Ultrasonic Assisted Reduction of Hot-Tearing During High-Speed DC Casting of 6000 Series Aluminum Alloys

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Abstract

This work presents results of preliminary investigations concerning the effect of ultrasonic vibrations on the solidification structure and hot-tearing susceptibility of 6000 series aluminum alloys in high-speed direct chill casting processes. A pilot DC caster was used to produce billets of 82–97 mm in diameter. Ultrasonic vibrations were introduced directly into the mold through a high-amplitude ceramic sonotrode, the tip of which was positioned at different distances from the melt crystallization front. The cast billets were then investigated for the microstructure and hot tearing susceptibility. It is shown that the ultrasonic treatment leads to a significant reduction in hot tearing susceptibility, and at the same time to a rise in mechanical properties of the alloys. The results suggest that at least two ultrasonic effects contribute to these improvements. The first one is cavitation which results in forming more refined and uniform microstructure of alloys. The second one is acoustic streaming which is responsible for macro agitation of melt in the sump. This causes the liquid-solid system to approach an equilibrium state that results in increasing the fraction of eutectic phase solidified at the grain boundaries of α-Al phase.

Keywords

Ultrasonic vibration • Hot-tearing susceptibility • Microstructure • Phase composition • Cavitation • Acoustic streaming

Introduction

High-intensity ultrasonic vibrations have been long recognized as an attractive tool to improve the solidified structure of light metals, particularly during DC casting of aluminum alloys. A large body of literature in this area shows that introduction of ultrasonic vibrations into molten aluminum alloys results in significant refinement of their solidified structure and improve their quality. The results of these investigations are summarized, for example, in [1, 2]. One of the mechanisms of structure refinement is ultrasonic cavitation assisted dispersion of refiner particles in the melt just before casting. In this case, ultrasonic vibrations can be introduced in the melt flowing through a launder. An example of such a process is ultrasonic DC casting of Al–Si hypereutectic alloys where AlP particles are exploited as a refiner of primary silicon [3, 4]. Another way to refine the solidified structure is to introduce ultrasonic vibrations directly into the melt in a mold. In this case, ultrasonic cavitation can be helpful in dispersing the refiner particles or breaking the growing dendrites in the sump just before or during the metal solidification. However, care should be taken to suppress acoustic streaming of melt in the sump, and thus to prevent the melt overcooling inside the mold which may result in coarsening the grains of primarily

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A.P. Ratvik (ed.), *Light Metals 2017*, The Minerals, Metals & Materials Series,
DOI 10.1007/978-3-319-51541-0_119

solidified phases. A typical example where this problem occurs is Al–Si hypereutectic alloys. As it has been shown in our previous work [4], improvement in design of hot top ultrasonic treatment unit can not only suppress the acoustic streaming, but makes it controllable and useful for producing billets with more refined and uniformly distributed grains of primary silicon.

This study presents one more technique for ultrasonic treatment where both the cavitation and acoustic streaming are helpful in increasing the productivity of DC casting process and improving the mechanical properties of the produced billets. The goal of this study is to investigate the effect of ultrasonic treatment on hot-tearing susceptibility of 6000 series aluminum alloys in high-speed direct chill casting process. Ultrasonic vibrations were introduced directly into the mold of a DC caster through a high-amplitude ceramic sonotrode to produce 82–97 mm billets. Then, the billets were investigated for the microstructure, hot tears and mechanical properties.

Experimental and Instrumentation

A pilot DC caster was used to produce billets of 82–97 mm in diameter and about 2 m in length using hot top molds. The melt was supplied to the mold through a launder. Casting temperature measured in the pouring launder was kept constant at a level of 690 ± 10 °C. The casting speed was varied in the range of 300–600 mm/min at an interval of 50 mm/min. The chemical compositions of alloys examined in this study are presented in Table 1. A commercial Al–5Ti–B master alloy was used as a grain refiner.

Ultrasonic vibrations were generated by an ultrasonic sonoprocessor (DG2000, Telsonic, Swiss) with the maximum power of 2 kW, using a piezoceramic transducer operated at a frequency of 20 ± 1 kHz. To introduce the vibrations in the melt, a high-amplitude ceramic sonotrode was used. The sonotrode was made of silicon nitride, had length and diameter of 465 and 48 mm, respectively. The vibration amplitude of sonotrode tip was measured by means of a laser displacement sensor (Keyence, LK-G35) in air conditions. Depending on the power supply, the vibration amplitude was varied from 40 to 70 µm on peak-to-peak base. Most of experiments in this study were performed at an amplitude of 60 µm. As the sonoprocessor had a built-in option to maintain the vibration amplitude at a constant level irrespective of the acoustic impedance of processing liquid, it was considered that the amplitude in melt was the same as that in air. Other details on the sonotrode characteristics can be found in our earlier publications [4, 5].

The casting procedure was as follows. About 400 kg of aluminum alloy was melted and superheated to a desired temperature in an electric furnace. The grain refiner was added to the melt in an amount of 2–4 kg/t, and then the melt was agitated and degassed by argon with a rotary-injector system. The tip of ceramic sonotrode was preheated up to the melt temperature using a small electric furnace. After starting the casting process, the sonotrode was moved to the hot top area and immersed into the melt coaxially with the mold. The sonotrode tip was fixed at a certain distance, L_S from the top edge of the mold. The ultrasonic power, transferred to the melt, was ranged from approximately 500 to 1000 W depending on the sonotrode vibration amplitude and immersion depth. Ultrasonic vibrations were continuously introduced into the melt sump during the casting process until it is finished. After that, the sonotrode was moved back to the preheating furnace.

As-obtained billets were investigated for the occurrence of hot-tear cracks by using an ultrasonic non-destructive testing equipment. Also, billets were cut at the appropriate intervals to observe the crack morphology. Samples were cut out of different areas of the billets to investigate the microstructure of alloys. Besides, specimens for tensile test were cut along the casting direction at the half-radius location and machined according to JIS14A [6].

Experimental Results

Effect of Ultrasonic Treatment on Hot Tearing Susceptibility

The results showed that the susceptibility to hot tearing during the casting is significantly reduced when ultrasonic vibrations are introduced into the melt sump. The results of typical experiments are shown in Table 2.

As seen from the Table 2, the ultrasonic treatment allows the casting speed to increase by 100–150 mm/min as compared to conventional casting. The effect of ultrasonic treatment depends on the alloy composition, billet diameter and distance L_s (sonotrode immersion depth). The smaller the diameter and the larger the immersion depth, the greater is the

Table 1 Chemical composition of alloys

	Si	Mg	Cu	Fe	Mn	Cr	Eutectic fraction (wt)
Alloy 1	0.82	0.95	0.35	0.3	0.08	0.13	0.024
Alloy 2	0.7	0.85	0.35	0.3	0.08	0.13	0.016
Alloy 3	1.4	0.85	0.2	0.25	0.4	0	0.048

Table 2 Maximum casting speed for various alloys at different conditions

Alloy	Billet diam (mm)	Maximum casting speed (mm/min)		US power (W)	Distance L_S (mm)
		Conventional	US casting		
Alloy 1	82	350	450	520–550	40–20
	82	350	500	760–880	0 to −20
	97	300	400	750–900	0 to −20
Alloy 2	82	350	450	620	20
	82	350	500	760	0
Alloy 3	82	400	550	640–970	0 to −20
	97	350	470	620–950	0 to −20

increase in casting speed with ultrasonic treatment. Negative values of L_s mean that the sonotrode tip was fixed below the mold top edge. Exceeding the maximum casting speed caused hot cracking which started from the billet center. In most cases, the cracks had a three branch star shape.

Billet Microstructure

Investigation of microstructure at the billet center, surface and half-radius distance revealed that α-Al grains tend to be more rounded and finer grained after the ultrasonic treatment. Typical images of the grain microstructure are shown in Fig. 1. It is seen that some parts of grains at the billet center (d) and half-radius (e) have dendritic branches. On the other hand, in the billet obtained in ultrasonic assisted casting, no dendritic branches are observed. Another important finding is that the ultrasonic vibrations improve the uniformity of grain microstructure. Table 3 presents typical average diameter of α-Al grains, D_{Al} and the corresponding standard deviation, σ_D. This data was obtained by image processing of several images taken at the center part of a billet of alloy 3. It is seen that both the values of D_{Al} and σ_D significantly decreased after the ultrasonic treatment. Also there was a tendency for D_{Al} and σ_D to vary with the sonotrode tip position, LS. However, this variation is statistically insignificant in the present experimental conditions. Thus, the above improvement in the microstructure of αAl grains can be one of the reasons for reduction of the hot tearing susceptibility obtained in the present study.

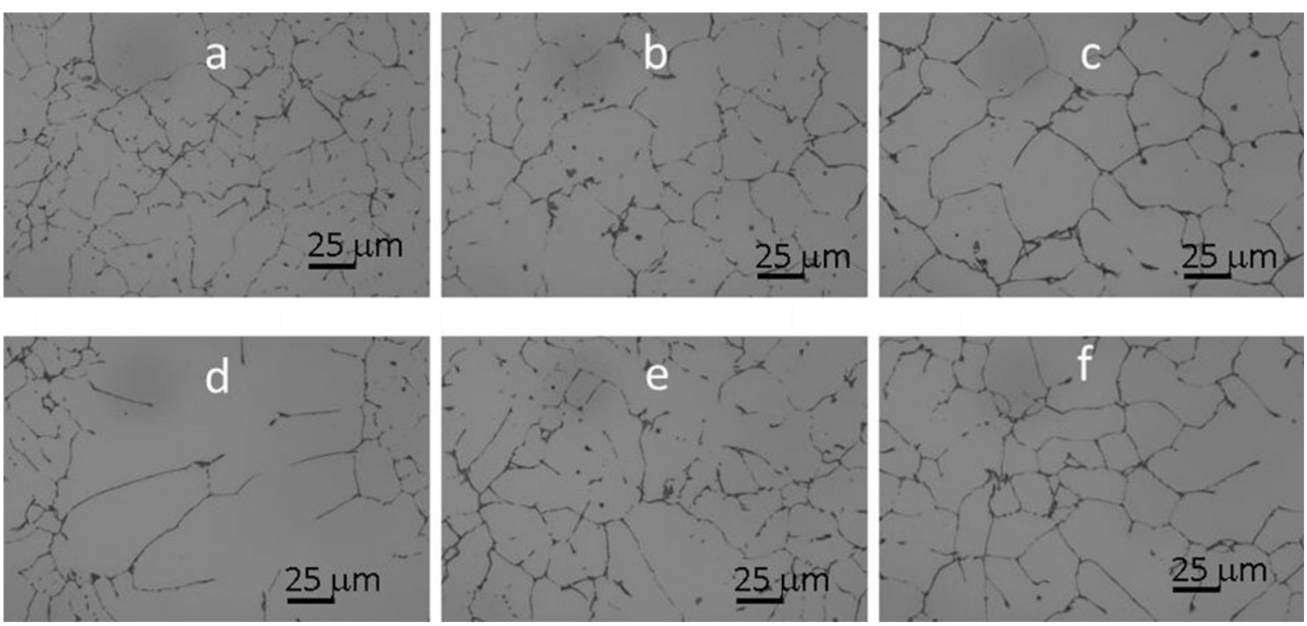

Fig. 1 Microstructure of billet (Alloy 3) at the center (**a**, **d**), half-radius (**b**, **e**) and surface (**c**, **f**) obtained in ultrasonic assisted DC casting (**a**–**c**) and conventional (**d**–**f**) casting

Table 3 Average diameter of α-Al grains, D_{Al} and its standard deviation, σ_D for the center part of billet of alloy 3

	Conventional casting	Ultrasonic assisted casting	
		L_S = 0 mm	L_S = −20 mm
Average diameter, D_{Al} (μm)	90.1	64.1	54.3
Standard deviation, σ_D (μm)	30.4	14.0	11.3

Effect of Ultrasonic Treatment on Phase Composition

As readily seen from Fig. 1, the billet microstructure is composed of αAl grains and a more low-melting films formed on the grain boundaries. The films are viewed in Fig. 1 as black areas. Prediction of the phase composition with JMatPro software revealed that these films can contain such phases as eutectic, Mg_2Si, α- and β-AlFeSi compounds and some other phases, depending on the alloy chemical composition. However, for the sake of simplicity, hereinafter these phases will be referred as to eutectic phase. The eutectic fraction, thus determined, is presented in Table 1.

A more careful analysis of the microstructural data indicated that the fraction of eutectic phase after ultrasonic treatment becomes larger as compared to conventional casting. Moreover, the fraction was found to vary with the sonotrode immersion depth. Figure 2 shows the fraction of surface area, γ_e occupied by eutectic phase at the billet center as a function of the casting speed for a number of conventional and ultrasonic casting process. Open dots correspond to the data without hot tears, while the solid dots denote those with hot tears. The data were obtained by image processing of ten images for each experimental conditions.

The data reveal that when alloy 1 was cast at a speed of 400 mm/min with ultrasonic irradiation, switching the ultrasonic field off resulted in hot tearing and decreasing the fraction of eutectic phase. Another example is ultrasonic assisted casting of alloy 2. An increase of immersion depth of sonotrode by 20 mm caused increasing the eutectic phase fraction and made it possible to produce a hot-tear-free billet. In the case of alloy 3, an increase of the sonotrode immersion depth led also to increasing the value of γ_e. However, too high of a casting speed caused hot tearing.

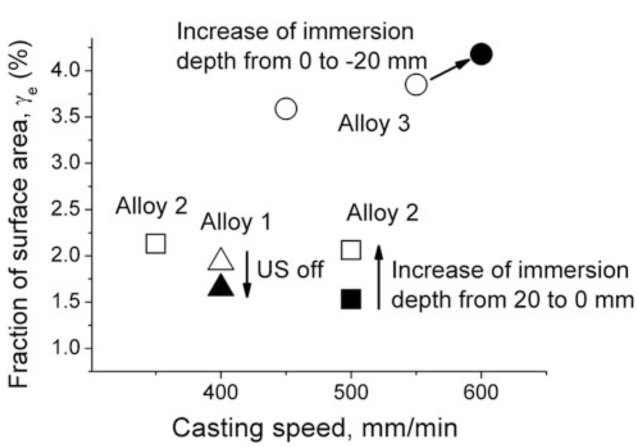

Fig. 2 Fraction of surface area corresponding to eutectic phase as a function of casting speed for different alloys

Tensile Test Results

Results of tensile test indicated two effects of ultrasonic treatment on the mechanical properties of alloys. The first one is an increase in tensile and yield strength, and in elongation. The second one is a significant reduction in scattering of all these mechanical properties. Typical data are presented in Table 4 for alloy 3. The data were obtained by performing several tensile tests of HO/T6 treated specimens followed by statistical treatment of measurement results.

Similar improvements in mechanical properties have been obtained for the other alloys. For example, the average values of tensile strength, yield strength and elongation of specimens cut out from the half-radius parts of as-casted billets of alloy 2 are (conventional casting/ultrasonic casting) 370/372, 322/332 MPa and 12.3/15.5%.

Discussion

The above results can be explained as follows. It is well known that ultrasonic irradiation in liquids causes cavitation and acoustic streaming. As it has been shown in our previous work [5], the threshold value of vibration amplitude necessary for a stable cavitation to be generated in liquid aluminum is approximately 10 μm (p–p). Since the sonotrode vibration amplitude in the present experiments is much higher than the threshold one, it is evident that a high-intensity cavitation field is formed in the melt sump. Cavitation produces shock waves and microjets in the sump that concentrate energy onto interfaces between the melt and growing crystals in the mushy zone. This may results in the αAl grain refinement and vigorous agitation of melt in the mushy zone, causing the liquid-solid system to

Table 4 Mechanical properties of alloy 3 produced by conventional and ultrasonic casting

Experimental conditions		Tensile strength (MPa)		Yield strength (MPa)		Elongation (%)		Casting speed (mm/min)
		Average	St.dev	Average	St.dev	Aver	St.dev	
Conventional		387.6	6.8	320.4	3.8	16.2	5.1	400
UST	$L_S = 0$ mm	392.7	0.6	323.3	1.6	18.4	0.9	550
	$L_S = -20$ mm	391.9	0.7	322.6	1.3	18.2	1.3	550

St.dev standard deviation

approach an equilibrium state. Acoustic streaming is defined as a steady fluid motion caused by the attenuation of ultrasonic waves in fluids. In the present experimental conditions, the velocity of acoustic streaming in the sump can reach as high as 0.5 m/s. This assumption is based on the results of our earlier study on the acoustic streaming in molten aluminum [7]. Such a high velocity flow should efficiently agitate the melt in the sump at macro level that can cause the tip rounding effect of αAl grains in a similar way as in semi-solid processing. Thus, the agitation and homogenization of the melt due to cavitation and acoustic streaming may lead to a faster approach to the equilibrium state may help and, as a result, the amount of eutectic phase and film thickness between Al grains is increased. This phenomenon is assumed to be another reason for the reduction of hot tearing susceptibility in the present experiments.

Schematically, the variation in hot tearing susceptibility with the amount of eutectic phase can be represented by Fig. 3. When the amount of eutectic phase is relatively small, microvoids and micropores can be formed between α-Al grains as shown in Fig. 3a. Such defects can originate cracks during solidification at high levels of thermal stress. On the other hand, the probability of crack initiation is much less when the intergranular space is filled with the eutectic phase, as shown in Fig. 3b. Such a mechanism of hot tearing is well known from relevant literature [8].

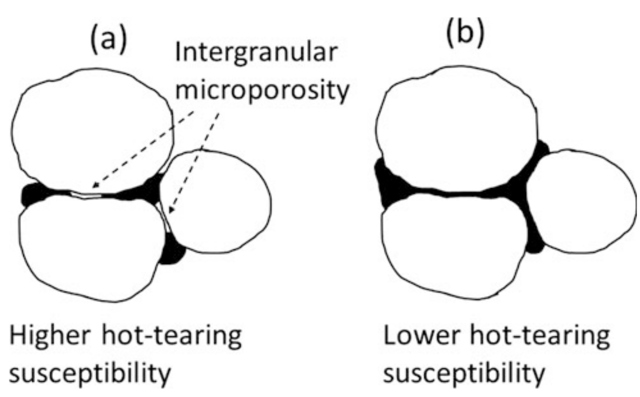

Fig. 3 A representation of hot tearing mechanism

Conclusions

The present investigation shows the potential of using ultrasonic vibrations to reduce ho tearing susceptibility during DC casting of 6000 series aluminum alloys. Ultrasonic vibrations were introduced directly into the mold of a DC caster through a high-amplitude ceramic sonotrode to produce 82–97 mm billets. Then, the billets were investigated for the microstructure, hot tears and mechanical properties. Based on the investigation results, the following conclusions were made.

(1) Ultrasonic treatment leads to a significant reduction in hot tearing susceptibility that allows to increase the casting speed from 300 to 400 mm/min typical for conventional casting to 450–550 mm/min for ultrasonic casting. Generally, the casting speed was dependent on the alloy composition.
(2) Billets produced by the ultrasonic casting have higher tensile and yield strength, and elongation as compared with conventionally produced billets. In addition, scattering in the mechanical properties was significantly decreased after the ultrasonic treatment.
(3) These improvements are explained by the following three effects induced by application of ultrasonic vibrations in the melt: refinement of α-Al grains, uniformity of microstructure and approaching the liquid-solid system in the melt sump to equilibrium state. It is suggested that acoustic cavitation and acoustic streaming are responsible for the above effects.

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