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Characteristics of Micro-Machining Using Two-Dimensional Tool Vibration

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ABSTRACT

This paper discusses the feasibility of improving micro-machining accuracy by using two-dimensional(2-D) vibration cutting. Vibration cutting is generated by two piezo actuators arranged orthogonally : one is actuated by a sine curve voltage input, and the other is actuated by a phase-shifted sine curve voltage. A tool attached to the vibrator oscillates in a 2-D elliptical motion, depending on the frequencies, amplitudes, and the phase shifts of two input signals and the workpiece feedrate. Along the elliptical tool locus, cutting is done in the lower part, and non-cutting is done in the upper part. By this way a unique feature of 2-D vibration cutting, that is, air lubrication between a tool and chips, is caused. Another unique feature of 2-D vibration cutting was experimentally verified, that is, some negative thrust force occurs as the direction of chip movement on a tool rake face is reversed. Those features not only help chips flow smoothly and continuously but also reduce cutting force, which results in a higher quality machined surface. Through tool path simulations and experiments under several micro-machining conditions, the 2-D vibration cutting, compared to conventional cutting, was found to result in a great decrease in the cutting force, a much smoother surface, and much less burr.

Keywords : Two-dimensional(2-D) vibration cutting, Piezo actuator, Elliptical locus, Micro-machining

1. Introduction

High-precision micro-machining technology for manufacturing optics such as non-spherical mirrors and flat lenses has been in progress. Because audio/video products need to be compact and comfortable, core optical parts, such as fresnel lenses and diffraction gratings, continue to become more miniaturized and multi-functioned while their profiles become more complicated. This is why high-precision micro-machining is becoming more important than ever.

In general, the size effect inevitable in micro-machining, which makes the specific cutting force large, causes such undesirable problems as form deformation, chatter, and burr, all of which deteriorate the quality of optical parts in terms of both form accuracy and surface roughness[1]. Many studies have attempted to develope new methods to overcome the above mentioned problems. The studies are on stiff structures with low thermal error of machine tools, micro-feeding mechanism, and the micro-machining process itself.

Vibration cutting is an attempt to decrease the size effect by the use of intermittent air lubrication between a vibratory tool and chips[2, 3, 4]. This study aims at investigating the effects of two-dimensional(2-D) vibration cutting on cutting force, surface roughness, burr and so on. A tool vibrator composed of two piezo actuators is developed, and a control program to generate an appropriate tool motion is developed.

2. Model of two-dimensional vibration cutting

One-dimensional vibration mechanism, in which a

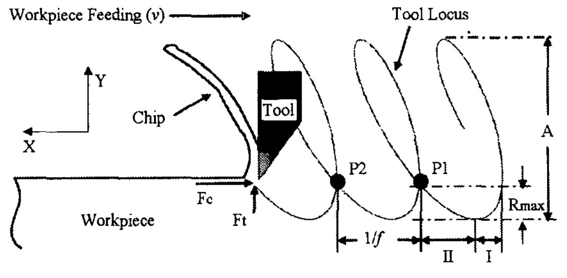


Fig.1 Principle of 2-D Vibration Cutting

horn is used to achieve a vibration of high frequency and quite large amplitude, was proved very effective in decreasing the cutting force[2]. In comparison, 2-D tool vibration has the additional advantage of being able to generate a variety of tool paths by combining two-axis vibratory tool movements.

Fig. 1 shows the principle of two-dimensional vibration cutting. Assuming amplitude A, frequency f, phase shift Φ , and workpiece feedrate v in the 2-D vibration cutting, the tool locus is expressed by equations (1). The tool is engaged in down-cutting during period I, while it cuts the workpiece upward during period II. Therefore, cutting forces are expected to increase during period I and decrease in period II. Then, in the rest of a cyclic tool locus, the tool is not in contact with the workpiece. In this way the whole cycle repeats.

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

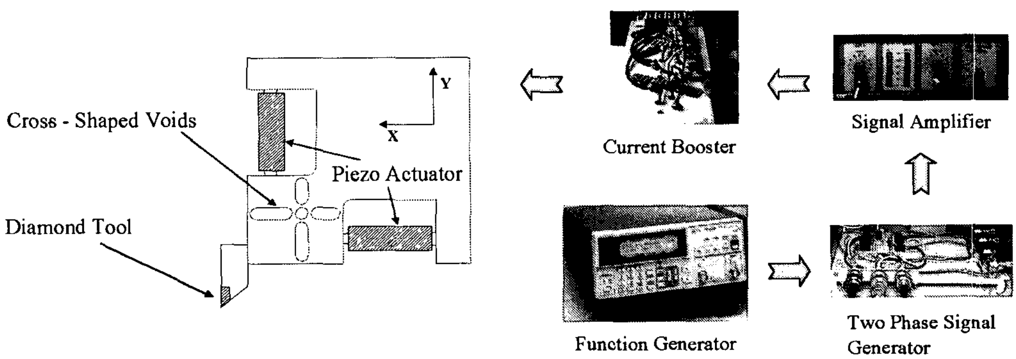
The theoretical maximum surface roughness (Rmax) can be calculated, depending on the tool vibration parameters. Assuming that Φ is constant , Rmax is expressed as equation (2).

$$R_{\max} \propto F\left(\frac{1}{A}, \frac{1}{f}, v\right) \qquad (2)$$

Phase shift Φ , which affects the tool locus pattern, should be selected in order to obtain an appropriate tool locus once the depth of cut and the feedrate are given. Theoretically, the larger the amplitude, the higher the frequency, and the slower the feedrate, the machined surface becomes smoother. In reality, however, because too slow a feedrate lowers the cutting efficiency and a vibration mechanism has its own limited dynamic characteristics, such parameters as amplitude, frequency, and feedrate must be decided appropriately considering those factors.

3. Piezo-driven 2-D vibrating tool support

Fig. 2 shows the structure of a piezo-driven 2-D vibrating tool support and its actuation signal generating system. Two PZT actuators are located perpendicularly to each other in a metal plate, which is shaped for the tool holder to be elastically deformed in the X and Y directions by the PZT actuating forces. In order to remove the cross-interference of each axis displacement, cross-shaped voids are devised in the tool holder. If a sine wave generated from a function generator is inputted to a two-phase signal generator, two sine waves with a phase shift Φ , corresponding to a required tool pattern are outputted. Using a two-channel signal amplifier, the two-phase signals are amplified enough to actuate the



(a) Structure

(b) Actuating signal generator

Fig. 2 Piezo Driven 2-D Vibrating Tool Support

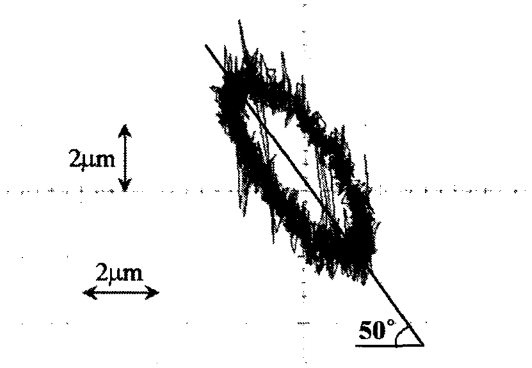


Fig. 3 Measured Tool Loci of the 2-D Vibrating Tool

PZT actuators. A current booster is needed to make the PZT actuators respond quickly and well to a rapid input.

Fig. 3 shows an example of the elliptical tool loci measured by gap sensors when the frequency is 1kHz, the phase shift is 45°, and the amplitudes of the two axes are about 5μm. The slope of the tool loci is about 50°.

Table 1 shows the experimental measurements of static/dynamic stiffness of both tool supports used for conventional and vibration cutting. The static stiffness of both principal direction and thrust direction is larger for conventional cutting than for vibration cutting. In contrast, for the dynamic stiffness, the principal component becomes much bigger for vibration cutting than for conventional cutting. That is why vibration cutting is expected to be more useful than conventional cutting in achieving better accuracy, especially in micro-machining.

Table 1 Stiffiness of Tool Supports : unit(N/μm)

	Conventional cutting		Vibration cutting	
	Principal	Thrust	Principal	Thrust
Static Stiffness	11.93	116.74	9.06	5.77
Dynamic Stiffness	1.43	4.44	21.10	3.93

4. Machining Experiments

4.1 Experimental apparatus

Fig. 4 shows a schematic diagram of the experimental apparatus set up for the 2-D vibration cutting. A desk-top machine tool is composed of an XY table with a resolution of 1μm, and a Z-axis column with a resolution of 0.17μm. The 2-D vibrating tool support is fixed at the tool mount on the column slider, whereas for the conventional cutting, a tool is fixed directly at the tool mount. Cutting force and tool displacements were measured with a tool dynamometer and gap sensors.

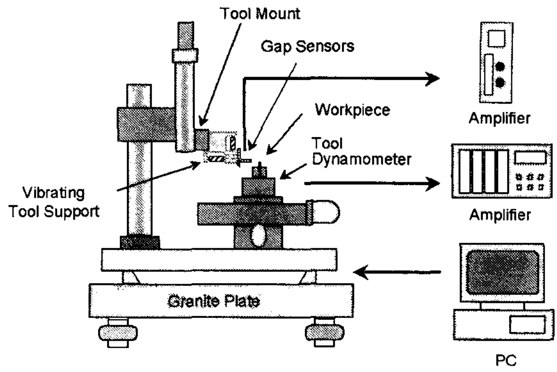


Fig. 4 Schematic diagram of experimental

4.2 Cutting conditions

The cutting parameters, i.e., the depth of cut and the feedrate, were varied, whereas the vibration parameters were fixed to appropriate values in accordance with the physical characteristics of the tool vibrator. Table 2 summarizes the experimental conditions used in this study.

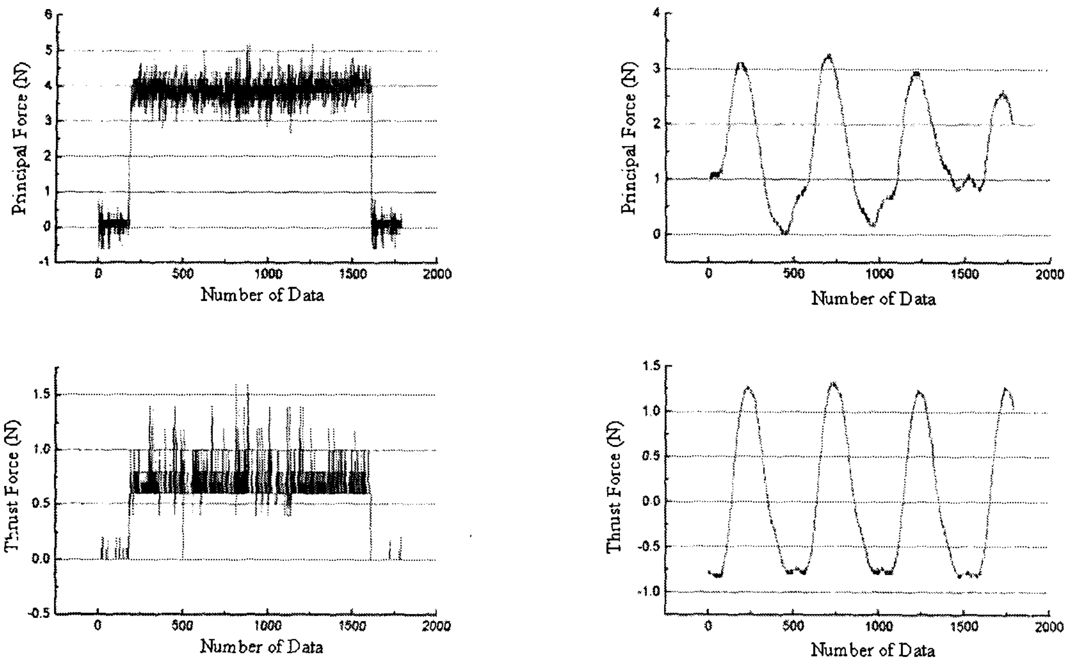
Table 2 Condition for 2-D Vibration Cutting

Tool	Artificial Diamond	
Workpiece	70-30 Brass	
Cutting Condition	Depth of Cut	1, 1.25, 2, 3, 4, 5 [μm]
	Feedrate	0.5, 1, 2, 3, 4 [mm/sec]
Vibration Condition	Phase	45°
	Frequency	1 [kHz]
	Amplitude	5 [μm]

5. Experimental results

5.1 Cutting force

With a diamond tool of arc 180° , feedrate of 1 mm/sec, and depth of cut of 1~5 μm, the behavior of the cutting force was investigated during cutting. Figures 5(a) and 5(b) respectively show the principal and the thrust cutting forces for conventional and vibration



(a) Conventional Cutting

(b) 2-D Vibration Cutting

Fig. 5 Measured Cutting Forces : Principal, Thrust

cutting. While the levels of the cutting forces for conventional cutting were almost constant with some noises, those for vibration cutting periodically changed in sinusoidal fashion. This fact justifies the model described in Fig. 1, in which the tool cuts down gradually to the deepest point in period I, whereas the depth of cut decreases to zero in period II. The fact also proves that there is even a region in a cycle of the elliptical tool motion where the thrust force becomes negative.

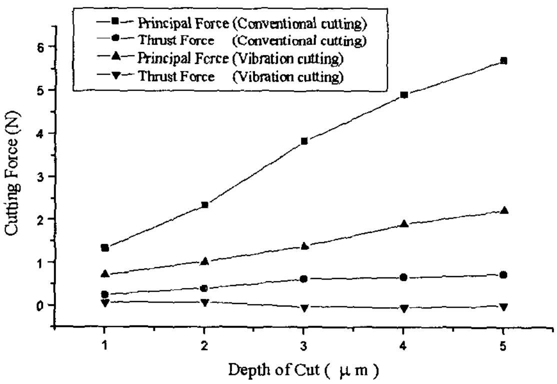


Fig. 6 Comparison of Cutting Forces between Conventional and Vibration Cutting

Fig. 6 shows comparisons of the average cutting force from 1 to 5 μm depth of cut. The principal force for the vibration cutting ranged from 0.7N to 2.2N, depending on the depth of cut, which is about half as much as that for conventional cutting. The thrust force for the conventional cutting ranged from 0.3N to 0.7N, while it was nearly zero for the vibration cutting. It is thought that the much smaller cutting force for the vibration cutting is mainly due to the air lubrication – intermittently provided by the tool vibration- between the tool and chips.

5.2 Surface roughness

The effects of vibration cutting on surface roughness was investigated by varying the depth of cut or cutting speed with a diamond tool of arc 180° . Fig. 7 shows the comparative effects of the depth of cut for vibration cutting and conventional cutting. The surface roughness for conventional cutting fluctuated a little below a depth of cut of 2μm. This may be because of unstable cutting such as ploughing due to too shallow depth of cut, compared to the tool edge radius. For vibration cutting, however, the surface roughness was stable, even in the region of less than 2μm, and better than that of

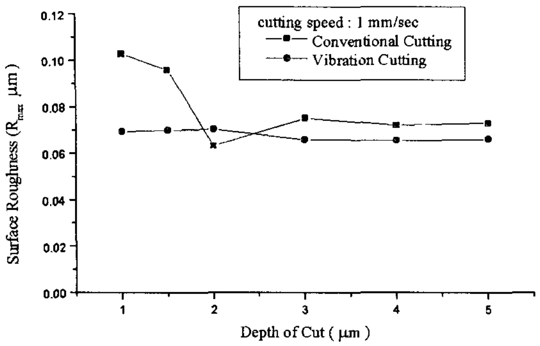


Fig. 7 Surface Roughness versus Depth of Cut

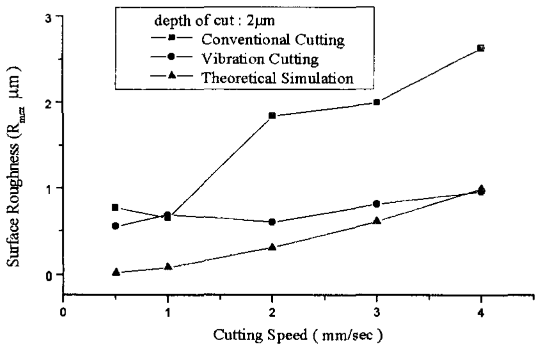
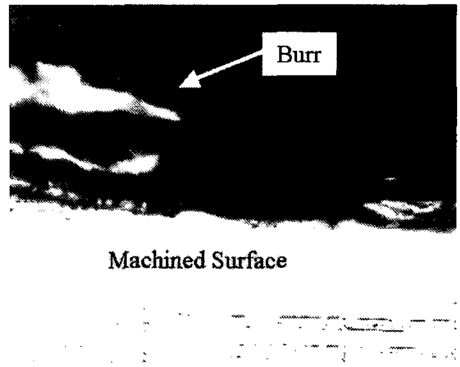
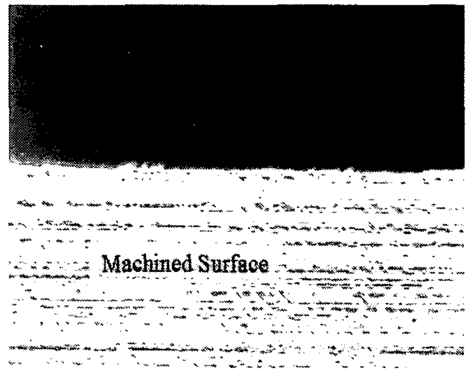


Fig.8 Comparison of Surface Roughness between Simulation and Experiments



(a) Conventional Cutting
(after 5 passes with depth of cut 5μm)



(b) 2-D Vibration Cutting
(after 20 passes with depth of cut 5μm)

Fig. 9 Comparison of Side Burrs

conventional cutting. A comparison of surface roughness according to cutting speed is shown in Fig. 8. The surface roughness for conventional cutting worsened as cutting speed increased, whereas for vibration cutting it improved and was almost independent of cutting speed. Moreover, over a cutting speed of 2㎜/sec, the surface roughness became closer to a theoretical value.

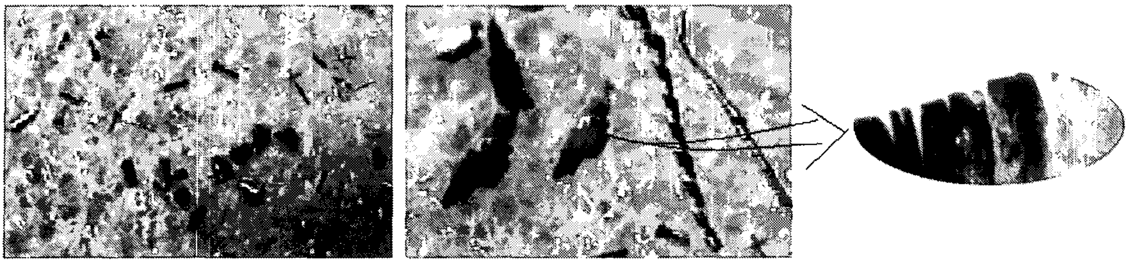
5.3 Burr

The effects of vibration cutting on burr was investigated when cutting 1 ㎜-thick brass plates with one edge of a diamond tool of arc 90°. Because the generation of burr is known to be closely related to depth of cut rather than cutting speed[5], depth of cut was varied while cutting speed remained constant at 1 ㎜/sec.

Fig. 9 shows a comparison of the side burrs that are generated at the edge of machined surfaces. In conventional cutting, thick burr is formed at the depth of cut of 5 ㎛, whereas in vibration-cutting, burr is hardly found at the depth of cut of 5μm even after 20 passes.

5.4 Chip

Fig. 10 shows a comparison of chips produced by two cutting modes. With the depth of cut constant at 1 ㎛, the chips produced by conventional cutting changes from the continuous type to the shear type as cutting speed increases. For vibration cutting, the chips were of the continuous type over the entire range of speed. In addition, the continuous chip for vibration cutting is composed of many small lamellas, which is differentiated from that for conventional cutting. Lamellas are thought to be formed as a result of periodic tool vibration. In general, continuous chips result in high surface quality. Another chip feature by vibration cutting is that chip thickness changes according to tool vibrating motions, and the thinnest part of the chip is likely to be torn off. Fig. 10 (c) shows tears periodically spaced in the chip edge by vibration cutting.



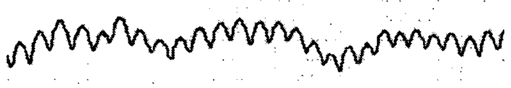
(a) Conventional Cutting (b) Vibration Cutting (c) Tears of Chip Edge by the Vibration Cutting

Fig. 10 Comparison of Chips

5.5 Profile

Fig.11 shows some machined surface profiles caused by vibration cutting. The high frequency waves shown in Fig. 11 are due to the vibration motion, and the low frequency waves are due to 60Hz electric power noise induced through the signal amplifier. Although the noise level of about 8V (Fig. 11(a)) is reduced to below 1V (Fig. 11(b)), the influence of the noise still remains. Fig.11 (c) shows a simulated machined surface profile with the same electric power noise as in Fig 11(b). A comparison between Figures 11(b) and 11(c) proves that, without the power noise, the tool vibration motion would be the only dominant factor for determining the machined surface profile.

(a) Noise level 8V



(b) Noise level 1V

(c) Noise level 1V

Fig. 11 Machined Surface Profiles by the Vibration Cutting
(a), (b) : measured,
(c) : simulation
(depth of cut : 1 μm, feedrate : 4mm/sec)

6. Conclusion

A two-dimensional vibration mechanism using two piezo actuators was devised and its performance for micro-machining was investigated in comparison with conventional cutting. It was concluded that 2-D vibration cutting has many advantages over conventional cutting. The advantages are as follows:

(1) The dynamic stiffness of tool support is increased
(2) The average cutting force level is reduced.
  (a) By about half to one-third for the principal force
  (b) To nearly zero for the thrust force
(3) The surface roughness is improved by up to three and one-half times
(4) The amount of burr is greatly reduced
(5) Smooth and continuous chips are formed over a wide range of cutting conditions.

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