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Kinematics and tool-workpiece separation analysis of vibration assisted milling

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Abstract: High-accuracy precision or micro components made of hard and brittle materials are increasingly in demand in many applications owing to the superior physical, mechanical, optical, or electronic properties offered by these materials. Mechanical machining, primarily milling, is the main shaping method used to achieve tight tolerances and high quality surface finishes on those hard materials, but excessive tool wear and poor surface integrity is a pressing challenge. Vibration assisted machining can significantly reduce cutting forces, enhance surface integrity and extend tool life, but the application of vibration assistance to milling has received little attention due to the complexity of kinematics and dynamics of this process. This paper investigates the kinematics of vibration assisted milling. Generic kinematic equations of VAMILL are firstly formulated, and then three types of tool-workpiece separation mechanism is proposed and the requirements to realize each type of separation are discussed through kinematic analysis and simulation. Finally, an ABAQUS finite element model of vibration assisted milling is used to verify the proposed kinematic models and tool-workpiece separation types.

Keywords: vibration assisted machining; vibration assisted milling; kinematics modelling; tool-workpiece separation; cutting simulation; finite element modelling

1. Introduction

High-accuracy precision or micro components are increasingly in demand for various industries, such as biomedical engineering, MEMS, electro-optics, aerospace and communications [1-5]. Previously, non-conventional machining methods such as electrical discharge machining (EDM), electrochemical machining (ECM), laser machining, ion beam machining, and electro-beam machining, are adopted to machine hard and brittle materials. However, these machining methods have significant drawbacks on used on such materials, including low processing efficiency, high cost, and high environmental requirements. The alternative of precision mechanical machining, primarily milling at both conventional and micro scale, is believed to be the most versatile machining process, capable of generating a wide variety of complex components and structures from micro to macro scale due to its high precision and surface finish, and simple set-up [6].

In addition to tight tolerances and high quality surface finishes, many applications require the superior physical, mechanical, optical, or electronic properties of hard and brittle materials such as optical glass and technical ceramics. For example, brain implants for neurosurgery are made of semiconductor materials (silicon, gallium nitride, silicon carbide), some bio-sensors are made of piezoelectric materials (PZT, aluminum nitride, lithium niobate), some microfluidic devices are made of quartz glass and silicon, etc. Thus there is an imperious demand to manufacture precision products from such materials, but, these hard and brittle materials are difficult to machine because of their high hardness and usually low fracture toughness.

Continuous efforts to enhance machining performance have shown that applying high frequency vibration to the tool or workpiece can improve machining quality. This is known as vibration assisted machining (VAM). VAM is an external energy assisted machining method in which high frequency and small amplitude vibration is superimposed on the motion of the tool or workpiece to improve the material removal process. With appropriate machining and vibration conditions, the tool periodically loses contact with the chip, which changes the cutting mechanics and can improve

machining performance. VAM has been applied to several machining processes for use on hard materials, including turning [7-15], drilling [16-19], milling [20-24], and grinding [25, 26]. A unique feature of VAM is tool-workpiece separation (TWS), which brings many benefits including reductions in machining forces [18, 21], suppression of burr formation [8, 19], improved surface finish and form accuracy [9-13], and reduction of tool wear leading to extension of tool life [14, 15, 27-29].

In the turning process the calculation of tool-workpiece separation is relatively straightforward, and it is easy to impose vibration on the stationary cutting tool. Both 1D and 2D vibration assisted systems for turning process (linear vibration in the cutting direction and elliptical vibration motion in the plane of cutting and depth of cut directions, respectively) have been applied with success.

However, in the milling process the cutting velocity and uncut chip thickness are continuously changing, which makes the TWS mechanisms in vibration assisted milling (VAMILL) more complex than vibration assisted turning, and so complicates the application of VAM to milling process. Some research has been carried out on VAMILL recently. Shen et al. [22] investigated the effects of assisted ultrasonic vibration on the surface roughness of machined surfaces in micro-end-milling. Ding et al. [23] used two-dimensional vibration-assisted micro-end-milling to improve the machinability of hardened tool steel (HRC 55 and HRC 58) in order to improve its machinability. Zarchi et al. [24] investigated the effect of cutting speed and workpiece vibration amplitude on cutting forces. These experimental research has demonstrated the feasibility and benefits of VAMILL in improving machinability of hard materials, but, the kinematics, TWS and cutting mechanism of VAMILL are still not well understood. This paper attempts to fill this gap with a systematical investigation on the kinematics of VAMILL and discussion of typical TWS mechanisms. This will offer guidance on determination of optimal machining and vibration parameter sets, and also vibration assisted machining system design generally.

2. Kinematics of vibration-assisted milling

In VAMILL, high frequency and small amplitude vibration can be superimposed to the

motion of either the tool or the workpiece. According to the dimension of the vibration applied, vibration-assisted milling can be divided into two groups: 1D and 2D vibration assistance. In 1D VAMILL, vibration is applied either in the feed direction, i.e. feed-directional vibration-assisted milling (FVAMILL), or in the cross-feed direction, i.e. cross-feed-directional vibration-assisted milling (CFVAMILL). In 2D VAMILL, vibration is applied simultaneously in both the feed and the cross-feed directions (2DVAMILL).

Fig. 1 Schematic diagram of vibration-assisted milling

Fig. 1 shows a schematic diagram of vibration-assisted milling. The coordinate system used in this paper is defined as follows: the workpiece feed is in x direction; the cross-feed direction is in y direction, and axial depth of cut is in z direction.

The mathematical equation of the tool tip motion, (x, y) , without vibration imposed is as follows:

$$\begin{cases} x = r \sin \left[\omega t - \frac{2\pi(z_i - 1)}{Z} \right] \\ y = r \cos \left[\omega t - \frac{2\pi(z_i - 1)}{Z} \right] \end{cases} \quad (1)$$

where, r and ω are the radius and angular velocity of the cutter, z_i is the i^{th} cutter tooth, and Z is number of flutes.

If simple harmonic vibration is applied to workpiece, the vibration trajectory is:

$$\begin{cases} x_w = ft + A \sin(2\pi f_x t + \phi_x) \\ y_w = B \sin(2\pi f_y t + \phi_y) \end{cases} \quad (2)$$

where f is feed velocity, A and B are the vibration amplitudes, f_x and f_y are the vibration frequencies, ϕ_x and ϕ_y are the phase angles, in x - and y -directions, respectively. Then the relative displacement (x_i, y_i) between tool tip and workpiece become:

$$\begin{cases} x_i = ft + r \sin\left[\omega t - \frac{2\pi(z_i - 1)}{Z}\right] + A \sin(f_x t + \phi_x) \\ y_i = r \cos\left[\omega t - \frac{2\pi(z_i - 1)}{Z}\right] + B \sin(f_y t + \phi_y) \end{cases} \quad \begin{pmatrix} CFVAMILL: & A = 0, B \neq 0 \\ FVAMILL: & A \neq 0, B = 0 \\ 2DVAMILL: & A \neq 0, B \neq 0 \end{pmatrix} \quad (3)$$

TWS discussed in vibration-assisted machining is the rapid periodic interruption of constant tool workpiece contact. An appropriate pattern of TWS is the key to the success of VAMILL. Three different TWS mechanisms and their requirements are identified and described below.

3. Types of TWS in vibration-assisted milling

3.1 Type I TWS

Fig. 2 illustrates Type I TWS in vibration-assisted milling. Type I separation occurs in the current tool path when the component of the relative velocity between tool and workpiece in the cutting direction (i.e. tangential component) becomes opposite to the tool rotation direction. This causes the tool tip lag behind the workpiece so that separation occurs.

Fig. 2 Type I TWS during VAMILL process.

In position 1 of Fig. 2, the cutting direction component of the relative velocity between tool and workpiece is greater than zero, and the tool is in contact with the workpiece. When the tool has advanced to position 2 the cutting direction component of the relative velocity is equal to zero. At this point the tool is about to break contact with workpiece. In position 3 the cutting direction component of the relative velocity has become negative, i.e. in the direction opposite to the tool rotation, and the tool separates from the workpiece. It can be seen that during the period of time when the tool and workpiece lose contact, the cutting direction component of the relative velocity changes from zero to negative then to positive. In position 4 the tool regains contact with the workpiece. This type of TWS is similar to vibration-assisted turning.

Fig. 3 illustrates Type II TWS in vibration-assisted milling. Type II separation occurs in the current tool path when vibration displacement in the instantaneous uncut chip thickness (UCT) direction (i.e. tool radial direction) is larger than the instantaneous uncut chip thickness. This brings the tool instantaneously out of the workpiece and so tool-workpiece separation takes place.

Fig. 3 Type II TWS during VAMILL process.

direction is same as the instantaneous uncut chip thickness. At this point the actual instantaneous UCT is zero, and it is about to break contact with workpiece. In position 3 the vibration displacement exceeds the instantaneous uncut chip thickness, and the tool remains separated from the workpiece. Until the vibration displacement is equal to the instantaneous uncut chip thickness in position 4 the tool regains contact with the workpiece.

3.3 Type III TWS

In Types I and II separation, the effect of the uneven cutting path in the previous cut is ignored, but this can be significant when the depth of cut is comparable with the vibration amplitude. Fig. 4 illustrates this effect and Type III TWS in VAMILL. It can be seen that the current tool path with vibration assistance overlaps in some regions with the surface contour left by previous cutting path(s), hence in these overlapping regions the cutting tool edge may break contact with the workpiece and discontinuous chips are generated. As part of the material in the current cutting path has been removed by previous cutting path(s) periodic separation of tool-workpiece separation takes place.

Fig.4 Type III TWS during VAMILL process.

It should be noted that in most cases during VAMILL, Type I, II and III separation could happen simultaneously. There are circumstances where it is kinematically possible to obtain only a certain type of separation, as will be discussed in the following section.

4. Requirements of TWS

In this section, the requirements for three types of separation to occur will be discussed. In high speed milling, the feeding speed is much smaller than the tool rotation and high frequency vibration speed, so it is assumed that workpiece feedrate effect is negligible. This section focusses on the separation requirements for 1D VAMILL.

4.1 Type I separation requirements

In section 3.1 the occurrence of Type I separation is shown to be due to the relative velocity between the tool tip and the workpiece in the cutting direction. Differentiating Eq. (1), the relative velocity of the tool tip without vibration assistance, i.e. the nominal cutting velocity, V_t , becomes:

$$V_t = \omega r \quad (4)$$

Similarly, on the instantaneous cutting direction, the velocity components in x and y directions of the workpiece material are obtained through differentiating Eq. (2) as:

$$\begin{cases} V_x(t) = f + 2\pi A f_x \cos(2\pi f_x t + \phi_x) \\ V_y(t) = 2\pi B f_y \cos(2\pi f_y t + \phi_y) \end{cases} \quad (5)$$

4.1.1. Vibration in cross-feed direction (CFVA milling)

For this case $A = 0$ and the tool centre orbit turns into a harmonic linear locus along the cross-feed direction. To meet the requirements of the type I separation:

$$2\pi B f_y \cos(2\pi f_y t + \phi_y) \sin \theta \geq \omega r \quad (6)$$

Where θ is the tool rotation angle at time t . Rearrange Eq.(6):

$$\cos(2\pi f_y t + \phi_y) \sin \theta \geq \frac{\omega r}{2\pi B f_y} \quad (7)$$

Obviously Eq. (7) is solvable when

$$\frac{\omega r}{2\pi B f_y} < 1 \quad (8)$$

As shown in the simulation example in Fig.5, within a full circle of tool rotation, the region where Type I separations is likely to occur is

$$\theta_1 < \theta < \pi - \theta_1 \quad (9)$$

Where $\theta = \theta_1$ is the solution of Eq. (6-8)

In the angle range $[\theta_1, \pi - \theta_1]$, which is symmetric to the x axis, TWS takes place as shown in kinematic simulation results of Fig. 5 a). In Fig.5 b), the instantaneous cutting speed during a whole circle of tool rotation is given numerically by simulation.

Fig. 5 a) the region where Type 1 separation is likely to occur during one cycle of tool path and b) the relative velocity in cutting direction

From Eq.(7), it can be found that the range of the separation zones increases with the increase of the maximum vibration velocity, $2\pi Bf_y$, and the decrease of the nominal cutting velocity, ωr . When $\omega r > 2\pi Bf_y$, Eq.(7) becomes unsolvable and no Type I separation would occur in the whole cycle.

4.1.2 Vibration in feed direction (FVA milling)

For this case $B = 0$ and the tool centre performs a 1D sinusoidal vibration along the feed direction. Similarly to the previous case, the requirement for Type I separation to occur is

$$2\pi A f_x \cos(2\pi f_x t + \phi_x) \cos \theta \geq \omega r \quad (10)$$

Rearrange Eq.(10)

$$\cos(2\pi f_x t + \phi_x) \cos \theta \geq \frac{\omega r}{2\pi A f_x} \quad (11)$$

Eq.(11) is solvable when

$$\frac{\omega r}{2\pi A f_x} > 1 \quad (12)$$

Fig.6 shows a simulation of one full tool rotation cycle, Type I separations are likely to occur in the regions:

$$\theta < \theta_2 \text{ and } \theta > \pi - \theta_2 \quad (13)$$

which are symmetric to the x axis, TWS takes place as shown in kinematic simulation results of Fig. 6 a). In Fig.6 b), the instantaneous cutting speed during a whole circle of tool rotation is given numerically by simulation.

As before, Eq (11) shows that the range of the separation increases with the increase of the maximum vibration velocity, $2\pi Af_x$, and the decrease of the nominal cutting velocity, ωr . When the maximum vibration velocity is lower than the nominal cutting velocity, Eq. (11) becomes $\cos(2\pi f_x t + \phi_x) \cos \theta > 1$ which is unsolvable and no Type I separation would occur in the whole cycle.

Fig. 6 a) the region where Type I separation is likely to occur during one cycle of tool path and b) relative velocity in cutting direction

4.2 Type II separation requirements

Fig.7 Type II separation. a,b) schematic diagram and instantaneous uncut chip thickness in CFVAMILL; c,d) schematic diagram and instantaneous uncut chip thickness in FVAMILL

Type II separation depends on the relative displacement between the nominal uncut chip thickness and the vibration displacement. In conventional milling process, the instantaneous uncut chip thickness, h_D , can be expressed by

$$h_D = f_z \sin \theta \quad (14)$$

Where f_z is feed per tooth.

4.2.1 Vibration in cross-feed direction (CFVA Milling)

Considering the vibration in cross-feed direction as shown in Fig.7a), the instantaneous uncut chip thickness, h_{DV} , can be expressed by

$$h_{DV} = f_z \sin \theta - y_w \cos \theta \quad (15)$$

When $\tan \theta < \frac{y_w}{f_z}$, the uncut chip thickness becomes less than zero, thus Type II separation could occur as shown in the kinematic simulation results of Fig.7b). The separation region increases with the increase of y_w , but in this case the periodic separation cannot be achieved over the full cutting path, as shown in Fig.7b).

4.2.2 Vibration in feed direction (FVA Milling)

Considering vibration in the feed direction as shown in Fig.7c), the instantaneous uncut chip thickness can be expressed by

$$h_{DV} = f_z \sin \theta - x_w \sin \theta = (f_z - x_w) \sin \theta \quad (16)$$

when $f_z - x_w < 0$, the uncut chip thickness can be less than zero Type II separation will occur as shown in the kinematic simulation results of Fig.7d).

It can be seen that to achieve periodic Type II separation the vibration should be applied in the feed direction, and the vibration amplitude should be larger than the feed per tooth, but large vibration amplitude will increase tool wear and deteriorate the quality of the machined surface. Therefore, using periodic type II separation is not an ideal choice.

4.3 Type III separation requirements

Type III separation depends on the surface contour generated by previous tool paths, for which a mathematical expression is difficult to obtain. Rather than seeking a close-form analytical solution, this paper used numerical simulation method to obtain the requirements for Type III separation. The simulation was conducted using specific parameter sets in micro milling, but the findings can be generalized.

4.3.1 Vibration in cross-feed direction

The simulation in this section uses a 0.1mm diameter 2-flute end mills rotating at a speed of 5,000rpm. Feed per tooth and vibration amplitude are set as 6μm and 4μm respectively. Two typical vibration frequencies, odd and even multiples of the rotation speed respectively, are applied in the cross-feed direction to investigate their influence on the separation requirement. In the following sections, the vibration frequency

adopted in the simulation are 71 and 72 times of the spindle frequency respectively.

Fig. 8 shows the tool tip trajectory and uncut chip thickness when the applied vibration frequencies are odd and even multiple of the spindle rotation frequency, respectively. It can be seen in Fig. 8 (a) and (c) that the vibration in cross-feed direction changes the trajectory of the tool tip, which makes the uncut chip thickness fluctuate constantly, but does not cause the periodic TWS over the whole tool path. Although the vibration can increase the displacement of the tool tip in the cross-feed direction, the tool and the workpiece can be separated in the cutting in and cutting out regions as circled in Fig. 8(b) and (d). As the tool tip moves in the feed direction, the component of the vibration displacement in uncut chip thickness becomes less obvious, the separation time period of the tool and the workpiece decreases until TWS disappears altogether.

Fig.8 Type III separation in cross-feed direction. a,b) The trajectory of the tool tip and instantaneous uncut chip thickness when the vibration frequency is odd times of the spindle speed ; c,d) The trajectory of the tool tip and instantaneous uncut chip

thickness when the vibration frequency is even times of the spindle speed

In summary, the vibration applied in the cross-feed direction affects the trajectory of the cutting tool. When the applied vibration frequency is odd multiple of the spindle rotation frequency, the vibration increases the maximum cutting thickness significantly as shown in Fig. 8 (b), and this worsens the machined surface roughness. When the applied vibration frequency is even multiple of the spindle rotation frequency, the vibration does not change the maximum cutting thickness, and the average cutting forces are expected to be reduced. But regardless of the relationship between the applied vibration frequency and the spindle rotation frequency, larger vibration amplitude is needed to achieve TWS, so the separation time period varies and regularity is poor. As a result, it will cause larger self-excited vibration between the tool and workpiece, which might worsen the machined surface quality, reduce machining accuracy and tool life. Therefore, the vibration applied in cross-feed direction could reduce the average cutting force when using the appropriate vibration parameters, but it cannot achieve periodic separation and hence it is not suitable to use alone.

4.3.2 Vibration in feed direction

Fig.9 Type III separation in feed direction. a,b) The trajectory of the tool tip and instantaneous uncut chip thickness when the vibration frequency is odd times of the spindle speed ; c,d) The trajectory of the tool tip and instantaneous uncut chip thickness when the vibration frequency is even times of the spindle speed

Fig.9 shows the tool tip trajectory and uncut chip thickness when the applied vibration frequencies are odd and even times of the spindle rotation frequency, respectively. It can be seen from Fig. 9 (a) and (d) that the vibration in feed direction changes the trajectory of the tool tip, which makes the uncut chip thickness fluctuate constantly.

When the applied vibration frequency is odd multiple of the spindle rotation frequency, the peaks (troughs) of waves of the i^{th} tool tip trajectory overlap with the troughs (peaks) of waves of the $(i+1)^{\text{th}}$ tool tip trajectory as shown in Fig.9 (a). Thus if the vibration amplitude is larger than half of the feed per tooth, the tool tip and the workpiece are continuously periodically separated in the whole cutting process as shown in Fig.9 (b).

However, when the applied vibration frequency is even multiple of the spindle rotation

frequency, the peaks (troughs) of waves in the i^{th} tool tip trajectory overlap with the peaks (troughs) of wave in the $(i+1)^{\text{th}}$ tool tip trajectory as shown in Fig. 9 (c). These overlaps make the uncut chip thickness fluctuate constantly, but no Type III separation occurs during the whole cutting process as shown in Fig. 9 (d).

In summary, the vibration applied in feed direction affects the trajectory of the cutting tool. When the applied vibration frequency is even multiple of the spindle rotation frequency, and the vibration amplitude is greater than half of the feed per tooth, periodic Type III separation can be realized, which will improve machined surface roughness. When the applied vibration frequency is odd multiple of the spindle rotation frequency, the vibration will increase the maximum uncut chip thickness, which worsens the machining quality.

Thus, the vibration applied in feed direction can realize periodic Type III separation when using the appropriate vibration parameters and is preferable to that in cross-feed direction.

5. Finite element simulation of vibration-assisted milling

Due to the high frequency and small amplitude of the vibration applied in VAMILL, the separation time always less than 10^{-5} s, it's difficult to observe TWS experimentally. Finite element modelling of the cutting process has been developed as a mature technique, and both geometric parameters and physical/mechanical properties of the cutting tool and workpiece can be considered in FE cutting simulation. This has been shown to be an effective method to investigate the cutting process, particularly the hard to observe cutting phenomena of the chips formation [30-31], minimum chip thickness [32], temperature in the cutting zone [33], etc.

For the current work, a FE model was established using the commercial package ABAQUS/Explicit as shown in Fig.10, to verify the proposed kinematic model and three types of TWS. AISI 1045 steel is chosen as the workpiece material due to its popularity in plastic injection moulding industry. The cutter is set up as a rigid body in order to increase the simulation speed and exclude the effect of tool deformation on the cutting process. The cutting edge radius and minor cutting edge angle of the tool are

3 μm and 5° respectively. The nonlinear temperature and strain rate sensitive Johnson-Cook (JC) material model and Johnson-Cook damage model are used to describe the workpiece material behaviour.

Fig. 10. FE model of VAMILL

The primary equation of the JC model describes the flow stress as:

$$\sigma_y = [A + B(\varepsilon_p)^n][1 + C \ln(\dot{\varepsilon}_p^*)][1 - (T^*)^m] \quad (17)$$

where

$$\dot{\varepsilon}_p^* = \frac{\dot{\varepsilon}_p}{\dot{\varepsilon}_{p0}}, \quad T^* = \frac{T - T_0}{T_m - T_0}$$

Here, ε_p is the effective plastic strain, $\dot{\varepsilon}_p$ and $\dot{\varepsilon}_{p0}$ are the plastic strain rate and effective plastic strain rate used for calibration of the model respectively, T and T_0 are the current and reference temperatures respectively. The parameters A , B , n , C , m , T_m along with other parameters are extracted from Ref. [34].

FE simulations are carried out with three sets of machining parameters as shown in Table.1. The parameters used in the simulation No. 1-3 are selected by the proposed TWS requirements of each type to verify the correctness and reliability of the results

and conclusions obtained from the proposed kinematic models. As discussed above, vibration applied in feed direction is preferable to realize the type II and type III TWS, thus in the FE simulation No.2 and No.3, the vibration is applied in the feed direction, and for the FE simulation No.1, the vibration is applied in the cross-feed direction. Fig. 11-13 provide the chip formation process at various stages for simulation No. 1-3.

Table 1 Machining parameters used in the FE simulations

FE simulation No.	Spindle speed (rpm)	Feed per tooth (μm)	Vibration amplitude (μm)	Vibration frequency ($\times$ spindle frequency)
1	5,000	6 μm	4	71
2	5,000	6 μm	6	71
3	5,000	6 μm	4	27

Fig.11 shows a cutting progressing from a) to d) using the conditions No 1 in Table 1. At a) the vibration speed of the workpiece (v_{wf}) in the cutting direction is less than the linear speed of the tool tip due to tool rotation (ωr) and so the cutter removes material from the workpiece. At b) v_{wf} is equal to ωr , so there is no relative motion and separation is about to begin. At c) v_{wf} becomes greater than ωr so the tool tip lags behind the workpiece and Type I TWS takes place. Finally, at d) v_{wf} becomes equal to ωr , the tool regains contact with the workpiece and the cycle repeats. The simulation results verify the proposed Type I TWS in VAMILL.

Fig.11 FE simulation of Type I TWS in VAMILL

Fig.12 shows a similar progression for type II separation using the conditions No 2 in Table 1. At a) the instantaneous vibration displacement $x(t)$ of the workpiece in the feed direction is less than the instantaneous uncut chip thickness (h_D), so the cutter is in contact with the workpiece and material is removed. At b) $x(t)$ is equal to h_D , and at c) $x(t)$ becomes larger than h_D so the tool loses contact with the workpiece and Type II TWS takes place.

Fig.12 FE simulation of Type II TWS in VAMILL

Fig.13 shows a periodic separation due to the overlap of the current and previous cutting paths using the conditions No 3 in Table 1, in order to make the separation more distinct, a much lower vibration frequency used for this simulation. Fig.13a) shows the initial surface of the workpiece and Fig.13b) shows the contour left by previous cutting path. The cut progresses from b) to d) with workpiece vibration in the feed direction. It can be seen that, with the new cut profile being out of phase with the previous profile the cutter trajectories overlap and the tool will break the surface, causing a periodic type III separation.

Fig.13 FE simulation of Type III TWS in VAMILL

The proposed three types of TWS in VAMILL are obtained clearly in the FE simulations, and the TWS of each type is realized by using the machining parameters given by the kinematic models. The simulation results therefore verify the correctness and reliability of the separation requirements obtained from the kinematic analysis.

6. Conclusion

In this paper, three types of tool-workpiece separation in vibration-assisted milling process have been proposed and investigated through the kinematics simulation. The requirements for each separation type are discussed. The proposed three types of TWS in VAMILL and their separation criteria have been verified by the FE cutting simulation. The formulated kinematics and separation requirements are of great significance to

determination of optimal machining and vibration parameter sets, and for vibration-assisted machining system design. The following conclusions can be drawn:

- Periodic TWS occurs over the whole tool path when vibration with appropriate amplitude and frequency is applied on the feed direction, thus, for 1D VAMILL, vibration assistance in feed direction is preferable to cross-feed direction.
- Compared with types I and II TWS, , periodic separation can be easily realized through Type III TWS. For vibration applied in feed direction, two separation criteria should be satisfied, i.e. the vibration amplitude is larger than half of the feed per tooth, and the vibration frequency is odd times of the spindle rotation frequency.
- Both vibration frequency and amplitude have a significant influence on the TWS, inappropriate parameters result in large change on uncut chip thickness and impact force on the tool, and hence would worsen machining quality.

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Conflict of interest

The authors declare that there is no conflict of interest.

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