Study of motional parameters calculation and tooth cutting experiment based on the new type of tilt milling machine

Chuang JIANG*, Jing DENG*, Xiaozhong DENG***, Hua ZHANG**, Shaowu NIE** and Longlong GENG*
*School of Mechatronic Engineering, Northwestern Polytechnical University, 127 Youyi West Rd, Xi’an 710072, China
**School of Mechatronics Engineering, Henan University of Science and Technology, 48 Xiyuan Rd, Luoyang 471003, China
***Collaborative Innovation Center of Machinery Equipment Advanced Manufacturing, Henan Province, 48 Xiyuan Rd, Luoyang 471003, China
E-mail: dxz01@163.com

Received 16 December 2015

Abstract
To improve the machining efficiency and reduce the overall manufacturing cost, a new model of machining hypoid gears by tilt cutting method is setup. Unlike the traditional cradle-style mechanical machines, the new model has no cradle and eccentric drum, the tool swivel drum is controlled by NC system. Firstly, according to its special structure, the mathematical model of the machine tool is built, an algorithm is developed to calculate the motional parameters. After building the machine tool model by the software Vericut, cutting simulation is performed. Based on the comparison of gouge and excess amount between simulated model and theoretical model, the tooth cutting experiment is conducted. Then, measurement and rolling detection for the hypoid gears is performed. The results indicate the rationality, reliability and accuracy of newly designed model of the milling machine. Moreover, the proposed method of calculating the motional parameters is feasible, which would be meaningful for future industrial application.

Key words: Innovative milling machine, Hypoid gear, Parameters calculation, Cutting simulation, Machining experiment

1. Introduction

As we all know, machining technology of hypoid gears is closely related to the progress of machine tools. Since the appearance of hypoid generator, tilt method has been a breakthrough technology to produce hypoid gears. Compared with modified roll method, the tilt method has been widely employed in the gear industry because of its ability to effectively simplify the tool specifications and correct the tooth flank.

Currently, the traditional cradle-style machines are still the main equipment for quite a number of companies, especially in China. This type of machine tools still retains the cradle structure with a long drive chain and complex mechanical structure, which may result in some questions a few years later, such as serious wear, quickly reduced accuracy, difficult maintenance and hardly improved processing accuracy. At present, the most advanced CNC milling machines are the Gleason phoenix series and the Oerlikon C series, whose six-axis characteristics can greatly improve
the flexibility during processing and equivalently machine hypoid gears with the tilt method. However, this equipment as well as the cutting tool consumptions is too expensive to control the machining cost for most enterprises. Therefore, it is necessary and vital to develop a technology for machining hypoid gears by the new tilt milling machine.

A model of machining pinions of hypoid gears with tilt method is proposed, which still applies the structure of the tilt and swivel drum, and simulates virtual cradle by the linkage of X and Y axes. Instead of relying on the angles of cradle and eccentricity, the tilt angle is controlled independently as a parameter. As a result, a new algorithm to calculate the parameter of each axis is needed. There are many literatures to deal with free-form cutting methods using modern six-axis CNC machine. Among them, Lin et al. (1997) developed a mathematical model for defining the tooth geometry of spiral bevel and hypoid gear. Litvin et al. (2004) proposed a mathematical model to simulate the conventional cradle-type generator and convert the machine settings to modern six-axis CNC machine was also presented. Shih et al. (2007) put forward a universal face-hobbing model and a special one for a traditional machine with a cradle. Fan (2007) presented an algorithm for spiral bevel and hypoid gear produced by face-milling and face-hobbing processes conducted on CNC generator which are incorporated with the universal motions concept. On this basis, Simon (2010) deduced an algorithm for the execution of motions on the CNC machine based on the same relative position of the head cutter and the pinion on CNC hypoid generating machine and cradle-type machine. Mohsen et al. (2010) attempted to manufacture the spiral bevel gear using a three-axis CNC milling machine interfaced with an additional PLC module based on traditional discontinuous multicutting method accomplished be using a universal milling machine interfaced with an indexing work head. One year later, Simon (2011) certified the variation of the velocity ratio induced by a fifth-order polynomial function could result in reduction of the transmission error. Wang et al. (2011) derived a unity transformation model for flexible NC machining of spiral bevel and hypoid gear, the model could support various machining methods including generation machining and formation machining on five-axis machining center. Based on the spatial kinematics transformation theory, Tang et al. (2011) addressed the theory of the spatial kinematics transformation for the tilt method between traditional and NC machines with five axes linkages, and realized the parametric design by using of the system developed by himself. Shih et al. (2012) proposed a mathematical model of the five-axis CNC grinding machine, established a free-form flank correction methodology, the sensitivity of the polynomial coefficient is derived so as to the actual tooth surface could close to the theoretical one. Shih et al. (2013) established a mathematical model of the face-hobbed straight bevel gear based on the six-axial CNC milling machine. After converting the universal cradle-type machine settings to the six-axis nonlinear machine settings, a cutting experiment is conducted to verify the feasibility of the proposed model. Su et al. (2013) established a mathematical model of tilt method process according to coordinate transformation between the cradle-type hypoid generator and the six-axis CNC generator, the model could be used for simulating face milling and face hobbing process. On this basis, Su et al. (2013) conceived a new approach by applying
reverse tooth contact analysis to design a seventh-order polynomial function of transmission error for spiral bevel gears to reduce the vibration and noise and improve the loaded distribution. Alessio et al. (2013) used the ease-off methodology by mapping the gear deviations into equivalent pinion deviations and cumulatively compensated by applying corrective machine-tool settings to the pinion itself. By this way, the originally designed transmission properties can be restored with a high level of accuracy. Chen et al. (2015) gave a generic approach to CNC programming and post-processing for face milling, including a new mathematical model to calculate the cutter system location and orientation and a generic post-processing method to establish the machine kinematics chain and to compute the coordinates of the machine axes for the face-milling process. Zhang et al. (2015) devised a directly axis coordinate solving method of CNC hypoid generator by taking cutter axis vector as control objectives to transform the attitude of whole cradle type generator. Fan (2015) described the generalized theory of ease-off and applied it in tooth contact analysis of both face-milling and face-hobbing spiral bevel and hypoid gear with complex tooth surface modifications. Yang et al. (2015) also took advantage of ease-off topography technology to improve the transmission performance of gear pairs processed by CNC milling machine. Zhang et al. (2016) provided an approach to calculate the basic machine-tool settings of spiral bevel and hypoid gear manufactured by the duplex helical method, three reference points were defined to obtain the optimal settings of the six-axis CNC machine and an experiment was finished to validate the developed methodology.

In this paper, a new method to calculate parameters of each axis will be given from the perspective of relationship between the cutter axis vector and the workpiece axis vector.

2. Calculation model of tilt machining method

At present, the main equipment used tilt method including the traditional cradle-style machine tools represented by No.116 and the six-axis machine tools represented by Gleason phoenix II series. The traditional cradle-style machine tools have complex mechanical structure and hard to operate, which have eight parts to be adjusted manually, including tilt angle, swivel angle, eccentric angle, cradle angle, machine root angle, vertical slide, horizontal slide, and sliding base, increasing labor intensity greatly. The six-axis CNC milling machines with high flexibility have advantages in adjustability, and the machining accuracy and efficiency have been highly improved. The virtual cradle is simulated by the linkage of X and Y axes, and the tilt angle is equivalently transferred by the linkage of B and Z axes. However, every increase of axis for linkage on the NC machine tools will result in the increase of cost and complexity of algorithm. Combining both advantages of the traditional cradle-style machine tool and the six-axis CNC milling machine, a new model of machining hypoid gears by tilt method is proposed, with obsoleted linkages of B and the Z axes from the typical six-axis CNC milling machine, but employed swivel drum and tilt drum from the traditional design. Under the premise of accuracy and efficiency, the structure of the machine tool is simplified and the cost is reduced significantly.
Moreover, the algorithm could be simplified effectively.

2.1 Mathematical model of the milling machine

Taking advantage of the innovation concept mentioned above, the mathematical model of the milling machine is established as Fig.1. The new model retains the swivel drum and the tilt drum, the three linear axes and the swivel drum are designed to be controlled numerically. Besides, the swivel drum is independent of the virtual cradle and could move associated with other CNC axes.

As illustrated in Fig.1, $S_n$ is the coordinate system when the cutter axis and the workpiece axis are collinear, $O_n$ is the NC program zero-point with the coordinates $(0, 0, 0)$, point $M$ is the rotating center of workpiece-box. $S_n$ and
$S_a$ are auxiliary coordinate systems, coordinate system $S_b$ is rigidly connected to the tilt drum, $Z_c$ coincides with the
tilt drum axis, $I$ and $i$ are the machine tool tilt angle and total tilt angle. $S_f$ and $S_t$ are rigidly connected to the
cutter head and tilt drum, $\phi_f$ is the swivel angle, $S_i$ is rigidly connected to the machine tool. $S_r$ and $q$ is radial
distance and cradle angle. $S_{w'}$ is auxiliary coordinate system. $S_i$ is rigidly connected to the workpiece, the origin of the
coordinate system coincides with the crossover point of the hypoid gear. $E_m$ is vertical offset, $\Delta B$ is the modification of
workpiece-box position, $\Delta C$ is the modification of horizontal position of workpiece, $\phi_i$ is the workpiece rotation
angle, which is related to swivel angle $\phi_f$ $(\phi_f = \Psi(\phi_i))$. $L$ is the distance from the crossover point of hypoid gear to the
rotating center of workpiece-box, $\gamma$ is the machine root angle, $X, Y, Z$ are the coordinates of the three linear axes.

$r_t(u,v)$ and $n_t(u,v)$, respectively, are the position vector of a point on the flank surface and the unit normal vector
to flank surface, according to the relative position of cutter and workpiece, the tooth surface equation and the unit normal
vector can be obtained as below,

$$
r_t(u,v) = M_{ia} r_i(u,v)$$
$$n_t(u,v) = L_{ia} n_i(u,v)$$

(1)

Here,

$$M_{ia} = M_{ia} M_{m} M_{nf} M_{f/f} M_{fa} M_{wa}$$
$$L_{ia} = L_{ia} L_{mn} L_{nf} L_{f/f} L_{fa} L_{wa}$$

Where, $(u, v)$ is tool surface coordinate, $L_{ia}, L_{mn}, L_{nf}, L_{f/f}, L_{fa}, L_{wa}$ is formed by removing the last row and the
last column of $M_{ia}$, $M_{mf}, M_{fa}, M_{wa}$, $O_1 O_1$ is the last column of $M_{ia}$.

Then, the transformation matrices from $S_{w'}$ to $S_i$ can be expressed as the following system of equations,

$$
\begin{align*}
    a_{11} &= -\cos i \sin \Psi \cos \gamma - \sin i \sin \gamma \\
    a_{12} &= \cos \Psi \cos \gamma \\
    a_{13} &= -\sin i \sin \Psi \cos \gamma + \cos i \sin \gamma \\
    a_{21} &= \cos i \cos \Psi \\
    a_{22} &= -\sin \Psi \\
    a_{23} &= \sin i \cos \Psi \\
    a_{31} &= \cos i \sin \Psi \sin \gamma - \sin i \cos \gamma \\
    a_{32} &= \cos \Psi \sin \gamma \\
    a_{33} &= \sin i \sin \Psi \sin \gamma + \cos i \cos \gamma
\end{align*}
$$

(2)

$$
O_1 O_1 = \begin{bmatrix}
X \cos \gamma + Z \sin \gamma - \Delta C - L \\
Y \cos \phi_i + X \sin \gamma \sin \phi_i - Z \cos \gamma \sin \phi_i \\
Y \sin \phi_i - X \sin \gamma \cos \phi_i + Z \cos \gamma \cos \phi_i
\end{bmatrix}
$$

(3)

Where, $\psi = j_0 \pm m_s \varphi_s - q$, $j_0$ is the initial swivel angle, $m_s$ is the velocity ratio of shape gear relative to workpiece, $\varphi_s$ is the shape gear rotation angle.

### 2.2 Calculation of the motional parameters

Compared with the traditional cradle-style machines, the six-axis CNC machine has no tilt drum, swivel drum, eccentric drum and cradle structure, the function of the six-axis numerical control is achieved with the use of virtual cradle technology and the tilt angle equivalent conversion technology. Nevertheless, it is different for the model of the new type milling machine. On one hand, the machine retains the tilt drum and the swivel drum, on the other hand, it no longer uses eccentric drum and cradle structure. In addition, the swivel drum can be adjusted by NC system, so the machine tool needs a new matching algorithm.

Machining hypoid gears by using the tilt method, a shortest distance vector will always exists between the cutter axis and the workpiece axis, its size and direction vary with the rotation of the shape gear. It will be perfect to combine this vector with the calculation of the motional parameters of each axis, the movement principle of each axis can be easily explained in this perspective. Besides, the calculation process of the motional parameters will be simplified effectively. Establishing the shortest distance vector between the cutter axis with the workpiece axis as Fig.2.

![Figure 2: The Shortest Distance Vector Coordinate System](image)

In Fig.2, coordinate system $S_i$ and $S_f$, respectively, are rigidly connected to the workpiece and cutter, $S_c$ is auxiliary coordinate system, $Y_s$ represents the shortest distance vector direction, $Z_s$ coincides with cutter axis. The unit vectors of all axes shown in Fig.2 are expressed as $i_x$, $j_x$, $k_x (x = 1, f, s)$. Suppose $\mathbf{H}$ is the three-order unit matrix, according to Fig.1, the three vectors of the cutter coordinate system $S_i$ and the workpiece coordinate system $S_f$ are presented in machine tool coordinate system, the equations can be established:

$$
R_f = L_{mr}L_{rf}L_{fr}L_{fu}\mathbf{H}, \quad R_i = L_{mi}\mathbf{H}.
$$

Suppose $(i_f, j_f, k_f) = (R_f(i1), R_f(i2), R_f(i3))(i = 1, 2, 3)$,
(i, j, k) = (R(i), R(j), R(k))(i = 1, 2, 3), the following the equations can be obtained, \( j_s = k_j \times k_j \), \( k_s = k_j \), \( i_s = k_j \times j_s \). Vectors of \( S_s \) can be represented as,

\[
k_s(j, q(t)) = \begin{bmatrix} -\sin \sin(j(t) - q(t)) \\ \sin \cos(j(t) - q(t)) \\ \cos i \end{bmatrix}
\]

\[
j_s(j, q(t)) = \begin{bmatrix} \cos i \\ 0 \\ -\sin i \sin(j(t) - q(t)) \end{bmatrix}
\]

\[
i_s(j, q(t)) = \begin{bmatrix} -\frac{1}{2} \sin^3 i \sin(2(j(t) - q(t))) \\ \sin^2 i \sin^2(j(t) - q(t)) - \cos^2 i \\ \frac{1}{2} \sin 2j \cos(2(j(t) - q(t))) \end{bmatrix}
\]

Some conclusions can be reached from Eqs. (4), (5) and (6). In the first case, the auxiliary coordinate system \( S_s \) is just related to the virtual cradle angle and swivel angle. In the second case, the shortest distance vector varies with the motion of \( X \) axis, \( Y \) axis and the swivel angle. Finally, if the tilt angle is zero, the vectors of \( i_s, j_s, k_s \) will be constant values, the auxiliary coordinate system \( S_s \) is no longer affected by the virtual cradle angle and swivel angle, the position relationship with machine tool coordinate system will be fixed.

Because of some characters of the new model, the adjustment of tilt angle and the machine root angle are the same as the traditional machine tool, the swivel drum, \( X \) axis, \( Y \) axis and \( Z \) axis are controlled by the NC system, therefore, processing can be done only if the four motional parameters have been calculated. As an independent structure, the adjustment of swivel angle is different from the traditional machine tool, it has relation with the angle position, the basic swivel angle and the angle between the cutter axis projection in machine tool plane and its vertical direction, rather than the eccentric angle and the cradle angle. The swivel angle adjustment scheme is shown in Fig.3.

As illustrated in Fig.3, \( O_l \) and \( O_f \), respectively, represents virtual cradle center and cutter center, \( q \) is the rotation angle of the shape gear at the calculating reference point, \( l \) is the vertical direction vector of the line formed by connecting \( O_l \) and \( O_f \), \( j \) is the basic swivel angle, \( n \) is the cutter axis projection in machine tool plane.
Suppose $P_j$ is the unit vector of cutter axis before tilt angle adjustment. After adjusting the machine tool tilt angle to $I$, the unit vector of cutter axis will be $P_j'$, the angle between $P_j$ and $P_j'$ is $i_x$, that is to say, $P_j \cdot P_j' = \cos i_x$. According to Fig.1, it is easy to know that the tilt drum axis unit vector presented in machine tool coordinate system will be $P_c = (-\sin \delta, 0, \cos \delta)(\delta = 15^\circ)$, referring to Rodrigue formula, the following equation can be obtained,

$$\cos i_x = 1 + (1 - \cos I) \cdot M \cdot P_j + \sin I \cdot P_c$$  \hspace{1cm} (7)

Here,

$$M = P_c \times (P_c \times P_j)$$

The machine tool tilt angle $I$ can then be determined by Eqs. (7), the angle $\alpha$ between the cutter axis projection in machine tool plane and the $Y$ axis positive direction can be expressed as follows,

$$\tan \alpha = \frac{P_j'(I) \cdot j}{P_j'(I) \cdot i}$$  \hspace{1cm} (8)

The angle $\theta$ between vector $m$ and the $Y$ axis negative direction can be calculated with the information displayed in Fig.3, $\theta = 180^\circ - j - q$. Finally, the swivel angle can be determined by Eqs. (9),

$$J(t) = 180^\circ - \alpha + \theta \pm \phi_j(t)$$  \hspace{1cm} (9)

Based on the coordinate system $S_m$ in Fig.1, the relative position between the cutting tool and the workpiece is given as,

$$O_fO_t = O_fO_R + O_RO_m + O_mO_t + O_tO_f$$  \hspace{1cm} (10)

Here,

$$O_fO_R = \begin{bmatrix} -\Delta C \cos \gamma & 0 & -\Delta C \sin \gamma \end{bmatrix}^T$$
\[ O_mO_m = \begin{bmatrix} 0 & 0 & -AB + AC\sin \gamma \end{bmatrix} \]

\[ O_mO_f = \begin{bmatrix} 0 & E_m & 0 \end{bmatrix} \]

\[ O_f = \begin{bmatrix} S, \cos \theta & -S, \sin \theta & 0 \end{bmatrix} \]

Combining the Eqs.(4) to (6) and (10), each linear axis expression of the milling machine is

\[
\begin{aligned}
L_x (j(t), q(t)) &= O_f(O_f \cdot j_x (j(t), q(t), i = 0)) \\
L_y (j(t), q(t)) &= O_f(O_f \cdot i_y (j(t), q(t), i = 0)) \\
L_z (j(t), q(t)) &= O_f(O_f \cdot k_z (j(t), q(t), i = 0))
\end{aligned}
\]

(11)

The parameters needed to be calculated by the new arithmetic including the coordinate of X axis, Y axis, Z axis and swivel angle, up to now, are all deduced, the calculation method of the remaining parameters is the same as the conventional machine tools’.

3. Cutting simulation analysis

Based on the model of the new type milling machine and the proposed motional parameters calculation theory, a pair of hypoid gear is used as an example to simulation analysis. The geometric parameters are shown in Table 1, the cutting tool parameters and machine tool adjustment parameters are shown in Table 2. During programming, one degree will be divided into eight steps, part of the point positions of the three linear axes, swivel angle and workpiece rotary angle when machining a tooth are shown in Table 3. Where, C is the workpiece rotary angle, J is the swivel angle.

<table>
<thead>
<tr>
<th>Table 1  Geometrical parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
</tr>
<tr>
<td>Tooth number</td>
</tr>
<tr>
<td>Face width/mm</td>
</tr>
<tr>
<td>Shaft angle/°</td>
</tr>
<tr>
<td>Spiral hand</td>
</tr>
<tr>
<td>Offset /mm</td>
</tr>
<tr>
<td>Pressure angle/°</td>
</tr>
<tr>
<td>Spiral angle/°</td>
</tr>
<tr>
<td>Outer pitch diameter/mm</td>
</tr>
<tr>
<td>Full tooth depth/mm</td>
</tr>
<tr>
<td>Pitch angle/°</td>
</tr>
<tr>
<td>Face angle /°</td>
</tr>
<tr>
<td>Root angle /°</td>
</tr>
</tbody>
</table>
Building the 3D model of the new model in software Ug and importing it into software Vericut, configuring machine tool file with three setups due to rough and finish machining, establishing wheel blank and three cutting tools, then, simulation can be carried out after the NC program has been written. An instant condition in the processing is shown in Fig.4.

According to the mathematical model and tooth surface equation, the tooth surface points can be calculated by Matlab. Then, these tooth surface points are imported into Ug and the tooth surface will be obtained. After a series of operations, the 3D theoretical model can be established and be imported into Vericut. By overlapping the 3D theoretical model with the simulation model, the result is shown in Fig.5.

Aiming at checking the consistency of the simulation model with the theoretical model, the analysis of the gouge and excess amounts could be carried out after overlapping. The results are shown in Figs.6 and 7.

<table>
<thead>
<tr>
<th>Table 2  Machining parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Cutter radius/mm</td>
</tr>
<tr>
<td>Cutter blade angle /°</td>
</tr>
<tr>
<td>Total tilt angle /°</td>
</tr>
<tr>
<td>Machine tilt angle /°</td>
</tr>
<tr>
<td>Machine root angle /°</td>
</tr>
</tbody>
</table>

| Table 3  Part point positions of each axis |
|----------|---------------------------------|
| X        | Y                               | Z      | C               | J    |
| 43.1734  | 40.6561                         | -166.7413 | 156.9432 | -21.0000 |
| 42.9633  | 40.3699                         | -166.7413 | 156.0621 | -20.8750 |
| 42.7526  | 40.0842                         | -166.7413 | 155.1809 | -20.7500 |
| 42.5413  | 39.7990                         | -166.7413 | 154.2998 | -20.6250 |
| 42.3294  | 39.5142                         | -166.7413 | 153.4182 | -20.5000 |
| ...      | ...                             | ...    | ...            | ...  |
| -42.4808 | -19.3865                        | -166.7413 | -107.4018 | 16.5000 |
| -42.8217 | -19.4856                        | -166.7413 | -108.2829 | 16.6250 |
| -43.1628 | -19.5840                        | -166.7413 | -109.1641 | 16.7500 |
| -43.5040 | -19.6817                        | -166.7413 | -110.0452 | 16.8750 |
| -43.8455 | -19.7786                        | -166.7413 | -110.9264 | 17.0000 |
As illustrated in Fig.6, the convex gouge quantity is uniform with a 0.02 mm gouge amount covering the entire tooth surface. However, the concave gouges mainly exist in mean width of outer and addendum of inner, with the biggest amount is 0.02mm. The tooth root gouges are quite bigger, the biggest area reaches to 0.1mm. The reason is that the theoretical model doesn’t consider of the cutting tool ness, which is different from the simulation model. The nonuniformity of the concave gouges is induced by simulation accuracy.

Figure 7 reveals the distribution of excesses. The entire convex tooth surface is very homogeneous, with no excesses area existing. Meanwhile, the excess amount of 0.01mm exists in mean width of concave inner. In addition, the biggest excess amounts of 0.02mm exist both in the outer and inner tooth slot. By comprehensively analyzing the information reflected by Fig.6 and Fig.7, the sum of upper and lower limit deviation of convex and concave, respectively, are 0.02mm and 0.03mm. The results presented indicate that the simulation model is basically in line with the theoretical model. Thereby, the accuracy of the simulation cutting model is confirmed, and the feasibility of the design scheme about the new type milling machine model is certified.
4. Cutting experiment analysis

4.1 The feature of the milling machine

Based on the new algorithm and the proposed model above, the independent research and development of the milling machine is shown in Fig.8. The three linear axes, the workpiece axis and the swivel drum are all driven by NC system. After abolishing the cradle structure, the virtual cradle is simulated by the linkage of the $X$ and the $Y$ axes. The relative motion of the processed gear and the shape gear is the same as the traditional machine tools. The swivel drum could rotate synchronously with the virtual cradle and the swivel angle adjusted by NC system. The form of motion of the phoenix is six axes five linkages, which will increase the cost of the machine tool greatly. In spite of the new machine has the ability of five-axis linkage, the $Z$ axis doesn’t need linkage and the $B$ axis isn’t the CNC axis neither, thus the NC rotary table is no longer necessary. Therefore, the cost of the new machine tool could be brought down effectively, and the cost of hypoid gears is reduced accordingly.

![The New Type CNC Milling Machine](image)

Figure 8  The New Type CNC Milling Machine

4.2 Cutting experiment

In order to further verify the accuracy of the kinematic parameters calculated and the simulated model established, the cutting experiment is carried out. The gear is machined by Formate method and the pinion is machined by tilt method with the new type machine tool. In order to compare with the pinion processed by No.116, another cutting experiment is conducted meanwhile using the same basic processing parameters as the pinion processed by the new type machine. Afterwards, the measurement of the two pinions is conducted on the JD45+ measuring machine. The machining parameters and machine tool adjustment parameters of No.116 are shown in Table 4, the machining states and the measurement state are given in Fig.19, Fig.10, Figs.11 and 12.
Table 4  Machining parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Gear</th>
<th>pinion</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Gear</td>
<td>Convex</td>
<td>Concave</td>
</tr>
<tr>
<td>Cutter radius/mm</td>
<td>152.4</td>
<td>151.6</td>
<td>151.8</td>
<td></td>
</tr>
<tr>
<td>Cutter blade angle /°</td>
<td>22.5</td>
<td>31</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Radial distance/mm</td>
<td>162.16</td>
<td>178.32</td>
<td>149.36</td>
<td></td>
</tr>
<tr>
<td>Initial cutter angle/mm</td>
<td>48.39</td>
<td>62.52</td>
<td>60.49</td>
<td></td>
</tr>
<tr>
<td>Cradle angle /°</td>
<td></td>
<td>99.16</td>
<td>108.27</td>
<td></td>
</tr>
<tr>
<td>Eccentric angle /°</td>
<td></td>
<td>106.71</td>
<td>84.45</td>
<td></td>
</tr>
<tr>
<td>Machine tilt angle /°</td>
<td></td>
<td>53.83</td>
<td>46.57</td>
<td></td>
</tr>
<tr>
<td>Machine swivel angle /°</td>
<td></td>
<td>314.75</td>
<td>319.76</td>
<td></td>
</tr>
<tr>
<td>Blank position/mm</td>
<td>-1.79</td>
<td>10.91</td>
<td>-7.81</td>
<td></td>
</tr>
<tr>
<td>Blank offset/mm</td>
<td>0</td>
<td>45.20</td>
<td>27.72</td>
<td></td>
</tr>
<tr>
<td>Velocity ratio</td>
<td>0</td>
<td>12.27</td>
<td>10.4</td>
<td></td>
</tr>
<tr>
<td>Machine root angle /°</td>
<td>76.4</td>
<td>-4.4</td>
<td>-2.25</td>
<td></td>
</tr>
<tr>
<td>Sliding base /mm</td>
<td>0</td>
<td>25.24</td>
<td>18.34</td>
<td></td>
</tr>
</tbody>
</table>

Figure 9  Cutting Gear by Formate Method    Figure 10  Cutting Pinion by New Type Machine Tool

Figure 11  Cutting Pinion by No.116    Figure 12  The State of Measuring

During adjusting and processing, compared with the eight parts of No.116 need to be adjusted manually, the new
type machine tool is much simpler as it only has two parts need to be adjusted manually. The time used to correct the contact pattern will be shortened dramatically and the labor intensity also will be decreased. In addition, because quite a few manual adjustments are needed on No.116, the time consumption is longer, in the same time, the adjusting accuracy mainly depends on experience, which would be greatly affected by the factor of labor. Besides, the three linear axes and the workpiece axis of the new type milling machine are all driven by NC system. After having finished machining one tooth, the cutter doesn’t need to rotate with the cradle drum to return to the initial position, but can move in a straight line. Thus, the time used by the new type milling machine during the cutter return to the initial position is much shorter than that of No.116 milling machine. The time needed by each step during adjusting and processing by the two type milling machines is shown in Table 5.

<table>
<thead>
<tr>
<th>Table 5</th>
<th>The Time Consumption of The Two Type Milling Machines</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Adjusting</td>
</tr>
<tr>
<td>No.116 milling machine</td>
<td>7200</td>
</tr>
<tr>
<td>New type milling machine</td>
<td>1800</td>
</tr>
</tbody>
</table>

Referring to Table 5, the time used to adjust the new type milling machine is shortened by 75%, the time consumed during processing one tooth is reduced by 17.9%, the gear indexing time and the total processing time is reduced by 44.4% and 19.3%. Therefore, conclusion can be drawn that the machining efficiency of the new type milling machine is improved greatly.

Due to a series of errors (i.e., generator, cutting tool, fixture, workpiece, etc), reverse adjustment calculation needs to executed by the measuring machine. After the result is fed back to the milling machine, cutting experiment can be carried out again under the guidance of these data. Final measurement results are shown in Figs.13 and 14.
Figure 13  Measurement Results of The Pinion Machined by The New Machine

(a) Tooth Surface Error

(b) Index Error
As illustrated in Fig.13(a), by contrast with the actual tooth surface and the theoretical tooth surface, the biggest error of convex is 0.0321mm, which exists in addendum of inner. Besides, the biggest error of concave is 0.0136mm, existing in dedendum of outer. Both the pressure angle and the helix angle are all well agreed. As illustrated in Fig.14(a), the biggest errors of convex and concave are 0.0408mm and 0.0376mm, all existing in dedendum of outer. Both the pressure angle and the helix angle have slightly errors.

Moreover, Fig.13(b) demonstrates that the maximum index error and the total index error of the convex machined by the new type milling machine are 16.2 μm and 32.4 μm, these errors of the concave are 15.9 μm and 27.2 μm, both of the surfaces can reach to the accuracy grade of 6. However, Fig.14(b) demonstrates that the maximum index error and the total index error of the convex machined by No.116 are 22.5 μm and 43.1 μm, errors of the concave are 23.8 μm and 44.2 μm, both of the surfaces can only reach to the accuracy grade of 7. Accuracy grade of the index error of the pinion machined by the new machine is a grade higher than that of the pinion machined by No.116.

The measurement results demonstrate that the machining precision of the new type milling machine is better than No.116 milling machine. The accuracy of the machine tool and the correctness of the motional parameters are further proved. Then, rolling test of the pinion machined by new type milling machine is conducted and the actual contact area is compared with that of the theoretical tooth surface. The results of tooth contact analysis and the rolling test are shown in Figs.15 and 16.
According to Fig.16, the tooth contact areas are presented as bias-in form, which are consistent with the theoretical contact areas reflected by Fig.15. Therefore, the results meet the requirements of gear manufacturing.

5. Conclusions

By studying of motional parameters calculation and tooth cutting experiment based on the new type milling machine, the following conclusions can be drawn:

(1) A new model of machining hypoid gears by tilt cutting method is setup by taking advantage of the innovation concept, the formula to calculate the motional parameters is deduced with the new algorithm, which is applied into the cutting simulation. The comparison results of simulation model and the theoretical model in gouge and excess demonstrate the feasibility of the new model and the accuracy of the algorithm;

(2) The processing experiment is conducted by using the new type milling machine. The results of the timing and measurement by contrast with the pinion processed by No.116 indicate that the new machine tool is more efficient and more precise. The rolling test result of the pinion machined by the new type milling machine shows that the meshing performance is very well, further verified the accuracy of the new calculation model. Ongoing efforts are being made to optimize this algorithm, the authors anticipate that this paper could provide a reference for hypoid gear processing.

Acknowledgments

The authors are grateful to the National Natural Science Foundation Council of China, This project was performed under the Grant No. 51475141.
References


