Improved performance of brake discs

Project within FFI-Fordonsutveckling

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Content

1. Executive summary

The FFI-project “Improved performance of brake discs” is a cooperation between Scania and the Department of Applied Mechanics at Chalmers University of Technology. The purpose of the project is to develop a brake disc with improved overall performance and a better understanding of the processes that control the life of a brake disc.

The project has been conducted in close cooperation between the two participant organizations. At Chalmers the team consisted of PhD student Gaël Le Gigan and his supervisors Dr Tore Vernersson and Professor Roger Lundén. At Scania the project team consisted of employees from the Departments of Materials Technology, Brake Performance and Axle Development. The group at Chalmers has a deep knowledge of the thermomechanical loading and testing of brake components through research conducted within the competence centre CHARMEC (CHAlmers Railway Mechanics). In the present project this knowledge is applied to the braking of heavy trucks and several extensive testing campaigns were conducted using the full scale brake dynamometer at Scania. The team at Chalmers also provided the material modeling and FEM calculations performed within the project. The contribution from Scania further included test casted brake discs with different compositions and also provided important material data from static and dynamic testing at different temperatures as well as thermal properties of the investigated alloys. Moreover, Scania has determined properties of brake pad materials.

The project has been very successful and generated new knowledge both regarding which material parameters that control the overall performance of a brake disc and it has also led to improved testing and evaluation methods of full scale brake dynamometer experiments. In addition, the project has generated new insights regarding the thermomechanical fatigue modeling of alloys such as grey iron. Finally, a new brake disc alloy has been developed and patented and is currently used in an extensive field testing on trucks all over the world.

The work has generated results that has been published at a conference as well as in reports and a licentiate thesis will be presented during the fall of 2013. The project has further led to an open and effective cooperation between the involved departments at Scania and Chalmers. The work has also shown that further efforts are needed to improve the material modeling of grey iron alloys subjected to complex thermomechancial loadings. As a result of this, a continuation was proposed to Vinnova and the application was accepted in December 2013. The continuation project is entitled “Improved performance of brake discs – Stage 2” Dnr. 2012-03662. The new project will run between July 2013 and June 2015 with a focus on material modeling. At the end of the project the PhD student will obtain his doctorate degree.

2. Background

The purpose of this report is to summarize some of the most important findings in the FFI-project “Improved performance of brake discs” which is a cooperation between Scania and the Department of Applied Mechanics at Chalmers University of Technology.

When a vehicle's kinetic energy is converted into thermal energy in the brake disc and the pad during the braking process these components are exposed to high thermomechanical loads. The complex load case results in wear of the disc but also cracking due to thermomechanical fatigue. Both these phenomena can lead to impaired braking performance and safety problems. With the aim to increase vehicle performance and to reduce the number of replacements of discs and hence to reduce the cost, particularly in the form of inactive vehicles, Scania has initiated this work aimed at understanding the mechanisms that determine the lifespan of brake discs.

Today’s brake discs for trucks are made from grey iron and important characteristics include high thermal conductivity and preserved mechanical properties at elevated temperatures. Of course, it is also important that the friction and wear characteristics are as good as possible and it is important to note that these properties are directly related to the type of pad used. Different load cases can result in various modes of failure and a disc that meets certain requirements may be worse in other respects. Depending on where and how the truck is running, also the load on the disc will vary. To optimize the life of the brake discs is therefore very difficult. In the presented project, focus is on maximizing the life of the disc with respect to resistance against thermal cracking but other properties such as friction and wear must still be good.

As mentioned, brake discs may fail due to wear or due to extensive cracking caused by the repeated heating and cooling of the disc during braking. Of the two failure modes, cracking is presently the dominating cause for replacing a disc. The sensitivity of a disc to cracking and wear can be investigated by a full scale test using a brake dynamometer, see figure 1. In a so-called crack test a repeated specific braking cycle is applied and the crack growth is noted as a function of the number of brake cycles.

Figure 1. Disc with severe cracking (left) and overview of the full scale brake dynamometer (right).

In figure 2 an example of the measured temperatures during the experiments is shown. As seen, the disc reaches temperatures close to 750 °C.

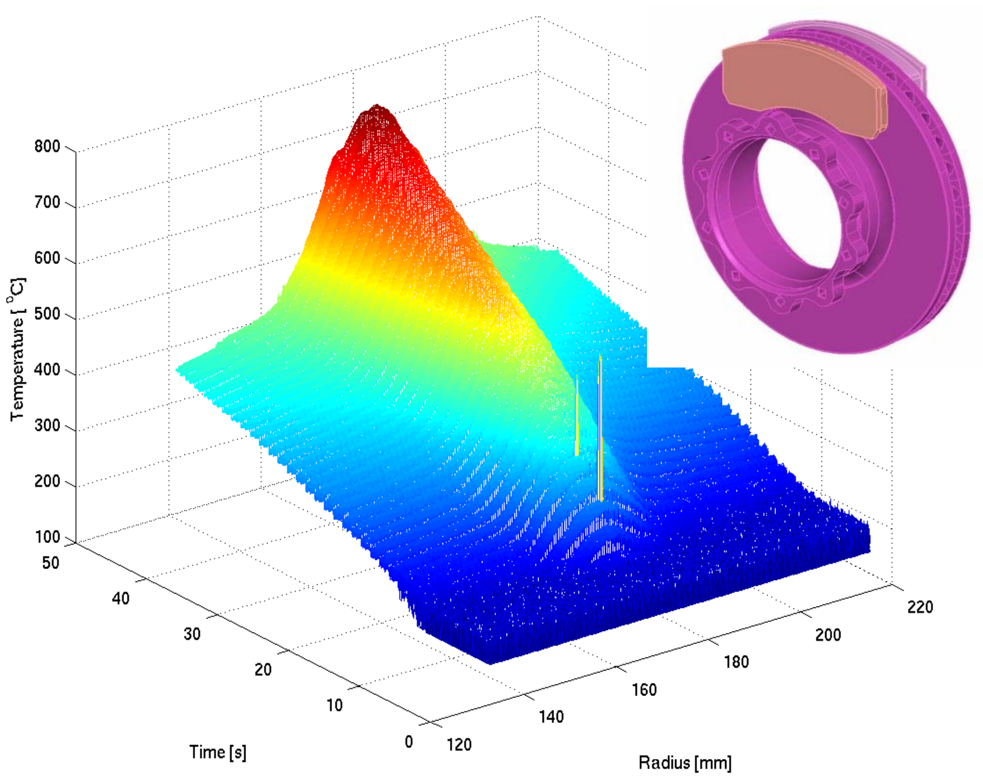

Figure 2. Example of the temperature evolution on the friction surfaces of the brake disc during a brake dynamometer test.

The heating of the disc during braking causes build-up of compressive stresses and plastic deformations and subsequently tensile stresses will develop when cooling down. If the process is repeated, cracks will initate and grow and finally the disc fails due to thermomomechanical fatigue. Figure 3 shows the number of cycles to failure for some different brake disc materials. As seen very large differences in fatigue life or number of cycles to failure is found. Thus it is important to investigate the mechanisms that control the fatigue life of a brake disc.

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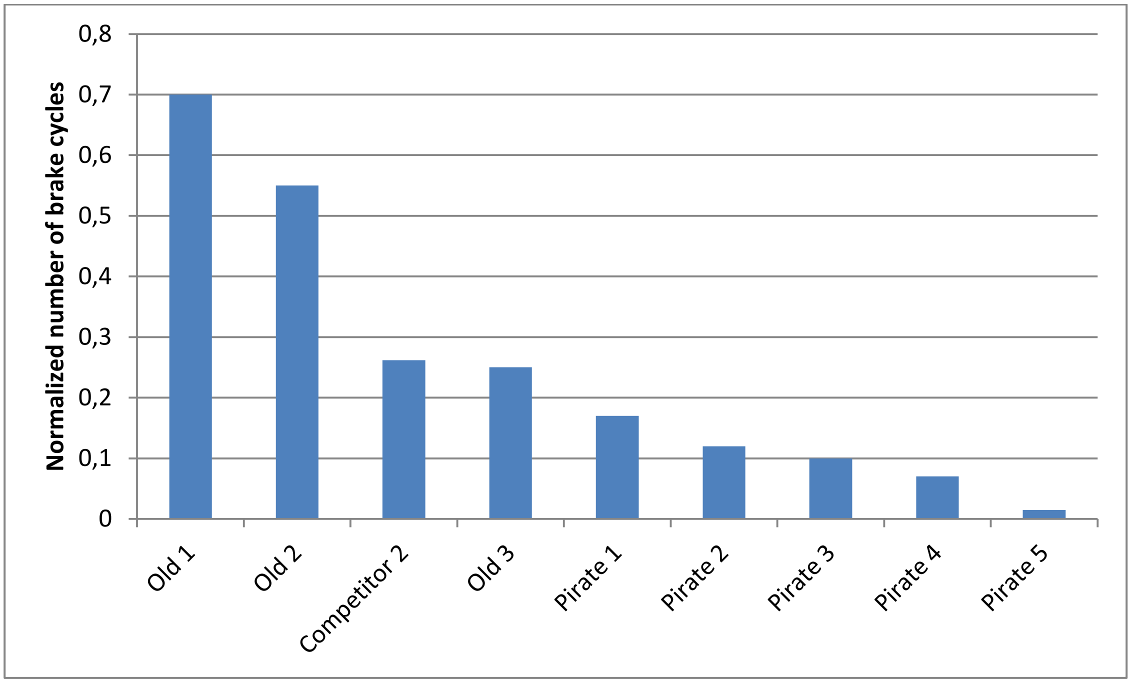

Figure 3. The number of brake cycles to failure (normalized, a value of 1 is considered to be a so-called run-out, i.e. the disc endured all the cycles in the test) for some different brake disc materials. All discs have the same geometry and are tested with the same type of brake pads.

3. Objective

The main objective has been to increase the knowledge of the different mechanisms that control the life and overall performance of brake discs for heavy trucks. This includes the development of methods to rank potential brake disc materials with respect to resistance to thermal cracking and also regarding wear and friction properties. Further, the project was expected to generate knowledge that allows for development of a new alloy for brake discs with improved overall performance. In addition, it is of highest importance to develop material models that will allow for optimization of the geometry of the brake discs and hence also the weight.

In the longer term, the project is expected to generate knowledge that can be used to determine whether other, lighter and more durable, materials than grey iron can be used for future disc brake systems when hybrid technology will be employed for regenerating parts of the braking energy.

4. Project realization

At Scania the Departments of Materials Technology, Brake Performance and Axle Development have been responsible for executing the project in close cooperation with the Department of Applied Mechanics at Chalmers University of Technology.

At Chalmers the team consisted of PhD student Gaël Le Gigan and his supervisors Dr Tore Vernersson and Professor Roger Lundén. The group at Chalmers has a deep knowledge of the thermomechanical loading and testing of brake components through research conducted within the competence centre CHARMEC (CHAlmers Railway Mechanics). In this project this knowledge is applied to the braking of heavy trucks and several extensive testing campaigns were conducted using the full scale brake dynamometer at Scania. The team at Chalmers also provided the material modeling and FEM calculations performed within the project. The Scania group was responsible for supplying test materials, i.e. test casted brake discs and pads. The contribution from Scania also included important material data from static and dynamic testing at different temperatures as well as thermal properties of the investigated alloys. Further, all brake dynamometer tests were performed using the experimental facilities provided by Scania. The analysis of the results from rig tests, material experiments and finite element calculations were discussed between the partners in a series of meetings at Scania and at Chalmers and also by telephone meetings and small seminars. In addition, a steering group with representatives from both Scania and Chalmers followed and controlled the progress of the project.

5. Results and deliverables

It must be emphasized that the project has been very successful and contributes both to the more general goals of the FFI-program but also to the more specific aims of the project. Below some of the more interesting results are presented.

As discussed above, the overall performance of a brake disc can be investigated by testing in a brake dynamometer. In this project the instrumentation techniques of the brake discs and pads during the different tests have been improved as well as the evaluation methods of the collected data. The localization of the heat into “hot spots” clearly shows that it is necessary to have knowledge of the local heat distribution in the disc. In figure 4 (left) a thermocamera has been used to measure the surface temperature distribution over the disc at the end of a brake cycle in the brake dynamometer. The results can be used to calibrate finite element calculations, see the right part of figure 4.

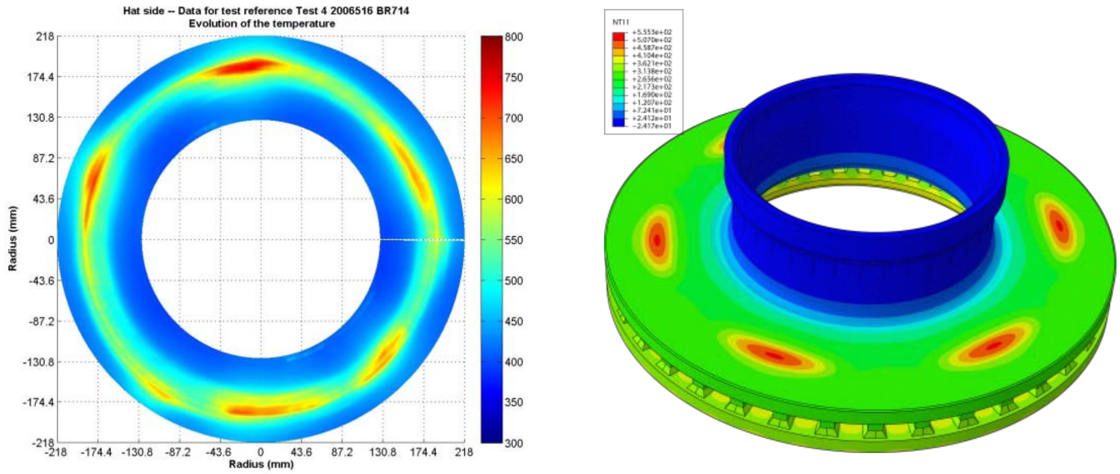

Figure 4. Measured (left) and calculated (right) temperatures on the surface of a disc.

Material properties

For brake discs of grey iron the investigations clearly show that one of the most important material characteristics for reducing disc cracking is a high thermal conductivity. This can be achieved with a high carbon content which gives a large amount of graphite that has a high thermal conductivity. In figures 5 and 6 the number of brake cycles to failure is shown as a function of heat conductivity (figure 5) and carbon content (figure 6).

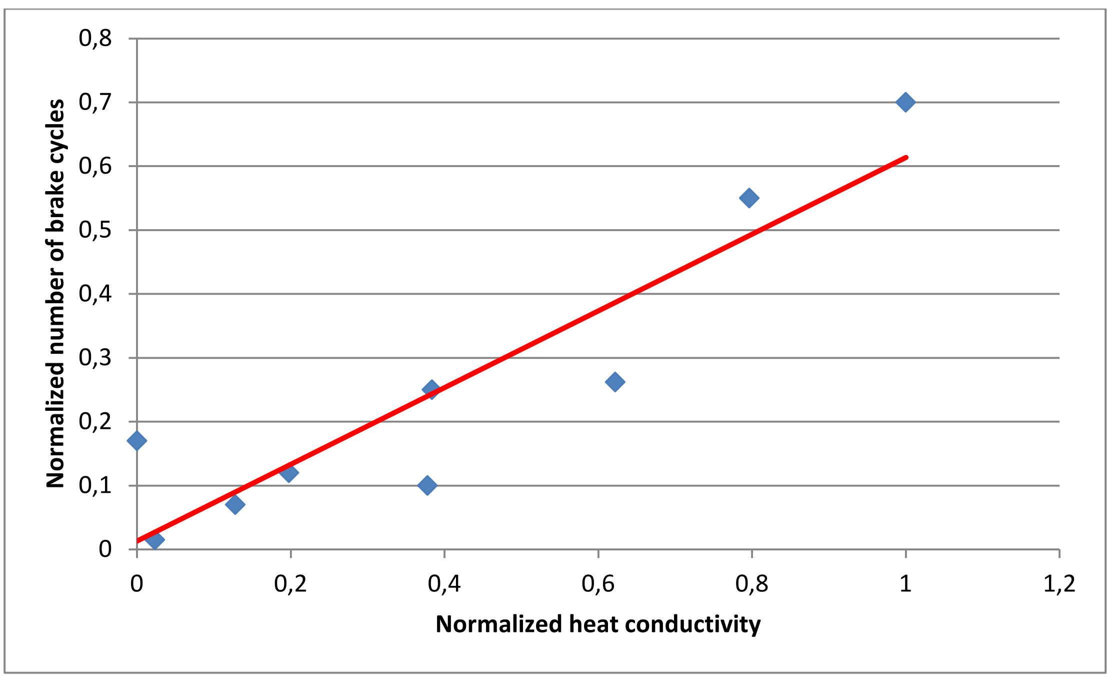

Figure 5. Brake cycles to failure in the crack test as a function of the normalized heat conductivity of the brake disc materials.

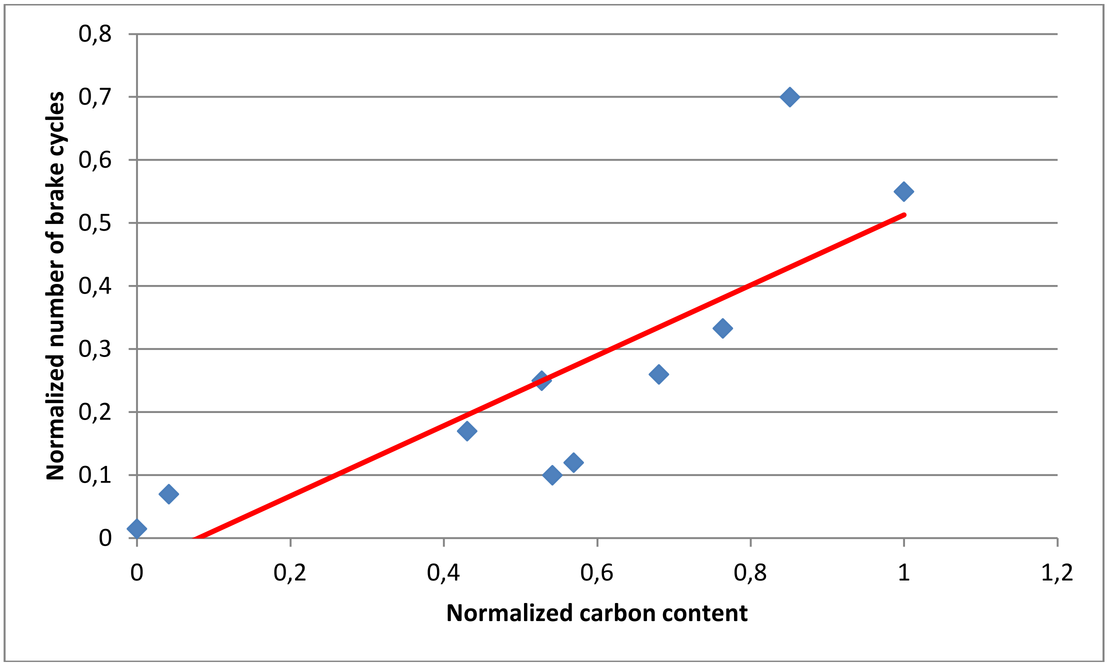

Figure 6. Brake cycles to failure in the crack test as a function of the normalized carbon content of the brake disc materials.

Material modeling

One important aim with the work has been to develop a material model that can be used to predict the performance of new brake disc geometries and to minimize their weight. A calibrated material model will also be useful for making life predictions and estimations of intervals for maintenance and disc replacements. As a first step in the development of such a model, a fully constrained test specimen subjected to repeated heating and cooling was investigated. During the test, the temperature was measured at different positions on the specimen. In figure 7 the calculated temperature profile is compared to the measured at some different points on the surface of the specimen. Since the specimen is constrained the thermal expansion (i.e elongation) is inhibited and the resulting force is measured. Figure 8 shows the measured resulting cyclic compressive and tensile thermal stresses compared to the values found using the developed material model and FEM-calculations.

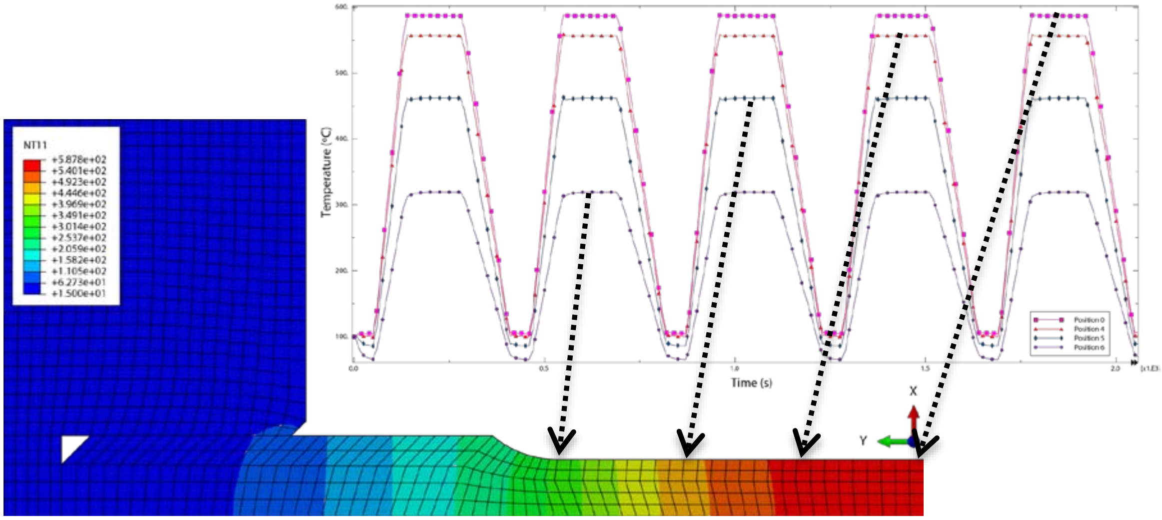

Figure 7. The upper graph shows the measured temperatures at different positions on a clamped specimen when heated using induction coils. The lower part shows the calculated temperatures on the corresponding parts of the specimen.

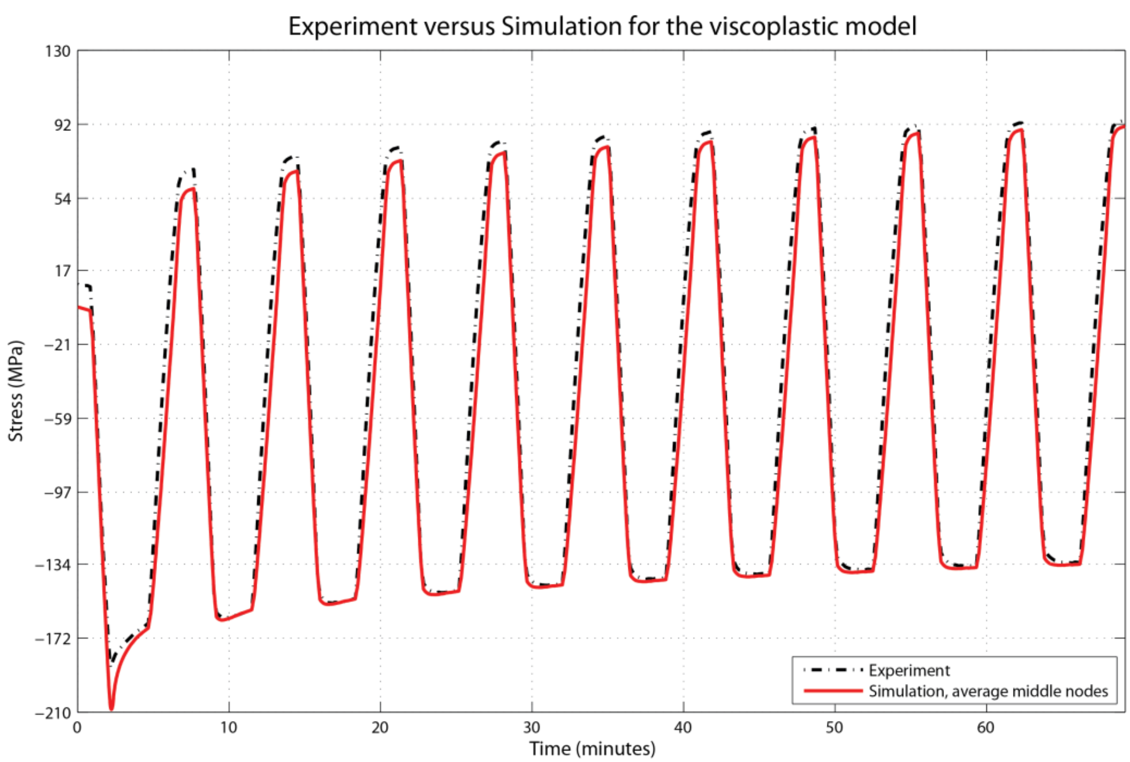

Figure 8. Measured and calculated stresses on a fully constrained test specimen subjected to cyclic heating and cooling.

Evidently, the agreement between calculated and measured thermal stress is very good. However, the deviation between calculated fatigue life and measured fatigue life is larger and in this aspect the model needs to be improved. Improving the material modeling will be the main part of the new continuation project which will start July 2013.

New brake disc alloys

A main industrial result of the gained new knowledge within the present project, is that a new brake disc alloy has been developed and patented. This material is a major candidate for introduction in the Scania fleet and is presently being evaluated in a field test. In figure 9 and table 1 a summary of the extensive and thorough investigations of the performance of brake discs casted in the new materials are presented.

In table 1 the three major performance aspects of the different alloys are summarized. The alloy denoted "New casting 2" is now being tested in an extensive field test on trucks all over the world.

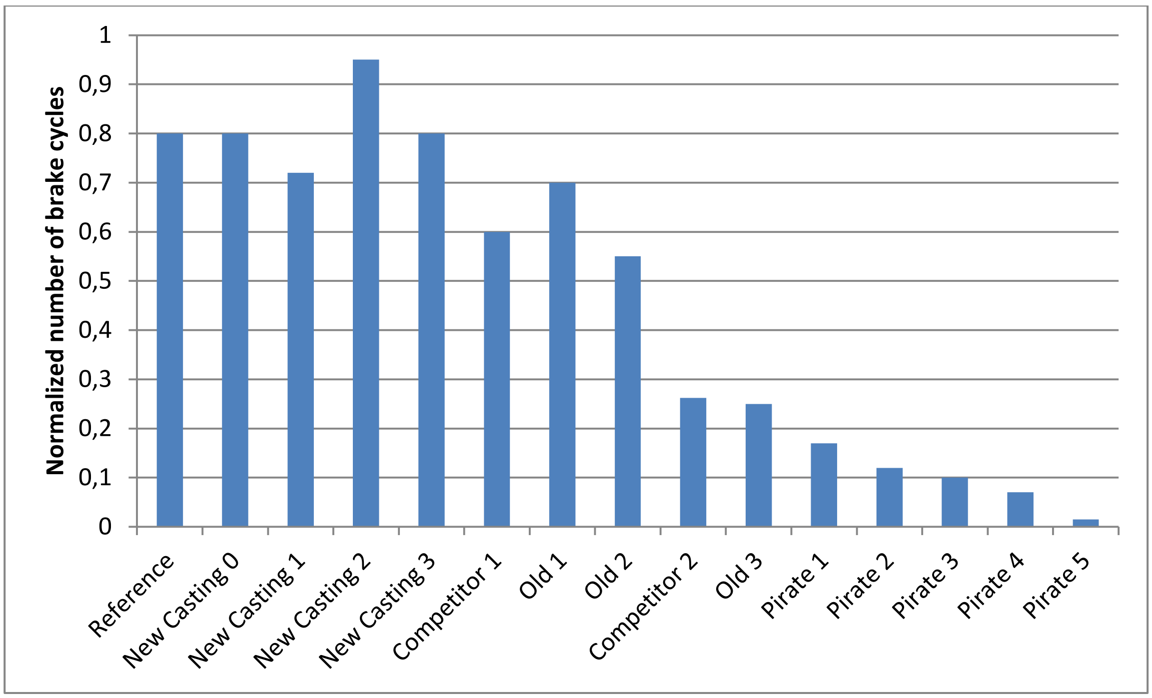

Figure 9. The performance of the new brake disc alloys compared to older data.

Table 1: Summary of performance of the new brake disc alloys compared to other selected alloys.

	Reference	*New Casting 1*	*New Casting 2*	*New Casting 3*	*Competitor*
Crack test performance	*Ref*	–	+	=	–
Wear of Disc	*Ref*	–	+	+	–
Wear of Pad	*Ref*	=	+	+	+

The + and – signs indicate a performance slightly better and slightly worse, respectively, compared to the reference.

5.1 Delivery to FFI-goals

The project's goal has in many ways contributed to the objectives of the FFI program. The development time of new brake disc concepts decreases due to the new developed methods for ranking of potential disc alloy candidates. The need of expensive and time consuming full scale experiments will decrease. The work conducted on developing calculation models for predicting the life of a brake disc and to optimize the weight and geometry will also decrease the number of experiments and thus decreasing the time to market. Further, within the project a new brake disc alloy has been developed and patented and is currently used in a large field test on trucks all over the world. It is likely that the new brake disc will be introduced in the Scania fleet during 2014.

The project has led to a close collaboration between the group at the Department of Applied Mechanics at Chalmers and Scania. It may also be mentioned that four different master theses have been made involving engineering students from three different universities. Two of these students are now employed by Scania. Furthermore, one person, Gaël Le Gigan, will during the fall of 2013 present his licentiate thesis at Chalmers University of Technology.

In summary, the project has contributed to the following objectives within the FFI program as stated below.

• The project has strengthened the competitiveness of the automotive industry in Sweden
• The project has promoted industry relevant research and development efforts
• The project has supported research and innovation environments where industry and academia collaborate.

6. Dissemination and publications

6.1 Knowledge and results dissemination

The gained knowledge is spread not only among the project partners but also presented at international conferences and through other open publications. Further, the results developed within this project can also be applied to other components that are subjected to repeated heating and cooling, such as cylinder heads or parts in the exhaust system. In this respect, the findings from this project will be used in a another FFI-project entitled “Fatigue of engine components – TMF and TMF/HCF interactions in cast iron, Dnr.2012-03625”.

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6.2 Publications

Academic publications:

- ”Thermomechanical fatigue of brake disc materials”,
  Gaël Le Gigan, Tore Vernersson, Roger Lundén
  Presented at Eurobrake 2012, Dresden, Germany

- “Improved performance of brake discs: State-of-the-art survey”,
  Gaël Le Gigan, 2011, Department of Applied Mechanics, Chalmers University of Technology, Göteborg, Sweden

- “Disc brakes for heavy trucks – an experimental study of temperatures and cracks”, Gaël Le Gigan et al, Department of Applied Mechanics, Chalmers University of Technology, Göteborg, Sweden, 2013 (in preparation).

Master thesis publications:

- ”High Cycle Fatigue Properties of Niobium Alloyed Gray Iron”
  Olov Johansson Berg, 2012, Master thesis, Department of Management and Engineering, University of Linköping, Sweden

- ”Mechanical Properties of Niobium Alloyed Gray Iron”
  Ivil Hanna, 2011, Master thesis, Aeronautical and Vehicle Engineering, Royal Institute of Technology, Stockholm, Sweden

- ”Tribometerprovning av nioblegerade bromsskivor”
  Mattias André, 2011, Master thesis, Industriell teknik och management, Maskinkonstruktion, Royal Institute of Technology, Stockholm, Sweden

- ”Termomekanisk utmattning av bromsskivematerial”
  Aso Fathulla och Armin Rakovic, 2010, Master thesis,
  Department of Technology, University of Örebro, Sweden

Internal reports:

- ”Brake Discs and Pads – Material Properties and Performance”
  Peter Skoglund, Internal Technical Report no 7009358, 2012

- ”Bromsskivor – Materialegenskaper och sprickresistans”
  Peter Skoglund, Internal Technical Report no 7000270, 2011, (in Swedish)

Patents:

- ”Gråjärnslegering samt bromsskiva innefattande gråjärnslegering”
  Patentskrift SE 535 043 C2, Patent meddelat 2012-03-27
  Peter Skoglund m.fl., (in Swedish)

7. Conclusions and future research

From a general point of view the cooperation between the staff involved at Chalmers and Scania is now well established and effective. Further, the gained knowledge is spread not only among the project partners but also presented at international conferences and through other open publications.

In more detail the project has generated the following.

- Methods for ranking brake disc materials with respect to
  - Friction properties
  - Wear properties
  - Resistance to thermal cracking
- Improved instrumentation techniques for measuring the heat distribution between disc and pad and within the disc during brake dynamometer testing.
- A new software for evaluating test data from the brake dynamometer.
- A patented new alloy for brake discs with increased life expectancy and improved overall performance.

The research performed within the project has shown that more effort is needed in order to improve the possibilities to model the behavior and fatigue life of a brake disc of grey iron subjected to thermomechanical fatigue. This is essential in order to facilitate and speed up the development of new brake discs with optimized geometry and weight. The new knowledge would also be applicable to other components of cast iron subjected to repeated heating and cooling closer to the engine and exhaust system. Thus, the successful concept of this project led to an application and prolongation in a new project “Improved performance of brake discs – Stage 2”. This application was granted by Vinnova in December 2012 and the new project will run between July 2013 and June 2015. In the up-coming project, the focus will be on material modeling and fatigue life predictions of brake discs. At the end of the project the Ph D student will obtain his doctorate degree.

8. Participating parties and contact person

The project was run by Scania CV and the Department of Applied mechanics at Chalmers University of Technology.

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