Proceedings of the 12th International Conference on
Aluminium Alloys, September 5-9, 2010, Yokohama, Japan

pp. 652-657

Refinement of Primary Silicon in Casting Aluminum Alloys via Application of Ultrasonic Vibrations to DC process

Sergey Komarov[1], Yasuo Ishiwata[1], Kazuhiro Oda[2]

[1] Nippon Light Metal Company, CDC, Kambara 161, Shimizu-ku, Shizuoka, Japan

[2] Nippon Light Metal Company, NRDC, Kambara 1-34-1, Shimizu-ku, Shizuoka, Japan

In the present study, high intense ultrasonic vibrations were applied to DC process in order to examine the ability of ultrasound to refine the grains of primary silicon in a model hypereutectic Al-17Si alloy containing of about 100 ppm P as a refiner. In the process, an ultrasonic horn, made of a heat-resistant material, was immersed into the melt flowing through a spout before pouring into a mould of DC casting machine to produce billets of 75 or 97 mm in diameter.
The results revealed that the grain sizes of primary silicon are significantly decreased when the ultrasonic vibrations are applied to the melt. The effect of ultrasonic refinement was found to be dependent on location in the billet and its size, assumably due to a difference in the resident time during which the primary silicon is solidified. The residence time was evaluated by numerical simulation. Further investigations of the billet microstructure with EPMA and PoDFA analysis suggested that the most likely reason for the grain refinement is the ultrasonic dispersion of P-containing particles in the melt.

Keywords: *DC casting, hypereutectic Al-Si alloy, ultrasonic vibrations, primary silicon, refinement mechanism.*

1. Introduction

Hypereutectic Al-Si alloys are widely used in the motor car industry and other areas where there is a need for good wear resistance, improved high temperature strength and elastic characteristics. In casting these alloys, it is common practice to add Fe, Mn, Ni and other additives which provide the required combination of the alloy properties. However, the presence of these elements in Al-Si melts is known to result in formation of coarse intermetallic inclusions. Besides, the melt solidification often occurs with growth of primary silicon to an unacceptable range even when grain refiners are added to the melt. Both the coarse silicon particles and intermetallics greatly deteriorate the alloy properties. Therefore, it still remains a challenge to achieve effective and economically competitive ways in order to prevent the structure coarsening of these alloys.
Ultrasonic vibrations have been long recognized as being an effective method to refine the as-cast structure of aluminum alloys. Starting from the pioneering work of Seeman and Menzel [1], a great body of experiments has been performed concerning the ultrasonic effects on structure of as-cast aluminum alloys. As for Al-Si alloys, extensive studies on their ultrasonic refinement have been conducted by the groups of Eskin[2,3] and Abramov[4,5] in Russia, and Osawa [6] in Japan. Nevertheless, the conditions under which the ultrasonic casting can be realized on an industrial scale still remain unclear. Recently, we have reported [7] about characteristics of ultrasonic cavitation in aluminum melts and its influence on the structure refinement of a number of hypereutectic and eutectic Al-Si alloys. It was shown that application of the ultrasonic vibrations to die casting process provides a way of improving mechanical properties of fabricated specimens.
The purpose of the present work is to examine possibilities for refining primary silicon of hypereutectic Al-Si alloys in a pilot scale ultrasonic-assisted DC process. Our main concern is to investigate the as-cast microstructure of the alloys and to elucidate the refinement mechanism.

2. Experimental set-up and conditions

A pilot vertical DC casting machine was used for investigation (Fig.1). The alloy containing 17%Si was melted in an electrical resistance furnace. About 100 ppm of P was added to the melt in the form of Al-Cu-P master alloy. The casting process began as the melt at temperature about 800^{O}C was poured through a spout into the casting machine mold to cast billets of 75 or 97 mm in diameter and about 2 m in length. The casting speed was varied in the range of 300~500 mm/min for the 75-mm billet and of 200~350 mm/min for the 97-mm billet.

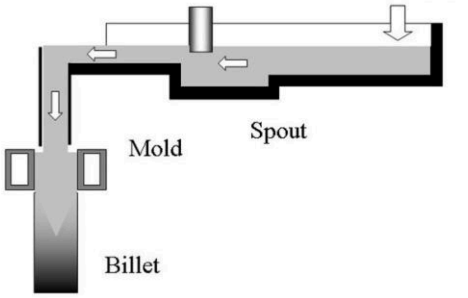

Fig.1 A schematic representation of DC casting process

Two different ultrasonic processors were used to introduce ultrasonic vibrations in the melt. They consisted of an ultrasonic generator, a magnetostrictive or piezoceramic transducer and a horn made of refractory Nb alloy or ceramic material. The horn tip diameter was 55 mm (Nb alloy) or 48 mm (ceramics). Zero-to-peak amplitude of the horn tip vibrations, measured in air, was 12 μm and 18 μm, respectively. The horn tip was immersed in the melt at a location close to the mold entrance as shown in Fig.1. Hence, the melt was treated before entering the mold.

After the casting, samples were cut out from different parts of the billets to examine the alloy microstructure by optical microscopy. Image processing of the microstructure pictures and their further quantitative treatment was made with ImagePro software. The structure refinement mechanism was investigated by electron probe microanalysis (EPMA) and porous disk filtration analysis (PoDFA). In the latter case, approximately 3 kg of molten metal was passed through a ceramic filter with pore size of 77 μm. Then, inclusions trapped by the filter were investigated.

3. Results and Discussion

3.1 Microstructure investigation

Figure 2 presents typical microstructure images of samples taken at a half radius distance (R/2) from the surface of a 75-mm billet produced by the conventional (a) and ultrasonic casting (b) process. In the figure, the dark particles correspond to the grains of primary Si. A comparison of these images clearly shows that the application of ultrasonic vibrations results in significant refinement of the initially coarse grains.

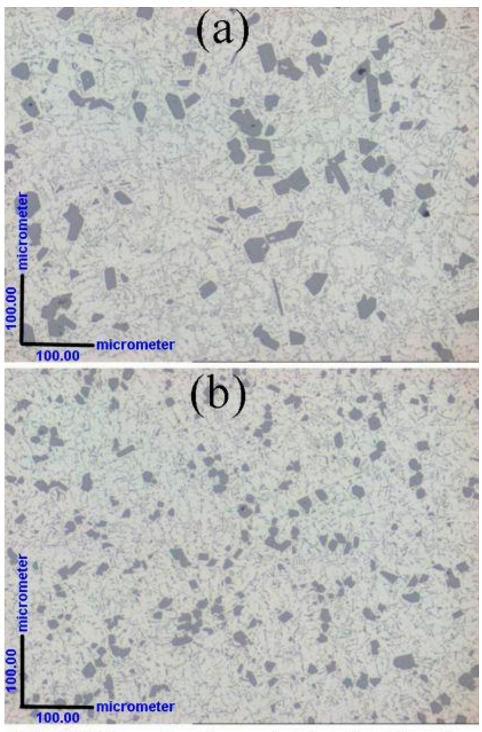

Fig.2 Microstructure obtained without ultrasonic vibrations (a) and with it (b).

An example of the size distribution of primary Si grains is shown in Fig.3 for three different places: the billet center, R/2 and surface. In this figure, the x axis represents size distribution by grain diameter d, while the y axis corresponds to numbers of the grains per 1 mm^2 of the sample surface, N. In the structure obtained by the conventional process (Fig.3a), the distribution is almost independent of location in the billet, and is relatively uniform with weakly pronounced maximums of N at d = 10~25 μm. Even at the maximums, N does not exceed 50 grains per 1 mm^2. On the other hand, the application of ultrasonic vibrations changes the distribution in such a

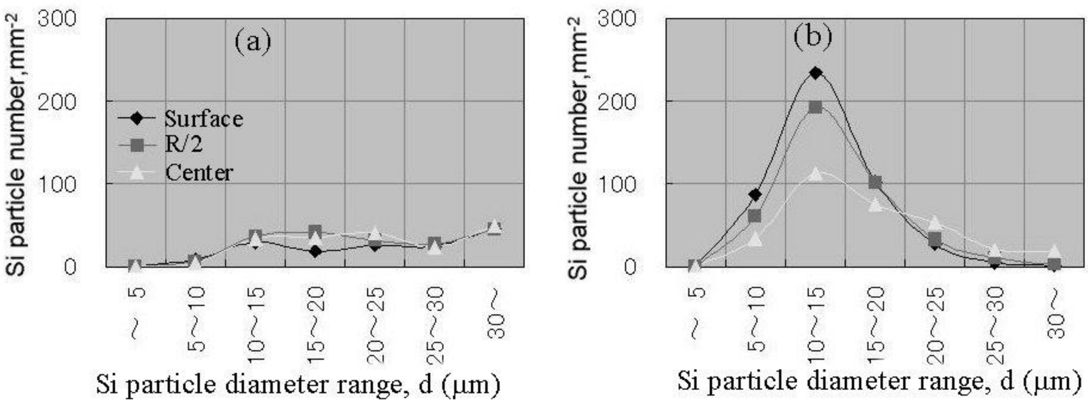

Fig.3 Distribution of Si particles in size. (a)-conventional, (b) – ultrasonic casting.

way that it becomes sharper with the clearly pronounced peaks of N at d = 10~15 μm. It is worthy of note that the peak value increases outward from the billet center.

Figure 4 summarizes the above results. In the figure, average diameter of primary Si particles plotted against distance from the billet center. As can be seen, in the conventional casting, the average diameter almost does not vary with the distance. However, in the ultrasonic casting, it is decreased with distance from the billet center. Thus, the data reveal that, in the vicinity of billet surface, the refinement effect of ultrasonic vibrations is larger than that at the billet center. The same tendency was observed in the 97-mm billets.

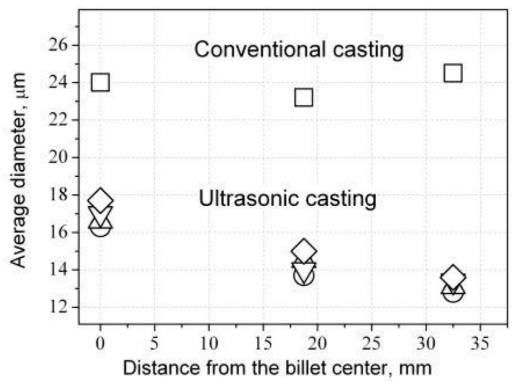

Fig.4 Dependence of Si particle average diameter on distance from the billet center.

3.2 Consideration on the refinement mechanisms

In order to elucidate the refinement mechanisms of primary Si grains, the billet samples were investigated with EPMA. Figure 5 presents typical results of the EMPA mapping of samples corresponding to ultrasonic (a,c) and conventional (b,d) casting. The upper (a,b) and lower (c,d) figures depicts respectively the distributions of Si (large red-colored particles) and P (fine dots) over the area investigated. Thus, the EPMA analysis also confirms the reduction in size of primary Si grains under the ultrasonic vibrations. In the conventional casting, P-containing particles, probably AlP, have a tendency to form agglomerates as it is readily seen in Fig. 5(d). Locations of representative agglomerates are indicated by arrows. A careful comparison of Figs.5(b) and (d) shows that positions of agglomerates correspond closely with those of the largest Si particles. It remains unclear whether the agglomerates were formed before or during the crystallization of primary Si grains. On the other hand, in the billet fabricated by the ultrasonic casting, the P-containing particles exist in the form of uniformly distributed single particles as indicated by white arrows in Fig.5(c). A reasonable explanation of this finding is that the ultrasonic treatment of the melt results in dispersion of the agglomerates of P-containing particles which serve as nuclei for the primary silicon.

The same conclusions are suggested by the PoDFA analysis, which quantifies the total area of inclusions trapped by filter per unit weight of melt. Although the phosphorus concentration in the melt was the same, the P-containing inclusion area was 2.36 and 1.04 mm^2/kg for conventional and ultrasonic casting, respectively. Such a large difference can be explained in terms of the above-mentioned agglomerate dispersion. Ultrasonically dispersed particles can get through the filter much easier than coarse ones. It is assumed that the agglomerate dispersion occurs when the melt

flows near the horn tip where a strong cavitation field exists. For the more details on possible dispersion mechanisms, the reader is referred to the appropriate publications, e.g. [8].
Another reason of the ultrasonic refinement effect can be an improvement in wettability of the refiner particles by the aluminum melt during passage of the particles through the cavitation field. Additional data on the improvement mechanism can be found in the literature, e.g. [3].

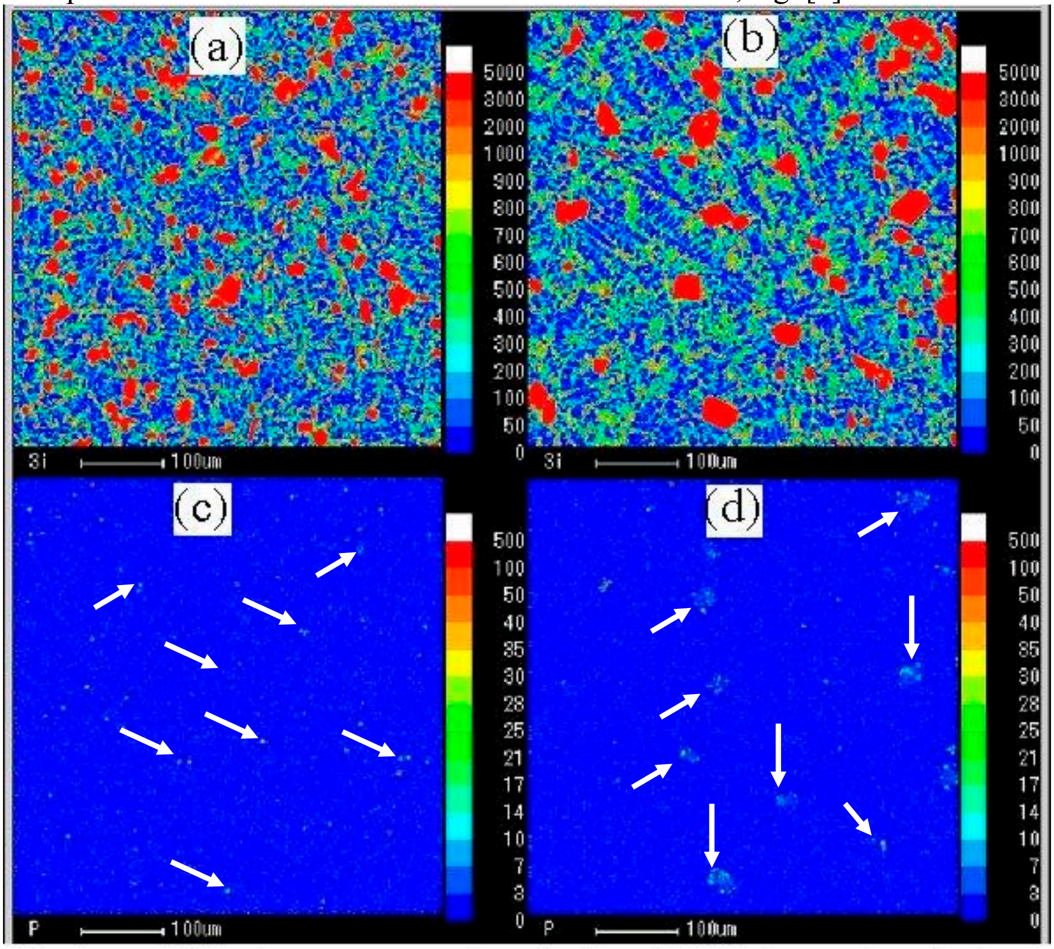

Fig.5 Results of EPMA mapping: (a,c) - ultrasonic casting, (b,d) - conventional casting.

3.3 Numerical simulation of casting process

In order to elucidate the experimentally obtained variation of ultrasonic refinement effect with location in the billet, the casting process was simulated numerically using the software ProCast. A number of experiments were performed to determine the heat-transfer boundary conditions at the mold/molten metal and billet/cooling water interfaces. In these experiments, time variations of temperature were measured at selected locations of billet during its solidification. Then, the boundary conditions were determined by the best fit between the calculated and measured temperature data. It was assumed that, as the ultrasonic vibrations are applied to the melt at a distance from the mold, ultrasonic does not alter the melt flow pattern in the mold.

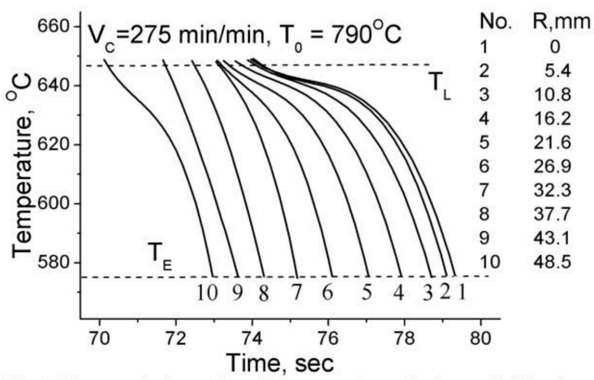

Fig.6 Time variation of melt temperature during solidification.

Figure 6 shows a typical set of calculated time-temperature histories for various distances, R from the center of a 97 mm billet. The simulation conditions were as follows: time step 0.1 s, casting speed, V_C = 275 mm/min, initial melt temperature, T_0= 790^{O}C. The upper and lower broken lines denote the liquidus and eutectic temperatures, T_L and T_E respectively. Similar data were obtained for the other casting conditions. Then, the experimentally obtained effect of ultrasonic vibrations on the average diameter of primary Si grains, d_A was plotted against the predicted residence time t_R. By t_R is meant the time during which the particles of primary silicon can exist in the melt between T_L and T_E. This time can be readily determined from the time-temperature curves exemplified in Fig.6.

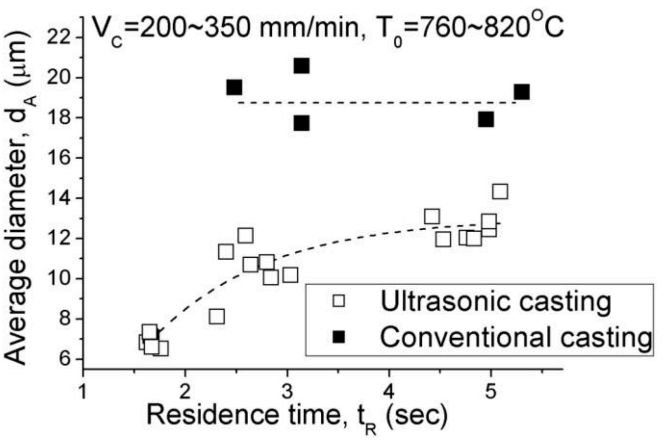

Fig.7 Dependence of Si grain average diameter on residence time

Figure 7 shows the plotting results for all casting used in the casting of 97 mm billet. The melt initial temperature was ranged from 760 to 820^{O}C. It is readily seen that in the conventional casting, d_A is independent of t_R. On the other hand, in the ultrasonic casting the size of primary Si grains is significantly decreased as the residence time becomes shorter. It is assumed that the reason is as follows. The Si grains, once formed at a temperature below T_L, may grow either by diffusion of Si atoms from the melt to the grain surface, or by coagulation of the grains with each other. In either case, the growth is possible only within a temperature range between T_L and T_E. Therefore, the shorter the residence time, the less opportunity for the grains to grow. Another factor influencing the growth rate is the grain number. Obviously, the greater the number, the more rapidly they can grow, be it diffusion and coagulation. In the conventional casting, as has been shown above, P-containing refiner particles present in the melts either as particle agglomerates or single particles with poorly wetted surfaces. Therefore, the number of initially formed Si grains is relatively low. Under these conditions d_A is unaffected by t_R since the tendency towards grain growth becomes weak. On the other hand, in the ultrasonic casting, there should exist a strong tendency of grain growth because the ultrasonically dispersed refiner particles cause formation of a great number of the primary Si grains. In this case, the grain diameter should increase to a greater extent as the residence time becomes longer.

4. Conclusions

In this study, high-intense ultrasonic vibrations were introduced to the Al-17%Si-0.01%P melt flowing through the spout of a pilot DC casting machine to produce billets of 75 or 97 mm in diameter. Examination of the billet microstructure after casting revealed a significant refinement of primary silicon grains in the ultrasonic casting compared to those in the conventional one. The ultrasonic refinement effect was found to be largest close to the billet surface, being decreased as the billet center is approached. The results of numerical simulation of the casting process showed that there is a direct relationship between the ultrasonic refinement effect and residence time of melt in the solidification zone.

Further EPMA and PoDFA investigations revealed that the ultrasonic vibrations cause dispersion of P-containing particles in the melt. This is assumed to be the main reason for the refinement effect. More specifically, the refinement mechanism is that the ultrasonically dispersed particles provide a much greater number of potential nucleation sites for the primary Si grains.

References

[1] H.Seeman and H.Menzel : Zs.Metall.1 (1947) 318-323.
[2] D.I.Eskin and D.G.Eskin: Ultrasonic Sonochemistry 10 (2003) 297-301.
[3] G.I.Eskin: *Ultrasonic Treatment of Light Alloy Melts*, (Gordon and Breach, Amsterdam, 1998) pp.111-170.
[4] V.Abramov, O.Abramov, V.Bulgakov and F.Sommer: Materials Letters 37 (1998) 27-34.
[5] O.V.Abramov: *High-Intensity Ultrasonics : Theory and Industrial Applications*, (Gordon and Breach Science Publishers, Amsterdam, 1998), pp.523-551.
[6] Y.Osawa, G.Arakane, S.Takamori, A.Sato and O.Ohashi : J.JFS 71(1999) 98-103.
[7] S. Komarov, K. Oda, Y. Ishiwata, T. Tsuchida, I. Okamoto : Proc. of 11th International Conference on Aluminum Alloys, 22~26 September 2008, Aachen, Germany, 307-314.
[8] Z.Guo, A.G.Jones, N.Li and S.Germana : Powder Technology 171 (2007) 146-153.