Research Programs

Fatigue Crack Growth Mechanisms in Al-Si-Mg Alloys

Research Team:

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Introduction

Due to the increasing use of cast aluminum components in automotive, aerospace, marine, and defense applications that involve cyclic loading, the fatigue and fatigue crack growth characteristics of aluminum castings have become of great interest. However, and despite the extensive research efforts dedicated to this topic, a fundamental and mechanistic understanding of the behavior of these alloys when subjected to dynamic, cyclic loading was still lacking and this became the focal point of this research.

Objectives

Several objectives were defined for this project and all of them have been achieved (see the "Salient Results and Related Publications" sections for details):

- Develop a fundamental understanding of the effects of microstructural constituents on fatigue crack growth behavior of Al-Si-Mg cast alloys considering the roles of α-Al dendritic structure, Al-Si eutectic phases, and Mg-Si precipitates.
- Determine the effect of heat treatment of fatigue crack growth.
- Predict fatigue crack growth behavior of Al-Si-Mg alloys in the near-threshold regime of crack growth (Region I, ΔKth) for both naturally initiated cracks (small cracks) and long cracks (non-conservative but commonly used in design)
- Establish near-threshold microstructural growth mechanisms for both small and long cracks.
- Assess the role of closure (interference at the tip of a growing crack) and the effectiveness of closure corrective techniques for design.
- Establish the crack growth mechanisms in Regions II and II of crack growth.
- Evaluate the fracture toughness behavior of Al-Si-Mg alloys.
- Perform a parallel analysis of the Linear Elastic Fracture Mechanics (LEFM) Elastic-Plastic Fracture Mechanics (EPFM/J-integral) methodologies to evaluate their applicability to light metal (more ductile) alloys especially in Region III and re-evaluate fracture toughness determination from fatigue crack growth data.
- Understand the effect of residual stress on fatigue crack growth and develop mathematical, experimental, and processing methodologies to decouple it from the total fatigue crack growth response.
- Design Al-Si-Mg alloys with enhanced fatigue properties.
- Optimize the alloy's microstructure (composition & processing) for improved fatigue resistance in different applications

Methodology

The objectives were achieved through a judicious selection of the experimental matrix including all critical material and processing (casting and heat treating) parameters, performing representative fatigue crack growth testing, and conducting an advanced and thorough analysis and interpretation of the results.

Five Al-Si-Mg alloys with fixed Mg contsnt (0.45%) and three Si levels 1, 7, and 13% were investigated. Si levels were selected such that each microstructural constituent specific to this class of alloys was individually represented, i.e. the primary α-Al dendritic structure in the 1%Si alloy; the Al/Si eutectic structure in the 13%Si alloys; and a hypoeutectic, hybrid structure in which the two phases coexist in the 7%Si alloys (alloys resembling the microstructure of commercial A356/357 alloys). The eutectic Si in the 7% and 13%Si alloys was studied in both unmodified (UM) and Sr-modified (M) conditions. A secondary dendrite arm spacing of 20-30 μm was consistently attained in all studied alloys. All alloys were grain refined to achieve the same grain size irrespective of alloy (three grain size levels were studied, but the majority of the studies were conducted on samples with a grain size in the 280-320 μm range).

Two peak-strength T61 heat treatments were applied to all samples: one using a room-temperature water quench (conventional quench) and the other using an uphill/reverse quench. The later treatment was designed to minimize residual stress. Despite the significant difference in residual stress, both procedures provided similar tensile properties and microhardness of the α-Al matrix for all alloys. To produce samples with increased ductility, a T4 heat treatment was also applied to the 7%Si alloys.

The microstructures of all alloys after heat treatment are presented in Figure 1. Porosity level was less than 0.005% in all alloys, so porosity effects on the crack growth were not significant.

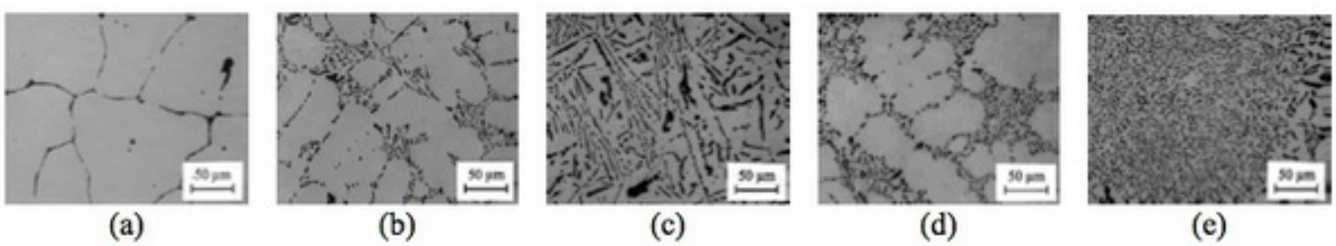


Figure 1. Alloy microstructures after heat treatment (etched with 1%HF for 10-15 seconds): (a) 1%Si; (b) 7%Si-UM; (c) 13%Si-UM; (d) 7%Si-M; (e) 13%Si-M.

The long fatigue crack growth testing was performed on compact tension, C(T), specimens and the small fatigue crack growth work was done on single corner notched rectangular specimens with a starting triangular corner flaw. All specimens were tested under K-control per ASTM E647 at R=0.1, in laboratory air at room temperature 24°C and relative humidity 40-50%. Threshold data were generated under decreasing K, while Regions II and III data under increasing K. Above 10^{-3} mm/cycle, the test was continued using a shallower K-gradient to obtain the steeper Region III data.

Salient Results and Related Publications:

The results of this study are presented below, grouped by topic, and the publications related to each topic are provided as further references for the readers.

A. Solution Treatment, Aging, & Uphill Quenching

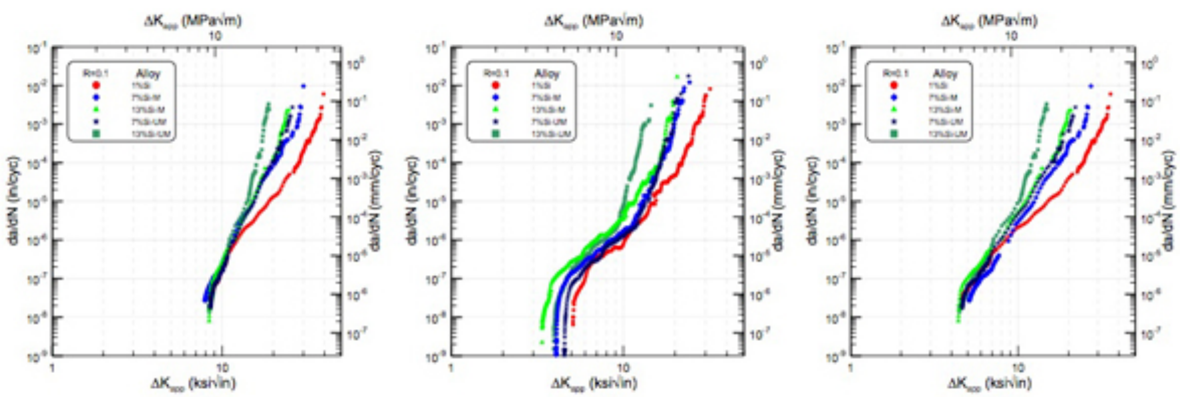
A laborious background work was performed for this study in order to detemine the appropriate casting and heat treating conditions for the five studied alloys. Based on these investigations, the solution treatment conditions able to preserve the morphological characteristics of the eutectic structures (avoid thermal modification of the unmodified eutectic Si structure) and the aging conditions able to provide consistent microhardness of the α-Al structure in all alloys were selected for the fatigue studies. Additional studies were performed to understand the mechanisms and optimize the parameters related to uphill quenching, an efficient methodology which can be used to produce residual stress free samples. Details on the mechanisms of solutionizing, aging, and uphill quenching along with their relation to Si content and their effects on mechanical properties can be found in the following three publications, References [1,2,3]:

References Section A

1. D.A. Lados, D. Apelian, and L. Wang "The Effects of Solution Treatment and Silicon Content on the Microstructure and Mechanical Properties of Cast Al-Si-Mg Alloys", submitted to ***The International Journal of Cast Metals Research***, 2006.
2. D.A. Lados, D. Apelian, and L. Wang "The Effects of Aging and Silicon Content on the Heat Treatment Response of Cast Al-Si-Mg Alloys", submitted to ***The International Journal of Cast Metals Research***, 2006.
3. D.A. Lados, D. Apelian, and L. Wang "Minimization of Residual Stress in Heat Treated Cast Al-Si-Mg Alloys Using Uphill Quenching: *Mechanisms and Effects on Static and Dynamic Properties*", submitted to the ***Journal of Materials Science***, 2006.

B. Residual Stress Effects on Fatigue Crack Growth - Mechanisms and Corrective Methods

It was found that residual stress has a crucial effect of the fatigue crack growth behavior of Al-Si-Mg alloys and significant design errors could occur if not understood and/or appropriately compensated for. Conventionally quenched samples showed unreasonably high fatigue crack growth thresholds for this type of cast aluminum alloys, in the 9-10 MPa√m (8-9 ksi√in) range, Figure 2(a), while the uphill quenched samples had thresholds in 3.5-5.5 MPa√m (3-5 ksi√in) range, Figure 2(b), a 100% difference entirely due to the presence of residual stress (all other parameters being kept constant). Besides the shift in threshold (all alloys had high thresholds due to high residual stress induced closure), residual stress also masked the effects of microstructure on thresholds (all alloys resulted in similar thresholds in high residual stress conditions). However, when residual stress was reduced, the microstructure/roughness of the alloys became operative and a threshold ranking of the alloys was observed. Details on the fatigue crack growth mechanisms in the presence and absence of residual stress as well as mathematical and experimental methodologies to correct for residual stress can be found in Reference [4]. Figure 2 shows the fatigue crack growth behavior of the five studied alloys in high residual stress conditions (Figure 2(a)), low residual stress conditions (Figure 2(b)), and high residual stress conditions after residual stress correction using a method developed by Lados and Apelian and named "the restoring force model" (Figure 2(c)).



(a) (b) (c)

Figure 2. Fatigue crack growth behavior of the five studied alloys in high residual stress conditions (a), low residual stress conditions (b), and high residual stress conditions after residual stress correction (c).

As far as residual stress measurement, two new and original X-ray diffraction techniques for measuring residual stress accounting for microstructural characteristics of cast Al alloys have been developed and details can be found in Reference [5].

References Section B

4. D.A. Lados and D. Apelian, "The Effect of Residual Stress on the Fatigue Crack Growth Behavior of Al-Si-Mg Cast Alloys: *Mechanisms and Corrective Mathematical Models*", **Metallurgical and Materials Transactions A**, vol. 37A, issue 1, pp. 133-145, 2006.
5. D.A. Lados, J.P. Nicolich, K. Macchiarola "Surface residual stress in automotive components: measurement and effects on fatigue life", SAE publications, Technical Paper # 2006-01-0323, 2006 (paper selected to be published in the **SAE Transactions 2006**).

C. Fatigue Crack Growth Mechanisms at the Microstructure Scale in Al-Si-Mg Cast Alloys

C.1. Microstructural crack growth mechanisms of small and long cracks in the near-threshold regime

The near-threshold long crack growth behavior of Al-Si-Mg alloys was dominated by closure mechanisms. The two main sources of closure were macro residual stress (introduced during quenching) and microstructurally induced fracture surface roughness. In the presence of high residual stress, the microstructure-induced closure played a secondary role, its effect being masked by residual stress, which controled the closure mechanisms. At low residual stress levels, the effect of microstructure became evident and the thresholds, ΔK_{th}, were found inversely proportional to the vol% eutectic Si, Figure 3(a). The higher the Si content/aspect-ratio the lower the roughness induced closure level, and the lower the threshold. These differences were attributed to the crack deflection pattern upon interaction with either grain boundaries (1%Si) or Si particles (7 and 13%Si), Figure 4. As a general trend, higher thresholds and lower near-threshold growth rates were achieved for coarser microstructures, which resulted in rougher fracture surfaces, and higher closure. In this context, larger SDAS, coarser Si particles, and non-homogeneous Si distribution had a better low long-crack ΔK performance. In the 7%Si alloys, no dependence of the threshold on grain size and matrix strength was observed.

Small crack behavior and the transition between different types of small cracks (mechanically-to-microstructurally-to-physically small) were strongly dependent on the alloy and a unique parameter defined as "microstructural characteristic dimension" (MCD). The oscillating crack growth behavior of microstructurally small cracks, Figure 3(b), represented a result of the "barrier role" played by the controlling microstructural characteristics of the alloys (grain boundaries in 1%Si and Si particles in 7 and 13%Si). The threshold ranking of the microstructurally small craks for 1%, 7%, and 13%Si alloys is thus expected to be the opposite of the long crack growth thresholds. The physically small cracks had less microstructural influence and behaved similar to the long crack except for the absence of closure. Closure corrective methods could only be used to derive the physically small crack growth behavior from long crack growth without the ability to capture microstructure effects. More details can be found in References [6,7].

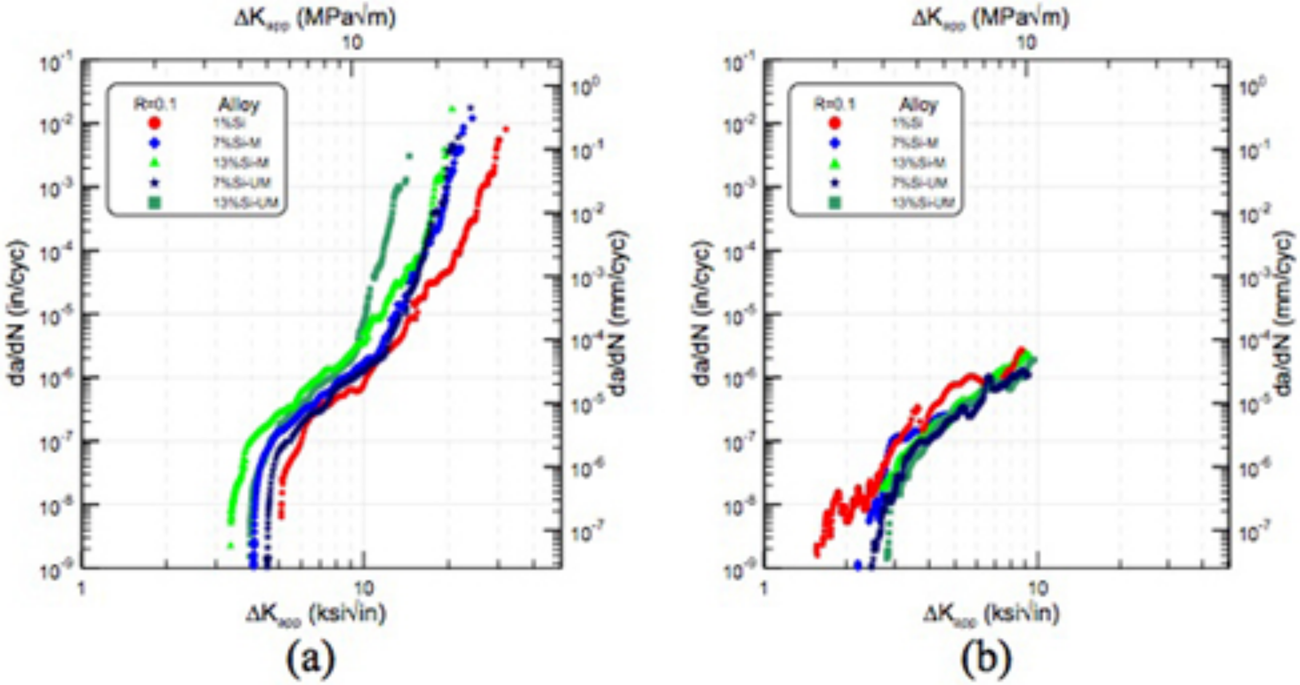


Figure 3. Fatigue crack growth data for 1, 7, and 13%Si cast Al-Si-Mg alloys with low residual stress: (a) long crack growth data and (b) small crack growth data.

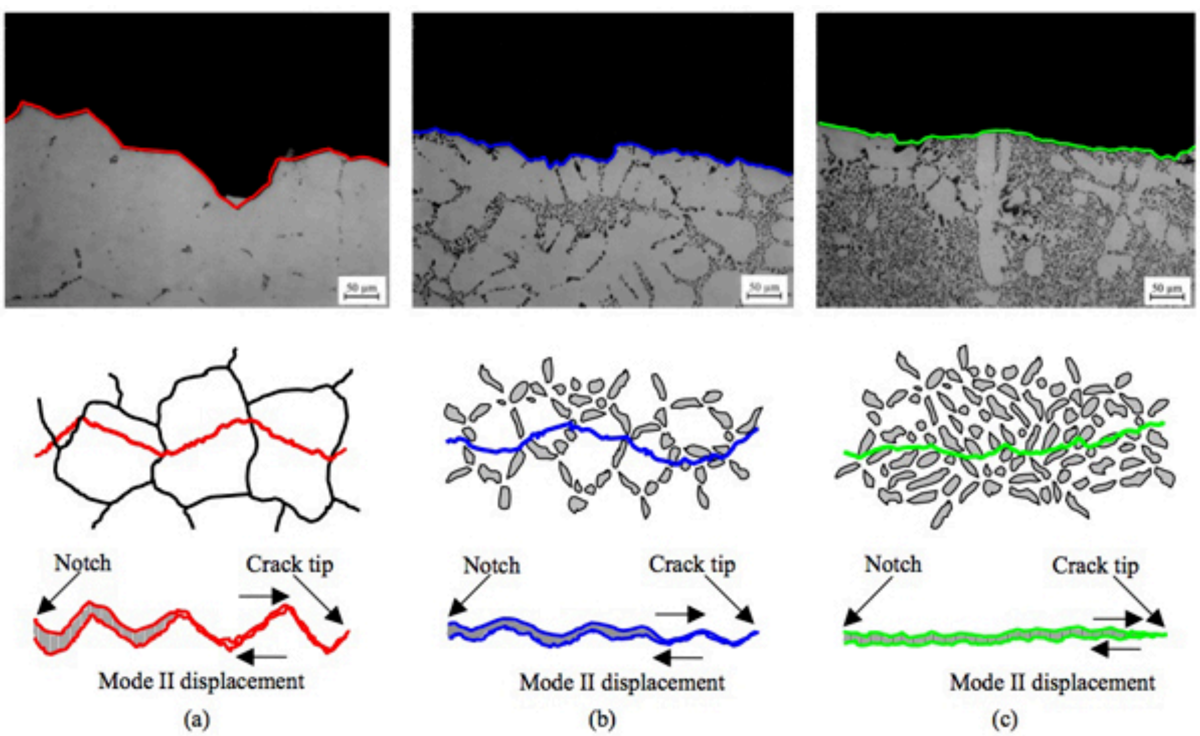


Figure 4. Crack path deflection patterns for three Al-Si-Mg alloys: (a) 1%Si; (b) 7%Si; (c) 13%Si (fractographic observations - top and crack path models - bottom); mode II displacement is also contributing to closure.

C.2. Microstructural crack growth mechanisms in Regions II and III

As closure effects became less significant, fatigue crack growth mechanisms became strongly dependent on the matrix strength, the interface strength between primary α-Al structure and eutectic Si particles, and the effective Si particles strength. With increasing ΔK from lower Region II to upper Region II and Region III, the fracture surface roughness increased. This increase was associated with a change in fatigue crack growth mechanisms. While a flat surface corresponds to a crack propagating along the Al dendritic structure, Figure 5(a), a rough surface is a reflection of a preferential growth through the Al-Si eutectic regions, Figure 5(b). These changes in mechanisms were explained using correlations of the plastic zone size at various ΔK levels with the microstructural features enveloped by it. Small plastic zones restricted the availability of damaged Si particles (or interfaces with the Al matrix) and therefore restrained the possibility of crack meandering. This was reflected in a flat appearance of the crack with sporadic Si encounters. At high ΔK, however, the larger plastic zone size permitted crack meandering through damaged Si particles away from the crack front, and this explained the preferential growth through the eutectic regions, Figure 6(a). The damage of the eutectic structure with increasing ΔK is shown in Figures 6(b) and 6(c).

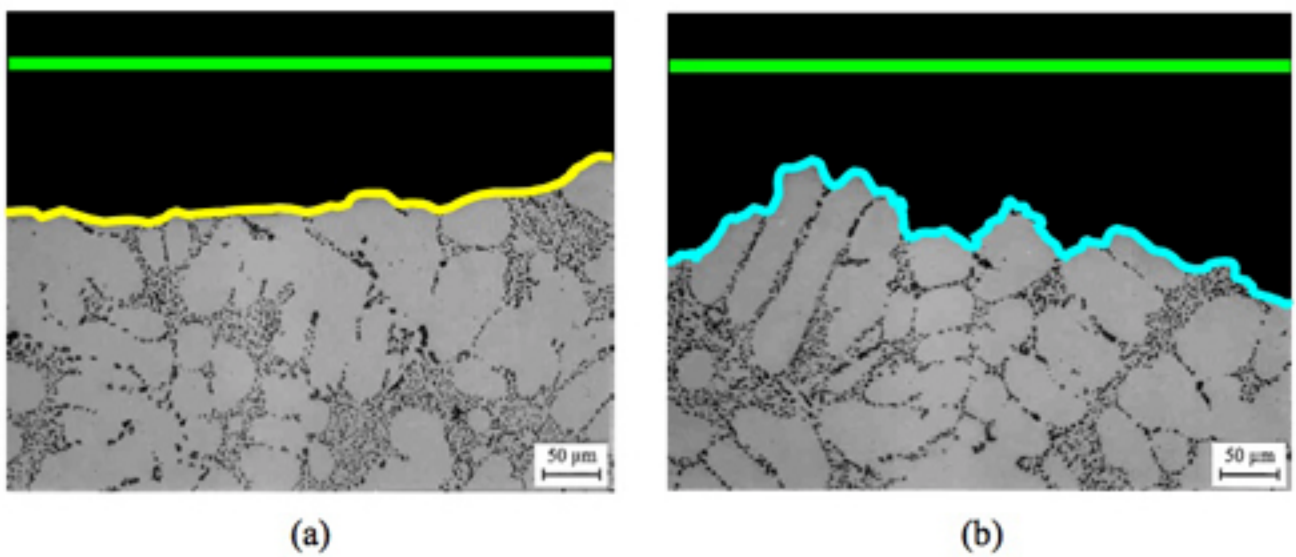


Figure 5. Changes in fracture surface roughness with increasing crack driving force for a Sr-modified 7%Si alloy: (a) lower Region II (ΔK~5.5 MPa√m) and (b) lower Region III (ΔK~12 MPa√m).

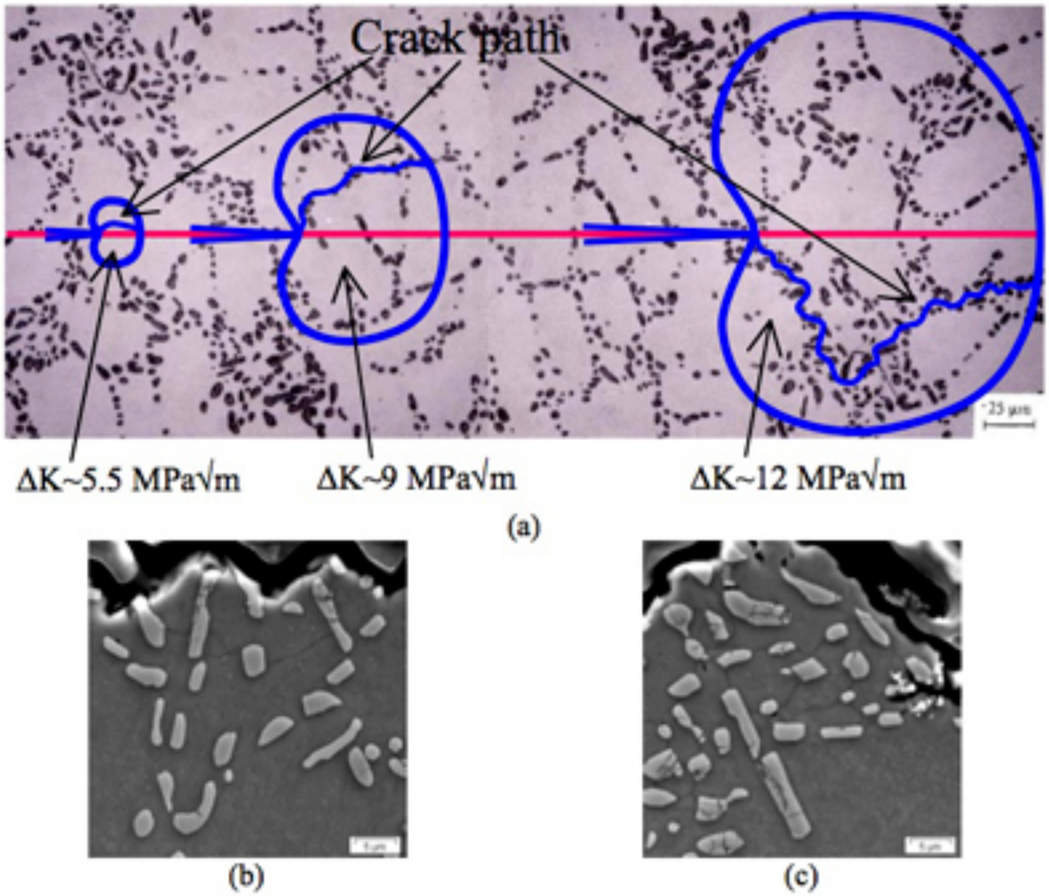


Figure 6. (a) Plastic zone size representation at the microstructural scale of a 7%Si alloy for different ΔK levels; enlargements of the damaged regions in the plastic zones at (b) ΔK~9 MPa√m and (c) ΔK~12 MPa√m.

In Region III, the crack advanced preferentially through the Al-Si eutectic regions, and very high crack growth rates in upper Region III were governed by ductile monotonic tearing. The alloys' behavior in this region correlated well with Si morphology, and a fracture toughness ranking based on Si morphology was observed. Modified and low Si content alloys showed higher fracture toughness.

Differences between the behavior of T4 and T61 samples were observed away from the closure affected regions. While T61 shows a better fatigue crack growth resistance in upper Region II, T4 leads to higher toughness. The behavior of the T4 samples in Region II is explained by considering alternative paths of low resistance available. In Region III, the increased plasticity levels at the crack tip resulted in more blunted cracks, increasing the crack growth resistance and fracture toughness.

In the grain size range investigated, grain size played a minimal role in the fatigue crack growth response of the studied alloys, due to the fact that fatigue crack growth advance was controlled by microstructural features smaller than the grain size (Si particles, SDAS). In the alloys with no eutectic Si (1%Si), grain size showed an effect similar to the one observed in wrought alloys.

Details on the mechanisms at the microstructure scale of Al-Si-Mg alloys in Regions II and III and can be found in Reference [7,8].

References Section C

6. D.A. Lados, D. Apelian, and J.K. Donald "Fatigue Crack Growth Mechanisms at the Microstructure Scale in Al-Si-Mg Cast Alloys: *Mechanisms in the Near-threshold Regime*", ***Acta Materialia***, vol. 54, issue 6, pp. 1475-1486, 2006.
7. D.A. Lados, D. Apelian, P.E. Jones, and J.F. Major "Microstructural Mechanisms Controlling Fatigue Crack Growth in Al-Si-Mg Cast Alloys", Paper at the 135th TMS Annual Meeting & Exhibition - Symposium in Honor of Art McEvily's 80th Birthday, San Antonio, TX, March 2006, ***Materials Science and Engineering A*** (in press).
8. D.A. Lados, D. Apelian, and J.F. Major "Fatigue Crack Growth Mechanisms at the Microstructure Scale in Al-Si-Mg Cast Alloys: *Mechanisms in Regions II and III*", ***Metallurgical and Materials Transactions A***, vol. 37A, issue 8, pp. 2405-2418, 2006.

D. Closure Mechanisms in Al-Si-Mg Alloys and Closure Correction Techniques

Crack growth behavior of small and long cracks was a subject of much research; the differences observed in the growth response were largely attributed to crack closure (or premature contact of the crack faces during the unloading part of the loading cycle). Most design problems based on linear elastic fracture mechanics (LEFM) use parameters determined from the propagation of "long cracks". However, it has been recognized that cracks, especially in early stages, are characterized by a "small crack" behavior and the advance of small cracks is not accurately described by long crack data. The use of long crack data can lead to significantly non-conservative estimates of the fatigue response and serious design errors. This is especially true for high cycle fatigue applications when most of the life of a component is spent in the realm of small crack behavior. Therefore, understanding closure and developing appropriate closure corrective techniques are critical for accurate design. A methodology introduced by Donald et al. based on the adjusted compliance ratio (ACR) was successfully applied to correct long crack growth data for Al-Si-Mg alloys with various levels of microstructure/roughness induced and residual stress induced closure, Figure 7. However, even though the adjusted compliance ratio (ACR) method was experimentally proven as an appropriate tool for closure correction, its applicability and general acceptance was limited due to the absence of a fundamental physical explanation of its intrinsic concepts. Therefore, a derivation of the ACR method using fundamental fracture mechanics principles was developed by Lados and Apelian, and more details can be found in Reference [10].

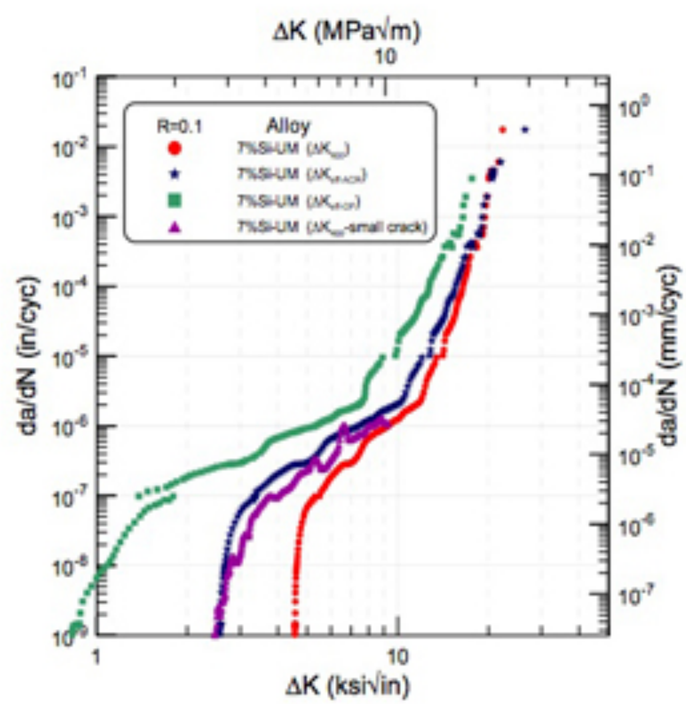


Figure 7. Comparison of long crack data, small crack data, and closure corrected data for an unmodified Al-Si-Mg cast alloy with 7%Si.

References Section D

9. D.A. Lados, D. Apelian, P.C. Paris, and J.K. Donald, "Closure Mechanisms in Cast Al-Si-Mg Alloys and Long-Crack to Small-Crack Corrections", ***International Journal of Fatigue***, vol. 27, issues 10-12, pp. 1463-1472, 2005.
10. D.A. Lados, D. Apelian, and J.K. Donald, "Fracture Mechanics Analysis for Residual Stress and Crack Closure Corrections", ***International Journal of Fatigue***, 2006 (*in press*).

E. Limitations of Elastic Definitions in Al-Si-Mg Alloys with Increased Plasticity

Linear elastic fracture mechanics describes the fracture behavior of materials and components that respond elastically under loading. This approach is valuable and accurate for the continuum analysis of crack growth in brittle and high strength materials; however it introduces increasing inaccuracies for low strength/high ductility alloys (particularly low-carbon steels and light metal alloys). In the case of ductile alloys, different degrees of plastic deformation precede and accompany crack initiation and propagation, and a non-linear ductile fracture mechanics approach better characterizes the fatigue and fracture behavior under elastic-plastic conditions.

To delineate plasticity effects in upper Region II and Region III of crack growth an analysis comparing linear elastic stress intensity factor ranges (ΔK_{el}) with crack tip plasticity adjusted linear elastic stress intensity factor ranges (ΔK_{pl}) was developed. To compute plasticity corrected stress intensity factor ranges (ΔK_{pl}), a new relationship for plastic zone size determination was developed taking into account effects of both plane strain and plane stress conditions ("combo plastic zone"). In addition, for the upper part of the fatigue crack growth curve, elastic-plastic (cyclic J based) stress intensity factor ranges (ΔK_J) were computed from load-displacement records and compared to plasticity corrected stress intensity factor ranges (ΔK_{pl}). A new cyclic J analysis was designed to compute elastic-plastic stress intensity factor ranges (ΔK_J) by determining cumulative plastic damage from load-displacement records captured in load-control (K-control) fatigue crack growth tests. The cyclic J analysis provided the true fatigue crack growth behavior of the material. A methodology to evaluate the lower and upper bound fracture toughness of the material (J_{IC} and J_{max} from $\Delta K_{FT(JIC)}$ and $\Delta K_{FT(Jmax)}$) directly from fatigue crack growth test data was developed and validated using static fracture toughness test results. A procedure to decouple and partition plasticity and tearing effects on crack growth rates was also developed. These findings are schematically presented in Figure 8 and further details can be found in Reference [11].

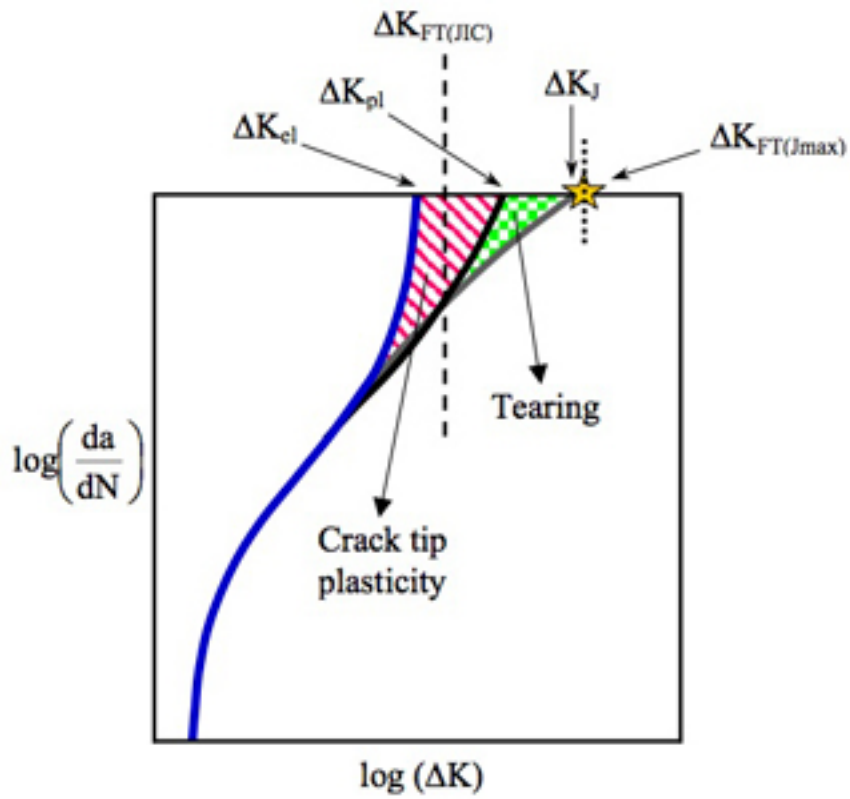


Figure 8. Enlargement of upper Region II and Region III showing the effects of plasticity and tearing and their respective interactions.

References Section E

11. D.A. Lados and D. Apelian, "Limitations of Elastic Definitions in Al-Si-Mg Cast Alloys with Enhanced Plasticity: *Linear Elastic Fracture Mechanics versus Elastic-Plastic Fracture Mechanics*", ***Engineering Fracture Mechanics***, vol. 73, issue 4, pp. 435-455, 2006.

F. Design and Life Predictions Using Fatigue Crack Growth Data - AFGROW Simulations

Reference [12] brings to attention a practical perspective to engineering analysis and design through a simple and effective method of utilizing fatigue crack growth data. Using AFGROW software an engineering problem can be approached in two ways. First, the software can be used (and it was used in Reference [12]) to rank and select an alloy for a given application based on experimental fatigue crack growth data on various existent materials. Second, the software can be used as an alloy/microstructure/heat treatment optimization tool for future alloy development and applications using fatigue crack growth resistance as an alloy design goal. In this case the desired operating conditions and the expected life are imposed, and the alloy, microstructure, and crack growth characteristics required to meet them are determined. The methodology Reference [12] can be tailored for both direct and reverse engineering problems for any material, process, and application (note that a condensed presentation of the effects of processing conditions and microstructure on the fatigue crack growth behavior of the studied Al-Si-Mg cast alloys can be found in Reference [13]). Other design applications and life predictions using AFGROW software for cases with and without residual stress can also be found in Reference [5].

References Section F

12. D.A. Lados and D. Apelian, "Fatigue Crack Growth Characteristics in Cast Al-Si-Mg Alloys - *Part II: Life Predictions Using Fatigue Crack Growth Data*", ***Materials Science and Engineering A***, A385, pp. 187-199, 2004.
13. D.A. Lados and D. Apelian, "Fatigue Crack Growth Characteristics in Cast Al-Si-Mg Alloys - Part I: Effect of Processing Conditions and Microstructure", ***Materials Science and Engineering A***, A385, pp. 200-211, 2004.