Towards a temperature dependent and probabilistic lifetime concept for nodular ductile cast iron materials undergoing isothermal and thermo-mechanical fatigue

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Abstract. In this investigation, the fatigue behaviour of a ductile cast iron with high content of silicon and molybdenum, was experimentally characterized by performing isothermal low cycle fatigue (LCF) tests as well as out-of-phase thermomechanical fatigue (OPTMF) tests within the temperature range RT – 500 °C. The studied material shows an embrittlement at temperatures nearby 400 °C. A possible explanation for the observed lifetime reduction is intergranular embrittlement (IE). A mechanism based lifetime model is proposed for assessing the lifetime. The model is based on the assumption that the crack advance per cycle is correlated with the cyclic crack tip opening displacement (ΔCTOD) attributed to the crack tip blunting caused by accumulation of plastic and creep deformations ahead of the crack tip. Intergranular embrittlement is accounted for by introducing a temperature and strain rate dependent prefactor in the crack growth law, which only acts in a certain temperature range. The model is calibrated for a GJS material and successfully applied to predict the lifetime of this material when undergoing isothermal and non-isothermal mechanical loadings. A probabilistic interpretation of the scatter of the investigated material is presented in conjunction with the random nature of the initial defect size distribution.

1 Introduction

Nodular ductile cast iron materials (DCI) provide a good performance at high temperatures, especially DCI materials with high content of silicon and molybdenum. Due to their good mechanical properties, castability and cost efficient production processes, the use of these materials for fabricating components undergoing thermomechanical fatigue (i.e. cylinder heads, turbochargers, motor housings) is widely spread. In order to guarantee the safety of these components the damage mechanisms involved in the crack initiation and propagation regimes must be carefully investigated and integrated into lifetime concepts.

For non-isothermal conditions, the time and temperature dependent damage parameter D_{TMF} [1] was successfully applied for describing the fatigue damage of numerous high temperature resistant alloys. This parameter accounts for the temperature dependent material properties, the cyclic stresses and plastic strains, fatigue crack closure as well as for creep accelerated fatigue crack growth. The lifetime assessment is performed by assuming that the crack growth per cycle is proportional to the crack tip opening displacement.
However, this model formulation does not account for IE damage. The presence of IE damage is related to a shorter fatigue lifetime and the modelling of DCI materials suffering from IE damage demands a new formulation.

The IE damage mechanism was studied by several authors [2-6]. Nevertheless there is no clear explanation for this phenomenon. It is known to be dependent on microstructural features, such as the graphite size and the eutectic cell wall size, where greater sizes should promote intergranular fracture [2]. Based on tensile testing, it was also studied in [3] how increasing the percentage of silicon, changes the fracture mechanism from a mix of dimpled and intergranular fracture to cleavage and intergranular fracture. This change of fracture mechanism is thought to be related with the presence of MgO particles in the eutectic cell wall region serving as crack initiation sites [4]. Another investigation [5] concludes that MgO inclusions serve as crack initiation sites and the amount of phosphorus segregation on the grain boundaries dictates the fracture mode within the IE temperature of ferritic DCIs. In the same study the amount of segregated phosphor is connected to the solidification cooling rates where slower cooling rates should enhance phosphorus segregation. The kinematics of the process seem to be unclear, however all authors observed a drop in the ductility of the material at the IE temperature for the conducted tensile tests. [6] observed that the ductility drop derived from the IE damage is also dependent on the strain rate of the performed tensile tests. In this work the IE damage was modelled based on tensile tests performed at different temperatures and strain rates including the effect of strain rate on the IE damage process. [6] and [7] investigated the strain rate

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