THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Thermomechanical behaviour of tread braked wheels

Material modelling and experimental investigations

Eric Voortman Landström

CHALMERS
UNIVERSITY OF TECHNOLOGY

Department of Mechanical and Maritime Sciences
Chalmers University of Technology
Gothenburg, Sweden, 2022

Thermomechanical behaviour of tread braked wheels
Material modelling and experimental investigations

Eric Voortman Landström

Technical Report No. 2022:11
This thesis has been prepared using LaTeX

Department of Mechanical and Maritime Sciences
Chalmers University of Technology
SE-412 96 Gothenburg, Sweden
Phone: +46 (0)31 772 1000
www.chalmers.se

Printed by Chalmers Reproservice
Gothenburg, Sweden, October 2022

You know, the worst thing about being a slave,
they make you work, but they don't pay you or let you go.
– Philip J. Fry, Futurama

Abstract

Tread brakes, also known as block brakes, are a type of friction brakes commonly used in the railway industry. They are a low-cost and low-maintenance solution compared to more complicated systems such as disc brakes or electrodynamic brakes. Modern composite brake blocks designed to lower noise emission, however, cause increased thermal loading of the wheel since these blocks attract and store lower amounts of the generated frictional heat compared to older cast iron blocks. Long-term drag braking may raise the temperature of the wheel rim by several hundred degrees. After cooling the resulting residual tensile stresses in the wheel rim may lead to a broken wheel. Also a permanent degradation of the pearlitic steel material is induced by the high temperatures.

In the first part of the present work, a finite element material model is calibrated using isothermal and anisothermal experimental data from testing of railway wheel steel specimens, accounting for the macroscale material changes which occur during typical thermomechanical cycles at long-term braking. Results are presented with main focus on comparing finite element simulations to experimental measurements of the thermomechanical cycles. Material deterioration by spheroidisation of the pearlitic material is modelled using a time-temperature dependent law.

In the second part, the material model is further evaluated using axisymmetric simulations of tread braked train wheels, and the wheel performance is evaluated according to current European standards. Results are presented that show a substantial increase in the magnitude of the modelled residual tensile stresses as compared to other widely-used material models.

In the third part, experiments and measurements on tread braked wheels are conducted in a full-scale test rig. It is found that the temperature distribution in the axial and circumferential directions on the wheel tread exhibits substantial variations which can be of importance in the understanding of the full thermomechanical behaviour of a wheel. Numerical simulations show that there is an increase in residual tensile stress at locally hotter areas, a phenomenon which has a potential to compromise the safety of the system.

Keywords: Railway wheels, tread braking, high temperature testing, full-scale brake rig testing, finite element analysis, thermal analysis, thermomechanical analysis

List of Publications

Paper A E. Voortman Landström, E. Steyn, J. Ahlström and T. Vernersson. Thermomechanical testing and modelling of railway wheel steel, Chalmers Applied Mechanics /CHARMEC, Gothenburg, 2022, 30 pp.
Submitted for international publication

Paper B E. Voortman Landström, T. Vernersson, R. Lundén. Improved modelling of tread braked wheels using an advanced material model,
Proceedings of EuroBrake 2022, 8 pp.

Paper C E. Voortman Landström, T. Vernersson, R. Lundén. Thermal measurements and analysis of tread braked wheels, Chalmers Applied Mechanics/CHARMEC, Gothenburg, 2022, 20 pp. *Extended version to be submitted for international publication*

Acknowledgements

This work has been performed at the Department of Applied Mechanics, Chalmers University of Technology during 2019–2022. It is part of the project SD11 “Tread braking – capacity, wear and life” within the Swedish National Centre of Excellence in Railway Mechanics CHARMEC (CHAlmers Railway MEChanics). The special support from Lucchini (in Sweden and Italy), from Faiveley Transport Nordic / Becorit / Wabtec, from Trafikverket´s Areas of Excellence and from the project reference group with members from Alstom (in Sweden, Germany and UK), Atkins Sverige, Faiveley Transport Nordic / Wabtec and Green Cargo is gratefully acknowledged.

The persons deserving my deepest gratitude are my supervisors Docent Tore Vernersson and Professor Emeritus Roger Lundén. I cannot express how grateful I am for all of the invaluable advice and guidance, the enjoyable interactions at lunch and the stalwart corrections of all of my writings. It would not have been possible to accomplish this work without you. I also want to give my thanks to Mr Jan Möller for all his contributions when making the brake test rig at Chalmers a reality.

Special thanks go to my co-authors Erika Steyn and Johan Ahlström from Industrial and Materials Science at Chalmers for performing all of the specimen testing and for all our fruitful discussions regarding the wheel material and its behaviour.

I would like to thank all of my friends and colleagues at the Division of Dynamics and the Division of Material and Computational Mechanics for the shared joys. You make the concept of Mondays easier to bear, and the workplace would be a much more boring place without you.

Finally, I would also extend my gratitude to the students I have met when teaching at Chalmers. Your frankly insane solutions to many problems always bring a smile to my face and I am happy to now call many of you friends. I sincerely hope that all of you have found our lessons as stimulating as I have, and I cannot wait to see how well you will do as practicing engineers.

The simulations in this project were performed by use of resources at Chalmers Centre for Computational Science and Engineering (C3SE) provided by the Swedish National Infrastructure for Computing (SNIC).

Gothenburg, October 2022
Eric Voortman Landström

Contents

Part I

Overview

CHAPTER 1

Introduction

1.1 Motivation

Tread braking or block braking is the most commonly used braking system for freight wagons throughout Europe. The braking action is performed by pressing the brake block(s) against the tread (running surface) of the wheel. The tread brakes should ideally provide the required braking capacity of the train for everything from normal service braking to extreme braking conditions. Furthermore, they should be robust when it comes to environment and variations in utilisation. At braking, the kinetic energy of the train is transformed into heat via friction; the heat then being partitioned between the wheel and the brake blocks. At the same time as this heating occurs, the wheel is in rolling contact with the rail. In particular, the small contact patch between the rail and the wheel is subjected to very high contact loads. Thus, the wheel is utilised as a friction-heated component, that at the same time is worn by brakes, and is subject to rolling contact loads. This means a very complex thermomechanical loading case where elevated temperatures and contact loads combine.

Up til now, mainly cast iron brake blocks have been used and they transferred large amounts of the friction heat, acting as a heat sink for the wheel and preventing very high temperatures. In an effort to reduce noise emissions caused by the wheel tread roughness resulting from braking with cast iron blocks, these brake blocks are to be phased out through noise regulation from EU, in favour of sintered or organic composite brake blocks. Sweden and Finland have been granted exceptions from these requirements until 2032 and cast iron blocks are thus still allowed on wagons in service, but other brake block materials will be dominating on wagons in international traffic. However, when using sintered or organic composite brake blocks, a larger part of the heat is absorbed by the wheel, possibly causing significant issues at long-term braking or at malfunctions when the brake blocks cannot retract. A wheel that has been subjected to an extreme tread braking event is shown in Figure 1.1.

Several incidents, where wheels were damaged or broken by thermomechanical effects have become issues, are published by the Joint Network Secretariat on the official website of the European Union. In 2016 cracked and broken wheels of the BA314/ZDB29 and BA004 types were investigated [1]. It was found that the failures were at least partially caused by thermal overload. Such incidents have resulted in new proposals for wheel utilisation and for amendments of standards and regulations, in particular with regard to thermomechanical pre-dimensioning and wheel design requirements. In addition, improved methods for detecting thermal overload of wheels and regulations regarding braking in traffic are proposed [1]. The main issue in these cases is often a combination of very high temperatures and thermomechanical stresses, stemming from build-up of temperature gradients in the wheels. This is problematic for the medium carbon wheel steel materials which are not explicitly designed for these temperatures, compared to modern high temperature alloys designed for use at temperature around 600 °C, such as Haynes 282 [2]. Previous investigations of the ER7 wheel steel have shown that static properties such as yield strength are significantly lower at temperatures above 400 °C, and that properties are reasonably stable only up to 300 °C [3]. Additionally, it has been shown that pearlitic wheel steels undergo a spheroidisation process above 450 °C, the rate of which increases rapidly above 500 °C [3]. Incidents of thermal overloads from, e.g., malfunctioning brakes are unlikely to totally disappear unless large investments in infrastructure or wagons are made. Therefore, it is crucial to understand the limits of the tread braking

Figure 1.1: Wheel damage due to an extreme tread braking event where the running surface has been gradually worn away and material has been rolled out axially.

system so that it can be utilised broadly in a safe and maintenance-efficient way.

1.2 Research objective

Improving the understanding of how thermomechanical load cases affect railway wheels would be beneficial for the railway industry as tread brakes are still the most common type of braking system utilised in freight. Moreover, tread brakes are also attaining increased interest for use on passenger trains, where they are employed in combination with other braking systems. To this end, significant efforts have previously been made both in testing and modelling. The present work, which is a part of the SD11 doctoral project at Chalmers Railway Mechanics (CHARMEC) has focused on thermal and thermomechanical effects of block braking. In particular, three main areas are to be investigated:

1. Extreme braking situations and safe limits for railway wheels

2. Temperature effects and rolling contact fatigue of wheels

3. Wear of braking components with a focus on temperature effects

The first area of the research project is reported in the present thesis. It focuses on the modelling of the wheel material behaviour at elevated temperatures and starts the verification work of the modelling approach by thermal and thermomechanical full-scale experiments using a brake rig. The objectives have been:

- Understanding how the ER7 wheel steel behaves when exposed to the cyclic thermomechanical loads that a tread braked wheel is exposed to during braking

- Improving and calibrating a material model that can be used for prediction of the thermomechanical behaviour of the steel

- Investigation of local heating phenomena in the form of hot spots and temperature banding on the tread of a blocked braked wheel

The focus in the second part of the project will be on full-scale experimental verification of finite element models employing the material model. Additionally, experiments and modelling of rolling contact behaviour are planned. The ultimate aim is to develop verified numerical models that can capture the most relevant behaviours, as well as to attain accurate experimental results suitable for calibration and verification of wheel behaviour during tread braking. The intention is that both numerical and experimental results should be accurate enough so that safety measures and maintenance decisions can be taken based on them.

1.3 Research collaboration

The work in this thesis has been carried out within the CHARMEC project SD11 *Tread braking - capacity, wear and life.* The experimental materials testing and characterisation was carried out in collaboration with Erika Steyn and Johan Ahlström working within the CHARMEC project MU36 *Material Characteristics in welding and other local heating events* at Chalmers Industrial and Materials Science. In project MU36, thermomechanical and hardness testings of wheel steel specimens were performed to gather the data used in the calibration process and in material model enhancements performed in the present work.

CHAPTER 2

The block braking system

2.1 Tread braked wheels

Tread brakes are one of the most common mechanical friction braking systems on railway vehicles. It is ordinarily used on freight wagons, but are also common on low-speed passenger trains and trams, often in combination with disc brakes and electrodynamic brakes. Consisting of an externally mounted pneumatic brake actuator which pushes brake blocks onto the running surfaces of the wheels, it is a robust, low-cost and low-maintenance braking system. It requires access only to pressured air to control the actuator and only a minimum of components are needed. A simplified illustration of the braking system can be seen in Figure 2.1, showcasing the brake–wheel–rail system with the thermal loading from the wheel–brake interaction and the wheel–rail rolling contact loading. This can be put in contrast with the more complex and expensive disc brakes which are mounted either on the wheel axle or on the wheel itself, as well as electrodynamic brakes. The latter would require electrification and is normally provided only on locomotives.

The block brakes promote adhesion to the rail by conditioning the wheel surface, which is beneficial for both traction and braking. Some drawbacks of the block braking system are however also evident. The use of the wheel as a frictional component may cause damage by excessive heating, especially with modern organic composite or sinter material brake blocks, when compared to older cast iron blocks. This may be in the form of local damage such as rolling contact fatigue or global damage including radial cracks leading to global failure of the wheel. In addition, due to roughness induced from deposition of metal (for cast iron blocks) and wear of the tread, the rolling noise levels from trains with block brakes compared to trains using disc brakes are higher, which has becoming a major environmental issue as detailed in Section 2.2. This is also the driving factor for the change from cast iron blacks to composite and sintered blocks which give less rolling noise. However, issues remain concerning performance of these brake blocks in,m e.g., winter conditions [4].

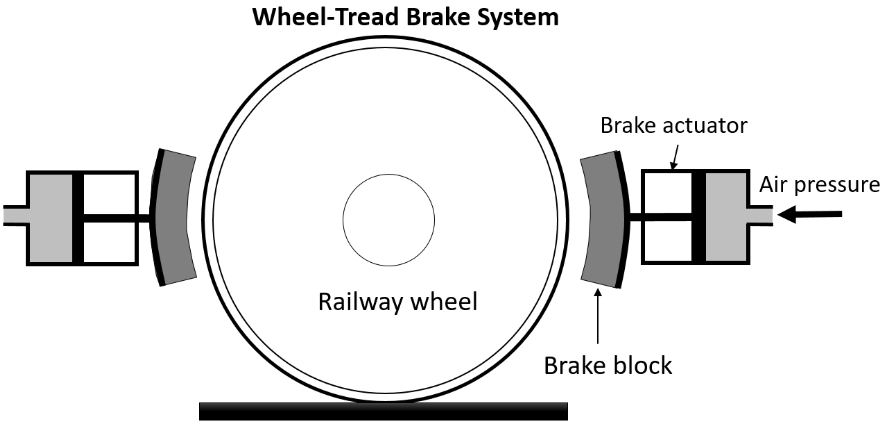

Figure 2.1: Simplified illustration of the wheel-tread braking system.

2.2 Noise

Significant efforts have been made to decrease the noise emissions from railway traffic. In 2001, the European Union enacted a directive concerning the interoperability of the Trans-European conventional rail network. The directive, 2001/16/EC, contained provisions for, amongst others, noise problems deriving from rolling stock and infrastructure [5]. This directive has then been continually updated and complemented in, e.g., 2008 by a technical specification for interoperability relating to the 'rolling stock' sub-system of the Trans-European high-speed rail system [6] (based on [7]). Further amendments were decided upon in 2011 [8] and then again 2014 [9], where the directives were to encompass noise of rolling stock in general. Intended to reduce the impact of environmental noise stemming from railway vehicles, this has had the effect of implicitly banning the use of cast iron brakes within most of the European Union, with Sweden and Finland being granted an exception until 2032.

When considering replacements of cast iron blocks, disc brakes would be a superior solution regarding noise when compared to tread brakes. However, this alternative would be very costly, in both short and long terms, given the large number of freight wagons with tread brakes to be rebuilt and maintained. Also, new wagons would be more costly.

Examples of different European projects on railway noise are EuroSABOT, Silent Freight, Silent Track and ERS (Euro Rolling Silently) in which Chalmers /CHARMEC was a partner, with the outcomes that non–cast iron brake blocks generate less rolling noise. This is because surface roughness levels are lower on wheels braked with alternatives to cast iron blocks. The cast iron blocks deposits molten cast iron particles on the wheel itself. The uneven surface then induces fluctuating contact forces leading to vibrations in the system and radiation of noise.

2.3 Thermal loading

At tread braking, the frictional heat generated in the area of contact is partitioned between block and wheel, and then further conducted from the hot wheel into the cold rail and the surrounding air through convection and radiation. Experimental studies [10]–[12] of railway tread braking in a brake rig was performed in order to investigate temperature distribution and evolution in wheel and blocks. The focus was on overall heat partitioning between wheel and blocks and the prediction of average temperature employing presumed constant contact pressures.

During braking hot spots with a wavelength of 6–20 cm may evolve on the wheel tread because of frictionally induced thermoelastic instability [13], [14]. The temperatures at hot spots or hot bands may be significantly elevated compared to the average temperatures, with damage being induced at positions exposed to high temperatures [15], [16]. This phenomenon is studied in the experimental part of **Paper C**, where the distribution and magnitude of the hot spots are showcased. By use of thermographic measurements, it can be seen that there is on average a distance of 16 cm between hot spots, but also that the temperature can differ by several hundred between adjacent areas. Also, these hot spots, although often stationary in time, are not necessarily evenly distributed over the entire wheel circumference. This can be seen in Figure 2.3, in which wheel temperatures for some chosen time instants are presented as detected using a thermographic camera. Figure 2.3 also includes the reflection of the wheel tread by the mirror, to the left in the thermographs, showing that the temperature distribution on the tread is approximately stationary with similar distances between the hot spots. The results indicate that the distribution is stationary and somewhat periodic in time, but also that one side of the wheel is significantly hotter.

Figure 2.2: Image showing hot bands forming on the wheel treads, indicating that heat flux is not evenly distributed

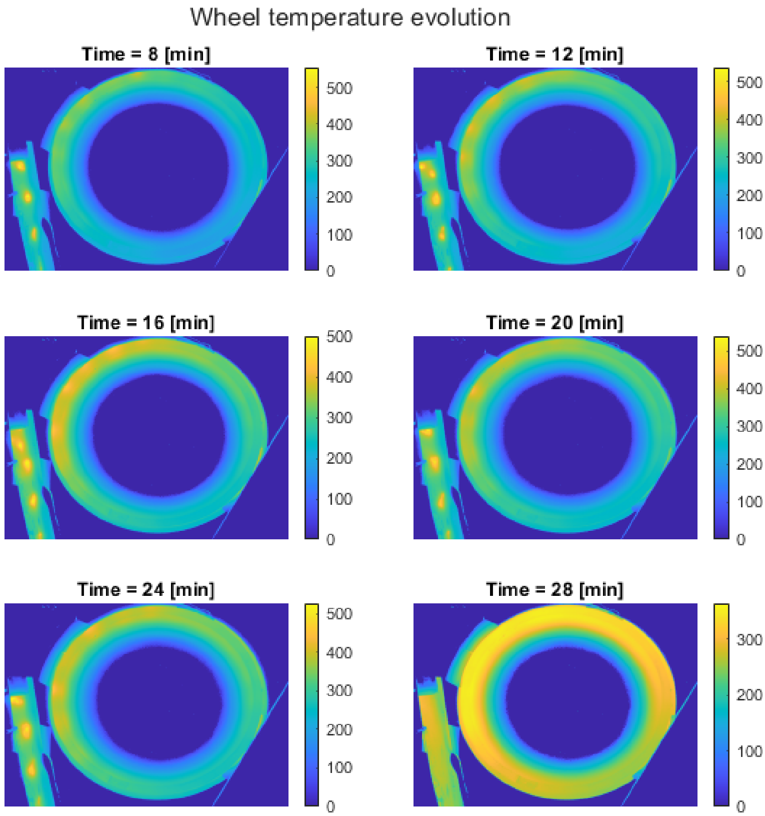

Figure 2.3: View of temperatures of a tread braked wheel at 30 kW as pictured by a FLIR X8400sc thermographic camera (emissivity 1.0 is used).

CHAPTER 3

Modelling and experiments

Significant work has been performed over the last decades with regard to modelling of the behaviour of steel for railway wheels at varying temperatures. This chapter gives a brief overview of these efforts that constitutes the basis for this thesis.

3.1 Mechanical modelling

Material modelling should capture the most important aspects of the mechanical behaviour, which will of course depend on the final usage. ER7 is a medium-carbon steel with a fine-lamellar pearlitic microstructure close to the rim and more coarse microstructure in web and hub. The properties are optimised with respect to loads commonly appearing in the rail–wheel system, in particular rolling contact and wear, and to achieve a low cost. It is nonetheless not a high strength steel, but having balanced strength and toughness properties [17]. Material modelling challenges arise due to the fact that there is a significant temperature range in which the wheel material will show viscous behaviour and also material degradation phenomena. In particular, at substantially elevated temperatures the yield strength is noticeably lowered. Early models such as the one described in [18], [19] approximated the behaviour as elastic-(almost) perfectly plastic. These models have found use both in industry and academia, but are not capable of exhibiting all of the above described phenomena. To accurately capture the material behaviour, a material model is required that is able to handle viscoplastic behaviour ranging from the almost rate independent plastic behaviour at lower temperatures to the strongly rate dependent behaviour at higher temperatures.

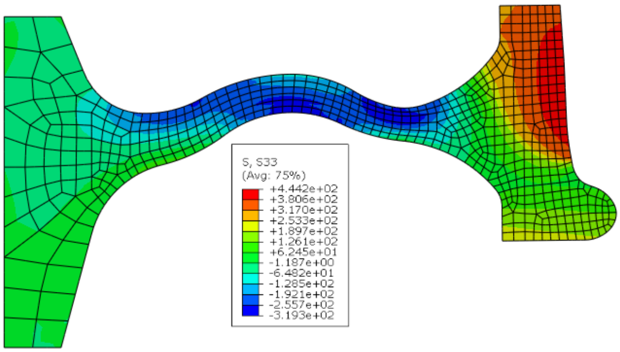

Figure 3.1: Axisymmetric finite element model showing circumferential residual stress after 50 kW braking for 45 min.

The Chaboche nonlinear hardening model [20], [21] has been used as a basis for some previous advanced material models [22], with modifications to accommodate behaviour at higher strain rates and during relaxation. The material can show very strong isotropic hardening or softening depending on the temperature level, which can be captured within the standard framework of the Chaboche model. Finally, at very high strain rates, modifications may be necessary for controlling the ratchetting behaviour of the model, which is known to overestimate ratchetting [21]. The model parameters of the plasticity model has then been calibrated for the pearlitic ER7 steel based upon cyclic strain-controlled tests [22], [23] and cyclic stress-controlled tests [22]. In the present work, the model is extended to allow for calibration towards cyclic anisothermal force-controlled tests, both for the material in the wheel web and for the heat treated and harder material in the rim.

3.2 Thermal modelling

Average tread temperature of the wheel can be obtained by accounting for the heat partitioning between the brake block(s), the wheel and the rail [10]. Simplified approaches are often used which employ an a priori assumption on the partitioning of the heat flux, and thus determining the temperature of the wheel and the brake blocks. One common method is to base the partitioning of heat by considering the material properties of the two materials in sliding contact. Such methods have the drawback that the evolution of the temperature will not modify the a priori assumption. Another approach is to utilise one or two thermal resistances in-between the two parts [24], [25], mimicking a 'third-body' layer that controls the heat. Additionally, assumptions regarding the influence of the rail siphoning heat from the wheel can affect the final temperatures of the system as modelled in [26]. Convection and radiation then provide heat transfer to the surroundings by classical formulae.

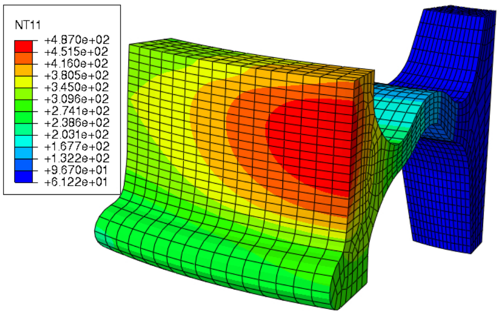

Figure 3.2: Finite element model of a sector of a railway wheel showing a possible temperature distribution on the wheel tread.

Commonly, the thermal analysis is performed separate from the mechanical one using a presumed block–wheel contact pressure distribution and coefficient of friction implying a known heat distribution and any effect on temperatures resulting from the actual mechanical behaviour is ignored. Compared to fully coupled thermal–stress analyses, this sequential coupling method has the advantage of being computationally light compared to solving the nonlinear coupled equations. The sequentially coupled solution is often considered to be accurate enough and one then considers that the contact conditions can be predetermined for the mechanical and the thermal solutions. In particular, for the models where the thermal solution stems from non-contact methods such as the simplified methods described above, the effect of thermal deformation in the contact is disregarded [27]. Very little has been done using a fully coupled thermomechanical analysis [28]–[30]. Averaging of temperature is sufficient for most analyses, but for detailed studies it may not be, in particular at higher temperatures, when local material behaviour may be of interest.

3.3 Thermomechanical analysis

The wheel material shows varying mechanical behaviour depending on temperature and strain rate. At intermediate temperatures of 200–400 °C, the steel shows some viscous behaviour noticeable when highly loaded or when exposed to constant stress during longer times. Additionally, strain cycling has shown significant isotropic hardening, in particular at temperatures around 300 °C. The material becomes substantially weaker when the temperature approaches and exceeds 500°C. At 600° and above, it has a very small elastic region and any significant loads result in permanent deformation. For the material in a wheel, the temperature variations and the related stresses that arise, together with external loads, form a statically indeterminate system and the stresses are redistributed with respect to local stiffnesses and deformations.

For this reason, accurately characterising the stress response of the material with varying temperature is required to fully model its behaviour. The most common ways are to either determine parameters of the specific material model at several chosen constant isothermal temperature levels, or more uncommonly to a priori decide upon the temperature-dependence as a set function [31]. Both of these methods would typically employ data from isothermal tests at some predetermined temperature levels.

For the analyses performed in this work, the former method was chosen. However it was also chosen to calibrate the model parameters using anisothermal test results. Because the parameter values from the isothermal calibration are determined independently, it may produce non-physical behaviour during interpolation between temperature levels and unexpected results may thus arise in an anisothermal setting. For example, it was in the present work discovered that the equations controlling static relaxation, which were calibrated for isothermal load cases, was negatively affecting the anisothermal simulations by relaxing material that was still under load.

In addition, effects that are predominately anisothermal may not be evident from typical isothermal experiments. In the experiments at temperatures above 400 °C performed in [3], [22], [23] test specimens were initially held (stress free) for one or two hours in an oven to attain a uniform and stationary temperature distribution in the specimen. This, however, also activated time-dependent material changes, i.e., spheroidisation of the pearlite, implying that the material was no longer virgin (as produced) at the time of testing.

3.4 Thermomechanical experiments

Thermomechanical material testing differs from normal mechanical testing by also controlling the temperature variation of the test specimen. This is required when simultaneously varying thermal and mechanical effects may be of interest. The addition of the thermal dimension complicates the testing significantly, as the specimen thermal expansion interferes with the strain control. A common way of compensating is to consider free thermal expansion and then adding force or strain on top to achieve desired results [32]–[34]. To avoid slow heating, induction heating was preferred due to its rapid heating of specimens, although it should be noted that only the specimen surface is directly heated and that mainly conduction changes the temperature of the interior of the specimen. The rapid heating is beneficial since it prevents spheroidisation of the pearlite that would result from slow heating, allowing testing of an almost virgin material.

From tread braking simulations, it was determined that the total strain in the wheel rim largely remained within 40-60% of the thermal strain, i.e., the thermal expansion that occurs due to heating. It was decided to constrain the total strain of the specimens to percentages of the thermal strain to evaluate the thermomechanical behaviour, which induces mechanical (elastic and plastic strains) in the specimen. The total strain was chosen to be 0-100% of the thermal strain in steps of 25% to both encompass the determined values of 40-60%, but also to consider extreme cases of full constraint and free expansion. Because of the restriction on the total strain of the specimen, compressive and tensile stresses were induced during heating and cooling respectively, as seen in Figure 3.3. Variations of this method, such as rapid heating of specimens to a desired temperature before applying a mechanical cycle, also enables characterisation of the material deterioration when the process evolves during the mechanical cycling. A summary of the thermomechanical experiments are given in **Paper A**, with a full description of them found in [35].

Material softening from pearlite deterioration is found in the first thermomechanical cycle, where the stress range is significantly larger than the following cycles, see Figure 3.3. No further change occurred in the second and later cycles, indicating that the transformation had reached steady state. It is likely that thermal cycles lasting much less than 45 minutes would show a more gradual deterioration given the time dependence, see [3]. The change in the first- cycle is partially explained by kinematic hardening shifting the average stress, but the thermal softening actually accounts for a 20% reduction in stress range. This deterioration was confirmed with hardness measurements given the relationship between hardness and yield strength [36], [37], and scanning electron microscopy showing the microstructural effects as typical spheroidisation of the cementite lamellae in the pearlite [35].

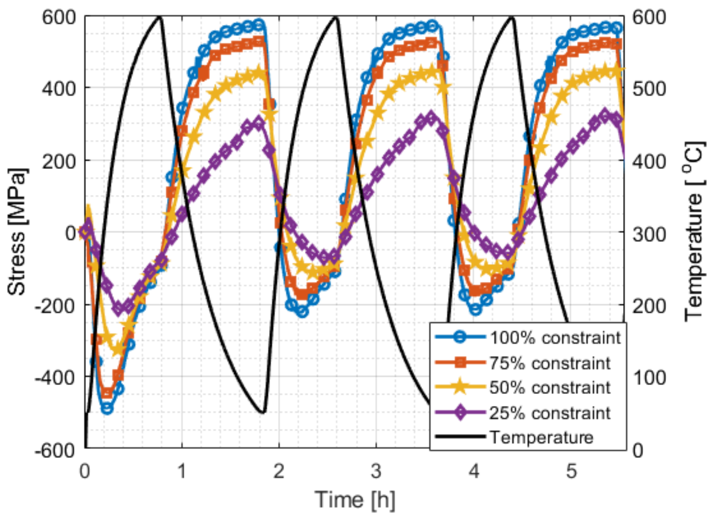

Figure 3.3: Stress and temperature for the thermomechanical experiments with a maximum temperature of 650 °C.

3.5 Brake test rig

Ordinarily, brakes are tested in specially built and certified brake test rigs, often called dynamometers (dynos). These rigs conventionally consist of several flywheels driven by a motor, which simulate the inertia of the rail vehicle. Mechanical complexity and size are common issues with flywheel test rigs. To allow for full–scale testing of the material model calibrated in **Paper A** and used in **Paper B**, a brake rig designed for testing of block brakes has built at Chalmers University of Technology. An electric motor coupled to comparatively small flywheels, also utilised as pulleys for a belt drive, is used to provide the energy for the system. This is a comparatively uncommon idea which has recently gained interest [38]. The standard test is intended to be 50 kW braking at a constant speed of 60 km/h [39].

The rig has been purposely designed to be flexible, with potential to add an additional electric motor to allow for higher power braking and also investigations of rolling contact fatigue by the addition of a "rail-wheel" to simulate the wheel–rail contact. Additionally, mounted in a standard 20 feet container, the brake rig has the potential to be moved for relocation or for long term storage.

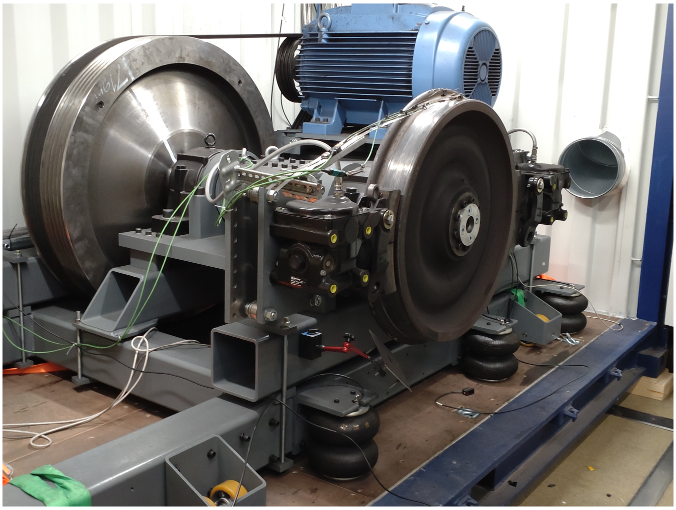

Figure 3.4: Brake test rig at Chalmers.

CHAPTER 4

Summary of Included Papers

4.1 Paper A

In order to determine the thermomechanical behaviour of wheel steel during tread braking, a combined experimental and finite element study of ER7 wheel steel is performed. Thermomechanical specimen testing is performed for various combinations of anisothermal cycles and mechanical constraints designed to mimic actual brake cycles. Hardness testing is also performed to quantify material deterioration. These thermomechanical experiments combined with data obtained from previous isothermal experiments on the same material then form the basis for the calibration of a novel variant of a viscoplastic material model which includes a deterioration factor. The results show good adherence to all anisothermal and isothermal loading cycles. The results also demonstrate that anisothermal testing and simulation is necessary to completely understand the material behaviour during thermomechanical loading.

4.2 Paper B

The objective of is here to investigate and examine the capabilities of a novel material model, calibrated using anisothermal and isothermal experimental data, when employed in detailed braking simulations corresponding to brake test rig conditions. To achieve this, an axisymmetric finite element model of a standard freight wheel exposed to tread braking is used to assess the performance of the material model. The finite element model accounts, in a simplified fashion, for residual stresses introduced by the rim hardening process at wheel manufacturing and also for variations in material properties based on typical hardness values for a wheel cross section.

A range of braking situations are assessed to achieve different loads and temperatures, by mimicking downhill braking at constant speed for a prolonged time period. The results show that the anisothermally calibrated material model predicts substantially larger residual stresses compared to previous models. These new results compare better with real-world experience of wheel response to tread braking.

4.3 Paper C

Here, the temperature distribution and evolution on a wheel tread was studied during 30 kW and 50 kW braking scenarios using a novel brake test rig. A thermographic camera was utilised to capture images of the tread and the wheel rim during the braking to assess hot spots, complemented by sliding thermocouples for the average tread temperatures. The experiments show that the temperature distribution is non-uniform, with noticeable and almost stationary hot spots around the wheel circumference.

Simulations using the thermomechanically calibrated material model indicates that there is a measurable increase in average and maximum residual stresses localised around the hot spots. The magnitude of the stresses are increased with higher hot spot temperature, suggestion that analyses of only average temperatures may underestimate induced damage.

CHAPTER 5

Concluding remarks and future work

Paper A presents an overview of the material model used in the present work together with the thermomechanical and hardness experiments performed to gather the necessary data. A representative part of the gauge section of a testing specimen is modelled and subjected to the thermomechanical loading used in the experiments with the material model calibrated to give good correspondence. The model is able to capture the thermomechanical behaviour of the specimens as well as the isothermal behaviour both for longer-term strain-controlled testing and short-term ratchetting.

The model is then utilised in **Paper B** where it is compared to previously utilised material models as well as to a specific UIC material model, calibrated for the 50 kW 45 min braking case, for several different drag braking scenarios between 30 and 60 kW of brake power. This causes maximum temperatures between 400 and 800 °C, giving a wide span of testing conditions. Results indicate that the new model shows significantly larger residual tensile stresses in wheel rims. It also shows improved computational behaviour when compared to similarly complex material models.

In **Paper C**, the analyses are extended by investigation of the temperature distribution for a tread braked wheel using a new full-scale brake test rig at Chalmers with thermographic imaging combined with sliding thermocouples. Finite element analyses are then used to estimate the effect a significant variation in temperature magnitude and distribution may have on the residual stresses in the circumferential direction of the wheel. The results indicate that the assumption of a uniform temperature distribution may not be conservative and that the hot spot formations have a measurable effect on the residual stress state, ultimately affecting safe usage limits of the wheel.

With these results, parts of the research objectives have been fulfilled. One limitation has been experimental verification and comparison of the modelling to full-scale results, which is intended to be in focus onward. Improving the capabilities of the brake test rig at Chalmers will enable experiments concerning controlled rolling contact fatigue conditions. This is one of the main reasons for damage of railway wheels and a substantial cost driver in the railway industry. For this reason, efforts will also be made on experiments concerning the material behaviour at high strain rates, for which data currently is lacking due to the need for specialised testing equipment.

Creating a finite element model with the capacity of performing thermomechanical rolling contact analyses with a varying temperature distribution may also require usage of 3D models rather than axisymmetric ones, in particular for varying temperature distributions. It is likely that the computational cost of the model will increase significantly, partially because of the inclusion of 3D effects such as moving contact loads and partially because of fatigue evaluations. Strategies to minimise this impact will likely be of importance, in particular for stability of the material model which will be a main task going forward.

Future work is intended to continue on the main track of determining the braking limits, life and study of wear processes of the tread braking system. In particular, continued development of the Chalmers brake rig will allow experiments involving rolling contact fatigue of wheels and wear of braking components with a particular focus on temperature effects. This, in conjunction with the calibrated model from **Paper A**, would enable a material model that can cover several of the most critical issues present for the tread braking system. It is foreseen that the limits will be accurate enough to allow for the tread braking system to be utilised broadly in a safe and maintenance efficient way.

References

[1] "JNS Procedure: Broken Wheels," ERA Joint Network Secretariat, 2019.

[2] R. Brommesson and M. Ekh, "Modelling of cyclic behaviour of Haynes 282 at elevated temperatures," *Materials at High Temperatures*, vol. 31, no. 2, 2014.

[3] D. Nikas, J. Ahlström, and A. Malakizadi, "Mechanical properties and fatigue behaviour of railway wheel steels as influenced by mechanical and thermal loadings," *Wear*, vol. 366-367, pp. 407–415, 2016.

[4] T. Vernersson, A. Ekberg, and R. Lundén, "Swedish tests of LL brake blocks under winter conditions: winter 2020–2021," *Chalmers Mechanics and Maritime Sciences/CHARMEC*, 2021.

[5] "Directive 2001/16/EC of the European Parliament and of the Council of 19 March 2001 on the interoperability of the trans-European conventional rail system," *Official Journal of the European Union*, 2001.

[6] "Directive 2008/57/EC of the European Parliament and of the Council of 17 June 2008 on the interoperability of the rail system within the Community (Recast)," *Official Journal of the European Union*, 2008.

[7] "Directive 2002/49/EC of the European Parliament and of the Council of 25 June 2002 relating to the assessment and management of environmental noise - Declaration by the Commission in the Conciliation Committee on the Directive relating to the assessment and management of environmental noise," *Official Journal of the European Union*, 2002.

[8] "Commission Decision of 4 April 2011 concerning the technical specifications of interoperability relating to the subsystem 'rolling stock – noise' of the trans-European conventional rail system (notified under document C(2011) 658)," *Official Journal of the European Union, 20112011/229/EU*,

[9] "Commission Regulation (EU) No 1304/2014 of 26 November 2014 on the technical specification for interoperability relating to the subsystem 'rolling stock — noise' amending Decision 2008/232/EC and repealing Decision 2011/229/EU," *Official Journal of the European Union*, 2014.

[10] T. Vernersson, "Tread braking of railway wheels - noise-related tread roughness and dimensioning wheel temperatures : field tests, rig measurements and numerical simulations," *Doctoral Dissertation, Chalmers Applied Mechanics*, 2006.

[11] S. Teimourimanesh, T. Vernersson, and R. Lundén, "Thermal capacity of tread-braked railway wheels. Part 2: Applications," *IMechE: Journal of Rail and Rapid Transit*, vol. 230, no. 3, pp. 798–812, 2016.

[12] M. S. Walia, A. Esmaeili, T. Vernersson, and R. Lundén, "Thermomechanical capacity of wheel treads at stop braking: A parametric study," *International Journal of Fatigue*, vol. 113, pp. 407–415, 2018.

[13] R. Parker and P. Marshall, "The measurement of the temperature of sliding surface with particular reference to railway brake blocks," *Proceedings of the Institution of Mechanical Engineers*, vol. 158, pp. 209–229, 2022.

[14] J. Barber, T. Beamond, J. Waring, and C. Pritchard, "Implications of thermoelastic instability in automotive disc brakes under a drag brake application," *ASME Journal of Tribology*, vol. 107, pp. 206–210, 1985.

[15] M. C. Fec and H. Sehitoglu, "Thermal-mechanical damage in railroad wheels due to hot spotting," *Wear*, vol. 102, no. 1, pp. 31–42, 1985.

[16] S. Abbasi, S. Teimourimanesh, T. Vernersson, U. Sellgren, U. Olofsson, and R. Lundén, "Temperature and thermoelastic instability at tread braking using cast iron friction material," *Wear*, vol. 314, no. 1-2, pp. 171–180, 2014.

[17] A. Ghidini, M. Diener, and J. Schneider, *Wheels for freight cars: development and applications for heavy haul service*. Lucchini RS, 2010.

[18] "Definition of parameters for the thermomechanical calculation of wheels. Correlation between calculation and tests," *UIC Report B 169/RP17*, pp. 1–25, 2005.

[19] M. Fermér, "Flexible wheels for railway freight cars considering thermal and mechanical aspects of block braking," in *Proceedings of Tenth International Wheelset Congress*, Sydney (Australia), 1992, pp. 277–281.

[20] J. L. Chaboche, "Sur l'utilisation des variables d'état interne pour la description du comportementviscoplastique et de la rupture par endommagement," *Proc. Problemes non-linéaires de mecanique, Symposium franco-polonais*, pp. 137–159, 1979.

[21] J. L. Chaboche, "A review of some plasticity and viscoplasticity constitutive theories," *International Journal of Plasticity*, vol. 24, no. 10, pp. 1642–1693, 2008.

[22] A. Esmaeili, J. Ahlström, M. Ekh, D. Nikas, and T. Vernersson, "Modelling of temperature and strain rate dependent behaviour of pearlitic steel in block braked railway wheels," *Railway Engineering Science*, vol. 29, no. 4, pp. 362–378, 2021.

[23] A. Esmaeili, T. Vernersson, D. Nikas, and M. Ekh, "High temperature tread braking simulations employing advanced modelling of wheel materials," in *Proceedings International Heavy Haul Association Conference*, Sydney (Australia), 2015.

[24] T. Vernersson, "Temperatures at railway tread braking. Part 1: Modelling," *IMechE: Journal of Rail and Rapid Transit*, vol. 221, no. 2, pp. 167–182, 2007.

[25] T. Vernersson, "Temperatures at railway tread braking. Part 2: Calibration and numerical examples," *IMechE: Journal of Rail and Rapid Transit*, vol. 221, no. 4, pp. 429–441, 2007.

[26] T. Vernersson and R. Lundén, "Temperatures at railway tread braking. Part 3: Wheel and block temperatures and the influence of rail chill," *IMechE: Journal of Rail and Rapid Transit*, vol. 221, no. 4, pp. 443–454, 2007.

[27] *Thermal-stress analysis of a disc brake.* Abaqus Example Problems Manual, Simulia, Dassault Systèmes, Providence, RI (USA), 2006.

[28] D. Thuresson, "Thermomechanics of block brakes, Doctoral Dissertation," *Chalmers Applied Mechanics*, 2006.

[29] P. Dufrénoy and J. Brunel, "Thermal localizations in friction brakes," in *26th Brake colloquium and exhibition*, San Antonio (TX, USA), 2008.

[30] P. Dufrénoy and D. Weichert, "A thermomechanical model for the analysis of disc brake fracture mechanics," *Journal of Thermal Stresses*, vol. 26:8, pp. 815–828, 2003.

[31] H. Morch, L. Duchêne, and A. M. Habraken, "Visco-plastic chaboche model for nickel-based alloys under anisothermal cyclic loading," in *Proceedings 14th International Conference on Computational Plasticity - Fundamentals and Applications (COMPLAS 2017)*, Barcelona (Spain), 2017.

[32] P. Hähner and J. Bressers, "Thermo-mechanical fatigue: The route to standardization," *Materials at High Temperatures*, vol. 19, no. 4, 2002.

[33] P. Hähner, E. Affeldt, T. Beck, H. Klingelhöffer, M. Loveday, and C. Rinaldi, "Validated Code-of-Practice for Thermo-Mechanical Fatigue Testing," *European Commission/DG/JRC*, 43 pages, 2006.

[34] P. Hähner, C. Rinaldi, V. Bicego, *et al.*, "Research and development into a European code-of-practice for strain-controlled thermo-mechanical fatigue testing," *International Journal of Fatigue*, vol. 30, no. 2, pp. 372–381, 2008.

[35] E. Steyn and J. Ahlström, "Thermo-mechanical response of near-pearlite steel heated under restriction of thermal expansion (to be submitted for international publication)," *Chalmers Industrial and Materials Science*, 2022.

[36] E. J. Pavlina and C. J. Van Tyne, "Correlation of Yield strength and Tensile strength with hardness for steels," *Journal of Materials Engineering and Performance*, vol. 17, no. 6, pp. 888–893, 2008.

[37] N. Hamada and M. Sakane, "FEM analysis for Brinell hardness (the effect of inelastic material constants on Brinell hardness) (in Japanese)," in *Nihon Kikai Gakkai Ronbunshu, A Hen/Transactions of the Japan Society of Mechanical Engineers, Part A*, vol. 65, 1999, pp. 254–260.

[38] M. Leitner, “TU Graz implements novel brake test rig for rail vehicles,” https://www.tugraz.at/en/tu-graz/services/news-stories/tu-graz-news/singleview/article/tu-graz-realisiert-neuartigen-bremsenpruefstand-fuer-schienenfahrzeuge0/.

[39] CEN, “EN 13979-1 Railway applications - Wheelsets and bogies - Monobloc Wheels - Technical approval procedure - Part 1: Forged and rolled wheels,” CEN, Brussels, Belgium, Tech. Rep., 2011.