

The Influence of Two Different Casting Moulds on the Fatigue Properties of the Al–Si–Cu Cast Alloy

L. Hurtalová, E. Tillová, M. Chalupová, J. Belan and M. Uhrčík

Abstract The most widely used technologies for founding Al castings are sand casting and die casting (gravity casting; high pressure die casting; low pressure die casting; vacuum die casting; squeeze casting or squeeze forming). The lower cooling rate setting used for casting into a sand mould (sand casting) causes a coarse granular structure and lower values of mechanical properties. Higher cooling rate settings used for casting into a metallic mould (chill casting) causes fine-grained structures and higher values of mechanical properties. The present study provides information about the effect of casting into two different moulds on the fatigue properties of the heat treated AlSi9Cu3 cast alloy. Fatigue fracture surfaces were observed using a scanning electron microscope (SEM) after the fatigue test. The results show that the existence of casting defects and different morphologies of structural parameters (especially eutectic Si particles and Fe-rich intermetallic phases) has considerable influence on fatigue properties in both types of experimental materials. The results show that the fatigue lifetime is longer for samples casted into a metallic mould (chill casting) (average fatigue lifetime for 10^7 of cycles = 68 MPa) compared to casting the same materials into a sand mould (sand casting) (average fatigue lifetime for 10^7 cycles = 39 MPa).

Keywords Fracture surface of aluminium alloy · Fatigue properties of aluminium alloy · Sand casting · Chill casting

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1 Introduction

The need for aluminium alloys with good toughness, high strength, adequate damage tolerance capability, good fatigue resistance and good corrosion resistance for use in applications in the aerospace, automotive industries as well as in commercial products led to study of the properties and structure of these materials [1]. Microstructure factors that influence mechanical properties of aluminium alloys were described in previous studies [2–4] and therefore their effects on fatigue properties were studied.

The fatigue of all engineering components is termed “fatigue lifetime”. Fatigue lifetime is measured by the number of cycles that the material can withstand before fatigue damage occurs [5]. The fatigue properties of Al-casting alloys are strongly related to their microstructure [6]. The microstructure of Al-casting alloys consists mostly of eutectic (a mechanical mixture of α -phase = matrix and eutectic Si particles); α -phase and different intermetallic phases [2–4]. The Si and intermetallic (second) phases— Al_2Cu , Mg_2Si , Al_3FeSi and $\text{Al}_{15}(\text{FeMn})_3\text{Si}_2$ are harder than the α -matrix, therefore if the localized stress level surpasses the material yield strength, there will be some deformation of the α -phase matrix while the hard phases may fracture or experience some decohesion from the α -matrix, thus forming micro-voids [7]. Previous work has shown that the most important metallurgical parameters affecting the Al-alloy’s resistance to fatigue are the amount and size of casting defects (micro-porosities, oxide inclusions and shrinkage porosities), secondary dendrite arm spacing (SDAS), α -matrix, Si-particles and Fe-rich phases [6–8]. Porosity is the most common defect found in Al–Si casting alloys and is the major cause of rejection of such castings, as it often results in poor mechanical properties such as limited strength and ductility, varying fracture toughness, irregular crack initiation and crack propagation characteristics, as well as a lack of pressure tightness [9]. According to Gao [8] Si-particles size and also distribution have a significant effect, but the influence of their shape was negligible. However, according to Moreira [7], the morphology and size of the second phases are important factors causing stress concentration in the α -matrix around them. Rounded Si particles and small second phase particles cause lower stress concentration levels and delay the fatigue crack nucleation [7].

The aim of this article is to present the changes of fatigue properties in secondary AlSi9Cu3 cast alloys caused by the application of two different casting methods. This paper publishes the authors own experimental results.

2 Experimental Material and Procedures

The experimental material is the cast AlSi9Cu3 alloy (prepared from recycled aluminium scrap) delivered by the companies Uneko, spol.s.r.o. (sand casting) and Confal a.s. (chill casting). The samples for fatigue tests were extracted from circular

Table 1 Chemical composition of experimental materials

AlSi9Cu3—sand casting—Uneko, spol.s.r.o.											
Element	Si	Cu	Mn	Zn	Mg	Fe	Ni	Ti	Sn	Pb	Al
(wt%)	10.7	2.4	0.25	1.0	0.26	0.9	0.1	0.05	0.02	0.00	Remainder
AlSi9Cu3—chill casting—Confal a.s.											
Element	Si	Cu	Mn	Zn	Mg	Fe	Ni	Ti	Sn	Pb	Al
(wt%)	9.4	2.4	0.24	1.0	0.28	0.9	0.05	0.04	0.03	0.09	Remainder

bars (sand casting— $\varnothing 20 \times 300$ mm; chill casting— $\varnothing 18 \times 150$ mm). Experimental materials were not modified or grain refined. Chemical composition of both experimental materials was checked using arc spark spectroscopy and is shown in Table 1.

Samples for mechanical and fatigue tests were prepared by lathe-turning and milling operation from circular bars. The fatigue tests of sand chill samples were carried out using a rotating bending fatigue machine—ROTOFLEX operating at 30 Hz, load ratio $R = -1$ and at room temperature of 20 ± 5 °C. In this type of machine, a sample with a round cross section is subjected to a deal-weight load while bearings ensure rotation. A given point on the circular test section surface is subjected to sinusoidal stress amplitude from tension on the top to compression on the bottom with each rotation [10]. The fatigue tests of chill cast samples were done on the Vibrophores Amsler 50–250 HFP 5100 testing machine with the symmetrical push-pull load and at room temperature of 20 ± 5 °C.

The microstructural details were analysed using the light microscope Neophot 32 (analysis of Si-particles, pores and intermetallic phases) and using the scanning electron microscope VEGA LMU II (for analysis of the chemical composition of intermetallic phases). The fatigue fracture surface observation was done on the scanning electron microscope VEGA LMU II. The samples for metallographic analysis 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 at an optical microscope by standard etcher Dix-Keller and 0.5 % HF).

3 Results and Discussion

3.1 Characterisation of Microstructure

The defects, the morphology of eutectic and the morphology of intermetallic phases have an important effect on the ultimate mechanical properties of the casts. Al–Si alloys usually contain Si and sometimes Mg or Cu as the main alloying elements, together with various impurities such as Fe, Mn, Zn or Cr. These elements go into solid solution but they also form different intermetallic phases. The formation of these phases should correspond to successive reaction during solidification—Table 2 [11–13].

Table 2 Reactions occurring during solidification of AlSiXCuX alloys [14]

Reactions	Temperature (°C)
α —dendritic network	580–620
Liq. \rightarrow α -phase + Si + AlFe ₅ Si	555–570
Liq. \rightarrow α -phase + Si + Mg ₂ Si + Al ₈ FeMg ₃ Si ₆	500–540
Liq. \rightarrow α -phase + Si + Al ₂ Cu + Al ₅ Mg ₈ Si ₆ Cu ₂	470–500

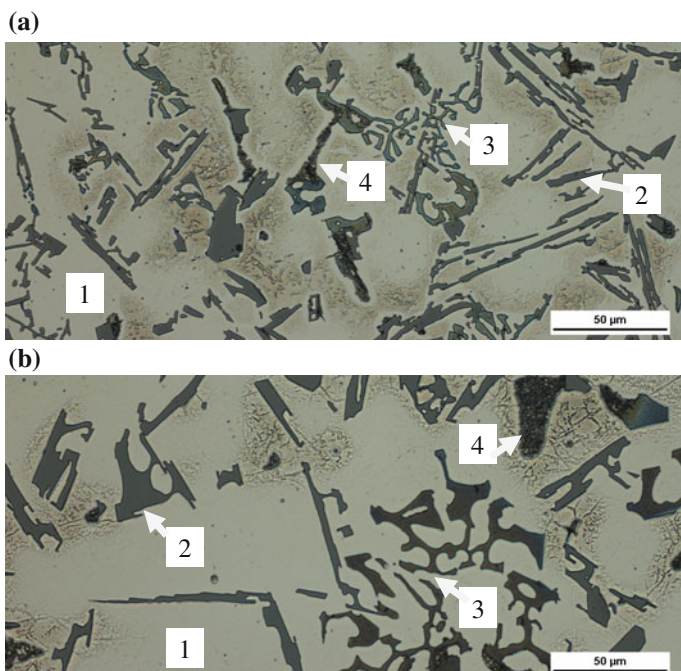


Fig. 1 Microstructure of secondary AlSi9Cu3 alloy cast into two different mould 1— α -phase, 2—eutectic Si-particles, 3—Fe-rich phases, 4—Cu-rich phases, etc. 0.5 % HF. **a** Chill casting; **b** sand casting

Typical microstructures of the experimental materials AlSi9Cu3 in as-cast state are shown in Fig. 1. The microstructure of the recycled Al–Si–Cu cast alloy consists of dendrites α -phase (light grey—Fig. 1—1), eutectic (mixture of α -matrix and dark grey eutectic Si-phases—Fig. 1—2) and variously types of intermetallic phases (Fig. 1—3, 4).

The fineness of dendrites in the material cast into a metallic mould is lower when compared to the material cast into a sand mould (Fig. 2). Eutectic Si in the untreated state in the alloy casted into the sand mould is manifested as larger needles (Fig. 1b—2) than in samples cast into the metallic mould, which influences the decreasing tensile strength. Eutectic Si in the untreated state observed in the

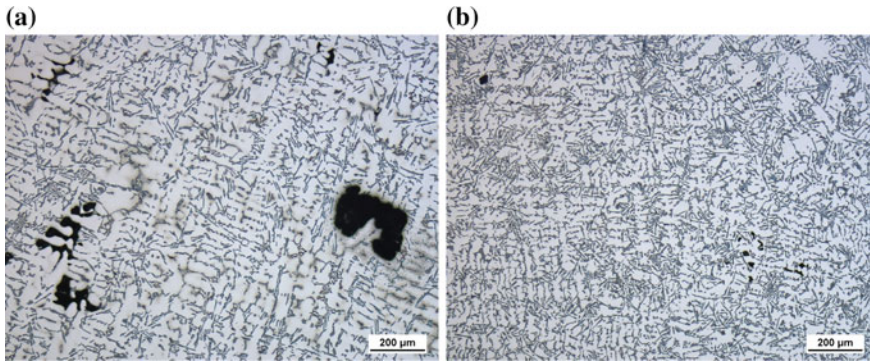


Fig. 2 Effect of casting methods on porosity in AlSi9Cu3 alloy, etc. Dix-Keller. **a** Alloy cast into the sand mould (sand casting); **b** alloy cast into the metallic mould (chill casting)

AlSi9Cu3 alloy cast into the metallic mould is manifested as little needles (Fig. 1a—2), thinner than the platelets observed in samples cast into the sand mould. The quantitative assessment results show that the average area of eutectic Si particles in alloys cast into the sand mould is 976.58 and 737.55 μm^2 in alloys cast into the metallic mould. The intermetallic phases have a greater size in the alloys cast into the sand mould in compared to alloy cast into the chill mould, too (Fig. 1).

The effect of the casting on porosity is shown in Fig. 2. Massively occurring porosity and shrinkages were observed in recycled AlSi9Cu3 cast alloys cast into the sand mould. Porosity was higher by about 10 % (see Fig. 2a) than in materials cast into the metallic mould. It influences the degradation value of mechanical properties. Materials cast into the metallic mould had almost zero porosity (Fig. 2b). This is probably related to the slower cooling rate in sand casting [15].

3.2 Fatigue Behaviour

The results of fatigue tests carried out on samples extracted from experimental circular bars are presented in the S/N (stress amplitude vs. cycles to failure) diagrams in Fig. 3. The number of cycles that the samples had to reach without breaking was 10^7 for materials cast into the sand mould, and 2×10^7 for materials cast into the chill mould. The samples that reached these numbers of cycles without breaking are defined as run-out. The range of fatigue lifetimes for 10^7 cycles was from 29 to 49 MPa from which average value of fatigue lifetime for 10^7 cycles was observed 39 MPa in material casted into the sand moulds (Fig. 3a).

The range of fatigue lifetime for 2×10^7 cycles was from 50 to 80 MPa from which average value of fatigue lifetime for 2×10^7 cycles was observed 67.5 MPa in materials cast into the metallic mould (Fig. 3b). The predicted value of fatigue lifetime for 10^7 cycles for materials cast into the metallic mould was 68 MPa

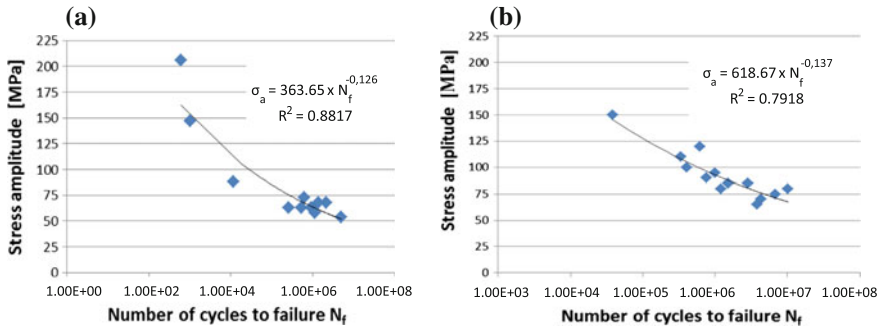


Fig. 3 Effect of two different casting moulds on fatigue properties of secondary AlSi9Cu3 cast alloy. **a** S/N fatigue data for material cast into a sand mould; **b** S/N fatigue data for material cast into a metallic mould

according to Basquin's equation obtained from the diagram (Fig. 3b). The fatigue resistance was found to be by about 43 % higher in the push-pull test than in the rotating bending test due to the different material volumes under high stress, but also due to the different casting methods that had been used for the production of the experimental samples.

3.3 Fractography Analysis of Fatigue Fracture

The process of fatigue consists of three stages [10]: crack initiation (stage I); progressive ("stable") crack growth across the component (stage II); and a final sudden fracture of the remaining cross section of the component (stage III). Stages I and II are also called the fatigue region. The features responsible for crack initiation were studied in the samples on SEM after the fatigue test. Within the fatigue test boundaries we established that high stress amplitude causes a small fatigue region and a large region of final static rupture for both experimental samples (cast into a sand mould—Fig. 4a, or metallic mould—Fig. 5a).

The SEM metallographic analysis of fracture surfaces confirmed the key role of porosity, which was the point of fracture crack initiation in both types of samples. The initiation sites were pores (casting defects) of irregular shape, near the surface of the samples, initiating the crack propagation (Figs. 4b, c and 5b, c).

The sand cast samples have more initiation sites as shown in Fig. 4b, compared to the chill casted samples that had always only one initiation site during the experiment—Fig. 5b. The initiation sites for samples cast into sand moulds were more concentrated at one point with the decreasing stress amplitude.

Stages II and III for samples cast into a sand mould: The area of the stable crack propagation (Stage II) is characterised by transcrystalline fatigue fracture of α -phase with smooth areas (Fig. 6a). The smooth areas were identified as Fe-rich phases and

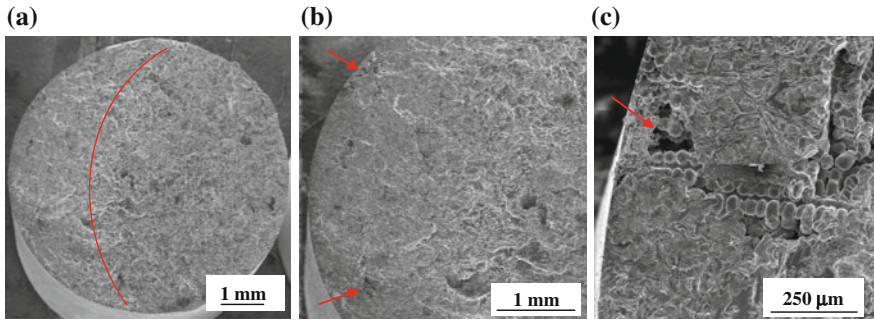


Fig. 4 Fractography analysis of fatigue fracture on samples cast into a sand mould. **a** Fracture surface of a fatigue samples; **b, c** the initiation sites (stage I)

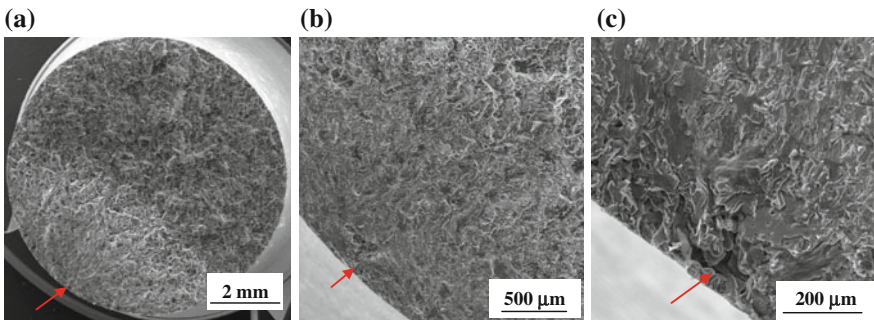


Fig. 5 Fractography analysis of fatigue fracture on samples cast into a metallic mould. **a** Fracture surface of a fatigue samples; **b, c** the initiation sites (stage I)

Si particles using SEM (BSE) and EDX analysis. The typical aspect of fatigue—striations—were observed only in few isolated cases in an area between Stage II and Stage III of fatigue fracture.

The last stage (Stage III) consisted of a transcrySTALLINE ductile fracture with plastic strain ranges of Al matrix (α -phase) and transcrySTALLINE cleavage fractures of Si particles and also brittle iron intermetallic phases (Fig. 6b). The transcrySTALLINE ductile fracture is related to the Cu-rich intermetallic phases, too.

Stages II and III for samples cast into a metallic mould: The area of the stable crack propagation (Stage II) is characterised by transcrySTALLINE fatigue fracture of α -phase that forms fine relieves; intercrystalline fatigue fracture of iron intermetallic phases (smooth areas) and transcrySTALLINE fatigue fracture of eutectic silicon (Fig. 7a). The smooth areas were identified as Fe-rich phases and Si particles using SEM (BSE) and EDX analysis. The typical aspect of fatigue—striations—were observed only in few isolated cases.

Fracture surface of the static fracture (Stage III—Fig. 7b) is characterised by mixed transcrySTALLINE ductile and cleavage fracture. The transcrySTALLINE cleavage

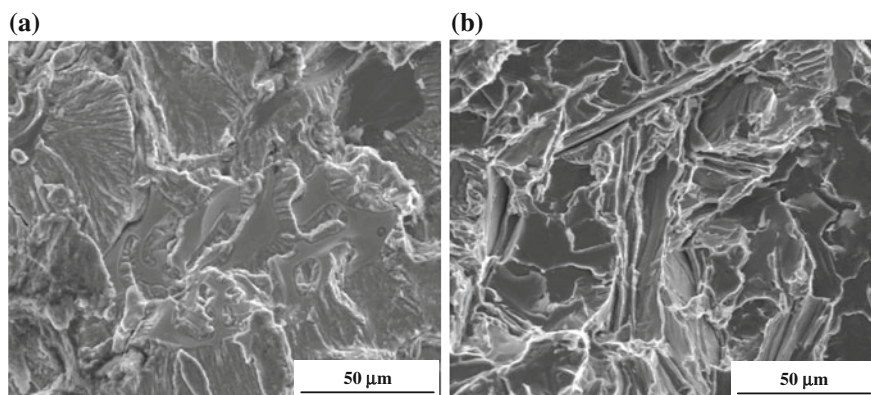


Fig. 6 Fractography analysis of fatigue fracture on samples cast into a sand mould. **a** The fatigue fracture surface (stage II); **b** the static fracture (stage III)

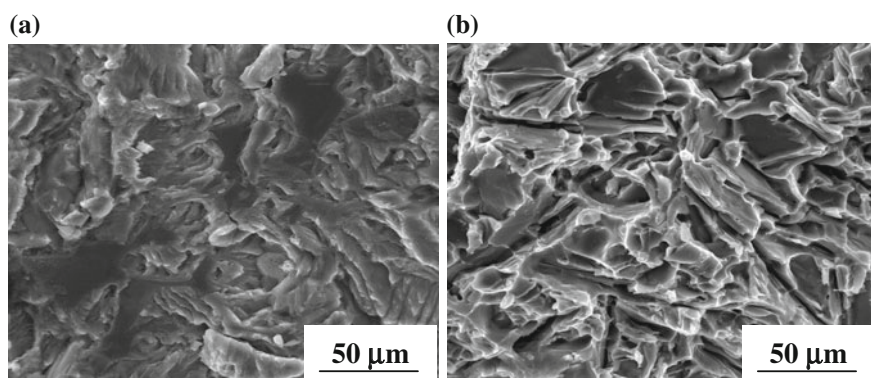


Fig. 7 Fractography analysis of fatigue fracture on samples cast into a metallic mould. **a** The fatigue fracture surface (stage II); **b** the static fracture (stage III)

fracture related to eutectic silicon occurring in platelets—in metallographic samples in form of needles, and also with brittle iron intermetallic phases. The transcrystalline ductile fracture with dimples morphology is related to matrix (α -phase) and Cu-rich intermetallic phases.

4 Conclusions

This study confirmed the negative influence of porosity, the morphology of eutectic Si particles and Fe-rich intermetallic phases on the fatigue lifetime of AlSi9Cu3 cast alloys that were cast into a sand or metallic mould without modification or grain

refinement. This work confirms that the different casting methods generate different microstructures and different amounts of porosity. The structural parameters were larger in samples cast into a sand mould and these samples had a higher volume of porosity than the samples casted into a metallic mould.

The study shows that samples cast into a metallic mould have a fatigue lifetime which is about 43 % longer for 10^7 cycles in the push-pull test (68 MPa), compared to the material cast into a sand mould during rotating bending test (49 MPa). The pores (casting defects) initiate the fatigue crack propagation in both types of samples. The hard and brittle eutectic Si particles and Fe-rich intermetallic phase causes transcrystalline and intercrystalline fatigue fracture and transcrystalline cleavage fracture; matrix with Cu-rich intermetallic phases transcrystalline fatigue fracture and transcrystalline ductile fracture.

Even though the Al cast alloy should primarily have transcrystalline ductile fracture, this study confirmed that the microstructure causes predominance of the transcrystalline cleavage fracture because of the presence of Si a Fe-rich particles (their morphology) in the microstructure.

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