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Modeling and Simulation Research of Ball End Mill Rake Face

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According to the structure of the ball end mill and the cutter grinding principle, a mathematic model related to the ball blade rake face and circumference blade rake face was established. On the Solidworks platform, the rational motor program was compiled and the machining process of the ball end mill rake face was simulated. Through the analysis of the simulation results, the accuracy of the rake face mathematical model was proved. The ball end part has the proper S-shaped arc blade. The ball blade was smoothly connected with the circumference blade. The ball blades had a relatively large positive rake angle and were rationally distributed. All these provided the basis for the development of low-cost and high-profit CNC cutter grinding devices.

1. Introduction

High-speed cutting technique is finding more and more applications in the development of the manufacturing industry. Thus, there is a high requirement of the high-speed cutting tools. As an emerging efficient tool developed over the recent several decades, ball end mill is mainly used for the rough and fine machining of complex surfaces. Due to the dotted line contact with the machining surface, it can be used flexibly and its structure is more complex. With the rapid development of the automobile industry, the die industry and the machine tool industry, there is a significant growth in the demands of the ball end mill. However, China only several ball end mill manufacturers, including Avic Shaanxi Aeronautic Carbide Tool Company and Shanghai Tool Works Co., Ltd. The annual productivity is extremely low and the quality cannot reach the international leading standard (Ni, 2006). Foreign countries mainly adopt six-axis linkage machine tool for the production, thus resulting in the high price of imports to China. After an in-depth analysis of the cuter grinding characteristics and formation principle of the ball end mill rake face, this paper puts forward a new ball end mill rake face mathematical model and adopts the generatrix of the saucer wheel as the generatrix of the rake face. The motor is quite simple and only calls for the adjustment of some machining parameters, so it can machine the ball blade rake face and the circumference rake face at one time, achieve the smooth connection of the blade form, ensure the sound S-shappe blade and rational rake angle and reduce the manufacturing cost of the ball end mill.

2. Ball blade rake face machining

Ball end mill is made up of two parts, the ball end and the blade handle. In order to turn out ball end mill with a proper structure on the tool grinder, it is necessary to establish a rake face model based on the blade curve. Since the grinding wheel's machining of the rake face is an approximate machining, the grinding wheel forms a series of scattering cutter location points on the milling cutter workblank instead of the dispersion of a continuous movement. Due to that, the practical machining surface might not be a continuous helicoidal surface (Ma, 2009).

To achieve the cutter grinding of the ball end mill and ball blade rake face, it is necessary to not only conduct regular rotation revolving around ball end mill axis after the adjustment of the grinding wheel's posture, but also have translational motion along three axes, the X-axis, the Y-axis and the Z-axis. The position relation between the grinding wheel and the ball end mill is shown in Figure 1 (He and Li, 2009).

BBe is the rake face groove bottom curve of the ball end mill. When the grinding wheel and the workpiece conduct relative movement, the great circle circumference of the grinding wheel, P_0PPe, remains tangent to the groove bottom curve, BBe, and forms the spiral groove rake face on the workpiece. During the cutter

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grinding process of the rake face, the great circle circumference of the grinding wheel is first tangent to the groove bottom curve, B. At last, the lowest point of the grinding wheel, Pe, is tangent to the end point of the groove bottom curve, B. Since the lead angle of various points on the profile of the spiral groove is different, the profile of the spiral groove is the twisted surface. In order to avoid the interference and tangency of the grinding wheel and the workpiece's spiral groove, the installation angle, α should be larger than the spiral angle by 1～3°. Assume the spiral angle as β. Then $\alpha=\beta+(1\sim3°)$ (He, 2005). In order to increase the universality of the cutter grinding method, revolved the grinding wheel's circumference end around the great circle of the grinding wheel by the angle of "b." The following three coordinate systems were established (Figure 1):

Workpiece coordinate system $\sigma=[O; X, Y, Z]$: *O* is fixed on the center of the ball end;

Grinding wheel coordinate system $\sigma_S=[O_S; X_S, Y_S, Z_S]$: O_s is in the center of the grinding wheel's great circle; $O_sX_sY_s$ is on the surface of the grinding wheel's great circle; Z_s is perpendicular to $O_sX_sY_s$.

Machine tool coordinate syste, $\sigma_0=[O_0; X_0, Y_0, Z_0]$: For the convenience of calculation, assume the initial position of the machine tool coordinate system $\sigma_0=[O_0; X_0, Y_0, Z_0]$ is overlapped with that of the workpiece coordinate system $\sigma=[O; X, Y, Z]$. The origin of coordinate is located in the center of the ball end, *O*.

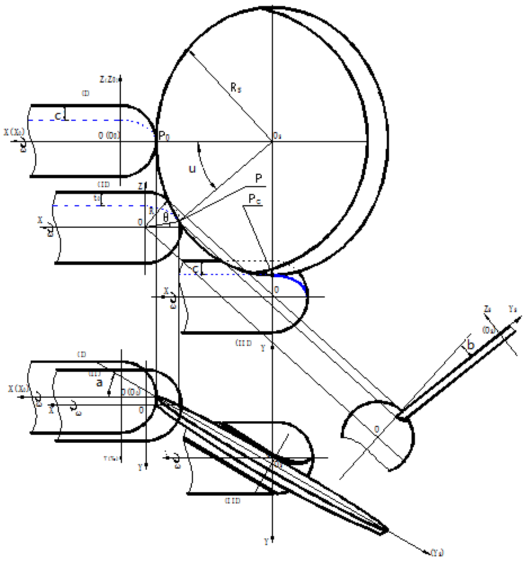


Figure 1: Cutter grinding movement relation diagram of the ball end mill rake face

(1) Solution of the equation of the circumference of the grinding wheel, P_0PPe, in the machine tool coordinate system, $\sigma_0=[O_0; X_0, Y_0, Z_0]$:

$$\begin{pmatrix} X_{S0} \\ Y_{S0} \\ Z_{S0} \end{pmatrix} = \begin{pmatrix} \cos a & 0 & \sin a \\ 0 & 1 & 0 \\ -\sin a & 0 & \cos a \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos b & -\sin b \\ 0 & \sin b & \cos b \end{pmatrix} \begin{pmatrix} R_S \cos u \\ -R_S \sin u \\ 0 \end{pmatrix} + \begin{bmatrix} -R-R_S \cos a \\ R_s \sin a \\ 0 \end{bmatrix}$$

$$= \begin{pmatrix} R_S \cos a \cos u - R_S \sin a \sin b \sin u - R - R_S \cos a \\ -R_S \cos b \sin u + R_s \sin a \\ -R_S \sin a \cos u - R_S \cos a \sin b \sin u \end{pmatrix} \quad (1)$$

Among them, Rs stands for the diameter of the grinding wheel, R for the diameter of the ball end mill, α for the deflection angle of the perpendicular Z-axis of the grinding wheel's great circle, b for the deflection angle of the horizontal X-axis of the grinding wheel's great circle.

(2) Solution of the equation of the radial normal vector, $\vec{P_S}$, of the grinding wheel's great circle in the machine tool coordinate system

The equation of the radial normal vector, $\vec{p}_{S0}$, of the grinding wheel's great circle in the grinding wheel coordinate system can be expressed as:

$$\begin{pmatrix} P_{S0X} \\ P_{S0Y} \\ P_{S0Z} \end{pmatrix} = \begin{pmatrix} \mathrm{R_S}\cos u \\ 0 \\ -\mathrm{R_s}\sin u \end{pmatrix} \tag{2}$$

The equation of the radial normal vector, $\vec{P}_S$, of the grinding wheel's great circle in the machine tool coordinate system can be expressed as:

$$\begin{pmatrix} P_{SX} \\ P_{SY} \\ P_{SZ} \end{pmatrix} = \begin{pmatrix} \cos a & 0 & \sin a \\ 0 & 1 & 0 \\ -\sin a & 0 & \cos a \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos b & -\sin b \\ 0 & \sin b & \cos b \end{pmatrix} \begin{pmatrix} \mathrm{R_S}\cos u \\ 0 \\ -\mathrm{R_S}\sin u \end{pmatrix}$$

$$= \begin{pmatrix} \mathrm{R_S}\cos a\cos u - \mathrm{R_S}\sin a\cos b\sin u \\ \mathrm{R_S}\sin b\sin u \\ -\mathrm{R_S}\sin a\cos u - \mathrm{R_S}\cos a\cos b\sin u \end{pmatrix} \tag{3}$$

(3) The solution of the normal vector, $\vec{P}_C$, of the groove bottom curve of the ball end mill

BBe, the groove bottom curve of the ball end mill, is a spiral line on the ellipsoid surface. Its equation can be expressed as below:

$$\begin{pmatrix} X_{C0} \\ Y_{C0} \\ Z_{C0} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\omega & -\sin\omega \\ 0 & \sin\omega & \cos\omega \end{pmatrix} \begin{pmatrix} -R\cos\theta \\ 0 \\ (R-c)\sin\theta \end{pmatrix} = \begin{pmatrix} -R\cos\theta \\ -(R-c)\sin\theta\sin\omega \\ (R-c)\sin\theta\cos\omega \end{pmatrix} \tag{4}$$

Where, ω stands for the angle that the ball end mill revolves around the X-axis. Conduct derivation of θ , then:

$$\vec{Q}_{C\theta} = \begin{pmatrix} Q_{CX_\theta} \\ Q_{CY_\theta} \\ Q_{CZ_\theta} \end{pmatrix} = \begin{pmatrix} R\sin\theta \\ -(R-c)\cos\theta\sin\omega \\ (R-c)\cos\theta\cos\omega \end{pmatrix} \tag{5}$$

Conduct derivation of ω, then:

$$\vec{Q}_{C\omega} = \begin{pmatrix} Q_{CX_\omega} \\ Q_{CY_\omega} \\ Q_{CZ_\omega} \end{pmatrix} = \begin{pmatrix} 0 \\ -(R-c)\sin\theta\cos\omega \\ -(R-c)\sin\theta\sin\omega \end{pmatrix} \tag{6}$$

The normal vector, *Pc*, on the BBe groove bottom spiral line is:

$$\vec{P}_C = \vec{Q}_{C\theta} \times \vec{Q}_{C\omega} = \begin{pmatrix} P_{CX} \\ P_{CY} \\ P_{CZ} \end{pmatrix} = \begin{pmatrix} (R-c)^2\sin\theta\cos\theta \\ (R-c)R\sin^2\theta\sin\omega \\ -(R-c)R\sin^2\theta\cos\omega \end{pmatrix} \tag{7}$$

(4) Solution of the point of tangency, P, between the grinding wheel's circumference, P_0PPe, and the groove bottom spiral line, BBe.

To ensure the tangency of the grinding wheel's circumference, P_0PPe, and the groove bottom spiral line of the ball end mill, BBe, the radial normal vector of the grinding wheel's great circle, P_0PPe, and the BBe normal vector of the ball end mill at the tangency point should be overlapped with each other, namely:

$$\frac{P_{SX}}{P_{CX}} = \frac{P_{SY}}{P_{CY}} = \frac{P_{SZ}}{P_{CZ}} \tag{8}$$

Substitute the above equation into the below Eq. (9), then

$$\begin{cases} \dfrac{R_S(\cos a\cos u-\sin a\cos b\sin u)}{(R-c)^2\sin\theta\cos\theta}-\dfrac{R_S(\sin a\cos u+\cos a\cos b\sin u)}{(R-c)R\sin^2\theta\cos\omega}=0 \\ \dfrac{R_S\sin b\sin u}{(R-c)R\sin^2\theta\sin\omega}-\dfrac{R_S(\sin a\cos u+\cos a\cos b\sin u)}{(R-c)R\sin^2\theta\cos\omega}=0 \end{cases} \quad (9)$$

When θ is of a fixed value, the equation set has a group of solution, ω,u, corresponding to it(Ren et al., 2001).Employ the root solution equation and set values according to θ to work out the correspondingω,u. Ten a series of tangency points, P, can be worked out based on Eq. (9).

(5) Solution of the relative movement trace between the workpiece and the grinding wheel.

Convert the coordinate of the tangency point on the spiral line within the groove bottom, $\sigma_0=[O_0; X_0, Y_0, Z_0]$, and the coordinate of the tangency point on the grinding wheel's circumference so as to work out the relative movement trace in the machining process of the workpiece and the grinding wheel (Shi et al., 1994). It can be expressed as below:

$$\begin{pmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{pmatrix}=\begin{pmatrix} X_{C_0} \\ Y_{C_0} \\ Z_{C_0} \end{pmatrix}-\begin{pmatrix} X_{S0} \\ Y_{S0} \\ Z_{S0} \end{pmatrix}$$

$$=\begin{pmatrix} -R\cos\theta \\ -(R-c)\sin\theta\sin\omega \\ (R-c)\sin\theta\cos\omega \end{pmatrix}-\begin{pmatrix} R_S\cos a\cos u-R_S\sin a\sin b\sin u-R-R_S\cos a \\ -R_S\cos b\sin u+R_s\sin a \\ -R_S\sin a\cos u-R_S\cos a\sin b\sin u \end{pmatrix} \quad (10)$$

If b=0°, (11) can be obtained:

$$\begin{pmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{pmatrix}=\begin{pmatrix} X_{C_0} \\ Y_{C_0} \\ Z_{C_0} \end{pmatrix}-\begin{pmatrix} X_{S0} \\ Y_{S0} \\ Z_{S0} \end{pmatrix}=\begin{pmatrix} R(1-\cos\theta)+R_S\cos a(1-\cos u) \\ R_S(\sin v-\sin a)-(R-c)\sin\theta\sin\omega \\ (R-c)\sin\theta\cos\omega+R_S\sin a\cos u \end{pmatrix} \quad (11)$$

3. Circumference blade rake face machining

When the grinding wheel conducts spiral movement relative to the ball end mill, the circumference that the grinding wheel and the workpiece contact arc forms the spiral groove on the workpiece. During the manufacturing process of the ball end mill, the machining of the ball blade and the circumference blade are finished at once. Therefore, after the cutter finishes the grinding of the ball blade, the grinding wheel conducts the spiral movement relative to the workpiece and the enveloping surface of the grinding wheel's generatrix movement is the circumference blade rake face (Zhu, 2000). The relative movement relation and the position relation between the grinding wheel and the milling cutter's workblank during the machining of the circumference blade rake face are shown in Figure 2.

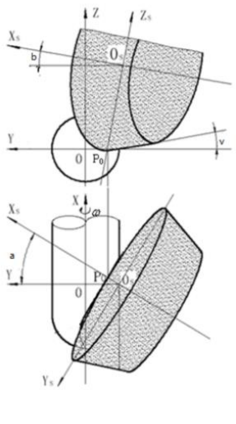


Figure 2: Position relation between the grinding wheel and the milling cutter's workbank of the circumference blade rake face

After the ball blade rake face is formed based on the above method, B point reaches B_e point. (Figure 3) The outer circular cone generatrix of the grinding wheel conducts the axial movement revolving around the axis of the ball end mill and forms the circumference rake face.

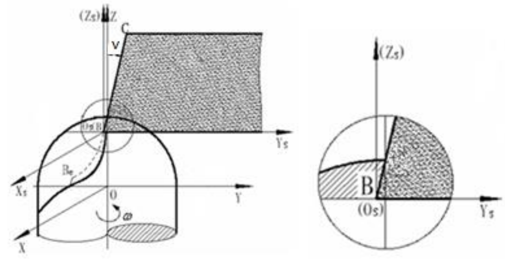


Figure 3: The transition between the ball blade rake face and the circumference blade rake face

If the circumference blade rake face is the orthogonal spiral surface, the circumference blade rake face equation (He, 2005) can be expressed as:

$$\begin{cases} X = R_1 \cos\omega \\ Y = R_1 \sin\omega \\ Z = \dfrac{P_z}{2\pi}\omega \end{cases} \tag{12}$$

Where, R_1 stands for the radius of any point on the circumference blade rake face, and the calculation formula of R_1 can be expressed as:

$$R_1 = \sqrt{X^2 + (X-R)^2 \tan^2 v} \tag{13}$$

v stands for the included angle between the generatrix and the axis of the grinding wheel, namely the semi-conicity of the circular cone grinding wheel.

4. Machining and simulation of the ball blade rake face and the circumference blade rake face

From the mathematic model of the ball end mill rake face, the change of any parameter can change the structure of the milling cutter to different degrees. In order to more directly verify the accuracy of the mathematical model, quantitative analysis was conducted to study the influence of cutter grinding parameters on the rake face structure so as to avoid the waste of time and materials brought by multiple on-site trial cuts. VB programming language was employed to conduct secondary development of Solidworks. The Boolean difference set calculation principle between the physical objects [8] was adopted to establish a set of cutter grinding simulation situation of the ball end mill rake face. In the system, various cutter grinding parameters or blank dimensions can be interactively changed so as to directly obtain different shapes of the milling cutter. The simulation result is shown in Figure 4.

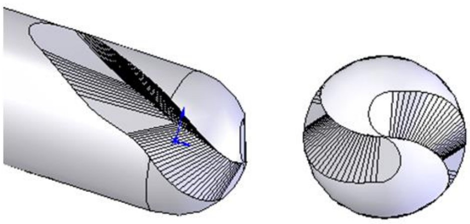
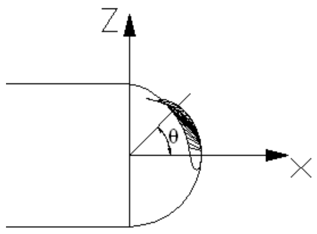


Figure 4: Rake face simulation result

5. Ball blade rake face and rake angle distribution

The ball blade rake face is a group of special curved surfaces. Its intersection with the ball surface is the blade-shaped curve of the ball blade. Since the normal vector of every point on the ball blade is changing, the reference plane of the ball blade rake face is also changing. Θ is defined as the included angle, or rake angle, between the ligature of the point and center of the ball blade on the profile, and the projection of the rake face. (Figure 6)



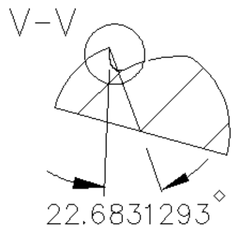


Figure 5: Ball blade angle, θ *Figure 6:Measurement of the ball blade rake face*

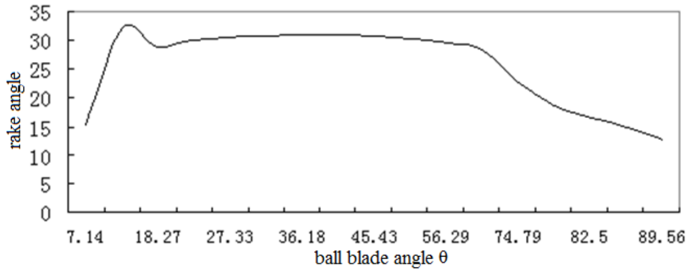


Figure 7: Ball blade angle θ-rake angle distribution diagram

6. Conclusions

From Figure 4, it can be seen that the mathematical model of the ball end mill rake face can grind the mill with a proper structure, machine the ball blade rake face and the circumference rake face at one, achieve the smooth connection and facilitate the discharge of cuttings. The cutting edge of the ball end part features a S-shaped arc blade. There is no sharp corner on the blade and the ball blade goes through the axial center of the milling cuter, which is conducive to the stability of the tool's cutting process. From Figure 7, it can be seen that the rake angles of the ball blade rake face are all relatively large positive large, with the largest one being large than 32° and the smallest one being 12°. The distribution of rake angles increases first and then decreases from the top of the ball end to the outer edge. In other words, the rake angle near the top of the ball blade is relatively small, the rake angle in the center is relatively large and the rake angle near the circumference is relatively small. All in all, the rake angle distribution is relatively proper.

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