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ScienceDirect
Acta Materialia 59 (2011) 4990–4998
Acta MATERIALIA
www.elsevier.com/locate/actamat

Statistical assessment of fatigue crack initiation from sub-surface hydrogen micropores in high-quality die-cast aluminum

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Received 29 March 2011; received in revised form 21 April 2011; accepted 22 April 2011
Available online 26 May 2011

Abstract

It has recently been discovered that micropores on the order of a few microns agglomerate in a high density in the sub-surface layer of aluminum alloys that have been produced in a high-quality die-casting process. It is known that fatigue behavior is dominated by the existence of the micropores. In the present study, geometrical parameters defining the relationship between fatigue crack initiation and micropores have been investigated using high-resolution X-ray microtomography, combined with two kinds of statistical analysis. It has been revealed that consideration of micropore pairs is necessary, and a number of parameters for paired micropores that may be strongly associated with fatigue crack initiation have been extracted and statistically evaluated. It is concluded that the mean diameter between paired micropores, and the mean distance to the casting surface, are predominant in fatigue crack initiation.
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Keywords: X-ray tomography; Fatigue crack initiation; In situ observation; Pore; Al–Si alloy

1. Introduction

The casting process inevitably introduces a variety of casting defects and defective microstructures detrimental to the mechanical properties of cast aluminum alloys. Well-known examples are porosity, intermetallic particles and entrapped oxide films. It has been well documented that these defects are especially deleterious to the fatigue behavior of cast aluminum alloys. One of the most detrimental defects in such alloys is porosity, which is caused by both shrinkage and precipitation of supersaturated hydrogen [1]. For example, it has been reported that fatigue cracks are initiated from porosity located at or near the specimen surface in about 92–100% of specimens in Al–Si alloys produced through various processes, such as gravity casting [2,3], low-pressure permanent-mold die casting [4], and high-pressure die casting [5]. In addition, Li et al. have shown that the formation of fatigue cracks is dominated by the highest local stress–strain concentration caused by the presence of a pore adjacent to the free surface [6]. It has therefore been assumed that in cast aluminum alloys the time necessary for fatigue crack initiation can be substantially ignored, and almost all fatigue life is spent in crack propagation, even in the high-cycle-fatigue regime [7] that dominates crack initiation in other materials.

However, it can be readily imagined that this tendency is more or less dependent on pore size. For example, McDowell et al. have shown in their model analysis that incubation life (i.e., the time for both crack nucleation

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doi:10.1016/j.actamat.2011.04.049

and propagation within the influence of a micro-notch root field) is about 50–70% of the total life of 50 μm pores, but only about 20–30% of the total life of 200 or 400 μm pores in the high-cycle-fatigue regime of an A356-T6 alloy [8]. Zhang et al. have examined the effects of the cooling rate during solidification on the fatigue life of a cast A356 aluminum alloy, and have concluded that when pore size is below a critical size of ~80 μm, due to a relatively high cooling rate during solidification, fatigue cracks are initiated from a near-surface eutectic microconstituent and not from pores [9].

Additionally, it has recently been discovered that micropores on the order of a few microns are agglomerated in high density in the sub-surface layer (typically within 20–30 μm from the casting surface) of aluminum alloys that have been produced in a high-quality die-casting process [10]. Although the size of such micropores is significantly smaller (4–5 μm on average) than the above-mentioned well-known casting defects, fatigue behavior was found to be dominated by the existence of the micropores. It has been reported that such micron-order-sized micropores are distributed in high density (approximately 8000 pores mm^{-3} in the above-mentioned high-quality die-cast aluminum alloy, and ~700,000 pores mm^{-3} in standard aluminum alloys), except in pure aluminum [1,10–12]. Since porosity is formed through the precipitation of supersaturated hydrogen, which is usually unavoidable due to the hydrogen solubility gap at the melting temperature of aluminum, it is physically impossible to completely eliminate micropores from aluminum alloys [11,13]. It is reasonable to assume that a dominant fatigue crack is initiated from one or a few detrimental pores. Therefore, if the geometrical nature of detrimental micropores can be directly related to fatigue crack-initiation behavior, it is expected that fatigue properties may be optimized by eliminating such detrimental pores. This technique would offer more effective and realistic microstructural control than one based on the evaluation of average pore size and/or pore population [14,15].

This study reenacted the observation of fatigue crack initiation caused by micropores in a cast aluminum alloy, using high-resolution X-ray microtomography, an excellent technique that enables three-dimensional (3-D) quantitative measurement, through in situ observation, of all the microstructural features in a specimen, together with identification of micropores serving as fatigue crack initiators.

2. Experiments

An AC4CH alloy, designated in the JIS standard, was employed in the experiments. The alloy had a chemical composition of 7.04 Si, 0.35 Mg, 0.115 Ti, 0.09 Fe, 0.008 Ni, 0.0065 Mn, 0.0025 Cu, and balance Al in mass%. Specimens were sampled from automotive components, so that the casting surface was preserved as one of the four specimen side surfaces. The components were cast using the new injection (NI) process, and then tempered to a T6 temper condition with a solution heat-treatment for 18 ks at 803 K, followed by artificial aging for 18 ks at 443 K. The NI process is a low-speed mold-filling die-casting process in which air pressure is used to directly fill melting liquid into the mold and to give pressure through the plunger. Owing to low hydrogen content, casting can conduct heat treatment and welding. Two types of fatigue specimens were prepared; an ordinary plate specimen of 15 (length: L) × 5 (width: W) × 2 mm (thickness: B) and a parallelepiped specimen of 0.4 (L) × 0.6 (W) × 0.6 mm (B) in gauge section with bonded end tabs for laboratory fatigue tests and in situ observation under synchrotron radiation, respectively. All the specimen surfaces, other than the casting surface, were polished using a 1-μm-grade diamond abrasive.

Tension-to-tension fatigue tests were performed with a 49 N servo-hydraulic fatigue-testing machine at room temperature in air. Sinusoidal loading was applied with a load ratio, R, of 0.1, and a frequency of 30 Hz. In total, 40 specimens were prepared and tested at a maximum constant stress of 160 MPa. The casting surface had been removed in seven of the 40 by polishing, in order to investigate the effects of the surface condition. All the specimens were classified according to types in origin of the fracture. Variations in fatigue life were described using a two-parameter Weibull distribution function with mean ranking.

X-ray tomography was performed at the undulator beamline, BL47XU, of the SPring-8. An experimental hutch is located about 49 m from the X-ray source in this beam line. A monochromatic X-ray beam with a photon energy of 20 keV was used to observe the entire cross-section of the specimen and a region of about 622 μm in height. Image slices were reconstructed from a series of projections based on the conventional filtered back-projection algorithm. The gray value in each dataset was calibrated, unless otherwise noted, so that the linear absorption coefficient of -10 to 80 cm^{-1} fell in an 8-bit gray-scale range between 0 and 255. Isotropic voxels with 0.503 μm edges were achieved in the reconstructed slices. The threshold value for obtaining binary images was chosen as the median between the linear absorption coefficient peaks of air and the aluminum matrix. To suppress inaccuracies originating from image noise, only micropores over 23.168 voxels in volume were counted as micropores in the quantitative analysis. The other details of the tomography observation are available elsewhere [1,11].

The in situ loading stage [16] allowed specimens to be scanned under cyclic loading. Fatigue test conditions were identical to the laboratory fatigue tests except for the application, in this case, of a maximum constant stress of 130 MPa. In addition, the stress amplitude was reduced by about 19% compared to the laboratory fatigue tests, in order not to overlook the instance of fatigue crack initiation. In total, 21 specimens were prepared and tested. A first tomographic scan was performed before loading in each specimen, and a second scan was performed after fatigue crack initiation was confirmed with radiographs. All

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