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Effects of microstructure and temperature on fatigue behavior of E319-T7 cast aluminum alloy in very long life cycles

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Abstract

The effects of microstructure and temperature on the fatigue behavior of a commercial Al–Si–Cu alloy used in automotive engine components were investigated for lifetimes as long as 10^9 cycles using ultrasonic fatigue instrumentation operating at 20 kHz. The primary finding of this study is that the influence of microstructure on the cyclic properties is greater than the influence of the testing temperature. Fractographic studies indicated that most fatigue cracks initiate from microshrinkage pores located at or very near to the specimen surface, while a much smaller number of cracks initiate from twin boundaries. Increasing test temperature resulted in a modest decrease in endurance limit by about 12% from 20 to 150 °C, while a significant decrease in endurance limit by about 23% was observed from 150 to 250 °C at high number of cycles. Using fatigue data developed in this study, a statistical model, the random fatigue-limit model (RFL), was evaluated for its utility in estimating fatigue behavior in the gigacycle regime.

Keywords: Fatigue; Cast aluminum alloy; Temperature; Frequency; Microstructure

1. Introduction

The use of cast aluminum alloys in automotive structural applications is growing rapidly because of the need to reduce weight. There is a need for understanding the fatigue behavior of these alloys in the very high cycle regime. Ultrasonic fatigue instrumentation, operating at a frequency of 20 kHz, has been used to reduce testing time and to examine very long life fatigue behavior [1]. It may also be used for rapid generation of crack growth data and threshold stress intensities and offers the possibility to study very slow fatigue crack growth rates far below the conventional threshold at 10^{-10} m/cycle.

Accelerated testing is especially important when fatigue properties of cast materials are studied. Microstructural variability causes pronounced scatter of endurance data, and characterization of these materials requires testing sufficiently high numbers of samples to include statistical variation in the material characterization. However, the question of whether fatigue behavior determined by ultrasonic methods is comparable to that determined at conventional frequencies needs further examination.

Caton et al. [2] performed ultrasonic fatigue experiments on the cast aluminum alloy W319-T7, which is similar to the E319-T7 alloy investigated here. They compared their results with endurance data measured at 40 Hz using conventional servo-hydraulic fatigue testing equipment [3]. For the conditions investigated, i.e. load ratio $R = -1$ and temperature 20 °C, no frequency influence on endurance lifetimes was found for lifetimes below 10^7 cycles, where data from tests at 40 Hz were available. Since ultrasonic experiments were run to 10^9 cycles, an unexpected phenomenon in aluminum alloys, namely the existence of an endurance limit in W319-T7 was demonstrated. Fatigue cracks predominantly initiate at porosity

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in this alloy, and the endurance life is almost exclusively spent propagating the crack to fracture. Cycling at or below the endurance limit stress may cause crack initiation; however, these cracks do not propagate to failure. The endurance limit in W319-T7 could only be observed by cycling specimens into the gigacycle regime, since latest failures occurred in the regime of 5×10^7 cycles. Cyclic properties of this material are sensitive to the microstructure, since coarser microstructures contain larger defects and crack propagation rates of small fatigue cracks is accelerated.

Besides the microstructure, the testing conditions (e.g. mean loads, corrosive environments) influence the measured cyclic properties of aluminum alloys. Here the influence of testing temperature will be studied in more detail. It is well known that stress-controlled fatigue strength generally decreases at elevated temperatures. Engler-Pinto Jr. et al. [4] found a modest decrease in fatigue life between 20 and 150 °C for E319-T7 aluminum alloy using servo-hydraulic testing equipment at cycling frequency of 40 Hz. The temperature effect was more pronounced for other cast aluminum alloys, such as W319-T7, A356-T6 and AS7GU-T64. Shyam et al. [5] studied the small crack propagation in cast aluminum alloy W319 at 20, 150 and 250 °C at 30 Hz and found that the effect of temperature on small crack growth rate between 20 and 150 °C was negligible, but the crack growth rates increased by an order of magnitude at 250 °C. Srivatsan et al. [6] found that for 7055 aluminum alloy tested at 27 and 190 °C at a frequency of 5 Hz, an increase in test temperature had a detrimental influence on fatigue life of specimens oriented transverse to the rolling direction, while little influence was found for longitudinally oriented specimens.

The commercial cast aluminum alloy 319 is used for cylinder heads, where peak temperature as high as 250 °C can be reached in service. Therefore, it is important to understand the fatigue behavior in this temperature regime. The objective of this study is to determine the influences of microstructure and temperature on fatigue behavior of cast aluminum alloys under fully reversed loading conditions ($R = -1$) using the ultrasonic fatigue technique.

2. Experimental

2.1. Material

The cast aluminum alloy, E319, examined in this study, has a nominal composition of (by wt%) 7.61 Si, 3.28 Cu, 0.22 Mg, 0.33 Mn, 0.70 Fe, 0.65 Zn, 0.11 Ti, 0.012 Sr and balance Al. The typical microstructure of E319 is shown in Fig. 1a. The light gray features are primary α aluminum dendrite arms; the dark gray region is the Al–Si eutectic region. The secondary dendrite arm spacing (SDAS) is measured as the distance between centers of adjacent dendrite arms. Shrinkage porosity and intermetallic phases typical of this alloy can also be seen in Fig. 1a. Another shrinkage pore at higher magnification is shown in Fig. 1b. It will be shown later that shrinkage pores are the primary initiation sites for fatigue cracks in this alloy.

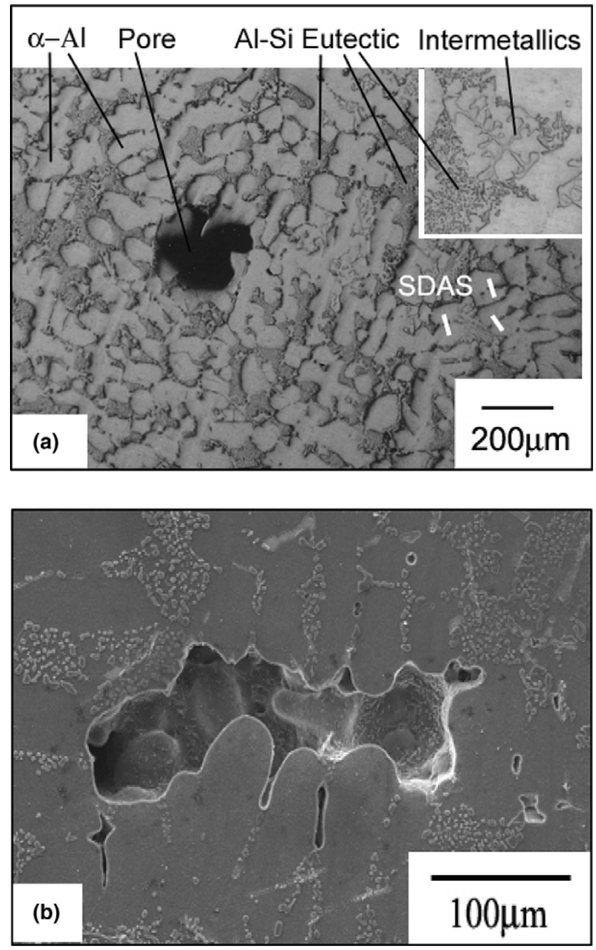

Fig. 1. (a) Optical microstructure of cast aluminum alloy E319. (b) Typical microshrinkage pore.

Plates were cast with a copper chill positioned along the edge in order to control the solidification rate; this ensures that the microstructure is essentially uniform along the isotherms of the casting and that the microstructure becomes increasingly coarse, in terms of pore size, SDAS, eutectic silicon morphology and the intermetallic particle morphology, as the distance from the chill increases. Rectangular bars were sectioned from the regions with average SDAS of 30 and 70 μm, which are thereafter referred to as the "low" and "medium" SDAS and which have porosity levels of 0.26% and 0.87%, respectively. All bars underwent a T7 over-aged heat treatment consisting of an 8 h solution heat treatment at 495 °C followed by boiling water quench at about 90 °C and 4 h of aging at 260 °C. Heat treated bars were then machined to the final dimensions shown in Fig. 2. The mechanical properties, determined from conventional mechanical tests, at three temperatures are summarized in Table 1. Young's modulus values were taken from [4].