Porosity Control and Fatigue Behavior in A356-T61 Aluminum Alloy

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ABSTRACT
Much work has been done, in recent years, to characterize the factors that cause porosity in aluminum castings, and to analyze the impact of porosity or microstructural parameters on fatigue life. What has yet to be done is systematically separate out the effects of dendrite arm spacing and largest pore size from each other, and from the underlying chemical and process parameters that influence both the microstructure and defect structure. This is the objective of the work described in this paper.

The factors influencing porosity in A356 aluminum castings are reviewed. The results of the analysis of an A356 alloy fatigue test database, covering a wide range of microstructural scale, pore size and stress, are then presented. Degradation in fatigue life, caused by increasing pore size and secondary dendrite arm spacing, is quantified as a function of stress amplitude, and the relative impact of each is discussed. It is shown that the impact of both largest pore size and the dendrite arm spacing is most severe at high stress amplitudes, with a tendency for the dendrite arm spacing effect to die away toward lower stress amplitudes.

INTRODUCTION
Porosity is the most common casting defect that foundries must battle and, thus, it is very important that both the foundryman and casting buyer thoroughly understand it and its effect on the properties of the casting. Depending on the application, the size and/or quantity of porosity to be allowed may vary considerably. High-performance aerospace castings will generally allow none, while commercial automotive cylinder heads will have critical requirements in areas like the combustion face, and noncritical automotive parts that exhibit high complexity, such as intake manifolds, may have very relaxed standards. While universal perfection would be nice, it comes at a cost, and this should be born in mind as each part’s integrity limits are determined, based on its functional requirements.

The objective of this work was to gain an understanding of the degree to which microstructural scale, as characterized by the dendrite arm spacing (DAS), and defect structure (pore size) influence the fatigue performance of the A356-T61 aluminum casting alloy over ranges of commercial interest. The factors controlling porosity in this alloy system will be briefly reviewed. The results of a parametric analysis of the impact on fatigue life of the major parameters of stress amplitude, largest pore size and secondary dendrite arm spacing will then be presented, and the practical implications of the results discussed.

BACKGROUND
Factors Controlling Porosity
Before looking, in detail, into the factors that influence the fatigue life of cast A356, the factors that influence the formation of porosity in this alloy system should be reviewed. Of particular interest to this work are the classes of porosity, commonly called gas porosity or microshrinkage. Large-scale macroshrinkage is generally a result of an unfed hot spot, and is beyond the scope of this work. Those interested in the prediction and control of borderline hot spots are referred to various porosity criteria functions as they are applied in solidification modeling, which have been reviewed by Huan and Berry among others.

The topics of gas or microshrinkage porosity have been covered by a number of authors, including Fang and Granger, Tynelius, Major and Apelian, and Zou, Shivkumar and Apelian. The major factors include hydrogen content, local freezing rate, local temperature gradient and alloy treatments such as modification or grain refinement. Figure 1 shows the effects of three of these. Note that the quantity of porosity increases with hydrogen content but is very dependent on the solidification rate.

The impact of strontium modification is also shown. Sr is frequently said to encourage hydrogen pickup. In fact, as seen in Fig. 1, Sr yields a larger quantity of porosity at any given hydrogen content. Grain Refinement can also influence microporosity, since the largest pores in a sample are usually at grain boundaries. Figure 2 shows the effect on largest pore size of adding particulate grain refiners. Another important factor influencing pore size is the cleanliness of the melt, as shown in Fig. 3. Oxide films can cause pores to appear, which may be a factor of three or more times larger than they would otherwise be in clean metal.

Fatigue Behavior of A356
The increasing application of aluminum castings as automotive suspension components has spawned great interest in the fatigue behavior of the A356 alloy system. The Society of Automotive Engineers (SAE) has done a round-robin evaluation of the alloy’s low-cycle fatigue performance and fracture toughness, as a function of microstructure, and some very good work has been done on the effect of porosity on fatigue performance by Couper, Neeson and Griffiths, and Ting. The comparison of these works shows one
problem in interpreting the literature in this area. Not all authors examine all parameters. This is an observation as opposed to a criticism, as no one can study everything within reasonable time constraints.

The SAE work does not mention porosity, concentrating almost exclusively on microstructural scale; this despite visible porosity in some micrographs. This is important, as porosity can become a systematic confounding influence in such an analysis since the pore size will vary with cooling rate, while the DAS is similarly varying. The other two works study porosity, irrespective of the scale of the microstructure although, presumably, a constant DAS would have been adhered to.

The work by Couper, Neeson and Griffiths started as an attempt to optimize the heat treatment of the alloy for fatigue life. It rapidly changed to a study of the impact of porosity on fatigue, when it was found that porosity in the specimens was controlling the fatigue life to a greater extent than was the heat treatment. In fact, the authors could plot the fatigue life of various heat treatments, including T4 and T6, on the same curve if the axes were cycles-to-failure versus the interaction parameter of [stress amplitude x initiating pore size]. The data was analyzed via fracture mechanics to yield a failure/no failure curve, based on the largest initiating pore from which the fatigue crack would start.

Ting analyzed the fatigue life of alloy 319 as a function of pore size, again using fracture mechanics. A maximum pore length of 187 µm was calculated, above which the pores would begin to degrade the fatigue life and below which they would not. Relationships to predict fatigue life were also generated.

PROCEDURE

Two sources of starting material were available for this study. The first consisted of end-chill cast A356 alloy blocks from the prior work of Apelian, Major and Tynelius. Each of the alloy and gas variations studied during that work were cast in duplicate with one end-chilled casting being sectioned for the porosity study and the other being heat-treated and retained for the fatigue study reported here. For the exact method of alloying, gas control, casting, heat treatment, etc., the reader is referred to that work.

Figures 4 and 5 show the two designs of end-chilled castings used in this work. Later, end-chill castings containing traces of antimony

Fig. 2. Plot of largest pore size present in A356 alloy for a given hydrogen level and temperature gradient. Two conditions are shown. A grain-refined alloy will exhibit smaller pores than will one that has not been so treated.

Fig. 3. Plot of largest pore size in a population of samples. Each point is a separate sample plotted with largest pore attached to an oxide film on one axis and largest nondirt-related pore on the other.

Fig. 4. Schematic drawing of original end-chilled mold built of stainless steel-lined fiberboard and mounted on a water-cooled copper chill box. The casting face of the chill box is only 3 mm thick with water sprayed along the surface. Drainage is arranged such that box remains water filled, once turned on.

Fig. 5. Adaptation of end-chill mold to sand casting. Molds sit over same chill box (bottom left in photograph) as drawn in Fig. 4. Pattern contains an integral gating system and alignment bosses.
in addition to strontium were cast, to allow the impact, or lack thereof, of Sb contamination via the scrap stream to be looked at. These were cast using a sand-cast end-chill (Fig. 5) arrangement as opposed to the fiberboard and steel mold (Fig. 4) used in the previous work. Solidification was identical in both designs, as the same water cooled copper chill was used and it easily overpowered any variation in solidification due to the comparatively insulating walls.

The other source of test material consisted of permanent-mold test castings. These castings were made using a version of a vertically parted mold, originally designed by the Aluminum Association.9 The Aluminum Association mold is, essentially, a vertical-step mold with varying section thicknesses. Although not as rigorously controllable as an end-chilled casting, the version of the AA mold, used in this study, had the experimental advantage of being comparatively poorly fed. As a result, the pores that were formed showed slightly more of the elongated interdendritic character, generally referred to as microshrinkage porosity. This is frequently a misnomer, since such pores generally nucleate at existing gas pores and are drawn out into the classic shrinkage shape during subsequent solidification. A more accurate term would be shrinkage-aggravated gas porosity.

Though not well fed, the AA mold did not normally show hotspots and, thus, the difference between the microstructures was not extreme. The end-chill castings showed mostly spherical gas porosity, except very near the chill.2 Each mold allowed a wide range of solidification rate-dependent microstructures to be studied, in combination with a wide range of pore sizes as controlled by the gas level of the metal. Figure 6 shows radiographs of slices taken vertically through each type of mold, with data on the scale of microstructure to be expected in various locations.

The specimens machined from the end-chill cast blocks and AA mold test castings for fatigue tests were button-head grip-insert fatigue specimens, with a 1/4-in. (0.64 cm) gauge diameter. A drawing of the specimen appears in Fig. 7. Testing was done on commercial closed-loop servo-hydraulic test machines using hydraulic grips. Test conditions were fully reversed axial loading to preset load amplitudes. The samples were tested to destruction, and the cycles-to-failure were recorded for each. The cycle rate was 30 Hz. Samples were sectioned from a range of locations to cover the DAS, and maximum pore size range is listed in Table 1.

After testing, one half of each fatigue specimen was split in half, axially, and metallographically prepared. From this, two quantities were manually measured: the maximum pore length or diameter characteristic of the sample and the DAS. A macro picture of three of the samples appears in Fig. 8a, to show the wide range in pore size covered, while Fig. 8b shows the extremes of DAS.

A more rigorous analysis would have used the actual pore that initiated the fatigue crack. This pore was, however, seldom easy to identify and an SEM survey of each fracture would have been necessary for the smaller pores. This was prohibitive, due to the time requirements that would have been imposed on the large database of samples being tested.

The fully reversed stress condition does not easily lend itself to a fracture analysis, as deformation of the fracture surface is virtually certain during the compressive half of the cycle. Thus, a survey of the crack face was intentionally limited to a check for inclusions or oxide films that would have invalidated the result of that particular test. Such samples were very few and were immediately discarded. The final number of fatigue tests included in the data set of this work was 201.

**Statistical Data Reduction**

The database of fatigue results was analyzed, using multiple regression analysis as described in the prior work on porosity.3,4 Predictors examined included maximum pore size, DAS, Sr content, addition of grain refiner, mold type and Sb content. The single response was the fatigue life expressed as cycles-to-failure and properly transformed as described ahead. Any difference in pore morphology between the end-chill castings and the AA castings was handled via the category predictor parameter “mold,” which was allowed to assume values of either AA or EC for Aluminum Association versus end-chill cast samples, respectively.

![Fig. 6. From right to left are radiographs through thin slices of a high-gas end-chilled casting, a high-gas AA casting, a low-gas AA-casting and an AA casting poured with a short riser. The last was included to illustrate borderline feeding condition achieved in this version of the AA mold, as a macroshrink appears in the center. DAS numbers are shown on leftmost AA mold and up the side of the end-chilled casting.](image)

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<th>Table 1. Parameters and Ranges Studied</th>
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![Fig. 7. Fatigue bar geometry.](image)
RESULTS

It should be noted that care must be taken in this type of analysis to make sure that the data set be properly analyzed before any models are constructed. The degree of conformance to a normal distribution of each numerical parameter must be checked, and transformations made as necessary to ensure this for both the individual parameters and any interaction parameters that one wishes to evaluate.

A good example is the response variable in this work. Figure 9 shows a comparison of the shape of the distribution of the raw fatigue values, compared with the distribution of the same data subjected to a natural log transform. The ln transform gives a far more normal distribution and is, therefore, the correct choice; this is not surprising, given the nature of fatigue curves. Note that a perfectly normal distribution cannot generally be achieved for every parameter. In fact, this is not necessary, as modern statistical routines are quite robust when given sufficient data, but one should try to come as close as possible and avoid badly skewed distributions.

Because the analysis is multiple linear regression, the linearity of the relationship between the predictor variables and the response must also be explored. Examples of this are shown in Fig. 10 for the interaction parameters between stress amplitude and either DAS or largest pore size. These plots are made from the raw data, and it should be kept in mind that the largest pore size interaction plot includes all DAS influence and vice versa.

Once models are constructed, care should be taken that the impact of any outliers in the dataset are taken into account, so that they can be eliminated. In this work, only three points out of 204 were evaluated as outliers and eliminated from the analysis.

Two of the models constructed by multiple regression from the dataset of this work appear in Tables 2 and 3. Table 2 shows a model that includes most of the parameters included in Table 1. A number of parameters are important and show high confidence, as indicated by the significance number, which approaches zero for a parameter with which a strong and certain relationship to the response variable has been found.

For the DAS, for example, the t-Value shows the relative strength of the parameter, in comparison to the others, while the significance number of 0.0006 is read as saying that the relationship found between the predictor and the response has only a 0.06% chance of being due to random chance alone. Compare this with the antimony content, which is the worst parameter in Table 2. The t-Value for Sb is some four orders of magnitude less than the strongest parameters in the model. This shows that its effect of the prediction is very small.
As well, its significance number of 0.952 means that there is a 95.2\% chance that the relationship between the Sb content and the response variable is due to random chance alone. Normally, a greater than 5\% (0.05) significance value for a parameter is sufficient cause to reject it from the model. On this basis, the only important parameters in Table 2 are the intercept, DAS, and the interaction parameters of $\sigma_A \times \ln[DAS]$ and $\sigma_A \times $Largest Pore Size. This model is included mainly to display the parameters that had little direct influence on the fatigue life.

A smaller model built with only the significant parameters is shown in Table 3. This model has a correlation coefficient of 0.84, meaning that it explains 84\% of the variation in the dataset. Considering the scatter normally inherent in fatigue testing and the fact that the actual pore responsible for nucleating the fatigue crack was not measured for each test, this was considered very good.

Results from the model of Table 3 are output as prediction plots. Figure 11 shows the fatigue life, plotted as a function of maximum pore size, for two different stress amplitudes. The error bars shown are 95\% confidence intervals. Note that the maximum pore size axis has been plotted on a log scale to stress the fact, visually, that the degradation in fatigue life with increasing pore size is less at small pore sizes but becomes more serious as the pore size increases.

Figure 12 is designed to show the comparative influence of porosity and DAS. The topmost pair of curves shows predictions for both small and large DAS values at a small pore size, while the bottom-most pair of curves shows the same comparison DAS values, but at a large pore size.

### DISCUSSION OF RESULTS

The results of this work highlight the importance of porosity control in the production of fatigue critical structural components. Once the parameters of stress amplitude, largest pore size and DAS, which directly control the fatigue life, are properly accounted for, the indirect parameters, such as modifier content and grain refinement practice, lose their significance. This is not to say that these are unimportant; quite the contrary, they have a strong influence on the largest pore size.3,4

Of particular interest is the relationship between fatigue life and largest pore size. At 85 MPa, the drop in fatigue life between 30 \(\mu\)m
and 100 μm, predicted by the model of Table 3, is roughly 7%, rising to 20% at 250 μm. At 500 and 1000 μm, this rises to 38% and 63%, respectively. As can be seen in Fig. 11, the effect only becomes worse at higher stress amplitudes.

Thus, controlling the maximum pore size in a given casting is important and, if necessary, the reduction in fatigue life should be allowed for by designing to a reduced number consistent with the capabilities of the foundry and process in question. The maximum pore size allowed in any area of a casting agreed to as fatigue critical between the foundry and customer would, and should, become a quality control parameter for the foundry to work to.

The plot of largest pore size and DAS, shown in Fig. 12, shows that the effect of increasing DAS becomes smaller as the stress amplitude is reduced. The spread between the curves of large versus small pores also decreases, but not to the same extent seen for the DAS. Also, of interest to the designer is the variability in the fatigue prediction. This is best seen in Fig. 12. The 95% confidence bars are smallest for the topmost curve of fine microstructure and small pores. The confidence intervals become larger with increasing DAS and/or pore size.

CONCLUSIONS

1. The parameters that directly affect fatigue life include the largest pore size, DAS and, of course, the stress amplitude. Once these are taken into account, the indirect parameters, which are important in determining the largest pore size, lose their significance.
2. The parameter that had the largest impact on the fatigue life was the largest pore size.
3. The impact of the secondary DAS on the fatigue life was weaker than that of the largest pore size and tended to decrease with decreasing stress amplitude.
4. Greater variability in the results can be expected as both the DAS and pore size increase.
5. At the stress levels studied in this work, Sb contamination of Sr-modified alloys had no detectable influence on the fatigue life.
6. The difference in pore morphology for the two molds used in this work failed to show as a dependable predictor.

REFERENCES