Grinding force of profile-grinding bearing rail platform for ballastless track slabs

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Abstract

High-precision grinding for CRTS Ⅱ ballastless track slabs is needed before these slabs are laid on high-speed rails. Thus, the current study focuses on the grinding force of profile-grinding bearing rail platforms. First, the formulas of cutting force and sliding friction force of a single diamond grit are analyzed. Second, an experimental method using a scanning electronic microscope is proposed to analyze the samples of bearing rail platform after grinding as well as to calculate the number of cutting grits and sliding grits in the grinding arc. Third, the mathematical models of cutting force and sliding friction force are established based on the four grinding profiles of the bearing rail platform. Last, the grinding force formulas of the profile-grinding bearing rail platform are deduced. The current study analyzes the parameters that influence the grinding quality of the bearing rail platform to promote track slab grinder optimization.

Keywords: Grinding force; Profile grinding; Track slab; Bearing rail platform

1 Introduction

To meet high-speed railway plane line and profile conditions, CRTS Ⅱ ballastless track slabs should use a special high-precision grinding machine for bearing rail stations before the slabs are laid on the high-speed rail [1-3], as shown in Fig. 1. The grinding precision of bearing rail platform has a direct impact on ride comfort and stability of high-speed railway. The grinding efficiency and quality of the bearing rail platform is directly related to the grinding force, which is an important indicator to evaluate grinding performance. Thus, if the grinding force is extremely weak, the bearing rail station may have good processing quality but low productivity; if the grinding force is extremely strong, the rail station grinding precision may be affected, the grinding wheel wear may increase, or the grinder may be damaged[4-5]. Many scholars at home and abroad have done a lot of work about the grinding force of different grinding material research, and established many empirical models which expressed the mathematical relationship between the grinding force and principal grinding parameters [6-9].

Grinding on the rail platform of ballastless track slabs is classified as profile grinding, which involves both peripheral and face grinding in which the force condition is complex. Therefore, proposing the mathematical model of the grinding force, and controlling the grinding force is necessary to protect the quality and process safety of the bearing rail platform.

FIGURE 1 Grinded bearing rail platform

2 Calculation model of single-diamond-grit grinding force

A single diamond grit is assumed into a cone of apex angle 2θ. Then, a single diamond grit-grinding model is built, and the calculation model of the single-diamond-grit grinding force is solved [10-12]. The distribution and height of the diamond grinding wheel surface are random. Grain cutting action is closely related to the cut depth, where single-grain-grinding force can be classified into cutting force and sliding friction force.

2.1 CALCULATION MODEL OF SINGLE-DIAMOND GRIT CUTTING FORCE

Regardless of the sliding friction, the force condition of a single-diamond grit cuts the work piece with grinding depth a_p, as shown in Fig. 2(a). The cutting force dF_x acts on the abrasive cone vertically, as shown in Fig. 2(b) [13].

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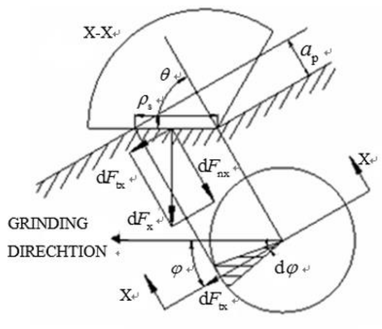
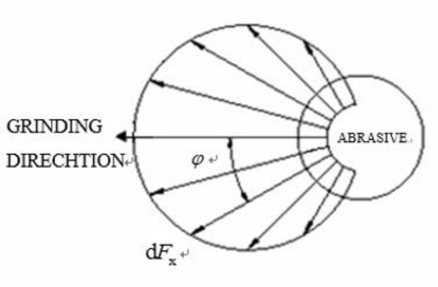


(a) X-X section abrasive



(b) Range of cutting force F_x

FIGURE 2 Single-diamond grit cutting force

The single-diamond grit cutting force is expressed as [14-15].

$$F_{tc} = \frac{\pi}{4} F_p a_p^2 \sin\theta \quad , \qquad (1)$$
$$F_{nc} = F_p a_p^2 \sin\theta \tan\theta$$

where F_p is the unit grinding force, F_{tc} is the abrasive tangential force; F_{nc} is the abrasive normal force, a_p is the grinding depth, and θ is the semi-abrasive tone angle.

2.2 CALCULATION MODEL OF SINGLE DIAMOND GRIT SLIDING FRICTION FORCE

When a single grain slides on the surface bearing rail station with grinding depth a_p, the formula of the single-grain cutting force is [14-15].

$$F_{ts} = \mu SHV \quad , \qquad (2)$$
$$F_{ns} = SHV$$

where: F_{ts} is the sliding abrasive tangential force; F_{nc} is the sliding abrasive normal force; HV is Vickers hardness; μ is the sliding friction coefficient;

$$\mu = \frac{A\sin\theta + \cos(\cos^{-1} f - \theta)}{A\cos\theta + \sin(\cos^{-1} f - \theta)}$$

S is the abrasive contact area with the bearing rail platform;

$$S = 1 + \frac{\pi}{2} + \cos^{-1} f - 2\theta - 2\sin^{-1}\frac{\sin\theta}{(1-f)^{1/2}}$$

and f is the dimensionless shear stress value associated with the material.

3 Test analysis of cutting and sliding abrasive number

The cutting grind number inside the grinding arc can be obtained by using a KYKY-2800B scanning electron microscope (Figure 3), sampling the surface of the bearing rail platform after grinding, and determining the surface groove distance by scanning electron microscopy.

FIGURE 3 Scanning electron microscopy and related equipment

The basic test process is described as follows: Sample gold plating → Sample room pre-vacuum → Start electron microscope → Sample room deflated → Place sample → Sample room vacuum pumping → Obtain images → Data analysis.

From the sample image shown in Figure 4, the cutting traces can be observed in the cut bearing rail platform (the groove indicated in the figure).

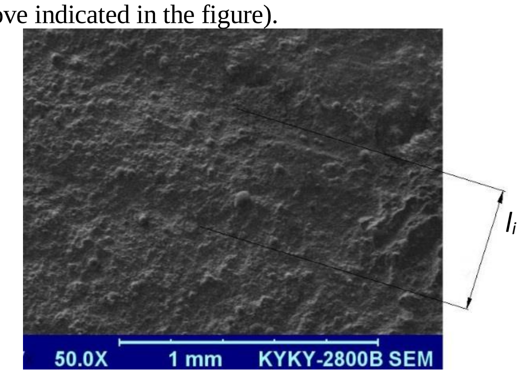


FIGURE 4 Sample surface image of bearing rail station after grinding

According to each image magnification, the distance l_i between the two cutting abrasives can be calculated proportionally for each image. Taking n as the samples, we can obtain the average distance $\bar{l} = \sum_{i=1}^{n}(l_i)/n$ in per-unit cutting abrasive. The cutting grain number per unit length is $N_{lc} = 1/\bar{l}$. Finally, we can determine the cutting grain number unit area as $N_{sc} = N_{lc}^2 = 1/\bar{l}^2$. By using the same test equipment, the total grain number N_{total} can be obtained from the diamond wheel unit area, and the sliding abrasive number per unit is $N_{ss} = N_{total} - N_{sc}$.

4 Total abrasive number inside the grinding arc

Figure 5 shows the special diamond wheel of the grinding ballastless track slabs that distribute abrasive belts and blank tapes.

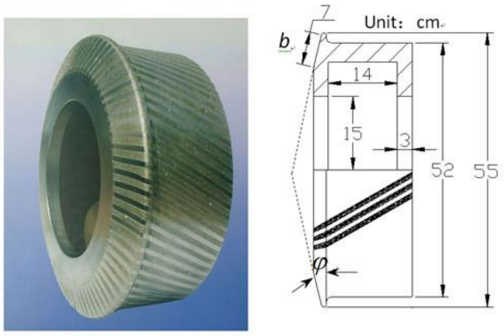


FIGURE 5 Diamond wheel structure

The total number of grains through the grinding arc unit time is

$$N = \eta V_s B N_{total} , \tag{3}$$

where η is the percentage of grains in the total grinding area; V_s is the feed rate of the work piece; B is the cutting width; and N_{total} is the calculated number of grains per unit area, including grinding force and sliding friction force.

5 Calculation model of grinding force on grinding profile

The grinding force can be divided into three mutually perpendicular components, namely, the cutting grinding force F_x along the wheel tangential, the axial grinding force F_y along the wheel axial, and the radial grinding force F_z along the wheel radial [16-19].

The profile grinding of the diamond wheel for the bearing rail platform is classified into surrounding grinding and face grinding, and the grinding section profile of the bearing rail platform is composed of line segment I between points *a* and *b*; arc segment II between points *b*, *c*, and *d*; arc segment III between points *d* and *e*; and line segment IV between points *e* and *f*. Given a grain in each segment, the force analysis is shown in Figure 6. F_{ti} , F_{ni} represent the tangential force and the normal force of a single grain, respectively, in profile i .

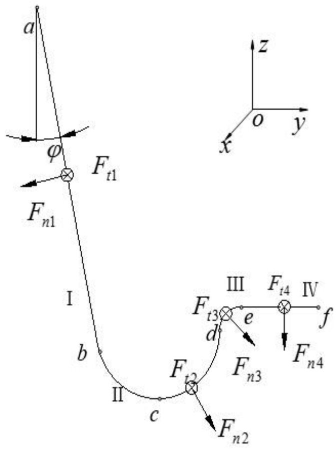


FIGURE 6 Bearing rail station profile segment and force analysis

5.1 GRINDING FORCE FORMULA ON PROFILE I

The processing of profile I occurs during the face grinding of the diamond wheel, i.e., the conical diamond wheel grinds the plane, in this case, R_1=55 cm, $b = 7cm$.

Figure 7 shows the established face grinding equivalent model. $\rho = R_1/\cos\varphi$,where θ_1 is the angle of the element of the cone, which is associated with the grinding thickness a_p. The area shown in S_{11}, S_{12}, S_{13} is calculated respectively as follows:

$$S_{11} = \rho^2 \tan\theta_1 \left(1/\cos\theta_1 - 1\right)/2$$

$$\begin{aligned} S_{12} &= \int_0^{\theta_1} \left(2\rho b - b^2\right)/2 d\theta - S_{13} \\ &= \left(2\rho b - b^2\right)\theta_1/2 - S_{13} \end{aligned}$$

$$S_{13} = \left(\rho - b\right)^2 \tan\theta_1 \left(1/\cos\theta_1 - 1\right)/2$$

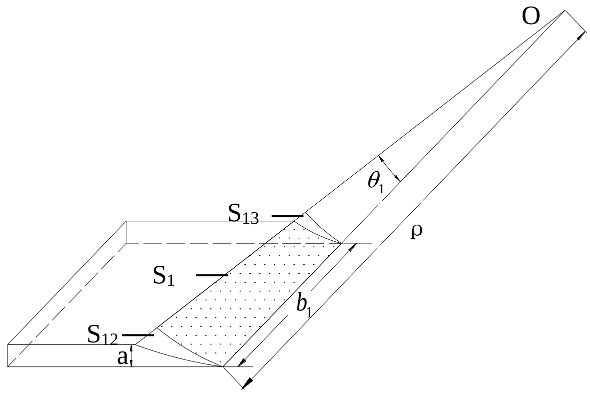


FIGURE 7 Grinding equivalent model I of the wheel face grinding

We take the surface area needed for grinding as follows:

$$\begin{aligned} S_1 &= S_{11} + S_{12} \\ &= \rho^2 \tan\theta_1 \left(1/\cos\theta_1 - 1\right)/2 + \left(2\rho b - b^2\right)\theta_1/2 \\ &\quad - \left(\rho - b\right)^2 \tan\theta_1 \left(1/\cos\theta_1 - 1\right)/2 \\ &= \left(2\rho b - b^2\right)\left[\tan\theta_1 \left(1/\cos\theta_1 - 1\right) + \theta_1\right]/2 \end{aligned}$$

5.1.1 Calculation formula of cutting force

The cutting abrasive number passing the grinding arc per unit time is shown as $N_{ts1} = N_{ss} S_1 \left(\omega\cos\varphi\right)/\theta_1$, where ω is the angular velocity of the diamond wheel.

The calculation formula of the cutting force in profile I is

$$\begin{aligned} F_{x1} &= N_{tc1} F_{t1} = N_{tc1} F_t \\ F_{y1} &= -N_{tc1} F_{n1} \cos\varphi = -N_{tc1} F_n \cos\varphi . \\ F_{z1} &= -N_{tc1} F_{n1} \sin\varphi = -N_{tc1} F_n \sin\varphi \end{aligned} \tag{4}$$

In this formula, "-" indicates that the positive coordinate axis is opposite.

5.1.2 Calculation formula of sliding friction force

The sliding abrasive number passing the grinding arc per unit time is

$N_{ts1} = N_{ss} S_1 \left(\omega \cos\varphi \right) / \theta_1$

The calculation formula of the sliding friction force on profile I is

$$
\begin{aligned}
F'_{x1} &= \mu \sum_{i=1}^{n} S_i HVN_{its1} \\
F'_{y1} &= -\sum_{i=1}^{n} S_i HVN_{its1} \cos\varphi \ . \\
F'_{z1} &= -\sum_{i=1}^{n} S_i HVN_{its1} \sin\varphi
\end{aligned}
\tag{5}
$$

5.2 GRINDING FORCE FORMULA ON PROFILE II

Figure 8 shows the established face-grinding model II of a diamond wheel, where the shaded areas, arc l_{ab} and l_{bc} (as shown in Figure 6), correspond to the grinding areas S_{21} and S_{22}.

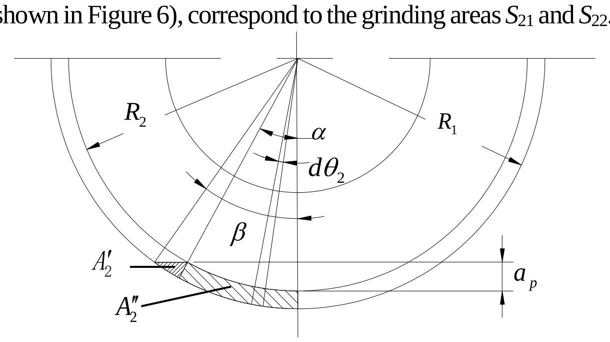


FIGURE 7 Face grinding model II of diamond wheel

The S_{21} area is composed of the area of S'_{21} and that of S''_{21}, which use the mathematical model of right angle trapezoid and isosceles trapezoid, respectively, where

$$S'_{21} = [(\overset{\frown}{l}_{bc} - \overset{\frown}{l}_{ab}) / \overset{\frown}{l}_{bc} + 1](\beta - \alpha) R_1 (\overset{\frown}{l}_{bc} - \overset{\frown}{l}_{ab}) / 2 \ ,$$

$$S''_{21} = \int_0^{\alpha} (2R_1 - l_0) \overset{\frown}{l}_{ab} / 2 \mathrm{d}\theta_2$$

The S_{22} area is composed of the area of S'_{22} and that of S''_{22}, which use the mathematical model of triangle and isosceles trapezoid, respectively, where $A'_{22} = (\beta - \alpha) R_1 \overset{\frown}{l}_{bc} / 2$, $A''_{22} = \int_0^{\alpha} (R_1 + R_2) \overset{\frown}{l}_{bc} / 2 \mathrm{d}\theta_2$ and $\alpha = \arccos\left(R_2 - a_p \right) / R_2$, $\beta = \arccos\left(R_2 - a_p \right) / R_1$.

Thus, we can obtain

$$
\begin{aligned}
S_{21} &= \int_0^{\alpha} (2R_1 - l_0) l_0 / 2 \mathrm{d}\theta_2 + [(\overset{\frown}{l}_{bc} - \overset{\frown}{l}_{ab}) / \overset{\frown}{l}_{bc} + 1] \\
&\quad * (\beta - \alpha) R_1 (\overset{\frown}{l}_{bc} - \overset{\frown}{l}_{ab}) / 2
\end{aligned}
$$

and

$$S_{22} = (\beta - \alpha) R_1 \overset{\frown}{l}_{bc} / 2 + \int_0^{\alpha} (R_1 + R_2) \overset{\frown}{l}_{bc} / 2 \mathrm{d}\theta_2 \ .$$

5.2.1 Calculation formula of cutting force

The cutting abrasive number passing the grinding arc per unit time is $N_{ts2} = N_{ss} \omega S_2 / \beta$.

The calculation formula of the cutting force on profile II is

$$
\begin{aligned}
F_{x2} &= N_{tc2} F_{t2} = N_{tc2} F_{\mathrm{t}} \\
F_{y2} &= \int_0^{\varphi} \cos\theta F_{\mathrm{n}} N_{st} V_{\mathrm{s}} R_0 \mathrm{d}\theta = \sin\varphi F_{\mathrm{n}} N_{st} V_{\mathrm{s}} R_0 \\
F_{z2} &= -(\int_0^{\varphi} \sin\theta F_{\mathrm{n}} N_{st} V_{\mathrm{s}} R_0 \mathrm{d}\theta + 2\int_{\varphi}^{\pi/2} \sin\theta F_{\mathrm{n}} N_{st} V_{\mathrm{s}} R_0 \mathrm{d}\theta) \\
&= -(1 + \cos\varphi) F_{\mathrm{n}} N_{cuts} V_{\mathrm{s}} R_0
\end{aligned}
\ , \tag{6}
$$

where φ =21.8°; $R_0 = 2\overset{\frown}{l}_{bc} / \pi$.

5.2.2 Calculation formula of sliding friction force

The sliding abrasive number passing the grinding arc per unit time is $N_{ts2} = N_{ss} \omega S_2 / \beta$.

The calculation formula of the sliding friction force on profile II is

$$
\begin{aligned}
F'_{x2} &= \mu \bar{S} HVN_{ts2} \\
F'_{y2} &= \int_0^{\varphi} \cos\theta \bar{S} HVN_{ss} V_{\mathrm{s}} R_0 \mathrm{d}\theta = \sin\varphi \bar{S} HVN_{ss} V_{\mathrm{s}} R_0 \\
F'_{z2} &= -\left(\int_0^{\varphi} \sin\theta \bar{S} HVN_{ss} V_{\mathrm{s}} R_0 \mathrm{d}\theta + 2\int_0^{\pi/2} \sin\theta \bar{S} HVN_{ss} V_{\mathrm{s}} R_0 \mathrm{d}\theta \right)
\end{aligned}
\ , \tag{7}
$$

where $\bar{S}$ is the average contact area of sliding abrasives.

5.3 GRINDING FORCE FORMULA ON PROFILE III

The face grinding model III of a diamond wheel corresponds to a rectangle, and the area of the rectangle is $S_3 = \alpha R_3 l_{cd}$.

5.3.1 Calculation formula of cutting force

The cutting abrasive number passing the grinding arc per unit time is $N_{ts2} = N_{ss} \omega S_2 / \beta$.

The calculation formula of the cutting force on profile III is

$$
\begin{aligned}
F_{x3} &= N_{tc3} F_{\mathrm{t}} \\
F_{y3} &= F_{\mathrm{n}} N_{sc} V_{\mathrm{s}} R'_0 \ , \\
F_{z3} &= -F_{\mathrm{n}} N_{sc} V_{\mathrm{s}} R'_0
\end{aligned}
\tag{8}
$$

where $R'_0 = 2\overset{\frown}{l}_{cd} / \pi$.

5.3.2 Calculation formula of sliding friction force

The sliding abrasive number passing the grinding arc per unit time is $N_{ts3} = N_{ss} \omega S_3 / \alpha$.

The calculation formula of the sliding friction force on profile III is

$$
\begin{aligned}
F'_{x3} &= \mu \bar{S} HVN_{ts3} \\
F'_{y3} &= \int_0^{\pi/2} \cos\gamma \bar{S} HVN_{ss} V_{\mathrm{s}} R'_0 \mathrm{d}\gamma = \bar{S} HVN_{ss} V_{\mathrm{s}} R'_0 \ \cdot \\
F'_{z3} &= -F'_{y3} = -\bar{S} HVN_{ss} V_{\mathrm{s}} R'_0
\end{aligned}
\tag{9}
$$

5.4 GRINDING FORCE FORMULA ON PROFILE IV

Grinding profile IV is classified as edge grinding. The grinding area $S_4 = b_4 l_4$, where b_4 is grinding width and l_4 is the contact arc.

5.4.1 Calculation formula of cutting force

The cutting abrasive number passing the grinding arc per unit time is $N_{tc4} = N_{st}\,\omega R_3 S_4 / l_4 = N_{st} \omega R_3 b_4$.

The calculation formula of the cutting force on profile IV is

$$\begin{aligned} F_{x4} &= N_{tc4} F_{t4} = N_{tc4} F_t \\ F_{y4} &= 0 \\ F_{z4} &= -N_{tc4} F_{n4} = -N_{tc4} F_n \end{aligned} . \quad (10)$$

5.4.2 Calculation formula of sliding friction force

The sliding abrasive number passing the grinding arc per unit time is $N_{ts4} = N_{ss} \omega R_3 b_4$.

The calculation formula of the sliding friction force on profile IV is

$$\begin{aligned} F'_{x4} &= \mu \bar{S} HV N_{ts4} \\ F'_{y4} &= 0 \\ F'_{z4} &= -\bar{S} HV N_{ts4} \end{aligned} . \quad (11)$$

5.5 GRINDING FORCE FORMULAS OF PROFILE-GRINDING BEARING RAIL PLATFORMS

From the grinding force analysis of the four section profiles, the grinding force formulas of the profile-grinding bearing rail platform have been obtained. Thus,

$$\begin{aligned} F_x &= F_{x1} + F_{x2} + F_{x3} + F_{x4} + F'_{x1} + F'_{x2} + F'_{x3} + F'_{x4} \\ F_y &= F_{y1} + F_{y2} + F_{y3} + F_{y4} + F'_{y1} + F'_{y2} + F'_{y3} + F'_{y4} \\ F_z &= F_{z1} + F_{z2} + F_{z3} + F_{z4} + F'_{z1} + F'_{z2} + F'_{z3} + F'_{z4} \end{aligned} . \quad (12)$$

6 Summary and conclusion

(1) Based on the curve shape of bearing rail platform, the grinding force model is established by integration method, which is used to analyze the contributions of three mutually perpendicular components of the grinding force on grinding profile.

(2) The model indicates that grinding force depends on material removal modes, mechanical properties and grinding conditions, and different materials removal modes lead to different influence degree of grinding parameters on the grinding force.

(3) Examining the profile-grinding force model of CRTS II ballastless track slabs for bearing rail station and analyzing the key link and other related factors that influence the quality and productivity of track grinding promote the improvement of the track grinding process and provide a special CNC theoretical basis for research design and optimization of the CRTS II ballastless track slabs.

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