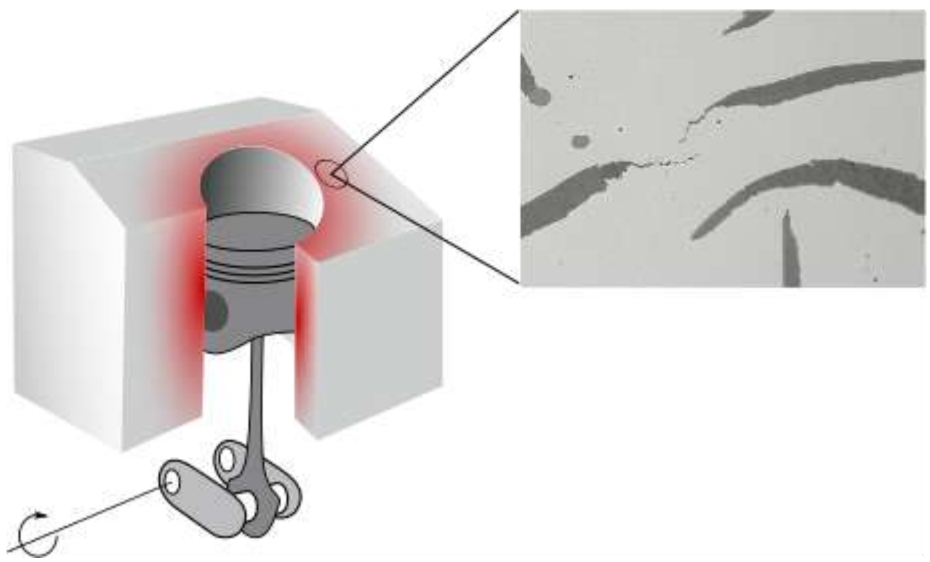
FFI

Fatigue of Engine Materials - TMF and TMF/HCF Interactions in Cast Irons



Project within FFI Fordonsutveckling

Authors: Viktor Norman and Peter Skoglund

Date: 160426

Content

1. Executive summary

The heavy-vehicle automotive industry is constantly subjected to higher demands. In particular, new European emission standards are formulated with the intention of improving the environmental friendliness of newly-produced vehicles through reduced exhaust emission. In one way or another, this implies a successive improvement of the engine efficiency, which in turn, inevitably will require a higher combustion pressure and temperature. This is a respectable challenge for future engine constructions, but also for the engineering materials used to embody them. As higher thermal and mechanical loads must be sustained, there is a higher rate of wear, and consequently, a negative effect on the extent of the engine lifetime.

The aim of the present project is to confront the expected increase in rate of wear, henceforth referred to as fatigue, by studying the effect on materials typically employed in heavy-vehicle engines, namely cast irons. Foremost, the intention has been to improve the understanding of the physical mechanisms of fatigue in these materials, in order to develop a lifetime estimation method designated to assist the mechanical design of heavy-vehicle engines. In particular, the quantified aim of the project was to develop a model capable of predicting the fatigue life in TMF and TMF-HCF tests within a factor of two.

In essence, a large set of thermo-mechanical fatigue (TMF) and combined thermo-mechanical and high-cycle fatigue (TMF-HCF) tests has been conducted at engine load conditions on laboratory specimens of lamellar, compacted and spheroidal graphite irons. In this way, these three different material groups have been experimentally compared and the associated fatigue mechanism has been studied. In particular, a new property related to TMF-HCF conditions has been identified and measured. Regarding the fatigue mechanism, it has been affirmed to consist of the initiation, propagation and coalescence of numerous microcracks. Based on this, a successful lifetime assessment model was formulated, allowing good estimations of the fatigue life of laboratory specimens subjected to both TMF and TMF-HCF conditions.

2. Background

The automotive industry constitute a significant part of the Swedish export, about 10 percent of the total exported value in 2013[1], to which one forth is contributed by the heavy-vehicle industry. Today, the need of heavy-vehicle transportation is extensive, for instance 86 percent of the domestic cargo transported was made by heavy-vehicles in Sweden in 2010[2], but also the demands on environmentally accepted transport are increasing. The European Union regularly formulates new European emission standards to which automotive manufacturers have to conform. Thus, there is an emerging challenge for heavy-vehicle manufacturers to fulfil the upcoming demands on emission, which in the long run will require a significant increase in engine efficiency implying higher combustion pressures and temperatures.

The above demands have called for more sophisticated engine design methods, as well as improved methods to evaluate any conceived design solution. A mechanical designer might not know how well his or hers solution qualifies until a prototype physically exists; a wait which can be very long, not to mention the additional prototype production cycles eventually required due to the iterative nature of the design process. With the advent of modern computational power, this inconvenient situation is hoped to be circumvented. If the mechanical designer was to be given reliable simulation tools, the dependence on prototype evaluation would be less striking, since mistakes related to the physical behaviour of the components could be avoided already at the conceptual design level. Thus, an idealistic goal would be to be able to construct an entire vehicle virtually and to evaluate it before manufacturing an optimal real version.

Today, there are already many computer tools commercially available, such as computer-aided design (CAD) and computer-aided manufacture (CAM) software, finite element (FE) software to perform mechanical analyses and more, which often are used in the design process. However, when it comes to life estimation of engine components, there is much less to choose from. This is a consequence of the complex behaviour of materials and the fact that different materials act very differently regarding their fatigue and failure mechanisms. Therefore, there is a need to investigate and characterise the fatigue behaviour of the materials employed in heavy-vehicles in order to develop accurate virtual evaluation tools. In addition, the present project also aids the ongoing engine development directly since a better understanding of the limits of the materials alleviates the understanding of the components. These limitations imposed by the material will remain a matter of relevance, especially since higher combustion pressures and temperatures eventually are demanded which will enforce even stricter requirements in the future.

[1] The foreign commerce of Sweden in 2013, issued by Kommerskollegium in 2014

[2] Rapport 2012:8, issued by Trafikanalys in 2012

3. Objective

The objectives of this project have been formulated as research questions, which are summarised into the following three:

i.) How is the material degraded? What are the physical mechanisms responsible for the successive deterioration towards a state beyond operation ability?
ii.) How is the fatigue life affected by a variation in the load conditions? By which factors does the life of the materials decrease as the thermal and mechanical loads are increased?
iii.) Given a proper definition of material failure and the exact load situation, how can the critical point when the material fails be estimated with a reasonable accuracy?

The answers to these questions are supposedly not independent. Rather, they are likely correlated, implicating that the outcome of one is applicable on the others. The strategy has been to perform an extensive experimental investigation in order to have a rich physical idea of the fatigue processes which in turn has been used to estimate the fatigue life as the load condition is varied.

The above formulated research questions are expected to lead to the fulfilment of the purpose of the project, which is to characterise the fatigue behaviour and mechanisms in order to also develop an accurate life estimation method for the heavy-vehicle industry.

4. Project realization

The first important outcome of the work is the large set of fatigue data generated. Foremost, this includes the measured variation of the fatigue life, *i.e.* the number of cycles to failure, as the maximum temperature, the mechanical strain range and the HCF are varied, which most commonly is presented as strain-life curves, see Figure 1. Strain life curves are presented in the published papers, see Section 6.2, and are very useful in a comparative analysis. However, on their own, the academic value is low since drawing strain life curves will only indicate the fatigue resistance without giving the physical explanations. Nevertheless, the strain life curves obtained for the tested materials have allowed the investigation to answer the research question *ii).*

Regarding research question *i),* the main results acquired concerned the fatigue process of microcracking and the supposed relation with the measurable quantity defined as the elastic modulus during partial unloading, *i.e.* the unloading modulus. This relationship, connecting the instantaneous value of the unloading modulus with the concurrent state of progressed microcracking, was anticipated by Haenny and Zambelli (Haenny1983a) and supported by the metallographic investigations in this project. Accordingly, it has been established that all fatigue tests conducted, including both TMF and isothermal LCF tests, manifested an identical response in the percentage change of the unloading modulus for each cast iron type, see Figure 2. Consequently, it is clearly indicated that the fatigue process can be generalised to include both LCF and TMF conditions. More importantly, this also suggests that the existence of a general model, capable of covering both fatigue modes with the same set of equations, is possible.

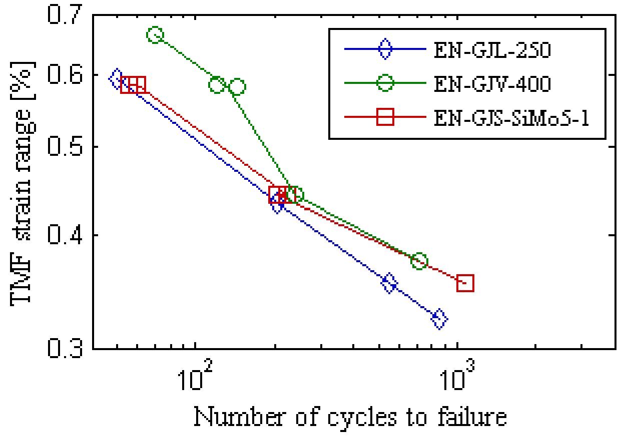


Figure 1: Strain-life curve acquired for 100-500°C temperature cycle.

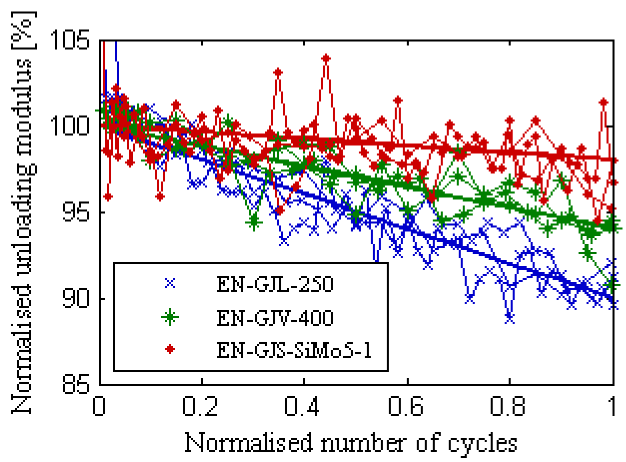


Figure 2: The percental evolution in the unloading modulus as a function of number of cycles normalised to the number of cycles to failure.

The main achievement of the project work was the identification of the newly discovered fatigue property which relates the ability of a material to resist a superimposed HCF load, namely the TMF-HCF threshold. This is an important property in all applications which are subjected to superimposed low-amplitude loads. The threshold is most easily visualised by drawing a plot with the number of cycles to failure as a function of the HCF strain range, with the temperature cycle and the total mechanical strain range fixed; denoted as a TMF-HCF plot. In this way, the TMF-HCF resistance of different cast irons could be conveniently compared, see Figure 3. Effectively, the studied SGI is observed to be the most resistant to superimposed HCF loading compared to CGI, followed by LGI. Equally important, the TMF-HCF threshold has been observed to be almost independent of the underlying TMF cycle, *i.e.* it does not depend on variables such as the maximum temperature and the total mechanical strain range, which is a convenient property. As a consequence, it is reasonable to believe that it could take on the same value for most TMF conditions, perhaps even for LCF conditions. In particular, it is possible that the threshold has a similar value in both in-phase and out-of-phase configurations.

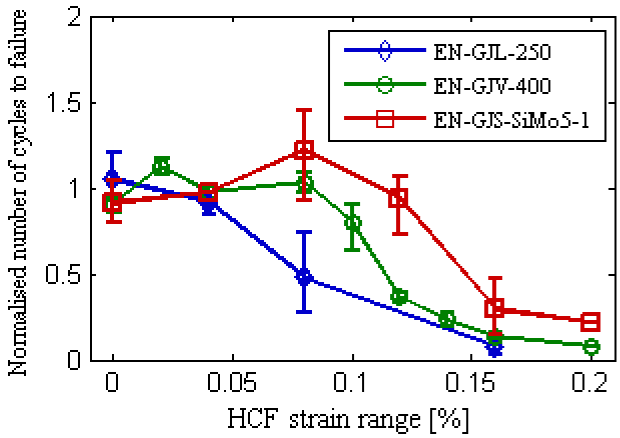


Figure 3: Normalised TMF-HCF plot with reference to the lifetime obtained above the threshold.

An expression to estimate the lifetime of specimens subjected to TMF and TMF-HCF loading was developed. From this equation, a simple expression of the threshold value could be deduced from which its influence on other parameters is estimated. As expected, it is noted that a combination of a low elastic modulus and a low Paris exponent is favourable for a good TMF-HCF resistance. In addition, the expression also makes an estimate of the HCF frequency dependence of the threshold. Thus, through this expression, it is possible to estimate the TMF-HCF threshold of other untested cast irons grades solely from static and TMF tests.

The proposed model, which was developed to deal with the research question *iii)*, considers the propagation of an average microcrack in an attempt to simulate the experimental observation made here and by other investigators. Furthermore, the model supposes that the average crack propagation rate follows Paris law and that the coefficients and exponents associated with this relation are the same for the TMF cycle and all the HCF cycles. It is important to note that this is a highly simplified approach, since it is very likely that at least the Paris coefficient should have a temperature dependence. The advantage on the other hand, is the acquisition of analytical expressions which allow a convenient manipulation and comparison with experimental data, which has been shown to be more than acceptable for the tested LGI and CGI materials. However, in the case of the SGI material, the threshold is slightly underestimated.

Some of the assumptions made have been verified by experiments in order to further justify the model. For instance, the effect of crack closure has been investigated and it was verified that an assumption of zero crack closure level is applicable. Furthermore, regarding the growth of microcracks, the average crack length was measured after different fractions of the total fatigue life to be compared with the crack lengths estimated by the model, see Figure 4. Even though there are experimental difficulties to obtain representative average crack lengths, the comparison affirms that the evolution of the average crack length is not far from the evolution predicted by a Paris law.

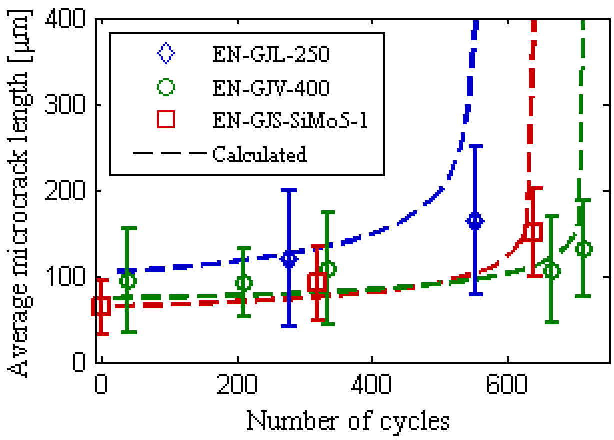


Figure 4: Measured and predicted microcrack growth in a TMF test with 100-500°C temperature cycle and 0.37% mechanical strain

5. Results and deliverables

5.1 Delivery to FFI-goals

The project has in many ways contributed to the objectives of the FFI program. The results of the project will be used in the development of new advanced material models that will enable reliable fatigue life simulations. This will decrease the need of expensive and time consuming full scale experiments and as a consequence also the time to market of new components. Further, the project has led to a close collaboration between the group at the Department of Engineering Materials at Linköping University and Scania. This has resulted in the start of a new 2-year project funded by Scania and including also MAN. The purpose of the new project is to suggest a new alloy for exhaust manifolds with doubled fatigue life when subjected to combined TMF and HCF loadings. The doctoral student will also present his Ph. D. thesis within the frames of the new project. Further, it may be mentioned that a minor cooperation also has been initiated with the Department of Applied Mechanics at Chalmers University of Technology, resulting in a common publication. Furthermore, one person, Viktor Norman, has presented a licentiate thesis in September 2015. Finally, two students have conducted thesis work within the frames of the project and one of the students are now employed at Scania.

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 and a number of drivers of change have been identified and invoked during the project as seen below.

- One bachelor and one master thesis work, as well as one student project, have been carried out within the project.
- A project together with an external partner, namely Applied Mechanics department at Chalmers University of Technology, has also been conducted which resulted in one academic paper.
- The work has been presented in a number of conferences and seminars, for instance in one UTMIS (utmattningsnätverket i Sverige) autumn seminar, the Xth International Symposium on the Science and Processing of Cast Iron and the 3rd International Workshop on Thermo-Mechanical Fatigue, as well as at regular seminars at the Division of Engineering Materials at Linköping University.
- The project has also been presented as a poster at "innovation day" at Scania, including also visitors from the VW-group.
- A continuation project has also been started by the initiative of Scania and Linköping University in cooperation with MAN that is based on the outcome of the present ffi-project.

6.2 Publications

- Damage evolution in compacted graphite iron during thermomechanical fatigue testing, International Journal of Cast Metal Research, 2016
- Thermo-mechanical and superimposed high-cycle fatigue interactions in compacted graphite iron, International journal of Fatigue 80 (2015) 381-390
- The effect of superimposed high-cycle fatigue on thermo-mechanical fatigue in cast iron, International Journal of Fatigue 88 (2016) 121-131

- Fatigue of heavy-vehicle engine materials- experimental analysis and life estimation, licentiate thesis
- Combined thermo-mechanical and high-cycle fatigue in Silicon-Molybdenum spheroidal graphite iron, International Journal of Fatigue, submitted
- Thermomechanical fatigue of grey cast iron brake discs for heavy vehicles, to be submitted for international publication

7. Conclusions and future research

It has been clearly demonstrated that small cracks are induced in cast irons during the typical load conditions encountered in heavy-vehicle engines. Likewise, it has been shown that these cracks are responsible for the final failure as they propagate and successively are linked-up. In contrast to most metals, where the free surface is the most prominent fatigue crack initiation site, the small cracks are initiated homogeneously within the material.

In view of these facts, it becomes clear that measures that could be done to enhance the service lifetime of engine component through surface treatments, such as removing notches, protective coatings, shot peeing, laser treatment etc., may not be the most efficient. Even though many such methods may impede surface crack initiation, microcracks are still initiated beneath the surface and the service lifetime would only be fairly improved. Similarly, corrosion issues should not be of a major concern, as long as the growth rate of environmentally-assisted cracks starting from surfaces exposed to a corrosive environment, is less or in the same order as the growth rate of internal microcracks.

If one wishes to optimise the lifetime of cast iron engine components, one should rather focus on the graphite-matrix microstructure, which clearly governs the rate of microcrack initiation. For instance, as it has been shown in this work, casting defects in the matrix formed during solidification are very likely to induce such cracks. Thus, a good aim would be to avoid having defects larger than the typical size of the graphite structure, even though this might imply quite a metallurgical challenge. Regarding the graphite structure itself, it does not come as a surprise that different graphite morphologies result in different crack initiation propensities. As it has been demonstrated, compacted graphite iron seems to be advantageous in this regard, and most likely also spheroidal graphite iron if the influence of defects is attenuated.

Post heat treatments, which in principle only alter the properties of the matrix, are another potential method to prolong the lifetime. Hypothetically, it is likely that the microcrack growth rate can be modified by changing the structure of the matrix, *i.e.* switching between pearlite, ferrite, martensite, bainite or any combination. Therefore, it is suggested that the effect of post heat treatments on microcrack growth should be investigated if one seeks to optimise the fatigue resistance without replacing cast iron for another material.

Regarding life estimation, the lifetime assessment model proposed here has given satisfying estimates; thereby fulfilling one of the main purposes of this project work. On the other hand, it is undoubtedly a simplification of the complex fatigue mechanism, and therefore, cannot answer to all possible phenomenological aspects imposed by the underlying physical processes. For instance, it is not investigated how well it deals with in-phase TMF or isothermal LCF conditions. In order to further generalise, it is believed that a deeper understanding of the nature of the microcrack growth is required. In particular, better knowledge about the local stress field adjacent to the graphite phase and how it affects the growth of a microcrack is important. For instance, it could bring light to the observed temperature dependence of the crack growth, which up to now, only is incorporated as an unpredictable temperature dependence in different model coefficients.

Looking further, the next step would be to consider life estimation of entire components based on the findings presented here. In this regard, there are two challenges that need to be dealt with. Firstly, the formulation of constitutive models capable of assessing the thermo-mechanical constitutive behaviour in cyclic loading is of uttermost importance. This is quite a challenge since many different deformation mechanisms come into play, such as plasticity and creep effects, not to mention the already complicated behaviour of cast irons. Secondly, there is a need to study the transition from a microcrack to a macrocrack regime and the extent of the latter. Capturing these two physical aspects of cast iron materials in models, *i.e.* the constitutive and long crack growth behaviour, is believed to be the key for more reliable lifetime assessment of heavy-vehicle engine components.

8. Participating parties and contact person

The project was run by Scania CV and the Department of Engineering Materials at Linköping University.

Contact persons:

Linköping University:
Professor Johan Moverare
johan.moverare@liu.se

Scania CV AB:
Peter Skoglund (project manager)
peter.skoglund@scania.com