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EFFECT OF ULTRASONIC VIBRATION ON THE SOLIDIFICATION OF 35CrMo STEEL

The effect of ultrasonic vibration on the microstructure, elimination of casting defects and distribution of alloyed elements at macro-scale during solidification of 35CrMo steel has been investigated. Results show that ultrasonic treatment has a significant effect on the grain refinement, especially the fragmentation of the secondary dendritic arms of the studied steel. Density of the casting defects decreases and the alloyed elements are seen more even distribution at macro-scale with the introduction of ultrasonic vibration. Meanwhile, the ultrasonic vibration works more efficiently in the longitudinal direction than in the radial, and its efficiency declines with the distance from the radiator increasing.

Keywords: ultrasonic vibration; solidification; segregation; defects

1. Introduction

Mechanical properties of the alloys can be improved through the elimination of the casting defects, non-metallic inclusions and by the grain refinement [1]. Refinement of the microstructures can be achieved by chemical and physical methods [2]. Addition of the master alloys/minor elements is a chemically based approach, which is used most for its simplicity and efficiency, such as Al-Ti-B/C are used as grain refiners for the aluminum alloys and magnesium alloys, while Nb, V and Ti for the steels [3,4]. However, the approach has detrimental effects [5] on the mechanical performance, and fails in degassing of alloys. Nowadays, the popular physical way to improve the micro-structure of alloys is the electromagnetic stirring, which can get rid of non-metallic inclusions, apart from the effective refinement of grains and degassing. But, as indicated by previous investigation [6], poor grain refinement at the center of the billet takes place, because of the sharp reduction of electromagnetic force, especially for the cast ingot with large diameter [2].

Ultrasonic vibration is a prevailing physically-based approach used in the solidification of light alloys for its high efficiency in grain refinement and degassing [7-9]. But such investigations is restricted in the metals with high melting point, for corrosion and reactivity of the radiator at high temperatures [1]. Similar research in steel once carried out by Liu and her co-workers [10] has shown that the grains were refined, and the mechanical properties were enhanced for the injection of ultrasonic energy. However, there are no convincing evidences in literature to suggest the elimination of defects and the macro segregation of the alloyed elements for the steels, which need further investigation.

In this paper, a radiator made of Si_3N_4 ceramic was prepared and a die casting of 35CrMo steel was done. Effects of ultrasonic vibration on the grain refinement, elimination of the casting defects and macro-segregation of the alloyed elements were observed and discussed.

2. Materials and methods

Bars of 35CrMo (0.344C-0.95Cr-0.19Mo-0.56Mn-0.21Si-0.018P-0.005S-0.0032Al-Fe, wt.%) were used in the investigation, the liquidus and solidus temperatures for the steel are about 1486°C and 1437°C, respectively. A medium frequency induction furnace with 600 kg capacity was used to melt the bars under the protection of argon atmosphere. When the temperature of the molten melt reached 1600°C, it was poured into an sand mold full of argon gas within 30 second. The mold of 250 mm in diameter and 350 mm in height was made of sodium silicate and quartz sand and its wall inside was brushed with zircon powder. During the cooling of the ingot, perlite and argon gas were used for the heat insulation and to prevent the oxidation of the melt, as illustrated in Fig. 1a. For the ultrasonic treatment, as soon as the pour of the melt was finished, a resonance frequency of 19 KHz with an amplitude of 0~15 μm was applied immediately, and till the end of cooling. The ultrasonic vibration was introduced by a cylindrical radiator of 50 mm in diameter at the center of the mold and with 50 mm immerged in the melt, a sketch of which is shown in Fig. 1a. When cooled down, the ingot was knocked

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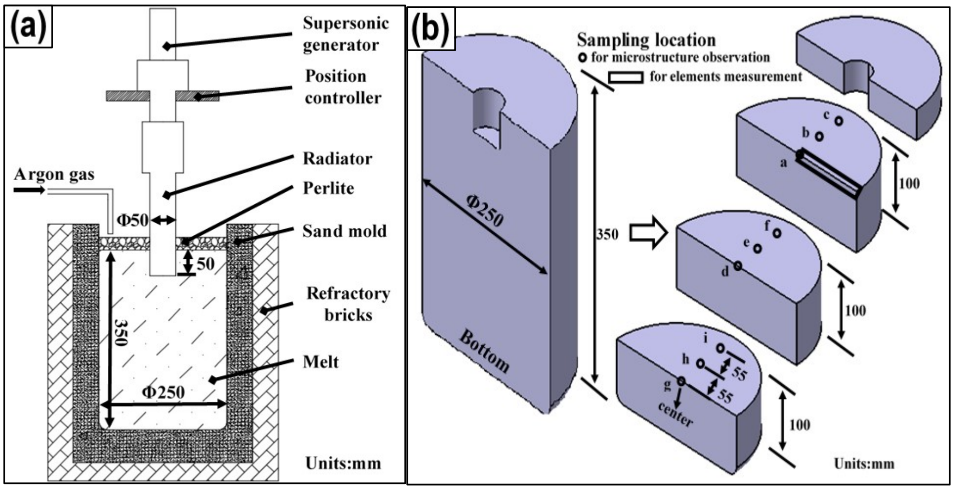
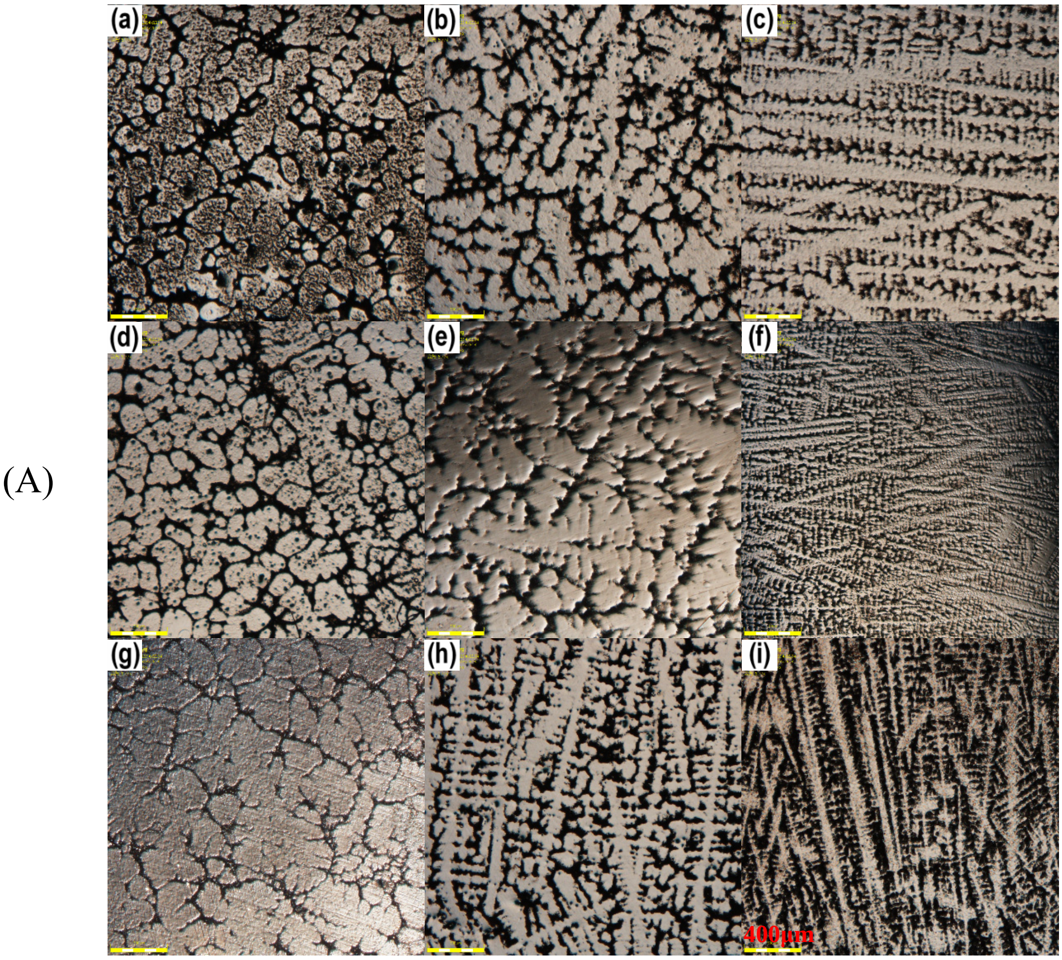


Fig. 1. Schematic representation of the casting of 35CrMo steel (a) and sampling location in the cast ingot (b)

out of the mold, then sliced along the axis section in accordance with Fig. 1b The samples for the observations were acquired by electrospark wire-electrode cutting at different locations (labeling of them were presented in Fig. 1b). All samples were grinded and polished, and those for the metallographic observations were further treated with a solution containing picric acid (5 g) + H_2O(100 ml) + HCl(2 ml) + detergent(4 g) at 60 ~ 70°C for 4 ~ 6 minutes. Examination of the defects distribution and micro-structures was performed using a Olympus DSX500i microscopy, and the elements content was analyzed by a inductively coupled plasma spectrometry (Optima 7000 series).

3. Results

Representative metallographic micro-structures at different locations of the cast ingots treated with and without ultrasonic vibration are illustrated in Fig. 2. Obviously, roses like grains



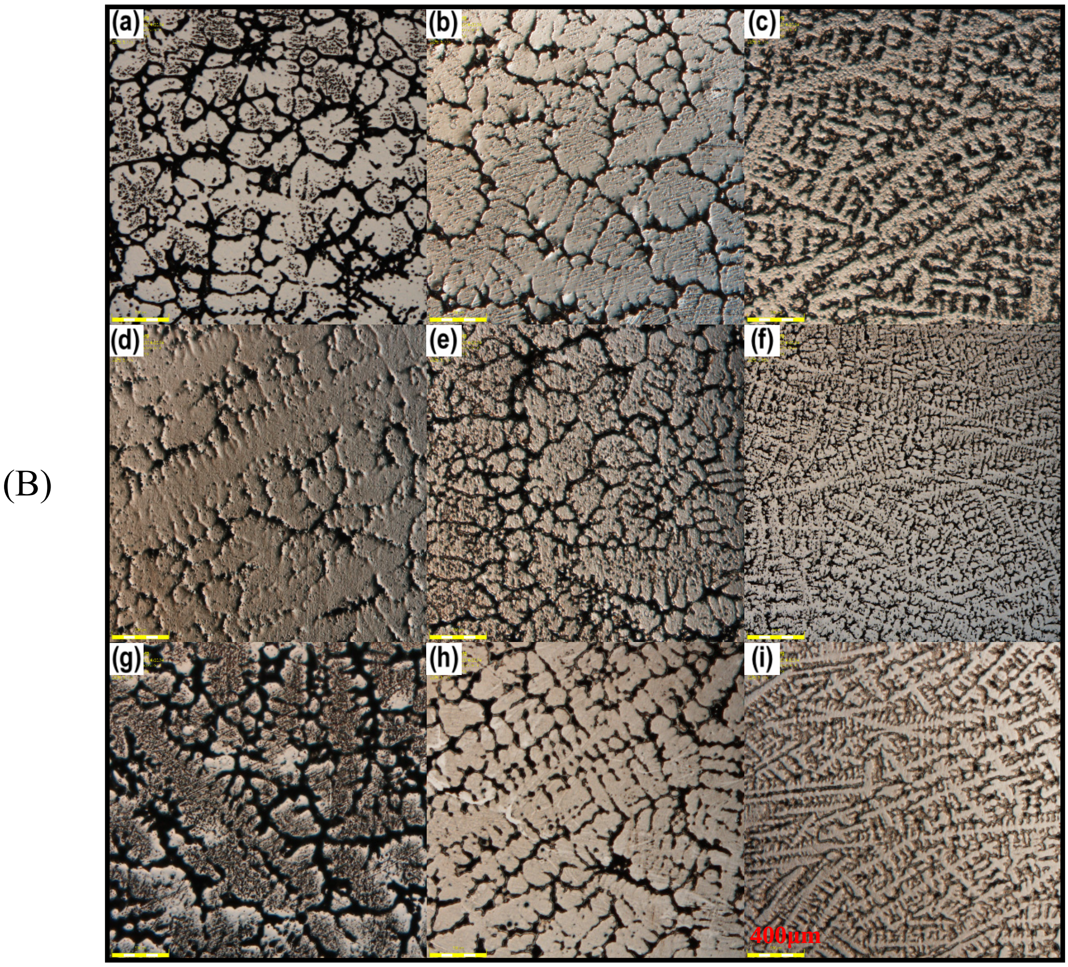


Fig. 2. Microstructures of the cast samples at different locations with ultrasonic vibration (A) and without (B)

and coarse dendrites spread throughout the sample which has not experienced ultrasonic treatment. However, for the sample applied by ultrasonic vibration, much finer grains with uniform size are formed, equiaxed grains tend to be found, notably under the radiator, and the secondary dendritic arms are greatly shortened at the edge, with the primary ones far longer than that of the samples untreated ultrasonically. Additionally, the metallographic observation also displays, the micro-structure along the radial direction of the ingot is harder to control compared with the longitudinal direction.

Typical defects (porosity and inclusions) distribution at the top of the ingot with different distance from the center is presented in Fig. 3. The number and size of the defects decrease for the introduction of ultrasonic vibration, especially at the edge of the ingot. Distribution of the elements is characterized by macro-segregation ΔC, which can be calculated through the running concentration C_i and the nominal concentration C_0 [11,12]. Fig. 4 exhibits the measured macro segregation profiles for C, Cr and Mo. Evidently, the appliance of ultrasonic vibration to sample also results in the more even distribution of elements.

As the experiment results indicated above, the introduction of the ultrasonic vibration in the solidification of the steel is conducive to improve the microstructures and the distribution of the elements as a whole, but its efficiency declines with the distance to the radiator increasing, especially in the radial direction of the radiator.

4. Discussion

The microstructure of the cast ingot is dependent on the nucleation stage and later growth condition. Both sufficient nuclei and subsequent growth are crucial to obtain fine grain structure. There are two main mechanisms proposed regarding the grain refinement of ultrasonic vibration during solidification: cavitation-induced dendrite fragmentation and heterogeneous nucleation [13].

Cavitation from the introduction of ultrasonic vibration can give rise to numerous bubbles in the melt. Then these bubbles implode and contribute to the prompt rise in temperature and pressure in a small space [14-17], generating micro-jet and shock waves of 400 m/s speed and with liquid of 10^{10} K/s cooling/heating rate rushing into the collapsed bubbles [18-20]. Due to the force and shock waves, fragmented arms of the dendrites and broken interfaces between the collapsed bubbles and the melt are formed. With the acoustic streaming, they are pushed into the melt rapidly, which increased the number of nuclei quite much. Meanwhile, the lower nucleation temperature and undercooling

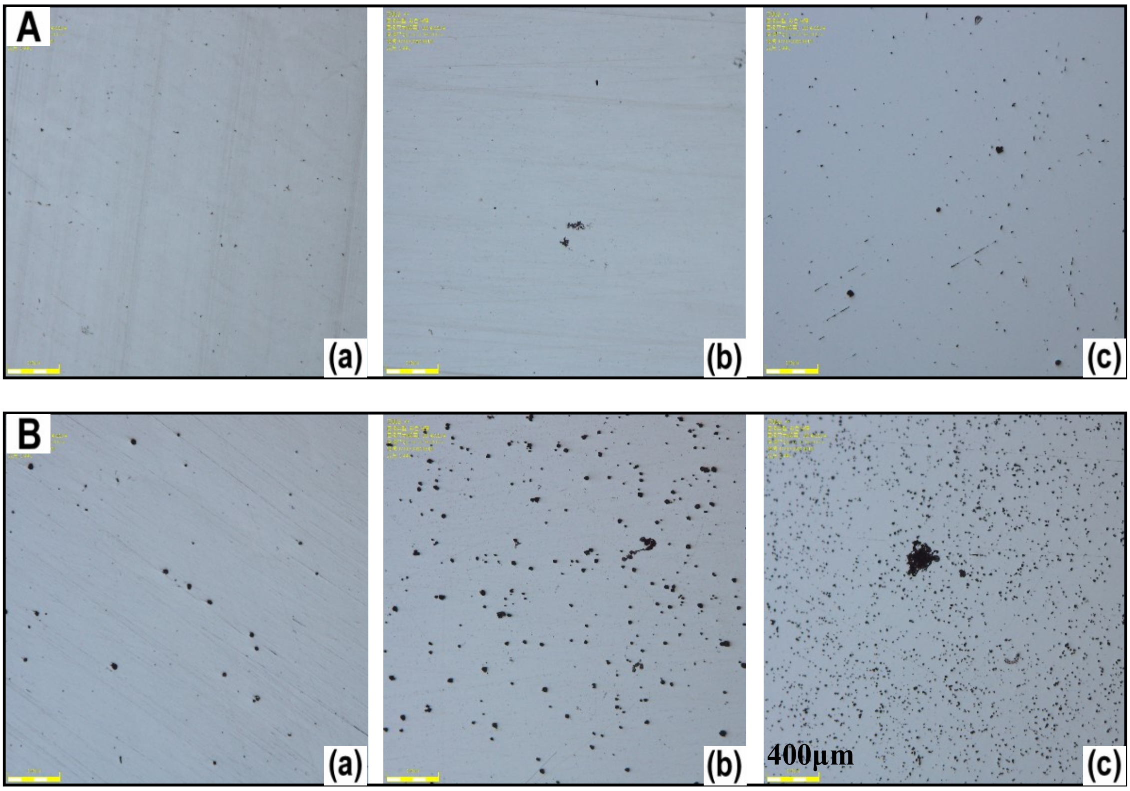


Fig. 3. Defects distribution for the samples ultrasonic vibration treated (A) and not treated (B) with different distance from the center of the ingot

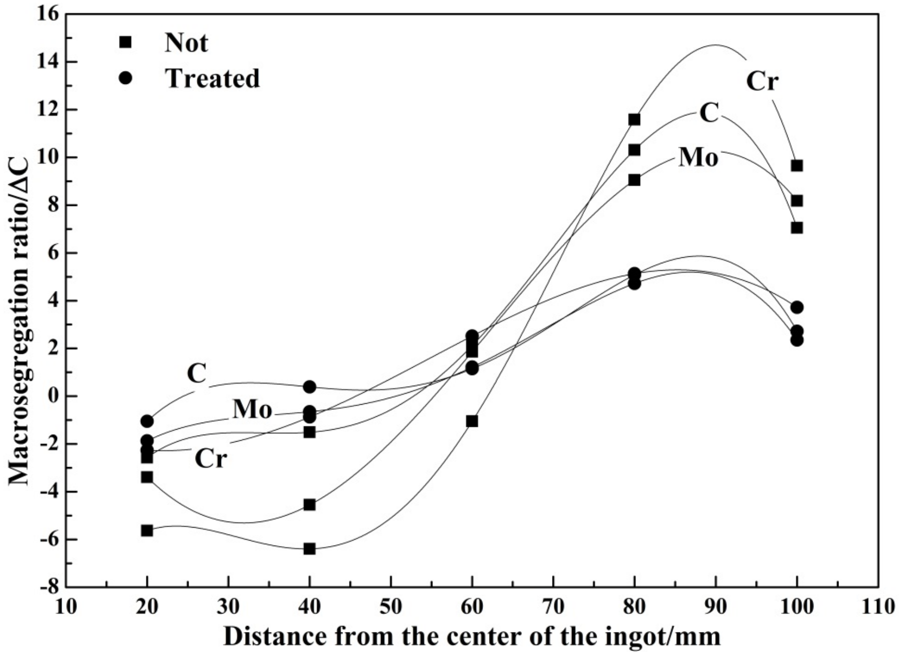


Fig. 4. Macrosegregation profiles of in 35CrMo steel with and without ultrasonic vibration. $\Delta C = (C_i - C_0)/C_0$, C_i, running concentration, C_0, nominal concentration

caused by ultrasonic vibration [21,22] promote the growth of those nuclei into grains, leading to the finer grain structure. It is clear in Fig. 2 that for the treated sample, the grain size is smaller, and the subsidiary arms of dendrites at the edge are much shorter, but with longer primary ones. The condition without ultrasonic vibration facilitates the propagation of the subsidiary dendritic arms, but it is detrimental to the growth of the primary ones, making the matrix occupied by heavy subsidiary arms.

During solidification, the mechanism for segregation is the partitioning of solute elements between the solid and liquid phases. The strong mixing power from ultrasonic vibration on the melt and two-phase zone can bring about the high pressure

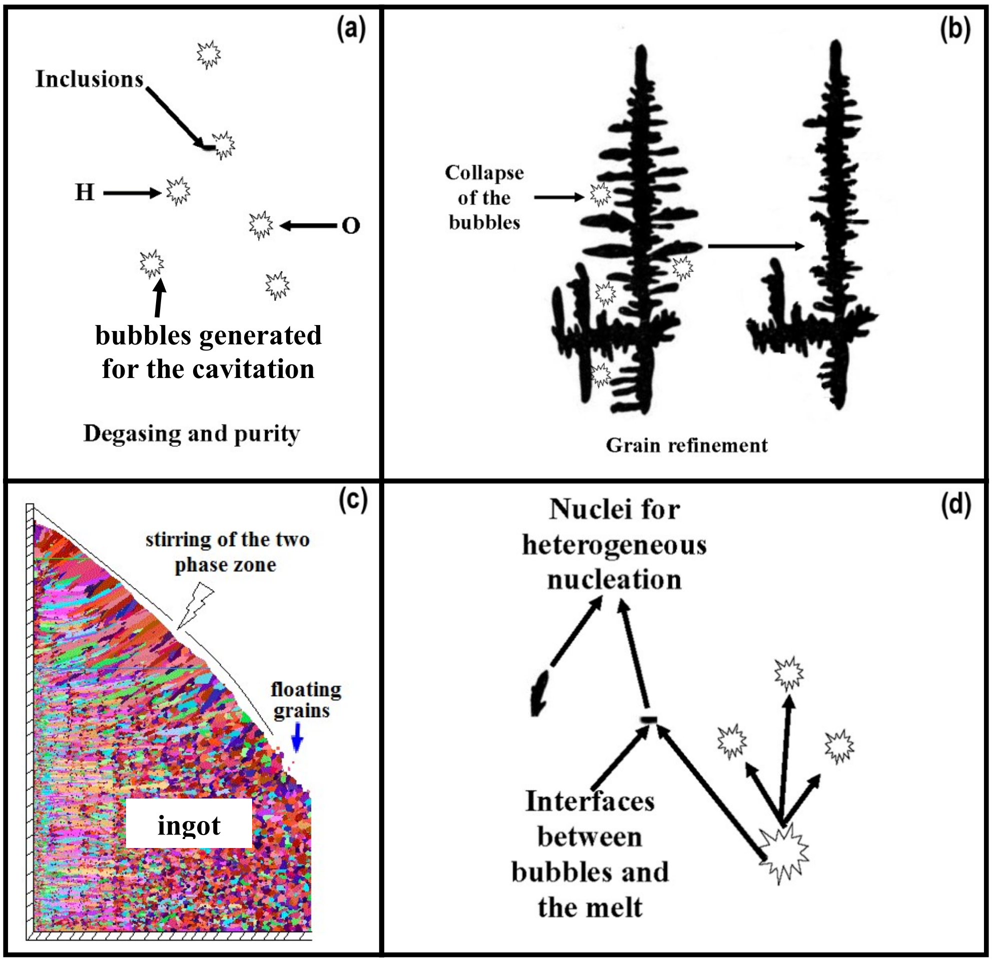


Fig. 5. Schematic diagram for the mechanism of ultrasonic vibration on the solidification (a) degasing and purity, (b) fragmentation of the secondary dendrites, (c) stirring of the two phase zone, (d) increase of the nuclei

and the fast flow of the melt. As a result, the decohension of grains and the fragmentation of dendritic arms from the matrix are caused, re-melting of the solid phase, and finer grains – all these lead to the uniform distribution of alloyed elements.

A large number of bubbles created by cavitation in the melt, aside from doing good to the grain refinement, act as carriers of gas and other non-metallic inclusions. Oxygen and hydrogen in the melt continuously enter the bubbles under the strain of vapor pressure. As the bubbles migrate to the atmosphere, the oxygen and hydrogen atoms decrease. Moreover, other non-metallic inclusions attached to the bubbles [23] are also removed from the melt As a consequence, the defects caused by gas and other non-metallic inclusions reduce accordingly. Finally, the operation mechanism of the ultrasonic vibration to the 35CrMo steel is shown schematically in. Fig. 5

5. Conclusions

The effects of ultrasonic vibration on the micro-structure and macro-segregation of 35CrMo steel during solidification were investigated for the first time. Grain refinement was obtained for the induction of ultrasonic vibration, especially the fragmented subsidiary arms of dendrites, so are the elimination of defects and the macro-segregation of alloyed elements. It indicates that the ultrasonic vibration also works for the steel, and the dominant mechanism for grain refinement is likely due to the fragmentation of the secondary dendrites and increase of the nucleation sites caused by ultrasonic vibration.

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