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High cycle fatigue damage mechanisms in cast aluminium subject to complex loads

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ABSTRACT

This article is dedicated to the high cycle fatigue behaviour of cast hypo-eutectic Al–Si alloys. In particular, the AlSi7Cu05Mg03 alloy is investigated. It presents the results of a vast experimental campaign undertaken to investigate the fatigue behaviour, and more specifically the fatigue damage mechanisms observed under complex loading conditions: plane bending with different load ratios, fully reversed torsion and equibiaxial bending with a load ratio of $R = 0.1$. A specific test set-up has been designed to create an equibiaxial stress state using disk shaped specimens. A tomographic analysis is also presented with the aim of characterising the micro-shrinkage pore population of the material.

It is shown that two distinct and coexisting fatigue damage mechanisms occur in this material, depending on the presence of different microstructural heterogeneities (i.e. micro-shrinkage pores, Silicon particles in the eutectic zones, Fe-rich intermetallic phases, etc.). Furthermore, it is concluded that the effect of an equibiaxial tensile stress state is not detrimental in terms of high cycle fatigue. It is also shown that the Dang Van criterion is not able to simultaneously predict the multiaxial effect (i.e. torsion and equibiaxial tension) and the mean stress effect for this material.

1. Introduction

The need to increase performance while at the same time reducing costs in the manufacturing and transportation industries leads to components that are subject to increasingly severe mechanical loading conditions. As such, it is possible to find components submitted to cyclic stress states that have very high mean stress and a high degree of stress triaxiality. For these conditions, which can be defined as "extreme", the fatigue damage mechanism as well as the fatigue strength are, in most cases, completely unknown. Hence, problems are encountered when designing such components, as existing fatigue criteria have difficulties predicting these loading conditions and the fatigue data necessary to identify the criteria parameters are practically non-existent.

The fatigue design of cast aluminium diesel engine cylinder heads, used in the automotive industry, is an example of this type of problem. These components have a very complicated geometry due to the admission, exhaust and cooling passages and the valve control system, but are essential to the correct operation of the engine (see Fig. 1). In order to ensure that these components conform to their required specifications, numerical modelling techniques are employed [1,2]. The results from these simulations show that certain zones of these components are subjected to complex multiaxial cyclic stress–stain states, including high mean stress. This loading mode is the result of the superposition of residual stresses caused by the fabrication process (i.e. gravity sand casting) and the subsequent heat treatment, the thermal stresses resulting from in-service conditions, stresses due to the assembly of the engine (e.g. bolting loads) and the alternating stress due to the variation in pressure of the fluids in contact with the thin wall sections in the fatigue critical zones. Hence, the high cycle fatigue design of these components requires the use of a fatigue criterion which is adapted to the material and the specific loading conditions. The object of this work was to develop an appropriate criterion for this application. This criterion will be presented in a future publication. The present article focuses on the experimental investigation, with particular attention given to the investigation of the fatigue damage mechanisms for different loading modes occurring in the cast aluminium alloy in question.

An extensive literature review has highlighted the fact that there exists a large amount of uniaxial fatigue data for this material, for example in rotating bending, plane bending or uniaxial tension–compression loading conditions [3–14]. However, this data is often limited to load ratios of either $R = -1$ or $R = 0.1$ and very little, if any, data is available for biaxial tensile loads and torsion.

The principal aims of the work presented in this article are: (a) to investigate the effect of different loading modes (i.e. bending with different load ratios, torsion and equibiaxial bending) on the fatigue response of the cast aluminium alloy, AlSi7Cu05Mg03-T7 and (b) to highlight the role of the different microstructural

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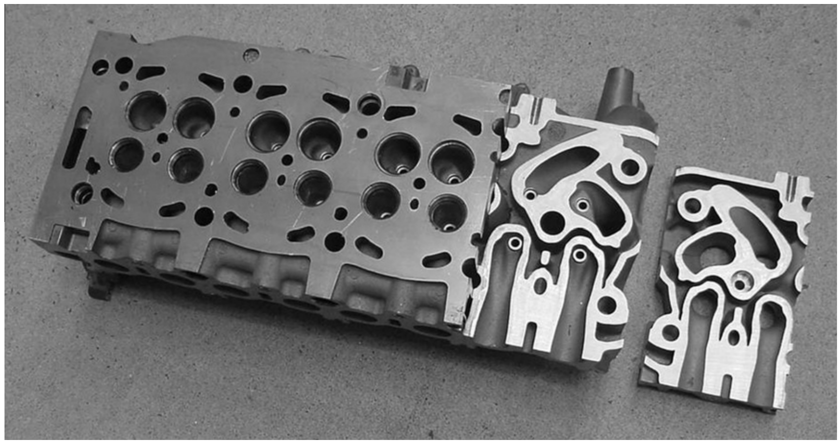

Fig. 1. The PSA diesel engine cylinder head. The upper surface is the engine block mating surface. The right end of the cylinder head has been sectioned via a horizontal cut.

Table 1
Mechanical properties of AlSi7Cu05Mg03-T7.

0.2% Yield stress σ_Y (MPa)	Ultimate tensile strength σ_{uts} (MPa)	% Elongation A%
250–260	318–330	5.0–5.7

heterogeneities on the fatigue damage mechanisms observed under the different loading modes.

2. Specimen extraction and the material: AlSi7Cu05Mg03-T7

2.1. Specimen extraction

Fatigue specimens were made from material taken directly from cylinder heads (see Fig. 1) manufactured by PSA for use in automotive diesel engines. The cylinder heads were gravity sand cast. During the casting process titanium and boron are added to the liquid metal in order to refine the size of the alpha-phase dendrites. Strontium is added to modify the shape of the silicon eutectic particles. The cast components are subsequently heat treated using the following procedure:

- Solution heat-treatment for 5 h at a temperature of approximately 540 °C.
- Water quenching at a temperature of approximately 70 °C.
- Tempering at 200 °C for 5 h.
- Cooling in ambient air.

The resulting mechanical properties of the material are listed in Table 1.

The casting of specimens using a specific ‘‘specimen shaped mould’’ can have the disadvantage that the material may not have the same microstructural and mechanical properties as the material resulting from the real industrial manufacturing process. It was therefore decided, in collaboration with the industrial partner, PSA, to slightly modify a limited number of cylinder heads in order to have a much larger volume of material from which fatigue specimens could be extracted. This was done by reducing the length of the inlet and exhaust cores (see Fig. 2a). The resulting modified cylinder heads have blocked inlet and exhaust passages on the engine block mating surface (see Fig. 2b). This resulted in a layer of material with a maximum thickness of approximately 8 mm, from which the specimens, described in more detail later, were extracted.

It is of course possible that these modifications to the casting process result in changes to the material properties. In particular, the Dendrite Arm Spacing (DAS), the hardness and the size and distribution of micro-shrinkage pores may have been affected. Therefore, a detailed investigation of these properties, before and after modification of the casting process was done and very little variation of these quantities was found.

The DAS was measured in four different zones of the engine block mating surface. An average DAS of 80 ± 10 μm (based on 10 measurements per zone) was found. The average Brinell hardness (based on 20 measurements) is 104 ± 3 HB. The size of micro-shrinkage pores found in 16 different zones (of approximately 20 × 15 mm) randomly positioned on the mating surface were measured using an optical microscope and the image analysis program, Visilog. The surface area of the micro-shrinkage pores was measured to be between 6×10^{-2} and 4×10^{-4} mm^2. Table 2 shows the comparison of these measurements between a modified and an unmodified cylinder head for four different locations on the mating surface.

In addition, measurements of the pore size and distribution have been done by tomography and are discussed below.

2.2. Material and pore characterization

Fig. 3 shows the material microstructure created as a result of the process described above. The material is composed of alpha-phase dendrites with an average Dendrite Arm Spacing (DAS) of approximately 80 μm. The eutectic silicon particles are fine and spherical. The dark feature in Fig. 3 is a casting defect (i.e. a micro-shrinkage pore) caused by the shrinkage of the molten liquid during solidification. In a complicated gravity cast component like a cylinder head it is difficult to completely eliminate this type of defect. The presence of intermetallic phases can also be distinguished.

In order to characterise the size and spatial distribution of the shrinkage pores in the cast aluminium alloy used in the cylinder heads, the tomography technique was used in collaboration with the MATEIS laboratory of INSA Lyon. The investigation was done using a Phoenix/X-ray v/tome/x tomography. The analysis was conducted on a specimen taken from the mating surface of a modified cylinder head. The volume of scanned material was equal to $3.5 \times 4 \times 6.5$ mm^3. A voxel size of $5 \times 5 \times 5$ μm^3 was used. After post-treatment of the tomographic images it is possible to determine the size distribution of the pores as well as their sphericity, *s*. The determination of the sphericity is done by the marching cube