Finite Element Analysis of the Wear Fatigue of Rails with Gradient Structures

Jian Wang[1,2,3], Caizhi Zhou[4,*]

[1] School of Civil Engineering, Southwest Jiaotong University, Chengdu 610031, China

[2] MOE Key Laboratory of High-speed Railway Engineering, Southwest Jiaotong University, Chengdu 610031, China

[3] National Engineering Laboratory for Technology of Geological Disaster Prevention in Land Transportation, Southwest Jiaotong University, Chengdu 610031, China

[4] Department of Materials Science and Engineering, Missouri University of Science and Technology, Rolla, MO 65409, USA

Abstract: We performed the finite element modeling for the first time to analyze the effect of gradient structures (GS) on the wear fatigue-resistant of rails in the rolling-sliding contacts. We found that GS can enhance the wear fatigue-resistant of rails by reducing the maximum horizontal and vertical displacements on the surface of rails. The thicker GS layers, the better the performance is. For a fixed GS layer thickness, increasing the surface yield strength can effectively reduce surface displacements. The outcome from this study can provide the design guideline for processing the gradient structures in the rail steels to obtain superior mechanical properties.

Keywords: Wear fatigue; gradient structure; finite element; rails

* Corresponding author.

E-mail address: zhouc@mst.edu

1. Introduction

Wear fatigue of rails is the major factor affecting the safety and service life of railways on heavy haul rails. Currently, there are mainly two ways to improve the wear fatigue of the rail: (a) optimize the shape of the rail section through design or grinding, especially for sharply curved rail [1], (b) reinforce the strength of rails through material processing ([2]). Although increasing the strength of the whole rail can improve the wear fatigue performance of the rail, it will make the rolling contact fatigue (RCF) even worse. Because the wear fatigue resistance and RCF resistance of the rail are mainly controlled by the strength and ductility of the rail steel [3], respectively, which are two competing properties of most metals.

Recently, surface treatments on the rail steel attract lots of attentions, as they can greatly increase the surface hardness of rails through creating a surface gradient structure (GS). These surface gradient structures are polycrystalline with gradient grain sizes [4-7]. Normally, the top surface layer possesses nano/ultrafine grains, and the grain size increases in the depth direction [4]. According to the Hall-Petch relationship [8], the strength of polycrystalline materials increases with the decrease of the grain size, thus the gradient structure in metals can enhance the surface strength/hardness and keep the ductility of the whole rail at the same time [9]. In that case, the use of surface treatment techniques can enhance wear fatigue resistance of the surface layer, at the same time improve RCF performance of the whole rail. However, the gradient layer is thin compared with the base material and the traditional rule of mixture is not valid to estimate the properties of materials with gradient structures [10]. It is still not well understood how the gradient structure affects the wear fatigue resistance of the rail steels and what microstructure characteristics play the dominated roles during the rolling-sliding contacts.

In this study, we performed the finite element modeling for the first time to analyze the effect of gradient structures on the wear fatigue-resistant of the rail steels. The layer thickness and surface yield strengths are varied in our calculations to identify the key factors affecting on the wear fatigue performance of rail steels.

2. Finite element model and material properties

To mimic the real wheels and rails, we used a circular segment of 1/6 wheel with the radius of 347.35 mm and a thickness of 162 mm, and a rail part with the length of 200 mm long and the height equal to 40 mm as shown in Figure1(a). The inner side of the wheel was rigidly constrained by a reference point in the center and acted as an axle. A similar model has already been used in previous studies of the wheel-rail wear fatigue damages and provided accurate predictions of the wheel-rail contact deformation [11, 12]. Normally, surface treatment technologies, such as the induction hardening processing [13], can achieve a gradient structure at the depth about 10 mm. Thus, we vary the thickness of gradient structures from 2mm to 10 mm in our model to analyze the GS thickness effect. The deformation on the rails with and without GS layers are evaluated after 30 cyclic loadings [11].

The material properties for normalized AISI 1070 steels are used for both of the wheel and the rail with Young′s modulus, E = 183 GPa, Poisson's ratio, ν = 0.3 [11], and the yield stress, σ_Y = 300 MPa. The Chaboche nonlinear kinematic hardening model is used to simulate the plastic behavior of the rail, which is calibrated by the experimental data presented in ref. [14] shown in Figure 1(b). Data used for comparison were taken from the cross-section near the center of the rail to avoid the influence from the boundary constrains.

3. Results and discussion

Figure 2 compares the distributions of the equivalent plastic strain and displacements for the original and GS rail steels. The predicted horizontal displacement on the original rail surface is about 300 μm and the plastic strain reduced from 0.337 on the surface to 0.003 at the depth of 10 mm, both of which are consistent with recent experimental results [11]. From Figure 2(a), we can see that, compared with the original rail, GS rails can effectively reduce the degree of plastic strain on the rail surface, as the areas under the equivalent plastic strain curves decrease with the increase of the GS thickness shown in Figure 2 (a). In addition, a peak appears on the equivalent plastic strain curves and the height of the peak decreases with the incensement of the GS thickness. In the GS rails, the peak locates close to the interface between the GS layer to the base material, while for the original rails, the peak appears both on and underneath the surface. Based on the classic spherical or cylindrical model [15, 16], the peak value of equivalent plastic strain should initially locate underneath the contact surface. After cyclic loading, the second peak appeared on the contact surface as a result of the expansion of the yielding area under the cyclic loading [12]. Compared with the original rails, the GS completely eliminated plastic strain on the surface after the cyclic loading, since the equivalent plastic strain curve drop back to the base line on the surface in Figure 2(a).

In Figure 2(b) and (c), both of the horizontal and vertical displacement curves show the similar trend that the maximum displacement always appears on the surface and the value decreases along the depth direction. In addition, the maximum horizontal displacement decreases with the increment of the GS layer thickness and the displacement on the original rail is larger than all those in GS rails. The displacement curves normally have a stable portion, which is almost perpendicular to the surface. Then the curve starts to bend back to the low displacement region in the depth direction. The width of the transition area from the maximum to minimum displacements is wider in thinner GS. Recent wear tests [11] demonstrated that the wear damage on rails always shows two forms, one called "lamella like structure" with cracks formed parallel to the surface, another called "flake like structure" with cracks formed tilted to the surface. Both of them are controlled by the displacement near the rail surface. The lamella structure is mainly caused by the large difference of the horizontal displacement in the depth direction, while the flake structure results from the difference on the combination of the horizontal and vertical displacements along the depth direction. From Figure 2(b) and (c), we can see that the GS layer can not only reduce the maximum displacement on the surface of the rails, but also narrow the transition area from the maximum to the minimum values. That effectually reduces the possibility and area for the crack nucleation during cyclic wear loading, so enhances the wear fatigue performance of the rails.

In the gradient structure, the surface layer normally carries the smallest grain and the highest yield strength [17]. The grain size on the surface can be strongly influenced by the surface treatment methods and post annealing processing, which changes the surface yield strength of processed rails [18, 19]. To analyze the influence of the surface yield strength of the GS layer on the deformation of rails, we varied the surface yield strength of the GS layer from 300 MPa to 600 MPa for a fixed GS thickness equal to 5mm. The predicted results for different cases are shown in Figure 3. It is clear that the area under equivalent plastic strain curve decreases with the increase of the surface yield strength. While the heights of peaks for the difference surface yield strengths are almost the same with the value about 0.18 and the peak on the plastic strain curve always locates near the interface between the GS layer and the base material. From the horizontal displacement curves shown in Figure 3(b), we can see the large surface yield strength can effectively reduce the surface displacement in the horizontal direction and also reduce the width of the transition area from the maximum displacement to the minimum. While the vertical displacement curves almost overlap each other in Figure 3(c) and is insensitive to the change of the surface yield strength in GS layers.

4. Conclusions

In summary, GS layers can enhance the wear fatigue-resistant of the rail steels by reducing the plastic strain and the surface displacements. For a fixed GS layer thickness, increasing the surface yield strength can minimize the difference of the horizontal displacement between the surface and base materials. That can reduce the possibility and area for the crack nucleation during cyclic wear loading. The newfound understanding presented here can provide the guideline for design and optimization of the gradient structures in metallic systems.

Acknowledgement

J.W. appreciate the support from the National Natural Science Foundation of China (NSFC: 51308474) and the Fundamental Research Funds for the Central Universities (No.2682017CX005). C. Z. gratefully acknowledges support from NSF CAREER Award (CMMI-1652662).

References

[1] H.-Y. Choi, D.-H. Lee, C.Y. Song, J. Lee, International Journal of Precision Engineering and Manufacturing, 14 (2013) 619-625.

[2] W.J. Wang, H.M. Guo, X. Du, J. Guo, Q.Y. Liu, M.H. Zhu, Engineering Failure Analysis, 35 (2013) 206-218.

[3] R. Ordóñez Olivares, C.I. Garcia, A. DeArdo, S. Kalay, F.C. Robles Hernández, Wear, 271 (2011) 364-373.

[4] K. Lu, Science, 345 (2014) 1455.

[5] R. Yuan, I.J. Beyerlein, C. Zhou, Mater. Res. Lett., 5 (2017) 251-257.

[6] S. Huang, J. Wang, N. Li, J. Zhang, C. Zhou, Computational Materials Science, 141 (2018) 229-234.

[7] S. Huang, J. Wang, C. Zhou, JOM, 70 (2018) 60-65.

[8] R.W. Armstrong, Materials Transactions, 55 (2014) 2-12.

[9] X.C. Liu, H.W. Zhang, K. Lu, Science, 342 (2013) 337-340.

[10] R. Kulagin, Y. Beygelzimer, Y. Ivanisenko, A. Mazilkin, B. Straumal, H. Hahn, Materials Letters, 222 (2018) 172-175.

[11] W. Daves, W. Kubin, S. Scheriau, M. Pletz, Wear, 366-367 (2016) 78-83.

[12] W.K. Kubin, M. Pletz, W. Daves, S. Scheriau, Tribology International, 67 (2013) 132-139.

[13] S. Zhang, J. Xie, Q. Jiang, X. Zhang, C. Sun, Y. Hong, Materials Science and Engineering: A, 700 (2017) 66-74.

[14] Y. Jiang, H. Sehitoglu, International Journal of Plasticity, 10 (1994) 579-608.

[15] K.L. Johnson, Contact mechanics, Cambridge university press, 1987.

[16] L. Kogut, I. Etsion, Journal of Applied Mechanics, 69 (2002) 657-662.

[17] P.P. Sarkar, P.C. Chakraborti, S.K. Sen, Materials and Manufacturing Processes, 25 (2010) 85-91.

[18] S. Chang, Y. Pyun, A. Amanov, Materials, 10,188 (2017) 1-12.

[19] W.J. Wang, J. Hu, J. Guo, Q.Y. Liu, M.H. Zhu, Wear, 311 (2014) 130-136.