Integrated Experimental, Analytical, and Computational Design for Fatigue Crack Growth Resistance in Cast Aluminum Alloys

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Abstract

Long and small fatigue crack growth (FCG) studies at various stress ratios have been performed on solution-strengthened A535-F and precipitation-strengthened A356-T6 cast aluminum alloys. Microstructures were altered through processing and chemistry in order to systematically investigate the individual and combined effects of materials’ characteristic microstructural features on FCG. Mechanisms of FCG at the microstructural scale of the studied alloys were identified at various growth stages, and load-microstructure-damage mechanisms design maps were created. Complementary to this work, a fracture mechanics methodology for data treatment and reduction has been developed for long-to-physically small crack growth corrections, and an original material science-based model that further compensates for the microstructurally small crack growth behavior was created and validated. A computational toolset has been constructed for microstructure-specific FCG simulations. FCG response is represented by the superposition of material’s matrix and secondary phase behavior, with phase property data generated using a novel microhardness indentation technique. Actual microstructural images are used as the basis for meso-scale simulations to make numerical evaluations of the FCG response and to optimize the materials for FCG resistance. Examples on the application of these methods and tools will be given as they relate to design for FCG resistance, life predictions, and material optimization.

Keywords: Cast aluminum alloys; Fatigue crack growth; Microstructural mechanisms; Fracture mechanics; Computational modeling

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1. Introduction

Strength-to-weight and processing advantages make light metals desirable materials for structural applications in the transportation sector including ground, air, and water vehicles. Fatigue crack initiation and propagation are critical considerations in structural design and material/process development and optimization. Extensive research efforts have been dedicated to this topic [1,2], yet a fundamental understanding of the crack growth mechanisms at the micro-/nano-structural scale of various light metal alloys used in fatigue-critical applications has yet to be established. There is a critical need to appropriately generate, interpret, and use experimental FCG data to develop methods and tools for accurate life predictions and design with reduced safety factors.

Microstructure sensitive-based approaches to FCG experimentation and modeling have grown in importance in recent years out of the need to optimize light metals’ structural performance. Cast aluminum alloys have been extensively investigated with respect to multiple microstructural variables, including secondary phase morphology/distribution, chemical composition, intermetallic content, solidification rate, grain size, and heat treatment/precipitate systems [3-5]. These studies indicate the significant effects that changes in the materials’ microstructures have on the FCG response, and further understanding of the microstructural mechanisms is needed.

Complementary to experimentation and establishing FCG mechanisms, modeling efforts ought to be performed to reflect the observed phenomena and translate them into design tools. Microstructure-based models have been successfully achieved in several research efforts [6-8] as tools for simulating and predicting crack interactions with microstructural features (i.e., grains, secondary phases). These tools are both analytical and computational models that characterize FCG resistance with respect to microstructural features and/or develop physics-based models for crack growth. Integrated Computational Materials Engineering (ICME) models have been further developed in an attempt to bridge various operative size scales in FCG phenomena (from atomic interactions to structural component performance), and to better understand the complex interplay between materials characteristics, processing conditions, and design variables. Overall, however, unified and integrated design methods and tools for FCG resistance are still lacking, and they need to be developed through further research.

### Nomenclature

| Symbol | Description |
|--------|-------------|
| a      | half crack length (internal crack) or crack length (surface crack) |
| ACR    | adjusted compliance ratio |
| (da/dN)MSC | microstructurally small crack growth rate |
| (da/dN)PSC | physically small crack growth rate |
| ∆Keff-ACR | effective stress intensity amplitude with ACR correction |
| ∆Kapp | applied stress intensity amplitude |
| ∆KMSC | microstructurally small crack stress intensity amplitude |
| ∆Kplastic | plastic component of the stress intensity amplitude |
| ∆KPSC | physically small crack stress intensity amplitude |
| ∆σapp | applied stress amplitude |
| dn | proportionality constant reflecting the deviation from elastic behavior |
| Kmax | maximum applied stress intensity |
| Knorm | normalized stress intensity, including the combined effect of ∆K and Kmax |
| Λ | ratio of microstructurally small to physically small crack growth rate |
| m | microstructural barrier sensitivity exponent |
| n | dimensionless ratio of crack length to crack length plus the distance to the next barrier |
| nk | Kmax sensitivity exponent |
| ns | critical value of n in the subsequent zone at which slip initiates |
| ν | Poisson’s ratio |
| R | stress ratio |
| σys | microscopic cyclic yield strength within the plastic zone ahead of the crack |
In this research, FCG mechanisms in A535-F and A356-T6 alloys were identified with respect to controlling characteristic microstructural features. Several novel design tools will be introduced (a methodology for long crack growth data treatment, a small crack growth predictive model, load-microstructure-damage design maps, and a computational modeling toolset) as they relate to design for FCG resistance, and examples of their use will be provided. The nomenclature provides the background for the equations presented and discussed in Section 3.4.

2. Materials selection, processing, and fatigue crack growth testing

Cast aluminum alloys A535-F and A356-T6 were investigated in this study. Materials, compositions, and processing conditions were designed to isolate characteristic microstructural features of the alloys and study their individual and combined effects on FCG. Secondary phases and grain structures of the alloys are shown in Figure 1. The specifics of the studied alloys and their variants are as follows:

- **Cast Al-7%Mg: A535 (solution hardened); two grain sizes (75 and 450 μm); as-cast (F condition)**
- **Hypo-eutectic cast Al-7%Si-0.35%Mg: A356 (Mg-Si precipitation strengthened); two secondary dendrite arm spacings (SDAS; 45 and 90 μm); two grain sizes (500 and 1300 μm); unmodified and Sr-modified eutectic Si structure; T6 (peak strengthened: solutionized at 540°C for 1.5 hrs, boiling water quench, and aging at 155°C for 12 hrs). Grain refinement was done by adding Al-5%Ti-1%B, and eutectic Si modification using Al-10%Sr master alloy (the average particle size and aspect ratio for the unmodified / Sr-modified eutectic Si particles are: 4.5 μm and 0.50 / 1.3 μm and 0.88).**

![Figure 1. Typical microstructures of (a,b) A535-F and (c,d) A356-T6. Grain structures are revealed with Barker’s reagent and polarized light.](image)

Long FCG tests were performed for all alloys according to ASTM E647 standard [9] using compact tension, C(T), specimens with dimensions 63.5 mm x 61 mm x 10 mm. Constant stress ratio tests (R=0.1, 0.5, and 0.7) and constant Kmax tests with variable stress ratio were conducted. Small FCG tests were done on corner flaw tension, CF(T), specimens. These specimens had a gage cross-section of 10 mm x 5 mm. The notch size varied from 200 to 300 μm, as appropriate for the microstructure of the alloy. All small FCG experiments were performed at R=0.1. Both long and small crack growth tests were run at room temperature, relative humidity 20-50%, and cyclic frequency 20 Hz (except for upper Region III of crack growth when the frequency was lowered to 10 Hz).

3. Fatigue crack growth mechanisms at the microstructural scale and analytical design tools

Mechanisms of crack growth have been systematically studied following the experimental plan outlined before, along with optical and electron microscopy work, in order to elucidate crack-microstructure interactions at different growth stages from threshold to Region III. Long FCG mechanisms will be presented first, followed by the small FCG mechanisms, and then analytical methods for long-to-small crack growth corrections and design maps will be introduced and discussed.
3.1. Changes in long fatigue crack growth mechanisms with increasing applied driving force

Fracture surface profiles for A535-F and A356-T6 at different ∆K values are shown in Figure 2. For each alloy, FCG mechanisms change as the driving force, ∆K, increases. In A535-F, crack propagation is predominantly transgranular at low applied driving force, mixed transgranular/intergranular at intermediate driving force, and mostly intergranular at high driving force. Microstructural constituents smaller than the grain size (i.e., SDAS) control the mechanisms of crack growth in A356-T6 alloys. Crack propagation is predominantly crystallographic through the α-Al matrix at low driving force, then changes to mixed-mode crystallographic and interactions with eutectic Si particles located in interdendritic areas at intermediate driving force, and finally occurs mainly along/through Si particles in the large eutectic colonies located at grain junctures at high driving force. Mechanisms of crack propagation are further affected by microstructural variations as described in Section 3.2.

Figure 2. Fracture surface profiles at R=0.1 for (a-c) A535-F – 75 μm grain size; A356-T6 (d-f) unmodified – 90 μm SDAS – 1300 μm grain size, (g-i) Sr-modified – 90 μm SDAS – 1300 μm grain size, (j-l) Sr-modified – 45 μm SDAS – 1300 μm grain size, and (m-o) Sr-Modified – 45 μm SDAS – 500 μm grain size.
3.2. Effects of microstructural features and loading conditions on long fatigue crack growth mechanisms

Effects of grain size in A535-F (75 versus 450 μm) on long FCG data and mechanisms have been studied. It can be seen, Figure 3(a), that the large grain size material has greater FCG resistance in the near-threshold regime than the small grain size material. This is associated with a higher degree of roughness-induced closure in the coarse-grained material, as the crack is deflected at grain boundaries.

Crack growth mechanisms in A356-T6 alloys have been studied with respect to two eutectic Si morphologies (unmodified and Sr-modified), two SDAS (45 and 90 µm), two grain sizes (500 and 1300 µm), and three stress ratios (R=0.1, 0.5, 0.7). FCG plots showing experimental results for each of these conditions are shown in Figures 3(b)-3(e). Figure 3(b) shows the effects of grain refinement on the A356-T6 alloys, indicating again that the larger grain size material has a higher crack growth threshold. This occurs because the coarse-grained material has less grain boundary area over which the Si phase is distributed, therefore causing larger crack deflections due to interactions with heterogeneously distributed Si clusters (increased roughness-induced closure), and thus a higher FCG threshold. In Figure 3(c), it can be seen that a lower SDAS decreases the FCG threshold, while increasing the toughness of the material. Both effects are associated with the distribution of Si particles along dendrite cell boundaries. With lower SDAS and more dendrite cell boundary area, Si particles are well distributed and create less roughness-induced closure (lower threshold), while also help to dissipate the applied stresses (increased toughness). Figure 3(d) indicates that Sr-modification improves low cycle fatigue behavior and increases the fracture toughness of the material. Angular, plate-like eutectic Si particles in the unmodified condition create stress concentrations that facilitate crack advance whereas the spherical Sr-modified Si particles homogenize stresses and effectively lower the local driving force.
Finally, in Figure 3(e), it can be seen that increased stress ratio shifts FCG curves to lower applied stress intensity due to mean stress effects and lower magnitude of closure.

### 3.3. Microstructural effects on small fatigue crack growth data and mechanisms

Small FCG behavior has been experimentally evaluated for A535-F (450 μm grain size; initial flaw is 300 μm) and A356-T6 (Sr-modified, 45 μm SDAS, 500 and 1300 μm grain size; initial flaw size is 200 μm). A comparison between long and small FCG data is shown alongside corresponding SEM fractographic images of the small crack growth specimens in Figure 4. Figure 4(a) shows a lower threshold and higher growth rates for the microstructurally-small crack in the A535 alloy, as well as an acceleration/deceleration behavior in early stages. Deceleration was observed at crack growth rates of 7x10^{-7} and 1x10^{-6} mm/cycle, and from the fractography work, this behavior was directly correlated with the crack’s interactions with grain boundaries, Figure 4(d).

Microstructurally-small FCG data for the A356-T6 alloy with small grain size (500 μm) are shown in Figure 4(b). Inflections in the FCG curve (acceleration/deceleration) can be seen at crack growth rates of 3x10^{-7} and 2x10^{-6} mm/cycle; these are attributed to the crack’s interactions with the eutectic Si phase observed on the fracture surface at the corresponding crack lengths, Figure 4(e). Deceleration is found again to correspond to the crack’s interactions with the Si phase. It was observed that, for small cracks, FCG lifetime is enhanced with smaller grain size, because there are an increased number of interactions and of greater magnitude.

Figure 4. Small versus long FCG data at R=0.1 and fractographic panoramas showing small crack-microstructure interactions for (a,d) A535-F – 450 μm grain size; A356-T6 (b,e) 500 μm grain size and (c,f) 1300 μm grain size.
The physically-small FCG curves in Figures 4(a)-4(c) have been obtained by performing closure corrections on the long FCG test data using the adjusted compliance ratio (ACR) technique [10,11]. As these closure corrections are fracture mechanics-based tools, the resulting physically small FCG data are not able to predict the microstructurally-small crack growth behavior of the material, and further materials science-based models need to be developed to obtain microstructurally-small FCG data from long FCG tests.

3.4. Development of long-to-small crack growth corrective techniques and analytical design tools

As seen in Section 3.3 significant differences exist between the long and small crack growth responses in the near-threshold regime. These differences, if not appropriately compensated for, can introduce very large errors in design and life predictions, especially for high-cycle fatigue that is predominantly controlled by the threshold behavior. Fundamentally, long, physically small, and microstructurally small cracks are differentiated by closure effects, the breakdown of continuum mechanics, and the extent of plasticity at the crack tip, respectively. These phenomena have been uniquely addressed in this study, and the novel methodology and results are summarized here using the example of A535-F alloy.

3.4.1. A methodology for closure corrections and data normalization (a fracture mechanics-based correction)

Closure is addressed first, using the ACR method, and a data normalization procedure is introduced to calculate the physically small crack driving force. The steps followed in this procedure are given in Equations (1)-(3).

\[
\Delta K_{\text{eff-ACR}} = ACR \times \Delta K_{\text{app}} \quad (1)
\]

\[
K_{\text{norm}} = \Delta K_{\text{eff-ACR}}^{1-n_K} K_{\text{max}}^{n_K} \quad (2)
\]

\[
\Delta K_{\text{PSC}} = K_{\text{norm}} \times (1 - R)^{n_K} \quad (3)
\]

This model weights the relative contributions of $\Delta K$ and $K_{\text{max}}$ to the crack driving force at different stress ratios through the introduction of the $K_{\text{max}}$ sensitivity parameter $n_K$. This parameter is on the order of 0.1 for A535-F and Al alloys in general, and indicates that dynamic contributions to the overall driving force due to $\Delta K$ are much larger than static $K_{\text{max}}$ effects.

3.4.2. A physically-to-microstructurally small crack corrective model (a materials science-based correction)

A two-stage model has been developed to predict microstructurally-small FCG behavior from the closure-corrected long FCG experimental data. Driving force for the microstructurally-small crack, $\Delta K_{\text{MSC}}$, is calculated by considering EPFM and effects associated with cyclic hardening of the matrix and crack tip blunting. Equations (4) and (5) were developed to relate the experimental physically-small and microstructurally-small crack driving forces using the parameter $\Delta K_{\text{plastic}}$.

\[
\Delta K_{\text{MSC}} = \sqrt{\Delta K_{\text{PSC}}^2 - \Delta K_{\text{plastic}}^2} \quad (4)
\]

\[
\Delta K_{\text{plastic}}^2 = \frac{\sigma_y^2 (1-\nu^2) \ln \left[ \sec \left( \frac{\pi \sigma_{\text{app}}}{2 \sigma_y} \right) \right]}{\pi \alpha_n (1-\nu^2) \sigma_{\text{app}}^2} - \frac{\Delta K_{\text{PSC}}^2 \sigma_{\text{app}}}{2 \alpha_n \sigma_y^2} \quad (5)
\]

Crack interactions with discrete microstructural features (i.e., grains or secondary phases) are considered based on a model proposed by Navarro and de los Rios [12,13], in which acceleration/deceleration is a consequence of blocked slip at grain boundaries. Crack growth is impeded by the successive barriers until a critical stress is activated across the grain boundary and a dislocation source is unlocked, allowing the crack to propagate into the next grain. The parameter $\Lambda$ in Equations (6) and (7) is introduced to relate the physically small and microstructurally small crack growth rates by the dimensionless parameters $n$ (ratio of crack length to crack length plus the distance to the next
barrier), $n_s$ (critical value of n in the subsequent zone at which slip initiates), and $m$ (microstructural barrier sensitivity exponent). Taking grain size information for A535, typical values for the $\alpha$-Al matrix ($v=0.33$, $d_n=0.6$, matrix $\sigma_{ys}$ varying from 140 to 340 MPa due to cyclic racheting) and experimental long crack growth data, a comparison between the predictions of the new model and experimental microstructurally small FCG data was made and is presented in Figure 5(a) with very good agreement.

$$\left(\frac{da}{dN}\right)_{MSC} = A \left(\frac{da}{dN}\right)_{PSC}$$

(6)

$$A = \left[ \frac{n_s}{n} \left( \frac{1-n_s^2}{1-n_s^z} \right) \right]^{1/2}$$

(7)

It is necessary to also consider the statistical nature of microstructurally small FCG behavior. In cases where multiple coupled degrees of freedom exist, it is useful to employ a Monte Carlo method in order to make statistical predictions for the component lifetime. To accomplish this, the grain size of the A535 alloy is represented by a normal distribution (mean value = 418 $\mu$m and standard deviation = 87 $\mu$m) and pseudo-random grain samples are extracted using the Ziggurat algorithm. Equations (4)-(7) are then applied to the grain sample to predict a FCG curve. Finally, statistical component lifetime and S-N curves can be predicted as a function of applied stress using the predicted FCG curves and a weight function to relate stress intensity and crack length, Figure 5(b).

3.4.3. Dual-parameter load-microstructure-damage design maps and applications

Upon the understanding of the FCG mechanisms at the microstructural scale the alloys, dual-parameter load-microstructure-damage design maps have been built to uniquely provide connecting pathways between experimental FCG data, microstructures, and design parameters by enabling predictions of crack growth response under any $\Delta K - K_{max}$ loading combination for any positive stress ratio. Maps are generated by correlating FCG data at various stress ratios (R=0.1, 0.5, 0.7) with the transitions in mechanisms observed in the fractography work, and plotting the resulting domains. Characteristic design maps for A535-F and A356-T6 alloys are shown in Figure 6. These are valuable tools for evaluating and monitoring component behavior under actual application conditions, judicious scheduling of component inspections, and selecting, developing, and optimizing cast aluminum alloys for FCG resistance (or adjusting the loading conditions to meet material’s capabilities when possible). These combined materials-design tools will lead to “cross-pollination” in materials use, increased design confidence and accuracy, and beneficial weight, safety factor, and cost reductions in structural components.
4. Development of a microstructure-specific computational model

Experimental results in the previous sections have indicated the significant effects microstructural features (grain structures, secondary particles morphology/distribution, etc.) have on the FCG behavior of a material/component. It is therefore necessary to develop computational design tools that consider the effects of a material’s characteristic microstructure on the FCG response. First, a technique for measuring $D$-Al matrix/eutectic Si particle interface toughness, as well as Si particle fracture toughness will be introduced. Then, a computational toolset will be discussed, along with examples of its application to design for FCG resistance.

4.1. A novel indentation technique for measuring intrinsic properties of microstructural phases

A novel method for determining $\alpha$-Al matrix/eutectic Si particle interfacial energy, independent of particle morphology, was developed using indentation techniques (microhardness testing). He and Hutchinson [14,15] formulated an analytical solution, Equation (8), describing crack deflection along an interface relating the competing energy release rates of the interface and the matrix material.

$$G_d = \frac{1}{1-\alpha} \left| \frac{d}{|c|} \right|^2$$

$G_d$ is the energy release rate of the interface, $G_p^{\text{max}}$ is the critical energy release rate of the matrix, $\alpha$ is Dundur’s first parameter, and $d$ and $c$ are complex valued functions of the cracked geometry. $G_p^{\text{max}}$ is calculated from a FCG test on an Al-1%C alloy (representing the $\alpha$-Al matrix), and the interface toughness was calculated to be 8.4 kJ/m$^2$.

Eutectic Si particle fracture toughness was also calculated using microhardness indentation. Following a procedure described by Moradkhani et al. [16], a relationship between the extent of microcracking at the indent and the critical stress intensity was developed, Equation (9).

$$K_{IC} = \zeta \left( \frac{E}{HV} \right)^\frac{1}{2} t^\frac{1}{2} p^\frac{1}{2} A^\frac{1}{2}$$

$K_{IC}$ is the fracture toughness of the particle, $\zeta$ is a constant (0.016±0.004), $E$ is the elastic modulus of the particle, $HV$ is the Vickers hardness of the particle, $P$ is the applied load, and $t$ and $A$ are the thickness and area of microcracks.
around the indent. A rank-ordered cumulative distribution estimate on 50 measurements was conducted, and the results were found to agree well with the Fréchet extreme value distribution with parameters $\alpha=3.13$ (shape) and $s=0.547$ (scale), and an average Si particle fracture toughness value of 1.21 MPa$\sqrt{m}$.

4.2. Microstructure-specific long fatigue crack growth ICME modeling

An elastic finite-element model has been developed in MATLAB using the level set method [17] to track the crack tip position and discontinuities in nodal displacement. Real microstructures are created by sampling micrographs of the material and converting them into binary domains. The crack propagation through the $\alpha$-Al matrix was modeled using experimental FCG data for an Al-1\%Si-0.35\%Mg alloy in T6 condition (representing also the behavior of the $\alpha$-Al matrix in the A356-T6 alloys), a J-integral to evaluate the local stress intensity (magnitude of growth), and a maximum circumferential stress criterion (direction of growth). Si particles, due to their brittle fracture behavior and low critical stress intensity, are assumed to break at a critical principal stress along the plane normal to this stress. The “in-situ composite” material (A356-T6) is modeled by superimposing the behavior of eutectic Si particles and the $\alpha$-Al matrix (represented by Al-1\%Si-0.35\%Mg in T6 condition).

Quasi-static simulations are conducted in K-constant FCG tests, and for each simulation, the growth rate is averaged across the entire image so that a significant area of the microstructure is sampled and all averages are used to create every data point in Figure 7(a). Very good agreement is observed in Region III, and conservative results were obtained in Region II. It is noted that the numerical predictions in Region II agree well with the closure-corrected physically small crack growth data. These differences occur because the computational model uses long FCG data and does not incorporate closure effects, which play a significant role in Region I and lower Region II, but not in upper Region II and Region III. Additionally, in Figures 7(b) and 7(c), crack interactions with eutectic Si particles are shown at two stress intensities (middle Region II and Region III). In both instances, the same Si particle is fractured, but it can be seen that at higher stress intensity, the crack is able to deflect more and interact with a thinner (easier to break) section of the particle. This difference illustrates the mechanisms of crack propagation at different stress intensities: at low driving force the crack interacts with particles that lie directly in front of it, whereas at high stress intensity it can deflect to preferentially interact with weakened sections/particles.

5. Conclusions

In this work an integrated design philosophy has been presented, incorporating three key areas of research: experimental characterization, analytical and computational modeling, and the development of novel and more accurate tools for material/component design for FCG resistance. Experimental studies revealed the fundamental
microstructural mechanisms of long and small crack growth in cast A535-F and A356-T6 alloys. For both alloys it is found that, for small cracks, a finer grain size improves the FCG lifetime. In contrast, for long cracks and when closure phenomena are operative, a coarse grain structure improves FCG behavior. Several other microstructural characteristics of A356-T6 were examined, and microstructural mechanisms of crack growth were rationalized and understood in terms of the morphology and spatial distribution of the eutectic Si phase.

Analytical and computational studies were carried out based on observations from the experimental work in order to construct predictive design tools. An analytical model was created to predict small crack growth behavior from experimental long FCG data, and enables statistically-based estimations of component lifetime. Additionally, a computational model incorporating crack-secondary phase interactions has been developed based on sampling of actual microstructural images and a novel technique for measuring particle toughness. In parallel with these tools, dual-parameter load-microstructure-damage design maps were developed to provide domains of microstructural mechanisms of crack propagation that can be readily used for materials/component design for FCG resistance.

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