Surface topography modeling and analysis of camshaft generated by swing grinding process

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Abstract
In conventional grinding (CG), camshafts with wide profiles suffer from poor quality and low efficiency because the large contact area between the grinding wheel and camshaft profile limits the diffusion of grinding temperature, leading to burning defects. Swing grinding (SG) can mitigate these problems as it involves a reciprocating motion along the axis of the grinding wheel; however, the lack of understanding of machined surface topography has restricted its application. Therefore, in this study, a surface topography prediction model was proposed that based on the distribution, shape, and trajectory of grains. The model was verified through experiments, and the mean error was 12% for \( R_{ax} \) and 9% for \( R_{ay} \); the roughness along the grinding direction was \( R_{ax} \), and the roughness along the vertical grinding direction was \( R_{ay} \). Compared to CG, SG has a 3% lower \( R_{ay} \). The influence of the wheel speed and feed rate in SG is consistent with that in CG. \( R_{ax} \) exhibited a periodic trend with an increase in the swing amplitude and a monotonically decreasing trend with an increase in the swing frequency. The variation trend of \( R_{ay} \) with the swing amplitude was the same as that of \( R_{ax} \). Furthermore, \( R_{ay} \) exhibited a nonlinear increasing trend with an increase in swing frequency.

Keywords Swing grinding · Camshaft · Surface topography · Modeling and simulation · Roughness

1 Introduction
The camshaft is a key component of a marine diesel engine. Rapid wear can occur easily under high temperatures and impact loads during operation. A high-precision and high-quality camshaft profile is key to ensuring a long service life of camshafts. Conventional grinding (CG) can easily cause grinding burns and out-of-tolerance shapes and positions when machining camshafts with a wide profile. Swing grinding (SG) can ensure high-efficiency and high-quality machining of camshafts with a wide profile by using a narrow grinding wheel, increasing the periodic reciprocating movement along the axial direction of the grinding wheel and making the feed movement along the radial direction of the grinding wheel.

The grinding of camshaft grinding by scholars involves improving production efficiency, camshaft machining system design, constant grinding depth, grinding force simulation, and so on. Krajnik et al. [1] proposed novel modeling to increase productivity, which include instantaneous geometry, kinematics, and temperature of any workpiece shape for cam grinding cycle optimization methods. Chen et al. [2] established a mathematical model of the cam profile error, and obtained the relationship between the cam profile error and the following position error. Xiong et al. [3] derived a grinding force calculation model suitable for camshaft grinding. The grinding force simulation of cam machining is realized by the grinding force model and MATLAB tool. The surface quality of cam grinding affects its performance, so it is necessary to study the formation and characteristics of cam grinding surface topography.

At present, the modeling methods of grinding surface topography can be roughly divided into three categories: empirical modeling, theoretical modeling, and finite element modeling. Empirical modeling primarily comprises surface topography modeling methods based on data analysis and machine
learning; this is because these methods are simple and easy to operate, have high prediction accuracy, and have strong self-learning abilities [4]. However, these methods have the disadvantages of limited prediction range and the significant influence of human factors [5–7]. Furthermore, marine diesel camshafts are produced in small batches, with few experimental samples. In the finite element simulation method, simple models can be used to replace complex problems and solve them. Complex grinding mechanisms involved in the grinding process are difficult to observe with the naked eye or even with instruments. Most scholars have studied surface topography by grinding single abrasive grains. Zhou et al. [8] simulated the grinding of ceramic materials by using finite elements and determined the surface roughness of workpiece grinding through displacement change. Grinding is the cutting process of thousands of abrasive grains on the surface of a workpiece; therefore, it is insufficient to analyze only single abrasive grains.

The current mainstream prediction method involves theoretical modeling as it ensures better understanding of the difference in the surface topography caused by the interaction between the grinding wheel and workpiece, contact method, and grinding characteristics. The general theoretical modeling process can be divided into two steps [9]: In the first step, a surface topography model of the grinding wheel is established; in the second step, according to the kinematic relationship between the grinding wheel and workpiece, combined with the grinding principle, the surface topography is predicted. The movement of the grinding wheel in the grinding zone is closely related to the formation of the surface [10].

Two methods are commonly used to perform the first step. In one of the methods, it is assumed that the abrasive grains have a simple geometric shape and are randomly distributed; subsequently, a surface model of the grinding wheel is established [11, 12]. In the other method, a measuring instrument is used to measure and reconstruct the surface topography of the grinding wheel; Ding et al. [13] used this method to reconstruct the surface topography of a grinding wheel through FFT and Johnson transformation. Dai et al. [14] reconstructed the surface topology of a single-textured CBN wheel by using the Johnson transform and its inverse transform.

The workpiece surface topography is generated by establishing a grinding material removal mechanism. Liu et al. [15] presented the development of models that describe the surface-generation process for micro end milling. Xun and Rowe [16] studied the generation method of grinding surface topography and simulated the grinding force during the grinding process. Wen [17] assumed that the abrasive grain height obeyed a Gaussian distribution and established a motion trajectory equation to simulate the surface topography of the workpiece. Nguyen et al. [18] established an abrasive grain cutting trajectory and mapped it to the workpiece surface coordinate system to obtain the three-dimensional topography of the ground workpiece surface.

At present, the formation mechanism of the surface morphology of SG and the influence of the grinding process parameters on the formation of the surface morphology need further investigation. SG motions are similar to that of ultrasonic vibration grinding (UVG).

In the past decades, undeformed cutting thickness has been used to evaluate grinding performance [19]. Li et al. [20] used a Doppler vibrometer to verify that tiny radial vibrations were the primary reason for the formation of short wear debris. Zhou et al. [21] found that the matching phase difference (MPD) can be used to characterize the matching relationship between the ultrasonic vibration parameters and grinding process parameters. Sun et al. [22] studied UG cylindrical grinding and found that the micro-spiral chip pocket micro-grinder (MAT-HCP) had good chip evacuation performance and improved wear resistance. Zhou et al. [23] found that applying axial vibration increased the number of dynamically active grains, produced a uniform undeformed chip thickness, and reduced the surface roughness.

The cam width of the marine diesel engine is larger than the width of the grinding wheel. When CG is used, the cam edge cannot be ground. In CG, camshafts with wide profiles suffer from poor quality and low efficiency because the large contact area between the grinding wheel and camshaft profile limits the diffusion of grinding temperature, leading to burning defects. Therefore, SG is used to grind wide-profile cams.

There were few studies on the mechanism of SG, so this paper will carry out theoretical research on SG. Considering the complex grinding trajectory, the surface topography generated by SG was modeled and analyzed in this study. This article is structured as follows. First, the modeling process of the model is introduced, including the working principle of SG and the simulation process of the surface topography of the grinding wheel and workpiece. Second, two-dimensional evaluation parameters are selected to characterize the surface topography of the SG, i.e., the roughness along the grinding direction $R_{ax}$ and the roughness along the vertical grinding direction $R_{ay}$. Subsequently, the influence of the conventional parameters and two-dimensional swing parameters on the surface topography and surface roughness in SG is discussed. The swing-simulated surface was compared and in good accord with the measured workpiece surface under the same grinding conditions.

## 2 Surface topography modeling and verification

### 2.1 Principle of SG

Camshaft swing grinding is based on CG, in which a low-frequency and high-amplitude swing is applied along the axis of the grinding wheel to realize cylindrical grinding.
Figure 1a shows the working principle of SG. In the coordinate system used in this study, the x-axis is along the direction of movement of the camshaft feed, the y-axis is parallel to the axis of the grinding wheel, and the z-axis is along the direction of movement of the grinding wheel frame. The grinding depth is \( a_p \); the wheel speed is \( v_w \); the wheel rotation speed is \( n_s \); the radius of the grinding wheel is \( R \); the angular velocity of the grinding wheel is \( \omega_s \); and the radius of the grains is \( R_g \). A and \( f \) are the swing amplitude and frequency, respectively, and the feed rate is \( V_w \).

The grinding mechanism of SG is significantly different from that of CG; the grinding topography of the machined surface is also different. Therefore, it is necessary to study the formation mechanism of the SG surfaces. The trajectory of a single abrasive grain is described below. Assuming that the grinding start time is \( t_0 = 0 \) s, the initial phase angle is 0°. The abrasive grains at the contact point of the grinding wheel workpiece are considered the starting point. In this study, cylindrical grinding was simplified to surface grinding. Thus, the trajectory equation of a single abrasive grain in SG is as follows:

\[
\begin{align*}
    x(t) &= R \cos \left( \omega_s t - \frac{\pi}{2} \right) \pm V_w t \\
    y(t) &= A \sin \left( 2\pi f t + \frac{\pi}{2} \right) \\
    z(t) &= R \sin \left( \omega_s t + \frac{\pi}{2} \right) + R + R_g - a_p
\end{align*}
\]

The “±” in \( x(t) \) represents two different grinding methods. “+” means down grinding and “−” means up grinding. The commonly used grinding method is down grinding. That is, the grinding wheel and the workpiece rotate in the same direction in the tangential direction. In the equation above, \( R \) is the radius of the grinding wheel (mm), \( \omega_s \) is the angular velocity of the grinding wheel (rad/s), \( V_w \) is the workpiece feed rate (mm/min), \( A \) is the swing amplitude (mm), \( f \) is the swing frequency (Hz), \( R_g \) is the grain radius (mm), and \( a_p \) is the grinding depth (μm).

### 2.2 Modeling of wheel topography

The geometry and distribution of the grains on the grinding wheel significantly affected the surface roughness of the workpiece. The grinding surface was modeled based on the trajectory of the grains on the grinding wheel surface. However, the actual grains were irregular in shape. Considering that there was a large negative rake angle during the grinding process, the shape of the grains was assumed to be spherical [24]. Furthermore, the following assumptions were made regarding the grinding process and the grains:

1. The grains on the surface of the grinding wheel were spherical. The spatial distribution and size of the grains were uniform, and their height was Gaussian.
2. In theoretical research, the influence of elastic deformation, plastic deformation, and grinding heat during the grinding process is not considered. Therefore, in this study, the material was assumed to be an ideal metal.
3. The swing amplitude and frequency were stable during the SG process.
4. In theoretical research, for the convenience of calculation, it is assumed that when the grinding wheel is in contact with the workpiece, the grinding time is \( t = 0 \) s, and the initial phase angle of swing grinding is 0.

Figure 2 shows the step analysis of the grain-modeling process on the surface of the grinding wheel. In Fig. 2, \( m \) is the circumferential direction of the grinding wheel, and \( n \) is the direction of the axis of the grinding wheel.
The distance \( L \) between the grains and the position of each grain can be expressed by the following equation:

\[
\{ G_{ij} \} = \left\{ \begin{array}{c}
G_{ij}^x \\
G_{ij}^y 
\end{array} \right\} = \left\{ \begin{array}{c}
G_{0,0}^x + i \cdot \Delta x \\
G_{0,0}^y + j \cdot \Delta y 
\end{array} \right\}
\tag{2}
\]

In the equation above, \( G_{ij} \) represents the position of the center of each grain on the plane. \( G_{0,0}^x \) and \( G_{0,0}^y \) indicate the positions of the center of the first grain on the x-axis and y-axis, respectively. In addition, \( \Delta x = \Delta y = L \). The equation used for calculating the grain spacing \( L \) is as follows:

\[
L = 137.9M^{-1.43} \sqrt[\frac{\pi}{32-S}]
\tag{3}
\]

In the equation above, \( M \) is generally defined as the number of holes in a sieve in 1 square inch. \( S = 32 - (V_g/2) \) is the grinding wheel structure parameter, and \( V_g \) (%) is the grain concentration.

The geometry and distribution of the grains on the grinding wheel significantly affected the surface morphology of the workpiece. The grains were characterized by their size and height. It was assumed that the surface of the grinding wheel was composed of several spherical grains with a diameter of \( d_g \). The maximum grain diameter, \( d_{g_{\text{max}}} \), and average grain diameter, \( d_{g_{\text{avg}}} \), were calculated using the following equations [25]:

\[
d_{g_{\text{max}}} = 15.2M^{-1}
\tag{4}
\]

\[
d_{g_{\text{avg}}} = 68M^{-1.4}\tag{5}
\]

The diameter \( d_g \) and height \( h_i \) of the grains were used to approximate the Gaussian distributions \( P(d_g) \) and \( P(h_i) \) [26]. The two equations used are as follows:

\[
P(d_g) = \frac{A_1}{\sigma \sqrt{2\pi}} \exp \left(- \frac{1}{8} \left( \frac{d_g - d_{g_{\text{avg}}}}{\sigma} \right)^2 \right)
\tag{6}
\]

\[
P(h_i) = \frac{1}{\sigma \sqrt{2\pi}} \exp \left(- \frac{(h_i - \mu)^2}{2\sigma^2} \right)
\tag{7}
\]

In Eqs. (6) and (7), the standard deviation is \( \sigma = (d_{g_{\text{max}}}-d_{g_{\text{avg}}})/3 \), and the average is \( \mu = d_{g_{\text{max}}} \).

There are many cutting points on spherical grains. In this study, the highest point of the grains was selected as the cutting point. A bilinear interpolation algorithm was used to refine the grids further, and each grain was labeled. The row is denoted by \( m \), the column by \( n \), and the height of the grain by \( h_{mn} \); the row number, column number, and height are registered in the matrix \( H(m*n) \).

### 2.3 Establishment of abrasive grains trajectories

The generation of the surface topography of the workpiece was similar to that of the grinding wheel surface. Extraction of the remaining grinding height was crucial for evaluating the workpiece surface topography generation, as shown in Fig. 3.

In Fig. 3, \( W(i*n) \) represents the grinding height in the Z-direction of the \( i \)th row (circumferential direction) and \( j \)th column (axial direction) in the coordinate system \( O-XYZ \). The height of the grain in the first row and first column of the
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The grains on the surface of the grinding wheel were separated by a distance of $L$. There was a delay of $L/V_s$ in the rotation time; thus, the phase difference can be obtained using $2\pi n_s L/V_s$. Therefore, the trajectory of the second grain in the first cross-section can be obtained as follows:

\[
\begin{align*}
    x_1^1(t) &= R \cos \left(\omega_s t - \frac{\pi}{2}\right) + V_w t \\
    y_1^1(t) &= A \sin \left(2\pi f t + \frac{\pi}{2}\right) \\
    z_1^1(t) &= R \sin \left(\omega_s t + \frac{\pi}{2}\right) + R + H(1, 1) - a_p
\end{align*}
\] (8)

Similarly, the trajectory of the $n$th abrasive grain on the $n$th column on the surface of the grinding wheel can be obtained as follows:

\[
\begin{align*}
    x_n^1(t) &= R \cos \left(\omega_s t + \frac{n \pi}{L/V_s}\right) - \frac{\pi}{2} + V_w \left(t + \frac{n \pi}{L/V_s}\right) \\
    y_n^1(t) &= A \sin \left(2\pi f \left(t + \frac{n \pi}{L/V_s}\right) + \frac{\pi}{2}\right) \\
    z_n^1(t) &= R \sin \left(\omega_s \left(t + \frac{n \pi}{L/V_s}\right) + \frac{\pi}{2}\right) + R + H(2, 1) - a_p
\end{align*}
\] (9)

The same sampling point on the workpiece surface was ground by abrasive grains of different heights because the speed of the grinding wheel was much greater than that of the workpiece. In this study, the grinding sampling point map of the abrasive grain $G$ on the workpiece surface is denoted by $P$. The grinding point map $P$ was ground thrice, and the grinding points were $P_1$, $P_2$, and $P_3$. The abrasive grains heights were $H_{G1} > H_{G2} > H_{G3}$. The remaining heights of the workpiece surface were $W_{G1} > W_{G2} > W_{G3}$. The final remaining topography on the actual workpiece surface was determined by the grit $G_1$. Therefore, the minimum value in the $W_G$ matrix was compared.

\[W(i, j) = \min(W_G(i, j))\] (11)

Figure 4 shows the simulation diagram of the surface topography of the grinding wheel when the mesh of the grain was $M = 120$. The simulation generation process was controlled by the grinding wheel mesh $M$, the distance between the grains $L$, mean value $\mu$, and variance $\sigma$.

2.4 Estimation of surface topography characterization

The grinding surface topography map is composed of a matrix, and different characterization parameters are evaluated according to the different characterization concept equations to quantify the surface topography. The one-dimensional roughness parameter, $R_a$, is often used to quantify the surface topography. In the CG process, there are only the rotating movement of the grinding wheel and the workpiece feeding movement. However, in SG, which is based on CG, a simple harmonic motion is added along the $y$-axis. In this study, two-dimensional surface roughness, $R_{ax}$ and $R_{ay}$, were selected as the characterization parameters of the SG surface topography. $R_{ax}$ was the cross-sectional roughness along the grinding direction, and $R_{ay}$ was the cross-sectional roughness perpendicular to the grinding direction. Figure 5 shows the topography of the grinding wheel and grinding
camshaft surface. Figure 5a shows the grinding texture of the camshaft surface, and Fig. 5b is a partially enlarged view of Fig. 5a. The surface topography in Fig. 5b was determined using \( V_s = 80 \text{ m/s} \), \( V_w = 1800 \text{ mm/min} \), \( a_p = 3 \mu\text{m} \), \( A = 2 \text{ mm} \), and \( f = 20 \text{ Hz} \). Figure 6 shows the cross-sectional profile along the grinding direction and perpendicular to the workpiece grinding direction.

The calculation process of the surface roughness \( R_a \) is as follows:

1. Evaluate \( \bar{Y} \) such that the upper and lower areas of the line are equal; \( \bar{Y} \) is the average value of all \( z_i \) or \( z_j \) values, and \( N \) is the number of data points within the sampling length of the workpiece:

   \[
   \bar{Y}_i = \frac{1}{N} \sum_{i=1}^{N} z_i \quad \text{or} \quad \bar{Y}_j = \frac{1}{N} \sum_{j=1}^{N} z_j
   \]  

   (12)

2. Calculate the average roughness value of the intercepted section (for example, the \( m \)-th section):

   \[
   \bar{R}_{mi} = \frac{1}{N} \sum_{i=1}^{N} |z_i - \bar{Y}_i| \quad \text{or} \quad \bar{R}_{mj} = \frac{1}{N} \sum_{j=1}^{N} |z_j - \bar{Y}_j|
   \]  

   (13)

The total average roughness of the workpiece can be obtained by averaging the individual \( R_m \) values and dividing by the total number of rows; this is referred to as the average surface roughness.

\[
R_{ax} = \frac{1}{i} \sum_{m=1}^{i} \bar{R}_{mi} \quad \text{or} \quad R_{ay} = \frac{1}{j} \sum_{m=1}^{j} \bar{R}_{mj}
\]  

(14)

“\( i \)” and “\( j \)” in Eqs. (11) and (14) have the same meaning.

In the equation above, \( i \) and \( j \) are the number of data points along the grinding direction and perpendicular to the grinding direction, respectively. In Fig. 5, \( R_{ax} \) is 0.29 \( \mu\text{m} \), and \( R_{ay} \) is 0.33 \( \mu\text{m} \). Figure 7 is the flow chart of the surface topography modeling of SG.

### 2.5 Experimental verification

The SG experiment was carried out on a camshaft with a base circle diameter of 90 mm, and the accuracy of the surface topography prediction model was verified. SG experiments were performed using a V-CBN wheel (280 \times 52 \times 100 \times 5 \times 50). The wheel is \( \phi 280 \) mm in outer diameter, \( \phi 52 \) mm in inner diameter, 5 mm in thickness, 50 in wheel structure parameters, and 100 in wheel concentration. This wheel is suitable for grinding both hard and brittle materials. The steps of the SG experiment are shown in Fig. 8. The measuring instrument used in this experiment is Japan’s Olympus DSX1000 digital microscope with a magnification range of 20–7000 \times \). Accuracy can reach to the micron level. The grinding process parameters used in the experiments are listed in Table 1.

CG is a special case of SG with swing parameters \( A = 0 \text{ mm} \) and \( f = 0 \text{ Hz} \). Table 2 presents the laser scanning
microscope measurement image and grinding topography simulation image obtained from the CG and SG camshaft surface tests. The three wheel speeds were $V_{s1} = 50$ m/s, $V_{s2} = 60$ m/s, and $V_{s3} = 65$ m/s. The other parameters were $M = 120$, $R = 62.5$ mm, $V_w = 1800$ mm/min, $a_p = 3$ μm, $A_1 = 0$ mm, $A_2 = 2$ mm, $f_1 = 0$ Hz, and $f_2 = 1.5$ Hz. Table 2 is the comparison of shape measurement diagram and simulation diagram of CG and SG at different $V_s$.

The wheel speed played a significant role in the X-direction. The swing parameters played a significant role in the Y-direction and would generate the additional force on the Y-axis. The grinding rate in the X-direction was greater than that in the Y-direction, which led to a more obvious interference of abrasive grains in the X-direction. To better compare SG and CG, Ray was added to characterize the grinding surface topography. As shown in Fig. 9, based on the comparison between the roughness values of the SG experiment and simulation, the average errors of the $R_{ax}$ and $R_{ay}$ models were 12% and 9%, respectively. $R_{ay}$ was larger than $R_{ax}$. $R_{ax}$ really should not be 0 during CG. Linear feed was used in this model, and the simulation assumed that the material had no interference between grains deformation and grinding. $R_{ax}$ was very small compared to $R_{ay}$, so set $R_{ax}$ to 0 in regular grinding. So this article did not compare the $R_{ax}$ of SG and CG.

The material removal rate for grinding effective abrasive grains is $Z_w' = \frac{(V_s \cdot N_d)}{t}$. During the simulation, under the same material removal rate, the $R_{ay}$ of SG could reduce by 3% compared with CG.

The prediction model ignored the vibration of the machine tool, wear of the grinding wheel, rigidity of the grinding wheel, and other influencing factors. The vibration of the machine tool causes the grains to deviate from the ideal trajectory during the grinding process. The wear of the grinding wheel also causes a certain deviation in the prediction.

### 3 Analysis of SG on surface topography

In this section, a single-factor experiment and an orthogonal experiment were selected to analyze the influence law of the established prediction model under different grinding process parameters. The single-factor experiment was designed to control the influence of non-research factors on the experiment, and only one factor which affects the effect indicators was considered for analyzing the effects of the influencing factors. An orthogonal experiment was designed to examine the interaction and coupling between the factors and identify the most influential factors and the best combinations to determine the influence of the grinding process parameters on SG.
3.1 Single-factor analysis of SG

Four factors and six levels were selected. $M$ was 120. $V_r$, $V_w$, $f$, and $A$ were the influencing factors. $Rax$ and $Ray$ were used as evaluation indicators of surface topography. Table 3 lists the typical values of the SG grinding process parameters and the value range of the simulation test. Figure 10 shows the grinding surface topography for different grinding process parameters. Figure 11 shows the relationship between the SG grinding process parameters and the surface roughness. Figure 10a shows that as $V_r$ increased, the surface quality increased, and the surface roughness decreased. Furthermore, when $V_r$ increased, the average thickness of the abrasive grains decreased. Figure 10b shows that as $V_w$ increased, the surface quality decreased, and the surface roughness increased. When $V_w$ became small, the grains would be active for a long time in the same working area. The trajectories of the adjacent grains overlapped. Therefore, shallow and narrow grooves were formed on the ground surface, and the ground surface quality was good. When $V_w$ increased, the opposite effect would be observed. Figure 10c shows that as $f$ increased, the surface quality increased, and the surface roughness decreased. When the swing frequency increased, the reciprocating grinding interference per unit grinding time increased, and the surface material of the workpiece became smoother. Figure 10d shows that as $A$ increased, the surface quality increased, and the roughness decreased. When $A$ was very small, the exercise path of the abrasive grains surface was relatively small, and the roughness was high. In the actual processing, the smaller $A$ was, the smaller the impact...
on the crushing and extraction of grains, and the surface quality improved. With an increase in \( A \), the reciprocating grinding interference of the grains on the workpiece surface increased. The effects of the grinding process parameters on the surface quality are shown in Table 4. Depending on the relative rate of change (RR_simulation), the degree of impact of \( R_{ax} \) and \( R_{ay} \) was sorted, and the sorting of their separate dimensions led to the following results: \( A > V_s > f > V_w \) and \( A > f > V_s > V_w \). The degrees of influence were similar.

The special features of SG are the swing amplitude and swing frequency; therefore, it is necessary to study the two swing parameters. Figure 12 shows the relationship between the rate of change in roughness with increasing swing frequency and amplitude.

Table 2 Comparison of shape measurement diagram and simulation diagram of CG and SG at different \( V_s \)

| Vs (m/s) | 50 | 60 | 65 |
|----------|----|----|----|
| Topography | | | |
| Experimental Surface | | | |
| Topography_SG | | | |
| Simulate Surface | | | |
| Topography_SG | | | |
| Simulate Surface | | | |
| Topography_CG | | | |

![Fig. 9 Comparison of swing grinding experiment and simulation roughness](image)

Table 3 Typical grinding parameters and simulation value ranges

| Group | Grinding process parameters | Typical parameters | Simulation value range |
|-------|-----------------------------|--------------------|-----------------------|
| Group NO.1 | \( V_s \) m/s | 80 | 60, 70, 80, 90, 100, 110 |
| Group NO.2 | \( V_w \) mm/min | 1800 | 1800, 2000, 2200, 2400, 2600, 2800 |
| Group NO.3 | \( f \) Hz | 2 | 2, 4, 6, 8, 10, 12 |
| Group NO.4 | \( A \) mm | 2 | 2, 4, 6, 8, 10, 12 |
Comparison of surface topography under different grinding process parameters.

(a) $V_w = 1800$ mm/min, $f = 2$ Hz, $A = 2$ mm

(b) $V_s = 80$ m/s, $f = 2$ Hz, $A = 2$ mm

(c) $V_s = 80$ m/s, $V_w = 1800$ mm/min, $A = 2$ mm

(d) $V_s = 80$ m/s, $V_w = 1800$ mm/min, $f = 2$ Hz

Fig. 10 Comparison of surface topography under different grinding process parameters. a $V_w = 1800$ mm/min, $f = 2$ Hz, $A = 2$ mm. b $V_s = 80$ m/s, $f = 2$ Hz, $A = 2$ mm. c $V_s = 80$ m/s, $V_w = 1800$ mm/min, $A = 2$ mm. d $V_s = 80$ m/s, $V_w = 1800$ mm/min, $f = 2$ Hz
In Fig. 12, with an increase in $A$ and $f$, the rate of change of $R_{ax}$ was $-8.3\%$ and $-7.0\%$, respectively (“−” indicates a decrease in roughness, and “+” indicates an increase in roughness). The rate of change of $R_{ay}$ with an increase in $A$ and $f$ was $4.1\%$ and $18\%$, respectively. $A$ had a significant influence on $R_{ax}$, and $f$ had a significant influence on $R_{ay}$.

As $A$ increased, changes in both $R_{ax}$ and $R_{ay}$ showed trends similar to those of the cyclical changes. With an increase in $f$, the variation trend of $R_{ax}$ was an approximately monotonically decreasing function, while $R_{ay}$ exhibited a nonlinear increasing trend.

### 3.2 Orthogonal experimental analysis of SG

An orthogonal experiment with four factors and three levels was designed to determine the most sensitive factors influencing the ground surface topography. The four factors were...
Nine sets of simulation experiments were designed. Table 5 lists the nine sets of experiments. Due to the large volume of the camshaft and the high experimental cost, the model accuracy of the model was first verified in Sect. 2.5. Orthogonal experiments use the simulation value to study the influence law, and the value of the simulation value follows the value range of the actual processing technology. \( R_{ax} \) and \( R_{ay} \) were selected as the evaluation indices of the surface topography.

The results of the orthogonal experiments are presented in Table 6. At the \( i \)th \((i = 1, 2, 3)\) level, the mean roughness \( R_{ax} \) was represented by \( K_{ri} \) and the mean roughness \( R_{ay} \) was represented by \( G_{ri} \).

According to the orthogonal analysis, the priority order of the influence of the factors on \( R_{ax} \) and \( R_{ay} \) were \( V_s, A, f, V_w, \) and \( A, V_s, f, V_w, \) respectively. \( R_{ax} \) and \( R_{ay} \) exhibited similar rankings for the influencing factors.

The selection of the optimal surface roughness in SG is shown in Fig. 13. The smallest choice for \( R_{ax} \) was \( A3B2C1D3; V_s = 150 \text{ m/s}, V_w = 2000 \text{ mm/min}, f = 2 \text{ Hz}, A = 10 \text{ mm}. \) The \( R_{ax} \) value was 0.235 \( \mu \)m. The smallest choice for \( R_{ay} \) was \( A2B1C2D3; V_s = 100 \text{ m/s}, V_w = 1800 \text{ mm/min}, f = 6 \text{ Hz}, A = 10 \text{ mm}. \) The \( R_{ay} \) value was 0.345 \( \mu \)m.

In Fig. 5a, \( R_{ax} \) is along with the rotational and working directions of the camshaft. \( R_{ay} \) is along the camshaft width direction and camshaft non-working direction. Even if \( R_{ay} \) increases, a smaller \( R_{ax} \) along the rotation direction of the camshaft is better; this is beneficial for the practical application of the camshaft. Under these conditions, the values of \( R_{ax} \) and \( R_{ay} \) are slightly smaller and more suitable for the grinding of marine diesel camshaft machining.

**Table 4** Degree of influence of the grinding process parameters on the surface roughness of grinding

| Degree of influence of the grinding process parameters | \( R_{ax} \) | \( R_{ay} \) |
|------------------------------------------------------|--------------|--------------|
| Wheel speed \( V_s \) (m/s)                          | +++          | ++           |
| Feed rate \( V_w \) (mm/min)                         | –            | –            |
| Swing amplitude \( A \) (mm)                         | ++++         | +++++        |
| Swing frequency \( f \) (Hz)                         | ++           | +++          |

**Table 5** Simulation orthogonal experimental design (grinding process parameters)

| Number | Wheel speed \( V_s \) (m/s) | Feed rate \( V_w \) (mm/min) | Swing frequency \( f \) (time/min) | Swing amplitude \( A \) (mm) | Results |
|--------|------------------------------|-------------------------------|-----------------------------------|-----------------------------|---------|
| NO.1   | A1                           | B1                            | C1                                | D1                          | 0.245   | 0.346   |
| NO.2   | A1                           | B2                            | C2                                | D2                          | 0.268   | 0.392   |
| NO.3   | A1                           | B3                            | C3                                | D3                          | 0.266   | 0.336   |
| NO.4   | A2                           | B1                            | C2                                | D3                          | 0.264   | 0.345   |
| NO.5   | A2                           | B2                            | C2                                | D1                          | 0.239   | 0.359   |
| NO.6   | A2                           | B3                            | C1                                | D2                          | 0.265   | 0.368   |
| NO.7   | A3                           | B1                            | C3                                | D2                          | 0.268   | 0.385   |
| NO.8   | A3                           | B2                            | C2                                | D3                          | 0.235   | 0.346   |
| NO.9   | A3                           | B3                            | C2                                | D1                          | 0.242   | 0.351   |

Fig. 12 Relationship between the swing parameters, roughness, and roughness change rate (a swing amplitude, b swing frequency)
Conclusions

In this paper, a surface topography prediction model of a camshaft generated by SG was developed. The formation mechanism of the swing-grinding surface topography can be analyzed using this model. The following conclusions can be drawn based on the outcomes of this study.

1. The prediction model was accurate and efficient. The two-dimensional evaluation parameters $R_{ax}$ and $R_{ay}$ were appropriate for characterizing the surface topography generated by SG. The mean errors of the predictions for $R_{ax}$ and $R_{ax}$ were 12% and 9%, respectively.

2. SG resulted in a better surface roughness than CG. During the simulation, under the same material removal rate, the $R_{ay}$ of SG could reduce by 3% compared with CG.

3. $R_{ax}$ and $R_{ay}$ exhibited different changing laws with changes in the grinding process parameters. The variation in $R_{ax}$ and $R_{ay}$ with conventional parameters of SG was the same as that with conventional parameters of CG. However, $R_{ax}$ and $R_{ay}$ of SG changed periodically with an increase in the swing amplitude. With an increase in the swing frequency, $R_{ax}$ decreased linearly, and $R_{ay}$ increased nonlinearly. The separate dimensions of $R_{ax}$ and $R_{ay}$ were ordered as $A > V_s > f > V_w$ and $A > f > V_s > V_w$, respectively.

In summary, the results of this work will (hopefully) revitalize the modeling subject area and provide the theoretical foundation for future analyses and optimization of SG. Further research is still needed to improve the simulation accuracy of the proposed approach. The effect of SG...
on the performance of camshafts is an important topic for future research.

**Author contribution** Guochao Li put forward the main analysis ideas for the article, revised the article, and supervised the project. Jie Lu completed the modeling, data analysis and processing, and the writing of the thesis. Honggen Zhou provided labor and financial support. Baojiang Dong was responsible for the collation and analysis of the experimental data. Jianzhi Chen, Li Sun, and Fei Yang were responsible for the construction of the experimental equipment.

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**Data availability** All data generated or analyzed during this study were available by email to the author (lujie9319@163.com).

**Declarations**

**Ethics approval and consent to participate** The authors’ consent to participate. The work contains no libelous or unlawful statements, does not infringe on the rights of others, or contains material or instructions that might cause harm or injury.

**Consent for publication** Consent for publication Informed consent was obtained from all individual participants involved in the study.

**Conflict of interest** The authors declare no conflict of interest.

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