Experimental investigation on the effects of machining parameters on surface integrity in form grinding of rail material

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Abstract. Rail grinding is an essential measure for the maintenance of railway infrastructure, and the machined surface integrity of rail material plays a crucial role in ensuring the safety, stability and service performance of the railway network. In this paper, an electroplated diamond grinding wheel was employed to re-profile the rail surface. Meanwhile, single-factor experiments on the form grinding of rail material were designed and carried out by virtue of the self-developed rail grinding platform under dry grinding condition based on proper machining parameters. The effects of machining parameters on the surface roughness, subsurface micro-hardness, plastic deformation, and surface morphology were investigated, respectively. The experimental results revealed that the surface roughness and subsurface micro-hardness increase with the increase of feed speed and grinding depth, while decrease with the increase of wheel peripheral speed. The thickness of subsurface plastic deformation layer and the degree of plastic flow increase with the increase of grinding depth, and the thickness of subsurface plastic deformation layer ranges from 7 μm to 14 μm with the change of grinding depth.

1. Introduction

As one of the most crucial infrastructures in the railway transportation system, rail steel plays an indispensable role in ensuring the reliable and stable operation of railway network. The ever-increasing train speed and traffic volume pose a series of challenges to the railway industry for the reason that the defects generated by the dynamic wheel/rail contact are more prone to come into being under harsher and more complicated service condition, such as surface spalling, head checks, squats, studs and corrugation [1-2]. The aforementioned rail flaws pose a huge threat to the safe and smooth operation of the trains. Therefore, rail grinding has been adopted as a vital rail maintenance practice to restore the acceptable profile of rail head.

Rail grinding successfully applied in the actual field can be divided into face grinding [3] and peripheral grinding [4]. Currently, the researches on rail grinding primarily concentrate on face grinding instead of peripheral grinding, especially peripheral form grinding. Zhang et al. [5] carried out a research on the influence of abrasive grain size on the rail grinding performance by virtue of face grinding, and they found that better surface integrity can be achieved by finer abrasive grains due to the lower roughness. Wang et al. [6] investigated the effects of abrasive material and hardness of grinding wheel on the rail grinding properties by means of face grinding, and the experimental results showed that ZA grinding wheel brought about higher surface roughness. They also found that the
surface roughness decreases with the hardness increase of grinding wheel. Gu et al. [7] studied the effects of grinding wheel rotational speed on the rail grinding behavior via face grinding, and the experimental results revealed that the width of the wear grooves and the surface roughness of the ground rail surface decrease as the grinding wheel rotational speed increases. Nevertheless, there are very few experimental investigations available addressing the effects of machining parameters on the surface integrity in form grinding of rail material, which indicates that the form grinding of rail material lacks adequate and systematic researches. Therefore, it is a great necessity to perform the investigation of surface integrity via form grinding under different machining parameters. The surface integrity of the machined workpiece plays a significant role in affecting the tribological behavior during the process of wheel/rail interaction [8].

In this work, an electroplated diamond grinding wheel is utilized to re-profile the rail surface. Meanwhile, single-factor experiments on the form grinding of rail material are designed and conducted under dry grinding condition based on appropriate machining parameters. The effects of grinding parameters on the surface integrity (i.e., surface roughness, subsurface micro-hardness, plastic deformation and surface morphology) in form grinding of rail material are experimentally investigated.

2. Experimental details

2.1 Materials and methods

The experimentally-employed material is a kind of Mn-steel rail (Chinese brand: U71Mn) which is made from high carbon steel to possess excellent anti-wear performance and high fatigue toughness. U71Mn rails (60 kg/m) are extensively utilized in Chinese railway network, and the microstructure is pearlite [9]. The chemical composition of the rail material is given in Table 1.

| Material | C       | Mn      | Si     | S       | P        | Fe        |
|----------|---------|---------|--------|---------|----------|-----------|
| U71Mn    | 0.65-0.76 | 0.70-1.20   | 0.15-0.58 | ≤0.025   | ≤0.03    | Balance   |

The rail form grinding experiments were performed on the self-developed rail grinding platform, and its schematic is shown in Figure 1(a). During the process of rail form grinding, the circumferential contour of the grinding wheel can perfectly envelop the cross-sectional profile of the rail head. An electroplated diamond grinding wheel with nickel-cobalt being the metal binder was employed for the reason that it has the comprehensive advantages of good heat-resistance and wear-resistance properties, high grinding efficiency, and high abrasive consolidation strength, as shown in Figure 1(b). The abrasive grain size of the grinding wheel is 80 mesh.

![Figure 1. (a) Schematic of rail form grinding platform; (b) experimentally-used electroplated diamond grinding wheel.](image-url)
2.2 Experimental parameters and characterization means of surface integrity

Single-factor form grinding experiments of rail material are designed on the basis of three crucial grinding parameters, i.e., wheel peripheral speed $v_w$, feed speed $v_f$, and grinding depth $a_c$. The machining parameters are displayed in Table 2. The grinding mode adopted in this study is down grinding, and the experiments were performed under dry grinding condition.

| Experimental group | Wheel peripheral speed $v_w$ (m/s) | Feed speed $v_f$ (m/min) | Grinding depth $a_c$ (mm) |
|--------------------|-----------------------------------|-------------------------|-------------------------|
| 1                  | 21.67, 25, 28.33, 31.67, 35       | 0.45                    | 0.07                    |
| 2                  | 25                                | 0.25, 0.35, 0.45, 0.55, 0.65 | 0.07                    |
| 3                  | 25                                | 0.45                    | 0.05, 0.07, 0.09, 0.11, 0.13 |

The tested specimens were sampled right in the middle of ground rail head by wire electric discharge machining (WEDM). The machined surface roughness $R_s$ and $R_z$ were measured perpendicular to the feed direction by a surface profilometer (RTEC-UP Dual Mode, USA). The subsurface micro-hardness HV$_0.1$ was measured along the section vertical to the grinding direction via a Vickers micro-hardness tester (HV-1000, China), the loading value and dwelling time were set as 100 g and 15 s, respectively. Each set of measurement was repeatedly performed 3 times and the averaged value was taken as the final results. The ground surface morphologies were characterized using a stereo microscope (VHX-1000, Keyence, Japan). After mounting, grinding with metallographic abrasive papers and fine polishing, the cross section of the sample piece was etched with 4% nital and was observed by means of an optical microscope (DMI5000 M, Leica, Germany).

3. Experimental results and analysis

3.1 Influence of machining parameters on surface roughness

The variations of surface roughness with the change of machining parameters are presented in Figure 2, from which it can be found that $R_s$ and $R_z$ display the same change trend but the change rate is different. It can be revealed from Figure 2(a) that the surface roughness decreases with the increase of wheel peripheral speed, which is attributed to the fact that the number of abrasive grains involved in grinding per unit time increases as the wheel peripheral speed increases, thus bringing about smaller grinding force and plastic deformation, and finally decreasing the surface roughness. From Figure 2(b), it can be found that the surface roughness increases with the increase of feed speed for the reason that the rail material removal rate per unit time augments when the feed speed increases, which can cause more serious plastic deformation, finally resulting in larger surface roughness. Figure 2(c) reveals that the surface roughness increases with the increase of grinding depth. This is caused by the reason that the grinding force and plastic deformation increase when the grinding depth increases, which intensifies the ploughing and extrusion effect between the abrasive grains and rail workpiece, eventually engendering rougher machined surface. As per [10], the surface roughness $R_s$ of the ground rail surface should not exceed 10 μm, while the surface roughness $R_z$ is not specified. Apparently, the surface roughness $R_s$ procured in this study meets the aforementioned requirements.
Figure 2. Variations of surface roughness with the change of machining parameters: (a) wheel peripheral speed; (b) feed speed; (c) grinding depth.

3.2 Influence of machining parameters on subsurface micro-hardness

The variations of subsurface micro-hardness with the change of machining parameters are displayed in Figure 3, from which it can be seen that rail material presents remarkable work hardening phenomenon after form grinding. According to Figure 3(a), the subsurface micro-hardness decreases with the increase of wheel peripheral speed, which is due to the fact that the smaller grinding force and larger grinding temperature generated under higher wheel peripheral speed weaken the plastic deformation, thus undermining the work hardening effect. As per Figure 3(b) and Figure 3(c), the subsurface micro-hardness increases with the increase of feed speed and grinding depth, which is attributed to the reason that larger grinding force generated under higher feed speed and larger grinding depth is the dominant factor influencing the plastic deformation, finally enhancing the working hardening effect.

Figure 3. Variations of subsurface micro-hardness with the change of machining parameters: (a) wheel peripheral speed; (b) feed speed; (c) grinding depth.

3.3 Subsurface plastic deformation characteristics

The OM micrographs of subsurface plastic deformation under various grinding depth are shown in Figure 4, from which it can be found that the subsurface microstructure within the plastic deformation region is elongated and refined along the grinding speed direction, and the thickness of subsurface plastic deformation layer (namely the degree of plastic deformation) increases with the increment of grinding depth. The thickness of subsurface plastic deformation layer ranges from 7 μm to 14 μm with the change of grinding depth. The formation of the subsurface plastic deformation layer represents the occurrence of work hardening phenomenon during the grinding process, eventually enhancing the surface micro-harness of rail material. As the grinding depth increases, the interaction between the abrasive grains and rail surface is enhanced and thus larger grinding force and higher grinding temperature are generated, which intensifies the extrusion and ploughing effects of the abrasive grains, ultimately thickening the subsurface plastic deformation layer.
3.4 Machined surface morphology features

The typical machined surface in form grinding of rail material is shown in Figure 5, from which it can be seen that the ground rail surface is shiny, clean and no surface burns are observed.

![Figure 5. Typical machined surface in form grinding of rail material.](image)

The ground surface morphologies under different grinding depth are presented in Figure 6. It can be found that the ground rail surface morphologies are dominated by scratches (namely feed marks or grooves) and plastic flow. During the process of grinding, the rail material is deformed plastically and flows towards the sides of scratches when the abrasive grains rub, plough and cut the rail surface. Furthermore, the degree of plastic flow becomes more conspicuous as the grinding depth increases. It can be also seen from Figure 6 that the width and depth of the grooves on the machined surface become larger with the increase of grinding depth, indicating that the ground rail surface quality deteriorates gradually, which maybe results from the combined influence of the higher grinding temperature and larger grinding force caused by the increasing undeformed grinding thickness of single abrasive grain under larger grinding depth.

![Figure 6. Ground surface morphologies under varied grinding depth: (a) \(a_e=0.05\) mm; (b) \(a_e=0.09\) mm; (c) \(a_e=0.13\) mm.](image)
4. Conclusions
In this work, the effects of machining parameters on surface integrity in form grinding of rail material under dry grinding condition were experimentally investigated, and the following conclusions can be drawn:

(1) The surface roughness increases with the increase of feed speed and grinding depth, while decreases with the increase of wheel peripheral speed.

(2) Rail material displays obvious work hardening phenomenon after form grinding. The subsurface micro-hardness decreases with the increase of wheel peripheral speed, while increases with the increase of feed speed and grinding depth.

(3) The thickness of subsurface plastic deformation layer ranges from 7 μm to 14 μm as the grinding depth increases. The thickness of subsurface plastic deformation layer increases with the increase of grinding depth, which can enhance the micro-hardness and mechanical strength.

(4) The ground rail surface morphologies are dominated by scratches and plastic flow, and the degree of plastic flow becomes more pronounced with the increase of grinding depth. Also, the width and depth of the grooves on the machined surface become larger as the grinding depth increases, which signifies that the ground rail surface quality deteriorates gradually.

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