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Numerical Simulation and Experimental Study of Conical Cycloid Gear Profile in Face Milling on Five-Axis Milling Machine Tool

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Abstract: In order to improve processing surface quality and efficiency of the conical cycloidal gear, the techniques of face-milling conical cycloidal gears were presented. The mathematical model of the effective cutting ellipse of the face mill was established. The front inclination angle and tilt angle were employed to solve the problems of local interference and global interference respectively. The geometrical model and five-axis numerical control (NC) simulation model of face-milling conical cycloid gear were then established accordingly, and the optimal tool path was obtained. NC simulation shows that the parameters are set reasonably, the machining track is even and smooth, and there is no interference. Finally, the face milling cutter was used to realize the machining of the precision conical cycloidal gear on the five-axis computer numerical control (CNC) milling machine tool, which has verified the feasibility and effectiveness of the machining method of milling conical cycloidal gear with face mill.

Keywords: conical cycloid gear; face milling; front inclination angle and tilt angle; experimental verification

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五轴端铣锥形摆线齿轮齿形的数值模拟与试验

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摘要: 为了提高锥形摆线齿轮齿面的加工质量和效率, 提出端铣锥形摆线齿轮的工艺技术. 建立端铣刀有效切削椭圆的数学模型, 提出利用前倾角和侧倾角分别解决端铣刀局部干涉与刀杆碰撞干涉问题的方法. 建立端铣锥形摆线齿轮的几何模型和五轴数控仿真模型, 获得其刀具轨迹. 数控仿真结果表明: 各参数设置合理, 加工轨迹均匀顺畅, 无加工干涉. 在五轴数控铣床上利用端面铣刀实现精密锥形摆线齿轮的无过切加工, 验证端铣锥形摆线齿轮的加工方法的可行性和有效性.

关键词: 锥形摆线齿轮; 端铣; 前倾角和侧倾角; 试验验证

Cycloid reducer has many advantages, such as high efficiency (over 90%), high speed ratio (above 80%), high bearing capacity, compact structure, and so on. It has a wide range of applications in industry. However, due to the precision machining problem of the cycloidal gear tooth surface, it is

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impossible for us to produce high quality cycloid reducer, a large number of high-grade cycloid reducers all rely on imports. The main defects of the domestic cycloid reducer are poor transmission accuracy, unstable motion, low bearing capacity and low service life. These problems arise from the finishing process of cycloidal gear profile. In recent years, several scholars from home and abroad have carried out extensive research on cutting and grinding methods, transmission characteristics and dynamic characteristics of cycloidal gear. Wang, *et al*^[1-2] proposed the method of processing the convex surface of the cycloid using end face hobbing method. Liu, *et al*^[3] studied the process method of roll cutting cycloid gear profile. Jiang^[4] proposed a computer numerical control (CNC) machining system of cycloidal gear grinding machine. Chen, *et al*^[5] developed a CNC machining system for cycloid gear. Qi, *et al*^[6] established the milling force model of rigid tooth profile and elastic tooth profile for cycloidal gear. Liu, *et al*^[7] investigated the machining method of inner-translational and all-cycloid gears based on the study of gear meshing mechanism and the basic characteristics of cycloidal profile curve. Wang, *et al*^[8] analyzed the mechanism and characteristics of finger-type conical enveloping cutting. Chen, *et al*^[9] researched the cutting and grinding mechanism of the conical gear tooth profile. Stephen^[10] decomposed the complex tool-path problem of multi-axis numerical control (NC) machining into three sub-problems: local, regional and global trajectory generation. Jensen, *et al*^[11] proposed a tool selection method based on the principle of curvature matching. Li, *et al*^[12] conducted a tool global interference detection in five-axis numerical control machine tool based on the principle of coordinate transformation in order to reduce the amount of calculation and improve the NC machining efficiency. The calculation method of the compensation vector of each type of cutter was studied based on the existing computer aided manufacturing (CAM) software UG^[13]. Wang, *et al*^[14] eliminated the limit phenomenon of compensation vector by rotating the radius compensation vector position at the interpolation point. Fan, *et al*^[15] put forward an improved milling algorithm for end milling impeller runner bottom. Zhao, *et al*^[16] proposed an improved equal-residual height algorithm for tool path generation of free-form surfaces. Qi, *et al*^[17] proposed an efficient tool axis vector adjustment algorithm based on *K-D* tree and tool discreteness. Xu, *et al*^[18] proposed the machining method of face milling the tooth profile of cycloidal gear with face mill instead of ball end mill.

At present, the tooth surface of the cycloidal gear is finished by using the “grinder” and the “finger blade cutter”. Because of the grinding heat and side milling flutter and other reasons, the tooth profile accuracy and surface quality of cycloid gear are poor. The transmission accuracy, transmission stability and the life of the reducer of cycloid reducer are greatly reduced. Therefore, this paper presents the machining method of face-milling conical cycloidal gears by face mill. Based on the numerical simulation of the face milling path of the conical cycloid gear, the face milling of the conical cycloid gear is completed by using the five-axis NC machine tool. The research will provide a new way for the machining of the new variable section cycloidal gears.

1 Design of Conical Cycloid Gear

Conical cycloidal planetary transmission is a typical variable cross-section cycloid drive, which belongs to a less tooth difference planetary transmission. Its basic component is a conical cycloid needle wheel, a conical cycloid wheel and an output mechanism, etc. The any cross section of the new transmission is essentially a common cycloid wheel drive, that is, any cross section of the conical cycloid planetary transmission meets the law of engagement.

In the case of the same cycloidal wheel thickness, the contact area between the variable section cycloidal gear and the pin teeth is larger than that of the conventional cycloidal gears. Therefore, this new structure has the following advantages: uniform force, small wear and tear, compact structure,

high transmission efficiency, long service life. Figure 1 shows machining method of face-milling conical cycloidal gears by face mill, figure 2 shows the conical cycloidal gear and the pin wheels and figure 3 shows the conical cycloidal gear.

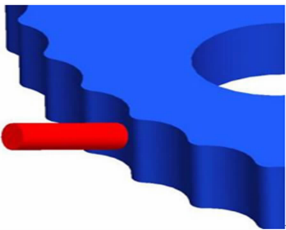


Fig. 1 Face milling of cycloidal gear profile
图 1 摆线轮廓的面铣

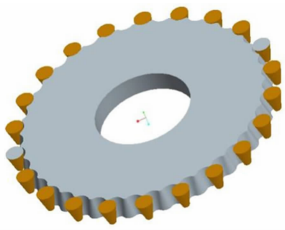


Fig. 2 Mate of conical cycloidal gears
图 2 锥形摆线齿轮的配合

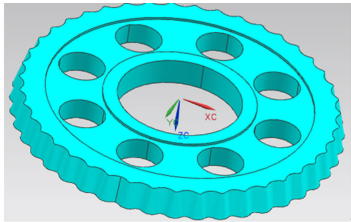


Fig. 3 Conical cycloidal gear
图 3 锥形摆线齿轮

2 Five-Axis Milling Method

Based on the geometric elements of the tool in contact with the workpiece during machining, the five-axis milling is divided into face milling and side milling. Surface is machined through point contact with the edge of face milling cutter, which is defined as face milling. In face milling, the curvature of the cross-sectional shape of the tool envelope can be varied within a wide range, and the curvature of the tool can be adapted to the curvature of the curved surface, and the machining performance is good. Surface is machined through line contact with the cutting edge on the circumference of a milling cutter, which is defined as side milling.

In side milling, the tool can extend into the surface channels of some parts to solve a number of processing problems that are not easy to solve with face mill. Side milling is most suitable for the processing of ruled surface parts. But the cutting force is relatively large, the tool in the processing process is very easy to distort.

3 Theoretical Research on Tool Path Planning of Five-Axis Face Milling of Conical Cycloid Gear Profile

In the five-axis machining, the geometrical meshing relationship between the face mill and the machined surface is very complex. The determination of the effective cutting width and tool posture is the basis of tool path planning, and it is necessary to study it deeply. The effective cutting ellipse can simplify the complicated 3D geometrical meshing relationship between the face mill and the workpiece surface into a two-dimensional problem, so the effective cutting ellipse has a wide application in the five-axis end milling. At present, the effective cutting ellipse is one of the most effective methods to study the five-axis face milling.

3.1 Establishment of Effective Cutting Ellipse Mathematical Model of Face Milling Cutter

A local coordinate system x_1 - y_1 - z_1 is established at the cutter contact point C_c on the tool contact trajectory, which is shown in figure 4. Where x_1 is the tangential direction of the tool contact trajectory, z_1 is the normal direction of the design surface, $y_1 = z_1 \times x_1$, and y_1 is the machining row direction. The tool coordinate system x_c - y_c - z_c is established on the tool, where O_c is the center point of the bottom circle of the face milling cutter, x_c is the direction of the

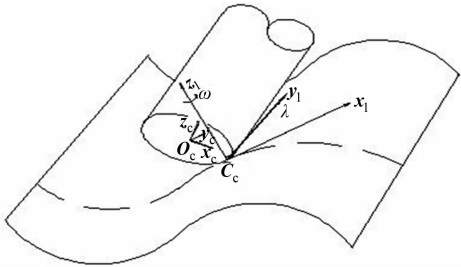


Fig. 4 Establishment of coordinate system
图 4 坐标系的建立

tool contact, and \mathbf{z}_c is the tool axis. The position of the tool relative to the local coordinate system $\mathbf{x}_1\text{-}\mathbf{y}_1\text{-}\mathbf{z}_1$ can be expressed by its tool inclination angle (λ, ω) , where λ is the forward inclination angle, ω is the angle of the tool rotating counterclockwise along the axis. When the \mathbf{z}_1 -axis coincides with the \mathbf{z}_c -axis ω is defined as zero. The value range of ω is from 0° to -90° . In the process of five-axis machining, the cutting edge of the face mill is located at the bottom of the milling cutter, and the center of the tool has no cutting edge and its theoretical linear velocity is zero. In order to avoid contacting of the cutter center and workpiece and local interference between the cutting edge and the workpiece, face milling cutter is often rotated an angle λ around the y axis. Only when the inclination angle λ is within the appropriate angle range, can the tool vector be inclined to the processing direction, so as to realize the “drag knife” milling in the face milling process. Otherwise, the “top knife” milling will occur. ω is called the roll angle, which is the angle of the tool rotates counterclockwise along axis \mathbf{z}_1 . When \mathbf{z}_c is in plane $\mathbf{x}_1\mathbf{z}_1$, it is defined as zero, which is in the range of -90° to 90° . When machining complex surfaces, the roll angle ω is used to avoid collision and interference between the tool and the workpiece. The projection of the bottom edge of the end milling cutter to the section $\mathbf{y}_1\text{-}\mathbf{z}_1$ is an ellipse, which is called an effective cutting ellipse, as shown in figure 5.

The coordinates of a point \mathbf{C} on the bottom edge of the end mill with radius r can be expressed in the tool coordinate system $\mathbf{x}_c\text{-}\mathbf{y}_c\text{-}\mathbf{z}_c$ in terms of $\mathbf{C}_c=(r\sin \theta \quad -r\sin \theta \quad 0)^T$, where θ is the angle from the negative direction of the \mathbf{y}_c -axis vector to the point \mathbf{C} on the bottom edge of the tool. For face milling cutter, the cutter locates in the center of the cutter coordinates. In the workpiece coordinate system, the tool location point can be expressed in the following

$$\mathbf{Q}=\mathbf{C}_c+(-r\cos \lambda \cdot \cos \omega)\mathbf{i}+(-r\cos \lambda \cdot \sin \omega)\mathbf{j}+(r\sin \lambda)\mathbf{k}.$$

(1)

In the local coordinate system, the coordinates of the point \mathbf{C} on the bottom edge of the end mill are expressed in the local coordinate system $\mathbf{x}_1\text{-}\mathbf{y}_1\text{-}\mathbf{z}_1$ in terms of

$$\mathbf{C}=\begin{bmatrix} \mathbf{x}_1 \\ \mathbf{y}_1 \\ \mathbf{z}_1 \end{bmatrix}=\begin{bmatrix} \cos \omega & \sin \omega & 0 \\ -\sin \omega & \cos \omega & 0 \\ 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} \cos \lambda & 0 & \sin \lambda \\ 0 & 1 & 0 \\ -\sin \lambda & \lambda & 0 \end{bmatrix}(\mathbf{O}_c+\mathbf{C}_c)=$$

$$\begin{bmatrix} \cos \omega & \sin \omega & 0 \\ -\sin \omega & \cos \omega & 0 \\ 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} \cos \lambda & 0 & \sin \lambda \\ 0 & 1 & 0 \\ -\sin \lambda & 0 & \cos \lambda \end{bmatrix}\left(\begin{bmatrix} -r \\ 0 \\ 0 \end{bmatrix}+\begin{bmatrix} r\sin \theta \\ -r\sin \theta \\ 0 \end{bmatrix}\right)=$$

$$\begin{bmatrix} -r[\cos \lambda \cdot \cos \omega \cdot (1-\sin \theta)+\sin \omega \cdot \cos \theta] \\ r[\cos \lambda \cdot \sin \omega \cdot (1-\sin \theta)-\cos \omega \cdot \cos \theta] \\ r\sin \lambda \cdot (1-\sin \theta) \end{bmatrix}.$$

(2)

The tool cutting ellipse obtained by projecting the end mill cutting edge to a plane $\mathbf{y}_1\text{-}\mathbf{C}\text{-}\mathbf{z}_1$ perpendicular to the tool feed direction \mathbf{x}_1 is

$$\mathbf{E}(\theta)=\begin{bmatrix} 0 \\ -r\sin \lambda+r\sin \lambda \cdot \cos \theta \\ r\cos \lambda \cdot \sin \omega-r\cos \lambda \cdot \sin \omega \cdot \cos \theta-r\cos \omega \cdot \sin \theta \end{bmatrix}.$$

(3)

The equation of cutting ellipse can be obtained from equation

$$y^2\sin^2 \lambda+z^2(\cos^2 \omega+\sin^2 \omega \cdot \cos^2 \lambda)+2yz\cos \lambda \cdot \sin \lambda \cdot \sin \omega+2rz\sin \lambda \cdot \cos^2 \omega=0.$$

(4)

The major and minor radius of ellipse $\mathbf{E}(\theta)$ are those respectively as $a=r$ and $b=r|\sin \lambda \cos \omega|$. In the local coordinate system $\mathbf{x}_1\text{-}\mathbf{y}_1\text{-}\mathbf{z}_1$, the center coordinates of the ellipse $\mathbf{E}(\theta)$ are $y_0=r\cos \lambda \sin \omega$, $z_0=-r\sin \lambda$.

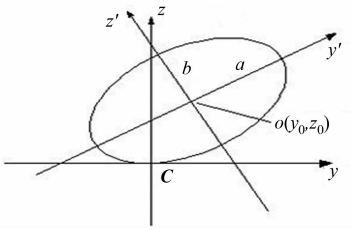


Fig. 5 Effective cutting ellipses for face milling
图 5 用于端面铣削的有效切削椭圆

The coordinate system $o-y'-z'$ is established by taking the major axis of the ellipse as y' , the minor axis as z' , and the coordinate origin $o(y_0, z_0)$ as the origin. The standard equations for the effective cutting ellipses of the face milling cutter in the coordinates $o-y'-z'$ are as follows.

$$\begin{aligned} & \left(\frac{y'}{r}\right)^2 \left(\frac{z'}{r \sin \lambda \cdot \cos \omega}\right)^2 = 1, \\ & y' = (z - r \cos \lambda \cdot \sin \omega) \cos \phi + (y + r \sin \lambda) \sin \phi, \\ & z' = -(z - r \cos \lambda \cdot \sin \omega) \sin \phi + (y + r \sin \lambda) \cos \phi. \end{aligned}$$

When the tool radius $r=3$ mm, the side angle $\omega=0^\circ$, the shape and position of effective cutting ellipse for the end mill change with the forward inclination angle λ , which is shown in figure 6. The analysis shows that with the increase of the forward inclination angle λ , the long axis a of the effective cutting ellipse is fixed and the length of the minor axis b is increased. So the cutting area and the effective cutting radius of the cutter decrease with the increase of the forward inclination angle λ . When the tool radius $r=3$ mm, the forward inclination angle $\lambda=-5^\circ$, the shape and position of effective cutting ellipse for the end mill change with side inclination angle ω , which is shown in figure 7 ($\omega=0^\circ, 15^\circ, 30^\circ, 45^\circ, 60^\circ$). The increase of the side inclination angle ω will move the center of the ellipse $E(\theta)$ to the right side of the axis y . Simultaneously the angle between long axis of the ellipse and the axis y' becomes larger, and the short axis length b will be reduced. As a result, the ellipse becomes more and more slender, leading to the reduction of actual cutting area.

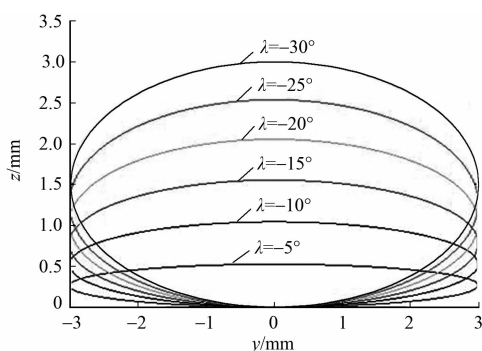


Fig. 6 Relation between effective cutting ellipse and rake angle λ

图 6 有效切削椭圆与前倾角 λ 间的关系

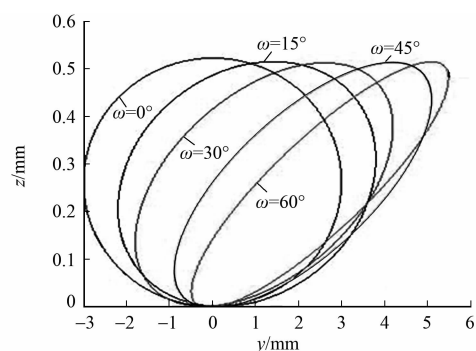


Fig. 7 Relation between effective ellipse and inclination angle ω

图 7 有效椭圆与侧倾角 ω 间的关系

3.2 Judgment and Avoidance of Interference in Face Milling of Cycloidal Gear Profile

The five-axis CNC milling machine has two rotary axes in addition to three-direction translation axes, so the capability of controlling milling cutter vector is very strong. Because the tool vector often changes, so that the tool is very easy to interfere with the machining surface. Therefore, interference detection is required during tool path planning. Local processing interference is also known as the cutter head interference or over-cutting interference. Tool curvature interference refers to the interference when the radius of the cutter is greater than the radius of the surface curvature. Over-cutting appears between the tool and the workpiece surface, which is known as tool over-cutting interference. Interference between milling cutter and non-processing parts such as fixture and milling machine tool is called global interference, which is also known as collision interference. This paper presents a method to avoid tool interference by adjusting the tool rake angle and side inclination angle. At first set the range: tool rake angle $\omega=0^\circ$, side inclination angle $-2^\circ \leq \lambda \leq -5^\circ$. Then the curvature of the surface is calculated and the interference is determined. If interference occurs, calculate and adjust the rake angle λ according to the surface shape and tool size. If the interference occurs after adjusting tool rake angle, the side inclination angle ω needs to adjust. The actual processing shows that the value of λ and ω is too large, which not only will reduce the milling efficiency, but also will deteriorate the cut-

ting tool conditions.

In milling the cycloid gears with end mills on a five-axis machine, the tool axis interference (global interference) may appear when the side inclination angle ω is not selected properly, which is shown in figure 8. If the tool radius r and tool axis rake angle λ are selected improperly, the tool tip interference (local interference) will occur, which is shown in figure 9. So considering the cutter shaft interference and cutting efficiency, the face milling cutter is used to process the cycloid gear in the five axis machine tool, and the side inclination angle ω of the cutter shaft is taken to be 0° . In order to avoid the interference of cutter curvature, the effective cutting radius of the face milling cutter should be less than the minimum radius of cycloid gear profile curvature.

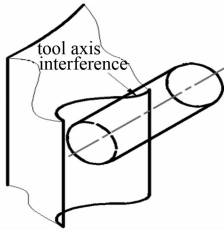


Fig. 8 Interference of cutter shafts

图 8 刀轴的干涉

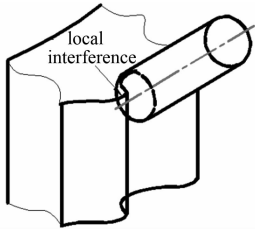


Fig. 9 Local interference in face milling

图 9 面铣中的局部干涉

4 Simulation and Experiment Verification of Face Milling of Cycloidal Gear Profiles

4.1 Simulation Equipment and Experiment Equipment

In this paper, a numerical control machine model with rotary axes B and C is established in software powermill, which is used to simulate the machining of conical cycloid gear profiles. The NC model is established based on the five-axis linkage vertical machining center (German DMG DMU 40 monoBLOCK). The simulation model of five-axis NC milling machine with rotary axes B and C established in software powermill is shown in figure 10. And the rotation direction of the rotary shaft is around the y and z axes, respectively. In order to ensure the authenticity and accuracy of simulation, the simulation model of fixture is also established. Figure 11 shows the German DMG five-axis vertical machining center used in this experiment. The numerical control system of the machine tool is Heidenhain TNC 530. The machine tool fully meets the processing requirements of the conical cycloid gear.

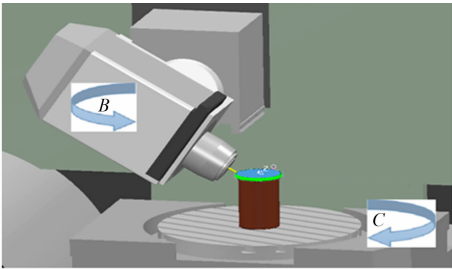


Fig. 10 Five axis milling machine model
图 10 五轴铣床模型

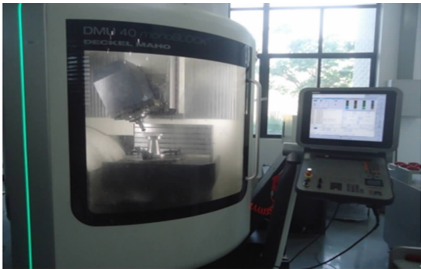


Fig. 11 Five axis machining center
图 11 五轴加工中心

4.2 Numerical Simulation and Experimental Verification of Layered Milling Cycloidal Gear (Rough Machining)

When the cylindrical milling cutter is used to machine the cycloid gear, the milling cutter will be subjected to large radial force, and the deformation of the milling cutter is large, which seriously affects the machining accuracy. In order to reduce the deformation of the cutter and improve the machining precision, a new method of machining cycloidal gear profiles with layered milling is proposed in this paper. The principle of layered side milling is shown in figure 12. When using the layered milling, the contact area between the cutter blade and the blank is relatively small, the milling force and

the milling deformation is small. The raw material used for cycloidal gears in the milling experiment is hard aluminum. The holes are machined on the drilling machine and lathe before machining cycloid tooth profile. Figure 13 shows the tool path of face milling the cycloidal gear. The rough process parameters of the conical cycloidal gear is shows table 1. Figure 14 shows the rough machining of conical cycloid gear. Figure 15 shows the cycloid gear after rough machining.

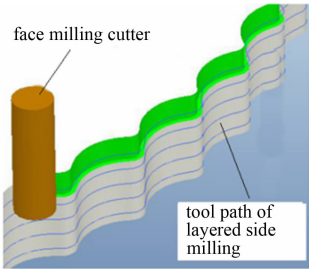


Fig. 12 Layered side milling
图 12 分层侧铣

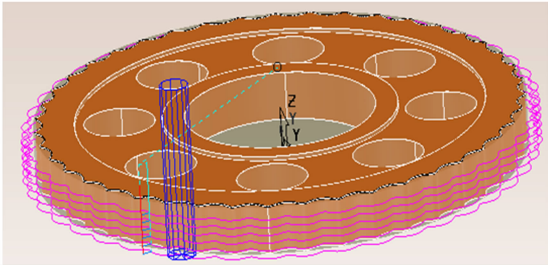


Fig. 13 Tool path of side milling
图 13 侧铣刀具路径



Fig. 14 Rough milling
图 14 粗铣

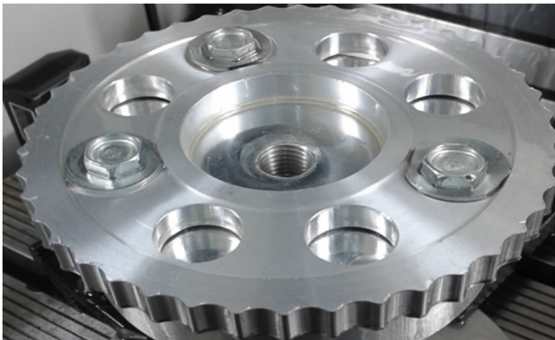


Fig. 15 Cycloid gear after rough milling
图 15 粗铣后的摆线齿轮

4.3 Numerical Simulation and Experimental Verification of Finish Face Milling of Conical Cycloidal Gear Profile

The cutter is a flat face milling cutter with a hard alloy tungsten carbide and a diameter of 6 mm. The machining parameters of face milling conical cycloid gear is shown table 1.

Tab. 1 Process parameters of conical cycloidal gear

表 1 圆锥摆线齿轮的加工工艺参数

Process name	Tool	Spindle speed/ $r \cdot \text{min}^{-1}$	Feed rate/ $\text{mm} \cdot \text{min}^{-1}$	Down milling and up milling	Cutting depth/mm	Machining allowance/mm
Rough machining of tooth profile	$\phi 8$ flat bottomed cylin- drical milling cutter	3 500	1 000	Down milling	0.2	0.1
Finishing tooth profile	$\phi 6$ flat bottomed cylin- drical milling cutter	8 000	800	Down milling	0.1	0

In the face milling process, the cutter is inclined to an angle with respect to the end face of the cycloidal gear. The face milling cutter makes a straight reciprocating motion along the outline of the cycloid gear in addition to its high-speed rotation. The end cutting edge of the cutter is used to cut the tooth profile to form a tool path similar to the line cutting process. Figure 16 shows the tool path of face milling of the conical cycloid gear. The comparison between the results of the simulation be seen in figure 17. Figure 18 shows face milling conical cycloid gear on the five axis milling machine. Figure 19 shows the conical cycloid gear prototype after precision face milling. The actual processing results of the conical cycloid gear can be seen in figure 19. It is proved that the tool path planning method of the face milling of cycloidal gear tooth profile is correct and feasible.

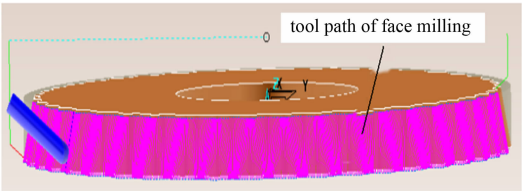


Fig. 16 Tool path of face milling of conical cycloid gear

图 16 面铣锥形摆线齿轮刀具路径

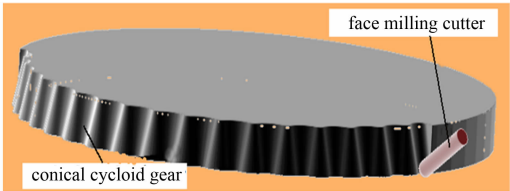


Fig. 17 Simulation model of precision face milling of conical cycloid gear profile

图 17 圆锥摆线齿轮精密端面铣削仿真模型



Fig. 18 Face milling of conical cycloid tooth

图 18 面铣锥形摆线齿轮



Fig. 19 Conical cycloid gear prototype after precision face milling

图 19 精密端面铣削后的摆线齿轮样机

4.4 Roughness Measurement Results of Cycloid Gear Profile

The average value of the measured surface roughness is $R_a=0.537\ 7\ \mu\text{m}$, which has reached the requirement of the conventional grinding method with a roughness value of $R_a=0.8\ \mu\text{m}$. Therefore, the roughness of the tooth profile of the processing sample can reach the standard.

5 Conclusions

1) A method of non-interference tool path generation for face milling of conical cycloidal gear profile is proposed on five-axis NC machine tool. Considering the machining characteristics of the conical cycloid gear profile, the mathematical model of effective cutting ellipse of face milling cutter is established based on the rake angle and the side inclination angle of the cutter. The effect of tool rake angle and side inclination angle on the effective cutting radius is studied. A method is proposed to solve the problems of local interference and the collision interference of face mill by using the tool rake angle and side inclination angle respectively.

2) Based on the analysis of the characteristics of ball end milling cutter and face milling cutter, the machining method of the tooth profile of the cycloidal gear on five axis CNC milling machine is presented based on the comparison of the characteristics of peripheral milling and face milling. The geometric model and five-axis NC simulation model of face-milling cycloidal gear are established. In the face milling process, the face milling cutter is inclined to an angle with respect to the end face of the cycloidal gear. The face milling cutter makes a straight reciprocating motion along the outline of the cycloid gear in addition to its high-speed rotation. The end cutting edge of the cutter is used to cut the tooth profile to form a tool path similar to the line cutting process. The method integrates the merits of the side milling and plunge milling cycloidal tooth profile, which not only overcomes the shortcomings of large axial profile deformation and poor surface quality of plunge milling cycloidal gear profile, but also solves the problem of large radial deformation and radial runout of the milling cutter in side milling.

3) It is feasible to realize the processing of the conical cycloid gear by the adoption of the peripheral rough milling and the precision face milling. The average value of the measured surface roughness is $R_a=0.5377\ \mu\text{m}$, which has reached the requirement of the conventional grinding method with a roughness value of $R_a=0.8\ \mu\text{m}$ and the tolerance value is $0.169\ \text{mm}$. The research has laid an important foundation for the production and engineering application of the conical cycloid drive, and has certain reference value to the similar parts processing.

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