

Fatigue Behavior of Aluminum Alloys under Multiaxial Loading

Qigui Wang
General Motors Co.

Guoqiu He
Tongji University

Yucong Wang
General Motors Co.

ABSTRACT

Fatigue behavior of aluminum alloys under multiaxial loading was investigated with both cast aluminum A356-T6 and wrought alloy 6063-T6. The dominant multiaxial fatigue crack preferentially nucleates from flaws like porosity and oxide films located near the free surface of the material. In the absence of the flaws, the cracking/debonding of the second phase particles dominates the crack initiation and propagation. The number of cracked/debonded particles increases with the number of cycles, but the damage rate depends on loading paths. Among various loading paths studied, the circle loading path shows the shortest fatigue life due to the development of complex dislocation substructures and severe stress concentration near grain/cell boundaries and second phase particles.

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1. INTRODUCTION

Aluminum alloys have been increasingly used in automotive industry because of their high strength to weight ratio particularly after heat treatment. As many of their applications in automobiles involve cyclic loading, fatigue properties of the alloys are critical to their success.

In the past couple of decades, great attention has been drawn in understanding of fatigue behavior of aluminum alloys. Numerous studies have shown that under uniaxial loading fatigue resistance of aluminum alloys strongly depends upon the existence of flaws, such as porosity and oxide films in the materials. The maximum flaw size has been recognized as the most important parameter in determining the fatigue properties of aluminum alloys, 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, 5, 8, 14, 15, 16, 17].

When the pores and oxide films are smaller than a critical size, or where the material has no flaws, the cracked/debonded second phase particles and persistent slip bands become the fatigue crack initiation sites [6, 13, 17, 18]. As a result, 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.

The study of aluminum alloys under multiaxial loading is still limited [19, 20, 21, 22, 23], not only because of the cost and complexity of multiaxial fatigue testing but because of the increased difficulty in modeling of multiaxial fatigue. The presence of orthogonal stresses in various combinations of phase angle and proportionality complicates the problem beyond the simple mean stress effect that challenges uniaxial fatigue. Whereas stress- and strain-based solutions successfully predict fatigue behavior in uniaxial fatigue, these approaches have proven inadequate in multiaxial fatigue [23].

To understand the mechanisms of multiaxial fatigue damage and particularly the influence of second phase particles on multiaxial fatigue, two commonly used aluminum alloys A356 (Al-7%Si-0.4%Mg) and 6063 (Al-0.4%Si-0.7%Mg) were chosen as the microstructure of 6063 wrought alloy is very similar to the matrix (Al + Mg/Si precipitates) of A356 casting alloy after heat treatment. Both alloys were subject to different loading

paths. After testing, fracture surfaces were examined in the SEM and dislocation structures were evaluated by TEM. The damage mechanism related to the loading paths was also discussed.

2. EXPERIMENTS

2.1. Materials and Fatigue Specimens

Specimens used for microstructure analysis and multiaxial fatigue testing were made of A356 and 6063 aluminum alloys. The A356 material used in this study was unmodified and produced by a gravity sand casting. The average grain size is about 0.8 mm and secondary dendrite arm spacing (SDAS) is about 75 μm . The 6063 material was machined from commercially extruded wrought aluminum billet. The average grain size is about 350 μm . The detailed chemical compositions of the testing alloys are given in Table 1. Before machining, both alloys were subject to a T6 heat treatment including solutionization at 535 °C for 5 hrs, water quench at 70°C, and aging at 160°C for 4 hrs.

Table 1. Chemical compositions of A356 and 6063 alloys.

Alloy (wt%)	Fe	Si	Cu	Mg	Mn	Zn	Cr	Ti	Al
6063	0.19	0.45	0.03	0.71	0.03	0.01	0.01	0.02	Balance
A356	0.09	6.6	<0.01	0.36	<0.01	<0.01	<0.01	0.15	Balance

Multiaxial fatigue specimen geometry for both alloys is shown in Fig. 1. Both outside and inside surfaces of the thin-walled tube in gauge section were axially polished to minimize machining marks.

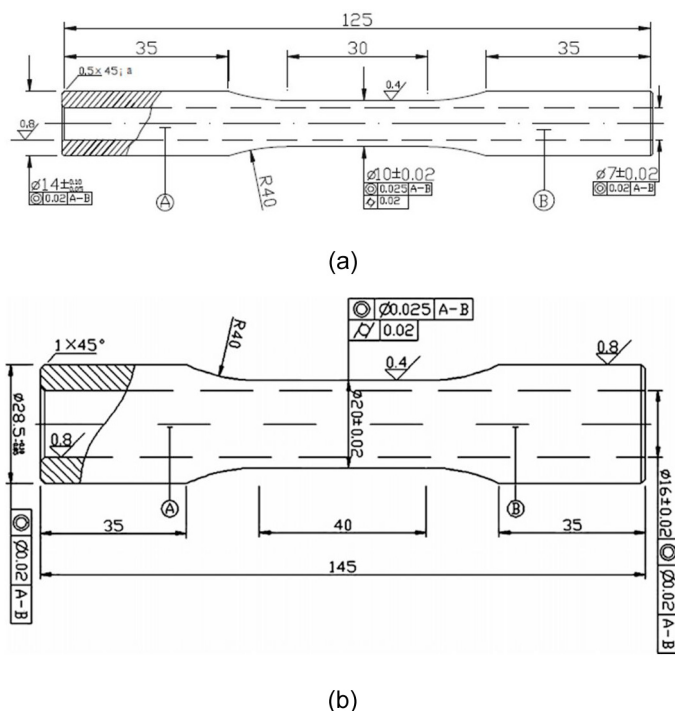


Figure 1. Multiaxial fatigue specimen geometry for 6063-T6 (a) and A356-T6 (b) alloys (dimensions in mm).

2.2. Fatigue Testing

Multiaxial fatigue testing was performed in a servo-hydraulic MTS (809) machine with a combined tension and torsion loading. All fatigue tests were conducted at room temperature of 20°C. For the 6063-T6 alloy, the fatigue testing was stress-controlled and the output strain was recorded by an extensometer. The cyclic loading frequency was 15 Hz and the stress ratio was equal to -1 for both axial and torsional loading. Under the same equivalent stress amplitude of 93MPa, four non-proportional loading paths were chosen including circle, ellipse, square and rectangle, and the proportional loading path was also included, see Table 2. For the A356-T6 alloy, both stress-controlled and strain-controlled fatigue tests were conducted. In strain-controlled testing, cyclic loading frequency was 0.5 Hz and output stress was recorded. Strain components in the specimen were evaluated using a MTS tension-torsional extensometer with a gauge length of 25mm. Fully reserved axial and torsional strain ranges of sinusoid waves were used in the testing. The equivalent strain rate was maintained at 0.004s^{-1} . In this study, the strain-controlled fatigue tests were conducted with equivalent strain amplitudes varying between $\pm 0.18\%$ and $\pm 0.30\%$ under both circle and proportional loading paths. In the stress-controlled testing, the material was loaded under the same equivalent stress amplitude of 145 MPa with five different loading paths including proportional, circle, axial ellipse, torsional ellipse, and diamond, see Tab.3. The equivalent stress amplitude is defined as

$\sigma_e = \sqrt{(\sigma_1)^2 + (\sigma_3)^2}$, where $\sigma_1 = \sigma$ is the axial stress and $\sigma_3 = \sqrt{3}\tau$ is the shear stress. Fatigue life is defined as the number of cycles at which a 10% drop from the maximum tensile or shear stress occurs. To evaluate damage evolution during fatigue, some fatigue tests were interrupted at scheduled cyclic cycles.

2.3. Microstructure and Fractographic Analysis

Optical microscopy was used to examine multi-scale discontinuities and microstructure in sectioned specimens. Quantitative metallography was carried out in an image analyzer on the polished faces of the specimens. Particle cracking during fatigue process was quantified by counting and measuring the cracked and uncracked particles on specimens fatigued to any given number of cycles or to failure. A total of 3000-5000 particles were examined for each specimen. The metallographic specimens were sectioned from various locations at least 3 mm below the fracture surfaces with the examined surfaces parallel to tension axis.

Crack initiation and local damage was evaluated on fracture surfaces in a scanning electron microscope (SEM), and the chemical composition of secondary phases on fracture surfaces was measured by an energy dispersive X-ray (EDX).

To evaluate micro damage evaluation, TEM specimens were prepared by first reducing the sample thickness down to about 50 μm using carborundum paper and then using twin-jet electro-polishing with an electrolyte consisting of 10% HNO_3 and 95% $\text{CH}_3\text{CH}_2\text{OH}$ to get a foil about 20 nm thick with a

Table 2. Loading paths employed in fatigue testing of 6063-T6 alloy.

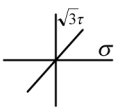
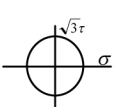
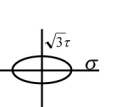
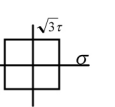
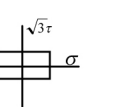
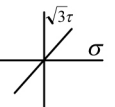
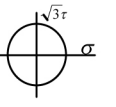
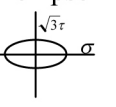
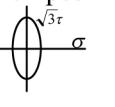
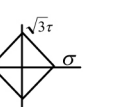
	Proportional	Circle	Ellipse	Square	Rectangle
Loading path					
Ratio of ($\sqrt{3} \tau : \sigma$)	1:1	1:1	1:2	1:1	1:2
Control waveform	sinusoidal	sinusoidal	sinusoidal	trapezoidal	trapezoidal
Phase difference (θ)	0°	90°	90°	90°	90°

Table 3. Loading paths used in fatigue testing of A356-T6 alloy.

	proportional	circle	axial ellipse	torsional ellipse	diamond
Loading path					
Ratio of ($\sqrt{3} \tau : \sigma$)	1:1	1:1	1:2	2:1	1:1
Phase difference (θ)	0°	90°	90°	90°	90°

wedge hole. TEM observations were conducted on a Hitachi H-800 transmission electron microscope operated at 200 kV, equipped with a conventional double tilting stage.

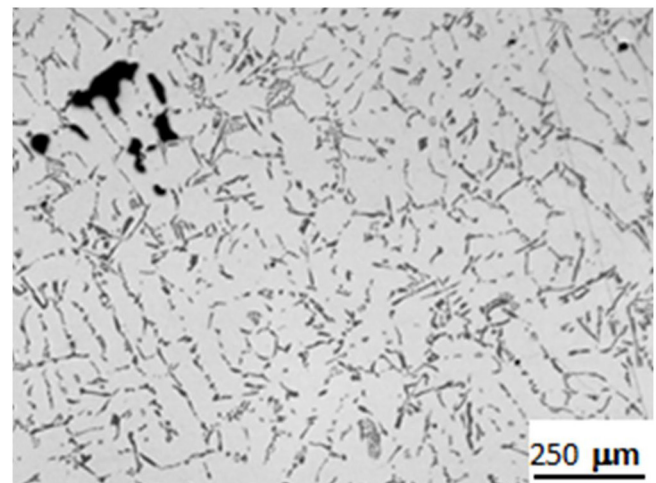
3. RESULTS AND DISCUSSION

3.1. Microstructure

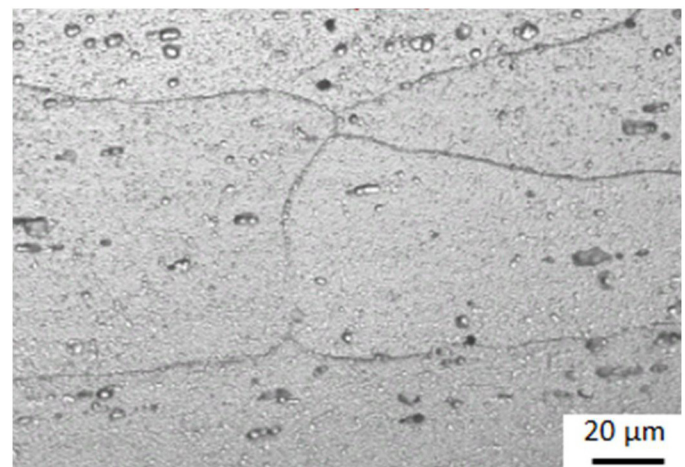
Fig. 2 shows the typical microstructure of the alloys studied. A356-T6 is a casting alloy belonging to hypoeutectic Al-Si family with a microstructure composed of primary aluminum dendrites (light grey), eutectic silicon and intermetallic particles (dark grey), together with macro-or micro-flaws such as porosity (black), Fig. 2a. 6063-T6 is a wrought alloy which consists of mainly aluminum solid solution (matrix) and a very small amount of intermetallic particles. After chemical etching, the grain boundaries become obvious, Fig. 2b. It should be noted that the microstructure of 6063-T6 alloy is very similar to the aluminum dendrites of A356-T6 alloy, consisting of Al and Mg/Si precipitates.

3.2. Fatigue Properties

Figs. 3 and 4 show the fatigue properties of 6063-T6 alloy tested under different loading conditions. When the material is subjected to the same equivalent cyclic stress, uniaxial loading shows the longest life but non-proportional (circle) loading leads to the shortest life, Fig. 3. Among various non-proportional loading cases, the circle loading path gives the shortest fatigue life, Fig. 4.



(a)



(b)

Figure 2. Typical microstructure of (a) A356-T6 and (b) 6063-T6 alloys.