The 3-D finite element analysis of press fitting process in railway wheel-set

Soheil Sarabandi¹, Hesam Soleimani², Saeed Mahmoudi³

¹ Institute of Industrial and Control Engineering, Universitat Politecnica de Catalunya, Barcelona, Spain,
² Faculty of Engineering, Department of Mechanical Engineering, Ferdowsi University of Mashhad, Mashhad, Iran,
³ Department of Mechanical Engineering, Najafabad Branch, Islamic Azad University, Najafabad, Iran,

Abstract

Variations in loadings of rolling contact components lead to a change in contact forces between surfaces. These forces are the main cause of rolling contact damages such as fatigue. Residual stresses are a major issue in railway wheel structures and it is appropriate to reduce such stresses. The aim of this paper is to estimate residual stresses in railway wheel due to hub to rim and axle to hub fitting process. A nonlinear three-dimensional model of stress is applied for analyzing stress field during press fitting process. An elastic-plastic finite element model is developed to model variable thermal loading in railway wheel. Finally, results of three dimensional finite element analysis showed a good agreement to field observations.

Keywords: residual stress, thermal loading, press fitting process, finite element, railway wheel

1- Introduction

Wheel, rail and weld fracture in railway structures occurs because of many factors such as improper fitting during press fit process of wheels to the axel, residual stresses in wheels, inappropriate welding quality (inadequate pre-heat, wrong adjustment of rail gaps, no balance

¹ Corresponding author, PhD, Email address soh.sarabandi@gmail.com.
temperature condition, no stress release and etc.), fatigue in wheel and rail, large impacts from faulty wheels (sharp edges and flanges) and etc. the points with maximum stresses are the best choices that cracks may initiate and consequently propagates. For this reason, identifying these regions and calculating the amount of stresses can be very helpful in non-destructive inspection and life estimation methods.

The residual stress that is produces because of manufacturing procedures in railway wheel structure can be changed according to mechanical stresses during working condition. These stresses are affected by thermal operations during manufacturing process. In recent decades, different research works are performed to estimate residual stresses. These stresses has an important role in mechanical components by removing the surface materials [1]. According to the significance of exact analyzing of these forces and the effect of manufacturing residual stresses on the amount of such forces in contact areas, the application of numerical methods in this field is very important [2-5].

Okagata [6] studied on fatigue strength of Japan railway wheel and presented a fatigue design methodology for high speed railway wheel by considering the effect of manufacturing conditions on fatigue strength of materials. In references [7-13], some of these problems are solved using experimental, analytical and finite element procedures. Considerable amount of studies are conducted on the effect of different parameters on fatigue crack growth such as initial crack angle and type of loading [14-16]. Masoudinejad performed a vast range of researches on the effect of residual stresses on fatigue crack propagation in rim wheels. Masoudinejad et al. studied on fatigue crack growth and life estimation of rim wheels by considering the effect of contact and thermal stresses. The results of their study revealed that the crack growth in Iranian wheel-rail structures with no residual stress contains shear modes of II and III [17-21]. Maousdinejad also investigated on calculating the stress field of manufacturing process in wheel structure. He developed a three dimensional elastic-plastic finite element model to estimate the stress field. The comparison of such stress field to experimental results of other researches led to an acceptable agreement [22].

In many of the aforementioned researches, residual stresses are calculated by means of numerical simulation and finite element method. Unfortunately, available techniques for residual stress estimation in wheel/rail structures are quite simple. Finite element model requires fine and tiny
mesh to reach more exact results. Therefore, a simple model is not able to achieve an exact stress field under the effect of thermal loads.

In this paper, a three dimensional elastic-plastic finite element method is applied on the real profile of railway wheel in order to anticipate stress distribution according to press fitting process. Simulation of manufacturing process consists of two parts: nonlinear transient thermal analysis and nonlinear structural analysis.

2- Governing equations

Press fitting is an approach to produce residual stresses in the structure. In this approach, elastic pressure of the material is mostly used. The main challenge in this method is its high sensibility to manufacturing tolerances and its cost. The function in radial symmetry problems is defined as \( F = F(r) \), so the equilibrium equations are as follows:

\[
\frac{\partial(h\sigma_r)}{\partial r} + \frac{1}{r} \frac{\partial(h\tau_{r\theta})}{\partial \theta} + \frac{h(\sigma_r - \sigma_\theta)}{r} + hR = 0
\]

\[
\frac{\partial(h\tau_{r\theta})}{\partial r} + \frac{1}{r} \frac{\partial(h\sigma_\theta)}{\partial \theta} + \frac{2(h\tau_{r\theta})}{r} + h\Theta = 0
\]

(1)

The thickness \( h \) is constant in Eq. (1) and its form is changed as:

\[
\frac{d\sigma_r}{dr} + \frac{1}{r} (\sigma_r - \sigma_\theta) + R = 0 \quad , \quad \Theta = 0
\]

(2)

According to the nature of axisymmetric problems and because of symmetry in tangential body forces, \( \Theta \) is considered as zero and stress components of \( (\sigma_r, \sigma_\theta) \) and radial body force are a function of \( r \) (radius). It should also be noted that the shear stress \( \tau_{r\theta} \) is zero.

So, the equilibrium equations are presented according to the derivatives of Airy stress function as:

\[
\left( \frac{d^2}{dr^2} + \frac{1}{r} \frac{d}{dr} \right) \left( \frac{d^2F}{dr^2} + \frac{1}{r} \frac{dF}{dr} \right) = 0
\]

(3)

Eq. (3) can be simplified to Eq. (4) that the \( F \) stress function can be obtained by direct integration and the obtained result is shown as Eq. (5).

\[
\frac{1}{r} \frac{d}{dr} \left( r \frac{d}{dr} \left( \frac{1}{r} \frac{dF}{dr} \right) \right) = 0
\]

(4)
\[ F = A \ln r + B^2 \ln r + C r^2 + D \]  

(5)

Where A, B, C and D are integration constants and can be achieved using boundary conditions. The D constant is not used in stress component equations because all equations depends on only the derivatives of F stress function. So, by substituting in Eq. (5), stress components are achieved as:

\[ \sigma_r = \frac{1}{r} \frac{dF}{dr} = \frac{A}{r^2} + B(1 + 2 \ln r) + 2C \]  

(6)

\[ \sigma_\theta = \frac{d^2 F}{dr^2} = -\frac{A}{r^2} + B(3 + 2 \ln r) + 2C \]  

(7)

If B is considered as zero (B should be considered as zero in order to achieve only one amount for displacement [6]). So the following result is obtained:

\[ \sigma_r = \frac{A}{r^2} + 2C, \quad \sigma_\theta = -\frac{A}{r^2} + 2C \]  

(8)

Two boundary conditions are required for obtaining two constants. By assuming a thick-walled pressure vessel with inner radius of a and outer radius of b under internal pressure of \( P_i \) and external pressure of \( P_e \), the boundary conditions are as follows:

\[ \sigma_r = -P_e \quad \Leftrightarrow \quad r = b \]

\[ \sigma_r = -P_i \quad \Leftrightarrow \quad r = a \]

Therefore,

\[ A = \frac{a^2 b^2 (P_e - P_i)}{b^2 - a^2} \]  

(9)

\[ 2C = \frac{P_i a^2 - P_e b^2}{b^2 - a^2} \]  

(10)

By considering \( P_i = P \) and \( P_e = 0 \) substituting Eq. (9) and Eq. (10) in Eq. (8), following equation is achieved:

\[ \sigma_r = -\frac{a^2 b^2 P}{(b^2 - a^2) r^2} + \frac{a^2 P}{b^2 - a^2} \]  

(11)

\[ \sigma_\theta = \frac{a^2 b^2 P}{(b^2 - a^2) r^2} + \frac{a^2 P}{b^2 - a^2} \]  

(12)

Variations of \( (\sigma_r, \sigma_\theta) \) in radial direction are shown in Fig. 1.
3- Finite element analysis

Wear in wheel occurs because of train motion on the rail and such wear enhances by passing time. The wheel has a special profile in its contact position to the rail. This profile changes in form under the effect of wear phenomena. Thus, wheel/rail structure disassembles after a while and new profile is provided again by machining. Each machining process leads to a reduction in the wheel thickness up to the point that it will be useless.

So, in such wear condition for railway wheel, it is designed in two parts: 1) hub, 2) rim. The part that is related to the special profile is placed in rim. The S1002 wheel profile that is applied in Iranian railway wheel system is used for geometrical modeling of the wheel. Coordinates of 497 points is extracted from an 8-degree polynomial in order to enhance precision of modeling. Exact modeling of wheel profile is very significant because it has enormous effect on contact stress field of the wheel. Other parts of the wheel’s cross section are modeled by means of related standard (Fig. 2). The selected wheel for this study is rim type wheel with 920 mm diameter that is selected as new wheel diameter in Iranian railway system.

In order to model the contact between hub and rim, the 0.2 friction coefficient is selected to define contact elements. In this model, reduction in temperature causes contraction to provide an appropriate fitting process with no thermal effect on stresses. Fig. 3 shows different parts of the model of rim-wheel before and after the assembly.

Material model of rim-wheel is considered as elastic-plastic behavior with linear kinematic hardening. The wheel material model is defined as homogeneous and isotropic. Stress-strain curve for different temperatures and final model with its elements are shown in Fig. 4 and Fig. 5, respectively.

Manufacturing process of rim-wheel contains machining the internal surface of an old wheel in its rim part. In this step, the desired clearance fit is prepared for internal surface of rim. Next step relates to two wheels that are connected to an axle and are moved on the rail to be mounted on a fixture for machining the outer surface of hub. In this step, clearance fit for outer surface of the hub is provided and its surface finishing process is satisfied.

In practical application, the rim is put into the oven in order to fit to the hub. Heating is applied using electromagnetic induction method. The coils which are placed around the rim cause electromagnetic field and this field provide the required heat. In manufacturing of rim-wheel,
hub is fitted directly to the axle. The maximum radial clearance fit between hub and axle after fitting process is 0.15 mm. after fitting the hub, the rim is fitted to the hub by means of thermal method. In this method, the rim is placed in a position and is will be expanded because of heating treatment and its inner radius increases. Then it is placed on the hub and it releases the heat as time passes and it is fixed on the hub. The maximum radial clearance fit between rim and hub is 0.75 mm. clearance fits are applied by thermal expansion method and do not have any effect on stress solution. Temperature of the rim is controlled by thermo-meters (with maximum allowable temperature of 250 centigrade degrees) and the oven will be turned off after ensuring that a complete fitting is occurred between hub and rim. It can be concluded that in such manufacturing procedure, only the rim is departed from the hub after passing all allowable exfoliations and consequently only the rim is replaced and hub is remained on axle. This method saves lots of material and time and is very cost effective.

A considerable part of passenger wagon wheels are of rim types. Tolerance of fitting the rim and hub produces a pressure between these two parts and such fitting pressure is the cause of static friction force between hub and rim. The static friction force prevents relative movement of rim on the hub during working condition. there are different parameters that reduce this force and increase the possibility of rim slide on hub such as manufacturing and assembling factors (surface roughness, clearance fit, surface alignment and etc.) and working factors (breaking using break shoe). Inner diameter of rim is measured using micro-meter in workshop and it can be 1.1 to 1.5 millimeters lower than the outer diameter of the hub. Displacement in the direction of wheel motion is considered as zero and the fitting process of thermal contraction is considered with no effect on stresses.

After heating to the rim up to a specified temperature, hub is placed in the rim from the top position and by means of a high-precision machine. After this initial fitting process, some time is needed for these parts to release their heat. During cooling step, rim and hub contact surfaces applies high pressure together and consequently stresses are produced in these regions. Finally, after mounting the rim on the hub, a ring is put around the hub in order to prevent the rim movement from one side of the hub. This ring will not departed from the wheel until the rim properly functions. The process of mounting the ring contains two main parts: at first, a part of the ring is placed in a step, then by moving the rim and hub, other parts of the ring are mounted in the step.
Required parameters for heat transfer analysis contains thermal conductivity and specific heat. Thermal conductivity (k) is defined as the ability of material to transfer thermal energy by conduction that is a transitive property and its unit is $W/m\cdot{}C$. Temperature dependent mechanical properties for steel wheel are estimated. Also data are required to define Young modulus (E), Poisson’s ratio ($\nu$), thermal expansion coefficient ($\alpha$) and stress-strain relations in different temperatures in order to achieve stresses in structural analysis. Such parameters are defined as input of finite element analysis. Stress-strain curves in different temperatures are shown in Fig. 4.

4- Results and discussion

Maximum and minimum thickness of the rim are considered as 75 and 35 millimeters, respectively. In the present analysis, radial clearance fit between hub and rim are defined as 0.75 and 0.35 millimeters in its maximum and minimum modes, respectively. The friction coefficient is also selected as 0.4 for the highest value and 0.1 for its lowest value. The maximum value of clearance fit between hub and axle is set as 0.15 mm. radial and Von-Mises stresses in contact area of hub and rim (fitting pressure) are calculated for each of the aforementioned cases. The required moment for sliding the rim on hub can be achieved by fitting pressure and friction coefficient.

Results of the modeling of rim with maximum thickness of 75mm and maximum friction coefficient of 0.4 and different clearance fit values (the maximum is selected as 0.75 mm and the minimum is 0.375 mm) are shown in Fig. 6 to Fig. 8. Fitting pressure or the pressure between rim and hub is calculated from radial stresses between rim and hub. This pressure is not uniform and can also be calculated for different friction coefficients and clearance fits between hub and rim. Corresponding results are shown in Fig. 9.

Results of rim modeling with 75 mm thickness and 0.3 friction coefficient and by considering different values for clearance fit are shown in Fig. 10 to Fig. 12. Fitting pressure (the pressure between rim and hub) is calculated from radial stresses that are present between contact surfaces of rim and hub. Fitting pressure values for different clearance fits, 75 mm rim thickness and 0.3 friction coefficient are shown in Fig. 13.

Von- Mises stress results for a 75 mm thickness rim, 0.2 friction coefficient and different clearance fit values are shown in Fig. 14 to Fig. 16. Fitting pressures for the same rim thickness, friction coefficient and clearance fit values are also shown in Fig. 17. It can be inferred that the
Von-Mises stress increases as clearance fit and fitting pressure increase. The Von-Mises stress also decreases by reducing the friction coefficient between rim and hub.

5- Conclusion
In this paper, a three dimensional finite element analysis study is carried out in order to simulate residual stresses in rim-wheel and to develop the residual stress of fitting process. Three dimensional nonlinear finite element analysis is applied for calculating residual stresses. Clearance fit between hub and rim creates a pressure between their contact areas which prevent the rim to slide on hub. Such clearance fit is provided by variable thermal loading steps. There are different parameters that cause a reduction in friction coefficient and increase the likelihood of rim slide on hub. These factors consist of manufacturing and assembly parameters (clearance fit and surface roughness) and operation parameters (mechanical residual stresses). According to performed analysis, friction coefficient does not have any considerable effect on fitting pressure and fatigue life. So, surface roughness that is in direct relation to friction coefficient has no effect on radial clearance fit. Finally, following conclusions can be inferred from results of this paper:

1- Results of finite element analysis shows that the stress distribution is very important and high stress level has significant effect on crack initiation.

2- Results revealed that stress is very sensitive to thermal loading. Therefore, this parameter has considerable effect on thermal treatment process of railway wheel.

3- Circumferential stress results in the wheel confirms that these amount are effective on crack initiation until the stress values has high values.

4- It can be inferred from the results that if the clearance fits are exactly observed, the friction force between wheel and rail will not be able to cause rim slide on hub.

5- Friction coefficient does not have considerable effect on fitting pressure and consequently variations in surface roughness do not have direct effect on friction coefficient and rim slide.

In this paper, residual stresses in railway wheel are estimated due to fitting process. Next researches needs to consider interaction of other parameters and also to study on the effect of parameters such as process type, boundary conditions and material properties in railway wheel field.
References

[1] Hadipour M., Alambeigi F., Hosseini R., Masoudinejad R., “A study on the vibrational effects of adding an auxiliary chassis to a 6-ton truck”, *Journal of American Science*, 7(6), pp. 1219-1226 (2011).

[2] Masoudi Nejad R., Farhangdoost Kh., Shariati M., “Numerical study on fatigue crack growth in railway wheels under the influence of residual stresses”, *Engineering Failure Analysis*, 52, pp. 75-89 (2015).

[3] Masoudi Nejad R., “Using three-dimensional finite element analysis for simulation of residual stresses in railway wheels”, *Engineering Failure Analysis*, 45, pp. 449-455 (2014).

[4] Salehi S.M., Farrahi G.H., Sohrabpoor S., Masoudi Nejad R., “Life Estimation in the Railway Wheels under the Influence of Residual Stress Field”, *International Journal of Railway Research*, 1(1), pp. 53-60 (2014).

[5] Ghahremani Moghadam D., Farhangdoost Kh., Masoudi Nejad R., “Microstructure and Residual Stress Distributions Under the Influence of Welding Speed in Friction Stir Welded 2024 Aluminum Alloy”, *Metallurgical and Materials Transactions B*, 47(3), pp. 2048-2062 (2016).

[6] Okagata Y, Kiriyama K, Kato T., “Fatigue strength evaluation of the Japanese railway wheel”, *Fatigue Fract Eng Mater Struct.*, 30, pp. 356–71 (2007).
[7] Siva N. L., Bernard K., “Prediction of residual stresses in low carbon bainitic–martensitic railway wheels using heat transfer coefficients derived from quenching experiments”, *Computational Materials Science*, 77, pp. 153–160 (2013).

[8] Siva N., Bernard K., “Thermo-mechanical modelling of residual stresses induced by martensitic phase transformation and cooling during quenching of railway wheels”, *Journal of Materials Processing Technology*, 211(9), pp. 1547–52, (2011).

[9] Lin K.Y., Huang J.S., “Analysis of residual stresses in railroad car wheels based on destructive test measurements”, *Theoretical and Applied Fracture Mechanics*, 12(1), pp. 73–86 (1989).

[10] Moyar G.J., “An analysis of the thermal contributions to railway wheel shelling”, *Wear*, 144(1-2), pp. 117–38 (1991).

[11] Shen X. H., Yan J., Zhang L., Gao L., Zhang J., “Austenite Grain Size Evolution in Railway Wheel during Multi-Stage Forging Processes”, *Journal of Iron and Steel Research*, 20(3), pp. 57–65 (2013).

[12] Seo J. W., Kwon S. J., Jun H. K., Lee D. H., “Effects of residual stress and shape of web plate on the fatigue life of railway wheels”, *Engineering Failure Analysis*, 16(7), pp. 2493–507 (2009).

[13] Tawfik D., Mutton P. J., Chiu W. K., “Experimental and numerical investigations: Alleviating tensile residual stresses in flash-butt welds by localized rapid post-weld heat treatment”, *Journal of Materials Processing Technology*, 196(1-3), pp. 279–91 (2008).

[14] Masoudi Nejad R., Farhangdoost Kh., Shariati M., “Three-dimensional simulation of rolling contact fatigue crack growth in UIC60 rails”, *Tribology Transactions*, 59(6), pp. 1059-1069 (2016).
[15] Masoudi Nejad R., Farhangdoost Kh., Shariati M., Moavenian M., “Stress intensity factors evaluation for rolling contact fatigue cracks in rails”, Tribology Transactions, 60(4), pp. 645-652 (2016).

[16] Shariati M., Masoudi Nejad R., “Fatigue Strength and Fatigue Fracture Mechanism for Spot Welds in U-Shape Specimens”, Latin American Journal of Solids and Structures, 13(15), pp. 2787-2801 (2016).

[17] Shariati M., Mohammadi E., Masoudi Nejad R., “Effect of a new specimen size on fatigue crack growth behavior in thick-walled pressure vessels”, International Journal of Pressure Vessels and Piping, 150, pp. 1-10 (2017).

[18] Masoudi Nejad R., “Rolling contact fatigue analysis under influence of residual stresses”, MS Thesis, Sharif University of Technology, School of Mechanical Engineering, 2013.

[19] Masoudi Nejad R., Salehi S.M., Farrahi G.H., “Simulation of railroad crack growth life under the influence of combination mechanical contact and thermal loads”, in 3rd International Conference on Recent Advances in Railway Engineering, Iran, 2013.

[20] Masoudi Nejad R., Salehi S.M., Farrahi G.H., Chamani M., “Simulation of crack propagation of fatigue in Iran rail road wheels and Effect of residual stresses”, In: Proceedings of the 21st International Conference on Mechanical Engineering, Iran, 2013.

[21] Masoudi Nejad R., Shariati M., Farhangdoost Kh., “3D finite element simulation of residual stresses in UIC60 rails during the quenching process”, Thermal Science, 21(3), pp. 1301-1307 (2017).

[22] Masoudi Nejad R., Shariati M., Farhangdoost Kh., “Effect of wear on rolling contact fatigue crack growth in rails”, Tribology International, 94, pp. 118-125 (2016).
Soheil Sarabandi received the MSc degree from Ferdowsi University of Mashhad, Iran; He is currently a PhD in Automatic Control, Robotics and Computer Vision, Universitat Politècnica de Catalunya (UPC), Barcelona, Spain. His research interests are in the areas of finite element, motion design, kinematics & Dynamics of robot.

Hesam Soleimani got his MSc. degree from Ferdowsi university of Mashhad. He was a member of Mashhad Urban and Suburban Railway Operation Company (MUSROC) and worked on wheel/rail wear mechanism. He is an expert on this field now and working on same projects.

Saeed Mahmoudi was born in 1988 in Najafabad, Iran. He graduated from Islamic Azad University, Najafabad Branch with a Mechanical Engineering BS degree. He obtained his MS degree in Mechanical Engineering from Islamic Azad University, Najafabad Branch. Currently, he is furthering his Mechanical Engineering education at Islamic Azad University, Najafabad Branch as a PhD candidate.

List of Figure caption

Fig. 1. Stress distribution in the thickness of a thick-walled cylinder
Fig. 2. Geometry of rim-wheel cross section with 920 mm diameter
Fig. 3. Different parts of rim- wheel before and after assembly. a) field observations before assembly, b) field observation after assembly
Fig. 4. Temperature dependent stress-strain data applied in simulation of thermal treatment of wheel [18]
Fig. 5. Elements of rim- wheel model
Fig. 6. Von- Mises stress for radial clearance fit of 0.75 mm
Fig. 7. Von- Mises stress for radial clearance fit of 0.5 mm
Fig. 8. Von- Mises stress for radial clearance fit of 0.4 mm
Fig. 9. Fitting pressure for different clearance fit values
Fig. 10. Von- Mises stress for radial clearance fit of 0.75 mm
Fig. 11. Von- Mises stress for radial clearance fit of 0.5 mm
Fig. 12. Von- Mises stress for radial clearance fit of 0.4 mm
Fig. 13. Fitting pressure for different radial clearance fit values
Fig. 14. Von- Mises stress for radial clearance fit of 0.75 mm
Fig. 15. Von- Mises stress for radial clearance fit of 0.5 mm
Fig. 16. Von- Mises stress for radial clearance fit of 0.4 mm
Fig. 17. Fitting pressure for different radial clearance fit values
Fig. 1
Fig. 2
Fig. 3
Fig. 4
Fig. 6
Fig. 8
Fig. 11
Fig. 13
Fig. 16
Fig. 17