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X-Ray Tomography Investigation of Fe-rich Intermetallics in AlSi Alloys

P. Mikołajczak ^{a,b,*}, L. Ratke ^b

^a Institute of Materials Technology, Poznan University of Technology, Piotrowo 3, 60-965 Poznan, Poland

^b Institut für Materialphysik im Weltraum, German Aerospace Center DLR, Linder Höhe,
51147 Köln, Germany

*Corresponding author. E-mail address: Piotr.Mikolajczak@put.poznan.pl

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Abstract

Iron exists as a common impurity element in AlSi foundry alloys. The main consequence of the presence or adding of iron to AlSi alloys is the formation Fe-rich intermetallics with especially deleterious β -Al₃FeSi. This work aims to identify the role of fluid flow on the microstructure and intermetallics in Al-9 wt.% Si-0.2/0.5/1.0 wt.% Fe alloys directionally solidified under defined thermal and fluid flow conditions and extensively uses 3D x-ray tomography to get a better insight into their morphology and formation. The results have revealed the growth of larger and more dense β -Al₃FeSi intermetallics in the specimen centre as an effect of forced flow. The reconstructions confirmed that the course of number density at the specimen cross section increases from the specimen edge to its centre.

Keywords: Aluminum alloys, Intermetallics, β -Al₃FeSi, X-ray tomography, Melt flow

1. Introduction

Aluminum alloys are characterized by good thermal and electrical conductivity, excellent corrosion resistance, sound castability and high specific strength. They are replacing traditional materials in the areas of electrical conductors, construction, transportation, packaging, aerospace and machinery to achieve greater weight reduction.

The main impurities that exist in recycled Al-Si foundry alloys are iron, manganese, copper, and zinc. Iron is considered the most harmful element since its presence enhances the precipitation of many iron intermetallic phases [1,2]. The main microstructural consequence of adding iron to Al-Si foundry alloys is the formation of the β -Al₃FeSi phases. Hard and brittle β -Al₃FeSi (labelled also β -AlFeSi, β , platelets, needles, β precipitates) have detrimental influence on the alloy properties. These phases cause porosity [3], lower fluidity [4], act as stress concentrators [5] and promote crack initiation and lower fatigue

life. β -Al₃FeSi intermetallics increase hardness, reduce impact strength, machinability, but lower soldering of the casting in permanent molds and high pressure die casting.

The possibility of changing β -Al₃FeSi plates into less harmful phases or structure morphology can be a chance for industry to gain better quality of the castings. One of the methods being discussed in the last years is artificial melt flow, generated e.g. by rotating magnetic field (RMF) [6,7]. The present paper studies fluid flow effects during directional solidification of AlSiFe alloys using tomographic investigations with the Phoenix Nanotom™ in order to obtain information on the micro scale in 3D. Till now only a few x-ray studies have been performed on the β phases.

In the current paper we have concentrated on the 3D distribution and morphology of β formed in the specimens solidified directionally in Artemis-3 [6,7] special furnace in controlled temperature and flow conditions.

2. Methodology

This study comprises three aluminum alloys with 9 wt.% Si and 0.2, 0.5 and 1.0 wt.% Fe prepared from pure components: Al (99.999% Hydro Aluminium Deutschland GmbH), Si (Crystal Growth Laboratory, Berlin, Germany) and Fe from ferroaluminum (50 wt.% Al-50 wt.% Fe, Goodfellow Cambridge Ltd, UK). The melt was prepared in an electric resistance furnace using a graphite crucible and degassed with argon. No modifier was used. Specimens with 8 mm diameter and 120 length were processed in Artemis-3 facility, which allows directional solidification of metal alloys under controlled conditions [6,7]. The cylindrical specimens were solidified directionally upwards with a temperature gradient $G=3$ K/mm and solidification velocity $v=0.04$ mm/s, with and without fluid flow induced inside the specimen by a rotating magnetic field (RMF) with 6 mT at a frequency of 50 Hz, inducing first azimuthal flow and additionally secondary flows in radial and axial directions [8].

The six solidified samples were cut at a height of 50 mm from the bottom to the shape of a needle with quadratic cross section (Fig. 1.) with dimension of $0.9 \times 0.9 \times 8.0$ mm. The three dimensional measurements were done with x-ray tomography system Phoenix nanotom™ (Phoenix |X-Ray GmbH) with 180 kV / 15 W ultra high performance nanofocus x-ray tube producing a volume of $2304 \times 2304 \times 2304$ voxels and a pixel size of 1.0 μ m. Image corrections and ring artefact corrections were applied before the final three dimensional reconstruction. The information gathered in a full scan was reconstructed in "datos|x-reconstruction v 1.5.022" software (GE Sensing and Inspection GmbH) and the image analysis was performed using VGStudio Max 1.2, and processed with Gauss filter. Volume segmentation was carried out by choosing suitable gray levels applying global thresholding.

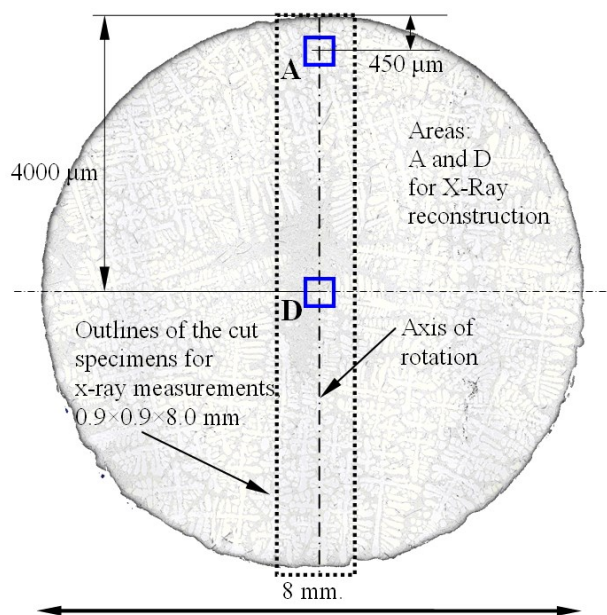


Fig. 1. A microstructure on the cross-section of the specimen of Al-9wt.%Si-1.0wt%Fe solidified under influence of RMF

3. Results and discussion

Fig. 2 a-l present x-ray tomography pictures for three Al-9 wt.% Si-0.2/0.5/1.0 wt.% Fe alloys concerning specimens solidifying without (0 mT) and with fluid flow (6 mT), taken in areas A (the specimen edge) and D (the specimen centre). Iron intermetallics have been marked with different shades of cyan whereas both α -Al phase and the eutectic are transparent. Owing to Fe absorption for x-rays being significantly different from that of primary α -Al and the eutectic, phases which contain Fe are clearly discernable. Visual accuracy is limited by 1 μ m resolution obtained in the x-ray nanotom, as well as small thickness of β platelets ranging from 0.5 μ m to 8 μ m.

In particular areas (cubes) in Fig. 2 one can observe a qualitative increase in number density and size of precipitated iron intermetallics along with the increase in the Fe content regarding the Al-9 wt.% Si-0.2 wt.% Fe and Al-9 wt.% Si-0.5/1.0 wt.% Fe alloys. Iron intermetallics for the Al-9 wt.% Si-0.2 wt.% Fe are smaller and more concentrated, their shape being far from the one of a platelet. For the Al-9 wt.% Si-0.5/1.0 wt.% Fe alloys intermetallics take the shape of platelets (Figs. 2 h, k and l).

In the specimen centre (area D) for Al-9 wt.% Si-0.5/1.0 wt.% Fe alloys (Fig. 2 g, h, k, l) the influence of melt flow is evident: it has caused formation of larger and more dense phases, some have about 100 μ m length and occupy nearly the whole reconstructed cube ($500 \times 500 \times 500$ μ m). Large β have not been formed in the Al-9 wt.% Si-0.2 wt.% Fe alloy, however the number density of intermetallics has grown. For the specimen Al-9 wt.% Si-1.0 wt.% Fe solidified without melt flow (area D) a large β -Al₅FeSi platelet has emerged therein (Fig. 3). The β -Al₅FeSi platelet also shows significant traces of dendrites. The presented β is coincident to results gained in [9,10,11].

It is also visible in the Al-9 wt.% Si-0.2/0.5/1.0 wt.% Fe alloys larger β platelets in the centre (area D) than outside (area A) for solidification with melt flow. The influence of melt flow on β phases is visible in area D in Al-9 wt.% Si-0.5/1.0 wt.% Fe alloy specimens. It is estimated qualitatively that there are more intermetallics and bigger platelets. The x-ray measurement of Al-9 wt.% Si-1.0 wt.% Fe shows formation of larger β -Al₅FeSi phases in the sample's centre (area D). Area A represent no noticeable change in volume and size of β under the influence of melt flow.

Fluid flow effect on the microstructure of the Al-9 wt.% Si-0.2/0.5/1.0 wt.% Fe alloys seems properly marked by the x-ray tomography and the results comply with earlier researches [7], where Steinbach proved appearance of a centre enriched in Si and Fe in samples solidified under the influence of melt flow (RMF). Current study and [13,14] revealed larger β in the center, but only x-ray showed increased number density of intermetallics. Moreover, in consequence of segregation and the dendrite free area, the sample centre saw formation of longer β platelets, with the increase in length from about 150 to 250 μ m [13]. X-ray investigations confirm the results of [13], where eutectic segregation has been visually observed in the centre and chemical composition has been confirmed with EDX, whereas metallographic sections have not shown more frequent occurrence of very long β in the centre. Histograms gained from metallographic sections in [13] particularly displayed large amounts of small β -Al₅FeSi platelets with length about 5-50 μ m.

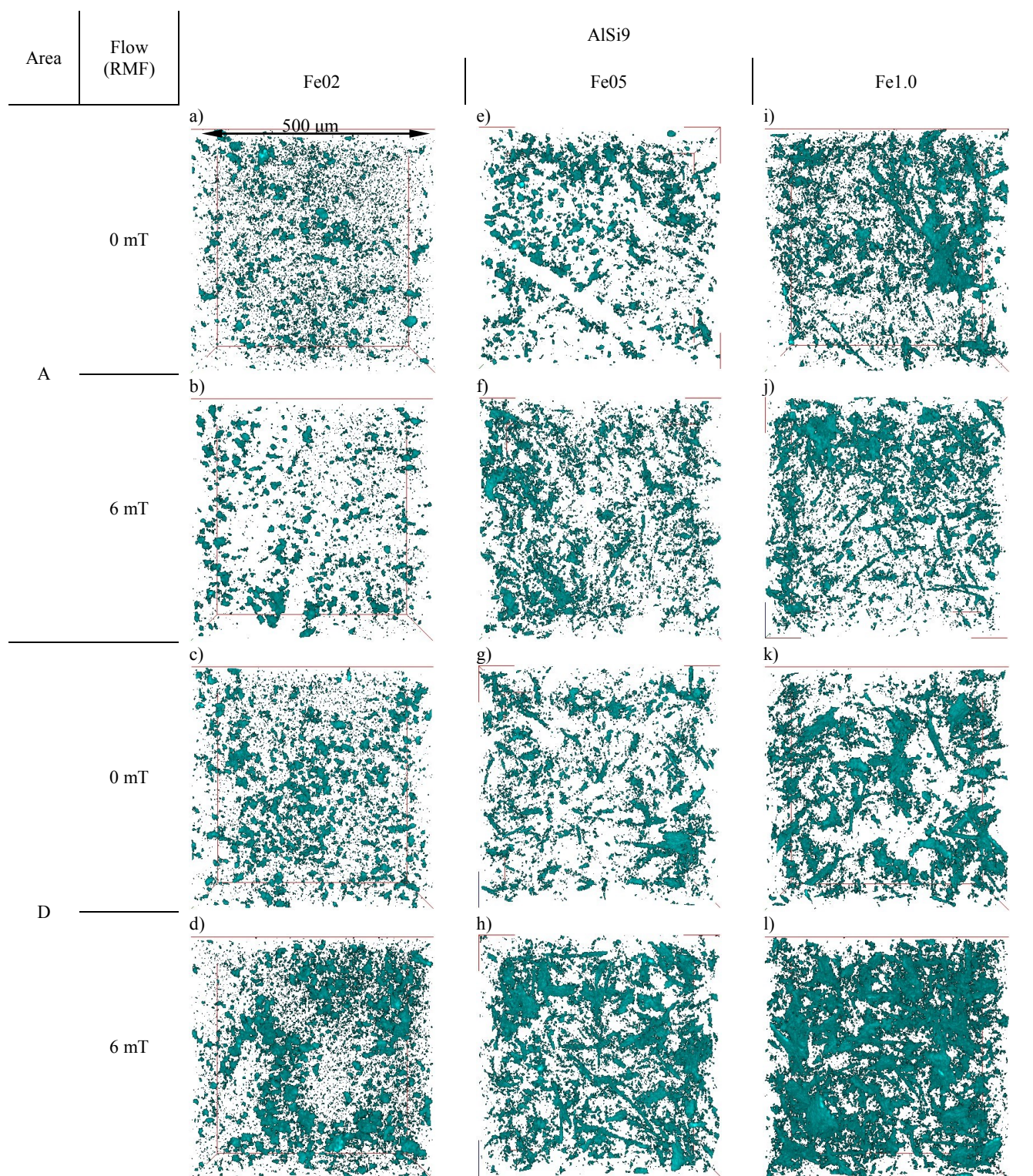


Fig. 2. 3D x-ray microtomography of Al-9 wt.% Si-0.2/0.5/1.0 wt.% Fe alloys solidified without (0 mT) and with (6 mT) melt flow. Iron rich intermetallics (in cyan) presented in the regions near specimen edge (area A) and in the specimen center (area D) against the background of dendrites and eutectics (transparent)

In Fig. 2 the density of intermetallics in the specimen centre (area D) is slightly higher than on the outside (area A) and the outcomes of x-ray tomography demonstrate compliance with the course of number density $n\beta$ at the specimen cross section in [13] increasing from the specimen edge to its centre.

4. Conclusions

X-Ray tomography investigations have confirmed increase in number density and size of precipitated iron intermetallics along with the increase in the Fe content. In the specimen centre (area D) for Al-9 wt.% Si-0.5/1.0 wt.% Fe alloys (Fig. 2g, h, k, l) the influence of melt flow is evident: it has caused formation of larger and more dense phases. Area A presented no noticeable change in volume and size of β under the influence of melt flow. Large β have been found with traces of dendrites. The study revealed larger β platelets in the centre (area D) than outside (area A) for solidification with melt flow. Results have confirmed the investigations of fluid flow effect on 2D microsections: larger β in the center and the course of number density at the specimen cross section increasing from the specimen edge to its centre.

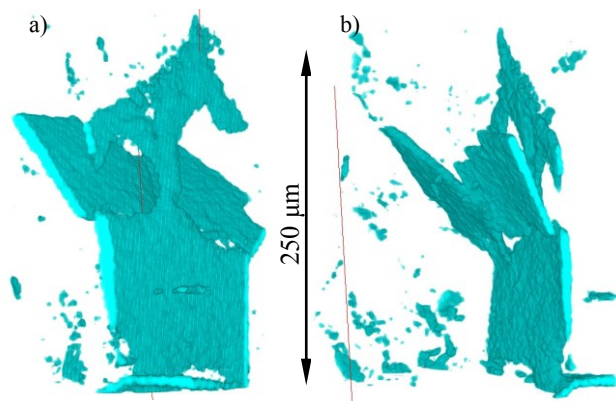


Fig. 3 a and b. Two views of the same group of β platelet intermetallics in AlSi9Fe1 alloy solidified without stirring.

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