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Effect of porosity on the fatigue strength of cast aluminium alloys: from the specimen to the structure

Pierre OSMOND[a,]*, Viet-Duc LE[a,b,c], Franck MOREL[b], Daniel BELLETT[b] and Nicolas SAINTIER[c]

[a]*PSA Groupe, 18 rue des fauvelles, 92256 La Garenne-Colombes cedex, France*
[b]*Arts et Métiers ParisTech, Campus Angers – Laboratoire LAMPA – 2 Bd du Ronceray, 49035 Angers Cedex 1, France*
[c]*Arts et Métiers ParisTech, Campus Bordeaux – Laboratoire I2M – Esplanade des Arts et Métiers, 33405 TALENCE Cedex, France*

Abstract

The fatigue strength of cast aluminium alloys is known to be greatly affected by different defect types related to the manufacturing process, particularly microshrinkage pores created during the solidification phase of the casting process. Even if certain classification procedures are given in the standard ASTM E155-15 [1], the presence of defects is not readily related to the capacity of a component or a structure to meet the requirements of the mechanical technical specifications.
The present study aims at establishing a clear link between certain microstructural features and the average fatigue strength. This is possible by looking for the average size of critical defects and using a relevant statistical analysis. More exactly, the Murakami approach based on the statistics of extremes is employed. The main originality of this work lies in the application of this approach to the case of a real structure submitted to high cycle fatigue damage: engine cylinder heads, used in the automotive industry. Indeed, both fatigue tests and microstructural characterizations are carried out on cylindrical specimens and real structures. The specimens are subjected to uniaxial and multiaxial loading conditions [2]. Original fatigue tests, developed by PSA to load in-service critical regions, are carried out on cylinder heads. Systematic analyses of fatigue failure surface are conducted to obtain the statistics of critical defects at the origin of the failures for both specimens and structures.
In parallel, critical regions and the associated local loading mode in the structure are characterized by an appropriate high cycle fatigue analysis. The latter, combined with the fatigue test data and the statistical analysis of the critical defects, leads to a discussion about the size effect and an approach is proposed for a relevant fatigue design procedure.

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Keywords: High cycle fatigue, Cast aluminium alloys, Defect containing materials, Size effect, Fatigue design procedure

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1. Introduction

The cast aluminium alloys are widely used in automotive industry due to their relative good strength combined with a low density and an excellent conductivity. These alloys are commonly employed for chassis and engine components which are, for the most part, subjected to mechanical cyclic loads and present a serious risk of mechanical fatigue. In order to avoid fatigue crack initiation and ensure the component resistance, appropriate design methodologies have to be developed. They are mostly based on an appropriate fatigue criterion, whose identification is carried out by fatigue tests performed on test specimens, who's size is generally quite different to the size of the fatigue critical zones found on the real manufactured components.

The fatigue strength of cast aluminium alloys is known to be greatly affected by different types of microstructural heterogeneities due to the manufacturing process. According to this process and subsequent treatment, the microstructural features can be significantly modified especially in terms of eutectic components (silicon particles and iron-based intermetallics) and casting defects, notably micro-shrinkage pores and gas porosity. Despite the significant effort to characterize and understand the influence of these microstructural heterogeneities on the High Cycle Fatigue (HCF) behaviour of these alloys [2][7], the development of design methodologies taking into account the effect of defects on the fatigue life prediction of structures is still under progress [8][10]. However, in spite of the presence of defects, car manufacturers must ensure a targeted level of reliability of their components and structures. In the case of pores, manufacturers set up control procedures via X-ray inspection for defect detection and to reject components containing defects presenting an unacceptable risk of failure. Even if some classification procedures are given in the standard ASTM E155-15 [1], the presence of defects cannot be readily related to the capacity of a component or a structure to meet the requirements of the mechanical technical specifications. Thus, the definition of material defect requirements is in most cases based on the manufacturers experience, without quantitative justification. With a yearly production of 3 million engines, the optimization of production costs is a major challenge for the PSA Groupe. This justifies the need to development methods to define robust acceptance criteria.

A first step is to provide a clear link between defect features and the fatigue strength. This requires a precise understanding of the fatigue damage mechanisms associated with the microstructural features under high cycle fatigue loading conditions. This has been done for three different aluminium alloys in previous work undertaken by the authors [2][11].

The present study aims at establishing a link between features of the micro-shrinkage porosity and the average fatigue strength. This is done by using the classical approach introduced by Murakami [12] and formalized in the international ASTM standard [13]. It is applied to both test specimens and a real structure: an engine cylinder head. The use of a real structure is the opportunity to highlight the possible size effect between the test specimens used to identify the fatigue criterion and the component to be designed. The capacity of the method to account for different defects distribution parameters is tested by applying the approach to two aluminium alloys elaborated by different casting processes: gravity die casting and gravity lost foam casting. Throughout this exercise, the method proposed by Murakami to extrapolate the average size of the critical defects to objects to other dimensions is compared to the alternative method proposed by Makkonen [14]. Finally, based on the joint analyses of the average critical defect size in the specimens and the structure, a relevant fatigue design procedure accounting for size effect is proposed.

2. Materials & experimental conditions

2.1. Materials microstructure and properties

Two cast aluminium alloys, referred to as alloys A and B, are investigated in this study. These denominations are consistent with those used in the other published results [2][9][15]. These alloys were elaborated by either gravity die casting or lost foam casting and were both subjected to a T7 treatment.