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Review Article

Optimization of Cutting Parameters for Milling TC4 Materials with Spiral Corn Milling Cutter

S Xiao*, X Lou, R Yan

Yibin Vocational and Technical College, Yibin, 644003, China

ABSTRACT

To solve the problem of spiral corn milling cutting TC4 material force inequality and low efficiency, single blade model and cutting force model of spiral corn milling cutter were both analyzed in this paper. By using AdvantEdge FEM software to set the related corn mill cutter blade structure parameters, blade parameters, and network partition, etc. we got the in-process cutting force and temperature simulation figure of spiral corn milling cutter while processing, and on the basis of these simulation parameters, process verification is conducted. The result shows that the analysis of the milling force of spiral corn milling cutter may optimize the cutting parameters, improve the efficiency of difficult-to-machine materials and reduce the tool wear of the cutters while processing TC4 materials.

Keywords: Spiral corn milling cutter; AdvantEdge FEM; Cutting force model; TC4

INTRODUCTION

Spiral corn end milling cutter with stagger arrangement can provide better chip separating performance, reduce the cutting force of each tooth, and ease the chip removal process. With the cutting thickness of each tooth increases, the cutter tooth avoids the hardened layer on the surface. A staggered cutter tooth is conducive to the penetration of cutting fluid, which is suitable for heavy cutting. It's highly efficient and is widely used in the processing of difficult-to-machine materials. Yet there is little research on the cutting force. Milling force, as an important parameter in the milling process, always affects the vibration of the whole cutting system, the surface quality of the workpiece and the wear condition of the cutter teeth, Therefore, it is of great significance to conduct and analyze digital modeling, to further understand the milling mechanism, to improve the design of machine tools, cutting tools and fixtures, and to optimize the cutting process parameters and geometric parameters of cutting tools.

At present, the research on cutting force model in the milling process is mature both home and abroad. For example, the linear cutting force model proposed by Altintas Y [1], which takes the dynamic cutting force as a function of the instantaneous cutting thickness. Wan Min et al. [2] also put forward the exponential function model. These studies are mainly focused on the overall milling cutter, but researches on cutting force model of spiral corn milling cutter are few. The cutting force model of the spiral corn milling cutter is established in this paper. With AdvantEdge FEM software simulation performed, it provides a technical reference for the optimized selection of cutting parameters for spiral corn milling cutter, which improves the machining surface quality of parts, and therefore increases the machining accuracy [3-5].

Milling dynamics model of spiral corn end mill

Single blade mathematical model: As shown in Figure 1, define rectangular coordinate system (X,Y,Z) with milling cutter center as Z-axis, the coordinate system (u,v,w) is established with the center of the blade as the origin. Making the plane of the cutting edge coincide with the plane of the coordinate system of the blade, the vector from the tip to the center of the blade [6] is expressed as:

$$V_{IC} = -\sin\Phi I_r i + \cos\Phi I_r j + I_z k \tag{1}$$

I_r: The radial offset of the XY Plane

I_z: The radial offset of the blade center to the inner axis of the XY plane

In practice, there are many shapes of blades for the different needs of blade manufacturers and machining. Typical rectangular and convex triangular blades were used for modeling analysis, as shown in Figures 2 and 3. The blade is simplified into two parameters of Length 'b' and Width 'a'. The convex triangular blade can be defined by four parameters as the radius R of the arc cutting edge with O_c as the center of curvature, the distance from the center of the blade O' to the center of curvature of the cutting edge O_c O_f, plus blade boundary (θ_s, θ_e). The coordinates of any point on the

Correspondence to: Xiao Shanhua, Associate Professor, Yibin Vocational and Technical College, Yibin, 644003, China, E-mail: yb_99888@163.com

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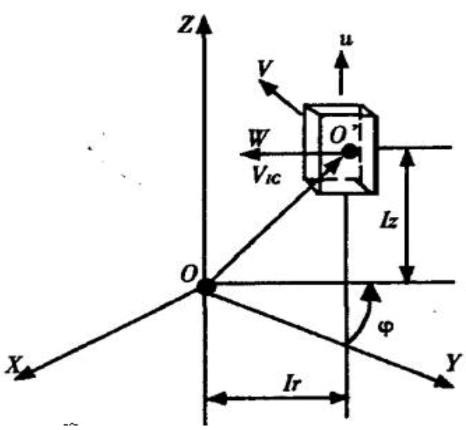

Figure 1: Location vector of blade center to the cutter.

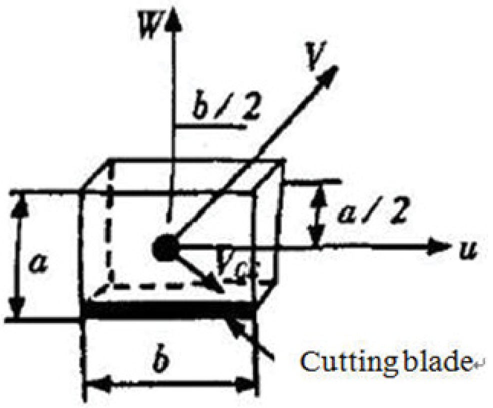

Figure 2: Rectangular blade cutter and parameters.

cutting edge of the blade are defined by the vector in the coordinate system (u,v,w):

$$V_{CE} = u*i + v*j + w*k \tag{2}$$

For the rectangular blade: -b/2 ≤ u ≤ b/2, v=0, w=a/2;

For a convex triangular blade, the formula can be derived as [7,8]:

$$\begin{cases} u = R*\cos\gamma, v = 0, w = -R*\cos\gamma + o_f \\ \gamma = \theta + \sin^{-1}\left((o_f\cos\theta)/R\right); \theta_s \le \theta \le \theta_e \end{cases} \tag{3}$$

Special attention should be paid to u,v,w plane calibration of the blade surface and blade coordinate system, as shown in Figure 4, it contains cutting edge (as v=0). In the coordinate system X,Y,Z, the blade is rotated to define its position on the cutter. The rotation of blade around Y-axis leads to Angle δ, the rotation of blade around the X-axis leads to Angle β, and the rotation of blade around the Z-axis leads to Angle Φ (Figure 5). As is shown in formula (4):

$$R_X(\beta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\beta & -\sin\beta \\ 0 & \sin\beta & \cos\beta \end{bmatrix};$$

$$R_y(\delta) = \begin{bmatrix} \cos\delta & 0 & -\sin\delta \\ 0 & 1 & 0 \\ \sin\delta & 0 & \cos\delta \end{bmatrix}; \tag{4}$$

$$R_z(\Phi) = \begin{bmatrix} -\sin\Phi & -\cos\Phi & 0 \\ \cos\Phi & -\sin\Phi & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

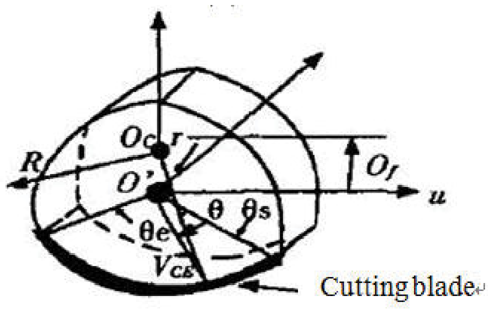

Figure 3: Triangular blade shapes and parameters.

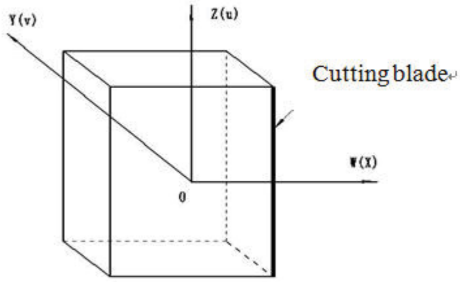

Figure 4: Tool and blade coordinate system.

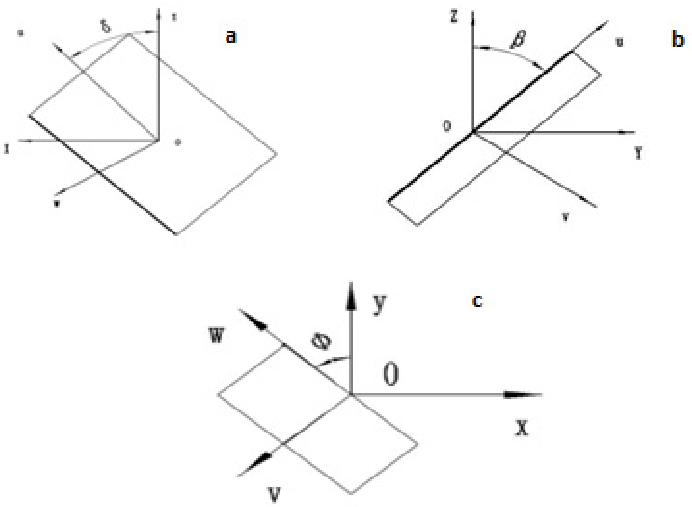

Figure 5: Positioning angle of corn milling cutter blade. (a): rotation of blade around Y-axis leads to Angle δ; b): rotation of blade around the X-axis leads to Angle β; c): rotation of blade around the Z-axis leads to Angle Φ.

After rotating the corn milling cutter blade around the X, Y and Z axes, the transformational matrix is as follows:

$$T = Rx(\beta) \times Ry(\delta) \times Rz(\Phi), \text{ then } V_C = T \times V_{CE} = [T]\begin{bmatrix} u \\ v \\ w \end{bmatrix}$$

The final position of the cutting edge in the cutter coordinate system is shown in Figure 6, as shown in equation (5)

$$V_d = V_{IC} + V_C \tag{5}$$

$$\begin{aligned} &= [-sin\Phi(usin\delta - wcos\delta + I_r) - cos\Phi sin\beta(ucos\delta + wsin\delta) \\ &\quad - vcos\Phi cos\beta]i + [cos\Phi(usin\delta - wcos\delta + I_r) \\ &\quad - sin\Phi sin\beta(ucos\delta + wsin\delta) - vsin\Phi cos\beta]j \\ &\quad + [cos\beta(ucos\delta + wsin\delta) - vsin\beta + I_z]k \end{aligned}$$

From equation (5) we can see, if the blade center point (I_r, I_z) and

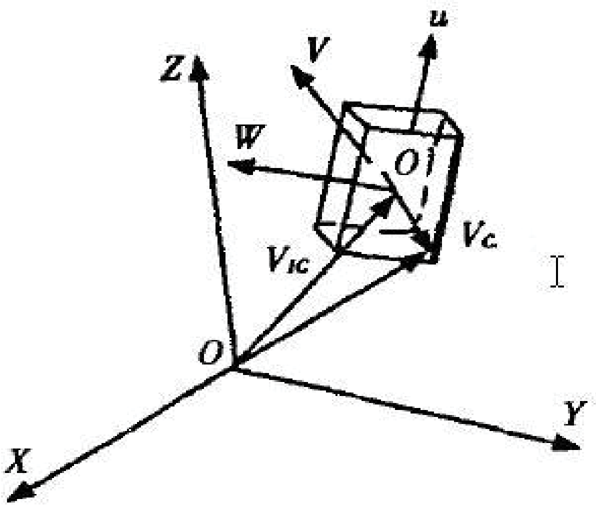

Figure 6: Final position vector of the blade.

the rotation angle of the blade (Φ,β,δ) are both set, the blade size (a,b,R,θ_s,θ_e) and the cutting position height Z can be calculated from the above.

Modeling cutting force of spiral corn milling cutter: In the modeling of corn milling cutter's 3d cutting edge profile and the cutting force, by dividing the blade into M micro-cutting units along the axial direction, the upper end $P_h(x_{j,k}+1, y_{j,k}+1, z_{j,k}+1)$ and $P1(x_{j,k}, y_{j,k}, z_{j,k})$ of the k^{th} cutting edge element on the cutting edge j can be calculated by equation (5). Parameters are as following:

1. Cutting force coefficient K_{tc}, K_{rc}, K_{ac}: cutting force coefficients in tangential, radial, and axial directions
2. Cutting microelement dF_t, dF_r, dF_a: tangential, radial and axial cutting elements
3. Blade force coefficient K_{te}, K_{re}, K_{ae}: Blade force coefficients in tangential, radial, and axial directions
4. G (Φ_{jk}): Unit step function, to determine whether the current cutting edge is involved in cutting
5. dz_{jk} represents microelement height; the formulation is:
   $$dz_{jk} = dz_{jk+1} - z_{jk}$$
6. ds_{jk} is micro blade length, the equation is
   $$ds_{jk} = \sqrt{(x_{jk+1} - x_{jk})^2 + (y_{jk+1} - y_{jk})^2 + (z_{jk+1} - y_{jk})^2}$$
7. Φ_{jk} represents micro radial contact Angle, defined as:
   $$\Phi_{jk} = arctan\left[\left(y_{jk} + y_{jk+1}\right) / \ \left(x_{jk} + x_{jk+1}\right)\right], \text{ or}$$

$$\begin{cases} g(\Phi_{jk}) = 1, \Phi_{st} \le \Phi_{jk} \le \Phi_{ex} \\ g(\Phi_{jk}) = 0, \Phi_{jk} < \Phi_{st}, or\, \Phi_{jk} > \Phi_{ex} \end{cases} \tag{6}$$

In equation (6), there are two milling methods: down milling and up milling. When using down milling, it is stable and the machining quality is good, the cutting in and out angle can be described as Φ_{st}=л-arccos (1-a_e/R) or Φ_{ex}= л; When using up milling,the stability is poor, and the cutting in and out angle can be described as

$$\Phi st = 0 or \Phi ex = arccos\left(1 - ae / R\right);$$

8. The current cutting-edge microelement feed per tooth set as f_{zjk}, and is defined as:

$$f_{zjk} = [(\Phi_{jk} - \Phi_{(j-1)k}) f_r] / 2\pi + R_{jk} - R_{(j-1)k} \tag{7}$$

The f_r in (7) is the feed per revolution; R_{jk} is the radial distance from the current cutting edge element to the milling cutter center, described as:

$$R_{jk} = \sqrt{(x_{jk} + x_{j(k+1)})^2 + (y_{jk} + y_{j(k+1)})^2} \times 0.5$$

According to the instantaneous rigid model, after the integration of the above definition or description, the cutting force acting on the microelement is expressed as (8) [9,10].

$$\begin{cases} dF_{tjk} = g(\Phi_{jk})(K_{tg} f_{zjk} \sin\Phi_{jk} dz_{jk} + K_{te} dS_{jk}) \\ dF_{rjk} = g(\Phi_{jk})(K_{rg} f_{zjk} \sin\Phi_{jk} dz_{jk} + K_{re} dS_{jk}) \\ dF_{ajk} = g(\Phi_{jk})(K_{ag} f_{zjk} \sin\Phi_{jk} dz_{jk} + K_{ae} dS_{jk}) \end{cases} \tag{8}$$

In (8), the cutting forces in the X, Y and Z directions can be obtained through coordinate transformation [11,12], which can be expressed in (9):

$$\begin{bmatrix} dF_{xjk} \\ dF_{yjk} \\ dF_{zjk} \end{bmatrix} = g(\Phi_{jk}) \times \begin{bmatrix} -\cos\Phi_{jk} & -\sin\Phi_{jk}\sin\Phi_{jk} & -\cos\Phi_{jk}\sin\Phi_{jk} \\ \sin\Phi_{jk} & -\sin\Phi_{jk}\cos\Phi_{jk} & -\cos\Phi_{jk}\cos\Phi_{jk} \\ 0 & \cos\Phi_{jk} & -\sin\Phi_{jk} \end{bmatrix} \times \begin{bmatrix} dF_{tjk} \\ dF_{rjk} \\ dF_{ajk} \end{bmatrix} \tag{9}$$

The instantaneous cutting force, as shown in equation 10, can be obtained by integrating along the X, Y and Z axes and summing the cutting forces acting upon each cutter tooth:

$$\begin{bmatrix} F_X \\ F_Y \\ F_Z \end{bmatrix} = \begin{bmatrix} \sum_{J=1}^{N}\sum_{K=1}^{M} dF_{xjk} \\ \sum_{J=1}^{N}\sum_{K=1}^{M} dF_{yjk} \\ \sum_{J=1}^{N}\sum_{K=1}^{M} dF_{zjk} \end{bmatrix} \tag{10}$$

Simulation of cutting force of spiral corn milling cutter

AdvantEdge FEM is special finite element software for metal cutting simulation. This software avoids the cell distortion caused by large volume deformation through continuous redrawing and adaptive mesh technology. By setting the cutting parameters and structural parameters of the cutter and workpiece in AdvantEdge FEM software, the actual cutting conditions of TC4 [13,14] material are simulated to obtain the required target parameters, such as cutting force, cutting temperature, etc.

Cutting parameter selection: The corn milling cutter used in the experiment is shown [15] in Figure 7, cutting tools and parameters as shown in (Tables 1 and 2).

AdvantEdge FEM simulation parameter setting: When setting the blade parameters and geometry TAB of the cutter in AdvantEdge FEM software, we need to set the length, width, height, back angle of the end face cutter, side angle, front angle of the end edge, blunt radius of the side edge, radius of the edge arc, rounded cutting edge radius of the end face etc. Setting the structure parameters of corn milling cutter blade is shown in Figure 8. It is necessary to set parameters such as the number of chip slots for corn milling cutters [16,17], the number of blades on the chip slots, the spacing between blades, spiral Angle, cutter diameter and so on. Setting parameters of the inserted blade arrangement is shown in Figure 9.

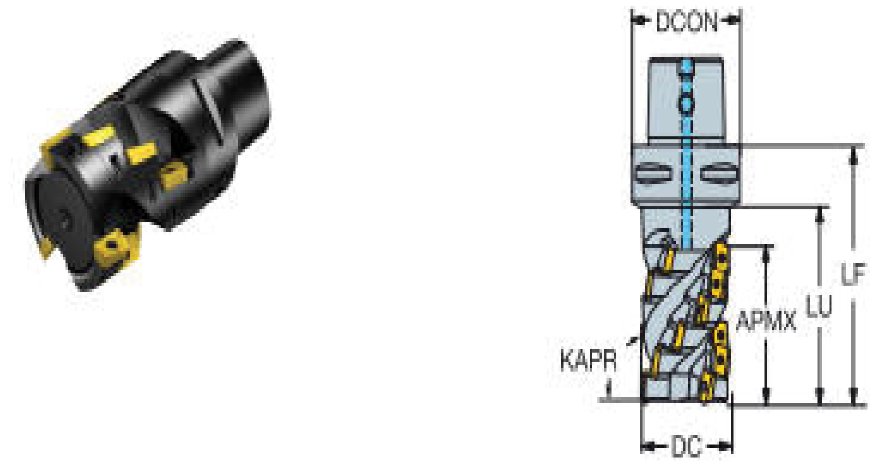

Figure 7: Corn milling cutter diagram.

Table 1: Structure parameters of corn milling cutter.

Diamater (D)	Height of the blade (H)©©	Length between each blade (L)	Number of blades	Font angle	Rear angle	Helix angle	Max cutting depth
Φ63	18	10	3	10°	11°	45°	43

Table 2: Cutting parameters and materials.

Depth (a_p)	Width (a_e)	Speed (V_c)	Feed (f_z)	Method	Material
20	15	35	0.05	Down Milling	TC4

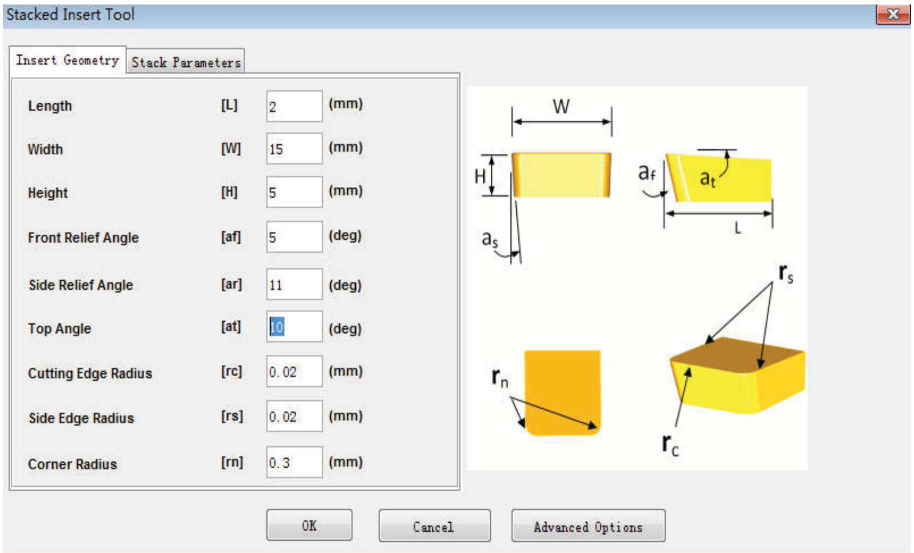

Figure 8: Setting of corn milling cutter blade structure parameters.

AdvantEdge FEM meshing network: Enter the workpiece interface and click advanced options. Parameters such as the maximum and minimum cell size of the grid, grid change gradient, curve precision, and node density of edges are shown in Figure10. The divided meshing network in this section is shown in Figure11.

AdvantEdge fem simulation result: After the above-mentioned parameters are set, the computational model is input to verify the feasibility of the model, and F_x, F_y, F_z simulation mechanical diagrams are obtained, as is shown in Figure 12, so as the simulated cutting temperature, shown in Figure 13.

Analysis of the influence of milling force on cutting parameters: According to the F_X, F_y, F_z simulation mechanics diagram, temperature diagram, further analysis of its impact on the amount of milling can be conducted.

Analysis of the influence of milling force on spindle speed: The curve analysis of spindle speed and cutting force is shown in Figure 14, with continuous increase of spindle speed when corn milling cutter is milling TC4 material, both F_x and F_y in cutting forces tend to decrease; but when the main speed is greater than 3500r/min, F_x and F_y in cutting force will increase when spindle speed is increasing.

Analysis of the influence of milling force on feed: When spindle speed at n=3500r/min and cutting depth at ap=0.35 mm, the change curve of the effect of feed amount upon cutting force is shown in Figure 15. With the feed per tooth increases, the cutting forces F_x and F_y decrease gradually. When the feed per tooth is 0.13 mm, cutting forces F_x and F_y reach the minimum value. In the actual processing, titanium alloy has is more serious processing hardening layer. When the feeding amount is small, corn milling cutter blade

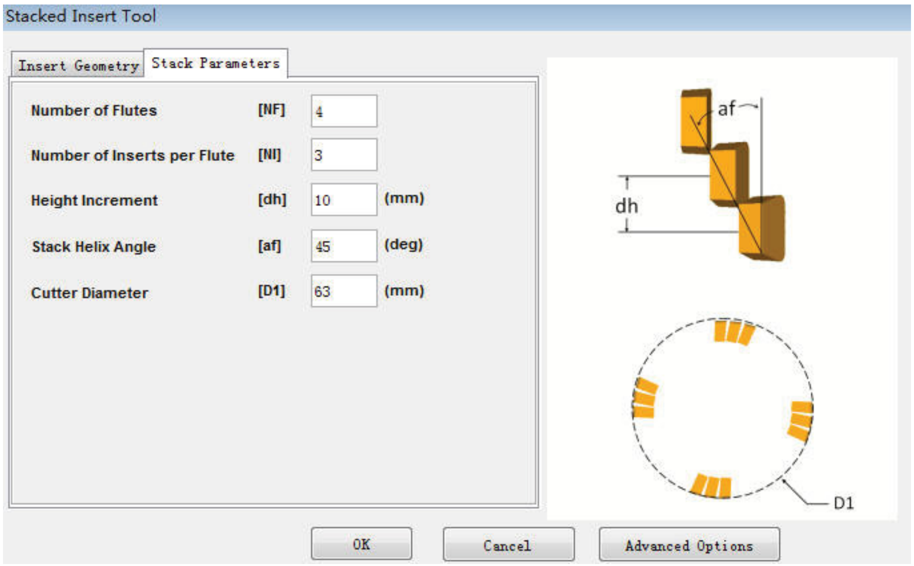

Figure 9: Corn milling cutter arrangement parameters.

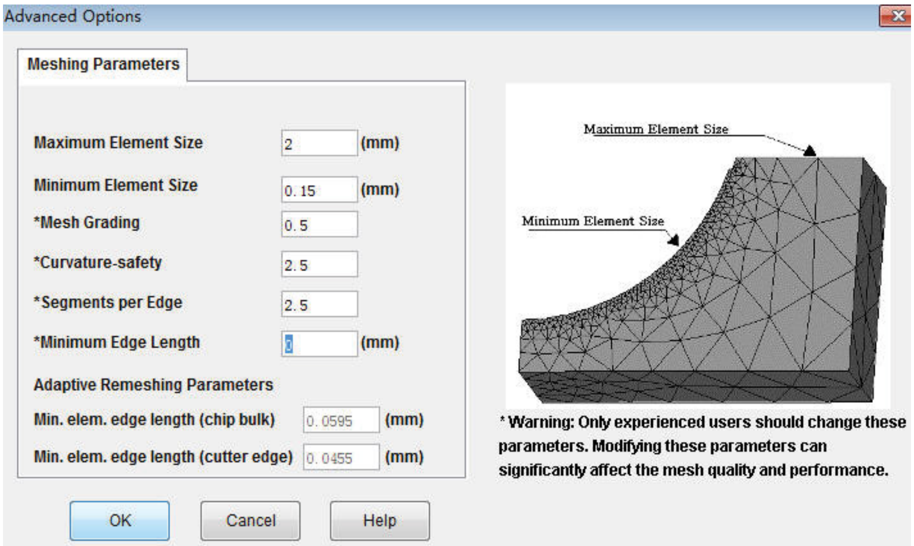

Figure 10: Meshing Parameters.

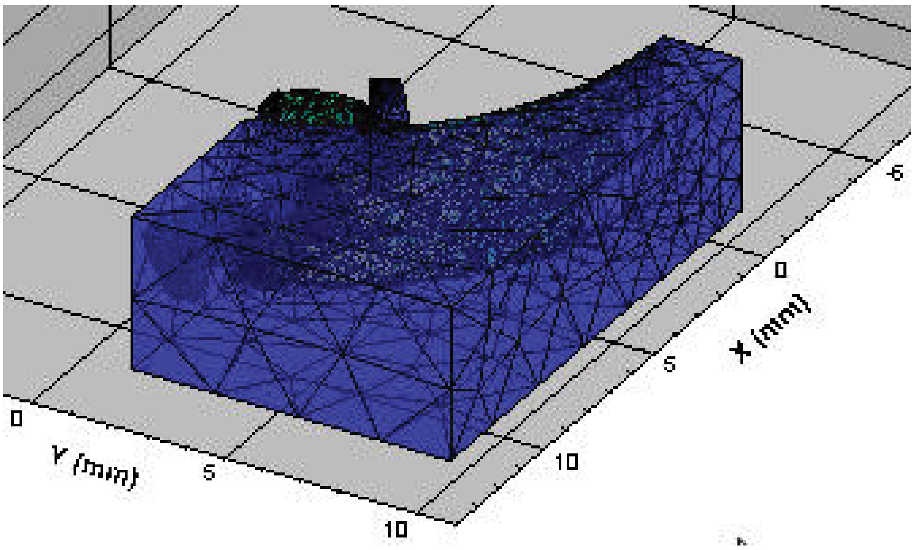

Figure 11: Meshing Grid Network.

mainly works on the surface of the hardened layer, and the cutting force is large; When the feed is greater than the thickness of the machining hardening layer, the blade can completely cut through the entire machining hardening surface, cutting force F_x, F_y reduce instead, with the increase of each tooth feed, the cutting layer thickness also increases, so does the cutting volume and cutting force.

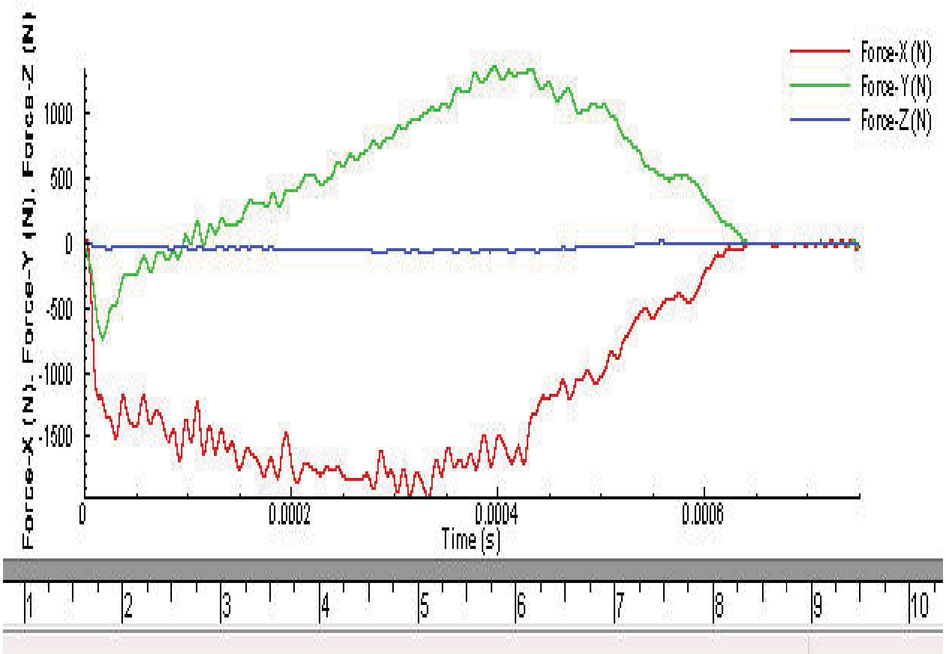

Figure 12: Simulation diagram.

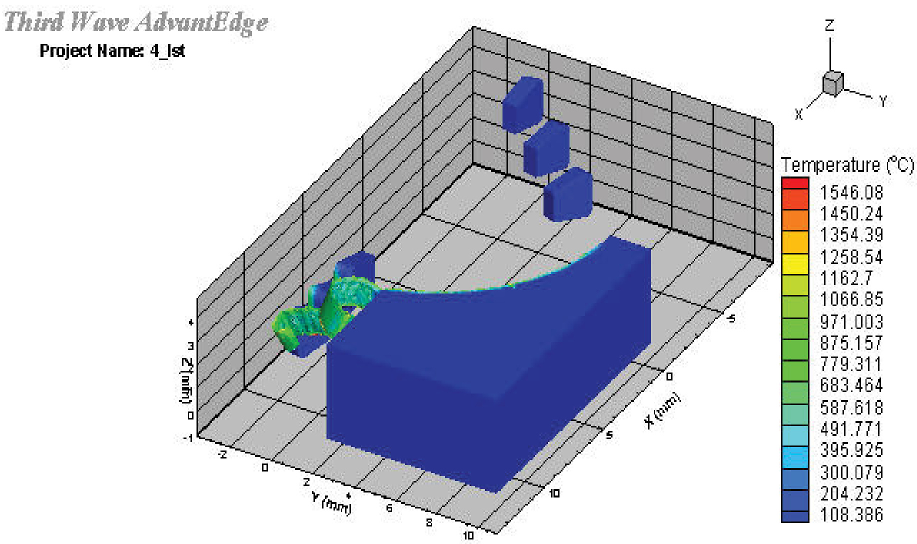

Figure 13: Simulated cutting temperature diagram.

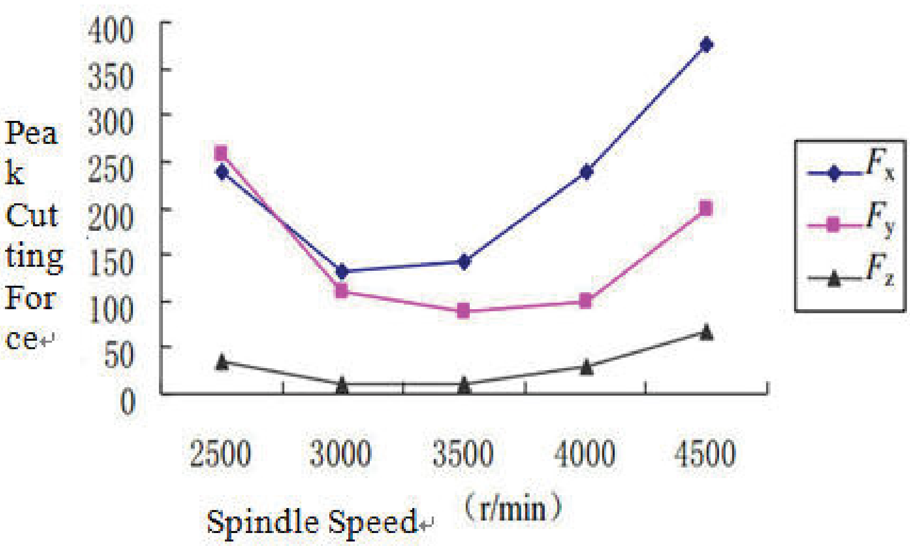

Figure 14: Influence of spindle speed on cutting force.

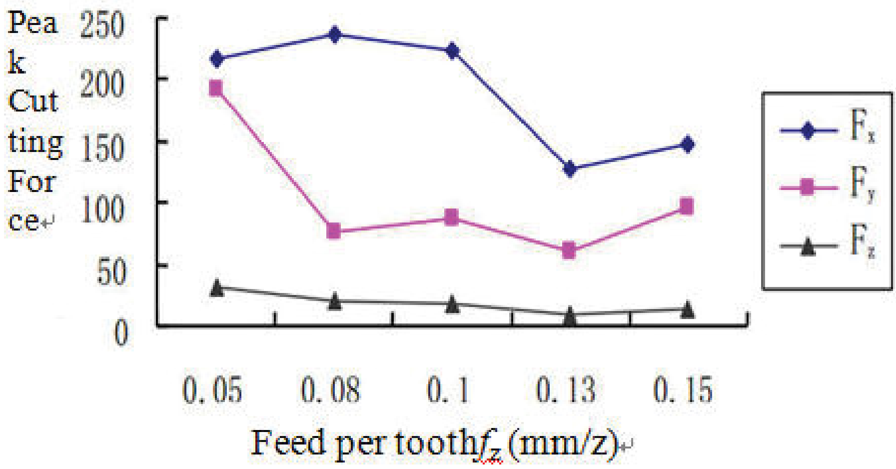

Figure 15: Influence of feed per tooth on cutting force.

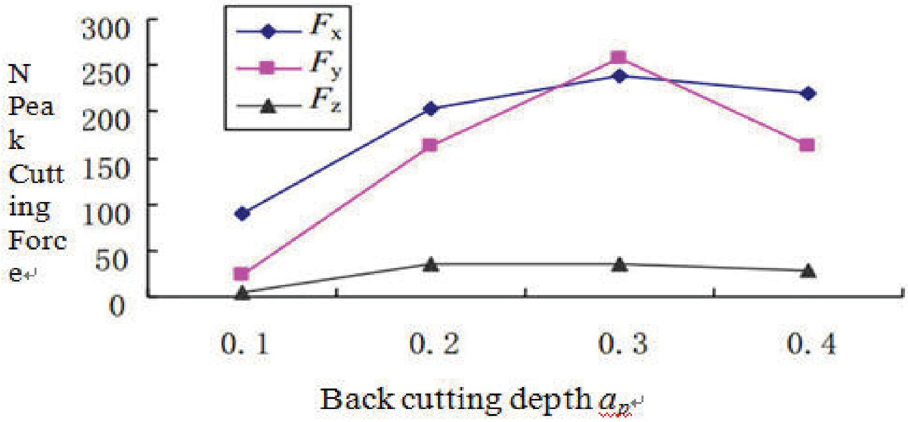

Figure 16: Influence of milling force on back cutting depth.

The impact of milling force upon the back cutting depth: In the experiment, the spindle speed was 3500 r/min, and the feed per tooth was 0.15 mm/tooth. The curve of the impact of milling force upon back cutting depth can be shown in Figure 16. With the increase of the back cutting depth, the cutting forces F_x and F_y increased significantly. When the back cutting depth is more than 0.3mm, the cutting force in both directions of F_x and F_y decreases obviously.

CONCLUSION

In this paper, the milling force modeling of spiral corn cutter and the simulation of Advant-Edge FEM are taken as the research objects. Modeling experiments and milling force experiments were carried out, and cutting force parameters were established and simulated by the software. The simulation results are applied to the selection of cutting parameters of TC4 materials to obtain more reasonable cutting parameters, which can provide a reference for the selection of processing parameters for difficult-to-machine materials. Also ideally reduces tool wear, improves tool life, saves machining costs and achieves better economic benefits.

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