STATISTICAL DESCRIPTION OF LARGEST PORE SIZE IN MODIFIED AL-SI ALLOYS

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Abstract
Casting defects in AlSi7Mg alloys are owing to the processing technology inseparable features of final products. The porosity consisting of gas pores or microshrinkages is the most decisive factor influencing the fatigue life of castings. Extreme value statistic method has been shown a suitable procedure for prediction of a size of the largest defects, which can occur in real castings, which are substantially larger than the area of a control specimen prepared for defect distribution analysis. In this contribution application of Murakami’s statistical method based on the description of the largest extreme value distribution to the evaluation of porosity in AlSi7Mg alloy prepared by casting technologies with two types of modifiers, namely Sr and Na is presented. The results of statistical analysis are compared with the fatigue performance of specimens manufactured from particular materials.

Keywords: Cast AlSi7Mg alloy, Porosity, Murakami’s statistical method

1. Introduction
Fatigue properties of aluminum castings are sensitive to the defect size. In recent years, the maximum defect size has been recognized as the most important parameter determining the fatigue properties of aluminum castings. The larger the maximum defect size, the lower the fatigue strength. In the presence of imperfections the fatigue strength is primarily affected by them, the effects of chemical composition, heat treatment or solidification time, as reflected by dendrite arm spacing and the sizes of eutectic silicon and intermetallic particles are relatively low [1].

A cast AlSi7Mg alloy with two different modifiers was analysed in this study. The choice between sodium or strontium as modifier is determined by many factors. Sodium is accepted as the more potent modifier, but the rapid fade, fume evolution and low controllability of sodium additions has led to its gradual replacement by strontium in the majority of foundries [2].

One of the roles of modifier is a control of porosity dispersion in casting, whether caused by gas or shrinkage, [2]. The mechanism of porosity redistribution is not precisely understood. The increased freezing range of modified alloy due to the reduced eutectic temperature leads to large semi-solid regions in the casting. This leads to longer feeding paths to counteract shrinkage and to the possibility that it becomes blocked. This results in lower porosity in the feeders/risers and higher in the bulk of the casting. There are also arguments for easier pore nucleation due to the reduced surface tension of modified melts. If pores are easier to form, then they will occur earlier during solidification and thus be more numerous, smaller and better dispersing in the casting [2].

Modified AlSi alloys were produced and examined metallographically in this work. Two definitions of equivalent pore size, namely in terms of area1/2 and in terms of Maximum Feret Diameter (MFD), were used in the evaluation of pore severity observed on polished cross-sections. The statistical description of the largest pore size uses the Murakami’s method based on the Largest Extreme Value Distribution (LEVD) [1, 3]. The implication on the role of pores in fatigue is discussed.

2. Experimental material and methods
Three sets of cast AlSi7Mg alloy were used in the experiments. The same basic material was used for production of sets A and B. Set A was modified with pure...
Na and set B modified with pure Sr and cast in a steel shell mold. Set C was produced using AlSi7Mg with Sr modification and the sand casting process.

Five bars for the sets A and B and three bars for the set C were separately cast. All the specimens were heat treated to the T6 regime. Metallographic specimens were extracted from the cast bars. The structural analysis applying metallographic techniques on polished cross sections was carried out. Typical microstructures are shown in Fig. 1.

The microstructure is characterized by primary dendrites of α-phase (solid solution Si in Al with maximal solubility limit 1.59 % at eutectic temperature 577 °C) together with an eutectic structural compound E = (α + Si) located between the secondary dendrite arms. The silicon as eutectic phase grew as thin, interconnected rods in α-phase because Na or Sr modifiers to the liquid metal were used. The modified silicon rods appeared as round particles on the metallographic section, Fig. 1. The structure and secondary dendrite arm spacing (SDAS) were similar in cases of steel shell mould cast specimens regardless of the modifier. The SDAS value for the sand cast specimens was larger than that for the shell molding, Tab. 1.

Casting porosity was studied on metallographic specimens using a light microscope. However, random 2-D sections through pores cannot provide good estimates of the largest defect size without further data analysis. Furthermore, pores originating fatigue fractures observed on fracture surfaces are significantly larger than pores observed on the metallographic sections regardless of the alloy [1, 4]. Therefore, the largest pore size expected in a cast component has to be estimated by extrapolation of the statistical description of the equivalent pore sizes obtained by metallography [1]. Here, the Murakami’s method for the characterization of the pore size population according the LEVD method, [5], based on the evaluation of the largest defect size in many fields of view was applied. The image analysis program NIS Elements 3.0 for extensive and detailed measurement of pore features was used.

Because the shape of casting defects is not the same in all cases, according to the defect origin (gas pores, microshrinkages), different definitions of pore severity (or equivalent pore size), namely in terms of area^{1/2} and Maximum Feret Diameter, in the investigation of polished cross sections were used, [1, 3]. The scheme of measurement of defects is shown in Fig. 2. For the largest pore sizes evaluation the 50 x magnification was used. The control area of metallographic measurements was S_0 = 1.86 mm^2.

The equivalent defect size, area^{1/2}, was obtained from measured area by the image analysis software; examples of such determination are shown in Fig. 2. The Maximum Feret Diameter was measured as the maximum distance between pairs of parallel lines tangent to the two-dimensional outline of a defect, shown in Fig. 2, too.
Fig. 2 shows that the two definitions of equivalent pore size give quite different results when applied to the two pores, one rounded and the other elongated. Pore A yields the value of area\(^{1/2}\) = 261 µm and Maximal Feret Diameter = 593 µm; pore B is characterized by area\(^{1/2}\) = 220 µm and Maximal Feret Diameter = 332 µm. Although the shape of defects is different, the area\(^{1/2}\) is quite similar for both of them. The difference between values of Maximum Feret Diameter characterizing measured defects is substantial.

3. Porosity evaluation and LEVD plots

The results of the largest pore size characterization according to the LEVD method, [5], are plotted in Fig. 3. Since all data in the LEVD plots fulfill the linear dependence, the Gumbel statistical distribution describes all data sets. The LEVD plots using the area\(^{1/2}\) parameter are shown in Fig. 3a and the plots using the Maximum Feret Diameter parameter in Fig. 3b. Although the same largest defects were measured, the use of different parameters characterizing the pore size give different results because of the role of defects shape as explained in Fig. 2.

The slope of the regression line is an indicator of the defect distribution. Inspection of Fig. 3 shows that set A has the largest scatter among the three materials while set B and C have similar and reduced scatter. As far as the influence of the modifier, defect average size and scatter of measured values were smaller in the Sr-modified specimens than in the Na-modified specimens. The sand cast method involved pores that are smaller and less scattered than the steel shell mold casting.

Generally, set A modified by pure Na has the largest pores. The smallest sizes of the largest defects were measured for the set C modified by Sr and obtained by sand casting. In the case of specimens cast to steel shell mold, smaller defects sizes on specimens from set B, modified by Sr, were measured.

The comparison of plots in Fig.3 shows also in absolute values differences between defects sizes predicted from measurements on cross sections of metallographic specimens using the area\(^{1/2}\) values.

The differences between porosity measured on metallographic specimens, described by LEVD plots, shown in Fig. 3b, where the MFD values were used, have similar trend as in case of LEVD plot for area\(^{1/2}\) values. In addition, in this case, the smallest defects sizes on the Sr modified specimens were measured. In this case, the largest defects obtained on sand cast specimens compared to defects sizes on steel shell molding specimens were smaller and the scatter in data was smaller too.

4. Porosity prediction and implication for fatigue

The largest defects sizes expected in a given area S was used to compare the influence of modifiers on porosity, Na for the set A and Sr for the sets B and C, and the influence of production technology on porosity size population. In order to correlate the largest values of defects with fatigue properties of studied alloys extrapolated values of the largest pores expected in areas responsible for fatigue damage were obtained from the LEVD description of the
different sets of materials. The predicted largest defects sizes for two different cross-sectional areas, i.e. $S = 10 \text{ mm}^2$, which is representative of the highly stressed cross section of a rotating bending specimen, and $S = 100 \text{ mm}^2$, representative of a small casting, are shown in Tab. 1.

**Table 1**

<table>
<thead>
<tr>
<th>Prediction of the largest defect size for:</th>
<th>$S = 10 \text{ mm}^2$</th>
<th>$S = 100 \text{ mm}^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set</td>
<td>SDAS $[\mu m]$</td>
<td>area $^{1/2}$ $[\mu m]$</td>
</tr>
<tr>
<td>set A</td>
<td>32</td>
<td>186</td>
</tr>
<tr>
<td>set B</td>
<td>30</td>
<td>148</td>
</tr>
<tr>
<td>set C</td>
<td>40</td>
<td>99</td>
</tr>
</tbody>
</table>

In all cases the predicted largest defects sizes expressed in terms of area$^{1/2}$ are larger than the critical defect size for fatigue crack initiation (in Sr modified cast A356 alloy, the critical defect size at the fatigue limit is in the range of 25-50 $\mu m$, [6]). However, not only the size of casting defects influences fatigue lives of castings, but also their shape and localisation towards the free surface of casting, porosity population and its occurrence in clusters can play a role and, last but not least, also the defects origin can be of significance [1, 4, 7].

A final comment to the results presented in Tab. 1 relates to the observation that predicted MFDs values of the largest pores are about twice of these derived from area$^{1/2}$ equivalent sizes. Naturally, a significant influence has to be expected on predicted residual life calculations in fatigue as they are assumed to be the initial crack size.

To assess and rank the influence of largest pore size both in terms of MFD and area$^{1/2}$, the AFGROW structural life prediction program was used [8]. The input data needed to run AFGROW include: i) crack growth data: $dK/dN$; empirical Paris law coefficient and exponent, $C$ and $m$ plane strain fracture toughness, $K_{IC}$, and plane stress fracture toughness, $K_C$; ii) maximum applied load, stress ratio, constant amplitude in the case of interest; iii) geometry and dimensions of the component, initial flaw geometry, size, and location.

The material data were taken from [9]; the loading conditions from testing performed at University of Parma on similar cast material, [4]. Information related to iii) are: rotating bending geometry $R$=-1, smooth 6-mm-dia section, initial surface crack size equal to the largest pore size.

**Fig. 4** Predicted influence of the largest pore size on the fatigue life of rotating bending specimens of AlSi7Mg at two applied stress levels.

Fig. 4 shows the results of the simulations of lifetime for two stress levels and different initial crack sizes. The influence of the largest pore size prediction on fatigue life is immediately determined entering in the plot with the data of Tab. 1 and selecting the applied maximum stress. An example is given in Tab.2 for a stress amplitude $S_a = 100 \text{ MPa}$ and a reference area $S = 10 \text{ mm}^2$. Data in Tab.2 demonstrate an approximately factor-of-two influence on calculated fatigue life in dependence of material set. Similarly, a factor-of-two is found comparing the life predictions based on either the area$^{1/2}$ or the Maximum Feret Diameter.

**Table 2**

| Predicted number of cycles for stress amplitude $S_a = 100 \text{ MPa}$ and reference area $S = 10 \text{ mm}^2$ |
|-------------------------------------------------|------------------|-------------------|
| Set                                             | area $^{1/2}$ $[\mu m]$ | $N_f$ [cycles] | Max. Feret Diameter $[\mu m]$ | $N_f$ [cycles] |
| set A                                           | 186               | $2.3 \times 10^5$ | 377                         | $1.1 \times 10^5$ |
| set B                                           | 148               | $3 \times 10^6$  | 279                         | $1.6 \times 10^6$ |
| set C                                           | 99                | $4 \times 10^6$  | 180                         | $2.3 \times 10^6$ |

5. **Conclusions**

The casting porosity has a strong influence on fatigue properties of castings produced from Al-Si alloys. Therefore, the largest pore size prediction is a suitable tool for fatigue life prediction and for comparison of different materials. In this study the same base alloy, AlSi7Mg, modified with Na or Sr, was used for production of specimens using either steel shell mold casting or sand casting. The following conclusions can be drawn from this study:
Murakami’s statistical method for the porosity description and the largest defects sizes prediction can be applied for studied alloys, because all values in LEVD plots fulfill a linear dependence.

Two parameters were used for defect characterization, namely Maximum Feret Diameter and area$^{1/2}$ parameter.

AlSi7Mg modified with Na contains defects of larger size than the Sr modified alloy.

Use of a simple fracture mechanics model demonstrated the important role of the initial crack size estimate, which is assumed to be equal to the largest pore size expected in a reference volume, on the predicted fatigue life of a material.

Predicted fatigue lives, based on the Maximum Feret Diameter, are larger than the predicted fatigue life based on the area$^{1/2}$ parameter.

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