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A Practical CNC Grinding Algorithm for Ball-End Mill and the OpenGL Simulation of the Algorithm

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Abstract. This paper presents a detailed algorithm that can be used in grinding a ball-end mill with a five-axis CNC grinding machine. To obtain a high-precision algorithm, a mill mathematical model is required before the profile of the mill gets parameterized. So the profile of the mill can be indicated by a group of parameters. We can set a unique local coordinates system for each grinding part. Then, with the mathematical model, the relative motions between the workpiece and the grinding wheel can be gotten. The NC code can be obtained easily. If we transmit the NC code to a simulation software based on OpenGL and make a 3D simulation before machining the mill, the NC code could get an effective test.

1. Introduction

The ball-end mill can play an irreplaceable role in complex surfaces machining for its high adaptability. It is being widely used in military, energy, medical, communication, transportation and some other fields for high-speed machining. As the manufacturing industry developing, higher requirements have been put forward for ball-end mill. The demands for high quality ball-end mill are becoming more and more urgent. The designing, grinding and the simulation of the ball-end mill have attracted many researchers' attention now.

In previous studies, it is very hard to satisfy all the requirements of cutting angle, Core-diameter and rake angle simultaneously [, ]. When grinding a relief, these studies can exactly control normal relief while can’t make it in orthogonal relief[ ], which can easily cause the ball-head not round enough.

This paper proposes an algorithm for ball-end mill based on a five-axis CNC grinding machine hardware. The algorithm can satisfy all the three parameter requirements in helical groove grinding. It can also accurately control both the normal relief and the orthogonal relief. This algorithm can help to develop a relevant CAM software, and can also give references to the machining of some other high-speed cutter tools, such as drill cutters.
2. Organization of the Text

2.1. Modeling of ball-end mill grinding

Five grinding parts constitute the mathematical model of a ball-end mill: Gash out, Body clearance, Tip clearance, Mill groove and Relief. Every part is fixed with its own geometry parameters [3]. For example, the mill groove is fixed with two parameters: Core diameter and Rake angle. And the mill relief is fixed with another two parameters: Land-width and Relief angle.

The mill cutting edge consists two sections: a S-shape section on ball head and a helical section on mill cylinder (Fig.1).

![Figure 1. The major cutting edge](image1)

![Figure 2. The cross-section of a mill](image2)

The helical mill groove can be used when milling a plane. To strike a balance between stiffness and debris removal ability, the mill have certain requirements on the Core-diameter D. To make sure the mill can be sharp enough, the mill have certain requirements on the parameter of Rake angle $\gamma$.

As a result of relief, the friction between workpiece and ball-end mill decreases when milling. Generally, Relief has two kinds: flat relief and round relief [3]. The model of flat relief can also be seen in Fig.2: BA represents Relief 1’s Land-width, CB represents Relief 2’s Land-width. The angle formed by the line BA and line PA represents the Relief angle 1 and the angle formed by the line CB and line PA represents the Relief angle2.

![Figure 3. The coordinate system on the CNC machine](image3)

![Figure 4. The cutter group model](image4)

2.2. The structure of the hardware five-axis CNC machine.

The algorithm is based on a CNC grinding machine. Figure 3 show the coordinates system on the machine. The machine coordinates system is right handed. Point O represents the origin of the machine coordinate system. If you see the coordinates system from the top, the clockwise rotation of the workpiece is the forward rotation of the C vector. If you see the coordinates system from the left, the anticlockwise direction rotation of the workpiece is the forward rotation of the B vector. A
common installation way of grinding wheels is shown in Fig.4, a disc grinding wheel, a plain grinding wheel and a cup wheel are all all installed in right cutter group [4, 5].

2.3. The algorithm for ball-end mill.

The projection of the plain grinding wheel on the end surface of the barstock is an ellipse, when grinding the mill groove. The least distance from the points on ellipse to the axis of cylinder is equal to the core-radius of the mill. A helical surface can be obtained if the tangent line of the grinding wheel moves around the cylinder axes according to a helical angle $\beta$. If a plane which is perpendicular to the cylinder axes cuts the helical surface, a curve can be obtained on the intersection, and the rake angle on this curve is just the rake angle of the mill. Once the cutting angle confirmed, the rake angle and Core-diameter $D$ chosen, the relative motions required in manufacturing can be obtained accurately.

The manufacturing of relief consists two parts: the cylinder part and the ball-head part. Fig.5 shows the method to grind relief 1 on a mill. Firstly, rotate the grinding point to the horizontal level, and then rotate the point to a relief angle, grind the point through the grinding wheel tangent line. If the cutting angle needs to change, we can do that through changing the angle between the wheel and the axes of the cylinder. The manufacturing of the ball-head relief is conducted along with an S-shaped curve. On the curve at any point there is a cross section perpendicular to the curve (Fig.6) [6, 7]. The relief grinding of the ball-head section can be regarded as a chain of discrete points along with the S-shaped curve, and the CNC machine will conduct a make-up among these discrete points [7]. The five-axis coordinates for Relief 1 grinding at any point $P(\theta)$ are as follows.

\[
\begin{bmatrix}
X \\
Y \\
Z \\
A \\
C
\end{bmatrix} = \begin{bmatrix}
Lc - \cos(\theta) (Lc + R - L,j) + Y0 \sin(\theta) - X0 \cos(\theta) \\
X0 \sin(\theta) + Y0 \cos(\theta) - L + \sin(\theta) (Lc + R - L,j) - Lz \\
Y0 - \tan(\beta) * 180/\pi + \theta1 \\
\text{atan}(-x3 \cdot (\cos(\theta1) - z3 \cdot \sin(\theta1)))*180/\pi
\end{bmatrix}
\]

(1)

\[
\theta1 = a \tan\left(\frac{\cos(\theta1) \cos(\theta) \cos(Qie) + \sin(\theta) \sin(Qie)}{\cos(Qie) \sin(\theta0)}\right) \\
\psi = \sin(\theta) * \tan(\beta0) * 180/\pi ;
\]

The Relief 2 grinding is quite like Relief 1. Difference is just to shift the grinding point by the width of relief 1 and raise the angle as is shown in Fig.7.
The five-axis coordinates for Relief 2 grinding at the point P (θ) are as follows.

\[
\begin{bmatrix}
X \\
Y \\
Z \\
A \\
C
\end{bmatrix} = \begin{bmatrix}
Lc - \cos(\theta) (Lc - Lj + R) + Y0 \sin(\theta) - X0 \cos(\theta) \\
X0 \sin(\theta) + Y0 \cos(\theta) + \sin(\theta) (Lc - Lj + R) - L - Lz \\
Y0 \\
\psi - \tan(\beta) * 180/\pi + \theta1 \\
\tan\left(\frac{x3}{(z3 * \sin(\theta1) - y3 * \cos(\theta1))}\right) * 180/\pi
\end{bmatrix}
\]

(2)

Figure 5. The relative position for relief 1 grinding

Figure 6. Cross-section perpendicular to S-shaped curve

Figure 7. The relative position for relief 2 grinding

\[
\theta1 = a \tan\left(\frac{\cos(\theta0) \cos(\theta) \cos(Qie) + \sin(\theta) \sin(Qie)}{\cos(Qie) \sin(\theta0)}\right)
\]

\[
\psi = \sin(\theta) \tan(\beta_0) * 180/\pi;
\]

\[
\begin{bmatrix}
X0 \\
Y0 \\
Z0
\end{bmatrix} = \begin{bmatrix}
- \cos(\theta) Rz \cos(Qie) - R \sin(\theta) - Rz \sin(\theta) \sin(Qie) \cos(\theta0) \\
- \sin(\theta0) \sin(Qie) \cos(\theta1) Rz + \sin(\theta1) \cos(\theta) \sin(\theta0) + \cos(\theta) \cos(\theta0) \sin(Qie) Rz \\
- \sin(\theta0) (-Rz \cos(Qie) \sin(\theta) - \cos(\theta1) Kz \cos(\theta0) + \cos(\theta) Rz) \\
- \sin(\theta0) Rz \sin(\theta1) \sin(Qie) - \cos(\theta0) \sin(\theta1) Kz - \sin(\theta0) \cos(\theta1) \cos(\theta) \\
+ \cos(\theta1) (-Rz \sin(\theta) \cos(Qie) + \cos(\theta) \cos(\theta0) \sin(Qie) Rz + \cos(\theta) Rz)
\end{bmatrix}
\]
3. Simulation and manufacturing performance
In order to test the effectiveness of the proposed algorithm, a 3D simulation was conducted with a software based on OpenGL [8]. As is shown in Fig. 9, we simulated a ball-end mill with following parameters: $\beta=35^\circ, \gamma=15^\circ, R=3.000\text{mm}, D=3.600\text{mm}$, Cutting angle=$8^\circ$, relief 1 angle=$8^\circ$, relief 2 angle=$16^\circ$, Land width $K=0.500\text{mm}$, cutting angle on cylinder is $4^\circ$, cutting angle on the ball head is $20^\circ$, cutting angle on gash out is $0^\circ$, Cylinder helical angle and Ball-head helical angle are both $35^\circ$, the cup wheel radius is $50.000\text{mm}$, the plain wheel radius is $62.500\text{mm}$. Using the parameters to simulate and manufacture, the end-mill we got at last is shown in Fig.8 and Fig. 9.

![Figure 8. Simulation result of a ball-end](image)

![Figure 9. Manufacturing result of a ball-end mill](image)

Problems found in simulation and manufacturing. There must be some inevitable deviations on the hardware machine, which can influence the quality of the mills. So, the algorithm should be able to calculate the influence and offset the impact of machine deviation. Concretely, the relief appears rough at the connection point between the cylinder and the ball head. A cup wheel was used to grind the relief part. The wear and tear increases as the time went by, making the round angle changed gradually. The wear and tear of the cup wheel could be compensated, if the radius and the flange length of the grinding wheel are adjusted.

4. Conclusion
The algorithm proposed in this paper for ball-end mill manufacturing could satisfy the requirements of manufacturing based on this machine structure. According to the 3D-simulation test and manufacturing test, the algorithm presented in this paper proves reliable.

5. Parameters that are relative to the calculation
Qie the cutting angle.
R the nose radius.
R1 the radius of a grinding wheel.
$\beta$ the helix angle of the cylinder.
$\beta_1$ the helix angle of the ball head.
$L_c$ the distance from the standard point to the end plane of the barstock.
$L_j$ the distance from the standard point to the circle centre of C-axis.
$K_L$ the land width of relief 1.

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