THREE-DIMENSIONAL FINITE ELEMENT SIMULATION OF RESIDUAL STRESSES IN UIC60 RAILS DURING THE QUENCHING PROCESS

by

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The aim of this paper is to develop means to predict accurately the residual stresses due to quenching process of an UIC60 rail. A 3-D non-linear stress analysis model has been applied to estimate stress fields of an UIC60 rail in the quenching process. A cooling mechanism with water spray is simulated applying the elastic-plastic finite element analysis for the rail. The 3-D finite element analysis results of the studies presented in this paper are needed to describe the initial conditions for analyses of how the service conditions may act to change the as-manufactured stress field.

Keywords: *residual stress, stress field, quenching process, thermal load*

Introduction

The residual stresses of railroad rails are influenced by the heat treatment during the manufacturing process. In recent decades, numerous studies have attempted to estimate the residual stresses. Masoudi Nejad [1] estimated the residual stresses resulted from heat treatment in the railway mono-block wheels by an elastic-plastic 3-D finite element model. The obtained results from this study have shown that the residual stresses' values obtained from the heat treatment are of significant values and their effect on the crack initiation and fatigue life can not be disregarded [2]. Masoudi Nejad *et al.* [3] presented a 3-D elastic-plastic finite element simulation for the estimation of residual stresses resulting from the manufacturing process and service condition in wheels of railroad in Iran railroad. Masoudi Nejad [4] investigated the stress distribution due to press fitting process of a bandage wheel and mechanical residual stresses due to wheel/rail operation. Finally, the effect of residual stresses on the fatigue life is assessed using the damage mechanics methods. Salehi *et al.* [5] presented the prediction of fatigue life and crack propagation in a bandage wheel due to the stress field caused by mechanical loads and press fitting process of a bandage wheel.

The object of several investigations on manufacturing processes is to show a layer of compressive residual stress on the surface of parts to inhibit propagation of cracks. The effects of the residual stress and metal removal on the contact fatigue life have been estimated by Seo *et al.* [6, 7]. Okagata *et al.* [8] evaluated the fatigue strength of Japanese railway wheel and presented the fatigue design method of the high-speed railway wheel by considering the effect of

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manufacturing conditions on the fatigue strength of the material. In the literature [9-15], some of these issues are studied using some experimental observations, analytical calculations and FEA calculations within various contexts.

Biempica *et al.* [16] provides a detailed study of the development of residual stresses in an UIC-60 rail and their reduction by means of roller straightening. Ringsberg and Lindback [17] carried out a 3-D analysis to determine the residual stresses that appear during cooling and straightening. Zhan and Wang [18] described an improved rail-head hardening technology with adopting new induction heating coil, new coolant and cooling devices and new cooling mechanism. The work of Skyttebol *et al.* [19] represents a complete description of the finite element technique application for prediction of residual stresses in a flash-butt welded rail.

Most of the previous described studies have estimated the residual stresses using numerical simulations and finite element method in the rail. Unfortunately, existing techniques for estimation of residual stresses of the rail problems are simple models. Finite element models of this nature generally need a fine mesh to obtain accurate results [20-22]. The simple model can not obtain accurate stress field results of rail under the influence of thermal loads. In this paper, a 3-D elastic-plastic finite element method, using the true geometry of an UIC60 rail, has been used to model and accurately predict the stress distribution due to the quenching process. The quenching process simulation consisted of two parts, a non-linear transient thermal analysis and a non-linear static structural analysis. The heat treatment process cools the head of the rail much faster than its web. The head of the rail is sprayed with water. The web of the rail has not been cooled as rapidly.

Finite element modeling and residual stress

Residual stresses can be induced during the manufacturing of a rail, typically to improve its performance. Those stresses can be modified by service loading, sometimes to such an extent that the benefits of the manufacturing stresses are completely negated. However, this process generates the higher tensile hoop stress that could contribute to appearance of the rail-head fatigue cracks. They reduce the fatigue strength and exacerbate the effect of cracks and material defects. The rail made of the UIC60 profiles that are currently utilized in railway system was selected. The rail UIC60 profile is shown in fig. 1. The rail length equals the length between the two sleepers and is equal to 600 mm. Due to symmetry of the rail, only one half of the distance is modeled. For the stress analysis in railway rail, the 3-D elastic-plastic finite element method is used. In fig. 2 is shown the elastic-plastic behavior at different temperatures

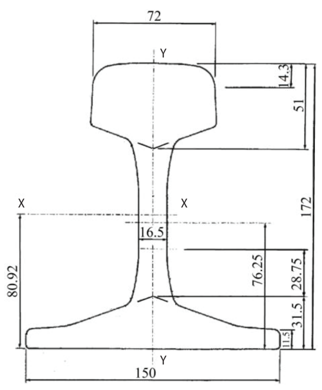


Figure 1. Rail profile, type UIC60 [mm]

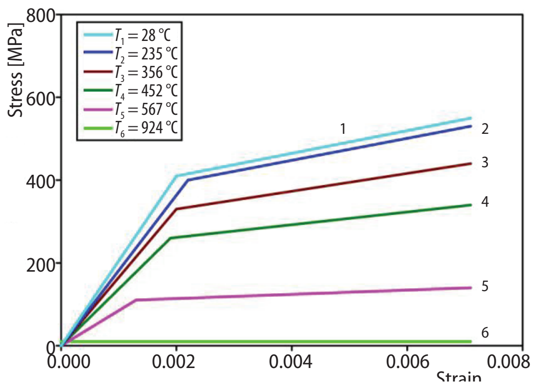


Figure 2. Mechanical material data for railway rail

using a bilinear isotropic hardening model. In this simulation for residual stress, the two parts of analysis used: the non-linear thermal analysis and the non-linear static structural analysis. The non-linear thermal analysis determined the temperature distribution of the rail that varies over time, was used as an input load for the non-linear static structural analysis. In finite element software, exists the possibility to use the thermal analysis of a model for structural solution. Figure 3 shows the finite element modeling of a rail in manufacturing process, for residual stress analysis. The model mesh has 16421 eight-nodded elements with three translational degrees of freedom at each node with quarter point node locations.

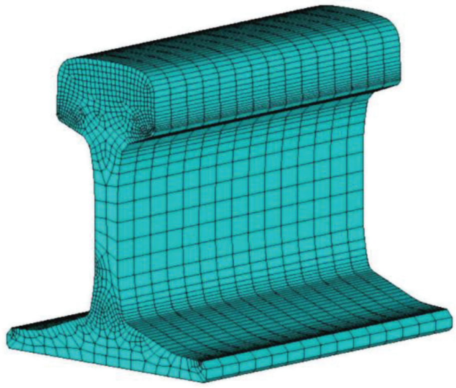


Figure 3. Finite element modeling of rail

The quenching process consists of several steps, each of which imposes different boundary conditions on the model. A schematic of the process is shown in fig. 4, which represents the ambient environment imposed on the rail head. The rail is assumed to be initially at a uniform temperature (921 °C). The quenching process consists of six nozzles; the upper surface of the rail has three nozzles, and each side of rail has a nozzle and the bottom has a nozzle. Conduction in the rail itself occurs during the quenching process. The input parameters included material properties, temperatures, time, and boundary conditions, which were thought to affect the residual stress field. The parameters required for the analysis of the heat transfer, included the thermal conductivity and specific heat. Thermal conductivity, k, the ability of the material to conduct heat energy, is described. This value variation with temperature is given as an input to the application. Since this was the heat transfer analysis, including the free expansion, so the specific heat at constant pressure of the material, c_p, is used. In this paper, the density is constant and equal to 7860 kg/m^3 were considered. The heat capacity variation with temperature has been defined as input for the software. The convection occurs from all the rail surfaces during the quenching process. The heat transfer coefficient for rail to air is 27 W/m^2°C and the heat transfer coefficient for the portion of the rail tread, which is exposed to the water spray during the quenching process, is 3042 W/m^2°C. Radiation from all surfaces of the rail is permitted during the heat transfer analysis. For this purpose, two parameters are used to determine the radiation heat transfer: the Stefan-Boltzmann constant, $\sigma = 5.67 \cdot 10^{-8}$ W/m^{2}K^4 and the surface emissivity, $\varepsilon = 0.96$.

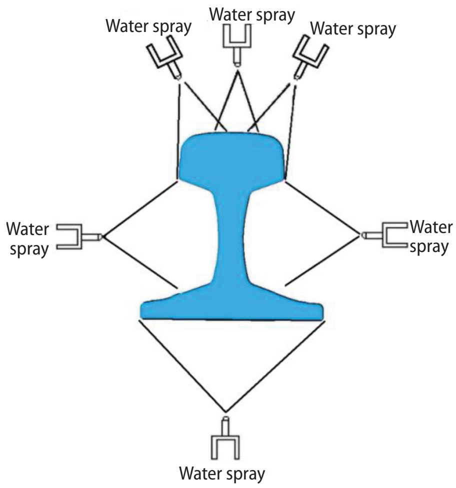


Figure 4. The schematic diagram of the cooling mechanism

One of the most important factors in residual stress forming is a type of constraint in the structure, which means that the two different displacement boundary condition show different residual stresses. In this analysis, two sides of the rail are bounded by using the displacement boundary condition.

Results and discussion

Figure 5. shows the temperature-time histories of three nodes in the model (on the head surface of the rail, the web of the rail and another at the foot of the rail), beginning at the initial temperature, 921 °C, through the quenching, and finally to room temperature at the end of the cooling down.

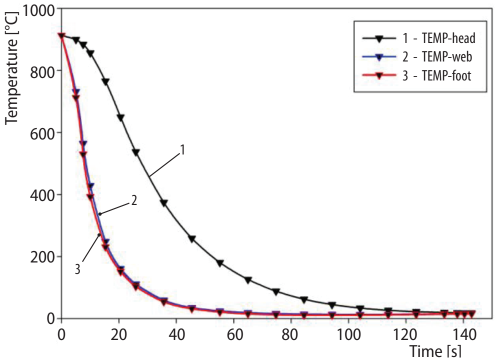
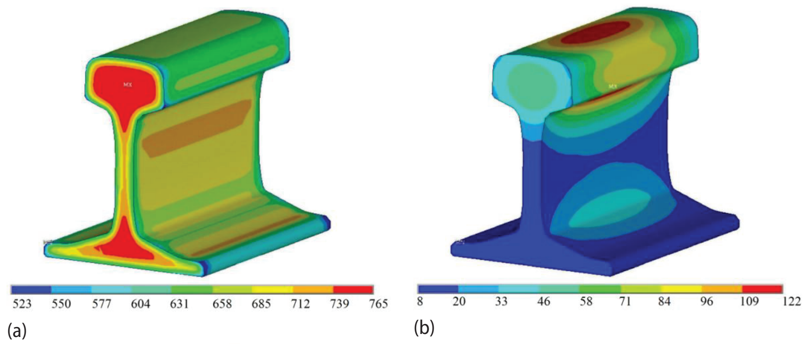


Figure 5. Baseline temperature-time history of three nodes during the quenching process

The non-linear transient thermal analysis yields the time-dependent temperature field, which causes the estimation of the residual stresses, since the temperature varies with location and time. As already mentioned in the analysis of air and water heat transfer coefficients are assumed constant. Figure 6 shows the temperature distribution due to the quenching process in the thermal model. According to fig. 6, the effects of water spray on the rail cooling are visible.



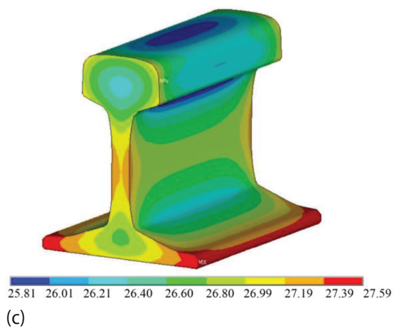


Figure 6. Contour plots of the temperature distribution [°C] due to the quenching process: (a) t = 5 s, (b) t = 75 s, (c) t = 150 s
(*for color image see journal web site*)

Figure 7 illustrates the contour plots of the stress field. For UIC60 rails, the magnitude of von Mises stress appears to be 639 MPa, after this process, and the tendency of von Mises stress is not symmetrical at the upper and the bottom side. The magnitude of this stress is higher than the yield strength of the steel rail, since the rail is plastically deforming. The residual tension at the rail-head surface, which tends to initiate cracks opening, will promote their growth through the tensile layer. Thus, this analysis shows that the fatigue cracks were initiated at a depth of 14 mm below rail-head surface.

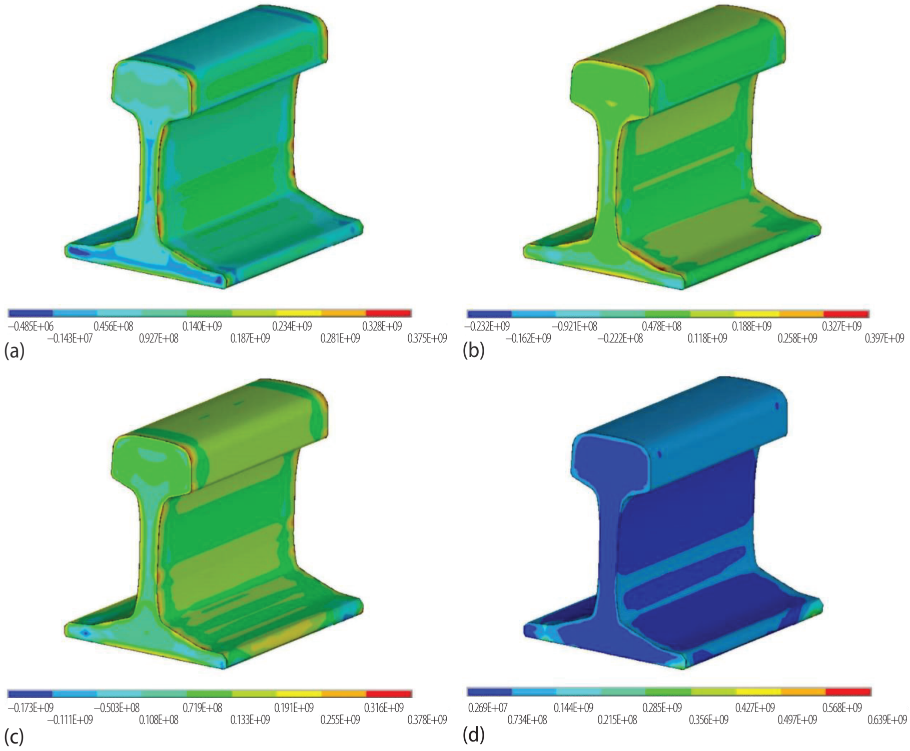


Figure 7. Stress field due to the quenching process of rail analysis; (a) x-direction, (b) y-direction, (c) z-direction, and (d) von Mises
(*for color image see journal web site*)

The variation of the stress distribution over the rail-head width, during the quenching process, as a result of the thermal gradient, is plotted in fig. 8. The vertical axis in fig. 8 denotes stress (MPa) and the horizontal axis is rail-head width (mm). The residual stresses of the rail height from finite element method approach are presented in fig. 9. The maximum axial stress, for a given probability, can be obtained from fig. 9. The maximum axial stress for the baseline model is 241 MPa.

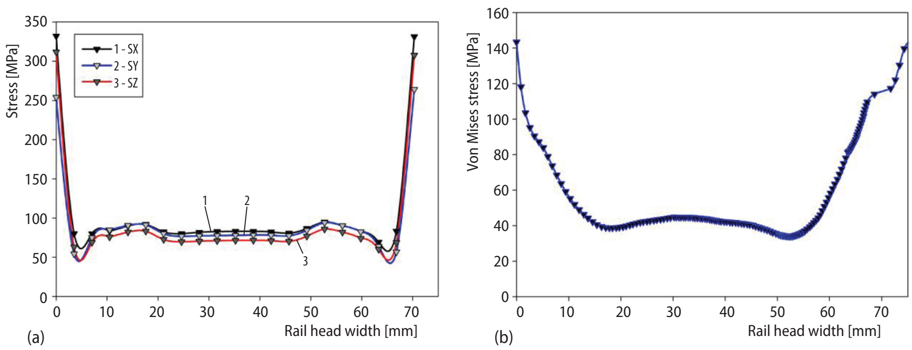


Figure 8. Stress distribution over the rail-head width during the quenching process; (a) the x-, y-, and z-direction, (b) von Mises

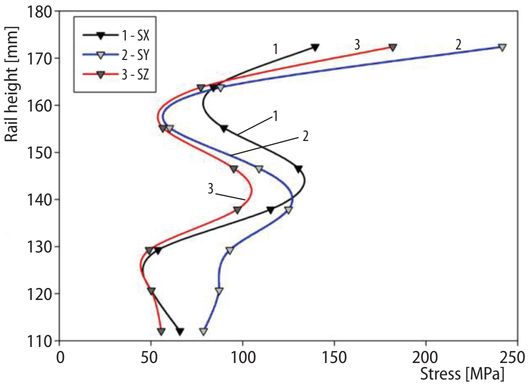


Figure 9. Stress in terms of the rail height

Conclusions

The 3-D finite element analysis for simulation of residual stresses in UIC60 rails is developed in this paper, which is based on the residual stresses from the quenching process. For this purpose, the non-linear 3-D finite element analysis is used for residual stress. The following conclusions can be drawn.

- The finite element analysis results show the very significant stress distribution. The resultant stress field has a high value and its effects are not negligible for the crack initiation.
- The results revealed that the stress field is highly sensitive to the variable thermal loads. Therefore, this factor significantly affects the stress field of rails during the quenching process.
- The results confirmed the magnitude of the stress in the rail since this has been identified as a reasonable means of assessing the possibility of fatigue cracks to initiate.
- The UIC60 rails are rail-quenched using a water spray to induce the beneficial residual compressive stress at the rail-head surface.
- Results of the baseline analysis suggest the presence of a 14 mm thick residual stress layer with stresses as high as 639 MPa in an UIC60 rail. Therefore, the residual stresses have a significant effect on the fatigue life.

In this paper, the residual stresses in the rail caused by the stress field from the quenching process of an UIC60 rail have been investigated. In the further future work, a quantitative comparison between detailed finite element analysis and experimentally measured strain and rail deformation will be presented. In addition, other effects, such as the process parameters, boundary conditions and material properties need to be included in the rail.

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