INVESTIGATION OF UNEQUAL PITCH BALL-END MILLING CUTTER FOR CHATTER SUPPRESSION IN THIN-WALL CFRP SURFACE MILLING

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ABSTRACT

Carbon fiber reinforced plastic (CFRP) thin-walled parts have increasingly been used in high-end equipment to achieve further weight reduction. The smooth surface of these CFRP thin-walled parts is required for better mechanical performance, usually achieved by efficient surface milling. However, surface milling of thin-walled parts is prone to chatter with poor surface quality. Machining chatter is mainly caused by the feedback between the uneven cutting thickness and the dynamic cutting force, which leads to continuous vibrations. Chatter suppression has been investigated in isotropic metal or ceramic machining for years, such as employing unequal pitch cutters to reduce the variation of dynamic cutting thickness. However, CFRP is featured with strong anisotropy. Thus the instantaneous cutting depth keeps changing with the tool encountering the material with different fiber orientations, resulting in significant cutting force fluctuations. In turn, these fluctuations will aggravate the dynamic cutting thickness change. As a result, the chattering is more significant and challenging to control in surface milling of thin-walled CFRP. Currently, few studies focused on the design of unequal pitch cutters specifically for CFRP milling. This paper proposes an optimal design method for the angle between the teeth of the ball-end milling cutter. The influence of fiber cutting direction on dynamic cutting thickness was analyzed, and the calculation method of tooth angle was established. Two types of unequal pitches ball-end milling cutters with four edges were designed for thin-wall CFRP surface milling. The results show that using a ball-end milling cutter with different angles between four teeth can effectively suppress chatter in thin-wall CFRP milling. Under the same process parameters, the surface roughness of the designed cutter is reduced by 50% compared with the ordinary ball-end milling cutter.

1 INTRODUCTION

Carbon fiber reinforced plastic (CFRP) has become the preferred material for high-end equipment manufacturing due to its superior characteristics such as lightweight, high strength, and good fatigue resistance [1,2]. The continuous improvement of the performance of aviation, aerospace, and other high-end equipment determines that the structural components of CFRP equipment are developing towards the direction of large size and thin-wall, such as rocket tanks, aircraft barrel segments [3,4], etc. To obtain better mechanical properties, it is necessary to mill the surface of CFRP components, and the surface quality requirements are very strict, to ensure the service performance of high-end equipment[5,6,7]. Unfortunately, when the surface of a thin-walled CFRP member is milling because the workpiece itself has the characteristics of weak rigidity, the dynamic characteristics of the machining process change greatly, under the continuous action of the cutting edge, it is easy to chatter phenomenon. In addition, due to the anisotropy and laminated characteristics of CFRP [8,9], the chattering behavior is more complex and the vibration is more difficult to control. Chatter will lead to irregular material removal, seriously reduce the quality of the processed surface, and even directly cause a scrap of the workpiece, which seriously restricts the application of CFRP in high-end equipment. Therefore, it is urgent to suppress the chattering behavior of thin-walled CFRP surface milling and improve the surface machining quality.

To suppress chatter behavior in machining thin-walled parts, scholars have done a lot of research in the past decades, aiming at revealing chatter mechanisms and finding methods to suppress chatter in machining, and made much important progress. So far, the self-excited vibration between the tool and the workpiece, namely regenerative chatter, is considered to be the most important form of chatter in milling thin-walled parts [10-12]. During milling, the vibration between the tool and the workpiece will lead to a change in cutting thickness, leaving ripples on the machined surface, which in turn will affect the subsequent cutting process [13]. At present, the methods to suppress chatter are as follows: to predict the machining stability region by dynamic modeling and select reasonable process parameters to suppress chatter; Through the use of an auxiliary support fixture to improve the workpiece stiffness, vibration suppression process; Chatter suppression machining by selecting vibration suppression tool. Among them, the selection of a vibration suppression tool to improve machining stability has the advantages of being simple, and low-cost.

The end milling cutter with the unequal angle between teeth is defined as the unequal pitch milling cutter. The unequal-pitch milling cutter disturbs and regenerates the chattering effect through its irregular angle between teeth, which inhibits chatter in the milling process to some extent. During milling, the previous cutter tooth and the current cutter tooth will leave a vibration grain on the surface of the object being machined during milling. For a conventional equal-pitch milling cutter, the phase of the two vibration grains is fixed. However, for milling cutters with unequal pitch, the phase of the ripple will change due to the irregular chatter effect of the angle between teeth. The change of phase will disturb the regeneration chatter in the milling process and change the cutting thickness in the milling process, thus reducing the vibration in the milling process and increasing the stability of the milling system. Tlusty et al.[14] conducted numerical simulation on the stability of milling cutters with different geometric shapes such as unequal spacing or jagged cutting edges, and the research mainly showed the effectiveness of unequal spacing cutter teeth in vibration suppression. For a characteristic milling system, it is very difficult to obtain the optimal spacing angle by simulating the stability of different spacing. On this basis, Altintas et al.[15] adopted the analytical milling stability domain model to more realistically analyze the milling stability of unequal distance milling cutter. E.brudak et al. [16] proposed a new analysis and design method to optimize the distribution angle of unequal distance cutter teeth and verified through experiments that the reasonably designed milling cutter with unequal distance cutter teeth distribution angle could improve the stability of the milling process. Shirase et al.[17] took unequal pitch helical end milling cutter as the research object and established the milling force model and surface quality model of its machining process respectively. Through relevant tests, it was found that the unequal pitch helical end milling cutter had better performance in suppressing chatter in the machining process, and the surface quality produced by the helical end milling cutter was also better than that produced by the equal pitch milling cutter.

Through the above research, it can be found that the tool with unequal pitch has a good effect on suppressing chatter in milling homogeneous materials such as vibrating metal. However, CFRP has strong anisotropy, and the instantaneous cutting depth changes constantly when the tool rotation meets the material with different fiber orientations, resulting in greater cutting force fluctuation and a more significant chatter phenomenon, which is difficult to control. To suppress chatter in the CFRP milling process by using tools with unequal tooth spacing, it is necessary to design a reasonable angle between teeth according to the chatter mechanism of CFRP milling. At present, there are few kinds of research on the design of unequal pitch cutting tools for CFRP milling. Therefore, by analyzing the chatter mechanism of CFPR milling and the influence of fiber direction on milling chatter, this paper proposes an optimal design method for ball-end milling cutter tooth angle based on the idea of additional damping minimization. Based on this, two ball-end milling cutters with four blades and unequal tooth spacing were designed, and experiments on thin-wall CFRP milling were carried out compared with ordinary ball-end milling cutters, and the effectiveness of the designed cutters on suppressing chatter in CFRP milling was verified. This study is of great significance for improving the surface milling quality of thin-walled CFRP and ensuring the equipment performance of such CFRP components.

2 DYNAMIC CHARACTERISTICS ANALYSIS OF CFRP MILLING SYSTEM

To suppress chatter in the CFRP milling process by designing tools, it is necessary to explore the physical nature of chatter in milling. Because of the strong anisotropy of CFRP, the interaction between cutting edge and fiber is complex, and the chattering behavior is closely related to fiber cutting direction and other factors. Therefore, based on the essence of vibration, this section analyzes the influence of the chatter mechanism and fiber direction on milling chatter and provides a basis for tool design.

2.1 Displacement feedback response analysis

When milling a thin-walled CFRP workpiece, the workpiece has weak stiffness, and the machine spindle and workpiece are simplified into a vibration system of two degrees of freedom[18]. As shown in Figure 1, the cutting motion consists of the rotation *n* of the tool and the radial feed *f* of the tool along the workpiece, and the average cutting thickness is h_0. Set $\Delta(t)$ is the vibration displacement of the workpiece relative to the tool, $F(t)$ is the milling force acted by the tool on the workpiece, the dynamic cutting thickness is caused by the vibration displacement generated by the tool and the workpiece under the action of the cutting force, the dynamic displacement can be defined as the displacement between the current tool tooth and a tool tooth in the previous cycle.

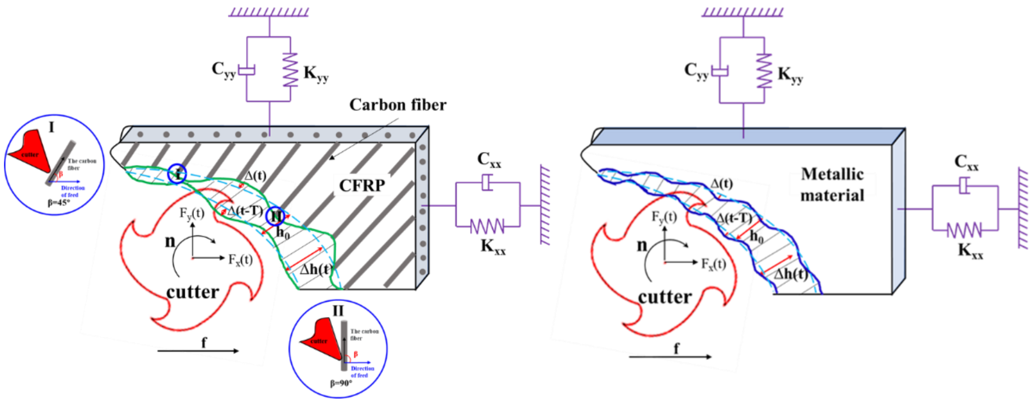


Figure 1: Regenerative chatter mechanism in CFRP milling.

When milling, $F(t)$ acts on the workpiece to produce dynamic displacement $\Delta(t)$; On the other hand, $\Delta(t)$ causes instantaneous cutting thickness $h(t)$ to change around its mean h_0, which in turn causes cutting force $F(t)$ to change. Different from metal materials, CFRP is affected by fiber cutting direction during processing. Dynamic cutting force and dynamic cutting thickness change more greatly with tool rotation to different directions, and chatter behavior is more complex, which will be discussed in detail in the next section. As shown in Figure 2, dynamic milling force and cutting thickness in the cutting process are feedback to each other. It must also be seen that $h(t)$ is related not only to the dynamic displacement $\Delta(t)$ of the blade at the time (see the inner surface of the shaded part in Figure 1), but also to the vibration $\Delta(t\text{-}T)$ of the tool's previous tooth (see the outer surface of the shaded part in Figure 1). It follows that there is delayed feedback of vibration displacement.

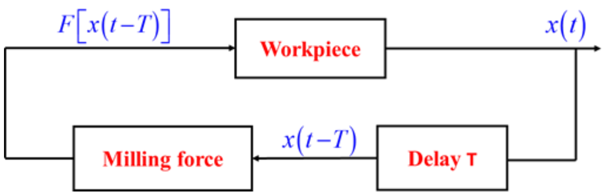


Figure 2: Displacement delays feedback system.

Assume that in the cutting process suddenly encounter an interference, the cutting force immediately obtains a dynamic increment ΔF(t), and ΔF(t) acts on the workpiece to cause vibration Δ(t), the latter makes the instantaneous cutting thickness changes Δh(t), resulting in a second change of cutting force Δ F'(t). Under certain conditions, when the first cutter teeth are cut, the fluctuation of cutting force will increase, ΔF'(t)> ΔF(t). Similarly, when the second cutter teeth are cut, there will be ΔF''(t)> ΔF'(t). So over and over again, ΔF(t) and Δ(t) rise and rise, and finally form a strong self-excited vibration.

The milling motion equation of thin-walled CFRP surface can be written as follows:

$$\begin{bmatrix} m_x & \\ & m_y \end{bmatrix}\begin{Bmatrix} \ddot{x}(t) \\ \ddot{y}(t) \end{Bmatrix}+\begin{bmatrix} c_x & \\ & c_y \end{bmatrix}\begin{Bmatrix} \dot{x}(t) \\ \dot{y}(t) \end{Bmatrix}+\begin{bmatrix} k_x & \\ & k_y \end{bmatrix}\begin{Bmatrix} x(t) \\ y(t) \end{Bmatrix}=\begin{Bmatrix} -\Delta F_x(t) \\ -\Delta F_y(t) \end{Bmatrix} \tag{1}$$

Among them:

$$\begin{bmatrix} c_x & \\ & c_y \end{bmatrix}=\begin{bmatrix} \dfrac{\delta_x}{\omega} & \\ & \dfrac{\delta_y}{\omega} \end{bmatrix} \tag{2}$$

δ_x and δ_y are hysteretic damping coefficients.

The dynamic increment $\Delta F(t)$ of cutting force can be expressed as:

$$\Delta F(t)=a_p K(\beta)\Delta h(t) \tag{3}$$

where, the axial cutting depth is a_p, $K(\beta)$ for the transformation of the fiber cutting angle of the cutting force coefficient （N/mm^2）.

To find the relationship between dynamic cutting thickness $\Delta h(t)$ and the relative vibration $\Delta(t)$ between the tool-workpiece. Enlarge and straighten the shadow part in Figure 1, and draw it in Figure 3. The cutting tracks of adjacent tool teeth corresponding to smooth cutting are expanded into two parallel lines, which are h_0 apart. The wavy lines around these two straight lines are respectively the cutting tracks $\Delta(t)$ and $\Delta(t-T)$ of two adjacent cutter teeth, and the difference between the two is the instantaneous cutting thickness under the condition of vibration cutting:

$$\Delta F(t)=a_p K(\beta)\Delta h(t) \tag{4}$$

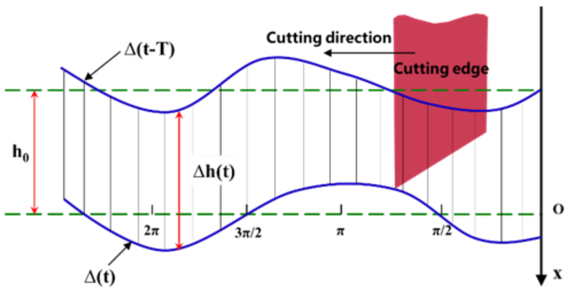


Figure 3: CFRP milling path of two adjacent cutting edges.

Considering the case where $\Delta(t)$ is equal amplitude harmonic, the critical state between stability and instability, set:

$$\Delta(t)=a_0\cos\omega t \tag{5}$$

The:

$$\dot{\Delta}(t)=-\omega a_0\sin\omega t \tag{6}$$

The time s required by each rotation of the tool is:

$$T = \frac{60}{n} \tag{7}$$

From the preceding, the phase difference between adjacent cutter teeth is:

$$\varepsilon = \omega T = (2k-1)\pi - 2\tan\left(\frac{\pi}{2} - \frac{\omega T}{2}\right) \quad k = 1, 2, ... \tag{8}$$

Substituting Eq. (8) into Eq. (4), get:

$$\begin{aligned} h(t) &= a_0 \cos\omega t - a_0 \cos(\omega t - \varepsilon) + h_0 \\ &= h_0 + a_0 \left[(1 - \cos\varepsilon)\cos\omega t - \frac{1}{\omega}\omega \sin\varepsilon \sin\omega t \right] \end{aligned} \tag{9}$$

Set:

$$1 - \cos\varepsilon = A, \quad \sin\varepsilon = B \tag{10}$$

Obtained:

$$h(t) = h_0 + A\Delta(t) + \frac{B}{\omega}\dot{\Delta}(t) \tag{11}$$

The dynamic variation of cutting thickness around its mean h_0 is:

$$\Delta h(t) = h(t) - h_0 = A\Delta(t) + \frac{B}{\omega}\dot{\Delta}(t) \tag{12}$$

Substituting this formula back to Eq. (3), the dynamic cutting force expression can be obtained:

$$\Delta F(t) = a_p K(\beta)\left[A\Delta(t) + \frac{B}{\omega}\dot{\Delta}(t) \right] \tag{13}$$

This formula indicates that the exciting force is controlled by both the vibration displacement and the vibration velocity, and proves that the delay feedback of displacement is equivalent to the simultaneous feedback of displacement and velocity.

Substituting Eq. (13) into (1), obtained:

$$\begin{bmatrix} m_x & \\ & m_y \end{bmatrix}\begin{Bmatrix} \ddot{x}(t) \\ \ddot{y}(t) \end{Bmatrix} + \begin{bmatrix} c_x + c_{11} & \\ & c_y + c_{22} \end{bmatrix}\begin{Bmatrix} \dot{x}(t) \\ \dot{y}(t) \end{Bmatrix} + \begin{bmatrix} k_x + k_{11} & \\ & k_y + k_{22} \end{bmatrix}\begin{Bmatrix} x(t) \\ y(t) \end{Bmatrix} = \begin{Bmatrix} -\Delta F_x(t) \\ -\Delta F_y(t) \end{Bmatrix} \tag{14}$$

Where the additional damping is as follows (15), and the additional damping is as follows (16):

$$c_{11} = \frac{a_p K_{tc}(\beta) B}{\omega}, \ c_{22} = \frac{a_p K_{rc}(\beta) B}{\omega} \tag{15}$$

$$\mathrm{k}_{11} = a_p K_{tc}(\beta) A, \ \mathrm{k}_{22} = a_p K_{rc}(\beta) A \tag{16}$$

This is a motion equation of free vibration of a two-degree-of-freedom system, and its stiffness coefficient and damping coefficient are composed of two parts: one is the stiffness and damping of the workpiece itself, and the other is the additional stiffness and damping of the cutting process caused by the delay feedback of displacement, namely the "regeneration effect". According to Eq. (10), A>0, and usually have $k_{11}<k_x$, $k_{22}<k_y$; means that the additional stiffness of the cutting process is positive and far less than the stiffness of the workpiece system itself. Therefore, the additional stiffness can only slightly increase the total stiffness of the system but has no substantial influence on the characteristics of the system. However, it can be seen from Eq. (10) that B can be positive or negative, which is determined by the phase difference ε. when $\varepsilon=\pi\sim 2\pi$, $B=\sin\varepsilon<0$, additional damping $a_pK(\beta)B$ is negative, the size of the fiber cutting angle β and axial cutting depth a_p decision, when the $c_x+c_{11}<0$ and $c_y+c_{22}<0$, that is the total damping of the system becomes negative, and self-excited vibration occurs.

Therefore, according to the above analysis, when the cutting depth is constant, the additional damping term is affected by the cutting force coefficient and phase difference. If additional damping can be minimized by reducing the cutting force coefficient and changing the time delay (cutting layer parameters and cutting time intervals per tooth), system chatter can be effectively suppressed.

2.2 Calculation of CFRP milling force coefficient

It can be seen from the analysis of the above section that the additional damping is the main cause of chatter in thin-walled CFRP milling, and the additional damping is affected by the milling force coefficient and phase difference. As CFRP is composed of multi-directional fiber layering, the cutting edge will act on different fiber cutting angles instantaneously with the rotation of the tool during milling, as shown in Figure 4. The relationship between the fiber cutting angle β and the tool rotation angle φ is:

$$\beta = \begin{cases} \lambda - \phi \, , & \phi \le \lambda \\ 180^\circ - (\phi - \lambda) \, , & \phi > \lambda \end{cases} \tag{17}$$

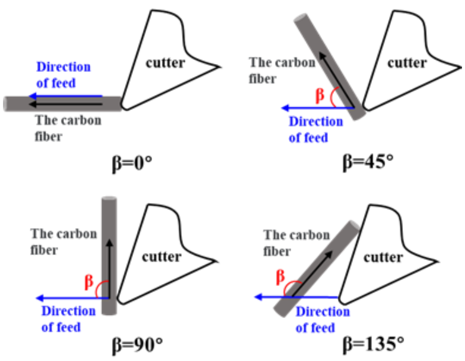


Figure 4: The variation of fiber cutting angle with tool rotation angle.

The ball-end milling cutter is capable of various surface milling because of its self-adaptive method loss, so this study solved the CFRP milling force coefficient of the ball-end milling cutter. In the modeling research of milling force, the milling force model established by Altintas[19] has been widely applied and studied. Milling force is regarded as a function of the milling area and processing workpiece and milling cutter milling edge contact length, the cutter milling edge is dispersed into some tiny units, each tiny unit for force analysis, through the micro cutting edge and gets the overall force in the process of processing. In milling CFRP, the cutting force is considered to vary with the fiber cutting angle, so the micro milling force at any point on the milling edge is:

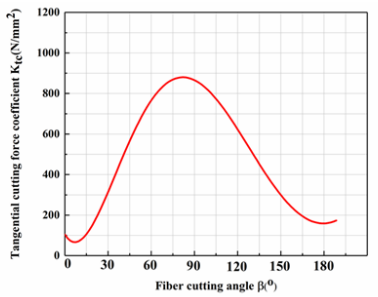
$$\begin{cases} dF_t = K_{tc}(\beta) \cdot h \cdot db + K_{te}(\beta) \cdot ds \\ dF_r = K_{rc}(\beta) \cdot h \cdot db + K_{re}(\beta) \cdot ds \\ dF_a = K_{ac}(\beta) \cdot h \cdot db + K_{ae}(\beta) \cdot ds \end{cases} \tag{18}$$

Because of the laminated characteristics of CFRP, the same cutting edge will cut to different fiber layers at the same time, and the fiber cutting angle of different fiber direction layers is not the same at this time. To simplify the calculation, the same fiber direction layer of material is superimposed together, and the cutting length is denoted as S_j. In the process of ball-end milling, there will be multiple milling micro-elements involved in milling on the same milling edge at the same time, but the milling forces of micro-elements are different due to the different positions of milling micro-elements. The milling forces of the j milling edge can be obtained using integration, and the global milling forces in X, Y, and Z directions can be obtained as follows:

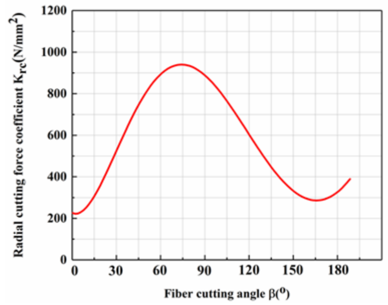
$$\begin{cases} F_{xj} = \int_{Z_{1j}}^{Z_{2j}} (dF_{x,0^o})dz + \int_{Z_{3j}}^{Z_{4j}} (dF_{x,45^o})dz + \int_{Z_{5j}}^{Z_{6j}} (dF_{x,90^o})dz + \int_{Z_{7j}}^{Z_{8j}} (dF_{x,135^o})dz \\ F_{yj} = \int_{Z_{1j}}^{Z_{2j}} (dF_{y,0^o})dz + \int_{Z_{3j}}^{Z_{4j}} (dF_{y,45^o})dz + \int_{Z_{5j}}^{Z_{6j}} (dF_{y,90^o})dz + \int_{Z_{7j}}^{Z_{8j}} (dF_{y,135^o})dz \\ F_{zj} = \int_{Z_{1j}}^{Z_{2j}} (dF_{z,0^o})dz + \int_{Z_{3j}}^{Z_{4j}} (dF_{z,45^o})dz + \int_{Z_{5j}}^{Z_{6j}} (dF_{z,90^o})dz + \int_{Z_{7j}}^{Z_{8j}} (dF_{z,135^o})dz \end{cases} \tag{19}$$

In the experiment of one-way plate milling, a four-blade ball-end cutter with hard alloy was selected, the tool radius R was 5mm, the spiral angle β_0 was 30°, and the three-way milling force of the cutter was measured. Within each tool rotation cycle, an average of 20 points were selected to carry out milling force coefficient calibration according to the milling force calculation method. Since axial milling force has little influence on chatter, axial milling force was not considered in this study. The variation curves of radial and normal milling force coefficient along with fiber tangential angle are shown in Figure 5. The results show that the effect of cutting angle on milling force is obvious. It is found that the curve obtained by polynomial fitting is in good agreement with the experimental results when sixth-degree polynomial fitting is used. The fitting results of the cutting force coefficient are as follows:

$$\begin{cases} K_{tc}(\beta) = 8.675\beta^6 - 158.3\beta^5 + 1053\beta^4 - 3061\beta^3 + 3516\beta^2 - 697.6\beta + 104.7 \\ K_{rc}(\beta) = 6.005\beta^6 - 110.8\beta^5 + 754\beta^4 - 2226\beta^3 + 2327\beta^2 + 252\beta - 77.03 \end{cases} \tag{20}$$



(a) Tangential cutting force coefficient $K_{tc}(\beta)$



(b) Radial cutting force coefficient $K_{rc}(\beta)$

Figure 5: Cutting force coefficient.

3 DESIGN OF UNEQUAL PITCH BALL-END MILLING CUTTER

As can be seen from the above section, another important factor affecting the additional damping is the phase difference, and the tool with unequal pitch can change the time delay, that is, the cutting amount and cutting time interval of each tooth, to reduce the additional damping term and achieve effective vibration suppression of chatter. However, at present, there is almost no tooth angle optimization for CFRP milling chatter. In this section, according to the physical nature of regenerative chatter in CFRP milling, a tooth angle optimization scheme for four edge ball-end milling cutter is proposed.

According to the CFRP milling force coefficient solved above, the angle between teeth is θ_j. As can be seen from Eq. (15), when the axial depth of the tangent and workpiece natural frequency is constant, $|K_{tc}(\beta)B|, |K_{rc}(\beta)B|$ is minimized to eliminate additional damping and suppress chatter.

$$\begin{gathered} S_1 = K_{tc}(\beta)B = K_{tc}(\beta)\sum_{j=1}^{N} \sin\omega T_j \\ S_2 = K_{rc}(\beta)B = K_{rc}(\beta)\sum_{j=1}^{N} \sin\omega T_j \end{gathered} \tag{21}$$

Considering the dynamic balance of the cutter, the angle between the teeth of the four-edge ball-end milling cutter with unequal tooth spacing is generally divided into two kinds: the opposite angle between the teeth is equal and the angle between the teeth is arithmetic sequence distribution. When the angles between opposite teeth are equal,

$$\begin{gathered} \theta_1 = \theta_3 \\ \theta_2 = \theta_4 \\ \theta_1 + \theta_2 = \pi \end{gathered} \tag{22}$$

When the angle between the teeth is distributed in an arithmetic sequence,

$$\begin{aligned} &\theta_{j+1} = \theta_j + \Delta\theta \quad j = 1,2,3 \\ &2\times\theta_1 + 3\times\Delta\theta = \pi \end{aligned} \tag{23}$$

The influence of inter-tooth angle on the cutting parameters of each tooth is shown in Figure 6. When the CFRP workpiece is milling, the previous machining tool tooth and the current machining tool tooth will leave a vibration grain on the surface of the processed object during milling. For the conventional constant tooth spacing milling cutter, the phase of the two vibration grains is fixed. However, for milling cutters with unequal pitch, the phase of the ripple will change due to the irregular chatter effect of the angle between teeth. The change of phase will disturb the regeneration chatter in the milling process and change the cutting thickness in the milling process, thus reducing the vibration in the milling process and increasing the stability of the milling system.

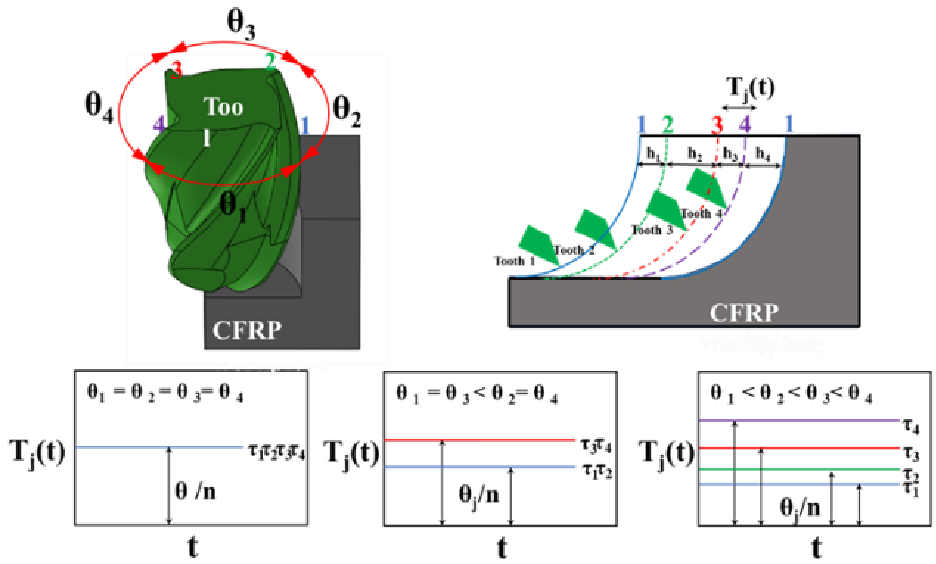


Figure 6: Effect of tooth angle on dynamic cutting thickness.

The range of θ_1 is set to be 60°~120°, calculated ｜S｜ according to Eq. (21), Figure 7 shows the variation trend of ｜S｜ with θ_1 in the angle distribution between the two teeth. It can be seen from Figure 8 and Figure 9 that ｜S｜ is minimum when θ_1=100°, and the dynamic balance of the tool is considered at the same time. Therefore, the corresponding Angle distribution between teeth is [80°,100°,80°,100°] and [60°,100°,80°,120°] respectively.

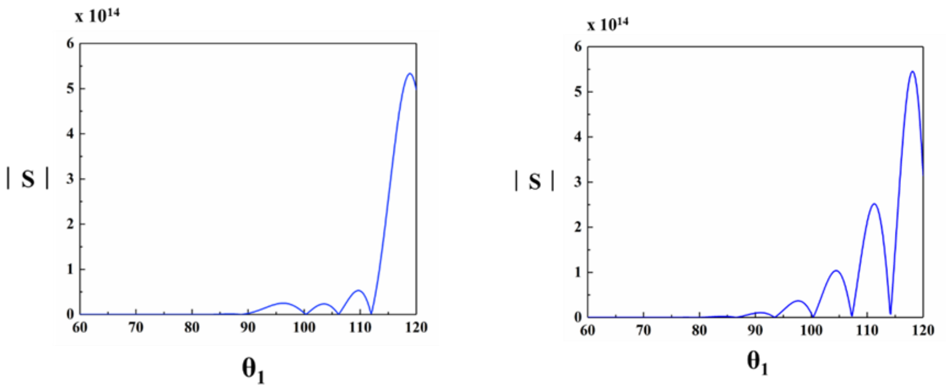


Figure 7: The trend of ｜S｜ with θ_1.

4 EXPERIMENTS ON SURFACE MILLING OF THIN-WALLED CFRP

To verify the effectiveness of the optimized tooth angle design on chatter suppression in thin-wall CFRP milling, CFRP surface milling experiments were carried out respectively. The milling state was determined by monitoring the milling force during machining and observing the surface quality of the workpiece after machining.

4.1 EXPERIMENT AND METHOD

All milling experiments were completed in the five-axis machining center, and the cutting tools were two kinds of ball-end milling cutters with unequal tooth pitch and ordinary ball-end milling cutters designed above, as shown in Figure 8. The diameter of the cutter was 10mm and the spiral angle was 30°. 5mm×10mm×3mm thin-walled CFRP workpieces are selected for the workpieces, and the layering direction is $[0/45/90/135]_{16}$. The specific properties of the materials are shown in Table 1.

Parameters	Value
Longitudinal tensile strength	2840MPa
Transverse compressive strength	165 MPa
Longitudinal Young's modulus	160 GPa
Transverse Young's modulus	8.97 GPa
Poisson's ration	0.28
The glass transition temperature of the resin	165 ℃

Table 1: Properties of CFRP.

Figure 8: Unequal pitch ball-end milling cutter.

The workpiece adopts the cantilever clamping method, that is, one end of the workpiece is clamped, milling the other end, the first-order natural frequency of the workpiece is 217Hz, and the second-order natural frequency is 360Hz by the hammer experiment. The experimental device is shown in Figure 9. Two sets of process parameters were used for milling each cutter respectively, namely, the speed of 3000rpm, the cutting depth of 1mm, the speed of 5000rpm, the cutting depth of 2mm, and the feed speed of 300mm/min. The milling force was monitored during the experiment. To identify whether chatter occurs in the milling process, the time domain signal of the milling force is transformed by FFT to obtain the frequency spectrum, and the quality of the machining surface and frequency domain signal of the milling force are judged respectively.

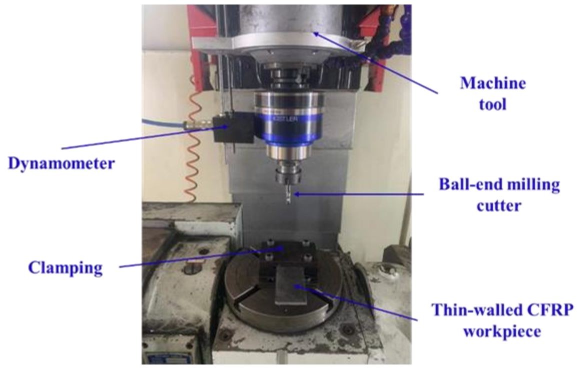


Figure 9: Milling experimental machining and measuring equipment.

4.2 RESULTS AND DISCUSSION

The surface quality of the machined workpiece was observed and its roughness was measured. The frequency spectrum of the milling force time domain signal was obtained by FFT transformation. The experimental results of 3000rpm and 1mm cutting depth were shown in Figure 10, and the experimental results of 5000rpm and 2mm cutting depth were shown in Figure 11. Figures (a), (b) and (c) respectively represent the ordinary ball-end milling cutter [90°,90°,90°,90°], the ball-end milling cutter [80°,100°,80°,100°], and the ball-end milling cutter [60°,100°,80°,120°].

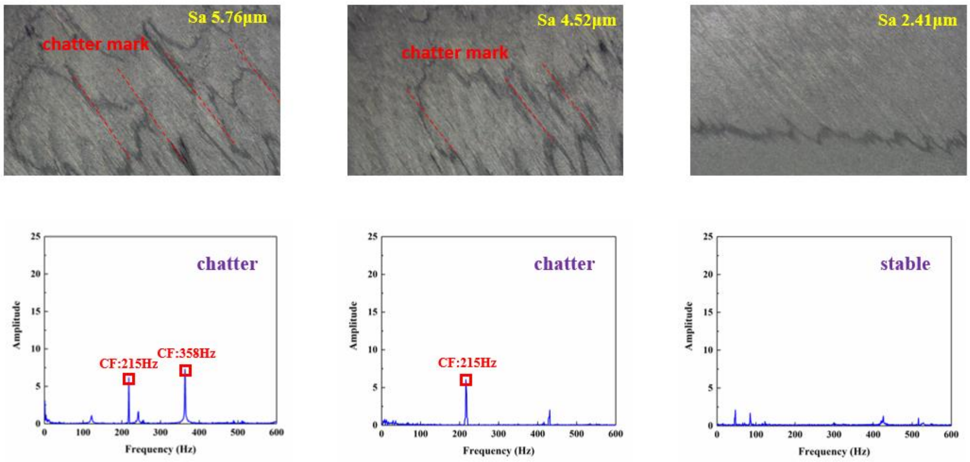


Figure 10: The machining surface quality and milling force spectrum are obtained with the speed of 3000rpm and the cutting depth of 1mm.

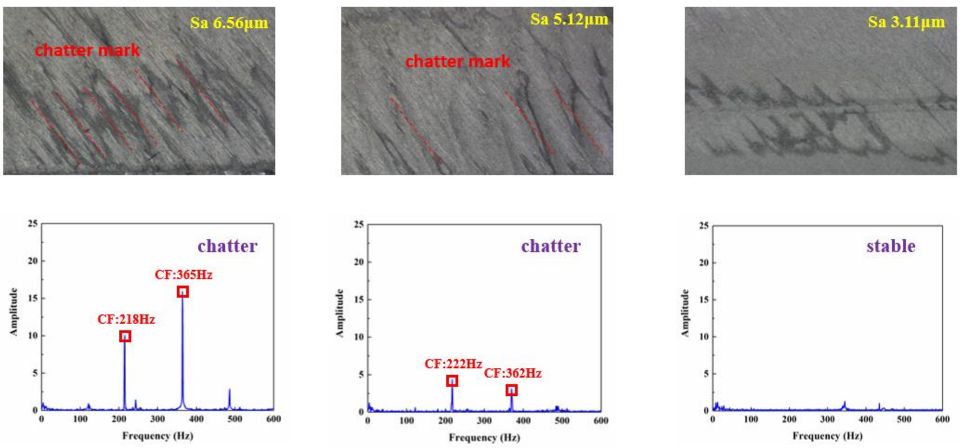


Figure 11: The machining surface quality and milling force spectrum are obtained with a speed of

5000rpm and a cutting depth of 2mm.

As can be seen from the figure, when the three cutting tools respectively use two groups of process parameters to process, the workpiece state is consistent. When the ordinary ball-end milling cutter is used, as shown in figure10 (a) and Figure 11 (a), vibration marks appear on the workpiece surface after machining, the vibration marks are uniformly distributed, and the workpiece roughness reaches 6.56μm. Cross-layer milling is evident on the surface of the workpiece after machining. This phenomenon is due to the strong chatter of the workpiece during machining, which leads to the removal of different layers of materials. From the perspective of the spectrum, the peak value near the natural frequency of the workpiece is large, namely the chatter frequency (CF) of 215HZ, 358Hz and 218Hz, 365Hz, indicating that the workpiece is in the chatter state during processing.

As shown in Figure 10 (b) and Figure 11 (b), a small amount of vibration marks appeared on the workpiece surface when the ball-end milling cutter [80°,100°,80°,100°] with unequal tooth pitch was used for machining, but the distribution of vibration marks was irregular, and the workpiece roughness was reduced to 4.52μm to a certain extent. From the surface of the workpiece, the multi-layer material is also removed in part of the machining area, indicating the existence of unstable milling in the machining process. On the spectrum, the peak value is also large near the natural frequency of the workpiece, however, the peak value is significantly lower than that of an ordinary ball-end milling cutter, and the natural frequencies at the peak value are 215Hz and 218Hz. Indicating that the workpiece has a slight chatter during processing. But the machining quality is better than that of an ordinary ball-end milling cutter, which indicates that the angle distribution between teeth has a certain chatter suppression effect.

When a ball end milling cutter with unequal pitch was used [60° 100° 80° 120°], in figure 10(c)and figure 11 (c), No vibration marks were found on the workpiece surface, and no peak appeared near the natural frequency of the workpiece on the spectrum. The workpiece roughness reached 2.41μm, which can be judged that the workpiece was in a stable milling state during processing. It shows that the angle distribution between teeth has a good chatter suppression effect in CFRP milling.

5 CONCLUSIONS

In this paper, by analyzing the displacement feedback effect of the thin-wall CFRP milling system and the influence of fiber cutting direction on chatter, it is concluded that the negative damping effect is the main factor leading to chatter. Based on the idea of minimizing negative damping, a method for calculating the angle between the teeth of the ball-end milling cutter to suppress chatter was established, and the verification experiment of thin-wall CFPR milling was carried out. The results show that the ball-end milling cutter [60°,100°,80°,120°] with different angles between four teeth can effectively suppress chatter in thin-wall CFRP milling. Under the same process parameters, the surface roughness of the designed cutter is reduced by 50% compared with an ordinary ball-end milling cutter.

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