

Lifetime Assessment of Cylinder Heads for Efficient Heavy Duty Engines Part I: A Discussion on Thermomechanical and High-Cycle Fatigue as Well as Thermophysical Properties of Lamellar Graphite Cast Iron GJL250 and Vermicular Graphite Cast Iron GJV450

Thomas Seifert
 Offenburg University of Applied Sciences

Philipp von Hartrott
 Fraunhofer IWM

Kristopher Boss and Paul Wynthein
 John Deere Engine Works

ABSTRACT

Cast iron materials are used as materials for cylinder heads for heavy duty internal combustion engines. These components must withstand severe cyclic mechanical and thermal loads throughout their service life. While high-cycle fatigue (HCF) is dominant for the material in the water jacket region, the combination of thermal transients with mechanical load cycles results in thermomechanical fatigue (TMF) of the material in the fire deck region, even including superimposed TMF and HCF loads. Increasing the efficiency of the engines directly leads to increasing combustion pressure and temperature and, thus, lower safety margins for the currently used cast iron materials or alternatively the need for superior cast iron materials. In this paper (Part I), the TMF properties of the lamellar graphite cast iron GJL250 and the vermicular graphite cast iron GJV450 are characterized in uniaxial tests and a mechanism-based model for TMF life prediction is developed for both materials. The model can be used to estimate the fatigue life of components by means of finite-element calculations (Part II of the paper) and supports engineers in finding the appropriate material and design. Furthermore, the effect of the elastic, plastic and creep properties of the materials on the fatigue life can be evaluated with the model. However, for a material selection also the thermophysical properties, controlling to a high level the thermal stresses in the component, must be considered. Hence, the need for integral concepts for material characterization and selection from a multitude of existing and soon-to-be developed cast iron materials is discussed.

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INTRODUCTION

Increasing the efficiency of heavy duty internal combustion engines is directly related to increasing specific power and, thus, increasing combustion pressure and temperature. One key component of the engine is the cylinder head which must withstand these higher temperatures and higher pressures. The path of increasing loads intensifies design conflicts, as e.g. associated with the fire deck of cylinder heads: the deck should be as thin as possible to avoid critical thermal stresses during the low frequency thermal transients but sufficiently thick to avoid failures due to the high frequency combustion pressure. A superficial solution of the design conflict is the usage of superior cast iron materials. Vermicular graphite cast iron show higher strength than the classically used lamellar graphite cast iron. However, due to the lower thermal conductivity of vermicular graphite cast iron (Figure 1), higher thermal stresses may arise.

Different cast iron materials are currently used for cylinder heads of efficient heavy duty engines. Further existing or soon-to-be developed cast iron materials are potential candidates for more efficient engines as well. An appropriate choice of the material that can withstand the increased loadings and still meets the technological and economic requirements is hard to identify without numerous expensive and time-consuming bench tests. Reliable methods for materials characterization, materials selection and fatigue life assessment via finite-element calculations are necessary.

For the comparison of the behavior of different materials with respect to high-cycle fatigue (HCF), which is relevant for the water jacket side of the cylinder head, the elastic mechanical properties and corresponding stress-life fatigue curves including mean stress effects are required. For a comparison of the thermomechanical fatigue

(TMF) properties, which are relevant for the fire deck, elastic and inelastic mechanical as well as thermophysical properties must be considered and a model for TMF life prediction is necessary. A simple approach to compare materials with respect to their high temperature performance is the thermal stress index χ [1]:

$$\chi = \frac{\sigma_{CY} \cdot \lambda}{E \cdot \alpha_T} \quad (1)$$

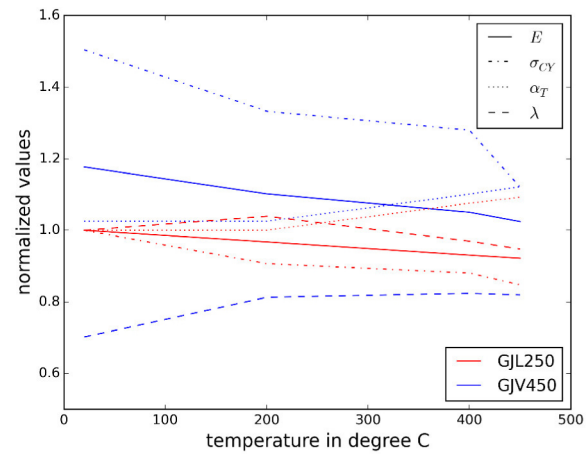
It considers thermophysical properties, namely the heat conductivity λ and the coefficient of thermal expansion α_T as well as mechanical properties, namely Young's modulus E and the strength of the material, where the cyclic yield stress σ_{CY} (0.2 %-offset yield stress obtained from stress-strain hysteresis loops) is used here. The higher the thermal stress index is (i.e. the lower E and α_T and the higher σ_{CY} and λ) the lower is the capability of the material to build up thermal stresses during transient thermal loading. A comparison of the temperature dependent properties and the resulting thermal stress indices for the lamellar graphite cast iron GJL250 and vermicular graphite cast iron GJV450 are shown in Figure 1.

The thermal stress index indicates that there might be a slight advantage for the vermicular graphite cast iron GJV450 compared to the lamellar graphite cast iron GJL250 for higher temperatures. However, the thermal stress index is just a simple phenomenological indicator of the high temperature performance of materials. In case of such slight differences, it does not allow for conclusions with respect to the TMF behavior. A more fundamental materials characterization and model is required for the comparison of the TMF performance of different materials.

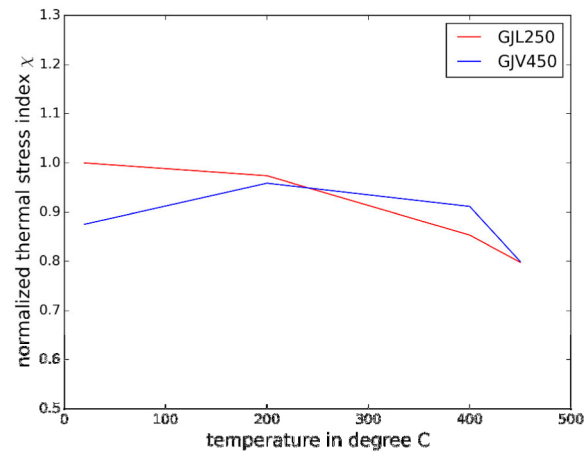
For the assessment of TMF occurring at the fire deck, on the one hand the time and temperature dependent cyclic plasticity is important, i.e. besides E and σ_{CY} also hardening and creep properties must be considered. On the other hand the time and temperature dependent growth of early initiated TMF cracks is the dominant damage mechanism [2, 3] so that also fatigue crack growth properties must be included in the choice of the material. Indeed, the loading situation at the fire deck is even more complicated due to HCF loads resulting from the combustion pressure that are superposing the TMF loads (TMF/HCF) and that might result in an increased crack growth rate [4, 5]. Thus, the TMF, TMF/HCF and HCF life prediction of cylinder heads and an appropriate choice of material and design is a challenging task.

It is the aim of this paper (Part I) to compare the TMF behavior of the lamellar graphite cast iron GJL250 and the vermicular graphite cast iron GJV450 for close-to-service loading conditions of efficient heavy duty engines. To this end, both materials are characterized in uniaxial low-cycle isothermal fatigue (LCF) and TMF tests. The experimental results are used to develop an advanced mechanism-based model for TMF life prediction for the material that is based on elastic-, plastic- and creep-fracture mechanics. Furthermore, the needs for an integrated material characterization are discussed, considering TMF, TMF/HCF and HCF as well as the thermophysical

material properties. In Part II of the paper, the model for TMF life prediction is applied to assess the TMF life of cylinder heads by means of finite-element calculations.



a.



b.

Figure 1. Comparison of mechanical properties (Young's modulus E and cyclic yield strength σ_{CY}) and thermophysical properties (coefficient of thermal expansion α_T and thermal conductivity λ) (a) and thermal stress index χ (b) of lamellar graphite cast iron GJL250 and vermicular graphite cast iron GJV450. A higher thermal stress indicates that the material builds up lower thermal stresses under thermal transients. All values are normalized with the room temperature value for GJL250, respectively.

EXPERIMENTAL

In this section, the investigated materials, the testing conditions for materials characterization and selected experimental results are presented.

Material

Round specimen with a diameter of 7 mm in the gauge length are used for the uniaxial LCF and TMF tests made of the lamellar graphite cast iron GJL250 and the vermicular graphite cast iron GJV450. The specimens are machined from material directly taken out from the fire deck valve bridge region of heavy duty engines.

cylinder heads. The surface finish for the specimens was done by lapping. Further finishing does not improve the surface quality due to the roughness caused by cutting graphite inclusions. Representative micrographs of both cast iron materials are shown in Figure 2.

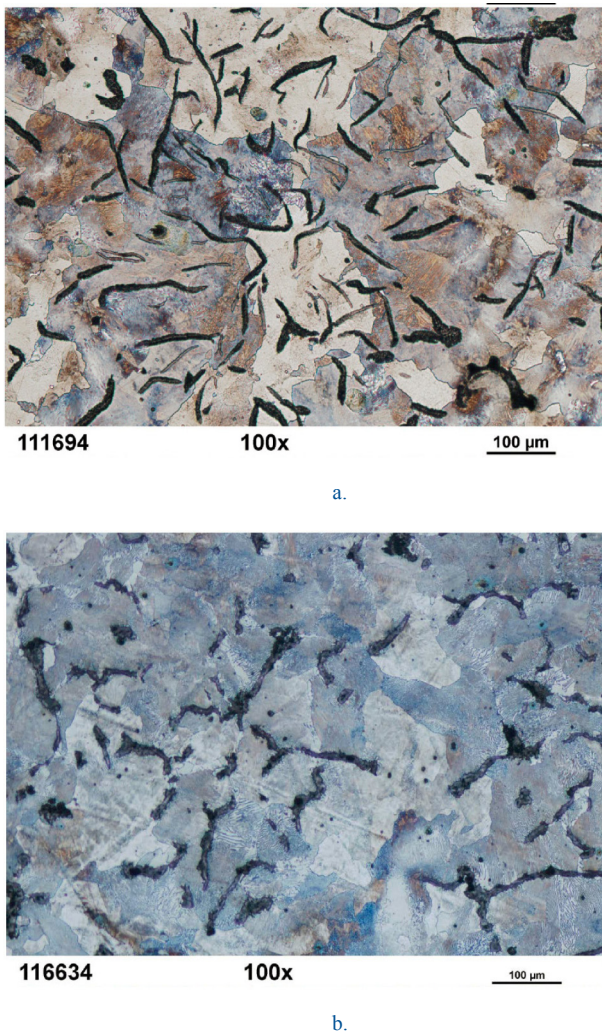


Figure 2. Micrographs (etched) showing the graphite morphology and the pearlitic matrix of GJL250 (a) and GJV450 (b).

Setup and Procedure

The experiments were performed with a universal servo-hydraulic testing machine of Instron Ltd. The elongation in the gauge length was measured with a Maytec extensometer, which comes into contact with the specimen with ceramic rods. The gauge length was 10 mm. The specimens are heated inductively. The temperature of the specimen is measured with three NiCr-Ni thermo-couples in the gauge length to monitor the homogeneity of the temperature distribution. Strain and temperature histories are controlled with self-made software programmed in LabView.

Strain-controlled isothermal complex low-cycle fatigue (CLCF) [6] tests were conducted at 20, 200, 300, 400 and 450 °C with both materials. The CLCF tests are composed of a non-periodical part and

a periodical part. In the nonperiodical part, a few loading cycles are used with different strain rates and hold times in tension and compression. Based on the measured information on strain rate effects, stress relaxation and the hardening, the material properties of viscoplastic constitutive equations can be determined for application in finite-element calculations. The results of the non-periodic part of the CLCF tests are shown together with their description with the viscoplastic constitutive model in Part II of the paper. In the periodical part of the CLCF test, the specimen is cycled to failure with a constant strain amplitude under fully reversed loading with strain ratio of -1 and constant strain rate of 10^{-3} 1/s as usual for LCF testing. The strain amplitudes are chosen such that fatigue lives in the LCF as well as in the beginning of the HCF regime are obtained. The fatigue lives span over three orders of magnitudes so that the slope of life-curves can be reliably determined.

The isothermal CLCF tests are supplemented by strain controlled out-of-phase TMF tests, representing the situation of constraint thermal strains in the valve bridge region. The maximum temperature in all tests is 450 °C, while the minimum temperature is either 150 or 250°C. A hold time of 60 s is used at maximum temperature. The tests were performed according to the TMF standard ISO 12111. The cycle periods of the TMF tests were typically a factor 10 to 20 longer than those of the CLCF tests.

The fatigue life of the specimen is defined as the number of cycles corresponding to a decrease of 5 % in the stress value extrapolated over the tensile stress-number of cycles curve when the stress falls sharply. For the used geometry, this corresponds to the appearance of a semi-circular surface crack with a length of approx. 1 mm.

Results

In Figure 3, mechanical strain-life plots for the isothermal LCF and the TMF tests are shown for both materials. The symbol x indicates tests with failure outside the gauge length. Such failures only occurred for tests with GJL250 where also higher scatter is observed. The higher scatter is typical for lamellar graphite cast iron with the relatively sharp lamellar graphite inclusions acting as initial stress concentrations and, thus, as crack initiation sites.

GJV450 shows a stronger temperature dependency of the fatigue life for equal mechanical strain range than GJL250. Also the TMF tests for GJV450, all with maximum temperature of 450 °C, show lower fatigue life for the equal strain amplitude compared to the isothermal LCF tests at 450 °C.

For higher mechanical strain range GJV450 shows a higher TMF life than GJL250. For lower mechanical strain ranges, the data suggests the opposite behavior: the TMF lives are higher for GJL250 than for GJV450. However, on the basis of the relatively low number of tests, this cannot be validated.