Ultrasonics 87 (2018) 166–181

Contents lists available at ScienceDirect

Ultrasonics

journal homepage: www.elsevier.com/locate/ultras

Study on the separation effect of high-speed ultrasonic vibration cutting

Xiangyu Zhang, He Sui, Deyuan Zhang *, Xinggang Jiang

School of Mechanical Engineering and Automation, Beihang University, Beijing 100191, China

ARTICLE INFO

Article history:
Received 13 April 2017
Received in revised form 16 January 2018
Accepted 20 February 2018

Keywords:
Separation effect
Ultrasonic vibration cutting
Clearance angle
Cutting force
Cutting chip

ABSTRACT

High-speed ultrasonic vibration cutting (HUVC) has been proven to be significantly effective when turning Ti-6Al-4V alloy in recent researches. Despite of breaking through the cutting speed restriction of the ultrasonic vibration cutting (UVC) method, HUVC can also achieve the reduction of cutting force and the improvements in surface quality and cutting efficiency in the high-speed machining field. These benefits all result from the separation effect that occurs during the HUVC process. Despite the fact that the influences of vibration and cutting parameters have been discussed in previous researches, the separation analysis of HUVC should be conducted in detail in real cutting situations, and the tool geometry parameters should also be considered. In this paper, three situations are investigated in details: (1) cutting without negative transient clearance angle and without tool wear, (2) cutting with negative transient clearance angle and without tool wear, and (3) cutting with tool wear. And then, complete separation state, partial separation state and continuous cutting state are deduced according to real cutting processes. All the analysis about the above situations demonstrate that the tool-workpiece separation will take place only if appropriate cutting parameters, vibration parameters, and tool geometry parameters are set up. The best separation effect was obtained with a low feedrate and a phase shift approaching 180 degrees. Moreover, flank face interference resulted from the negative transient clearance angle and tool wear contributes to an improved separation effect that makes the workpiece and tool separate even at zero phase shift. Finally, axial and radial transient cutting force are firstly obtained to verify the separation effect of HUVC, and the cutting chips are collected to weigh the influence of flank face interference.

1. Introduction

As a non-traditional machining method, ultrasonic vibration cutting (UVC) has been widely applied in the machining of difficult-to-machine alloys [1–3], brittle materials [4–6], composite materials [7–10] and even the animal tissues [11]. Compared to conventional cutting (CC), the tool-workpiece separation effect during the cutting process due to the additional tool/workpiece vibration is regarded to be the primary reason for its huge advantages, such as cutting force reduction [12,13], cutting temperature reduction [14,15], tool life enhancement [16] and surface quality improvement [17,18]. However, there exists a critical cutting speed in UVC that restricts the application of UVC at extremely low cutting speeds (<60 m/min) [19]. In this regard, the machining efficiency of UVC is relatively low and needs to be improved for further development.

Recently, high-speed ultrasonic vibration cutting (HUVC) was proposed [20,21]. Compared to UVC and CC, it can break through the critical cutting speed and increase cutting efficiency to a maximum value of 90% (weighted by equivalent material removal rate) in the machining of Ti-6Al-4V alloys. In HUVC, the cutting tool vibrates at an ultrasonic frequency (about 20 kHz) along the feed direction. Despite the cutting efficiency increase, the use of HUVC can result in average cutting force reduction, tool life enhancement [20] and surface quality improvement [20,21]. These benefits are ascribed to the tool-workpiece separation effect. Therefore, it is of great importance to deeply understand the separation effect based on the kinematics principal of HUVC.

As for UVC, the kinematics principal is mainly studied through cutting state analysis (i.e., continuous cutting and intermittent cutting) [19,22]. The studies are mainly about the cutting duration and noncutting duration modeling [23–25] which are based on the tool path model, particularly on the model of the tool path relative to the workpiece [26]. However, this type of kinematic analysis is focused on UVC, which has a vibration direction parallel to the cutting direction. As for HUVC, the kinematics principal is quite different from that of UVC due to the different tool vibration direction. Moreover, the research about UVC kinematics analysis are mostly based on an ideal cutting process, which means a sharp

* Corresponding author.
E-mail address: zhangdy@buaa.edu.cn (D. Zhang).

https://doi.org/10.1016/j.ultras.2018.02.016
0041-624X/

cutting edge with a large enough clearance angle and no tool wear. In this regard, the traditional analysis method does not provide results that are applicable to real cutting states. As demonstrated by Sui [20], the kinematics analysis of HUVC is also based on ideal models that ignore the influence of real tool geometry and cutting states. In the analysis, the working cutting edge is merely the tooltip, which is not the case during an entire cutting process. Therefore, a comprehensive separation model based on the kinematics analysis of HUVC should be given for the guidance of the cutting process.

In this paper, a comprehensive separation model based on the kinematics analysis of HUVC is proposed. The tool path and finishing surface profile caused by the feed-directional tool vibration are firstly described. Then the separation effect is analyzed in detail in consideration of the influence of tool geometry. Three real cutting situations are analyzed: (1) cutting without negative transient clearance angle and without tool wear, (2) cutting with negative transient clearance angle and without tool wear, and (3) cutting with tool wear. Despite traditional continuous cutting and complete separation states, a partial separation state is introduced due to the flank face interference caused by the negative transient clearance angle and tool wear. All these cutting states and the influence of flank face interference on the separation effect are discussed afterwards. Finally, experiments are carried out to verify the availability of the proposed model. Transient axial and radial thrust cutting force signals are obtained to verify the existence of the separation process during HUVC through the duty cycle values while various cutting chip types are collected to prove the influence of flank interference on the chip formation process.

2. Kinematic analysis of HUVC

2.1. Modeling of the cutting tool and workpiece

The HUVC process is schematically illustrated in Fig. 1. In this figure, a cylindrical-coordinate system is defined for the rotatory workpiece. r, θ, and z denote the radial, rotatory, and feed displacement, respectively. As demonstrated by Sui [20], HUVC is a precision machining method that has a small depth of cut of about 0.01–0.1 mm. Thus, the tool nose round should be considered, and the cutting edge can no longer be regarded as a sharp straight line. As clearly shown in this figure, a_p, n, and f are the three cutting parameters (depth of cut, spindle speed and federate, respectively) and d is the diameter of the workpiece finishing surface. The working cutting edge is from the tooltip (P_1) to point P_2. P is an any point on the working cutting edge, and its cylindrical-coordinate position is given as $P(r, \theta, z)$.

The cutting tool schematic of geometry is illustrated in Fig. 1(b) in detail. A rectangular Cartesian coordinate system is defined relative to the tool, and X', Y', and Z' denote the vertical direction oriented to the tool insert, the horizontal direction oriented to the tool insert, and the feed direction, respectively. As clearly shown in this figure, r_ε is the tool nose radius, ε_P is an auxiliary angle with which to determine the position of point P, y'_P is the displacement along the Y' axis from the tooltip (P_1) to point P, and it is another variable with which to determine the position of point P with another coordinate, z'_P. The relation is given in the following form:

$$\begin{cases} y'_P = r_\varepsilon - r_\varepsilon \cos\varepsilon_P \\ z'_P = r_\varepsilon \sin\varepsilon_P \end{cases} \quad 0 \leqslant \varepsilon_P \leqslant \arccos\frac{r_\varepsilon - a_p}{r_\varepsilon} \tag{1}$$

2.2. Tool path and finishing surface profile

The tooltip path is illustrated in Fig. 2 in detail. A helix path is formed on the workpiece surface when the feed motion and tool vibration are combined. As clearly shown in Fig. 2(a) and (c), overlaps of the tooltip path periodically occur. To easily describe the motion state of the cutting tool, tool motion is analyzed on the extended outer surface of the cylindrical workpiece. In Fig. 1(b), the tool is sliced into infinitely thin sections in the feed plane due to the feed-directional vibration. The light green[1] plane in Fig. 1(b) is a section of the given point (P) and is determined by the coordinate y'_P or the correspondingly auxiliary angle (ε_P). The motion state of this section is illustrated in Fig. 3. As clearly shown in this figure, r_n is the rounded cutting edge radius ($r_n \ll a_p$, which is negligible in Fig. 1), and $\gamma(\varepsilon_P)$ and $\alpha(\varepsilon_P)$ are the real rake angle and real clearance angle on the $y' = y'_P$ feed plane, respectively. These two angles can be approximately computed using the following formula (see Appendix A):

$$\begin{cases} \gamma(\varepsilon_P) = \operatorname{arccot}\left(\cot\frac{\varepsilon_P}{2}\cot\gamma_n\right) \\ \alpha(\varepsilon_P) = \arctan\left(\cot\frac{\varepsilon_P}{2}\tan\alpha_n\right) \end{cases} \tag{2}$$

where γ_n and α_n are the nominal rake angle and nominal clearance angle, respectively. Due to the existence of the rounded cutting edge, the real position of point P is at the lowest position of the cutting edge, to which the tool coordinate system is affiliated. The flank face profile can be described by the following equation:

$$z' = G(x') \quad 0 \leqslant x' \leqslant s - \Lambda \tag{3}$$

where s is the tool thickness and Λ is the distance along axis X' between point P and the farthest point on the rake face.

As illustrated in Fig. 3, tool motion is regarded as the combined results of the translation motion for the whole flank face profile on the extended workpiece cylindrical plane. The position of point P, both in the workpiece coordinate and tool coordinate, is defined as the zero point. Thus, the tool motion function is calculated the same as the tool vibration function, using the following formula:

$$\begin{cases} z_v = A\sin 2\pi F t \\ x_v = V_c t \end{cases} \quad 0 \leqslant t \leqslant T \tag{4}$$

where x_v is the rectangular coordinate of θ after the outer surface of cylindrical workpiece extended, and the relation between them is calculated as follows: $x_v = (d + y')\theta$. V_c, F, A, and T are cutting speed, vibration frequency, vibration amplitude and vibration period, respectively. After the coordinate transformation, tool coordination and workpiece coordination are uniform. For any given point ($Q(x', z')$) at the flank face profile in Fig. 3, the time parameter is given as t_Q, and then the coordinate transformation from the tool coordinate to the workpiece coordinate is given by the following formula:

$$\begin{bmatrix} x \\ z \end{bmatrix} = \begin{bmatrix} -x' + V_c t_Q \\ z' + z_v(t_Q) \end{bmatrix} \tag{5}$$

Therefore, the motion path in the extended workpiece coordinate system can be given in the following form:

$$\begin{cases} z(\varepsilon_P, x', t) = A\sin[2\pi F t + \phi(x')] + G(x') \\ x(\varepsilon_P, x', t) = V_C t - x' \end{cases} \quad 0 \leqslant x' \leqslant s - \Lambda,\ 0 \leqslant t \leqslant T \tag{6}$$

where $\phi(x')$ is an offset value of the motion path of point Q from zero point, and it can be computed as follows:

$$\phi(x') = \frac{2\pi x'}{V_c T} \tag{7}$$

As shown in Fig. 3, in a vibration cycle, the flank face profile moves along positions, ① → ② → ③ → ④, according to the

[1] For interpretation of color in Figs. 1, 5 and 13, the reader is referred to the web version of this article.