Observation on the Formation of β-Al$_5$FeSi Phase Depending on the Content of Fe in Aluminium Cast Alloy

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This work examines the effect on the formation of second Fe phase group Al-Fe-Si: Al$_5$FeSi in aluminium alloy containing the iron of 0.123 wt. %, 0.454 wt. % and 0.655 wt. %. Studies were focused on the size and content of Al$_5$FeSi changes and their effect on the porosity formation and mechanical properties in AlSi7Mg0.3 cast alloys. One of the key problems of these phases is their harmful morphology effect on to properties (mechanical, fracture, fatigue and so on) of aluminium casts. The increasing usage of recycled metals for production new casts is the main factor which influences content of iron in composition of aluminium cast alloys. The observation with using scanning electron microscope (SEM) and energy dispersive X-ray analysis (EDX), optical microscopy and quantitative analysis software confirms enlarging of the β-needles phases particles and size of pores with increasing of iron content.

Keywords: β-Al$_5$FeSi formation, iron in aluminium cast alloys, porosity of aluminium cast alloys,

1 Introduction

Regulations and directives from instances such as EU are sanctioned with the aim to both decrease the amount of toxic gasses released to the atmosphere and to utilise used metal scrap. The choice of whether to use alloys based on primary aluminium (low Fe levels, high cost) or secondary aluminium (moderate/high Fe levels, cheaper) for a cast product is often a commercial decision. However, a compromise may be necessary between the desire for reduced metal cost and the need to maximise casting productivity via reduced defect formation and to minimise the deleterious effect of iron on mechanical properties [1-6]. Therefore is important to study this type of microstructural components.

The iron (Fe), as major impurity element in Al-alloys is frequently acquired for non-high pressure die casting operations usually at levels ranging from ~ 0.25 to 0.8 wt. %, being most common with values around 0.4-0.8 wt. % and for high pressure die casting operations usually contain up to 1.5 wt. % of Fe from Al scrap during the recycling procé [4,7]. Liu et al. [8] reported that solubility of iron is approximately 1.8 wt. % at 655 °C in liquid pure Al but only 0.0052 wt. % at 450 °C in solid pure Al. Therefore, almost all the iron will precipitate from liquid Al alloys in the form of iron-rich intermetallics. The iron-rich intermetallic phases are groupen into three major morphology: polyhedral or star-like, Chinese script or skeleton like and polyhedral [1,2,4-6,8,9]. Šerák et al. [10] describes principles of reduction the deleterious effect of iron on the properties of Al-Si cast alloys. First principle is change in crystallization of iron-rich phases. This is possible by the mean of addition of some elements into the melt: Mn, Co, Cr, Be, Ni. This addition causes changes of harmful morphology of phases to less harmful especially Chinese script or skeleton like. Second principle is heat treatment of alloy, but here are two possibilities: heat treatment of the melt or of the casting. Both of the methods lead to fragmentation of selected iron-rich phases into smaller particles. Third principle present decrease in iron content into the acceptable level or full removing of iron in ideal case. This method uses high difference between the iron content in upper and bottom regions of crucible [10,11]. In secondary aluminium alloys is iron separated from molten aluminium, but not always it is economical. Among various Fe-rich intermetallic phases in Al-Si cast alloys (α-Al$_5$Fe$_2$Si; Al$_3$Fe(FeMn)$_2$Si; β- Al$_5$FeSi; π-Al$_5$Mg$_2$FeSi$_6$ and δ-Al$_5$FeSi$_5$), the β-Al$_5$FeSi needles (platelets) are considered as the most deleterious compounds since their edges act as stress concentration sites, facilitating crack inciation in the matrix [1,2,9,12-13]. The formation of Fe-rich intermetallic phase’s group β is connecting with two possibilities of decreasing the properties of aluminium alloys. First is the brittleness of Fe rich phases and the second porosity, whose reduces the ductility of Al-Si alloys. The brittleness led to formation of cracks in Fe-rich phase’s region. Cracks are caused with existing gas or shrinkage problems arising during solidification. If there are cracks the gas go deep into the dendritic mesh and the porosity is forming [14,15]. Therefore porosity is a leading cause in the reduction of mechanical properties, particularly elongation and fatigue resistance, as well as a loss of pressure tightness and a degradation of the surface appearance in cast parts [3,16,17]. A lot of work shows that the ultimate tensile strength of aluminium alloys did not relate to the average volume fraction of porosity, but with the length, shape or the size of the pore in the cross-section surface [17]. Also the harmfull effect of the Al$_5$FeSi phases morphology (2D brittle needles and 3D long platelets) was investigated in a lot of works, but the quantitatively understanding of the size and distribution of the Fe-phases are of paramount importance in the physical metallurgy of recycling Al alloys, and in the manufacturing of high-quality components for the transportation industry [18]. Therefore this

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study describes effect of different iron content on formation of Fe-needles phases without special solidification, casting or other condition and their effect on to porosity and mechanical properties in secondary AlSi7Mg0.3 cast alloys.

2 Experimental procedure

The chemical compositions of the secondary AlSi7Mg0.3 alloys prepared for present study are reported in Table 1; they were characterized by the different contents of the Fe (0.123 wt. % – material A, 0.454 wt. % – material B and 0.655 wt. % - material C). Experimental bars with dimensions 300 mm length and diameter 20 mm were casted into the sand mould (Fig. 1a). From these bars were made samples for mechanical test (Fig. 1b). The experimental materials were not modified, grain refined or heat treated. The addition of Fe were performed in order to study influence of higher Fe content in aluminium alloys, which may occur mainly during use of scrap for production of cast components especially casts in mechanical, electrical engineering, automotive and aerospace industries for shipbuilding, and so on [17].

The amount of Fe is higher for experimental materials, and is expected the effect of this element on mechanical properties and formation of porosity. It is well known that this amount leads to the formation of a Fe-rich intermetallic phase’s group called “beta or β-needles phase” and these phases deteriorate the properties too, because of their morphology (sharp - edged needles). The formation of intermetallic phases and porosity in experimental material was studied by using Thermo-calc software, light microscope NEOPHOT 32 with quantitative analyser software NIS Element 4.0 and scanning electron microscope VEGA LMU II with EDX analysis. Metallographic samples have been selected from the bars (Fig. 1a), which were standard prepared for metallographic observations such as – wet ground on SiC papers, DP polished with 3 μm diamond paste followed by Struers Op-S, etched by 0.5 % HF and H₂SO₄ for the highlighting of Fe-intermetallic phases. The results of quantitative analysis represent the measured values on about twenty-five field of each set of samples.

3 Experimental results

The investigation of the basic microstructure showed that microstructure of each experimental material (A, B, C) consists of α-phase dendrites, eutectic (it is mechanical mixture of α-phase and eutectic silicon) and different intermetallic phases. The thermo-calc prediction (Fig. 2) of phase’s formation and EDX analysis (Fig. 3 - point and mapping) confirmed presence of these intermetallic phases in microstructure of experimental material:

- Fe-rich intermetallic phases in needles form: Al₅FeSi,
- Fe-rich intermetallic phases in form of skeleton-like: Al₁₅(FeMg)₂Si₂
- Mg-rich intermetallic phases in form of script-like: Al₅Fe₂Mg₃Si₆ and Al₁₅FeMg₃Si₆

Tab. 1 The chemical compositions of experimental materials (in wt. %)

| Material | Al   | Si   | Fe   | Cu   | Mn   | Mg   | Zn   | Ti   |
|----------|------|------|------|------|------|------|------|------|
| A        | 92.253 | 7.028 | 0.123 | 0.013 | 0.009 | 0.354 | 0.036 | 0.123 |
| B        | 91.673 | 7.340 | 0.454 | 0.021 | 0.009 | 0.302 | 0.020 | 0.118 |
| C        | 91.486 | 7.315 | 0.655 | 0.030 | 0.010 | 0.292 | 0.028 | 0.120 |

Fig. 1 The experimental material (a) bars; (b) testing specimens

Fig. 2 Thermo-calc prediction of phase formation in AlSi7Mg0.3 cast alloys.
The β-phases crystallizes as thin plates that look like needles in the cross section. This phase is mostly associated with iron levels greater than 1 wt. %. The authors [19] examined that enough iron segregation occurs during solidification to cause and the β-phase is to form, even when the iron level is much less than 1 wt. %.

The experimental results of metallography observation (Fig. 4) and quantitative analysis (Table 2) demonstrated that iron phases content increase with increasing content of wt. % Fe. Also were obtained that iron content determines the shape of these needles. This needles are longer with sharper ending and curved shape (Fig. 4b) and also wider (Fig. 4b, c). These results relate with findings of authors [19] which confirmed that the higher the iron content is, the longer and wider are the needles. In any case, results show that higher Fe content leads to growing length of Fe-rich needles intermetallic phases which is not good with regard to properties. The removing of Fe from the melts is a very costly process [20,21]. Therefore it is important to study how this elements influence the properties of aluminum materials. The importance for this study was porosity formation and mechanical properties changes.

Sacinty et al. [22] examined that the β platelets grow twice as big when the Fe concentration is doubled and this, in turn, increases shrinkage porosity and leads to a 3-fold decrease in the tensile elongation values. To examine the effect of the Fe content on the porosity formation in experimental materials were specimens subject to quantitative analysis of area size and volume fraction of porosity (Fig. 4 and Table 3). The results point that the biggest area size of porosity is in material C which declare bigger influence of Fe-rich needles on to formation of porosity in experimental material. The maximum volume fraction shows that the biggest content of porosity is in

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**Fig. 3** Microstructure evaluation by using SEM observation, etch. 0.5 % HF. (a) mapping analysis; (b) point analysis of Fe needles.

**Fig. 4** The Al5FeSi phases formation and their quantitative assessment in experimental materials. (a) alloy A; (b) alloy B; (c) alloy C.

**Tab. 2** The quantitative analysis of Al5FeSi phase

| Material | A    | B  | C    |
|----------|------|----|------|
| The average length of Al5FeSi [µm²] | 24.49 | 35.43 | 41.93 |
| The average volume fraction of Al5FeSi [%] | 1 | 2.3 | 2.6 |

**Tab. 3** The quantitative analysis of pores

| Material | A    | B  | C    |
|----------|------|----|------|
| The max. area size of pores [µm²] | 125723.4 | 125066.4 | 219627.1 |
| The max. volume fraction of pores [%] | 3.8 | 5.6 | 3.2 |
materia B (Table 3 and Fig. 4). These results probably related with morphology of Fe needles. These are more sharpened as in as cast state which relate with higher stress concentration.

The mechanical properties results demonstrated changes depending on Fe content too (Table 4). While these structural changes are reflected by a modest improvement in the ductility, ultimate tensile strength (UTS) and Brinell hardness (HBW 5/250/15) are comparable for all material (A,B,C). The differences were about 5 or 7 % which is negligible. The authors [22] mention in their work that hence, limiting the Fe content of the primary AlSi7Mg0.3 alloy to 0.12 wt. % is worthwhile and pays off with superior microstructural features and mechanical properties. According this experimental study is possible to demonstrated that increasing amount of Fe have negative effect to greater formation of needles iron rich phases, but mechanical properties are not significantly affected.

| Material | A  | B  | C  |
|----------|----|----|----|
| UTS [MPa]| 140| 150| 147|
| HBW 5/250/15 | 52 | 55 | 54 |
| Ductility [%] | 1.45 | 1.91 | 1.58 |

4 Conclusions

The results presented in this paper refer about influence of different Fe content on formation of Fe needles phase and porosity in the secondary AlSi7Mg0.3 cast alloy. There have been observed these changes during experimental work:

- The microstructure of experimental material is created with α-matrix, eutectic and intermetallic phases: Al₅FeSi, Al₁₅(FeMg)₂Si₂, Al₅Fe₂Mg₂Si₆ and Al₅FeMg₃Si₆. The higher amount of Fe in chemical composition lead to formation rather Al₅FeSi then Al₁₅(FeMg)₂Si₂ phase.
- The metallography observation and quantitative analysis show that with increasing Fe content increase the length of Fe needles phases and their volume fraction. The quantitative assessment of porosity shows that 3.7 times higher amount of Fe (0.454 wt. % - alloy B) caused formation smalls pores with their higher volume. The 5.3 times higher amount of Fe (0.655 wt. % - alloy C) lead to formation larger pores with small volume on cross section. In any case, results show that higher Fe content leads to growing length of Fe-rich needles intermetallic phases and creating of larger pores which is not desirable.
- The results of mechanical tests demonstrated on to maximum properties in state (B) with 0.454 % of Fe (UTS = 150 MPa, HBW = 55, and A = 1.91 %). It relate with smallest size of porosity despite the fact that there is a large volume of porosity. The material A has the lowest properties, but differences were very small.

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