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3D Finite Element Analysis of Cutting Forces in the Process of Machining Rectangular Microchannels

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Abstract: In the process of machining rectangular microchannels, severe friction occurs between the chip and the side face of the machined microchannel. The cutting forces have great effect on the miniature cutting tool. Thus, 3D FEM is adopted to study the cutting forces. The influences of the depth of the machined microchannel t, the cutting depth a_c, the cutting width a_w, the rake angle γ_o and the cutting speed v on the cutting forces are investigated. Results show that the main cutting force F_z and the thrust force F_y increase with the increase of t, a_c and a_w and have no obvious change with v. Moreover, F_z decreases and F_y increases as γ_o increases.

Keywords: Cutting force, FEM, microchannel.

1. INTRODUCTION

Microchannels which have currently been the focus of a number of studies are often manufactured on solid materials by microfabrication technology and have characteristic dimensions on the order of hundreds of microns. Nowadays, methods for machining microchannels mainly include: LIGA, wet and dry etching, EDM, and laser machining [1-4]. All of these methods are either costly or complex. Therefore, in order to meet the requirements of high efficiency and low cost, a miniature cutting tool is developed for fabricating rectangular microchannels by using conventional turning [5] or shaping method, as shown in Fig. (**1**). Due to its small size, the tool is easily broken once on encountering large cutting forces.

When machining rectangular microchannels, microchannels are not formed until one stroke or revolution. Except the first stroke or revolution, other strokes or revolutions are a kind of constrained cutting [6]. At this moment, the lateral deformation of the chip is constrained by the side face of the machined microchannel. Serious friction between the chip and the side face of the machined microchannel leads to a rapid increase of cutting forces, which intensifies the working condition of the cutting tool. However, previous research is mostly focused on free cutting, in which the lateral deformation of the chip is not constrained [7, 8]. Until now, research on the influence of the lateral deformation of the chip by the cutting forces has not been reported. Nowadays, most of the studies on cutting forces are mainly based on experimental studies. In the present experiments, the cutting forces are generally small, the cutting force signals are seriously disturbed by the vibration of conventional machine tools and other factors, so it is difficult to test them accurately by experimental methods. Thus, FEM is employed to simulate the cutting operations for predicting the cutting forces. In the past, 2D models were usually adopted to simulate cutting operations [9] and 3D simulation is time-consuming and is not reliable in terms of prediction accuracy. Nowadays, the increase of hardware and software power and efficiency makes 3D models effective to simulate actual machining processes. Hence, in this paper, 3D FEM is carried out to study the cutting forces in the process of machining rectangular microchannels.

2. EXPERIMENTAL PROCEDURE

FEM simulations were carried out by using the commercial software DEFORM 3D V.10.2. The workpiece, whose material is copper, is defined as an elastic-plastic object initially meshed with 50,000 elements, as shown in Fig. (**2**), while the tool was modeled as a rigid object. In order to simplify the FEM model, a perfectly sharp cutting edge was assumed. During simulations, the workpiece wasset as static and the tool moved at a set speed. The friction factor between workpiece and the tool was set as 0.15. A relatively large workpiece was used so that localized deformation was not affected by boundary conditions or the workpiece size. The chip formation process was simulated as plastic flow and the separation of the chip material from the workpiece was achieved by continuous remeshing. The detailed simulated cutting conditions are shown in Fig. (**3**) and Table **1**.

3. RESULTS AND DISCUSSION

Through adjusting the cutting parameters, such as the depth of the machined microchannel t, cutting depth a_c,

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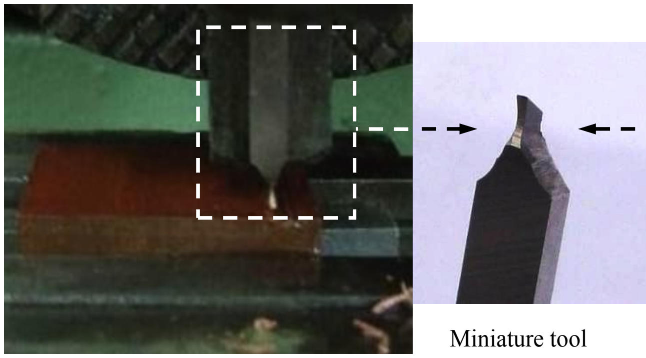

Fig. (1). Fabricating rectangular microchannels by using conventional turning or shaping method.

cutting width a_w, rake angle $\gamma_{\circ}$ and cutting speed v, rectangular microchannels can be fabricated under different cutting conditions. Next, the influences of these cutting parameters on the cutting forces have been investigated.

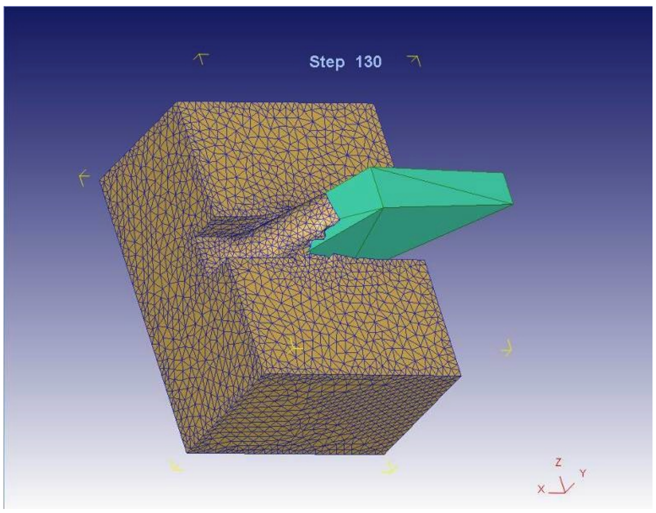

Fig. (2). 3D FEM simulation model.

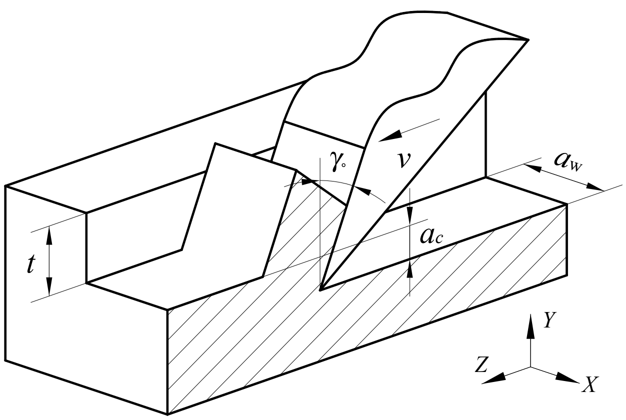

Fig. (3). Schematic diagram of cutting rectangular microchannel.

3.1. Depth of the Machined Microchannel *t*

As shown in Fig. (**4**), the main cutting force F_z and the thrust force F_y increase with the increase in t, no matter how much the a_c is. As mentioned above, the lateral deformation of the chip is constrained by the side face of the machined microchannel. When the chip flows out, severe friction occurs between the chip and the side face of the machined microchannel. As t increases, the contact area between the chip and the machined microchannel increases, leading to an increase in the cutting forces.

Table 1. Detailed simulated cutting conditions.

No	Parameters	Value
1	Rake angle $\gamma_{\circ}$ (°)	24, 16, 8, 0
2	Clearance angle(°)	5
3	Inclination angle(°)	0
4	Cutting edge angle(°)	90
5	Minor cutting edge angle(°)	2
6	Cutting width a_w (mm)	0.3, 0.6
7	Cutting depth a_c (mm)	0.2, 0.3, 0.4
8	Cutting speed v (mm/s)	400, 800, 1200
9	Depth of the machined microchannel t (mm)	0, 0.2, 0.5, 0.8

3.2. Cutting Depth a_c and Cutting Width a_w

As shown in Fig. (**5**), no matter how much the t is, F_z and F_y increase markedly with a_c. F_z and F_y in larger cutting width (a_w=0.6mm) are always greater than those in smaller cutting width(aw=0.3mm). As a_c and a_w increase, the volume of the material to be removed is increased so that the deformation resistance and friction is increased. So, more cutting power is required to separate the chip from the workpiece, leading to an increase in the cutting forces. In addition, it can be seen that under the same cutting conditions, the cutting forces in cutting rectangular microchannel are higher than those in orthogonal cutting.

3.3. Rake Angle $\gamma_{\circ}$

Fig. (**6**) shows that F_z decreases and F_y increases with the increase in $\gamma_{\circ}$. As $\gamma_{\circ}$ increases, the tool can be cut into metal easily and the chip can flow smoothly. As a result, less chip deformation occurs which leads to a rapid decrease inthe main cutting force F_z. However, the thrust force F_y does not decrease but increase with the increase in $\gamma_{\circ}$. This is because F_y, which is the thrust component of the resultant cutting force, not only decreases with the decrease of chip deformation, but also increases with the increase of $\gamma_{\circ}$. In

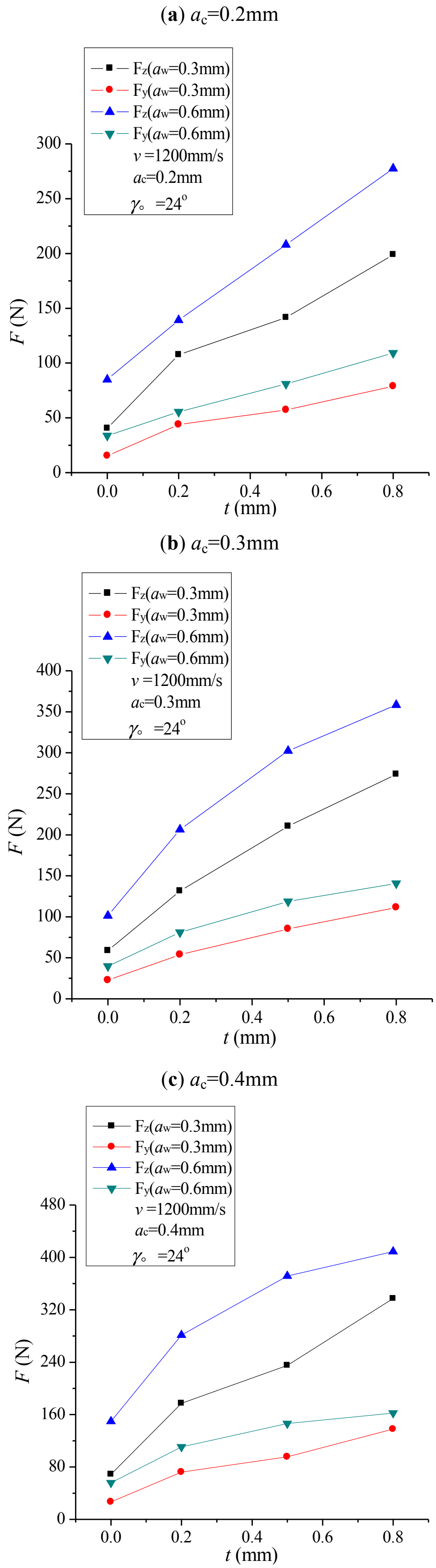

Fig. (4). Cutting forces F versus depths of the machined microchannel t under different cutting depths a_c.

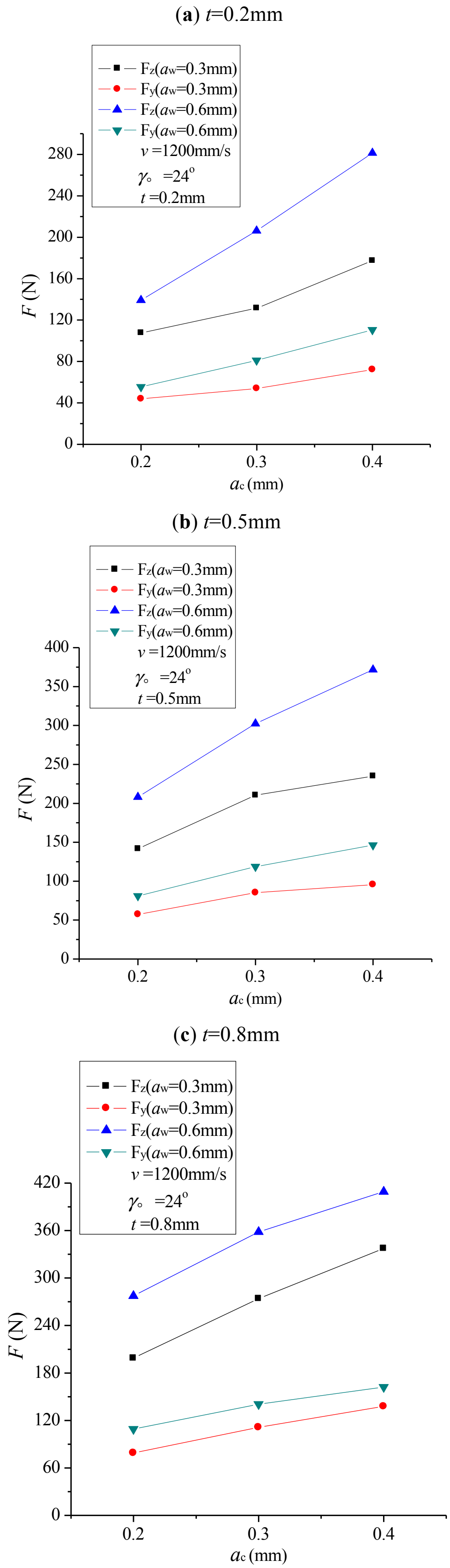

Fig. (5). Cutting forces F versus cutting depths a_c under different depths of the machined microchannel t.

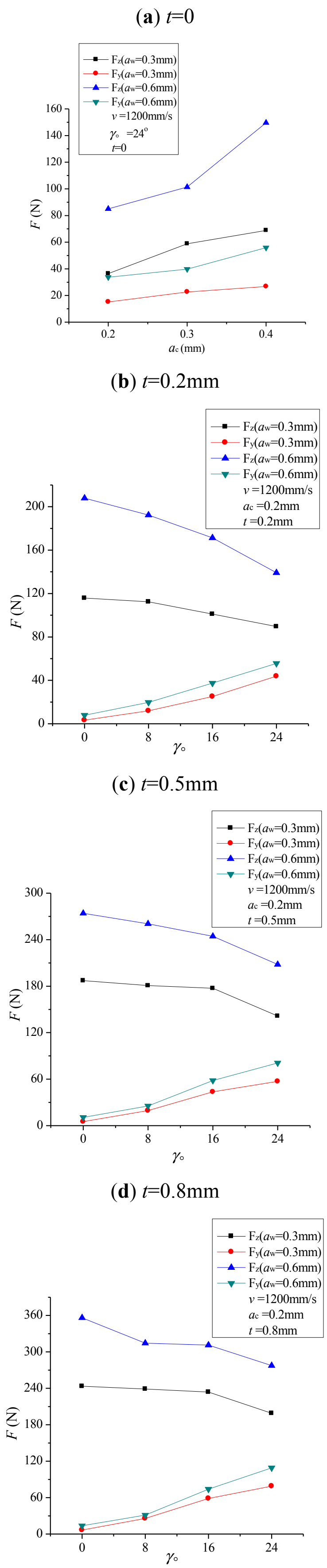

Fig. (6). Cutting forces F versus rake angle $\gamma_\circ$ under different depths of the machined microchannel t.

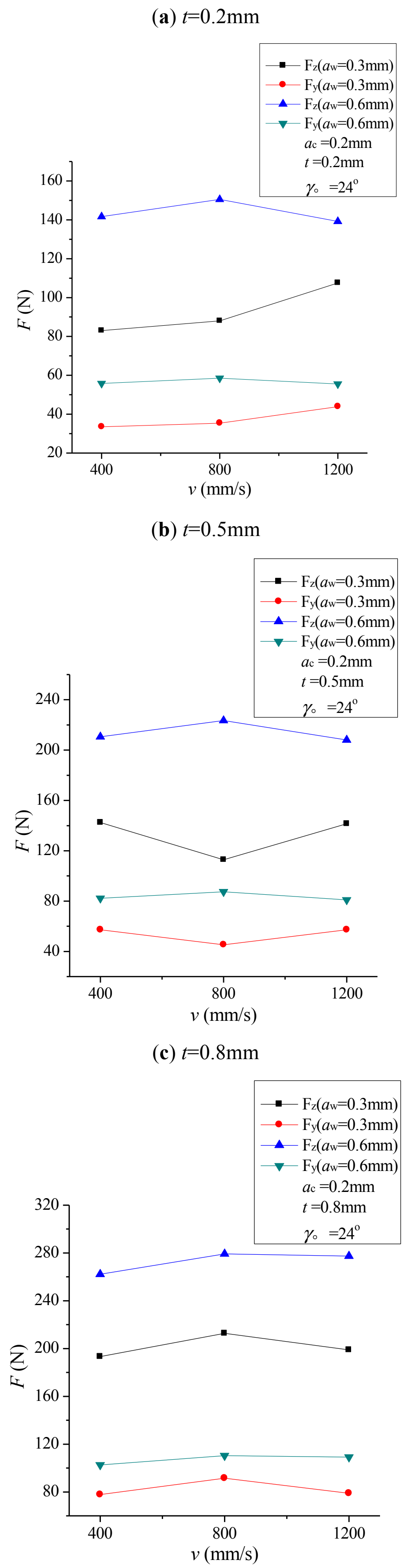

Fig. (7). Cutting forces F versus cutting speed v under different depths of the machined microchannel t.

the present experiments, the increased amount of F_y due to the increase of γ_o is larger than its decreased amount due to the decrease in chip deformation.

3.4. Cutting Speed *v*

As shown in Fig. (**7**), no matter how much the *t* is, F_z and F_y have no obvious change as *v* increases from 400 to 1200mm/s. It can be concluded that the lateral deformation of the chip changes little with the cutting speed *v*.

CONCLUSION

3D FEM is adopted to study the cutting forces in the process of machining rectangular microchannels. The influences of depth of the machined microchannel *t*, cutting depth a_c, cutting width a_w, rake angle γ_o and cutting speed *v* on the cutting forces are investigated. Some important experimental results are stated as follows:

The main cutting force F_z and the thrust force F_y increase with the increase in *t*. F_z and Fy increase with the increase in a_c and a_w. As γ_o increases, less chip deformation occurs and leads to a rapid decrease in F_z. While F_y does not decrease but increase with the increase in γ_o . F_z and F_y have no obvious change with *v*.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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