A New Grinding Method for Rail Profiling

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Abstract. Grinding is a commonly used method for grinding rails including railway and subway. Rail profiling is a preventive grinding process to remove the worn layer on the rail surface while maintaining the required rail profile. A typical rail grinder consists of 48 or 96 straight grinding wheels, angled at between -65°~+65°, in order to cover the entire rail contour. these grinding wheels are fed vertically, and the rail profile is generated through a piece-wise linear approximation. The parting lines between adjacent grinding wheels may form some sharp ridges along the rail profile. If happens, it would cause the stress concentration higher than the arc formed profile of CHN60 type rail by 36%, hence very detrimental to rail fatigue life. To address this problem, a new grinding method is proposed here by feeding the grinding wheels circumferentially along the surface contour thereby forming a harmonic feeding motion longitudinally. Not only will this method generate arc formed rail profile without parting lines but also can reduce the number of grinding wheels required. The proposed method is formulated as an optimization problem by defining the minimization of the sum of impulse from harmonic feeding motion of grinding wheel as the objective function along with the constraints including specified grinding smooth rail profile. The developed algorithm has been used to design a selected rail grinding process, showing that five wheels would be sufficient to cover the entire contour, with their respective radius of 128.4mm, 182.3mm, 254mm, 182.3m, 128.4mm respectively, distributed at the respective angle range of [-65.0,-48.2]°, [-48.2,-38.5]°, [-38.5,+ 38.5]°, [+38.5,+48.2]°, [+48.2,+65.0]°, and feeding at the respective harmonic frequency of 2.7Hz, 2.1Hz, 1.3Hz, 2.1Hz, 2.7Hz.

Introduction

Grinding technology[1]started since the 20th century, in which, the need for grinding train has become a regular maintenance procedure for high payload and high-speed rail that is being performed in all railway companies worldwide. Grinding rails accurately has significant impact towards railway safety and the service life of the rail: 1) plastic deformation that occurs on the surface of the rail, as well as the micro-scale cracks can be eliminated through proper grinding; 2) the surface profile of the rail can be optimized to reduce the contact force and friction between the wheel and rail, hence reduce wear, lower the maintenance cost for rails, and more importantly, increase the safety of train transits; 3) if grinding procedures are performed properly, properties of steel designed for the rail can be guaranteed, and therefore increase the service life of the rail, which in turn reduce the cost per use of the rail; 4) grinding can smoothen the surface of the rail, which can also reduce the wear of the rail and increase the reliability of the railway system, which in turn reduces the operation cost; 5) proper grinding can reduce vibration and noise when the train is in motion, this increases passenger comfort. The following fig.1 and fig.2 show examples of worn rail layer and part of the grinding procedures.

Fig. 1 Examples of worn rails (Left: Top surface worn-out, Right: Edge worn-out)

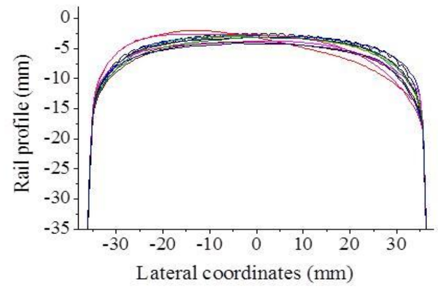


Fig. 2 The surface profiles of rails that are worn-out at various levels

PGM-48 and GMC-96 are the two most commonly used rail grinders, they consist of 48 or 96 straight grinding wheels that are angled between -55^o ~ +45^o or -70^o ~ +20^o to the rail surface profile. To accommodate different grinding requirements, adjustment of grinding wheel angle, overlay grinding and multi-layer grinding techniques are often used, but these result in overlapping of grinded layers and multiple parting lines that form acute ridge angles and sharp ridges along the contour. The rail contour and the specifications after grinding is shown in Fig.3.

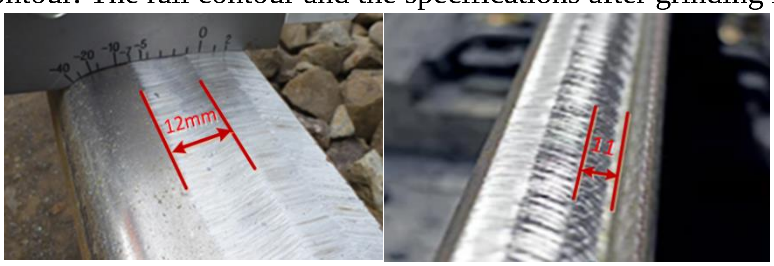


Fig.3 The lateral width specification of a grinded rail surface (unit: mm)

Following the required specifications[2], a rail surface profile that is designed in this work is shown in Fig.4. In sections I, II and III, multiple straight lines of various lengths, which are in turn connected by arcs with radius of 2mm, were used to create the profile. The standard rail profile and the grinded rail profile are both shown in Fig.5 It can be noticed that there are certain differences in the two profiles, especially at +13^o and +42^o of the gauge angle, the maximum profile difference are 0.5mm and 0.6mm respectively.

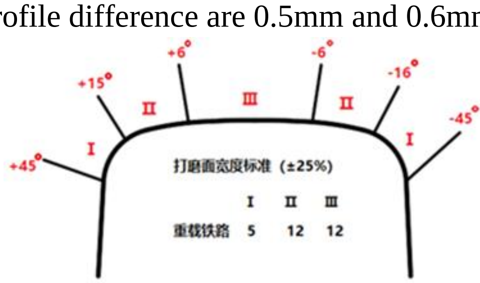


Fig.4 Grinding specification for heavy load rail

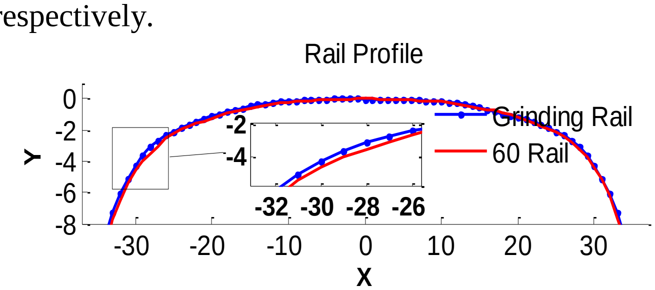
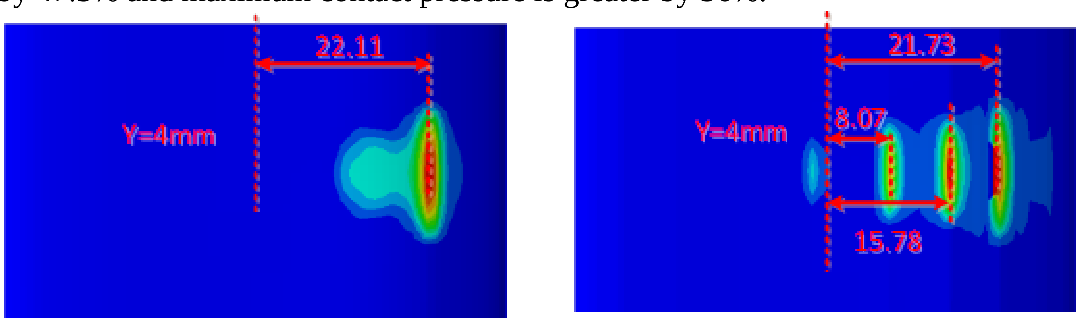


Fig.5 Standard 60 rail profile vs grinding rail profile

1.Wheel-Rail Contact Force Analysis

A co-simulation of wheel-rail contact[3,4] between 60 standard rail, grinded rail and LMA wheel was performed using Hypermesh and Abaqus. In specific, an analysis was done to evaluate the effect of the contact of wheel to the two rails under the shift amount of Y=4mm. Using hexahedral C3D8R mesh, a total of 149878 elements were produced. The axle load was 22 tons, rail cant was set as 1:40, coefficient friction μ=0.3, material density $\rho=7.85\times10^{3}kg/m^{3}$, Poisson's ratio ν=0.3.During the analysis for LMA-60 rail, when the lateral displacement Y is 4mm, the lateral distance between the contact point to the center line of the rail is 22.11mm, with an elliptical area of 82mm^{2}.The maximum Von-Mises stress is 902MPa and maximum contact pressure is 1478MPa. Under the same conditions but with a LMA-grinding rail, three contact spots that are similar to, but are not exactly elliptical shapes occurred, in which the center of the main contact areas are 21.73mm and 15.78mm away from the center line of the rail. With the biggest contact area of 50mm^{2}, the maximum Von-Mises stress is 1328MPa, and maximum contact pressure is 2010MPa. Comparing the two scenarios, it can be noticed that the contact area with a LMA-grinding rail is 39.0% smaller than that of a LMA-60 rail, maximum stress is greater by 47.3% and maximum contact pressure is greater by 36%.



a)LMA-60rail pairing b)LMA-grinding rail pairing

Fig.6 Comparison between the two pairing (Y=4mm)

From the above results, it can be seen that during the initial grinding stage, the ridge lines that remain on the surface of the rail cause great difference in contact properties between the rail and the wheel, and this includes the reduction of contact area, increase in contact stress and pressure. These lead to the increased worn out rate of both the train wheel and the rail. In real-life operations, as the payload of a train increase, the ridge lines are removed quickly, but the initial occurrence of the ridge lines directly affect the wear and damage of the train wheel and rail. In an extremely complexed operation environment, this causes metal fatigue on the rail and affects the overall structural integrity of the rail.

2 Optimization calculation method

This section discusses about the optimization of the grinding system which aims at minimizing the number of required grinding wheels, increase grinding efficiency and achieving the desired grinding contour using multi-constrained optimization algorithms. A new grinding method is therefore proposed here by feeding the grinding wheels circumferentially along the surface contour thereby forming a harmonic feeding motion longitudinally.

In terms of the grinding vehicle, the vehicle speed is set as V_c = 10km/h, which also means that the grinding wheels are moving at a longitudinally at speed V_c. Assuming there are n grinding wheels on the vehicle, each with a radius of R_i (i =1…n). The grinding wheel with largest radius is located on the top of the rail, with progressively smaller grinding wheels are located beside it, i.e. $R_{2\ldots n} \le R_i$. The maximum grinding wheel rotation speed is n_ω = 3600 rpm and with lateral harmonic motion at the track guiding groove, where the linear velocity of the i^{th} grinding wheel on the curve is defined as υ_i, with period of T_i, grinding arc length of l_i and the corresponding angle as φ_i.The following fig.7 and fig.8 shows a cross section of a rail with the grinding wheels on top performing harmonic feeding motion.

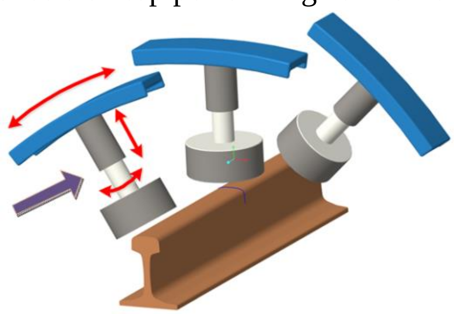


Fig.7 Cross section of rail with grinding wheels performing harmonic feeding motion

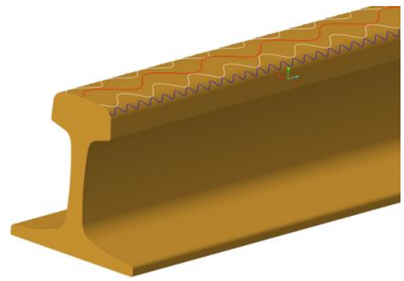


Fig.8Grinding wheels performing path sketch

2.1)Constraints of functions. In order to guarantee the longitudinal and transverse profiles are smooth and up to CHN60 rail profile, there should be no ridge lines on the longitudinal direction of the rail, and no intersecting points along the transverse section. Suppose the overlapping grinding section along the longitudinal direction of the rail is $\bar{R}_i$, and the grinding intersection angle at the transverse section as φ_i', the constraints are then defined as follow:

2.2)Longitudinal harmonic wave intersection constraining $\bar{R}_i$. The rail profile is of a curved surface, but the grinding wheels are flat, according to contact mechanics, it is known that the contact area between is the grinding wheel and the rail is of elliptical shape. The following fig.9 shows overlapping section. Let the major axis of the contact area ellipse be R_i, and the overlapping grinding section, due to the reciprocating motion of the grinding wheel, be $\bar{R}_i$. Then the following equations(1) are proposed.

$$\begin{cases} \dfrac{2\times R_i - \bar{R}_i}{V_C} \ge T_i \\ T_i = \dfrac{2\times l_i - \bar{l}_i}{\upsilon_i} \end{cases} \text{where } (0.1 \le k_{ri}, k_{li} \le 0.3) \text{ , } \bar{R}_i = k_{ri}\times R_i, \bar{l}_i = k_{li}\times l_i \quad (1)$$

Through the analysis of the motion, the following equation (2) is proposed:

$$\upsilon_i \ge \frac{(2-k_{li})\times l_i \times V_C}{(2-k_{ri})\times R_i} \quad (2)$$

Where T_i is the harmonic cycle of the i^{th} grinding wheel, k_{ri} k_{li} are the coefficient of coincidence, l_i, φ_i are the arc length and angle of the i^{th} grinding wheel respectively.

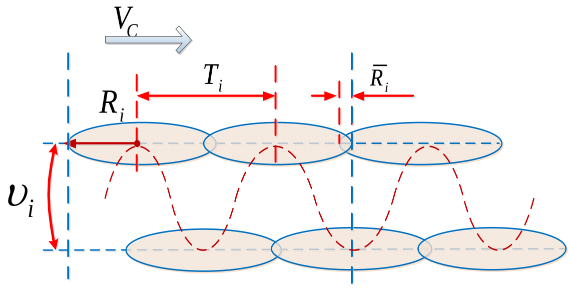


Fig.9 Overlapping section due to reciprocating motion of grinding wheel

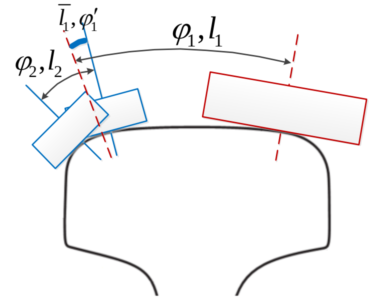


Fig.10 Schematic diagram showing the constrain of intersecting angle on the transverse section

2.3) Constraints of the intersecting angle φ_i' on the transverse section. Along the arc of the transverse section of the rail, there also exist overlapping area due to reciprocating grinding motion, and the arc length of the intersecting area is $\bar{l}_i$. The transverse plane is made up of arcs of various radius and lines of various lengths, let the intersecting angle of each overlapped area be $\varphi_i'(k_{\varphi i} \bullet \varphi_i \le \varphi_i' < 0)$; and the overlapping arc length above the grinding curve l_i be l_i'. The fig.11 shows constrain of intersecting angle. According to statistical data, the grinding area should be limited between $\varphi \in [-65, 65]^\circ$, and the corresponding rail contour arc length be L = 108.44mm (i.e. within lateral coordinate of $x \in [-36, 36]$ mm). the following equation(3) is proposed:

$$\begin{cases} \sum_{i=1}^{n}(l_i - l_i') \ge 108.44 \\ l_i' = k_{li} \bullet l_i \qquad (0 < k_{li} \le 0.3, 0 < k_{\varphi i} \le 0.3) \\ \sum_{i=1}^{n}\left|\varphi_i - \varphi_i'\right| \ge 130^\circ \end{cases} \tag{3}$$

Since the transverse plane of the rail is not made up of arcs and lengths of same radius and lengths, let the arc lengths l_i be a function of the corresponding angles. is set as $l_i = g(\varphi_i)$.

2.4)Constraint on the grinding time on the transverse section. It was mentioned that the grinding vehicle is moving at a speed of V_c = 10km/h or 278mm/s, let period T_1 of harmonic motion of grinding wheel 1, which is located on the top of the rail, be the upper limit. Assume there are n grinding wheel, the period of harmonic motion of each grinding wheel T_i ($I = 2 \ldots n$) should be smaller than T1, the equation(4) is as follows:

$$\begin{cases} T_1 \ge T_i (i = 2 \ldots n) \\ T_i = \dfrac{2\pi}{\omega_i} \end{cases} \tag{4}$$

2.5)Objective function .2.2 objective function $f_{min}(p)$ of the sum of impulse from harmonic feeding motion of grinding wheel.Let $f_{min}(p)$ be the lowest impulse value of the grinding wheel, and assuming there is impulse due to *n* grinding wheels, this means that $f_{min}(p)$ is proportional to the number of grinding wheels, angular velocity ω_i of the transverse motion, and the radius of curvature $\overline{r_i}$ of the arcs that make up the entire rail profile. the following equation(5) is proposed:

$$f_{min}(p) = \sum_{i=1}^{n} \int_{t=0}^{T_i} m_i \omega_i^2 \overline{r_i} dt \tag{5}$$

3 Calculations

The profile of the cross section of CHN60 is made of five sections of three different arcs of various radius, R300, R80 and R13. In which, the intersecting angle between R80 and R13 is ±13o, and that of R80 and R300 is ±2o. From engineering experience, in order to reduce design Variables, the following parameters are assume: $V_C = 278mm/s$, $n_{max} \le 24$, $R_i \le 254mm$, $J_{max} \le 10$, $\varphi_i \in (-65, 65)^\circ$, $\delta_{ij} = k_{pi} p_i$ .Using genetic optimization algorithm[5] with multi-constrained method and linear weighted sum method, solving for the two objective functions mentioned above, it is concluded that the optimum number of grinding wheels is 5, with radius of 128.4mm, 182.3mm, 254mm, 182.3m, 128.4mm respectively, distributed at respective angle range of [-65.0,-48.2]°, [-48.2,-38.5]°, [-38.5,+ 38.5]°, [+38.5,+48.2]°, [+48.2,+65.0]°, and feeding at the respective harmonic frequency of 2.7Hz, 2.1Hz, 1.3Hz, 2.1Hz, 2.7Hz. and the results can be adjusted and simplified to adapt to the engineering application.

4 Conclusion

1) The typical rail grinding profile is generated through a piece-wise linear approximation.it would cause the stress concentration higher than the arc formed profile of CHN60 type rail by 36%, hence very detrimental to rail fatigue life.

2) A new rail grinding method is proposed by feeding the grinding wheels circumferentially along the surface contour thereby forming a harmonic feeding motion longitudinally. the optimization of the grinding system which aims at minimizing the number of required grinding wheels, increase grinding efficiency and achieving the desired grinding contour is proposed.

3) The new rail grinding method can smoothen the surface of the rail, which can also reduce the wear of the rail and increase the service life of the rail, which in turn reduces the operation cost.

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