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Original research paper

DETERMINATION OF RESIDUAL STRESS IN THE RAIL WHEEL DURING QUENCHING PROCESS BY FEM SIMULATION

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Abstract. *Residual stresses of the rail wheels are influenced by heat treatment during the manufacturing process. The quenching process during the manufacturing results in the residual stresses within the rail wheel that may be dangerous for the rail wheel during its operation. Determination of the residual stress in the rail wheel is important for understanding the damage mechanisms and their influence on the proper work of rail wheels. This paper presents a method for determining the residual stresses in the rail wheel during the quenching process by using the directly coupled thermal-structural analysis in ANSYS software.*

Key Words: *Rail Wheel, Residual Stress, FEM, Thermal Load*

1. INTRODUCTION

Modeling and computer simulation get an increasing importance in research projects in the field of physics, engineering, biology, medicine, etc. In engineering many technical processes can be simulated using the finite element method (FEM). Miltenović et al. [1] presented a method for determining the friction generated heat in a contact between the wheel and the rail during normal operation using the transient structural-thermal analysis. One of the most important issues in railway wheels is the residual stress state. The residual stress, as unavoidable during manufacturing, is an important influence factor for the damage of wheels and rails; moreover, it can be assessed by the computer simulation.

The residual stress is defined as a tensile or compressive force within a material, such as steel, without application of thermal gradient or an external force. Residual stresses are the product of phase transformation, plastic deformation or thermal effects such as the process of contraction upon cooling. Newton's laws require that the compressive residual

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stresses at the surface of a material are balanced by tensile stresses within the material [2]. The residual stresses in rail wheels can be caused mechanically due to wheel/rail operation, or due to the press fitting process of a bandage wheel, as well as during the quenching process. The object of several research studies of manufacturing processes of railway wheels was to show a layer of the compressive residual stress on the surface of parts to inhibit crack propagation. The effects of the residual stress and metal removal on the contact fatigue life were estimated by Seo et al. [3, 4]. Furthermore, Okagata [5] evaluated the fatigue strength of a railway wheel produced in Japan and presented the fatigue design method of the high-speed railway wheel by considering the effect of manufacturing conditions on the fatigue strength of the material.

The residual stresses of the rail wheel are primarily caused by the heat treatment process. Wang [6] in his study showed the heat treatment process of a 36” (914 mm) freight car wheel manufactured by Griffin Wheel Company. He simulated the ideal and the non-ideal heat treatment processes and the effect on the residual stress after on-tread braking. For the analysis, he used the class U wheel with the carbon content varying from 0.67% to 0.77% as specified by the Association of American Railroads (AAR). Yu [7] performed a simulation of cooling after the rail heating process by using the finite element method (FEM). He obtained the result that the residual stress caused by water cooling was bigger than that of the air cooling process. Handa [8] researched the influence of the wheel/rail tangential traction force on thermal cracking of railway wheels. In the FEM analysis he used temperature - dependent material data of the wheel steel. He concluded that the residual stress was the main cause of the tread thermal cracking and the wheel/rail tangential force.

As Masoudi Nejad indicates in [9], most of the above mentioned authors estimated the residual stress by using numerical simulations and the finite element method in rail on simple models with coarse mesh which provided inaccurate/questionable results in the case of thermal loads. Therefore, he estimated the residual stresses which were obtained during the heat treatment process of the railway mono-block wheels, by using the elastic-plastic finite element model [9]. The analysis was performed by the sequential weak coupling of the thermal and structural field while neglecting dependence of the coefficient of thermal expansion on temperature and gravity effects. The noted author determined that the residual stress obtained during the heat treatment process had the significant value representing an important factor for the crack initiation and fatigue life [10]. The same author applied a similar approach [11] to accurately predict the residual stresses due to the quenching process of the UIC60 rail by using the FEM.

This paper presents a method for residual stresses determination in the rail wheel during the quenching process by using the directly coupled thermal-structural analysis. In addition to the method used for the analysis, the novelty of the presented research is that the thermal expansion coefficient changes with temperature, as well as gravitational forces, are taken into account. The analysis is also performed for the ER8 steel grade according to EN 13262:2009 [12], which is common on European railways.

2. RAIL WHEEL MANUFACTURING PROCESS

UIC CODE 510-2 contains the conditions relating to the design and maintenance of wheels and wheel sets for coaches and wagons used on international services. It covers wheel diameters from 330 to 1000 mm and indicates the permissible axle loads from the standpoint of stresses of the metal used for the wheel and the rail.

UIC CODE 510-2 contains detailed coordinates of the wheel rim line. It is valid for a nominal track gauge of 1435 mm and cannot be readily applied to other track gauges. Fig. 1 represents the wheel profile which is used for further analysis.

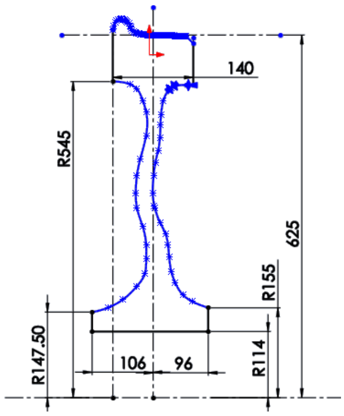


Fig. 1 Rail wheel profile (SolidWorks sketch)

The rail wheels are manufactured by casting (in some cases by forging). After this, they are heat treated to get a specific hardness and reheated to remove the undesired residual stress that remains in the wheels after casting/forging. The heat treatment of the rail wheels is the most important step in the manufacturing process since it gives them adequate mechanical properties. The material properties depend on the cooling rates in the different parts of the wheel. A goal of the heat treatment is to homogenize the microstructure of the rim in radial and circumferential direction. The heat temperature goes from 800 to 920^{o}C. After the homogenization, the rims are quenched with a water spray on the tread surface by using the water spray equipment shown in Fig. 2. The quenching process consists of several steps, each of which imposes different boundary conditions on the model.

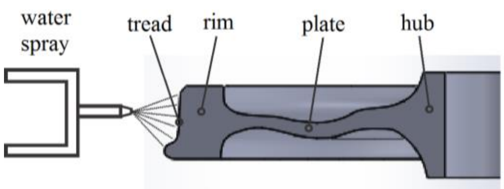


Fig. 2 Wheel quenching equipment

The quenching process of the rail wheel increases the steel strength, improves wear resistance and induces the desirable residual stress in the rim. The water spray quenches the hot rail wheel rim which cools and shrinks. Under the wheel rim, the steel that is still hot has the reduced yield strength due to high temperature. The cooling of the rim causes it to shrink compressing the plate of the wheel. In that case, the yielding occurs. After quenching the wheels are placed in a tempering furnace at approximately 500°C for two to five hours [2], which reduces the residual stress. During this phase, there is a tension between the cooler outer rim and the hotter underneath part of rim and the plate. At the end, the rail wheel is exposed to the ambient temperature. This heat treatment process results in the beneficial residual compressive stresses in the rail wheel rim. These stresses contribute to the prevention of the formation of rim fatigue cracks in railroad service.

The phases of the heat treatment are given in Table 1.

Table 1 Phases of heat treatment

Phase	Process	Duration	Film coefficient [W mm^{-2} C^{-1}]		Bulk temperature °C
			Tread	Other	
1	Pre-quench	2 min	2.837×10^{-5}	2.837×10^{-5}	Ambient temperature
2	Quench	4 min	0.001766	2.837×10^{-5}	Ambient temperature
3	Pre-reheat	2 min	2.837×10^{-5}	2.837×10^{-5}	Ambient temperature
4	Reheat	2 hr	2.837×10^{-5}	2.837×10^{-5}	510
5	Cooling	10 h	2.837×10^{-5}	2.837×10^{-5}	Ambient temperature

3. Simulation

For the heat treatment simulation, a direct coupled thermo-mechanical analysis was performed to estimate the residual stress, as a result of manufacturing, within the rail wheel with the wheel diameter 1250 mm. The analysis was carried out at the ambient temperature of 21.6°C for the wheel made of the steel with carbon content of 0.56% (steel grade ER8 – EN 13262:2009) [12]. The Young's modulus of the rail wheel material was considered as a temperature dependent parameter, as given in Table 2, with the Poisson ratio value of 0.3. The bilinear kinematic hardening model was used, which also included the mentioned temperature dependence for the Yield Strength and Tangent Modulus, as given in Table 3. The thermal material properties (Thermal Conductivity, Specific Heat and Thermal Expansion Coefficient) were also counted in terms of temperatures, as given in Tables 4 and 5.

The FEM model was made as a 2D axisymmetric model with 4894 nodes which form 1529 elements.

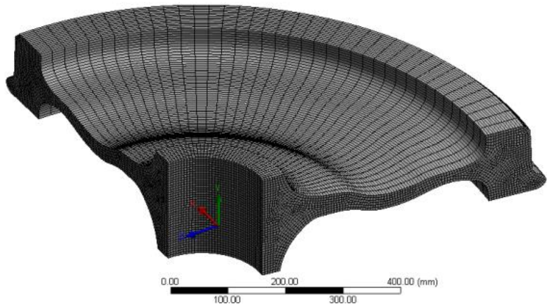


Fig. 3 Finite element mesh of rail wheel

Table 2 Mechanical material properties

Temperature °C	Young's Modulus (MPa)
25	2.06×10^5
100	2.02×10^5
200	1.96×10^5
300	1.88×10^5
400	1.8×10^5
500	1.7×10^5
600	1.6×10^5
700	1.49×10^5
870	42403

For the analysis the wheel rail was assumed to be initially at the uniform temperature of 920 °C. For the analysis phases, duration and boundary conditions (film coefficients and temperatures) were defined according to data given in Table 1. Thus, the heat transfer coefficient from the wheel to air was set to 28.37 W/m^{2}C, as well as for the other parts of the wheel, except for the phase when the tread was exposed to the water spray during the quenching process when the heat transfer coefficient was 1766 W/m^{2}C. It is necessary to mention that the convection occurred at all rail wheel surfaces during the analysis of the quenching process, while the radiation from all surfaces of the rail was omitted during the heat transfer analysis.

The analysis was conducted with the influence of gravity forces in the negative direction of y axis (Fig. 3).

Table 3 Yield Strength and Tangent Modulus - bilinear kinematic hardening

Temperature °C	Yield Strength (MPa)	Tangent Modulus (Pa)
22	663	20000
100	650	13300
300	543	13300
500	354	6250
600	185	2500
700	46	1200

Table 4 Thermal material properties – Thermal Conductivity and Specific Heat

Temperature °C	Thermal Conductivity (W/mK)	Specific Heat (J/kgC)
21.11	49.831	457.58
37.78	49.405	465.24
93.33	47.964	490.9
148.89	46.483	516.53
204.44	45.023	542.15
260	43.401	567.77
315.56	41.8	593.44
371.11	40.161	619.06
426.67	38.481	644.69
482.22	36.763	670.3
537.78	35.002	695.97
593.33	33.203	721.6
648.89	31.365	747.26
704.44	29.588	772.89
760	27.569	1853.6
815.56	25.203	635.31
871.11	25.913	643.47
926.67	26.624	651.64

Table 5 Thermal material properties – Coefficient of thermal expansion [3]

Temperature °C	Coefficient of thermal expansion K^{-1}	Temperature °C	Coefficient of thermal expansion K^{-1}
25	1.09×10^{-5}	400	$1,31 \times 10^{-5}$
100	1.09×10^{-5}	500	$1,38 \times 10^{-5}$
200	1.14×10^{-5}	600	$1,46 \times 10^{-5}$
300	1.24×10^{-5}	700	$1,51 \times 10^{-5}$

6. Results and Discussion

The results of the performed analysis of the heat treatment process of the rail wheel are discussed for the distribution of the temperature field as well as the residual stress.

6.1. Temperature

Fig. 4 shows the temperature-time history of the whole heat treatment process of the rail wheel with the maximal and minimal temperature at the beginning of the analysis and during the quenching, reheating and cooling processes.

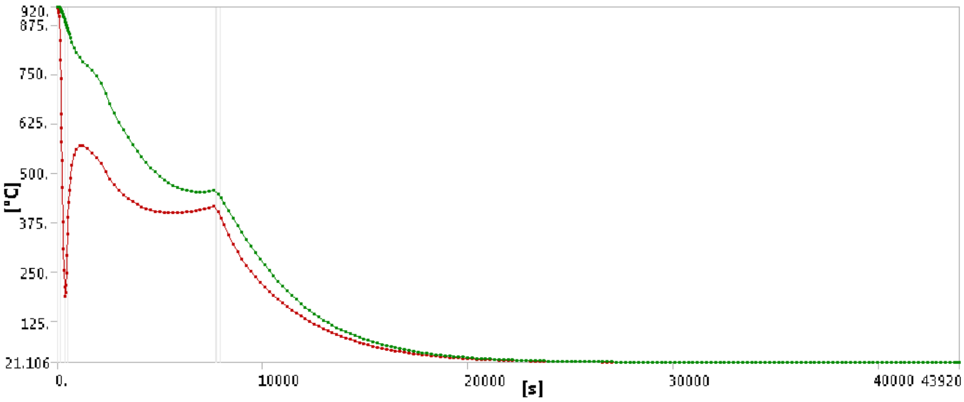
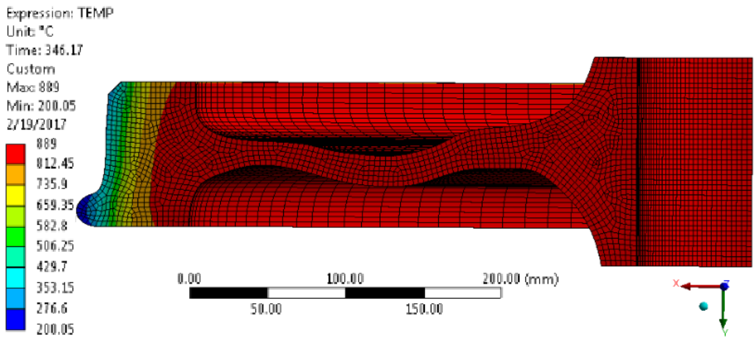
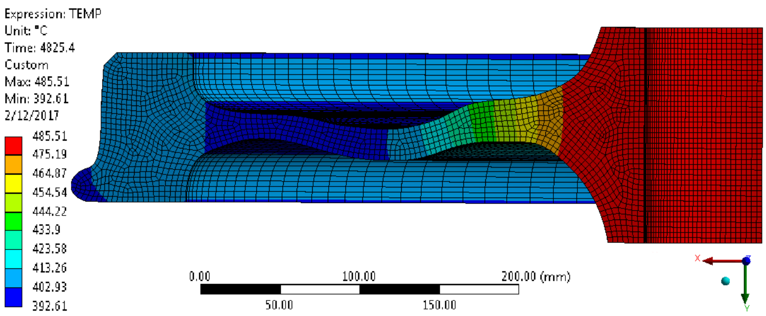


Fig. 4 Maximal and minimal temperature of rail wheel during heat treatment

It can be noticed from Fig. 4 that the minimal temperature during the quenching goes down to 200°C, during the reheating this temperature raises while the maximal temperature decreases all the time. During the cooling, the maximal and minimal temperatures slowly descend from the starting temperature of 920°C to the ambient temperature.



a) After 346.17 seconds - quenching



b) After 4825.4 seconds - reheating

Fig. 5 Temperature distribution of rail wheel during heat treatment

Fig. 5 shows the temperature distribution through the whole wheel at the beginning of the analysis and during the quenching, reheating and cooling process in the FEM model. It can be noticed that the temperature only on the thread decreases to the temperature of about 200^{o}C during the quenching (Fig. 5a), after which during the reheating (Fig. 5b) this temperature increases to around 400^{o}C, while during the cooling phase the temperature of the whole rail wheel slowly decreases to the ambient temperature.

6.2. Residual stress

The heat treatment involving a tread quenching process (Fig. 2), is used to resist cracking generation at and near the tread, so the contraction of the steel allows the formation of compressive residual stresses in the outer portion of the rim, as shown in Fig. 6. The stress is usually termed circumferential representing a predominant distribution of compressive stress around the rim circumference.

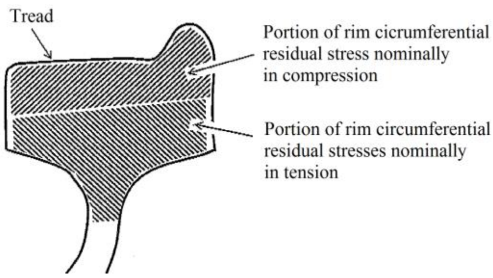


Fig. 6 Rim circumferential residual stresses after tread quenching process [12]

The normal stress-time histories of the whole heat treatment process of the rail wheel are shown for the maximal and minimal normal stress in the circumferential (Fig. 7) and axial (Fig. 8) direction at the beginning of the analysis and during the quenching, reheating and cooling process. On the diagrams, the compressive stress is indicated as negative, while the tensile stress is with positive values.

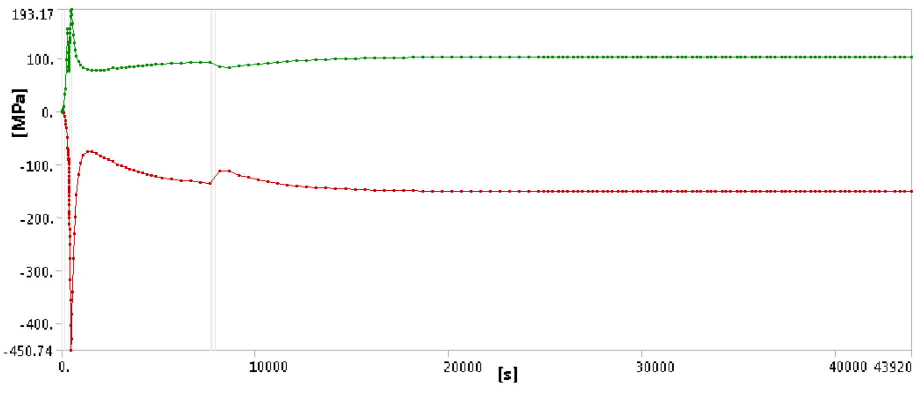


Fig. 7 Maximal compressive and tensile stresses of rail wheel in axial direction

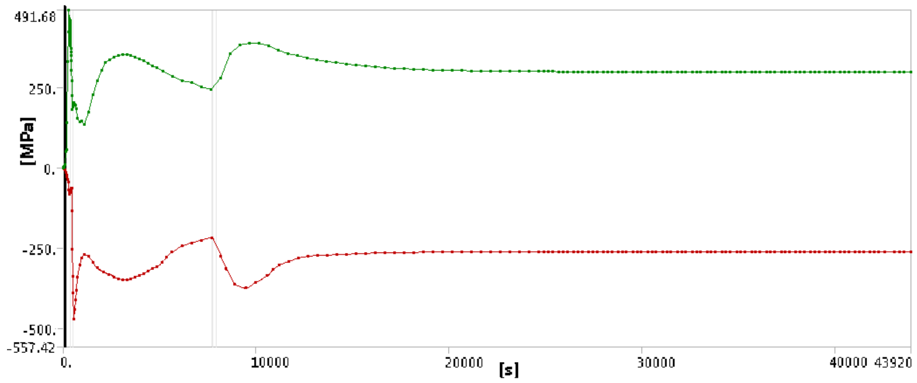


Fig. 8 Maximal compressive and tensile stresses of rail wheel in circumferential direction

Regarding maximal normal stress in the axial direction (Fig. 7), it can be noticed that both the compressive and tensile stresses increase to around -450 MPa and 200 MPa during the quenching, while during the reheating and cooling these stresses reach stable values of the maximal residual stresses of -150 MPa and 100 MPa. For the normal stress in the circumferential direction (Fig. 8) after some fluctuations of the stresses during the quenching, reheating and the beginning of the cooling stable values of the maximal residual stresses of around -280 MPa and 290 MPa are established at the ambient temperature.

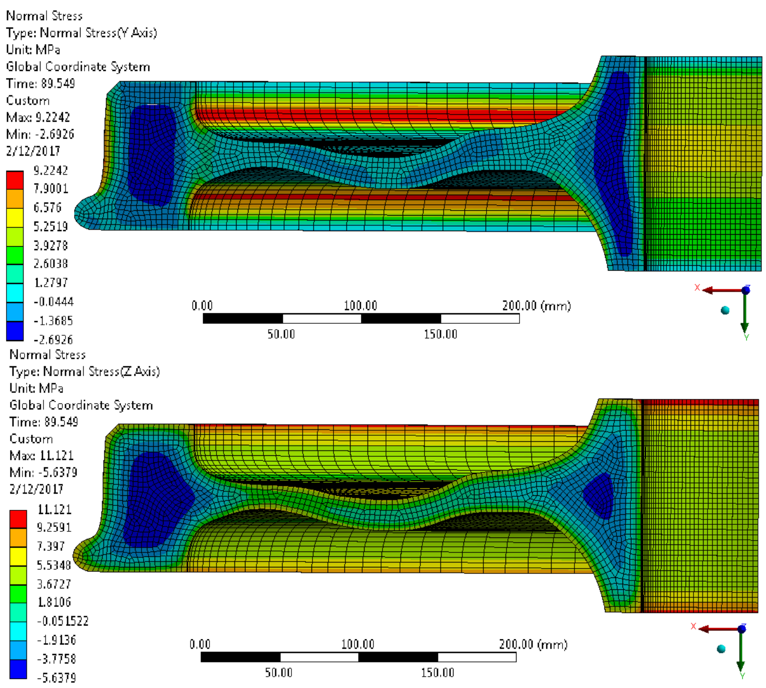


Fig. 9 Circumferential and axial stresses of rail wheel after 89.5 seconds – pre-quenching

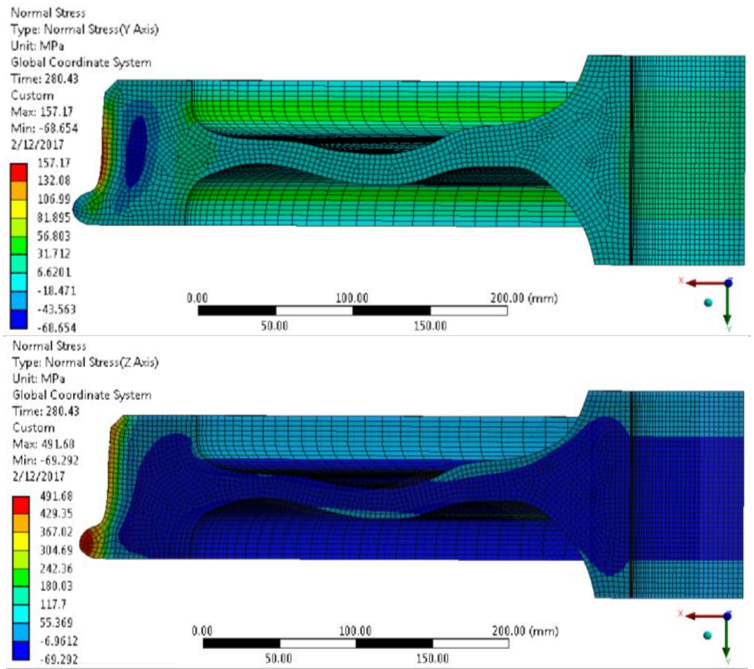


Fig. 10 Circumferential and axial stresses of rail wheel after 280.4 seconds - quenching

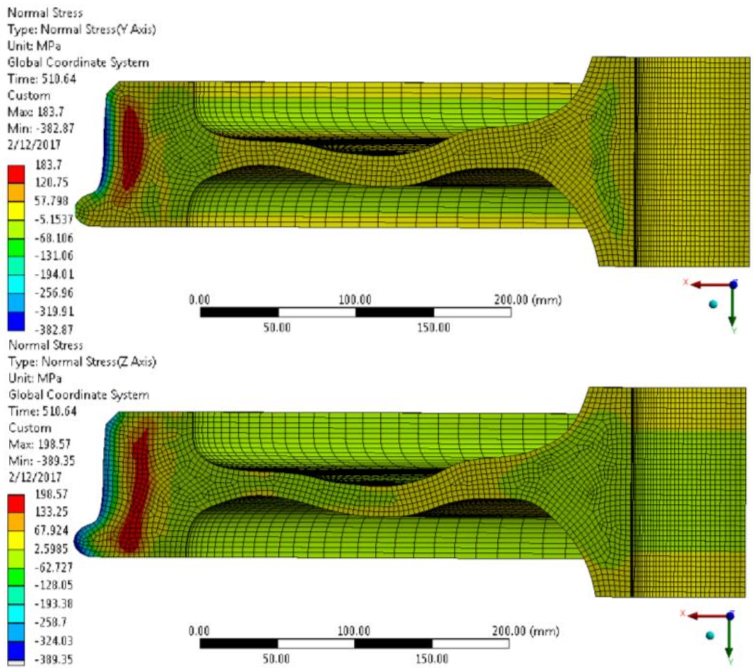


Fig. 11 Circumferential and axial stresses of rail wheel after 510.6 seconds - reheating

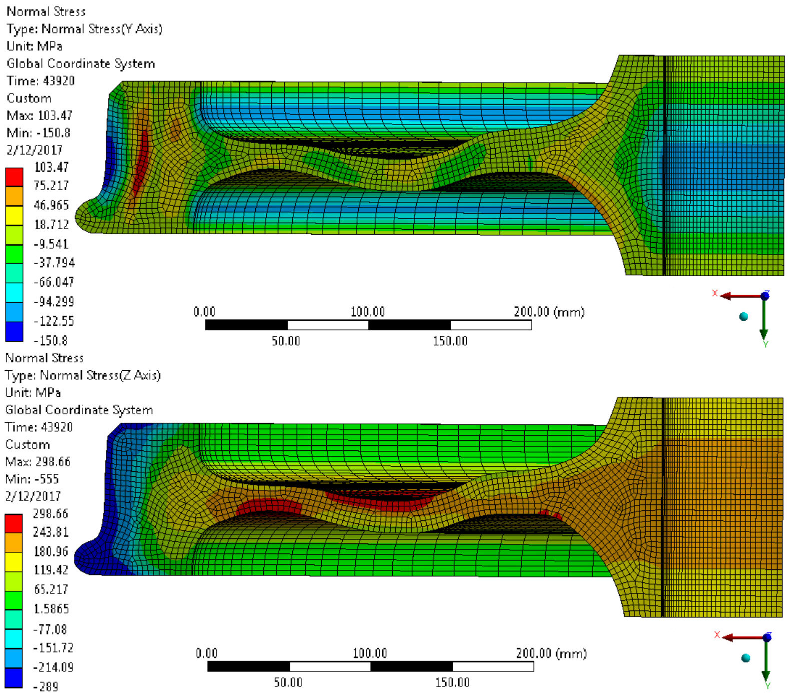


Fig. 12 Circumferential and axial stresses of rail wheel after 43920 seconds - cooling

The distribution of the normal stress in the circumferential and axial directions of the rail wheel during heat treatment is illustrated in Figs. 9 to 12, so that the results for the axial direction are indicated in the legend as Y Axis (the normal to the cross section), while for the circumferential direction as Z Axis. Fig. 9 shows the low values of thermal stresses at the beginning of the simulation. During the quenching (Fig. 10) the tensile stress grows very fast at the tread surface (157 MPa and 491 MPa) while the compressive stress prevails in the interior of the wheel (-68 MPa and -69MPa). In progress of the reheating, (Fig. 11), there is a change in the distribution area of compression and tension. The compressive stress appears at the tread surface (-382 MPa and -389 MPa), while the tensile stress is high in the middle of the rim (183 and 198MPa). For the cooling phase it is characteristic that the normal stresses reduce to the circumferential and axial residual stresses declining slightly over time (Fig. 12). Moreover, the tensile residual stress moves from the upper middle (Fig. 11) to the center middle of the rim (Fig. 12) which is consistent with the Fig. 6, while the compressive residual stress remains at the tread surface. From Fig. 12 it is seen that the axial residual stress nominally in tension in the middle of the rim reaches 103 MPa, while the axial residual stress nominally in compression at the tread surface is -150 MPa. The same figure indicates that the circumferential residual stress nominally in tension in the middle of the rim comes to between 65 and 119 MPa, while the circumferential residual stress nominally in compression at the tread surface amounts to -289 MPs. The maximal value of the circumferential residual tensile stress of 298 MPa is exposed at portions of the plate and the hub and it is not relevant. It is clear from Fig. 12 that there are the compressive region at/near the tread and the tension region below the compressive layer. Thus, it follows from Fig. 12 that the separated surface is initiated at the depth at approximately 40 mm below the tread surface of the rail wheel.

7. Conclusion

With modern computer simulation tools it is possible to simulate residual stress occurrence as an effect of the applied technological processes of production. The results of the implemented finite element analysis in the research of the rail wheels subjected to the heat treatment process show some very significant facts about stress distribution. The results reveal that the stress field is highly sensitive to variable thermal loads. Therefore, this factor significantly affects the stress field of the rail wheels during the heat treatment process and is taken into account for the determination of residual stress during the quenching process by using the directly coupled thermal-structural analysis. The results of the performed analysis are discussed for the distribution of the temperature field as well as the residual stress.

The results relating to the temperature distribution on the wheel tread indicate the temperature decrease during the quenching, the temperature increase during the reheating and finally slow cooling of the whole rail wheel to the ambient temperature.

The results relating to the stress distribution show the maximal and minimal normal stress in the circumferential and axial direction at the beginning of the analysis and during the quenching, reheating and cooling process. The normal stress is growing very fast during the quenching nominally in tension at the tread surface, while at the same time in compression in the interior of the wheel. Redistribution of the compression and tension happens during the reheating, so that the compressive stress deploys at the tread surface and the tensile stress in the middle of the rim. During the cooling, the normal stresses decline to the residual stresses over time. The region of the compressive residual stress remains at the tread surface while the region of the tensile residual stress moves further from the upper middle to the center middle of the rim.

The values of the circumferential and axial residual stresses, as well as the position of the surface separating the compressive region of the tensile one depend on the geometry, material properties and heat treatment process parameters that are for the analyzed railway mono-block wheel in a good agreement with those achieved in [9, 13] as confirmed by field measurements.

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