

Correlation between Scatter in Fatigue Life and Fatigue Crack Initiation Sites in Cast Aluminum Alloys

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ABSTRACT

High cycle fatigue tests at a constant positive mean stress have been performed on a Al-Si-Cu cast aluminum alloy. The Random Fatigue Limit (RFL) model was employed to fit the probabilistic S-N curves based on Maximum Likelihood Estimate (MLE). Fractographic studies indicated that fatigue cracks in most specimens initiate from oxide films located at or very close to specimen surface. The RFL model was proved to be able to accurately capture the scatter in fatigue life. The cumulative density function (CDF) of fatigue life determined by RFL fit is found to be approximately equal to the complementary value of the CDF of the near-surface fatigue initiator size.

CITATION: Zheng, X., Engler-Pinto, C., Su, X., Cui, H. et al., "Correlation between Scatter in Fatigue Life and Fatigue Crack Initiation Sites in Cast Aluminum Alloys," *SAE Int. J. Mater. Manf.* 5(1):2012, doi:10.4271/2012-01-0920.

INTRODUCTION

With the increasing requirements for higher fuel efficiency and lower emissions, cast aluminum alloys as a light weight metal are used in more and more engine components such as cylinder heads and blocks. A common durability concern in these engine components is high cycle fatigue (HCF) due to cyclic firing pressure during engine operation. Positive mean stresses, which consist of thermal, residual and assembly stresses are usually present at the critical areas of HCF durability.

For many years, cast aluminum alloys have received numerous studies on the fatigue properties. The dominant factor for the durability of cast aluminum alloys is the presence of casting defects such as shrinkage/gas pores, oxides and other inclusions, which serve as primary sites for fatigue crack initiation. Seniw et al. [1] investigated the influence of pore size, morphology, and location on the fatigue properties of A356 aluminum and concluded that cracks tend to initiate from large pores located close to a free surface. Boileau and Allison [2] observed that fatigue cracks initiate from shrinkage pores that are located very close to the specimen surface. For cast aluminum alloys with relatively small or no porosity, Couper et al. [3] and Jang et al. [4]

recorded that fatigue crack initiation may occur by slip mechanism; additionally, Zhang et al. [5] observed that debonding of Si particles from Al matrix served as the fatigue initiator. In addition to porosity, oxide films may also form during casting process. Wang et al. [6] observed that fatigue cracks initiate from oxide films in HIP-ed and thus pore-free A356-T6 alloys; they indicated that, for a given defect size, oxide films appear to be less detrimental to fatigue life compared to porosity. All these studies agree that the fatigue resistance depends not only on the type of initiation site (i.e. pores, oxide films, Si particles or slip mechanism), but is also influenced by the size, shape and location of the initiating casting defect.

It has been widely concluded that the number of cycles required to initiate a crack is small relative to the total fatigue life in cast aluminum alloys. Therefore, the fatigue life is dominated by the fatigue crack propagation period and the initiation life is generally considered to be negligible. A number of models based on fracture mechanics have been developed [7, 8, 9] to describe the fatigue crack propagation from initial near-surface porosity. Based on this argument, specimens with larger initial casting defects must experience shorter fatigue life. In other words, for fatigue cracks

initiating from near-surface casting defects, the defect size provides a major cause of the scatter in fatigue life.

To account for the scatter in fatigue life, probabilistic S-N curves were determined by considering the statistical distribution of fatigue life at any stress level. Life regression models such as modified Basquin model and Random Fatigue Limit (RFL) model [10] were employed to fit the probabilistic S-N curves. Engler et al. [10] concluded that the Random Fatigue Limit model performed better than the Modified Basquin model for the 319 cast aluminum alloys. The RFL model provides a useful empirical approach to describe the curvature observed in the S-N data. It can also be observed that the median fatigue strengths estimated from the RFL model are in very close agreement with the staircase estimates [10].

Although RFL model provides a consistent median fatigue limit with staircase prediction, the estimation of distribution of fatigue life is still empirical. Further investigation is required to increase the confidence of the estimation of the scatter in fatigue life.

The objective of this paper is to relate the estimation of the scatter in fatigue life by RFL model to the statistical distribution of fatigue initiator size. An attempt is made to correlate the cumulative probability of fatigue life estimated by RFL model at a given stress level with the cumulative probability of near-surface fatigue initiator size for each specimen.

MATERIAL AND EXPERIMENTAL METHODS

MATERIAL

The cast aluminum alloy investigated in the present study is from the Al-Si-Cu family. This alloy was specially cast to generate a higher than normal content of oxide inclusions. Specimens were taken from cast plates measuring $210 \times 150 \times 16$ mm in a region where the secondary dendrite arm spacing (SDAS) ranged from 15 to 30 μm . After casting, the alloy underwent a T64 under-aged heat treatment.

EXPERIMENTAL METHODS

All fatigue specimens were machined using low stress turning with a diameter of 7.62 mm. HCF tests were performed by stress control method on a hydraulic testing machine at 20 Hz at room temperature. A constant mean stress at 165 MPa was chosen for all tests. The criterion for HCF failure was final fracture.

All fracture surfaces of the fatigue-tested samples were examined using a scanning electron microscope (SEM). Tensile loading were applied to runout samples to break each sample to two pieces. The fatigue initiation sites were identified. For those non-porosity fatigue crack initiator, energy dispersive X-ray (EDX) was carried out on them to acquire the chemical spectra. The area of each fatigue crack initiator was projected to a plane normal to the applied load

and was measured by image analyzer software. The size of the fatigue initiation defect was defined as the equivalent diameter of a circle which has the same area as the measured area. The distribution of the equivalent diameters was analyzed the commercial statistical software, Minitab.

RANDOM FATIGUE LIMIT (RFL) MODEL

To account for the variation of fatigue life, the Random Fatigue Limit model, which was originally proposed by Pascual and Meeker [11], was employed to fit the probabilistic S-N curves. The RFL model assumes that there is a probabilistic fatigue endurance limit for an infinite number of cycles, which follows a Weibull distribution. The RFL model has been successfully used by Engler et al. [10] to fit the high cycle fatigue data for 319 cast aluminum alloys and the very high cycle fatigue data for Al-Si and Al-Si-Cu cast aluminum alloys [12]. The RFL model is given by the following equation:

$$\ln(N_f) = B_0 + B_1 \ln(S_a - S_L) + \xi \quad (1)$$

where ξ represents the scatter in the number of cycles to fracture, B_0 and B_1 are empirical constants, and S_L is the *infinite-life* fatigue limit of the specimen, which is a random variable, as it varies from specimen to specimen. This fatigue limit is assumed to follow a Weibull distribution, as follows:

$$S_L = e^{\ln(\eta) + \ln(-\ln(1-P))/\beta} \quad (2)$$

where P is the probability of failure (at an infinite number of cycles), and β and η are the shape and scale parameters for the Weibull distribution, respectively.

To get a best fit of the model, the above five parameters were determined based on the Maximum Likelihood Estimate (MLE). For a given stress amplitude, S_a , the likelihood can be defined as follows:

$$L = \prod_{i=1}^n f(N_F^i, \{p\}) \cdot \prod_{j=1}^m [1 - F(N_R^j, \{p\})] \quad (3)$$

where n corresponds to the number of failed specimens and m is the number of runouts, $f(N_F^i, \{p\})$ is the probability density function, $F(N_R^j, \{p\})$ is the cumulative density function, and $\{p\}$ are the parameters that define the distribution. The likelihood function is shown schematically in Fig. 1.

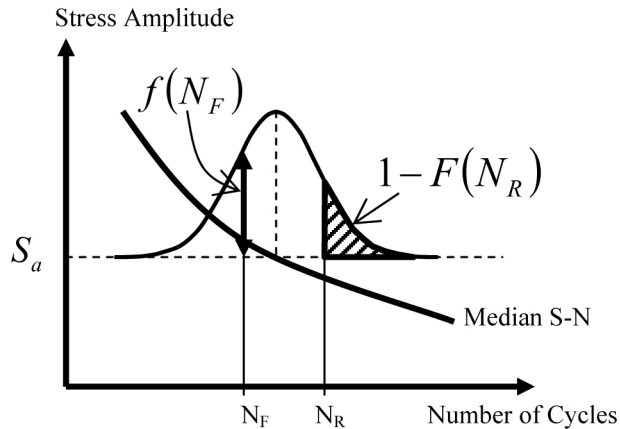


Fig. 1. Likelihood function definition for RFL model for failures (N_F) and runouts (N_R) [10]

RESULTS AND DISCUSSION

S-N RESULTS

The HCF test results and corresponding probabilistic S-N curves fitted by RFL model were presented in Fig. 2. The values of the five fitting parameters in the model are listed in Table 1. Among the 26 tested samples, 21 samples failed at cycle numbers less than 10^7 , while 5 tests were discontinued at cycle number of 10^7 . These discontinued samples are termed as runouts which are indicated by arrows in Fig. 2. The number beside each arrow represents the number of runouts at corresponding stress amplitude. The bold curve (B50) represents the 50% failure probability. The other percentile curves, e.g. 0.01 (B01), 0.1 (B10), 0.9 (B90) and 0.99 (B99), are also plotted to illustrate the variability in fatigue life estimated by the RFL model.

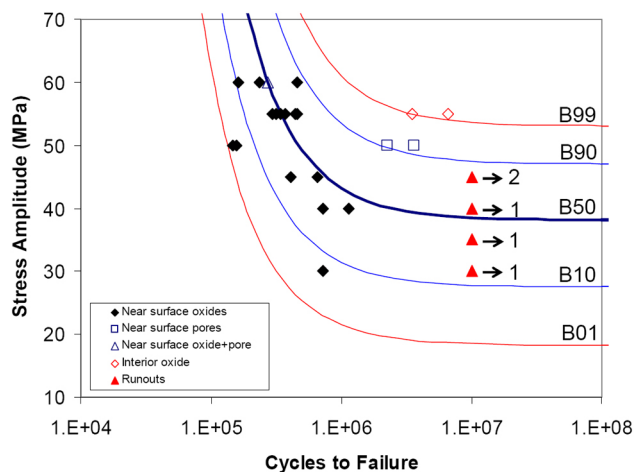


Fig. 2. RFL fit for HCF test results

Table 1. Values of fitting parameters in RFL model

B_0	B_1	ξ	η	β
15.3	-0.88	0.17	40.7	5.7

FATIGUE CRACK INITIATION

The types and nature of fatigue crack initiators were identified by fractographic studies. Oxide films and pores were found as crack initiators. Fatigue crack initiation sites were found for 23 samples including two broken runout samples while no features of fatigue crack initiation and propagation were detected for the other three runout samples. The detailed nature of the fatigue crack initiation sites were described in Table 2. The fatigue crack initiator types for all failed specimens are also marked by different symbols in Fig. 2.

Table 2. Statistics of fatigue crack initiators

Types	Location	Number of samples
Oxide film	At or near surface	18
	Interior	2
Pore	At or near surface	2
Combination of oxide film and pore	At or near surface	1

The oxide films, which served as fatigue crack initiators, were observed as “dark” areas relative to the crack propagation region (Fig. 3a) using optical microscope. Fig. 3b shows the secondary electron image of the “dark” feature in Fig. 3a. The oxide film was outlined by the red line. To confirm the chemical composition, EDX analysis was performed on the dark feature. The presence of relatively high levels of oxygen and magnesium were identified in Fig. 3c, which implies that the dark feature is probably an “old” oxide film. Old oxide films with higher levels of O and Mg tend to be thicker and flatter than “young” oxide films, which consist of nearly pure alumina [13, 14]. According to Nyahumwa [13], old films are usually formed during the melting process while young films are folded into the melt during the filling of the mold. A possible young oxide film was shown in Fig. 4a. The EDX analysis results in Fig. 4b present much lower counts of O and Mg than the chemical spectrum in Fig. 3c. There seems to be no study to date that compared the effects of oxide film types (“old” vs. “young”) on fatigue resistance; Nyahumwa [13] has suggested that young oxide films should probably be more damaging due to the lack of bonding with the matrix compared to old oxide films. In the present study, it was not always possible to distinguish between old or young oxide films.