Research on vacuum-electromagnetic casting of IN100 superalloy ingots

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Abstract

In order to improve the inner quality of superalloy master alloy ingots, the new technology of superalloy vacuum-electromagnetic casting, i.e. applying electromagnetic stirring (EMS) to the solidification process of superalloy vacuum casting was developed. The effect of EMS on the inner quality of IN100 superalloy ingots was studied with EPMA and optical microscope. The results show that while an EMS with 50 Hz frequency and 60 A current is imposed, the equiax crystals of IN100 superalloy ingots can be effectively refined and increased, and the central shrinkage porosity and the dendritic segregation of IN100 superalloy ingots are greatly reduced, so the inner quality of IN100 superalloy ingots is obviously improved.

Keywords: Vacuum-electromagnetic casting; Electromagnetic stirring; Superalloy; Ingots

1. Introduction

Commonly, the composition of a casting superalloy is composed of many kinds of alloying elements. Because there are many active elements in the composition of casting superalloys and the impurity content is strictly controlled, the superalloy casting is usually manufactured by two-ply vacuum casting, i.e. the raw materials are melted and cast into a master alloy ingot in a vacuum induction furnace, then the master alloy ingot is re-melted and casted into foundry goods in a vacuum induction furnace [1]. However, the master alloy ingot made by vacuum casting (VC) usually have quality problems of coarse grain, more shrinkage porosity, and more serious segregation, which reduces the percent of pass of superalloy casting.

It has been demonstrated that electromagnetic stirring (EMS) has advantages of refining the internal structures of the ingot, reducing the segregation and shrinkage cavity, and minimizing internal cracks [2,3]. EMS has been applied to continuous casting of aluminum alloys, copper alloys and steel [4–7]. In the present study, in order to improve the inner quality of superalloy master alloy ingots, the new technology of superalloy vacuum-electromagnetic casting (V-EMC), i.e. imposing EMS to the solidification process of superalloy vacuum casting was developed, and the effect of EMS on the inner quality of superalloy ingots was studied.

2. Experimental

2.1. Experimental apparatus and principle

The main experimental apparatus consists of a VIM-10 modified vacuum-induction furnace, a set of ingot mold and a rotating electromagnetic stirrer with one pole pair and three-phase alternating currents, as shown in Fig. 1. The ingot made of austenitic steel is located in the electromagnetic stirrer, and the ingot height is 250 mm and the interior and outer diameter is 80 and 100 mm, respectively.

After inputting three-phase alternating current, the electromagnetic stirrer produces a rotating magnetic field and the liquid metal in the rotating magnetic field induces eddy currents which travel in the direction perpendicular to the magnetic field. The interaction between the external magnetic field and the eddy currents will produce an electromagnetic force whose action is perpendicular to...
both the magnetic field and induced currents. This force, or more precisely its tangential component, will drive the liquid metal in the rotation direction of the magnetic field. Electromagnetic-stirring intensity can be controlled through adjusting the value of the alternating current inputted into EMS.

2.2. Experimental procedure

The superalloy used in this study is IN100 alloy having the following composition (wt%): 0.15C, 8.7Cr, 14.5Co, 2.8Mo, 5.2Al, 4.6Ti, 0.83V, 0.6Fe and rest Ni.

Samples were prepared in a VIM-10 modified vacuum-induction furnace. Approximately 7 kg charges were melted and superheated to 1823 K for 10 min. Then the melt was cooled down to 1723 K and subsequently poured into an austenitic-steel mold. After waiting for 10 s, the EMS with 50 Hz frequency and 60 A current was imposed. Some ingots were also cast under conditions of no EMS. In all case, the vacuum during melt treatment was $6 \times 10^{-2}$ Pa.

The specimens for macrostructure examination cut from the casting ingots were chemically etched with 50 ml HCl + 15 g CuSO$_4$ + 3.5 ml H$_2$SO$_4$. The grain size and equi-axed fraction were estimated according to the ASTM standard [8]. An EPMA-1600 electron probe microanalysis was used to determine the dendritic segregation ratio of main elements.

3. Results and discussion

3.1. Macrostructure

Fig. 2 shows the macrostructure of superalloy ingots transverse section. In the absence of electromagnetic field, the solidification structure of ingots consists of three types of crystals, i.e. proceeding from the ingot surface toward the ingot center: (1) a very thin zone at the ingot surface; (2) a zone of coarse columnar crystals; (3) a zone of coarse equi-axed crystals in the center portion. While in the presence of electromagnetic field, it is found that the solidification structures of ingots is remarkably refined. Particularly, the equi-axed grain average size is reduced from 2.8 to 0.78 mm, and the ratio of equi-axed grain is increased from 67% to 75%.

This result may be explained as follows: the forced convection generated by the EMS can cause that the dendritic arms at the solidification front are broken and subsequently dispersed in the whole melt pool, which create more effective crystal nucleus. Furthermore, the forced convection in the melt pool can also accelerate the uniform of the bath composition and temperature. Those factors favor the formation of equi-axed crystals [9]. As a result, the equi-axed grains are refined and the ratio of equi-axed grains is increased.

3.2. Central shrinkage cavity and porosity

The central shrinkage cavity and porosity of ingots is a kind of metallurgic defects, and the quality of ingots can be improved by reducing the central shrinkage cavity and porosity. Fig. 3 shows the solidification structure of IN100 superalloy ingots. In the absence of electromagnetic field, the length of central shrinkage cavity and porosity is 87 mm, while in the presence of electromagnetic field, the length of central shrinkage cavity and porosity is 54 mm. It
should be noted that the central porosity and cavity are greatly reduced and shifted up by imposing EMS to the solidification process of superalloy vacuum casting, so the quality of IN100 superalloy ingots is obviously improved.

In the solidification process of superalloy vacuum casting, the feeding power is composed of surface tension, pressure and gravity force, and the feeding resisting force is the viscosity resistance. Based on the theory of metal solidifying and fluid mechanics, the mathematical model describing the feeding capacity of superalloy vacuum casting can be expressed as [10]:

\[
\frac{u}{D} = \frac{d^2G}{32\mu\Delta T\eta} \left\{ \frac{G}{\Delta T\eta} \left[ \frac{4\sigma}{\delta} + P_0 - P' + \gamma h\right] + \gamma \right\}
\]

(1)

where \( u \) is the feeding velocity of liquid metal, \( D \) the average diameter of the grains, \( d \) the diameter of the intercrystal porosity, \( G \) the temperature gradient of the solid–liquid zone, \( \mu \) the kinematic viscosity of liquid metal, \( \Delta T \) the crystallizing-point range, \( \psi \) the coefficient, and \( \eta \) the ratio of the feeding pathway length to the solid–liquid zone thickness, \( \sigma \) the surface tension of liquid metal, \( P_0 \) the atmospheric pressure, \( P' \) the vacuum, \( h \) the feeding head height, and \( \gamma \) the gravity of liquid metal.

From Eq. (1), it can be seen that the far smaller external pressure \( P_0 - P' \) leads to that feeding capacity of liquid metal is rather lower, so there are more central shrinkage cavity and porosity in the superalloy ingots made by vacuum casting.

When imposing reasonable EMS to the solidification process of superalloy vacuum casting, the feeding power should be composed of surface tension, pressure, gravity force and electromagnetic force, and the feeding resisting force is the viscosity resistance. Then the mathematical model describing the feeding capacity of superalloy vacuum-electromagnetic casting can be expressed as

\[
\frac{u}{D} = \frac{d^2G}{32\mu\Delta T\eta} \left\{ \frac{G}{\Delta T\eta} \left[ \frac{4\sigma}{\delta} + P_0 - P' + \gamma h\right] + \gamma + \rho R \omega^2\right\}
\]

(2)

where \( \rho \) is the density of liquid metal, \( R \) the bath radius, and \( \omega \) the rotational velocity of liquid metal.

Assuming \( n \) is the ratio of the feeding capacity in superalloy vacuum-electromagnetic casting to the feeding capacity in superalloy vacuum casting, \( n \) can be expressed as

\[
n = \frac{G/\Delta T\eta(4\sigma/d + P_0 - P' + \gamma h) + \gamma + \rho R \omega^2}{G/\Delta T\eta(4\sigma/d + P_0 - P' + \gamma h) + \gamma}.
\]

(3)

In the case that an EMS with 50 Hz frequency and 60 A current is imposed, the parameters used in the feeding capacity calculations of IN100 superalloy are listed in Table 1. The value of \( n \) was 4.8 when the parameters listed in Table 1 were applied to Eq. (3). This result indicates that the feeding power of liquid metal is increased by imposing EMS, so the feeding capacity of superalloy vacuum casting is largely increased. Furthermore, because the grain is increased and refined by imposing EMS, the flow resisting force of liquid metal is reduced, which also favors the increasing of the feeding capacity in superalloy vacuum casting. As a result, the liquid metal can pass successfully the liquid–solid area, so that the central shrinkage cavity and porosity formed in the prophase of solidification process can be fed effectively.

3.3. Dendritic segregation

The degree of dendritic segregation can be described by the dendritic segregation ratio \( S_R \). The less the deviant between \( S_R \) and 1 is, the lighter the degree of dendritic segregation is. The \( S_R \) can be expressed as [11]

\[
S_R = \frac{C_{\text{max}}}{C_{\text{min}}}
\]

(4)

where \( C_{\text{max}} \) is the element maximum concentration in solidification structure and \( C_{\text{min}} \) the element minimum concentration in solidification structure.

The \( S_R \) measured by EPMA is shown in Fig. 4. In the absence of electromagnetic field, there is severe dendritic segregation in IN100 superalloy ingots, therein, the severity subsequence of normal segregation is Ti, Mo, Cr, and the negative segregation element is Co. While in the presence of electromagnetic field, although Mo and Ti are also normal

| Parameter \( \gamma \) \( (N/m^2) \) | \( \rho \) \( (kg/m^3) \) | \( \Delta T \) \( (^\circ C) \) | \( \sigma \) \( (N/m) \) | \( G \) \( (C/m) \) | \( \eta \) |
|---|---|---|---|---|---|
| Value | 8.16 \times 10^4 | 8.16 \times 10^3 | 85 | 1030 \times 10^{-3} | 200 | 10 |

| Parameter \( d \) \( (m) \) | \( h \) \( (m) \) | \( R \) \( (m) \) | \( \omega \) \( (rad/s) \) | \( P \) \( Pa \) |
|---|---|---|---|---|
| Value | 1 \times 10^{-3} | 0.15 | 3 \times 10^{-2} | 39 | 6 \times 10^{-2} |

Table 1. Parameters used in the feeding-capacity calculation of IN100 superalloy V-EMC.
Segregation element, the every element deviant between \( S_R \) and 1 has become smaller. Thus, it can be seen that the dendritic segregation of superalloy ingots is greatly reduced by EMS.

Because the dendritic segregation usually generates in the solidification process, it can be found that the reasons that the dendritic segregation of superalloy ingots is greatly reduced though analyzing the effects of the EMS on the solidification process. In the absence of electromagnetic field, with generating and growing of primary phase during superalloy solidification process, there are the enrichment of normal segregation element and poverty of negative segregation element at the solidification front. While in the presence of electromagnetic field, the forced convection generated by the EMS largely reduces the solute-enrichment degree at the solidification front and accelerates the uniformity of the bath composition, which limits generating the dendritic segregation. Furthermore, the equi-axed grain is remarkably refined and increased by the forced convection generated by the EMS, which also favors lightening the dendritic segregation.

### 4. Conclusions

The results of these IN100 superalloy V-EMC and conventional VC experiments lead to the following conclusions:

1. Through imposing electromagnetic stirring to the solidification process of superalloy vacuum casting, the equi-axed crystals in the superalloy ingots can be effectively refined and increased, and the central shrinkage porosity and the dendritic segregation of superalloy ingots are greatly reduced. The inner quality of superalloy ingots is obviously improved.
2. The feeding capacity of superalloy liquid metal can be increased by imposing EMS to the solidification process of superalloy vacuum casting, which leads to that the central pipe and shrinkage porosity of superalloy ingots are obviously improved.
3. In the superalloy ingots made by vacuum casting, there is severe dendritic segregation, thereinto, the severity subsequence of normal segregation is Ti, Mo, Cr, and the negative segregation element is Co. while in the superalloy ingots made by vacuum-electromagnetic casting, because the EMS can refine and increase the equi-axed grain and accelerate the uniformity of the bath composition, the dendritic segregation of superalloy ingots is largely relieved.

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