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Study on predictive model of cutting force and geometry parameters for oblique elliptical vibration cutting

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ABSTRACT

Elliptical vibration cutting (EVC), as one of the promising methods for ultra-precision machining, has aroused many scholars' attention. However, few studies focused on the basic mechanism of oblique EVC. In the present study, an analytical force model of oblique EVC has been developed, which only use the material properties, tool geometry and the physical laws of deformation. The transient thickness of cut and transient shear angle are considered in the proposed model. Based on the analysis of oblique EVC mechanism, the geometric parameters of oblique ultrasonic vibration assisted turning (UVAT) are predicted by this model, which are in good agreement with the experimental results available in the literature. The transient cutting force components of orthogonal EVC are also predicted, results of which are in accord with the experimental results. Thus this model is available to predict the geometry parameters and cutting force of the orthogonal EVC accurately. In addition, the proposed model can also be applied to predict geometric parameters and cutting force components of oblique EVC.

1. Introduction

Vibration-assisted machining (VAM) has been applied to difficult applications successfully, such as the diamond turning of brittle materials [1], the creating of microstructures [2,3], the economically producing of precision macro-scale components in hard alloys or composite materials [4,5] which can be used to improve the fabrication process. Elliptical vibration cutting (EVC) worked as a two-dimensional VAM (2D VAM) has been studied widely, as a result, this technique has been proved to be one of the most promising method with superior performance for cutting force reduction, high-quality surface finishing and long tool life [6,7].

Different from conventional turning (CT) [8,9] and one-dimensional vibration turning (1D VT) [10,11], EVC is a complex turning process. In order to better understand the advantages of EVC, it is of great importance and necessity to study the special material removal mechanism and to reveal the variation of cutting parameters like shear angle, rake angle and transient thickness of cut (TOC) etc. during turning.

In previous studies, several researches have already been carried out to assess the cutting force during the machining process, especially in the orthogonal EVC. Cerniway [12] and Negishi [13] applied the Arcona's linear model [14] to develop an elliptical cutting force model, respectively. In addition, Negishi's model was made for groove cutting. However, the two models were only based on chip area, contact length and work-piece properties. The transient shear angle was set as a constant. Ma [15,16] investigated a separating type ultrasonic EVC and proposed a thrust cutting force model, then he clarified the reason of machining accuracy improvement caused by ultrasonic EVC, which was verified by experiment; then a three-dimensional separating type ultrasonic EVC cutting force model which involves feed force and thrust force were proposed. And the reason of burr suppressing was clarified and verified experimentally. Zhang [17] proposed an analytical force model for orthogonal EVC. In this model, the transient TOC, transient shear angle and transition characteristic of friction reversal were investigated. Bai [18] used a non-equidistant shear zone model to predict the shear angle, tool-chip friction angle and shear stress, then an orthogonal EVC force model considering transient TOC and transient shear angle was proposed. Although Zhang and Bai both divided the EVC process into three stages, and assumed three different shear angles according to three stages, actually the shear angle in each stage of EVC is changing all the time. Thus it is inadequate to make such an assumption. Besides, a divergence of opinion appears when it comes to the method to obtain the value of shear angle in reverse kinetic-friction stage. Nosouhi [19] presented a kind of novel analytical model for predicting force in EVC by using LuGre dynamic friction model, but

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Nomenclature

a	semi-major amplitude in x axis direction (μm)
b	semi-minor amplitude in y axis direction (μm)
f	vibration frequency (Hz)
v_c	nominal cutting speed (m/min)
i	inclination angle (deg.)
Doc	nominal depth of cut (mm)
w	width of cut (mm)
t	time (s)
θ	transient velocity angle (deg.)
ϕ_n	normal shear angle (deg.)
ϕ_{nj}	$j=1,2$; 1, oblique cutting-like stage; 2, reverse kinetic-friction stage
ϕ_i	oblique shear angle (deg.)
ϕ_{ij}	$j=1,2$; 1, oblique cutting-like stage; 2, reverse kinetic-friction stage
θ_n	normal angle of resultant cutting force direction (deg.)
θ_{nj}	$j=1,2$; 1, oblique cutting-like stage; 2, reverse kinetic-friction stage
θ_i	oblique angle of resultant cutting force direction (deg.)
θ_{ij}	$j=1,2$; 1, oblique cutting-like stage; 2, reverse kinetic-friction stage
η	chip flow angle (deg.)
η_j	$j=1,2$; 1, oblique cutting-like stage; 2, reverse kinetic-friction stage
γ_n	normal rake angle (deg.)
γ_{wra}	working rake angle (deg.)
$\vec{v_s}$	transient shear velocity (m/min)
$\vec{v_t}$	transient tool velocity relative to the work-piece (m/min)
$\overrightarrow{v_{ct}}$	transient chip velocity relative to the tool (m/min)
α	angle between $\vec{v_t}$ and machined surface (deg.)
η_e	first iterative value of η (deg.)
k	iteration counter
$\vec{R}$	resultant force (N)
$\vec{N}$	force component normal to the tool rake face (N)
$\vec{f}$	friction force between chip and tool rake face (N)
β	friction angle between $\vec{R}$ and $\vec{F_n}$ (deg.)
β_j	$j=1,2$; *1*, oblique cutting-like stage; *2*, reverse kinetic-friction stage
τ_s	shear stress (N/mm^2)
A_s	shear plane area (mm^2)
$\vec{R'}$	projection of resultant force $\vec{R}$ on normal plane P_n (N)
$\vec{F_p}$	principle cutting force along x axis (N)
$\vec{F_t}$	thrust cutting force along y axis (N)
$\vec{F_n}$	normal cutting force along z axis (N)
$\vec{F_s}$	shear force on shear plane (N)
$\overrightarrow{F_{ns}}$	shear force perpendicular to shear plane (N)
TOC_t	transient thickness of cut (μm)
λ	angle between tool rake face and direction perpendicular to material surface (deg.)
t_A	the moment tool edge passes the cutting-start point A (s)
t_B	the moment tool edge passes the bottom point B (s)
t_C	the moment tool edge passes the maximum TOC_t point C (s)
t_D	the moment tool edge passes the friction-reversal point D (s)
t_E	the moment tool edge passes the cutting-end point E (s)
t_P	the moment tool edge passes the transient contact point P in previous cycle (s)
$x'y'z'$	orthogonal machine coordinate system
xyz	machine tool coordinate system
P_n	normal plane to cutting edge
P_v	velocity plane which includes $\vec{v_s}$, $\vec{v_t}$ and $\overrightarrow{v_{ct}}$

the transient TOC and shear angle were still considered as a constant. All studies mentioned above aimed at orthogonal EVC. Shamoto [20] proposed an analytical model of 3D EVC which had an inclination angle. However, the transient TOC and transient shear angle were overlooked. Thus it is necessary to propose an analytical force model which can predict the cutting force and reveal the characteristics of real cutting process accurately for EVC turning, especially for the understanding of EVC mechanism.

As mentioned above, few studies focused on investigating the mechanism and characteristics of cutting force of EVC, especially the oblique EVC. In the present research, a three-dimensional separating type EVC (orthogonal EVC with an inclination angle called Oblique EVC) was investigated and a force model had been proposed to study the cutting mechanics. In order to reveal the characteristics of oblique EVC cutting process, the cutting process was divided into three stages on the basis of its mechanical properties [17,18]. This paper mainly discussed two stages, considering the dominant time of each stage in one EVC cycle. Two important parameters which are time-varying including transient TOC and transient shear angle were taken into consideration. The proposed model only relies on the material properties, tool geometry and the physical laws of deformation. Furthermore, the experimental results from previous study were implemented to verify the analytical model.

2. Principle of oblique EVC

This paper investigated an orthogonal EVC with an inclination angle, which was illustrated in detail in Fig. 1. Fig. 2 shows the oblique EVC cutting process, x axis is perpendicular to the cutting edge; y axis is perpendicular to the machined surface; z axis is aligned with the cutting edge and is perpendicular to the xy plane at the same time; x' axis is aligned with the work-piece feed direction; z' axis is perpendicular to the x' and $x'y'$ plane is parallel to the machined surface. In orthogonal EVC, angle i is equal to zero, Cartesian coordinate system (x, y, z) completely coincides with Cartesian coordinate system (x', y', z'). All factors like force, shear and chip flow vectors lie on the $x'y'$ plane. However, in oblique EVC, directions of shear, friction, chip flow and resultant cutting force can be resolved into the Cartesian coordinate (x, y, z).

In oblique EVC, several important planes were defined, such as shear plane, rake face, machined surface xz, and normal plane P_n or xy plane. Tool trajectory is parallel to the normal plane P_n. When the tool is driven by transducers or piezoelectric stacks at frequency f with semi-major axis amplitude of a in the x axis direction and semi-minor axis amplitude of b in the y axis direction, the trajectory of tool tip is an ellipse. In addition, work-piece is fed with a nominal cutting speed v_c along the x' axis, so the tool motion locus relative to work-piece can be expressed in Cartesian coordinate (x, y, z) as follows:

$$\begin{cases} x(t) = a\ \cos(2\pi ft) - v_c t\ \cos\ i \\ y(t) = -b\ \sin(2\pi ft) \end{cases} \tag{1}$$

The tool velocity relative to work-piece can be obtained by the time-derivative of the tool position: