

Lifetime Assessment of Cylinder Heads for Efficient Heavy Duty Engines Part II: Component-Level Application of Advanced Models for Thermomechanical Fatigue Life Prediction of Lamellar Graphite Cast Iron GJL250 and Vermicular Graphite Cast Iron GJV450 Cylinder Heads

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ABSTRACT

A complete thermomechanical fatigue (TMF) life prediction methodology is developed for predicting the TMF life of cast iron cylinder heads for efficient heavy duty internal combustion engines. The methodology uses transient temperature fields as thermal loads for the non-linear structural finite-element analysis (FEA). To obtain reliable stress and strain histories in the FEA for cast iron materials, a time and temperature dependent plasticity model which accounts for viscous effects, non-linear kinematic hardening and tension-compression asymmetry is required. For this purpose a unified elasto-viscoplastic Chaboche model coupled with damage is developed and implemented as a user material model (USERMAT) in the general purpose FEA program ANSYS. In addition, the mechanism-based D_{TMF} model for TMF life prediction developed in Part I of the paper is extended to three-dimensional stress states under transient non-proportional loading conditions. The material properties of the plasticity model are determined for lamellar graphite cast iron GJL250 and vermicular graphite cast iron GJV450 from isothermal and non-isothermal uniaxial tests. The methodology is applied to obtain a TMF life prediction on two cast iron cylinder heads for heavy duty diesel engine applications made from both cast iron materials. It is shown that the life predictions using the developed methodology correlate very well with observed lives from two bench tests in terms of location as well as number of cycles to failure.

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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. A critical region in cylinder heads is the valve bridge area of the combustion chambers. These areas are subjected to higher temperatures and are constrained by the rest of the structure which remains relatively cold and behaves elastic. Upon heating, the valve bridge experiences high compressive stresses at high temperature which lead to inelastic deformations. Upon cooling, it experiences tensile stresses at cold temperature. This out-of-phase (OP) thermomechanical loading condition causes thermomechanical fatigue (TMF) cracks to initiate and propagate into the coolant jacket which leads to loss of function of the engine.

Experimental dynamometer design iterations are expensive, time consuming, lead to a significant increase in the design cycle time and, in many cases, to overdesigned components. Computational methods allow for faster and more efficient design iterations and better understanding of the physics of deformation and damage. With guidance from these methods, the component geometry could be optimized via computer simulations and the number of bench tests could be reduced significantly. Ideally, hardware testing would serve as a design confirmation method rather than a design iteration tool.

Computational methods for thermomechanical life prediction of cast iron cylinder heads require two equally important steps. In the first step, a transient nonlinear structural finite-element analysis (FEA) is performed. To obtain reliable stress and strain fields in the simulation, an appropriate constitutive model is needed for the description of time and temperature dependent cyclic plasticity as well as the tension-

compression asymmetry, especially for lower-grade cast iron materials. Appropriate plasticity models, however, are not available by default in the typically used FEA programs as ABAQUS and ANSYS. However, models were developed for the description of the tension-compression asymmetry of cast iron materials under cyclic loading conditions, e.g. using a combination of a Chaboche-type unified viscoplastic model [1, 2, 3] with the porous plasticity model of Gurson [4]. Another effective approach for capturing the asymmetric behavior of cast irons relies on continuum damage mechanics (CDM) concepts where an internal state variable is used to describe damage evolution in the material. The damage effect can be activated in tension and deactivated in compression [5, 6, 7]. The description of the crack closure point (damage deactivation) occurs when passing from tension to compression, and the crack opening point (damage activation) occurs when passing from compression to tension.

In the second step, the computed local stresses and strains enter a lifetime model to predict the fatigue life of the component. Reliable lifetime models for TMF problems are rare. Purely phenomenological models, as e.g. the Manson-Coffin relation, the Smith-Watson-Topper parameter or the Ostergren parameter, cannot reproduce the dependency of damage on the stress-temperature history appropriately. The well-known Sehitoglu model [8] incorporates damage accumulation due to fatigue, oxidation and creep. However, it uses a purely phenomenological model for fatigue. Hence, there is a need for a reliable lifetime model that captures the actual damage mechanism, namely the growth of TMF cracks, and that is able to reproduce the dependency of crack growth rates on cycle times, strain amplitudes, mean stress and temperature [9]. A starting point for a mechanism-based model is the description of crack growth under cyclic loading with fracture mechanics load parameters [9, 11, 12]. The advantage of these models is that they contain a relatively small number of adjustable parameters and that the dependency on multi-axial stress states can be derived [13].

In this paper (Part II), a Chaboche-type unified elasto-viscoplastic model coupled with damage (following the CDM approach) is developed that meets the requirements for thermomechanically loaded cast iron material. The model is implemented as a user material model (USERMAT) in the general purpose FEA program ANSYS. The predicted stress-strain response from the calibrated model is compared with experimental uniaxial tests under isothermal and non-isothermal conditions for lamellar graphite cast iron GJL250 and the vermicular graphite cast iron GJV450. In addition, the mechanism-based D_{TMF} damage model for TMF life prediction, developed in Part I of the paper and using elastic-, plastic- and creep fracture mechanics for the description of TMF crack growth rates, is extended to three-dimensional stress states. The plasticity model and damage model are integrated into a TMF life assessment method and are applied to assess the lives of heavy duty diesel cylinder heads made from both materials.

MULTIAXIAL TIME AND TEMPERATURE DEPENDENT PLASTICITY MODEL

Lower-grade cast iron materials exhibit a significant asymmetric stress-strain response in tension and compression. In addition, high temperature cyclic loading requires the use of kinematic hardening with viscous effects. The developed unified Chaboche-type viscoplastic model combined with CDM is capable of capturing the above effects quite well. In the following, the model is described before the determination of the material properties of the model is addressed.

Model description

Based on CDM concepts, the effective stress tensor is defined as

$$\bar{\sigma}_y = \sigma_y / (1 - D) \quad (1)$$

where D is a scalar damage variable. The effective backstress tensor, describing kinematic hardening of the material, is

$$\bar{X}_y = X_y / (1 - D). \quad (2)$$

The stresses are computed from the elastic strain,

$$\bar{\sigma}_y = \bar{C}_{ijkl} (\epsilon_{kl} - \epsilon_{kl}^{th} - \epsilon_{kl}^{vp}), \quad (3)$$

where $\bar{C}_{ijkl}$ is the effective 4th order isotropic elasticity tensor.

The thermal strain is obtained from the thermal expansion coefficient α^{th} and the temperature change with respect to a reference temperature

$$\epsilon_{ij}^{th} = \alpha^{th} (T - T_{ref}) \delta_{ij} \quad (4)$$

δ_{ij} is the second order identity tensor. Based on the normality condition, the viscoplastic strains are calculated by integration of the flow rule

$$\dot{\epsilon}_{ij}^{vp} = \frac{3}{2} \dot{p} L_{ijkl} \frac{\bar{\beta}_{kl}}{\bar{\beta}_{eq}}. \quad (5)$$

$\bar{\beta}_{kl} = (\bar{\sigma}'_{kl} - \bar{X}_{kl})$ is the relative stress where $\bar{\sigma}'_{kl}$ denotes the deviator of the effective stress tensor. $\bar{\beta}_{eq}$ is the von Mises equivalent of the relative stress. For this application, isotropic hardening is not considered. The viscoplastic multiplier $\dot{p}$ is represented by the power law

$$\dot{p} = \left\langle \frac{\bar{\beta}_{eq} - R_0}{K} \right\rangle^n. \quad (6)$$

R_0 is the initial yield stress. The kinematic hardening rule is

$$\dot{\alpha}_{ij}^{(i)} = L_{ijkl} \left(\frac{\bar{\beta}_{kl}}{\bar{\beta}_{eq}} - B^{(i)} \alpha_{kl}^{(i)} \right) \dot{p} \quad (7)$$

where $X_k^{(i)} = (2/3)C^{(i)}\alpha_k^{(i)}$, $B^{(i)}$ and $C^{(i)}$ are material properties that describe the evolution of the backstress. The total backstress tensor is computed as the sum of $i = 1, 2, 3, \dots$ backstress tensors. The CDM equivalent strain principal allows the determination of the operator L_{ijkl} such that

$$\bar{\sigma}_{ij} = L_{ijkl} \sigma_{kl} \quad (8)$$

The tension-compression asymmetry is captured by full damage activation in tension and deactivation of damage in compression. To prevent numerical difficulties, the transition between tension and compression is described with a smooth continuous function. Further information on the used CDM approach is given in [5, 6, 7].

Generally, damage may come from several sources including brittle, fatigue and creep damage. For the critical areas in these specific applications, the loading is mainly out-of-phase where cavitation creep damage is unlikely to occur. In addition, for practical reasons, only few cycles are usually simulated in the FEA. Thus, fatigue damage is computed as a post-processing step and not using a coupled approach. Therefore, only brittle damage is accounted in the constitutive model to allow for modeling the asymmetric behavior. Hence, damage is expressed in terms of the three principal stresses as a power function in the following form [5]:

$$D_b = \left\langle \frac{\sqrt{\langle \sigma_I \rangle^2 + \langle \sigma_{II} \rangle^2 + \langle \sigma_{III} \rangle^2} - C_0}{C} \right\rangle^m \quad (9)$$

Determination of Material Properties

The material properties of the plasticity model are determined on the basis of isothermal complex low-cycle fatigue tests (CLCF) as shown in Figure 1 and Figure 3 and OP-TMF tests similar to those shown in Figure 2 and Figure 4 for both materials, GJL250 and GJV450 (see Part I of the paper). For both materials, the model is calibrated with a single kinematic hardening term, i.e. $i=1$ in equation (7). In the CLCF tests different strain amplitudes, different strain rates and hold times in tension and compression are used to gain enough information for the determination of the material properties. For the determination of the material properties a gradient-based, non-linear iterative optimization technique is used that is implemented into the Thermomechanical Fatigue Analysis Tools (TFAT) software [10]. The optimization starts by setting physically reasonable initial estimates for the properties and

specifying the upper and lower bounds. The optimization process is repeated several times where each time the bounds are adjusted to make sure that the numerically determined optimum values fall within acceptable and physically meaningful ranges.

For the GJL250 material, the model is calibrated using the experimental results of the CLCF tests at 23, 200, 300, 400 and 450 °C, all with a maximum strain range of 0.6 %. Only one kinematic hardening term is used. An example of the model description of the experimental data for GJL250 at 300 °C is shown in Figure 1. Figure 1(a) shows the applied strain history and Figure 1(b) shows the stress response as measured along with the simulated stress by the model. The model captures the kinematic hardening of the material quite well even with only one kinematic hardening term. In addition, the viscous part of the model allows accurate description of both strain-rate dependence as well as relaxation during hold times in tension and compression. Finally, the lower-grade material, GJL250, shows a significant asymmetric behavior where the stress in compression is approximately 40 % higher than that in tension for the same strain amplitude. This behavior is also well described by the model. The experimental stress-strain response for this test along with the model description is shown in Figure 1(c).

To validate the determined material properties for non-isothermal loading conditions, the model is used to calculate the OP-TMF tests, which were performed with a minimum temperature of 150 or 250 °C and a maximum temperature of 450 °C. An example of an OP-TMF test between 250 and 450 °C is shown in Figure 3. Figure 3(a) shows the imposed temperature and total strain history for the first five cycles of this test, the experimental and model stress histories are shown in Figure 3(b) and the corresponding stress-strain response is shown in Figure 3(c). The model describes the TMF conditions very well based on the material properties that are determined from isothermal conditions.

A very similar process is used for the determination of the material properties for GJV450. To this end, the experimental results of the CLCF tests at 23, 200, 300, 400 and 450 °C with a maximum strain range of 0.6 % are used. In this case, the model is calibrated with two kinematic hardening terms. An example of the model description is shown in Figure 2 for experimental data at 400 °C. Figure 2(a) shows the applied strain history, and Figure 2(b) shows the stress response as measured along with the simulated stress by the model. The model describes kinematic hardening of the material very well. In addition, the viscous part of the model allows accurate description of both strain-rate dependence and relaxation during hold times in tension and compression. It is shown in Figure 2(b) that the higher-grade material, GJV450, shows less of an asymmetric behavior than the GJL250. The stress in compression is only about 20 % higher than that in tension for the same strain amplitude. This behavior is also well simulated by the current model. The experimental stress-strain response for this test along with the model description is shown in Figure 2(c).