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Thermal Stress Analysis of Rail Wheel

Keerthan Prabhu[1], M S Aditya[2], Ramesh C G[3]

[1]*Student, Department of Mechanical Engineering, Sir MVIT*
[2]*Student, Department of Mechanical Engineering, Sir MVIT*
[3]*Professor, Department of Mechanical Engineering, Sir MVIT, Bengaluru, Karnataka, India*

Abstract - *Nucleation and growth of fatigue cracks occur in railway wheel stems from different factors such as wheel-rail rolling contact, thermal loads between wheel-rail and wheel brake block induced in braking process. Also, increasing speed and axle loads of wheels aggravates these factors. These cracks will reduce wheel life and even in severe cases it may leads to derailment of rail. Thermal stresses are usually generated when the brakes are applied, that is the brake pads are pressed against the brake disc. Consequently, this compel mechanical and thermal analysis of wheels and the prediction of crack behavior under thermo-mechanical loads. The solid modeling of rail wheel has been carried out using CATIA and the meshing was performed with HYPERMESH. Thermal analysis was carried out to analyze whether the wheel has sufficient strength to sustain the thermal loads, generated due to application of brake, using Optistruct solver. It has been observed that maximum stress of 236.5 MPa induced in the rail wheel and it is within the permissible limit of 355 MPa.*

Key Words: Wheel, Friction, Disc Brake, Failure, residual stresses, Thermal Crack

1. INTRODUCTION

Rail transport commenced in mid-16th century in Germany in the form of horse-powered funiculars and wagon ways. Modern rail transport commenced with the British development of the steam locomotives in the early 19th century. Railways are a safe land transport system when compared to other forms of transport. Railway transport is capable of high levels of passenger and cargo utilization and energy efficient.

Brake System-Disc brakes consist of a brake rotor which is attached directly to the wheel. Hydraulic pressure from the master cylinder causes a caliper (which holds the brake pads just outside the rotor) to squeeze the brake pads on either side of the rotor. The friction between the pads and the rotor causes the vehicle to slow and stop. Disc brakes have limited self-energizing action making it necessary to apply greater hydraulic pressure to obtain sufficient braking force. This is accomplished by increasing the size of the caliper piston.

Disc brakes are exposed to large stresses during routine and hard braking. Disc brakes generate an opposing braking torque there by converting kinetic energy to heat. High decelerations, typical of passenger vehicles are known to generate stresses of higher magnitude. When hydraulic pressure is applied to the caliper piston, it forces the inside pad to contact the disc. As pressure increases the caliper moves to the right and causes the outside pad to contact the disc. Braking force is generated by friction between the disc pads as they are squeezed against the disc rotor. When the disk temperature is increased by friction heat during braking, the heat often causes dimensional instability of the disk, permanently modifying the runout or disk thickness variation of a disk. Since disc brakes do not use friction between the lining and rotor to increase the braking power as drum brakes, they are less likely to cause a pull. The friction surface is constantly exposed to the air, ensuring good heat dissipation, minimizing brake fade. It also allows for self- cleaning as dust and water are thrown off, reducing friction differences.

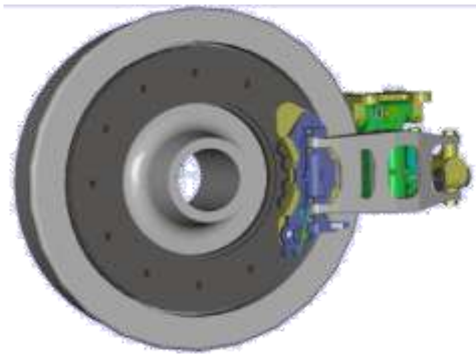

Fig-1: Disc Brake

2. LITERATURE REVIEW

This section of the paper reviews the previous studies, which are assisting to introduce the current study. Some of them are direct and the others are indirectly related to the current study. However, it is useful to develop the recent idea.

Keysor [1] identified the fact that stress cracks in the plate portion of the wheel were initiated primarily by repeated braking applications, which develops large heat concentrations at the wheel-brake interface. This elevated temperature condition in the wheel rim induces expansion in the radial direction, resulting in highly concentrated stress patterns in the plate portion of the wheel, which may result in wheel failure.

Greenfield et al. [2] acknowledged that the efforts to minimize the effects of mechanical and thermal stresses induced to braking, includes increasing the surface area for better heat dissipation, increasing the metal volume for added strength and modifying the configuration of the plate that connects the hub and the rim.

Pramod Murali Mohan,[3] analysis was carried out to study the behavior of wheel for varying loading conditions. It was observed that excessive braking of wheel leads to thermal overloading which results in fatigue, crack propagation leading to fracture and wear. In order to prevent damages, measures are to be taken for consistent wheel monitoring process and examination of residual stresses in order to prevent fracture.

M s et al 4, an attempt has been made using analytical and numerical modeling of thermal effects during long-term braking for maintaining a constant speed on a down-grade railroad for different velocities and their breaking regimes. This approach could significantly decrease the probability of crack appearance caused by thermal loads.

Jay Prakash Srivastava [5], summarizes the works of early investigations and recent advances in modeling the heat transfer conditions required to estimate the temperature distribution at the contact zone. This abridged technical documentation envisions attracting more research in the area to improve wheel–rail set design and performance standards to extend enhanced safety and comfort to rail transport operation.

M. M. Khonsari, et al. [6] The heat partitioning coefficients in the rail and the brake shoe contacts with the wheel are incorporated in the model. These heat-partitioning coefficients can be used to evaluate the temperature field in the wheel and the brake shoes. It is shown that the wheel contact temperature is confined to a very thin depth within the surface layer (approximately 6% in the radial direction), but the rest of the wheel is at the bulk temperature

Wilson et al., [7], observed that the temperature of the wheel tread can reach 315°C(600°F) when a train travels down a long grade and the brakes are applied. carefully planned experiments were conducted and finite element (FE) models were developed with the purpose of exploring and quantifying the effect of thermal radiation exchange between a hot wheel and the adjacent bearing.

Yaktine et al.,[8], a method and apparatus for sensing the temperature of bearings of vehicles travelling along a track was disclosed, the apparatus included a linear array infrared detector positioned adjacent to the track. The output from the linear infrared detector was scanned at a scanning rate that was regulated according to the vehicle's velocity and the output was compared to predetermined thresholds to indicate excessive heat produced by the wheels and the bearings.

A V Anil Kumar et al. [9], The new multi axial fatigue model was applied to the fatigue initiation life prediction of wheel/rail contact problem. An attempt using nonlinear finite element analysis was used for stress computation and a sub-modeling technique was used to improve the efficiency and accuracy. The stress history was then used to calculate the fatigue life. A numerical example was implemented and compared with field observation of failure pattern. The effect of several parameters, namely wheel diameter, vertical loads, material hardness, fatigue strength and material ductility, on the fatigue damage in railroad wheels was studied using the proposed model.

3. MODELLING

Modelling includes drawing of the profile (RDSO 91146 worn wheel) in 2D and then revolving the profile to get a 3-D wheel structure. Further holes, chamfers, fillets were created. Modelling has been carried out using CATIA V5R19 software. The figure shown below depicts the model of the rail wheel.

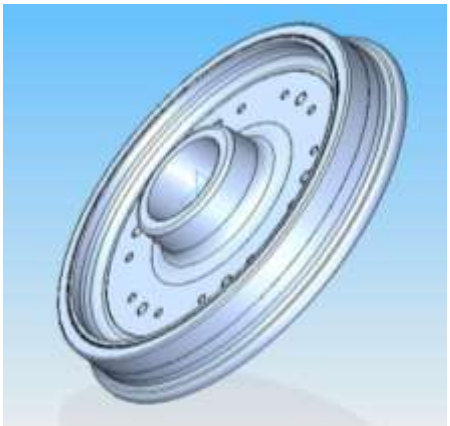

Fig- 2: Isometric view of rail wheel

4. ANALYSIS

Mesh generation is the first step in analysis wherein the entire model of rail wheel is divided into number of small elements for obtaining the solution using finite element method. The accuracy of the results depends on the quality of the mesh, so it is important to maintain a high-quality mesh in order to get accurate results. HYPERMESH software was used for meshing.

Table-1: Material Properties

SL NO.	PROPERTY	SYMBOL	VALUE	UNITS
1.	Density	ρ	7850	Kg/m^3
2.	Young's Modulus	E	210	GPa
3.	Thermal Expansion Coefficient	α	$1.1*10^{-5}$	K^{-1}
4.	Thermal Conductivity	K	47	mW/mmK
5.	Specific Heat	C	440	J/KgK

Material properties were added initially to the model imported from CATIA in IGES format. The properties of the material were shown in the above table.

Cross section of the wheel was chosen and meshed using solid Penta and hexa elements. This section was revolved; however, washer command was used near the holes so that finer mesh of smaller sizes could be created because holes act as stress risers. The parameters maintained are as follows:

1. Global element size is 5mm.
2. Warpage is 5.09, aspect ratio is 5, skew is 45° and jacobian is 0.5.

The figure below shows the final mesh created.

Fig-3: Meshed Wheel

Boundary conditions is imparted on meshed wheel which includes Ambient temperature of 45°C, Brake-wheel interface temperature of 160°C and a constraint on wheel hub restricting all degrees of freedom except rotation about Z-axis.

After applying boundary conditions the model was solved to obtain various results like values of stresses,strains etc.

5. RESULTS

The analysis is carried out using the Optistruct solver and the results are viewed in Hyperview. The result plots and graphs are shown below:

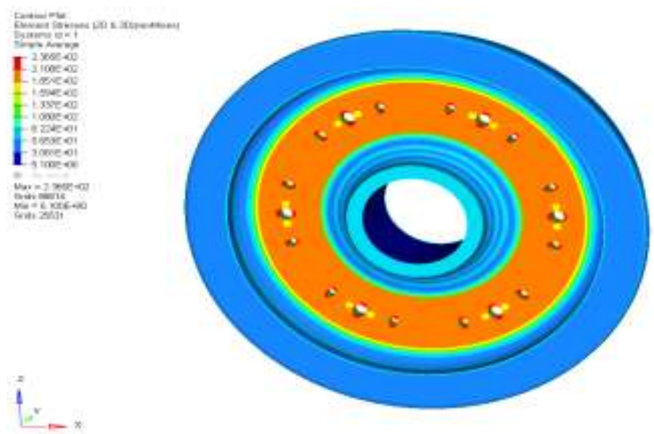

Fig-4: Vonmises stress

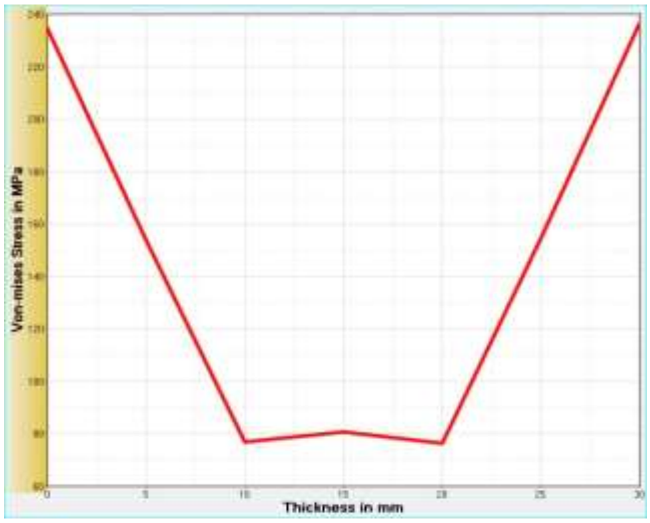

Fig- 5 : Vonmises stress variation along thickness of wheel

Von Mises stress is a value used to determine if a given material will yield or fracture. It is used for ductile materials, such as metals. If the von Mises stress of a material under load is equal or greater than the yield limit of the same material then the material will yield.

In the graph Fig 5, the von mises stress variation along the thickness of the wheel web across the holes is shown. At the outer surface we find the maximum stress of 236 MPa and as the thickness increases there is a drop in the stress value.

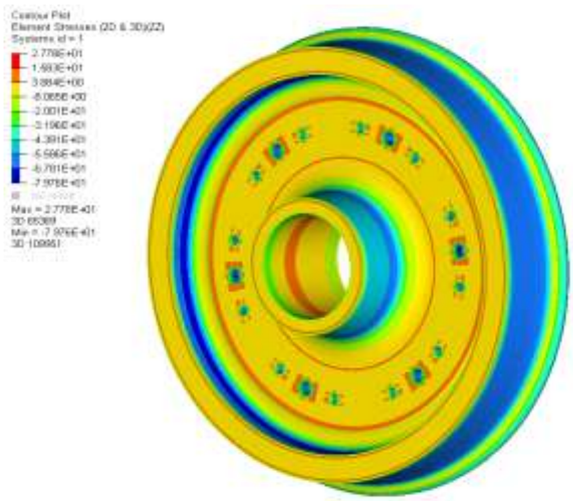

Fig-6: Axial stress

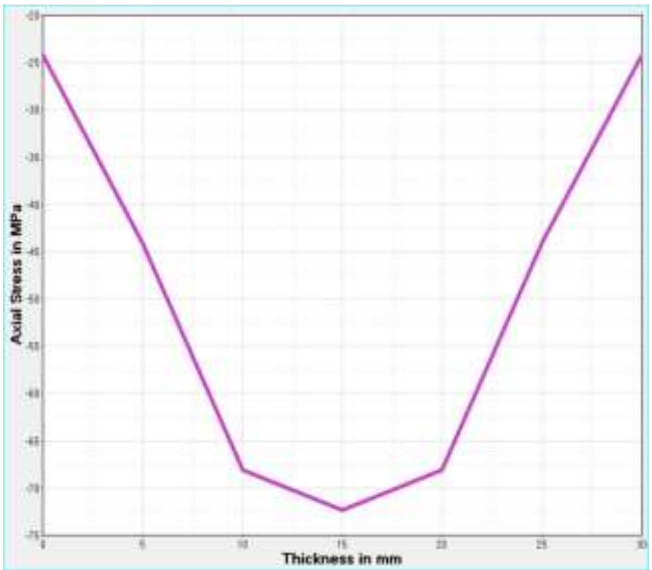

Fig-7: Axial stress variation along thickness of wheel

Axial stress is the normal stress parallel to the axis of wheel symmetry. In this case, Axial compressive stresses are induced hence the value of stress is negative and it reaches a maximum value of 72.5 MPa at the center of the wheel web thickness as shown in graph Fig 7.

6. CONCLUSIONS

The yield strength of the wheel material is 540 MPa and factor of safety is taken has 1.5 hence allowable stress is taken as 355MPa.

From the above analysis, it can be observed that maximum stresses developed due to temperature generated during braking are well within permissible limit. Therefore, it can be concluded that wheel have required strength to withstand the thermal loads.

Finite element analysis of the metro rail wheel shows that maximum stress or peak stress in certain area is considerably low. Hence Manufacturer may have look at the following aspects;

- Material optimization
- The overall weight reduction
- Fatigue analysis of the wheel may be considered to understand and estimate the life of the metro rail wheel.

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