Ultrasonic-assisted Improvement of Solidification Structure in DC Casting of Aluminum Alloy

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Abstract

This work presents results of investigation conducted in Nippon Light Metal Co.,ltd and Tohoku University aiming at improvement of solidification structure of hypereutectic Al-Si alloys due to application of ultrasonic vibrations to DC casting process. It is shown that ultrasonic vibrations can greatly refine the crystals of primary silicon in 75~178 mm billets, if vibration amplitude exceeds a certain level, however the structure uniformity was strongly dependent on the location of ultrasonic introduction at the DC caster. Laboratory-scale experiments and numerical simulation have been also performed to elucidate the ultrasonic-related phenomena, particularly cavitation and acoustic streaming, and to optimize the ultrasonic treatment conditions.

Introduction

It has been long recognized that high-intensive ultrasonic vibrations offer a promising tool to improve the structure of metals, particularly hypereutectic Al-Si alloys [1~2]. These alloys are widely used in many applications due to their high wear resistance, low thermal expansion coefficient and excellent strength to weight ratio. However, these alloys have low ductility and limited workability, mainly due to formation of coarse particles of primary silicon. Therefore, the ultrasonic treatment of hypereutectic Al-Si alloys is usually aimed at refining the primary silicon particles.

The practical application of ultrasonic treatment of molten aluminum, however, faces a number of serious challenges. To achieve the above-mentioned effect, ultrasonic vibrations should be introduced directly into the melt to produce a cavitation field in it. Usually the ultrasonic treatment is performed before or during casting at a temperature of $750^{O}C$ or higher by using a submerged sonotrode, which must be made of a stable and elastic refractory material, and must be resistant to cavitation erosion. The above requirements impose strict limitations on the choice of materials which can be used to make sonotrode for molten aluminum treatment. The second challenge is related to the difficulties of obtaining a uniformly refined structure in industrial casting processes such as direct chilling (DC) casting. And third challenge concerns amount of molten metal which can be processed using one ultrasonic sonotrode. This is of great practical importance for industrial processes which need to be cost-effective and energy-efficient.

The main goal of this work is to develop a new type of large-size high-amplitude ceramic sonotrode and a novel method of ultrasonic DC casting capable of producing industrial sized billets of hypereutectic Al-Si alloys with fine and uniformly distributed particles of primary silicon. The present paper consists of three parts. 1) Design and examination of large-sized ceramic ultrasonic sonotrode in molten aluminum, 2) Application of the developed sonotrode to DC casting process and investigation of microstructure of produced billets, 3) Investigation of ultrasound-related phenomena using water model and numerical simulation.

Development of large-size high-amplitude ceramic sonotrode

Commercially available ultrasonic installations are usually equipped with titanium sonotrodes. Our attempts to use these sonotrodes to treat molten aluminum indicated that their performance is far from satisfactory because of their unacceptably short lifespan and high level of melt contamination. Also, there was an attempt to use titanium sonotrodes, the tip of which was made of a Nb-4%Mo alloy which has a very high melting point and low solubility in molten aluminum. The lifetime of this sonotrode was much higher than that of steel and titanium alloy, however it was still too short for industrial applications. Therefore, in the first stage, we made an attempt to develop a ceramics sonotrode.

Generally, ultrasonic equipment is designed to operate at a resonant frequency within a specified bandwidth. In the present work, an ultrasonic equipment set with frequency bandwidth of 19~21 kHz was used. Hence, the sonotrode design must ensure stable operation within this frequency range. Additionally, the following requirements must be also met to satisfy industrial application: 1) the working tip diameter, D_t > 40 mm, 2) total length, L > 400 mm, 3) vibration amplification coefficient, M >2.5. This coefficient is defined as a ratio of the vibration amplitude of the sonotrode working tip, A to that of the transducer connection joint,A_0.

A ceramic material Ceracompo S was used to fabricate sonotrodes. Ceracompo S© is a hot-press sintered Si_3N_4- based ceramics developed by Nippon Light Metal Co.,Ltd [3]. The relation between the length and resonant frequency of barbell-shaped sonotrode was determined from simulation of the sonotrode vibrations by ANSYS software. Then, guided by the simulation results, a number of barbell sonotrodes was fabricated and examined for their performance. Figure 1 presents a typical data set obtained from the simulation results, namely lengthwise distributions of displacement (a) and internal stress (b). In the figure, the left end corresponds to the transducer connection, while the right one is the sonotrode working tip. Positive and negative values correspond to tension and compression, respectively. As the maximal amplitude of ultrasonic vibrations of the transducer connection part is 18 μm(p-p), the left end of the sonotrode is vibrated at the same amplitude. As for the right end, its vibration amplitude is 50 μm (p-p) yielding the amplification ratio, M to be approximately 2.8. In Fig.1(b), contour of internal stress reveals that the maximum tensile stress is located at the left end of the narrower cylindrical part, and its value is equal to approximately 125 MPa. The maximum tensile stress of Ceracompo S, σ_{UT} was estimated to be 450MPa. Therefore, the predicted amplitude of internal stress does not exceed 30% of σ_{UT} that is considered as a safe level protecting the sonotrode from failure.

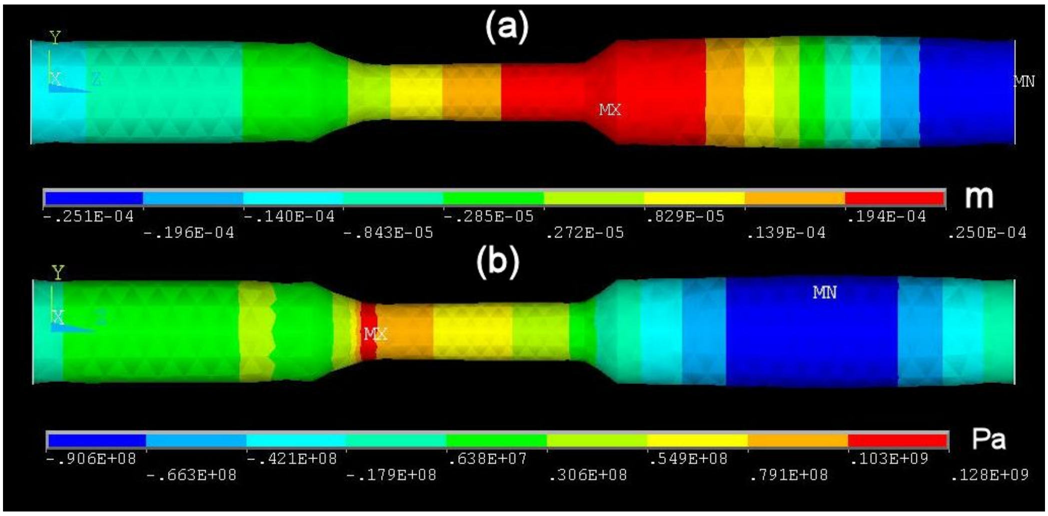


Figure 1. Lengthwise distributions of displacement (a) and internal stress (b) amplitudes.

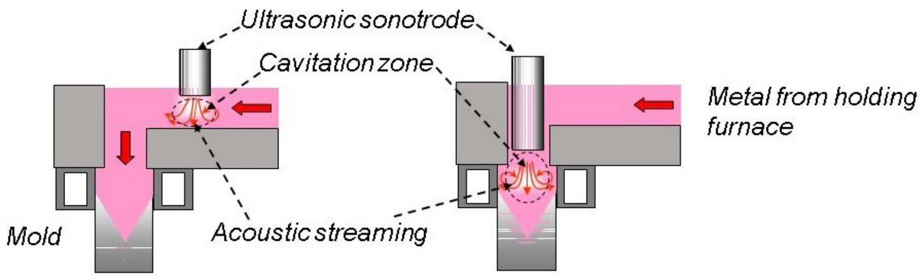
Figure 2. Appearance of barbell ceramic sonotrode

Figure 2 shows a typical barbell-shaped ceramic sonotrode fabricated according to the ANSYS simulation results. Its diameter and length is 48 mm and 465 mm respectively. Experiments revealed that such a sonotrode is capable of producing high-intense cavitation in molten aluminum at the immersion depth up to 160 mm. The service life of the sonotrode tip was estimated to be longer than 2000 hours. This is several ten times longer than the service life of existing Nb-made sonotrodes.

Ultrasonic DC casting

At least two methods of ultrasonic DC casting have been proposed in the past. In the first one, ultrasonic vibrations are introduced in the melt while it flows through a distribution launder (called hereinafter “launder UST”). In the second method, a sonotrode is immersed in the melt in the top part of hot-top to introduce ultrasonic vibrations directly into an area above the DC caster mold (called hereinafter “hot-top UST”). Both the casting processes are schematically represented in Fig.3 (a,b).

Both methods have been examined using a pilot vertical DC casting machine. An alloy containing 17%Si was melted in an electrical resistance furnace. A predetermined amount of Al-Cu-P master alloy was added to the melt to reach the P content of 100~300 ppm. This is a commonly used technique to facilitate formation of primary silicon grains and make them finer. The melt was poured through a launder into the casting machine mold to produce billets of 75 ~ 203 mm in diameter at the casting speed in the range of 100~500 mm/min depending on the billet diameter. In the hot-top UST casting, the sonotrode was positioned coaxially with the DC mold in the melt. This method was examined only for billets of 178 and 203 mm. Also, billets of the same sizes were cast without ultrasonic treatment (conventional casting) for comparison. The samples were cut out from areas located at the billet surface (S), half-radius (R/2) and center (C), and prepared for the structure investigation according to the standard metallographic procedures. Optical microscopy (OM) and image analysis were used to investigate the alloy microstructure.



(a) (b)

Figure 3. A representation of (a) launder UST and (b) hot-top UST casting.

The results revealed that neither launder nor hot-top UST casting are capable of producing billet with fine and uniformly structure Si especially in large billets. Figure 4 presents typical OM views of the microstructure of 178-mm billets produced by various methods. In conventional casting (a), though the Si particles are uniform in size, they are very coarse. In launder UST casting (b), Si particles are very fine at the billet surface, but become much coarser with distance from it. A similar tendency can be observed in the microstructure obtained during hot-top UST casting (c,d).

Addition of Al-Cu-P master alloy to Al-Si alloy causes formation of AlP particles, which can serve as nucleation sites for primary Si particles [3]. In the melt, AlP particles tend to agglomerate each other. Besides, impurities like dissolved hydrogen have a strong tendency to be adsorbed onto their surface. Both agglomeration and adsorption reduce the particle effective surface area which can be used as nuclei.

Introduction of ultrasonic oscillations causes breakage of the particle agglomerates and removes the impurities from the particle surface when the melt passes through the cavitation zone. This results in significant increase of nuclei available for solidification of primary Si crystals. In this situation, the nucleation rate becomes dependent on the melt cooling rate. Therefore, at the bullet surface where cooling rate is much faster than that at the billet center, nucleation of Si crystals is enhanced. This is the main reason why the launder UST casting yields non-uniform distribution of Si particles in size. As for the hot-top UST, although the structure becomes finer (Fig.4 (3a~4c)), the size of Si particles is non-uniform. Besides, the Si particles tend to form agglomerates, especially at the billet center as observed in Figs.4 (a,b).

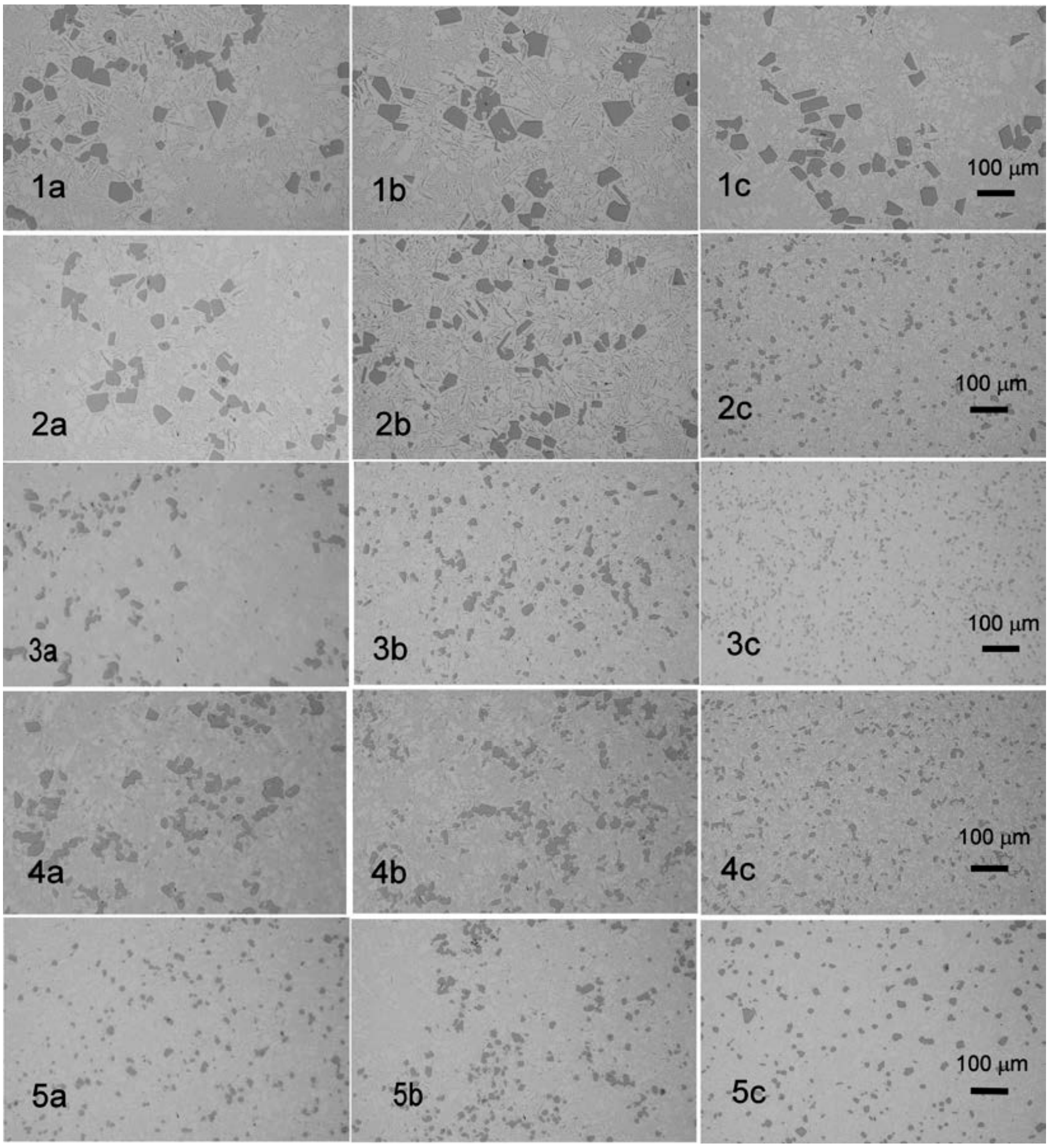


Figure 4. Microstructure images of samples taken at the center (a), half-radius (b) and surface (c) of a 178-mm billet produced by different casting methods : the conventional casting (1), launder UST casting (2), hot-top UST (3,4) casting, novel hot-top UST casting with controlled melt flow (5).

In order to elucidate the reason whereby the particles form agglomerates and to investigate the potential for further improvement of ultrasonic casting, water model experiments and numerical simulation were performed. In the water model experiments, PIV (Particle Image Velocimetry) method was employed to investigate characteristics of flow under the tip of sonotrode immersed in a water bath using a transparent acrylic resin cylindrical vessel. A water-cooled Ar lighting source was applied to generate a visual laser sheet through the water bath in the immediate vicinity of the sonotrode tip along the sonotrode center line. Movement of Al particle tracer was recorded by a high-speed camera at a frame rate of 125 fps. The other experimental details can be found in our earlier paper [4].

The mathematical model reflects actual phenomena occurring in a sonificated liquid. It is well known that a high intense cavitation zone is formed in the immediate vicinity of sonotrode surfaces when the vibration amplitude and corresponding acoustic pressure exceeds, P the Blake threshold [5]. Cavitation zone contains tremendous number of tiny bubbles which arise, oscillate and implode when ultrasound wave is propagated through a water bath. Interaction between the wave and bubbles causes a radiation force to act on the bubble, known as the primary Bjerknes force [6]. As a result, the bubbles begin to move in the direction of ultrasound wave propagation and involve the surrounding liquid into a steady motion known as acoustic streaming. The interaction between the wave and bubbles result also in a strong attenuation of acoustic pressure with distance from the sonotrode tip. These two phenomena, namely cavitation and acoustic streaming are the key factors influencing the ultrasonic treatment efficiency.

Based on the above physical background a model was developed and implemented using the freely-available package OpenFOAM. The model content are not explained here due to space limitations. Many details can be found in our recent publication [4]. Briefly, the model involves solving the linearized Helmholtz equation for a bubbly liquid, which can be represented in a general form as [7]:

$$\nabla^2 P + k_m^2 P = 0 \qquad (1)$$

where P is the acoustic pressure amplitude, k_m is the complex wave number defined as:

$$k_m^2 = \frac{\omega^2}{c^2}\left(1 + \frac{4\pi c^2 N R_0}{\omega_0^2 - \omega^2 + 2ib\omega}\right) \qquad (2)$$

where ω is the angular frequency of the ultrasonic wave in liquid, ω_0 is the resonant frequency of bubble, c is the sound velocity in water, R_0 is the undisturbed bubble radius, i is imaginary unit, b is the damping factor and N is the bubble number density.

ω_0, b and N are appropriate functions of physical properties of liquid and bubble gas, size, R_0 and volume ratio, β of cavitation bubbles, as well as ultrasound wave frequency. Boundary conditions were set according to the experimentally measured amplitude of sonotrode tip. The only two following assumptions had to be made to solve Eq.(1) numerically and, thus to predict the attenuation of acoustic pressure in liquid. The first one is that β is proportional to the acoustic pressure amplitude, P_A as $\beta = CP_A$, where C is the coefficient equal to 2.0×10^{-9}. The second one is that the bubble radius, R_0=200 μm. Then, the predicted values of acoustic pressure were used to calculate the Bjerknes force, F_B acting on a bubble of volume V according to the following equation

$$\boldsymbol{F_B} = -\langle \boldsymbol{V} \nabla \boldsymbol{P} \rangle \qquad (3)$$

where the bracket indicates the time averaging. This force was includes into Navier-Stokes equation to predict the velocity of acoustic streaming.

Figure 5 shows the results of PIV measurements (a) and numerical simulations (b) of acoustic streaming for the case where the vibration amplitude, A was 40 μm(p-p). It is readily seen that the values and directions of velocity vectors are in good agreement with each other. Notice that Fig.5(b) depicts only the right half of the area where the acoustic streaming occurs because its axial symmetry

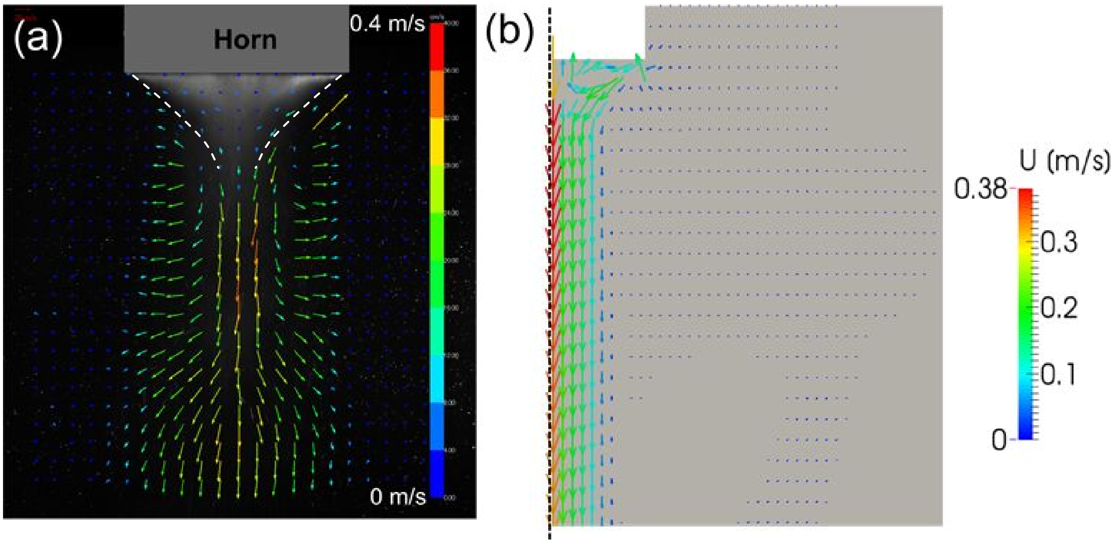


Figure 5. Typical vectors of acoustic streaming velocity obtained experimentally (a) and numerically (b).

Then, properties of molten aluminum and hydrogen bubbles were introduced into the above model to simulate the acoustic streaming in aluminum melt. Typical results of predicted velocity vectors are presented in Fig.6. A comparison of acoustic streaming in water (Fig.5a) and molten aluminum (Fig.6) reveals that the streaming velocity in aluminum does not exceed 0.2 m/s that is slower by approximately 40% compared to streaming velocity in water. However, even such a comparatively slow streaming can greatly affect the efficiency of ultrasonic treatment in casting process. This influence can be explained at least by two reasons. The first one is as follows. The above-mentioned effect of ultrasonic assisted activation of refiner particles can be expected when the particles-containing melt passes through the high-intense cavitation zone in the vicinity of the sonotrode tip. Location of this zone in water is shown by two broken lines in Fig.5(a). Since only a part of molten aluminum can pass through such a cavitation zone, this is considered as one of the reasons of the lower efficiency of the launder UST and hot-top UST (Fig.3). The second reason is that the acoustic streaming causes strong convection in the molten bath under the sonotrode tip. In the case of hot-top UST, convection results in an intense heat transfer from the melt to the caster mold causing a significant drop in the melt temperature. This inevitably leads to coarsening of primary silicon particles and their agglomeration. Thus, there is a need to control the flow of molten aluminum in order to improve the efficiency of ultrasonic processing. This motivated us to design a new unit for ultrasonic treatment of melt in DC casting process. Below is a brief explanation of the unit design and application results.

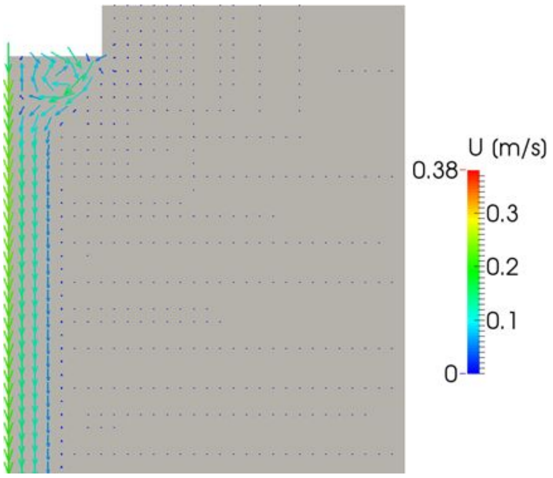


Figure 6. Predicted vectors of acoustic streaming in molten aluminum at A=40 μm

The main design idea was to confine the space under the sonotrode tip in such a way that, first, all molten aluminum passes through the cavitation zone and, second, convection of melt under the sonotrode tip becomes weaker. Figure 7 presents a schematic drawing of ultrasonic treatment unit designed for this purpose. The internal space above the mold is bounded by cylindrical wall and bottom plate made of a refractory material. A tapered inlet hole is drilled at the bottom plate center. The sonotrode tip is positioned above the hole coaxially with it at a distance of H from the bottom plate. Thus, all melt passes through the cavitation zone and then enters

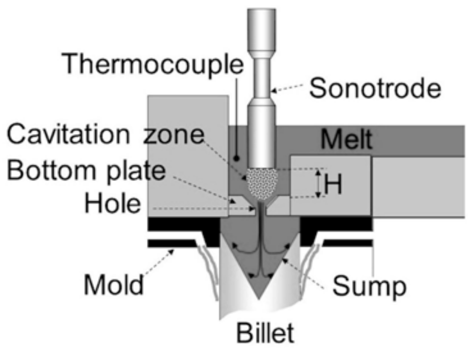


Figure 7. A representation of unit for hot-top UST casting with controlled melt flow.

into the mold cavity (sump) where solidifies. Arrows show the melt flow pattern. Experiments revealed that the treatment efficiency of this novel method is influenced by distance H and amplitude of sonotrode tip vibrations. Thus, by optimizing the conditions of the novel UST casting, the ultrasonic refinement effect and uniformity of the billet structure can be significantly improved, as shown in Fig.4 (5a~5c). The casting conditions are: casting speed 275 mm/min, melt temperature in the hot top 780^{O}C, distance H = 25 mm, vibration amplitude 48 μm (p-p). It is seen that the size of Si particles is much smaller compared to the other ultrasonic treatment techniques. Besides, the particle distribution is more uniform irrespective of location in the billets.

Finally, amount of molten metal which can be treated by using one sonotrode was clarified. Figure 8 summarizes some data concerning the dependence of ultrasonic refinement effect, R_E (a) and structure non-uniformity degree, *STD* (b) on the molten metal flow rate. Figures at the dots indicate the billet size. R_E was defined as

$$R_E = (D_0-D)/D_0 \qquad (4)$$

where D_0 and D are the average diameters of primary silicon particles obtained in conventional and UST casting, respectively. The average diameters were determined as a result of double averaging, one over the billet radius R at four locations at R=0, R=R_0/2, R=3R_0/4 and R=R_0 (R_0 is the billet radius); the other within each location on the basis of image processing of the 10 optical microscopic images.

As can be seen from Fig.8(a), R_E decreases with the melt flow rate. Although the launder UST yields greater R_E, non-uniformity degree is rather large as shown in Fig.8(b). On the other hand, the improved hot-top UST yields a much uniform structure, although the values of R_E are slightly smaller. Some well-balanced combination of R_E and STD are outlined by the dashed circles in Fig.8. Thus, the improved casting technology provides better results in terms of structure uniformity and refinement of billets of up to 203 mm produced by using one ceramic sonotrode. The refinement effect remains significant up to the metal flow rate of 20 kg/min. The other details can be found in our previous publication [8].

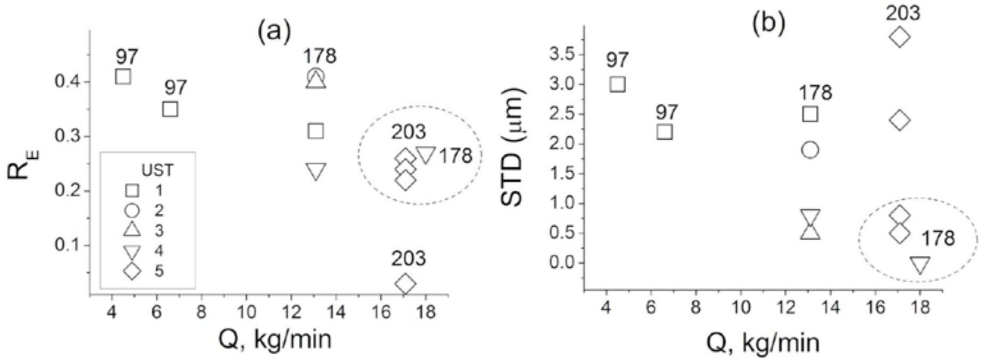


Figure 8. Dependence of R_E and *STD* index on metal flow rate: 1: launder UST, 2,3: hot-top UST, 4,5 : improved hot-top UST.

Conclusions

The present work was undertaken to design a new large-sized ceramics sonotrode and use it to develop a novel ultrasonic DC casting technology in order to produce billets of Al-17%Si alloys with fine and uniform microstructure. The following conclusions can be drawn from the present results.

1) The developed ceramics sonotrode of 48-mm diameter has revealed a great durability and good performance in producing high-intense cavitation zone. Barbell shape makes it possible to easily achieve very high values of vibration amplitudes at the sonotrode tip that is necessary for industrial application.

2) High amplitude vibrations result in generation of strong acoustic streaming under the sonotrode tip. Water model experiments and numerical simulation revealed that the streaming velocity can be as high as 0.4 m/s in water and 0.2 m/s in molten aluminum. This can cause a detrimental effect on the billet structure, particularly making the particles of primary Si coarse and non-uniformly distributed.

3) Then, a novel process of ultrasonic casting has been developed and implemented to produce Al-17%Si billets of 75~203 mm in diameter. The new process combines the design of hot top unit with arrangement of sonotrode in the unit and, when compared to the existing methods, provides better results in terms of structure uniformity and refinement effect. The results suggest that up to 20 kg/min of molten metal can be effectively treated by using one ceramic sonotrode.

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