

Lifetime Prediction of EN-GJV 450 Cast Iron Cylinder Heads under Combined Thermo-Mechanical and High Cycle Fatigue Loading

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ABSTRACT

This paper reports on the evolution of cracks in the cylinder heads of a large V8 Diesel engine during cyclic engine tests. The observations are compared with the predictions of a lifetime model for combined thermo-mechanical (TMF) and high cycle fatigue (HCF) loading, which is based on a fracture mechanics analysis of microcrack growth in viscoplastic solids and assumes that the crack advance per cycle is proportional to the cyclic crack tip opening displacement. Since the material of the cylinder heads, the cast iron EN-GJV450, exhibits the typical features of cast iron, namely pressure dependence of the yield stress, dilatancy and tension-compression asymmetry, the Gurson model is applied and combined with the viscoplastic Chaboche model. This constitutive model together with the lifetime model is implemented into a finite element code as a user defined material routine. Published model parameters for the considered cast iron are used to carry out the simulation of the engine test. This simulation comprises a CFD analysis to determine the heat transfer coefficients, a thermal analysis of the load cycle and the mechanical analysis. The thermal analysis reproduces the temperatures at various measuring points sufficiently accurately. Finally, the mechanical analysis predicts the location and orientation of the cracks in the valve bridges correctly in all cases. However, the lifetime predictions are rather conservative compared to the tests (by a factor of 1 to 5 in lifetime). This is discussed and explained by the fact that the cracks were detected in the tests only when they had already spread over a substantial fraction of the valve bridge width. To describe this situation a long-crack analysis would be necessary, which is not yet included in the applied lifetime model.

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1. INTRODUCTION

High temperature components of combustion engines experience loading histories, which comprise low-frequency thermal cycles due to the cruising cycles of the vehicle, and high-frequency mechanical loads caused by the combustion pressure and by inertial forces. The stresses resulting from the thermal cycles often exceed the yield stress at critical locations, which leads to the formation of cracks after a relatively small number of cycles (low-cycle fatigue, LCF). If the stresses are mainly caused by the temperature cycles, one speaks of thermo-mechanical fatigue (TMF). Besides the severe TMF cycles, which typically last a few minutes to hours,

engine components experience high-cycle fatigue (HCF) loading with frequencies of 10 to 50 Hz. These HCF cycles alone would initiate cracks only after a very large number of cycles if ever, but they can promote the growth of the cracks that have been nucleated by the TMF cycles. Traditional lifetime estimation concepts such as the Coffin-Manson law [1, 2] usually fail when applied to TMF loading. Similarly, Miner's rule is unlikely to describe the TMF/HCF interaction properly. For the design of high temperature engine components reliable lifetime models are economically advantageous, since a design process based on bench and field tests is expensive and time-consuming compared to computer-based design. Besides the traditional fatigue lifetime models of Coffin and Manson,

Smith, Topper and Watson [3] and similar approaches, a more elaborate methodology has been proposed by Sehitoglu et al. [4, 5, 6]. Their approach regarding fatigue damage is phenomenological rather than being based on micromechanical fatigue mechanisms, which may be considered as a drawback. The mechanism-based lifetime model used in this paper is based on the assumption that under LCF and TMF conditions microcracks nucleate early so that microcrack growth controls the lifetime. The model was developed previously in a series of publications [7, 8, 9, 10, 11] and successfully applied to a large number of alloys [9, 12] including the cast iron materials EN-GJS 700, EN-GJV 450 and EN-GJL 250 [10, 11, 13, 14, 15, 16, 17]. The aim of the present paper is therefore to demonstrate the applicability of the mechanism-based lifetime model to the cylinder heads of a large V8 Diesel engine. The engine tests are described in Section 2, while the relevant features of the model are briefly summarized in Section 3. Section 4 describes the adjustment of the model to LCF and TMF tests for the cast iron material EN-GJV 450 used in the cylinder heads. Subsequently the engine tests are simulated using a finite element implementation of the lifetime model, and the results are compared with the tests.

2. ENGINE TEST

The engine test was done with a vertically mounted V8 four stroke diesel engine with eight separate cylinder heads, common rail injection, turbocharger and inter-cooler (Figure 1). The major specifications of the engine are summarized in Table 1. The material is the cast iron EN-GJV 450 with vermicular graphite inclusions in a ferritic-pearlitic matrix. This material combines the positive properties of cast iron having spherical (GJS) or lamellar (GJL) graphite inclusions. It has higher strength than GJL and better thermal conductivity than GJS.



Figure 1. V8 truck engine [Source: www.man.eu]

Table 1. Technical data of the V8 Diesel engine considered

Displacement	16162 cm ³
Stroke	157 mm
Bore	128 mm
Cylinders	8
Cylinder head	Single (one per cylinder)
Valves per cylinder	4
Emission standard Euro	5
Power	570 kW at 1800 1/min
Torque	3200 Nm at 1500 1/min

The cylinder heads were mounted on the engine block and cyclically heated and cooled by controlled operation of the engine with a cycle time of eight minutes (four minutes for heating and four minutes for cooling). Superimposed is a mechanical load due to the ignition pressure, which is 21 MPa (with small fluctuations) during the heating phase and 5 MPa in the cooling phase.

Before the fatigue tests, the temperatures of the eight cylinder heads were measured during several thermal cycles. The measured temperatures are used to calibrate the results of the thermal transient simulation to be described later. To measure the temperatures, special cylinder heads equipped with NiCr/NiAl-thermocouples were prepared. The thermocouples were positioned in bore holes of 3 mm diameter located 5 mm below the combustion-chamber roof. A high-temperature adhesive was used to fix the thermocouples in the bore holes. Apart from the bore holes, the geometry, material and attachments are identical to the standard cylinder heads. Figure 2 shows the computer-aided design (CAD) model of the cylinder head with the positions and numbers of the temperature measuring points. For visualization purposes, the CAD model shows the plane situated 5 mm below the combustion-chamber roof that cuts the bore holes of the thermocouples. A1 and A2 are the outlet, E1 and E2 the inlet bore holes; Inj denotes the injector bore hole.

During the engine test the maximum temperatures occurred at the end of the heating phase at point 4 (exhaust-exhaust valve bridge). In the following, all temperatures (expressed in °C) are normalized by the maximum measured temperature. For all eight cylinder heads, the normalized maximum temperatures lie between 0.83 and 1 (Table 2). At points 3 and 5 the average temperatures are about 16 % lower than at point 4. The lowest temperatures are measured at the intake-intake valve bridge (point 10) due to the cool inlet air. The normalized temperatures there lie between 0.71 and 0.77 at the end of the heating phase.

Whereas the temperature distribution in the cylinder head is very inhomogeneous at the end of the heating phase, it is rather homogeneous at the end of the cooling phase with normalized temperatures between 0.087 and 0.175 at all measuring points. The small spread of the temperature values

in the cooling phase is also illustrated in Figure 3, which shows the measured temperatures during three thermo cycles for cylinder head 4 (ZK4).

Table 2. Normalized measured temperatures at the valve bridges at the end of the heating

Cylinder head number	E1-E2 (No. 10)	A1-E2 (No. 3)	A2-E1 (No. 5)	A1-A2 (No. 4)
1	0.724	0.745	0.767	0.833
2	0.741	0.781	0.776	0.995
3	0.759	0.778	0.809	0.96
4	0.774	0.79	0.851	1
5	0.755	0.774	0.807	0.953
6	0.729	0.762	0.783	0.922
7	0.755	0.778	0.724	0.976
8	0.712	0.741	0.88	-

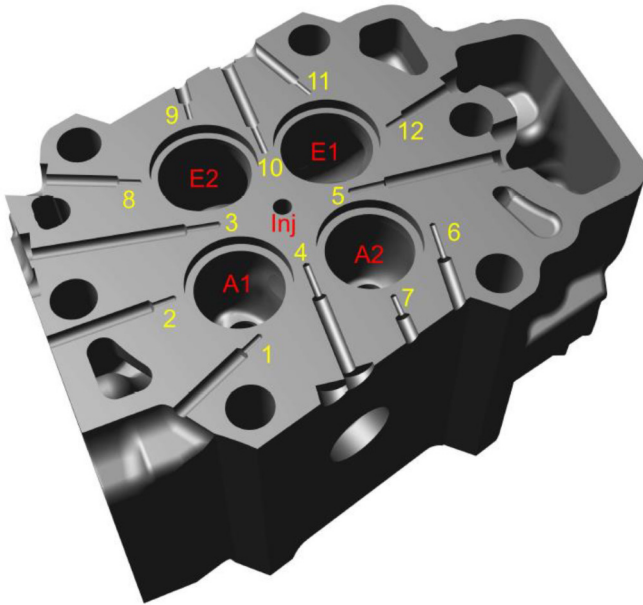


Figure 2. Cylinder head for temperature measurement

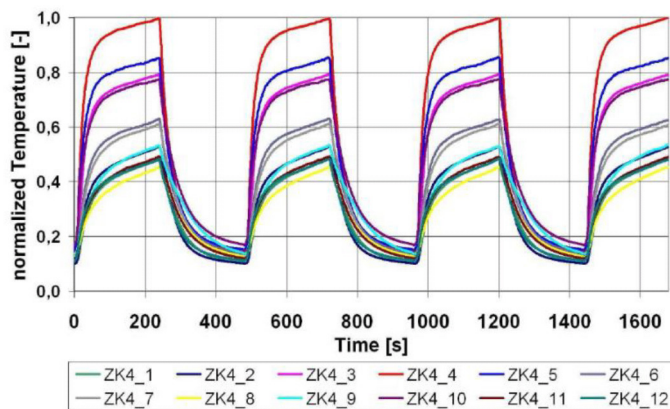


Figure 3. Measured temperatures at 12 positions in cylinder head 4, three thermal cycles

After measuring the transient temperatures, the cylinder heads equipped with thermocouples were replaced by standard cylinder heads without bore holes for thermocouples. In the standard engine test the maximum engine running time is 1000 h. This corresponds to 7500 thermal cycles (eight minutes per cycle). The engine test was stopped every 150 h and the eight cylinder heads were dismantled and checked for cracks. The detectability limit is assumed to be in the order of 500 μm . This is the smallest crack size found in component experiments of identical cylinder heads which were heated up with a gas burner. Cylinder heads with cracks were replaced by new ones, while those without cracks were remounted on the engine block. After the inspection, the run was continued for another 150 h.

In the following, observed cracks are described by a combination of the position where the crack initiated and of the crack growth direction. For example A2-E1 means that a crack occurred at outlet bore hole 2 and then initially grew towards inlet bore hole 1. The number of cycles at which the cracks were detected is presented in a normalized manner, i.e. they are divided by the lowest lifetimes predicted by the model to be described in the next section.

As expected, the first crack was observed in the cylinder head with the highest temperature (cylinder head 4). After 2.17 cycles (normalized value) a crack was found at the valve bridge between outlet A2 and inlet E1 (type A2-E1) with a surface crack length of 4.9 mm (Figure 4). After inspection, cylinder head 4 was replaced by a new one. There, a crack was observed, again at A2-E1, after an additional 5.42 normalized cycles. The surface crack length was 6.0 mm. Cylinder heads 2 and 5 also showed cracks at A2-E1 after 7.59 normalized thermal cycles with 4.2 mm (cylinder head 2) and 4.4 mm surface crack length (cylinder head 5). Another crack occurred after 9.75 normalized cycles in cylinder head 3 with 3.4 mm surface crack length at A2-E1. Finally, after 10.84 normalized cycles, cylinder head 7 had developed a crack with 2.1 mm length at A2-E1. Table 3 in Section 5 summarizes the detected surface crack lengths and the corresponding number of thermal cycles. Also included are the lifetimes predicted by the model.

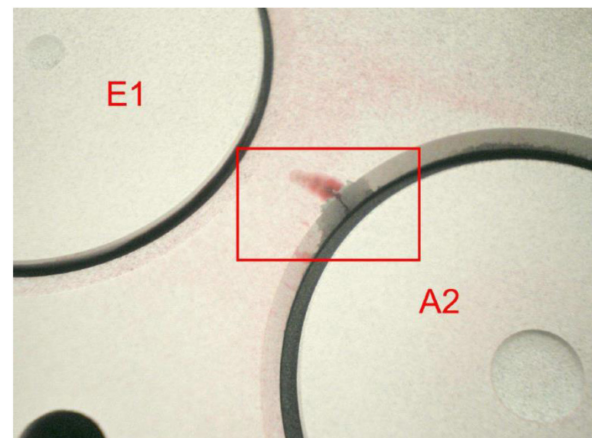


Figure 4. Crack occurring in cylinder head 4 during gas engine test, position A2-E1

3. LIFETIME AND VISCOPLASTICITY MODELS

Lifetime Model

The lifetime model applied in the present study was initially proposed by Schmitt et al. [7] for LCF or TMF loading of austenitic steel without superimposed HCF cycles. It assumes that microcrack growth controls the lifetime under these conditions and that the crack growth increment per cycle is related to the cyclic crack tip opening displacement, $\Delta CTOD$. $\Delta CTOD$ is calculated approximately in closed analytic form using methods of time- and rate-dependent fracture mechanics [18, 19, 20, 21]. The number of cycles to failure is defined, somewhat arbitrarily, to be reached when the crack length is 1 mm. The final result is that the number of cycles to failure is inversely related to a dimensionless damage parameter, called D_{TMF} , which is calculated from the stress and strain amplitudes and the stress-temperature-time history of a representative cycle. These quantities are directly measured in uniaxial fatigue tests or obtained from finite element analyses of components.

Later the model was extended to include superimposed HCF [9], also under multiaxial loading conditions [11]. Qualitatively, superimposed HCF acts as follows: in addition to the crack growth caused by the large LCF or TMF cycle, each HCF cycle causes a crack growth increment according to the $\Delta CTOD^{HCF}$ in the HCF cycle. This $\Delta CTOD^{HCF}$ is calculated assuming elastic unloading from, and reloading to, the state prescribed by the large LCF or TMF cycle. Thus the large cycle controls the mean stress of each HCF cycle, and therefore its contribution to crack growth considering the mean stress dependent crack closure effect. If the effective stress intensity factor range, which includes the crack closure effect, is below a threshold value, the HCF cycle does not contribute to crack growth. Otherwise it contributes according to the calculated effective $\Delta CTOD^{HCF}$. (Actually the transition from no crack growth below the threshold to growth above the threshold is smoothed in the model). The integration of the crack growth law over the HCF cycles within a LCF or TMF cycle is carried out numerically. For a complete set of the model equations the reader is referred to Ref. [17]. For a 10 % chromium steel [9] and for cast iron materials [10, 16, 17] the model was found to describe both, the evolution of the microcrack length, measured with the replica method, and the lifetime under LCF/HCF and TMF/HCF loading conditions consistently.

Viscoplasticity Model for Cast Iron

The lifetime model described above is applied within the finite element framework in conjunction with a viscoplasticity model. In the present work, a Chaboche-type model is combined with the Gurson model to account for the dilatancy caused by the graphite particles in cast iron [8, 13, 14, 16, 17]. This viscoplasticity model provides stress and strain amplitudes for the lifetime model. Since fatigue cracks are usually located at the specimen surface rather than in the bulk, their effect is not

included in the constitutive plasticity model. Actually they have little effect on the specimen compliance until very late in the lifetime.

The viscoplasticity model is implemented into ABAQUS/Standard as a user defined material routine in an efficient manner [22]. The lifetime model can either be integrated in the material routine or evaluated during postprocessing.

4. APPLICATION OF THE MODEL TO CAST IRON EN-GJV 450

The reports [16, 17] describe results of various types of fatigue tests on cast iron EN-GJV 450. LCF and LCF/HCF tests were performed as well as TMF and TMF/HCF tests on round specimens with 7 mm diameter and 10 mm gauge length. All test data and measured lifetimes are summarized in the Appendix (Table A.1 and A.2). In the LCF tests strain amplitudes ϵ_a^{LCF} between 0.2 % and 0.3 % were applied either with a constant strain rate of 0.001 s^{-1} or a frequency of 5 Hz, independent of the strain amplitude. The LCF tests were carried out in the temperature range 20 °C to 500 °C. The TMF tests ran either with a temperature rate of 10 K s^{-1} for heating and cooling or following a predefined temperature-time curve. The minimum temperature in all TMF and TMF/HCF tests was 50 °C, the maximum θ_{max} was 400 °C, 425 °C or 450 °C. The compliance factor cmp in Table A.2 describes the ratio between the mechanical and thermal strain in the experiment. Superimposed HCF loading had amplitudes ϵ_a^{HCF} between 0.03 % and 0.1 % and a frequency f^{HCF} of either 5 Hz or 50 Hz. Furthermore, TMF and TMF/HCF tests were carried out with 60 seconds dwell time at minimum total strain.

It should be noted that the LCF and TMF strain amplitudes given in Table A.1 and A.2 are defined for the slowly varying strains around which the HCF loading oscillates. Hence, to obtain the total amplitude within a LCF or TMF cycle the HCF amplitude must be added.

The tests were modeled by applying the respective strain and temperature histories to an 8 node linear brick finite element representing the uniaxial stress state in the experiment. The calculations were carried out with parameters of the combined Chaboche/Gurson model, which were obtained in [16] by adjusting the model to the measured mechanical response. Three LCF or TMF load cycles were applied in order to reach a stabilized stress-strain hysteresis. The third loading cycle was used for the evaluation of the lifetime model. Only at the reversal points of the large cycle, the HCF loading was simulated to prove that the behavior in the HCF cycles is indeed elastic, as assumed in the LCF/HCF model and already stated in [10, 17].

Figure 5 shows a comparison of the measured lifetimes $N_{f,exp}$ and the model predictions $N_{f,sim}$, which are also given in Table A.1 and A.2. Although a wide range of loading conditions is considered, the model is able to describe most of the data.