Reducing Porosity in 35crmo Steel Sand-Cast by Ultrasonic Processing

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Abstract. The influence of ultrasonic processing on porosity defects of 35CrMo steel sand-cast ingot was studied. A self-developed ultrasonic-introduced method was applied to carry out the ultrasonic experiment. The acoustic pressure and melt velocity field were calculated through numerical simulation, which plays an auxiliary role in the analysis of the influence of ultrasound on the molten steel. Comparing the porosity of ultrasonic castings and direct castings, the results reveal that ultrasonic processing could reduce the porosity defects of ingot significantly, thus the mechanical properties of castings could be significantly improved. The ultrasound tends to attenuate when propagating in the steel melt. The porosity at the central area of ingot reduced more apparent than that at the edge area. In addition, the mechanism of the effect of ultrasound on porosity reduction was also discussed.

1. Introduction

Porosity defect is a very common phenomenon in steel castings, which will depress the mechanical behavior and resistant to corrosion of the steel castings. In previous work, it was discovered that the application of ultrasonic fields during metal solidification can produce a range of benefits, such as refine grain [1, 2], suppress segregation [3, 4], remove gas [5-7], remove inclusion [8, 9], and improve tensile strength and mechanical property [10-12]. However, many of these researches aim at non-ferrous metals, only a few studies focused on the high-melting-point metal, such as steel. As a result of ultrasonic treatment, the mechanical behavior and consolidated structure of 1Cr18Ni9Ti stainless steel were promoted. The coarse dendrite was broken into fragments by ultrasonic treatment and the well-distributed equiaxed microstructure was achieved [13]. The tensile strength and elongation of T10 steel was enhanced remarkably after ultrasonic processing. With the increase in ultrasonic power, grain refinement is more obvious [14]. After the ultrasonic treatment of low carbon steel melt, good degassing and fine grain can be obtained [15]. The microstructure of the treated zone was refined and equiaxed grains were refined after ultrasonic treatment [16].

The objective of this work was to investigate the treatment of 35CrMo steel sand-cast by ultrasonic processing. The ultrasonic processing of 35CrMo steel during solidification was carried out by using a self-developed ultrasonic-introduced method. Based on the experimental results, the influence of ultrasound on the porosity defects of ingot was analyzed.
Ultrasonic treatment, as a new technology to improve materials performance, is widely applied in the metal solidification molding process. Many studies have found that the ultrasonic treatment has many advantages, such as refining grain, reducing the porosity, degassing, and enhancing the material mechanic performance [1-5]. However, most studies about ultrasonic treatment technology mainly focused on non-ferrous metals [1-5], little application at high-temperature alloy, such as steel. One of the main reason is that the ultrasonic radiator, which propagating ultrasound into the steel melt, is easy to be corroded in high-temperature steel melt. In this matter, it is difficult to import ultrasound into melt. Liu et al. treated T10 steel by using ultrasound introduced from the lateral, and studied the solidification microstructure, segregation, mechanical properties, and anticorrosion property under different ultrasonic powers. Although this method avoided corrosion of the booster, the loss of energy was still considerable, leading to low efficiency of ultrasonic application. Li et al. have done research on the material properties of the booster, and concluded that Mo-Al2O3-ZrO2 ceramic metal tube which could endure corrosion at high temperature and high frequency vibration was fitful for introducing ultrasound into steels. But, that method faces the difficulty of processing metal ceramic tube. Kang et al. adopted an innovative method for introducing ultrasound into the melt. The metal to be treated and the radiator which was placed upward in the experiment were processed as a unit piece, and the metal was melted by induction coils while ultrasonic vibration was introduced from the bottom of steel metal directly, avoiding erosion and power attenuation to the maximum extent. The refinement of solidification microstructure, the fragmentation of inclusions and the improvement of the mechanical property of 304 stainless steel are researched based on this newly proposed method. Although, this method can avoid the corrosion of the radiator and the attenuation of ultrasound, due to the small samples, only small-scale experiment was carried out.

An innovative method for introducing ultrasound into the steel melt is proposed in this paper. A T-shaped ultrasonic waveguide and an anti-corrosion radiator material, which can avoid erosion of the radiator and power attenuation to the maximum extent, are used to propagate ultrasound into melt. With the aid of the computational fluid dynamics (CFD) software, the pressure field and velocity field of steel melt are simulated when introducing the ultrasound. The action area of ultrasonic treatment is studied in this way. The ultrasound field was applied to the molten 35CrMo steel during the solidification process to study the effect of ultrasonic treatment (UST) on the microstructure and porosity defects of the steel. In the meantime, the experiment without ultrasonic processing was conducted as a control group.

2. Experimental procedure
As shown in Table 1, the chemical composition of the 35CrMo steel used in this experiment is listed. The melting point of the steel measured by the melting point tester is 1530°C, so it has a high requirement for ultrasonic waveguide and radiator. A novel T-shaped ultrasonic waveguide is adopted to introduce ultrasound into the high temperature melt. This waveguide structure avoids the direct thermal radiation effects of high temperature to the ultrasonic amplitude and transducer. The radiator is fabricated by ceramic material, which can resist high-temperature corrosion and introduce ultrasound into steel melt effectively. Ultrasound is generated by an ultrasonic generator (0-400 W, 21 kHz), and the radiator (Si3N4 ceramics) is connected with the end of ultrasonic horn (titanium alloy).

Two hundred kg of 35CrMo steel turned into molten state with the action of a medium frequency induction; then the steel melt was poured into a sand-cast mould of ⌀200 mm × 300mm. The heat insulating material was put on the surface of molten metal for 5 min. Then the radiator was put into the molten steel with 50 mm insertion depth form the surface of the melt. And the ultrasonic action time was set to 2 minutes. At the same time, the cooling system kept working to protect the ultrasonic equipment. The 35CrMo steel castings was finally cooled to normal atmospheric temperature (18°C ~24°C) after ultrasonic processing. The same experiment was repeated without ultrasonic processing. In order maintain the consistency with the experimental group, without ultrasonic processing was defined as 0 W ultrasound. Fig. 1 illustrates the apparatus of ultrasonic casting.
Figure 1. Schematic diagram of the apparatus of ultrasonic casting.

Table 1. Compositions of 35CrMo steel (wt. %)

|   | C   | Si  | Mn  | Cr  | Mo  | Ni  | P  | Fe |
|---|-----|-----|-----|-----|-----|-----|----|----|
|   | 0.32| 0.25| 0.45| 0.85| 0.19| 0.025| 0.025| Bal. |

After cooling, specimens were sampled from the same position of two ingots with and without ultrasonic processing. The sampling position was shown in Fig. 2 (a). They were ground, polished and then corroded. The macrostructures of the samples were observed by a metallurgical microscope (OLYMPUS DSX500) and scanning electron microscope (SEM). The tensile test was carried out by using a MTS 810 Universal Testing Machine with a crosshead speed of 0.05 mm/s. The dimensions of tensile specimen were shown in Fig. 2 (b).

Figure 2. Diagrammatic sketch of samples: (a) sampling position at the longitudinal-section of 35CrMo ingot, (b) the size of tensile samples (in mm).
3. Numerical simulations

3.1. Geometry model for numerical simulation
The numerical simulation of 35CrMo steel melt was based on Fluent. In order to reduce the computational complexity, the three-dimensional axial symmetric model was simplified to two-dimensional model to simulate. Fig. 3 shows the geometry model which was used in CFD calculation. The radiator of $\varnothing 50$ mm is inserted into the fluid vertically with 50 mm depth in the container of $\varnothing 200 \times 300$ mm. The ultrasound with power 400 W and frequency 21 kHz was introduced into the fluid along the direction of gravity.

3.2. Solution of the geometry model
In order to facilitate the calculation, the following hypotheses were put forward in this paper [17]:
① the flow of molten steel was stable, viscous and incompressible; ② the heating effect of ultrasound on molten steel was neglected; ③ the natural convection caused by density variation was neglected; ④ the oxidation reaction doesn’t occur during the ultrasonic processing on molten steel.

Because turbulence flow maybe form during ultrasonic treatment, the governing equations totally include 4 sets of equations. The continuous equation is showed in Eq. (1); N–S equation is showed in Eq. (2) and Eq. (3); turbulence equation is showed in Eq. (4) and Eq. (5); turbulence dissipation equation is showed in Eq. (6).

\[
\frac{\partial u_i}{\partial x_j} = 0 \quad (1)
\]

\[
\rho \frac{\partial (u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_j}\left(\mu_{eff} \frac{\partial u_i}{\partial x_j}\right) + \frac{\partial}{\partial x_j}\left(\nu_{eff} \frac{\partial u_j}{\partial x_i}\right) + \rho g_i \quad (2)
\]

\[
\mu_{eff} = \mu + \mu_t = \mu + \rho \frac{k^2}{\varepsilon} \quad (3)
\]
\[ \rho \frac{\partial (u_i k)}{\partial x_i} = \frac{\partial}{\partial x_i} \left[ \left( \mu + \frac{\mu}{\sigma_k} \right) \frac{\partial k}{\partial x_i} \right] + G - \rho \varepsilon \quad (4) \]

\[ G = u_i \frac{\partial u_i}{\partial x_j} \left( \frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j} \right) \quad (5) \]

\[ \rho \frac{\partial (u_i \varepsilon)}{\partial x_i} = \frac{\partial}{\partial x_i} \left[ \left( \mu + \frac{\mu}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_i} \right] + c_1 \frac{\varepsilon}{k} G - c_2 \frac{\varepsilon^2}{k} \rho \quad (6) \]

In the above equations, \( \rho \) is fluid density, \( u \) is the velocity, \( \mu \) is laminar viscosity coefficient, \( \mu_t \) is turbulent viscous coefficient, \( k \) is the turbulence energy, \( g \) is acceleration of gravity, \( \varepsilon \) is the turbulence energy dissipation rate while \( c_1, c_2, \sigma_k, \sigma_\varepsilon \) are empirical constants whose value are 1.44, 1.92, 0.09, 1.0 and 1.3.

The simulation condition is set as transient, and the detail settings of boundary conditions are shown as below:

Pressure inlet: The line representing radiator tip is set as the pressure-inlet boundary, which introducing ultrasound into the fluid. The assumption is established that the inlet pressure is a Gaussian distribution along the radial of the radiator tip. Meanwhile, it is a sine function over time, with the same frequency as the radiator. The inlet-pressure was generated by the reference of User-Defined Functions (ANSYS, Inc., US). The acoustic pressure expression is shown as below:

\[ P = \frac{P_0}{\sqrt{2\pi\sigma_0^2}} e^{\frac{-y^2}{2\sigma_0^2}} \sin 2\pi f t \quad (7) \]

In the Eq. (7), \( P_0 \) can be considered as a constant while \( \sigma_0 \) is the standard deviation of Gaussian distribution, which is greater than one-third of the radius of radiator tip, that is to say the pressure at the edge of radiator tip is almost zero, \( f \) is the ultrasonic frequency of 21 kHz. The largest value of \( P \) is 825 kPa, determined by the calculation with dynamic mesh model. In this work, \( \sigma_0 \) is set as 5.0×10⁻³ m. Therefore, the constant \( P_0 \) is deduced to be 8 kPa m.

Pressure outlet: In this case, the pressure outlet boundary is considered to be one atmosphere (0.1013 MPa).

Wall boundary: The rest of boundaries are set as wall boundary, and the thermal transmission on two sides of the wall boundary is neglected. Table 2 shows the boundary setting for calculation, including the length, boundary condition and boundary type of each boundary line.

| Boundary line | Length/mm | Boundary conditions | Boundary type |
|---------------|-----------|---------------------|--------------|
| fa            | 250       | Axis                | Symmetry     |
| ef            | 100       | Wall 1              | Wall         |
| de            | 300       | Wall 2              | Wall         |
| cd            | 75        | Outlet 1            | Pressure-outlet |
| bc            | 50        | Deform 1            | Wall         |
| ab            | 25        | Inlet               | Pressure-inlet |
4. Results and discussion

4.1. Effect of ultrasound on pressure field and velocity field in steel melt

![Figure 4](image)

Figure 4. Calculated results: (a) acoustic pressure distribution, (b) melt velocity distribution.

Fig. 4 shows the calculated results of acoustic pressure distribution and the melt velocity field of steel melt. Fig. 4(a) presents the acoustic pressure amplitude distribution when the ultrasonic power is 400 W. It can be concluded that the sound pressure amplitude away from the radiator region is relatively small, even close to zero. Fig. 4(b) illustrates the melt velocity distribution. As observed, the molten steel is driven by the volumetric force at high velocity along the axis of radiator. The ultrasound plays an agitation role in the steel melt.

4.2. Effect of ultrasound on porosity of the ingot

Fig. 5 presents the porosity photographs of longitudinal sections of ingots with and without ultrasonic treatment. It can be seen that the porosity of the 35CrMo steel with 400 W UST is lower than that of specimens with 0 W UST, and that the trapped cavities are smaller. Furthermore, the porosity of specimens increases with the distance from sampling point to radiator increase. Later in this article, the character d will represent the distance from sampling point to radiator for convenience.

As shown in Fig. 6, the porosity percentage of the samples at the longitudinal position with and without ultrasonic treatment is obtained. The percentage of porosity with ultrasonic treatment can be reduced to some extent. The porosity percentage of the samples decrease at different distances from radiator tip. The porosity percentage of sample taken from conventional direct castings is 10.38% (d=30 mm), and 4.35% (d=120 mm). The porosity percentage of sample taken from 400 W ultrasonic castings is 4.57% (d=30 mm), and 4.15% (d=120 mm). The degree of porosity reduction near the radiator face is greater than that of far away from the radiator face. It can be concluded that the ultrasonic intensity decreases as the increase of d.
Figure 5. Porosity in longitudinal sections of specimens: (A) with 0 W UST, (B) with 400 W UST.

Figure 6. Porosity percentage of samples at different distances from the radiator with and without UST.

Fig. 7 demonstrate the tensile-testing results of 35CrMo steel ingot by direct casting and ultrasonic casting. The results reveal that the application of ultrasonic processing has greatly improved the mechanical properties of ingot. It shows that the tensile strength and percentage elongation of the steel castings are enhanced from 634 MPa and 1.7% to 657 MPa and 4.06% (d=30 mm), 636 MPa and 2.24% to 652 MPa and 3.35% (d=60 mm), 638 MPa and 2.3% to 645 MPa and 3.36% (d=90 mm), respectively. However, they are only a little improved at 120 mm distance from the radiator. Previous studies have reported that the porosity has a considerable effect on the mechanical properties of the casting ingots.
From Fig. 6 and 7, it can be concluded that the improvement of mechanical properties of 35CrMo steel ingot was closely related to porosity reduction.

![Figure 7. Mechanical properties of the ingot cast by DC and UC (400 W):](image)

(a) tensile strength, (b) elongation.

4.3. Mechanism of the effect of ultrasound on porosity reduction

In the solidification process of molten steel, many small shrinkage cavities are formed due to the thermal expansion and contraction of the material, and the liquid metal failed to replenish in time, resulting in the porosity defects.

Previous studies have shown that ultrasonic processing could effectively remove the gas in liquid metal. The ultrasonic cavitation effect produces a large number of cavitation bubble. The growth process of cavitation bubble is a continuous pulsating diffusion process of expansion and contraction. The cavitation bubble grow up and float to the molten steel surface during the ultrasonic processing. The gas content in the melt decreased significantly, and the outside liquid metal is easier to penetrate into the cavity, thus inhibiting the formation of porosity.

Looking from other side, in the later stage of solidification, the mutual contact of the dendrites generated earlier divide the liquid steel into a plurality of small closed regions, which will result of the formation of the porosity. The grain refinement can significantly reduce the development of dendrite, which is beneficial to the feeding. Moreover, the long dendrite will be broken into pieces by ultrasonic treatment. Consequently, the casting will become denser and the porosity is reduced.

Combined with results of numerical simulation and experiment, the ultrasound tends to attenuate when propagating in the molten steel. As ultrasound power increases, the porosity of ingot reduces strikingly. This leads to the phenomenon that the porosity at the central area of ingot reduced more apparent than that at the edge area.

5. Conclusion

Using a novel ultrasonic import method to treat solidification process of 35CrMo steel sand-cast, the results showed that ultrasonic treatment can reduce the porosity defects of ingot casting. Due to the attenuation characteristic of ultrasound when propagating in the melt, this leads to different porosity reducing levels at different positions of the ingot casting. The porosity reduced more apparent in the center area of the ingot. As the ultrasonic power increases, the porosity of ingot is strikingly reduced. This research will provide a reference for the application of ultrasonic processing in the high temperature alloy steel, and promote the industrial applications of ultrasonic processing.

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