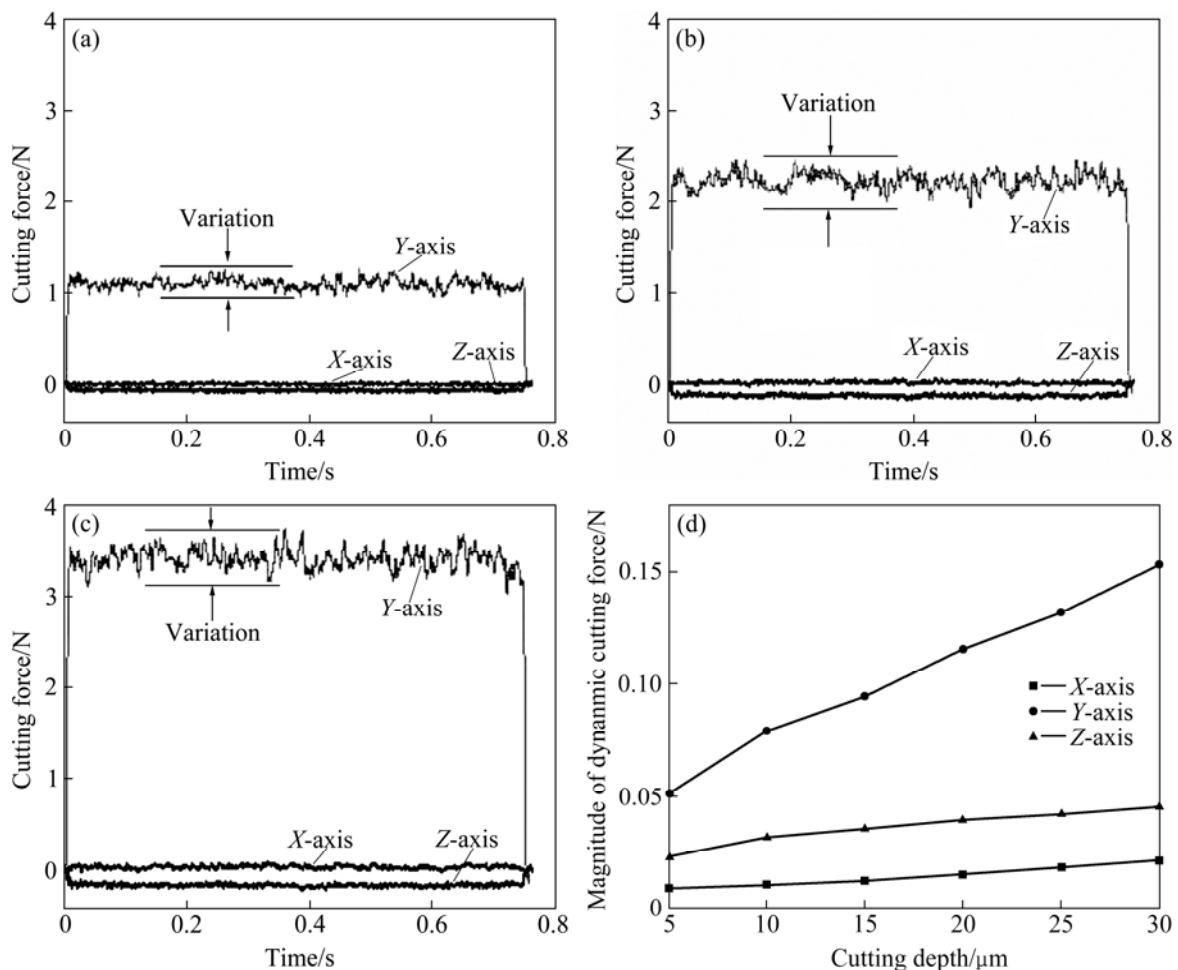


Fig.4 Results of cutting force at different cutting depths of 10 μm (a), 20 μm (b), 30 μm (c) and dynamic variation of cutting force (d)

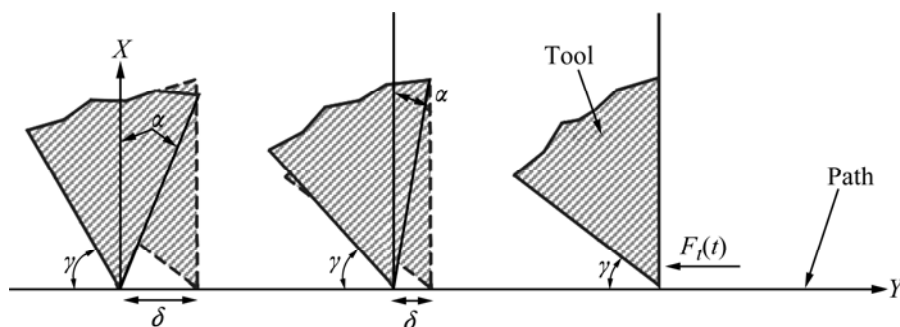


Fig.5 Variation of rake angle (α) and clearance angle (γ) in machining process

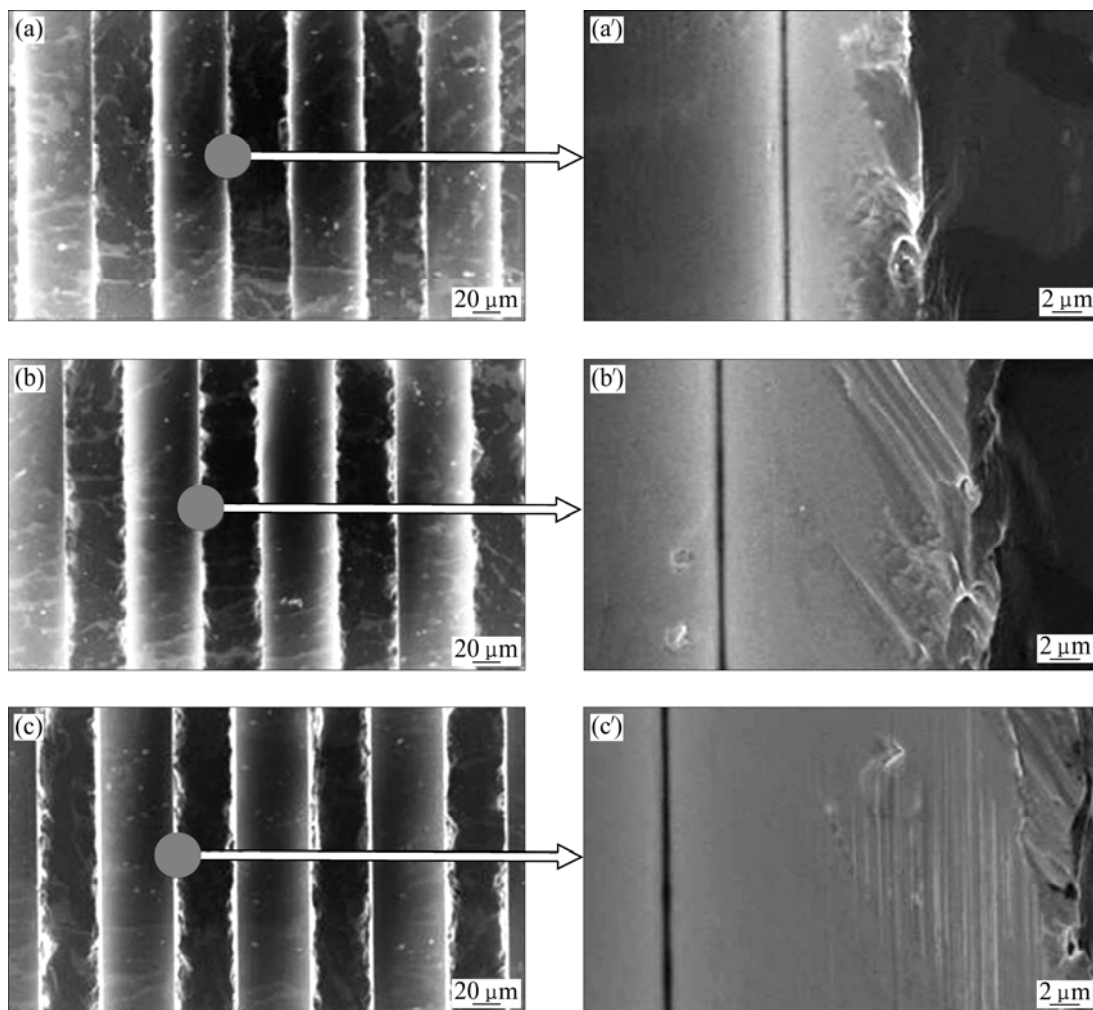


Fig.6 Results of machined surface and burr formation on machining channel pattern at different cutting depths: (a, a') 10 μm ; (b, b') 20 μm ; (c, c') 30 μm

Fig.8(b), under cutting depth of 20 μm , R_a is 2.4 nm and R_z is 30 nm. In Fig.7(c), under cutting depth of 30 μm , R_a is 2.8 nm and R_z is 36 nm. Most of measured results show that the machined surface in micro channel pattern is affected by the tool deflection caused by the parameters such as rake angle, clearance angle and cutting direction. With the fundamental machining results, the mold with various aspect ratio is fabricated.

In Fig.8, the results of machined surface with increasing aspect ratio are obtained by step-by-step method with the cutting depth of 10 μm on machining of micro channel pattern. As a whole, burr formation of edge position on fabricated channel pattern is increased with increasing aspect ratio. With increasing aspect ratio, deformation of entrance position represents the influence of tool deflection, as shown in Fig.8(c).

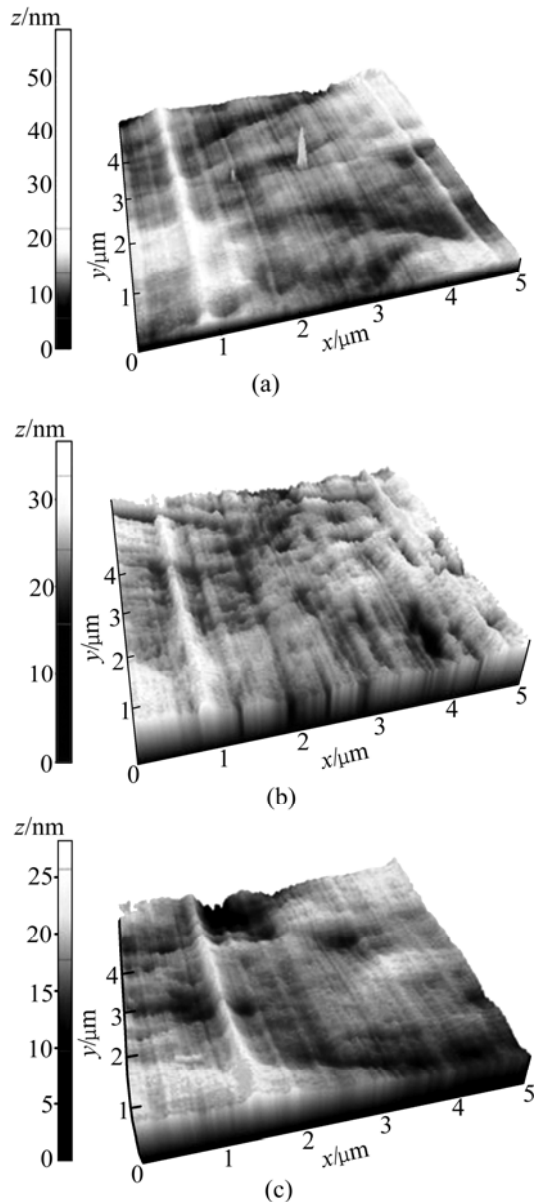


Fig.7 Results of surface roughness on bottom position of machining channel pattern: (a) $R_a=2.0$ nm, $R_z=28$ nm, cutting depth 10 μm ; (b) $R_a=2.4$ nm, $R_z=30$ nm, cutting depth 20 μm ; (c) $R_a=2.8$ nm, $R_z=36$ nm, cutting depth 30 μm

4 Conclusions

1) The influence of tool deflection on machined surface is experimentally verified by machining of micro channel pattern by using orthogonal cutting process and the analysis of tool deflection is performed using cantilever beam model.

2) The results of FEM simulation represent that tool deflection is linearly increased with increasing cutting depth and most of tool deflections are observed at the end part of tip.

3) On measured cutting force, the influence of tool deflection is observed through the results of increasing dynamic variation of cutting force with increasing cutting

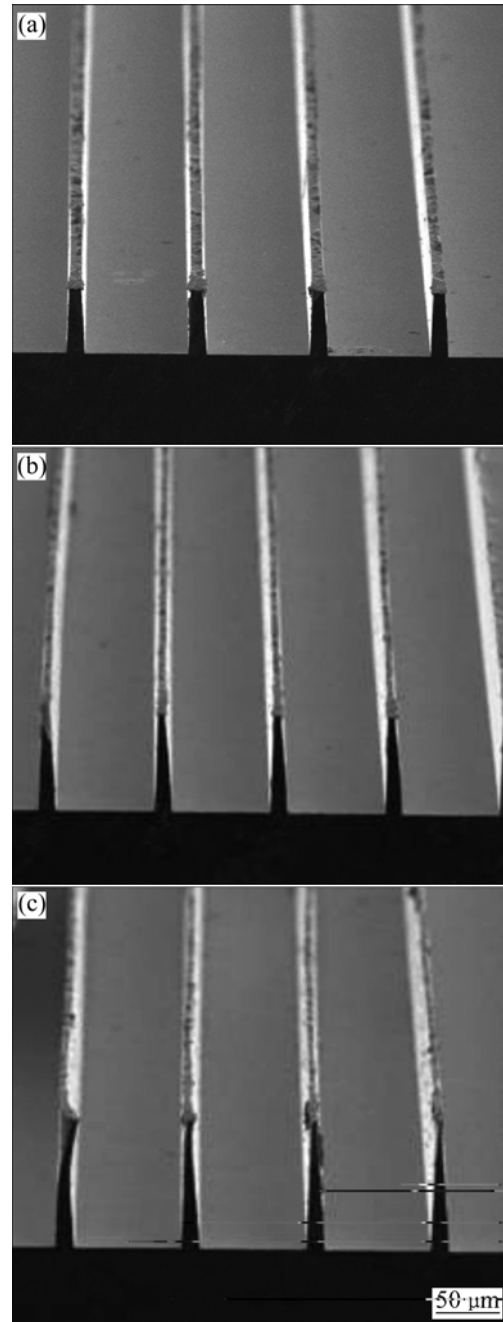


Fig.8 Results of machined surface with increment of aspect ratio on machining micro channel pattern: (a) h 50 μm , pitch: 95 μm ; (b) h 75 μm , pitch: 95 μm ; (c) h 100 μm , pitch: 95 μm

depth.

4) On machined surface, the influence of tool deflection is observed through the results of increased surface roughness of R_a and R_z with increasing cutting depth.

5) Burr formation on edge position of machined surface is increased in proportional to increasing of cutting depth. And its height has fluctuating values like the result of cutting force due to tool deflection.

6) With the results of fundamental machining, the pattern mold with various aspect ratio is fabricated.

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