THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY IN SOLID AND STRUCTURAL MECHANICS

Modelling of cyclic and viscous behaviour of thermomechanically loaded pearlitic steels

Application to tread braked railway wheels

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Abstract

In service, railway wheel and rail materials are subjected to high stresses and, in some cases, elevated temperatures. The high stresses are caused by the rolling contact between wheel and rail. Furthermore, heat generated from tread braking and/or sliding between wheel and rail gives additional stress due to constrained thermal expansion. The main goal of this thesis is to improve modelling of the temperature dependent cyclic and viscous behaviour of pearlitic wheel and rail steels subjected to thermomechanical loadings.
Finite element (FE) analyses are carried out of generic heavy haul wheel designs subjected to thermal loading from high power drag braking. In these analyses, the results from using a plasticity and a viscoplasticity model are compared. Both models are calibrated against results from cyclic strain controlled (low strain rate) experiments with hold-time of ER7 wheel steel at different elevated temperatures. The comparison shows an increasing influence of the choice of material model with power of the drag braking.
Also, a methodology to simulate full scale brake rig tests is developed. It includes an axisymmetric thermal analysis, a 3D structural wheel-rail contact analysis and a 3D structural analysis with a traversing contact load. The wheel material behaviour is modelled by a plasticity model calibrated against cyclic strain controlled (low strain rate) experiments of ER7 steel. In addition, the influence of important operational parameters such as axle load, maximum vehicle speed and block material is investigated with respect to the ratchetting life of the wheel tread.
To improve the modelling of the behaviour of ER7 steel for a wider range of loading rates and multiaxial loading, a viscoplasticity model is adopted and calibrated against test data of ER7 steel at different temperatures for slow cyclic strain controlled tests with hold-time, ratchetting tests with rapid cycles and cyclic biaxial tests. A simulation of a brake rig experiment is used to highlight the importance of using the viscoplasticity model in the prediction of the ratchetting fatigue life.
Finally, a cyclic plasticity model incorporating phase transformations is developed to examine what phases and residual stresses that are obtained in a railway wheel after repeated short term local heating followed by rolling contact. This model can be used to study thermal damage mechanisms in rail and/or wheel steels that may lead to initiation of cracks (e.g. squats (studs) in rails and crack clusters in wheels).

Keywords: Railway wheels, pearlitic steel, tread braking, rolling contact fatigue, full-scale brake rig testing, plasticity, viscoplasticity, ratchetting, finite element analyses, phase transformations

Preface

The work presented in this thesis was carried out at the Division of Material & Computational Mechanics, Department of Industrial and Materials Science, at Chalmers University of Technology between December 2013 and January 2019. It was conducted as a part of the activities within the National Centre of Excellence in Railway Mechanics CHARMEC (CHAlmers Railway MEChanics www.charmec.chalmers.se), under the project name MU32 - "Modelling of thermomechanically loaded rail and wheel steels". The project has been supported by CHARMEC's industrial partners. Especially the support from Lucchini Sweden, Bombardier Transportation, Faiveley Transport, SJ and voestalpine is gratefully acknowledged. The project was partly financed within the European Horizon 2020 Joint Technology Initiative Shift2Rail through contract no. 730841 – In2Track.

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I would like to express my deepest gratitude to my main supervisor Prof. Magnus Ekh and my co-supervisors Dr. Tore Vernersson and Prof. Johan Ahlström for their invaluable guidance, continuous support, encouragement and commitment during these years. It has been very instructive and also fun to work together. The work in this thesis would not have been possible to accomplish without the contribution of my supervisors.

Also, special thanks goes to the co-authors of the appended papers Dimitrios Nikas, Mandeep Singh Walia and Prof. Roger Lundén from CHARMEC and also Kazuyuki Handa and Katsuyoshi Ikeuchi from the Railway Technical Research Institute (Tokyo, Japan) for the knowledge exchange and cooperation we had in preparing the papers.

I would like to take the opportunity to thank all my friends and colleagues at the Division of Material & Computational Mechanics and the Division of Dynamics, for making a nice and friendly working environment. It was a pleasure to work with all of you.

Last but definitely not the least, I would like to give a special thank to my family for their endless support.

Gothenburg, December 2018
Ali Esmaeili

Thesis

This thesis consists of an extended summary and the following appended papers:

Paper A	A. Esmaeili, T. Vernersson, D. Nikas and M. Ekh. High temperature tread braking simulations employing advanced modelling of wheel materials. *Proceedings of the 11th International Heavy Haul Association Conference (IHHA 2015) Perth.* 2015, Pages 44-51
Paper B	A. Esmaeili, M. Singh Walia, K. Handa, K. Ikeuchi, M. Ekh, T. Vernersson and J. Ahlström. A methodology to predict thermomechanical cracking of railway wheel treads: from experiments to numerical predictions, *International Journal of Fatigue*, Volume 105, 2017, Pages 71-85
Paper C	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. *To be submitted for international publication*
Paper D	A. Esmaeili, J. Ahlström and M. Ekh. Modelling of cyclic plasticity and phase transformations during repeated local heating events in rail and wheel steels. *To be submitted for international publication*
Paper E	M. Singh Walia, A. Esmaeili, T. Vernersson and R. Lundén. Thermomechanical capacity of wheel treads at stop braking: A parametric study, *International Journal of Fatigue*, Volume 113, 2018, Pages 407-415

Paper A - D were prepared in collaboration with the co-authors. The author of this thesis was responsible for the major progress of the work, *i.e.*, took part in planning the papers, developing of numerical models, carrying out the numerical simulations, analyzing results and writing the main parts of the papers. In Paper E, the author of this thesis contributed in developing the numerical models and analyzing the results.

Contents

Part I

Extended Summary

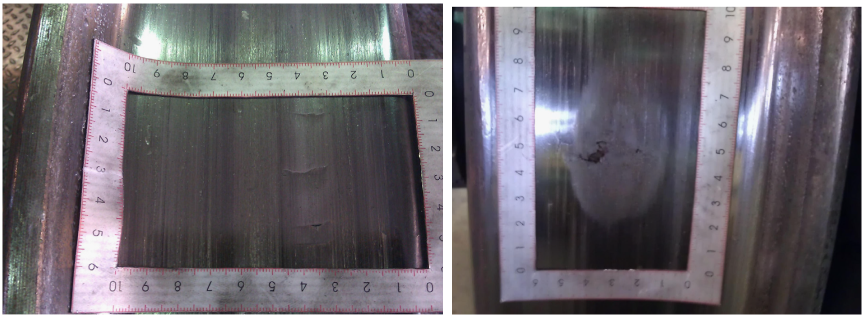
1 Introduction

1.1 Background and motivation

Due to increasing axle loads and running speeds of trains the maintenance costs and the number of disturbances in the railway operations have in the recent years increased. Rolling contact fatigue (RCF), wheel wear and tread damage are reasons for premature wheel removal and major cost factors for railroad and car owners. Furthermore, the performance of rails and wheels is important for the safety of railroads operations. Hence, there are many challenges for the metallurgists, engineers, and railway managers responsible of railway operations, cf. [1].

The common operational experience is that wheel tread cracking associated with different damage mechanisms is caused by a combination of thermal and mechanical loading, though normally one of these being the dominating cause of the damage [2–4]. The temperature elevation in (tread) braked wheels usually occur when kinetic energy of the running train transforms into frictional heat [5]. It means that when the brake blocks are pressed towards the tread of the rolling wheel, frictional heat is generated in the wheel–brake block contact. Also, poor adhesion in the wheel–rail contact might result in sliding of the wheel on the rail surface. The sliding can be caused by a poorly adjusted brakes, frozen or defect brakes, or high braking forces in relation to the available wheel/rail adhesion etc. [6, 7]. The sliding may develop a localized region of high temperature on both the rail and the wheel tread due to the generated heat from frictional sliding between the wheel and the rail track [8].

In addition to the temperature elevation, the wheel tread material is subjected to rolling contact stresses and also stresses induced by constrained thermal expansion. The rolling contact loading between a rail and a wheel tread, results in a multiaxial stress state with a combination of compression and shear [9].



(a) (b)

Figure 1.1: (a) Thermal cracks extending in an axial/radial direction and (b) wheel flat. Figures from [10].

In this thesis an attempt is made to understand and numerically model the mechanical behaviour of the near pearlitic wheel steel ER7 (produced according to the standard EN13262 [11]) when it is subjected to operational conditions, i.e. combined thermal and mechanical loadings. We try to highlight the impact of elevated temperatures on RCF and investigate the potential damage mechanisms. Also, we perform life predictions and analyse various operational parameters that limit the wheel tread life during stop braking scenarios.

However, the main goal of this study is to tailor a material model that is capable of capturing the mechanical behaviour of the ER7 wheel steel when subjected to thermomechanical loading. A robust and accurate material model is a key ingredient for an accurate structural finite element (FE) analyses as well as fatigue analyses of the components.

The efforts in this thesis are a step towards improvement of railway industry guidelines/standards for wheels design and capacity limits.

1.2 Aim and scope of research

An important question is how the wheel steel ER7 behaves under the operational thermomechanical loading conditions and how this can be modelled. The main goal of this study is to adopt and customize modelling of the behaviour of the wheel material subjected to cyclic multiaxial mechanical and thermal loading. In fact, the material model is a key component when developing simulation tools that can predict temperature and stress fields in railway components e.g. in the vicinity of the wheel-rail contact. Also, it is desirable to investigate damage mechanisms and develop a method for prediction of the failure of the wheels. Thereby providing a basis to establish limits for operational parameters e.g. maximum axle load, maximum vehicle speed and criteria for structural design of the wheels. To reach this goal a number of tasks are explored within this thesis:

- The cyclic and viscous material behaviour of a pearlitic wheel steel are studied using available low cycle fatigue (LCF) tests including uniaxial strain-controlled experiments, uniaxial ratchetting experiments and biaxial experiments conducted at room temperature and at elevated temperatures. Accordingly, a plastic material model (**Paper B**) and viscoplastic material models (**Paper A** and **Paper C**) are formulated to account for the observed phenomena with focus on cyclic hardening/softening, ratchetting, multiaxial behaviour and viscous behaviour of the material.

- The influence of generic wheel design on the global wheel behaviour is investigated using FE analysis in **Paper A**. The main goal of this study is to improve the modelling of wheel materials subjected to thermal loading due to tread braking and also to highlight the importance of viscoplastic material modelling.

- Thermomechanical cracking of railway wheel treads, due to rolling contact and repeated stop braking by tread brakes, is studied using results from full-scale brake rig experiments. A method for the structural FE analyses of the test conditions as well as criteria for predictions of crack initiation fatigue life are investigated in **Paper B**. Also, based on the developed FE models, a parametric study involving operational parameters such as axle load, maximum vehicle speed, deceleration, block material and initial wheel temperature is conducted in **Paper E** where the influence of these parameters on the components' fatigue life are studied. These analyses are performed using a plastic material model.

- The influence of short term local friction heating in railway operations is investigated in **Paper D**. A cyclic plasticity model incorporating phase transformation kinetics describing transformation and evolution of volume fraction of different phases has been developed. The material model has been included in FE simulations in order to compute residual stresses in the vicinity of the wheel-rail contact.

2 Braking and damage of railway wheels

2.1 Tread braked railway wheels

Tread (block) braking is still one of the most common braking systems on railway vehicles. Block braking is commonly used on freight wagons but also on passenger trains, often in combination with disc brakes and electrodynamic brakes. The tread braking action is carried out by pressing one or several brake block(s) against the tread (running surface) of the wheel. The tread is also in rolling contact with the rail, see Figure 2.1. The wheel tread material is subjected to a multiaxial state of stress due to rolling contact between the wheel and the rail. Simultaneously, the tread material experiences elevated temperatures due to frictional heat generated between wheel and brake block.
Nowadays, a brake block is generally manufactured from cast iron, organic composite or sintered material, see [12]. Depending on the brake block material it has been observed from experiments that during tread braking the temperature on the wheel tread might be unevenly distributed resulting in high local temperatures such as "banding" and "hot spots" [13].

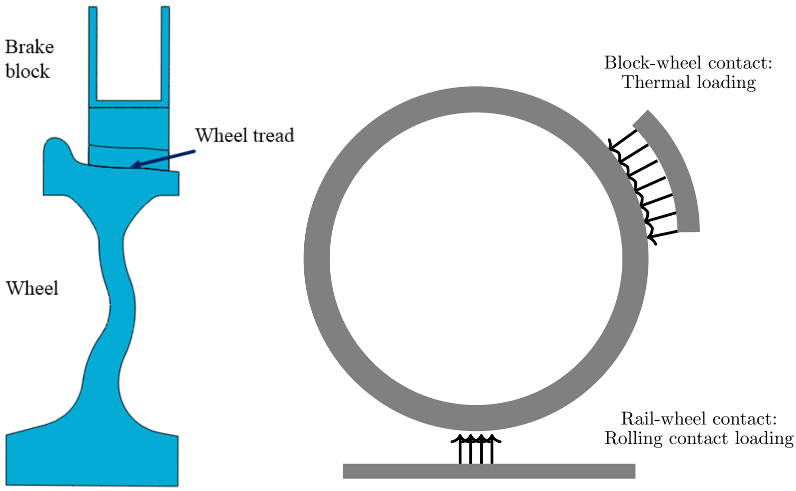


Figure 2.1: Schematic diagram of wheel, block and rail subjected to combined thermal and contact loading.

Drag braking

Drag (downhill) braking is applied in order to maintain a constant train speed by braking with an approximately constant brake force for a relatively long time. Due to the long braking time the temperature of the wheel often increases throughout the wheel rim and even deep into the wheel web. The resulting constrained thermal expansion influences the global behaviour of the wheelset in terms of axial rim displacements during and after braking, and also residual stresses after braking. These aspects are important to consider when designing a wheel to fulfill the requirements according to the European standards.

Stop braking

On the other hand, stop block braking is carried out by pressing the block brake on the tread for a rather short time. In this regard, the thermally affected zone is only a small region close to the contact zone with a high temperature gradient. Usually, the temperature elevation due to stop braking and drag braking is lower than what is required to reach the austenitization temperature of the wheel steel.

2.2 Wheel skidding

Wheel skids (slide) typically occurs during braking when a wheel pair is accidentally locked and the wheel slides (skids) against the rail. Possible causes are malfunctioning braking system, low friction due to frost, wet leaves, or other types of contamination on the rail surface [1, 6, 14]. During the wheel sliding, the wheel surface is heated, sometimes causing a sufficiently high temperature to result in austenitization of the material (800-1000 °C). When the wheel unlocks, the wheel often cools down sufficiently fast to cause martensitic White Etching Layer (WEL) formation [15, 16]. The volume expansion due to martensite formation after one heating pulse gives compressive residual stresses within the brittle martensitic volume, and tensile residual stresses in the un-affected pearlite/ferrite (base material) volume beneath it [17, 18]. If repeated heating occurs in the same spot, the surface layer can either re-austenitise or re-order into a tempered martensite state [18–20]. Due to volume shrinkage of the tempered martensite, it is subjected to high tensile stresses, which is a well-known factor influencing e.g. fatigue initiation.

2.3 Damage in railway wheels

Wheel damage can broadly be distinguished as wear (where the surface material is gradually worn off) and cracks in the material due to e.g. RCF, thermal damage and thermomechanical fatigue (TMF)[1]. RCF in wheels is the result of rolling contact loading which causes a multiaxial state of stress with rotating principal stress directions. Typically, RCF damage can be categorized as *surface* or *subsurface* RCF depending on the initiation position of the cracks [9]. Surface RCF is a common damage phenomena and is related to relatively high traction in the rail–wheel contact (due to traction, braking, curving, etc.). If the wheel–rail friction is sufficiently high, the position of maximum shear stress is found closer to the surface increasing the risk of plastic deformation and crack initiation at the wheel tread [21]. When the wheel/rail material in rolling contact is subjected to repeated applications of high friction loads, the surface material will deform plastically. If material hardening and residual stresses are not sufficient to prevent further accumulation of plastic strains, cracks will eventually form when the fracture strain is exceeded [22, 23] (see Figure 2.2).

Figure 2.2: Surface damage from surface initiated fatigue. Figure from [24].

A temperature increase in wheels might lead to thermal damage and detrimental failure (see Figure 2.3). During the braking action a considerable frictional heat is generated which is transferred to the wheel tread and results in temperature elevation in the wheel material. The thermal loading induces a restrained thermal expansion, which results in tensile residual stresses as the wheel cools. If the tensile stress is sufficiently high, radial cracks form on the surface [9, 25, 26]. Also, in case of drag braking in which the duration of the braking time is rather long, significant axial rim displacements can be obtained (and consequent derailment in severe cases). In addition, a temperature increase significantly influences the strength of the material. For instance, in pearlitic steels, cyclic hardening is observed around 325°C (due to strain aging). However, above this temperature, cyclic softening due to thermal activation of dislocations occur and at sufficiently high temperatures, material degradation in terms of pearlite spheroidisation further decreases the cyclic strength [14].

The brakes of a railway wheelset may lock the wheels and make them slide along the rails. At the point of sliding, material will be worn away from the wheel tread whereby a flat surface known as "wheel flat" is formed. The local temperature often exceeds the austenitization temperature of the wheel material. As the wheel starts rolling again, a very rapid cooling ensues due to conduction into the large volume of cold steel surrounding the wheel flat. This results in the formation of brittle martensite beneath the wheel flat cf. [8]. Hence, the resulting damage is not only present at the surface but also under the flattened surface in terms of changed microstructure and residual stresses, and cracks often form adjacent to the wheel flats [1, 27].

A comprehensive review of high temperature fatigue, creep and environmental effects may be found in reference [3, 28].

(a) (b)

Figure 2.3: (a) Surface appearance of tread thermal cracks on railway wheel in service, figure from [29]. (b) Radial thermal crack propagating through the rim into the wheel disc.

3 Material modelling

A main scope of this study is the proposal of a constitutive model capable of accurate predictions of the mechanical behaviour of ER7 wheel material, allowing for reliable predictions of the thermomechanical fatigue life of the wheel tread. In this context, the proposed constitutive model should be able to capture the main features of ER7 wheel material behaviour. For example, under cyclic loading, phenomena like cyclic hardening/softening, Bauschinger effect, ratchetting and shakedown behaviour can occur. Also, the temperature influences the characteristics of the material due to e.g. thermally activated diffusion processes such as material degradation in terms of spheroidisation of the cementite lamellas, [30, 31]. Furthermore, if the temperature reaches the austenitization temperature, phase transformation in the material is expected.

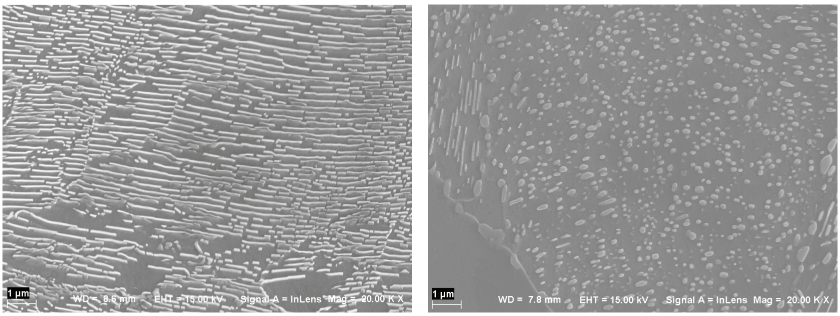
The base material model used in this thesis, which is denoted the Chaboche model in the remaining of the text, is plasticity or viscoplasticity with combined nonlinear isotropic and kinematic hardening, see e.g. [32]. In addition, a model to predict the transformation kinetics of the pearlitic steel during the thermal heating and cooling is introduced.

3.1 Pearlitic steels

Railway wheels are generally forged and heat treated. It is desirable to obtain a combination of good strength, wear properties and relatively low cost, and because of this, medium carbon pearlitic steels are often used. The ER7 grade (produced according to the standard EN13262 [11]) with around 0.55 wt.% carbon is one of the standard grades used in wheels for freight trains and for many passenger coaches in Europe. The wheels are rim chilled; a heat treatment yielding a microstructure of the wheel tread that consists of mostly pearlite with some 5–10 vol. % pro-eutectoid ferrite, cf. [33]. The rim chilling increases the yield strength of the material and introduces compressive stresses in the rim. After this heat treatment the letter "T" is added to the material designation. However, in this thesis the commonly used name ER7 will be used.

In order to examine the behaviour of ER7 subjected to thermal and cyclic loading, uniaxial strain-controlled LCF experiments, at temperatures from 20°C to 625°C were carried out by Nikas et al [33]. A 30 min. hold time with a constant strain in compression is included in the tests which reveals the viscous behaviour of the material in terms of stress relaxation. The strain rate in the cyclic part of the tests is rather low

$(5 \times 10^{-4}\text{s}^{-1} \leq \dot{\epsilon} \leq 5 \times 10^{-3}\text{s}^{-1})$.
Furthermore, to characterize the ratchetting behaviour of the ER7 material for medium to high loading rates uniaxial stress-controlled ratchetting experiments at elevated temperatures 200°C-500°C were conducted and reported in [34]. These tests cover medium to high loading rates with frequency 0.5-5 Hz (which results in $3 \times 10^{-3}\text{s}^{-1} \lessapprox \dot{\epsilon} \lessapprox 9 \times 10^{-2}\text{s}^{-1}$).
Finally, in order to enhance the understanding of the material behaviour under more complex loading conditions, similar to the conditions close to the wheel-rail contact, biaxial strain-controlled LCF experiments with alternating tension/compression and torsion loading at temperatures 20°C-400°C were conducted and reported in [34].
From the experiments it was found that with exposure of the material to temperatures above room temperature, some viscous behaviour could be observed already at 250-300°C. A hardening process is taking place around 300°C due to strain aging with locking of the dislocations by interstitials [35]. At 400°C, an increase in the mobility of dislocations, results in a softening of the material. At even higher temperatures, the material exhibits significant softening, as a result of continued increase of the dislocations' mobility combined with microstructural degradation (spheroidisation), see Figure 3.1.



(a) *(b)*

Figure 3.1: Scanning electron micrographs of pearlite microstructure after heat treatment. (a) Initial lamella break up, and (b) complete spheroidisation. Figures from [34]

These conclusions are also confirmed by the results of the ratchetting experiments shown in Figure 3.2. In that figure it can be observed that at 300°C the material exhibits the lowest accumulation of strain out of the four temperatures examined, which is due to the strain aging mechanism. The highest ratchetting rates are obtained for the two higher temperatures.

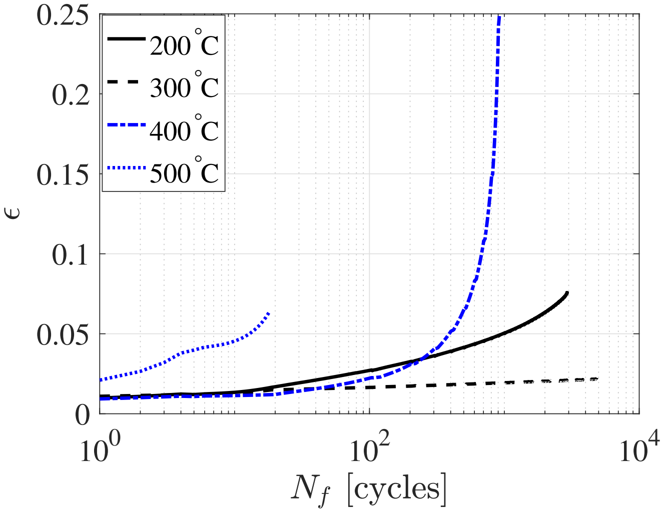


Figure 3.2: Strain at mean stress ($\sigma = \sigma_m$) vs number of cycles to fatigue (from the uniaxial ratchetting experiments conducted and reported in [34]) at temperatures 200°C, 300°C, 400°C and 500°C. The specimens were subjected to cyclic loading with $\sigma_m \pm \sigma_a = 100 \pm 500$ MPa where σ_m is the mean stress and σ_a is the amplitude stress (engineering stresses, not compensated for decreasing cross sectional area).

Since the experiments in [33] and [34] have been conducted during the course of this thesis work, more advanced material modelling has been possible to explore during the later part of this work. Table 3.1 gives an overview of what experiments on ER7 that has been used for material model calibration in each of the appended papers.

Table 3.1: Overview of what experiments that has been used for model calibration in the appended papers.

Experiment	Paper A	Paper B	Paper C	Paper D	Paper E
LCF	✓	✓		✓	✓
LCF with hold-time	✓		✓		
Ratchetting			✓		
Biaxial LCF			✓		

3.2 Plastic material model

The Chaboche plasticity model [32], with mixed nonlinear isotropic and kinematic hardening is employed in **Paper A**, **Paper B**, **Paper D** and **Paper E**. In order to identify

the model parameters of the plasticity model for the pearlitic steel ER7 we have used the cyclic part of the LCF strain-controlled experiments.
In **Paper D**, the model parameters for the martensitic and austenitic phases are identified against monotonic strain-stress data from [18] and from JMatPro6.0, respectively. This is discussed further in Section 3.4.

The LCF experiments sometimes show cyclic softening. This can be modelled using either negative evolution of isotropic hardening or a dependence of the accumulated plastic strain on the dynamic recovery of the kinematic hardening, see Chaboche 2008 [36], Brommesson 2014 [37]. In the current work an isotropic hardening R is adopted to capture the nonlinear cyclic softening/hardening with the following evolution equation:

$$\dot{R} = \dot{\lambda}\, b \left(-Q \,\frac{\partial f}{\partial R} - R \right) \tag{3.1}$$

where $\dot{\lambda}$ is the plastic multiplier, f is the (von Mises) yield function and b, Q are material parameters. The nonlinear evolution of the kinematic hardening $\boldsymbol{X}$ is described by the Armstrong and Frederick (AF) model [38]:

$$\dot{\boldsymbol{X}} = \dot{\lambda} \left(-\frac{2}{3}\, C \,\frac{\partial f}{\partial \boldsymbol{X}} - \gamma\, \boldsymbol{X} \right) \tag{3.2}$$

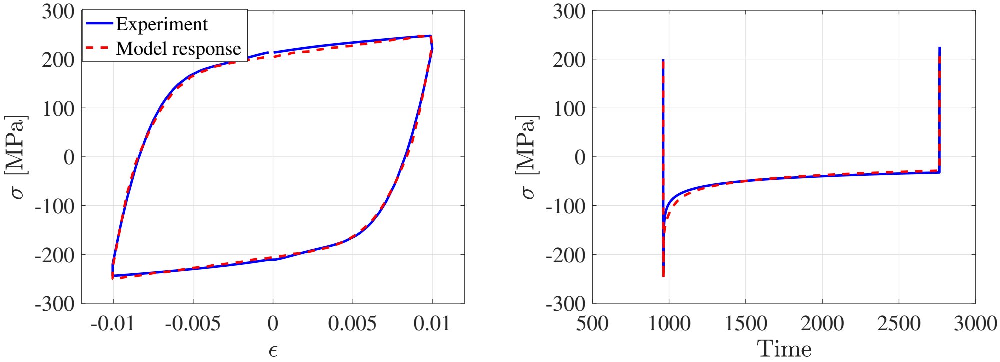
where C, γ are material parameters. Often a number of kinematic hardening variables with different evolution characteristics is used to increase the accuracy of the model predictions.

3.3 Viscoplastic material model

A proper material model for ER7 in a tread braking simulation, should be able to cover the range from nearly rate independent (plastic) behaviour at low temperatures to significant rate dependent behaviour at higher temperatures. The high temperatures due to the thermal loading at braking result in slow time dependent behaviour such as creep, relaxation and static recovery of the wheel material. In a viscoplasticity model this is captured by an overstress function $\eta(f)$ and static recovery of the hardening variables. In **Paper A**, where only thermal (slow) loading is considered, the Chaboche plastic material model is extended to account for rate dependence by adopting a Norton overstress function together with static recovery. Then the model parameters are identified against the LCF strain-controlled test data which are conducted at low loading rates

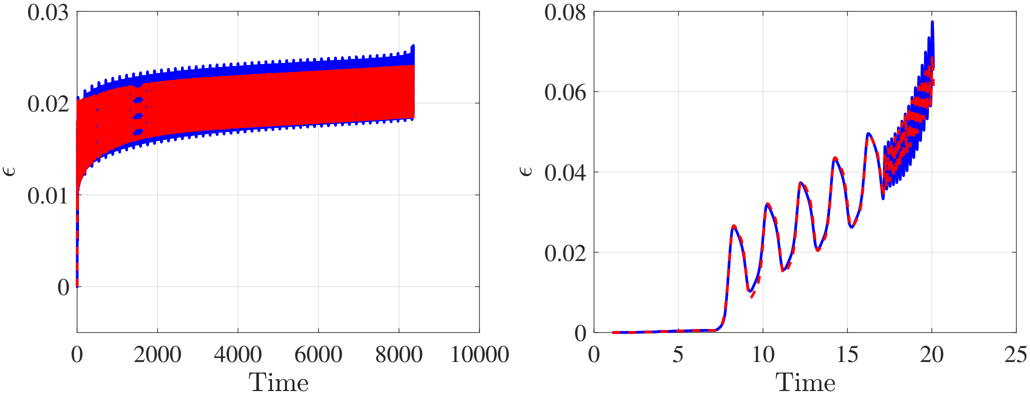
$5 \times 10^{-4}\text{s}^{-1} \leq \dot{\epsilon} \leq 5 \times 10^{-3}\text{s}^{-1}$ that also includes a hold time to characterize the stress relaxation of the material at elevated temperatures.

However, in **Paper C**, since the combination of frictional thermal loading (slow loading rate) and RCF mechanical loading (fast loading rate) is considered, the viscoplasticity model should be able to capture the material behaviour at a wide range of loading rates. Different approaches have been suggested in literature to capture wide loading rate ranges and associated physical mechanisms in viscoplasticity models. In Liang, Khan (1999) [39] different constitutive viscous models and their performance to predict the response of BCC and FCC metals are examined. The formulations of the models correspond to overstress functions of exponential type. The models are capable of capturing the response for a wide range of loading rates. Furthermore, different overstress functions and their behaviour are examined in Chaboche 2008 [36] where it is concluded that the exponential and sinh (proposed by Delobelle) overstress function yield similar responses. To limit the stress values at very high strain rates a possibility is to use a limit/dynamic yield surface cf. Ekh [40], Becker-Hackenberg [41], and thereby for such strain rates obtain a reduced rate dependence. In **Paper C** we choose to use the Delobelle sinh function. In addition to the uniaxial strain-controlled test data ($5 \times 10^{-4} \leq \dot{\epsilon} \leq 5 \times 10^{-3}\text{s}^{-1}$) with hold time, the uniaxial ratchetting test data ($3 \times 10^{-3} \lessapprox \dot{\epsilon} \lessapprox 9 \times 10^{-2}\text{s}^{-1}$) are used to identify the parameters of the viscoplasticity model and characterize the rate dependent behaviour of ER7 at wide range of strain rates. Examples of simulation results from **Paper C** are shown in Figures 3.3 and 3.4.



(a) *(b)*

Figure 3.3: Modelling of cyclic and viscous phenomena at 600 °C for 1 % strain amplitude (a) stress vs strain (at $\dot{\epsilon} = 5 \times 10^{-3}\text{s}^{-1}$) for the cycle before the hold time (captured by the hardening variables) and (b) relaxation behaviour captured by the overstress function and the static recovery.



(a) *(b)*

Figure 3.4: The predictions of the viscoplasticity model against the ratchetting experimental data during the entire life of the specimen at (a) 300 °C and (b) 500 °C. Experimental results are shown in blue whereas the predictions of the viscoplasticity model are shown in red.

However, it should be noted that the calibration against all cycles in the ratchetting experiments (Figure 3.4) causes a decrease in the accuracy of the simulations of the initial ratchetting cycles. The evolution of the kinematic hardening in the Chaboche model has been further extended in literature see, e.g., Ohno & Wang 1993 [42], Jiang & Sehitoglu [43], Bari & Hassan 2002 [44], Chaboche 2008 [36] with the purpose to improve ratchetting or mean stress relaxation predictions. So, as a future work, it worth investigating the capability of these models to increase the accuracy of the model predictions during the entire specimen's life.

In addition, since the rolling contact loading causes a multiaxial state of stress in the wheel tread material, the viscoplasticity model should be able to predict the multiaxial behaviour of the material accurately. The AF model for evolution of the kinematic hardening has been reported, cf. Burlet and Cailletaud (1987) [45], Chen 2005 [46], to over-predict the multiaxial ratchetting. Hence, a modification of the dynamic recovery of the kinematic hardening was proposed by Burlet & Cailletaud (BC) [47]. If also static recovery is included in the model the evolution equation for $\boldsymbol{X}$ can be written as

$$\dot{\boldsymbol{X}} = -\dot{\lambda}\frac{2}{3}\,C\,\frac{\partial f}{\partial \boldsymbol{X}} - \dot{\lambda}\,\gamma\,\left(\beta\,\boldsymbol{X} + \frac{2}{3}\,(1-\beta)\,\left(\boldsymbol{X} : \frac{\partial f}{\partial \boldsymbol{X}}\right)\,\frac{\partial f}{\partial \boldsymbol{X}}\right) - \left(\frac{|\boldsymbol{X}|}{M}\right)^{m-1}\,\frac{\boldsymbol{X}}{\tau} \tag{3.3}$$

where $\beta \in [0,1]$ is the BC model parameter and M, τ, m are static recovery parameters. This model has been used in **Paper C**. It is shown in [48] that the BC model is able to capture the multiaxial ratchetting behaviour of the pearlitic rail steel R260 rather good. As the final step of the parameter identification in **Paper C**, the experimental data obtained from the biaxial tests are employed to identify the multiaxial hardening parameters of the BC model.

3.4 Phase transformation model

In **Paper D** a model for the transformation kinetics of pearlitic steel during the thermal heating and cooling is introduced.

Phase transformations

Diffusional phase transformations are modelled using isothermal transformation diagrams (IT-diagrams). The main phases that can exist in medium to high carbon steels are austenite (a), ferrite (f), pearlite (p), cementite (c), bainite (b) martensite (m) and tempered martensite (tm). Accordingly, the phase transformations that we considered in **Paper D** are:

1. Austenitization of ferrite, pearlite, cementite and bainite, i.e. f, p, c, b $\rightarrow$ a (heating above austenite transition temperature)

2. Austenite to ferrite, pearlite and bainite, i.e. a $\rightarrow$ f, p, b (slow cooling)

3. Austenite to martensite, i.e. a $\rightarrow$ m (rapid cooling)

4. Martensite to tempered martensite, i.e. m $\rightarrow$ tm (tempering (heating) above 160°C)

5. Tempered martensite to austenite i.e. tm $\rightarrow$ a (heating above austenite transition temperature)

Mechanical behaviour of phases

The plastic Chaboche material model introduced in Section 3.2 is employed in **Paper D** to simulate the mechanical behaviour of each individual phase and the model parameters are identified against the stress-strain data available for each phase. Due to lack of experimental data for austenite, the mechanical properties of austenite are predicted using JMatPro6.0 software. For the base material pearlite/ferrite the uniaxial LCF strain-controlled test data performed on ER7 are employed for calibration of the material model. Moreover, the experimental and estimated data available for un-tempered martensite (as-quenched martensite) and tempered martensite from [18] are employed for the model calibration. These data are from compression tests at temperatures from 25 to 275°C while data for higher temperatures are estimated using JMatPro6.0.

Dilatometry

The thermal expansion/contraction characteristics of the considered near-pearlitic steel, upon heating to 980°C and then cooling to room temperature are examined by dilatometry experiments, reported in [18, 49]. Observations from dilatometry experiments are used to characterize the evolution of specific volume changes of the material as a function of temperature. The volume expansion is assumed to be linear with temperature (and isotropic) in each phase. Further, to account for different densities of the phases a transformation expansion strain for each phase is applied, see e.g. [50]. For a dilatometry experiment (no external stress) of two heating cycles the prediction from the model presented in **Paper D** and experiments (from [18]) are shown in Figure 3.5.

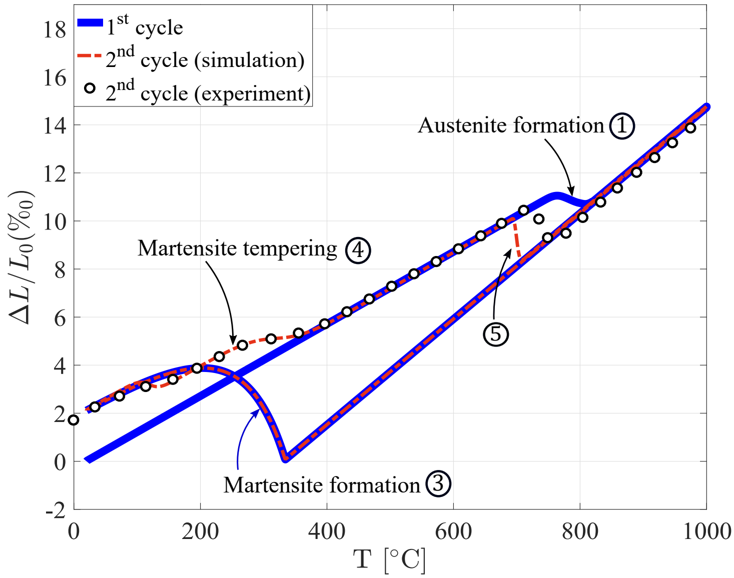


Figure 3.5: Evolution of strain on heating and cooling of martensite, pearlite and austenite at higher temperatures. The experimental data from [18] are shown only for the 2^{nd} run of tempering. The circled numbers refer to the phase transformation steps introduced in Section 3.4

4 Finite element simulations of railway wheels subjected to thermomechanical loadings

Simulation of drag braking

A goal in **Paper A** is to perform predictions and analyze the results of the axial rim displacement and residual stresses for different wheel designs when subjected to drag braking load cases. During tread braking, the frictional heat is partitioned between the wheel and the brake block at their contact interface and, since the wheel is rotating, the heat is also conducted from the hot wheel into the cold rail [51]. Temperatures build up in the wheel and introduce a change of the global wheel behaviour, i.e. axial rim displacements during and after braking (including change of the wheelset guage), and also residual stresses after braking [52]. The thermal capacity of tread brakes can be limited by this global thermomechanical behaviour of the wheels [53], but also by how the elevated temperatures influence the rolling contact fatigue damage introduced to the tread [29].

Simulations of the global wheel behaviour require knowledge of the temperature distribution in the wheel and of the material response at elevated temperatures. In the literature, global wheel temperatures are often analyzed using some simplifying assumptions on heat generation and heat partitioning in the system, allowing for the wheel temperatures to be determined from a purely thermal analysis cf. [54]. Material models used for the thermomechanical assessment of the wheel behaviour are generally of plasticity type [55, 56], but viscoplasticity models are also used [52]. In **Paper A** we assume a condition of a severe thermal loading (high power drag braking) and investigate the sensitivity of the choice of material model on the calculated wheel behaviour. To this end, the global behaviour of the wheel, i.e. axial rim displacement during and after braking and also residual stresses after braking, is studied for a plasticity model (see Section 3.2) and a viscoplasticity model (Section 3.3). The study shows that the choice of material model is important for simulation results of the wheel behaviour for situations when substantial stresses build up in the rims of wheels during braking.

Simulation of RCF for tread braked wheels

Wheel tread damage caused by RCF is a source for premature machining of wheels, which shortens their expected service life [57]. An overview of wheel tread damage and also thermal effects is given in [9]. The study of RCF often starts out from Hertzian contact theory [23] and utilization of Shakedown maps for assessing the damage. However, for a detailed study of the impact from combined thermal and mechanical loads, as imposed by braking and rolling contact, numerical modelling using the finite element method is here preferred. In previous work within CHARMEC [58], a combined experimental and numerical approach is taken to study thermal cracks on the wheel tread. Simulation results are compared to test-rig results of repeated stop braking (initial speed 160 km/h, 20 tonne axle load, sinter material brake block), conducted in collaboration with the Railway Technical Research Institute (RTRI) in Tokyo Japan. Numerical modelling of the frictional rolling contact during braking was found to give a calculated ratchetting fatigue life that was in reasonable agreement with the experimental brake rig results. A material model of plasticity type was employed and the traversing contact load on the wheel tread was based on the assumption of Hertzian contact theory.

In **Paper B** and **Paper C**, the detailed study of wheel tread material behaviour when subjected to thermomechanical loading from simultaneous braking and rolling contact loads is continued. In this regard, the conditions observed in the brake rig experiments are again used as input in the numerical analysis, now introducing results from two additional brake rig tests of repeated stop braking, see Table 4.1.

Table 4.1: Test conditions for the three studied braking cases. Axle load is 20 tonnes.

Brake block type	Sinter	Sinter	Composite
Initial speed [km/h]	160	130	160

Paper B introduces a 3D computational framework that allows for the analysis of the wheel tread material subjected to thermal and mechanical loading when employing a plasticity model for the material behaviour. The FE-modelling in this study involves sequential thermal and mechanical analyses conducted in three steps.

1. Heat partitioning between brake block, wheel and rail during stop braking is accounted for in axisymmetric thermal analyses using models developed in [51, 59].
2. Normal wheel-rail contact is simulated for indentation type of loading (without friction) using a detailed FE-model to obtain pertinent contact patches and pressures.
3. Wheel temperature histories, obtained in the first step, and the rolling contact pressures, obtained in the second step, are finally applied together with tangential stress (assuming partial slip) as a traversing loading in a 3D structural analysis.

The modelling aims at reproducing brake rig experiments and for this reason three different thermal patterns on the treads of the wheels are introduced. They account for so-called "hot bands" between the brake block and the wheel that occur during braking because of frictionally excited thermoelastic instabilities [60, 61]. The material response of the wheel is evaluated by studying the ratchetting strain of the material in the vicinity of the wheel–rail contact. In **Paper C** the analyses are repeated using the tailored viscoplasticity model for the material behaviour.

Two methods for assessing fatigue life are utilized in **Paper B**; one is based on ratchetting failure (RF) and the other is based on LCF damage [62, 63]. It is found, for the considered types of stop braking, that the LCF damage mechanism has a low influence on the failure of the material and that ratchetting failure is the dominant damage mechanism. Based on a comparison between the wheel tread fatigue life obtained from test-rig results and the fatigue life predicted by the simulation results with the adopted model assumptions, an estimate of the critical strain ϵ_{c} that controls the ratchetting life is obtained in **Paper B**.

Accounting for rate dependent behaviour of the material, by employing the viscoplastic material model in **Paper C**, it is observed that the total ratchetting strain during one braking cycle predicted by this viscoplasticity model $\Delta\epsilon_{\mathrm{r,v}}$ is lower than the total ratchetting strain predicted by the plasticity model $\Delta\epsilon_{\mathrm{r,p}}$. For instance, for the simulation of tread braking in the case of using sintered brake block with one hot-band (50 mm) between the wheel and the rail and initial velocity 160 [km/h] we observed that $\Delta\epsilon_{\mathrm{r,v}} \approx 0.1\Delta\epsilon_{\mathrm{r,p}}$. The over-prediction of the ratchetting by the plastic material model is expected since it does not account for strain rate dependent behaviour (hardening) of the material. To be specific, the plasticity model assumes the same material behaviour as in the slow strain-controlled LCF tests. In this regard, when using the viscoplastic material model, the estimated value of the critical strain ϵ_{c} is decreased, accordingly.

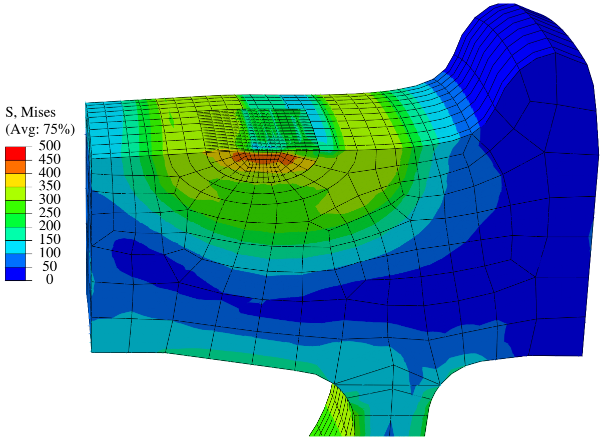


Figure 4.1: von Mises stress for the area in the vicinity of the contact zone with the wheel tread temperature of 530°C

Finally, in **Paper E** the plasticity model and the methodology for simulation of tread braking developed in **Paper B** are used to assess the influence of important operational parameters on the wheel tread fatigue life. These parameters are axle load, maximum vehicle speed, deceleration, block material, initial wheel temperature and friction coefficient between wheel and rail. The results of the parametric study also show how the variations of operational parameters influence the peak braking temperatures and rolling contact loads. One conclusion from the calculated ratchetting fatigue lives is that temperatures above about 450°C have a strong detrimental influence on the ratchetting life of railway wheel treads. Further analyses indicate that material hardening due to dynamic strain aging for temperatures in the range 300–400°C results in a longer fatigue life.

Simulation of double wheel flat

In **Paper D**, the aim is to simulate the influence of a repeated short term local friction heating in railway operations on the residual stresses generated in the thermally affected zone of a pearlitic steel. As an example of loading, a "double wheel flat" loading is considered which is defined by the situation when two wheel flats partially or fully overlap each other. The consequent temperature elevation due to local friction heating might be significant, above austenite transition temperature, and in the pearlitic steels this results in phase transformations. The temperature dependent differences in thermal expansion, density and mechanical properties between the phases result in residual stresses which can cause thermal damage. The simulations are performed using the material model

described in Section 3.4.
In this regard, two examples are considered. In the first example, a (short term) thermal cyclic loading case is applied to an axisymmetric ER7 disc sample and the residual stresses in the disc are investigated. To define a thermal loading that mimics a double wheel flat case, a proper heat influx (see, [20]) is applied on the upper surface of the disc sample. In the second example, the effect of combined (short term) cyclic thermal loading and cyclic mechanical (rolling contact) loading on a 3D wheel model is studied. The purpose of the second example is to investigate the influence of the applied rolling contact loading on the generated residual stresses (due to thermal loading and phase transformations).

In both examples, it is observed from the FE analyses that below the transformed martensite layer, high tensile residual stresses are generated. Depending on the number and duration of the heating events the tensile residual stresses are generated within either the base material or the tempered martensite layer, see Figure 4.2. Since the tempered martensite material is rather brittle it is more susceptible to crack initiation. In the second example, it is observed that the rolling contact loading reduces the tensile residual stresses, cf. **PaperD**.

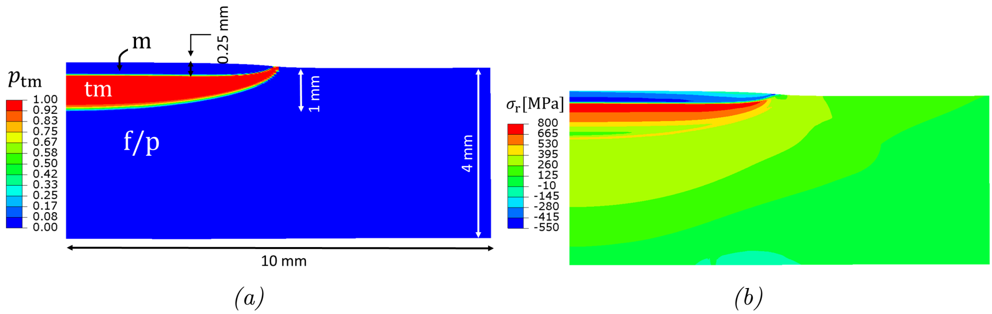


Figure 4.2: Simulation results of a purely thermal double wheel flat loading after the final cooling to 20°C. (a) Tempered martensite fraction (denoted "p_{tm}") (b) Radial residual stresses (denoted "σ_r" with values in MPa). In figure (a), m denotes the martensite layer, tm the tempered martensite layer and f/p the base (pearlitic/ferritic) material.

5 Research collaborations

The work in this thesis has been carried out within the CHARMEC project MU32 "Modelling of thermomechanically loaded rail and wheel steels". This project has been conducted in collaboration with the CHARMEC project MU28 "Mechanical performance of wheel and rail materials". In MU28 mechanical tests have been performed on pearlitic steels at elevated temperatures. These give knowledge and understanding of how the material behaves in realistic loading situations which have been used in the current project to formulate and calibrate the material models. Also, the CHARMEC project MU30 "Modelling of properties and damage in wheel and rail materials" has helped with preparation and analysis of the experimental data. In addition, the development of phase transformation model is carried out in collaboration with MU30. The project has been collaborating with the CHARMEC project SD10 "Enhanced mechanical braking systems for modern trains" where e.g. simulations of the contact between brake block and wheel including temperature elevation have been developed. Full-scale tests featuring three series of repeated stop braking cases have been performed by the Railway Technical Research Institute (RTRI) in Japan and the results have in this project been compared to finite element simulations.

6 Summary of appended papers

6.1 Paper A

The main goal of this study is to improve the modelling of wheel materials subjected to thermal loading due to tread braking and also to highlight the importance of viscoplastic material modelling. In this regard, finite element analyses of generic heavy haul wheels, subjected to high power drag braking loads, are carried out and comparisons between analyses with plastic and viscoplastic material models are shown. Results are presented for simulated global wheel behaviour, i.e. axial rim displacements during and after braking, and also residual stresses after braking. A conclusion is that the results obtained for a generic wheel with an S-shaped web, which builds substantial stresses in the wheel rim during braking, is rather sensitive to the choice of material model. Substantial differences are found already at 400 °C. Moreover, the results indicate that a generic Low-stress wheel, which builds lower stresses in the rim during braking, is less affected by the choice of material model. However, at temperatures above about 500 °C also the results for this wheel are significantly affected by the choice of material model.

6.2 Paper B

In this study, thermal cracking of railway wheel treads is studied by full-scale brake rig tests and finite element simulations. The main goal of the paper is to perform thermomechanical rolling contact fatigue life predictions. The wheel tread material is subjected to simultaneous mechanical and thermal loads due to rolling contact and stop braking, respectively. Full-scale tests featuring three series of repeated stop braking cases have been performed at the Railway Technical Research Institute (RTRI) in Japan in a brake rig featuring a tread braked wheel that is in rolling contact with a railwheel. The brake rig test conditions have been simulated numerically using the finite element method where the effect of "hot bands" on the tread is accounted for as indicated by the experimental findings. Stresses induced by temperature from braking as well as tractive rolling contact loading on the tread are considered. The mechanical response of the wheel material ER7 is obtained from a plastic Chaboche material model calibrated against data from cyclic strain-controlled experiments which were performed under isothermal conditions from room temperatures up to 625 °C. Finally, a strategy for prediction of fatigue life with respect to ratchetting failure is discussed.

6.3 Paper C

Block braked railway wheels are subjected to thermal and rolling contact loading. The thermal loading results in high temperatures and thermal stresses which cause slow time dependent processes such as creep, relaxation and static recovery of the wheel material. At the same time, the rolling contact loading is applied very fast. This paper is focused on material modelling of pearlitic steel for a wide range of loading rates at elevated temperatures. The starting point is a viscoplastic model including nonlinear isotropic and kinematic hardening. The Delobelle overstress function is employed to capture strain rate dependent response of the material. The model also includes static recovery of the hardening to capture slower viscous (diffusion dominated) behaviour of the material. Experiments for the pearlitic steel ER7 in terms of cyclic strain-controlled uniaxial tests with hold-time, uniaxial ratchetting tests including rapid cycles and biaxial cyclic tests with alternating tension/compression and torsion are used to calibrate the material model. These experiments were performed under isothermal conditions at different temperatures. In the ratchetting tests higher loading rates are obtained and these have been used to calibrate the high strain rate response of the viscoplastic model. The paper is concluded with a numerical example of a block braked wheel where the importance of accounting for the viscoplastic modelling is highlighted.

6.4 Paper D

Short term local friction heating in railway operation might occur when a railway vehicle's wheelset skids along the rail (for example in emergency braking). The consequent temperature elevation might be significant, up to 1000°C, and in the pearlitic rail and wheel steels this results in phase transformations. The temperature dependent differences in thermal expansion, density and mechanical properties between the phases result in residual stresses which can cause thermal damage in railway rail and wheel steels. Previously, within our research group, FE modelling incorporating phase transformation kinetics describing transformation and evolution of volume fraction of austenite, martensite, pearlite, ferrite, cementite and bainite has been developed. The FE modelling has included the coupling between a thermal and mechanical analysis in order to compute residual stresses in the vicinity of the wheel-rail contact. In the previous work, the hardening behaviour of the phases was modelled as purely isotropic.
However, the kinetics and the constitutive relations in the FE modelling are improved in the current study, with the purpose to increase the accuracy of the predicted residual stresses in railway applications. To capture the dilatation effects on martensite tempering, two distinct un-tempered and tempered martensitic phases are introduced. The experimental results for cyclic loading of pearlitic steels show that kinematic hardening is dominant. In this regard, the mechanical behaviour of the phases is modelled by a plastic model accounting for mixed nonlinear isotropic and kinematic hardening. In addition, identifications of the plastic model parameters for ferrite, pearlite and martensite phases are conducted. The model seems to be successful in handling phase transformations and phase dependent thermal expansion. The predicted residual stress fields generated due to heating events are reasonable and agree well with experimental observations. Finally, the influence of rolling contact loading on the residual stresses, induced by friction heating, is investigated. The results show that over-rollings reduce the level of the generated tensile residual stresses. But, some residual stresses and strain localization due to the phase transformations remain and can influence fatigue properties locally.

6.5 Paper E

During tread braking, the treads of railway wheels are subjected to a complex loading due to combined rolling contact and thermally induced stresses. In revenue traffic the running mode of the train varies and the operational parameters will influence the life of the wheels. To prevent excessive damage, it is therefore important to understand at which operational conditions wheel damage becomes unacceptable. The current study aims to find limits for tread braking with respect to the influence of thermal stresses on RCF of the wheel tread when subjected to repeated stop braking. A parametric study, using 3D FE simulations and involving operational parameters such as axle load, maximum vehicle speed, deceleration, brake block material and initial wheel temperature, is carried out for a new wheel with an S-shaped web. Additional analyses investigate impact from wheel geometry by studying a wheel with a straight web and a wheel with a thin (worn) rim. The effects of simultaneous thermal loading from wheel–block frictional contact during braking and mechanical loading, due to the traversing wheel–rail rolling contact, are studied in an uncoupled thermomechanical analysis.A temperature-dependent plasticity model is utilized to characterize the material behaviour during braking. In the vicinity of the wheel tread, damage evolutions for the studied brake load cases are evaluated. The results show that high tread temperatures, in particular temperatures above 450°C, have a strong detrimental influence on the RCF formation and, hence, also on the thermomechanical capacity of the wheel. On the other hand, it is found that for braking temperatures between 300°C and 400°C, the fatigue resistance is increased due to strain hardening effects. In addition, the parametric study points towards actual braking load cases that can give such temperatures in terms of initial speeds, axle loads, etc. Wheels having straight webs and S-shaped wheel web exhibit the same fatigue life of their treads, whereas a reduction in wheel rim thickness promotes ratchetting due to increased flexural stresses from the mechanical wheel–rail contact loading.

7 Concluding remarks

In **Paper A**, two material models have been calibrated against LCF uniaxial strain-controlled experimental data for the pearlitic wheel steel ER7, one viscoplastic material model that can capture the stress response of the material both in terms of cyclic and viscous behaviour, and one plasticity model that can capture the stress response of the material only in terms of (rate independent) cyclic behaviour. Simulation results are presented for the global wheel behaviour of two generic wheel designs subjected to high power (drag braking) thermal loading. The wheel designs are a traditional S-shaped wheel and a Low-stress wheel. The results indicate that the S-shaped wheel is more sensitive to the choice of material model than the Low-stress wheel. This is due to the fact that the S-shaped wheel builds substantial stresses in the wheel rim during braking.

In **Paper B**, a methodology to simulate the conditions in full scale brake rig experiments is presented. The brake rig tests were performed with repeated stop braking cycles using sintered brake block and organic composite brake block. During rig testing, the wheel was subjected to thermomechanical loading due to combined tread braking and wheel–rail contact loads. In the tests, the occurrence of thermoelastic instabilities (TEI) with locally higher tread temperatures is observed. The TEIs are here caused by sintered brake blocks while the organic composite brake block usually results in evenly distributed temperature on the wheel tread. From test rig experiments (see also [64]), it is observed that cracks appeared in the area on the wheel tread that is traversed by the wheel–rail-wheel contact. Moreover, sintered brake blocks result in shorter wheel life in comparison to organic composite brake blocks. This can be explained by the presence of local high temperatures on the wheel tread due to the TEI phenomena. The TEI phenomena is accounted for in the FE thermal analysis by using simplified thermal patterns on the wheel tread. To perform the structural FE analysis, a material model of plasticity type, with a combination of nonlinear isotropic and kinematic hardening, was calibrated against data from LCF strain-controlled tests of ER7 steel at different temperatures. The model is able to capture the (rate independent) cyclic behaviour of the material.

In the structural FE analysis, fatigue of the tread material was predicted with a ratchetting type of criterion and with an LCF damage criterion. Results indicated that the LCF damage was lower than the ratchetting damage and that it could not predict the reduction in life for more sever braking cycles. The predicted number of brake cycles to crack initiation presuming a critical ratchetting strain ϵ_c of approximately 1.6 was found to be in good correspondence with brake rig results. In addition, the analyses indicate that temperatures higher than about 450°C, for the stop braking cases considered here, result in considerable increase in the ratchetting strain which causes shorter fatigue lives of the wheel. On the other hand, for lower temperatures, in the temperature range 300°C–400°C, a lower ratchetting damage is predicted due to the influence of dynamic strain aging in the material.

Moreover, in **paper E** the influence of important operational parameters such as axle load, maximum vehicle speed, deceleration, block material, wheel web design, wheel rim thickness, initial wheel temperature and friction coefficient between wheel and rail was investigated using the simulation methodology developed in **Paper B**. Here, fatigue lives were predicted using the same ratchetting criterion. The results of the parametric study show how variations of operational parameters influence the peak braking temperatures and rolling contact loads. The predictions indicate also here that for the loading conditions which result in temperatures higher than 450°C, a substantial decrease in the ratchetting life of the wheel tread is expected. However, for the conditions that result in temperatures in the range 300 – 400 °C then fatigue life increases relatively. Wheel web design does not have an impact on ratchetting life for identical in-field conditions. Contrarily, a wheel with reduced wheel rim thickness is more prone to ratchetting, resulting in shorter ratchetting life, compared to a new wheel in the same in-field conditions, due to a higher wheel rim flexibility and a slight increase in temperatures. The results imply that a worn wheel in revenue service, which has a thin rim resulting from consecutive machining and tread wear (smaller wheel rolling diameter than new wheel), will have an even lower fatigue life than the thin rim case considered in the present study since the temperatures of the wheel would be even higher.

A main challenge in the simulations of tread braking applications is the large difference in loading rate of the very fast rolling contact loading and the slow thermal loading caused by braking. The rate dependent (viscous) behaviour of ER7 steel was not accounted for in **Paper B** and **Paper E**. The main goal of **Paper C** is to account for the material's cyclic and viscous behaviour at different elevated temperatures. In this regard, a viscoplasticity model is calibrated against LCF uniaxial strain-controlled tests with hold-time (to capture slower viscous diffusion dominated behaviour) at elevated temperatures and uniaxial ratchetting tests including rapid cycles at elevated temperatures. The viscoplastic material model includes nonlinear isotropic and kinematic hardening. In the viscoplasticity model the Delobelle overstress function is utilized which can capture the material behaviour at a wide range of strain rates rather well. However, to capture the stress relaxation (diffusion dominant) behaviour in the material, the model is extended by a static recovery term. Furthermore, since the rolling contact loading on the wheel results in a multiaxial stress condition, biaxial strain-controlled tests on the material at elevated temperatures have been conducted and reported in [34]. In this context, we further extend the hardening of the model by including the Burlet-Cailletaud model. The capabilities of the material model is examined by simulating a full-scale test rig experiment reported in **Paper B**.

It is observed from the simulation results that the predicted ratchetting strain using the viscoplasticity material model during a braking cycle is significantly lower than the corresponding result from the plasticity model, developed in **Paper B**. Moreover, it is observed that including the effect of multiaxial hardening in the material model does not show a visible effect in the predicted ratchetting during a braking cycle.

In **Paper D**, a cyclic plasticity model incorporating phase transformations from near pearlitic steel to austenite, and then to martensite was developed to examine what residual stress fields that is obtained after repeated short term local heating (wheel skidding) and rolling contact loading on a wheel tread. The presented model is an improvement as compared to the model developed in [49]. The kinetics and the constitutive relations in the FE modelling are improved in this study, with the purpose to increase the accuracy of the predicted residual stresses. In order to examine the capabilities of the developed material model, two FE examples are considered; the first one simulates a "Double wheel flat" loading and is used to investigate the result of a frictional heating (pure thermal load) in terms of phase fractions and residual stress in the thermally affected zone. In the second example after each heating event, rolling contact loading is imposed on the wheel tread, to study the effect of over-rolling on the thermal residual stresses. It is observed from the FE analyses that below the transformed martensite layer, high tensile residual stresses are generated. Depending on the number and duration of the heating events the tensile residual stresses are generated within either the base material or the tempered martensite layer. Since the tempered martensite material is rather brittle it is more susceptible to crack initiation. Also, it is observed that the rolling contact loading reduces the tensile residual stresses.

Limitations and future works

There are aspects in **Paper B**, **Paper C** and **Paper E** that are simplified in the test rig experiments and FE simulations which might need be investigated in future studies:

1. One general observation is that the calculated ratchetting lives, in terms of number of stop braking cycles, are short for the studied cases as compared to observations in revenue traffic. One reason is that the position of the wheel–rail contact has been modelled as laterally fixed to the rolling circle of the wheel. Accounting for the inherent variation of this position for a train running on a track will result in substantially longer lives of the treads before the onset of RCF damage.

2. The presumptions of a constant banding pattern for all brake cycles also result in

over-prediction of obtained ratchetting while in reality the pattern changes from one brake cycle to the next (see [58]).

3. In addition, to avoid too long computational time, the simulated ratchetting results obtained for a few wheel revolutions are assumed to be representative for hundreds of wheel revolutions during a stop braking cycles. Hence, the progressive (cyclic) behaviour of the material e.g. shakedown or varying ratchetting rate is not fully captured.

4. The FE simulations of tread braking of railway wheels are very computationally expensive. The reason is that 3D models are required and that the wheels are subjected to very many loading cycles. Other finite element approaches such as sub-modelling techniques and arbitrary Lagrangian-Eulerian formulations [65] could be considered in future works.

Another limitation is that the viscoplasticity model in Paper C is calibrated for the strain rate of range $5 \times 10^{-4} \leq \dot{\epsilon} \leq 10^{-1}$ [1/s] while the simulations of brake rig experiment suggest a range of strain rate $10^{-7} \leq \dot{\epsilon} \leq 100$ [1/s] due to the applied thermomechanical loading. To validate or improve the predictions of the viscoplasticity model, it is desirable to conduct experiments on ER7 at high strain rate e.g. using Split-Hopkinson pressure bar [66, 67].

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