

Fatigue Behavior and Life Prediction for Aluminum Castings in the Absence of Casting Flaws

2011-01-0193

Published
04/12/2011Qigui Wang and Peggy Jones
General Motors Company

Copyright © 2011 SAE International

doi:10.4271/2011-01-0193

ABSTRACT

Cast aluminum alloys are increasingly used in cyclically loaded automotive structural applications for light weight and fuel economy. The fatigue resistance of aluminum castings strongly depends upon the presence of casting flaws and characteristics of microstructural constituents. The existence of casting flaws significantly reduces fatigue crack initiation life. In the absence of casting flaws, however, crack initiation occurs at the fatigue-sensitive microstructural constituents. Cracking and debonding of large silicon (Si) and Fe-rich intermetallic particles and crystallographic shearing from persistent slip bands in the aluminum matrix play an important role in crack initiation. This paper presents fatigue life models for aluminum castings free of casting flaws, which complement the fatigue life models for aluminum castings containing casting flaws published in [1].

INTRODUCTION

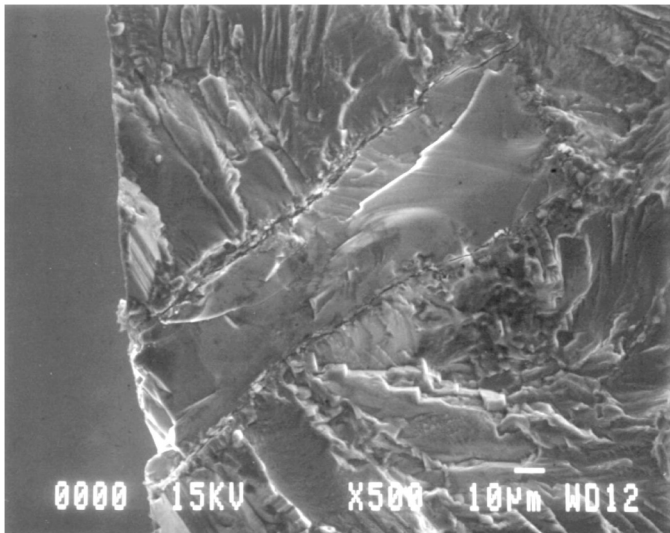
Fatigue properties of cast aluminum components are strongly dependent upon the existence of flaws, such as porosity and oxide films produced during casting. In fact, the maximum flaw size has been recognized as the most important parameter in determining the fatigue properties of aluminum castings, where generally the larger the maximum flaw size, the lower the fatigue strength for a given fatigue life [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12]. In the presence of casting flaws, the fatigue initiation life is negligible and the total fatigue life is spent in propagation of a fatigue crack from such flaws. The fatigue life of the aluminum castings containing casting flaws can then be estimated by either long or short crack models, which have been reported by the authors [1, 6, 7, 9, 10, 11, 12, 13] and others [3, 4, 5, 8, 14, 15, 16, 17].

However, in many structural castings over 90% of the microstructure is sound material, and the process is designed to produce sound material where the highest stresses are applied. Where the pores and oxide films are smaller than a critical size or where the casting has no flaws, the cracked/debonded eutectic particles and persistent slip bands become the fatigue crack initiation sites [6, 13, 17, 18]. Figs 1 and 2 show examples of fatigue cracks initiated from the cracked/debonded eutectic particles and persistent slip bands, respectively. In these locations, the cycles spent on crack initiation by cracking or debonding the eutectic particles or forming persistent slip bands can significantly increase the total fatigue life. Because of the complexity of microstructural constituents in various cast aluminum alloys, it has long been a challenge to estimate the fatigue life of aluminum castings containing no flaws, particularly if the variation in microstructural constituent size and distribution is considered.

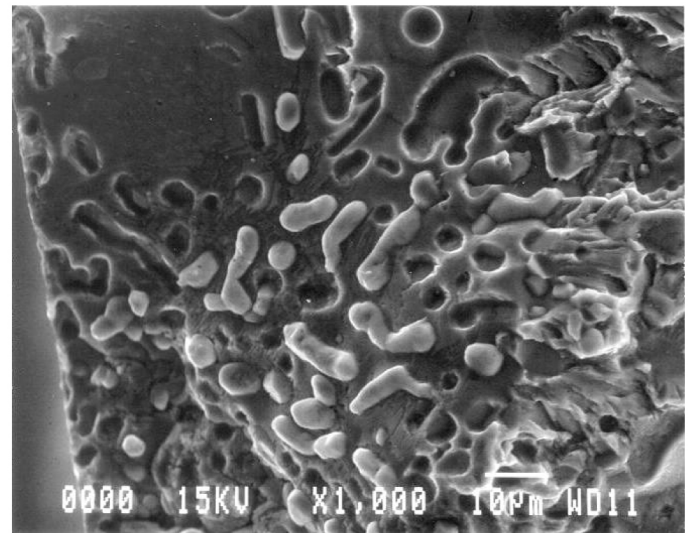
In this work, micromechanics-based life models have been developed to estimate the fatigue life of aluminum castings spent in both crack initiation and propagation from the cracked/debonded eutectic particles and persistent slip bands (PSB) [13]. The Extreme-Value Statistics (EVS) approach is used to estimate characteristics of size and shape of eutectic particles, dendrites cells, and grains based on two dimensional metallographic data. To validate the model prediction, both A356 and 319 alloy castings were made with various microstructures by sand casting and lost foam casting. The microstructure variation was achieved by changing cooling rate and by adding a grain refiner and a eutectic silicon modifier. To minimize casting flaws, all aluminum castings employed in this work were made from clean and well-degassed melts, and were hot isostatically pressed (HIPed) before machining. The characteristic size and shape populations of eutectic particles and dendrite

**Documents**

Document Sharing Hub

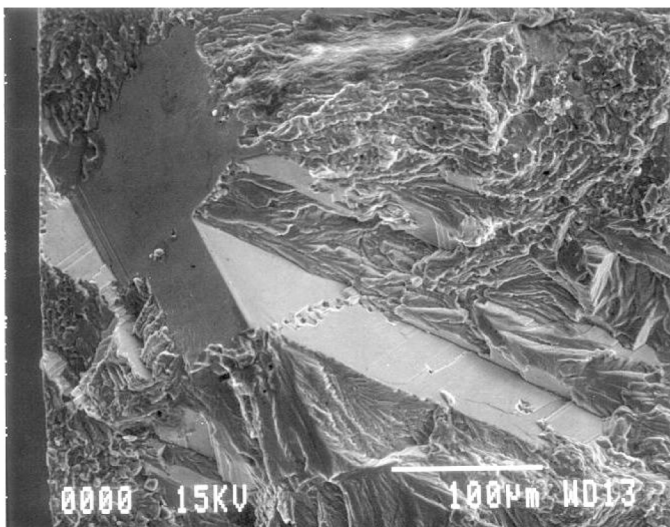


(a)

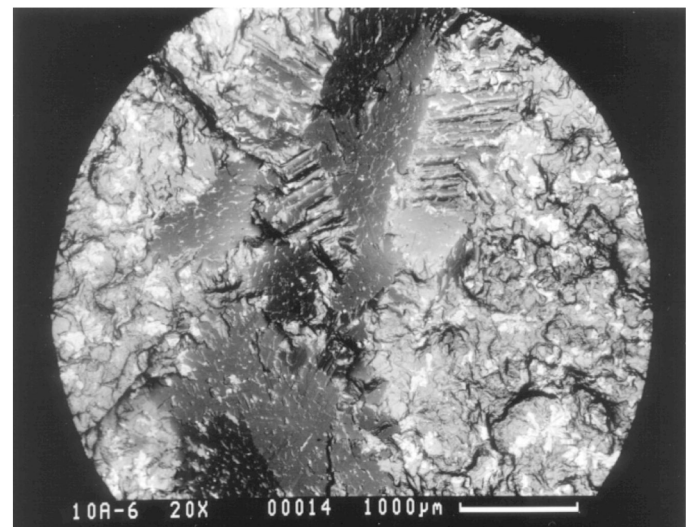


(b)

Figure 1. Fatigue cracks initiated from a cracked eutectic particle of π -Al₉FeMg₃Si₅ phase (a) and from debonded eutectic Si particles in an A356 alloy (b).



(a)



(b)

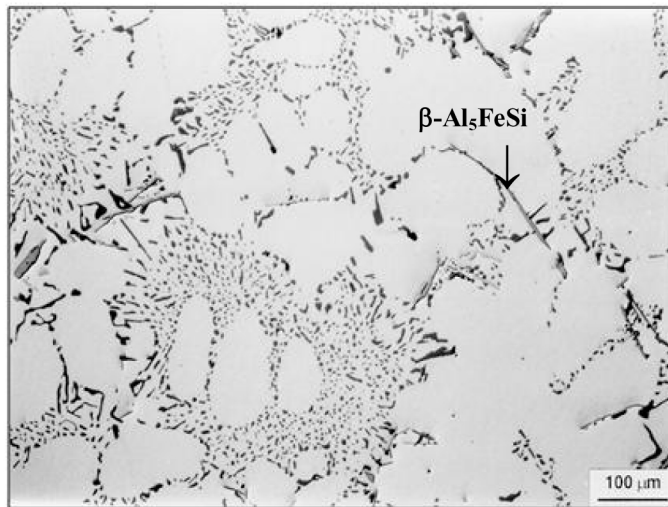
Figure 2. Fatigue cracks initiated from the persistent slip bands in an A356-T6 alloy having SDAS of 70µm (a) and a coarse grained 319-T7 alloy having SDAS of 80µm (b).

grains and cells were measured metallographically with a Clemex image analyzer.

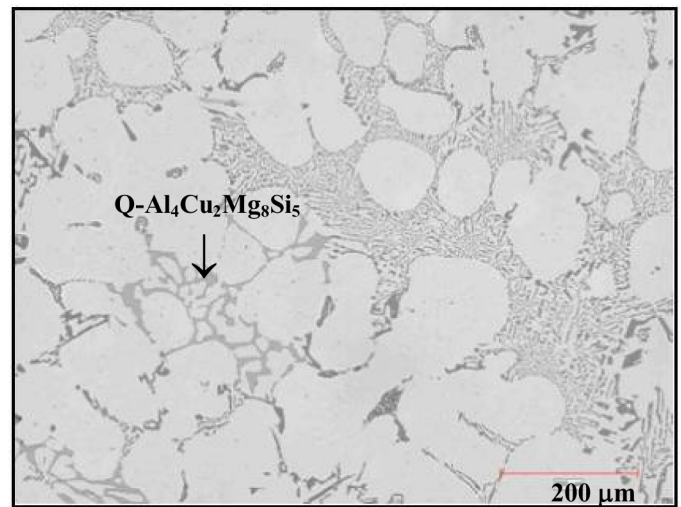
EXPERIMENTS

Two base alloys of A356 (Al-7%Si-0.4%Mg-0.15%Fe) and 319 (Al-7%Si-3.5%Cu-0.4%Mg-0.5%Fe) were used in this work. Both alloys were cast in both end-chill sand molds to make plates and lost foam shape castings. The cooling rate during solidification in end-chill sand castings varies from 10°C/s near the chill to 0.1°C/s at the location 200 mm away

from the chill. In lost foam casting, the cooling rate is about 0.1°C/s. A more detailed description of alloy melting and casting procedures was given elsewhere [1, 7]. Prior to machining, the castings were subjected to a T6 heat treatment for A356 alloy (solution treated at 540°C for 6 hrs, water quenched at room temperature, and aged at 170°C for 6 hrs) and a T7 heat treatment for 319 alloy (solution treated at 493°C for 10 hrs, quenched into agitated 70°C water, and aged at 250°C for 8 hours), respectively. To produce fatigue data representing flaw-free samples, all castings were HIPed



(a)



(b)

Figure 3. Typical microstructures of A356 alloy (a) and 319 alloy (b).

at 520°C (for A356 castings) or 490°C (for 319 castings) and 100 MPa for 2 hrs before heat treatment. Cylindrical fatigue specimens, with a parallel gauge section 20 mm long and 7.6 mm in diameter were prepared from the heat-treated samples according to ASTM standard E466. All the fatigue specimens were tested under load or strain control using axial push-pull sinusoidal loading.

Typical microstructures of both A356 and 319 alloys, as shown in Fig. 3, are comprised of an aluminum matrix, which is strengthened by Mg_2Si and/or Al_2Cu precipitates and, to a far lesser extent, by Si precipitates, and a dispersion of eutectic silicon particles and Fe-rich intermetallics. Compared with 319, A356 has a relatively simple microstructure which does not have Q ($Al_4Cu_2Mg_8Si_5$) phase eutectic particles and θ (Al_2Cu) precipitates [19–20]. The distribution of eutectic particles in both alloys is significantly affected by cooling rate during solidification. Fig. 4 shows coarse and fine microstructures in an A356 alloy. In coarse microstructures (large SDAS), the dendrite cells are large and the eutectic particles are clustered along the limited cell and grain boundaries. As a result, the individual dendrite cell is isolated by a thick eutectic wall, and it behaves as an individual dendrite grain. By contrast, in fine microstructures (small SDAS) eutectic particles are less concentrated on dendrite cell boundaries. During deformation, the dislocations can move across the dendrite cell boundaries where there are no eutectic particles to block them. These dislocations are only stopped at grain boundaries during deformation.

MULTI-SCALE FATIGUE (MSF) LIFE MODELS

FATIGUE CRACK INITIATED FROM SECOND PHASE PARTICLES BY CRACKING OR DEBONDING

In coarse microstructures (large SDAS, secondary dendrite arm spacing, $> 50\mu m$), the dendrite cell walls act as grain boundaries because they are surrounded by a nearly continuous array of eutectic particles. The sizes of second phase particles are similar to the dendrite arm spacing, especially in the unmodified microstructure. The fatigue life ($N = N_p$) can be predicted by a short crack propagation model assuming that a fatigue crack initiated from a second phase particle at the first cycle ($N_i = 0$) [13].

$$N = N_i + N_p = N_p = C_1 (\epsilon_{max} \sigma_a \sigma_{ys}^{-1})^n d_{eq}^q \quad (1)$$

where C_1 , n , and q are material-related constants; σ_a is the stress amplitude; σ_{ys} is yield strength; ϵ_{max} is the maximum total strain during loading cycle; and d_{eq} is the equivalent circle diameter of the initial crack-like second phase particle size.

The criterion for cracking or debonding of second phase particles is given as [13]:

$$\sigma_p = 4\phi\beta\alpha' \mu_m \gamma_{max}^* \quad (2)$$