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PROBABILISTIC THERMOMECHANICAL FATIGUE CRITERIA FOR SPHEROIDAL GRAPHITE CAST-IRONS

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ABSTRACT

This paper proposes a method to establish and identify a probability density function characterizing the low-cycle fatigue lifetime for a cast-iron between 300 and 600°C. The method is initiated with a quantitative analysis of the microstructure of the material, which provides the initial probability distribution of graphite particles size. After identifying a given probability density function of particles, one can transport it into a lifetime probability density function using a growth law involving a macroscopic measure of the inelastic loading over a cycle. Several parameters of the growth law are finally estimated from a given set of fatigue experiments on specimens providing a criterion enabling a very satisfying matching between computed and experimental lifetime.

KEYWORDS

Cast-iron, Probabilistic fatigue criteria, Microcracks propagation, Thermal-Mechanical Fatigue

INTRODUCTION

Car engines and exhaust systems tend to be exposed to elevated temperatures and severe thermal gradients. The standard computational design process [1,2] implies the development of thermal-mechanical fatigue (TMF) criteria that must provide predictive lifetime estimations for various thermal and mechanical loading conditions. Spheroidal and compacted graphite cast irons are widely used in the automotive industry to produce exhaust manifold and turbochargers as they present a very good compromise in terms of cost, mechanical properties at elevated temperatures and cast ability. However, graphite particles are well known to be preferential crack initiation sites in the fatigue process, particularly in the high-cycle fatigue regime [3].

The present paper specifically addresses the influence of graphite particles in the TMF process and its variability for such alloys as fractography analysis combined with finite element models exhibit their significant role in TMF micro-cracks propagation. Graphite particles are therefore here taken as a defect population on which TMF cracks initiate, playing exactly the same role as pores for aluminium alloy in [4]. Their population is estimated thanks to microstructure image analysis before being introduced in the

computational approach used to design engine parts against TMF. A probabilistic criterion is then proposed taking into account graphite particles as micro cracks initiation zones and integrating a micro crack propagation law to describe damage evolution.

MATERIAL, MICROSTRUCTURE AND DAMAGE INVESTIGATION

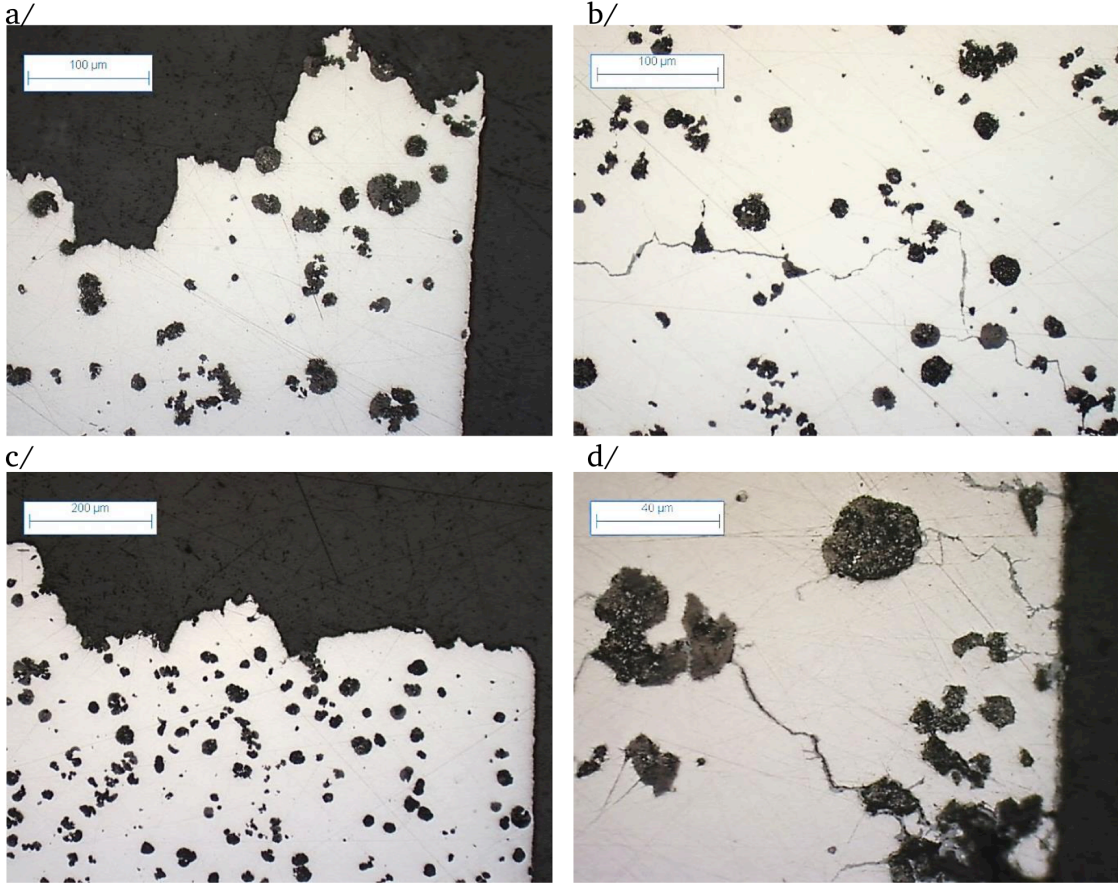


Fig. 1 : Fractography of LCF tested specimens at 300°C (a/ and b/) and at 500°C (c/ and d/)

SiMo spheroidal graphite cast-iron is widely used by the automotive industry for exhaust systems. The specific material used for this study is perfectly adapted for high temperatures application such as exhaust manifold and present a ferritic structure up to 850°C. The study focuses here on the Low Cycle Fatigue (LCF) of this cast-iron between 300 and 600°C. With conventional LCF lifetimes [1], it allows analysis of the damage produced by the cyclic viscoplasticity without risks of high interference with corrosion phenomena or effects induced by the temperature history, typical in the case of thermomechanical fatigue [5].

| Temperature (°C) | Number of tests | $\Delta\epsilon(\%)$ | Lifetime |
|------------------|-----------------|----------------------|----------|
| 300 | 8 | 0.6-0.8 | 260-1650 |
| 350 | 6 | 0.7-2.0 | 10-610 |
| 500 | 10 | 0.5-0.8 | 410-3700 |
| 600 | 9 | 0.5-2.0 | 70-8190 |

Tab. 1: Low Cycle Fatigue tests condition summary

A complete experimental basis was carried out for this alloy on specimens with a microstructure similar to the one observed in industrial structures (exhaust manifolds and turbochargers). It is constituted of the tests at 350 and 600°C [1] and completed with tests at 300 and 500°C. For the latter ones hold times in tension or compression have been added in order to evaluate the influence of the mean stress on the lifetime. The database is summarized on Table 1. Some specimens extracted from the experimental basis were analysed to quantify the influence of the microstructure on the lifetime and on fatigue damage mechanisms for this alloy. At 300°C, as shown in Figure 1.a and .b, the propagation occurs in the matrix while the crack path seems highly oriented by graphite nodules distribution. At 500°C (Figure 1.c and .d), the same conclusions could be drawn.

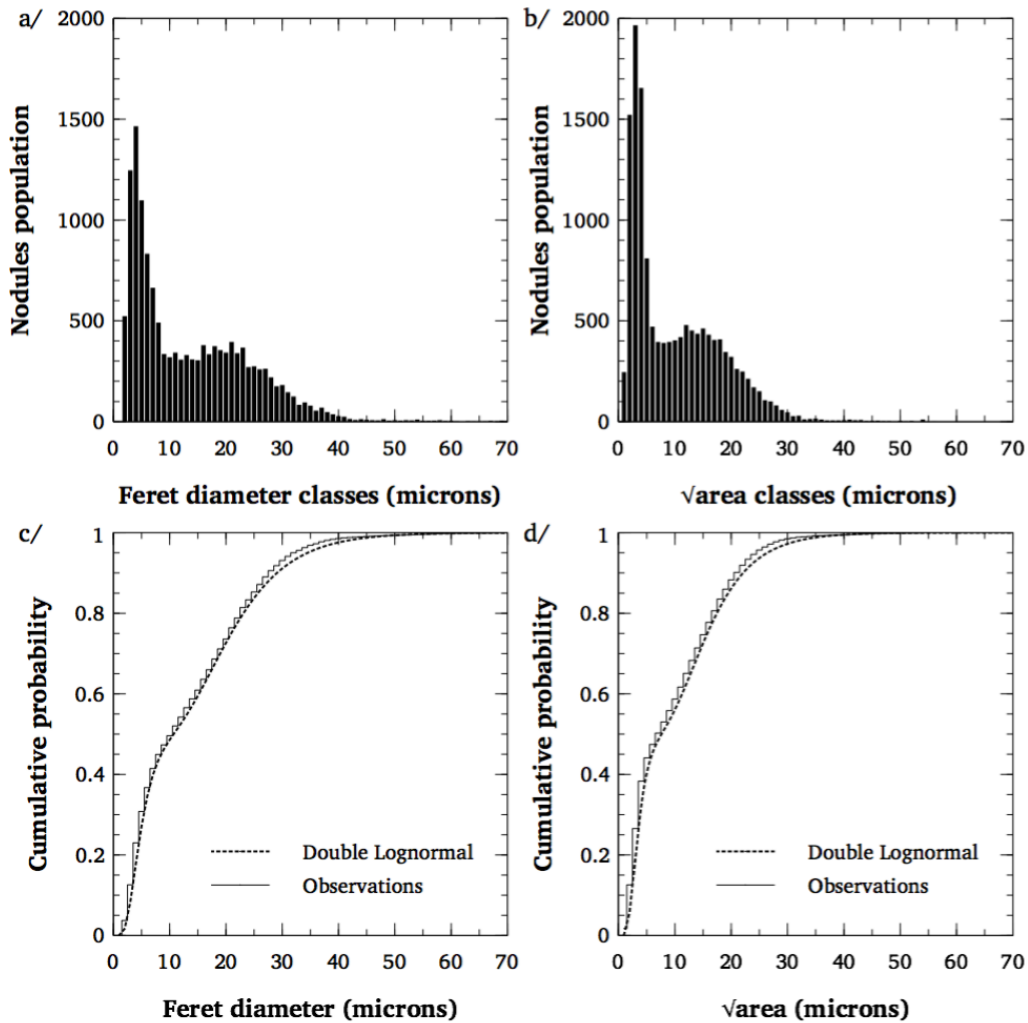


Fig. 2 Histogram of pores populations based on their Feret diameter (a/) and their \sqrt{area} (b/). Pore size probability estimated by a double Lognormal distribution for Feret diameter (c/) and \sqrt{area} (d/)

Regarding these observations, completed by several analyses in the literature [6], graphite nodules appear again to play an important role in the crack micro-propagation with crack paths concentrated around the larger nodules. Considering that there are no casting defects such as pores in the studied material, we therefore assume here that the fatigue crack initiation occurs in the vicinity of the larger graphite nodules and that knowledge of their size distribution is of prime importance in the study of the damage of this spheroidal graphite cast

iron. Many samples from both fatigue specimens but also exhaust manifolds or turbochargers were analysed by Scanning Electron Microscopy (SEM). The obtained images were processed using ImageJ software following a precise procedure for counting the number and measuring the size and shape of the graphite nodules, inspired by the work of [4] and [7]. Statistical analysis of the size of graphite nodules was performed from the measurement of their Feret diameter or the square root of their surface \sqrt{area} . Figure 2.a and .b show the histograms of the nodules population distributed to the classes of the two types of measures. 14,059 nodules were detected with Fret diameter between 1.4 and 69 μm and \sqrt{area} between 0.83 and 53.8 μm . In both cases, two populations of nodules seem to appear: one characterized by very small nodules but with a majority of the total population and the other with nodules of medium size for a smaller and more dispersed sample. In accordance with what has already been observed by Pedersen et al.[7] and as seen in Figure 2.c and .d, these histograms are correctly described, in both cases, by double lognormal distributions.

FATIGUE CRITERION

Failure at the macroscopic scale is the resulting action of the evolution of irreversible processes that occur at the material microscopic scale. For the studied spheroidal cast-iron, macroscopic failure can be linked to the progressive damage of each of its constituent phases [8, 9]. From a mesoscopic point of view, damage can occur as spheroid rupture, ductile damage in the ferritic matrix or spheroid/matrix debonding. These micro-mechanisms of failure occurs in the material controlled by the macroscopic loading imposed to a representative volume element [10]. We therefore propose to describe the fatigue damage of the studied cast iron as well as its variability on the basis of the work of Charkaluk et al [4] for the criterion mathematical form and of Maurel et al.[11] for the micro-propagation law. In fact, the probability of failure of an elementary volume element is described using the probability of finding a graphite nodule of size a within this elementary volume according to the formula:

$$p_f = \int_a^{a_f} \frac{da}{(W_d/\gamma_d)^{k_d} + (W_e/\gamma_e)^{k_e}} ; W_d = \int_{cycle} \sigma : d\varepsilon ; W_e = \int_{cycle} \sup[tr(\sigma), 0] : d\varepsilon^e \quad (1)$$

$\gamma_d, \gamma_e, k_d, k_e$, four parameters to be identified. a is a random variable representing the nodule size. a_f is the size of macroscopic crack that correspond to the rupture of a representative volume element. As Charkaluk et al., it seems first logical to choose a critical size a_f of 2mm which is commonly used to describe the appearance of a crack at the macroscopic point of view. Finite element calculations analysis allows assuming that the first crack will appear at the larger nodule within a representative elementary volume. Indeed, the spacing between nodule seems large enough to first neglect inter nodules interaction for crack initiation. This criterion form is however relatively simple because it presupposes that in terms of propagation, there is no interaction between this main crack and the other ones initiated from smaller nodules. It nevertheless allows having an estimation of the lifetime variability. To keep the proposed mathematical form, a reasonable hypothesis to take into account both the nodules interaction and the associated reduction in lifetime is to choose a smaller value for a_f . In the following, a value of 1mm will therefore be used.

RESULTS AND DISCUSSIONS

In our case, the proposed model does not allow conventional analysis of the lifetime in an energy versus number of cycles to failure diagram. Here a number of cycles to failure has to

be linked with a given pair of dissipated energies. The criterion parameters are then optimized in order to match the experimental lifetime and the mode of the number of cycles to failure distribution (number of cycles of maximum probability). The results of this least-square optimization are presented in Table 1.

| Parameters | γ_d | γ_e | k_d | k_e |
|-----------------|------------|------------|-------|-------|
| Optimized value | 5,3 | 6,5 | 2,3 | 1,9 |

Tab. 2: Optimized parameters for the probabilistic criterion

To perform the optimization process, the probability of failure is here simply considered as lognormal:

$$p_{f,(W_d,W_e)}(N) = \frac{1}{2\pi N\sigma(W_d,W_e)} \exp\left[-\left(\frac{\ln(N)-\mu(W_d,W_e)}{2\sigma(W_d,W_e)}\right)^2\right] \quad (2)$$

Its parameters $\sigma(W_d, W_e)$ and $\mu(W_d, W_e)$ are optimized from the histogram of the number of cycles to failure. This latter is obtained from the nodules statistics. A number of cycles to failure is indeed computed for each non-empty class of nodule size with equation 1. The log normal parameters are then easily identified with the computation of the mean value and the standard deviation of the identified population. As seen of Figure 3.a, for different level of dissipated energy, the lognormal distribution fits correctly with the computed histogram of number of cycles to failure. For a given pair (W_d, W_e) , the distribution mode is given by:

$$N_{computed} = \exp\left[(\mu(W_d, W_e) - \sigma(W_d, W_e))^2\right] \quad (3)$$

This predicted lifetime value is compared to the experimental one on Figure 3.b which underline a very good matching between computed and experimental lifetime.

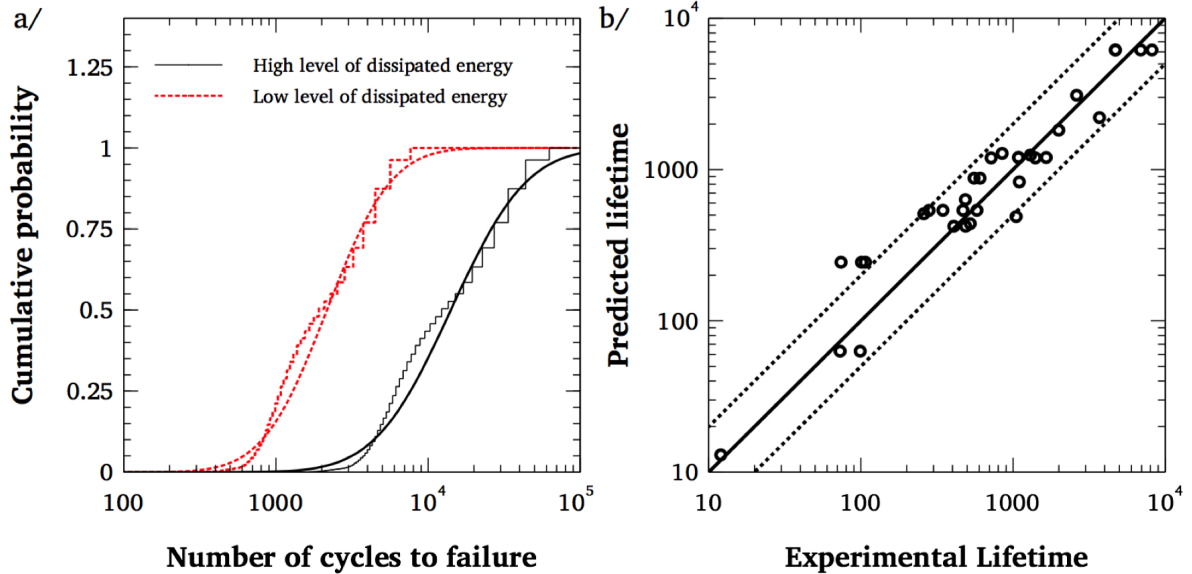


Fig. 3 a/ Cumulative probability functions for two levels of dissipated energy densities. b/ Experimental lifetime versus Computed highest probable lifetime

CONCLUSION

This paper proposes a novel method to estimate the probability density distributions of low-cycle fatigue lifetime for a cast-iron, based on the estimation of a graphite spheroids (taken

as defects) probability density throughout the analysis of SEM images. Double lognormal distributions give a good representation of the variability of the spheroids size and a lifetime probability density function is proposed thanks to a criterion involving energy densities representative of the loading conditions and a crack growth law. The criterion parameters are optimized to have the estimated lifetimes that match with the experimental observations. The proposed criterion provided predictive results for the studied alloy. Lifetime probability is in the same time explicitly computed to be used as an input to a stress-strength interference method.

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