Effect of Ultrasonic Treatment on the Solidification Microstructure of Die-Cast 35CrMo Steel

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Abstract: The effects of ultrasonic treatment (UST) on the solidification microstructure of a 35CrMo steel cast ingot were investigated. To avoid the erosion of a high-temperature melt, a T-shaped ultrasonic waveguide unit was used to introduce ultrasonic vibrations into a 35CrMo steel die casting melt. The experimental results show that the microstructure of the ingot was refined by ultrasonic treatment. While the microstructure of untreated 35CrMo steel is coarse dendritic grains, after the introduction of ultrasonic treatment, the solidification microstructure transforms from coarse dendritic to equiaxed grains, and the dendrites are also refined. Samples from different positions of the ingots were subjected to different ultrasonic effects, and the effects on grain refinement also varied due to the severe attenuation of the ultrasound in the melt. The mechanisms of grain refinement using ultrasonic treatment for 35CrMo steel melt are presented.

Keywords: 35CrMo steel; casting; solidification microstructure; ultrasonic treatment; grain refinement

1. Introduction

The ultimate quality of casting products is related to many factors, one of the most important factors being the solidification structure. Casting defects, produced during solidification, will be reflected in casting products and affect service life. The primary problem for carbon steel casting is incomplete elimination of solidification defects, such as coarse columnar crystals, porosity, segregation, inclusions, etc. Ultrasound, a high-energy sound wave, can generate a series of nonlinear effects, such as cavitation and acoustic streaming, when propagated in materials. Many researchers have found that ultrasound can refine the solidification structure significantly for casting when introduced into the solidification process; however, research regarding solidification structure refinement by ultrasonic treatment is mainly concentrated on light metals, such as aluminum, magnesium, copper, etc. Using a water-cooled ultrasonic resonator to treat commercial Al-based alloys can reduce the mean grain size, vary the phase distribution, and obtain a greater material homogeneity [1]. Introducing ultrasonic cavitation into aluminum A356 alloy can obtain a globular/non-dendritic microstructure and refine the grain size [2]. Ultrasonic treatment of AZ91 magnesium alloy has a significant effect on the grain size and the sphericity of α-Mg dendrites, as well as on the size, continuity, sphericity, and distribution of intermetallic particles [3]. Application of ultrasonic vibrations to modify the solidification microstructure of Sb-20%Sn alloy can refine the grain size and increase the volume fraction of the peritectic SnSb phase [4]. High-intensity ultrasonic vibration of the Al-Si-Cu alloy not only promoted the formation of small α-Al globular grains, but also modified the eutectic silicon [5]. The morphology of the α phase was modified from coarse rosette-like structures to fine globular ones, with the application of ultrasonic vibrations to the Mg-8Li-3Al alloy [6].
However, application reports regarding ultrasonic treatment of steel materials are relatively few in number, especially for iron and steel production applications. The solidification structure and properties of 1Cr18Ni9Ti stainless steel were improved after ultrasonic vibration. The growing long dendrites were broken into pieces and a uniform, equiaxed microstructure was obtained [7]. The tensile strength and ductility values of T10 steel were significantly improved by ultrasonic treatment. In addition, the grain size was refined with an increase in the ultrasonic power [8]. Good degassing and refinement results of low carbon steel could be obtained after the melt was ultrasonically treated [9]. The microstructure of the treated area was significantly refined, and equiaxed grains were obtained using ultrasonic treatment. It should be noted that fragmentation of inclusions occurred due to ultrasonic treatment [10]. Although there are some research results regarding the application of ultrasonic vibrations on the steel solidification process, the samples were small and limited.

In the present study, the effects of ultrasonic treatment on the cast microstructures of φ200 mm 35CrMo steel casting ingots were investigated. In order to overcome the corrosion of the ultrasonic radiator and the thermal radiation of the ultrasonic transducer by the high-temperature molten melt, a T-shaped ultrasonic waveguide unit was employed to introduce ultrasonic vibrations in the melt, and microscopy was used to study the effects of the solidification structure between direct casting (DC) and ultrasonic treatment (UST).

2. Materials and Methods

To investigate the effects of ultrasonic treatment on the solidification microstructure of a high temperature alloy, 35CrMo steel was collected from a commercial plant (Wuxi, China) for use in these experiments. The chemical composition of 35CrMo steel is listed in Table 1.

<table>
<thead>
<tr>
<th>Chemical Composition</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Cr</th>
<th>Mo</th>
<th>Ni</th>
<th>P</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass fraction</td>
<td>0.32</td>
<td>0.25</td>
<td>0.45</td>
<td>0.85</td>
<td>0.19</td>
<td>0.025</td>
<td>0.025</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

Schematic diagram of sand-cast of 35CrMo steel under ultrasonic processing is shown in Figure 1. The ultrasonic casting apparatus (self-research and development) used in this study are illustrated in Figure 2. A T-shaped ultrasonic waveguide unit has been discussed in detail in previous work [11]. Ultrasonic treatment was applied using a metallurgical generator (Weihai Guosheng Sonitech Co., Ltd, Weihai, China), of which the input power was 0–400 W, the resonance frequency was 20 ± 2 kHz, and the amplitude of vibrations was 10 μm (measured in air on an ultrasonic horn (Polytec Gmbh, Berlin, Germany) with a vibrometer). The ultrasonic radiator (emitter area of 7850 mm², made of Si₃N₄ ceramics, self-research and development) connected to the end of an ultrasonic horn (made of TC4 titanium alloy, self-research and development) was inserted into molten steel. A specimen weighing 200 kg was melted at medium frequency induction at 1803 K (1530 °C), and controlled at this temperature for 600 s, then the molten melt was poured into the sand-cast mold measuring φ200 mm × 600 mm. The liquid steel surface was covered with an insulation material and held for 15 min. Then, the ceramics ultrasonic radiator, which was preheated at 1530 °C, was inserted to approximately 50 mm beneath the melt surface in order to perform ultrasonic stirring at 400 W and a frequency of 21 kHz. An Argon gas atmosphere protected the 35CrMo steel molten pool. A thermocouple (Shanghai Feilong Meters & Electronics C., Ltd, Shanghai, China) was used to monitor the melt temperature in order to control the superheat. At the same time, a cooling system was maintained in order to protect the ultrasonic waveguide devices. With the same experimental conditions, the corresponding test was repeated without ultrasonic treatment. The experiments were repeated several times in order to interpret the results of the experimental conditions.
3. Results and Discussion

3.1. Effects of Ultrasonic Treatment on the Microstructure of the Ingots

Figure 4 shows the as-cast microstructures of the φ200 mm 35CrMo steel-casting ingot, at a 20 mm distance from the radiator tip, determined using direct casting (DC) and ultrasonic treatment (UST). Compared to conventional casting, it was found that, in the edge of the ultrasonic casting, a large number of long-strip dendrites exist. Meanwhile, the conventional ingot showed a large number of secondary dendrites. However, in the ultrasonic casting there were less secondary dendrites. In the
R/2 part of the ingots, it can be observed that cellular dendrites and the grain size of the conventional casting ingot are coarse. After the application of UST, the equiaxed grains began to appear in the UST ingot, and the microstructure tended to coexist with the equiaxed grain and fine dendrite grains. In the center part of the ingots, equiaxed grains began to grow, and some coarse dendrite grains still existed using conventional DC casting. With the application of UST, the grains of the ingots are all fine equiaxed grains. Thus, it can be seen that the microstructure of the samples, which were cut from a cross-section near the ultrasonic radiator tip of the casting ingot, can evidently be refined from the edge to the center using ultrasound.

Figure 4. Microstructures of ingots at a 20 mm distance from the radiator tip.

Figure 5 shows the microstructures of the φ200 mm 35CrMo steel casting ingot, using DC and UST, at a distance of 100 mm from the radiator tip. It is clear that the macrostructures of the ingots are transformed from long-strip dendrites into short-coarse dendrites, from the edge to the center, using conventional DC casting. A small amount of equiaxed grains began to appear in the R/2 and center part of the casting ingots. Compared with the conventional DC casting ingot, the microstructures of
the UC casting ingot transitioned from fine dendrites to fine equiaxed grains, from the edge to center. Although little remains of the short-coarse dendrite structure in the center part of the 35CrMo steel ingot, the average grain size of the UST ingot is obviously refined compared with conventional DC casting. It can be observed that, with an increase of the distance from the radiator tip, the effects of the ultrasounds on grain refinement tended to attenuate. Fortunately, ultrasonic melt treatment can refine the solidification microstructure of 35CrMo steel at a distance of 100 mm from the ultrasonic source.

**Figure 5.** Microstructures of ingots at 100 mm distance from the radiator tip.

Figure 6 shows the microstructures of the φ200 mm 35CrMo steel casting ingot, using DC and UST, at a distance of 200 mm from the radiator tip. In the center part of the ingot, the solidification microstructures show short-coarse dendrites and equiaxed grains. However, the equiaxed grain ratio
in the UST casting ingot is larger than that of conventional DC casting. In the edge of the ingot, there are less secondary dendrites when using UST than DC. In the R/2 part of the ingot, there are coarse dendrites in the DC ingot and fine dendrites in the UST ingot, so the microstructures of the casting ingot have been relatively refined. The above-mentioned results indicate that, with the increase of distance from the ultrasonic source (ultrasonic radiator), the grain refinement from ultrasounds decreases.

Figure 6. Microstructures of ingots at 180 mm distance from the radiator tip.

3.2. Discussion

Due to a lack of convincing evidence, there is a great deal of controversy regarding the refinement mechanisms of ultrasonic treatment, and a number of refinement theories have been proposed. Up to now, two prevailing hypotheses have been proposed based on the cavitation phenomenon. One is cavitation-enhanced nucleation, due to nucleus activation and/or heightened supercooling [12], and
the other is cavitation-induced dendrite fragmentation, arising from the shock wave generated by the collapse of cavitation bubbles [13].

For 35CrMo steel, the liquid-solid temperature range (about 50 °C) is rather narrow when compared with Al and Mg alloys, and the melt temperature is very high (up to 1560 °C). When the heating power is cut, the cooling rate is much higher; thus, 35CrMo steel tends to form a network of primary crystal dendrites in a very short period of time. Additionally, the network of primary crystal dendrites leads to a relatively larger melt viscosity (about 3.5 mPa·s). Consequently, the network of primary dendrites and higher melt viscosity must hinder the possibility of dendrite fragmentation from ultrasonic cavitation shock waves [14]. The cavitation bubbles can release tremendous amounts of energy during the collapsing process, and a hot pot will form, in which the local transient temperature and pressure can reach 5000 K and 5 GPa, respectively [15]. According to the Clausius-Clapeyron equation [16], the high pressure must substantially improve the theoretical melting temperature, and, in turn, enlarge the degree of melt undercooling [17]. As a consequence, the nucleation rate is accelerated, leading to significant grain refinement. In addition, the shock waves and micro-jet induced by the collapse of cavitation bubbles can clean the surface of inclusions by breaking the gaseous films; thus, the poorly wetted inclusions can be sufficiently wetted by the melt, which activates it to serve as the solidification nuclei [18]. As a result, the number and inoculation potency of inclusions increase after ultrasonic treatment, which supplies more nucleation sites for the crystallization of nuclei, resulting in much smaller grains.

4. Conclusions

In this paper, a new ultrasonic waveguide unit was used to introduce ultrasonic vibrations in a steel melt. The main goal of this study was to investigate the effects of ultrasonic treatment on the microstructure of 35CrMo steel, based on the use of acoustic energy to perform the melt treatment. The ultimate goal of this is to eventually develop a casting technique for carbon steel. With respect to the refining and modification of microstructures using ultrasound, the main conclusions to be obtained from the experiments are:

1. Compared with the microstructures of ingots, between conventional direct casting and ultrasonic casting, it can be found that ultrasonic treatment can be used to refine the solidification structure of 35CrMo steel, and can transform the microstructure from coarse dendritic to short staggered dendritic. To some extent, the solidification structure changed from dendritic to equiaxed grains after the introduction of ultrasonic treatment.

2. The microstructures from different positions in the samples, which are subjected to different ultrasonic acoustic pressures during ultrasonic treatment, show that there is a severe attenuation of ultrasounds in the molten melt. The closer the samples are to the radiator, the stronger the effect of ultrasonic treatment, and the more remarkable the refinement of the microstructures.

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Author Contributions: Gen Liang and Daheng Mao conceived of and designed the experiments; Gen Liang performed the experiments; Gen Liang and Chen Shi analyzed the data; Yajun Zhou contributed reagents, materials, and analysis tools; and Gen Liang wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

References


