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The Fatigue lifetime of AlZn10Si8Mg cast alloy with different percentage of iron

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Abstract

To increase the proportion of Al-cast alloys in a variety of industrial applications, it appears useful to control their fatigue behavior. In general, that behavior is affected by many factors, such as chemical composition, heat treatment, inclusions etc. The problem with utilization of the Al-scrap as a material for casting the Al-Si alloys lies in the fact that the scrap, unfortunately as a rule, is contaminated with iron. The Fe-rich intermetallics, formed during the solidification process, appear in a great variety of shapes and sizes. The most important are platelets or needles Al_5FeSi, because they greatly decrease mechanical and corrosion properties of Al-cast alloys. The effect of the brittle Fe-rich phases on the fatigue properties in the secondary self-hardening AlZn10Si8Mg cast alloys with different percentage of iron (0.150 and 0.559 wt. %) was studied. Microstructure of alloys and the 3D-morphology of phases were analyzed by the optical and SEM microscopy. Rotating bending fatigue tests were realized for a defined number of cycles 3×10^6. The results show that with increasing the content of Fe, the area proportion and the average length of Al_5FeSi phases increased a significant influenced on the fatigue life and pores formation.

Keywords: secondary cast aluminum alloys, iron intermetallic phases, fatigue properties

1. Introduction

Importance of the secondary aluminium production was increasing year after year. In the year 1976, the world production of the secondary aluminium was 18 % and in the year 2008 production increased to 31.6 %. All the Al-

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alloy products are recyclable. At present, 95% of aluminium used in automotive industry can be recycled at the end of its operation. Additionally, aluminium can be recycled without loss of quality because its atomic structure does not change during the melting (DAS, 2010; Schlesinger, 2014; Kuchariková, 2016). This is related to the requirement to optimize the mechanical properties with a combination of a suitable structure to achieve the best properties of the alloy using the available methodologies.

The commercial secondary (recycled) Al-alloys always contain Fe, often as undesirable impurity and occasionally as a useful minor alloying element. Depending on the quality of the incoming ore and the control of the various processing parameters and other raw materials, the primary molten Al-metal typically contains between 0.02 - 0.15 wt. % iron, with ~ 0.07 - 0.10 % being the average (Schlesinger, 2014; Taylor, 1999). The secondary Al-alloys (produced from Al-scrap) contain the higher background iron levels than the primary metal. In an amount 0.3 - 0.5 wt. % Fe prevents sticking of a casting onto the metal mould (for casting under pressure), increases the strength and in larger quantities also the heat resistance. At the higher contents (0.3 - 0.5 wt. %) of Fe, it primarily causes formation of the Fe-intermetallic phases. The more important are the α- $Al_{15}FeMn_3Si_2$ and the β- Al_5FeSi phases. The Chinese script morphology of the α-iron phase occurs during the eutectic solidification. The β-iron phase is mostly associated with greater iron levels, roughly the location of the eutectic trough on the Al-Si-Fe phase diagram (Samuel, 2017; Taylor, 2012; Tillová, 2010). The β-Al_5FeSi phase is considered as the most critical among the iron intermetallics, as it significantly reduces the alloy's ductility and fracture toughness. Existing in the form of thin platelets that appear as needles in the microstructure, the size of these β-platelets or needles is controlled by the iron content and the solidification conditions of the alloy. In comparison, the α-iron phase, due to its compact morphology, is less harmful to the mechanical properties (Li, 2017; Samuel, 2017; Shabsestari, 2004; Taylor, 2012; Tillová, 2010).

The metallographic studies have shown that pores are nucleated along the long sides of the β-platelets. However, in spite of the harmful effect of these Al_5FeSi-platelets as pore nucleation sites, their presence also appears to limit the pore growth. The size and density of the Fe-based intermetallic phases are increased with increasing % of Fe, also the dimensions of the defects and porosity of casting (Boromei, 2010; Moustafa, 2009). The higher content of Fe imposes the negative influence on the strength and the plastic properties, as well as on the corrosion resistance (Ceschini, 2009; Samuel, 2017; Taylor, 2012; Hurtalová, 2016). Control of the iron level is thus technically important, especially where the production of critical components is concerned. There are different measures adopted to neutralize the harmful effect of the needle-like Fe-phase: rapid solidification, addition of neutralizers such as Mn, Co and Cr, melt superheat, the Sr-modification and the non-equilibrium solution heat treatment (Bolibruchová, 2017; Kuchariková, 2017).

Cast Al-Zn-Si-Mg has been developed in the recent years as a new generation of an Al-alloy for automobile industry (Castella, 2018; Rosso, 2013; Rosso, 2015; Závodská, 2017a). The increasing use of the high integrity shaped cast Al-components, under repeated cyclic loading, has focused considerable interest on the fatigue properties of the cast Al-alloys. Fatigue failure is considered as the most common problem that occurres in automotive engineering industry by which the vehicle components fail under conditions of dynamic loading. It is well known that the fatigue behavior of Al-castings is very sensitive to casting defects, namely porosity, segregations and shrinkage; the crack initiation and crack propagation energy are affected by these defects as well (Boromei, 2010; Shabsestari, 2004; Taylor, 1999; Tillová, 2010; Závodská, 2017b). The present study is a part of a larger research project, which was conducted to investigate and to provide the better understanding of properties of the secondary (recycled) Al-Si cast alloys. The main objective of this work was to study the bending fatigue properties in the secondary cast alloys (new self-hardening AlZn10Si8MgMn alloy) with different iron contents.

2. Experimental procedure

The materials used in experiment were the secondary (scrap-based, recycled) AlZn10Si8Mg cast alloys with different percentage of Fe (0.150 and 0.559 wt. %). It is a self-hardening alloy that is particularly used when good strength values are required without the need for the heat treatment. The low iron content (0.150 wt. %) has a beneficial effect on the mechanical properties, which can also be traced to good fatigue strength. The widest application of AlZn10Si8Mg cast alloys are mechanical engineering, hydraulic castings, textile machinery parts, cable car components, mould construction and big parts without the heat treatment (www.alurheinfelden.com). Actually, there is an increasing tendency to use Al-alloys for innovative green product development. This self-hardening alloy is tested as a possible replacement for a conventional alloy AlSi7Mg (Castella, 2018; Rosso, 2013).

The test bars (ø 20 mm with length 300 mm) were produced from AlZn10Si8Mg ingots, by process of the sand casting in company UNEKO, Zátor, Ltd. Czech Republic. The sand casting is the simplest and the most widely used casting method. The melt was not modified or refined (Závodská, 2017a; Závodská, 2017b). Chemical composition of the alloys, determined by spectrometry, is given in Table 1. Consequently, the test specimens for the fatigue tests were produced by machining (Fig. 1a).

Tab. 1 Chemical composition of AlZn10Si8Mg alloys (wt. %)

alloy	Si	Zn	Fe	Mg	Cu	Ti	Ni	Bi	Sb	Al
A	8.69	8.73	0.150	0.382	0.003	0.071	0.0379	0.003	0.0078	rest
B	9.11	8.14	0.559	0.307	0.011	0.067	0.0015	0.004	0.0076	rest

The self-ageing starts when the castings are removed from the mould. Casting of AlZn10Si8Mg alloys obtained after first day of natural ageing approximately 50 % at room temperature, after the second and the third day approximately 80% and the increase of strength is normally completed 8 days later. Moreover, without the heat treatment the risk of component's deformations, which can occur during the different steps of heat treatment, is completely eliminated; those deformations are the main reason for majority of the component's faults, (www.alurheinfelden.com).

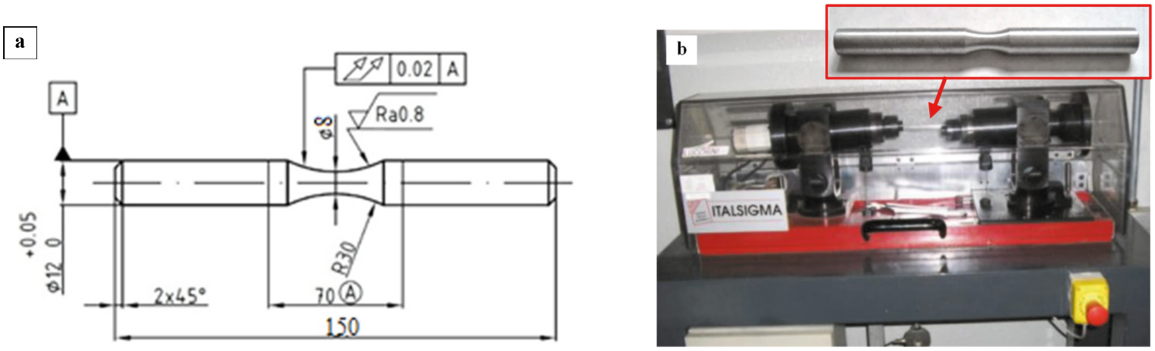

Fig. 1 a) the shape and dimensions of the specimen for fatigue test; b) the experimental testing device for rotating bending fatigue tests in Department of Mechanics, Politecnico di Milano, Italy - detail, where the sample is clamped

The formation of the Fe-rich intermetallic phases and porosity in experimental material was studied by using the light microscopy (NEOPHOT 32), scanning electron microscopy (VEGA LMU II) linked to the energy dispersive X-ray spectroscopy (EDX analyser Brucker Quantax). Metallographic samples have been selected from the fatigue test bars, which were prepared for metallographic observations according to standard, such as - wet ground on SiC papers, DP polished with 3 μm diamond past followed by Struers Op-S, etched by MA and H_2SO_4 for the highlighting of Fe-intermetallic phases. Some samples were also deep-etched for 30 s in HCl solution in order to reveal the 3D morphology of the phases. The quantitative metallography was carried out on an Image Analyzer (NIS Elements 4.2) to quantify the amount and size of the Fe-rich phases. In order to minimize the statistical errors in determinations, 25 micrographs for each specimen were assessed; a relative error of less than 0.05 % was sought.

The fatigue tests were realized in Department of Mechanics, Politecnico di Milano, Italy, on an experimental device for rotating bending fatigue testing, shown in Fig. 1b. To ensure the reproducibility of the measurement and the comparability of the measured results, the same conditions were set for each measurement. During the rotation, the stress at the gauge length was changing from maximum tension to maximum pressure, according to sinusoidal law. It means that this was an asymmetrical load with a stress asymmetry ratio R = -1, at room temperature T = 20 ± 5 °C. The testing device was powered by an electric motor and the load frequency depends on its speed, which in this case was 30 Hz. Recording of the number of applied cycles was determined using the speed counter. The accuracy of the load parameter determination is given by the error of the length of the loaded arm, the dimensions of the specimens and the accuracy of the weight determination. Rotating bending fatigue tests were realized on testing specimens (15 pcs) from two different series of production (alloy A - 0.150 % Fe and alloy B - 0.559 % Fe). The total length of the specimen was 150 mm and the gauge diameter d_0 = 8 mm, with geometry presented in Fig. 1a.

3. Results

The microstructure (Fig. 2) of the recycled AlZn10Si8Mg cast alloys, with different amounts of iron, consists of the α-phase dendrites, eutectic and various types of intermetallic phases. The α-matrix precipitates from the liquid as the primary phase in the form of dendrites and is nominally comprised of Al and Zn. The eutectic phase (crystals of Si in α-matrix) have been identified as the major constituent, silicon particles are like small grains of poorly rounded, thickened grains and were observed on the periphery of the α-phase dendrites. The intermetallic phases were identified by combination of the EDX results and the light microscopy observation - Chinese script - Mg_2Si phase, needles - Al_5FeSi phase and the ternary eutectic Al-$MgZn_2$-Cu (Závodská, 2017b).

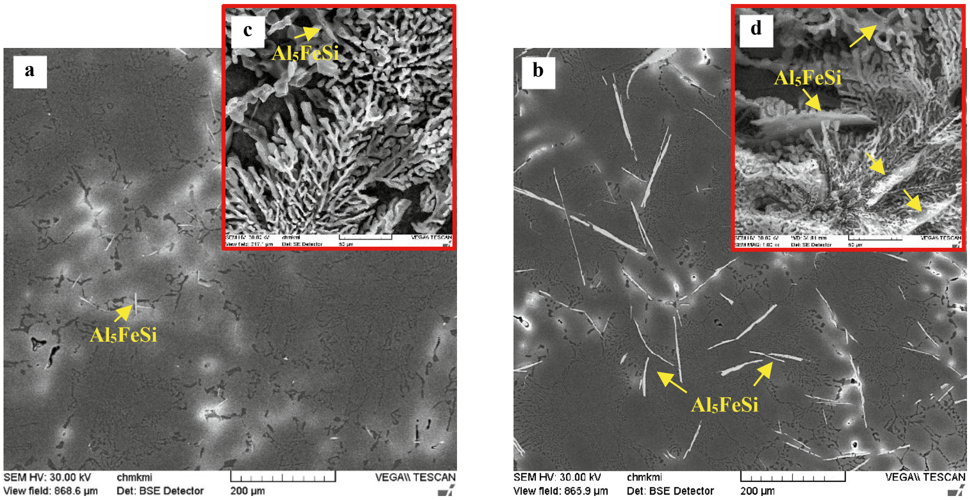

Fig. 2 Microstructure of AlZn10Si8Mg cast alloys: a) distribution of Fe-needles in alloy A; b) distribution of Fe-needles in alloy B, etch. H_2SO_4, SEM, BSE; c) morphology of phases in alloy A; d) morphology of phases in alloy B, deep etch. HCl

In the alloy A, compared to the alloy B, is visible that eutectic silicon has a slightly coarser structure on the edge in the α-phase and the Al_5FeSi needles are shorter and thinner. Observation with the BSE (back scattered electron) makes possible to highlight the Fe-phase (bright needles). Comparison of distributions of the Fe-needles in the microstructures of alloy A and alloy B can be seen in Figs. 2a, b. It is obvious that alloy with the higher content of iron (alloy B) contains more Fe-needles. It is possible to see the 3D shape of eutectic silicon and Al_5FeSi platelets (Figs. 2c, d). Silicon has crystallized in the form of fine bars and grows as clusters from a single nucleating site. It can be seen that the morphology of eutectic silicon of alloys A and B is the same (fine bars).

It was also observed that in the alloys A and B; the size, amount and thickness of the iron based β-Al_5FeSi are different (Fig. 2). Due to increasing the iron content it was measured that the average length of Al_5FeSi needles increased from 20.98 µm to 27.71 µm and needles were observed as the thicker ones. The area proportion of the Al_5FeSi phases increased with increasing content of iron, as well, from 0.9 % to 2.15 % (+238 %). The maximum length of the Fe-needles was increasing from 69.88 µm to 108.62 µm (Fig. 3a). Sporadically, the Fe-needles as long as over 108 µm were found in alloy B. The thickness of the iron phases is about 10 µm (Fig. 3b), but in both experimental alloys it does not exceed the critical length of the Fe-needles of over 400 µm (Taylor, 2012).

The results show that at the stress level of 100 MPa, the alloy A withstood more cycles (about 35 % more) compared to the alloy B; at the stress level of 90 MPa, the alloy A withstood about 45 % more cycles than alloy B, while at the stress level of 80 MPa the difference was only 15 % more compared to the alloy B. When the stress level was decreasing, the difference in the number of withstood cycles of alloys A and B was small. With the higher content of

Fe (0.559 %), the number of cycles of the fatigue tests is decreasing down to 70 MPa, where the change occurs and the material can then withstand more cycles. The main cause for difference in the number of cycles was the porosity of the individual materials and it was associated with percentage of iron in the specimens (Fig. 4b). The fatigue limit at number of cycles $3x10^6$, for specimen A was obtained for $\sigma_a = 60$ MPa, for alloy B was obtained for $\sigma_a = 70$ MPa, what is representing an increase by 16 %. Results have shown that the higher content of Fe reduced the fatigue lifetime in the short and medium life-time regime (< 10^6 cycles). It has no effect or it slightly increases the fatigue life-time for the long life-time regime (≫ 10^6 cycles).

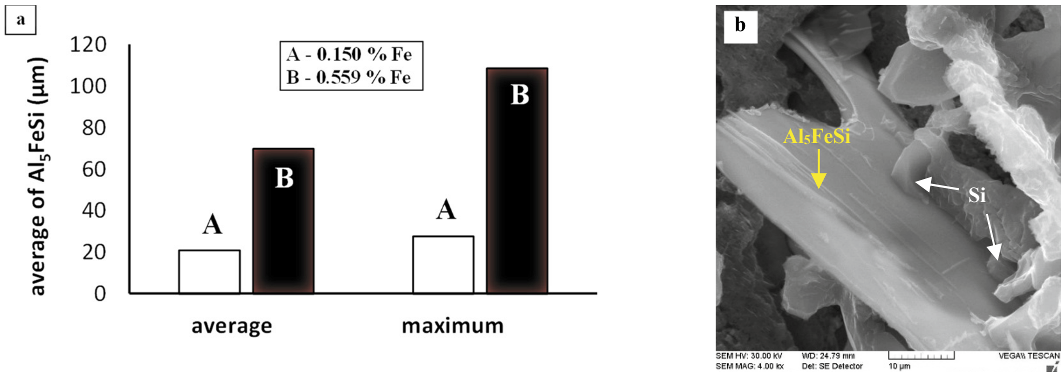

Fig. 3 Influence of Fe on Al_5FeSi needles in AlZn10Si8Mg cast alloys - a); b) morphology and thickness of Fe-needles, deep etch. HCl, SEM

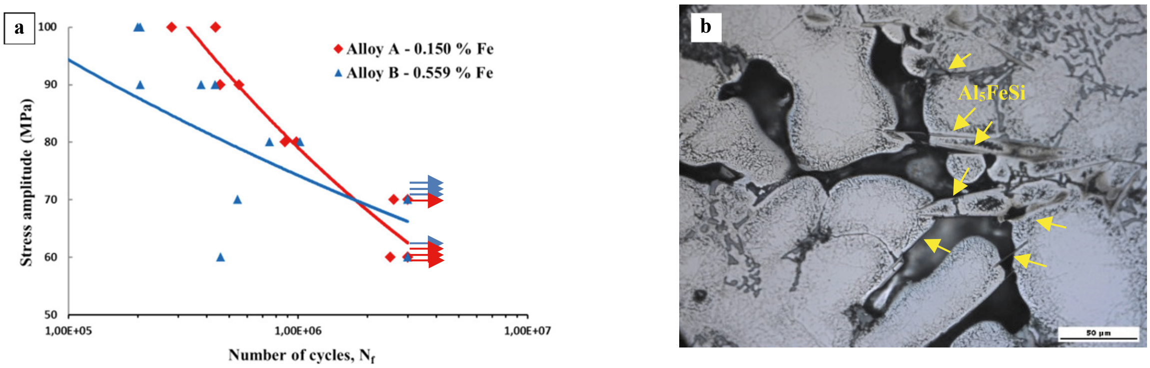

Fig. 4 Effect of iron of fatigue lifetime of AlZn10Si8Mg cast alloys - a); b) effect of iron phases on porosity formation, etch. MA

4. Conclusions

Based on the experimental results, the following conclusions can be drawn:

- The microstructures of the recycled (secondary) alloys AlZn10Si8Mg with different content of Fe, are the same and consist of α-phase, eutectic and various types of intermetallic phases; eutectic Si morphology has the same shape in alloys A and B - fine bars, that grow from one nucleation site, but the Si bars in alloy B are finer, probably because of the faster cooling rate;
- The size of the needle-like Al_5FeSi phases and their distribution are greatly affected by the amount of iron. With the increasing content of Fe, the area proportion and the average length of the Al_5FeSi phases has increased; pores were nucleated along the Al_5FeSi needles with thickness of approximately 10 μm;
- The AlZn10Si8Mg alloy with 0.150 % Fe has the fatigue limit $\sigma_a = 60$ MPa at $3x10^6$ cycles. In alloy B with the higher content of Fe (0.559 %) the higher σ_a was reached and it is shown that, although the percentage of Fe is higher, the fatigue limit increased by 16 %; it was also found out, that the higher content of Fe reduced the fatigue lifetime in the short and medium life-time regime (< 10^6 cycles). It has no effect or it slightly increases the fatigue life-time for the long life-time regime (≫ 10^6 cycles).

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