The Effect of Cooling Rate on Properties of Intermetallic Phase in a Complex Al-Si Alloy

M. Tupaj *, A.W. Orłowicz, M. Mróz, A. Trytek, O. Markowska
Department of Casting and Welding, Rzeszow University of Technology, al. Powstańców Warszawy 12, 35-959 Rzeszów, Poland
*Corresponding author. E-mail address: mirek@prz.edu.pl
Received 15.04.2016; accepted in revised form 01.06.2016

Abstract

The cooling rate is one of the main tools available to the process engineer by means of which it is possible to influence the crystallisation process. Imposing a desired microstructure on a casting as early as in the casting solidification phase widens significantly the scope of technological options at disposal in the process of aluminium-silicon alloy parts design and application. By changing the cooling rate it is possible to influence the course of the crystallisation process and thus also the material properties of individual microstructure components. In the study reported in this paper it has been found that the increase of cooling rate within the range of solidification temperatures of a complex aluminium-silicon alloy resulted in a decrease of values of the instrumented indentation hardness ($H_{IT}$) and the instrumented indentation elastic modulus ($E_{IT}$) characterising the intermetallic phase occurring in the form of polygons, rich in aluminium, iron, silicon, manganese, and chromium, containing also copper, nickel, and vanadium. Increased cooling rate resulted in supersaturation of the matrix with alloying elements.

Keywords: Al-Si alloy, Intermetallic phase, Cooling rate, Silicon primary crystals and matrix indentation

1. Introduction

Iron, apart from its harmful effect on mechanical properties of aluminium-silicon alloys, is introduced in quantities as high as up to 2% Fe [1] to reduce the tendency to adhere to metal moulds. Iron can be also introduced to aluminium-silicon alloys unintentionally, as a result of dissolving steel in-cast inserts not removed from the circulating scrap used to prepare liquid metal [1]. Some importance has also the economic aspect, as aluminium-silicon alloys contaminated with iron are less expensive. The maximum solubility rate of iron in aluminium at 650°C is 0.05% [2] which results in development of iron-containing intermetallic phases in iron-containing aluminium-silicon alloys, such as e.g.: β — AlFeSi ($Al_5FeSi$) [3], α — AlFeSi ($Al_8Fe_2Si$) [2], π — AlFeSi ($Al_8Mg_3FeSi_6$) [4]. Dimensions of iron-containing intermetallic phases increase with increasing content of iron in the alloy and with decreasing cooling rate [5, 6].

According to numerous authors [1, 6–10], shape of iron-containing intermetallic phases is affected by value of the quotient Fe : Mn : Cr (cf. Table 1). Al low content of manganese and chromium, these phases are needle-shaped [1]. Increase of manganese content contributes to creation of phases in the form of Chinese script [7]. In alloys containing above 0.40% Mg, one can observe a trend towards precipitation of phases with the Chinese script shape [10]. Increased content of chromium favours creation of phases in the form of polygons. Beryllium introduced in small quantities changes the needle-like shape of phase β into Chinese-script and/or polygonal forms [8, 9].
2. Research methodology

An aluminium-silicon alloy 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, Al to balance, was obtained in an induction furnace with a capacity of 5 kg. Modification with copper-phosphorus master alloy was performed at temperature 950°C. In order to differentiate the cooling rate, a water-cooled chill was designed at the metal mould base. To determine the course of the cooling process, two thermocouples were mounted on the mould cavity half-thickness lines (with mould dimensions 400 mm × 120 mm × 40 mm) at casting heights of 10 mm and 90 mm. The temperature vs. time curves were the base on which the cooling rate in the range defined by solidification beginning and end temperature was determined. Liquid metal with temperature 920°C was poured into a metal mould preheated to 300°C. From a plate-shaped casting, at heights 10 mm and 90 mm from the chill base, specimens for tests were cut and prepared further by means of grinding and polishing technique. In case of specimen no. 1 taken at a distance of 10 mm from the chill face, the cooling rate was 5.1°C/s (this work), while the specimen no. 2 taken at the distance of 90 mm from the chill face was cooled at rate 1.5°C/s. Results of examination concerning the specimen no. 2 are presented in [14]. The specimen no. 1 was subject to examination with the use of VEGA XMH scanning electron microscope (TESCAN), equipped with x-act adapter for chemistry microanalysis (Oxford Instruments) and INCA EDS analysis software, in order to identify the iron-rich intermetallic phase. The specimen was also subject to examination of chemistry of both intermetallic phase and matrix of the alloy. The next step included evaluation of the nanoindentation hardness \( H_I \) and nanoindentation elastic modulus \( E_I \) with the use of Nanoindentation Tester NHT (CSM Instruments).

3. Research results

Fig. 1 shows microstructure of the alloy cooled at rate 5.1°C/s. Fig. 2 presents example results of studies aimed at disclosure of intermetallic phase rich in iron.
Fig. 1. Microstructure of aluminium-silicon alloy with matrix containing primary silicon, eutectic silicon, and intermetallic phase precipitates with diversified shape, cooled at rate of 5.1°C/s

Fig. 2. Results of identification of iron-rich precipitates of intermetallic phase (polygons, isolated and clustered in star-like formations) for the alloy cooled at rate 5.1°C/s

Examination of distribution of alloying elements (mapping) has revealed that the intermetallic phases rich in iron were precipitates in the form of polygons. For a selected precipitate of such iron-rich intermetallic phase, microanalysis of chemistry was performed as shown in Fig. 3.

The obtained results allowed to conclude that the phase contains 12.0% – 14.3% Fe. Further, aluminium and silicon are prevailing components, but also manganese, chromium, copper, nickel, and vanadium are present.

Nanoindentation tests were carried out with the use of a diamond indenter B-L 32 with Berkovich-type tip. The maximum value of load force was 20 mN. The indenter loading and unloading rate for all of the analysed microstructure components was 40 mN/min. The maximum load force application time was 15 s.

The measurements were taken for precipitates of silicone and iron rich intermetallic phases as well as for the matrix. The results in the form of averages from 3 measurements are given in Table 4.

4. Summary and conclusions

In a complex aluminium-silicon alloy containing 0.56% of iron, cooled at rate 5.1°C/s, presence of intermetallic phase was found containing 12.0–14.3% Fe, rich in aluminium (58.3–59.9%), silicon (11.0–11.5%), manganese (3.8–4.5%), and chromium (4.1–4.7%), containing also copper (3.2–4.8%), nickel (1.7–2.4%), and vanadium (1.0–1.1%). The phase was characterised, compared to this obtained as a result of cooling at rate 1.5°C/s [14], with a higher content of aluminium, copper, and nickel and lower content of iron, silicon, manganese, chromium,
and vanadium. The effect of these differences consisted in a
decrease of values of the analysed properties ($H_I$ -
nanoindentation hardness, $E_I$ - nanoindentation elastic modulus).
In case of silicon precipitates, the obtained values of the analysed
parameters were practically the same, as chemical composition of
these precipitates remained virtually unchanged. Slightly lower
values can be explained by smaller dimensions of precipitates
which enable them to be plunged plastically in the matrix in the
course of indentation. As far as the matrix is concerned, it has
been found that with increasing alloy cooling rate, the analysed
material properties improved, which is a result of increased
supersaturation of the matrix with alloying elements.

References

Compounds in Al-Si Die-Casting Alloys: Their morphology
and conditions under which they form. AFS Transactions.
146, 231-238.


Role of iron in the formation of porosity in Al-Si-Cu–based
casting alloys: Part III. A microstructural model. Metallurgical and Materials Transactions A. 30A, 1657-
1662.

fracture behaviour of A356 alloys with different iron
13(4), 215-222.

intermetallic phases in the Al corner of the Al-Si-Fe system.

intermetallic in Al-7Si castings. Materials Science and
Technology. 14, 738-742.

formation in Sr modified Al-11.5 wt% Si die casting alloys.
AFS Transactions. 107, 117-125.

formation of β-FeSiAl₃ and Be-Fe phases in Al-7Si-0.3Mg
alloy containing Be. Materials Science and Engineering A.
190, 165-172.

Fe additions on the microstructure and mechanical properties
of A357.0 alloys. Metallurgical and Materials Transactions
A. 26A, 1195-1205.

AlMgSiFe crystals. Zeitschrift für Metallkunde. 88, 142-146.

Microstructure evolution in presence of the transition metals
(Fe, Mn, and Cr) in the Al-Si alloys. Biuletyn Instytutu
Odlewnictwa. 6, 4-11. (in Polish).

on iron-rich plate-type compounds in aluminium-silicon

crystallization behavior of iron – containing intermetallic
compounds in 319 aluminium alloys. Metallurgical and

Materials Properties of Iron-rich Intermetallic Phase in a
Multicomponent Aluminium-Silicon Alloy. Archives of
Foundry Engineering. 15(1), 111-114.