

Effect of Ultrasonic Melt Treatment on Microstructure and Mechanical Properties of 35CrMo Steel Casting

Chen Shi^{1,2}, Fan Li^{1,2}, Gen Liang^{1,2}, Daheng Mao^{1,2}

¹Central South University, State Key Laboratory of High Performance Complex Manufacturing, Changsha 410083, Hunan

²Central South University, College of Mechanical and Electrical Engineering, Changsha 410083, Hunan

*Corresponding author e-mail:1627460337@qq.com

Abstract. Effects of different power ultrasonic on microstructure and mechanical properties of 35CrMo steel casting were investigated using optical microscopy (OM), scanning electron microscopy (SEM) and hardness testing. A self-developed experiment apparatus was used for the propagation of ultrasonic vibration into the 35CrMo steel melt to carry out ultrasonic treatment. The experimental results showed that compared to the traditional casting, ultrasonic treatment can obviously change the solidification microstructure of 35CrMo steel, which is changed from coarse dendrites to fined dendrites or equiaxed grains. With the increase of ultrasonic power, equiaxed crystal is remarkably refined and its area is broadened. The micro porosity percentage of ingot casting decreases significantly and the porosity defects can be suppressed under ultrasonic treatment. The mechanical properties of 35CrMo steel ingot after heat treatment were enhanced by ultrasonic treatment: the maximum tensile strength is improved by 8.4% and the maximum elongation increased by 1.5 times.

1. Introduction

The traditional methods of casting to produce large size ingots are easy to produce macro and micro defects such as coarse grains, composition segregation and porosity. The microstructure of ingots could not be controlled precisely. Ultrasonic assisted casting is a new type of solidification method developed for the manufacture of high performance aluminum and magnesium alloys recently. Ultrasonic energy is used to control the grain shape, grain orientation and precipitate state in the solidification process of light alloy. According to the literature [1] and literature [2], scientists found that the solidification process of AZ91 magnesium alloy could be refined obviously by introducing ultrasonic wave in the casting processing. The microstructure of 7050 and 7085 aluminum alloy could be refined and the second phase could be ameliorated by ultrasonic treatment. Literature [3-4] reported the possible use of ultrasonic for the degassing of aluminum alloy melt. Literature [5] studied that the microstructure of Al-Si alloy was refined by high intensity ultrasonic and the Si phase distributed more evenly. Literature [6] reported that mechanical properties of AlSi9Cu3 alloy was enhanced by ultrasonic melt treatment.

However, most of the researches on ultrasonic processing technology focused on the nonferrous metals, or the technology of ultrasonic treatment could only be used to deal with small size steel



samples in high temperature alloy steel [7-13]. Literature [11] studied the effect of different ultrasonic power on microstructure, macro segregation, mechanical properties and corrosion resistance of the ingots. In literature [12], scientists realized the ultrasonic treatment of 304 stainless steel melt using a cell block method and investigated the its effect on the solidification structure of 304 stainless steel. The studies show that the solidification structure of the ingots is improved to some extent by ultrasonic. However, how to introduce ultrasonic into steel melt for a long time is a bottleneck of the ultrasonic casting of alloy steel. The conventional ultrasonic wave guide rod is easily corroded in the molten steel after a long duration. Our research group optimized the structure of ultrasonic guide rod, and made a kind of T type ultrasonic wave guide rod which could avoid the effect of high temperature thermal shock of the molten steel on the ultrasonic transducer and effectively introduced the ultrasonic into the high temperature melt. The tool head could resist the high temperature corrosion of steel melt for a long time. In literature [14], the researcher found the T-shaped ultrasonic waveguide unit could avoid the corrosion of the high-temperature melt. In literature [15], researchers optimized the structure and length of the ultrasonic waveguide unit.

In this paper, effects of different power ultrasonic on microstructure and mechanical properties of 35CrMo steel casting were investigated, the self-developed T type ultrasonic guide device was adopted to introduce ultrasonic into steel melt. OM and SEM analysis methods were used to research the changes of the solidification microstructure, defects and mechanical properties of 35CrMo steel ingots. The research of this paper may provide a reference for the production of large steel casting.

2. Experimental device and method

2.1. Experimental device

The experimental device that shows in Figure 1 includes an ultrasonic generator (the range of generator power can vary between 0W and 600W , the frequency of generator is $21 \pm 0.2\text{kHz}$, the output amplitude is $10\mu\text{m}$), a T type ultrasonic wave guide device, an ultrasonic transducer, and a sand casting mold whose effective cavity is $\Phi 200 \times 400 \text{ mm}$. The T type of ultrasonic wave guide device consisted of two stages ultrasonic horn, ultrasonic tool head is connected by screw threads to the ultrasonic horn, then the generator is connected to the transducer which is equipped with a cooling fan.

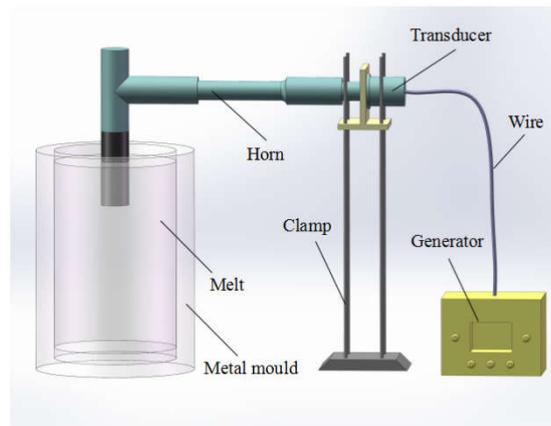
2.2. Experimental method

The material used in the experiment is 35CrMo steel whose main chemical composition is shown in Table 1. In Figure 1, the raw material of 35CrMo steel was warmed to a completely liquid state in medium frequency furnace. After removing slag from the mold, molten steel was poured into the prepared sand casting mold which was preheated. Then some heat insulating material was used to cover the surface of mold. Sand casting mold kept thermal insulation about 15 minutes. The ultrasonic guide rod that was preheated to the $1530 \text{ }^\circ\text{C}$ was inserted into molten steel. The insertion depth of ultrasonic guide rod was 50mm from the liquid surface. Then the molten steel was treated by the ultrasonic wave. The ultrasonic guide rod was removed from the molten steel when it had worked about 5 minutes. Then the treated molten steel cooled in the nature. Experiments were carried out with the ultrasonic power of 0W, 150W, 300 W and 450 W under the same conditions in order to explore the effect of different ultrasonic powers to the solidification structure of 35CrMo steel.

Several analysis samples were removed from the different position of the ingots. The samples were analyzed by the type of Olympus-DSX500 optical microscope after the samples were treated by rough grinding, fining grinding, rough polishing and fining polishing. At the same time, the ingots that dealt with different power ultrasonic treatment quenched at $850\text{ }^\circ\text{C}$. Dumbbell shaped tensile samples were prepared and tested tensile mechanical properties according to the national standard GB/T 228.1-2010 metal material tensile test (normal temperature test) method from the same site of ingots.

Table 1. Chemical composition of 35CrMo steel for experiment (mass fraction, %).

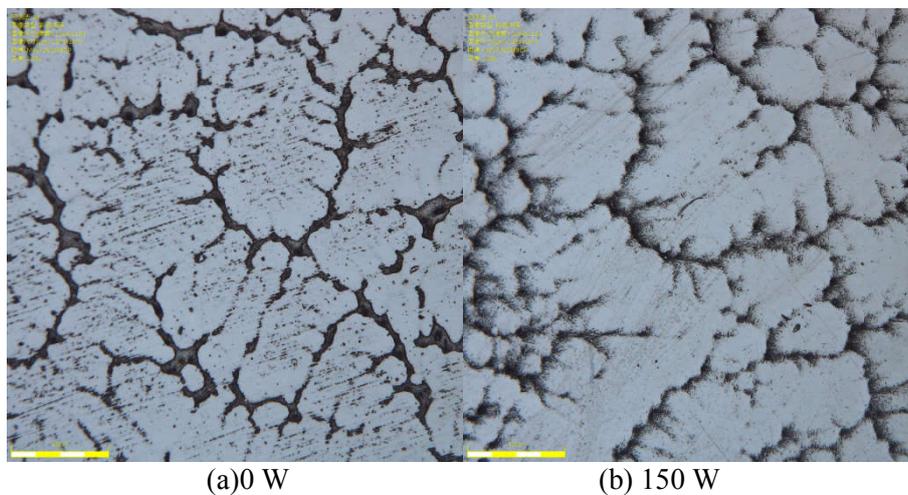
	C	Mn	Si	P	S	Cr	Mo	Fe	
Standard value	0.32~0.40	0.40~0.70	0.17~0.37	≤ 0.035	≤ 0.035	0.80~1.10	0.15~0.25	Bal.	
Measured value	0.34	0.47	0.26	0.019	0.005	0.95	0.19	Bal.	

**Figure 1.** Schematic diagram of ultrasonic melt treatment.

3. Result and discussion

3.1. Effect of ultrasonic on the structure of 35CrMo ingots

Figure 2 shows the changes of solidification structure of 35CrMo steel with different power ultrasonic melt treatments. The solidification structure mainly manifests as coarse dendrites when the ultrasonic power is 0 W. When the ultrasonic power reaches 150 W, the grain size has no obvious changes. The columnar crystal morphology become smaller and shorter, and the grains are refined gradually while the ultrasonic power comes to 300 W. By the time the ultrasonic power is 450 W, the proportion of equiaxed grains is enhanced and the grains are refined obviously. So ultrasonic treatment can obviously change the solidification microstructure of 35CrMo steel from coarse dendrites to fined dendrites or equiaxed grains, and the microstructure refinement effect become more obvious with the increase of ultrasonic power.



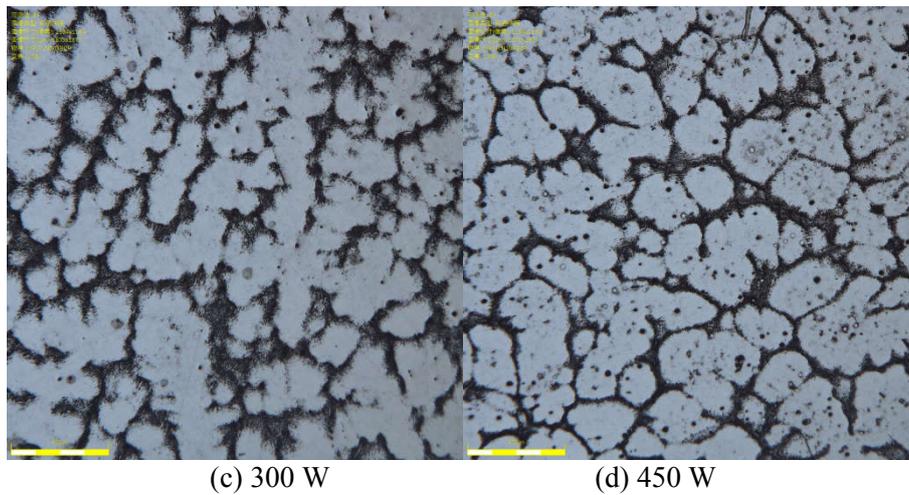


Figure 2. Solidification structure of 35CrMo ingot under different power ultrasonic treatment.

3.2. The effect of ultrasonic on the micro porosity of 35CrMo ingot

Figure 3 shows the microscopic morphology along the axial direction from the tail end of the ultrasonic guide rod. There are lots of micro porosity defects in the samples without ultrasonic treatment, but the micro porosity of the steel ingots which was treated by ultrasonic decreased significantly, and the porosity defects decrease obviously near the tail end of the ultrasonic guide rod. With the increase of the distance to the tail end of the ultrasonic guide rod, the effect of ultrasonic wave is weakened, and the influence of the porosity is reduced.

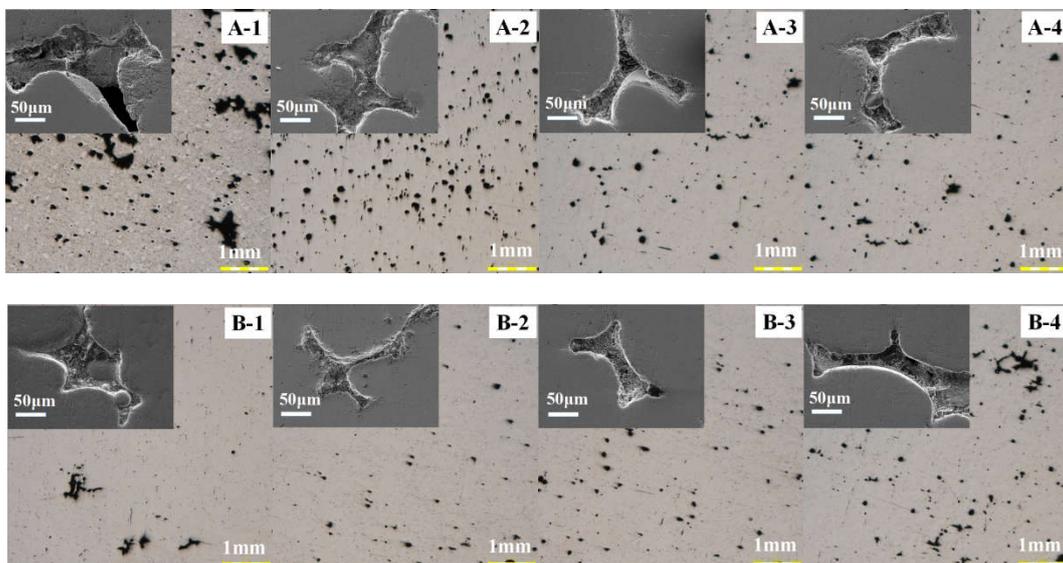


Figure 3. Change of microscopic morphology in different positions:

(A) ultrasonic power is 0W. (B) ultrasonic power is 450W.

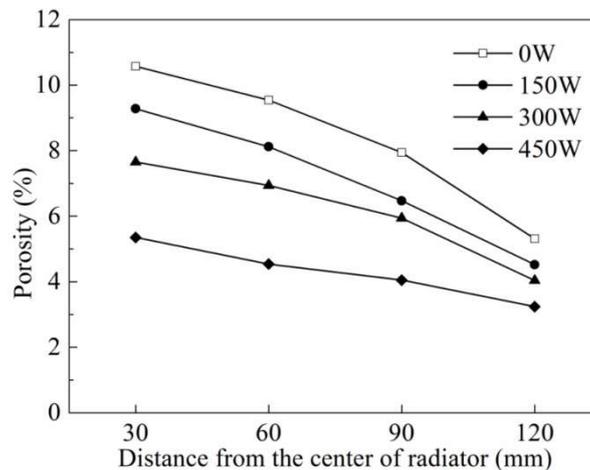


Figure 4. Percentage of porosity at different positions along the radial direction from ultrasonic guide rod.

Figure 4 shows the percentage of micro porosity along the radial direction from guide rod with different ultrasonic powers. The degree of micro porosity of 35CrMo ingot is different in the different positions along the radial direction, the micro porosity defects are mainly concentrated in the central region of the ingot. The percentage of micro porosity is decreased by ultrasonic treatment. With the increase of ultrasonic power, the porosity is obviously reduced: the micro porosity percentage at 30 mm distant from the guide rod is reduced from 10.38% to 5.35%, the micro porosity percentage at 120 mm distant from guide rod was declined from 5.31% to 3.24%.

3.3. Effect of ultrasonic on mechanical properties of 35CrMo ingot

Figure 5 shows the variation of mechanical properties (tensile strength and elongation) of 35CrMo steel with different ultrasonic power after the same heat treatments. The tensile strength of the sample is improved from 643MPa to 697MPa with the ultrasonic power changing from 0W to 450W, which means the tensile strength is enhanced about 8.4%. At the same time, the elongation rate of the sample is increased from 9.28% to 14.27% with the ultrasonic power of changing from 0W to 450 W. It means that the mechanical properties of 35CrMo steel are improved, which results from the grain refinement of 35CrMo ingot by ultrasonic melt treatment.

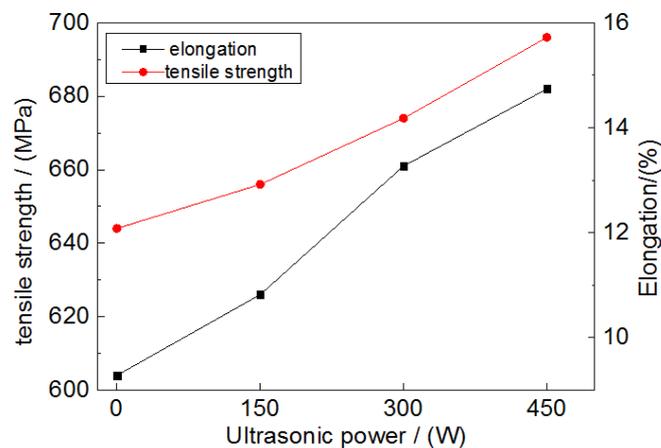


Figure 5. Mechanical properties of 35CrMo steel under different power ultrasonic treatment.

3.4. Results Discussion

The analysis results of solidification microstructure show that ultrasonic melt treatment is an effective technique to refine the microstructure. As a kind of high energy sine wave introduced into the molten steel, ultrasonic wave can produce a series of nonlinear effects. When the enough high power ultrasonic wave acts on the liquid medium, the amplitude of alternating pressure is larger than the static pressure P_0 in the liquid, the effect of negative pressure will not only offset the pressure but also form the local negative pressure zone in the negative pressure phase. When the negative pressure is greater than the binding force that is between the liquid molecules, the liquid is broken and formed a cavity, then generates cavitation bubbles, and in the next moment the cavitation bubbles are closed or broken by the positive pressure phase of sound. The cavitation bubbles absorb large amounts of heat from the steel melt around the bubble wall during the process of expansion. This process results in the under cooling of the melt temperature of the micro zone [15].

The driving force of liquid metal crystallization is [17]:

$$F_{rad} = \Gamma_{abs} \cdot \frac{e_1}{c} \quad (1)$$

where F_{rad} represents driving force, Γ_{abs} represents ultrasonic absorption capacity of materials, c represents propagation velocity of ultrasonic wave in melt, e_1 represents direction vector of ultrasonic propagation.

The attenuation equation of ultrasonic propagation in the melt can be described as [18]:

$$I_t(x) = I_{in} \exp[-2\alpha x] \quad (2)$$

where I_{in} represents ultrasonic input intensity, $I_t(x)$ represents sound intensity in the direction of propagation, x represents propagation distance, α represents attenuation coefficient.

Therefore, total ultrasonic energy absorbs by melt:

$$\Gamma_{abs} = \int_s I_t(x) dS \quad (3)$$

where dS represents infinitesimal region of vibration induces by ultrasonic waves in melts.

We can obtain from (1), (2) and (3):

$$F_{rad} = I_{in} \cdot S \cdot \exp(-2\alpha x) \cdot \frac{e_1}{c} \quad (4)$$

The driving force is positively correlated with the ultrasonic input intensity from type (4). Therefore, when the input intensity is too small, the driving force of sound pressure is smaller than the threshold of grain breakage by much, and it means that the effect of ultrasonic on solidification structure is not obvious, which can be observed from the comparison of Figure 2(a) with Figure 2(b). However, when ultrasonic power increases further, the sound pressure is enough to destroy the growing grain and makes the crystal vibrate violently, which can increase the number of nuclei during solidification and refine the grains. So when the ultrasonic power is from 300W to 450W, more refined grains can be got.

In addition, during the solidification, when solidification causes tiny shrinkage, the wall of shrinkage cavity will adhere to a large number of tiny bubbles, which are likely to hinder the liquid filling. While during the processing of the ultrasonic treatment, the bubbles attached to the dendrite

surface will separate from the dendrite into the liquid with the effect of ultrasonic vibration, and it can reduce the content of gas in micropore and make the liquid easier to penetrate into the micropore from the outside of the micropore, which can reduce the porosity defects of 35CrMo steel ingot obviously. Therefore, the mechanical properties of 35CrMo steel ingot can be enhanced due to the grain refinement and the decrease of porosity.

4. Conclusion

(1). The solidification structure of 35CrMo ingot is changed from coarse dendrite to fine equiaxed grain when the solidification process of cast 35CrMo steel was treated by ultrasonic. Grain refining effect was more obvious with the increase of ultrasonic power.

(2). Ultrasonic melt treatment could significantly inhibit the formation of micro porosity defects. The stronger the ultrasonic wave in the melt, the better the inhibition effect of micro porosity near the ultrasonic guide rod.

(3). The mechanical properties of 35CrMo steel ingot after heat treatment were enhanced by ultrasonic treatment. The maximum tensile strength had a 8.4% improvement and the maximum elongation increased by 1.5 times.

Acknowledgements

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