Study on Elliptical Vibration Cutting

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Summary:
The paper presents a new cutting method named "Elliptical Vibration Cutting". Synchronized two-directional vibration is applied to the cutting edge in the plane including the cutting direction and the chip flow direction. The chip formed is mainly pulled out by the tool while the tool moves in the chip flow direction, and then the tool is restored to the cutting point without cutting in each cycle of the vibration. Orthogonal cutting experiments of copper are carried out within a scanning electron microscope, and it is observed that the chip thickness and the cutting force are reduced remarkably by applying the method proposed.

Keywords:
vibration, cutting, chip

1. Introduction
The ultrasonic vibration cutting has been successfully applied to ultraprecision diamond cutting of difficult-to-cut materials, including steels [5, 7] and glass materials [6]. In the conventional vibration cutting, vibration is applied to the cutting tool only in one direction. Generally, the tool is vibrated in the cutting direction [2-8, 10] so that the tool is separated from the chip in each cycle of the vibration.

The present research presents a new cutting method named "Elliptical Vibration Cutting". Synchronized two-directional vibration is applied to the cutting edge in the plane including the cutting direction and the chip flow direction in such a way that the cutting edge forms an elliptical locus in each cycle of the vibration. Orthogonal cutting experiments of copper are carried out within a scanning electron microscope [9] in order to observe the cutting process directly and to measure the dynamic cutting force in each cycle of the vibration. The basic characteristics of the elliptical vibration cutting are clarified, compared with those of the ordinary cutting and the conventional vibration cutting.

2. Cutting principle
Figure 1 shows schematic illustrations of one cycle of the elliptical vibration cutting proposed. In the present method, the workpiece is fed at a nominal cutting speed, and elliptical vibration is applied to the cutting edge as shown in Fig. 1. As the maximum vibration speed is set to be higher than the cutting speed, the tool is separated from the chip in each cycle of the vibration. The cutting is taken place after re-entering of the elliptical vibration cutting proposed. In the present method, the tool only in one direction. Generally, the tool is vibrated in the cutting direction [2-8, 10] so that the tool is separated from the chip in each cycle of the vibration.

Orthogonal cutting experiments of copper are carried out within a scanning electron microscope [9] in order to observe the cutting process directly and to measure the dynamic cutting force in each cycle of the vibration. The basic characteristics of the elliptical vibration cutting are clarified, compared with those of the ordinary cutting and the conventional vibration cutting.

3. Theoretical analysis
The elliptically vibrated tool generates the finished surface in a period after it starts to cut workpiece in each cycle, and the finished surface has a regular wavy form as shown in Fig. 1.

The instantaneous cutting direction is not constant in this cutting. The instantaneous clearance angle is also changed, and it becomes minimum in the instant when the tool starts to cut. Therefore, the cutting conditions should be so chosen that the minimum clearance angle is positive in order to avoid interference between the tool clearance face and the finished work surface.

The theoretical roughness and the minimum clearance angle can be derived from the following fundamental equations.

Fig. 1 Principle of elliptical vibration cutting.

\[ x = a \cos(\omega t), \quad y = b \cos(\omega t + \phi) \] (1)

where \( a, b, \omega, t \) and \( \phi \) are horizontal amplitude, vertical amplitude, time, angular velocity and phase difference respectively.

The times \( t_1 \) and \( t_2 \) are defined as follows: at time \( t_1 \), the tool starts to cut, and then at time \( t_2 \) the tool passes the next highest point of the finished workpiece surface which remains after cutting. The pitch of the regular wave is equal to the distance

Annals of the CIRP Vol. 43/1/1994 35
which is given by the total relative movement of the tool and the workpiece in the cutting direction from $t_1$ to $t_2$:

$$
\frac{a \cos(\omega t_2) - a \cos(\omega t_1)}{v} + \frac{b \cos(\omega t_2 + \phi) - b \cos(\omega t_1 + \phi)}{v} = 2 \pi \omega \nu
$$

where $v$ is the nominal cutting speed. In addition, the vertical positions are equal at times $t_1$ and $t_2$:

$$
b \cos(\omega t_1 + \phi) - b \cos(\omega t_2 + \phi) = 0
$$

The times $t_1$ and $t_2$ are computed numerically from Eqs. (2) and (3) by applying Newton-Raphson Method.

At time $t_1$ when the vertical position $y$ is minimum, $y$ is equal to $-b$:

$$
b \cos(\omega t_1 + \phi) = -b
$$

From $t_1$ and $t_2$, the theoretical roughness $R_{th}$ is calculated by

$$
R_{th} = b \cos(\omega t_1 + \phi) - b \cos(\omega t_2 + \phi)
$$

The vertical and the horizontal components of relative velocity between the tool and the workpiece are $-b \sin(\omega t + \phi)$ and $-a \sin(\omega t + \phi)$ respectively. Thus, the critical cutting direction $\phi_1$, which is the angle between the instantaneous cutting direction and the nominal one at time $t_1$, is given by

$$
\phi_1 = \tan^{-1} \left( \frac{b \sin(\omega t_1 + \phi)}{a \sin(\omega t_1 + \phi)} \right)
$$

The nominal clearance angle needs to be greater than this critical value $\phi_1$.

Figure 2 shows the theoretical values of $R_{th}$ and $\phi_1$ plotted against frequency $f = \omega / 2 \pi$, where $a = 5 \mu m$, $b = 5 \mu m$, $\phi = \pi / 2$ rad and $v = 250 \mu m/min$ respectively. For example, Fig. 2 shows that the frequency and the nominal clearance angle need to be greater than about 2 Hz and 6° respectively in order to achieve surface roughness of less than 0.1 $\mu m$ under these conditions.

The requisite for the intermittent cutting is given by the condition that the maximum horizontal vibration speed is greater than the nominal cutting speed, or

$$
a \omega > \nu
$$

4. Experimental apparatus and conditions

Figure 3 shows a sketch of an orthogonal cutting device equipped with an elliptically vibrated tool developed. The cutting device is installed within a scanning electron microscope (SEM) in order to observe the cutting process directly and to measure the dynamic cutting force in each cycle. The tool is vibrated by two piezoelectric actuators (PZT) arranged at a right angle, and the cutting force is measured with a piezoelectric type dynamometer.

The vibration frequency was mainly changed among other parameters in the present experiments in order to analyze transition from the ordinary cutting, where the frequency is zero, to the elliptical vibration cutting. In addition, the conventional vibration cutting was conducted and its results were compared with the elliptical vibration cutting. In the conventional vibration cutting, the tool was vibrated mainly in the cutting direction, but the vibrating direction was slightly inclined to the thrust direction so that the tool was separated from the finished surface [2]. The inclination angle was about 9.5°.

The tool is made of high speed steel. Its rake and clearance angles are 0° and 30° respectively, and the measured radius of the cutting edge roundness is approximately 1 $\mu m$. Workpiece material is OFC (Oxygen Free Copper) with a thickness of 0.25 mm and a length of 5 mm in the cutting direction. The depth of cut is 10 $\mu m$ and the nominal cutting speed $v$, which is equal to the feeding speed of workpiece in the cutting direction, is 260 $\mu m/min$. The circular vibration with a radius of 5 $\mu m$ is applied, which gives $a = 5 \mu m$, $b = 5 \mu m$ and $\phi = \pi / 2$ rad. These conditions are kept constant except the conventional vibration cutting. The vibration frequency is varied in a range from 0 to 6 Hz. The instantaneous clearance angle always exceeds the critical value $\phi_1$ theoretically at frequencies higher than 0.40 Hz under these conditions (see Fig. 2). The workpiece surface is finished prior to each experiment under the same conditions as the corresponding cutting experiment.

5. Experimental results

Figure 4 shows typical SEM photographs of the chips obtained at various frequencies, while Fig. 5 compares the corresponding principal and thrust components of cutting force measured. The horizontal axis in Fig. 5 is time or phase of the vibration. The tool is located at the rightward end at zero phase (see Fig. 1).

Figures 4(a) and 5(a) show the results of the ordinary cutting, where the frequency is 0 Hz. The chip is relatively thick. The cutting forces are high and are kept almost constant.

The tool is not separated from the workpiece at frequency 0.12 Hz (refer to inequality (7)), and hence Figs. 4(b) and 5(b) show a stage of transition from the ordinary cutting to the elliptical vibration cutting. Significant wavy surface is left on the finished surface. The thrust force is relatively high, because the instantaneous clearance angle becomes negative and the clearance face interferes with the finished surface in such a way that the clearance face presses down the workpiece. The chip thickness is a little smaller than in the case of the ordinary cutting. The reason for this is considered to be as follows. There exists a period when the chip is pulled up by the tool moving upward, although the chip is mostly pushed down in this case. The negative thrust force shown in Fig. 5(b) proves the existence of such phenomenon, and this negative thrust force causes reduction in the chip thickness and hence reduction in the principal force especially during the negative period.

The cutting force is generated intermittently due to the
intermittent cutting at frequencies of 0.40, 1.20 and 6.00 Hz (refer to inequality (7)). The chip thickness obtained at these frequencies is much less than that of the ordinary cutting, and the cutting force is much reduced at the high frequencies. There exist longer periods of negative thrust force as shown in Figs. 5(c), (d) and (e). Such negative thrust force means that the frictional force on the rake face is reversed as compared to the conventional cutting. The absolute value of the negative thrust force is increased, as the frequency is increased. Thus, the chip thickness and the cutting force are found to be smaller at the higher frequency.

The peak-to-valley value of the wave left on the finished surface in Fig. 4(b) is about double of the vibration amplitude,
although the surface is pressed by the clearance face. The amplitude of the surface roughness shown in Fig. 4(c) is about 2μm, which is in agreement with the theoretical value given in Fig. 2. The surface roughness is reduced as the frequency is increased as predicted theoretically. For example, the theoretical roughness is less than 0.1μm at 2 Hz (see Fig. 2), and it is expected theoretically that the surface roughness can be less than 0.1μm when this technique is applied at practical cutting speed with an ultrasonically vibrated tool.

Figure 6 summarizes the shear angles, which are calculated based on the chip thickness and the depth of cut measured in the SEM photographs. The shear angle increases as the frequency is increased, and the value reaches to about 60° at 6.00 Hz. This extraordinarily high shear angle proves that the present cutting method is quite effective to control the nominal friction between the rake face and the chip.

The results obtained by the conventional vibration cutting are shown in Fig. 7. The average cutting force is reduced as compared to the ordinary cutting due to the intermittent cutting. However, the force measured during cutting and the chip thickness are as large as those obtained by the ordinary cutting.

6. Conclusions
A new cutting method named “Elliptical Vibration Cutting” is proposed in the present paper which is effective to reduce the chip thickness and the cutting force. Theoretical analysis and cutting experiments within a scanning electron microscope are carried out. The following remarks are concluded:

1. The chip thickness and the cutting forces are reduced significantly by applying the elliptical vibration as compared with the conventional cutting including the conventional vibration cutting.
2. The shear angle is much increased, as the frequency of the elliptical vibration is increased. It exceeded 60° at a frequency of 6.00 Hz under the present experimental conditions.
3. The theoretical roughness generated by the elliptical vibration is calculated, and it is predicted to be small enough for precision cutting.
4. The nominal clearance angle needs to be larger than the ordinary cutting so that the instantaneous clearance angle is always positive.

It is expected that these effects lead to various advantages such as improvement of machining accuracy, reduction of damage of the cut surface, and cutting of difficult-to-machine materials.

Reference
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