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Letter

Modification of solidification microstructure in hypo- and hyper-eutectic Al–Si alloys under high-intensity ultrasonic irradiation

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ABSTRACT

In this study, the effect of ultrasonic irradiation is investigated on the solidification microstructure of hypo- and hyper-eutectic Al–Si alloys. Significant grain refinement accompanying dendrite to equiaxed transition was observed for the primary solid in both the alloys. Analysis of cooling curves suggest that enhanced heterogeneous nucleation under ultrasonication is responsible for the refinement of the microstructure. In the region of the ultrasonic energy transfer, strong fluid flow effect resulted in predominant spheroidisation of the eutectic-Si plates.

1. Introduction

Al–Si alloys are amongst the most widely used industrial metallic alloys due to a combination of good castability, mechanical performance and corrosion resistance [1]. Modification of the complex solidification microstructure, aimed at improving the processability and the mechanical performance, has received continued research attention in these alloys. High-Si alloys are less receptive to α-Al grain refinement through established commercial grain refiners [2], apart from the increased susceptibility to fatigue failure from the unused inoculant particles. Moreover, the large amount of eutectic and primary coarse Si-flakes that form during solidification of the Al–Si alloys are not modified by grain refiners leading to reduced ductility and wear performance [3]. Chemical eutectic modification, though widely practiced, does not refine the primary α-Al grains and is suspected to contribute to the formation of porosity and hot tearing with poor surface finish [4]. To address the limitations of the chemical methods, microstructure modifications using physical fields such as, mechanical or electromagnetic stirring have been explored [5,6]. Ultrasonic irradiation, in particular, appears promising in cast Al–Si alloys as both the primary and eutectic modifications are reported [7,8] as well as refinement of the primary solid has been reported for both hypo [8] and hyper-eutectic [9] compositions. However, the effect of ultrasound on the eutectic-phase remains unclear and the origin of primary-phase modification is highly debated.

Following our previous work [8], the present work further investigates the effect of ultrasound irradiation on the solidification microstructures in Al–Si alloys encompassing hypo- and hyper-eutectic regions. The main objective is to investigate the exact nature of the modification covering the whole spectrum of phases in Al–Si alloys including primary α-Al, primary-Si and the eutectic. Subsequently, an attempt is made to identify the possible origin of the microstructural changes under ultrasonication.

2. Experimental

Hypo-eutectic Al–7 wt.% Si (Al–6.31Si–0.57Mg–0.27Fe–0.16Mn) and hyper-eutectic Al–16 wt.% Si (Al–16Si–0.37Fe–0.16Mn) alloy ingots were melted at 750 ± 5 °C and homogenised for 2 h in an electric resistance furnace. All alloy compositions are expressed in weight percent. In each experiment, 250 ± 15 g alloy was taken out in a clay-graphite crucible preheated at 750 °C, allowed to cool naturally while placed on a refractory slab, and ultrasonicated (at 20 kHz frequency, 25 μm amplitude) using a Ti–6Al–4V radiator (horn) immersed to 2 cm below the top melt surface. Experimental set up is described in detail elsewhere [8,10]. A thermocouple, connected to multichannel data logging system, was placed below the submerged radiator to record the cooling curves during solidification. Similar experiments were performed without ultrasonic treatment for comparison. Each experiment was repeated to ensure reproducibility. The solidified ingots (⌀ 50 mm, height 65–70 mm) were cut longitudinally in the middle, ground and pol-

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ished using SiC abrasive papers and 0.25 μm silica suspension, and investigated under a ZEISS Axioscop2 MAT optical microscope equipped with an automated Zeiss AxioVision image analyser.

3. Results

3.1. Effect of ultrasonic irradiation on the hypo-eutectic Al–Si alloy

Fig. 1a shows a typical microstructure observed in the Al–7 wt.% Si alloy ingots solidified without ultrasonic treatment. As evidenced in Fig. 1a, primary α-Al (light phase) has solidified as fully grown dendrites of few mm in length. The inter-dendritic eutectic (inset in Fig. 1a) consists of long plates and coarse faceted particles of Si (dark gray) in α-Al matrix. Al(Fe,Mn)Si intermetallic compounds of Chinese-script morphology (light gray) have also been observed (inset in Fig. 1a). Ultrasonic irradiation resulted in noticeable alteration of the solidification microstructure. Fig. 1b shows representative micrographs from the region of direct ultrasound energy transfer at 5 mm from the horn. The dendrites seen in the conventionally solidified ingot (Fig. 1a) are replaced by refined and equiaxed primary-Al particles (Fig. 1b). Dendrtitic α-Al was suppressed throughout the ingot and particle size showed only a marginal increase with distance from the horn. The decrease in the average α-particle size is an order of magnitude lower as compared to the conventionally solidified microstructure shown in Fig. 2a.

Si particles formed under ultrasonication are either compact polygonal, especially near the ultrasound horn, or thin and short platelets uniformly distributed between the α-Al particles (dark gray phase in Fig. 1b). No primary Si nucleation was detected in the cooling curve, suggesting that Si formed predominantly through the eutectic reaction. Eutectic is uniformly dispersed in the ultrasonicated microstructure (Fig. 1b) compared to large interdendritic eutectic pockets observed in the conventionally solidified ingots (Fig. 1a). Unlike primary α-Al that is refined throughout the ingot, a gradual increase in the eutectic volume and progressive reduction in the refinement effect is observed with distance from the horn. Beyond 20 mm from the horn, Si solidified as thick platelets although still shorter in length compared to the conventionally solidified ingots (Fig. 2a). Ultrasonication also promoted compact and refined Al(Fe,Mn)Si intermetallic particles around the horn rather than the complex Chinese-script morphology obtained through the conventional solidification route.

A comparison of the average α-Al and eutectic Si particle size (Fig. 2a), shows a clear evidence of the effectiveness of ultrasonication in refining the microstructure. It should be noted that α-Al particle size is measured as the average primary dendrite arm length in the conventionally solidified ingot. This is considered reasonable as an individual dendrite with its primary and secondary branches represents one grain in the solidified microstructure. Therefore, the primary dendrite arm spacing provides a better approximation to the grain size than the secondary dendrite arm spacing. Comparison between Fig. 1a and b appears to indicate that the secondary dendrite arm spacing in the conventionally solidified ingot is similar to the α-Al particle size in the ultrasonicated ingot. This may initially suggest a dendrite fragmentation mechanism being operative under ultrasonication leading to grain multiplication. However, no large particles, from fragmented primary arms (and their coarsening), were observed in the ultrasonicated microstructure. Analysis of the cooling curves, as will be discussed in a subsequent section, indicates that enhanced nucleation rather than dendrite fragmentation contributed to the observed grain refinement effect. The average eutectic Si size is measured from the largest dimension of individual particles (plates or compact). It is also noteworthy that ultrasonication modified the solidification morphology (as discussed earlier) in addition to refinement of the microstructure.

3.2. Effect of ultrasonic irradiation on the hyper-eutectic Al–Si alloy

The optical micrographs from the conventionally solidified hypereutectic Al–16 wt.% Si alloy ingot is shown in Fig. 1c. Its

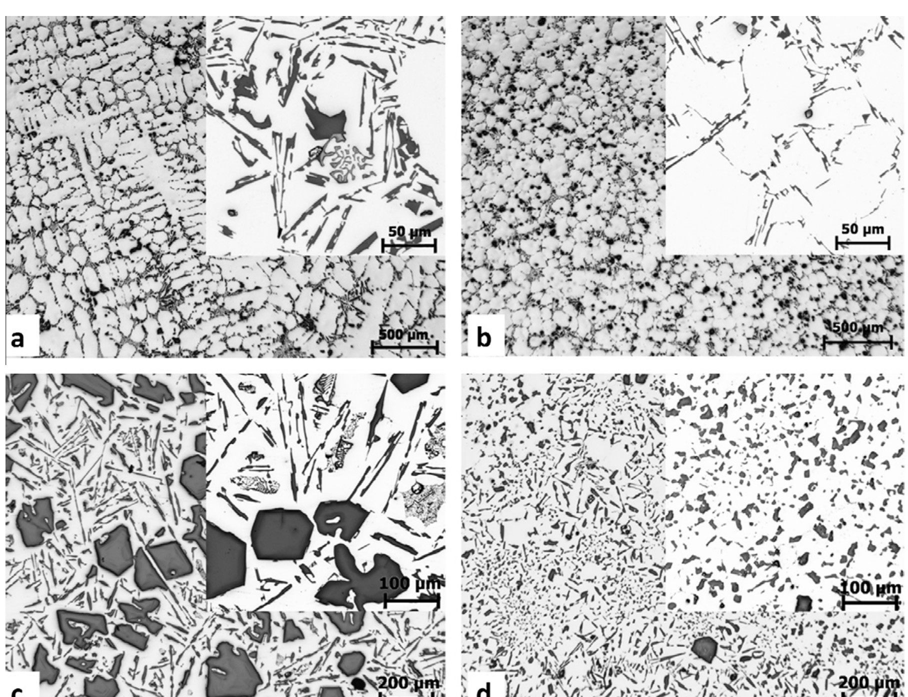

Fig. 1. Optical micrographs of the hypoeutectic Al–7 wt.% Si alloy ingot solidified (a) conventionally and (b) under ultrasonication. Micrographs from the hypereutectic Al–16 wt.% Si alloy are presented in (c) without and (d) with ultrasonic irradiation. Inset shows eutectic morphology.