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Life Estimation in the Railway Wheels Under the Influence of Residual Stress Field

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ABSTRACT

This paper presents the prediction of fatigue life and crack propagation in the railway wheel due to the stress field caused by mechanical loads and press fitting process of a railway wheel. A 3-D nonlinear stress analysis model has been applied to estimate stress fields of the railway wheel in press fitting process. Finite element analysis model is presented applying the elastic–plastic finite element analysis for the rail wheel under contact mechanical loads. Calculative analysis applying a finite element method (FEM) has been used to predict residual stresses. Then the stress history is used to calculate stress intensity factor (SIF) and fatigue life of railway wheel under service conditions. The effect of several parameters, vertical loads, initial crack length and friction coefficient between rim and hub/wheel, on the fatigue life in railway wheels is investigated using the suggested 3-D finite element model.

Keywords: Crack propagation, Life estimation, Residual stress, Finite element method, Stress intensity factor.

1. Introduction

Rolling contact fatigue (RCF) occurs at railroad wheel and many other mechanical applications. It has several shapes and is usually interacting with other shapes of surface damage. Ekberg, Kabo and Andersson [1] have made an effort to sort the present approaches to the RCF problem. Rolling contact fatigue (RCF) in railway wheel is caused by the rail/wheel contact and may result in initiation of surface and subsurface cracks. Fatigue performance of the wheels is a function of many factors, including service conditions, loading, material properties, environmental factors, and manufacturing processes. Rolling contact fatigue damage starts with the first mechanical operation, although it is very difficult to detect it, in fact microscopic subsurface cracks appear and propagate caused by the cyclic load applied to the railroad wheel .

The phenomenon of crack propagation during contact between wheel and rail has become one of the issues in railroad and a problem of intensive research in many scientific centers. Since this process is fast and uncontrolled, causes sudden break in rolling member. So, special attention is required to be paid to the life of rolling members. Fracture mechanics is widely used to predict crack growth life and several researchers have improved models to predict the stress intensity factors (SIFs). McDiarmid [2,3] defines the fracture plane as the plane which experiences the maximum principal stress Carpinteri et al and it has been proposed that the fracture plane coincides with the weighted mean principal stress direction[4,5]. Fatemi and Socie [6] relate the fatigue fracture plane to either a Mode I crack or a Mode II growth mechanism.

Dang van et al. [7] expanded a comprehensive approach to study rolling contact fatigue (RCF) phenomenon induced by repeated rolling or rolling–sliding wheel/rail contacts. They investigated cracks

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initiation and propagation in the rail head in a complex varying multiaxial stress regime due to Hertzian or non-Hertzian contacts. The use of finite element method (FEM) for the fatigue life analysis and modelling crack growth is a significant step in the development of appropriate models for the accurate simulation of the cracking process in railroad wheel. Great attempt has been put into finding suitable methods to represent cracking in FEM. Some recent important findings in the fatigue life analysis and modelling crack growth have been obtained by Guagliano and Vergani [8], Peng et al. [9], Wallentin et al. [10] and Sura et al. [11]. Liu et al. [12–14] have used the finite element method to calculate stress intensity factors (SIFs) in wheels, increasing the understanding of mixed mode stress intensity factors (SIFs). They calculate the rolling contact fatigue (RCF) damage by using a previously developed mixed-mode fatigue crack propagation model [14].

Most of the previous studies described above have estimated the crack initiation and crack propagation using numerical simulations and finite element method in mono-block wheel. Unfortunately, existing techniques for prediction crack propagation of the rail wheel problems are simple model. Finite element models of this nature generally need a fine mesh around the crack front to achieve accurate results. The simple model cannot obtain accurate stress field results of railway wheel under the influence of combination mechanical contact and thermal loads is also difficult to describe surface crack shape during fatigue calculation.

In this paper, a three-dimensional elastic-plastic finite element method using the true geometry of a railroad wheel has been used to model and accurately predict the stress distribution due to press fitting process and mechanical stresses due to wheel-rail operation. These stresses are applied as initial stresses for the fatigue crack growth analysis. Then, we present a three-dimensional model of crack growth in railroad wheel, rather than the quarter space assumptions often used previously. For this purpose, two kinds of the cracks in railroad wheels are applied; radial crack and circumferential crack. Therefore, the effect of variable thermal loads in press fitting process and various axial loads on the fatigue life is assessed by using damage mechanic methods. For this purpose, fatigue crack growth under dynamic loading is simulated in the three-dimensional model by using Franc3D software [15,16]. Finally, the effect of several parameters, vertical loads, initial crack length and friction coefficient between rim and hub/wheel, on the fatigue life in railroad wheels is investigated using the suggested 3-D finite element model.

2. Residual stress field

2.1 Residual stress field from press fitting process

Manufacturing process used in forming railroad wheels induced a wide variety of residual stresses. In the railway wheel manufacturing process, a heat treatment is used to decrease the risk of rim crack initiation by increasing the surface hardness. Under service condition, the thermal brake loading on rim wheel develops higher tensile residual hoop stress. In the press fitting process of a railway wheel, used rim in Iran railway, the stress distribution is created by a heat treatment which is performed to increase the space of the wheel rim by increasing the temperature of the. The stress distribution on the wheel has been reported to be altered due to press fitting process of a railway wheel. However, this process generates higher tensile hoop stress that could contribute to accelerate the formation of rim fatigue cracks. Fig. 1 shows schematic of railroad wheel.

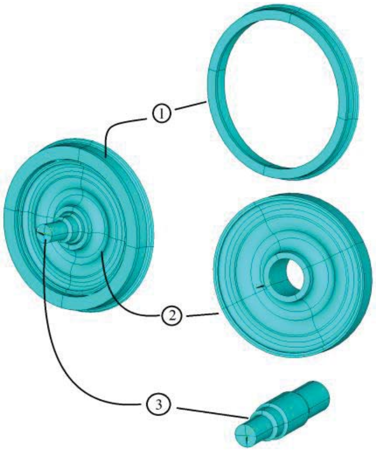


Figure 1: Schematic of railroad wheel, (1) Rim (2) Hub and web (3) Axle

The stress analysis in railroad rim wheel is carried out using three-dimensional elastic-plastic finite element method. Fig. 2 shows the elasto-plastic behavior at different temperatures using a bilinear isotropic hardening model. The temperature-dependent material properties are required for heat treatment analysis, and these are presented in Table 1. The model mesh has 45789 eight-noded elements with three translational degrees of freedom at each node with quarter point node locations. The mesh is refined in the contact zone between rim and hub/wheel where the maximum stresses are predicted. Also, the mesh is refined in the contact zone between axle and hub/wheel. The rim and hub/wheel surfaces and axle and hub/wheel surfaces are modeled as contact surfaces to avoid surface penetration under resultant compressive load by applying 0.2 for coefficient of friction. Fig. 3 shows finite element modeling of wheel in press fitting process for residual stress analysis

In this analysis, the center of wheel in either direction and outer wheel rim in one direction (perpendicular to the axis) is bounded by using displacement boundary condition.

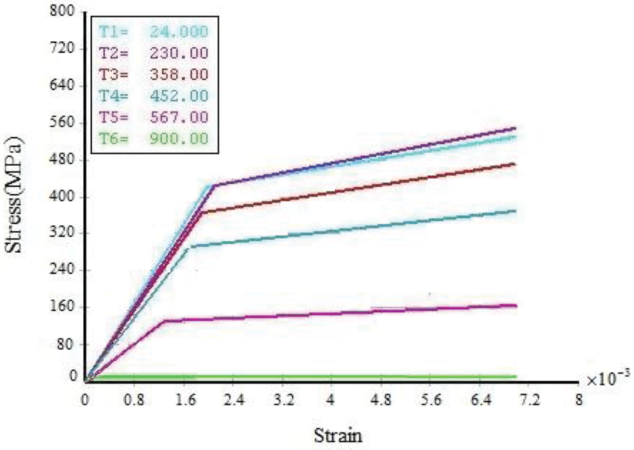


Figure 2: Mechanical material data for railroad wheel

Table 1. Material properties as function of temperature

T(°C)	E(MPa)	v	σ_y(MPa)	α(×10^{-6}/°C)
24	213	0.295	423	9.91
230	201	0.307	424.5	10.79
>450	170	0.321	291.2	11.27

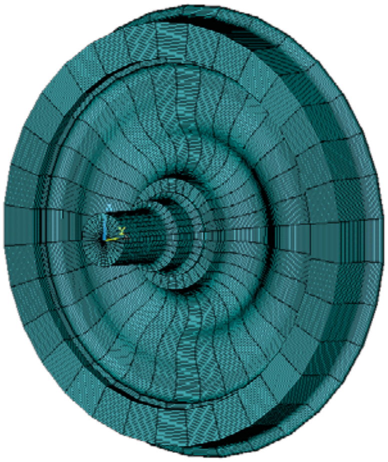


Figure 3: Finite element modeling of wheel in manufacturing process

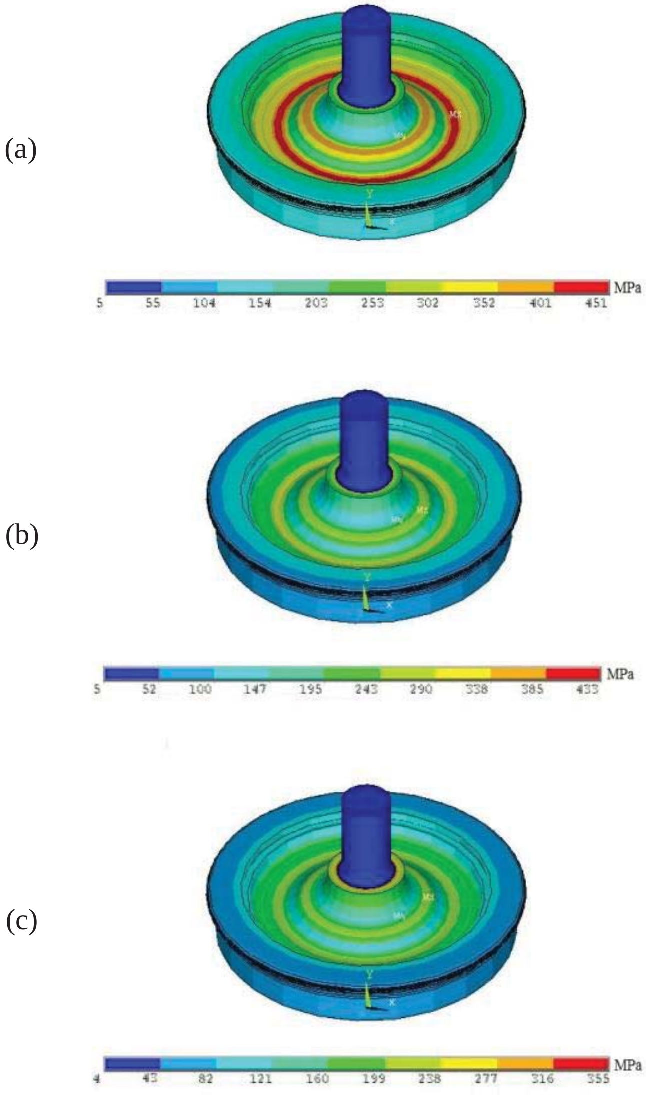


Figure 4: Contour plots of the residual stress after the press fitting process of railway wheel analysis for constant interferences: (a) for 0.75 mm, (b) for 0. 5mm, and (c) for 0.375mm.

The interference between rim and hub/wheel varies from 0.75 to 0.375. Figs. 4 (a-c) show the resulting stress distribution of rim wheel for different interferences. These show that the maximum stress reaches 451MPa (interference =0.75mm), which occurs at the rim and hub/wheel contact zone. For other interferences, these values are 433MPa (interference =0.5mm) and 355MPa (interference =0.375mm). According to Fig. 4 stress distribution in wheel by changing the interference domain from 0.75 to 0.5 mm decreases about 4% and by changing the interference domain from 0.5 to 0.375 mm decreases about 21%.

Fig. 5 depicts the curves of the contact pressure between rim and hub/wheel against the distance from rim for various interferences. According to Fig. 5 contact pressure between rim and hub/wheel in wheel by changing the interference domain from 0.75 to 0.5 mm decreases about 35% and by changing the interference domain from 0.5 to 0.375 mm decreases about 29%.

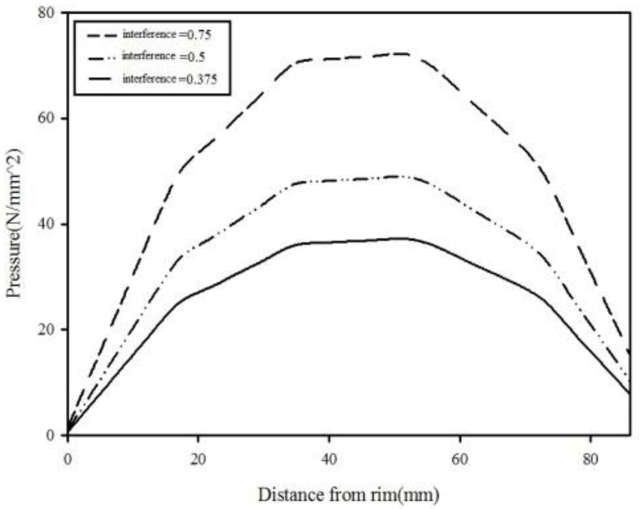


Figure 5: Contact pressure between rim and hub/wheel according to distance on rim wheel

2.2 Residual stress field from contact between wheel/rail

The 3D elastic– plastic finite element model of the contact between wheel and rail is shown in Fig. 6. Also, Fig. 6 shows the entire mesh and fine mesh near the contact zone. A bilinear kinematic hardening model is used for the wheel and rail. Isotropic hardening is not included in this model. The material properties shown in Table 1, has been used to study stress filed of a railroad wheel associated with a rail / wheel contact. Coulomb friction coefficient between the wheel and rails is selected as 0.28. 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. The vertical load applied on the wheel was 92 kN. The analysis procedure is adopted from ref. [14]. Fig. 7 shows the Von Mises stresses from two different section views. Thus, this analysis shows that the fatigue cracks initiate at a depth 3 mm below the tread surface of wheel.

3. Evaluation of Fatigue crack growth

Franc3D software is used for modeling and evaluation of fatigue crack growth. The finite element analysis results are input into Franc3D, a software developed by the Cornell Fracture Group [15-16]. Stress and displacement in different directions from press fitting process are applied as the initial condition for fatigue analyses. Fig. 8 shows finite element model of quarter space of railroad wheel. In Franc3D, we have this ability to observe the crack growth in 3D view. Here, a semi-elliptic defect is built into the model and within the wheel rim, dimension of initial crack is a=1mm, b=1mm, both of them are half of oval diameters and the propagation was simulated, up to a final length of 19 mm . Fig. 9 shows model and initial radial crack in the wheel. The definition of material properties, boundary conditions, solutions and method are the steps of the model. For configuration of model, we use the 3D element with for the node. Fig. 10 shows the configuration of model around the crack growth area. Fig. 11 shows the crack after 18 stages.

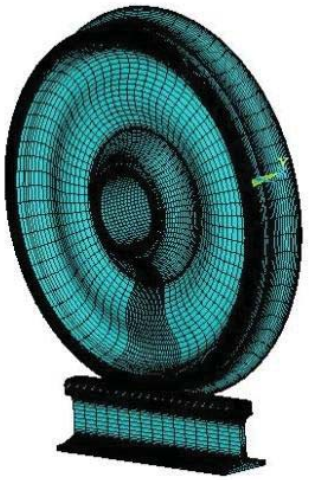


Figure 6: Finite element modeling wheel/rail contact

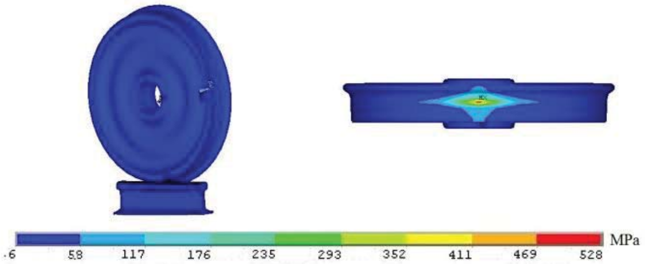
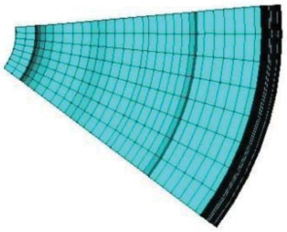


Figure 7: Contour plots of the von Mises stress after wheel/rail contact



(a)

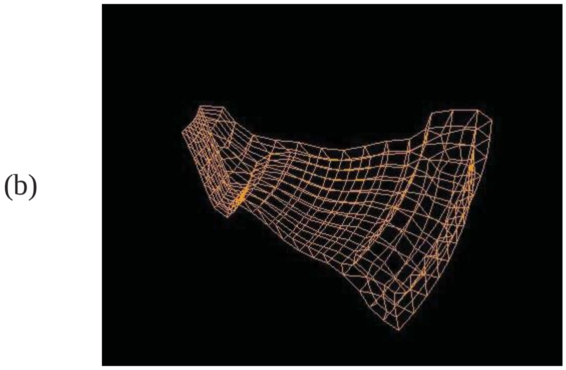


Figure 8: Finite element modeling of railroad wheel: (a) The quarter space of wheel model (b) Geometry model of wheel importing into Franc3D software

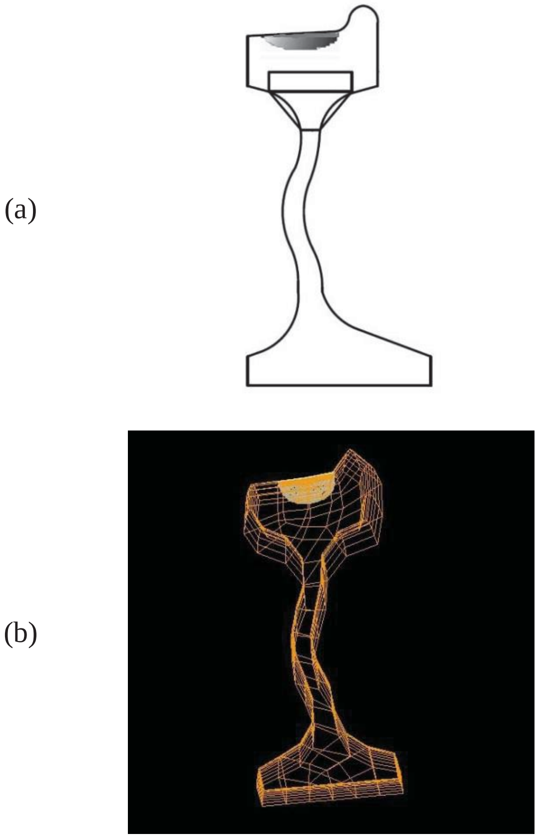
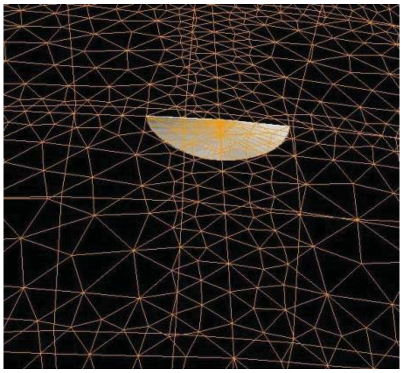


Figure 9: Crack position and configuration in the wheel rim, (a) schematic (b) in Franc3D software



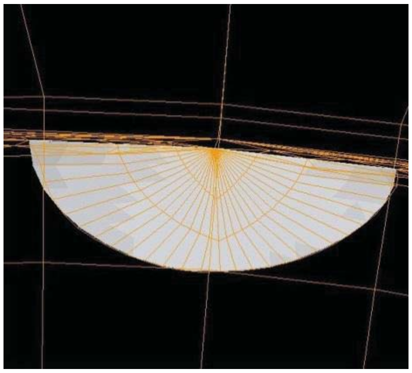


Figure 10: The final configuration of crack surface meshes and around it

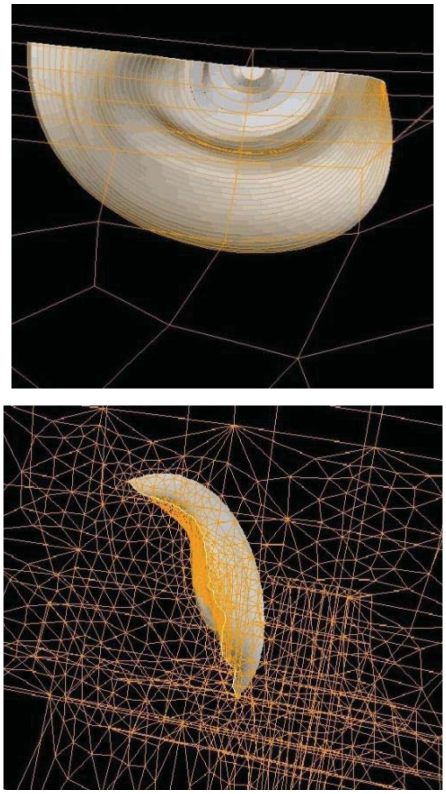


Figure 11: Crack after 18 stages growth

4. Stress intensity factor and crack growth model

Linear elastic fracture mechanics is applied to predict the strength of a railroad wheel in the presence of a crack. For this purpose, with the calculated SIF values, Franc3D uses the Paris model to estimate the crack growth rate. Stress intensity factors (SIFs) associated with three modes of fracture are calculated using the displacement approach. Crack propagation trajectories under mode-I and mode-II conditions are obtained using planar and maximum tangential stress crack-extension criteria [17].

The fatigue analysis was carried out by means of the BEM code of Franc3D according to the integral equations method as the following:

$$\frac{da}{dN} = C\,(K_{\max} - K_{\min})^{n} \qquad (1)$$

Where C and n are constants which are material properties. The constants used to calculate crack growth were:

$$C = 3.38 \times 10^{-12} \quad \frac{m}{cycle}$$

and n=3.

5. Results and Discussion

The influence of various factors, such as initial crack length, and friction coefficient between rim and hub/wheel and vertical loading, on the fatigue life of the wheels is investigated, using the presented methodology described above.

A railroad rim wheel under 92 KN vertical loading with different interferences (0.75mm, 0.5mm and 0.375 mm) and constant coefficient of friction (e.g. 0.2) is applied for the SIF and fatigue crack growth estimation. The SIF of different interferences for radial crack and circumferential crack are plotted in Fig. 12 and 13, respectively. Also, the fatigue life of different interferences for radial crack and circumferential crack are presented in Fig. 14 and 15, respectively.

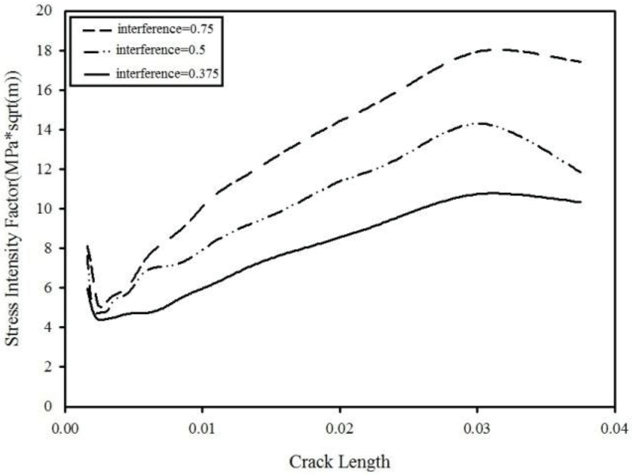


Figure 12: Stress intensity factor according to crack length for different interferences and radial crack

The effects of initial crack lengths are plotted in Fig. 16. A railroad rim wheel under constant vertical load (e.g. 92 KN), constant radial interference (e.g. 0.5mm) and constant coefficient of friction between the rim and hub/wheel (e.g. 0.2) with radial crack for different initial radial crack length (e.g. 0.25 mm, 0.5 mm, 1mm, 1.5 mm and 2 mm) are estimated. Different behaviors are observed for the fatigue life and radial crack.

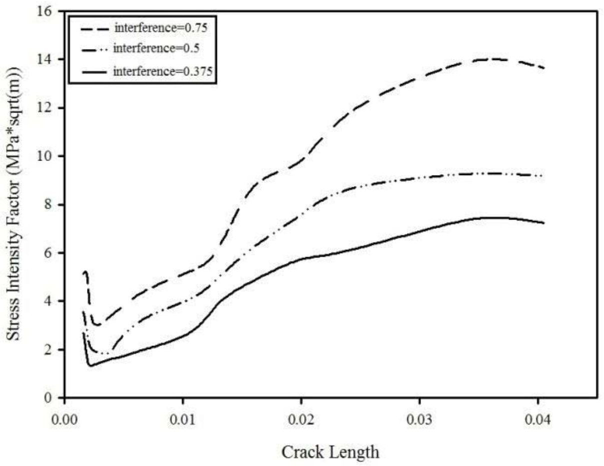


Figure 13: Stress intensity factor according to crack length for different interferences and circumferential crack

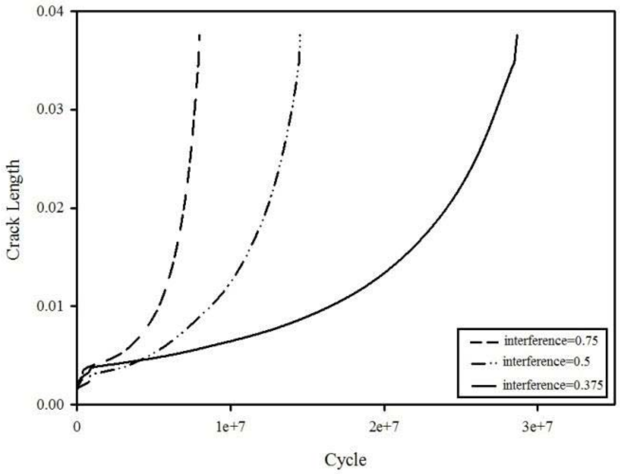


Figure 14: Fatigue life according to crack length for different interferences and radial crack

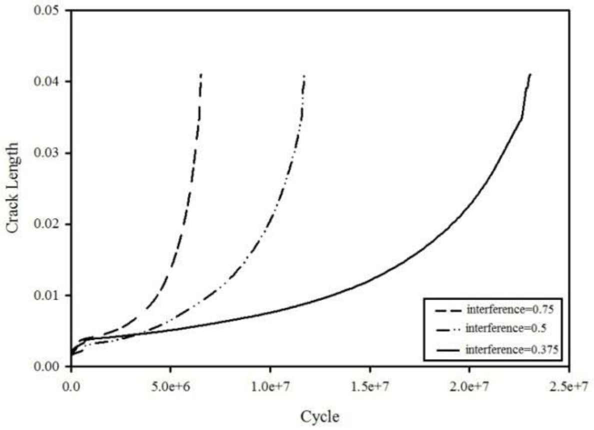


Figure 15: Fatigue life according to crack length for different interferences and circumferential crack

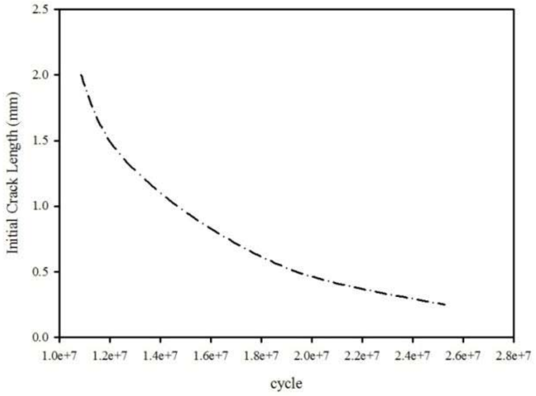


Figure 16: Initial crack length Effect on the fatigue life

The fatigue life of different friction coefficients between rim and hub/wheel (e.g. 0.1, 0.2, 0.3and 0.4), for a railroad rim wheel under constant vertical load (e.g. 92 KN), constant radial interference (e.g. 0.5mm) and constant initial radial crack length (e.g. 1mm) is presented in Fig. 17.

The fatigue life of the railroad rim wheel under different vertical loads (e.g. 92 KN, 120 KN, 150 KN and 198 KN) with constant radial interference (e.g. 0.5mm), constant initial radial crack length (e.g. 1mm) and constant friction coefficients between rim and hub/wheel (e.g. 0.2) is estimated and plotted in Fig. 18.

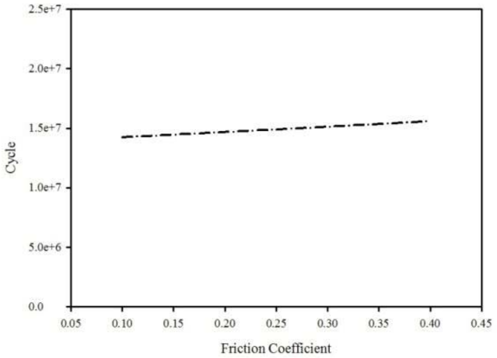


Figure 17: Effect of friction coefficient between rim and hub/wheel on fatigue life

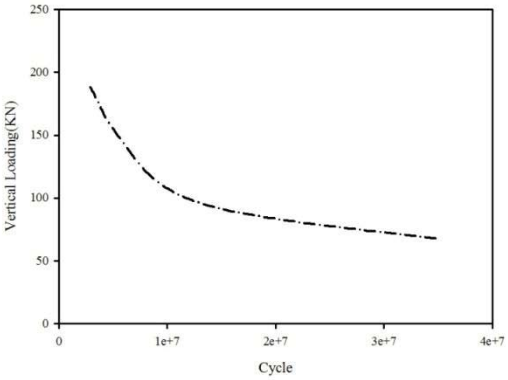


Figure 18: Vertical load Effect on the fatigue life

6. Conclusions

The fatigue crack growth analysis, based on the residual stresses from press fitting process and service condition, is developed in this paper, For this purpose, non-linear 3D finite element analysis is used for residual stress. The stress history is then applied to estimate the fatigue life by using Franc3D software under dynamic loading. Two different crack types were chosen from actual observations; radial crack and circumferential crack. The effect of several parameters on the fatigue life in railroad wheel is studied using the suggested finite element model. From this work the following conclusions can be made:

1. The finite element analysis results show the very significant stress distribution due to manufacturing process. The resultant stress field is high value and their effects are not negligible in the fatigue crack growth analysis.
2. The results revealed that stress field is highly sensitive to the material property and the interference between rim and hub/wheel. Therefore, these factors significantly affect the stress field of railroad wheels during press fitting process.
3. The results confirmed the magnitude of the circumferential stress in the wheel since this has been identified as the main cause of fatigue cracks to initiate and propagate.
4. The normal hoop stress has a significant effect on fatigue life. Tensile hoop stress reduces the fatigue life, while compressive hoop stress increases the fatigue life.
5. Fatigue life is relevant to the initial crack length, vertical load and coefficient factor between rim and hub/wheel. Fatigue life prediction shows an important difference with the field observation in the railroad wheel. Thus, other factors affecting the fatigue life require to be considered, such as initial material defects and braking loads.

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