Effect of interference on the press fitting of railway wheel and axle assemblies

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Abstract

Press fitting is one of the common fastening methods used to assemble mechanical components. It has also received considerable critical many industrial applications, for example, railway wheel and axle are usually assembled by press-fitting. This process generates high stress on the axle-fillet area and fatigue is generally initiated due to the stress concentration. This paper attempts to propose the stress distribution and deformation of a railway axle. Various interference clearances were analyzed using finite element method. The contact pressure at the axle wheel seat along the axial direction was examined as it significantly influences the press-fitted components life. The analytical results from Lame’s theory [1] were compared with finite element analysis results for the wheel and axle press-fitting process. The results obtained from both methods were in good agreement and the maximum relative error of the contact pressure is by 11.08 %. Additionally, the results show that the Von-Mises stresses on the axle wheel seat and fillet areas were found to be increased if the interference increased.

Keywords: Press Fitting, Railway Axle, Interference, Lame’s Theory

1. Introduction

Railway axle is the vital security component in railway vehicles, and it is assembled with the wheel by the press-fitting method. The axle might be damaged by any of excessive pressure, excessive interference, or improper lubricant. The damage could evolve into fatigue cracks and these cracks are easily initiated on the axle due to fretting behaviors. Thus, the reliability of interference fits is crucial to ensure the railway wheelset is safe in service. Press fitting is a traditional method for assembly of interference fitting parts, and the quality of the assembly has been extensively studied. The contact pressure in press-fitting produces residual stresses, for example, tangential and radial stresses in the wheel and the axle. The residual stress greatly influences the occurrence of fatigue on the parts in operation.

Previous research has established that interference can have an effect to the interface between the two parts by finite element analysis. However, far too little attention has been paid to railway wheelsets. Lame’s theory for thick-walled cylinder has been commonly used to predict the contact pressure of interference fit and deformation. However, the use of interference in the press-fitting has not been investigated. Partly, such an analytical theory is not adequate to predict residual stresses in press-fitting.
Sarabandi et al.[1] estimated the residual stress in railway wheels, due to press fitting, based on the nonlinear structural analysis and the nonlinear transient thermal analysis of the wheelset. They found that the stress distribution, due to thermal loading, is important and sensitive. Naderi [2] studied the stress intensity factor in railway wheelset by press fitting process. Hannemann and Sander [3] analyzed stress intensity factor and crack propagation, considering the effects of rotary bending and press-fitting. It was found that the press-fit load is important for the SIF solution. Marshall et al.[4] measured ultrasonic reflections to non-destructively determine contact conditions in the interference fit and investigated the wheel and axle interface with large contacts and gradual pressure variations. Zehsaz and Shahriary [5] investigated the effects of the coefficient of friction and interference on fretting fatigue strength of axles by using fretting damage parameters.

This research gives an account of the effect of interference on the wheelset press-fitting and variation of residual stresses with different interference clearances. The contact pressure and residual stresses were also evaluated analytically. The finite element analysis results confirmed that the analytic estimations can be employed to predict the stress distribution in the axle.

2. Materials and Methods

2.1 Interference Fit

Interference fits are widely used for mechanical attachment mechanisms because they are cost-effective and flexible. Concerning the wheelset assembly, shrink fitting or press-fitting can be used. However, press fitting is commonly used for assembling the wheel and axle because it is cheaper and faster. During the press-fitting, the axle wheel seat diameter is larger than that of the wheel hub bore. The assembled wheel and axle should meet the geometric requirements of some standard, e.g., EN 13261, EN 13262. The maximum and a minimum interference between the axle wheel seat and wheel hub bore are as follows [6]:

For shrink fitting,
\[ 0.0009 \, \delta \, dm \leq 2 \delta \leq 0.0015 \, dm \] (1)

For press-fitting,
\[ 0.001 \, \delta \, dm \leq 2 \delta \leq 0.0015 \, dm + 0.06 \] (2)

where \( dm \) is the mean diameter and \( \delta \) is the radial interference in mm.

2.2 Lame’s Theory for Thick-Walled Cylinder

Assuming the cylinder subjected to internal pressure is the wheel hub bore and the cylinder subjected to external pressure is the axle wheel seat, the stresses can be calculated by Lame’s theory.

Consider a small section of the cylinder, radial stresses \( \sigma_r \) and \( \sigma_\theta \) tangential stresses can be achieved as a function of radius:

\[
\sigma_r = \frac{r_i^2 P_i - r_o^2 P_o}{r_o^2 - r_i^2} - \frac{(P_i - P_o) r_o^2}{(r_o^2 - r_i^2) r_i^2}
\] (3)

\[
\sigma_\theta = \frac{r_i^2 P_i - r_o^2 P_o}{r_o^2 - r_i^2} + \frac{(P_i - P_o) r_i^2}{(r_o^2 - r_i^2) r_o^2}
\] (4)
When the wheel and axle are press-fit assemblies, it can be assumed that pressure $P$ is exerted all over the surface of the contact at the nominal radius, $r$. The magnitude of contact pressure, due to press-fitting assembly, can be calculated by summing the radial displacements of the inner and outer parts [7]. It was designated $r_i$ is the inside radius of the cylinder, $r_o$ is the outside radius, $P_i$ is the inner pressure and $P_o$ is the outer pressure. Where the subscripts $o$ and $i$ on Young’s modulus $E$ and Poisson’s ratio $\nu$ represent the inner and outer cylinder.

$$P = \frac{\delta}{r} \left[ \frac{1}{E_o} \left( \frac{r^2}{r^2 - r_i^2} + \nu_o \right) + \frac{1}{E_i} \left( \frac{r^2}{r^2 - r_o^2} - \nu_i \right) \right]$$

(5)

If the two members are the same material, $E_o = E_i = E$, $\nu_o = \nu_i$, equation (3) simplifies to

$$P = \frac{E \delta}{2r^3} \left[ \frac{(r_o^2 - r^2)(r^2 - r_i^2)}{(r_o^2 - r_i^2)} \right]$$

(6)

3. Finite Element Analysis

In this article, finite element analysis was employed to evaluate the stress distribution and deformation of the press-fit interference on the railway wheel and axle. The geometric model of the wheel and axle assembly is shown in figure 2. The S1002 wheel profile and hollow axle were used in the analysis. The inside diameter of the axle is 60 mm and the wheel hub diameter is 190 mm. The axle length is 2300 mm and the wheel and axle contact length is 185 mm.

The wheel and axle quarter model were established using the symmetric boundary condition to reduce the running simulation time. A linear elastic material behavior with Young’s modulus of 210 GPa and Poisson’s ratio of 0.3 [8] is defined for both wheel and axle material properties. A three dimensional (C3D8R) 8-node linear brick (hexahedral), reduced integration, hourglass control was used for the element type. The wheel and axle contact area have meshed with a refine meshed until the stress and contact pressure change lower than 1%. The total number of elements are 31,305 and 36,322, for the wheel and axle, respectively.

The contact surface interaction between the axle wheel seat and wheel hub was defined using a master-slave contact algorithm: the wheel hub surface was the master surface, and the axle wheel seat surface was the slave. A surface-to-surface interaction was defined with a finite sliding in the initial step. It is also required to be defined as an initial over-closure at the initial step. In the first step, the interference was resolved by automatic shrink-fit with a gradually removed slave node over closure during the step. A contact interaction property was defined as a penalty and the coefficient of friction was set to 0.6 to ensure tangential behavior. The sliding formulation was selected as “finite sliding” because the installation displacement was large. The flag indicating a non-linear geometry, Nlgeom, in the software, was set ON [9].

![Figure 2. The geometry of the wheel and axle assembly](image-url)
Figure 3 shows the boundary conditions of the symmetric finite element model: the symmetries of the wheel and axle assemblies used in the finite element analysis are: in the X-Y plane, \( U_z, \theta_x, \theta_y = 0 \). In the X-Z plane, \( U_y, \theta_x, \theta_z = 0 \) and at the right end of the axle YZ plane was constrained in the longitudinal direction, \( U_x, \theta_y, \theta_z = 0 \).

4. Results and Discussion
Several different interference clearances, ranging from 190 µm to 345 µm, obtained from Equations (1) and (2), were modeled and examined. The Equation (5) was used to determine the contact pressure distribution over the interface area. Analytical results and finite element analysis results were compared to determine whether the finite element analysis was acceptable and accurate. Table 1 shows the relative error in contact pressure for various interferences, between the finite element method and Lame’s theory. It also compares the maximum deformations of the wheel and axle between modeling and theory. The axle was compressed, and the wheel was expanded since the contact pressures were equal and opposite at the interface surfaces. When the interference continuously increases, the deformation of the wheel and axle get higher. The lowest relative error of maximum contact pressure was 1.64% with the same mesh size. The Von Mises stress distribution on press-fitted wheelset between FEM and the analytical methods can be compared in Figure 4. The Von Mises stress variation along the wheelset center radial axis from both results were similar and the values rapidly increased at the wheel hub inner surface and then gradually decreased towards the wheel rim outer surface. It can be noticed that FEM shows the maximum Von Mises stress at the wheel hub inner surface, but analytical results showed it at the axle hollow inner surface. Finite element and analytical results for the radial and tangential stress distribution along the central axis of the wheelset are shown in Figures 5 and 6. The radial stresses are zero at the inner surface of the hollow axle and outer surface of the wheel because they are unpressurized surfaces. The tangential stresses on the axle are maximum at the outer surface and minimum at the inner surface. However, maximum tangential stresses were at the inner surface and minimums were at the wheel outer surface. It can be seen the axial, radial, and tangential stress distribution of the wheelset in Figures 8 to 10.

Table 1. Contact pressure and maximum deformations along the radial direction for various interferences by finite element method (FEM) and Lame’s theory.

| Interference (µm) | Contact Pressure (MPa) | Relative Error % | Wheel Deformation (µm) | Shaft Deformation (µm) |
|------------------|------------------------|------------------|------------------------|------------------------|
|                  | Lame’s Theory | FEM            | Lame’s Theory | FEM            | Lame’s Theory | FEM            |
| 200              | 96          | 107            | 60.1         | 68.2            | -30.3         | -31.7          |
| 240              | 115         | 127            | 72.1         | 77.3            | -36           | -38.1          |
| 280              | 134         | 136            | 84.2         | 85.7            | -42           | -38.1          |
| 320              | 153         | 168            | 96.2         | 103             | -48           | -50.8          |
Figure 4. Von Mises stress along the centre of the wheelset radial axis.

Figure 5. Radial stress distribution along the centre of the wheelset radial axis.

Figure 6. Tangential stress distribution along the centre of the wheelset radial axis.

Figure 7. Von Mises stress distribution along the centre of the wheelset radial axis.

Figure 8. Axial stress distribution for wheel and axle assembly along the radial axis.

Figure 9. Radial stress distribution for wheel and axle assembly along the radial axis.
Figure 10. Tangential stress distribution for wheel and axle assembly along the radial axis.

Figure 11. Contact pressure at axle wheel seat.

Figure 12. Contact pressure distribution along the contact length vs interference clearance.

Figure 13. Von Mises stress distribution along the contact length vs interference clearance.

Figure 14. Axial stress distribution along the contact length vs interference clearance.

Figure 15. Radial stress distribution along the contact length vs interference clearance.

The variations of contact pressure along the axle wheel seat length vs interference are presented in Figure 12. By increasing the interference, the contact pressure was also increased with the same mesh size. Although the contact pressure, between the wheel and axle, was constant along the axle wheel seat length. Following Lame’s theory, the contact pressure obtained from the FEM varied along the contact length. The maximum contact interference pressure was in the middle of the axle wheel seat contact length for all interferences. This was explained by the assumption that, in Lame’s theory, the cylinder thickness was constant, but in the wheel model it was not. The Von Mises stress variation on the axle wheel seat is presented vs interference values in Figure 13. The axial, radial and Von Mises stresses
were significantly affected by interference clearances as set out in Figures 13 to 15. The results revealed that the maximum Von Mises stress occurred in the middle of the axle wheel seat contact area similar to the contact pressure.

5. Conclusion
This paper has discussed the reasons for the wheel and axle press-fitting assembly had a significant impact on the lifetime of the wheelset components. The stress distribution and deformation due to the press-fit interference effect were compared with the finite element method and Lame’s theory. The following conclusion can be drawn from this research:

The FEM model agree well with the theory to within 15% relative error, the maximum relative error of contact pressure is 11.08% and the minimum value is 1.64%, which means the results is considered acceptable. Therefore, Lame’s theory for a thick-walled cylinder was effective for the wheel and axle press-fitting analysis. However, the finite element method was more accurate and comprehensive than Lame’s theory. The comparing results show the results obtained from the FEM are greater than the analytical results because the wheel and axle are considered ideal cylinder surface for analytical calculation and the assembly parts had a complex geometry. These results confirmed that the critical stress occurred at the contacting surfaces of the wheel hub and the tangential stress was greatest among the three principal stresses.

Deformation during press-fitting along the radial axis was unfavorably affected and strongly depended on the contact pressure at the wheel and axle interface. One of the more significant findings to emerge from this study is that increasing amount of interference caused deformation to increase, smaller clearances benefit to press-fitted parts. Taken together, these results suggest that the press-fit effect should be accounted for a railway axle design.

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References
[1] Budynas R and Nisbett J K 2006 Shingley’s Mechanical Engineering Design 8th ed (New York: MC Graw Hill Eduaction)
[2] Sarabandi S Soleimani H and Mahmoudi H 2019 Sci. Iran 26(1) 367-374
[3] Naderi A 2018 Eng. Fail. Anal 94(7) 78-86
[4] Madia M Beretta B and Zerbst U 2008 Eng. Fract. Mech 75(8) 1906-1920
[5] Marhsall M B Lewis R Dwyer-Joyce R S Demilly F and Flament Y 2004 Proc. 14th International Wheelset Congress (Orlando, USA) 2(41) 17-21
[6] Zehsaz M and Shahriary P 2013 UPB Sci. Bull. Ser. D Mech. Eng 75(4) 71-84
[7] EN 13260:2009+A1:2010: Railway applications - Wheelsets and bogies - Wheelsets - Product requirements.
[8] Boresi R P 2013 Advanced Mechanics of Material 6 th Edition (USA: John Wiley & Sons, Inc)
[9] Yamamoto M and Ishiduka H 2017 Int. J. Fatigue 97 48-55
[10] Abaqus Analysis user’s manual vol I-IV.2010 (USA: Dassault Systèmes)