MODELING SMALL FATIGUE CRACK GROWTH IN CAST ALUMINUM ALLOYS

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ABSTRACT

The fatigue life of cast aluminum automotive engine components is, in some cases, controlled by the growth of small crack from pores rather than fatigue crack initiation. A method has been devised to efficiently measure the growth rates of small cracks initiating from micronotches produced by femtosecond pulsed laser machining. Two cast aluminum alloys, W319 with an overaged (T6) heat treatment and A356 with a peak aged (T6) heat treatment, were examined. The use of femtosecond pulsed lasers results in essentially no damage to the microstructure surrounding the notch. Both ultrasonic (20 kHz) and conventional (30 Hz) loading frequencies were applied to study the growth rate of small cracks at different nominal stress levels in the temperature range 20-250^{o}C. Increasing either the temperature or maximum stress led to increased growth rates at equivalent stress intensity factor ranges. The growth rates at 20 kHz was, however, found to be lower than the growth rates at 30 Hz. The growth rate variations with temperature, applied stress, frequency and heat-treatment can be modeled with a large-scale crack-tip plasticity based growth parameter.

1 INTRODUCTION

Increasing environmental concerns and the need for improved fuel efficiency continues to drive efforts to reduce vehicle weight. Weight reduction in power trains has been achieved, in part, by replacing cast iron with cast aluminum for engine blocks and cylinder heads. The demand for higher efficiency engines, however, has pushed the operating temperature envelopes for these engine components from 170 ^{o}C in earlier engines to well over 200 ^{o}C in recent engines (Smith *et al.* [1]). The increase in the maximum operating temperature requires a comprehensive evaluation of elevated temperature tensile, creep and fatigue properties of cast aluminum (Engler-Pinto Jr. *et al.* [2]).

It has been shown by Caton*et al.* [3] that the useful fatigue life of cast aluminum alloys can be predicted by utilizing the small fatigue crack growth behavior of cracks initiating from pre-existing porosity. The stress concentration resulting from the pores is high enough to make the crack initiation life a negligible fraction of the total life. While there have been a number of studies on the room temperature, small fatigue crack growth behavior of cast aluminum (for example, Ting and Lawrence Jr. [4]; Caton *et al.* [5]), the elevated temperature small fatigue crack growth behavior of these alloys has not been examined. While ambient temperature growth rate of small cracks can be examined by standard acetate replication techniques, this procedure is especially problematic for the study of small cracks at elevated temperature because of the requirement to cool the specimen to ambient temperatures before each replication. It has been shown by Joyce *et al.* [6] that the thermal cycling associated with the replication procedure severely reduces the fatigue lifetime for a near eutectic cast Al-Si alloy.

It is well known that the similitude assumption of linear elastic fracture mechanics (LEFM) is not valid for small fatigue cracks (Suresh and Ritchie [7]). This implies that the stress intensity parameter defined by LEFM cannot uniquely represent the stress and deformation field around the tip of a small crack. Edwards and Zhang [8] showed in two 7000 series aluminum alloys that this limitation can be avoided by correlating the measured plastic zone sizes for small cracks with the growth rates of small cracks. Shyam *et al.* [9] have recently shown that a crack tip plasticity based parameter can explain the variation in growth rates with temperature for the cast aluminum alloy W319. In this paper, we examine the small fatigue crack growth behavior of two cast aluminum alloys: W319 and A356. We also examine the potential for using ultrasonic fatigue to rapidly characterize the initiation and growth behavior of small crack from carefully prepared microdefects. The results indicate that a mechanism based small crack growth law can be formulated for life prediction across the operating temperature and stress range of cast engine components.

2 MATERIALS AND EXPERIMENTAL PROCEDURE

2.1 Materials

The material for this small fatigue crack investigation was produced using a wedge-shape casting, the details of which are described elsewhere (Caton *et al.* [5]). Two Al-Si-Cu alloys were investigated, W319 and A356, with the Si and Cu content being slightly higher for W319. Rectangular bars were cut from a region of the casting with an intermediate secondary dendrite arm spacing (SDAS). The average SDAS value for the W319 and A356 material was 70 and 60 μm, respectively. In order to localize crack initiation from micronotches, the rectangular bars were HIP'ed, thereby reducing the porosity to insignificant levels. The A356 alloy was given a T6 heat treatment consisting of a solution treatment at 540°C for 3 hours, followed by water quenching and then ageing at 190°C for 3 hours. The T6 heat treatment enhances the monotonic tensile yield properties and low to intermediate temperature fatigue properties (Engler-Pinto Jr. *et al.* [2]). The W319 alloy was given a T7 heat treatment consisting of a solution treatment at 495°C for 8 hours, followed by water quenching and then ageing at 260°C for 4 hours. The T7 heat treatment leads to a decrease in tensile yield strength but provides microstructural stability at higher operating temperatures (Engler-Pinto Jr. *et al.* [2]). The average monotonic tensile properties for all the temperatures of this small crack growth investigation for both the alloys are given in Table 1 (Boileau *et al.* [10]).

Table 1: Monotonic tensile properties of the two HIP'ed alloys A356 and W319 [10]

Alloy	Heat Treatment	SDAS (μm)	Temperature (°C)	0.2% σ_{ys} (MPa)	σ_{UTS} (MPa)	Elongation (%)
A356	T6	60	20	231	274	4.3
W319	T7	70	20	167	232	2.1
W319	T7	70	150	160	194	3.6
W319	T7	70	250	120	128	7.2

2.2 Experimental Procedure

Specimens for both ultrasonic and servohydraulic (conventional) small fatigue crack testing were machined from the heat treated rectangular bars. The diameter of the gage section was 5.1 mm for both kinds of specimens. Two additional 28 mm (for conventional fatigue specimens) and 50 mm (for ultrasonic fatigue specimens) were machined on the gage section of the specimens. The flats were machined to provide a plane of constant focus for laser machining and optical imaging of cracks. The larger radius of the flats for ultrasonic fatigue specimens was to accommodate the condition of mechanical resonance on the specimens. Details of the specimen geometry for conventional specimens (Shyam *et al.* [9]) and the methodology for ultrasonic specimen design (Mayer [11], Shyam *et al.* [12]) are available elsewhere. A Ti:sapphire femtosecond pulsed laser system was used to fabricate micronotches at the center of the fatigue specimens. Femtosecond lasers cause minimal damage to the surrounding microstructure. The machining procedure is described in Ref. [9].

All tests were conducted at a load ratio of -1.Servohydraulic tests were performed in load-control at a frequency of 30 Hz at temperatures of 20, 150 and 250°C for W319 and at 20°C for A356. The specimens were heated in a resistance furnace and the specimen temperature was controlled to within ± 2°C. Ultrasonic tests were conducted at a frequency of 20 kHz and at 20°C for A356. Gage-section stress for the ultrasonic specimens was calibrated and monitored by two strain gages. At both frequencies, crack lengths were measured using a Questar telescope and equipped with a digital camera. Fatigue crack propagation (FCP) curves were prepared using the stress intensity solutions given by Newman and Raju [13] for small semi-circular cracks in a finite plate. Only the tensile portion of the stress range was used to plot the FCP curves.

3 RESULTS AND DISCUSSION

An image of a crack that has initiated from a femtosecond laser micronotch for W319 at 150°C is shown in Figure 1. The use of femtosecond lasers results in minimal damage to the surrounding microstructure. The two major constituents of the microstructure, namely the light α-Al phase and the dark Al-Si eutectic region can be identified in Figure 1. Fatigue crack growth data for several different conditions for both W319-T7 (dark lines) and A356-T6 (light lines) are shown in Figure 2. The reported stress in Figure 2 is the maximum stress in the fatigue cycle and all tests were conducted at a load ratio of -1. Two different maximum stress levels were applied at 30 Hz for each of three different temperatures (20, 150 and 250°C) for W319. The crack growth rates are a strong function of applied stress and temperature. For example, at 150°C, increasing the maximum stress from 100 to 140 MPa increases the crack growth rate (at equivalent ΔK) by almost two orders of magnitude. Increasing the temperature at the same stress level (100 MPa) also increases growth rates. Fatigue crack propagation curves for the alloy A356 at a maximum stress of 120 MPa and frequencies of 30 Hz and 20 kHz are also shown in Figure 2, where a decrease in the crack growth rate (at equivalent ΔK) by almost an order of magnitude can be observed.

The observed behavior can be rationalized by considering the dependence of crack tip plasticity on stress, temperature and frequency. Under large scale yielding conditions, the plastic zone size at the tip of the crack can be described by the Bilby, Cottrel and Swinden (BCS) [14] model as

$$r_{pzs} = a\left[\sec\left(\frac{\pi}{2}\frac{\sigma_a}{\sigma_{ys}}\right) - 1\right] \tag{1}$$

where 'a' is the half crack length and σ_{ys} is the 0.2% offset tensile yield stress. In a cyclic loading situation, only a fraction of the resulting crack-tip monotonic displacement contributes to crack growth. This fraction can be accommodated by applying a scaling factor, which, in physical terms, can be slip irreversibility factor, ϕ (Wilkinson 2001 [15]). The expression for the plastic zone size which contributes to crack growth can now be given by

$$r_{pz} = \phi\, a\left[\sec\left(\frac{\pi}{2}\frac{\sigma_{\max}}{\sigma_{ys}}\right) - 1\right] \tag{2}$$

where $\sigma_{\max}$ is the maximum stress in the loading cycle. By assuming $\phi = 0.05$ (Shyam *et al.* [9]), we have plotted the crack growth rates with the plastic zone size parameter given by eqn (2) in Figure 3. The relevant yield stress values have been obtained from Table 1.

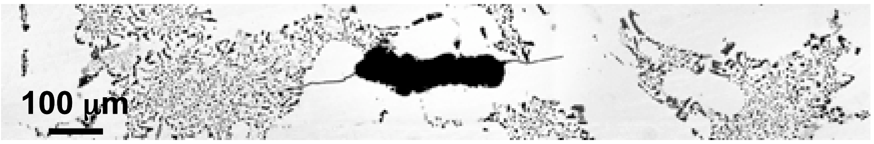

Figure 1: A small crack emanating from a femtosecond pulsed laser notch in W319.

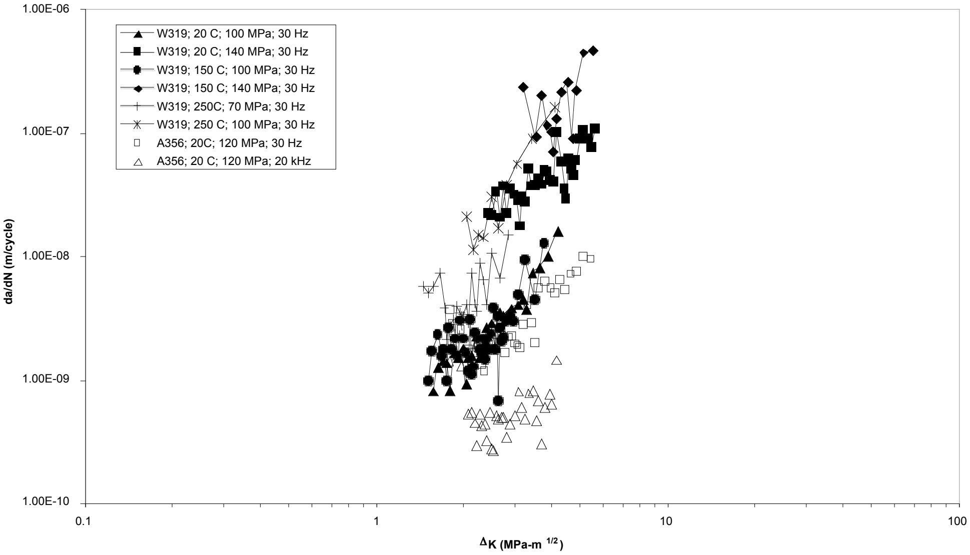

Figure 2: Small fatigue crack propagation curves for all different conditions in this investigation.

In Figure 3, small fatigue crack growth data (at 30 Hz) at four different stress levels, three different temperatures and two different alloys with different heat treatments has been incorporated. It is to be noted that the growth rate of small cracks loaded at a frequency of 30 Hz is within a narrow band (indicated by straight lines in Figure 3). The initial growth rate of the cracks initiated from the notches higher, with the growth rate initially decreasing as it grows away from the notch. This results from the additional driving force for crack growth coming from plasticity of the notch. Depending on the shape and size of the notch (which determines the notch stress/strain concentration factor), a growth rate minimum is observed before the crack starts growing from plasticity resulting from the crack alone. The growth rate of the cracks as they grow beyond the notch influenced zone generally follows the band outlined in Figure 3.

It can be seen in Figure 3 that the crack growth rates for the alloy A356 at a maximum stress of 120 MPa is lower, by nearly an order of magnitude, at an ultrasonic loading frequency of 20 kHz when compared to the growth rates at a frequency of 30 Hz. This kind of frequency effect has not been reported by other authors (e.g. Caton *et al*. [3]) for cast aluminum at room temperature. Scanning electron microscopic examination of the fracture surface does not indicate an obvious

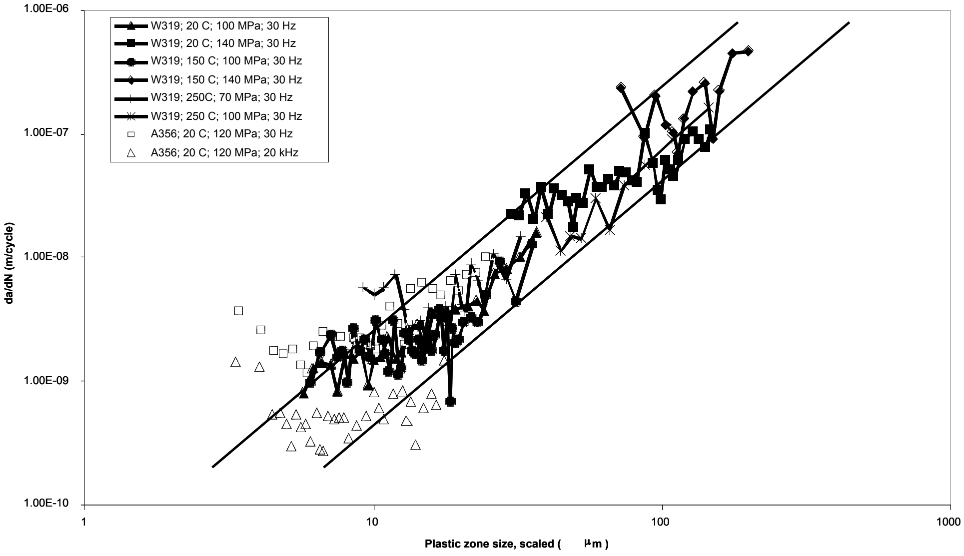

Figure 3: Small fatigue crack growth rates plotted with plastic zone size given by eqn (2).

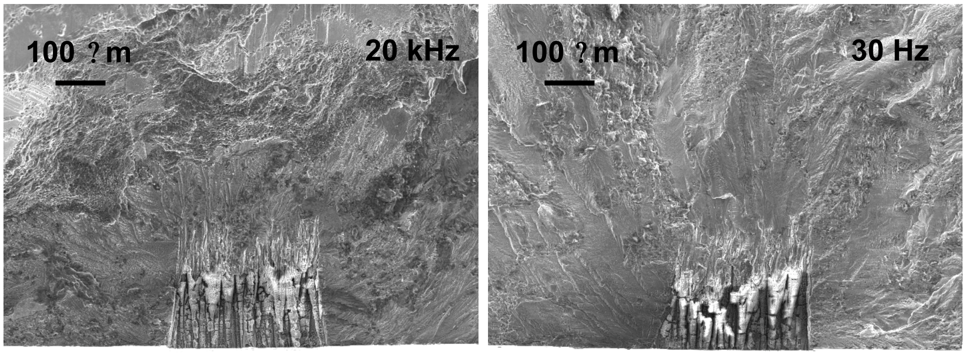

Figure 4: Comparison of A356 fracture surfaces fatigued at 20 kHz and 30 Hz at σ_{max}=120 MPa.

difference between ultrasonic and conventional frequency crack growth (Figure 4). From a crack-tip deformation standpoint, lower growth rates at a very high frequency are consistent with thermally activated mechanisms (lowering of yield stress) and a decrease in the slip irreversibility factor (decrease in value of ϕ in eqn (2)). Both these factors will tend to diminish reversed crack-tip plasticity and shift the high frequency growth rates to the left in Figure 3. Such a shift would make growth rate at ultrasonic frequencies to follow the band of conventional frequency crack growth. The success of a plasticity based parameter in predicting growth rates at different conditions signals that a fundamental small crack growth law can be derived for cast aluminum alloys. This underlying law can be used to predict the growth rate of cracks under all the complex temperature and stress conditions found in automotive engines.

4 CONCLUSIONS

The growth rate of small fatigue cracks examined in two cast aluminum alloys – W319-T7 and A356-T6 – increased as either temperature or stress level is increased at equivalent stress intensity. It was shown that crack growth rates are lower at a frequency of 20 kHz than at 30 Hz. A crack tip plasticity based parameter has been shown to explain the variation of small crack growth rates.

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