

The Modeling of Cutting Force in High-speed Milling for End Mill

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Abstract: Aiming at the varying cutting features of depth and thickness in high-speed milling, using mathematical methods to model the theoretical three-dimensional model of calculating cutting forces. First of all, according to the oblique cutting model, a cutting force model of flank edge was presented. The differential method was used in this process. The model was approached with calculating instantaneous chip thickness. Secondly, the bottom of cutting edge for differential along the vertical direction of cutting edges according to the orthogonal cutting model, calculating cutting force of infinitesimal. The cutting force model of cutting edge bottom was constructed by integral method. Merging the both upon, then the three-dimensional cutting force model is established. In the end, the model was programmed by means of the software Matlab. The result indicates that the numerical results agree well with experimental data, the maximum error values between simulation and measurement is 7.5 %. Copyright © 2014 IFSA Publishing, S. L.

Keywords: High-speed end mill, Cutting force, Model, Oblique cutting, Matlab.

1. Introduction

The metal cutting process is a process of interaction between tool and job, Milling is a cutting process with discontinuous contact between tool and job and variation in cutting thickness. Its mechanism is very complicated. Cutting force affects directly the tool wear, breakage and the stability of the processing system, it also influences the processing precision of the job. As end milling belongs to the complex three-dimensional cutting, involving many cutting parameters, it is difficult to conform the prediction of cutting force correspond to reality.

The method of estimating the average milling force in practical processing are mostly by empirical model using the multi-factor orthogonal regression test to establish the general index of exponential relationship [1] between cutting force and cutting

parameters. This method is simple, convenient, and played an important role in the research of processing. But for different processing conditions, a lot of test data were needed to collect and store, this spends a lot of time and cost. The milling forces predicted by experience models were usually the equivalent average force by curve fitting, and the actual milling forces were instantaneous changed. Finite element model can effectively simulate the chip formation process and cutting parameters such as stress, strain and temperature, residual stress [2], this is usually very time-consuming.

A. Qinglong [3], Y. Altintas et al [4] many scholars have a lot of research in the modeling of the milling force. Among the numerous cutting force modeling, the instantaneous rigid force model established by A. Yusuf [5] has a more widely application. The thinking of discretization process

makes the model has a high degree of accuracy and practicability in the simulation of instantaneous milling force. In view of the deformation feature of the process system with low stiffness, Q. Houjun [6] set up an elastic milling force model of low stiffness milling process system. Considering the change of cutting thickness and cutting width, X. Zhijie [7] established dynamic cutting force model of spiral end mill. Analyzing the regulation of the processing parameters effect on the tangential and radial cutting force coefficient when end milling the 4Cr16Mo die steel, Min Liu et al [8] put forward the simple and effective way to reduce the cutting force. Martelloti [9] analyzed the relationship between the movements of milling, and got the basic expression of cutting thickness by using geometry method only. Sabberwal [10] proposed the cutting force produced by the end milling spiral blade was decided by the cutting thickness and chip load (or unit cutting force coefficient). The cutting model of cutting thickness later was usually expressed by cutting thickness and cutting load. The cutting model produced by Kline [11] considered the influence of the bounce of cutting tool to the local cutting thickness. Sutherland [12] considered the influence of cutting tool's deformation to cutting thickness. Yang [13] divided the spiral cutting edge into a series of infinitesimal bevel cutting unit, using the data of orthogonal cutting to analyze the oblique cutting. Budak [14] divided the unit cutting force coefficient into shear component and blade friction component, and obtained these coefficients using curve fitting from the database of the orthogonal cutting. Although Yang and Budak decided the milling cutting edge into the discrete bevel cutting unit, but the flow stress of each oblique cutting unit was obtained by orthogonal cutting experiment data.

As it is difficult to predict the average friction coefficient on the rake face and the shear stress on the shearing surface in the cutting progress of the workpiece by using the stretching and friction test, so we obtained the unit cutting force coefficient by milling experiments or orthogonal cutting experiment when the cutting model is established. In the high speed machining for the same material and cutting tool material, the coefficient must be identified again when the angle of cutting tools and cutting parameters were not at the same. Although we can identify the unit cutting force coefficient through the orthogonal cutting experiment in some extent, but it hasn't shown the flow stress on the shear zone and the friction properties on the rake surface. Unit cutting force coefficient is a form of variation of flow stress essentially, and the calculation of flow stress on the shear area is the key to predict cutting force. So the cutting forces were all measured by cutting experiments in normal cutting model, and then got the flow stress by reverse analysis directly, and unit cutting force coefficient is obtained by conversion.

The finite element model actually get the constitutive relation of the materials by the test of material (tensile test or cutting experiment in high

speed and high temperature), and then calculate the flow stress by nonlinear numerical method indirectly. Becze [15] tried to calculate the milling force from Johnson-Cook material constitutive relation, getting the equivalent strain and equivalent strain rate of flow stress from the orthogonal cutting experiment, and then extended to the bevel cutting to get the milling force. But Becze's method needs to measure the equivalent strain and strain rate on the shear area through the orthogonal cutting experiment, it is difficult in practice. And with few direct calculation model, most of models based on the identification of the cutting force coefficient, its experimental process is very complicated. Besides, it considered few about the cutting force of the bottom of cutter's cutting edge, which is not conform to the three-dimensional milling practical situation of mill. In this paper, we focused on the stress analysis of the thermodynamic conditions and the cutting mill when cutting, using the micro cutting unit along the cutting edge axial integral, set up mechanical model on flank edge and bottom of the cutting edge of 4 cutting edge carbide end mill. This method begin with the constitutive equation of the job material, getting the distribution of strain, strain rate and temperature through the establishment of control equations on the bevel cutting shear area, and then calculating the cutting force using the Matlab.

2. The Geometric Model of a Milling Cutter

The method of establishing the geometrical model of end milling cutter is relatively mature. The spiral angle of cutting blade remained the same in the cylindrical helical end milling cutter. As is shown in the Fig. 1, the cutting edges are located in cylindrical envelope surface with the tool's radius r , each cutting edge can be seen as a helix with a spiral angle is λ_s .

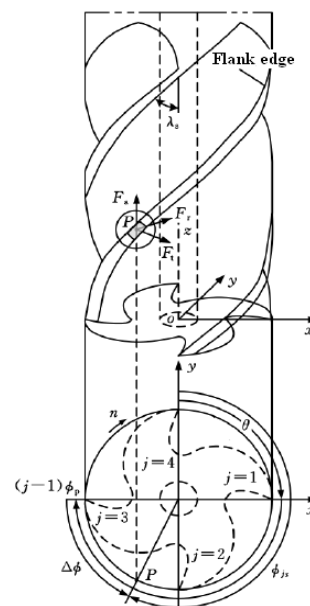


Fig. 1. End milling cutter geometry relationship.

3. Oblique Cutting Model

For research of processing operations with complex cutting blade (such as milling and drilling), the usual method is to divide the complex geometry shape cutting edge cutting into infinitesimal rectangular cutting or oblique cutting, so the analysis of the orthogonal cutting and oblique cutting model is the basis of establishing milling model. Literature [16] put forward the method of modeling by oblique cutting force and cutting heat, it can predict the cutting force of oblique cutting according to the material constitutive equation. To build the vertical milling cutting force calculation model, a brief introduction of oblique cutting model is given as follow. Reference plane associated with oblique cutting are base plane P_r , cutting plane P_s , normal plane P_n , shear plane P_{sh} , rake face of A gamma and equivalent plane P_e , as are shown in Fig. 2. On the reference plane, vectors are defined associated with oblique cutting, the x_o is direction of cutting speed, y_n is parallel to the cutting edge, z_c is the direction of chip flow. x_s is the direction of shear flow. Determining the angle of bevel cutting, including major cutting edge angle λ_s (equal to helix angle in milling), a rake angle γ_n in normal plane and shear angle Φ_n in normal plane, the chip flow angle η_c and shear flow angle η_s . In oblique cutting, the equivalent plane P_e is determined by the cutting speed and speed of chip. In the equivalent plane, bevel cutting mechanism can be regarded as the accumulation of 2D cutting state. Equivalent plane orientation can be determined by the equivalent plane angle:

$$\tan \eta_e = \frac{\tan \eta_c \cos \eta_s + \sin(\phi_n - \gamma_n) \sin \eta_s}{\cos(\phi_n - \gamma_n)}$$

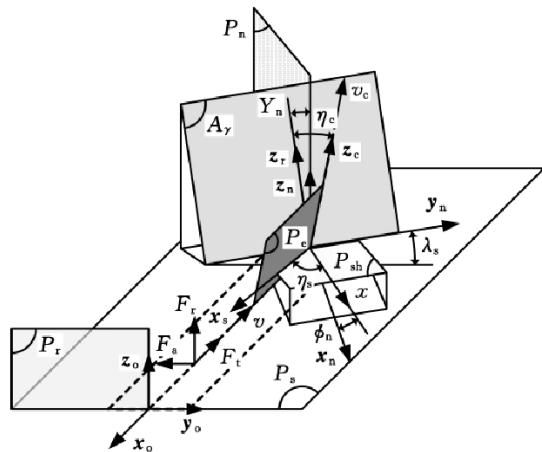


Fig. 2. Oblique cutting geometry relationship.

The shear direction is in the equivalent plane, so the available expression of shear flow angle is:

$$\tan \eta_s = \frac{\tan \lambda_s \cos(\phi_n - \gamma_n) - \tan \eta_c \sin \phi_n}{\cos \gamma_n}$$

According to the force balance on the chip, Moufki [17] got implicit equation of chip flow angle. With incompressible condition of plastic, that the normal velocity of the shear zone is constant, the shear chip speed is:

$$v_c = \frac{v \cos \lambda_s \sin \phi_n}{\cos \eta_c \cos(\phi_n - \gamma_n)}$$

In the expression, v is the cutting speed.

The measured friction factor in the process of metal cutting in were larger than the friction factor in general sliding friction test, but the friction factor will decreases with the increasing of cutting speed when the cutting speed exceeds to a certain value. On the equivalent plane P_e , the model of unequal division in shear zone, according to the variation of shear strain in the shear area, dividing shear into two unequal parts with the main shear plane P_{sh} , as is shown in Fig. 3. In the main shear plane P_{sh} , the shear strain rate reach to maximum.

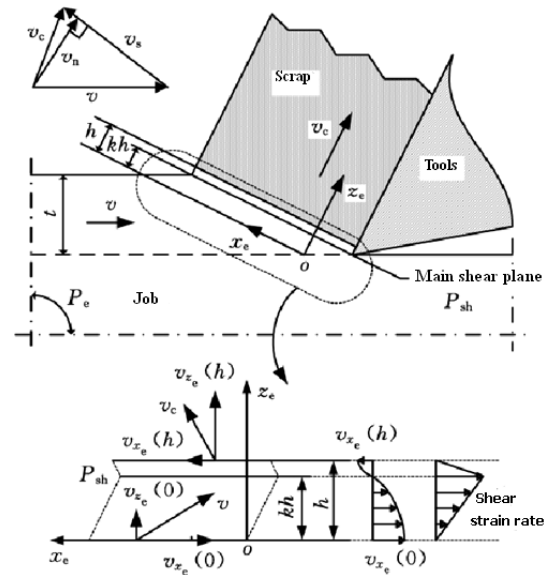


Fig. 3. The equivalent plane shear zone diagram.

4. The Establishment of the Milling Cutting Force Coordinate System

The experiment machine is Ouma MV610, z-axis is its principal axis, vertical upward as positive. the local coordinate system of cutting tool is established as shown in Fig. 1 with the x axis of the machine tool for the x-axis of the coordinate system, the left for positive, the y-axis according to the right-hand rule, the center of the circle in the mill's base plane is determined as the origin of coordinates. In the process of milling, the instantaneous cutting force which effects on the mill is a space force with continuous variation along the cutting edge. The research method is mainly to divided the mill along its axis direction into very thin infinitesimal, each

infinitesimal can be regarded as a cutting process of single cutting edge knife's oblique cutting, we modeled the infinitesimal cutting force model by using different theories and methods. To get the total milling force, we must integrate the cutting force on the infinitesimal along the cutter axis. The value range of integral calculating is the key to calculate correctly the milling force. Assuming that the cutting force on the infinitesimal with height of dz are the tangential force dF_c , the radial force dF_f and the axial force dF_p .

The position of cutting infinitesimal in the cutter's local coordinate system is shown in Fig. 4. (X'-axis is in the cutting plane that perpendicular to the cutting edge, Y'-axis coincide with the cutting edge and Z'-axis is perpendicular to the plane x'o'y') The angle between the two coordinate system is the cutter spiral angle β .

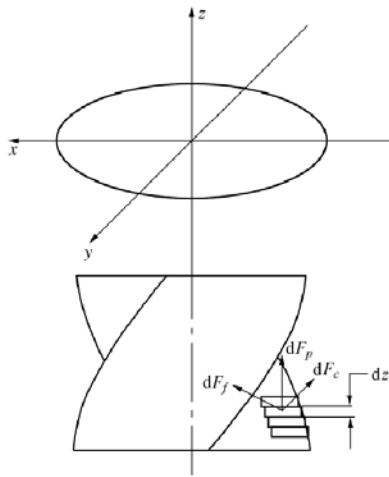


Fig. 4. The analysis of the force in the infinitesimal of the end mill.

5. The Model of the Oblique Cutting Force

During the process of actual cutting, milling is three-dimensional cutting process. The oblique cutting is the situation when the cutting edge and cutting direction isn't vertical in common three-dimensional cutting's.

Flat end mill commonly has two or more cutting edges that evenly distributed round its circumference, a few cutting edge cutting the job at the same time may appear during the milling process. The rotation angle of every point on the spiral mill's cutting edge changed with the mill's rotation direction, it has a lag angle or advance angle compare with the rotation angle in the basis plane. The value of the lag angle or advance angle ψ is the function of the value of the z-coordinate point.

$$\psi_j(z) = \frac{z \tan \beta}{r}$$

The lag angle at the position a_p .

$$\psi_\alpha = \frac{a_p \tan \beta}{r}$$

We choose the rotation angle at the base plane as the mill's rotation angle, then the expression of the infinitesimal position angle at the same height, at the time of t is:

$$\theta = \theta_0 + \psi_j(z) - 2\pi nt$$

Now we choose the 4 blade right-lateral end mill as the research object, we established the milling model, assuming that the radius of the mill is r , spiral angle is β , gear number is z , depth of cut is a_p , the radial cutting width is a_c .

5.1 The Model of Flank Edge Cutting Force

The cutting of the end mill's flank edge belongs to oblique cutting, its state coordinate system of cutting is shown in Fig. 5.

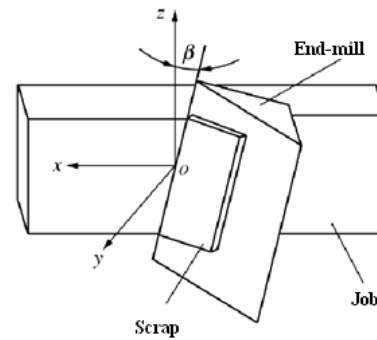


Fig. 5. The oblique cutting state of the flank edge.

The component of x-axis direction of the tangential force dF_c is

$$dF_c = dF \cos \theta_i \cos \theta_n \cos i$$

The component of y-axis direction of the tangential force dF_c is

$$dF_c = dF \sin \theta_i \sin i$$

In the expression: θ_n is the angle between the x axis and the resultant force F 's projection in the normal plane, θ_i is the inclined angle of the cutting speed, i is the angle between the shear plane and the plane xoy.

$$dF_c = dF (\cos \theta_i \cos \theta_n \cos i + \sin \theta_i \sin i), \quad (1)$$

Also, we can get that

$$dF_f = dF \cos \theta_i \sin \theta_n, \quad (2)$$

$$dF_p = dF(\sin \theta_i \cos i - \cos \theta_i \cos \theta_n \sin i), \quad (3)$$

The shear force can be express as the resultant force F_s 's projection in the shear direction according to the geometry

$$F_s = F[\cos(\theta_n + \phi_n) \cos \theta_i \cos \phi_i + \sin \theta_i \sin \phi_i]$$

It can be expressed as the product of the shear stress and shearing area

$$F_s = \tau_s A_s = \tau \left(\frac{a_p}{\cos i} \right) \left(\frac{h}{\sin \phi_n} \right)$$

From the two expressions above

$$F = \frac{\tau_s a_p h}{[\cos(\phi_n + \theta_n) \cos \theta_i \cos \phi_i + \sin \theta_i \sin \phi_i] \cos i \sin \phi_n}$$

In the expression: h is the depth of cut in the axial direction, the cutting force of each infinitesimal is

$$dF = \frac{\tau_s a_p dz}{[\cos(\phi_n + \theta_n) \cos \theta_i \cos \phi_i + \sin \theta_i \sin \phi_i] \cos i \sin \phi_n}, \quad (4)$$

In the expression: a_p is the instantaneous cutting thickness during milling

5.1.1. The Calculation of the Instantaneous Cutting Thickness

Set up the calculation coordinate system of cutting thickness as shown in Fig. 3 (the center of the cutter starts at the point O, feed direction is to the right, clockwise rotation). The track of the cutting edge has been simplified as circle in many researches, thus the instantaneous cutting thickness $a'_p = f_z \sin \theta$, in the expression: f_z is the feed rate for each tooth, θ is the angle position for mill's tool nose. Without considering the deformation and the eccentricity of the cutter, this assumption can meet the calculation requirements in some extent when calculating the instantaneous cutting thickness with the certain feed rate.

To make the cutting force with more accuracy, the more accuracy of instantaneous cutting thickness should be get. The compositions of actual process of mill are the translation of the mill and the rotation of its own axis, the track of the mill is a trochoid compounded by the motion above.

As is shown in Fig. 6, when the point M on the cutting edge move to the point E which on the j-1 rotation track of the cutter tooth, its rotation angle is θ . When the rotation angle of the cutter tooth is $\theta_1 = \theta$, point M move to point D, $|ED| = f_z$, the link between the point B and D intersect with the tack of the j-1 rotation at the point C To simplify the calculation, assuming that the center of mill is O and remain the

same during the cutter tooth's rotation movement track from E to C, prolonging the line BC and make line OA meet at right angles with the line BC at A, $\angle AOB = 0$.

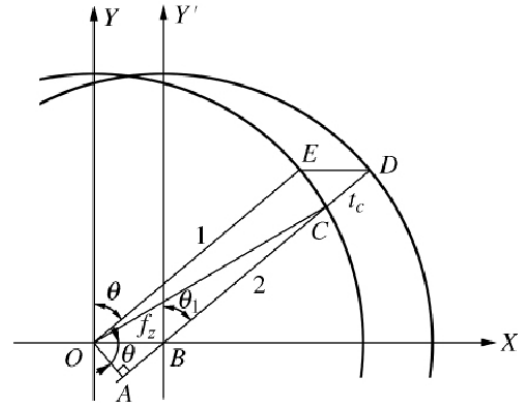


Fig. 6. The instantaneous cutting thickness of the single cutting edge.

So the instantaneous cutting thickness is

$$a_p = |CD| = |BD| - |BC| = R - |BC|$$

According to law of cosines

$$\begin{aligned} |BC|^2 &= |OC|^2 + |OB|^2 - 2|OC||OB|\cos \angle BOC = R^2 f_z^2 - 2Rf_z \angle BOC \\ \angle BOC &= \pi/2 - \theta - \angle EOC = \pi/2 - \theta - [\pi/2 - \arccos(f_z \cos \theta / R)] \\ &= -\theta + \arccos(f_z \cos \theta / R) \end{aligned}$$

$$a_p = R - \sqrt{R^2 + f_z^2 - 2Rf_z [-\theta + \arccos(f_z \cos \theta / R)]}$$

In the end, putting a_p into expression (4), we can get the cutting force of infinitesimal dF , putting it into expression (1) to (3), we can get the cutting force from the three direction. If you want to get the total cutting force of the end mill, you have to integrate the cutting force on the infinitesimal along the cutter axis. The value range of integral calculating is the key to correctly calculate the milling force. The value range of integral is often getting by calculating the angle.

Take right-hand mill for example to discuss the climb milling and up milling, for the convenient of calculating, we give some angles as are shown in the Fig. 4 and Fig. 5, the minimum cut-in angle is θ_{st} , the maximum cut-away angle is θ_{ex} , stipulating the starting point of each angle is the forward direction of y-axis, clockwise is positive.

5.1.2. Determining the Integrating Range of Up Milling

As is shown in the Fig. 7, during the up milling, the minimum cut-in angle is $\theta_{st} = \pi$, the maximum cut-away angle is θ_{ex} has to be calculated by the milling width and mill's size under the 4 conditions below:

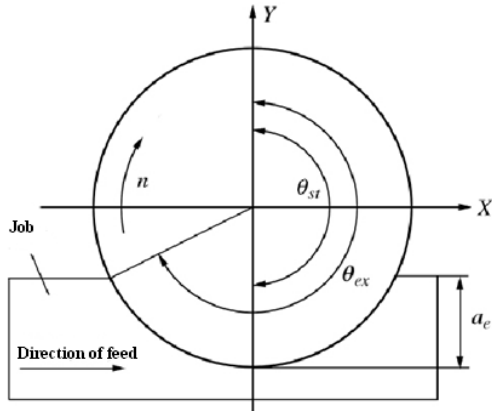


Fig. 7. Up milling.

- 1) When $a_e < r$, $\theta_{ex} = 3\pi/2 - \arcsin(1 - a_e/r) + \psi_a$
- 2) When $a_e = r$, $\theta_{ex} = 3\pi/2 + \psi_a$
- 3) When $r < a_e < 2r$, $\theta_{ex} = 3\pi/2 + \arcsin(1 - a_e/r) + \psi_a$
- 4) When $a_e = 2r$, $\theta_{ex} = 2\pi + \psi_a$

The size of $\theta_{ex}-\theta_{st}$ and ψ_a determine whether the cutting edge which its the axial depth of cut is a_p can all involved in cutting or not, so we discuss the bound of the integration under the following $\theta_{ex}-\theta_{st} \geq \psi_a$ and $\theta_{ex}-\theta_{st} < \psi_a$ two conditions. If the intersection angle in the number i edge line's end face is θ , the position angle at the bottom of the adjacent edge line is $\theta + 2\pi/N$.

1. If $\theta_{ex}-\theta_{st} \geq \psi_a$

1) When $\pi \leq \theta < \pi + \psi_a$, only part of the cutting edge go into the cutting, so the lower angle limit of integral should be π , upper limit of integral should be θ .

2) When $\pi + \psi_a < \theta \leq \theta_{ex} - \psi_a$, all of the cutting edge go into the cutting under the axial depth of cut, so the lower angle limit of integral should be $\theta - \psi_a$, upper limit of integral should be θ .

3) When $\theta_{ex} - \psi_a < \theta \leq \theta_{ex}$, part of the cutting edge has left the cutting area, but the above part still cutting, its lower angle limit of integral is $\theta - \psi_a$, upper limit of integral is θ_{ex} .

2. If $\theta_{ex}-\theta_{st} < \psi_a$

1) When $\pi \leq \theta \leq \theta_{ex} - \psi_a$, only part of the cutting edge goes into the cutting, so the lower angle limit of integral should be π , upper limit of integral should be θ .

2) When $\theta_{ex} - \psi_a < \theta \leq \pi + \psi_a$, all of the cutting edge go into the cutting under the axial depth of cut, so the lower angle limit of integral should be π , upper limit of integral should be $\theta_{ex} - \psi_a$.

3) When $\pi + \psi_a < \theta \leq \theta_{ex}$, part of the cutting edge has left the cutting area, but the above part still cutting, its lower angle limit of integral is $\theta - \psi_a$, upper limit of integral is $\theta_{ex} - \psi_a$.

5.1.3. Determining the Integrating Range of Climb Milling

As is shown in the Fig. 8, during the climb milling, the maximum cut-away angle is $\theta_{ex} = \pi + \psi_a$,

the minimum cut-in angle is θ_{st} has to be calculated by the milling width and mill's size under the 4 conditions below:

- 1) When $a_e < r$, $\theta_{st} = \pi/2 + \arcsin(1 - a_e/r)$
- 2) When $a_e = r$, $\theta_{st} = \pi/2$
- 3) When $r < a_e < 2r$, $\theta_{st} = 3\pi/2 - \arcsin(1 - a_e/r)$
- 4) When $a_e = 2r$, $\theta_{st} = 0$

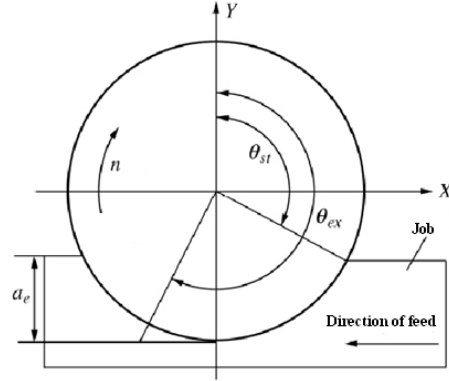


Fig. 8. Climb milling.

In a similar way, we discuss the bound of the integration under the following $\theta_{ex}-\theta_{st} \geq \psi_a$ and $\theta_{ex}-\theta_{st} < \psi_a$ two conditions.

1. If $\theta_{ex}-\theta_{st} \geq \psi_a$

1) When $\theta_{st} \leq \theta < \theta_{st} + \psi_a$, only part of the cutting edge go into the cutting, so the lower angle limit of integral should be θ_{st} , upper limit of integral should be θ .

2) When $\pi + \psi_a < \theta \leq \theta_{ex} - \psi_a$, all of the cutting edge go into the cutting under the axial depth of cut, so the lower angle limit of integral should be $\theta - \psi_a$, upper limit of integral should be θ .

3) When $\theta_{ex} - \psi_a < \theta \leq \theta_{ex}$, part of the cutting edge has left the cutting area, but the above part still cutting, its lower angle limit of integral is $\theta - \psi_a$, upper limit of integral is π .

2. If $\theta_{ex}-\theta_{st} < \psi_a$

1) When $\theta_{st} \leq \theta \leq \theta_{ex} - \psi_a$, only part of the cutting edge goes into the cutting, so the lower angle limit of integral should be θ_{st} , upper limit of integral should be θ .

2) When $\theta_{ex} - \psi_a < \theta \leq \theta_{st} + \psi_a$, all of the cutting edge go into the cutting under the axial depth of cut, so the lower angle limit of integral should be π , upper limit of integral should be $\theta_{ex} - \psi_a$.

3) When $\theta_{st} + \psi_a < \theta \leq \theta_{ex}$, part of the cutting edge has left the cutting area, but the above part still cutting, its lower angle limit of integral is $\theta - \psi_a$, upper limit of integral is $\theta_{ex} - \psi_a$.

5.2. The Modeling of the Cutting Force at the Bottom of the Cutting Edge

The bottom cutting edges of the end mill is also involved in the cutting. As the bottom cutting edges and the cutting speed always vertical, so the cutting

progress of the bottom cutting edges can be regarded as the orthogonal cutting. The resultant cutting force in the vertical cutting is the function of the shear stress t_s , frictional angle β , shear angle Φ_c , cutting width and feed rate.

$$F = \frac{t_s a_p a_e}{\sin \phi_c \cos(\phi_c + \beta - \gamma_o)}$$

In the expression: Except the frictional angle β and the shear angle Φ_c , other parameters can be obtained through consulting the related manual.

During the vertical cutting, the relationship between the cutting speed V , shearing velocity V_s and the speed of chip flow V_c is

$$V = V_c - V_s$$

$$V \times h_D = V_c \times h_{ch}$$

according to the incompressible of the metal material, we decompose the force above into the coordinate axis, substituting into the expression above, we can get

$$\cot \phi_c = -\tan \gamma_o + \frac{\Lambda_h}{\cos \gamma_o}$$

In the expression: $\Lambda_h = \frac{h_{ch}}{h_D}$

We calculating the cutting force choosing the value of the compression ratio of chip is 1.8, the shear angle $\Phi_c = 30.2^\circ$, frictional angle $\beta = 19.8^\circ$, after calculating, we get the $F = 68$ N, $F_x = 65.6$ N, $F_z = 17.5$ N.

So whole cutting force of the mill is the sum of the cutting force at side-edge and bottom.

6. The Consequence of the Experiment and the Simulation

According to the established model of the cutting force above, we can get the cutting force curve along the direction of the x-axis as is shown in Fig. 9 under the following condition that the speed of main spindle is 6000 r/min, feed per tooth is $f_z = 0.1$ mm/tooth, the cutting parameters are listed as follows: the axial depth of cut are $a_p = 1$ mm and $a_p = 2.5$ mm, the width of mill are $a_e = 2$ mm, $a_e = 3$ mm, $a_e = 6$ mm and $a_e = 12$ mm separately.

- 1: $a_p = 2.5$ mm, $a_e = 6$ mm Up milling curved
- 2: $a_p = 1$ mm, $a_e = 12$ mm Climb milling curved
- 3: $a_p = 1$ mm, $a_e = 3$ mm Up milling curved
- 4: $a_p = 1$ mm, $a_e = 2$ mm Up milling curved
- 5: $a_p = 1$ mm, $a_e = 2$ mm Climb milling curved

The Fig. 10 shows the measured value of the cutting force along the one rotation of the mill. The experiment condition are: The experiment machine is

machining center Ouma MV-610, the equipment of obtaining the value of the cutting force is the general contact-type dynamometer, the equipment of gathering the data is the Multifunctional acquisition meter, the frequency of sampling is 7000 Hz, the end mill is Kenna HA-DIN6542 end mill with 4 cutting edge, 12 mm diameter, spiral Angle is 55° and the work material is T8A high quality carbon tool steel with the rigidity is 42HRC. The cutting parameters correspond with the curve 4 in Fig. 9.

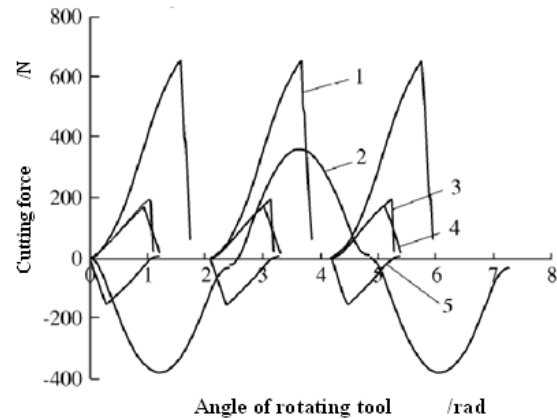


Fig. 9. The simulation value of the X-axis's cutting force.

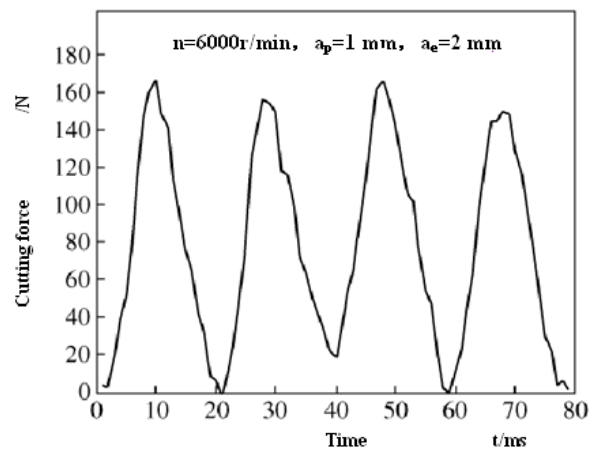


Fig. 10. The measured value of the X-axis's cutting force in high speed milling.

When the mill begin cutting, only part of the cutting edge go into the cutting, so the cutting force is very low at the beginning. After all of the cutting edge go into the cutting under the axial depth of cut and the cutting force will reach peak when the mill rotating, then the cutting force will become lower because of the decrease of thickness of cutting layer and will become 0 at last. Comparing the curve 4 in Fig. 9 with the Fig. 10, the change trend of the waveform and the value of the amplitude in the simulation cutting force is coincided well with the measured milling force.

7. The Results and Discussion

The model of flat end mill is established. The mill along the axial direction is discretized and the cutting force of the infinitesimal and the whole cutting force in the mill process are calculated by means of the numerical integration. The model of cutting force we established taking into account of the cutting in the flank edge and the bottom cutting edge which is conformed to the truth, and can simulate the force condition of the mill during milling well. The cutting force is simulated using the model we established and the verification test of cutting force has been done. The results show that the maximum error values between the simulation and the measurement is 7.5 %. As not consider the influence of the tool wear and radial run-out of the mill, the vibration in the manufacturing system and other influences, a certain error values between the simulation and the measurement still remained. The cutting force can be simulated well through this cutting force model during milling, and the foundation of the cutter's stress field can be laid by this model.

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