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Effects of surface defects on rolling contact fatigue of rail

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Abstract

Rolling contact fatigue damages on the surface of rail such as head check, squats are one of growing problems. Squats are originated from the white etching layer (WEL) or the dent on rail surface and accompanied with dark spots including cracks. Another form of rail surface damage, known as "Ballast imprint" has become apparent. This form of damage is associated with ballast particles becoming trapped between the wheel and the surface of rail. In this study, we have investigated whether the ballast imprint is an initiator of head check type cracks using the twin disc test and Finite element analysis. The tests were conducted using specimens with artificial defects. FE analysis were used to investigate stresses and strains in subsurface of defects. The test results show that cracks initiate and propagate in dents larger than a certain size.

Keywords : Rolling contact fatigue; Ballast imprint;

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1. Introduction

Rolling contact fatigue damages the surface of rails, resulting in the growing problem of head check and squats [1,2,3]. Squats are known to occur in straight and large-radius curved tracks while head checks mainly occur at the high rail of curves due to cyclic plastic strains. Squats are originated from the white etching layer (WEL) or the dent on rail surfaces, or caused by ratcheting from motive power units such as the locomotive. Squats are accompanied by dark spots including cracks which propagate toward the rail head, initially at a shallow angle. Once crack reach a depth of 3-5mm, they propagate downwards and ultimately lead to fracture[4,5,6]. Another form of rail surface damage, known as "Ballast imprint" has become apparent, which described in the UIC Code[2] as rail surface defects. This form of damage is associated with ballast particles becoming trapped between the wheel and the surface of rail and occur mostly in winter. Sharp bruising defects may lead to a notch effect and cause cracks or even

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fracture. Since rail fractures can cause derailment with loss of life and property, the understanding of rail fracture mechanisms is important for the reduction of rail surfaces damage. These defects are still one of the key reasons for rail maintenance and replacement. In this study, we have investigated whether the ballast imprint is the initiator of head check type cracks using the twin disc test and the FE (Finite Element) analysis. The tests were conducted using specimens with artificial defects. The FE analysis were used to investigate stresses and strains in subsurface of defects. Based on loading cycles obtained from FE analysis, fatigue analysis for each point was carried out.

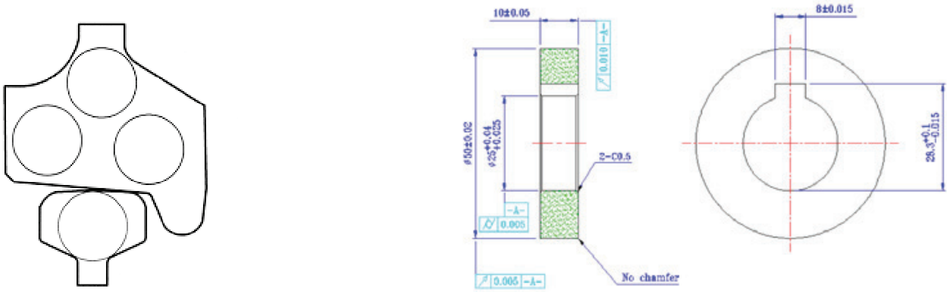
Nomenclature

$\Delta\gamma_{max}$	Shear strain range	$\Delta\sigma_{n,max}$	Maximum normal stress
σ_y	Yield stress	K	Material constant
τ'_f	Shear fatigue strength coefficient	γ'_f	Shear fatigue ductility coefficient
b	Fatigue strength exponent	c	Fatigue ductility exponent
G	Shear modulus	N_f	Cycles to failure

2. Rolling Contact fatigue test

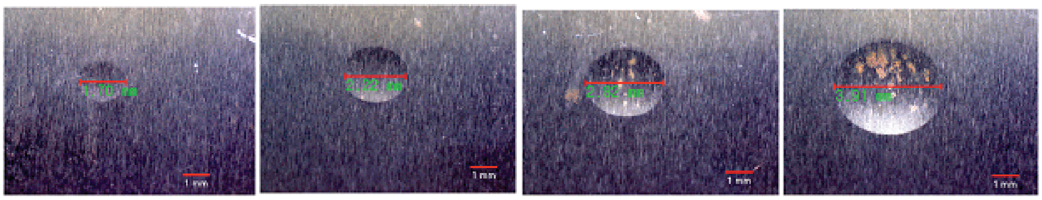
2.1. Test specimen and condition

Fig. 1 presents the configuration and the dimensions of specimens which were cut from wheel rims and rail head. The specimens were 50mm in diameter and 10mm thick. In order to keep the constant hardness of specimen on contact surface, the heat treatment process was applied. The contact surface was grinded to simulate the surface roughness of rail. The indenter of the Brinell hardness tester was used to make the surface defects to simulate ballast imprints on the surface of specimens. Fig. 2 shows the shape of dents created on the surface of specimens. In order to investigate the size effect of dent, Four types of defect were manufacutred on the rail specimen. The rail specimen is rotated at 500 rpm with the wheel specimen controlled to rotate to give a constant slide to roll ratio of 1 % slip and the contact stress between the rail and wheel specimens is 1600 MPa. The contact surface was sprayed with air to remove wear particles generated during the rolling contact fatigue test. The testing machine was stopped in every 1,000 cycles to observe cracks on the surface.



a) Typical locations of test specimen b) Specimen dimensions

Fig. 1 Configuration of specimen

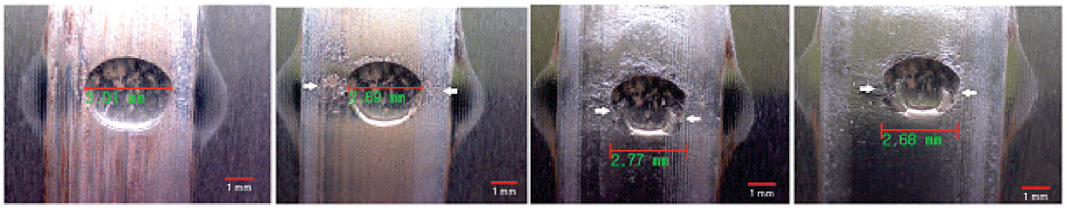


a) Dent 1 b) Dent 2 c) Dent 3 d) Dent 4

Fig. 2 Surface defect created using indenter of hardness tester

2.2. Test results

Tests were regularly interrupted to examine surface damages around dents. Fig. 3 shows a series of photographs from Dent 4 test captured a different cycles during the test. Dent 1 was rapidly reduced in size during the first few cycles and completely wore off and disappeared after 3,000 cycles. Dent 2 also wore off and disappeared after 9,000 cycles. In Dent 3, the edges of the dent were damaged at 6,000 cycles and a fatigue crack initiates at the sides of the central areas at 9,000 cycles. However at 12000 cycles, the large amount of wear resulted in the disappearance of all damages and cracks. In case of Dent 4, Damages appear at the edges and central area of the dent at 9,000 cycles. Cracks initiate at the sides of the central area and large pieces of the specimen broke off, increasing the diameter of dent. At 12,000 cycles a small amount of wear decreased the dent diameter. The test results show that cracks initiate and propagate in dents larger than a certain size.



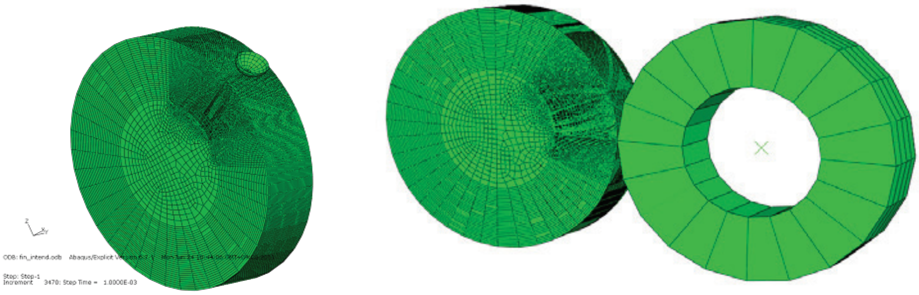
a) 3000 cycle b) 6000 cycle c) 9000 cycle d) 12000 cycle

Fig. 3 Progression of damages on Dent 4 specimen surface

3. Contact fatigue analysis

3.1. Finite element analysis

The finite element analysis was used to investigate stresses and strains around dents during the rolling contact. The contact fatigue test was simulated using the 3D elastic-plastic FE Model. The analysis was carried out using two models. First, an indenter simulation was used to model plasticity changes and residual stress that occurs when dents are produced using the indenter of hardness tester. For the analysis of the rolling contact fatigue test, plasticity and stress results from the indenter simulation were used as the initial condition and the wheel specimen was modeled as rigid bodies. Fig. 4 shows the finite element model.



a) Indenter simulation model b) Rolling contact analysis model

Fig. 4 Finite element model

3.2. Finite element analysis results for indentation

Fig. 5 shows the plastic deformation and the residual stress distribution that occurs when the load is applied to the indenter then removed. The deformed shape is maintained when the load is removed because the contact surface is modeled as elastic-plastic material. Since the contact stress exceeds the yield stress, residual stresses are introduced and the plastically-deformed material undergoes plastic hardening. A 1 mm displacement was applied to the indenter as the load conditions. However the residual deformation had a depth of 0.6 mm and diameter of 4.5 mm which is similar to Dent 4 in the test specimens. The maximum residual stress appears to be 500 MPa at the boundary of the dent, while the minimum residual stress is observed to 100 MPa at the inside of the dent.

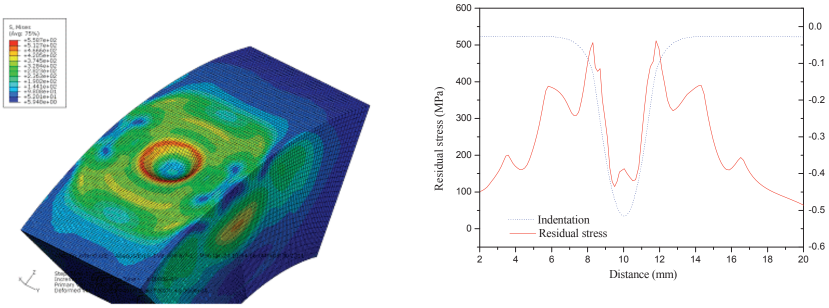
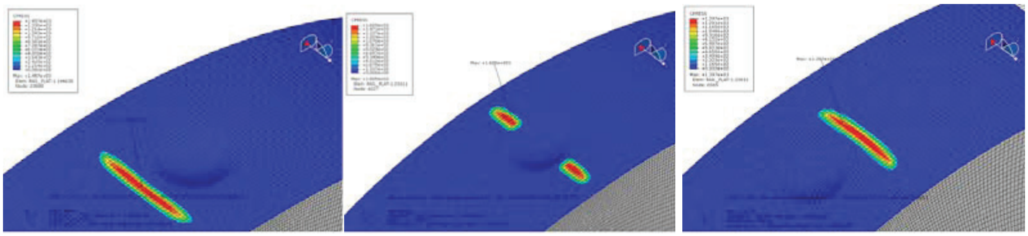


Fig. 5 Plastic deformation and residual stress distribution caused by indenter after load removal

3.3. Finite element analysis results for rolling contact

The plastic deformation and the residual stress resulting from the indenter analysis are applied as the initial condition for the rolling contact analysis. Fig. 6 shows contact pressure variations during rolling contact. Fig. 6 a) shows the contact pressure before the wheel specimen passes the dent. Since the wheel specimen was given a radius of 125mm, the contact pressure distribution appears with an elliptical shape by the point contact. Fig. 6 b) shows the contact pressure distribution when the wheel specimen passes through the middle point of the dent. Since the dent was produced as shown in the fig. 6 b), two contact surfaces were formed. Fig 6 c) shows the elliptical shape of the contact pressure after the wheel specimen passes the dent.



a) Stating point of dent b) Middle point of dent c) Ending point of dent

Fig. 6 Contact pressure variation during rolling

3.4. Fatigue analysis

Based on loading cycles obtained from FE analysis, fatigue life analysis on each point was carried out. Since shear strain is a dominant factor for contact fatigue damage, the following equation is applied to evaluate fatigue life [7,8].

$$\frac{\Delta\gamma_{\max}}{2}(1+K\frac{\sigma_{n,\max}}{\sigma_y})=\frac{\tau_f'}{G}(2N_f)^b+\gamma_f'(2N_f)^c \tag{1}$$

Figs. 7 - 9 show the stress history by contact point during rolling. When the load passes through the specimen, the maximum stress occurs at the contact surface. The maximum stress is observed at the middle point of the dent(M1). The magnitude of stress at the starting point of the dent(S1) was larger than that at the ending point(E1). Fig. 10 shows the resulting fatigue life estimation on the basis of stress and strain history from FE analysis. In order to investigate fatigue life by location, Fatigue analyses were performed for the starting point of the dent (S1), the middle (M1) and the ending point of the dent (E1). Fatigue life values are normalized with the corresponding values of M1. The shortest fatigue life is observed from the middle point of the dent(M1), while the longest fatigue life occurs at the endpoint of the dent(E1). The fatigue life of M1 was found to be 7 and 19 times shorter than that of S1 and E1, respectively. The results of the analysis indicate that cracks will occur in the middle point of the dent(M1). This result is consistent with observations from contact fatigue test results as shown in Fig. 3.

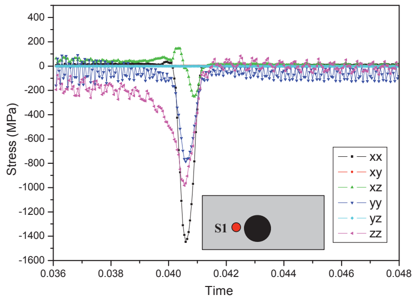


Fig. 7 Stress history at the starting point(S1)

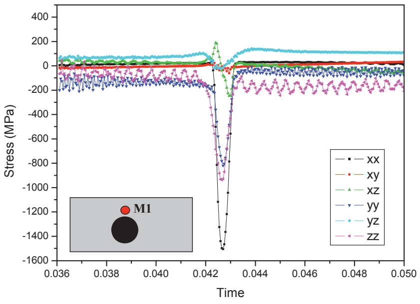


Fig. 8 Stress history at the middle point (M1)

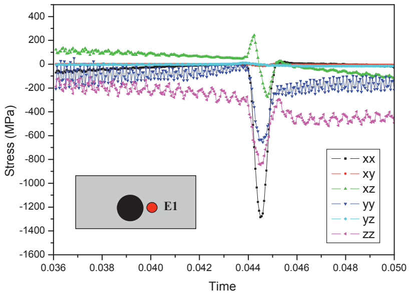


Fig. 9 Stress history at the ending point(E1)

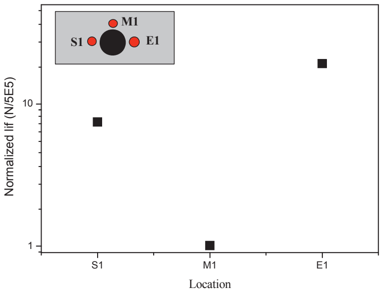


Fig. 10 Fatigue analysis results

4. Conclusion

In this paper, the contact fatigue test and the Finite Element analysis were performed to investigate the effect of ballast imprints on rolling contact fatigue damage. The following conclusions are obtained.

1. Contact fatigue tests showed that if the dent has a diameter which is shorter than a certain length, there are no damages to the area surrounding the dent and the dent disappears due to wear.
2. For larger dents such as Dent 4, Cracks initiate and propagate to cause large pieces of the specimen to break off. The test results show that cracks initiate and propagate in dents larger than a certain size.
3. Results of the finite element analysis and the fatigue analysis showed that the shortest fatigue life is observed from the middle point of the dent(M1). This result is consistent with observations from contact fatigue test results.

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