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Calculation of Strain Life Parameters for Die Cast Aluminum

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ABSTRACT:
Die cast aluminum is being used in more structurally demanding applications that are subjected to complex and often cyclic loading. Traditionally, strain-life fatigue parameters are determined following ASTM E606 specifications using machined test samples. The inherent nature of die cast aluminum is the near surface material is significantly more homogeneous than the subsurface, where a majority of the porosity resides. Therefore, traditional machined samples provide strain-life properties representative of core rather than skin behavior.

To obtain surface strain-life properties, cracks were induced on unmodified production castings. Using strain from experimental 3D image correlation and analytical finite element analysis, strain-life parameters for skin properties for 380.0 die cast aluminum were able to be back calculated. Results showed the strain-life parameters for as-cast surfaces were significantly better than the properties obtained from machined samples.

INTRODUCTION:
The influence of casting porosity and cast-in defects effects on cast aluminum fatigue has been rigorously investigated [1-4]. This approach has been satisfactory for casting methods that generate isotropic distributions of voids, such as sand or permanent mold casting. Since the surface of die cast aluminum (DCA) is inherently smoother with lower porosity, it is suspected that fatigue properties for as-cast DCA are significantly better than non-DCA components. Determination of surface DCA fatigue properties is not a trivial task since machining exposes voids and net-shape test bars would always contain a parting line in the gauge section.

Historically, die casting has been used for applications with complex geometry, tight dimensional tolerance, smooth surface and low relative cost. In the past few years significant interest in weight reduction in both on and off highway vehicles has led to greater utilization of die-cast components beyond the traditional applications such as covers and oil pans. These new applications are often load bearing, performance critical applications, such as suspensions and pedals that require a better understanding of the material properties.

A second observation is the majority of published cast aluminum properties are determined using Stress-Life fatigue behavior, a test where performance is benchmarked by a stress level producing no failures after a prescribed number of cycles. This assumes an endurance limit, commonly observed in steels, but well known to not exist in aluminum [5]. This methodology will inherently under-predict fatigue damage in materials lacking an endurance limit. Additionally, since die-cast aluminum lacks any significant ductility, this moderately stressed, long-life region is often the target of designers. The majority of the published data is generated from machined specimens with exposed subsurface and significant void populations leading to sub-surface initiated cracks. Since these cracks initiate at a quantifiable pre-existing defects, a reasonable amount of DCA crack growth data is also available. All of these properties are helpful to designers, but the benefits of DCA surface or skin properties is still open for debate.

Given that a traditional fatigue sample is not feasible, other methods to determine as-cast DCA fatigue performance were considered. In the case of die cast magnesium, Renner and Zenner [6] created custom tooling to produce webbed angles of various radii and thickness to produce viable samples. For the current study custom molds were ruled out due to high cost and lack of flexibility for testing alternate materials. Ultimately, the decision was made to use “production” castings and finite element (FE) analysis to determine loading conditions that would produce cracks in locations without parting lines, eject pin marks or other surface events. The location also had to be easily visible so crack initiation could be quickly detected.

PROCEDURES:
A fine mesh 3D modeling of the die cast 380.0 aluminum axle housing was used to determine loading that would produce failures at a desirable location (external, away from parting lines), and to calculate local linear elastic stresses and strains. After several iterations, a simple bending load 10° off axis in the basal plane would critically load the base of the web. Using the linear elastic model, local stress and strains were calculated for applied loads of 5 kN as shown in Figure 1. The details of the loading conditions are reported in the testing section of this paper. Using the FE results an approximate correlation between applied loads and local elastic stresses was determined for use in fatigue calculations.

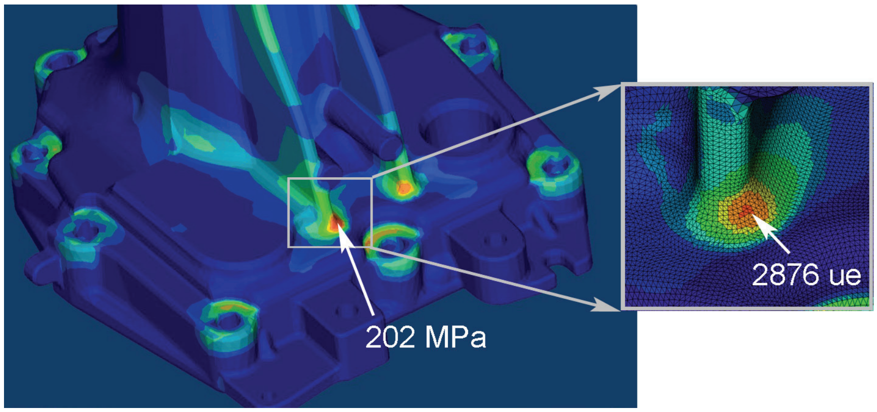

Figure 1 - Max Principal Stress at Load an applied load of 5 kN (1124 lbf) @ 10 Deg

Loading was applied using a 3 Hz sine wave with maximum force of 7.1 to 11. kN and an R-ratio of 0.1 The casting was rigidly mounted to the bed plate and bending loads were applied through a pivot joint mounted where, in normal operation an axle bearing is located . Based on finite element calculations, to generate cracks at the desired location, the casting was rotated 10 degrees off axis in the plane parallel to the floor. (Figure 5A). Crack initiation was observed using visual inspection, with a typical initial crack size of 10-15 mm (Figure 5B). When cracks were allowed to continue, complete failure occurred in a fraction of cycles needed to obtain a detectable crack. Testing was halted when the crack length significantly reduced the stiffness of the structure. This correlated to cracks greater than 60 mm, or at higher loads, catastrophic failure.

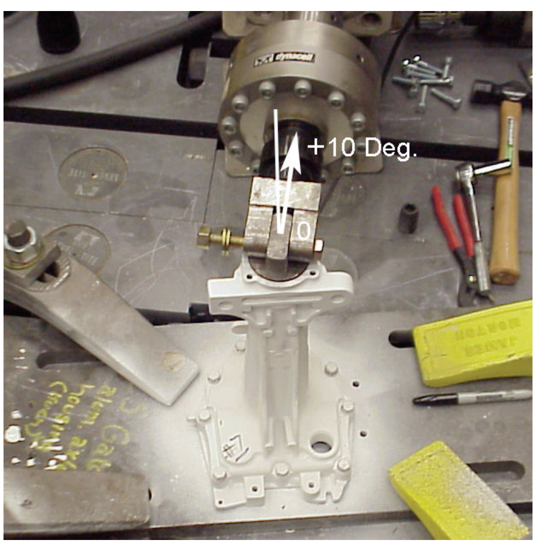

Figure 2A - Experimental setup showing loading direction and off axis rotation.

Figure 2B - Typical detectable crack. The maximum load on this sample was 2000 kN observed after 420,000 reversals

Strain measurements were obtained using gauges and photogrammetry (PG) [7] (Figure 3). Although PG has been shown to be an accurate method to collect strain results [8], strain gauges were used during initial setup to increase comfort level in the technology. Using an optical measurement system provided the ability to generate strain maps of the surface that would not be possible using conventional strain gauging (Figure 4).

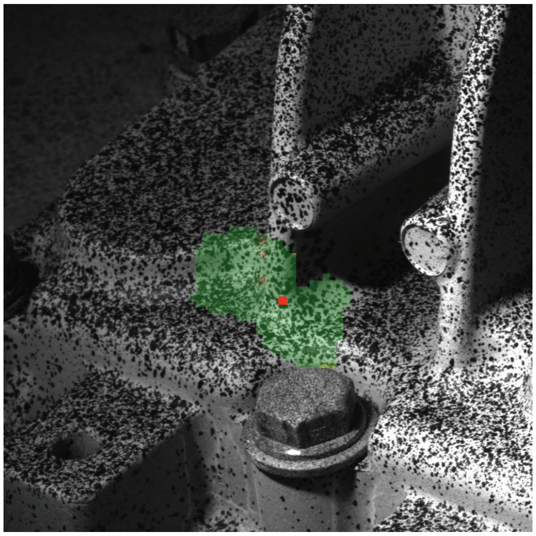

Figure 3 - Raw image from photogrammetry. Speckled paint is used to map the surface. Shaded region was mapped for this experiment.

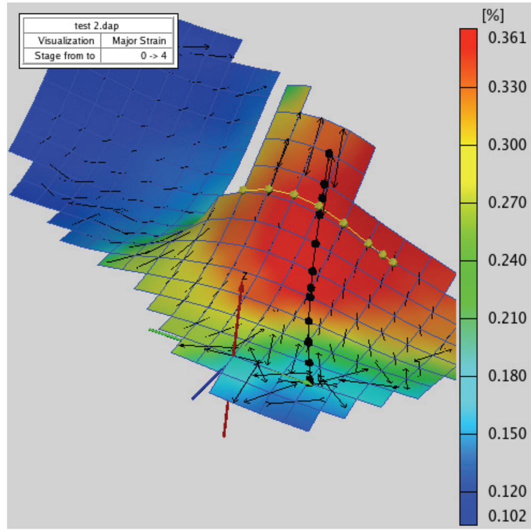

Figure 4 - Results of photogrammetry showing strains mapped in Figure 3.

Monotonic properties were obtained by machining samples from semi-flat sections of the casting (Figure 5A). In an attempt to maintain typical void density, minimal machining was done to as-cast surfaces. However it has been shown that except in the most severe case, porosity has minimal effect on tensile properties, but the same cannot be said for fatigue performance [9]. Constants for the strength coefficient, K and strain hardening exponent, n were determined assuming a Ramberg-Osgood stress-strain relationship (Eq. 1) and the result is shown in Figure 5B.

Figure 5A– Monotonic tensile samples were cut from casting. Distorted sample (i.e. #2) were not used.

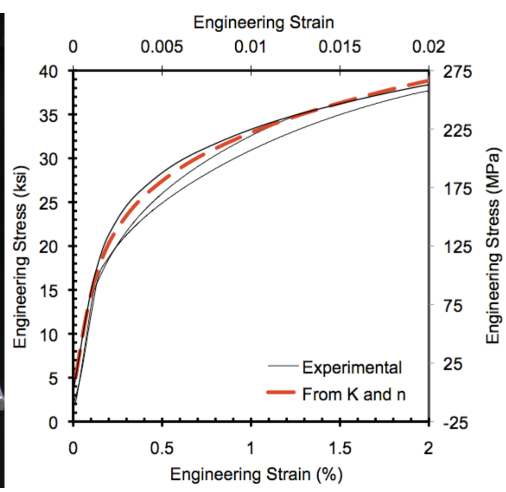

Figure 5B - Comparison of the several monotonic tests and average behavior generated using Equation 1.

$$e = \frac{s}{E} + \left(\frac{s}{K}\right)^{\frac{1}{n}} \quad \text{(Eq. 1)}$$

ANALYSIS:

At the onset of this experiment, there was a concern regarding the number of unknowns. Several assumptions had to be made regarding the basic performance of the material. Most notable is the monotonic Ramberg-Osgood parameters (K and n) were assumed to be equivalent to the cyclic constants (i.e. K=K' and n=n'). This assumption is somewhat speculative knowing DCA typically work hardens. The effect on overall strain life parameters needs to be carefully considered.

To calculate fatigue damage for each load level, local strains were measured with PG and local stresses were calculated using Equation 1 and are shown in Table 1. The hysteresis loops for each load level could then be generated as shown in Figure 6. Since the Coffin-Manson [10] strain-life fatigue constants in Equation 2 assume a mean stress of zero, additional analysis was needed. In this case the Smith-Watson-Topper equation [10] (Eq. 3) mean stress correction was used to account for damage from the non-zero mean strains. Total strain can be separated into elastic and plastic components (Eq. 4) so Equation 3 was dismantled into strain components as shown in Equations 5 and 6. The power law curve fit allows for the determination of slope and intercept values as graphically shown in Figure 7. Substituting back into Equations 4 and 5, the unknown materials constants, σ_f', b, ε_f' and c can be determined. Combining these with E, K and n obtained earlier, the strain-life parameters are known and are listed in Table 2.

$$\varepsilon_a^{total} = \frac{\sigma'_f}{E}\left(2N_f\right)^b + \varepsilon'_f\left(2N_f\right)^c \quad \text{(Eq. 2)}$$

$$\varepsilon_a \sigma_{\max} = \frac{\left(\sigma'_f\right)^2}{E}\left(2N_f\right)^{2b} + \sigma'_f \varepsilon'_f\left(2N_f\right)^{b+c} \quad \text{(Eq. 3)}$$

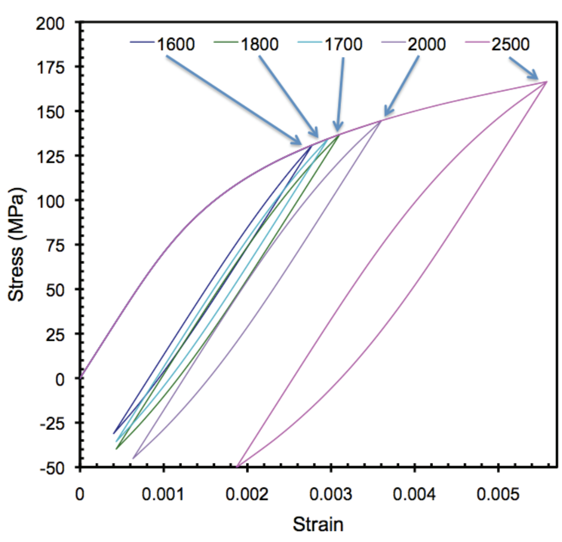

Figure 6 - Hysteresis loops from measured values for each load level.

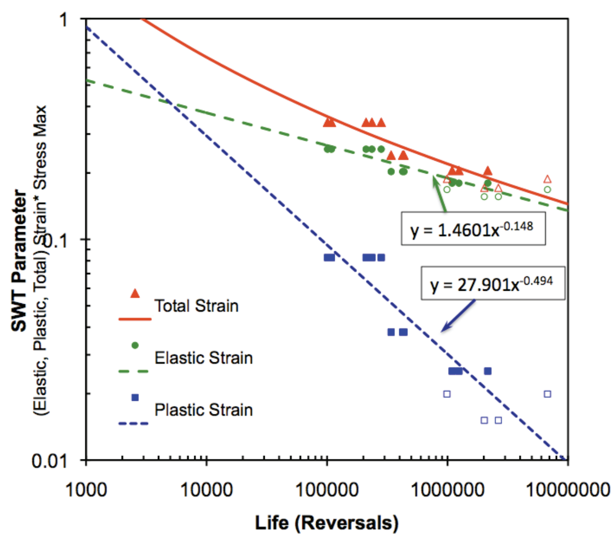

Figure 7 - Using the SWT equation, elastic and plastic constants were obtained from the experimental data.

Table 1 - Calculated life using measured strains and machined strain-life 383 DCA fatigue properties predicts shorter life than observed during component testing.

Load	Max. Meas. Strain	Meas. Strain Range	Max. Stress	Meas. Stress Range	Predicted Life 383 Al	Average Experimental Life
lbs	ue	ue	MPa	MPa	Cycles	Cycles
1600	2776	2376	131	162.1	460000	>1M
1700	2937	2521	134.5	170.1	352000	>1M
1800	3182	2750	136.9	176.7	287100	750000
2000	3604	2970	144.6	189.8	178000	200000
2500	5244	3383	166.5	216.8	64000	82000

$$\varepsilon_a^{total} = \varepsilon_a^{elastic} + \varepsilon_a^{plastic} \qquad \text{(Eq. 4)}$$

$$\varepsilon_a^{elastic}\sigma_{\max} = \frac{\left(\sigma'_f\right)^2}{E}\left(2N_f\right)^{2b} \qquad \text{(Eq. 5)}$$

$$\varepsilon_a^{plastic}\sigma_{\max} = \sigma'_f\,\varepsilon'_f\left(2N_f\right)^{b+c} \qquad \text{(Eq. 6)}$$

Table 2 Strain-life parameters for Die Cast 380 aluminum obtained in this study.

Fatigue Strength Coefficient	Fatigue Strength Exponent	Fatigue Ductility Coefficient	Fatigue Ductility Exponent	"Cyclic" Strength Coefficient	"Cyclic" Strain Hardening Exponent	Elastic Modulus
Sf'	b	Ef'	c	K'	n'	E
328.5	-0.0739	0.08493	-0.4203	522.1	0.2003	73900

Results:
Comparing strain-life results to historical machined 383 DCA properties with similar monotonic properties (Figures 8) clearly showed the life of the casting was much longer than the machined sample predicted (Figure 9). For additional comparisons, sand cast 356 and 319 aluminum results are shown. The 319 samples were custom manufactured to low porosity and then hipped to eliminate surface porosity [11]. As at short lives, it appears the 319 hipped samples performed similar to machined 383 DCA. At at longer life, were surface quality has a greater impact on crack initiation, the 319 hipped converged on the DCA properties generated in this experiment. It is suspected by the author that this is because subsurface defects controlled crack initiation at higher strains but additional investigation is needed.

Summary and Future Work:
The method proposed to obtain strain-life fatigue material properties from components rather than laboratory specimens appears to generate reasonable results. In the example given, existing DCA properties from machined samples would have severely under predicted the life of the component. The as-cast DCA properties calculated in this experiment suggest longer life than sand-cast aluminum at low and high strain levels. When sand cast surface conditions are optimized, DCA sill has a performance advantage, although less so at low strain levels.

Additional testing is planned at higher strains to better understand DCA performance at shorter lives when higher plastic strains are present. Also, tests to generate failures at alternate locations and in different components need to be completed to validate the process.

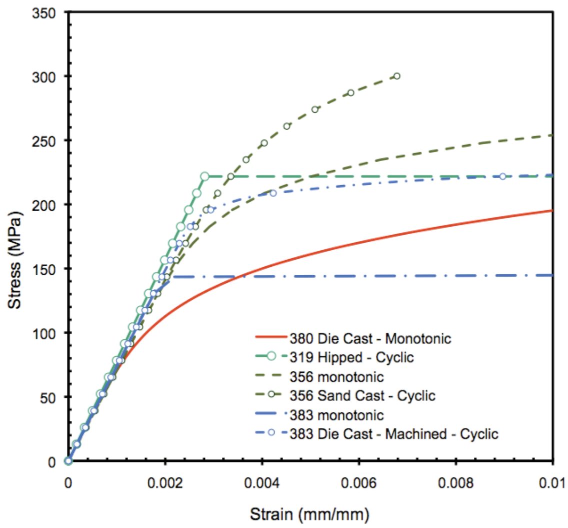

Figure 8 - Cyclic and monotonic curve for the 380 DCA used in this experiment as well as published values for various other cast aluminum grades.

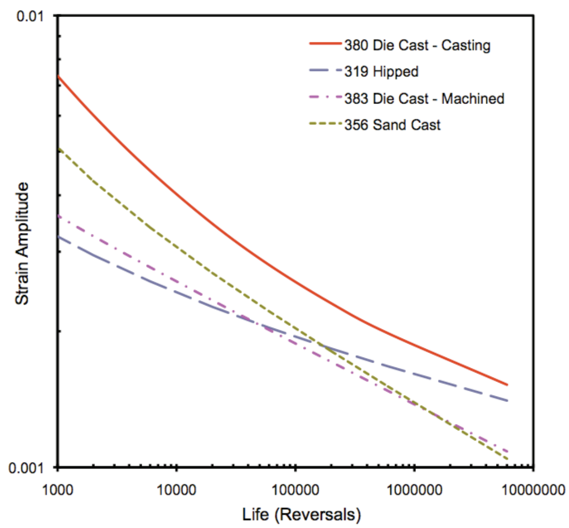

Figure 9 - Strain-life behavior for the 380 DCA used in this experiment as well as published values for various other cast aluminum grades. The 319 aluminum was hipped to optimize the surface properties and appears to have similar performance at low strain levels.

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