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A practical approach for simulation and manufacturing of a ball-end mill using a 5-axis CNC grinding machine†

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Abstract

This paper presents a detailed manufacturing model that can be used for grinding a ball-end mill using 5-axis CNC (computer numerical controlled) grinding machine. The profile of the helical groove can be calculated exactly using the given wheel profile and relative movements between the workpiece and the grinding wheel. The proposed model is related to some analytical, differential geometry and kinematics to control the motions of the workpiece and grinding wheels in grinding processes. The manufacturing model presented in this paper provides a practical and efficient method for developing the simulation software for the design and the manufacture of a ball-end mill.

Keywords: Ball-end mill; Helical groove machining; Cutting edge; CNC grinding machine; Grinding wheel

1. Introduction

Ball-end mills are widely used in industry for high speed milling operation and machining three-dimensional complicated surfaces, such as molds, sculptured dies, turbine blades and aerospace parts. The grinding of a ball-end mill with a complex geometry is related to some complicated processes in machining. The research on ball-end mill cutters manufacturing has drawn the interest of many researchers. Several related works on the aforementioned topics are concerned with the design and machining of the helical groove, cutting edge curves or take insights on some special cases in the design and manufacture [1-7]. The results and conclusions in some specific cases can hardly be applied to others in practice. Many commercial software for tool grinding has been developed and widely used in tool manufacturing industry. However, most existing software packages for ball-end mill simulation allow limited users to design, modify and manufacture the complex shapes of cutting edges located precisely on a spherical surface. This paper presents a practical model for developing the simulation software for the design and the manufacture of a ball-end mill. The objective of this study is to develop an effective approach for the grinding of a ball-end mill based on some analytical, differential geometry, kinematics and proper curvilinear coordinates to parameterize the kinematic geometry of relative motions between the grinding wheel and workpiece (ball-end mill). Fig. 1 shows the configuration of a 5-axis CNC machine for manufacturing of ball -end mill, which has five degrees of freedom: three axes in translation (X, Y, Z) and two axes in rotation (A, W).

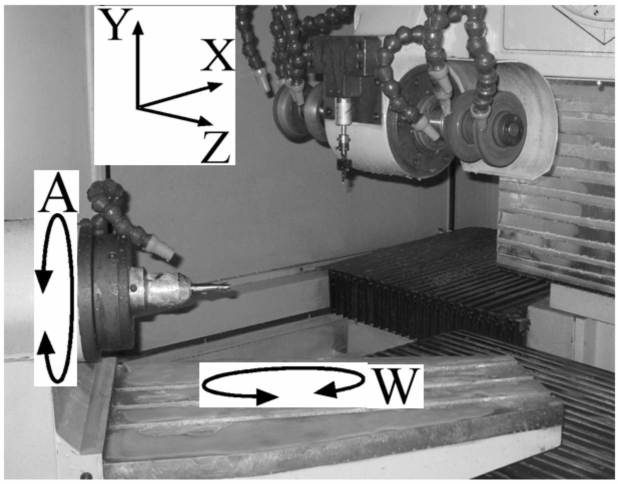

Fig. 1. The 5-axis CNC grinding machine for manufacturing of ball-end mills.

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2. Modeling of ball-end mill grinding

2.1 Helical flute grinding

The mathematical model for helical flute machining is based on the theory of enveloping and the fundamental analytical conditions of engagement between the generating tool surface and the helical groove surface [7, 8]

A coordinate system $O_tX_tY_tZ_t$ attached to the ball-end mill and a machine coordinate $O_mX_mY_mZ_m$ attached to the machine are employed. In coordinate system $O_wX_wY_wZ_w$ of the grinding wheel, the point P on the wheel surface profile can be expressed as:

$$R_w = \begin{Bmatrix} X_w(\theta,\delta) \\ Y_w(\theta,\delta) \\ Z_w(\theta,\delta) \end{Bmatrix} = \begin{Bmatrix} \left(\frac{D}{2} - \frac{\delta_0 - \delta}{tg\Omega}\right)\cos\theta \\ \left(\frac{D}{2} - \frac{\delta_0 - t}{tg\Omega}\right)\sin\theta \\ \delta \end{Bmatrix} \quad (1)$$

where D, δ_0 and Ω are given geometry parameters of the grinding wheel as shown in Fig. 2, the angle θ is the circumferential angle of the point P on the wheel profile, δ is the location of point P in Z_w -axis $(0 \le \delta \le \delta_0)$.

Fig. 2 shows the relative movement between the grinding wheel and workpiece in grinding processes based on the coordinates of machine and workpiece. To calculate and simulate the generation of a helical flute profile, the grinding wheel is assumed to be moving helically around a stationary workpiece by the translation $L\varphi/2\pi$ and rotation φ . The helical-groove surface generated in the coordinate system $O_tX_tY_tZ_t$ can be expressed as $R_t(X_t(\theta,\delta), Y_t(\theta,\delta), Z_t(\theta,\delta))$:

$$X_t = \left(\left(\frac{D}{2} - \frac{\delta_0 - \delta}{tg\Omega}\right)\cos\theta + T_y\right)\cos\varphi - \\ -\left(\left(\frac{D}{2} - \frac{\delta_0 - \delta}{tg\Omega}\right)\sin\theta\cos\beta - \delta\sin\beta\right)\sin\varphi \quad (2)$$

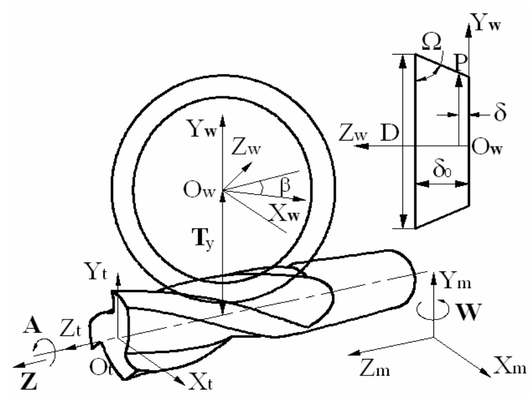

Fig. 2. Schematic for helical fluting grinding process and grinding wheel geometry parameters.

$$Y_t = \left(\left(\frac{D}{2} - \frac{\delta_0 - \delta}{tg\Omega}\right)\cos\theta + T_y\right)\sin\varphi + \\ +\left(\left(\frac{D}{2} - \frac{\delta_0 - \delta}{tg\Omega}\right)\sin\theta\cos\beta - \delta\sin\beta\right)\cos\varphi \quad (3)$$

$$Z_t = \left(\left(\frac{D}{2} - \frac{\delta_0 - \delta}{tg\Omega}\right)\sin\theta\sin\beta + \delta\cos\beta + \frac{L_p\varphi}{2\pi}\right) \quad (4)$$

where L_p is the pitch of helical flute, β is the intersecting angle and T_y is the vertical distance between the axes of the grinding wheel and the workpiece. The relative velocity of the surfaces V at the contact points must be orthogonal to the normal vector of tool surface N :

$$\overline{N}.\overline{V} = 0 \quad (5)$$

The flute profile is the projection of helical groove surface enclosed in the cylindrical part of ball-end mill to a cross-section plane perpendicular to the Z-axis. It can be found by selecting a proper value $Z_t = C$, where C is constant, and substituted into Eq. (2), (3) and (4). Fig. 3 shows the simulation result of the cross-section of the helical flute on the cylindrical part. The envelope equation of the enveloped curve in the cross-section of helical groove surface can be expressed by:

$$\frac{\partial X_t(\theta,\delta)}{\partial\theta}\frac{\partial Y_t(\theta,\delta)}{\partial\delta} - \frac{\partial Y_t(\theta,\delta)}{\partial\theta}\frac{\partial X_t(\theta,\delta)}{\partial\delta} = 0 \quad (6)$$

2.2 Grinding process of the rake face and the cutting edge

The spiral curve of the cutting edge of the ball-end mill, which has a constant pitch helical groove, is located on both the cylindrical and the spherical surfaces. The position of point G on the cutting edge curve located on the spherical surface (AC) can be represented as the parametric function [3]:

$$r(\theta_b, Z) = \left\{\sqrt{R^2 - Z^2}\cos\theta_b, \sqrt{R^2 - Z^2}\sin\theta_b, Z\right\} \quad (7)$$

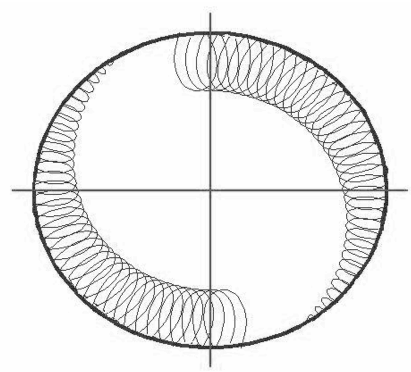

Fig. 3. Simulation result of cross-section of the helical flute.

where R is the radius of the ball-end mill and φ_b is the angle between the tangent vector dr of the point on the cutting edge and the tangent vector δr of the point on the generator curve. The angular parameter θ_b can be expressed as:

$$\theta_b = \frac{1}{2}\tan\varphi_b \ln\frac{R+Z}{R-Z} \tag{8}$$

The position of point G_c on the cutting edge curve located on the cylindrical surface (CD) can be represented as the parametric function as:

$$r(\theta_c, Z) = \{R\cos\theta_c, R\sin\theta_c, Z\} \tag{9}$$

where θ_c is the polar angle of the point G_c.The cutting edge curve must be a continuous curve, $r(\theta_c, Z) \in C^2$ continuity condition. At point C, $G \equiv G_c$, the polar angles of the point G and G_c satisfy. $\theta_c = \theta_b$.

We set up a movable coordinate system $GN_nT_nB_n$ located on grinding points G of cutting edge curve. T_n and N_n are the unit tangent and normal vector of cutting edge curve at G. The bi-normal vector B_n is the cross product of T_n and N_n. The equation of the cutting edge curves can be express as a vector-valued function of a parameter s $(a \le s \le b)$:

$$r = r\{\theta, Z\} = r(s) \tag{10}$$

According to differential geometry, the unit vector N_n, T_n and B_n with respect to the coordinate system $O_tX_tY_tZ_t$ can be calculated as:

$$T_n = \frac{dr/ds}{|dr/ds|} \tag{11}$$

$$N_n = \frac{d^2r/ds^2}{|d^2r/ds^2|} \tag{12}$$

$$B_n = T_n x N_n \tag{13}$$

At the contact points between ball-end mill and wheel surface, the relative velocity of the surfaces V_Σ must be orthogonal to the normal vector N of the surface:

$$N_G.V_\Sigma = 0 \tag{14}$$

The normal rake angle and first relief angles are defined as the tangential angle γ_n and α in the normal cross-section (P_n) at each grinding point G of the cutting edge (Fig. 4). The cutting edge and the rake face are ground and obtained synchronously during the rake face grinding process by using the conical surface of grinding wheel as shown in Fig. 5. The orientation and position of the grinding wheel and workpiece are determined by required normal rake angle γ_n, B_n and the instantaneous change in the unit tangent vector T_n along the cutting edge curve. At the first step of the grinding process, X,

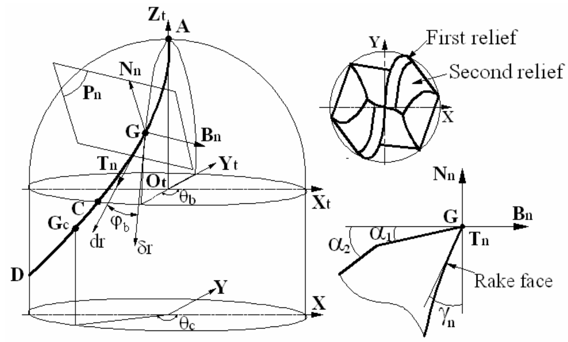

Fig. 4. Geometry of the spherical part and the cutting edge curve.

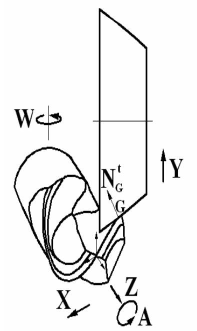

Fig. 5. Scheme for rake face grinding process.

Y, Z and W axes move at the same time to the approach distance of grinding. Then X and Z axes move forward and shift to the grinding face of the wheel and the cutting face of a ball-end mill. The A-axis is moving simultaneously with X, Y, Z and W to grind the required rake face and smooth cutting edge curve of the spherical part.

The depth of the helical groove can be ground by swinging the grinding wheel. After finishing the rake face grinding process of the spherical part, the Z and A axes move simultaneously to grind the helical groove in cylindrical part. Finally, the Y-axis moves upward in the vertical direction to exit the helical groove surface.

2.3 Grinding process of the relief faces

Fig. 6 shows the scheme for the first relief face grinding process. The orientation and position of the grinding wheel and workpiece are determined by the first relief angel α_1, B_n and the instantaneous change in the vector T_n at each grinding point G.

The grinding face of wheel contacts to the tip of the ball-end mill at point S on the grinding wheel surface. The A-axis and W-axis rotate to satisfy the relief angle α, then the X, Z, Y, A, and W axes start simultaneously to grind the first relief face from the tool tip to the end of relief face. During this grinding process, the grinding points on the wheel surface, which contact to cutting edge, change from point S to point E of the grinding wheel surface. After finishing the grinding process on the spherical part, the Z-axis moves forward and

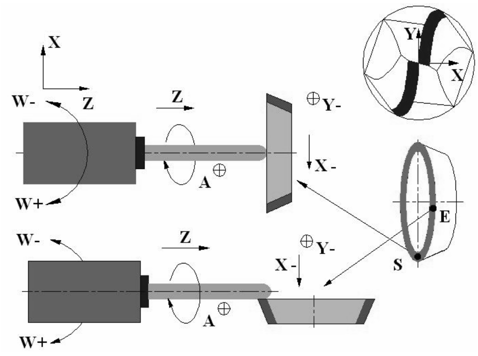

Fig. 6. Scheme for the first relief face grinding process.

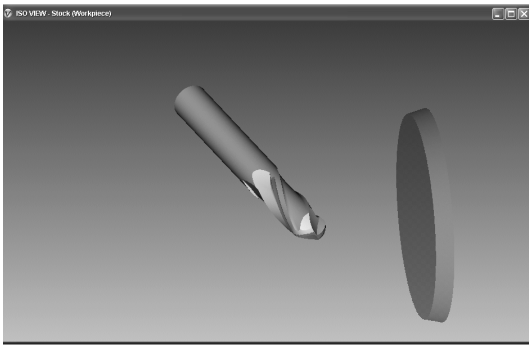

Fig. 7. Simulation result of ball-end mill grinding.

Fig. 8. The spherical part of machined ball-end mill.

the A-axis rotates simultaneously to grind the first relief face on the cylindrical part. Finally, the Y-axis moves upward to exit the first relief face. The second relief face can be ground by following the above sequence of the grinding process.

3. Simulation and grinding performance

In this section, we use the proposed model for the performance of a grinding simulation and manufacturing of a ball-end mill with the following design parameters: R=6 mm, helix angle is 30^0, $\gamma_n = 8^0$ and relief angles $\alpha_1 = 8^0$, $\alpha_2 = 25^0$.

The computer program will calculate and generate the NC code which is used for simulation of all grinding processes and manufacturing of ball-end mill using a 5-axis CNC grinding machine. Fig. 7 shows the simulation result of ball-end mill grinding by using proposed model and Vericut. Fig. 8 shows a ball-end mill sample was machined by using developed software. The simulation and measurement results of the manufactured ball-end mill are shown in Table 1.

Table 1. The simulation and measurement results of manufactured ball-end mill.

	Helix angle	Rake angle	relief angle
Simulation	30^0	7.7^0	8.2^0
Measurement	30^0	7.5^0	8.5^0

4. Conclusion

The modeling, simulation results, and grinding performance indicate that the manufacturing model presented in this paper provides a practical and efficient method to develop the simulation software for designing and predicting the proper ball-end mill geometry before manufacturing. The proposed model can be implemented readily and applied to develop the simulation software in a practical sense for the design and the manufacture of ball-end mills using a 5-axis CNC grinding machine.

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