Fatigue 2010

Fatigue crack growth behavior of surface crack in rails

Jungwon Seo*, Seokjin Kwon, Hynukyu Jun and Donghyeong Lee

Korea Railroad Research Institute, 360-1 Woram-dong, Uiwang, 437-757, Korea

Received 28 February 2010; revised 10 March 2010; accepted 15 March 2010

Abstract

Rolling contact fatigue damages on the surface of rail such as head check, squats are one of growing problems. Since rail fracture can cause derailment with loss of life and property, the understanding of rail fracture mechanisms is important for reducing damages on the surface of rail. In this study, a two-dimensionsal computational model was used to simulate the fatigue crack growth behavior at the surface of rail. The model considers the moving contact pressure and tangential force. Normal pressure of 1100MPa along with traction ratio in the range of -0.4 to 0.4 were investigated for a varing crack size. It has been revealed that the crack growth rate increases with increasing the crack length and start to decrease after a certain depth. When the traction force is applied, the crack growth rate increases to the depth of a/b = 0.3 but is similar over the depth of a/b=0.3 regardless of the magnitude of traction coefficient. However, in case the braking force is applied, the crack growth rate dramatically increases with increasing the crack length.

Keywords: Rolling contact fatigue, Crack growth, Rail

1. Introduction

The speed and axle load of railway vehicles is becoming faster and heavier, which lead to severe deformation which in turn results in fatigue damage at the contact surface between wheel and rail. Currently, the contact fatigue damages on the surface of rail such as head check, squats are one of growing problems [1-3]. Squats are known to occur mostly in large-radius curved tracks, and head checks occur at the high rail in curves by cyclic plastic strain. Squats are originated from the white etching layer (WEL) or dents on rail surface or by ratcheting caused by the traction of motive power car, and accompanied with dark spots including cracks. A crack generated on rail surface grows, in initial phase, at a shallow angle to the surface, then grows inward when reaching the critical crack length, and ends in fracture [4-6]. Since rail fracture can cause derailment with loss of life and property, the understanding of rail fracture mechanisms is important for reducing damages on the surface of rail. It has been known that the crack growth rate on rail surface depends upon the crack length and load type. Fracture of rail can be prevented by removing the crack before it reaches the critical length. Therefore, the crack growth rate needs to be estimated precisely according to the conditions of the track and load to develop maintenance plan against rail damages. The

* Corresponding author. Tel.: +82-31-460-5210; fax: +82-31-460-5814.
E-mail address: jwseo@krri.re.kr.

© 2010 Published by Elsevier Ltd. Open access under CC BY-NC-ND license.

Keywords: Rolling contact fatigue, Crack growth, Rail

doi:10.1016/j.proeng.2010.03.093
crack growth rate on rail surface depends upon the magnitude of the vertical force and traction force, the coefficients of friction of the rail surface and crack face, and also influenced by the magnitude of the hydrostatic pressure of the lubricant oil or water in the crack. Many studies have been conducted using various methods to investigate the influence of these parameters on the crack growth [7,8,9].

In this study, we have investigated the behavior of crack growth on rail surface by using the finite element analysis. The crack growth rate in their initial phase is largely influenced by contact load and traction force, however, whose influence decreases as the crack length increases. Since the crack growth rate is sharply accelerated due to bending load when reaching the critical length, the analysis of the behavior of growth up to the critical crack length is important. Therefore, the investigation on the behavior of fatigue crack growth was conducted under various conditions to evaluate the influence of the crack length and load conditions.

### Nomenclature

| Symbol | Description |
|--------|-------------|
| a      | Crack length |
| P(x)   | Normal contact load |
| Q(x)   | Tangential contact load due to friction coefficient |
| \(\mu_s\) | Friction coefficient between wheel and rail |
| \(\mu_c\) | Friction coefficient between crack face |
| \(K_{I}, K_{II}\) | Stress intensity factors for mode I, II |
| \(\Delta K_{eff}\) | Effective mixed mode stress intensity factor |

### 2. Fracture of Rail

The surface crack on rail surface grows up to the critical length by cyclic contact load, and afterwards, fractured by bending load. Fig. 1 shows an example of fractured rail piece from the track where electric motor cars run. The crack grew at approximately 45° from the rail head, and at 90° from the web, resulting in fracture. The rail section was cut into a specimen to investigate the behavior of the crack growth on the contact surface. To achieve clear visibility of the crack, the specimen was polished and etched with 2% nital etching solution. Fig. 2 presents the detail propagation of the rail surface crack. In the initial phase, the crack grew to 2.7 mm depth at 69° from the surface, and at 27 and 20° afterwards. At 8 mm deep from the surface, the crack divided into two at 47° downward and 39° upward, respectively. Since the downward crack grew faster than the upward one, the rail fractured.

Fig. 1. Fractured rail.  
Fig. 2. Behavior of crack growth on rail surface.
3. Finite Element Analysis

3.1. Model and Conditions of Analysis

The growth behavior of the crack on rail surface was analyzed with F.E. analysis. The direction of the crack on the surface of the fractured rail varied from 20 to 69° according to the depth. For this reason, the direction of the crack growth of the analysis model was assumed to be 30° at the surface and 45° from 8 mm deep. Fig. 3 shows the conditions and model of the analysis. The model was simplified into a 2-dimensional plain strain, with the inclined crack modeled on the rail surface. Moving hertz load in the direction of vehicle, the change in the stress intensity factor according to the loading was investigated. The traction load was modeled by applying friction coefficient to the vertical load, where the friction between the crack faces was applied with the Columb model. To investigate the influence of the traction load on the stress intensity factor, the analysis was conducted by varying the friction coefficient of the rail from -0.4 to 0.4. The friction coefficient between the crack faces was fixed to 0.2, and the modulus of elasticity and the Poisson’s ratio of the rail material were 209 GPa and 0.3, respectively. Equation (1) below expresses the traction load by vertical load and friction coefficient.

\[
p(x) = \frac{2P}{\pi a} (a^2 - x^2)^{1/2}, \quad q(x) = \mu \cdot p(x) \quad (1)
\]

The stress intensity factor was calculated with Equation (2). By assuming the displacement of the crack opening direction, Mode I, at the crack tip to be \( \zeta \) and the displacement in the crack sliding direction, Mode II, to be \( \eta \), the stress intensity factor can be calculated with the displacement at the crack tip. The \( \frac{1}{2} \) node elements were used at the crack tip to improve the accuracy of the analysis.

\[
K_I = \frac{E}{4(1-v^2)} \frac{\pi}{2L} \left(4\zeta_{c2} - \zeta_{c1} + \sigma_{c2}ight), \quad K_{II} = \frac{E}{4(1-v^2)} \frac{\pi}{2L} \left(4\eta_{c2} - \eta_{c1} + \eta_{c2}\right) \quad (2)
\]

Fig. 3. Analysis method and finite element model.

3.2. Analysis results and discussion

3.2.1. Crack Behavior by the Movement of Contact Load

The behavior of rail surface crack under rolling wheel was investigated. Three load conditions under vertical load, traction and braking forces were assumed, independently. The first condition was pure rolling condition
without tangential force ($\mu_s = 0.0$), the second condition was traction force applied in positive tangential force ($\mu_s = 0.4$), and the last condition was braking force applied in negative tangential force ($\mu_s = -0.4$). The load conditions of the analysis are presented in Fig. 4.

Fig. 5 shows the change in the stress intensity factor under the first load condition ($\mu_s = 0.0$). In the Mode I, it can be seen that the crack opens when the contact load approaches, and closes when the load is above the crack, and opens again when the load has passed over. In the Mode I, the value of the $K_I$ is zero while the crack is closed. In the Mode II, $K_{II}$ increases as the contact load approaches the crack, and the sign of the stress intensity factor is reversed when the load has passed over the crack, because the direction of the relative slip of the crack faces is reversed. Comparing the $K$ values in the Mode I and Mode II, that of the Mode II is greater than that of the Mode I, which means that the crack grows in Mode II. Fig. 6 presents the condition under traction force ($\mu_s = 0.4$), wherein the Mode I shows different status from the condition without tangential force. The crack opens as the load approaches it, and closed after the load has passed over. However, in the Mode II, the profile of the stress intensity factor is the same as that of the pure rolling condition, with a certain difference in the value. In Fig. 7 where braking force is applied ($\mu_s = -0.4$), both Mode I and Mode II show different profiles. In the Mode I, the crack remains closed while the contact load is approaching, then opens when the load has passed over. In the Mode II, the stress intensity factor has opposite sign to the condition under traction force.

![Fig. 4. Crack and direction of horizontal load.](image)

![Fig. 5. Change of stress intensity factor at the friction coefficient of $\mu_s = 0.0$.](image)
3.2.2. Change of Stress Intensity Factor by Crack Length

In order to investigate the change of the stress intensity factor according to the crack length, analysis was conducted by varying the crack length from \( a/b = 0.4 \) to \( a/b = 8.0 \), under the three load conditions of; pure rolling, and applied with traction and braking forces.

Fig. 8 shows the changes of the \( K_{II} \), \( \Delta K_{I} \), and \( \Delta K_{II} \) by the movement of the contact load under pure rolling condition. The patterns of the change of the \( K_{II} \) by the change of crack length were identical, except that the position of the maximum value changed as the crack length increased. The peak value increased sharply as the crack length increased, with the maximum value at \( a/b = 3.0 \), which decreased afterwards. As the crack length increased, the \( K_{II} \) (+) value by forward slip increased sharply but the \( K_{II} \) (−) value by backward slip did not change. \( \Delta K_{I} \) whose value remained less than 1 did not show significant change, while the \( \Delta K_{II} \) increased sharply as the crack length increased, and decreased after \( a/b = 3 \). Fig. 9 shows the change of \( K_{II} \) by change of crack length under traction force, where the pattern differs from the condition without friction coefficient. In the initial phase, both the values of the \( K_{II} \) (+) by forward slip and the \( K_{II} \) (−) by backward slip increased sharply according to the crack length. The change pattern of the \( K_{I} \) was symmetrical with reference to the horizontal axis. \( K_{II} \) decreased after a certain length of crack. The value of the \( \Delta K_{I} \) which was less than 2 decreased, while the value of the \( \Delta K_{II} \) increased as the crack length...
increased, then decreased after $a/b = 2$. Fig. 10 shows the change of $K_{II}$ by crack length under braking force, where the pattern differs from those without friction and under traction force. In the initial phase, the $K_{II}$ (-) by backward slip showed no significant change by crack length, however, the $K_{II}$ (+) by forward slip increased sharply after the load had passed over the crack. Under braking force, too, $K_{II}$ began to decrease again at a certain length of crack.

Fig. 11 presents the distributions of the maximum shear stress under said three conditions. At the shear yield strength of 255 MPa, the depth where plastic deformation occurred was $d/a = 2.2$. The depths of the plastic deformation under the three load conditions were similar, however, those of the maximum values differed from each other. In all the conditions, $K_{II}$ began to decrease at a certain crack length, which was $a/b = 3.0$ without friction, $a/b = 2.0$ under traction force, and $a/b = 3.0$ under braking force. This was thought to be related with the $d/a = 2.2$ which is the depth at which the plastic deformation is generated by contact force. Among the three cases, the $\Delta K_I$ and $\Delta K_{II}$ changes by greatest under the application of braking force. This is related with the directions of the horizontal load and the crack growth. It can be seen that the changes of the $\Delta K_I$ and $\Delta K_{II}$ increases under the load in the direction opposite to that of the crack.
3.2.3. Change of the Crack Growth Rate

The behavior of crack varies by the magnitude of the $\Delta K$ ($K_{\text{max}} - K_{\text{min}}$), and can be estimated with Equation (3) below. Since the behavior of the crack by rolling contact relates to both Mode I and Mode II, $\Delta K_{\text{eff}}$ is required, which can be calculated with Equation (4).

$$\frac{da}{dN} = C(\Delta K)^m$$  \hspace{1cm} (3)

$$\Delta K_{\text{eff}} = [\Delta K_I^4 + 8\Delta K_{II}^4]^{1/4}$$  \hspace{1cm} (4)

where, $da/dN$ is the crack growth rate per cycle, $\Delta K$ is the range of stress intensity factor, and $C$ and $m$ are the material constants.

![Fig. 12 Change of $K_{\text{eff}}$ by crack length and friction coefficient.](image)
Figure 12 shows the change of $K_{eff}$ by crack length and friction coefficient. At no friction coefficient condition, the crack growth rate $K_{eff}$ is the largest at the crack length of $a/e = 3$. However, as the friction coefficient increases, the $K_{eff}$ becomes maximum at shorter crack length, i.e., at $a/e = 2$ at the friction coefficient of 0.4. In the range of $a/b < 3$, $K_{eff}$ increased as the friction coefficient increases, however, in the range where $a/b$ is 3 or above, $K_{eff}$ remains almost the same regardless of the friction coefficient. This is because there was no influence of traction force.

In case the friction is applied in reverse direction (i.e., by braking force), the crack length at which the crack growth rate is the highest was $a/b = 3$, regardless of the magnitude of the braking force. In addition, the crack growth rate increased sharply as the friction coefficient increased. Different from the case where braking force was applied, crack growth rate increased according to the friction coefficient when the crack length was larger than 3. This shows that, under braking force, the influence of the tangential force applies to deeper area than in the direction of traction. When the friction is in the direction of traction, the difference in the crack growth rates was larger than that in the direction of braking, which shows that crack could grow faster during braking.

4. Conclusion

In this study, we have investigated the behavior of crack growth on rail surface by using the F.E. analysis. The direction of the crack observed in a fractured rail varied from 20° to 69° according to the depth as deep as 8 mm. At deeper position, the crack divided into two; one at 39° upward and another at 47° downward resulting in fracture. The results of the F.E. analysis showed that the behavior of the crack generated on rail surface varies by the load condition and crack length. The crack growth rate increased down to a certain depth from the surface, then decreased. Without friction force, the crack growth rate was the largest at the crack length of $a/e = 3$. The crack length at which the crack growth rate is maximum became shorter as the friction coefficient increased. However, the crack growth rate was highest at $a/e = 2$ when the friction coefficient was 0.4. When the friction coefficient was in opposite direction (braking), the crack growth rate was the largest at the crack length of $a/b = 3$, regardless of the magnitude of the braking force. It seems to be related with the depth $d/a = 2.2$ at which the plastic deformation is caused by tangential force.

Acknowledgement

This study has been carried out as a part of the study on preventive measures to reduce accidents and rail safety assessment technology. We appreciate all supports.

References

[1] Kondo K, Yoroizaka K, Sato Y. Wear Cause, increase, diagnosis, countermeasures and elimination of Shinkansen shelling, Wear 1996;191:199-203.
[2] UIC leaflet 712, Rail defects, 2002.
[3] Cannon DF, Pradier H. Rail rolling contact fatigue Research by the European Rail Research Institute, Wear 1996;191:1-13.
[4] Wang L, Pyzalla A, Stadbauer W, Werner EA. Microstructure features on rolling surfaces of railway rails subjected to heavy loading, Mater Sci Eng 2003;A359:31–43.
[5] Zhang HW, Ohsaki S, Ohnuma M, Hono K.: Microstructural investigation of white etching layer on pearlite steel rail. Mater. Sci. Eng 2006;A359:191-9.
[6] Baumann G, Fecht HJ, Liebelt S. Formation of white-etching layers on rail treads. Wear 1996;191:133-40.
[7] Ringsberg JW. Shear mode growth of short surface-breaking RCF cracks. Wear 2005;258:955-63.
[8] Wong SL, Bold PE, Brown MW, Allen RJ., A branch criterion for shallow angled rolling contact fatigue cracks in rails. Wear 1996;191:45-53.
[9] Dubourg MC, Lamaq V. A predictive rolling contact fatigue crack growth model: onset of branching, direction, and growth-role of dry and lubricated conditions on crack patterns. Transactions of the ASME 2002;124:680-8.