Research on the Effect of Cutting Parameters on Chip Formation and Cutting Force in Elliptical Vibration Cutting Process

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Abstract. Elliptical vibration cutting (EVC) has been widely concerned since it was proposed, and its unique characteristics such as friction reversal and intermittent cutting can effectively extend the tool life, improve the machined surface roughness and so on. The objective of this paper was to predict the behavior of cutting force. A method of predicting the behavior of cutting force based on the chip thickness under various cutting conditions is proposed. Based on the established tool motion model, the chip model was founded. By numerical simulation, the effects of cutting parameters on cutting force under various cutting conditions were studied. The results show that the chip thickness can be used to predict the behavior of cutting force.

1. Introduction
The predicting of cutting force has been playing an important role in characterizing the cutting process. Many researchers have been trying to predict cutting force in various ways. Considering the characteristic of friction reversal, X.Q Zhang divided the EVC process into three regions and established the cutting force models respectively [1]. Based on the analysis of oblique EVC, J.Q Lin developed an analytical force model of oblique EVC [2, 3]. W.L. Zhu studied the effects of cutting speed and cutting depth on cutting force by a series of EVC experiments [4]. The present research methods of predicting cutting force can be generally divided into two categories: 1) the cutting force modeling method. 2) the EVC experiment method. Different from the previous methods, this paper takes chip thickness as an indicator to predict cutting force. By establishing the chip thickness model, the parameters that affected the chip thickness were found. The effects of the parameters on cutting force were verified by numerical analysis.

2. Analysis of EVC
2.1. Principle of EVC Process
In EVC process, the tool is excited by two excitation sources with a certain phase difference, and the tool motion is coupled to form elliptical trajectory in space. The tool tip intermittently contacts the workpiece, as shown in Fig.1.
Fig. 1 shows two consecutive cutting cycles. Time $t_1$ to $t_2$ indicates the former cutting cycle which constitutes the chip upper boundary, time $t_3$ to $t_4$ indicates the present cutting cycle which constitutes the chip bottom boundary. Considering the relative position and velocity relationship between the tool and the workpiece, the tool path can be expressed as:

$$\begin{cases} x = a \cos(2\pi ft) + vt \\ z = c - [\text{NDOC} - c \sin(2\pi ft)] \end{cases}$$

(1)

Where $a$ is transverse amplitude, $c$ is vertical amplitude, NDOC is nominal depth of cut, $f$ is vibration frequency and $v$ is cutting speed.

2.2. Modeling of Chip Thickness

Consider two consecutive cycles and take the present cycle elliptical trajectory center as origin. Then the present cycle elliptical trajectory can be expressed as:

$$\frac{x^2}{a^2} + \frac{z^2}{c^2} = 1$$

(2)

Since the two cycles are continuous, the distance between the former cycle and the present cycle equals to the displacement of the tool relative to the workpiece in one cycle, so the former cycle elliptical trajectory can be obtained:

$$\frac{(x + \text{ufpc})^2}{a^2} + \frac{z^2}{c^2} = 1$$

(3)

Where $\text{ufpc} = v / f$. By solving Eq. (2) and Eq. (3) in $z$-component, the transient chip thickness can be obtained:

$$\text{chip}_z = \begin{cases} z_p & a - \text{ufpc} \leq x \leq a \\ z_p - z_f & -\text{ufpc} / 2 \leq x \leq a - \text{ufpc} \\ 0 & \text{otherwise} \end{cases}$$

(4)

Supposing depth ratio ($DR$) is the ratio of NDOC to $c$, the expression of transient chip thickness changes with $DR$ and Eq. (4) indicates $DR$ equals to 1. Using the same method, the remaining two cases of transient chip thickness can also be obtained.
Since the EVC chip thickness varies with the tool position, there should be a maximum value and the maximum value occurs at $p2$ when the tool is in the present cycle, then the maximum chip thickness can be expressed as:

$$
chip_{max} = \left\{
\begin{array}{ll}
\sqrt{c}\left(1 - \frac{(a - ufpc)^2}{a^2}\right) & \text{DR} = 1 \\
\sqrt{c}\left(1 - \frac{c^2 - DF^2}{a^2} - ufpc)^2}{a^2}\right) & \text{DF} \quad \text{DR} > 1 \\
\sqrt{c}\left(1 + DF\right) & \text{DF} \quad \text{DR} < 1
\end{array}\right.
$$

Where $DF = abs(c - NDOC)$.

3. Simulation and Discussion
The cutting force model in [5] shows that in EVC process, only the chip thickness can be obtained and other parameters have already been decided. So the cutting force can be predicted with the chip thickness. Numerical analysis is carried out by using ABAQUS finite element software. AL6061 is chosen to be the material of workpiece and the properties of AL6061 shows in Table 1.

| Property                  | Value          |
|---------------------------|----------------|
| Density (Kg/m$^3$)        | 2686           |
| Poisson ration            | 0.33           |
| Elastic modulus (GPa)     | 72.4           |
| Thermal Conductivity (W/m·k) | 166.9       |
| Thermal expansion         | 2.4e-5         |

The paper supposed DR equals to 1 and three sets of simulations were performed.

Figure 2. The influence of transverse amplitude on the maximum chip thickness and cutting force. ($c = 4 \mu m$, $f = 25$ KHz, $v = 50$ mm/s, $NDOC = 2, 4, 6 \mu m$)

As shown in Fig.2 (a), in three cases, the maximum chip thickness decreases with the increment of amplitude $a$. Increasing the amplitude $a$ will stretch the ellipse in $x$ direction, then elliptical curvature decreases in $z$ direction and the distance of the adjacent trajectory decreases in $z$ direction, the maximum chip thickness decreases, cutting force decreases, as shown in Fig.2 (b).
Figure 3. The influence of vertical amplitude on the maximum chip thickness and cutting force. 
\(a=4\mu m, f=25\text{Khz}, v=50\text{mm/s}, NDOC=2, 4, 6\mu m\)

As shown in Fig.3 (a), when \(DR=1\), amplitude \(c\) directly affects the depth of cut, cutting force increases with the increment of amplitude \(c\), as shown in Fig.3 (b). When \(DR>1\), with the increment of amplitude \(c\), the increased elliptical curvature in \(z\) direction contributes to increasing the maximum chip thickness, however, the horizontal axis of the ellipse trajectory will move to the workpiece surface in the meantime, which contributes to decreasing the maximum chip thickness and its extent is greater, so that the maximum chip thickness actually decreases and cutting force decreases. When \(DR<1\), the elliptical curvature increases with the increment of amplitude \(c\) and since the elliptical trajectory horizontal axis is above the workpiece surface, the maximum chip thickness increases, cutting force increases.

Figure 4. The influence of vertical amplitude on the maximum chip thickness and cutting force
\((a=4\mu m, c=4\mu m, NDOC=2, 4, 6\mu m)\)

According to the definition of \(ufpc\), cutting speed \(v\) is proportional to \(ufpc\) and vibration frequency \(f\) is inversely proportional to \(ufpc\). In three cases, the maximum chip thickness increases with the increment of \(ufpc\), as shown in Fig.4 (a). The increased \(ufpc\) enlarges the distance of adjacent ellipse in \(x\) direction and \(z\) direction. The maximum chip thickness increases and the cutting force increases as shown in Fig.4 (b).
4. Conclusion
In this study, the EVC chip model has been developed and numerical analysis has been conducted to verify the theoretical derivation. The following conclusions can be drawn from the study: 1) The chip thickness can be used to predict the behavior of cutting force. 2) The effects of cutting parameters on cutting force vary with the depth ratios.

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