

Improvement of Micro-machining Accuracy by 2-Dimensional Vibration Cutting

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1. Introduction

High-precision micro-machining technology has been progressing in order to manufacture optics such as non-spherical mirror and flat lens. In accordance with the needs for the audio/video products to be compact and comfortable, especially, optical core parts are continuing to be miniaturized multi-functioned like fresnel lens and diffraction grating. However, these lenses get complicated in profile and need higher form accuracy. This is why high-precision micro-machining is getting more important than ever.

In general, in micro-machining, the size effect increases cutting forces due to causes such undesired problems as form deformation, chatter and burr. These troubles deteriorate the quality of optical parts both in form accuracy and surface roughness. A lot of studies have been done developing new methods to overcome. Those are on stiff and low thermal structures of machine tool, micro-feeding mechanism to be controlled down to sub micron, and micro-machining process itself.

Vibration cutting is one of the attempts to increase micro-machinability. This research aim at investigating the two-dimensional vibration cutting and its effect on surface roughness, burr and so on. Elliptical vibration cutting mechanism is analyzed and experiments are carried out using a tool-vibrator composed of two PZT actuators.

2. Model of two-dimensional vibration cutting

One-axis vibration mechanism, in which a horn was used to achieve the vibration of high frequency and quite large amplitude, was proved very effective in decreasing cutting forces. But it has been mainly applied to turning. On the other hand the two-dimensional vibration mechanism has an additional advantage to be able to generate a variety of tool path by combining two-axis vibratory movements.

Assuming amplitude A , frequency f , phase ϕ and workpiece feedrate v in the two-dimensional vibration cutting, the tool locus is expressed by equation (1). Fig. 1 shows a model of the two-dimensional vibration cutting. While the tool is engaged in down-cutting, during the period C_I , it cuts the workpiece upward during the period C_{II} . Therefore the thrust cutting force changes from positive to negative.

$$\begin{aligned} X &= A \sin(ft + \phi) + vt \\ Y &= A \sin(ft) \end{aligned} \quad (1)$$

In the model, theoretical maximum surface roughness (R_{max}) can be calculated and it depends on the tool locus parameters as described in equation (1).

Assuming their relationship constant is expressed as equation (2). Because phase ϕ effects the pattern of tool locus, it would be desirable to select ϕ for an appropriate tool locus once depth of cut and feedrate are given.

$$R_{max} = F \frac{1}{A}, \frac{1}{f}, v \quad (2)$$

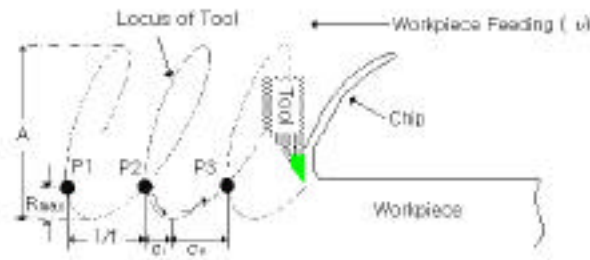


Fig. 1 2D Vibration Cutting

Theoretically, the larger amplitude, the higher frequency and the slower feedrate make the better surface. However, too slow feedrate lowers the cutting efficiency and a vibration mechanism limited dynamic characteristics, Therefore, amplitude, frequency and feedrate must be decided based on the actual system.

3. Experimental Apparatus

Fig. 2 shows the schematic diagram of the experimental apparatus. A micro-drilling machine tool composed of a xy table and a z-axis column is equipped with a tool two PZT actuators are located perpendicularly each other in the tool vibrator so that two-dimensional vibrational tool path is created. In order to remove cross-interference of each axis vibration, cross-shaped voids are devised in the tool vibrator. If a sine wave generated from a function generator is input to a two-phase signal generator, two sinusoidal signals with phase difference corresponding to a required tool pattern are output. The two-phase signals are amplified enough to actuate PZT actuators by a two-channel signal amplifier. A current booster is needed to make PZT actuators respond quickly well to a rapid input. Table 2 summarizes the vibration cutting conditions in this study.

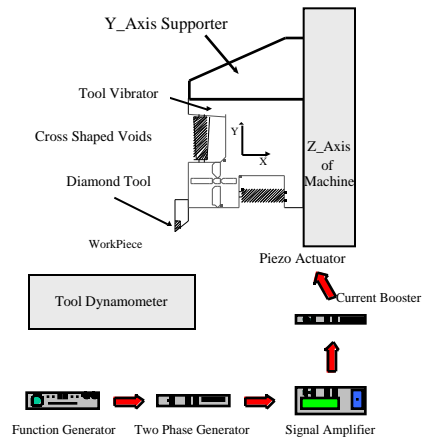


Table 1 Conditions in 2D Vibration Cutting


Tool	Diamond Tool	 Arc 180° Arc 90°
Workpiece	Brass(7-3)	
Cutting Condition	Depth of Cut (t_c)	1, 1.5, 2, 3, 4, 5 [μm]
	Feed Rate (v)	0.5, 1, 2, 3, 4 [mm/sec]
Vibration Condition	Vibration Type	Elliptical Vibration
	Frequency (f)	1kHz
	Amplitude (A)	5 μm

Fig. 2 Schematic Diagram of Experimental Apparatus for 2-D Vibration Cutting

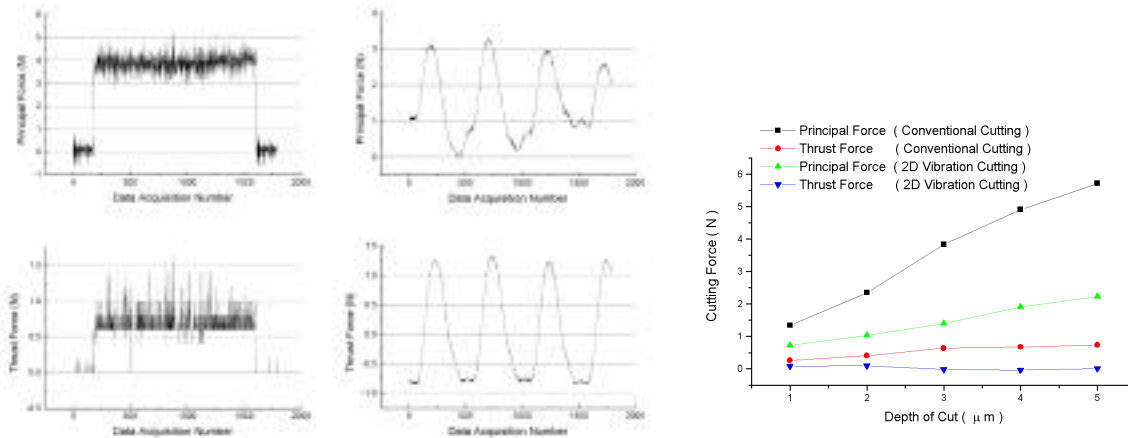
4. Experimental Results

4.1 Cutting Force

With a diamond tool of arc 180° and workpiece feedrate of 1mm/sec and depth of cut 1~5 μm , the behavior of cutting forces is investigated during cutting both in the mode of two-dimensional vibration and non-vibration.

Fig. 3(a), 3(b) shows cutting forces -principle, thrust- in the non-vibration cutting and in the 2-D vibration cutting respectively. While the cutting forces for non-vibration cutting are constant with a some fluctuation, those for vibration cutting change periodically in sinusoidal way. The cutting forces increase in the period of C_I and decrease in C_{II} and the whole cycle repeats. This fact justifies the model described in Fig. 1, in which in the period of C_I , the tool cuts down gradually to the deepest point, whereas in C_{II} the depth of cut decreases to zero. Around the end of C_{II} there is even a region where the thrust force gets negative.

Fig 4. shows the comparison of the average cutting forces over 1 μm to 5 μm of depth of cut. Principal forces for vibration cutting ranges from 0.7N to 2.2N depending on the depth of cut, which is almost half as much as those for non-vibration cutting. While thrust force for non-vibration ranges from 0.3N to 0.7N, that for vibration cutting is nearly zero. Much smaller cutting force increase of vibration cutting is thought mainly due to the air lubrication between tool and chip intermittently provided by tool vibration.



(a) Conventional Cutting (b) 2D Vibration Cutting Fig. 4 Comparison of Cutting Forces Between Non-vibration Cutting and Vibration Cutting
Fig. 3 Measured Cutting Forces ; Principal, Thrust Force

4.2 Surface Roughness

The effects of vibration cutting on surface roughness are investigated varying depth of cut or cutting speed with a diamond tool of arc 180°. Fig. 5 shows the comparison of surface roughness between vibration and non-vibration cutting versus depth of cut with a cutting speed of 1mm/sec. Surface roughness for non-vibration cutting fluctuates a little under a depth of cut of 2μm. This might be because of unstable cutting such as ploughing due to too small depth of cut compared to the tool edge radius. However, that for vibration cutting is stable even in the depth of cut less than 2μm and so better than that for non-vibration cutting. The comparison according to cutting speed with a critical depth of cut of 2μm is shown in Fig. 6. Surface roughness for non-vibration cutting gets worse as cutting speed increases, whereas that for vibration cutting is much better and almost independent of cutting speed. Moreover, it gets closer to the theoretical value over a cutting speed of 2mm/sec.

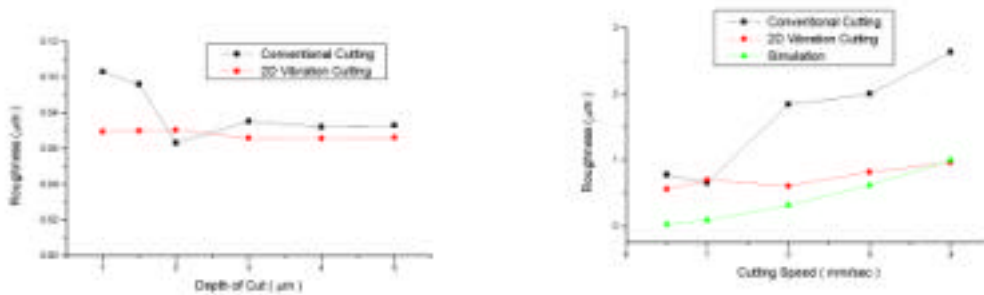


Fig. 5 Surface Roughness Versus Depth of Cut Fig. 6 Surface Roughness(Rmax) Comparison between Simulation and Experiment

4.3 Burr

The effect of vibration cutting on burr is investigated cutting brass plate 1mm thick with one edge of a 90°diamond tool. Since burr generation is known to be closely related to depth of cut rather than cutting speed, depth of cut is varied and cutting speed remains constant, or 1mm/sec. Fig. 7 shows the comparison of side burr, which generated in the edge of machined surfaces. In non-vibration cutting thick burr is formed even in a depth of cut as small as 1μm, whereas burr, in vibration-cutting, is hardly found even after 20passes with a depth of cut of 5μm.

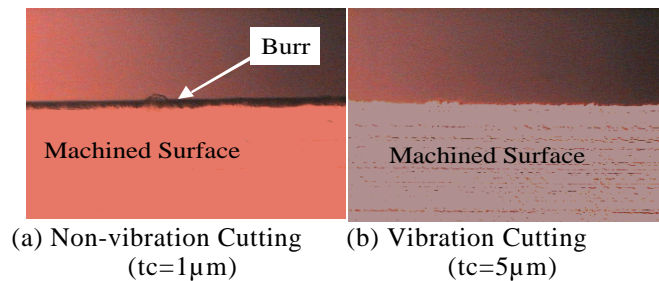


Fig. 4 Comparison of Side Burr

4.4 Chip

Fig. 8 shows the comparison of chips by two cutting modes. With depth of cut constant, or $1\mu\text{m}$, the type of chip by non-vibration cutting changes in such a way as from continuous to shear as cutting speed increases. That for vibration cutting is the continuous one over the entire range of speed. In addition, it is composed of many small lamellas which differentiates continuous chips of vibration cutting from that of non-vibration cutting. Lamellas are considered to be formed due to the periodical tool vibration. In general, continuous chips bring the high quality surface.

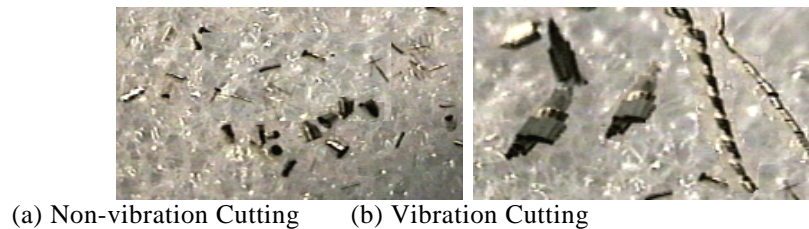


Fig. 5 Comparison of Chips

5. Conclusion

Two-dimensional vibration mechanism using two PZT actuators is devised and its performance for micro-machining is investigated in comparison with the conventional, or non-vibration cutting. The conclusion is that two-vibration cutting has many advantages over the non-vibration cutting. They are as follows:

- 1) Cutting force level is reduced;
 - (a) About half to one third for principal force
 - (b) Nearly zero for thrust force
- 2) Surface roughness is improved up to three and half times
- 3) Burr is largely reduced
- 4) Smooth and continuous chip is formed over the wide cutting conditions.

Reference

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