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Materials Properties of Iron-rich Intermetallic Phase in a Multicomponent Aluminium-Silicon Alloy

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Summary

Available technical literature includes a number of reports on harmful effects connected with elevated content of iron in aluminium-silicon alloys but in case of pressure castings, alloys containing up to 2% Fe can be used. This follows from lesser susceptibility of such alloys to sticking to surfaces of metal moulds. One effect of iron presence in aluminium-silicon alloys is precipitation of iron-rich intermetallic phases. In the study reported in this paper it has been found that in a multicomponent aluminium-silicon alloy, the indentation hardness (H_{IT}) and the elastic indentation modulus (E_{IT}) of intermetallic phases occurring in the form of polyhedrons and/or their conglomerates, rich in aluminium, iron, silicon, manganese, and chromium, containing also copper, nickel, and vanadium, are higher than those measured for silicon crystals. This feature can be used to intentional modelling microstructure of mechanical parts which are expected to show high resistance to abrasive wear.

Keywords: Al-Si alloys, Fe-rich intermetallics, Silicon primary crystals and matrix indentation

1. Introduction

Iron is the element invariably present in castings made of aluminium-silicon alloys, especially those manufactured by means of pressure casting techniques. The amount of iron introduced intentionally to an alloy can be as high as 2% [1] when reduction of the alloy's susceptibility to sticking to metal moulds is necessary, but uncontrollable iron quantities can also occur in the material as a result of presence of in-cast steel inserts not removed from the circulating scrap.

The maximum solubility of iron in aluminium at 650°C is 0.05% and decreases with decreasing metal temperature [2]. As a consequence, microstructure of aluminium-silicon alloys is characterised with occurrence of iron-containing intermetallic phases such as e.g. β-AlFeSi (Al_5FeSi) [3], α-AlFeSi (Al_8Fe_2Si) [2], α-AlFeSi ($Al_{15}Fe_3Si_2$), or π-AlFeSi ($Al_8Mg_3FeSi_6$) [4].

Volume share and size of iron-containing intermetallic phases increases together with increasing content of iron and silicon in the alloy and with decreasing cooling rate [5, 6].

β-AlFeSi phase crystallises in the form of platelets which on metallographic sections are visible as needle-shaped features. This particular precipitation form is considered undesirable as its presence creates favourable conditions for concentration of stresses and consequential nucleation of material microcracks. It is possible to reduce length of β-phase platelets by decreasing iron content and increasing the alloy cooling rate. Favourable for development of β phase is low content of manganese and chromium [1]. For the value of the quotient Mn : Fe = 0.5 in commercially manufactured aluminium-silicon alloys, the dominant phase is α-$Al_{15}(Fe, Mn)_3Si_2$ showing morphology of the Chinese script type. Phase α, more favourable in view of its shape, is stabilised by adding manganese and chromium. An addition of manganese acts in favour of development of precipitations of the Chinese script type [1, 7], while presence of chromium in the alloy is connected with occurrence of precipitations in the form of polyhedrons and their conglomerates forming star-like shaped particles. Beryllium, though regarded as an element harmful to human health, when introduced to the alloy in small amounts, results in the β phase changing its morphology to this of the Chinese script and/or polyhedral type [8, 9]. The shape of iron-containing intermetallic phase precipitations is also affected by content of magnesium and iron.

According to [3], in an alloy containing 0.57% iron and 0.39% magnesium, the authors observes a trend to predominance of π-$Al_8Mg_3FeSi_6$ and α-$Al_{15}Fe_3Si_2$ phases. With iron content increasing up to 0.97%, the trend for occurrence of β-Al_5FeSi phase intensified accordingly.

Authors of paper [10] observed a trend for precipitation of β-Al_5FeSi phase in alloys containing 0.35–0.40% magnesium. With higher content of magnesium, the prevailing type of precipitations represented π-$Al_9Mg_3FeSi_5$ phase with the Chinese script morphology.

According to [11], iron content increase from 0.5% to 3.0% is reflected in a gradual change in morphology of intermetallic phases from a platelet-like, through the Chinese script type, to solid polyhedrons. Introduction of an additive of 0.5–1.5% manganese and low Al-Si-Fe alloy cooling rate are favourable for development of precipitations characterised with the Chinese script morphology, while in case of high cooling rates, an addition of manganese as small as 0.1% is sufficient for precipitation of phases with this very morphology. An addition of manganese and chromium combined with increased Al-Si-Fe alloy cooling rate allows to avoid occurrence of intermetallic phase precipitations with platelet-like shapes.

It has been also found [12] that both in an alloy with hypoeutectic chemistry (7.8% Si) containing 1.12% Fe and in an alloy characterised with a nearly-eutectic chemistry (11.8% Si) containing 1.94% Fe, increasing the overheating temperature to 720°C, 800°C, 950°C, and 1000°C resulted in corresponding evolution of the observed shapes of iron-containing intermetallic phases including mainly the forms of long needles, short needles, short needles mixed with fine rounded particles; and fine rounded particles, respectively.

Authors of an other paper [13] report that in case of an alloy with hypoeutectic chemistry (5.94% Si) containing 1.48% Fe, the cooling rate of 10°C/min was favourable to creation of needle-(platelet-)shaped intermetallic phases. Increase of the cooling rate to 750°C/min resulted in occurrence of Chinese script-shaped precipitations, but when the cooling with rate as high as 9000°C/min, mainly polyhedral precipitations were observed.

The above-presented review of literature concerning intermetallic phases occurring in iron-containing aluminium-silicon alloys shows that there exists a wide range within which their chemical composition and morphology can be controlled.

Any modern approach to modelling microstructure of alloys requires establishing relationships between such properties of individual phase types as chemistry, morphology, and physical parameters including hardness and elasticity modulus. In studies on shaping microstructure of iron-containing aluminium-silicon alloys aimed at ensuring high resistance of the material to abrasive wear it is important to gain appropriate knowledge in this scope with respect to silicon precipitations, iron-rich intermetallic phases, and the matrix.

2. Research methodology

The aluminium-silicon with the following chemistry: 31.28% Si; 0.55% Mn; 1.41% Cu; 0.56% Cr; 1.10% Ni; 0.47% V; 0.56% Fe; 1.30% Mg; 0.005% Zn; 0.039% Ti; 0.0025% B; 0.05% P; and Al to balance, was prepared in an induction furnace with capacity of 5 kg. Modification with copper-phosphorus master alloy was performed at temperature 950°C. A metal mould with initial temperature of 300°C was poured with liquid metal at temperature of 920°C. From the cast plate with dimensions 400 mm × 120 mm × 40 mm, a specimen for the tests has been cut out an prepared by means of grinding and polishing. Next, the specimen was examined with the use of Tescan VEGA XMH scanning electron microscope equipped with Oxford Instruments INCA x-act adapter for chemistry microanalysis in order to identify possible presence of iron-rich intermetallic phase. Chemical composition analyses were performed both for such phase and for the alloy matrix. In the next step, the indentation hardness (H_{IT}) and the elastic indentation modulus (E_{IT}) were measured with the use of Nanoindentation Tester NHT manufactured by CSM Instruments.

3. Results and discussion

The following figures show the microstructure of the alloy (Fig. 1). Results of mapping aimed at determination of presence of alloying elements proved that iron-reach intermetallic phases occur mainly in the form of polyhedrons (Fig. 2). For a selected precipitation of iron-rich intermetallic phase, microanalysis of chemical composition has been performed (Fig. 3). It has been found that the phase contained 15.2–15.6% Fe, with significant content of aluminium and silicone, but also presence of manganese, chromium, copper, nickel, and vanadium could be observed.

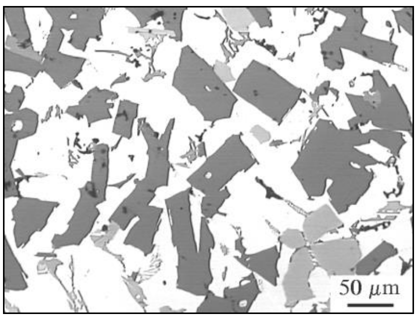


Fig. 1. Microstructure of the analysed aluminium-silicon alloy containing in its matrix precipitations of primary silicon, eutectic silicon, and intermetallic phases of various shapes

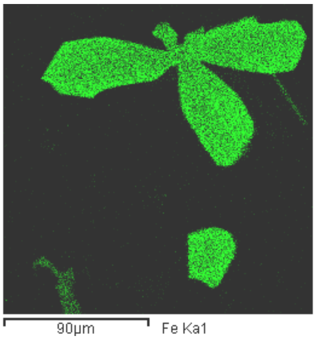
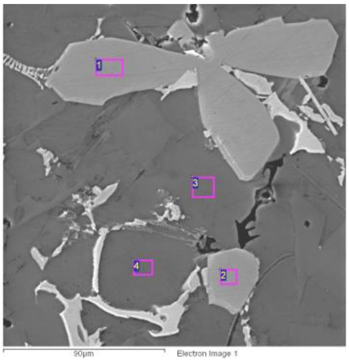


Fig. 2. Results of identification of iron-containing intermetallic phases (isolated polyhedrons and/or their star-shaped conglomerates)



Pt.	Al	Si	Mn	Cu	Cr	Ni	V	Fe	Mg
1	57.9	11.9	6.3	2.7	4.0	1.0	0.9	15.3	-
2	57.1	11.8	6.1	2.3	5.0	0.9	1.2	15.6	-
3	96.7	1.2	-	1.7	-	-	-	-	0.4
4	97.3	1.3	-	1.0	-	-	-	-	0.4

Fig. 3. Results of quantitative point analysis of polyhedral precipitations of iron-rich intermetallic phases and the matrix

Nanoindentation tests were carried out with the use of diamond Berkovich indenter tip B-L 32. The maximum value of the applied load force was 20 mN. Specimen loading and unloading rate for all microstructure components subjected to analysis was 40 mN/min. The maximum load force was applied for the period of 15 s.

The measurements have been carried out separately for silicon precipitations, iron-rich intermetallic phases, and the matrix. The results representing arithmetic averages from three measured values are listed in Table 1.

Table 1.
Measurement results compared to data quoted in literature

Intermetallic phase	Experimental data		Literature data	
	H_{IT} (GPa)	E_{IT} (GPa)	H_{IT} (GPa)	E_{IT} (GPa)
silicon	12.1	161	11.5 [14]	140.3 [15]
intermetallics (polyhedrons)	14.2	207	-	-
matrix	1.5	99	1,1 [16]	80 [16]

4. Summary

In a multicomponent aluminium-silicon alloy containing 0.56% iron, 31.28% Si; 0.55% Mn; 1.41% Cu; 0.56% Cr; 1.10% Ni; 0.47% V; 1.30% Mg, presence of intermetallic phase was found containing 15.3–15.6% Fe, rich in aluminium (57.1–57.9%), silicon (11.8–11.9%), manganese (6.1–6,3%), chromium (4.0–5.0%), but further containing also copper (2.3–2.7%), nickel (0.9–1.0%), and vanadium (0.9–1.2%). The dominant forms of these precipitations were polyhedrons and their conglomerates forming star-like shaped particles, showing indentation hardness (H_{IT}) and elastic indentation modulus (E_{IT}) values higher than those measured on silicon crystals. The values of the analysed materials properties of the matrix were higher than figures reported in the literature which can be attributed to its reinforcement with alloying element.

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