Porosity formation and fatigue properties of AlSiCu cast alloy

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Abstract. The need for aluminium alloys having a good toughness, high strength, adequate damage tolerance capability, good fatigue resistance and good corrosion resistance for use in the industries applications of aerospace, automotive and even commercial products led to study of the properties and structure of the AlSi9Cu3 cast alloy. The most important metallurgical parameters affecting the aluminium alloy's resistance to fatigue load are the amount, types and size of casting defects. Therefore quantitative analysis was used for determination of casting defects size by optical microscopy on metallographic sections and an analysis of the size distribution by extreme value statistics. The software NIS Elements was used for quantitative analysis of casting defects and results show that porosity have a great influence on to the fatigue properties of AlSi9Cu3 cast alloy.

Keywords: fatigue properties of aluminium alloys, quantitative analysis, porosity, extreme value statistic

1 Introduction

The most common aluminium alloys for automotive industry can be found in the groups of AlSi, AlSiMg and AlSiCu. These groups of aluminium alloys are the most versatile materials, comprising 85-90 % of the total aluminium cast parts produced by the automotive industry due to their highest strength-to-weight ratio, good thermal conductivity, excellent fluidity, hot tear resistance and feeding characteristics that allow casting intricate shapes such as engine blocks, cylinder head-sore chassis components [1-5]. These materials are important for their Si, Mg and Cu content, because Si considerably increase castability, tensile properties and hardness while Cu or Mg addition improve mechanical properties thanks heat treatment possibilities. The final mechanical properties of aluminium castings depends not only on chemical compositions (Si, Cu, Mg and Fe content) but on the solidification time, heat treatment, micro-voids, porosity, dendrite arm spacing, and distribution, shape and size of the silicon particles, second phases (especially Fe–rich phases) [6]. Bangyikhan [7] also pointed to the fact that: cast aluminium alloys are, at the best, only achieving and using one per cent of their potential mechanical properties, particularly in terms of fatigue life. The research shows that a great problem of lower mechanical and fatigue properties is the presence of oxides films, porosity and Fe-rich

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intermetallic phases in the castings [7,8]. Eady and Smith [9] also showed that pores could act as stress concentrators, initiation sites for fatigue cracks, and reduce tensile properties, particularly elongation.

Nowadays are known the new classification of defects and imperfections and is based on three-level approach [10, 11]:

I. Morphology (location) of defects (internal, external, geometrical);
II. Metallurgical origin of defects (gas-related defects, solidification shrinkage, shrinkage filling-related defects, undesired phases, thermal contraction defects, metal-die interaction defects, etc.);
III. Specific type of defects (the same metallurgical phenomenon may generate various defects at handling, finishing and machining operations).

In the past were developed three main point which should be used at producing casting for improving the casting quality [7, 12]: 1) control of the liquid metal prior to casting, 2) control of the pouring of liquid metal into the mould and any metal/mould reaction, 3) control of casting microstructure and defects during solidification. The problem is that in the casting are still presence of porosity which is not desirable for casting type of engine blocks, cylinder head-sore chassis components. These castings have a very complicated geometry which is essential to the correct operation of the engine. The consequences of fatigue damage are therefore not desirable. Fracture occurs after continuous accumulation of damage due to repeated mechanical, thermal or mechanic-thermal loading prior to failure. In the case of fatigue failure there is no macroscopic deformation of the solid. The whole process occurs in a micro volume at the crack tip or at a local site on the surface during the creation of a fatigue crack nucleus [13, 14].

The material group Al-Si-Cu are also used for components which work under condition of dynamic loading and that is why it is necessary to study the microstructure and properties of such alloys. Based on the knowledge above, a study was carried out to investigate the influence of porosity on the fatigue behaviour of secondary aluminium cast alloy of the Al-Si group (AlSi9Cu3) used extensively in automotive applications, which was casted into a metallic moulds at gravity die casting. The quantitative assessment was used in order to determine the nature of the porosity in secondary AlSi9Cu3 aluminium alloy. Also was used the analysis of casting defects according to Murakami's statistical method using Largest Extreme Value Distribution theory (LEVD) for prediction of largest defect size on the fracture surface. Statistical analysis of casting defects present in the structure has been shown to be an useful tool in the procedure of the fatigue life prediction.

2 Experimental material and methods

The experimental material was secondary cast AlSi9Cu3 alloy (prepared from recycled aluminium scrap) delivered from Confal a.s. company. The experimental material was delivered in form of ingots (Fig. 1a) and from these ingots were gravity die casted samples for experimental work into the metallic moulds (chill casting Fig. 1b). The experimental material was not modified or grain refined. The samples for mechanical and fatigue properties were made from the casted bars (Fig. 1b) with turning and milling operations. The dimension of samples were according to standards and regulations for mechanical and fatigue properties measurements. The chemical composition of the experimental material was checked out using arc spark spectroscopy, and it is shown in Table 1.

Table 1. The chemical composition of AlSi9Cu3 cast alloy according arc spark spectroscopy, wt. [%]

Si	Cu	Mn	Zn	Mg	Fe	Ni	Ti	Sn	Pb	Al
9.4	2.4	0.24	1.0	0.28	0.9	0.05	0.04	0.03	0.09	remainder

Mechanical properties were measured according to the following standards: STN EN ISO 6892-1:2010 and STN EN ISO 6506-1 [15, 16]. Hardness measurement for secondary aluminium alloy was performed using a Brinell hardness (HBW) tester with a load of 62.5 kp (1 kp = 9.81 N), 2.5 mm diameter ball and a dwell time of 15 s. Tensile strength (UTS) was measured using ZDM 30 testing machine. The evaluated UTS and HBW reflect average values of at least six separate specimens.

a) b)

Fig. 1. Experimental material

a) ingots delivered from Confal a.s.; b) gravity die casted samples for experimental work

Fatigue properties of chill casted specimens were carried out using Vibrophores Amsler 50-250 HFP 5100 testing machine with symmetrical push-pull load, and at a room temperature of 20 ± 5°C (Fig. 2). The dimensions of specimens for fatigue tests were ø18 x 150 mm. The stress amplitude was from 150 to 50 MPa and specified number of cycles for test was 2 x 10^7.

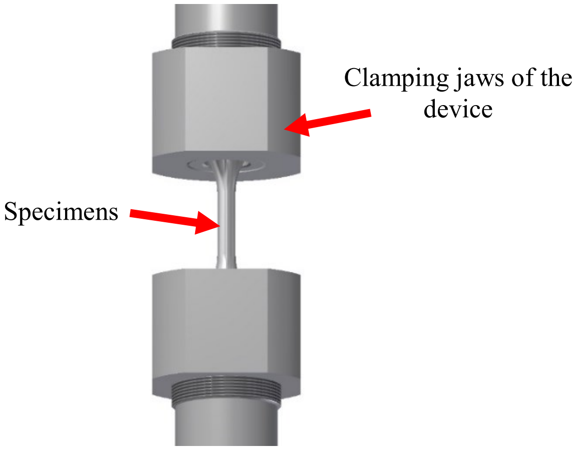


Fig. 2. The clamping scheme of fatigue samples for symmetrical push-pull load

The formation of macro-porosity in experimental material was analysed with using a MOTIC SM 2-168 microscope with the Moticam 1000 camera. The magnification was 7.5 times.

Light microscopy was used to analyse the microstructure and porosity of the material after fatigue tests. The main point was quantitative analysis of porosity in the specimens, which was carried out using a NEOPHOT 32 light microscope equipped with a computer running NIS Elements 4.2 image analyser software [17]. The pore size (area) and amount (surface fraction) were detected on longitudinal and transverse sections of the specimens. The resulting value of the measured parameters reflect average values of at least twenty-one separate measurements on each used specimens for fatigue tests. The specimens were prepared by standard metallographic procedures (wet ground on SiC papers, DP polished with 3 μm diamond pastes followed by Struers Op-S and etched for study underan optical microscope by standard etcher Dix-Keller and 0.5 % HF).

The results of quantitative analysis with using NIS Elements 4.2 analyser software (pore size) were completely used for Murakami's method on all fatigue experimental specimens. Murakami's method was applied to the characterization of the pore size population according to the largest extreme value distribution (LEVD) [18, 19]. The theory is based on the evaluation of the size of the largest defects on the controlled area marked - S_0 (field of view). The defect size was characterized in terms of the square root of its area (marked - $area^{1/2}$). The measurement was done on **n** number of the controlled areas. On each metallographic specimen at least 21 measurements were done (n = 21). The number of the controlled areas has to be sufficient for reasonable statistical description, but is dependent on specimen size and on chosen magnification. For this study a magnification of 100 x was used. According to the return period, marked – T ($T = S/S_0$), it is possible to predict defect sizes on areas larger than the controlled area [18, 19].

3 Experimental results and discussions

3.1 Mechanical properties

The results of as-cast AlSi9Cu3 mechanical properties are: the tensile strength 211 MPa, the Brinell hardness 98 HBW 2.5/62.5/15 and show that secondary material (experimental material) have suffice properties as the some primary material used for casting of automotive products.

3.2 Fatigue properties

Fatigue properties were measured on samples without heat treatment, modification or grain refining, i.e. as-cast state. The results of fatigue properties show Fig. 3.

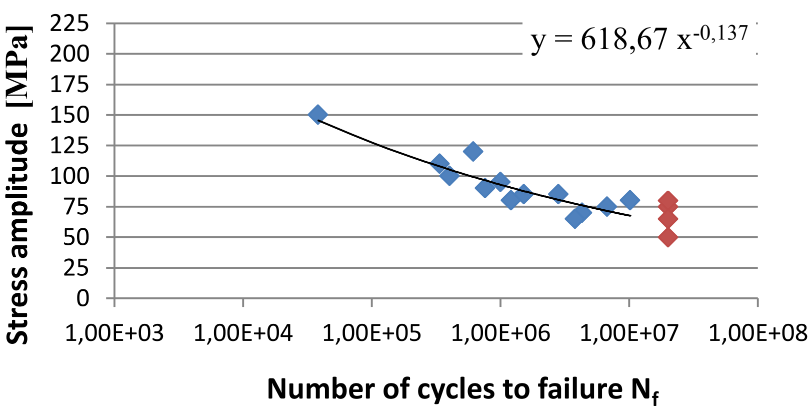
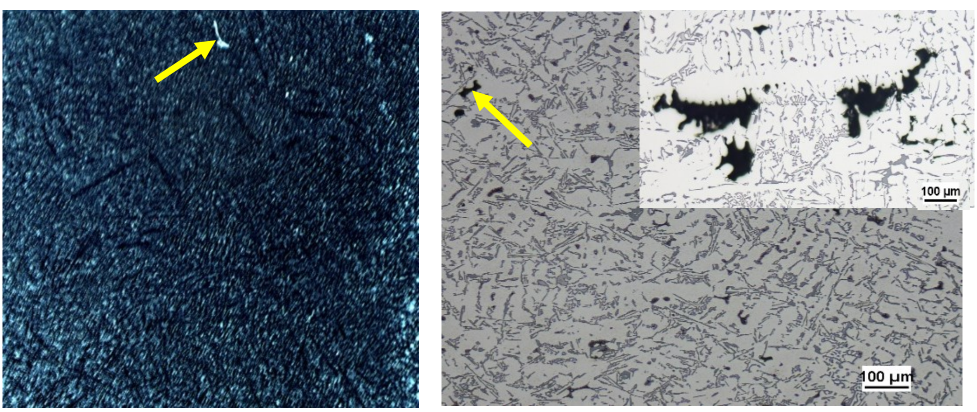


Fig. 3. Results of fatigue properties

The blue marks on the figure 3 represent specimens which were broken by load effect before reaching the specified number of cycles for fatigue test 2 x 10^7 and red are samples which were not broken before reaching the specified number of cycles for fatigue test 2 x 10^7 (the specimens that have reached these numbers of cycles without breaking are defined as run-out). The range of fatigue lifetime for 2 x 10^7 cycles was from 50 to 80 MPa → average value of fatigue lifetime for 2 x 10^7 cycles was about 67,5 MPa in experimental material (Fig. 3). The predicted value of fatigue lifetime for 10^7 cycles for material cast into the metallic mould was 68 MPa according to Basquin`s equation obtained from the diagram (Fig. 3). The specimens under stress amplitudes 70, 75 and 80 MPa were ones broken but ones not broken and reach the 2 x 10^7 cycles. There are assumptions that specimens which were broken have greater amount and size of defect as the specimens which were not broken under the same stress amplitude. Therefore were used quantitative and statistical methods of porosity evaluation in experimental material.

3.3 Porosity formation

The macro analysis of porosity formation in experimental material (Fig. 4a) confirmed existence of small amount of porosity in experimental material. The light microscopy analysis of porosity in experimental material after fatigue test showed presence of porosity, too (Fig. 4b). The analysis of macro-porosity and micro-porosity showed presence especially shrinkage porosity in experimental material (Fig. 4b).



a) b)

Fig. 4. Porosity formation in experimental material

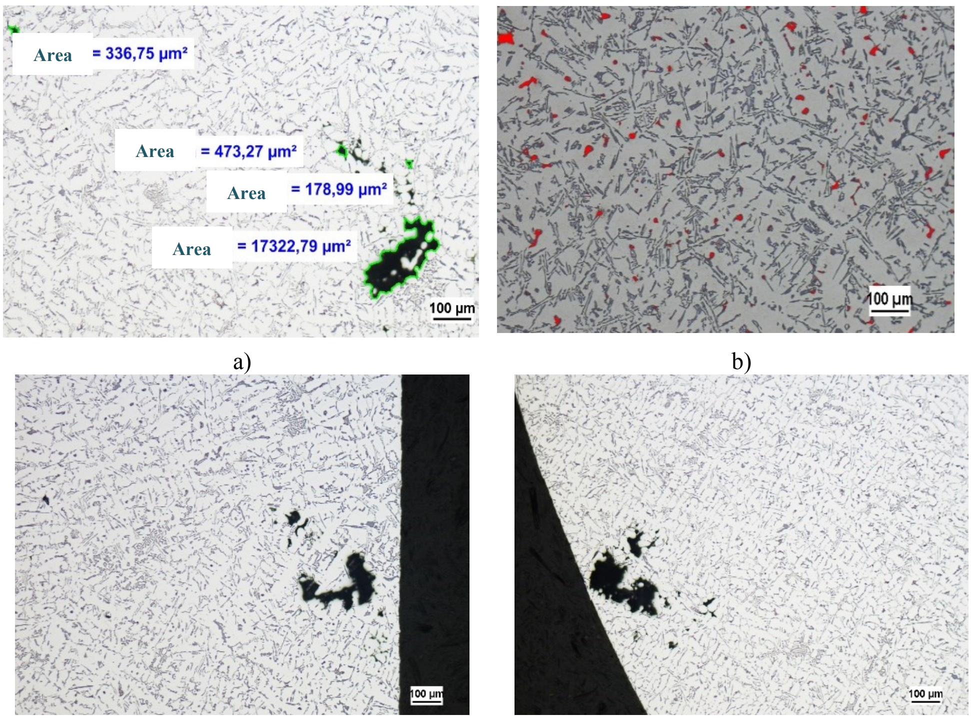
a) Macro analysis, 7.5x ; b), c) Light microscopy analysis, 100x

3.4 Quantitative analysis

The measurements of quantitative analysis were focused on size and amount of porosity in the specimens (Fig. 5). The evaluations were done on three samples marked A, B, and C. The specimen A was not broken under fatigue loading and B, C were broken under fatigue loading. The results of quantitative analysis are in Table 2. The measurements showed that the size of pores is different in longitudinal and transverse section. For prediction of largest porosity transverse section are especially used. Specimens A have smaller amount and size of porosity and therefore it is possibilities that this specimens will have better properties as the other (B, C) which have higher amount and size of porosity. The presence porosity near the surface of experimental specimens was clearly visible in both section (longitudinal and transverse) (Fig. 5c, d). The quantitative method also confirmed smaller amount of porosity in specimen A near the surface in comparison to specimens B and C.

Table 2. The results of quantitative analysis of porosity in experimental material

Specimens	Average pore size in transverse section	Average pore size in longitudinal section	Amount of porosity (surface fraction)
A	880.47 μm^2	1711.80 μm^2	0.04 %
B	3689.1 μm^2	6023.83 μm^2	0.7 %
C	7208.26 μm^2	3393.54 μm^2	1.2 %



a) b)

c) d)

Fig. 5. The quantitative analysis of porosity
a) pore size; b) amount of porosity; c) longitudinal section; d) transverse section

3.5 Largest extreme value distribution of porosity

Murakami's method was used for prediction defect size in all fatigue specimens. For this study results of the largest defect size for three samples (marked A, B and C) tested at the same stress amplitude of 80 MPa were used. The results are shown in Fig. 6 and Table 3. One of these samples was not broken after 2 x 10^7 (marked A - the specimens that have reached these numbers of cycles without breaking are defined as run-out), the two others (marked B and C) were broken before reaching the specified number of cycles for fatigue test 2 x 10^7 (Table 3). The largest defects size, measured on experimental samples, is presented as a Gumbel plot. The data were extrapolated for the values corresponding to the largest defects which could occur in area of S = 50 mm^2 marked on the **T** axis. The ratio between the projected area and the controlled area is $T = S/S_0$ = 26.82 in this study. The results of predicted defect size are shown in Table 3.

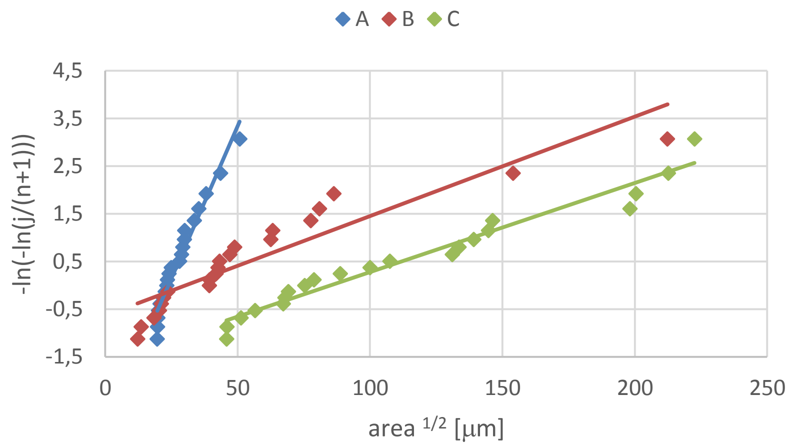


Fig. 6. The results of LEVD theory

Table 3. Results of quantitative method, LEVD theory and fatigue properties

Specimens	Measured maximum defect size at quantitative analysis [µm^2]	Predicted largest defect size with using LEVD [µm^2]	The number of cycles reached after fatigue test
A	2578.7	3338.69	20000086
B	23716.45	34993.9	10185036
C	49515.58	88026.1	1210151

The predicted defect size are higher in comparison with measured maximum defect size on fracture surface of specimens, but there is not possibilities to measure pores which are on fatigue fracture. The specimens were tested under the same stress amplitude but have other properties (Table 3). The specimen A had smallest defect size (predicted and measured) compared to other specimens and reach the highest number of cycles and was not broken. Specimen B had middle size of porosity and reach higher number of cycles in comparison to sample C, but was broken (did not reach 2 x 10^7 cycles). Specimen C had highest size of porosity comparison to A and B specimens and reach the smallest number of cycles up to failure of specimens under stress amplitude. These results shows that porosity have great influence to fatigue properties of materials.

Conclusions

The present study confirmed that secondary material have comparable mechanical properties as the some primary material. The gravity die casting into the metallic mould caused formation of porosity which have influence on the fatigue properties of experimental material.

Quantitative methods show that samples whose were not broken at the same stress amplitude have smaller amount and size of pores comparing to specimens which were broken.

The Murakami's method confirmed the presence of largest pores in the material which were broken, and using this method seems to be useful for prediction of the largest or limit pore size and how its size change (increase or on the other hand decrease – like in this study) fatigue lifetime. But of course it has some limitation. Calculated pore size is a little bit higher that can be observed in real materials and it validate the fact: the greater amount of pores the lower properties (UTS, hardness and fatigue properties as well) compared to materials with smaller amount of pores.

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