Simulation and evaluation of Processing Tracks in Both-sides Cylindrical Lapping Process

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ABSTRACT:

An analytical solution is derived for the processing tracks based on kinematics in the planetary both-sides cylindrical lapping system, in order to provide a fundamental theory for optimization of kinematic and geometric conditions. Firstly, through meshing the flat surface of lap to plenty of concentric circles, the processing tracks that are induced by the movement of contact points between circles and cylindrical surface of workpiece can be simulated. Secondly, through meshing the cylindrical surface to plenty of rectangular areas, the distribution uniformity of processing tracks can be evaluated numerically by counting the number of track points distributed in each meshed region and calculating a value of standard deviation. Two examples are provided and compared in different speed conditions, indicating that the method is feasible to be applied in the optimization of speed parameters combination.

Keywords: Kinematics, Processing track, Both-sides lapping, Cylindrical roller

1. Introduction

The cylindrical rolling bearings are commonly applied in high speed rotating machines under high pressure. The cylindrical roller, as the most important component of rolling bearing, has a large advantage of being loaded high pressure due to its linear contact with the bearing raceway. The geometric and dimensional accuracy of cylindrical rollers have great significance for mechanical performance and service life of rolling bearing.

The both-sides lapping mechanism has been applied widely in the planarization and finish processing of plane parts, such as silicon wafers, gauging block and mechanical seals, etc. In addition, it can be also used in lapping and polishing the outer diameter of cylindrical roller. Accuracy of size and straightness up to 0.125 μm, surface finish of 0.025 μm, and roundness of the parts up to 0.125 μm was achieved by John Indge in this mechanism. He proposed that the both-sides cylindrical lapping which can obtain the nanoscale surface finish and the multidirectional surface texture is typically different from the traditional centerless lapping [1-3].

The analysis of processing tracks is an important and typical solution to theoretically predict the workpiece's geometry accuracy and investigate the influencing factors [4-7]. So far, the research related to processing tracks in planetary both-sides cylindrical lapping is still scarce and needs further theoretical study. Therefore, in the paper, an analytical solution is derived for the processing tracks with its kinematics in the planetary both-sides cylindrical lapping system, in order to provide a fundamental theory for optimization of kinematic and geometric conditions.

2. Planetary Both-sides Cylindrical Lapping Machine

Fig.1 Schematic diagram of the planetary both-sides cylindrical lapping method

Fig.2 Schematic diagram of principle of processing tracks simulation
A both-sides lapping machine of planetary motion type for processing the cylindrical surface is illustrated in Fig.1, which employs such major components as upper lap, lower lap, carrier, sun gear and annular gear. The upper and lower laps that are positioned concentrically rotate in the opposite direction. The disc shaped carrier makes the rotation around its own center axis, and the circle orbital motion around laps' rotation axes, by driving sun gear and annular gear. More than two rollers are set in slots of each carrier and distributed radially between the two facing lapping laps mounted one above the other. Cylindrical rollers restricted by carrier make the translational cycloid movement and the rolling motion simultaneously.

3. Simulation principle

3.1 Definition of processing tracks

During processing, the roller's cylindrical surface contacts with each lap in line at an instantaneous moment. To simplify the process model and make illustration of processing tracks feasible, the flat surface on the lap is meshed to plenty of concentric circular curves, and then each circle intersect with contact line in a contact point. A path is generated due to each point's movement on roller's cylindrical surface. Processing tracks are defined as the set of all the interlaced paths.

3.2 Simulation of processing tracks

![Fig.3 Schematic diagram of kinematics relationships when cylindrical surface starts to contact circle](image1)

![Fig.4 Schematic diagram of kinematics relationships during cylindrical surface contacting with circle](image2)

Table 1: Definition of geometric and kinematics parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Descriptions</th>
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</tr>
</thead>
<tbody>
<tr>
<td>$D_{po}$</td>
<td>Radius of a defined circle of lap</td>
<td>$\varphi_{rc}$</td>
<td>Angle from roller center $O_r$ to line $OO_c$ around carrier center $O_c$</td>
</tr>
<tr>
<td>$D_{co}$</td>
<td>Distance from carrier center $O_c$ to origin point $O$</td>
<td>$\theta_{roll}$</td>
<td>Roller's rolling angle</td>
</tr>
<tr>
<td>$D_{rc}$</td>
<td>Distance from roller center $O_r$ to carrier center $O_c$</td>
<td>$\omega_a$</td>
<td>Lower plate rotation angular speed</td>
</tr>
<tr>
<td>$D_{pc}$</td>
<td>Distance from point $P$ to roller center $O_c$</td>
<td>$\omega_{rc}$</td>
<td>Carrier rotation angular speed around its own center $O_c$</td>
</tr>
<tr>
<td>$D_{pr}$</td>
<td>Distance from point $P$ to roller center $O_r$</td>
<td>$\omega_{co}$</td>
<td>Carrier circulation angular speed around plate's axis $O$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\omega_{roll}$</td>
<td>Roller's rolling angular speed</td>
</tr>
</tbody>
</table>

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The processing tracks on the cylindrical surface can be illustrated and described by calculating the coordinate values of each point relative to the roller’s center coordinate system at every moment based on kinematics.

Assuming that the roller’s cylindrical surface and the lap’s flat surface are both ideal. Because the roller’s rolling motion is determined by the rotation of carrier and lower plate rather than the circulation of carrier, the relative movement between cylindrical roller, carrier and laps can be respectively described in such a cartesian global coordinate system. Its origin point O is positioned at the rotational axis of laps. The points O_c and O_r are defined as the centers of carrier and roller respectively. The Z-axis is positioned vertical to the ground surface. The X-axis is fixed on the line OO_c, and the X- and Y-axes define a plane on which the geometric centers of roller and carrier move.

During processing, the roller’s cylindrical surface contacts with each circle of lap at one or two points P. At a unique angle of carrier’s rotation around its axis from the X-axis, the roller’s axis is just a tangent of the circle. At this moment, the cylindrical surface starts to contact the circle on the XOY plane. Fig.3 schematically illustrates the kinematics relationships in this case, and the relevant parameters are defined in Table 1. Hence, during the whole period that the cylindrical surface contacts with the circle, the variation range of carrier’s rotation angle $\varphi_{rc}$ can be obtained by the equation

$$\varphi_{rc} = [\pi - \arcsin \frac{D_{po}}{D_{co}}, \pi + \arcsin \frac{D_{po}}{D_{co}}]$$  \hspace{1cm} (1)

Within the above range of angle $\varphi_{rc}$, Fig.4 schematically illustrates the kinematics relationships during the cylindrical surface contacting with the circle. In the process, there may be one contact point or two contact points. In the figure, the angle $\varphi_{rc}$ is defined by the equation $\varphi_{rc} = \frac{\omega_{rc}}{t}$, the angle $\angle PO_cO$ is defined by the equation $\angle PO_cO = \pi - \varphi_{rc}$, and the distances $D_{po}$, $D_{co}$ and $D_{rc}$ have been defined. Hence, based on the cosine theorem of triangle $\Delta PO_cO$, a quadratic equation to obtain the parameter $D_{pc}$ is established and expressed as

$$D_{pc}^2 + D_{co}^2 - D_{po}^2 - 2D_{pc}D_{co} \cos \angle PO_cO = 0$$  \hspace{1cm} (2)

By solving the equation, the result of $D_{pr}$ is obtained and expressed as

$$D_{pc} = D_{co} \cos \angle PO_cO \pm \sqrt{D_{po}^2 - D_{co}^2 \sin^2 \angle PO_cO}$$  \hspace{1cm} (3)

Therefore, the distance $D_{pr}$ can be obtained by the equations

$$D_{pr} = D_{pc} - D_{rc}, \text{ when } D_{po} < D_{co}$$  \hspace{1cm} (4)

$$D_{pr} = D_{pc} + D_{rc}, \text{ when } D_{po} > D_{co}$$

Considering that the roller has a length along the axis, the value of $D_{pr}$ should be compared with the roller’s length $l$ after calculating the value of $D_{pr}$. If the distance $D_{pr}$ is shorter than the roller’s length $l$, the value of $D_{pr}$ is saved, otherwise, deleted. According to the above solution, the processing tracks generated by a circle may be one or two or none.

The other parameter for describing the processing tracks is the angle $\theta_{roll}$ of roller’s rolling motion. Assuming that the value of $\omega_{roll}$ related to the time has been obtained, the angle $\theta_{roll}$ related to the time is obtained by the following equation

$$\Delta \theta_{roll}(t) = \omega_{roll}(t) \cdot \Delta t$$  \hspace{1cm} (5)

$$\theta_{roll} = -90 + \int \omega_{roll}(t) dt$$  \hspace{1cm} (6)

When the time $t = 0$, the initial value of angle $\theta_{roll} = -90$.

Finally, a roller’s central coordinate system is defined. The Xr- and Zr-axes define the position of contact points on a circular section of cylindrical surface. The Yr-axis defines the position of contact points along the axis of cylindrical surface. Combining the distance $D_{pr}(t)$ and the angle $\theta_{roll}(t)$ that are related to the time, the position of contact point can be described in the roller’s central coordinate system and expressed as

$$x_r = r \cdot \cos \theta_{roll}(t)$$

$$y_r = D_{pr}(t)$$

$$z_r = r \cdot \sin \theta_{roll}(t)$$  \hspace{1cm} (7)

### 3.3 Evaluation of processing tracks

To evaluate the distribution of processing track points, the cylindrical surface is meshed to plenty of small rectangle regions by separating roller’s circle and axis. After that, a standard deviation is computed and used to evaluate the distribution of processing track points, by counting the number of points distributed in each region. The smaller value of standard deviation means the better distribution of processing track points, more helpful for promoting the roller’s
geometric accuracy. The standard deviation is expressed as

$$SD = \sqrt{\frac{\sum (n_i - \bar{n})^2}{N-1}} (i = 1, 2, \cdots, N)$$ (8)

where $n_i$ is the number of points in a region, $\bar{n}$ is the average of all the numbers of points in each region, and $N$ is the number of all the regions.

6. Results

For the simulation model according to the both-sides cylindrical lapping machine, the distance $D_{co}$ is 130 mm, the distance $D_{rc}$ is 40 mm. The roller has a radius of 10 mm and a length of 30 mm. The lap has an internal diameter of 75 mm and an external diameter 185 mm, and the lap is separated to 111 circles by a distance of 1 mm between each circle. The time is 10 seconds. In this paper, two examples as below are given for simulation and evaluation of processing tracks.

6.1 Simulation of processing tracks

Before simulation of processing tracks, the research of roller’s rolling angular speed $\omega_{\text{roll}}(t)$ was done, which can be obtained by the theoretical analysis and experimental observation. The simulations are carried out for two types of speed combination shown in Table 2. The results of roller’s rolling angular speed $\omega_{\text{roll}}(t)$ respectively in two above cases are both shown in Fig.5. The 3D view simulation results of processing tracks can be obtained, and transformed to the 2D view ones that are convenient for the observation. The partial 2D view simulation results in the same regions on the cylindrical surface are respectively shown in Fig.6 (a) and (b).

<table>
<thead>
<tr>
<th>No.</th>
<th>lower plate speed $\omega_a$</th>
<th>Carrier</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>circulation speed $\omega_{co}$</td>
<td>rotation speed $\omega_{rc}$</td>
</tr>
<tr>
<td>A</td>
<td>10 rpm</td>
<td>9 rpm</td>
</tr>
<tr>
<td>B</td>
<td>10 rpm</td>
<td>6 rpm</td>
</tr>
</tbody>
</table>

Table 2 Speed conditions of simulation

Fig.5 Results of roller’s rolling angular speed for two speed combinations
6.2 Evaluation of processing tracks

Based on the evaluation method mentioned above, the cylindrical surface is meshed to rectangle regions of total 900 by separating the circle of cylinder to 30 parts and the length of cylinder to 30 parts. Each region with a unique serial number (shown in Fig. 7) is distributed on a rectangle surface to which the cylindrical surface is transformed.

The number of processing track points distributed in each region is counted and drawn in the diagram of stair pattern. The statistics results of points for two speed combinations are respectively shown in Fig. 8 (a) and (b), where the horizontal axis is defined as the serial number of meshing region, and the vertical axis is defined as the number of track points in each region. The total number of all the points is defined as 17586, then, the standard deviation in conditions A is 5.3342, and another one in conditions B is 3.5459, and their comparison is shown in Fig. 8(c).
7. Discussion

It is seen from Fig.7 and Fig.8 that the simulation and evaluation results of processing tracks respectively in two different speed conditions are very different. In addition, the values of standard deviation respectively in conditions of A and B are also very different. Therefore, the analytical solution that deals with the processing track points is feasible, and can be used to analyze and numerically evaluate the distribution of processing tracks. The smaller the value of standard deviation is, the well-distributed the processing tracks are on the cylindrical surface. The value of standard deviation in conditions A is 5.3342, and the other one in conditions B is 3.5459, compared in Fig.8(c), hence the distribution of cylindrical processing tracks in conditions B is better than the one in conditions A.

8. Conclusions

An analytical solution is derived for the processing tracks based on kinematics in the planetary both-sides cylindrical lapping system. Firstly, the processing tracks induced by the movement of contact points on roller's cylindrical surface can be simulated, and secondly, their distribution uniformity can be evaluated numerically by counting the number of track points distributed in each meshed region and calculating a value of standard deviation. In this paper, two analytical examples respectively in conditions A and B are provided. As a result, the distribution of cylindrical processing tracks in conditions B is better than the one in conditions A. It is indicated that the method is feasible to be applied in the optimization of speed parameters combination.

9. Acknowledgements

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10. Reference


