THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

IN

SOLID AND STRUCTURAL MECHANICS

On improvement of brake discs for heavy vehicles

Experimental testing and material modelling

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Department of Applied Mechanics
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden, 2013

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Thesis for the degree of Licentiate of Engineering 2013:20

ISSN 1652-8565

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Cover:

Photo of cracked brake disc and visualization of its thermal image

Photo by Mats Löfstrand, Scania CV AB

Chalmers Reproservice

Gothenburg, Sweden 2013

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ABSTRACT

Disc brakes are commonly used in motorcycles, passenger cars, commercial vehicles, heavy-duty vehicles, passenger trains and landing gear of airplanes. Depending on the application, different types of brake discs can be found on the market with numerous designs, geometries and materials. The brake disc material commonly used for heavy-duty vehicles still is a traditional material based on grey cast iron due to its favourable performance and low cost. Gradual improvements of the thermal and mechanical properties of grey cast iron alloys have been introduced over the years. However, the properties of grey cast iron are not as well known as those of steel or aluminium alloys.

In the present work, Scania has initiated a collaboration project with Chalmers University of Technology aimed at a better understanding of the mechanisms that control the life of brake discs and at enhanced vehicle performance and reduced maintenance costs. Firstly, a state-of-the-art survey has been carried out with a review of brake disc technology and mechanisms related to brake disc life. Secondly, a uniaxial thermomechanical fatigue experiment has been analysed using analytical and numerical methods. The aim was to simulate temperature-induced stress and strain cycles and to estimate the life of the specimens based on the Coffin-Manson and Smith, Watson & Topper (SWT) laws. A simple analytical model available from the literature was implemented in order better to understand the concepts, which then was applied in a detailed finite element model. Thirdly, full-scale brake dynamometer experiments have been carried out and analysed with discs made from eight different materials at controlled torque, speed and cooling conditions. Disc surface temperatures were recorded by use of a thermocamera and local temperatures by use of thermocouples embedded in the brake discs. Wear properties, crack propagation and temperature loading were studied. Detailed analyses were performed on temperature data to reveal characteristics of the tested brake discs. From the results of the experiments, the main parameters influencing the life of brake discs were identified. Spatial fixation of bands and/or hot spots was found to have a major impact on disc life.

KEYWORDS: brake disc, cast iron, fatigue, cracking, hot spots, material testing, finite element analysis, drag braking, rig experiment

PREFACE

This work has been performed as part of the FFI project "Improved performance of brake discs" (Vinnova project 2009-01449), which is a collaboration between Department of Applied Mechanics at Chalmers University of Technology and Scania CV AB with financial support from Vinnova. The project started during the spring 2010. The project is associated with the activities in the Swedish National Centre of Excellence CHARMEC (CHAlmers Railway MEChanics, see www.chalmers.se/charmec).

I want to express my special gratitude and thanks to Professor Roger Lundén and Dr Tore Vernersson for their help, support and discussions that assisted my process of learning. I also would like to thank my colleagues at Scania CV AB and especially Dr Peter Skoglund for his general involvement in all aspects of the FFI project and Mats Löfstrand for his contributions to the full-scale experiments performed on the Scania brake dynamometer. The support from the project reference group with members from Scania is gratefully acknowledged. Professor Bengt Åkesson assisted in improving the manuscript.

I deeply express my appreciation to Nathalie Barbeau, Lisa Brutti, Philippe Joachim, Olivier Le Douarin, Sofia Lerjéus, Andrea Ricci Persson and other friends for their support, motivation and all happy moments.

Finally, I would like to express my love to my mother who never stopped believing in my ability to take up challenges and who supported me along all these years.

Gothenburg, October 2013

Gaël Le Gigan

THESIS

This thesis consists of a summary and the following appended papers:

Paper A Gaël Le Gigan, Roger Lundén and Tore Vernersson, Improved performance of brake discs: State-of-the-art survey, Chalmers Applied Mechanics, Gothenburg Sweden, 2011, 55 pp.

Paper B Gaël Le Gigan, Roger Lundén and Tore Vernersson, Thermomechanical fatigue of brake disc materials – Results from modelling and experiments. In *Proceedings Eurobrake 2012*, Dresden, Germany, 2012, 11 pp.

Paper C Gaël Le Gigan, Tore Vernersson, Roger Lundén and Peter Skoglund, Disc brakes for heavy vehicles – an experimental study of temperatures and cracks, Chalmers Applied Mechanics, Gothenburg Sweden, 2013, 24 pp. Submitted for international publication.

Appended papers were prepared in collaboration with the co-authors.

Paper A is an extensive literature survey on brake discs with focus on material properties, numerical models, disc geometry and design optimisation. The author of the thesis is responsible for gathering of information related to the subject and writing of the paper.

In Paper B, the author of the thesis is responsible for the simulations of thermomechanical fatigue (TMF) tests performed at Scania CV AB, for calibration of implemented material models and for writing the main parts of the paper.

In Paper C, the author of the thesis was involved in the design of the test instrumentation, carried out the analyses of the experimental data and wrote the main parts of the paper. In addition to this, the author of the thesis was present during parts of the rig experiments and actively contributed to improvements of the testing procedure in collaboration with the Brake Performance Team at Scania CV AB.

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Appended papers

Paper A

Paper B

Paper C

REVIEW AND SUMMARY

An introduction to the subject of the thesis is given and references are listed in **Papers A, B** and **C**. The present summary and reference list are intentionally made short. Further background information and references can be found in the state-of-the-art survey, which has been compiled in **Paper A.**

1 INTRODUCTION

The expansion of the commercial automotive market is due to an increased demand for commercial cars (trucks and busses) and industrial vehicles (heavy vehicles for farms, mines, etc). International competition calls for cost reductions, improvements of performances regarding maintenance, safety and reliability and also general improvements of technologies embedded in such vehicles. Improvements of brake discs respond to most of these aspects, although still employing the traditional technologies and materials.

1.1 Braking of trucks – overview

In order to reduce the speed of, e g, a heavy-duty vehicle, a pair of pads is pressed against a rotating disc, so-called brake disc or brake rotor, see Figure 1. By doing so, the kinetic or potential energy of the vehicle is converted into thermal energy. The braking constitutes a complex loading that results in a rapid increase of temperatures at the disc surfaces while a non-uniform contact between the brake pads and the disc is developing. This leads to wear of the disc and the pads. It may also cause initiation and growth of cracks in the brake disc as induced by stress variations that follow the cyclic heating and cooling processes.

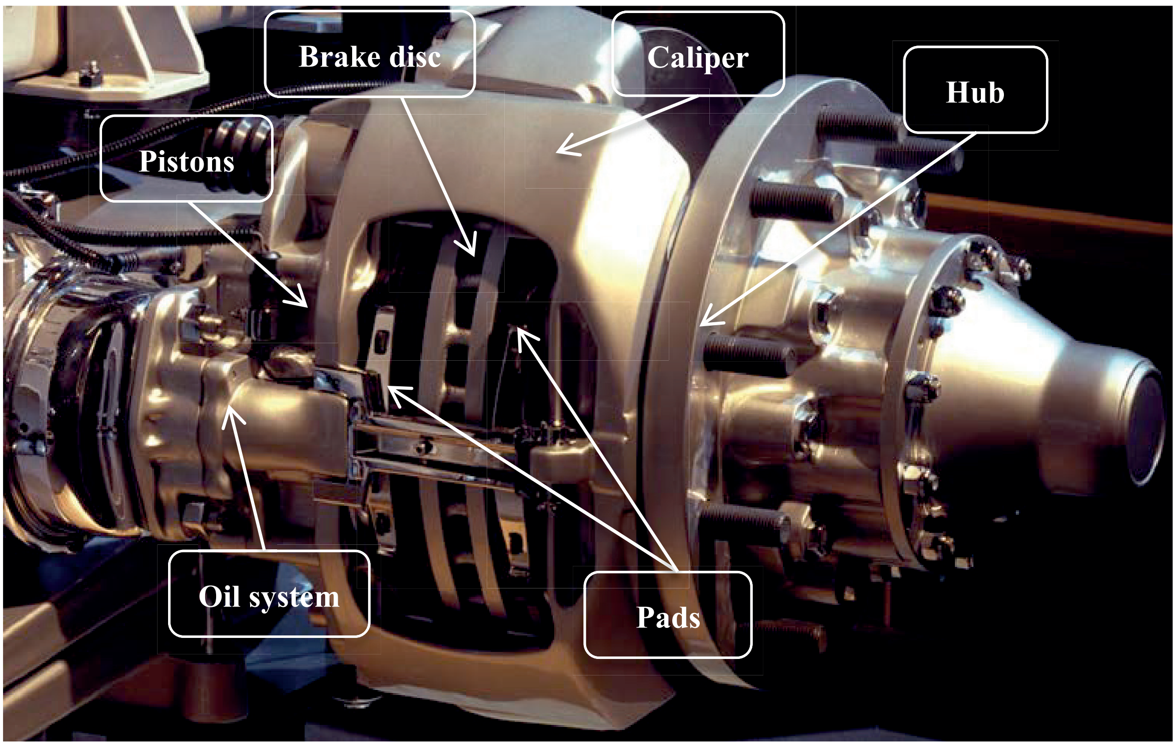


Figure 1 View of a disc brake system and hub of a commercial vehicle [1].

Three different types of braking can be defined. The first kind is "stop braking" where the speed is reduced until stop. The second is "normal braking", also known as 'snub braking', where the speed is decreased at general driving for safety reasons (e g, keeping the distance between vehicles) or changes in speed limits. The third one is "drag braking", also referred to as downhill braking, as the brakes are used for preserving speed when travelling down a gradient.

Characterization of brake disc lives at full-scale dynamometer testing often uses standardised testing methods and load cases of drag braking type. Such tests are designed to give accelerated testing as compared to in-service conditions and are considered to provide relevant life predictions.

The thermal energy generated at braking is transferred by conduction inside the brake components and by convection and radiation to the surrounding, see **Paper A**. The performance of a given brake disc design (with respect to phenomena such as wear, friction coefficient, brake fade and fluid vaporization) is controlled by the thermomechanical material properties and the tribological environment. Moreover, the brake disc design controls global disc deformations and convection cooling performance, and influences the build-up of thermal stresses. Hence, improvements of brake disc performance can be realised by modifying the material and/or brake disc design in appropriate ways.

Brake discs can be manufactured from different materials, see Table 1. The most commonly used brake disc material is grey iron [2] even though materials such as aluminium metal matrix composites and carbon ceramics also are used. Stainless steel is presently only used for motorcycles. Grey iron is a good compromise when considering cost to performance ratio. Carbon ceramic materials can provide an excellent performance, but at a high cost and are for this reason only used on, e g, racing cars. Brake discs made from aluminium metal matrix composites are in between these two materials when it comes to both performance and cost and are only used for passenger cars [3].

For heavy vehicles, the main focus for many years has been to improve grey iron, so-called flake graphite iron, by alloying with other chemical elements. Grey irons used in brake disc materials are defined by their chemical composition (percentage of, e g, carbon, silicon, manganese, sulphur and phosphorus) but not by their manufacturing processes which are similar for all alloys. A valuable feature of grey iron is that it is 100 % recyclable [4].

In Figure 2, the different phenomena involved in brake disc performance and their interactions are shown.

Table 1 Brake disc materials and their applications. Adapted from the Power Point presentation related to [5]

Brake disc material	Grey cast iron alloys	Aluminium Metal Matrix Composite (AL-MMC)	Stainless steel	Carbon Ceramic Composite
Cost	Cheap	Affordable	Expensive	Very expensive
Area of use	Ordinary vehicles & special competition vehicles [6]	Passenger cars	Motorcycles	High-speed luxury sports vehicles

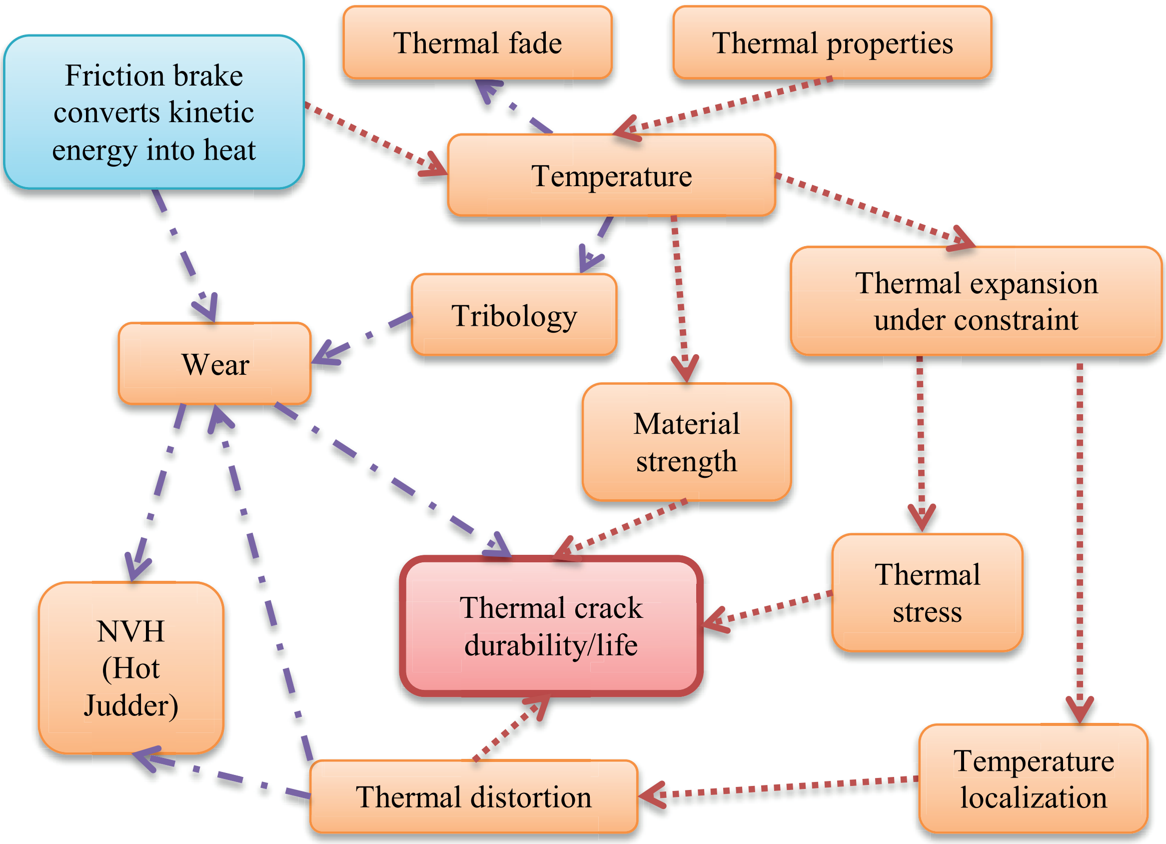


Figure 2 Function and performance of brake discs. The red dotted lines represent the contribution to thermal cracking while the magenta dashed-dotted lines define the links between other phenomena. Adapted from the Power Point presentation related to [5].

1.2 Aim of study

A brake disc with better resistance to thermal cracking and preserved wear and friction properties, see Figure 3, would lead to significant savings, particularly in the form of a higher utilization rate of the vehicle. In order to increase the performance of brake discs, thereby reducing the number of disc replacements during the life of the vehicle, Scania has initiated this work aimed at understanding the mechanisms that control cracking and disc life.

Figure 3 Example of wear (left), heat crazing (middle) and heat cracking (right) [7].

Finding an improved alloy for implementation on brake discs is a delicate task. In this thesis a combination of thermomechanical testing and full-scale brake rig experiments has been used to find the main influencing parameters. Thermomechanical fatigue testing on a specimen, taken from a brake disc, can be one way to characterize the material response. The influence from the complex load case induced by the pad-to-disc interaction is then simplified to a controlled thermomechanical loading. Testing methods for possible screening of candidate disc materials can give shorter developing times for brake discs. Nevertheless, a better characterization of the phenomena that arise at full-scale braking and which controls brake disc lives, is still required. This is a main point when it comes to improve brake disc material subjected to the actual thermomechanical loads that brake discs are exposed to at braking.

1.3 Method of research

In the present work, various methods of investigation have been used: literature studies, testing of material specimens, full-scale rig experiments and also modelling and numerical simulations.

The state-of-the-art survey, see **Paper A**, provides a thorough background to key parameters that are important for braking when it comes to thermomechanical aspects, temperature behaviour, wear, cracking and related testing and numerical simulations. Cooling performances and mechanisms are described. Fatigue and cracks are investigated and common approaches to life prediction are given with special consideration related to grey cast iron. Thermomechanical fatigue with damage models is described and crack initiation and propagation is discussed.

The analytical and numerical modelling (FE-method) in **Paper B** studies a thermomechanical fatigue (TMF) experiment performed in laboratory. A designated TMF testing rig was used and modelling and calibration of temperature and stress distributions and possible prediction of fatigue life are at focus in the paper. The work aims at computing the life of the specimen based on the thermal loading and the predefined boundary conditions and to investigate how the results can relate to the life of a full-scale brake disc.

Detailed results and analyses of full-scale brake rig experiments are reported in **Paper C**. Severe drag braking applications with cooling-down between cycles are performed for several brake disc materials. The measured temperature response as registered by thermocouples and a thermocamera is thoroughly analysed. Differences in temperature phenomena are identified and related to the life of the discs with respect to crack growth.

2 SUMMARY OF APPENDED PAPERS

2.1 Paper A

Improved performance of brake discs – State-of-the-art survey: An overview of disc braking and phenomena related to braking performance and disc life is given. In the study, different types of brake discs are introduced and some examples of ventilated brake discs are shown in Figure 4. It can be noted that solid discs also are used for some specific applications, e g, low-performance cars (on the rear axle) and the French high speed train (TGV). Influence of mounting of the disc part, which can be of so-called hat (integrated bell) or floating types, is discussed and related to its importance for cracking of the discs. Discs of a floating type allow for radial and axial heat expansion which reduces stresses, cracking and distortion as compared to discs of hat type where the disc is fixed to the hub via a hat shaped structure. However, the hat type of brake disc has some advantages, e g, easy to cast, low cost, one body (no internal vibrations induced at bell-disc interface). A brake disc of hat type (cast in one piece) is prone to coning and its constrained thermal expansion affects contact conditions during braking as illustrated in Figure 5.

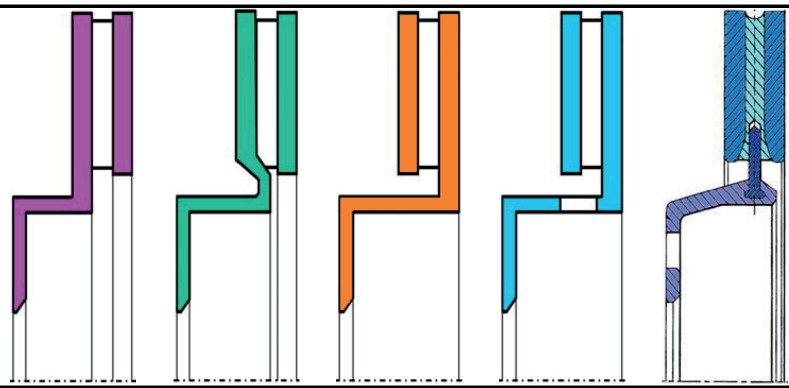
Type	Outer hat without neck	Outer hat with neck	Inner hat without holes in hat	Inner hat with holes in hat	Floating
Schematic drawing of cross-section of discs					

Figure 4 Basic configurations of ventilated brake discs. Adapted from [8]

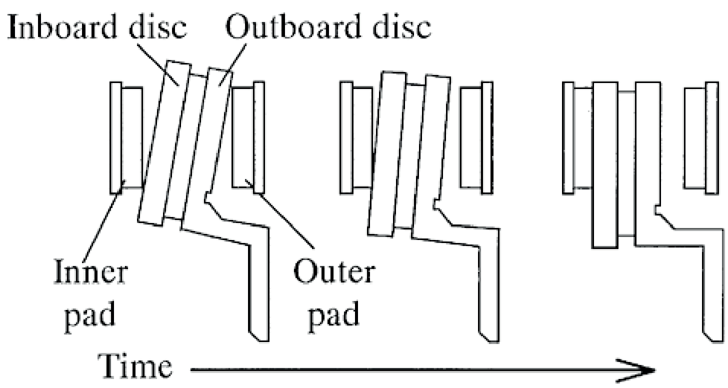


Figure 5 Schematic change in contact conditions between deformed rotor and pads after one brake application [9]. The left figure is showing the disc behaviour at braking, while the middle figure is the configuration when the disc is cooling down. The area of the disc near the inner radius is still in contact with the pad until the disc recovers its "normal" geometry when cooled to ambient temperature (right figure).

Ventilated brake discs as introduced in Figure 4 can have several types of cooling vane geometries and some examples are shown in Figure 6. Many variations exist for the vane shapes [10] and pillar shapes [11]. Tangential and curved vane discs are mounted in a way where the air is actively pumped. This design is also called directional vanes. The cooling influence of vanes in the discs for railway applications has been studied, e g, [12].

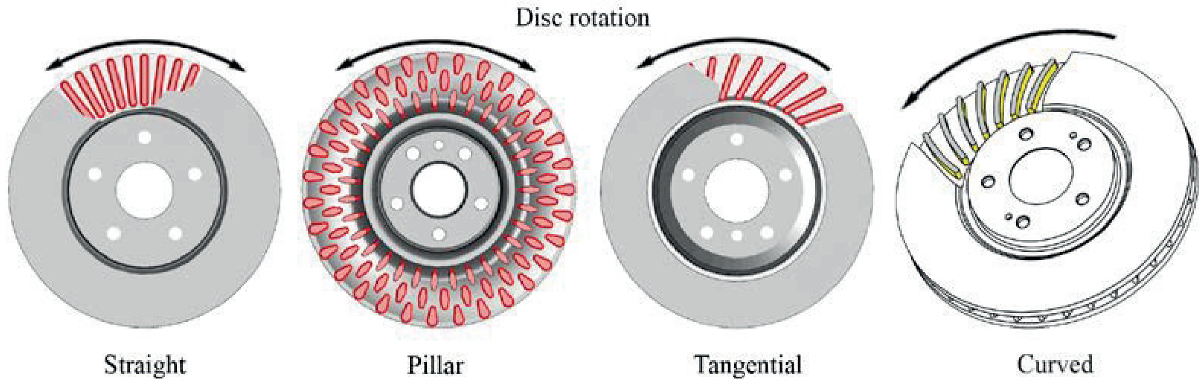


Figure 6 Examples of vane types available on the market. Adapted from [13] and [14]. Slotted or drilled discs can also be found, but no such configurations are shown here.

The mechanisms of heat generation and heat transfer in a disc brake system are also discussed [15], see Figure 7. At braking, the major heat transfer mechanism is initially conduction through the brake disc itself and the pads. Gradually, with longer periods of braking, the temperature in the disc increases, heat is conducted to surrounding structures and cooling increases by radiation and also by convection by air flowing through the vanes [16].

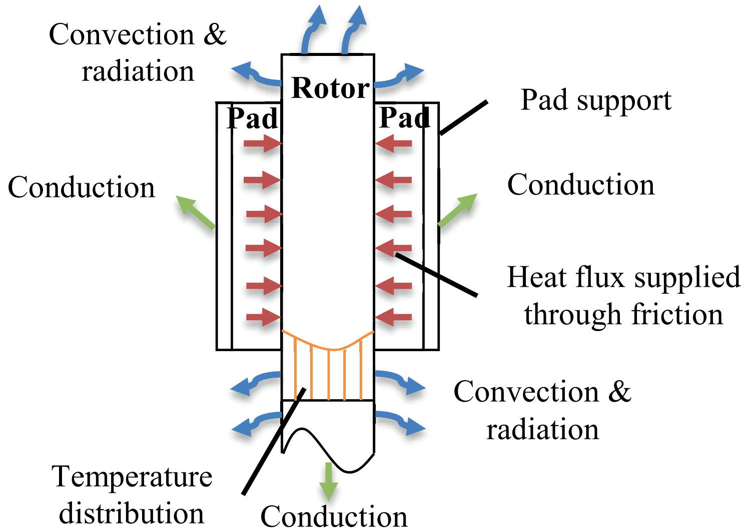


Figure 7 Heat transfer mechanism in a disc brake system [15].

A description of different grey iron alloys is presented and reasons are given as to why grey cast iron is still in use nowadays, highlighting the advantageous performance to cost ratio of this material. The role of the main chemical elements and the microstructure of grey iron alloys are discussed and thermophysical properties are introduced. Influence of temperature on the thermal properties of grey cast iron is illustrated. The manufacturing process has not been investigated. Fracture mechanisms and crack growth for grey cast iron and some relevant phenomena for this material, such as creep and thermal shocks, are surveyed.

2.2 Paper B

Thermomechanical fatigue of brake disc materials – Results from modelling and experiments: Thermomechanical fatigue (TMF) is a concept that expresses that a component is subjected to simultaneous thermal and mechanical loads of cyclic nature. Brake discs are typically thermomechanically loaded by the heat generated at the pad and disc interfaces and due to the mechanical constraints introduced by restrained thermal expansion within the brake disc itself. The material response of a brake disc at braking is difficult to evaluate and for this reason simplified experiments are usually performed with controlled boundary conditions. The present paper reports on efforts on analysing a TMF testing arrangement proposed for characterising brake disc materials. In the studied experiments, cyclic induction heating from 100 °C to 600 °C is performed on hourglass shaped specimens (taken out of a brake disc) that are constrained at its ends, see Figure 8. The idea thus is to produce a thermomechanical load that is similar to the one in a brake disc. The aim is to evaluate the TMF loading of the specimen by calibration of a suitable material model that at a later stage could be applied when analysing in-field braking or full-scale braking experiments as described and analysed in **Paper C**.

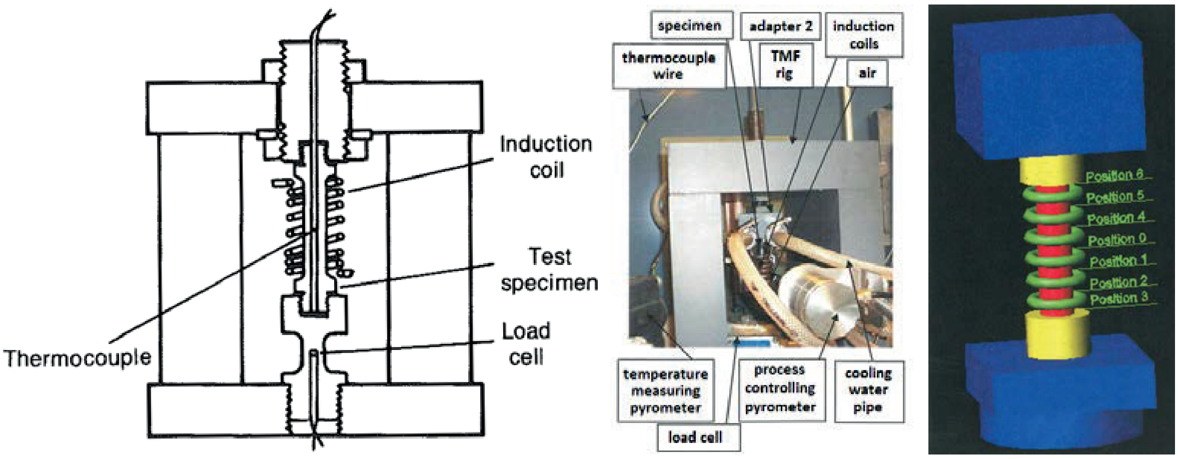


Figure 8 Schematics of TMF test (left), testing machine (middle) and thermocouple locations (right).

Two different approaches have been considered for analysis of the tests. First, an analytical approach is considered, where a simple bar constrained at both ends is studied under isothermal conditions with uniaxial stresses and strains. Two material models are implemented with temperature-independent material parameters: a mixed linear kinematic and isotropic hardening material model and a mixed linear kinematic and isotropic hardening material model with viscoplasticity. The life of the specimen is assessed using the Coffin-Manson relation but also using the Smith, Watson & Topper (SWT) approach.

The second approach means modelling of the actual TMF testing set-up both regarding the thermal problem and the thermomechanical fatigue problem. An FE-model is established to study the thermomechanical behaviour of the tubular (hollow cylindrical) test specimen and is also calibrated to the test results by an axisymmetric FE-model that mimics the tests performed in laboratory. The first step is to compute the temperature distribution in the specimen and then proceed to analyse the average stresses, see Figure 9.

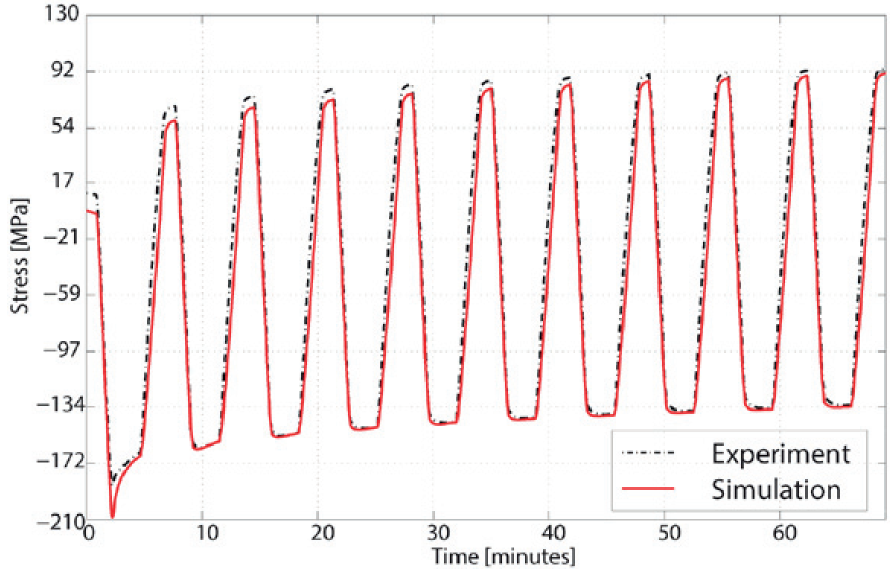


Figure 9 Measured and simulated stress histories for the first 10 temperature loading cycles. The simulations are based on an FE approach.

It is found that the analytical model give a life of 932 and 840 cycles according to the Coffin-Manson and SWT formulae, respectively, while an average of 216 cycles to failure has been observed in the experiments. These large deviations can be explained by the choice of the material constants used in Coffin-Manson and SWT that were not determined based on the tested brake disc materials but taken from literature. The numerical model makes it possible to simulate realistic response of the material and showed that local plastification only occurs at the centre of the specimen. It was observed that the stresses never exceed the yield strength in tension and that the failure is the result of accumulated residual stresses from plastification in compression.

2.3 Paper C

Disc brakes for heavy vehicles – an experimental study of temperatures and cracks: Brake rig experiments have been carried out on eight brake disc materials to find the life of the tested discs with respect to global cracking. Drag braking is performed at a constant torque of 2800 Nm for 45 s and with a constant speed of 425 rpm (corresponding to a truck speed of about 80 km/h). Temperatures are measured in the disc and the pads (thermocouples) and on the disc surface (thermocamera). The main focus in the work was on finding the key influencing parameters which control the life of the disc. The work has been divided into two parts: analysis of data from the thermocouples and analysis of data from the thermocamera. Figure 10 shows the full-scale brake dynamometer where the discs are mounted for an accelerated drag braking crack test.

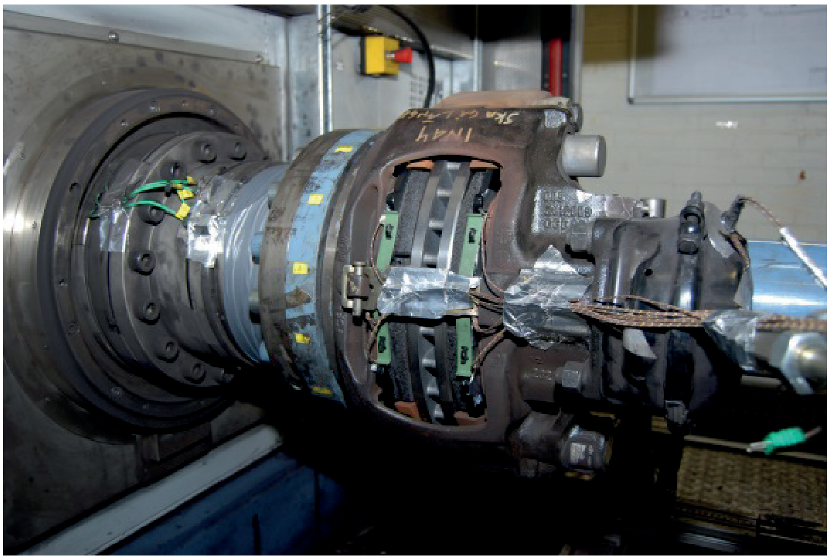


Figure 10 Brake dynamometer: close up of brake disc and caliper.

Seven of the eight disc materials studied show very similar thermal conductivities, at a given temperature, for the considered testing temperature ranges (25 °C to 900 °C). The remaining brake disc material shows a similar thermal conductivity at high temperatures while at lower temperatures it is up to 15 % lower. The chemical compositions of the tested brake discs are rather similar. The modifications mainly concern niobium and molybdenum content.

All tested brake discs exhibited hot spots and banding behaviours with more or less variations. An example of a thermal image generated at the end of the braking application is illustrated in Figure 11.

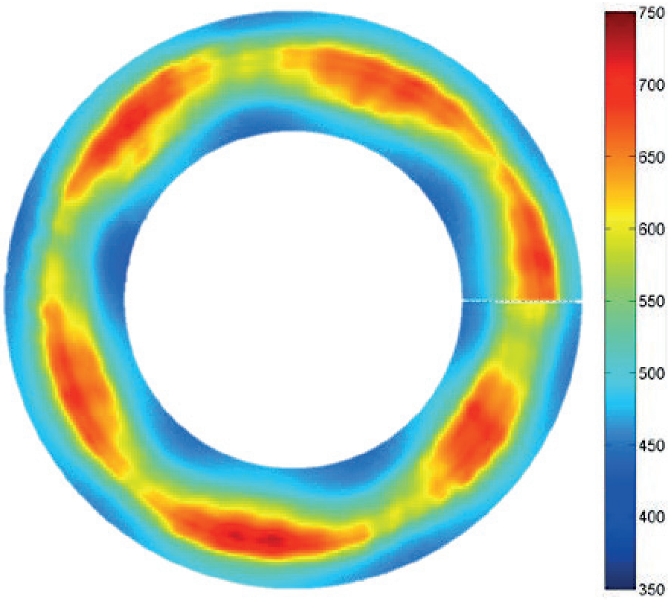


Figure 11 Example of thermal image showing hot spots located in one band.

Unexpectedly, it was found that the level of temperatures reached in the discs cannot be related to disc lives as some discs showed high maximum temperatures but still resulted in a longer life than some other discs with lower maximum temperatures. However, discs having long lives showed migration of hot spots and/or alternating bands, see examples in Figure 12. A general observation is an antisymmetric temperature behaviour between the two sides of brake disc. Vanes were found responsible for the hot spot pattern in the early part of the disc life for discs having a long life. A main result of this study is that spatial fixation of hot spots and band(s) on the disc are detrimental for the brake disc life. In addition to those findings, the pad material is important for the hot spot formation regarding fixation and peak disc temperatures.

The results for crack growth show a rather stable evolution of the crack length up to a length of 60 mm after which the crack growth rate increases substantially. However, the disc with the shortest life (a “pirate disc”) shows a much higher crack growth rate than the other discs. This disc has lower thermal conductivity than the others.

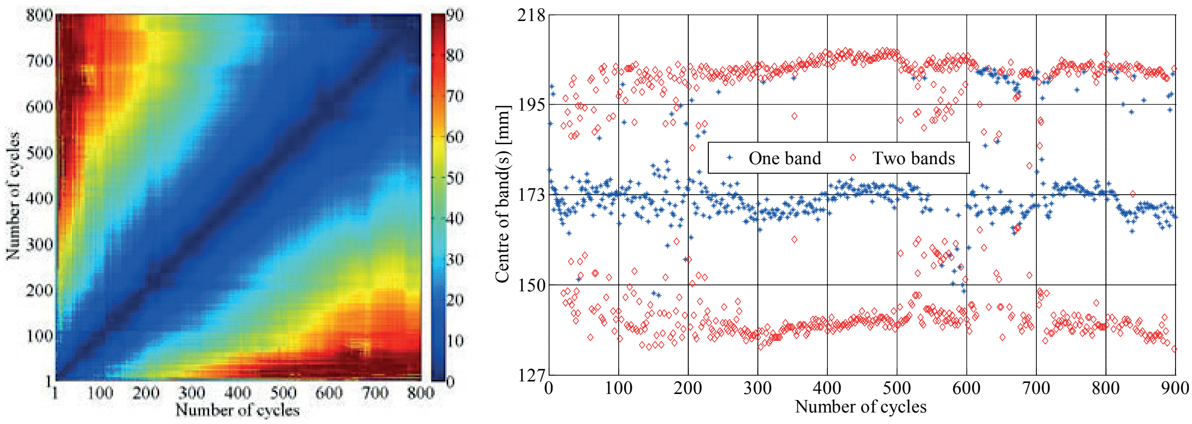


Figure 12 Example of angle shift (in degrees) showing hot spot migration (left) and variation of band(s) location (right).

3 CONCLUSION AND FUTURE PLANS

The state-of-the-art survey, presented in **Paper A**, gives an overview of the complex phenomena that influence the life of brake discs. Further, it shows the wide topics around braking applications (squeal noise, dust, etc) and the complex interactions that make it challenging to solve even a limited part of the related problems.

The simulations of a TMF test for characterization of brake disc materials performed in **Paper B** show that advanced material modelling, specifically aimed at cast iron materials, is required to capture the response of the brake disc materials. Moreover, assessment of fatigue laws from the literature gave mixed results, highlighting the importance of finding damage parameters for the actual studied material.

The detailed analyses of measured temperatures from brake rig experiments in **Paper C** point out the key phenomena that are important for the disc life. It has been demonstrated that the temperatures reached in the disc are not determining the disc life. Instead, the disc brake should not be prone to develop hot spots and band fixation in order to withstand crack propagation that causes disc failure and increased maintenance costs.

A continuation of the work reported here has already been approved by Vinnova in the FFI-project "Improved performance of brake discs, Stage 2". In this second part, the aim will be to improve the material modelling and fatigue life prediction of brake discs based on grey cast iron alloys. For doing so, a Mori-Tanaka type numerical model will be implemented that will be calibrated using isothermal and thermomechanical laboratory tests. In the end, the aim is to develop tools for optimising brake disc material and geometry with reduced cost of production and maintenance, and also improved performance with respect to thermomechanical fatigue.

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