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Determination of Effect of Residual Stresses Induced in Railway Wheels using Finite Element Approach

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ABSTRACT

One of the most important issues in railway wheels is residual stresses. It is desirable to produce less residual stresses when possible and to decrease the remaining residual stresses in the wheels.

The objective of this work is to provide an estimation of the residual stresses in the rail wheel caused by the stress field from heat treatment process of a railway wheel. A three-dimensional nonlinear stress analysis model has been applied to estimate stress fields of the railway mono-block wheel in heat treatment process. After forging or casting, railway wheels are heat-treated to induce the desirable circumferential compressive residual stress in the upper rim.

Finite element analysis model is presented applying the elastic–plastic finite element analysis for the rail wheel under variable thermal loads. Calculative analysis applying a finite element method (FEM) has been used to predict residual stresses.

Keywords *- Residual stress, Heat transfer Coefficient, Fatigue, Finite Element Method, Quenching process.*

1. INTRODUCTION

Residual stresses are stresses that remain in a solid material after the original cause of the stresses has been removed. The wheel manufacturing process after forging and rolling, wheels are austenitized, the rims are quenched with water spray and wheels are subsequently tempered. Residual compressive stresses in wheel rims are introduced during the rim quenching operation. Rim quenching process (known as heat treating) results in beneficial circumferential (hoop) residual compressive stresses in the wheel rim.

These compressive stresses are useful to help prevent rim fatigue cracks in railroad service and are thus a significant safety benefit for the user. For residual compressive hoop stresses to result in the rim from the rim quenching operation, plastic (permanent) deformation must take place. When the water spray quenches the hot, austenitic wheel rim, the rim cools and shrinks inwards. The steel below the quenched region is still hot and has reduced yield strength at that temperature.

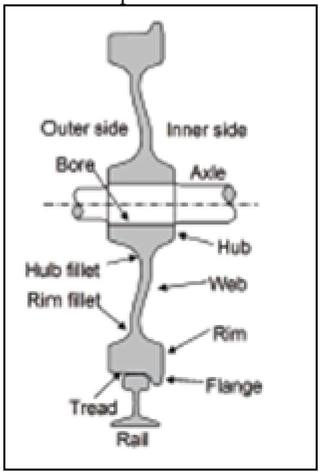


Fig 1: Cross Section and Description of a Wheel.

Fig 2: Railway Wheel Assembly.

The inner fibers of the rim and the plate are upset in compression by the colder, outer rim fibers and yielding occurs. This results in the lower part of the rim and the plate being in tension while the outer portion of the rim is in compression.

2. PROBLEM DESCRIPTION

The main objective of the project is as follows,

- To perform transient thermal to evaluate residual stresses induced in the railway wheel component.
- To find the sufficient Heat Transfer Coefficient Value to heating.
- To find the optimum heat input (temperature cycle).
- Also the study of effect of quenching rate on residual stress formulation in the railway wheel.

3. METHODOLOGY

- Generation of FE Model
- Assigning Materials and properties for the generated FE model.
- Application of Loads and Boundary conditions to the FE Model.
- Analysis of the FE Model with Loads and BCs using ANSYS Workbench V15.0 software.
- Performing transient thermal analysis to evaluate temperature distribution in railway wheel component.
- Performing structural analysis to evaluate residual stress distribution in railway wheel component.
- Comparing the analytical result with the theoretical result.

1. GEOMETRIC AND FE MODELING

3.1 Geometry

- FE Model of railway component has been done using ANSYS Workbench V15.0 software.
- The railway structure is consists of outer ring, hub, rim and flange.

The 3D solid is used for FE modeling of railway wheel.

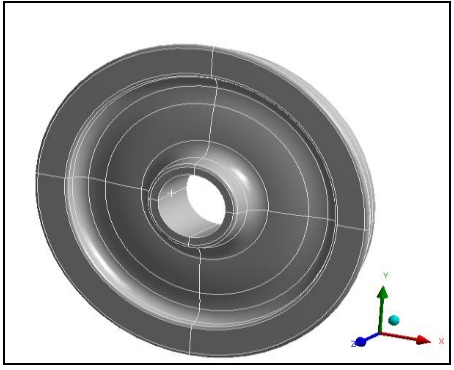


Fig 3: Geometric model Railway Wheel.

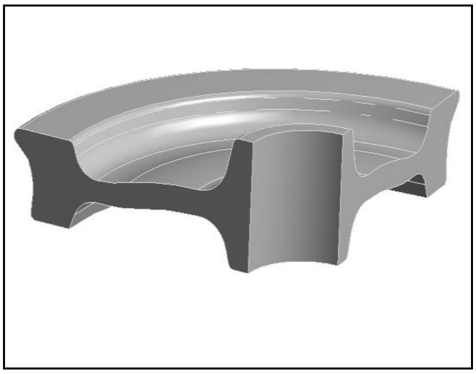


Fig 4: Section View of railway wheel.

3.2 Finite Element Modeling

In meshing of the railway component, SOLID70 element is used for thermal analysis with a global element size of 10mm with capturing all features. The FE model is shown in fig 5 and 6.

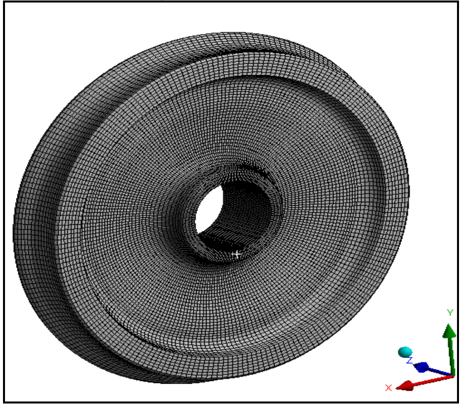


Fig 5: Railway Wheel FE Model.

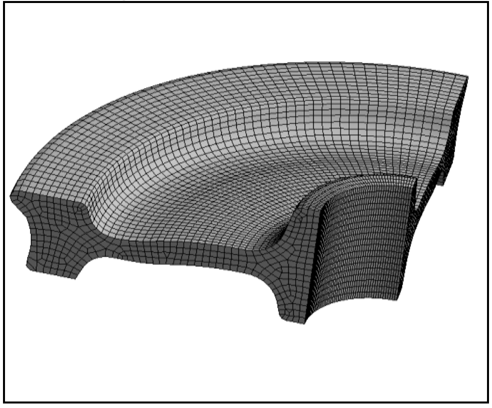
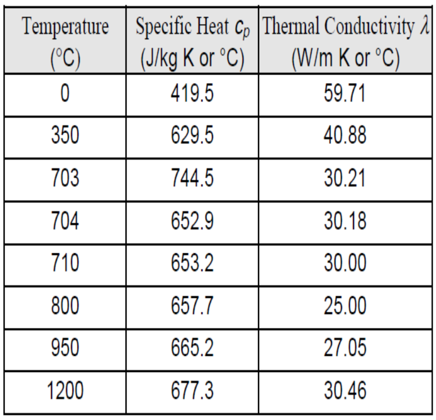


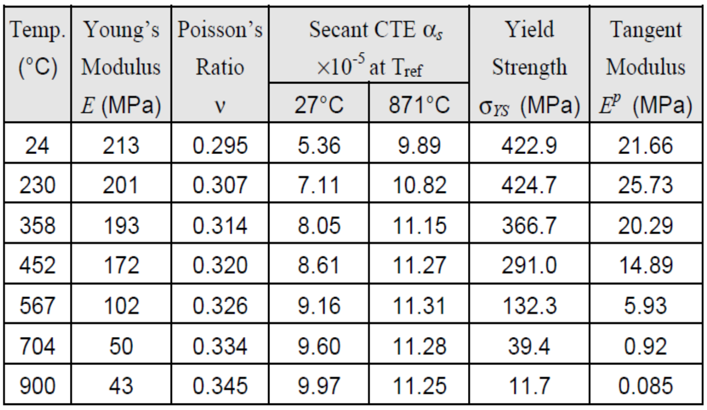
Fig 6: Section View.

3.3 Material Properties

The railway wheel is made of steel EN 13262 grade material. The thermal properties are listed in below tables 4.1.



Temperature (°C)	Specific Heat c_p (J/kg K or °C)	Thermal Conductivity λ (W/m K or °C)
0	419.5	59.71
350	629.5	40.88
703	744.5	30.21
704	652.9	30.18
710	653.2	30.00
800	657.7	25.00
950	665.2	27.05
1200	677.3	30.46



Temp. (°C)	Young's Modulus E (MPa)	Poisson's Ratio ν	Secant CTE α_s $\times10^{-5}$ at T_{ref}		Yield Strength σ_{YS} (MPa)	Tangent Modulus E^P (MPa)
			27°C	871°C		
24	213	0.295	5.36	9.89	422.9	21.66
230	201	0.307	7.11	10.82	424.7	25.73
358	193	0.314	8.05	11.15	366.7	20.29
452	172	0.320	8.61	11.27	291.0	14.89
567	102	0.326	9.16	11.31	132.3	5.93
704	50	0.334	9.60	11.28	39.4	0.92
900	43	0.345	9.97	11.25	11.7	0.085

Table 1: Material Properties for Thermal Analysis and Structural Analysis.

3.4 Load and Boundary Conditions

3.4.1 Thermal Analysis

The wheels are manufactured by forging technique. After forging they are cooled down to room temperature through different cooling techniques, we use water quenching technique. At the end of forging process, the wheel body will be around 920^{0}C, later they are cooled down to room temperature through quenching process. The analysis is carried out for 4 different cooling rates.

1. With heat transfer coefficient of 3042 W/m^{2}k.
2. With heat transfer coefficient of 2300 W/m^{2}k.
3. With heat transfer coefficient of 1100 W/m^{2}k.
4. With heat transfer coefficient of 200 W/m^{2}k.

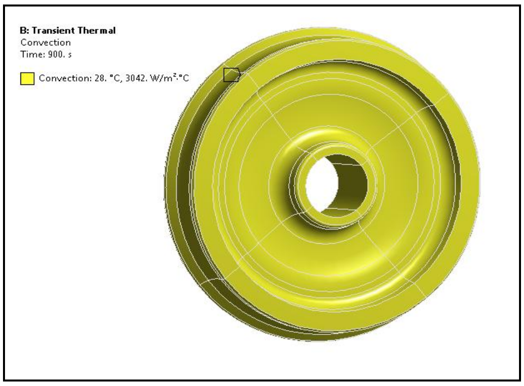


Fig 7: Convective Heat Transfer Coefficient Definition.

3.4.2 Structural Analysis

The structural evaluation is accomplished to evaluate the residual stresses induced on the wheel due to distinct quenching rates. Sequential thermo mechanical evaluation is done to assess the thermal distortion and residual stresses present in the railway wheel. The atmospheric air pressure of 1.013 bars is applied at convective wheel surface. The schematic illustration of Sequential coupled evaluation in ANSYS as seen in fig 7.

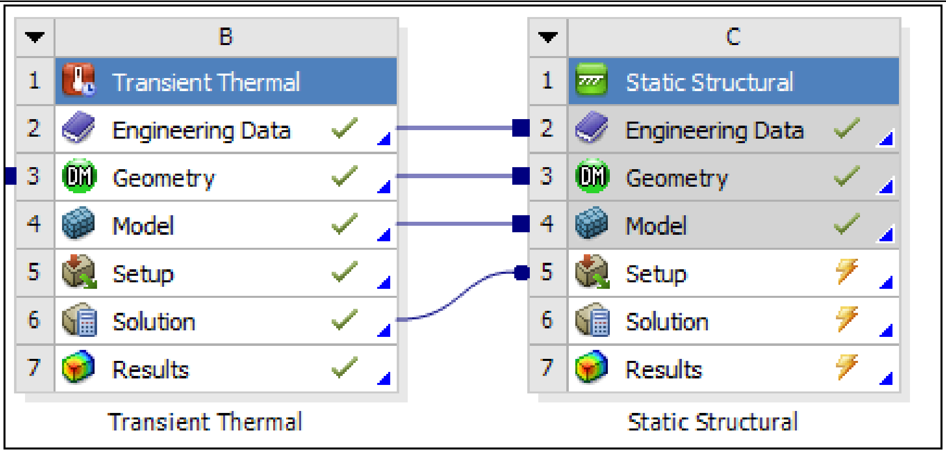


Fig 8: ANSYS Simulation Schematic Window - Sequential Coupled Field Analysis.

Static structural evaluation for the bottom wheel hub face of the railway wheel is constrained for Uz DOF as shown in fig 9**.**

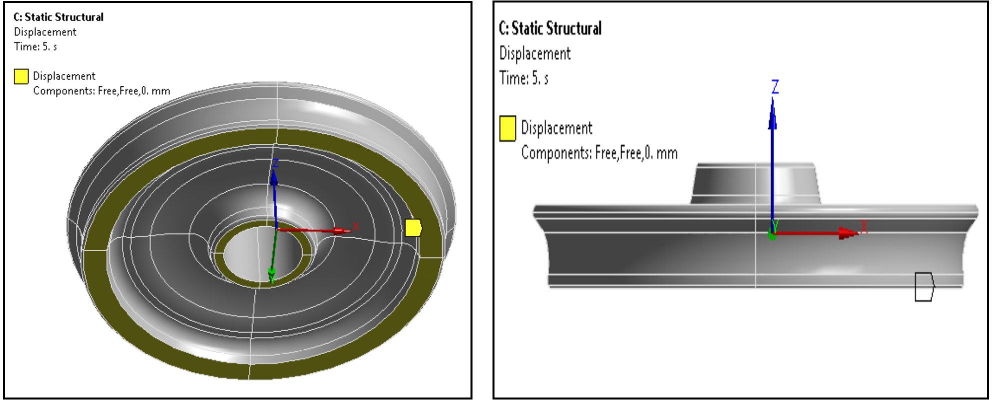


Fig 9: Boundary Condition for Transient Thermal Analysis.

2. RESULT AND DISCUSSIONS

5.1 Results

5.1.1 *Case1:* Thermal Analysis with 3042 w/m^{2}k Heat Transfer Coefficient.

5.1.1.1 Thermal Analysis

A.The forced convection (quenching) is used for the cooling of railway wheel with HTC value of 3042 W/m^{2}k. The initial temperature of wheel is considered as 920^{0}C. The transient thermal evaluation is carried out until it reaches room temperature i.e. 28^{0}C time period ~700Sec. The temperature distribution on the railway wheels in the course of cooling period is shown in fig 10 to 11.

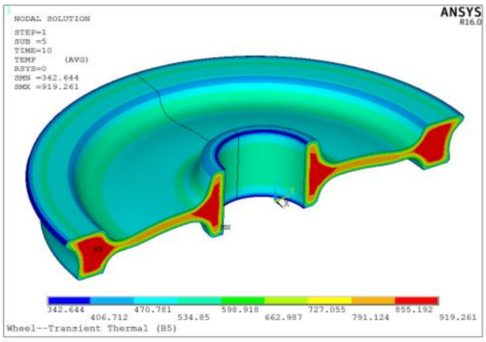


Fig 10: Temperature Distribution at 10Sec.

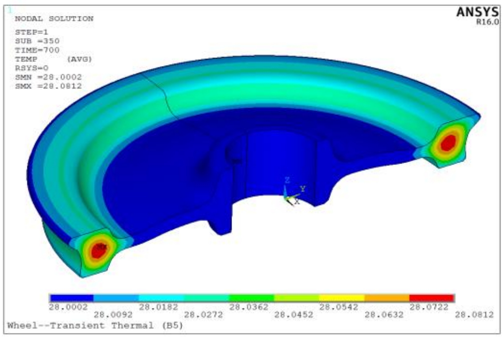


Fig 11: Temperature Distribution at 700Sec

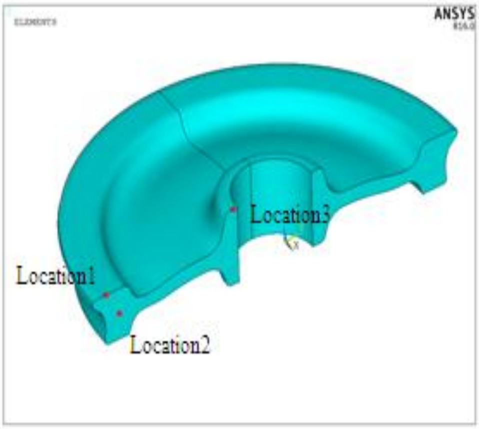


Fig 12: locations on the Rail Component

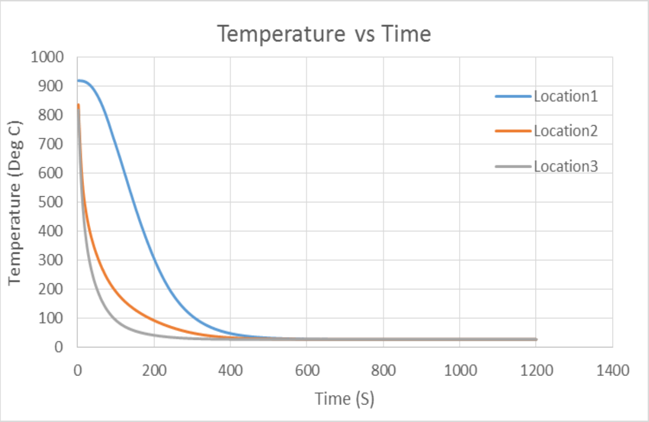


Fig 13: Temperature vs. Time.

The variation of temperature against cooling time is seen in fig 13. The maximum temperature 920^0C is seen at initial time. After ~700sec of cooling duration, the railway wheel temperature reaches to room temperature (28^0C) as proven. During initial cooling period, the core remains at high temperature and external surfaces of the wheels are cooled down quickly due to high quenching rates. This temperature difference causes increase in residual stress formation in the wheel structure. The wheel took approximately 700sec to reach room temperature of 28^0C.

5.1.1.2 Structural Analysis

The thermal distortion and residual stresses are common problems associated in heat treatment process. Due to uneven heating and cooling method results in thermal distortion and residual stress are induced in the structure. Sequential thermo mechanical evaluation is performed to evaluate the thermal distortion and residual stresses induced in the structural. The result from the thermal evaluation i.e. temperature data is mapped to structural analysis to consider the effect of temperature variation inside the wheel shape and atmospheric air pressure of 1.013bar is carried out to the wheel surface.

The residual stress caused inside the wheel during cooling process is shown in Fig 14. The maximum von-Mises stress within the wheel shape is 472MPa at 50sec and determined at wheel periphery.

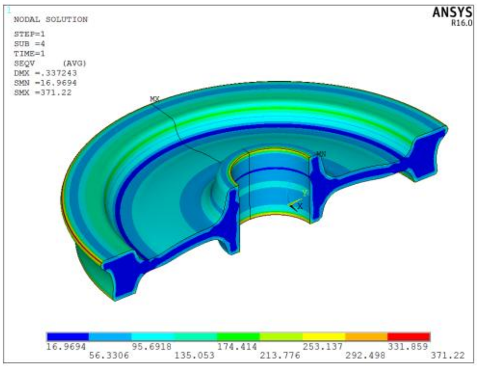
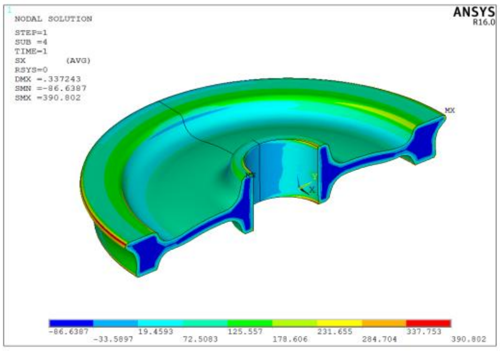


Fig 14: Von-Mises Stress at 10sec.

The tensile and compressive stress generated in the wheel structure all through cooling manner is shown in fig 15 and fig 16. The maximum tensile stress in the pipe structure is 496MPa at 50sec and maximum compressive stress is 597MPa at 10sec during cooling time. The tensile stress after cooling time is 51MPa.



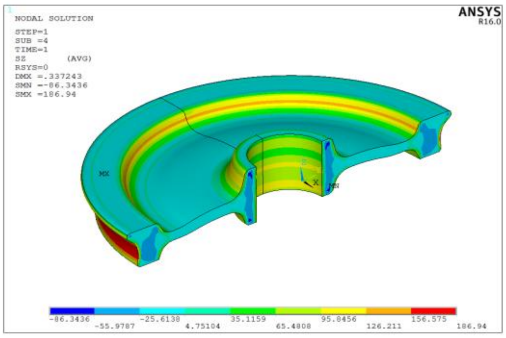


Fig 15: Normal Stress “X” at 10sec. Fig 16: Normal Stress “Z” at 10Sec.

The thermal distortion or deformation inside the wheel structure at some point of cooling manner is shown in fig 17. The most deformation inside the structure is 5.4 mm at 50sec. The displacement after cooling is 3.51mm.

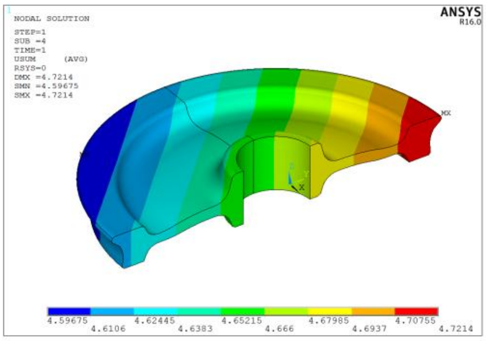
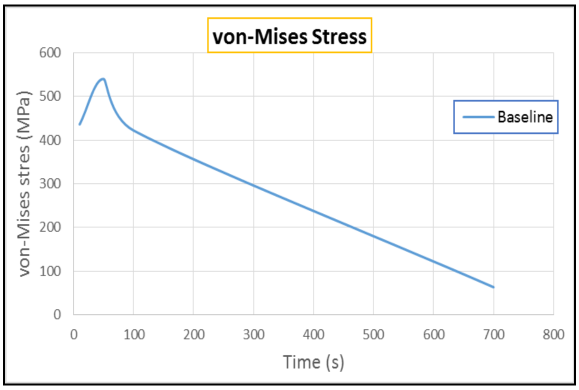


Fig 17: Displacement Plot at 10Sec.

The induced von-Mises stress and displacement in the wheel structure is listed in table 2.

Time (S)	Von-Mises Stress (MPa)	Displacement (mm)	Normal Stress X Direction, (MPa)	Normal Stress Z Direction, (MPa)
10	436	8.04	496	273
50	540	9.38	381	597
100	422	4.38	231	452
700	63	3.51	51	50

Table 2: Displacement and Von-Mises Stress.



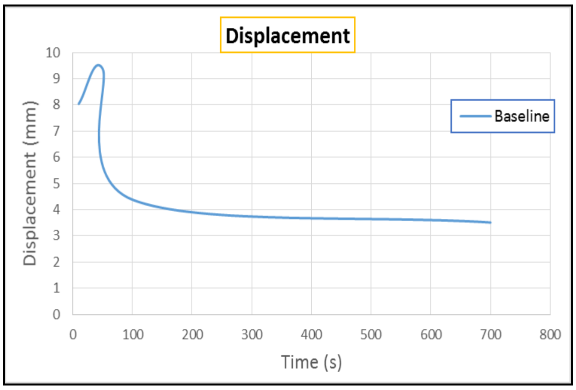


Fig 18: Von-Mises stress vs Time. Fig 19: Thermal distortion vs Time.

The variation of von-Mises stress and displacement with respect to cooling time is shown in Fig 18 and 19. The maximum von-Mises stress is 540MPa at 50sec and maximum displacement is 9.38mm at 50sec. The maximum stress is observed due to high temperature gradient exist in the model at time 50sec.

5.2 Discussions

5.2.1 Thermal Analysis

The comparison of temperature distribution in the wheel structure at different locations between 4 different iterations is shown in Fig 20 and 21.

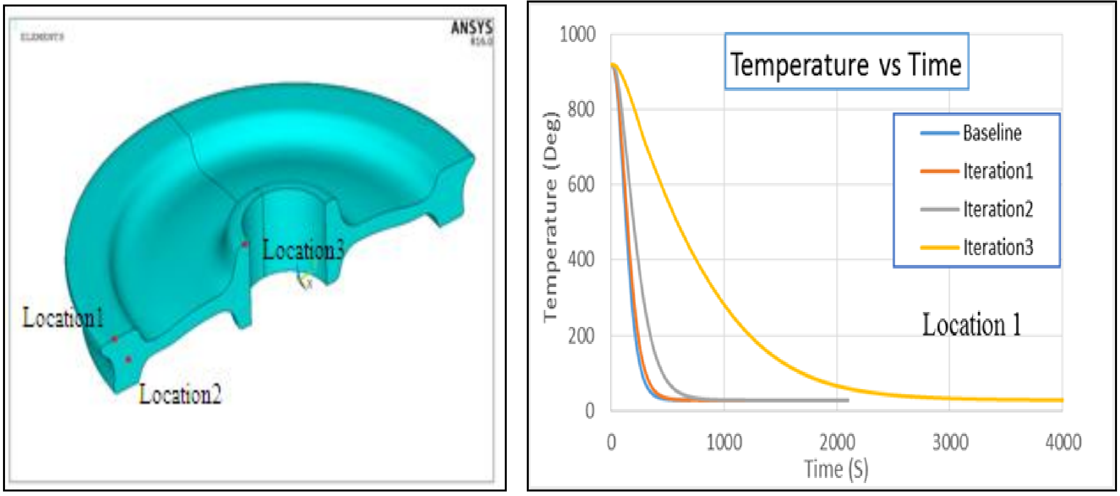


Fig 20: Comparison Temperature vs. Time.

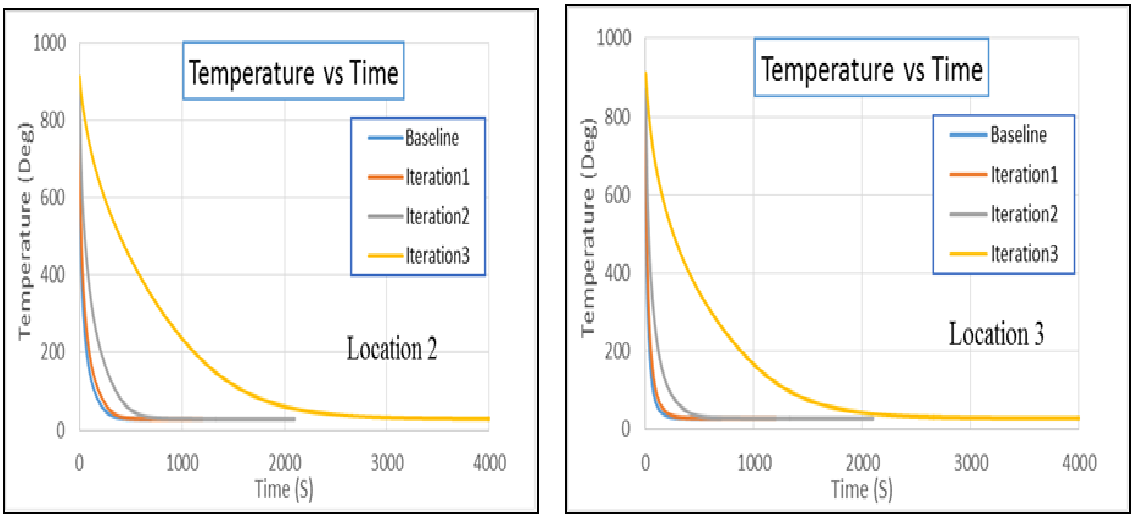


Fig 21: Comparison Temperature vs. Time.

From the graph it is observed that, for base line the railway wheel attains room temperature of 28^0C at 650Sec for HTC value of 3042 w/m^2c and for Iteration1 attains room temperature of 28^0C at 900Sec for HTC value of 2300 w/m^2 ^{0}C. And for Iteration 2 the railway wheel reaches room temperature at 1350Sec for HTC value of 1100 W/m^2 ^{0}C. For Iteration 4 wheel attains room temperature at 5200Sec for HTC value of 200 W/m^2 ^{0}C.

From the results, it is clear that HTC values are playing important role in heat transfer. The heat transfer rate is more for higher HTC values. For higher HTC values, the temperature gradient is more, results in higher residual stresses in the model. The cooling technique is managed by means of varying the cooling medium, the cooling flow rates or the interacting time of the medium with the wheel surface.

5.2.2 Structural Analysis

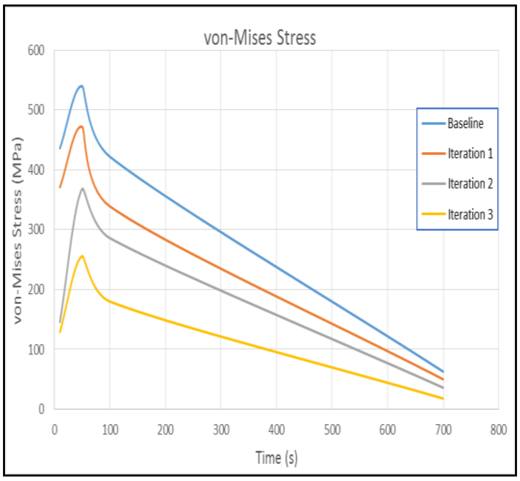


Fig 22: Von-Mises Stress v/s Iteration.

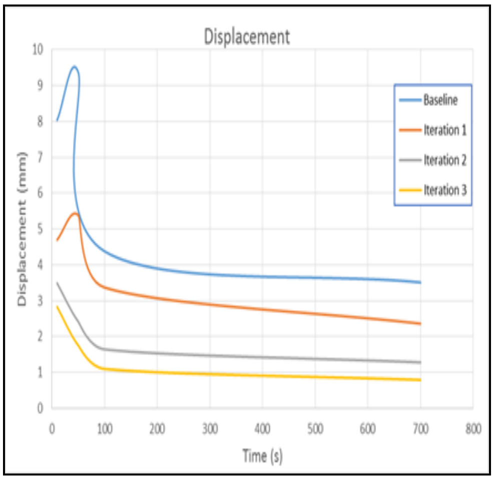


Fig 23: Displacement v/s Iteration.

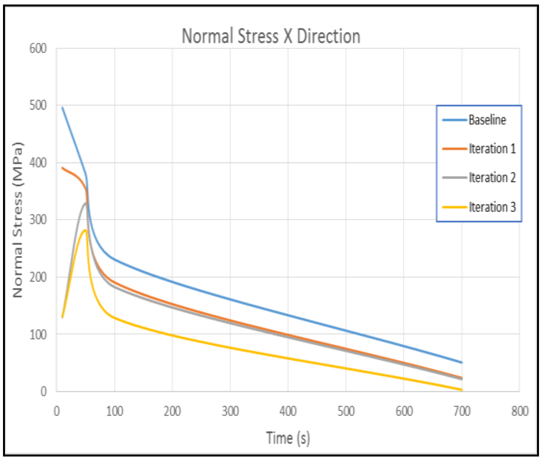


Fig 24: Normal Stress "X" v/s Iteration.

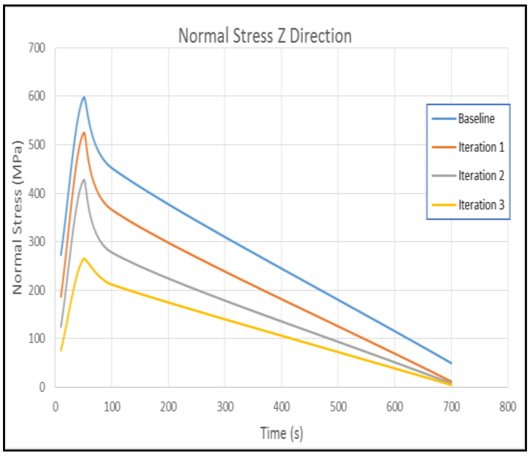


Fig 25: Normal Stress "Z" v/s Iteration.

3. CONCLUSION

From the FEA analysis we can draw the fallowing conclusions.

It is clear that HTC values are playing important role in heat transfer. The heat transfer rate is more for higher HTC values.

For higher HTC values, the temperature gradient is more, results in higher residual stresses in the model.

The cooling technique is managed by means of varying the cooling medium, the cooling flow rates or the interacting times of the medium with the wheel surface.

The managed cooling technique of the wheels is the most important heat treatment process. It especially defines microstructure and mechanical properties and consequently the quality of the product as seen in below image.

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