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# Simulation of Railroad Crack Growth Life under the Influence of Combination Mechanical Contact and Thermal Loads

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**ABSTRACT**

One of the most important issues in railroad wheels is the residual stresses. It is desirable to produce less residual stresses when possible and to decrease the remaining residual stresses in the wheels. The aim of this research is to predict the crack propagation detail in a railroad mono-block wheel in the presence of residual stress induced by manufacturing process and service conditions. A 3-D elastic-plastic finite element analysis, using the ANSYS/PDS tool is used to estimate the residual stress field and also the superposed alternating rolling contact stresses in a mono-block wheel. A three-dimensional finite element procedure is developed for analyzing fatigue crack growth in the wheels by using Franc3D software. Fracture mechanics is used to predict the crack growth life developed from a two-stage fatigue loading cycle where both mechanical loads and thermal loads are present. The results revealed that crack growth life is highly sensitive to the residual stress. Therefore, this factor significantly affects the crack growth life of railroad wheels during service conditions. In the present investigation, a number of parameters such as the axle load, crack size and coefficient of friction are studied using the proposed model.

## 1. Introduction

Rail vehicle steel wheels become useless for different reasons. Fatigue failure is more effective on wheel parts. There is a plastic changing form in the contact of the wheel and rail. Even in low level of loading after the first time of cyclic loading, the remaining tension in the body of the wheel is created and deformation of the plastic material changes to hard plastic. Because of these two effects, the response to the first load appears only as pure elastic that continues after several loading cycle. However, if the loading is strong enough, this will not happen. On the other side each of the cyclic loads create a small plastic deformation. Finally deformation of material in elastic mode will be raised and then the failure will happen. Ingsberg [1] presented a methodology for life prediction of rolling contact fatigue (RCF) and crack initiation. In other effort, Ringsberg and Bergkvist [2] proposed a 3D finite element model to estimate small crack propagation for rolling contact fatigue (RCF) loading. Also, there is a lot of research for analysis of the crack growth in railroad [3-5]. To find a critical crack, it is necessary to calculate stress intensity factors (SIF) and compare with critical factors. Several researchers presented different methods to estimate the fatigue fracture plane. McDiarmid [6, 7] defines the fracture plane as the plane which experiences the maximum principal stress. Carpinteri et al [8, 9] propose that the fracture plane coincides with the weighted mean principal stress direction. Fatemi and Socie [10] proposed to connect the fatigue fracture plane to either a Mode I crack or a Mode II growth mechanism. Guo and Barkey [11] have used a 2D finite element model and a

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uniaxial fatigue model developed by Fatemi and Socie [10] to calculate rolling contact fatigue damage. Sraml et al [12] used the Hertz contact theory to calculate the stress response and treat the multi-axial fatigue problem as a uniaxial fatigue problem. Ekberg et al [13] used the Hertz contact theory for stress calculation and multi-axial fatigue model proposed by Dang Van et al [14] to present a fatigue life prediction model for rolling contact fatigue problem (RCF). Liu et al [15, 16] developed a general subsurface crack propagation analysis methodology for the wheel/rail rolling contact fatigue (RCF) problem. Then the fatigue damage in the wheel is calculated by using a previously developed mixed-mode fatigue crack propagation model [17]. In this model, a new mixed-mode threshold stress intensity factor is developed using a critical plane-based multi-axial fatigue theory and the Kitagawa diagram [18]. For this purpose, an equivalent stress intensity factor defined on the critical plane is proposed to predict the fatigue crack growth rate under mixed-mode loading. The railroad wheel has the initial residual stress created by the manufacturing process, and this residual stress changes due to the mechanical stress caused by service conditions. The residual stresses of railroad wheels are influenced by the heat treatment during manufacture processing.

In this paper, a three-dimensional elastic-plastic finite element simulation is studied for the estimation of residual stresses resulting during manufacture processing and service condition in wheels of railroad in Iran railroad. The manufacturing process simulation consisted of two parts, a nonlinear transient thermal analysis and a nonlinear static structural analysis. The ANSYS Probabilistic Design System PDS) provides an effective tool to estimate the interactions between input parameters and output values. The heat treatment process cools the rim of the wheel much faster than the plate of the wheel. The rim of the wheel is sprayed with water. The plate of the wheel has not been cooled as rapidly. Therefore, the plate of the wheel does not contract at the same rate as the rim of the wheel. Output data will be used in Franc 3D software as input data for fatigue crack growth to assess the effect of variable thermal loads and various axial loads on the fatigue life by using damage mechanic methods. For this purpose, fatigue crack growth under dynamic loading is simulated in a three-dimensional space by using Franc3D software.

## 2. Finite Element Modeling and Residual Stress

### 2.1. Residual stress field under thermal loads

For simulating residual stress and the contact between the wheel and rail, ANSYS software with three-dimensional elastic-plastic finite element model is used. The wheel is modeled with a diameter of 920mm and UIC60 rail profile, Figure 1. The rail length equals the length between two sleepers. In this simulation for the calculation of the residual stress two parts of the analysis are used including the non-linear thermal analysis and the non-linear static structural analysis. In this software, there is the facility to use the thermal analysis model for the structural solution. The facility “Solid 70 in ANSYS” is used for the thermal analysis. The facility “Solid 185 in ANSYS” is used for the structural analysis. The thermal analysis consists of four steps including the high temperature step with water spray (about 2 minutes) then, the room temperature step (about 4 minutes), the elevated temperature draw (about 5 hours) and finally, the time for cooling in room temperature (about 6 hours). One of the most important factors in residual stress forming is the type of constraints in the structure. It means that different movement boundary conditions result in different residual stresses. In this analysis, the center of wheel in either direction and outer wheel rim in one direction (perpendicular to the axis) are bounded. For stress analysis for material in different temperature under service condition E= 205 GPa, $\vartheta = 0.29$ and yielding strength= 500 MPa. The thermal properties for manufacturing process as thermal conduction and temperature-dependent mechanical properties used as input data for steel wheel. Figure 2 presents the elasto-plastic behavior at different temperatures using a bilinear isotropic hardening model. Residual stress near the fracture stress effects on shear mode in surface cracks and causes deviation from original path. Figures 3&4 present distribution of residual stress in railroad wheel and von Mises stress according to wheel tread, respectively. For rail vehicle wheel, the magnitude of the von Mises stress appears to be 310 MPa and the tendency of von Mises stress is not symmetric at the upper and the lower sides of the wheel.

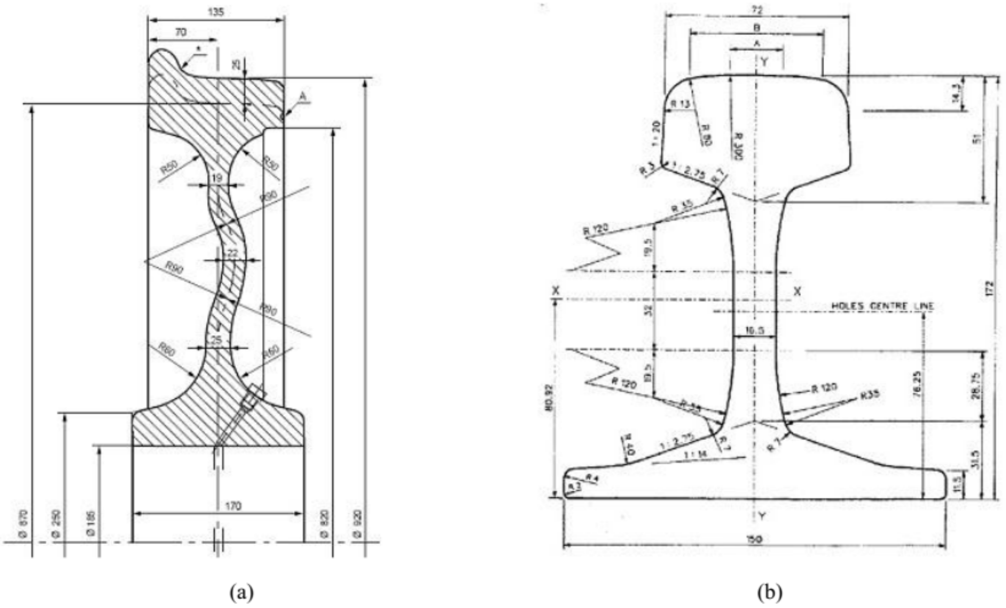


Figure 1. a) Surface section for mono-block wheel b) Surface section for UIC60 rail

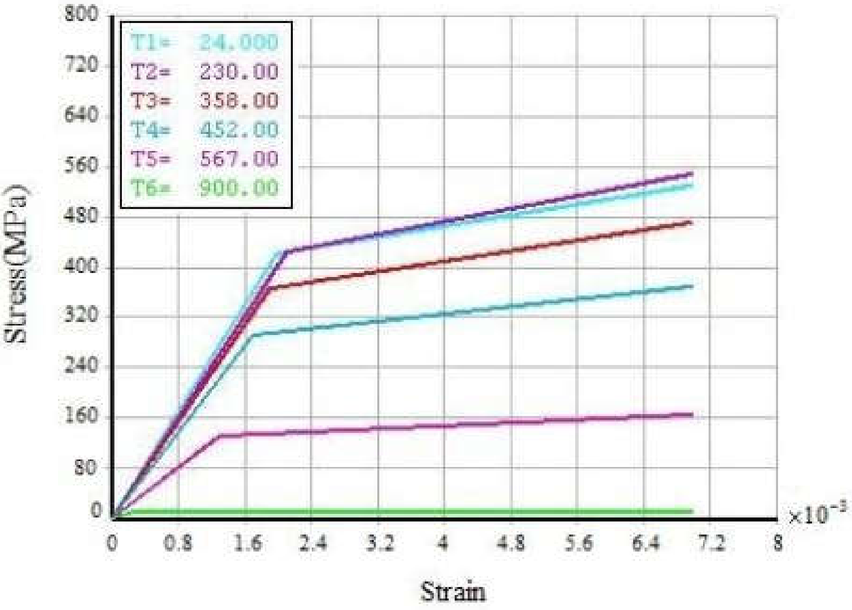


Figure 2. Mechanical material data for rail vehicle wheel

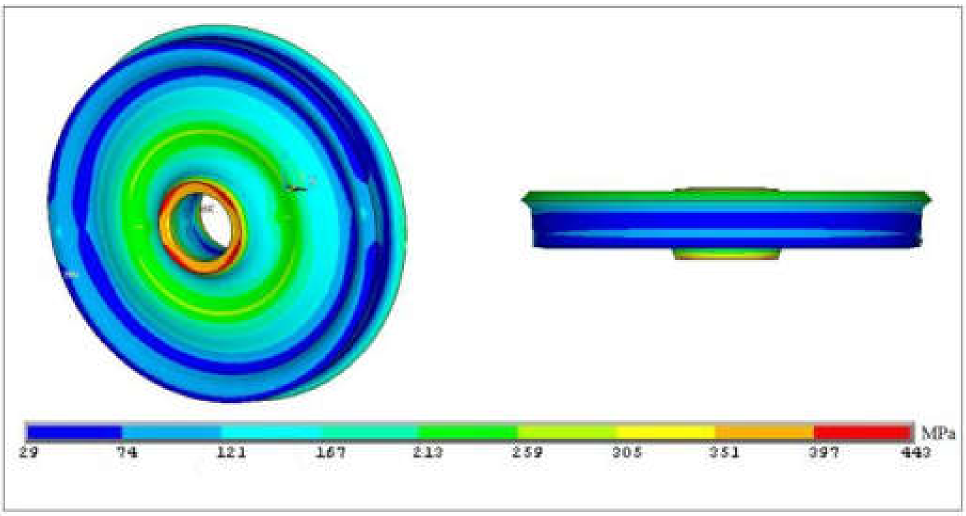


Figure 3. Distribution of residual stress in manufacturing process

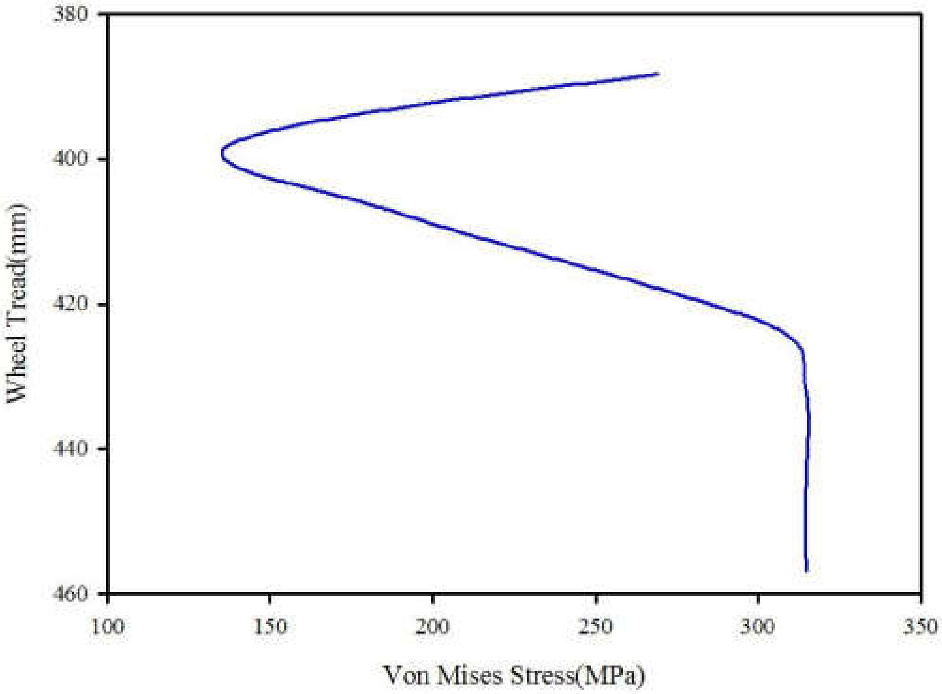


Figure 4. Von Mises stress according to wheel tread

## 2.2 Residual stress field under mechanical loads

The perfect wheel with true profile geometry is constrained to build the finite element model. Due to the non-linearity of contact analysis, fixed boundary conditions are applied to the two ends of the rail and a pilot point is applied to the wheel using rigid link elements. All the external loading and boundary conditions of the wheel are applied on the pilot point. In this analysis, lateral loading is not considered and the friction coefficient is 0.28. The mesh that was created in section 2.1, is applied to determine the residual stresses in this analysis. However, a finer mesh is used near the contact region as in Figure 5. Note that for the calculation of the residual stresses instead of inertia force, factor 1.5 is used [19]. Such that the vertical load that is applied on the wheel is equal to 92 kN.

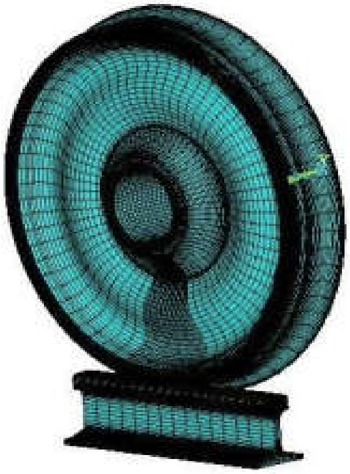


Figure 5. Finite element modeling of wheel/rail contact

Figure 6 shows the von Mises stresses due to contact of wheel and rail from several sections. In this case, the maximum von Mises stress occurs at 3 mm below the tread surface in the contact region and the stress in the other parts of the model is almost nil.

## 2.3. Crack propagation simulation

In this case, Franc 3D software for modeling is used. Because of modeling in ANSYS software data can be exported from ANSYS to Franc 3D software. These FEA results are input into FRANC3D by using a suite of software developed by the Cornell Fracture Group [20-22]. In Franc 3D, there is the ability to observe the crack growth in 3D view. Also, the residual stress can be imported to this software. In this case mounts of residual stress and displacement in different directions are saved in text files. Here, a semi-elliptic defect is built into the model and within the wheel rim. The dimension of the initial crack are a=2mm, b=1mm, while both of them are half of elliptic diameters and the propagation is simulated up to a final length equal to $a_f$ = 19 mm. Figure 7 shows geometry model of the wheel, initial radial crack and configuration of the model used. The highest mesh density can be watched in the crack growth area. The other steps for the modeling include defining the properties of the material, boundary conditions, solutions and the method for the modeling. For configuration of the model, 3D element with four nodes is used. By stress intensity factor (SIF), direction of the crack growth can be find. After finding the direction of the crack growth, the crack tip curve can be fitted out and this brings the crack into one step. After this, the material is re-

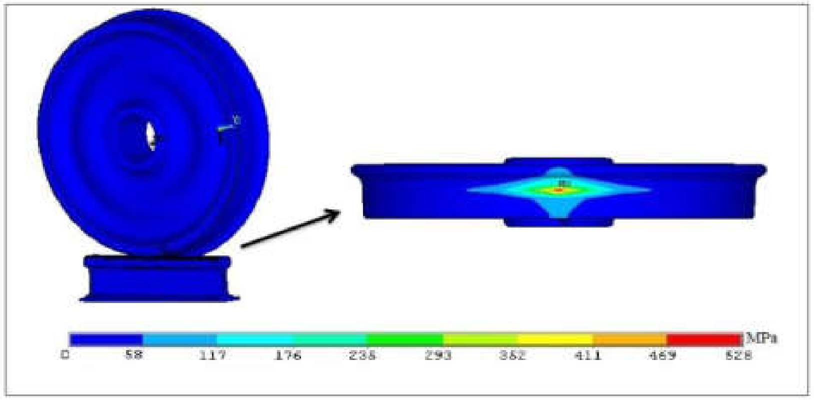


Figure 6. Distribution of stress due to contact between wheel and rail

configured and is prepared for the nest step of calculations. This stage is repeated in every step until the expected growth for the crack appears. Figure 8 shows the crack growth after 4 stages. Finally after feeding the necessary data and calculating the stress intensity factor (SIF), the fatigue life for the wheel is calculated.

## 3. Crack Growth Model

With the calculated SIF values FRANC3D uses the Paris model to estimate the crack growth rate. The fatigue analysis was carried out by means of the BEM code Franc3D according to the integral equations method. This is given as:

$$\frac{da}{dN} = C(K_{Imax} - K_{Imin})^n \qquad (1)$$

where C and n are constants which depend on the material properties. It should be noted that da/dN is a function of $\Delta K$. The constants used to calculate crack growth are:

$$C = 3.38 * 10^{-12}\frac{m}{cycle} \; and \; n = 3$$

## 4. Estimation of Crack Growth Life

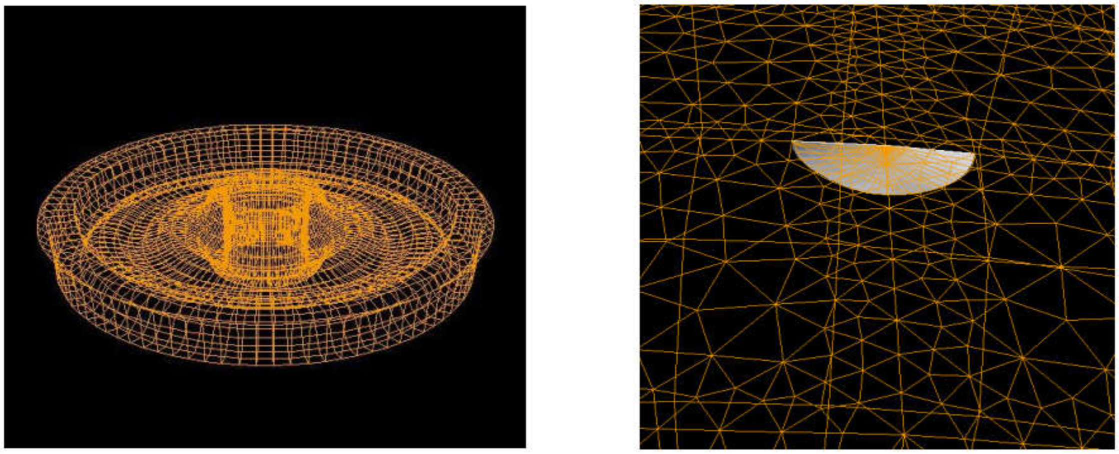
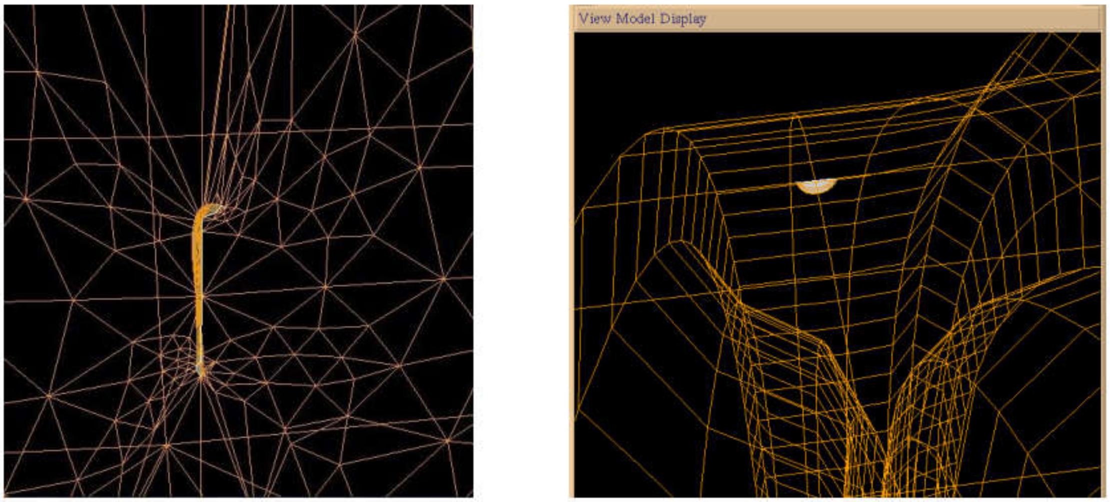

(a) (b)

Figure 7. a) Geometry model of wheel in Franc 3D software b) Geometry model of the initial crack in Franc 3D software



(a) (b)

Figure 8. Crack after 4 stages of growth a) top view b) ISO view

The influence of various factors on the fatigue life of the wheels is investigated by using the methodology that was described above. These factors are the vertical loading, initial crack length, and friction coefficient of wheel/rail contact. All other parameters are according to the [15]. Estimation of wheel fatigue life, was studied in three vertical loads on the wheel, which include 7, 10 and 15 ton. Figures 9&10 show the stress intensity factor (SIF) and the fatigue life as a function of crack length for different vertical loads, respectively. According to Figure 9 the stress intensity factor (SIF) in wheel by changing the load domain from 15 to 10 tons decreases about 31% and by changing the load domain from 10 to 7 tons decreases about 39%. As shown in Figure 10 the fatigue life increases about 58% by changing the load domain from 15 to 10 tons and increases 71% by changing the load from 10 to 7 tons.

The effect of the initial crack length on the fatigue life of a wheel for a radial crack and load equal to 10 tons, with the length of the crack that is calculated by using Equation (1). The initial length of the crack is assumed to vary from 25mm to 0.2mm. The results are shown in Figure 11. It can be observed that in changing the length of the crack from 1mm to 0.25mm, the wheel life increases for about 320%.

The friction coefficient is one of the factors that effects the fatigue life. The friction coefficient depends on the normal pressure and the sliding velocity parameters. The friction coefficients between the wheel and the rail are assumed to vary from 0.1 to 0.4. Figure 12 shows the effect of the friction coefficient and the loads (10 tons). According to Figure 12 by decreasing the friction factor, fatigue life will be increased, as well. Also when the friction coefficient changes from 0.2 to 0.3, the fatigue life decreases for about 33%. By changing the friction coefficient from 0.3 to 0.4 the fatigue life changes from 0.2 to 0.3.

## 5. Conclusions

This research provides a prediction of the crack propagation in the rail vehicle wheel that is caused by the residual stresses from the mechanical loads and the manufacturing processes. A 3-D nonlinear stress analysis model is applied to estimate the stress fields of the wheel in manufacturing processes and its service conditions. The stress history is then used to calculate the stress intensity factor (SIF) and the fatigue life of the wheel.

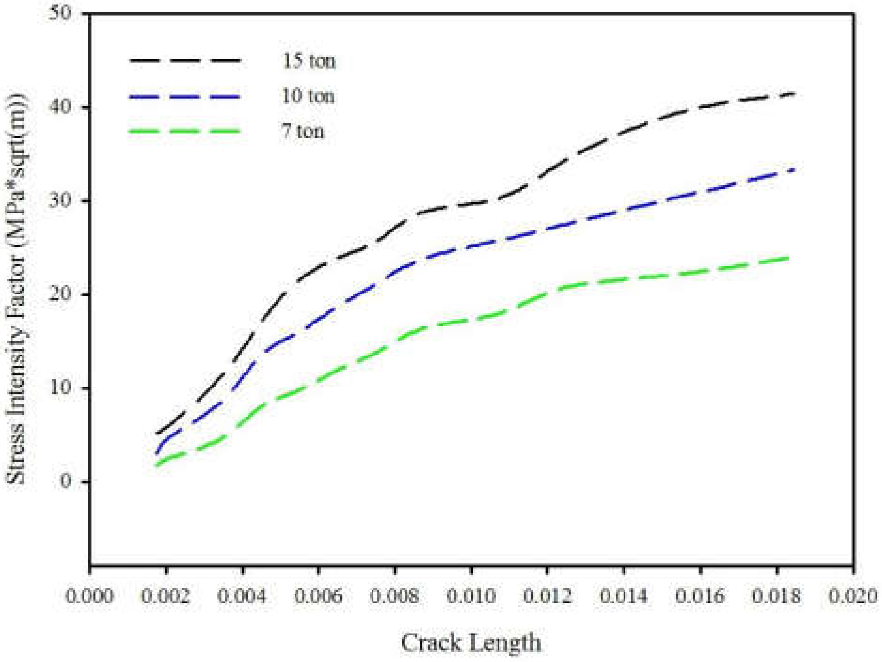


Figure 9. Stress intensity factor according to crack length for different loads

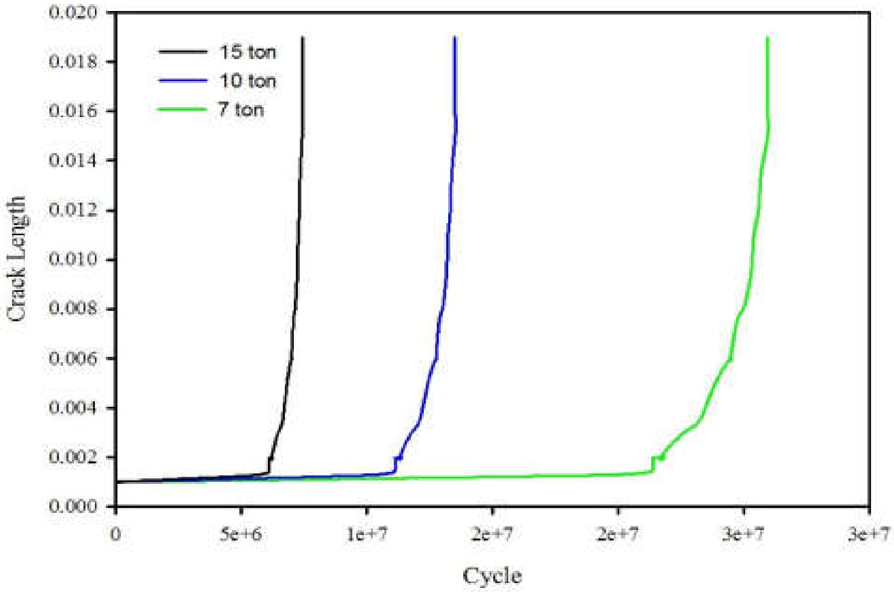


Figure 10. Fatigue life according to crack length for different loads

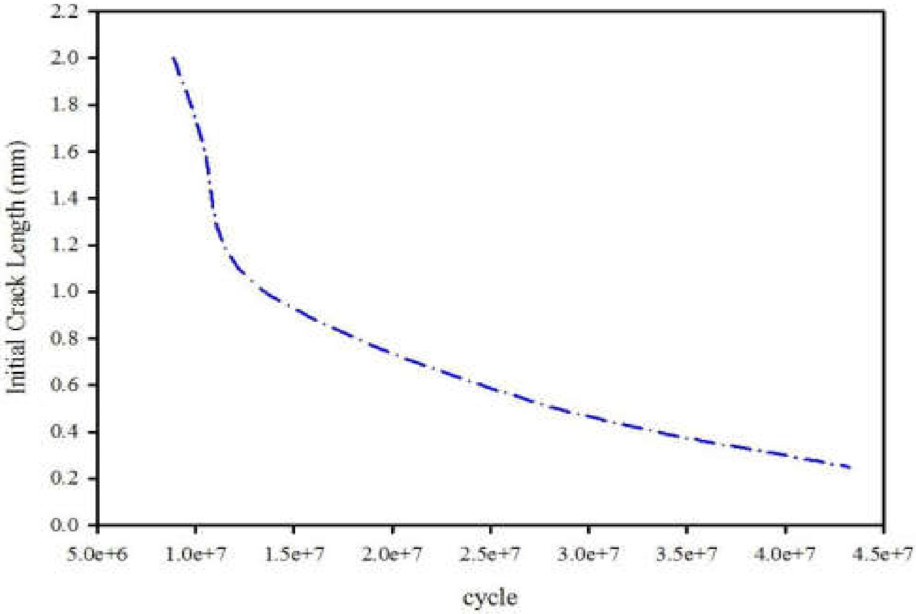


Figure 11. The effect of the initial crack length on fatigue life

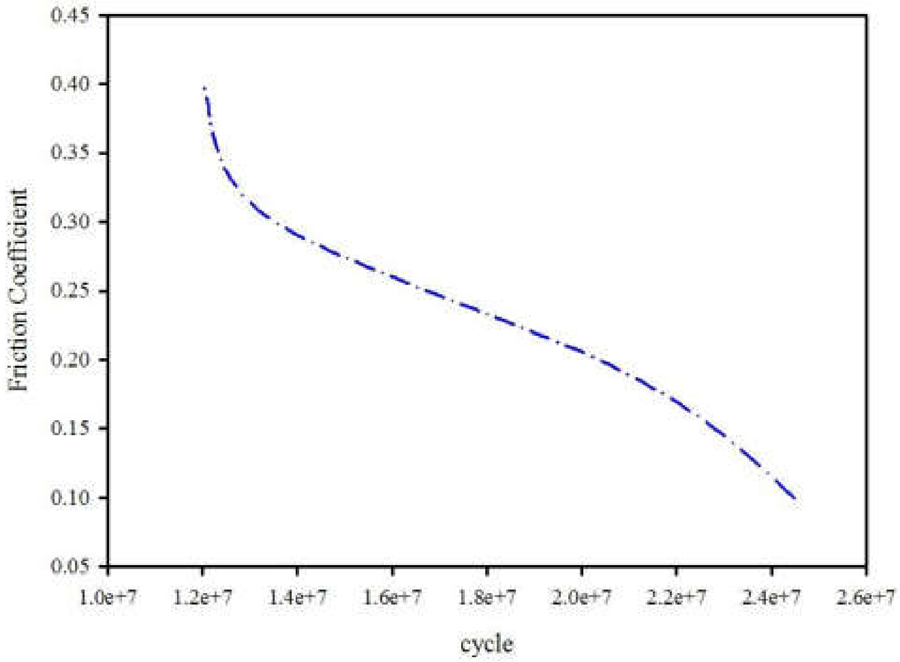


Figure 12. The effect of friction factor on fatigue life

It is assumed that the wheels are rim-quenched by using a water spray to induce beneficial hoop residual compressive stress at the surface of the tread.

The following conclusions can be made:

- The mechanical loading causes the state of the residual stresses for the wheel to change from one of compressive stress to tensile stress, and thereby affects the rim crack growth rate.
- According to the size of the residual stresses in wheels it is preferable to consider the wheel stress due to fatigue loading.
- The effect of the initial crack length on the fatigue life is studied. Shorter lengths have higher fatigue life. The initial cracks generally come from the manufacturing processes. These cracks propagate while the wheel is in operation. By controlling these stages it is possible to extend the wheel fatigue life.
- The slope of the fatigue-crack length diagram at the first section and along small cracks is very low. In other words, slight increase in crack length causes greater increase in its life. In this case the stress intensity factor (SIF) along too small cracks is more important than the stress intensity factor (SIF) along too big cracks.

In this research, the effects of different parameters on the fatigue crack growth in rail vehicle wheels are investigated. Future research may concentrate on the interactive effects of those parameters. Also, the influence of some other effects, such as the variable vertical loading, brake loading and the material defects can be studied.

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