Rolling contact fatigue analysis of rails under the influence of residual stresses induced by manufacturing

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Abstract
This study aims to analyze the rolling contact fatigue influenced by residual stresses caused by the contact of the wheel and rail and its manufacturing process. For this purpose, a rail available in Iran railway is used with an exact profile geometry. The location of maximum stress caused by the contact of wheel/rail for rail profiles can be calculated by three-dimensional elastic-plastic finite element model. Then, in order to estimate the stress distribution caused by rail manufacturing process, a thermal analysis with finite element method will be performed. Afterwards, the results of performed stress analysis will be used as input for three-dimensional crack growth and rail fatigue life estimation model to calculate the stress intensity factors and fatigue life according to the set of related parameters with boundary element method. Finally, three-dimensional finite element analysis results obtained show good agreement with those achieved in field measurements.

Keywords: Rolling contact fatigue, Manufacturing process, Finite element, Fatigue crack growth, Boundary element.

1 - Introduction
With regards to transfer of contact forces from rail to the wheel and therefrom to the wagon, the condition of the railways can play an important role in fatigue life of these parts. Contact force between rail/wheel affect the fatigue life to a large extent. These forces, affected by the geometry of rail and wheel, are dependent on the frictional and slippage attributes of wheel/rail and their material. Considering the importance of careful analysis of these forces and the effect of residual stress caused by manufacturing process of wheel and rail on the amount of these forces on the location of contact, employing numeral methods in this matter is of utmost importance [1-3]. There have been many attempts regarding the study of residual stresses [4-8]. Ringsberg et al. first analyzed how residual stresses affects useful life of rail, which is the same as fatigue crack growth time. Finite element analysis was used to construct the two-dimensional analytical model of cold iron rail and smoothening rolling [9]. Skyttebol et al. studied the residual stresses in rails caused by welding operation on fatigue crack growth. They studied the impact of movement of the wheel on the growth of studied crack, while considering the residual stresses effect. The
effect of load parameters on the axle, crack location and its size were also studied. The results showed that thermal stress effect is indeed significant important and of course the size of the crack and its growth are also notable [10].

There have been many researches in the area of studying effective parameters in fatigue crack growth such as the initial crack angle and type of load [11-14]. In the area of railways, Wong et al. studied shallow and angled cracks which under certain circumstances would turn into holes or traverse. Since the cracks that are getting deeper are more dangerous. They continued their research on such cracks [15]. Murakami et al. investigated the mechanisms that cause the fatigue crack to grow. The results show that the fatigue crack not only grows towards the direction of load but it also grows in the direction opposite to the load, but its growth towards the opposite side is less compared to the direction of load [16]. Chung et al. studied the phenomena of appearance of holes due to contact stresses and investigated the effect of following parameters: initial crack length, initial crack angle, contact pressure and hydraulic pressure. Using the two-dimensional finite element model, stress intensity factors of mode I and II were calculated; afterwards, strain energy theory was employed to show that the cracks were probably transformed into holes under these conditions. The results were then compared with the available experimental results [17].

Done extensive research has been done by Masoudi Nejad in the area of fatigue crack growth under influence of residual stresses in bandaged wheels. Masoudi Nejad et al. studied the fatigue crack growth and the estimation of bandage wheel life under the influence of contact stresses and residual stresses due to manufacturing process. The results of this research showed that the fatigue crack growth in the wheel of Iran railway without residual stresses, indicated crack growth mode as the mixed shearing mode of II and III [18-20]. In another study, Masoudi Nejad reviewed stress filed in railway wheel caused by the manufacture process. For this purpose, three-dimensional elastic-plastic finite element model has been proposed to estimate the stress field. Comparing the results of this research with field observation available in sources shows that they are similar to an acceptable degree [21].

Most attempts in this area were made in order to predict the crack initiation. In some other, works were done regarding the fatigue crack growth. But considering the Iran railway and residual stresses, not much attention is paid to fatigue crack growth. In this paper, with regards to
available parameters in Iran railway, first the residual stresses caused by manufacturing process and utilization of railway crack was simulated and then the results were used as input for fatigue crack growth with boundary element method.

2- Residual stress field
2.1- residual stress field caused by wheel/rail contact
For the simulation of residual stresses and the wheel/rail contact, the modeling was done with finite element model. Dynamic forces on each wheel in this analysis was 120kN and the applied torque was 101 N.m. In wheel/rail contact modeling, in order to calculate the stress distribution, the location of contact between rail and wheel will be located 70mm from the inner edge of flanges. The length of modeled rail, is the length of rail between two traverses and is equal to 600mm. wheels degree of freedom in the direction of applied force is not limited but is completely restricted towards the two other direction. Also, to the both sides of the rail, completely tangled boundary condition is applied. Wheel/rail interactions are arranged as surface-to-surface contact type. Details of different stages of different modeling and solving wheel/rail contact problem, through finite element model in accordance with [4]. With regards to fine meshing of wheel, rail surface was chosen as the main surface and surface of wheel’s head was chosen as secondary_surface. One of these two surfaces shall be chosen as the target surface and the other as the contact surface, as for this study, the surface of the rail head was chosen as the target and wheel’s fellow as the contact surface, due to its fin meshing. In order to analyze wheel/rail contact friction, material’s friction rate is assumed to be 0.3 in all directions [2]. The 3D elastic–plastic finite element model of the contact between wheel and rail is shown in Figure 1. Mechanical properties of rail and wheel are available in Table 1. Table 2 shows the finite element solution according to number of elements and maximum Von-Mises stress for wheel and rail profiles are also presented. So, the most appropriate number of wheels is 59441, as for rail, it is 29456. Based on the results of finite element analysis, the amount of von Mises stress, equals to 518 MPa. Figure 2 illustrates the stresses caused by wheel/rail contact.

Placement of Table 1
Placement of Figure 1
Placement of Table 2
2.2 residual stress field due to manufacturing process

In order to reduce the risk of crack formation on rail surface due to manufacturing process, a thermal operation is performed to increase the surface rigidity. Figure 3 shows the finite element modeling of rail in manufacture process for residual stress analysis. All other parameters such as material properties, boundary conditions, meshing and methods for the model are defined according to [21].

Residual stresses created on the surface of the rail due to different thermal loads during thermal operation are of great importance. They change because of mechanical stress caused by operation. The aim of various research on manufacturing process is to demonstrate the residual stresses on the surface of elements. Figure 4 illustrates the stress distribution caused by manufacturing process. For railway rail, the magnitude of von Mises stress appears to be 639 MPa after this heat-treatment.

3. Stress intensity factor and rail life estimation

Crack growth in rail under the influence of stress field caused by wheel/rail contact and manufacturing process with boundary element method, will be discussed. Also, three samples of existed cracks in railway rail will be studied: crack in rail head, crack in rail web, and crack in rail plate (Figure 5).

In order to simulate fatigue crack growth and estimation of fatigue life in rails, modeling was done in Franc 3D software which is designed by researchers at Cornell University. A real rail with cracks is illustrated through boundary element model in Figure 6. As can be seen in Figure 6-c, a smaller partitioning has been applied in order to achieve more accurate results around the crack. In this study, cracks number 1 and 3 are considered to have a semi-elliptical crack (Figure 7-a); as for cracks number 2, it is considered to be quarter-elliptical crack (Figure 7-b). The dimensions of the initial crack shown in Figure 7 are $a = 0.5$ mm and $b = 1$ mm.
The next stages of finite element model including: specifying material properties, meshing, boundary conditions and model-solving are performed and mentioned below. The forces that are applied to the rails include the vertical force by the weight of train and the other force is rolling resistance force, which enters the rails as the train passes through the wheels. This force is caused by rolling friction force that is applied on crack surface, making them slide on each other. After loading, the element part is meshed and then the stress analysis is performed via “BES” software. Afterwards, the values of stress intensity factor are calculated for each of three modes. Once the values of stress intensity factors are available, the crack growth direction can be predicted and crack growth rate becomes ideal. When the direction towards which the crack grows is recognized, the crack tip curve can be firmed in place and the crack can be grown by one level.

In order to grow the crack through boundary element method, first, the tip of crack should be divided into a certain number of elements. It is up to user to decide the number of divisions. These crack divisions are schematically illustrated in Figure 8-a. Then a hypothetical plane is placed in each for these newly created groups. This plane is perpendicular to the crack front side on the intended point. Polar coordinates are then used to calculate the stresses and displacements. This plane and the intended coordinate system are depicted in Figure 8-b.

Displacement vectors and polar coordinate are depicted in Figure 9. Displacement values are drawn via finite element relations; stress intensity factors then, are calculated based on these relations. Displacement values are calculated through equation 1.

\[
\begin{bmatrix} u \\ v \end{bmatrix} = 2(1+\nu) \frac{K_I}{E \sqrt{2\pi}} \begin{bmatrix} \frac{\cos \theta}{2} \left[ 1 - 2\nu + \sin^2 \frac{\theta}{2} \right] \\ \frac{\sin \theta}{2} \left[ 2 - 2\nu + \cos^2 \frac{\theta}{2} \right] \end{bmatrix} + 2(1+\nu) \frac{K_{II}}{E \sqrt{2\pi}} \begin{bmatrix} \frac{\sin \theta}{2} \left[ 2 - 2\nu + \cos \frac{\theta}{2} \right] \\ \frac{\cos \theta}{2} \left[ -1 + 2\nu + \sin^2 \frac{\theta}{2} \right] \end{bmatrix} 
\]

In order to find the direction of crack growth, the Maximum circumferential stress criterion is made use of. According to this criterion, the crack grows toward the direction where \( \sigma_{\theta}\theta \) is at maximum; or in other words, \( \sigma_{\theta}\theta = 0 \). In this case, \( \sigma_{\theta}\theta \) is calculated through equation 2:
\[
\sigma_{iw} = \frac{K_i}{\sqrt{2\pi r}} \sin \frac{\theta}{2} \cos^2 \frac{\theta}{2} + \frac{K_{ii}}{\sqrt{2\pi r}} \left( \frac{1}{4} \cos \frac{\theta}{2} + \frac{3}{4} \cos \frac{3\theta}{2} \right)
\]  

(2)

Here:

\[
\tan \frac{\theta_0}{2} = \frac{1}{4} \frac{K_i}{K_{ii}} + \frac{1}{4} \sqrt{\left( \frac{K_i}{K_{ii}} \right)^2 + 8}
\]

(3)

In this way, crack growth direction is recognized. The extent to which the crack length increases can be calculated through equation 4.

\[
a_i = a_{max} \left[ \frac{K_i}{K_{i, max}} \right]^b
\]

(4)

where, \(a_{max}\) is specified by the user. The power of \(b\) is also determined by the user and value is usually equal to the power of Paris equation. Crack growth and crack front new curve are illustrated in Figure 10.

Placement of Figure 10

Once the crack grows, the part is meshed again and is prepared to be solved. This is repeated for each stage until the crack is grown up to the desired value. Figure 11 illustrates the crack after 6 growth stages.

Placement of Figure 11

Crack was once again analyzed while applying stress distribution. Crack is grown for 22 stages until it reaches the critical point, being 42mm, which in the end leads to failure. Then, once the necessary data is entered and value of stress intensity factor are calculated, fatigue life is calculated for the intended rail. In order to obtain crack growth rate and fatigue life, existing equations [22-23] might be used. In this study, modified equation of Paris is made use of, which also takes into account the effects caused by fatigue crack closure. Based on this equation, growth rate is defined as follows [24]:

\[
\frac{da}{dN} = C (\Delta K_{eff})^n = C (K_{max} - K_{op})^n
\]

(5)

In that above mentioned equation \(\Delta K_{eff}\) is the effective stress intensity factor and equals to \(K_{max}\) maximum stress intensity factor and the stress level required for crack opening \(K_{op}\). \(C\) and \(n\) factors in this equation are material constants and are respectively considered to be 4.25 ×
10^{-9} \text{ m/cycle} \text{ and } 3.14 \text{ in this paper. Crack opening stress function, } f, \text{ is defined for plastic crack closure as follows [25, 26]:}

\begin{align}
f = \frac{K_{op}}{K_{max}} = & \begin{cases} 
\max(R, A_0 + A_1 R + A_2 R^2 + A_3 R^3) & R \geq 0 \\
A_0 + A_1 R & -2 \leq R < 0
\end{cases} 
\end{align} \tag{6}

Also, the factors for the above mentioned equation are calculated with:

\begin{align}
A_0 &= (0.825 - 0.34\alpha + 0.05\alpha^2)[\cos(\frac{\pi}{2}S_{\text{max}}/\sigma_0)]^{\frac{1}{\alpha}} \tag{7} \\
A_1 &= (0.415 - 0.071\alpha)S_{\text{max}}/\sigma_0 \tag{8} \\
A_2 &= 1 - A_0 - A_1 - A_3 \tag{9} \\
A_3 &= 2A_0 + A_1 - 1 \tag{10}
\end{align}

In these equations, \( \alpha \) is a finite factor for plane stress-strain condition and \( S_{\text{max}}/\sigma_0 \), ratio of maximum applied stress to stress flow (stress required to initiate plastic flow).

Number of cycles required for crack growth from the initial length, \( a_0 \) to the final crack length, \( a_f \), is presented in equation 11:

\begin{align}
N_{tot} = \int_{a_0}^{a_f} \frac{da}{C(\Delta K_{eff})^n} \tag{11}
\end{align}

As can be seen in Figure 12, crack growth prediction by Franc 3D software show good agreement with those achieved in field observation [27].

Placement of Figure 12

4. Results and discussion

Results for the stress intensity factors of mode I for tips cracks 1, 2 and 3 are illustrated respectively in Figure 13. As can be seen, mode I stress intensity factor in the presence of residual stresses due to manufacturing process is a positive value and has a noticeable impact on crack growth in rail. Increase in crack length is an aggravating factor of current condition. Therefore, as the crack length increases, the values of mode I stress intensity factor increase as well; thus, maximum mode I stress intensity factor of crack 1 for the initial crack growth will be 10mm.
Placement of Figure 13

Figure 14 show the stress intensity factors of mode II for cracks 1, 2 and 3 for different values of the initial crack length, respectively. Based on these diagrams, cracks with greater length are the reason for the increase in values of stress intensity factors. As shown in these figures, when the initial length of crack increases by 3 to 6mm, no significant change can be observed in mode II stress intensity factors. However, once the initial crack length rises up from 6 to 10mm, a significant change can be observed in this factor. Hence, as the crack length increases, mode II stress intensity factor grows and this is more significant in cracks with greater initial length.

Placement of Figure 14

Figures 15 show the stress intensity factors of mode III for cracks 1, 2 and 3 for different values of the initial crack length, respectively. Stress intensity factor of Mode III for each three crack types has increased as the initial crack length increased. Also, values of this stress intensity factor for crack 1 is higher than to the two other cracks, which indicates that the crack 1 is more important in comparison to the other two crack types.

Placement of Figure 15

With increase in the crack length, crack growth rate increases as well. This law applies to all cracks. The increase in crack growth rate is dependent on different factors such as initial crack angle, initial crack length and the amount of contact stresses. Since this research is based on altering a parameter while keeping the other influential factors in fatigue crack growth constant, here, dependency of fatigue life changes on initial crack length in rail, is illustrated in Figure 16.

Placement of Figure 16

Considering the results of stress intensity factor analysis under the influence of residual stresses in this subsection and the results without taking into account the residual stresses in previous subsection, it can be concluded that stress intensity factors in rail (without residual stress) are less than stress intensity factors in the presence of thermal residual stress and in utilization. In cracks with a length of less than 6mm, stress intensity factors undergo no significant change in case of increase in initial crack length. However in cracks with a length of more than 6mm, change in initial length of crack causes a significant shift in stress intensity factor.
With regards to results derived from fatigue life under influence of residual stresses, and results of fatigue life without taking into account the residual stresses in previous subsection, it can be concluded that fatigue life without considering residual stress is more than fatigue life while taking into account the residual stresses. Yet, as the applied stress increases, the difference between these two is decreased due to the fact that applied stress has more effect on fatigue life. Slope of the fatigue life curve in terms of crack length, in the first part and starting point of the curve, is very small over the crack length. Therefore, a small increase in crack length causes a great increase in fatigue life. Hence, stress intensity factor is more important over cracks of short length than in cracks with greater length. With a look at the analyses conducted, the importance of effect of residual stresses and crack length in crack growth analysis can be realized. If residual stress is not taken into account, the rail with have a higher fatigue life compared to the case where residual stress is taken into account. Also, initial crack length had a great impact on fatigue life in presence of residual stresses.

5. Conclusion

A 3D model was presented in this study for fatigue crack growth and estimating the rail fatigue life. In this paper, through linear elastic fracture mechanics and specifying factors affecting crack growth for three types of surface cracks on failure. Parametric failure analysis was conducted in specialized finite element Franc 3D software. In addition, the effect of stress distribution caused by rail manufacturing process on contact with the wheel, and stress field created by its contact with the rail and fatigue life were discussed. With regards to results of numerical analysis and comparing it with field observations in Iran railway. The most significant results of this study can be presented as follows:

1- Comparison of abovementioned results indicated that residual stresses caused by manufacturing process has a significant effect on fatigue life. In addition, hoop residual stress next to yield stress accounted for the shear mode having a high impact on circumferential crack and also caused the crack to deviate from main path.

2- Initial crack length plays an important role in fatigue life, in the way that the less this initial length is, the more fatigue life will be. Initial crack length generally depends on manufacturing
process and wheel/rail contact (utilization), with more control in these two areas, fatigue life may be increased.

3- with an increase in crack length, the absolute value of $K_H/K_I$ increases as well; consequently, increasing the initial angle of crack propagation. Changes in the angle due to varying lengths suggests that with increase in crack length, the tendency towards moving inward increases; in other words, the more crack length is, the more probable it is for the crack to become deeper.

5- Stress intensity factors for crack 1 is higher compared to cracks2 and 3 in rail; which is indicative of importance of surface cracks. In other words, fatigue life for surface cracks in rail is lower than cracks in rail head or rail web.

6- Slope of fatigue life curve in terms of crack length, in initial part and along small cracks is very low. In other words, a small increase in crack length lead to a great growth in life. Therefore, direction of stress intensity factor along small cracks is considered much more important than stress intensity factor along big cracks.

7- With a look at results obtained, it can be concluded that as the crack length increases, fatigue life decreases. Also, it is observed that the ratio of fatigue life changes in crack 1 is more than what it is in cracks 2 and 3.

Examining parameters affecting fatigue life, including: wheel/rail coefficient friction, initial crack length, changing rail profile, rail rigidity, breaking force and its effect on the rail, and structural defects of rail are relevant topics suggested for further research.

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Table 1.

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Table 2.

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<th>Number of wheel elements</th>
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