Influence of Turning Parameters on Surface Integrity of D840 Wheel Material

Lang Yu, Yanming Quan*, Peijie Liu, Junjie Wan
School of Mechanical and Automotive Engineering, South China University of Technology, Guangzhou, Guangdong, 510640, China
*Corresponding author’s E-mail: meymquan@scut.edu.cn

Abstract. The machined surface integrity of heavy-haul freight wheel is one of the direct factors which affects the wheel’s service performance and life. Based on the wheel turning parameters, single-factor experiments on D840 wheel material under dry cutting condition were performed. The changing laws including the surface work hardening, surface microstructure, surface roughness, and surface morphology were analyzed via micro-hardness tester, metallographic microscope, SEM and surface profilometer under different cutting parameters. The results show that the surface hardness and the hardening layer increase with the increase of feed and cutting depth within a certain range of cutting parameters. The surface amorphous layer and fiber layer thicken with the increase of feed and cutting depth. The fibrosis of proeutectoid ferrite in the plastic deformation layer and the extrusion deformation of the flake pearlite are obvious. Meanwhile, pearlitic lamellar spacing decreases gradually. The surface roughness increases with the increase of feed, and cutting speed a cutting depth have less effect on roughness.

1. Introduction
D840 wheel is one of the heavy-haul freight wheels which is commonly-used in China [1]. In recent years, railway wheels are more prone to produce various kinds of damages including tread wear, stripping, wheel rim crack and out of roundness with the increases of axle load and the running speed[2]. It is necessary to remove the damages to ensure rail transportation safety via wheel reprofiling technique before the wheel wear value exceeds the wheel size limit. At present, surface roughness is the only assessment factor to evaluate wheel reprofiling surface integrity. Nevertheless, other evaluation indexes are also the direct factors affecting the wheel/rail service properties and life span.[3]. Currently, the optimal values of characteristic parameter of tread surface integrity many are obtained from wheel/rail matching experiments. [4]. However, there is a lack of theoretical and experimental researches focused on the turning surface integrity of heavy-haul freight wheels. Turning parameters are the main factors influencing the machined surface integrity of workpieces. Thus, it is significant to conduct the surface integrity study of D840 wheel material based on the reprofiling parameters of heavy-haul freight wheels under different turning parameters. The surface integrity includes the geometric, physical and chemical states of workpieces and their corresponding surface properties [5]. X P Wu [6] studied the influence of different tools on surface roughness of wheel steel. The result shows that the surface roughness of wheel steel processed by circular curved cutting edge is larger than that of straight cutting edge, but the variation of surface roughness under different cutting parameters was not further analyzed. G Ding [7] uses GC4225 tool to cut wheel steel of CL60 material. Based on orthogonal experiment with the cutting parameters being the factors, the influence of cutting
parameters on the wheel surface roughness is studied through range analysis of surface roughness. But due to the large parameter difference between the experimental machining parameters and the actual wheel reprofiling parameters, it fails to reflect the actual surface quality. J X Wang [8] studies the effect of cutting speed and cutting depth on the surface roughness and residual stress of wheel tread with carbon content being 0.60%~1.7%. The result shows that cutting depth is the main factor affecting surface roughness and surface displays compressive residual stress at 0.05 mm≤ap≤0.2 mm. In summary, there are some deficiencies in the research on surface integrity of machined wheel material at present.

Based on the characteristic of larger feed of heavy-haul wheel turning parameters, D840 wheel rim material is selected as the research object. According to the actual wheel reprofiling condition, surface work hardening, the plastic deformation layer organization and surface roughness are analyzed based on single factor experiment of turning parameters on surface integrity of D840 wheel. This experiment research lays the theoretical basis to actively control the wheel turning surface integrity and to improve the performance of wheel/rail service property.

2. Experiment

2.1 Material and tool
D840 wheel material is chosen as the targeted material with the size of Φ50 mm×135 mm, which is obtained by wire electrical discharge machining around the area of wheel rim. The chemical composition and physical properties of D840 wheel material are shown in Table 1 and Table 2, respectively. GC4215 cutting tool is selected as the turning cutter, which is one kind of commonly-used turning tool of heavy-haul freight wheel. The parameters of cutting tool are: rε=4 mm, γ0=-6°, α0=6°, λs=-6°, kr=80°.

| Element | C   | Si  | Mn  | P  | S  |
|---------|-----|-----|-----|----|----|
| Content | 0.55~0.65 | 0.17~0.37 | 0.50~0.80 | ≤0.035 | ≤0.040 |

| Tensile strength (MPa) | Elongation (%) | Impact toughness (J/cm²) | Elastic modulus (Pa) | Shear strength (MPa) | Hardness (HV) |
|------------------------|----------------|--------------------------|----------------------|---------------------|--------------|
| 1057                   | 13.1           | 17.6                     | 2×10¹¹               | 686                 | 290.7        |

2.2 Turning parameters design
Single-factor experiments of cutting speed, feed, cutting depth under dry cutting condition are performed to study the influence of turning parameters on surface work hardening, plastic deformation layer organization and surface roughness via CKA6150i CNC lathe. The new cutting edge is used in the experiment of different cutting parameters. As per the heavy-haul freight wheel reprofiling parameters, cutting parameters of single factor are shown in table 3.

| Group | Cutting speed υ/(m·min⁻¹) | Feed f/(mm·r⁻¹) | Cutting depth ap/mm |
|-------|---------------------------|-----------------|---------------------|
| 1     | 50,60,70,80,90            | 0.6             | 1.0                 |
| 2     | 70                        | 0.4,0.5,0.6,0.7,0.8 | 1.0                 |
| 3     | 70                        | 0.6             | 0.6,0.8,1.0,1.2,1.4 |

2.3 Measurements of surface integrity
The testing samples with the size of 10mm×10mm×10mm are obtained by wire electrical discharge machining. Surface roughness at different positions along the direction of feed were measured by
TALYSURF CLI 1000 surface profilometer, each group of the specimens is repeatedly conducted 3 times and the averaged data is adopted as the final experimental results. The samples are corroded with 3% Nital after mounting, grinding and polishing. The polished surface is perpendicular to the axis of the workpiece rotation. The DMI – 3000M Leica metallographic microscope and FEI Quanta 200 scanning electron microscope are used to observe surface plastic deformation layer and microstructure, respectively. HV-1000 digital micro-hardness tester is used to measure the workpiece surface hardness from the surface to the center along the radial direction. The surface of hardness measurement is perpendicular to the axis of the workpiece rotation. The load value is 100 N and loading time is 15 s. 3 data points were tested at the same depth and the averaged data were adopted.

3. Results and analysis

3.1 Analysis of surface layer micro hardness

The changing law of surface micro hardness with the change of surface radial depth \( h_d \) on machined D840 wheel material under different cutting parameters is shown in Figure 1. Figure 1 shows that surface appears different degree of work hardening with the increase of the cutting parameters. Hardening rate is between 1.10 and 1.20, and the depth of hardening layer concentrates in 30\( \mu \)m ~ 40\( \mu \)m. The highest hardness occurs on the surface, while micro hardness decreases sharply until it reaches the matrix hardness between 290 HV to 300 HV with the increase of the radial depth of \( h_d \).

Figure 1(a) shows that the surface micro hardness decreases from 345.3 to 318.6HV and the hardening layer depth decreases when the cutting speed increases from 50m/min to 90m/min gradually with no change of feed and cutting depth. Cutting temperature is one of the factors that affects work hardening. Temperature rises rapidly with the increase of cutting speed, which shows softening effect on the surface material. In addition, contact time between the tool flank and the machined surface shortens. Thus surface plastic deformation is incomplete and hardening effect weakens. Figure 1(b) shows that feed has the most significant effect on the surface hardness. Work hardening degree increases rapidly when feed is more than 0.6mm/r. Surface hardness reaches to the maximum value of 355.7 HV when feed reaches to 0.8 mm/r. Cutting force and cutting thickness gradually increase with the increase of feed. So the extrusion friction between blunt round radius of the blade and the cutter flank on the workpiece material strengthens, and this leads to the deepening of the hardening layer, which means the obvious work hardening effect. Figure 1(c) shows that surface hardness fluctuates at 325HV and then appears the rising trend with the increase of cutting depth. But hardening degree is smaller than the machining hardening caused by the change of feed. The increase of cutting depth increases the circular arc of the cutter tip involved in cutting process. It intensifies the extrusion effect between flank and machined surface to some extent, thus increasing the surface hardness.

![Figure 1](image1.png)

Figure 1. Effects of cutting parameters on surface layer micro-hardness

3.2 Analysis of surface plastic deformation layer

Figure 2 shows the microstructure of the studied material which is a kind of rolling steel with excellent properties [9]. It illustrates that the microstructure of the studied material is formed by axial ferrite and flake pearlite. Figure 3 shows the microstructure of the plastic deformation layer of D840 wheel material after turning. Figure 3 illustrates that the lamellar pearlite orientation of wheel base material

![Figure 2](image2.png)

![Figure 3](image3.png)
is random. The boundaries of equiaxed proeutectoid ferrite and pearlite grain are clear. Pearlite grain from matrix to plastic deformation layer distorts and extrudes until it is crushed. Proeutectoid ferrite is stretched until it is illegible. Distorted ferrite and pearlite together form the amorphous layer on the surface. The pearlite lamellar spacing of plastic deformation layer is smaller than that of matrix material. It leads to increase of strength and hardness in the deformation layer and obstructs the further material deformation.

Figure 2. Matrix metallographic structure of D840 wheel material

Figure 3. Effects of cutting parameters on surface layer plastic deformation

Compared with the matrix structure of wheel material, the influence of cutting parameters on the plastic deformation layer of D840 wheel material is shown in Figure 4. The cutting parameters are (a) $v=70$ m/min, $f=0.6$ mm/r, $a_p=1.0$ mm; (b) $v=90$ m/min, $f=0.6$ mm/r, $a_p=1.0$ mm; (c) $v=70$ m/min, $f=0.8$ mm/r, $a_p=1.0$ mm; (d) $v=70$ m/min, $f=0.6$ m/r, $a_p=1.4$ mm. According to Figure 4, the surface of D840 wheel material appears amorphous layer whose thickness is $5\mu m$–$10\mu m$ after cutting. The fibrous layer with higher density whose thickness is between $20\mu m$ and $30\mu m$ is located beneath the amorphous layer. The matrix material is below the fibrous layer. Compared with figure 4(a) and (b), the thickness of amorphous layer and fibrous layer decreases with cutting speed increasing from $70$ m/min to $90$ m/min. The contact time between the tool and workpiece shortens and the plastic deformation degree exhibits a decreasing tendency. Compared with figure 4 (a) and (c), the thickness of the amorphous layer and fibrous layer increases when feed increases to $0.8 mm/r$. Meanwhile, the work hardening phenomenon enhances gradually. Compared with figure 4 (a) and (d), the thickness of amorphous layer changes little and the fibrous layer thickens obviously with the cutting depth increasing from $1.0$ mm to $1.4$ mm. The increase of cutting depth contributes to the friction between cutting tool and material, which makes plastic deformation layer thickness increase.

Figure 4. Effects of cutting parameters on surface layer plastic deformation

3.3 Analysis of surface roughness

The influence of cutting parameters on the surface roughness of the studied material is shown in Figure 5. Figure 5(b) illustrates that surface roughness increases rapidly with the increase of feed when $R_a \geq 5 \mu m$ and $f=0.8 \text{ mm/r}$. The machined surface roughness value depends on the height of the residual area, and the main factors influencing the height of the residual area are cutting feed and tool geometrical parameter based on theoretical surface roughness [10]. Thus surface roughness increases with the increase of feed under the same cutting tool parameters. Additionally, there are other factors
that affect the machined surface roughness containing burr, built-up edge, cutting edge unsmoothness, microstructure defects of the workpiece material etc. Figure 5(a) illustrates that surface roughness displays a slowly declining trend with the increase of cutting speed. Surface material is prone to produce burrs under lower cutting speed which causes rough surface. Cutting force reduces and cutting temperature rises when cutting speed increases. The thermal softening effect reduces the friction coefficient, which causes the surface roughness to decrease. Figure 5(c) illustrates that surface roughness increases slowly with the increase of cutting depth. Cutting force and cutting area increase when cutting depth increases, which intensifies the extrusion effect between the chip and the tool rake face. It is easy to form built-up edge. As a result, the surface becomes coarser.

4. Conclusion

Single-factor experiment and analysis are carried out on the surface integrity of D840 wheel material in this paper, and the main conclusions are as follows:

(1) Wheel surface material produces different degrees of work hardening under different cutting parameters. The surface hardness and the depth of hardening layer decrease with the increase of cutting speed. Feed has the most significant effect on the degree of hardening. Work hardening enhances with the increase of cutting depth.

(2) The wheel surface plastic deformation layer is composed of amorphous layer and fibrous layer. Plastic deformation layer has thinning trend with the increase of cutting speed, but displays different levels of thickening with the increase of feed and cutting depth. Pearlite lamellar spacing decreases continuously from the plastic deformation layer to the surface of amorphous layer, which makes surface material strength and hardness increase.

(3) Feed is the main factor affecting the surface roughness of wheel materials. The surface roughness increases obviously with the increase of feed, while the cutting speed and cutting depth have little influence on the surface roughness.

Acknowledgments

The authors gratefully acknowledge the National Natural Science Foundation of China (Grant No. 51675184) and the Provincial Science and Technology Project of Guangdong Province (Grant No. 2016A010102006).

References

[1] P Wang, L Gao. Numerical simulation of wheel wear evolution for heavy haul railway[J]. Journal of Central South University, 2015,22(1):196-207.
[2] G Donzella, M accoli, A hidini, et al. The competitive role of wear and RCF in a rail steel[J]. Engineering Fracture Mechanics, 2005(72):287-308.
[3] W J Wang, W Zhong, Q Y Liu, et al. Investigation on rolling wear and fatigue properties of railway rail[J]. Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology,2009,223(7):1033-1039.
[4] Y Jin, M Ishida, A Namura. Experimental simulation and prediction of wear of wheel flange and rail gauge corner[J]. Wear,2011,271:259-267.
[5] R Z Wang. Surface Integrity and Fracture Resistance of Engineering Metallic Materials and
Components[J]. China Surface Engineering, 2011, 24(4): 55-57.
[6] X P Wu. Research on Cutting Mechanism and Machining Process of Wheel Steel. Shanghai: Shanghai Jiaotong University, 2007: 30-45.
[7] G Ding. Analysis and Optimization of Locomotive Wheel Processing Technology[D]. Nanjing: Nanjing University of Science and Technology, 2012: 26-50.
[8] J X Wang, X Xue, Y J Lu. Study on Cutting Form and Surface Machining Quality of Wheel Tread under Reprofiling[J]. Advances in Materials Science and Engineering, 2017, 2017: 1-12.
[9] L Guo, J Cui, Q Z Liu. Processing Technology of Train Wheel and Analysis on Microstructure and Properties[J] FOUNDRY TECHNOLOGY, 2016(02): 389-392.
[10] Z H Zhou. Theory of Metal Cutting[M]. Shanghai Scientific and Technical Publishers, Shanghai