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The Effect of Grain Structure on Casting Durability Assessment in Al-Si Alloys.

Glenn Byczynski & Robert Mackay

Nemak of Canada Corporation

Abstract

Casting durability may be assessed by several methods. In industrial powertrain castings engineering design is linked to the assessment of casting properties in particular high cycle fatigue performance. In the past porosity has been shown to be the most deleterious microstructural constituent in Al-Si cast alloys. Porosity is nucleated by oxide biflims and evolves during solidification due to segregated hydrogen gas and/or liquid feeding difficulties in the mushy zone during solidification. Porosity and oxide films have been reported to control casting durability as assessed through the fatigue staircase and calculated -3σ plots.

The authors will show in this work that grain structure can also play a major role in terms of controlling fatigue life. Specifically the presence of columnar grains in non grain refined casting structures can lead to low and unpredictable fatigue lives. The mechanisms of fatigue failure due to grain structure are reviewed and the use of grain refiner (in-mold process) to improve fatigue performance and counteract undesirable structure are discussed.

Introduction

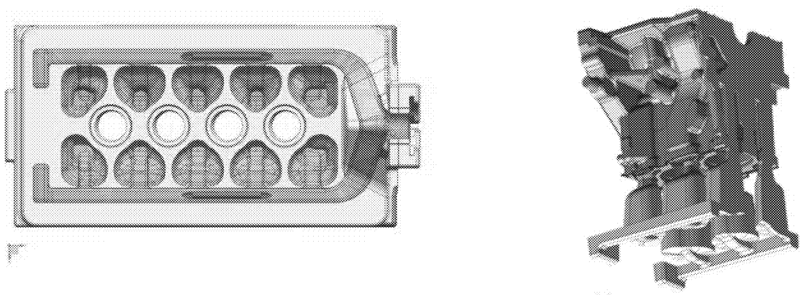
Engine blocks cast with Al-Si-Cu alloys in sand or semi-permanent molds often have demanding service requirements and push the design limits of these components. Cast component characteristics, pressure tightness and durability, are typically controlled by the presence of porosity and thus the need to understand and/or control dispersed porosity is paramount[1-7]. Dispersed porosity in thick cast sections can be reduced by employing melt treatments such as hydrogen degassing practices and filtration, particularly when changing the local casting component geometry to quicken the solidification time is not an option. Typically in sand casting operations in order to achieve higher fatigue performance in thicker casting sections a metallic chill is placed in the mold and in direct contact with the liquid metal that has filled the mold cavity.

Casting processes using the aluminum alloy 319 in precision sand or semi-permanent mold commonly use additions of Si modifiers (normally master alloys containing Sr or Na[4-6]) or grain refiners (e.g. Tibor or Al-5Ti-1B[3]). The use of these Si modifiers and/or grain refiners have profound effects on pore distribution within the cast structure as they will increase dispersed porosity throughout the casting at the expense of gross localized shrinkage while also modifying the Si structure, and/or reduce grain size[1].

Experimental Methodology

Casting Method

In precision sand casting a room temperature mold or core package is employed. The mold is composed of individual interlocking sand cores that can be produced in a variety of core making methods. One of the most popular is the phenolic urethane cold box method employing silica or zircon sand and a two part amine cured binder system. The assembled sand mold may be filled using gravity or various counter gravity methods e.g. Low Pressure or Electromagnetic or Mechanical Pump. Both counter gravity casting processes are capable of producing a controlled quiescent filling of the mold that reduces the formation of bifilms in the casting[9-11]. Bifilms are known to impair casting quality and fatigue and tensile performance. Metal front velocities are controlled to be well below 0.5 m/s , and the typical fill times can range from 17 to 25 seconds depending on the casting size. One of the key components of this casting process has been the use of in-mold grain refinement; meaning placement of the master alloy rod into the runner system of the casting. While unusual in application the precision sand rollover process (where the ingates become the feeding system after rotation of the mold) allows for adequate dissolution of the master alloy and sufficient grain refinement of the targeted areas (Figure 1.).



a) b)

Figure 1: a) Layout of runner system with In-mold placement of Tibor, b) location of bulkhead with respect to the rigging system.

Elevated Temperature Fatigue Staircase Method

Elevated temperature fatigue testing was conducted for this research to simulate cyclical stress conditions in an engine block of an operating engine. Fatigue test sample preparation and testing were carried out as per the ASTM E 466-96 protocol. TestStar^{TM} IIs fatigue software by MTS was used to monitor the sinusoidal axial fatigue at a frequency of 98Hz. The stress ratio was R = -1, (R is defined as $\sigma_{min}/\sigma_{max}$). Maintaining a test temperature of 150°C was done using resistance heater tape material (Omega) in direct contact with the test specimen. Temperature is monitored by a K-type thermocouple that is held in place on the reduced (gauge) section using 3M glass fiber electrical tape. It typically takes 3 to 5 minutes for the reduced gauge section to reach target temperature.

Each fatigue test was used to plot the fatigue staircase which can be described as follows: If a life goal of 10^7 cycles was achieved without a failure the test is considered a "run out" at a given stress level. A subsequent test would be conducted on a fresh fatigue test sample at an incrementally higher stress level (incremental step used for this research was 5 MPa). A sample not achieving the 10^7 cycle life goal is considered a failed test, and results in the next sample being tested at an incrementally lower stress.

The mean stress of the staircase study would be determined by taking the average stress of all the fatigue test samples which failed (higher value of stress) or all the fatigue test samples which passed (lower value of stress), whichever is lower in number. This was provided along with a standard deviation of the results. The logic of using the lower number of sample test results is to negate the effect of a poor estimate of starting stress[11-12].

The alignment process of the fatigue test frame performed is meant to addresses two types of possible misalignment—concentric and angular. The fatigue test frames are equipped with an alignment collar (MTS Model 609) that allows alignment in conjunction with a specimen fitted with 12 strain gauges that is connected with a computerized alignment data acquisition and analysis system (MTS 709). This is the system that is used to align the fatigue frames in accordance with ASTM E1012-05

Light Optical & Scanning Electron Microscopy

Microstructural assessment for porosity levels (area fraction and maximum pore diameter), and Secondary Dendrite Arm Spacing (SDAS or λ_2) within the engine block bulkhead sections were measured using the Clemex Image Analysis System (JS-2000). The λ_2 was measured by taking the line intercepts of at least 10 dendrites and then dividing by the number of secondary arms in the same intercept. Image Analysis (IA) systems were calibrated using a Clemex calibration scale before any cast structure features were measured. AFS Si Modification Rating was also performed using Light Optical Microscopy and comparing to the AFS Si Modification Chart. Grain size was assessed using stereomicroscopy to assess the presence of columnar grains.

Scanning Electron Microscope (SEM) analysis of the cast polished structure and the fracture surfaces of fatigue test samples were conducted using a JEOL JSM 5800 system. The observation of the fatigue test sample fracture surface was done in the Secondary Electron (SE) mode under magnifications ranging from 20X to 250X.

Results

Figure 2 shows the results of the fatigue staircase plot for chill bulkhead sections specimens with and without Tibor additions. The first difference that can be identified is the fact that the mean value of the staircase is marginally higher with Tibor is added. Secondly, the variation in performance (gauged here by the values of -3σ and 95% CI) is lower for the case when Tibor is added. The authors will set forth an argument that the reason for the above observations are influenced not by grain size, but the rather the suppression of columnar grains that straighten oxide bifilms in the gauge area of the test specimen.

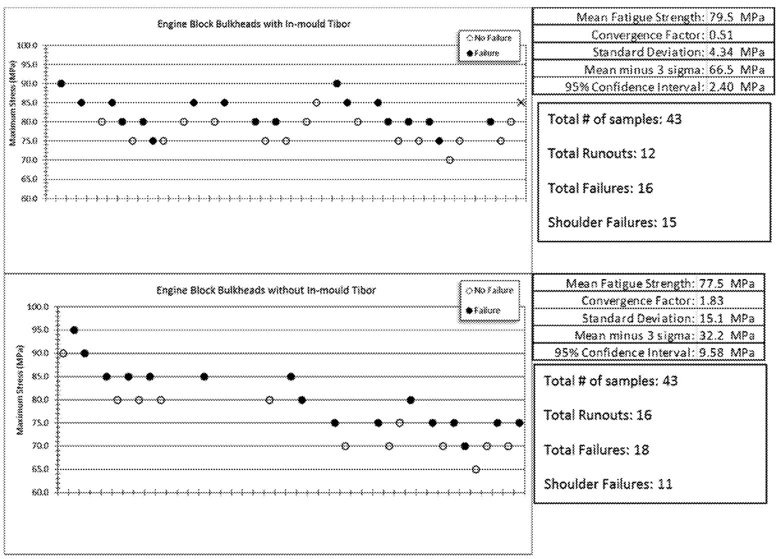


Figure 2: Summary of Fatigue Performance along with Statistical Results

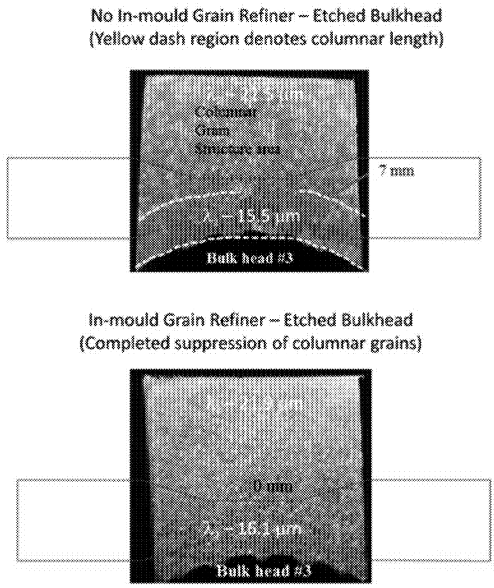


Figure 3: Microstructure of bulkhead with and without in-mold Tibor

In order to understand any difference in fatigue performance, both the bulkhead microstructure and fatigue fractography need to be assessed. Figure 3 shows both λ_2 and grain size of the bulkhead section where the reduced gauge section of the fatigue test bar is extracted. The λ_2 is not affected by the presence of in-mold Tibor, however the columnar grains are completely suppressed.

Fractographic analysis of the fatigue fracture surfaces reveal that all failures were initiated by an oxide film defect or an oxide induced shrinkage pore. In non grain refined castings consistent evidence of columnar grains were seen on the fracture surface (See Figure 2a). These appeared as "feathery grains" of almost featureless dendritic planes. Wrinkled remnants of oxide films were seen on the edges of these planar features suggesting that the columnar grains possibly impinged on and straightened existing bifilms as some authors suggest[13,14]. Specimens with in-mold Tibor additions no columnar grains were seen.

An additional factor that needs to be addressed is that both staircase plots have nearly the same number of samples that failed outside the gauge section and are to be considered a null test under the ASTM E466 protocol. Both regimes outlined in this study had to run nearly the same number of total test samples in order to achieve the 30 fatigue test samples to calculate the statistically relevant parameter for fatigue durability (e.g. -3σ). The main reason for this inconsistency is the λ_2 profile along the fatigue test samples. As shown in Figure 1, the fatigue test sample is extracted from just above the "half-round". The local geometry, wall thickness and position of the metallic chill result in the grip ends solidifying with coarser λ_2 than at the gauge section. As reported widely in the metallurgical literature fatigue performance drops with increasing λ_2. Refinement in grain structure due to the in-mold Tibor additions had no influence on the number of null fatigue tests that had to be performed.

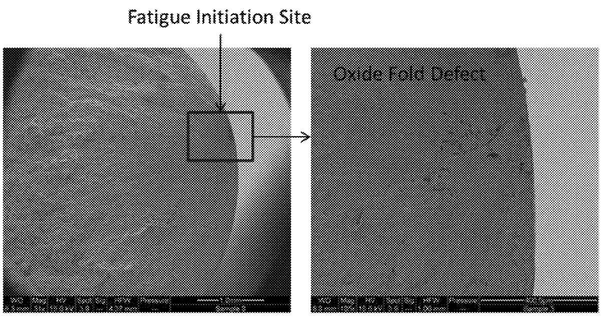


Figure 4a: SEM Image of Typical Fatigue Failure with In-mould Tibor

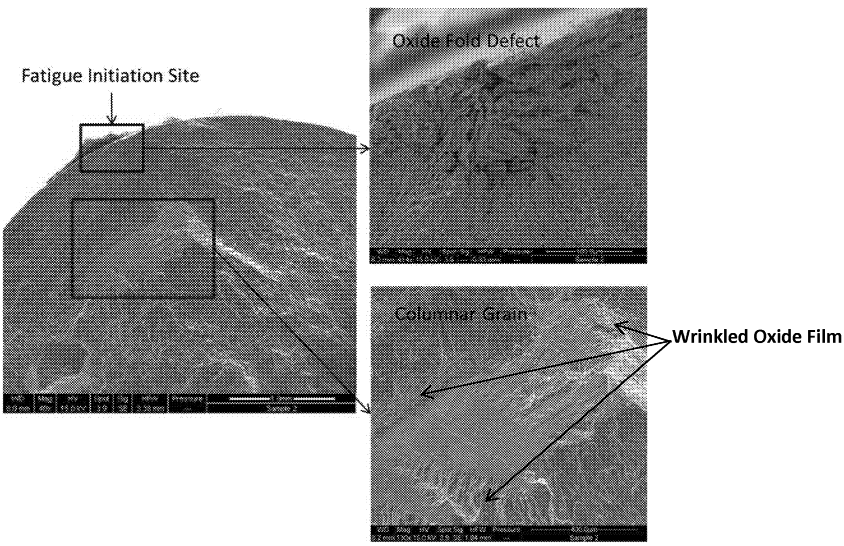


Figure 4b: SEM Image of Typical Fatigue Failure with no In-mould Tibor

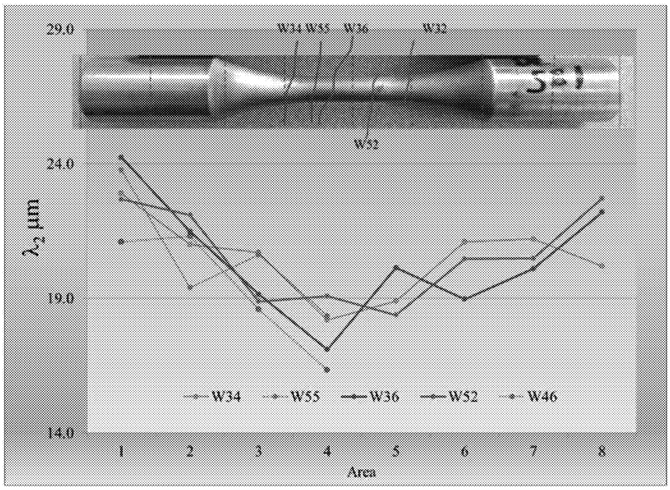


Figure 5: λ_2 profile along fatigue test bar.

Conclusions

This study set out to understand the role of in-mold grain refiner on fatigue staircase performance in industrial castings. The following conclusions can be drawn from this work:

1) Due to the presence of strong thermal gradients during solidification and particular sample orientation and sectioning (in this case axial fatigue sample perpendicular to the main direction of heat extraction) resultant columnar grains in the casting structure can negatively influence the fatigue life of aluminum castings

2) Columnar grains and oxide films were found to be collocated on the fatigue fracture surface of specimens with short fatigue lives. This leads to the suspicion that the two are inextricably linked and play a major role in the fatigue performance.

3) The addition of in-mold grain refinement reduced the degree of scatter in the fatigue test result, resulting in an improved -3σ value. This is thought to be related to (a) the provision of grain nucleation sites resulting in fine grain size and (b) the limitation of the exaggerating effect that columnar grains have on the size of oxide films (through their straightening and inflation) and consequently the limitation of the cumulative negative effects on fatigue performance

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