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CASTING PORE CHARACTERIZATION BY X-RAY COMPUTED TOMOGRAPHY AND METALLOGRAPHY

Casting porosity is the main factor influencing the fatigue properties of Al-Si alloys. Due to the increasing use of aluminum castings, porosity characterization is useful for estimating their fatigue strength. In principle, a combination of metallographic techniques and statistical pore analysis is a suitable approach for predicting the largest defect size that is critical for the casting. Here, the influence of modifiers and casting technology on the largest pore size population in AlSi7Mg alloy specimens is obtained and discussed adopting the Murakami's approach. However, porosity evaluation is a challenge in the case of microshrinkage pores, which are frequently found in industrial castings. Their complicated morphology prevents a reliable definition of an equivalent defect size based on metallographic techniques. This contribution reports the application of X-ray tomography to the 3D reconstruction of real pores in cast Al-Si alloys and provides insight into the complication of microshrinkage pore sizing by metallography.

1. Introduction

Cast Al-Si alloys are widely used in automotive applications for their excellent combination of mechanical and technological properties. Fatigue properties of aluminum castings are, however, sensitive to the casting defects [1]. Fatigue properties of aluminum shape castings are sensitive to the defect size. In recent years, the maximum defect size has been recognized as the most important parameter in determining the fatigue properties of aluminum shape castings. The larger the maximum defect size, the lower the fatigue strength. In the presence of imperfections, fatigue strength is little affected

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by chemical composition, heat treatment, or solidification time, as reflected by dendrite arm spacing and the sizes of eutectic silicon and intermetallic particles [2]. Casting defects have a detrimental effect on fatigue life by shortening not only fatigue crack propagation, but also the initiation period. The decrease in fatigue life is directly correlated to the increase of defect size [1].

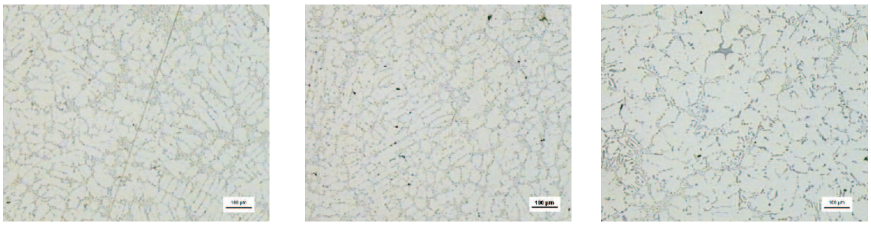
In this paper, a method of statistical pore size characterization by metallography is initially considered. Two definitions of equivalent pore size, namely in terms of area $^{1/2}$ and in terms of Maximum Feret Diameter, in the evaluation of pore severities observed on polished cross-sections were used. The statistical description of the largest pore size uses the Murakami's method based on the Largest Extreme Value Distribution (LEVD) [2]. Then, X-ray computed tomography (XCT) for the 3D shapes and distribution of casting defects in AlSi7Mg reconstruction was used. Special interest is devoted to microshrinkage pores irregular in shape. The XCT results to discuss metallographic issues in equivalent pore sizing criteria were used.

2. Experimental material

Three sets (A, B and C) of specimens of AlSi7Mg alloy were used in the experiments. The specimens for fatigue testing were prepared by machining from separately cast bars. The difference between bars depended on modifier used and casting process. Specimens of set A were modified by pure Na and cast in a steel mold, specimens of set B were modified by Sr and cast in steel mold while specimens from set C were modified by Sr and sand cast. All the specimens were heat-treated according to the heat treatment regime T6.

The structural analysis was carried out applying metallographic techniques and digital image analysis software NIS Element 5 on polished metallographic cross sections according to the Slovak standard STN 42 0491. Typical microstructures of the three sets of cast AlSi7Mg are shown in Fig. 1. The microstructure consists of primary dendrites of α-phase (solid solution of Si in Al) and eutectics (α-phase + Si particles). Si particles on the metallographic section were observed as round particles due to the optimal modification of the cast alloy.

The microstructure was also characterized determining the Secondary Dendrite Arm Spacing (SDAS) factor. Evaluation of SDAS was performed according to the line method (i.e. line length = 120 mm) [3]. The SDAS factor for the set A and B, both cast in steel mold, showed similar values (i.e. SDAS = 30 μm for the set A and 32 μm for the set B). For the sand cast set C, the measured SDAS value was 40 μm, Tab. 1.



a) set A - modified by pure Na, steel mold cast

b) set B - modified by Sr, steel mold cast

c) set C - modified by Sr, sand cast

Fig. 1. Typical microstructure of AlSi7Mg aluminum cast alloy

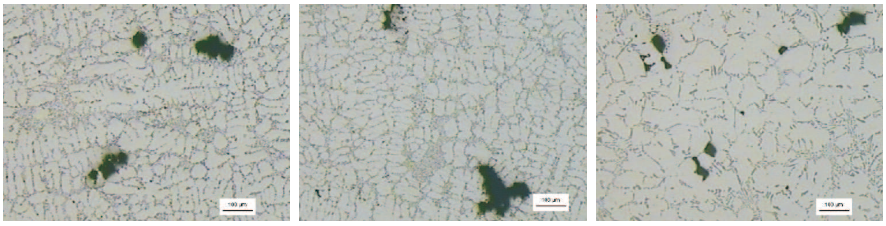
3. Results and discussion

3.1. Pore sizing by metallography

Comparison of different materials in terms of porosity suggests material ranking with respect to fatigue performance. Knowledge of the expected largest pore size and its location is a suitable information and can be obtained by metallography. Previous experiments used for correlation between the predicted largest defect sizes and actual sizes of defects responsible for the fatigue crack initiation used alternatively two equivalent parameters: the pore area$^{1/2}$ and the max. Feret diameter, [2, 4]. Those two parameters characterize the defect size population in different ways. But this is not unexpected because the equivalent defect size definition is complex in the case of microshrinkage pores of complicated morphology and interconnected shape.

3.1.1. Metallographic evaluation

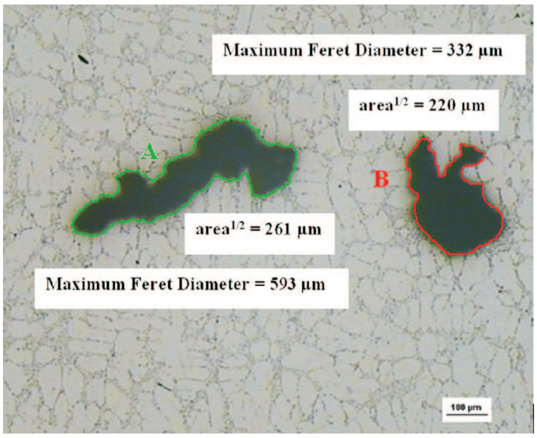
Metallography can be routinely used to study porosity in Al-Si castings. Typical porosity observed on the metallographic section of specimens is shown in the Fig. 2. The defects are different in the shape, size, amount and relative location among themselves and with respect to the free specimen surface. Casting porosity was extensively studied on the metallographic specimens using a light microscope. However, random 2D sections through pores cannot provide good estimates of the expected largest defect size without further data analysis. Furthermore, pores that originated fatigue fractures are significantly larger when observed on the fracture surface than pores measured on the metallographic sections regardless of the alloy. 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 [2].



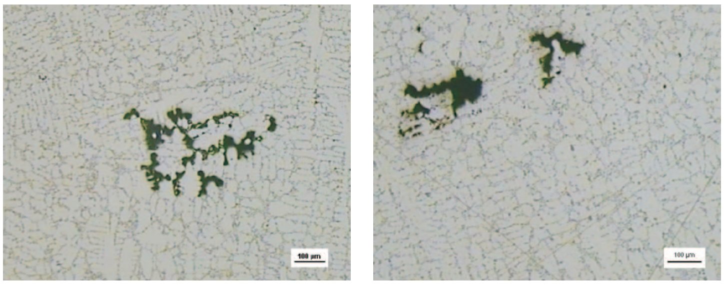
a) set A - modified by pure Na, steel mold cast *b) set B - modified by Sr, steel mold cast* *c) set C - modified by Sr, sand cast*

Fig. 2. Typical porosity of AlSi7Mg cast alloy

Fig. 3a shows two casting pores in AlSi7Mg alloy and the difference between two definitions of the equivalent pore size, namely the maximum Feret diameter (i.e. maximum distance between two points on the pore surface), [2], and area $^{1/2}$, [4], to define pore severity in fatigue. Quite different equivalent sizes are obtained because one pore in Fig. 3a is more rounded and another one is more elongated.



a) characteristic defect sizes measurement scheme



b) typical microshrinkage pores morphology

Fig. 3. Casting pores in AlSi7Mg observed by metallography

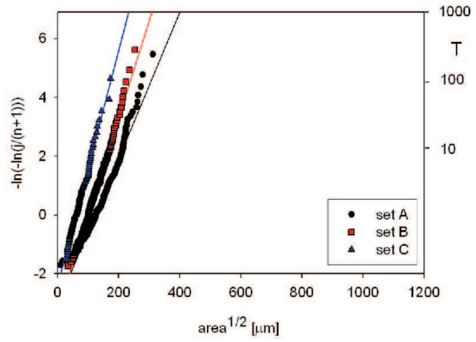
In some cases, there are difficulties to identify the real defect shape in the volume and corresponding characteristic defect size, which should be measured and used for the largest defect size prediction. Although cast defects on metallographic sections are observed as disconnected areas, they are probably branches of a single microshrinkage pore, Fig. 3b, sectioned during the metallographic specimen preparation. The casting defects observed in the present metallographic investigation were microshrinkage pores in all cases. Some of the observed defects were more rounded, i.e. Fig. 3a, but not as much as typical gas pores, [6].

There is no unique model how to measure and define the defect size of those microshrinkage defects observed in our case and typical for the Al-Si castings. Their presence is caused by the casting solidification. As different regions of a casting freeze, the shrinkage is compensated for by drawing liquid from neighboring areas, a process known as feeding. In long freezing-range alloys, feeding through the mushy zone is via small interdendritic channels. As solidification progresses, the ability to feed becomes more and more difficult due to the decreasing size of the channels. Eventually the channels freeze completely, isolating small areas from a supply of fresh metal. At this point any shrinkage occurring in these isolated areas causes a tension within the liquid, and voids may form to relieve this tension. These shrinkage pores may continue to grow into the interdendritic channels with the aid of any additional shrinkage. As a consequence of their growth mechanism, shrinkage pores tend to be composed of many long and irregular “arms”, [6].

3.1.2. Largest defect size prediction

The Murakami’s statistical method for the pore size evaluation was used, [4]. The method is based on the selection of the largest defect size present in a large number, n, of fields of view (i.e. controlled area S_0 dependent on image magnification) of polished metallographic sections. The equivalent size, area$^{1/2}$, of the largest pore within each region is recorded. The set of n observations of maximum sizes area$^{1/2}$, or $x_1, ..., x_n$, is used to determine whether the Gumbel distribution [4] gives a good fit. In a Gumbel plot ($y_j = -ln(-ln(j/(n+1)))$ vs. $x_{(j)}$) the data should lie close to a line. The fitted distribution is then used to estimate the size of the largest defect size in a given region S larger than the control area S_0, through the return period $T = S/S_0$, or to compare largest defects from control areas of different sizes [4].

Examples of largest pore size data sets entered into the Gumbel plot are shown in Fig. 4. Since each data set appreciably fulfills the linearity condition, the Gumbel statistical distribution can be used for fitting, extrapolation and comparison. The slope of the regression line is an indicator of the data scatter. Inspection of Fig. 4 shows that the set A (modified with Na and cast in steel mold) has the largest scatter among the three materials while the set B (modified with Sr and cast in steel mold) and the set C (modified with Sr and sand cast) have similar and reduced scatter. The results were analogous when we used either area$^{1/2}$ as an equivalent pore size or maximum Feret diameter. Estimates of the largest defects size expected in a given area *S* can be used to compare the influence of the modifiers, i.e. Na for the set A and Sr for the sets B and C, and production technology on porosity and fatigue.

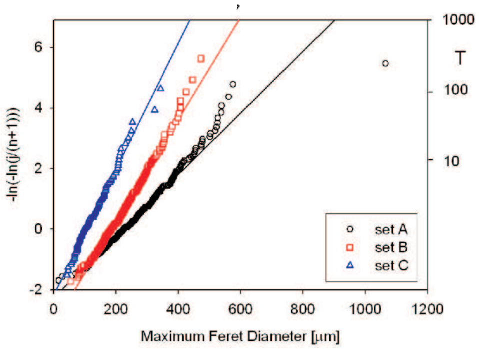


a) LEVD plot from area$^{1/2}$ data;

set A – modified by pure Na, steel mold cast,

set B – modified by Sr, steel mold cast

set C – modified by Sr, sand cast.



b) LEVD plot from maximu Feret diameter data;

set A   modified by pure Na, steel mold cast,

set B – modified by Sr, steel mold cast,

set C – modified by Sr, sand cast.

Fig. 4. Largest pore sizes in AlSi7Mg alloy according to the LEVD theory

In order to correlate the largest values of defects with fatigue properties of the studied AlSi7Mg alloy, the extrapolated values of the largest pores expected in areas responsible for fatigue damage were obtained from the Gumbel description of the different sets of materials. The largest defects sizes for two different cross-sectional areas were predicted; i.e. for the area S = 10 mm^2, which is representative of the highly stressed cross section of a rotating bending specimen, and area S = 100 mm^2, representative for a small castings, Tab. 1. In all cases, the predicted largest defects sizes expressed in terms of area$^{1/2}$ are larger than the critical defect size for the fatigue crack initiation (in Sr modified cast A356 alloy, the critical defect size at the fatigue limit is in the range of 25-50 μm, [1]). When the casting defect size is larger than this critical defect size for the fatigue crack initiation, [2], other microstructural features will play only the minor role in the fatigue crack initiation and the crack will be initiated preferentially on the casting pore.

Table 1.

Predicted largest defect sizes forAlSi7Mg alloy

Prediction of the largest defect size for:		S = 10 mm^2		S = 100 mm^2	
Set	SDAS [μm]	area$^{1/2}$ [μm]	Max. Feret Diameter [μm]	area$^{1/2}$ [μm]	Max. Feret Diameter [μm]
set A	32	186	377	283	612
set B	30	148	279	221	421
set C	40	99	180	159	295

3.3. Pore reconstruction by XCT

However, not only the size of casting defects does influence the fatigue life of castings. Their shape, origin and localisation with respect of the free surface can play a role, [1, 2, 8]. To obtain realistic information of actual pore shape, distribution within a material volume, a technique such as X-ray tomography (XCT), which is finding many applications in material science, [5], could be used. XCT exploits the penetrating power of a high density focused x-ray beam and it is based on a two-step procedure.

In the first step, a large number of XCT scans of a material volume are acquired. These scans are “front photos” of the specimen, representing pixel by pixel the absorption coefficient of the material crossed by x-rays. From these scans, cross-section images (i.e. slices) of the material volume are obtained with a back-projection algorithm. The second step of the procedure is the 3D reconstruction of pores from the series of slices. Original software has been developed to obtain all the pores inside the volume under investigation (i.e. a cylinder 4 mm in diameter and 1 mm in length shown in Fig. 5). Only the outer surface of each pore is stored as non-structured triangular surfaces according to the STL standard and finally smoothed.

The 3D shapes of cast defects found in Al-Si depend on the generation mechanism. Gas pores are usually approximately spherical in shape because they exist first as bubbles within the liquid. On the other hand, microshrinkage pores tend to be composed of many long and irregular “arms” as a consequence of their growth mechanism, [6]. The high spatial resolution of the

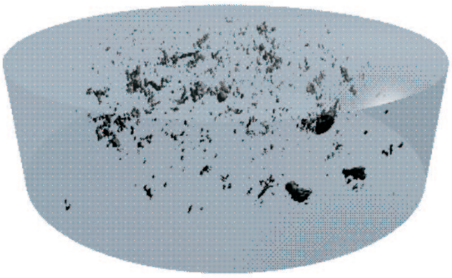
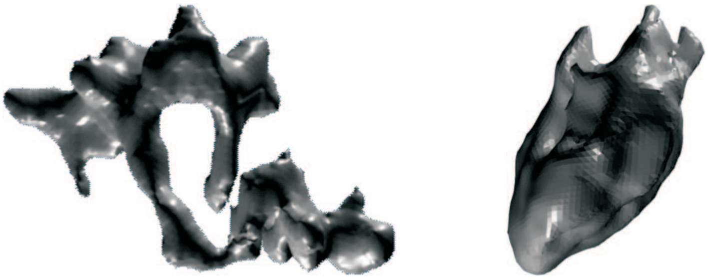


Fig. 5. Reconstruction of the porosity in a cylindrical volume of the specimen from AlSi7Mg cast alloy

present XCT equipment allows the reconstruction of the intricate geometry of microshrinkage pore, see Fig. 6, and of the defect distribution in the volume, see Fig. 5. By this method, not only the shape and size of defects can be reconstructed, but also their location to the free surface of specimen and also their mutual location can be controlled. Also the clusters of defect and spaces without defects can be detected.



a) complicated morphology *b) compact morphology*

Fig. 6. 3D models of casting defects identified by the X-ray tomography

Although not presented here, [7], the reconstructed pores can be embedded into a finite element model of the material volume to investigate the influence of parameters such as shape, size, vicinity, etc., on the internal stress distribution. For example, the complex, branched shape of the shrinkage pores can lead to larger stress concentration compares to the rounded gas pores.

3.4. Sectioning a microshrinkage pore

The branched appearance of microshrinkage pores poses a challenge to the metallographic characterization of largest pore sizes for fatigue model development. Metallographic methods were originally developed to quantify the role of inclusions, which are typically compact in shape, [2]. Since metallography observes a random material section under high magnification, it is unlikely that sectioning a pore exposes the largest pore dimension. However, in the case of a compact pore, i.e. gas pore, the largest size in a given area can be obtained by extrapolation of measured sizes if they fit a statistical distribution. On the other hand, clusters of observed defects such as in Fig. 2 and 3 cannot readily classified as a group of gas pores or as the result of sectioning through branches of one complicated microshrinkage pore. An example of a microshrinkage pore sectioning is visualized in Fig. 7, where isolated neighboring cavities are found. None of these pseudo-pores, even the largest one, has a size comparable to the size of the original pore. Therefore, guidelines for estimating representative pore sizes based on coalescence conditions of neighboring pores are needed. The scheme of Fig. 7 explains why the determination of the actual equivalent size of pores shown in Fig. 2 and 3 is not straightforward and criteria for pore vicinity and coalescence should be defined and which equivalent size parameter should be used (i.e. area ½ or max Feret diameter). An on-going FEM investigation of the effective stresses near pores of different kinds, [7], demonstrates that gas and microshrinkage pores of similar size in terms of max. Feret diameter give comparable stress concentration with negligible influence of pore morphology.

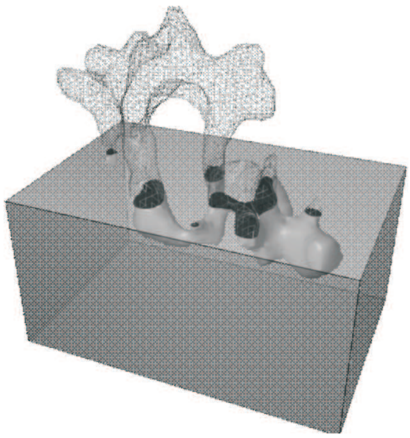


Fig. 7. Cross-section through 3D model of a microshrinkage pore and in black the resulting cluster of pores in the metallographic section

4. Conclusions

In this study, the same base alloy, AlSi7Mg, modified with Na or Sr, was used for the production of specimens using either steel die casting or sand casting. Metallography and X-ray tomography were used to characterize the cast porosity and its dependence from the technological parameters. Production technology and modifiers influence mainly the pore size distribution not the typical shape.

The following conclusions can be drawn from this study:

Murakami's statistical method for the pore size description and the largest defect size prediction can be applied to the present alloys, because data fulfill a linear dependence in the Gumbel plot.

Two alternative parameters for the equivalent defect size definition, i.e. maximum Feret diameter and area$^{1/2}$, gave similar relative statistical descriptions for the different production methods of AlSi7Mg.

AlSi7Mg specimens modified by pure Na contains larger defects than the Sr modificated specimens.

X-ray tomography gave a detailed and accurate description of casting porosity in terms of pore size, shape and distribution.

3D modeling of defects observed by x-ray tomography can be used to understand the influence of the complex shrinkage pore shape on metallographic technique of pore size characterization to be used for the fatigue life prediction.

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Charakteryzacja porów odlewniczych metodami rentgenowskiej tomografii komputerowej i metalografii

Streszczenie

Porowatość odlewów jest głównym czynnikiem wpływającym na właściwości wytrzymałościowe stopów Al-Si. Z uwagi na rosnące zastosowanie odlewów aluminiowych, charakteryzacja ich porowatości nabiera znaczenia dla oceny wytrzymałości zmęczeniowej. Uważa się, że właściwym podejściem jest zastosowanie kombinacji technik metalograficznych i statystycznej analizy porów, co umożliwia przewidywanie największego, krytycznego dla odlewu, rozmiaru defektów. W tej pracy wyznaczano i dyskutowano wpływ modyfikatorów i technologii odlewania na największy rozmiar populacji porów w próbkach stopu AlSi7Mg, przyjmując podejście Mirakami'ego. Ocena porowatości staje się jednak wyzwaniem w przypadku porów związanych z mikrokurczliwością, które występują często w odlewach przemysłowych. Ich skomplikowana morfologia powoduje, że trudno jest wiarygodnie zdefiniować równoważny rozmiar defektu w oparciu techniki metalograficzne. Przedstawione doniesienie zawiera opis zastosowania rentgenowskiej tomografii komputerowej do trójwymiarowej rekonstrukcji rzeczywistych porów w odlewie ze stopu AlSi i daje pogląd na temat komplikacji w wymiarowaniu porów związanych z mikrokurczliwością metodami metalograficznymi.