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on

Influence of Wheel Materials on Thermal Load of Braking

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ABSTRACT

This paper will study the influence of wheel materials on thermal loads as a result of block braking for stopping the train. Transient thermal analyses of 3D model of railway wheel for different velocities are performed using ANSYS v12.1 workbench. The analysis is done for two wheels having different material compositions (that is bainite steel wheel-new material and CL60 which is going to be used by Ethiopian national railway vehicle). Using the thermal output as input for the transient structural analysis different stresses concentrations are observed. The results obtained for the two wheels show that, wheel 2 (Bainitic) has excellent strength, toughness and good resistance to thermal damage due to better hardness. Therefore, Bainite steel can be applied to wheels in the railway systems.

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LIST OF ACRONYMS

A – Circumferential area of wheel treads

a – Deceleration of the vehicle

d – Diameter of wheel

F_b – Braking force

h - Heat convection coefficient

k_v- Air speed factor

k_{air}- Conductivity of air

KE – Kinetic energy at the tread of wheel

m – braking mass on the wheel

Nu - Nusselt number

P – Power generated at the tread of wheel

q – Heat flux generated at the tread of wheel

Re - Raynold number

r_w – Radius of wheel

S – Braking distance covered by the vehicle to rest

$t\ or\ t_b$ – Braking time taken by the vehicle to rest

V_{air} - Air speed

v_{air}- Kinematic viscosity of air

V_i – Initial velocity of the vehicle before braking

V_f - Final velocity of the vehicle

$\omega\ or\ \omega_o$ – Angular velocity of the vehicle

3D – three dimension

FE – Finite element

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CHAPTER 1: INTRODUCTION

1.1. Background

Railways have a long history in the world; it developed from crude tramways serving mines and other industries into long-distance goods and passenger transporter. Steam locomotives were a major step forward, starting from in the early 19th century with a locomotive built by Richard Trevithick and developed by the Stephenson's and used on the Stockton & Darlington Railway in 1825 and later on the Liverpool and Manchester Railway [1].

Railway transportation introduced to Africa around the middle of 19th century particularly in Egypt and South Africa in the 1860s and 1870s, with lines heading inland from the ports of Cape Town and Durban. After that up to the end of the century Tanzania, Sudan, Congo, Mozambique, Kenya, Uganda and other countries including Ethiopia carried out the railway construction [1].

In Ethiopia, railway transportation started giving service from Addis Ababa to Djibouti in 1917, even though the construction started in late 19th century. Its railway gauge is 1000mm and most part of the rail road used steel sleepers. The vehicle was using diesel locomotive to drive the passenger and freight trains. It had been the only railway line for years and stopped giving service since the end of 20th century.

Recently a new railway national network has developed, it will provide passenger and freight transportation for the most part of the country with electric source of power of locomotive and will be environmentally friendly. The Addis Ababa/Sebeta – Djibouti corridor is under construction and expected to start giving service in 2015.

The railway gauge is1435mm with concrete sleepers. The national railway network aim to construct 5060kms, trying to connect several areas within the country. The construction will have two phases and the first phase is under construction. This thesis will focus on fatigue fracture of freight car wheel of the new national railway infrastructure of Ethiopia. The freight vehicles have a carrying capacity of $\leq$ 70ton and axle load of $\leq$ 25t depending on the purpose they give [Source: Ethiopian Railways Corporation, Rolling Stocks Specifications].

1.1.1. Wheel

Around 1953, solid wheels were brought into practical service in Japan. Since then, the steel quality of the wheel material has been improved due to the development of continuous casting. At the same time, design procedure of wheel structure configuration has been designed by computer analysis. However, almost all materials for wheels are still plain carbon steels and the basic structure of the wheel has been unchanged, which consists of the hub, web, and rim. It seems that, the reason why both material and configuration have been stable for such long years is based on the concept of "simple is the best". Wheel plays one of the most important parts in supporting the whole vehicle and safety operation of the railway. It was assembled with a tire and a wheel center, before the development of the solid wheel. However, the reliability of the wheel was significantly improved after the development of hot rolling technologies for manufacturing the solid wheel [2].

In recent years, the technical trend of the wheel has become clearer: a specific characteristic of the wheel is required depending on the category of the service. Europe, U.S.A., and Japan have been leading the wheel technologies in the world. However, in Europe and Japan, their technologies are mainly focused on passenger cars including high-speed vehicles. On the other hand, in U.S.A., the share of wheels for freight cars is significantly high. Characteristics required for the passenger car and the freight car are not the same. The priority for passenger car wheels is reliability, so somewhat higher cost may be acceptable. On the other hand, for freight car wheels, the greatest interest concerns initial and maintenance cost [2].

A solid wheel of a railway vehicle consists of three parts, as shown in figure below. They include a hub, wherein an axle is inserted, a rim that contacts the rail, and a web that joins the two parts. The outer circumferential surface of the rim, which contacts the rail, is tread, and the projected part is flange [3].

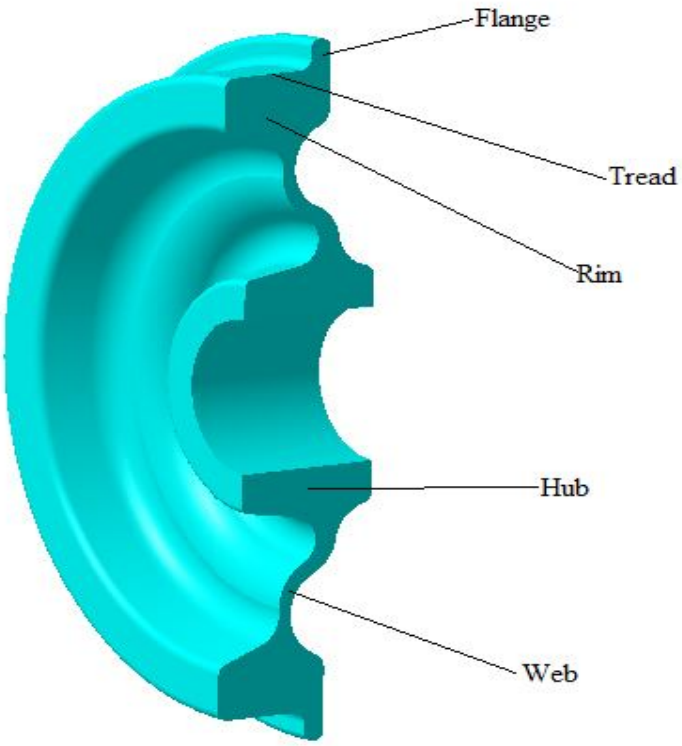


Figure 1. Parts of solid railway wheel

A railway wheel together with an axle is one of the critical parts that support the safe function of railway vehicles. Wheels support the entire weight of cars; so that, they cannot be designed as a failsafe structure where a backup system by other parts can be applied in case of a serious problem. Therefore, in terms of strength absolutely high reliability is required. Since “being unbreakable” is an important characteristic wheel, other characteristics than strength, such as wear resistance, thermal crack resistance, and noise/vibration, are often focused [4].

In recent years, increased axle loads and higher train speeds have led to larger wheel/rail contact forces. A lot effort has been made to optimize design wheel and rail. These trends have changed the major wheel rim damage from wear (slow deterioration of material) to fatigue (can causes unexpected fractures wheels). These failures may cause damage to rails, train suspensions and in some cases, serious derailment of the train. Damage accumulation due to fatigue, plastic deformation and

wear, significantly reduces the service life of the railway track and train components [5].

1.1.2. Carbon steel

Carbon steel is one of the most widely used materials in the industry throughout the world for nearly all of the same reasons: their costs, properties, ease of fabrication, availability, weldability, and so on. The term steel is usually taken to mean an iron-based alloy containing carbon in amounts less than about 2.2%. Carbon steels can sometimes termed as plain carbon steels or ordinary steels [5]. Carbon steel is a steel alloy consisting of iron, carbon and several other elements with maximum percentages. They are manganese, with 1.65% maximum, silicon, with a 0.60% maximum, and copper, with a 0.60% maximum. Other elements may be present in the steel in quantities too small to affect its properties [6]. However, sometimes silicon and manganese can be added in amounts greater than those limits [5].

There are four types of carbon steel based on the amount of carbon in the alloy. Lower carbon steels are softer and more easily formed and steels with higher carbon content are harder and stronger, but less ductile and harder to machine and weld. Below are the properties of the grades of carbon steel [6]:

- Low Carbon Steel – Composition of 0.05%-0.25% carbon and up to 0.4% manganese. Also known as mild steel, it is a low cost material that is easy to shape. While not as hard as higher-carbon steels, its surface hardness can be increased by carburizing.
- Medium Carbon Steel – Composition of 0.29%-0.54% carbon with 0.60%-1.65% manganese. Medium carbon steel is ductile and strong with good wear properties.
- High Carbon Steel – Composition of 0.55%-0.95% carbon with 0.30%-0.90% manganese. It is very strong and holds shape memory well, making it ideal for springs and wire.
- Very High Carbon Steel - Composition of 0.96%-2.1% carbon. Its high carbon content makes it an extremely strong material, though it is brittle and requires special handling.

In this paper, the two railway wheels that are going to be compared are carbon steel. Wheel 1 (CL60) have high carbon steel (0.6% carbon and 0.74% manganese) and wheel 2 (Bainitic) have low-medium carbon steel (0.19% carbon and 1.82% manganese).

1.1.3. Braking

Train braking is very importance and complex part of rail vehicles, due to its essential contribution on the safety of the rail traffic. This complexity results from the fact that during brake application numerous phenomena (mechanical, thermal, pneumatic, electrical, etc) occur. The actions of brake application take place in different parts of the train with varying intensities. And all must favorably interact for the intended scope, to provide efficient, correct and safe braking actions [7].

"Braking" means to control the movement of a moving body artificially, including making its speed decreased, arresting its movement or its acceleration trend. It is an artificial resistance and is much larger than the natural resistance generated by the other reasons during the period of train's running [8]. Generally, braking system of railway vehicles has a fundamental function for the safety as well as riding quality of passengers [9]. The braking action of the train is normally divided into two, according to the difference of usage [8]:

- Service Brake: - It is the braking action used to control speed of the train under normal condition, including the braking action required by the train when arriving at the station.
- Emergency Brake: - It is the braking action applied to stop the train as soon as possible under urgent conditions. Its action is very fast and the total braking ability of the train should be used.

There are different forms braking [8]:

- Disc braking: uses round disc which is installed on the axle or on both sides of the wheel plate. The disc is normally made of cast iron and brake pads normally made of composition material. At braking, the discs are clamped by brake pads (brake pads (linings) come into contact with the disc, applying equal and opposite forces on the disk) to impede rotation, creating braking force and converting train's kinetic energy into heat [10].

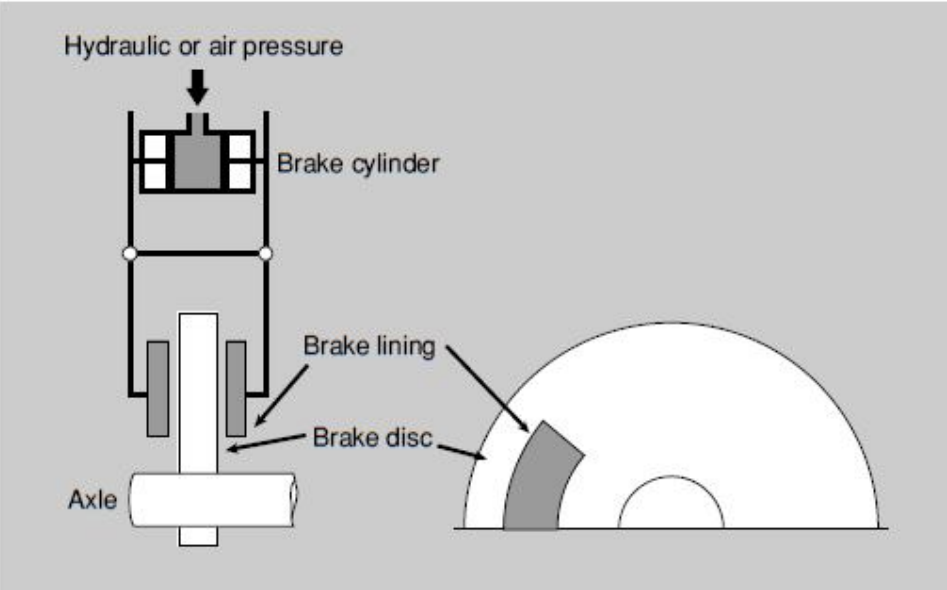


Figure 2. Disk brake mounted on axle [8]

- Tread braking: uses block-shaped brake shoes made of cast iron or other material. Tread braking on railway vehicles is still one of the most common braking systems. Block braking is the ordinarily used system on freight wagons and is also commonly used on passenger trains, often in combination with disc brakes and electro dynamic brakes. The braking action is carried out by pressing the brake block(s) against the tread of a wheel. The brake shoes that are pushed onto the running wheel treads and the train's kinetic energy is converted into heat energy by the mechanical friction between wheel treads and brake shoes. The traditional form of wheel tread brake consisting of a block of friction material which could be cast iron, wood or a composition material hung from a lever and being pressed against the wheel tread by air pressure in the air brake or atmospheric pressure in the case of the vacuum brake [9].

  Tread braking systems have advantages and disadvantages. They are simpler and cheaper than disc brakes (axle or wheel mounted), and they allow much more flexibility concerning space requirements compared to the other braking systems. Since block braking roughens the wheel tread, it improves the wheel-rail interface friction conditions at traction and braking. Unfortunately, the

roughness may also cause an increased level of rolling noise which is typical for trains with cast iron brake blocks [11].

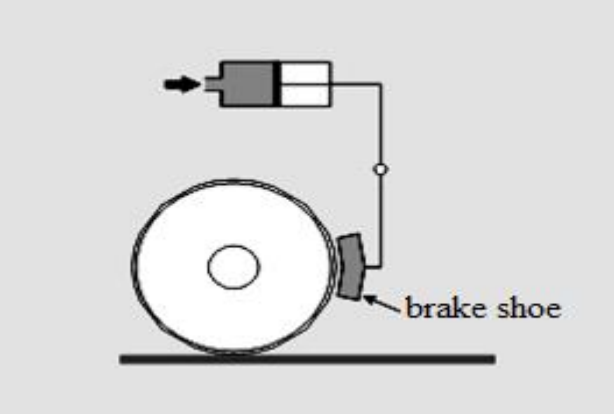


Figure 3. Tread braking system [8]

There are four different standard arrangements of tread braking system (one block per wheel, two blocks per wheel (tandem-one side and clasp-two side) and four blocks per wheel) shown in the figure below [12].

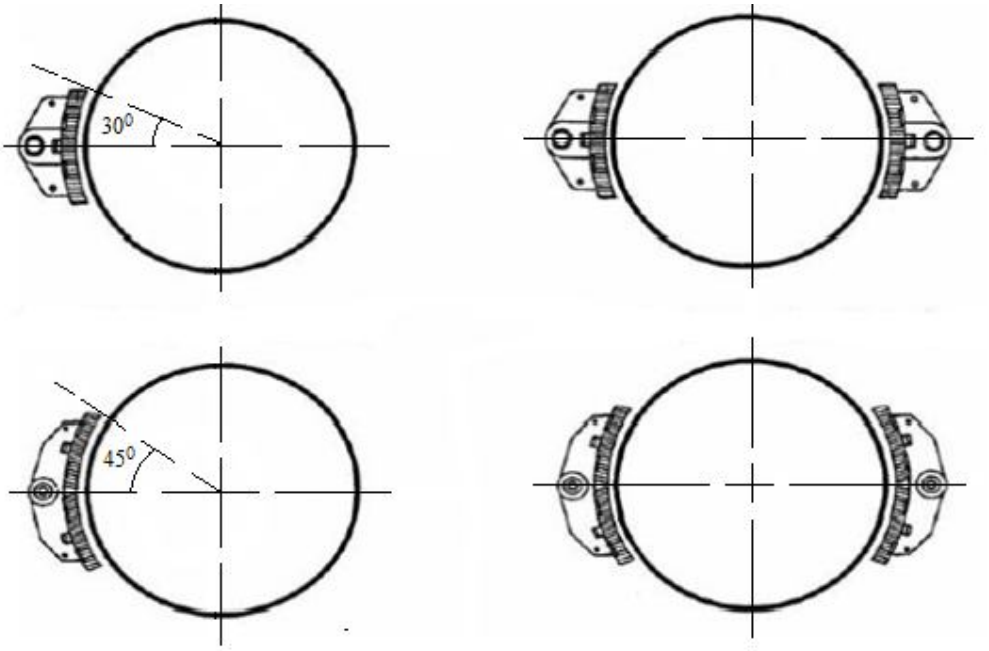


Figure 4. Different types of bloke brake arrangement on a wheel [12]

In the arrangement shown above, for one side block brakes the frictional heat created between wheel and brake will be greater on the block brake surface, because of its contact surface area, than the two blocks per wheel on one side.

Depending on how the command actions are transferred and how the braking forces are basically developed [7] classify brakes into:

- Handbrakes- are applied by hand action to a wheel or lever on the vehicle. They are generally used for securing unpowered (parked) vehicles against unexpected movement, not for braking actions while operating. That is why, they are usually known as parking brakes. Recently, some developments conducted to a kind of automation using a spring-applied concept, which release when compressed air for the basic pneumatic brakes is available. But, such braking system is mandatory for traction vehicles and passenger carriages, only a part of wagons must be provided with it.
- Pneumatic brakes- uses air pressure variations both to command and to apply the generating braking/releasing actions and forces. The vast majority of trains use compressed air, changing the level of air pressure in the brake pipe and determining a change in the state of the brake on each vehicle. In the case of straight air brake system, the increase of air pressure in the pipe determines the increase of air pressure in the brake cylinders of each vehicle. In the case of indirect air brake system, braking actions are commanded by decreasing the pressure in the train's brake pipe, generating by special features the increase of air pressure in the brake cylinders of each vehicle. In the same pneumatic category is also the vacuum brake system where the brakes on each vehicle are actuated by the action of atmospheric pressure over a specially created vacuum in the train's pipe as long as the brakes must be released.
- Electro-pneumatic brakes- have an electrical command while compressed air is used to increase the pressure in the brake cylinders of each vehicle to apply the brake blocks or pads for generating braking forces.
- Rail (track) brakes- are usually electric commanded and the braking force is achieved due to strong magnetic forces induced by large electromagnets hung under the vehicle's bogie, over the top surface of the rails. If the braking forces are generated by the frictional forces between the electromagnets and rails it is an electromagnetic rail brake. If the electromagnetic fields generate eddy currents in

the rails, creating forces acting in the opposite direction of the movement of the train, it is a linear eddy current brake system. On the same principle the rotary eddy currents brake system, the metallic mass being either the wheels, or discs attached to the wheel sets.

- Electric braking- is based on the reversibility of the electric engine, in particular the electric traction motors are reconnected in such a way that they act as generators which provide braking effort. Practically, the kinetic and/or the potential energy (while running on slopes) are converted into electric energy. If the power generated during braking is dissipated as heat through on-board resistors it is about a rheostatic (dynamic) braking.
- Regenerative braking- On electric railways, the conversion of train energy back into usable power by diverting the braking current into traction supply line, in the case of regenerative braking. Most regenerative systems include on board resistors to allow also rheostatic braking if the traction supply system is not receptive, the choice being automatically selected by the traction control system. The regenerative braking is suitable for hybrid vehicles and for diesel powered traction rail vehicles.
- Hydraulic brakes- use hydraulic oil. Depending on the achievement of braking forces, there may be hydrostatic due to oil pressure increasing or hydrodynamic when the kinetic energy of the vehicle is converted in the rotor of a hydraulic pump in heat which dissipates through the oil cooling system.

Regarding the brake system reaction in special cases, there are [8]:

- Automated brakes- in case of significant accidental drop of air pressure in the brake pipe all the vehicles of the train are submitted to an emergency brake action, independent of driver control.
- Non-automated brakes - in case of significant accidental drop of air pressure in the brake pipe, they do not determine brake command and even they can become inactive (unable to perform braking action).

The construction of the braking systems components (especially those mounted under the vehicle chassis or on the bogie) they must have low mass and suitable sizes and shapes to fit the rolling stock gauge. By design, the mechanical elements of the brake installation and mainly the riggings have to function correctly and optimally transmit forces, despite of the fact that the vehicle is empty or loaded at maximum capacity.

Maintaining effective braking actions must neither affect the environment, nor interact in any way with other systems, elements, and circuits of the track or vehicle. Braking system must be independent. Also, the centralized control of braking and release actions, and the transmission of braking commands along the whole train have to be simple, safe, effective with maximum reliability. The braking systems have to allow adequate brake and release levels, giving the driver the possibility to apply correctly the braking force targets to the instantaneous traffic conditions. And, the passengers or the transported goods comfort should not be affect by the achievable braking forces, neither due to decelerations and shocks along the train, nor by annoying vibrations and noises [7].

The thermal aspect around the contact region between stationary brake and a moving wheel can be studied by examining the heat transfer. The contact between wheel and brake causes friction heating of both bodies. When a brake is applied, the conversion of kinetic energy of moving masses into thermal energy takes place. This kinetic energy is dissipated between the two bodies and noticeably raises their temperature at the area of the sliding contact [13]. These will be the case for this research paper on two different materials of wheel.

1.1.4. Thermal energy

It's known that you can warm up cold hands by quickly rubbing them together. When car tires skid along a road, it results in burnt rubber. A power drill's bit can quickly become too hot to touch [14].

Experiments show that, an object and its surrounding temperature raise is due to friction and is directly related to the amount of mechanical energy lost. The well-known experimental demonstration was carried out by James Joule in the 1840's. Joule hung some weights from pulleys so that as they fell, they turned a paddle-wheel apparatus immersed in a bucket of water. The water's temperature raised because of the friction between the paddles and the water by an amount that was directly proportional to the distance that the weights fell. In our modern system of units, Joule found that raising the temperature of a kilogram of water by one degree Celsius required a loss in mechanical (gravitational) energy of approximately 4200 joules. Joule therefore proposed that this mechanical energy is not actually lost, but

converted into a new type of energy: thermal energy, which evident itself as an increase in temperature [14].

The temperature change caused by storing a given amount of thermal energy in an object depends not only on the object's mass, but also on what it is made of. Raising the temperature of a kilogram of water by one degree Celsius requires 4200 joules, but for a kilogram of wood, only about 1700 joules are required. For iron the value is only 450 joules, while for lead, a mere 130 joules will suffice to accomplish the same one-degree temperature increase (per kilogram). Each of these numbers is called the specific heat capacity of the corresponding substance. In general, the specific heat capacity is the energy required to raise the temperature, per kilogram of material, per degree of temperature increase:

$$Specific\ heat\ capacity = \frac{thermal\ energy\ input}{mass * temprature\ change}$$

Smooth surfaces, rubbed together, slide each other with very little conversion of mechanical energy to thermal energy. Rough surfaces, on the other hand, exert a lot of frictional force on each other and convert mechanical energy into thermal energy much more rapidly. This is because, the bump on the surfaces must be pushing against each other, then bending over, and finally bouncing back up as they move on. This pushing, bending, and bouncing converts the kinetic energy (from the overall motion) first into elastic energy and then partially back into kinetic energy of the tiny vibrations of the bumps. In other words, a uniform kinetic energy, with an object moving all in the same direction, is converted into kinetic and elastic energy that is unevenly distributed throughout the surfaces. This unevenly distributed energy gets passed back and forth among the particles that make up the surfaces, until its distribution is essentially random. This kinetic and elastic energy random arranged is what we call thermal energy [14].

In this paper, influence of wheel material on thermal loads of braking on freight vehicle of Ethiopian national railway wheel and another new wheel is analyzed. The freight vehicle is equipped with trade brake operated by electro-pneumatic system (air brake system) from the locomotive. The air brake system is mainly composed of control valve, brake cylinder, storage reservoir, automatic gap adjuster of bidirectional brake shoe and automatic adjuster of empty and heavy vehicle [2]. During block braking of rolling wheels, the kinetic energy is mainly converted into

heat within a relatively short time between the brake and wheel and it is the thermal load acting on the wheel.

1.2. Statement of Problem

Thermal load is one load type that can affect (damage) railway wheels. During braking there is frictional heat produced between wheel and block brake, this frictional heat is a thermal load on wheel. The thermal load will produce high stress on the wheel especially for a greater axle load and vehicle speed, which leads to wear. Wear on wheels can create discomfort for the transportation of goods; needs more maintenance cost, and will be a cause for more damage on the wheel. However the thermal load stress depends on the material property of the wheel; identification of a better material that can resist the effects of thermal load even for higher vehicle speed and axle load will help to prevent wear and goods ride discomfort; reduce maintenance cost and other damages. Therefore, how wheel materials property difference influence the stress concentration of thermal load will be studied by comparing two wheels having the same structure, but different in chemical composition and material property.

1.3. Objective

1.3.1. General objective

The main objective of this study is investigating the influence of wheel materials on thermal load during braking (block brake), for different velocities, using ANSYS software for analysis.

1.3.2. Specific objective

- 3D Modeling of the wheel using CATIA V5R16.
- Analyzing Transient Thermal and Structural analysis on wheel 1 and wheel 2 for different velocities.
- Comparing Transient Thermal and Structural analysis results of the two wheels for different velocities.
- Investigating which wheel has better resistance of stress due to thermal load of braking.

1.4. Scope and Limitation

Predicting the influence of wheel materials on thermal load is the main scope of this study, considering the thermal load during braking for two different types of wheel material (which are taken from the literature) and at different speeds using ANSYS software for analysis. The transient thermal and structural analysis uses ANSYS mechanical solver and used to determine the dynamic response of a wheel structure under the action of time and determine the thermal stress on the wheels.

The limitations of this research are shortage of data and references, need for high performance computer for the ANSYS analysis and not being able to compare more wheel material types.

1.5. Organization of the Thesis

This thesis contains five chapters presenting the research study. The content of each chapter is outlined below:

Chapter one outlines general information about the research conducted. The background, statement of problem, the general and specific objectives of the research and the scope and limitation are stated out. Chapter two covers the review of journals, articles, proceedings and publications which were referred during the work of the thesis. Chapter three discuss about the material, methods and condition of the research. The finite element modeling and the mathematical analysis for thermal load is also covered. Chapter four the results obtained from ANSYS transient thermal and structural analysis of the wheel, results discussion from the experiment of bainitic wheel from the literature and discussions based on these results are included. Chapter five covers conclusions drawn based on the outcome of the analysis, and recommendations for future application. In addition; there are list of points that help to continue the research on the same topic for future work.

CHAPTER 2: LITERATURE REVIEW

2.1. Introduction

Under this chapter of the paper, previous related research papers which are basic guide for the current work are reviewed. Some of them have a direct relation whereas the others have indirect relations with this paper. But the main principles they used and the major methodologies they follow will be a guide for the formulation of specific model and analysis in this paper.

Influence of wheel materials on thermal load of braking is the research subject of this paper. During braking there is frictional heat produced between wheel and brake (especially block brake), this frictional heat load will be applied to the wheels (wheel 1 and wheel 2) which have different chemical composition and property, but same structural dimension. The wheels will be compared for different running speeds (40, 65, and 100km/h). Some of the literatures that are assessed to be significant for research on wheel fracture are described below.

2.1. Wheel Material

The first railways wheels were used by horse drawn trains of wagons in coal mine. They were made of wood, which proved unsatisfactory as the loads carried inevitably grew heavier. As the industrial revolution progressed, the idea was developed further by adding cast iron or wrought iron to reduce wear on the wooden baulk. This evolved further of flanged wheels for the first time [15]. By the time steam locomotives came on the scene, in the early nineteenth century, wrought iron wheels and later steel wheels were developed which were strong enough to support heavy axle loads [16].

Zhang [17] investigated the suitability of carbide-free bainite steel for railway wheel materials. The low-medium carbon Si-Mn-Mo-V steel was designed to make railway wheels. Microstructures and mechanical properties have been studied and the mechanical properties (yield strength, ultimate tensile strength, hardness and so on) are superior to the CL60 plain carbon. The experimental low-medium carbon Si-Mn-Mo-V (Bainite) steel was designed and optimized on the basis of laboratory researches and small-scale trial, at wheel diameter of 840 mm. The Bainite steel with

sufficient silicon to prevent the precipitation of carbides during phase transformation at slow cooling rates, sufficient manganese for the purpose of increasing hardenability, and some other alloys, such as molybdenum and vanadium to achieve the desired hardenability for obtaining uniform hardness, finer grain size and higher tensile strength and toughness. The microstructure results indicate that the rim is mainly carbide-free bainite, and the mixed microstructure of bainitic ferrite and granular bainite are observed in web and hub. The impact energy is relatively high at room and/or subzero temperatures and it has excellent resistance ability to crack initiation and propagation.

2.2. Thermal Load

Thermal analysis is involved in almost every kind of physical processes and it can be the limiting factor for many processes. Therefore, its study is of vital importance, and the need for powerful thermal analysis tools is virtually universal. Furthermore, thermal effects often appear together with, or as a result of, other physical phenomena. The modeling of thermal effects has become increasingly important in product design including areas such as electronics, automotive, aerospace, railway, medical industries, etc [18]. The frictional heat is generated when two bodies slide against each other with a relative speed and a contact pressure. This frictional heat is generated at sliding or rolling interface of wheel/brake contact and wheel/rail contact [13].

2.2.1. Thermal load for disk braking

During disk-braking of rolling railroad wheels, the kinetic energy is mainly converted into heat within a relatively short time. In the process of disk braking, the brake pads that usually cover only a part of the annular brake area are in sliding frictional contact with the rotating wheel, thus leading to the periodic transient heat production over a sector of the brake surface.

Rossmanith [19] study the problem of braking of heavily loaded railway wheels and their thermo mechanical fracture. The wheels have the form of thick disks weakened by small surface cracks. They are periodically braked with friction in a random sequence of time intervals. The stresses formed in the course of braking and subsequent cooling attain the plasticity limit of the rail-wheel steel in tension and

compression. It is shown that, for locally heated and cooled disks, the cycles of thermo mechanical loading and unloading are responsible for the growth of fatigue cracks.

Gallo [20] analyzed wheels with web mounted disk brake using finite element thermal analysis and determined the behavior of wheel on the web.

2.2.2. Thermal load for tread (block) braking

Rolling contact and slip behavior between the wheel and the rail are intensively subjected to damage in wheel-rail systems. This happens because of the brake block pushed against the wheel tread to stop or slow down the vehicle and it creates friction through which energy is dissipated. The friction generates heat which results in deformation of the wheel and thermal stresses [21]. Pramod analyzed the behavior of freight car wheel due to thermal, structural and combined loading effect. The thermal load considered is between wheel and rail during braking. The structural loading considered the horizontal and vertical load acting on the wheel.

Aleksandar [22] studied the analysis calculation of the thermal load of the railway vehicle block-braked solid wheel on a selected line. Thermal analysis was done using the finite elements method, which was also used for finding wheel temperature and stress states in the simulated conditions. Computations were performed for two shoe positions at the tread of wheel when braking (for the regular allowable position and for the unallowable (irregular) position).

Caprioli [23] study of the effect of thermal loading imposed by block braking on wheel tread cracking using numerical analysis. Two-dimensional FE-simulations of elasto-plastic thermo-mechanical stresses during heating and cooling have been combined with analytical result of stress intensities for thermal cracks. It considered two load cases, brake malfunctioning (brakes are applied at constant speed) and stopping brake from high speed (130 km/h) with a high axle load. The analysis also determine the critical sizes for when existing surface cracks are prone to propagate under thermal loading and resulting crack length after propagation.

Milos [18] modeled the thermal analysis of a block-braked on wheel of a 444 class locomotive of Serbian Railways. The thermal analysis is done using analytical and

numerical modeling of wheel/brake with different velocities and with low and high pressure in brake installation.

Deshpande [24] studied on a specific problem observed after the change in braking system from tread braking to disc braking. The problem identified was spalling damage and investigation was carried out to determine effect of braking system on wheel spalling. Different mathematical models were utilized to calculate sliding velocities and interface temperature rise in the wheel during sliding. A Finite Element Model was developed for computation of temperature field in the wheel. Using this information, the extent of damage by tread braking system and disc brake system was computed.

Yung [25] investigates the effect of rail corrugation on the wheel-rail thermal contact pressure and temperature distributions during wheel braking. Various wavelengths, amplitudes of corrugated rail and braking speeds are considered. The results indicate that in the wheel rail contact area, the rail corrugation affects the contact pressure and temperature distributions significantly. A wavy contact pressure and temperature distributions on the rail surface resulted from corrugated rail.

As can be seen, almost all the research focus on thermal load due to braking (disk and block braking) analysis. The analysis is conducted using numerical and/or finite element software simulation of mostly wheel and rail components of railway. In the last research, experimental tests are made to generate new and better performance railway wheel.

CHAPTER 3: ANALYTICAL METHODS AND CONDITION

3.1. Introduction

Tread (block) braking is still one of the most common braking systems on railway vehicles. The action is carried out by pressing brake blocks against the tread of a wheel, which is also in rolling contact with the rail. The extensive use of tread brakes in metro and suburban applications has created a need for design guidelines or standards for wheels exposed to repeated stop braking [7].

Thermal analysis is the primary stage in the study of braking systems, because the temperature determines the thermo mechanical behavior of the structure. In the braking phase, kinetic energy transforms into thermal energy, resulting in intense heating of the railway wheel. This generates stresses and deformations, whose consequences are manifested by the appearance and the accentuation of cracks on treads of wheel, and eventually fractures of the whole wheel [18].

The freight car of national railway of Ethiopia will be used for the transportation of various goods from different directions of the country. The braking device is air braking mechanism mainly composed of control valve, brake cylinder, storage reservoir, automatic gap adjuster of bidirectional brake shoe (high friction) and automatic adjuster of empty and heavy vehicle. The wheel (diameter 840mm) material is the Chinese standard compliant CL60 steel, and the axle material is the Chinese standard-compliant LZ50 steel. The thermal analysis is going to be performed for braking freight car of the national railway of Ethiopia, with three different velocities (40 km/h, 65 km/h, and 100km/h). The list below shows the general technical parameters of the national railway of Ethiopia freight cars [Source: Ethiopian Railways Corporation, Rolling Stocks Specifications].

3.2. Dimension

Vehicles that operate on rail tracks shall be designed and maintained so that the geometric features of wheels and wheel sets are compatible with those of the railway tracks; to sustain safe operation of vehicles under all normal conditions on those routes where they are permitted to run [26].

The national railway of Ethiopia freight cars has a wheel diameter dimension of 840mm and its web structure is what is called s-web. The weight of the wheel is estimated 350kg [27].

Table 1. Component materials and dimension

Part name	Standard	Material	Dimension
Wheel 1	CL60 (TB/T 2708)	High carbon steel	Dia. = 840mm
Wheel 2	-	Low-medium carbon steel	Dia. = 840mm
Block brake	-	Gray cast iron	LxWxT= (305x84.074x31.75)mm

3.3. Materials

The common and inexpensive metals, steel has one of the highest values of elastic modulus. For this reason and because steel is relatively inexpensive and offers a very attractive combination of strength, ductility, and wear resistance almost all wheels and rails worldwide are made from plain carbon-manganese steel, which has a lamellar structure of iron and iron carbide.

Railway wheels are the key parts that must have better quality to wear resistance, thermal crack, fatigue and fracture leading to a sudden catastrophic failure. In the present time, the wheels are made of high carbon grade steels.

Wheel 1 (CL60) is a typically wheel steel with the carbon content of 0.60wt% and the microstructure is pearlite-ferrite. The chemical compositions of wheel 1 (pearlite-ferrite) and wheel 2 (Bainitic) wheel steels are shown in Table 2 and 5. The bainite steel is low-medium carbon Si-Mn-Mo-V steel with sufficient silicon to prevent the precipitation of carbides during phase transformation at slow cooling rates, sufficient manganese for the purpose of increasing hardenability, and some other alloys, such as molybdenum and vanadium. The addition of molybdenum and vanadium facilitate to achieve the desired hardenability for obtaining uniform hardness and is beneficial for achieving higher tensile strength and toughness [17].

Table 2. Chemical composition of CL60 wheel material [17]

Chemical element	C	Si	Mn	Mo	V	S	P	Cr	Ni	Cu	Fe
Amount (wt %)	0.6	0.26	0.74	_	_	0.003	0.01	≤ 0.25	≤ 0.25	≤ 0.25	Bal.

Table 3. Mechanical properties of CL60 wheel material at 25 ^{o}C [17]

Yield strength (MPa)	665
Ultimate tensile strength (MPa)	1020
Modulus of elasticity (GPa)	210
Poisson's ratio	0.3
Hardness (HB)	273
Elongation (%)	15

Table 4. Thermal properties of wheel 1 (CL60) material

Density (kg/m^3)	7850
Thermal conductivity (W/mK)	48.6
Specific heat capacity (J/kgK)	1499

Table 5. Chemical composition of Bainitic wheel (wheel 1) material [17]

Chemi. element	C	Si	Mn	Mo	V	S	P	Cr	Ni	Cu	Fe
Amount (wt %)	0.19	1.44	1.87	0.26	0.07	0.004	0.013	0.09	0.22	0.03	Bal.

Table 6. Mechanical properties of Bainitic wheel material at 25 ^{o}C [17]

Yield strength (MPa)	860
Ultimate tensile strength (MPa)	1090
Modulus of elasticity (GPa)	210
Poisson's ratio	0.3
Hardness (HB)	273
Elongation (%)	15

Table 7. Thermal properties of Bainitic wheel material

Density (kg/m^3)	7870
Thermal conductivity (W/mK)	50.2
Specific heat capacity (J/kgK)	1800

Table 8. Mechanical properties of block brake material [18]

Yield strength (MPa)	340
Ultimate tensile strength (MPa)	800
Modulus of elasticity (GPa)	212
Poisson's ratio	0.3
Hardness (HB)	273
Elongation (%)	15

Table 9. Material properties of brake material at 20 °C

Density (kg/m^3)	7200
Thermal conductivity (W/mK)	45
Specific heat capacity (J/kgK)	501

3.4. Conditions

The below tables show that the general technical parameters and condition of freight car of the national railway of Ethiopia [Source: Ethiopian Railways Corporation, Rolling Stocks Specifications]. The deceleration is taken from the light rail transient railway of Addis Ababa of the emergency braking, to see the maximum effect.

Table 10. Technical parameters of freight cars for national railway of Ethiopia

Railway Gauge	1435mm
Wheel Diameter	840mm
Axle Load	25t
Design Speed	100km/h
Loading Capacity	70t
Continuous speed	65km/h
Maximum electrical braking effort	400KN

Table 11. Geometrical dimensions and application parameters

Axle load (ton)	25t
Design speed (km/h)	100km/h = 27.78m/s
Braking force on one wheel, F_B (kN)	200
Radius of wheel – r_w (mm)	420mm=0.42m
Brake surface area for one bloke brake – A_b (m^2)	0.028
Ambient temperature (°C)	25
Deceleration (m/s^2)	1.5

3.5. Methods

The structural dimension of the freight vehicle wheel/brake is translated into 3D drawing by using CATIA V5R16. The 3D model of freight vehicle wheel is imported to ANSYS software. The simulation is carried out using only 3D wheel, in transient thermal analysis and then to transient structural analysis.

To simulate a process of braking of railway vehicles it is necessary to define an analytical model of a thermal analysis that describes the heating transfer of the heat generated by friction at surfaces which are in contact, between a railway wheel and braking blocks. Numerical calculation is done for the purpose of input for the ANSYS analysis and used to get thermal result (temperature).The transient thermal analysis will determine the temperature distribution on the wheel with time and the transient structural analysis will determine the strains and stress distribution on the wheel. The thermal result is an input for the structural analysis. The analysis is done for the wheel 1 and wheel 2 (which have the same structural dimension, but different chemical compositions and properties), for different velocities (40, 65 and100km/h). The results from the thermal and structural analysis are compared with the properties of the wheel materials.

3.5.1. Numerical thermal analysis of block brake and wheel

The thermal analysis of the braking system of railway vehicles requires a precise determination of the quantity of heat produced by friction, as well as the distribution of this energy between the railway wheel and the braking blocks. When the braking process occurs, blocks and railway wheel are in a sliding contact. The resulting force resists the movement so the train slows down and finally stops. The friction between the wheel and blocks always opposes motion and the heat is generated due to conversion of the kinetic energy. This thermal analysis will be done for different speed of the freight vehicle [18].

The conditions at wheel -brake thermal contact interfaces can be affected by many factors, such as roughness of the surfaces, oxides, lubricant, organic material and sand. This may cause a non-zero thermal contact (imperfect contact). In this analysis the interface thermal contact resistance has been ignored and the widely used

assumption [28] of perfect thermal contact between the two surfaces has been adopted.

Assumptions

- The train vehicle is running on straight rail track.
- Perfect thermal contact between the wheel and brake surfaces.
- Heat generated during braking is uniformly distributed around the periphery of the wheel.
- The kinetic energy was transformed completely into heat energy.
- Constant coefficient of friction between wheel and rail.

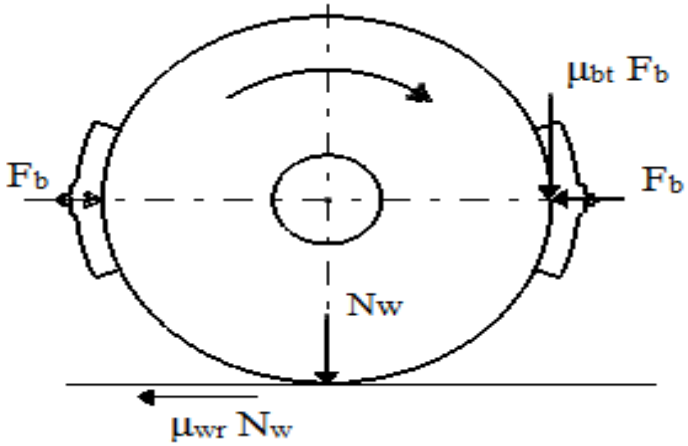


Figure 5. Forces on the wheel during braking

Initial braking speed (km/h)	40	65	100
Initial braking speed (m/s)	11.11	18.06	27.78

Even though different values of running velocity are listed, continuous running speed (65km/h) is the input in the equations below [18].

- Load acting on block brake = 100 KN = 100000 N
- Braking mass on one wheel acting on one wheel(m)= 20387.36 Kg

- Angular velocity:

To begin the calculation, the angular velocity is needed:

$$\omega_o = \frac{V_i}{r_w}$$

$$\omega_o = \frac{18.06}{0.42} = 43 rad/sec$$

Initial braking speed (km/h)	40	65	100
Angular velocity(rad/s)	26.45	43	66.14

- Kinetic energy:

$$KE = \frac{1}{2} \times m \times V_i^2$$

$$KE = \frac{1}{2} \times 20387.36 \times 18.06^2$$

$$KE = 3324807.366\, J$$

Initial braking speed (km/h)	40	65	100
Kinetic energy (J)	1258227.329	3324807.366	7866752.357

- Power generated:

$$P = \frac{KE}{t}$$

The time needed for braking

- Time:

$$t = \frac{V_i}{a} = \frac{18.06}{1.5} = 12.04$$

∴ Time = 12.04sec

Initial braking speed (km/h)	40	65	100
Braking time (sec)	7.41	12.04	18.52

$$P = \frac{KE}{t}$$

$$P = \frac{3324807.366}{12.02}$$

$$P = 276606.27\ W$$

Initial braking speed (km/h)	40	65	100
Power generated (W)	169801.26	276606.27	424770.65

Heat flux generated during braking:

In a braking action, the mechanical energy of the brake is transformed into heat energy (heat flux). This energy is transferred to the wheel and block brake approximately 95% and 5% respectively [29] during the braking phase.

$$q = \frac{0.95 \times P}{A}$$

- Area:

$$A = \pi \times r_w \times w$$

$$A = \pi \times 0.84 \times 0.09$$

$$A = 0.238\ m^2$$

- Heat flux:

$$q = \frac{0.95 \times 276606.27}{0.238}$$

$$q = 1104100.66\ MW/m^2$$

Initial braking speed (km/h)	40	65	100
Heat flux (W/m^2)	677778.14	1104100.66	1695513.1

- Braking distance

$$S = \frac{V_f^2 - V_o^2}{2a}$$

$$S = \frac{0^2 - (18.06)^2}{2 * 0.8}$$

$$S = 108.72m$$

Initial braking speed (km/h)	40	65	100
Braking distance (m)	41.14	108.72	257.24

- Heat convection

$$h = \frac{Nu \times k_{air}}{r_w}$$

$$Nu = 0.037 \times Re^{0.8}$$

$$Re = \frac{V_{air} \times r_w}{v_{air}}$$

$$V_{air} = k_v \times V_i$$

Where;

$k_v = 0.12$, $k_{air} = 0.0241$, $v_{air} = 12.34 \times 10^{-6}\ m^2/s$

$$V_{air} = 0.12 \times 18.06$$

$$V_{air} = 2.1672\ m/s$$

$$Re = \frac{2.1672 \times 0.42}{12.34 \times 10^{-6}}$$

$$Re = 73762.1$$

$$Nu = 0.037 \times (73762.1)^{0.8}$$

$$Nu = 290$$

$$h = \frac{290 \times 0.0241}{0.42}$$

$$h = 16.64 \frac{W}{m^2 k}$$

Initial braking speed (km/h)	40	65	100
Heat convection (W/m^2)	11.28	16.64	23.49

3.5.2.Modeling

The full model of wheel-brake-rail is modeled using Catia V5R16 in order to analyze the temperature and thermal stress on the wheel.

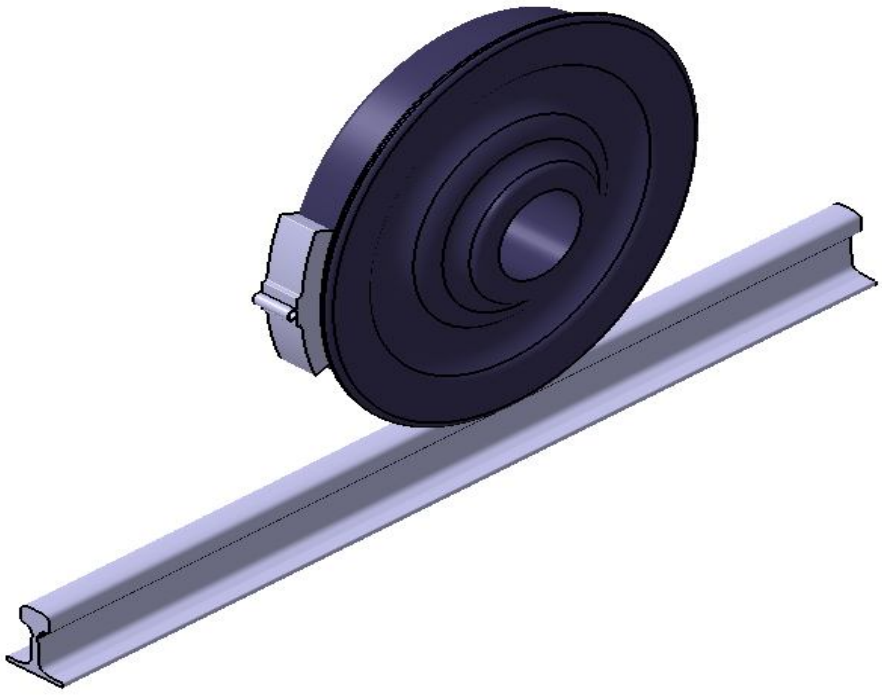


Figure 6. Isometric 3D view of Rail-Wheel-Brake model

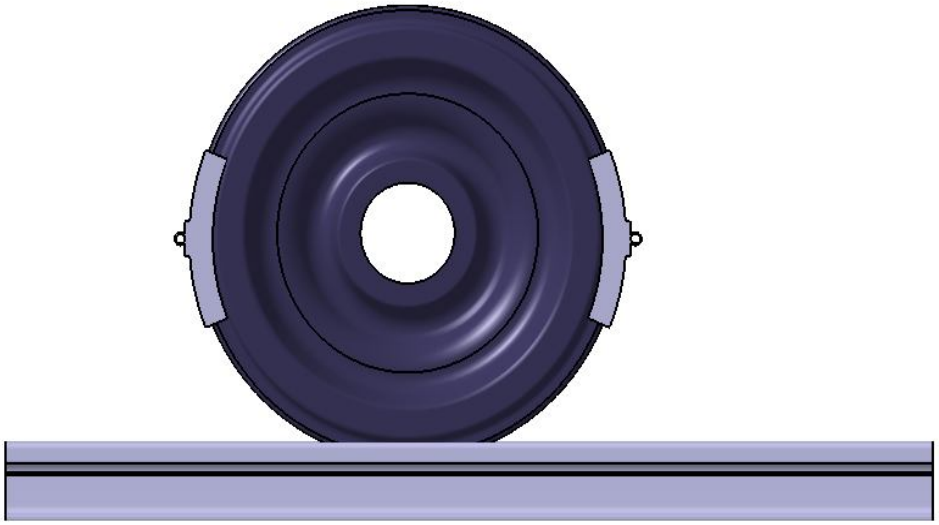


Figure 7. 3D view of Rail -Wheel-Brake model (showing bidirectional block brake)

3.5.3.Transient thermal analysis in ANSYS

ANSYS simulation allows engineers and designers to create practical prototypes of their designs operating under real world multiphysics conditions. As the range of need for simulation expands, one must be able to accurately predict how complex products will behave in real world environments where multiple types of coupled physics interact. Industry-leading software from ANSYS enables engineers and scientists to simulate the interaction between structural mechanics, heat transfer, fluid flow and electromagnetic all within a single, unified engineering simulation environment [30].

A FE thermal analysis is a finite element analysis that looks at how heat affects certain materials and engineering designs. This heat can come in the form of an environmental load such as an ambient temperature of a certain degree affecting a model, or due to friction in a system, effectively converting it into thermal energy. It can also come from processes of conduction through two solids, convection between a liquid and a solid, or radiation such as in space. The Finite element model developed to define the heat flux applied onto the wheel surface in order to analyze the thermal stress behavior during the braking [18].

3.5.3.1. Transient thermal analysis of wheels

The 3D model of the railway wheel and braking blocks is created using the Catia V5 software package. The modeled wheel used in the analysis is the same for different case. Because the wheels are different in material composition and properties, not in structural dimension.

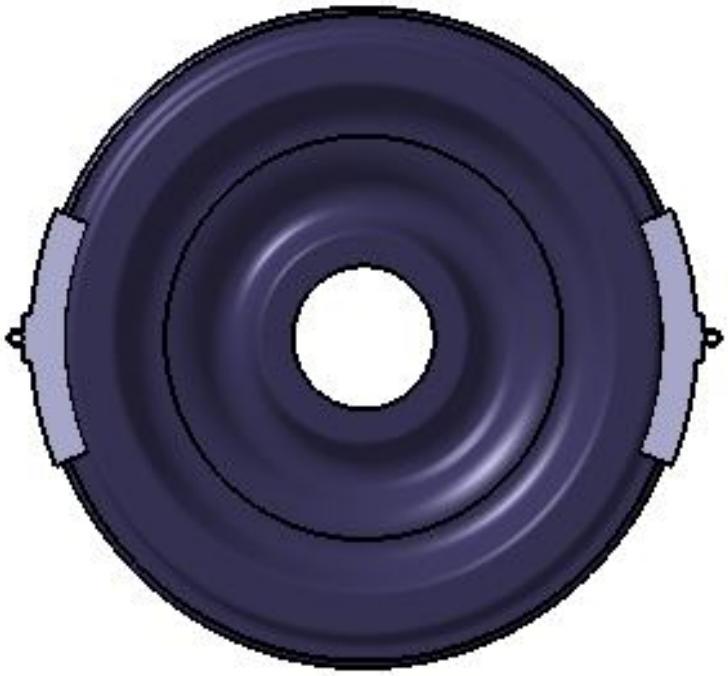


Figure 8. Left 3D view of wheel/brake modeling on Catia V5 software

Meshing

In the finite element analysis the basic concept is to analyze the structure, which is an assemblage of discrete pieces called elements, which are connected, together at a finite number of points called nodes. A network of these elements is called as a mesh. For this analysis, automatic mesh generating means were used in ANSYS rather than defining the nodes individually, after importing the wheel model to ANSYS workbench [22]. The finite elements used for the meshing were Free Tetrahedron. The number of generated nodes in the mesh is 17907and elements is 9710.

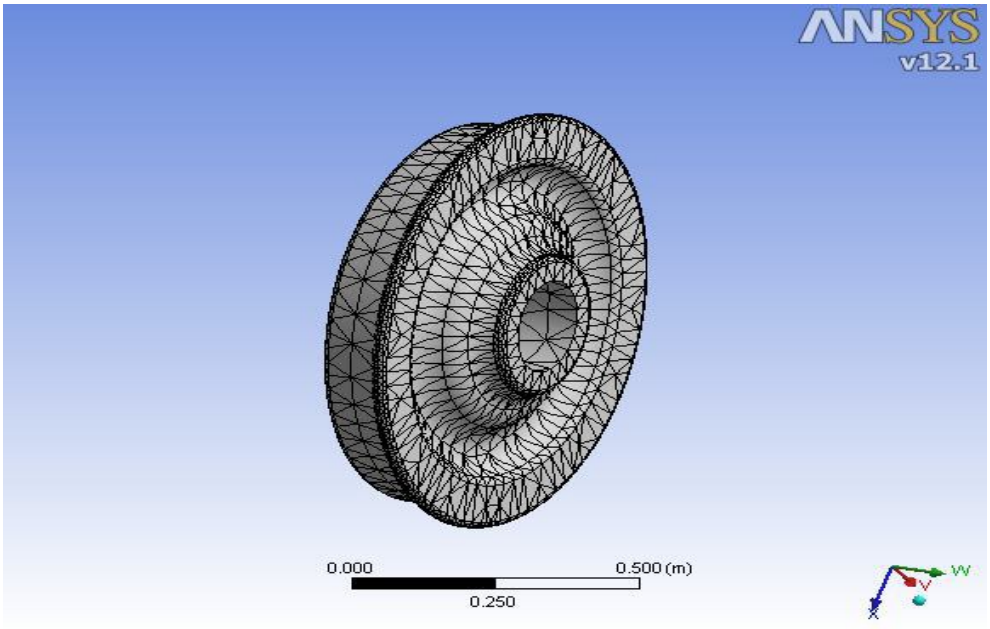


Figure 9. Wheel meshing in ANSYS workbench

Definition of the boundary condition

After completion of the finite element model and mesh, it is necessary to apply constraints and loads to the model. The analyzed railway wheel with braking blocks was subjected to thermal load of heat flux. As it is expressed before, the analysis is going to be done for different speeds and heat flux will vary within the braking time [22]. The heat flux applied on railway wheel tread surface, is assumed uniformly distributed around the wheel circumference, and is equal to the block brake heat flux. The applied heat flux is the same for the wheel 1 (CL60) and wheel 2 (bainitic), since the wheels are going to be analyzed with the same thermal load.

The heat flux applied on wheel at 40km/h is 6.7778 x 10^5 W/m^2.

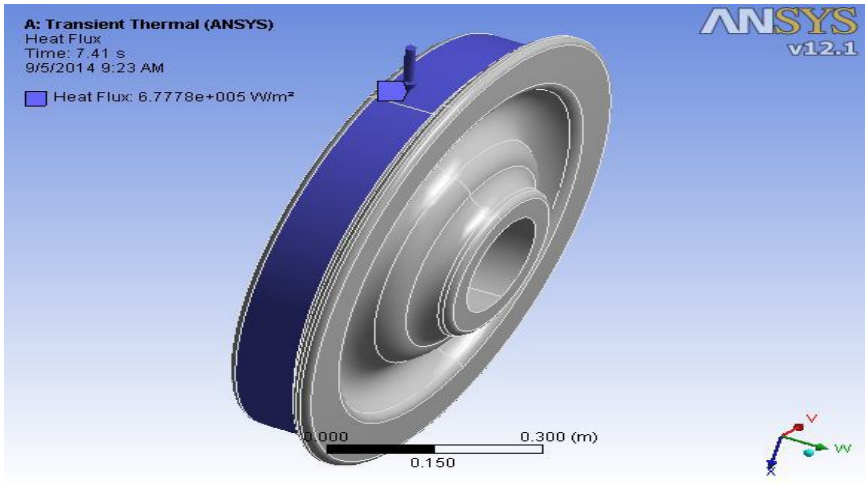


Figure 10. Heat flux applied on wheel at 40km/h

The heat convection from wheel at 40km/h is 11.28 W/m^2K.

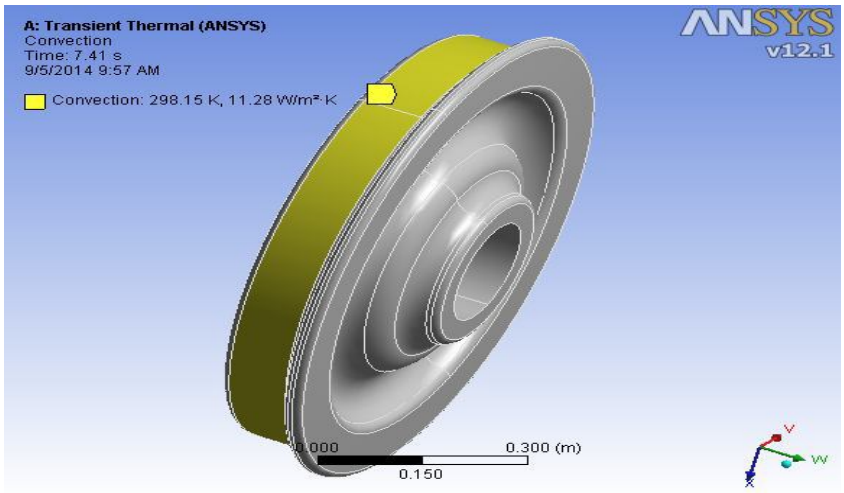


Figure 11. Heat convection from wheel at 40km/h

The heat flux applied on wheel at 65km/h is 1.1041x 10^6 W/m^2.

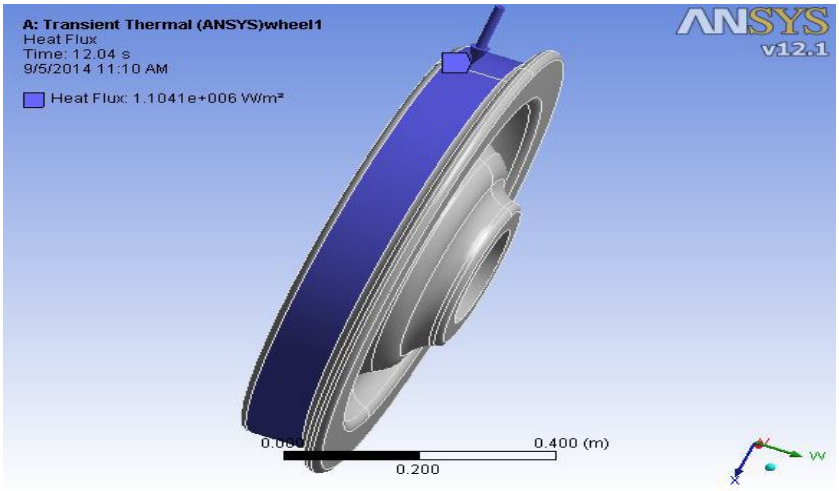


Figure 12. Heat flux applied on wheel at 65km/h

The heat convection from wheel at 65km/h is 16.64 W/m^2K.

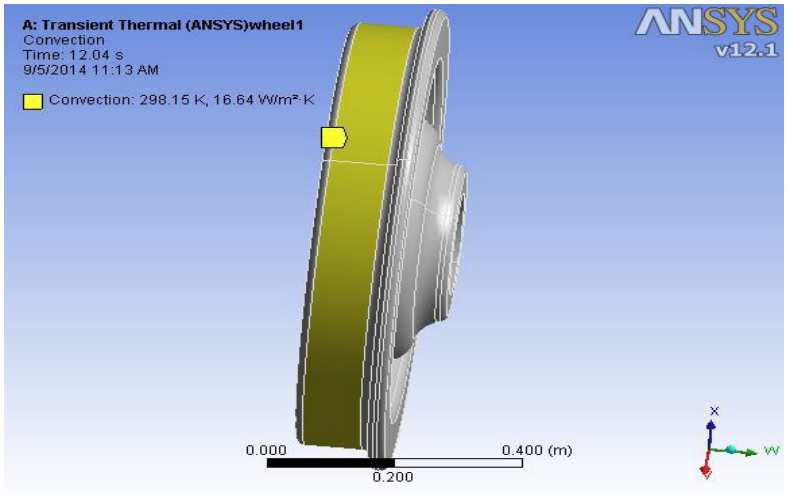


Figure 13. Heat convection on wheel at 65km/h

The heat flux applied on wheel at 100km/h is 1.695513x 10^6 W/m^2.

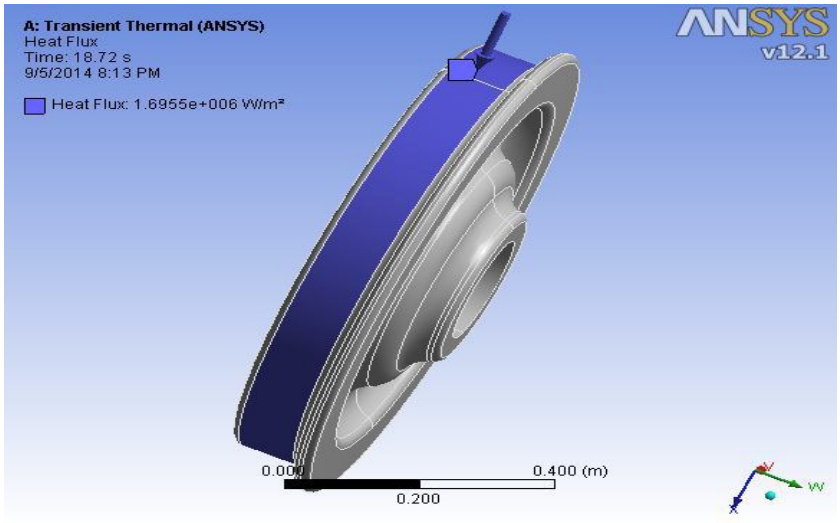


Figure 14. Heat flux applied on wheel at 100km/h

The heat convection from wheel at 100km/h is 23.49 W/m^2K.

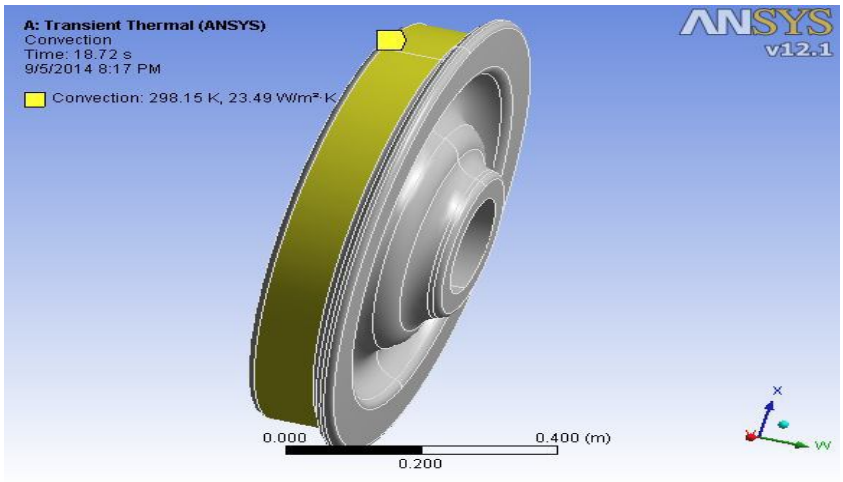


Figure 15. Heat convection on wheel at 100 km/h

3.5.4. Transient structural analysis in ANSYS

Transient structural analysis uses ANSYS mechanical solver and used to determine the dynamic response of a structure under the action of any general time dependent loads.

The transient structural analysis is done using the transient thermal analysis thermal output as input. By applying the thermal condition and initial condition (velocity) on the wheel different stress results are analyzed, for wheel 1 and wheel 2 of different velocities.

CHAPTER 4: RESULT AND DISSCUTION

4.1. Results of Thermal and Structural Analysis of Wheel 1 and Wheel 2

- **Thermal and structural analysis results for 40km/h**

Figures 16 and 17 show the temperature distribution on the tread of wheel 1 (394.54 K maximum and 274.74 K minimum values) and wheel 2 (385.18 K maximum and 276.13 K minimum values). The tread of wheel has maximum temperature that is in contact with the brake.

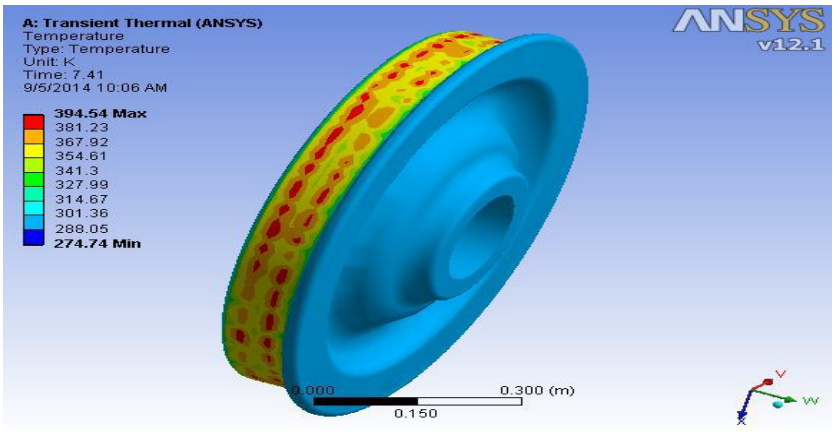


Figure 16. Temperature distribution during braking at 40km/h on wheel 1

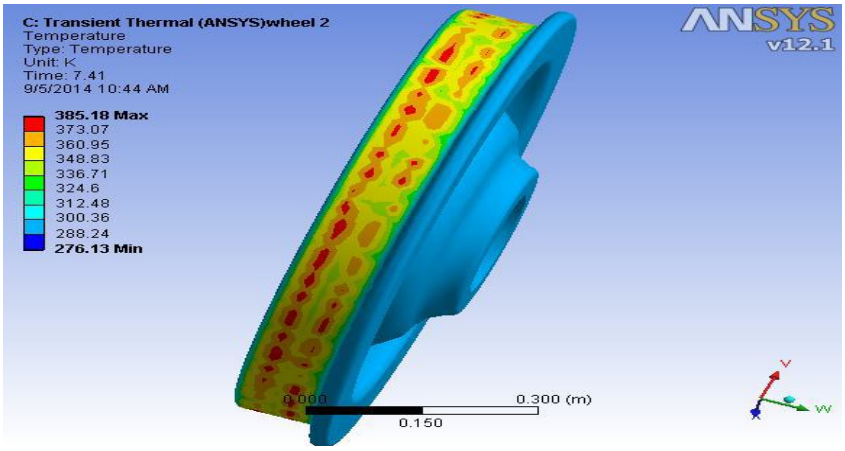


Figure 17. Temperature distribution on wheel 2 at 40km/h

The next figures (figure 18 and 19) demonstrate the Von-Mises distribution on wheel 1 (264.77 MPa maximum and 0.0188 MPa minimum values) and wheel 2 (237.2 MPa maximum and 0.0499 MPa minimum values). The wheel part that has maximum stress is the trade, which is in contact with the brake.

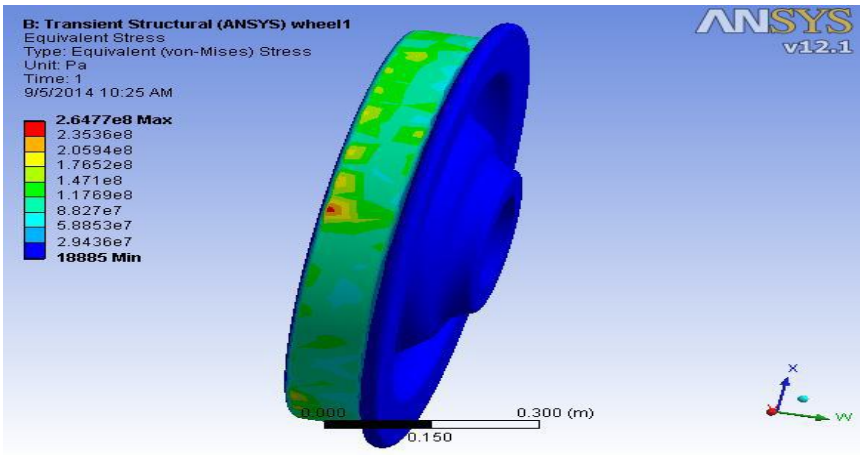


Figure 18. Von-Mises stress on wheel 1 at 40km/h

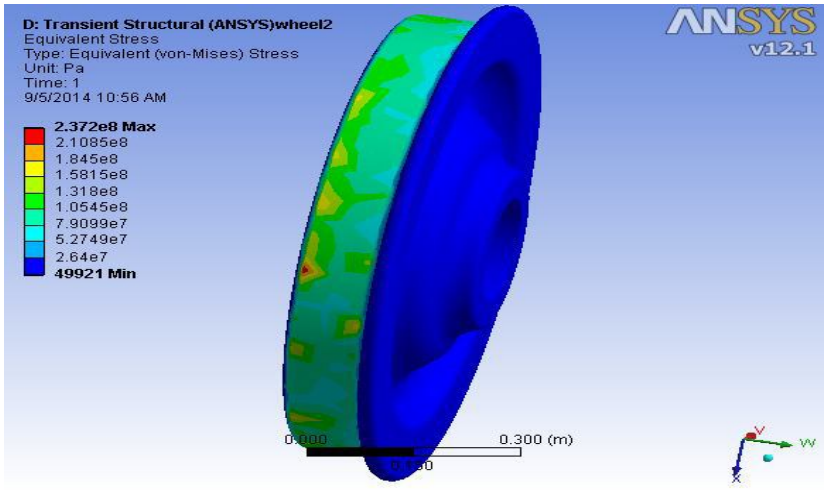


Figure 19. Von-Mises stress on wheel 2 at 40km/h

In the figures (20 and 21) below, the Von-Mises elastic strain on wheel 1 (13.24 x 10^{-4} maximum and 0.000944 x 10^{-4} minimum values) and wheel 2 (11.86 x 10^{-4} maximum and 0.00249 x 10^{-4} minimum values) are build.

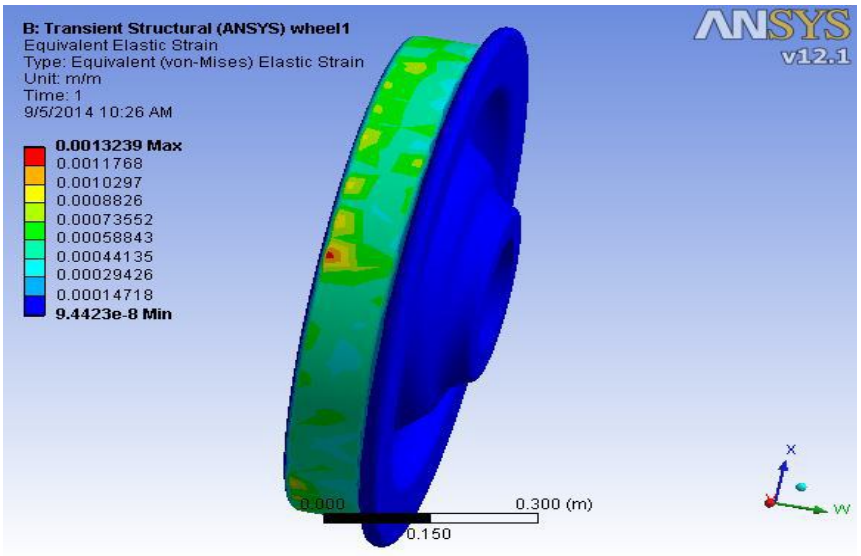


Figure 20. Von-Mises Elastic Strain on wheel 1 at 40km/h

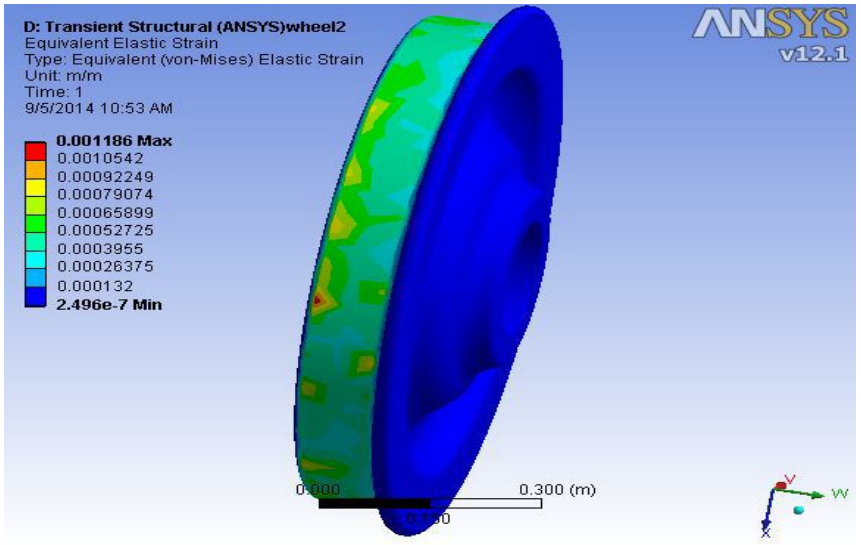


Figure 21. Von-Mises Elastic Strain on wheel 2 at 40km/h

Comparing the two wheels (Wheel 1- CL60 and Wheel 2- Bainitic) at a vehicle speed of 40km/h; wheel 2 has better result in every analysis as shown above. Since the contact (between wheel and brake) is on the trade part of wheel, the effect of thermal load is on it and can cause wear of material.

- **Thermal and structural analysis results for 65km/h**

Figures 22 and 23show the temperature distribution on the tread of wheel 1 (495.3 K maximum and K minimum values) and wheel 2 (475.85 K maximum and 261.3 K minimum values). The tread of wheel has maximum temperature that is in contact with the brake.

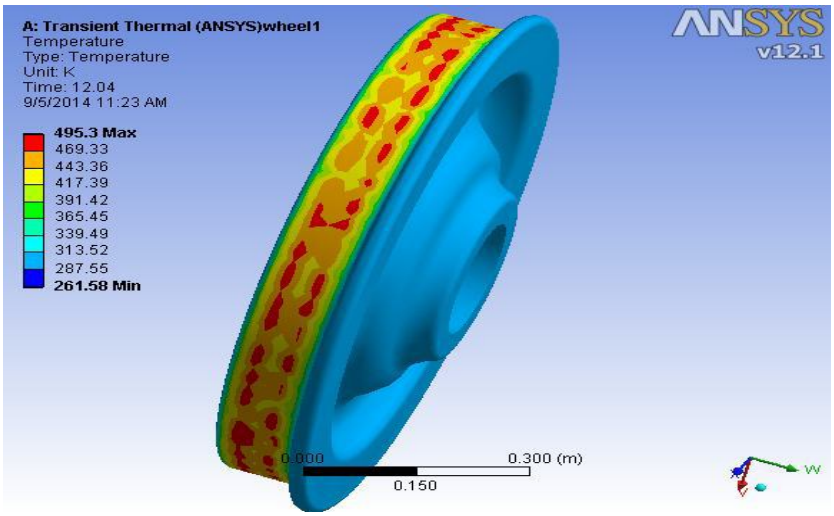


Figure 22. Temperature distribution during braking at 65km/h on wheel 1

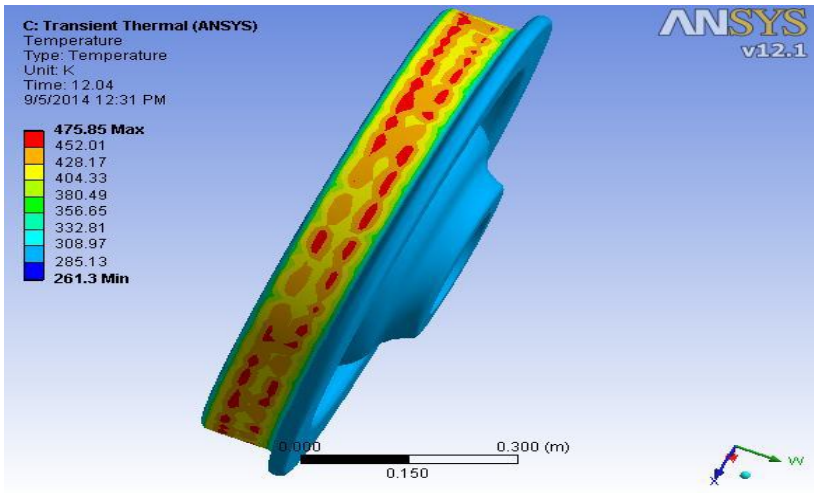


Figure 23. Temperature distribution on wheel 2 at 65km/h

The next figures (figure 24 and 25) demonstrate the Von-Mises distribution on wheel 1 (552.33 MPa maximum and 0.1064 MPa minimum values) and wheel 2 (494.41 MPa maximum and 0.0897 MPa minimum values). The wheel part that has maximum stress is the trade, which is in contact with the brake.

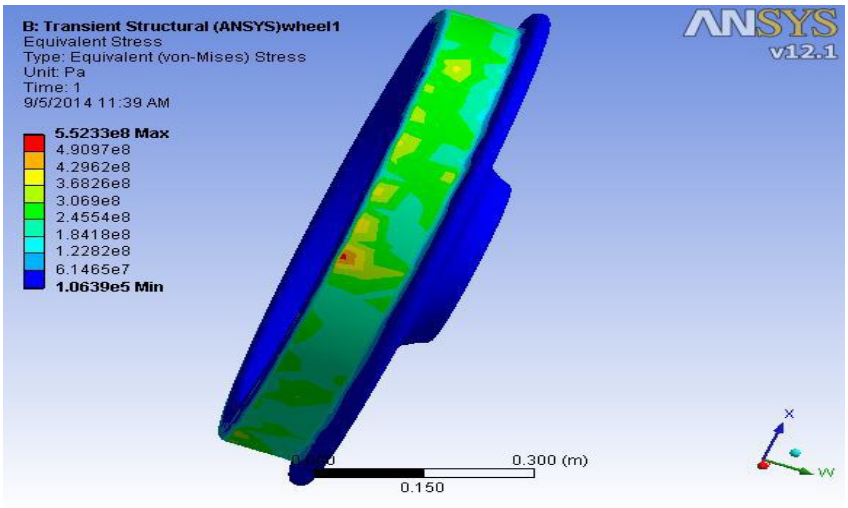


Figure 24. Von- Mises stress on wheel 1 at 65km/h

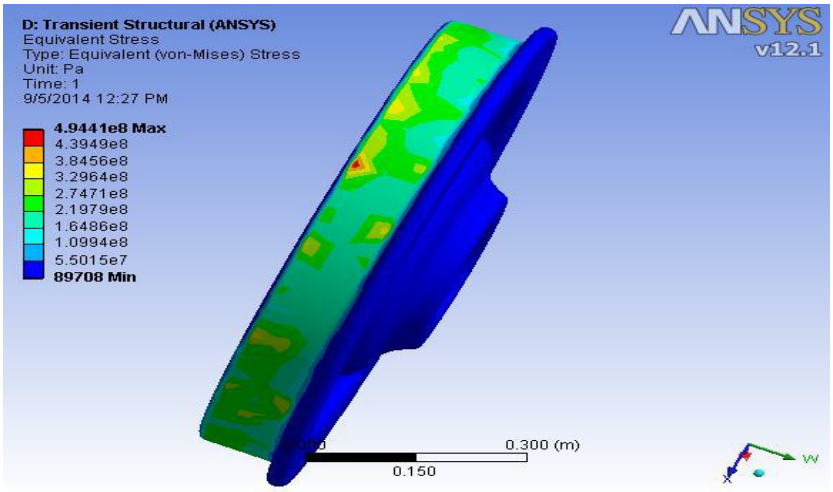


Figure 25. Von-Mises stress on wheel 2 at 65km/h

In the figures (26 and 27) below, the Von-Mises elastic strain on wheel 1 (27.617 x 10^{-4} maximum and 0.00532 x 10^{-4} minimum values) and wheel 2 (22.907 x 10^{-4} maximum and 0.00145 x 10^{-4} minimum values) are build.

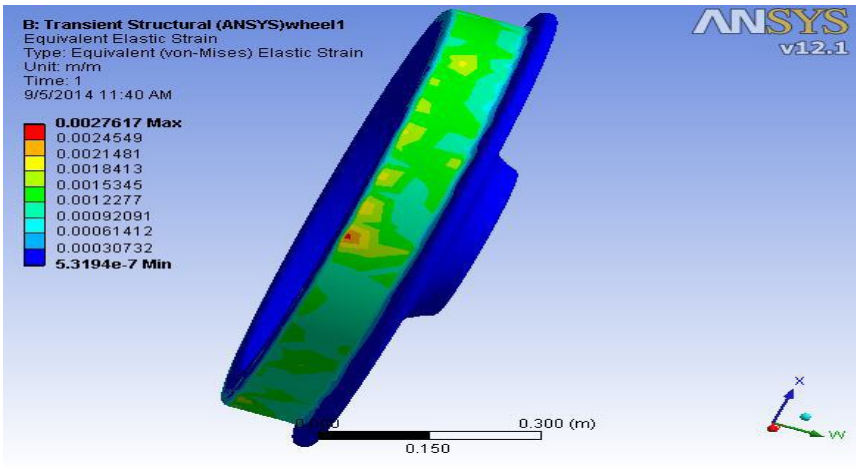


Figure 26. Von-Mises elastic strain on wheel 1 at 65km/h

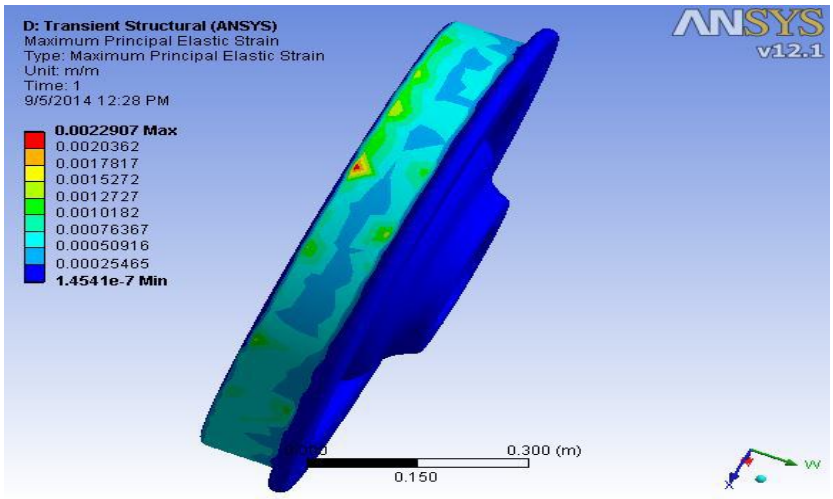


Figure 27. Von-Mises Elastic Strain on wheel 2 at 65km/h

Contrasting the two wheels (Wheel 1- CL60 and Wheel 2- Bainitic) at a vehicle speed of 65km/h; wheel 2 has improved result in every analysis as shown above. Since the contact (between wheel and brake) is on the wheel trade, the effect of thermal load can cause wear of material.

- **Thermal and Structural analysis results for 100km/h**

Figures 28 and 29 show the temperature distribution on the tread of wheel 1 (639.36 K maximum and 260.46 K minimum values) and wheel 2 (605.04 K maximum and 256 K minimum values). The tread of wheel has maximum temperature that is in contact with the brake.

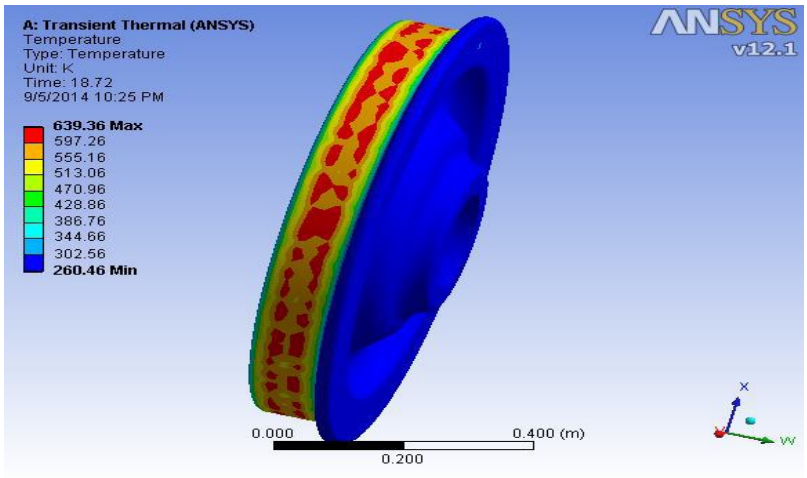


Figure 28. Temperature distribution during braking on wheel 1 at 100km/h

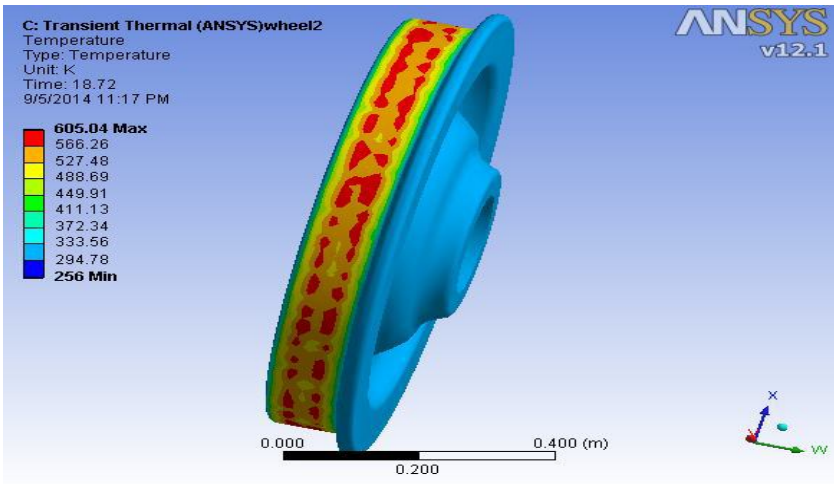


Figure 29. Temperature distribution on wheel 2 at 100km/h

The next figures (figure 30 and 31) demonstrate the Von-Mises distribution on wheel 1 (978.28 MPa maximum and 0.339 MPa minimum values) and wheel 2 (872.71 MPa maximum and 0.263 MPa minimum values). The wheel part that has maximum stress is the trade, which is in contact with the brake.

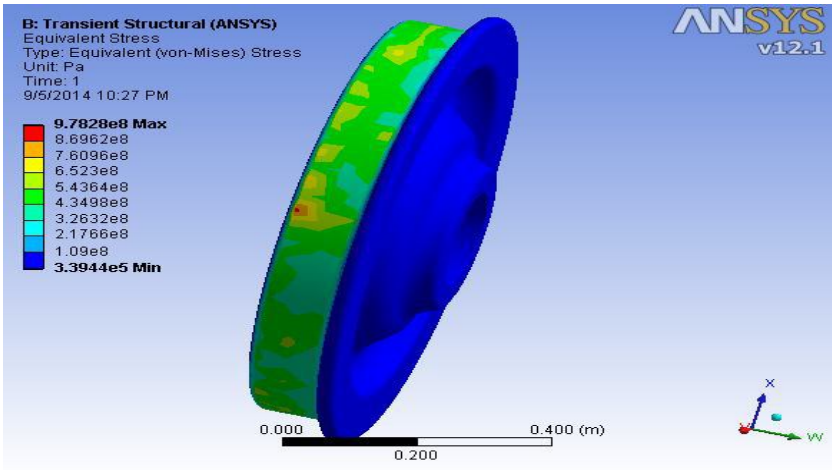


Figure 30. Von-Mises stress on wheel 1 at 100km/h

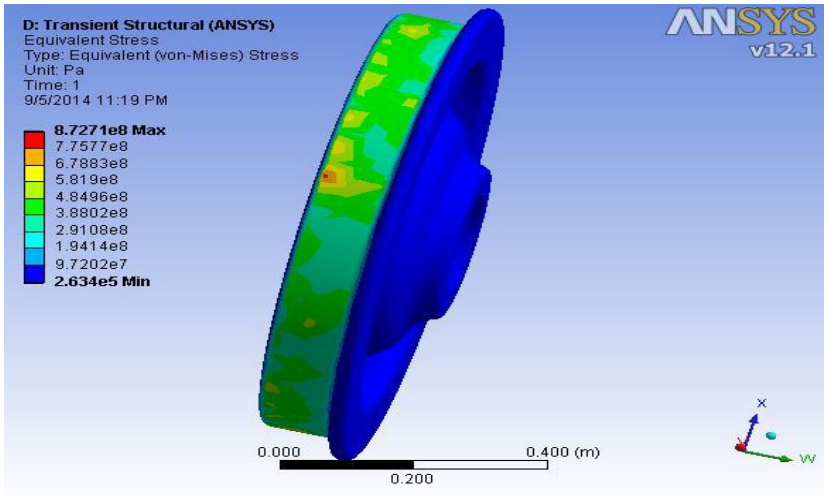


Figure 31. Von-Mises stress on wheel 2 at 100km/h

In the figures (32 and 33) below, the Von-Mises elastic strain on wheel 1 (48.914 x 10^{-4} maximum and 0.01697 x 10^{-4} minimum values) and wheel 2 (43.636 x 10^{-4} maximum and 0.01317 x 10^{-7} minimum values) are build.

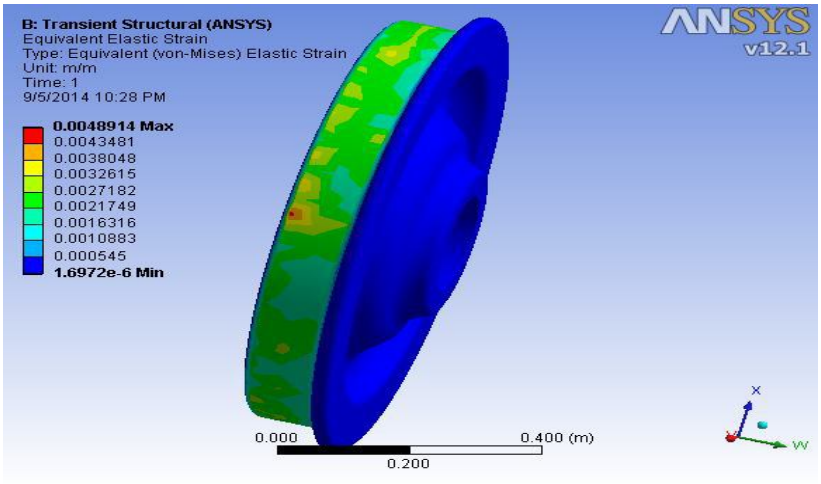


Figure 32. Von-Mises elastic strain on wheel 1 at100km/h

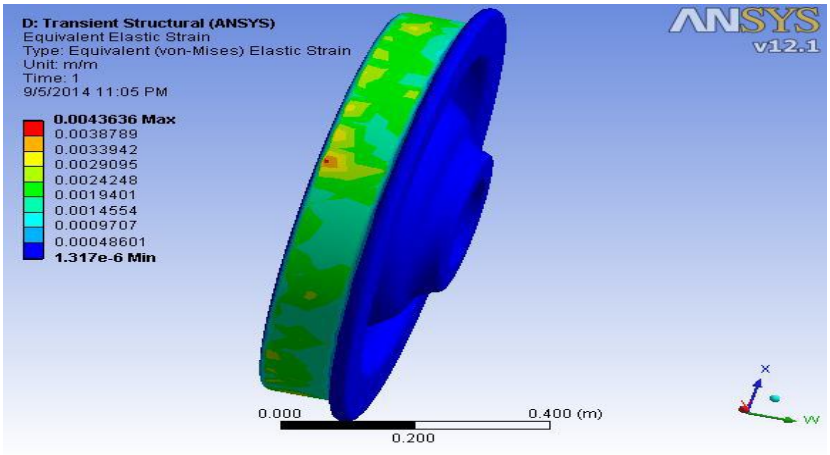


Figure 33. Von-Mises Elastic Strain on wheel 2 at 100km/h

Comparing the two wheels (Wheel 1- CL60 and Wheel 2- Bainitic) at a vehicle speed of 100km/h; wheel 2 has improved result in every analysis as shown above. Since the contact (between wheel and brake) is on the trade part of wheel, the effect of thermal load is on it and can cause wear of material.

4.2. Experimental Result of Bainitic Wheels

The low-medium carbon Si-Mn-Mo-V steel was designed to make railway wheels by forging and rolling. The slack quenching with water was conducted on the tread of rim section by programmed control to simulate isothermal heat treatment after being austenitized. Microstructures and mechanical properties have been studied and the mechanical properties of Bainite are superior to the CL60 plain carbon as shown in table 2 and 3. The microstructure results indicate that the rim is mainly carbide-free bainite, and the mixed microstructure of bainitic ferrite and granular bainite are observed in web and hub. To improve thermal damage, as well as the ductility and toughness at an equal ultimate tensile strength, the principle of the latest design for wheel steels is to decrease carbon content. The essence of the problem is carbon content leading to inhomogeneity in sections of wheels, because the microstructure and properties of medium carbon steels are too sensitive to a cooling rate, so low carbon content is preferred. The Bainitic wheel steel has higher hardenability compared with CL60 by metallographic structures and hardness profiles. The impact energy is relatively high at room and/or subzero temperatures and it have excellent resistance ability to crack initiation and propagation [17].

4.3. Discussion

The focus of this paper is on the contact temperatures (thermal load) due to braking of wheel. The contact (frictional) temperature between brake shoe and wheel can be estimated with the ANSYS analysis. Two different compositions of materials of wheel are considered. The materials microstructure and mechanical properties are studied in [26]. The ANSYS result for the two wheels with different velocities are:

Table 12. Summary of results of the two wheels due to thermal load of braking

Wheel type	Wheel 1 (CL60)			Wheel 2 (Bainitic)		
Velocity	40km/h	65km/h	100km/h	40km/h	65km/h	100km/h
Temperature (^{0}C)	121.39	222.15	366.21	112.03	202.7	331.89
Von-Mises Stress (Pa)	2.65 x 10^8	5.52 x 10^8	9.78 x 10^8	2.37 x 10^8	4.94 x 10^8	8.73 x 10^8
Von-Mises Elastic Strain (Pa)	0.0013	0.025	0.0049	0.0012	0.0023	0.0044

The temperature increases as the initial braking velocity increases for the two wheels. Stress and strain of the wheels also increases as speed of the rail vehicle increases. As it can be seen in the above ANSYS results and table, the values of each increase with the increase of vehicle braking speed. But, comparing the two wheels (wheel 1 and wheel 2), all results show that wheel 2 has better resistance to thermal load, as experimentally proved.

The temperature for the two wheels increases during braking (block braking) as the initial braking velocity of the vehicle increases. But comparing the wheels, the frictional heat (temperature) between wheel and block brake is lesser in wheel 2. This is because, The carbon content in wheel 2 is low as compare to wheel 1 and decreasing the carbon content in the material composition improve thermal damage resistance, as well as the ductility and toughness of the material.

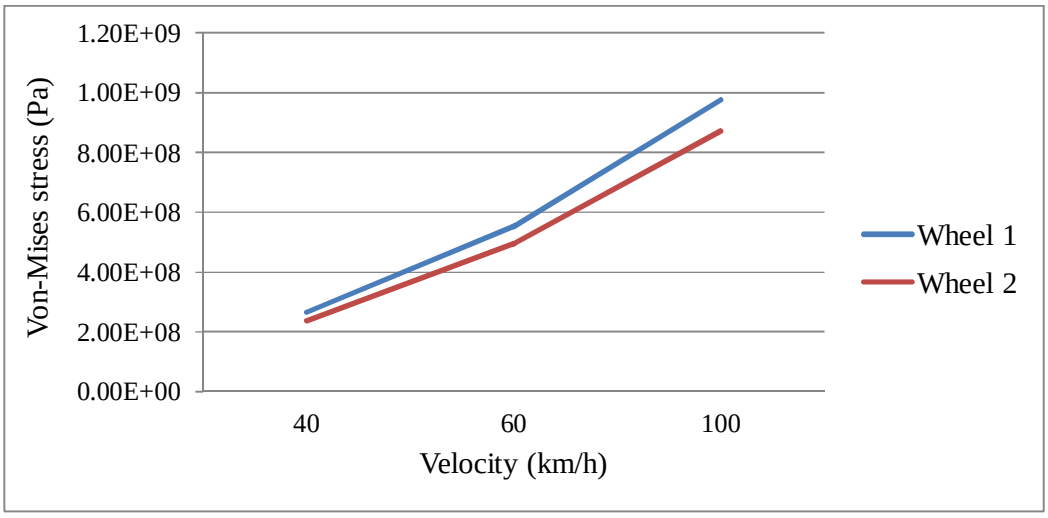


Figure 34. Velocity-stress graph for wheel 1 and wheel 2

In the graph above, the Von-Mises stress and vehicle velocity are given for two different wheels. The result shows that the stress on the wheels increases with increasing vehicle speed. Even though the stress increases for each wheel, the stress on wheel 1 is greater than the stress on wheel 2. This proves that wheel 2 material have better strength than wheel 1. This is because of the material composition difference, the addition of molybdenum and vanadium in wheel 2 (Bainitic) increased the hardness, strength and toughness of the material.

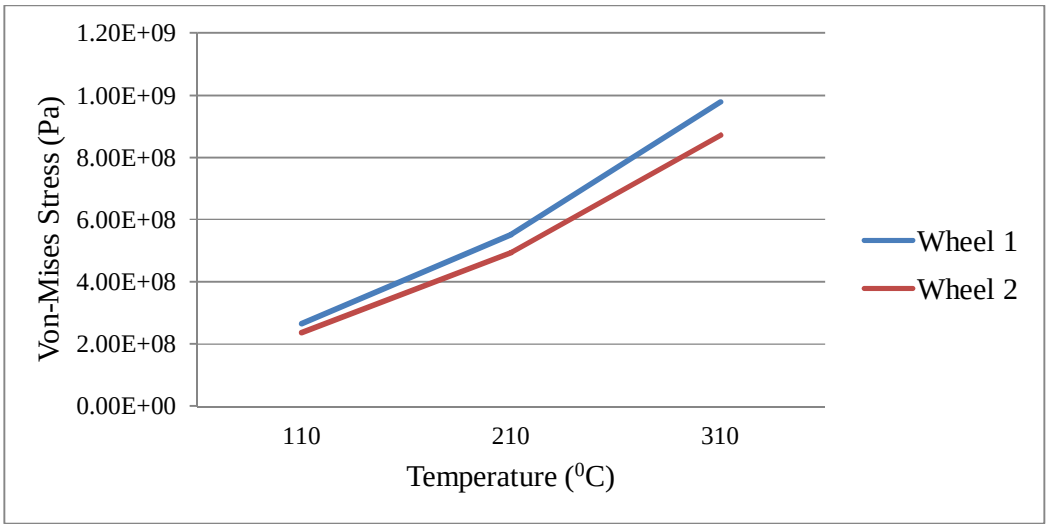


Figure 35. Temperature verses Von-Mises stress graph

In the graph above, the temperature and Von-Mises stress are given for two different wheels. The result shows that the stress on the wheels increases with increasing temperature. Even if the stress increases for each wheel, the stress on wheel 1 is greater than the stress on wheel 2. This proves that wheel 2 material have superior strength than wheel 1. This is because of the material composition difference, the addition of molybdenum and vanadium in wheel 2 (Bainitic) increased the hardness, strength and toughness of the material.

CHAPTER 5: CONCLUSION, RECOMANDATION AND FUTURE WORK

5.1. Conclusion

In this research, the influence of wheel materials on thermal load of braking is studied. During braking there is frictional heat produced between wheel and block brake, this frictional heat load is applied to wheel 1 (CL60) and wheel 2 (Bainitic) which have different chemical composition and property, but same structural dimension. The wheels are analyzed for different running speeds (40, 65, and 100km/h). The result obtained is that wheel 2 (Bainitic) is better in resisting thermal load stresses, because of its improved chemical composition and material properties.

Wheel 2 (Bainite) steel may provide improved performances, and minimize the sensitivity to high transient thermal damage and can provide longer life even if for high speed and heavy axle load freight transportation.

5.2. Recommendation

As it is said and analyzed before, the wheel 2 (Bainitic) material compositions is enhanced than that of wheel 1 (CL60). So it's better for Ethiopian Railway Corporation to use this wheel (wheel 2) for the national railway system by making further study.

5.3. Future Work

The following are suggested for future work as extensions and elaborations of this research.

- More investigation of wheel materials with experimental analysis.
- Additional study by considering vertical and horizontal loads.
- Further investigation by taking into account gradients of the track.
- Another study for wear out wheels.

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DECLARATION

I, the undersigned, declare that this thesis is my original work and has not been presented for any degree in any university and all the sources of materials used for the thesis have been duly acknowledged.

Frehiwot Alemayehu	_____	_____
Name	Signature	Date