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Probability density functions: From porosities to fatigue lifetime

E. Charkaluk [b], A. Constantinescu [c,*], F. Szmytka [a], S. Tabibian [a,b,c]

[a] Automotive Research and Innovation Division, PSA Peugeot Citroën, Route de Gisy, Vélizy-Villacoublay 78943, France
[b] LML, CNRS UMR 8107, Laboratoire Mécanique de Lille, Ecole Centrale de Lille, Cité Scientifique, 59650 Villeneuve d'Ascq, France
[c] LMS, CNRS UMR 7649, Laboratoire Mécanique Solides, Ecole Polytechnique, Route Saclay, 91120 Palaiseau, France

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ABSTRACT

This paper proposes a novel method to establish and identify a probability density function characterizing the fatigue lifetime. The method is initiated with a quantitative analysis of the microstructure of the material, which provides the initial probability distribution of defects. After identifying a given probability density function of defects, one can transport it into a lifetime probability density function using a growth law involving a measure of the loading over a cycle. Several parameters of the growth law are finally estimated from a given set of fatigue experiments on specimens and several techniques are discussed. The method is applied on real defect observations and lifetime data. The estimated lifetimes using the novel technique is of similar quality with standard estimation providing the probability density function of lifetime as an additional output. This output can be used directly as an input in a stress–strength interference method.

1. Introduction

The search for performance in lightweight and environmentally-friendly structures leads automotive companies to choose aluminum alloys as the preferred material for engine parts like pistons, cylinder blocks and cylinder heads. Among aluminum alloys, the A3XX series which contains components like silicon, magnesium and/or copper is commonly used due to its high strength to weight ratio, good machinability, corrosion resistance, optimum surface finish as well as its high thermal conductivity [1]. In the 3xx series, the A356 alloy is the preferred choice due to its enhanced tensile strength after heat treatment. Another popular choice for the manufacturing of cylinder heads and engine blocks is the A319, due to its excellent casting characteristics. The later also associates good mechanical properties to low cost component production, crucial energy efficiency and concomitant environmental benefits [2,3].

Cylinder heads have become one of the critical components during the last years in the engine design process, due to the increase of in-service temperatures combined to the mass decrease imposed by the environmental constraints. The main concern of the cylinder head is thermomechanical fatigue (TMF) as mentioned in a series of papers in the last decades [4–7]. The die casting process (DC) was commonly used to produce cylinder heads but has been recently often replaced with the Lost Foam Casting (LFC) process. Indeed, if the die casting process produces geometrically complex metal parts through the use of reusable molds, Lost Foam Casting permits to further reduce process cost and participates to the weight reduction goals by permitting much more degree of freedom (smaller radius in the geometries, complex shape, etc.). However Lost Foam Casting comes with a considerable change in the microstructure of the material. The major specificity of this process is indeed its relatively slow cooling rate when compared to the die casting process, i.e. 0.8 °C/s compared to 30 °C/s respectively [8]. The difference in cooling rate creates a coarser microstructure when measured in term of Dendrite Arm Spacing (DAS) or LFC alloys. Besides, residual porosity and inclusions (intermetallics, oxides), formed during the degradation of the polymeric pattern [9,10], are increased and clustered. Even if these phenomena do not reduce the overall mechanical properties of the material, they have an important impact on lifetime of components during in-service loadings.

Lifetime assessment of structures subjected to TMF is often a complex process due to the diversity and complexity of the involved mechanisms: plasticity, viscosity, microcrack propagation, etc. In spite of important advances in the field, the expressions of TMF criteria remain phenomenological and rarely take into account of the underlying microstructure. For instance, Weick and Aktaa [11] and Yamauchi et al. [12] analyzed a series of isothermal biaxial and thermal strain-controlled tests, respectively, which were conducted on tubular samples and proposed modified versions of the Manson-Coffin Low Cycle Fatigue criterion. Zouani et al. [13] developed an isothermal biaxial stress controlled

* Corresponding author. Tel.: +33 1 69 33 57 56.
E-mail addresses: eric.charkaluk@ec-lille.fr (E. Charkaluk), andrei.constantinescu@lms.polytechnique.fr (A. Constantinescu), fabien.szmytka@mpsa.com (F. Szmytka), shadan_tabibian@yahoo.com (S. Tabibian).

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Nomenclature

a	defect size	ϕ	fatigue parameter, i.e. function describing the size of the shakedown cycle
p_a	probability density function describing the defect size a	σ	stress
p_F	probability density function describing the failure probability at cycle N_F	ε	strain
$\widehat{\mu}$	mean value of a probability density function	ΔW	dissipated energy per cycle
$\hat{\sigma}$	standard deviation of a probability density function	σ_H	hydrostatic stress

experiment carried out on a particular circular sample and proposed a modified Morrow criterion. Other examples can be found in Socie and Fatemi [14,15]. Moreover, the extensions of Chaboche's initial formulation based on continuum damage mechanics [5,16,17] and energy-based formulations [18,19] could also be cited. Modifications of fatigue criteria based on the dissipated energy per cycle were also proposed for example in Park and Nelson [20] and in a series of papers by Amiable et al. [21,22]. The proposal by Amiable et al. [21] includes the maximal hydrostatic stress in the modification and has been recently compared with other criteria on steel in Fissolo et al. [23–25]. In the automotive industry, numerous phenomenological contributions in TMF lifetime assessment could also be found especially for aluminum alloys [5,17,26,18] and a recent comparison of some TMF criteria in [27] for LFC alloys. In spite of the recent development, there is still demand to better link between lifetime and the material microstructure. The objective of this paper to propose a step in this direction, by relating the variability of the microstructure with the one of lifetimes.

This article discusses in a first part a quantitative analysis of the microstructure of the A319 LFC alloy in terms of porosity. The analysis is based on Scanning Electron Microscopy (SEM) observations and digital postprocessing. The observed statistical distribution of porosities and intermetallics are then represented using different probability density functions. This initial distribution of defects, porosities and intermetallics are assumed to represent the precursors to the initiation of microcracks and as such affect the fatigue lifetime. In the second part, starting from the distributions of defects a fatigue lifetime prediction model is proposed. The model includes both micro-initiation and micro-propagation and provides both a standard fatigue life estimation and a probability density as a function of a damage parameter and the number of cycles to failure. Two different optimization schemes are used for the identification of the parameters in the fatigue model. Both are presented and their physical signification is discussed. The robustness of the model is discussed on TMF data for an A319 aluminum alloy.

2. Experimental database

The material studied in this paper is an aluminum–silicon alloy widely used in the automotive industry, A319, without heat treatment and obtained by a LFC process. Its chemical composition is given in Table 1. The exposure of this alloy at high temperature (above 150 °C) leads to a modification of its microstructure and mechanical properties as already discussed in [28,29]. Let us remark that the TMF of engine parts, defined as the initiation of visible cracks often occurs in regions of high temperature. In these regions microstructure and fatigue resistance are altered by the long term high temperature exposure, also denoted as "over-aging". Moreover, over-aging corresponds to a stabilization of both mechanical properties and microstructure under a long term exposure of the material to high temperature. In the present case, over-aging corresponds to an exposure of 200 h at 250 °C. As a consequence TMF criteria discussed next are built from experiments done on over-aged materials.

The thermomechanical fatigue behavior is estimated from strain-controlled Low Cycle Fatigue tests on over-aged specimens. The experimental database considered here consists of 35 tests, performed with a strain ratio $R_\varepsilon = -1$. Temperatures, strain and number of cycles to failure ranges are detailed in Table 2. All tests were conducted with a mechanical strain rate of $\dot{\varepsilon} = 10^{-3}\ s^{-1}$.

3. Quantitative analysis of microstructure

3.1. SEM observations analysis

The basic microstructure of the studied A319-LFC alloy consists of Al–Si eutectics, Iron containing α-AlFeSi ($Al_{15}Fe_3Mn_3Si_2$) and β-AlFeSi (Al_5FeSi) phases and Copper based eutectic θ-Al–Al_2Cu phases (see Tabibian et al. [29] for further details). Although all components may play a role in the microstructural damage mechanisms leading to fatigue, we assume that main role is played by the porosity in the cases studied next. This assumption is justified by the observation that micro-shrinkage zones are preferential initiation sites in terms of thermomechanical fatigue, due to their morphology. Therefore, only the statistical distribution of these microstructural defects will be discussed in the sequel.

Several material specimens extracted from fire decks of LFC cylinder heads have been analyzed by scanning electron microscopy (SEM). The obtained images were processed using the *ImageJ* software (http://rsb.info.nih.gov/ij/) following a precise procedure for counting the number and measuring the size of the pores. The evolution of the images obtained during the different steps of the image processing procedure are displayed in Fig. 2.

The protocol involves four steps:

(i) *Contrast and Brightness:* in the first step, the image is processed to optimize contrast and brightness in order to heighten the pores. The parts of the SEM picture corresponding to very dark areas outside of the specimen are removed to facilitate the treatment (top left panel in Fig. 2(1)).

(ii) *Grayscale threshold:* in the second step, the image is processed using a low/high threshold filter. This filtering is needed for the automatic edge detection and insures

Table 1
Chemical composition of LFC A319.

Si%	Mn%	Fe%	Mg%	Cu%	Zn%	Ti%	Ni%	Srppm	Pppm	V%	Zr%
7.18	0.15	0.43	0.32	3.17	0.19	0.05	0.010	0.020	0.010	0.006	0.002