Effect of flow management on ultrasonic melt processing in a launder upon DC casting

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Abstract
A promising strategy for upscaling ultrasonic melt treatment (UST) during direct-chill (DC) casting is through a strategically-placed flow management system in the launder. This aims at improving the melt residence time and acoustic pressure distribution, which ultimately optimizes the treatment efficiency. This work focuses on observing the effect of partitions and UST on the resultant grain refinement upon DC casting of an AA6XXX aluminum alloy with Zr additions. Billets 152-mm in diameter were cast in a pilot-scale DC casting facility: cases with and without partitions and with and without UST were compared. The effect of partitions on the UST efficiency was quantified through macro- and micro-structure observations and supported with acoustic pressure measurements. The positive impact of partitions on the grain refinement upon UST is demonstrated.

Keywords: Ultrasonic melt treatment, DC casting, structure refinement, melt-flow management, acoustic pressure measurement.

1 Introduction

Direct chill (DC) casting is a robust mainstream technology for producing wrought aluminium alloy billets/ingots intended for further downstream processing, such as rolling, extrusion or forging [1]. The grain structure is an important feature in cast products as it is linked directly to mechanical properties and performance. Fine and uniformly distributed grains are preferred as they typically indicate improved technological properties and better resistance to casting defects [2]. To refine grains In industrial casting practice, the common practice is to add grain refiner agents during casting, such as AlTiB master alloys for Al-alloys [1,3]. Ultrasonic melt treatment (UST) is an alternative technology of melt treatment that is both efficient and eco-friendly, with one of its main benefits being grain refinement of a cast product with the minimum or even without the addition of a costly grain refiner [4].

Although the benefits of UST in treating molten metal and refining the as-cast structure have been proven in the lab and pilot scale casting [5], treatment on a large scale typically requires the use of several UST sources [6]. Moreover, most of the trials of large-scale DC casting were performed with the UST in the sump of the billet, which, of course, limits the number of billets to be produced as at least one transducer is required per billet, thus multiplying the required investment and operation challenges for multi-billet production [4]. Therefore, to reduce the complexity of the setup and improve cost-efficiency thus increasing the likelihood for industrial adoption, the suggested solution for upscaling is to perform effective treatment of large-volume melts using a single ultrasonic source, while moving the location of the UST upstream to the melt flow on the launder.

Our previous work has demonstrated that UST treatment in a DC casting launder (launder UST-DC casting) is effective in refining the structure of billets from an AA6XXX with Zr additions [7]. The structure refinement was achieved through activation of potent substrates and fragmentation of primary intermetallics (Al_3Zr) [8]. Our previous lab-scale and numerical studies [9, 10] also suggested that there are possibilities to improve UST efficiency by deploying smart melt-flow management system in a form of partitions in the launder. These partitions aim to improve the UST treatment efficiency by harnessing the acoustic resonance conditions – via an increase in cavitation activity when the distance between partitions is approaching the wavelength of the ultrasonic transducer frequency [11], and improving the residence time – the time spent by the melt in the cavitation-active zone, the longer the better for melt treatment quality [4].

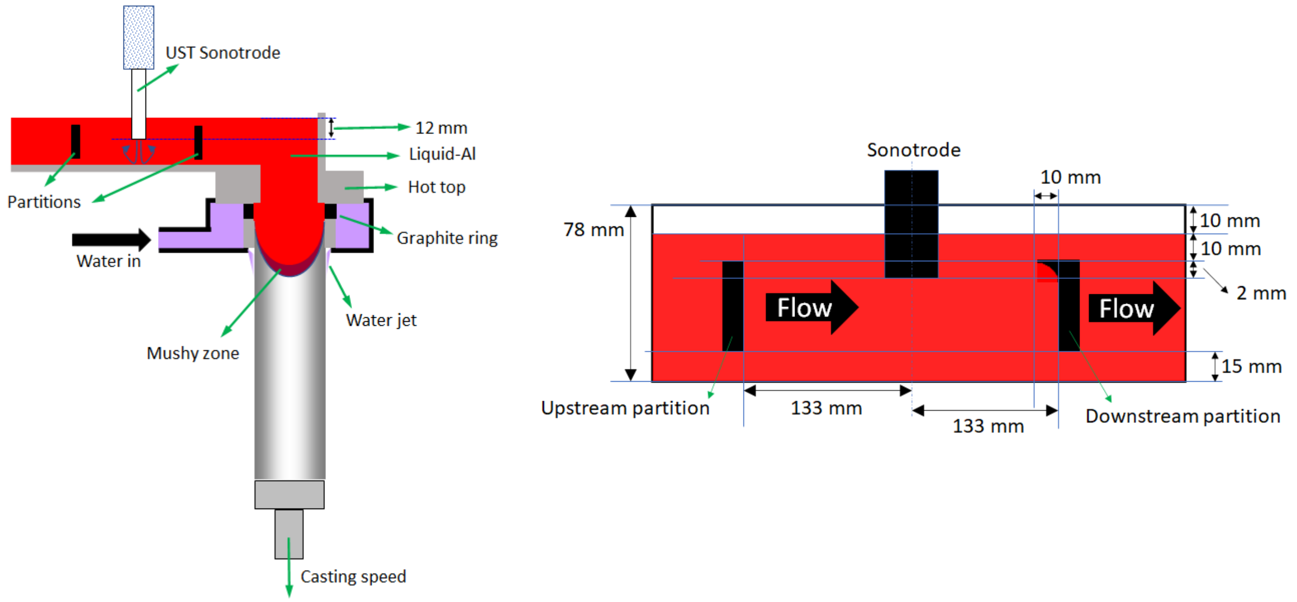
In this work we focus on assessing the effect of partitions and UST during DC casting of an AA6XXX alloy with addition of Zr. The effectiveness of the UST is assessed through structure observations (on both macro- and micro-length scale) supported by acoustic pressure measurements. On the macroscopic scale, the observations were carried out through etched macroscopic samples, while on the microscopic scale, in addition to microscopy analysis of anodized microstructure, grain size quantification was also carried out. Suggested directions for future research to further improve the UST efficiency are also provided. The outcome of this research acts as a proof of concept for the benefits of employing a flow management system in the launder during UST-DC casting, bringing UST one step further towards industrial-scale melt processing.

2 Materials and Methods

In this work, an AA6XXX-series aluminum alloy was used as the base alloy with an addition of 0.25 wt% Zr, but without any AlTiB grain refiner. In this case, Zr was used as an indicator of UST efficiency as it is known that its addition results in significant grain refinement in combination with UST [4, 5]. The chemical composition of the alloy was analyzed using optical emission spectroscopy (OES) and the average composition of the alloy is shown in Table 1. DC casting was carried out in the Advanced Metal Casting Centre (AMCC) of the Brunel Centre of Advanced Solidification Technology (BCAST), Brunel University London. The diameter of the billet was 152 mm and it was cast with a hot top. Two billets were cast at a casting speed of 140 mm min^{-1}; one billet was cast while the partitions were deployed in the launder, and as a reference the other cast was done without partitions. Each billet has a length of about 1 meter. The first 0.5 m of the billet was cast without UST, and after this length was reached, the UST was implemented through a sonotrode immersed into the melt in the launder. The schematic of the experimental setup is given in Figure 1a.

Table 1 Average chemical composition (wt%) of the alloy obtained through optical emission spectroscopy (OES).

Al	Si	Fe	Cu	Mn	Mg	Zr	Cr	Ti
Balance	0.75	0.24	0.76	0.49	0.63	0.25	0.10	0.05



(a) (b)

Figure 1 (a) Illustration of UST-DC-casting setup with the UST sonotrode positioned in the middle between the partitions before hot top (adapted from [12]). (b) Zoomed side-view of sonotrode and partitions.

The billets were cast at a pouring temperature of 730 ºC. A water-cooled 5-kW magnetostrictive transducer (Reltec) with a driving frequency of 17.3 kHz was utilized to power the sonotrode. To propagate ultrasonic power to the melt, a cylindrical Nb sonotrode with a working diameter of 40 mm was used. The input power of the transducer was 3.5 kW (corresponds to 30 µm peak-to-peak amplitude at the tip of the sonotrode). The tip was immersed approximately 12 mm below the melt surface and the sonotrode was positioned in the middle between the two partitions. A pair of partitions made of refractory material was deployed with the distance of 266 mm apart (1λ (sound wavelength) at the UST transducer frequency) in the launder. The position of the downstream partition (Figure 1b) was 200 mm upstream from the hot top. The partitions were designed in such a way so the melt could flow on top and at the bottom of partitions to avoid melt overflow and entrapment in the launder.

The cavitation activity was monitored through acoustic pressure measurements using a calibrated high-temperature cavitometer with specifications described elsewhere [13]. The cavitometer tip was immersed approximately 30 ± 5 mm below the melt with a distance of around 15 ± 5 mm from the downstream partition towards the sonotrode. 60

waveforms were obtained for each measurement with a duration each waveform 100 ms at a sample rate of 5 MHz. The conversion from raw electrical signal to acoustic pressure followed the procedure devised elsewhere [14].
For macroscopic structure observation, samples were cut from the billet along the entire radius. To reveal the grain structure, the samples were ground using SiC paper, then etched using Tucker's reagent. Meanwhile, for microscopic observation, the samples were cut from the central part of the billets. These samples were ground, mirror polished, anodized in 5 wt% HBF_4 using 20 VDC, and subsequently examined under an optical microscope (Zeiss Axio Scope.A1) with polarized light. The grain size was measured using the linear intercept method taken randomly on optical microscope images and statistical analysis was carried out.

3 Result and discussion

Acoustic pressure measurements show that generally the presence of partitions improves the acoustic pressure, i.e., the maximum pressure P_{Max} and average pressure P_{RMS} with partitions were 1086 ± 731 kPa, and 57 ± 20 kPa, respectively, while without partitions, P_{Max} and P_{RMS} were 507 ± 499 kPa, and 37 ± 13 kPa, respectively. While there was an approximately 50% increase in RMS acoustic pressure (P_{RMS}) when partitions were present, the maximum acoustic pressure (P_{Max}) increased twofold. This indicated more intense cavitation activity when partitions were employed. This phenomenon has been predicted in our previous work [7] through numerical simulation, showing that the presence of partitions enhances the acoustic pressure distribution between the partitions, which ultimately could improves the efficiency of the UST melt treatment.

Figure 2 shows the effect of UST on grain structure of the billet on the macroscopic level. One can see (Figure 2a and Figure 2c) that without UST feathery or columnar grain structures occurred in the billet. This type of structure is typically linked to poor grain refinement [15] and it is not preferred in industrial alloy production as it has inferior mechanical properties, such as lack of ductility and homogeneous deformability [16]. When UST was applied, the feathery region in the billet was suppressed, and the equiaxed grains finer than those in the billets cast without UST occupy most of the billet cross-section (Figure 2b and Figure 2d). The effect of UST seems to be more pronounced in the case of partitions in the launder. This demonstrates that UST promotes grain refinement in the billet, and partitions may add an extra contribution into it. McCartney [1] suggested two conditions must be fulfilled for the grain refinement to be effective; first, there should be numerous potent substrates introduced in the melt, and second, those substrates need to be activated, then Al grains can nucleate. Since the amount of Zr added in this alloy is beyond the solubility limit of Zr in liquid Al (~ 0.11 wt%), Al_3Zr particles form in the melt as primary intermetallics. Such particles are potent nucleants for Al grains [17] owing to their minimum crystallographic mismatch with the Al phase [18] but only when they are below a certain size [19]. One of the main structure refinement mechanisms using UST above the liquidus of aluminum is the refinement of primary intermetallics through enhanced nucleation and fragmentation [4], leading to multiplication of potent substrates in the melt. In our experiments the temperature of the melt in the point of UST was between 707 and 715 °C, which is about 10 °C below the liquidus of Al_3Zr phase. Therefore, the fragmentation of the primary intermetallics and nucleation of Al on them is the most likely reason for the observed grain refinement.

In order to properly assess the effectiveness of UST on structure refinement, we performed microscopic analysis of the grain structure from the central part of the billet where the grain structure from both parts of the billets (with and without UST) are equiaxed. In general, Figure 3 shows that the application of UST significantly reduced the grain size in both billets, i.e., cast without (Figure 3a – No-UST to Figure 3b – with UST) and with partitions (Figure 3c – No-UST to Figure 3d – with UST). Quantitative grain size analysis (Table 2) suggests that the presence of partitions did not alter the average grain size for casting without UST. But when the UST was activated, the presence of partitions assisted in improving the UST efficiency by an additional 10% refinement. This could be explained by the increase of cavitation activity caused by the resonance due to the presence of partitions as indicated by the result of acoustic pressure measurements. This verifies the numerical simulation results in our previous work [7] that partitions may provide a positive impact on structure refinement using UST.

The results obtained in this work demonstrate a proof of concept that the presence of partitions can help in improving the efficiency of launder UST-DC casting. This opens the possibility for further improvement of treatment efficiency by optimizing the design and placement of the partitions in the DC casting launder with the aim of attaining maximum acoustic pressure and optimum residence time. Some of the possible parameters to be examined in the future are the effect of sonotrode positioning with respect to partitions [9] during launder UST-DC casting, and also the geometry and positioning of the partitions [10]. Moreover, exploring the best position of UST with respect to the hot top/furnace would also be interesting as it is linked to the change of UST treatment temperature without altering the optimum casting temperature. The use of numerical simulation to obtain the best geometry and positioning of the partitions will be beneficial to minimize the trials and improve the efficiency of resources and time.

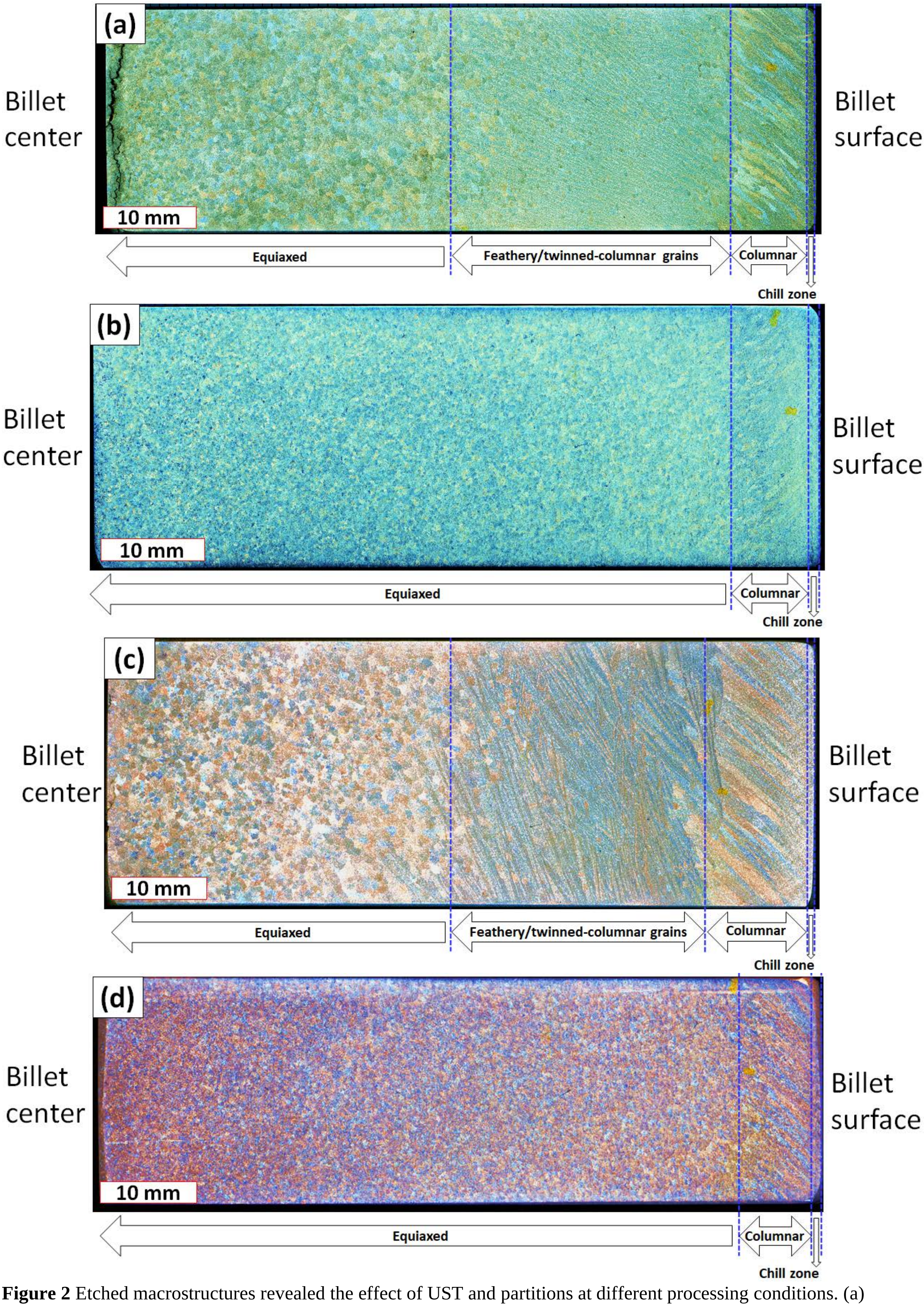


Figure 2 Etched macrostructures revealed the effect of UST and partitions at different processing conditions. (a) Without partitions and without UST, (b) without partitions but with UST, (c) with partitions but without UST, and (d) with both partitions and UST.

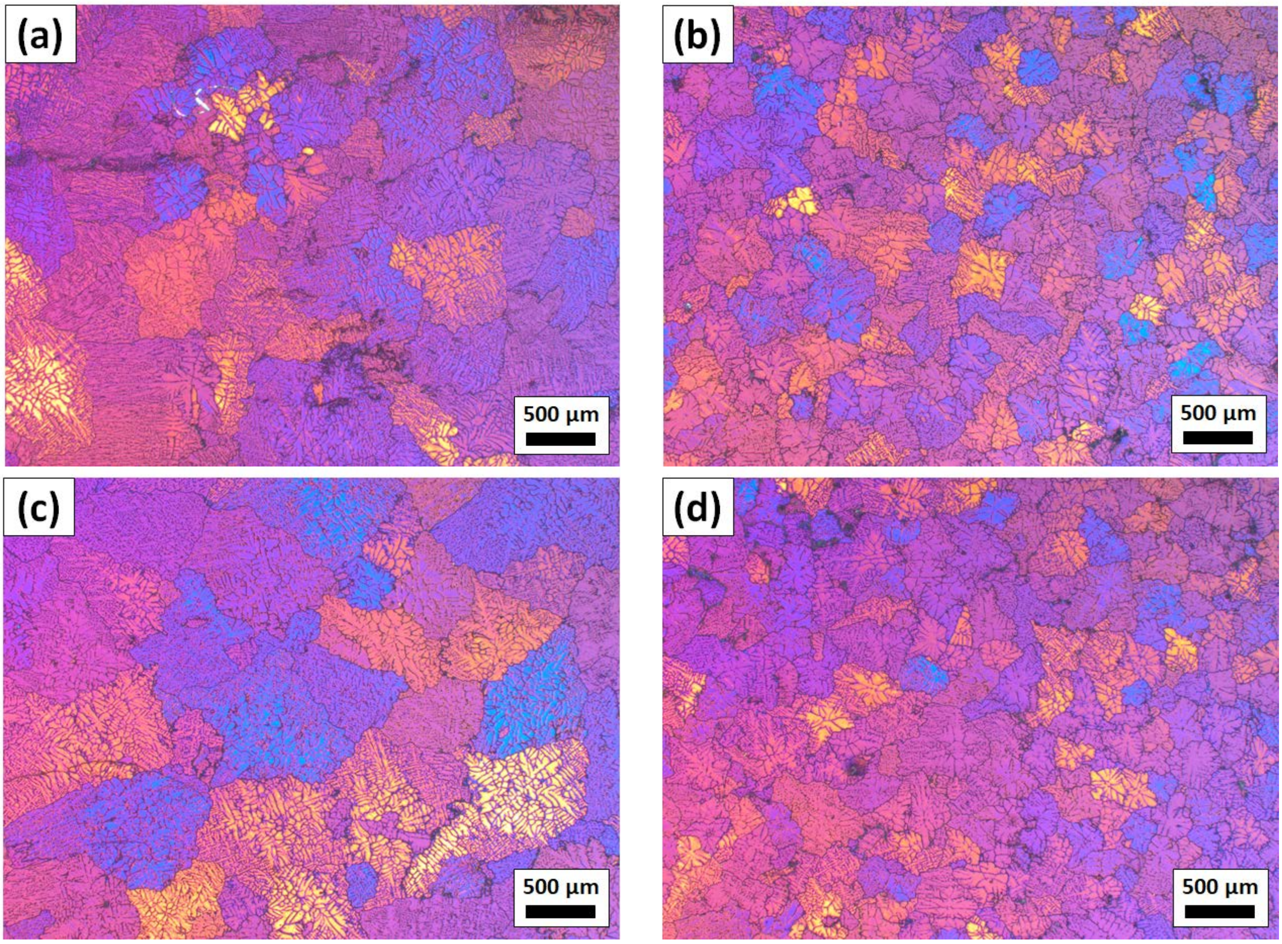


Figure 3 Typical microstructure at the center of the billet at different processing conditions (a) without partitions and without UST, (b) without partitions but with UST, (c) with partitions but without UST, and (d) with both partitions and UST.

Table 2 Quantitative grain size analysis under different processing conditions.

Avg. grain size on center of billets (µm)	With Partitions (WPT)	No Partitions (NPT)
No-UST	455 ± 50 µm	450 ± 40 µm
With-UST	220 ± 10 µm	240 ± 10 µm

4 Conclusion

This work focused on observing the effect of partitions on UST efficiency during DC casting of an AA6XXX aluminium alloy with an addition of Zr. The efficiency of UST was assessed through both acoustic pressure measurements using a cavitometer and structure analysis (on both macroscopic and microscopic length scales). The results demonstrated that UST was able to suppress the formation of feathery grains and refined the grain structure in the DC casting billets. The grain size decreased two-fold under UST. The presence of partitions in the launder during UST DC casting also positively impacted on structure refinement. This was shown by the increase of acoustic pressure; the maximum acoustic pressure (P_{Max}) being twice as high, while the root-mean square acoustic pressure (P_{RMS}) was 50% higher when the partitions were deployed. Meanwhile, from microstructure analysis, the grain structure in the center of the billet gained an additional 10% refinement when partitions were used during UST DC casting.

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