THE FRACTOGRAPHY STUDY OF FATIGUE FRACTURE SURFACES IN Al-Si CAST ALLOYS

L. Hurtalová, E. Tillová, M. Chalupová

Abstract

The contribution describes fractography study of the Al-Si fracture surface characteristics. The characteristics of an Al-Si fracture surface depend on structural parameters morphology and porosity. The morphology of structural parameters and porosity depends on used technologies of Al-Si cast founding. Recycled (secondary) aluminium cast alloys contain more additions that form various intermetallic phases in microstructure. It is necessary to study the fatigue fracture surfaces in order to observe the influence of structural parameters of different size, amount, dispositions, morphology, etc.. The fatigue fracture surfaces were observed using scanning electron microscopy – SEM after the fatigue test. The results showed that the existence of casting defects and different morphology of structural parameters (especially eutectic Si particles and Fe-rich intermetallic phases) has considerable influence on fatigue fracture surfaces in both types of experimental materials. The fatigue area of stable crack propagation region consists of transcrystalline fatigue fracture of α-phase with smooth areas (especially Fe-rich phases) (Stage II). Fatigue striations were observed very sporadically. The final phase (Stage III) of fatigue fracture consists of transcrystalline ductile fracture of Al matrix (α-phase - with plastic strain ranges) and Cu-rich intermetallic phases; and with transcrystalline cleavage fracture of Si particles and Fe-rich phases.

Keywords: Fatigue of Al-Si alloys, fatigue fracture surfaces, fractography analysis of Al-Si alloys

INTRODUCTION

The most widely used technologies of founding Al casting are sand casting and die casting (gravity casting; high pressure die casting; low pressure die casting; vacuum die casting; squeeze casting or squeeze forming) [1]. Melting and casting lead to formation of disturbing textures, such as casting disturbances and disturbances arisen by heat treatment. Lower cooling rate setting by casting into a sand mould (sand casting) causes granular structure and lower values of properties. Higher cooling rate setting by casting into a metallic mould (chill casting) causes fine-grained structure and higher values of properties. The lower mechanical properties and reliability of aluminium cast alloys can be principally caused by the presence of defects and inhomogeneities, which could be preferential fatigue initiation sites [2]. Fatigue is a problem that can affect any part or component that moves. Automobiles on roads, aircraft wings and fuselages, ships at sea, nuclear reactors, jet engines, and land-based turbines are all subject to fatigue failures [3]. The Al alloys fatigue lifetime study is important because of their application in automotive and aerospace

Lenka Hurtalová, Eva Tillová, Mária Chalupová, University of Žilina, Faculty of Mechanical Engineering, Department of Materials Engineering, Univerzitná 8215/1, 010 26 Žilina, Slovak Republic

industries [4]. The versatility of aluminium makes it the most widely used metal second to steel [5]. B. Zhang et al. [6] found that fatigue cracks initiated from porosity in the aluminium material solidified at slow cooling rates, while, as cooling rate increased, the fatigue cracks initiated from near surface eutectic microconstituents. The process of fatigue generally consists of three stages (Fig.1) [7]: 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 fatigue region. Fatigue fracture or failure of material under stress is significantly lower than yield stress. Fracture occurs after continuous accumulation of damage due to repeated mechanical, thermal or mechanic-thermal loading up to failure. In the case of fatigue failure there is no macroscopic deformation of the solid. The whole process occurs in a microvolume at the crack tip or at a local site on the surface during the creation of fatigue crack nucleus [8].

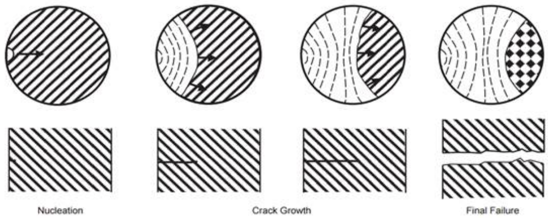


Fig.1. Three stages of fatigue fracture [3]

The present study is part of a larger research project, which was conducted to investigate and provide a better understanding of the influence of different casting methods, which change the structural parameter on the characteristics of the fracture surface in recycled (secondary) AlSi9Cu3 cast alloy. In particular, the fatigue fracture surfaces of a cast aluminium-silicon-copper alloy have been investigated.

EXPERIMENTAL MATERIAL AND PROCEDURES

The experimental materials are cast AlSi9Cu3 alloy (prepared from recycled of aluminium scrap) delivered from the companies Uneko, spol.s.r.o. (sand casting) and Confal a.s. (chill casting). AlSi9Cu3 cast alloy has lower corrosion resistance and is suitable for high temperature applications (dynamic exposed casts without extensive requirements on mechanical properties) - it means to max. 250°C. The samples for fatigue tests were extracted (lathe-turning and milling operation) from the delivered circular bars (sand casting - ø 20 x 300 mm; chill casting - ø 18 x 150 mm). The experimental materials were not modified or grain refined. Chemical composition of both experimental materials was checked out by using arc spark spectroscopy and is shown in Table 1.

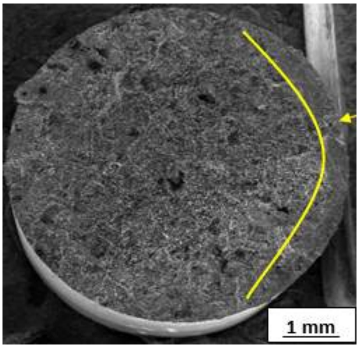
Tab.1. Chemical composition of experimental materials

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

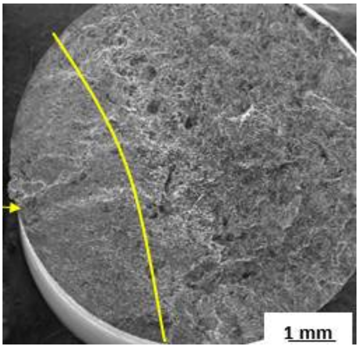
Fatigue tests of sand chill samples were carried out on a rotating bending fatigue machine - ROTOFLEX operating at 30 Hz, load ratio R = -1 and at room temperature of 20 ± 5°C. In this type of machine, a sample with a round cross section is subjected to a deal-weight load while bearings ensure rotation. 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 [7]. The fatigue tests of chill casted samples were carried out using Vibrophores Amsler 50 – 250 HFP 5100 testing machine with symmetrical push-pull load and at room temperature of 20 ± 5°C. The fatigue fracture surfaces were examined using scanning electron microscope VEGA LMU II after testing in order to find the features responsible for crack initiation.

RESULTS AND DISSCUSIION

The three stages of fatigue fracture were identified in both types of experimental material. Within the fatigue test boundaries we established that high stress amplitude causes small fatigue region and large region of final static rupture (Figs.2, 3). The decreasing stress amplitude leads to increasing fatigue region of stable cracks propagation (Figs.2, 3).

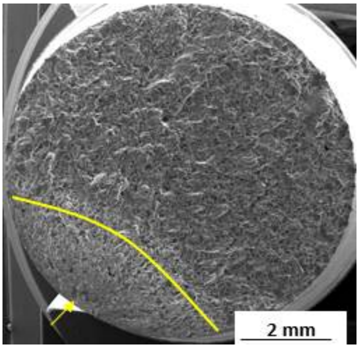


a

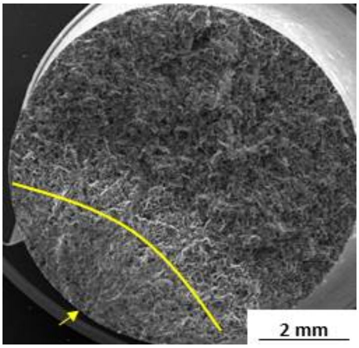


b

Fig.2. Typical fatigue fracture surfaces (Stage I, Stage II, Stage III) for experimental samples casted into a sand mould, SEM a) σ_a = 88 MPa, N_f = 11 560 cycles; b) σ_a = 54 MPa, $N_f = 5.10^6$ cycles



a



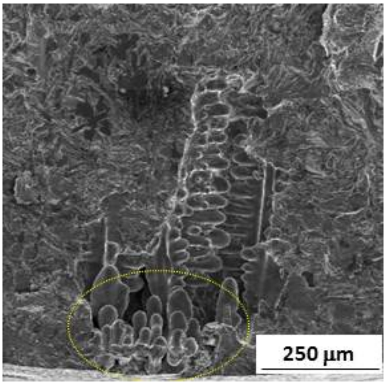
b

Fig.3. Typical fatigue fracture surfaces (Stage I, Stage II, Stage III) for experimental samples casted into a metallic mould, SEM a) σ_a = 85 MPa, $N_f = 2{,}8.10^6$ cycles; b) σ_a = 50 MPa, $N_f = 2.10^7$ cycles

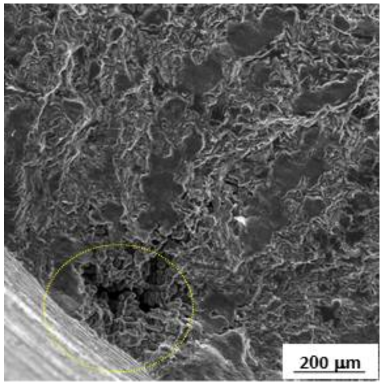
Stage I – initiation place

Fatigue fracture initiates at the maximal stress concentration on the surface of cyclic loaded solids [8]. 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 [9-11].

The studies shown that defects such as pores, microshrinkage and voids were identified as crack initiation place for both experimental materials. The occurrence of these cast defects is caused ba small solubility of hydrogen during solidification of Al-Si alloys. It was confirmed that if there are marked cast defects in the structure, they behave preferentially as initiation places of fatigue fracture. Cast defects were detected near the surface of the test fatigue samples. Details of initiation sites for both types of experimental materials show Fig.4.



a



b

Fig.4. Fractography analysis of the initiation sites (Stage I), SEM a) sand mould cast alloy; b) chill mould cast alloy.

The sand cast samples have more initiation sites compared to the chill cast samples that had always only one initiation site during the experiment. The initiation sites for samples cast into sand moulds were more concentrated at one point with the decreasing of stress amplitude.

Stage II – progressive "stable" crack propagation across the samples

The fatigue fracture surface was influenced very significantly by structural components (eutectic silicon, intermetallic phases) and their distribution in the cross section.

The stable growth region of samples cast into sand moulds is characterised by transcrystalline fatigue fracture of α-phase with smooth areas (Fig.5a). The smooth areas were identified as Fe-rich phases and Si particles by using SEM (Fig.5b). The typical aspect of fatigue - striations - were observed only in a few isolated cases in an area between stage II and stage III of fatigue fracture (Fig.5c).

The area of stable crack propagation for materials cast into a metallic mould (stage II) is characterised by transcrystalline fatigue fracture of α-phase which forming fine relieves; intercrystalline fatigue fracture of iron intermetallic phases and transcrystalline fatigue fracture of eutectic silicon and Fe-rich phases, too (Fig.6a). The smooth areas were identified as Fe-rich phases and Si particles by using SEM (Fig.6b). The typical aspect of fatigue - striations - were observed only in few isolated cases (Fig.6c).

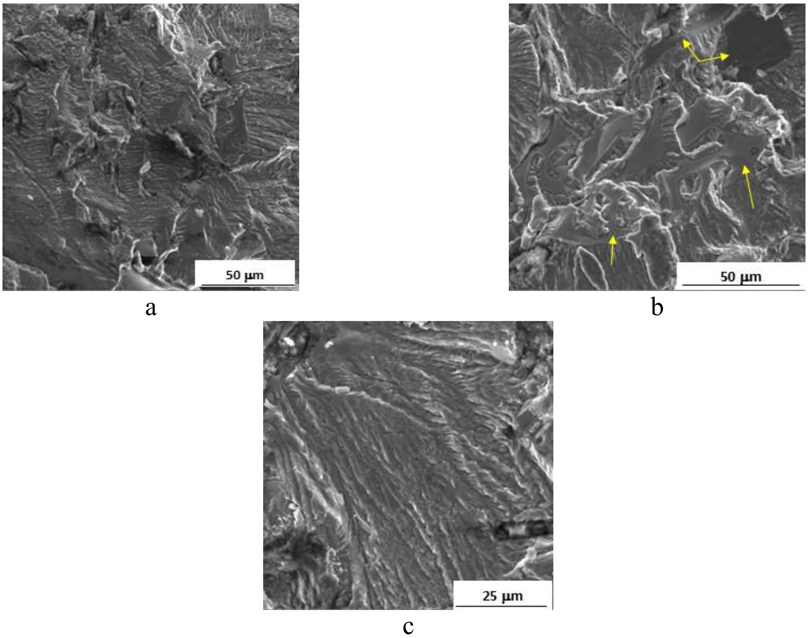


Fig.5 Fractography analysis of the stable crack propagation in samples casted into a sand mould (Stage II), SEM a) Stage II; b) smooth areas – Fe-rich phases and Si particles; c) area between Stage II and Stage III

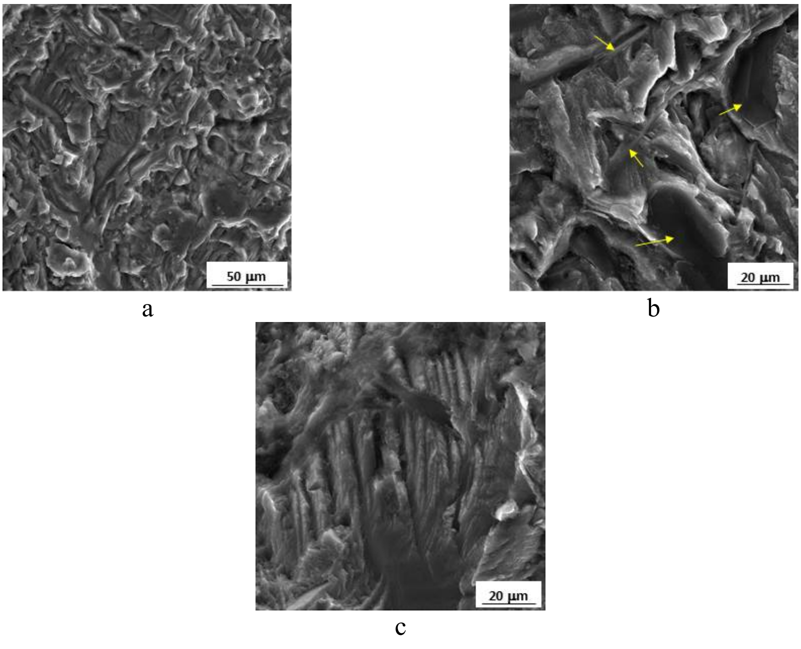
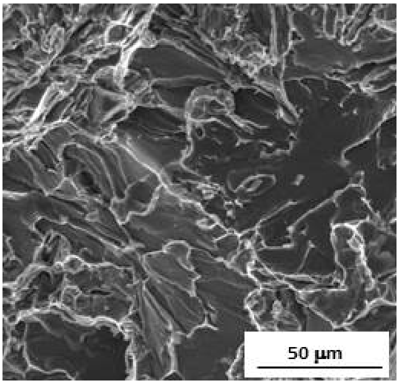
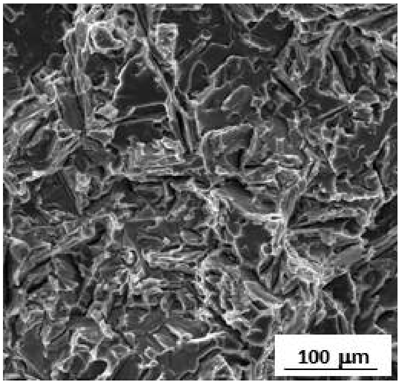


Fig.6 Fractography analysis of the stable crack propagation in samples casted into a metallic mould (Stage II), SEM a) Stage II; b) smooth areas – Fe-rich phases and Si particles; c) area between Stage II and Stage III.

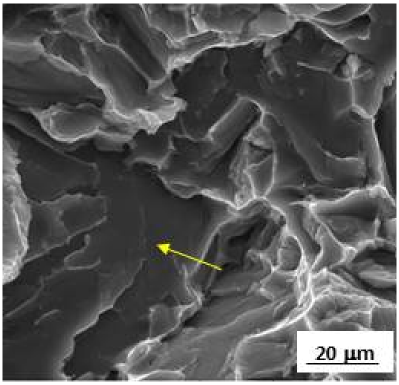
Stage III – final rupture



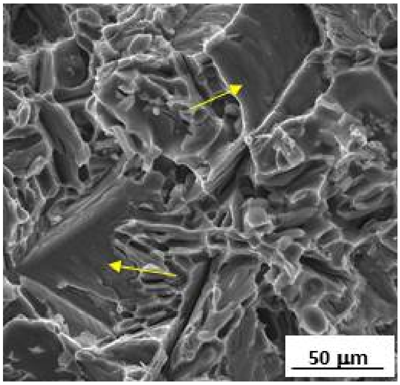
a



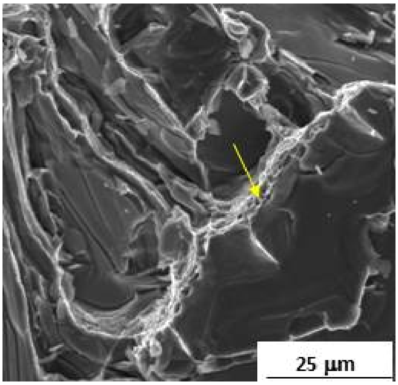
b



c



b



e

Fig.7 The final rupture fractography analysis of both experimental materials, SEM a) Stage III in sand mould samples; b) Stage III in metallic mould samples; c) fracture of Si particles; d) fracture of Fe-rich phases; e) fracture of Cu-rich phases.

The last stage for both types of experimental materials (stage III - Fig.7) consisted of a transcrystalline ductile fracture with plastic strain ranges of Al matrix (α-phase - Fig.7a,b) and transcrystalline cleavage fractures of Si particles (Fig.7c) and also brittle iron intermetallic phases (Fig.7d). The transcrystalline ductile fracture related with the Cu-rich intermetallic phases, too (Fig.7e).

CONCLUSSIONS

Different casting method caused changes in the morphology of structural components (eutectic silicon, intermetallic phases based on Fe). These morphologies significantly affect the fatigue fracture surface of experimental material. The pores (casting defects) initiated for fatigue crack propagation in both types of samples. The hard and brittle eutectic Si particles and Fe-rich intermetallic phase cause transcrystalline and intercrystalline fatigue fracture and transcrystalline cleavage fracture; matrix with Cu-rich intermetallic phases cause transcrystalline fatigue fracture and trancrystalline ductile fracture.

The fracture surface of the final rupture is formed from transcrystalline cleavage and ductile fracture. Transcrystalline cleavage fracture was dominant on the fracture surface. Transcrystalline cleavage fracture is related to the presence of large hexagonal plate-Si particles in the structure and also brittle iron intermetallic phases. The transcrystalline ductile fracture of Al matrix (α-phase) is observed in the smaller surface. Copper intermetallic phases lead to transcrystalline ductile fracture, too.

Acknowledgement

The authors acknowledge the financial support of the projects VEGA No. 1/0533/15,
KEGA No. 044ŽU-4/2014 and European Union - the Project ITMS 26110230117.

REFERENCES

[1] http://www.azom.com/article.aspx?ArticleID=1392, available on line 16.12.2014
[2] Avalle, M., Belingardi, G., Cavatorta, MP.: Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials Design and Applications, vol. 216, 2002, p. 25
[3] Fatigue – Chapter 14. ASM International. Elements of metallurgy and engineering alloys, 2008, p. 243
[4] Belan, J.: Key Engineering Materials, vol. 635, 2014, p. 9
[5] Uhríčik, M., Palček, P., Soviarová, A., Snopiński, P.: Manufacturing technology, vol. 14, 2014, no. 3, p. 467
[6] Zhang, B., Chen, W., Poirier, R.: Fatigue Fracture Engineering Material Structure, vol. 23, 2000, no. 5, p. 417
[7] Bokůvka, O., Nicoletto, G., Guagliano, M., Kunz, L., Palček, P., Nový, F., Chalupová, M. In: Fatigue of Materials at low and high frequency loading. EDIS, 2014, p. 146 ISBN 978-80-554-0857-6
[8] Palček, P., Chalupová, M., Nicoletto, G., Bokůvka, O.: Education Aid for multimedia lectures. CETRA, 2003, p. 177 ISBN 80-8070-103-2
[9] Moreira, MF., Fuoco, R.: AFS Transactions, vol. 2, 2006, p. 1
[10] Gao, YX., Yi, JZ., Lee, PD., Lindley, TC.: Acta Materialia, vol. 52, 2004, no. 19, p. 5435
[11] Bonollo, F., Tovo, R.: Fatigue in Al casting alloys: metallurgical aspects. TALAT Lecture 1254 EAA Europan Aluminium Associate, 1999