Density and solidification feeding model of vacuum counter-pressure cast aluminum alloy under grade-pressuring conditions

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Abstract: The density of vacuum counter-pressure cast aluminum alloy samples under grade-pressuring condition was studied. The effect of grade pressure difference and time on the density of aluminum alloys was discussed, and the solidification feeding model under grade-pressuring condition was established. The results indicate the grade-pressured solidification feeding ability of vacuum counter-pressure casting mainly depends on grade pressure difference and time. With the increase of grade pressure difference, the density of all the aluminum alloy samples increases, and the trend of change in density from the pouring gate to the top location is first decreasing gradually and then increasing. In addition, in obtaining the maximum density, the optimal grade-pressuring time is different for samples with different wall thicknesses, and the solidification time when the solid volume fraction of aluminum alloy reaches about 0.65 appears to be the optimal beginning time for grade-pressuring.

Key words: vacuum counter-pressure casting; grade-pressuring; density; solidification feeding

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Vacuum counter-pressure casting technology is a kind of advanced counter-gravity precision forming method, and its principle is vacuum filling mould under low pressure and crystallizing under high pressure, and meanwhile, the filling pressure difference and solidification pressure can be controlled. Accordingly, it has predominant filling hydrodynamics and solidification mechanics, which is the most feasible method of producing large scale, thin wall, complex and high-quality castings^[1-3]. However, the constant pressure difference is adopted in the solidification stage for conventional vacuum counter-pressure casting^[4-6]. But, with the development of solidification process under constant pressure difference, the solidification feeding channel of molten metal gradually reduces and solidification feeding resistance increases. Therefore, the constant solidification pressure difference is disadvantageous to effective feeding in the final stage of solidification, especially for large scale, complex and variable section castings. If the feeding pressure is

not increased promptly, the molten metal cannot feed timely and effectively for different wall thicknesses of castings, leading to potential formation of defects such as shrinkage cavity and porosity in the thicker sections of the castings.

Since the 1980s, the constant pressuring solidification process of counter-pressure casting had been investigated in China and abroad^[7-11]. It was considered that the solidification pressure could promote the liquid alloy flow toward feeding area through narrow channels among the solidified dendrites, resulting in the good feeding effect, fine grains and dense microstructures. Meanwhile, the solidification feeding models under constant pressure were established, and their solidification feeding characteristics and mechanisms were obtained. In 2009, Yu^[12] et al. proposed the grade-pressuring solidification process of vacuum counter-pressure casting, namely, at the stage of pressure holding, the solidification pressure difference was changed with solidification feeding course of different size, shape, wall thickness of castings, and two or more grade-pressuring actions were carried out, which further improved the solidification pressure for timely and effective feeding, leading to improved density of the castings. Xiong^[13] et al. investigated the effects of melt temperature on the density, microstructures and mechanical properties of vacuum counter-pressure cast

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A357 alloys under grade-pressurizing condition, and considered that the density and mechanical properties of the samples cast under grade-pressuring were affected by the melt temperature. The optimal density and mechanical properties were achieved at the melt temperature of 590 °C. The microstructures varied with the melt temperature as a result of the differences in the strengths of the feeding flow and dendrites. The powerful feeding flow caused by grade-pressurized solidification can induce stress on the dendrites, resulting in the collapse of the primary dendrite network to form equiaxed dendrites. Through further study on the effect of grade-pressuring process on the density of aluminum alloys, a grade-pressuring solidification feeding model is established to provide theoretical guidance for vacuum counter-pressure casting high-quality, large scale and complex aluminum parts with variable sections.

1 Experimental procedure

The grade-pressuring experiment was carried out with self-made VCPC type vacuum counter-pressure casting equipment. When the time of solidification holding pressure reached t_1 , the solidification pressure difference increased by ΔP_2 based on primary solidification pressure difference ΔP_1 , and the grade-pressuring began. The releasing pressure was performed until the grade-pressuring time reached t_2 . The grade-pressuring process graph of vacuum counter-pressure casting is shown in Fig. 1.

In the present experiment, plate samples with a width of 60 mm, a length of 150 mm and different wall thicknesses of 6 mm, 9 mm and 12 mm were used. The sand mould and aluminum alloy ZL205A were adopted, and the pouring temperature was set at about 720 °C. The grade-pressuring parameters of vacuum counter-pressure casting are shown in Table 1. Aluminum alloy plate samples obtained under grade-pressuring condition were cut into seven segments from the pouring gate to the top, respectively. The mould and cutting locations of the plate sample are shown in Fig. 2. Meanwhile, the density of each sample measured by the drainage method was compared with the theoretic density of ZL205A at 2.82 g·cm⁻³.

Fig. 1: Grade-pressuring process graph of vacuum counter-pressure casting

Fig. 2: (a) sample and mould; (b) sample cutting locations

2 Results and discussion

3.1 Effect of grade-pressure difference on the density of aluminum alloy

Under different grade-pressure differences, the density of samples at different locations is shown in Fig. 3.

Table 1: Grade-pressuring parameters of vacuum counter-pressure casting

No.	Vacuum degree (KPa)	Primary pressuring			Grade pressuring		
		ΔP_1 (KPa)	t_1 (s)	P_1 (KPa)	ΔP_2 (KPa)	t_2 (s)	P_k (KPa)
1	20	35	20	250	25	230	275
2	20	35	20	250	50	230	300
3	20	35	20	250	75	230	325
4	20	35	20	250	100	230	350
5	20	35	5	250	100	245	350
6	20	35	10	250	100	240	350
7	20	35	20	250	100	230	350
8	20	35	30	250	100	220	350
9	20	35	40	250	100	210	350

Fig. 3: Density of aluminum alloy samples at different locations under different grade-pressure differences: (a) 6 mm (sample thickness); (b) 9 mm; (c) 12 mm

It can be seen from Fig. 3 that the density of all the vacuum counter-pressure cast aluminum alloy samples increases with the increase of the grade-pressure difference. Under the same grade-pressure difference, the changing trend of the density from the pouring gate location to the top location is first decreasing gradually and then increasing. Therefore, higher grade-pressure difference should be used as much as possible in order to obtain dense and uniform microstructure.

3.2 Effect of grade-pressuring time on the density of aluminum alloy samples

Under different grade-pressuring times, the changing trend of the density of vacuum counter-pressure cast ZL205A aluminum

alloy samples with different wall thicknesses of 6 mm, 9 mm and 12 mm are shown in Fig. 4.

As seen from Fig. 4, the density of vacuum counter-pressure cast aluminum alloy samples was affected significantly by the grade-pressuring time. For the samples with different wall thicknesses, the grade-pressuring duration for obtaining maximum density was different. The optimal grade-pressuring durations for samples with 6 mm, 9 mm and 12 mm wall thickness were 240, 230 and 220 s, respectively.

Fig. 4: Changing trend of density of aluminum alloy samples under different grade-pressuring times: (a) 6 mm (sample thickness); (b) 9 mm; (c) 12 mm

3.3 Grade-pressuring solidification feeding model of vacuum counter-pressure casting

The solidification process of vacuum counter-pressure casting is directional solidification from the top to the bottom. In the initial stage of solidification, the solid skeleton of primary dendrite is connected, but the channels among dendrites can be interconnected into one, so the feeding channel can be simplified as gap-type channel. With the further development of the solidification process, the channels among dendrites are gradually closed by the newly grown dendrites, which form the closed area of isolated liquid. It is necessary to feed by greater solidification pressure difference. Through increasing the solidification pressure difference to carry out grade-pressuring, the newly grown dendrites will be broken or plastically deformed by the scouring force of feeding flow, and isolated liquid area will be re-connected to form similar pore channels, so the feeding channel can be simplified as the capillary channel of porous medium. The schematic of grade-pressuring solidification feeding of vacuum counter-pressure casting is shown in Fig. 5.

Fig. 5: Schematic of grade-pressuring solidification feeding of vacuum counter-pressure casting

During grade-pressuring solidification feeding of vacuum counter-pressure casting, its feeding channel is generally the capillary channel of porous medium, and liquid flow among dendrites complies with Darcy's law. Accordingly, the flow velocity of molten metal at a certain location among dendrites can be expressed as^[14]:

$$v_x = \frac{K}{\mu f_L} \Delta P \quad (1)$$

where v_x is the flow velocity of molten metal at the location X among dendrites, K is the infiltration coefficient, μ is the dynamical viscosity coefficient, f_L is the liquid volume fraction, and ΔP is the pressure difference.

Moreover, K and f_L are both position function, and the relationship between them is:

$$K = \gamma f_L^2 \quad (2)$$

where γ is the coefficient related to dendrite structure and dendrite arm spacing.

When the dendrite structure is same, γ is inversely proportional to the square of secondary dendrite arm spacing^[15], and it can be expressed as:

$$\gamma = C_1 \left(\frac{1}{\lambda_2} \right)^2 \quad (3)$$

where C_1 is the coefficient and λ_2 is the secondary dendrite arm spacing.

According to the research results obtained by Flemings et al^[16-17], the secondary dendrite arm spacing is proportional to local solidification time, and it can be expressed as:

$$\lambda_2 = C_2 t^{\frac{1}{3}} \quad (4)$$

where C_2 is the coefficient and t is the local solidification time.

The following Eq.5 can be obtained by substituting Eq.2, Eq.3 and Eq.4 into Eq.1.

$$v_x = \frac{C_1 f_L}{\mu C_2^2 t^{\frac{2}{3}}} \Delta P \quad (5)$$

During the solidification feeding process of vacuum counter-pressure casting, the pressure loss of molten metal at X location among dendrites can be expressed as^[18]:

$$\Sigma P = P_K - P_X = \frac{8 v_x \mu X}{\delta^2} \quad (6)$$

$$P_X = P_K - \frac{8 v_x \mu X}{\delta^2} \quad (7)$$

where P_X is the feeding pressure at the location X among dendrites, P_K is the solidification pressure, and δ is the size of feeding channel.

In the grade-pressuring solidification process of vacuum counter-pressure casting, P_K and ΔP can be expressed as respectively:

$$P_K = P_1 + \Delta P_2 \quad (8)$$

$$\Delta P = \Delta P_1 + \Delta P_2 \quad (9)$$

where P_1 is the primary solidification pressure, ΔP_1 is the pressure difference of primary pressuring, ΔP_2 is the grade-pressure difference.

The feeding pressure at X location among dendrites can be obtained by substituting Eq.5, Eq.8 and Eq.9 into Eq.7.

$$P_X = P_1 - \frac{8 C_1 f_L X}{C_2^2 \delta^2 t^{\frac{2}{3}}} \Delta P_1 + \left(1 - \frac{8 C_1 f_L X}{C_2^2 \delta^2 t^{\frac{2}{3}}} \right) \Delta P_2 \quad (10)$$

The solidification pressure of vacuum counter-pressure casting promotes the molten metal flow toward feeding area through narrow dendrite channels, which is named as extrusion and infiltration effect. The size of extrusion and infiltration effect can explain solidification feeding effect, which reflects the ability to eliminate shrinkage cavity and porosity. Moreover, the extrusion and infiltration ability can be evaluated by the total flow of molten metal passing through narrow channels among dendrites to solidification feeding area, and it may be calculated by Eq.11^[6, 11].

$$\Delta G = \frac{k(P_E + \frac{2\sigma}{r} - P_s - P_g)}{\mu\Delta L} F \cdot \Delta\tau \quad (11)$$

where ΔG is the metal capacity of extrusion and infiltration in shrinkage cavity, P_E is the pressure arousing extrusion and infiltration, P_s is the static pressure of molten metal, P_g is the pressure of separating out gas among dendrites, σ is surface tension of molten metal, L is depth of extrusion and infiltration, F is area of extrusion and infiltration, $\Delta\tau$ is time of extrusion and infiltration, and k is infiltration ratio.

The extrusion and infiltration ability of grade-pressuring solidification feeding of vacuum counter-pressure casting at X location can be obtained by substituting Eq.10 into Eq.11.

$$\Delta G = \frac{k[P_1 - \frac{8C_1f_LX}{C_2^2\delta^2t^3}\Delta P_1 + (1 - \frac{8C_1f_LX}{C_2^2\delta^2t^3})\Delta P_2 + \frac{2\sigma}{r} - P_s - P_g]}{\mu\Delta L} F \cdot \Delta\tau \quad (12)$$

It can be seen from Eq.12 that the extrusion and infiltration ability of grade-pressuring solidification feeding is mainly related to the primary solidification pressure, pressure difference of primary-pressuring, grade-pressure difference, static pressure of molten metal, pressure of separating out gas among dendrites, capillary pressure caused by surface tension, solidification time, liquid volume fraction, and size of feeding channel. Meanwhile, the grade-pressuring time has a great relationship with solidification time and liquid volume fraction. Therefore, when the primary-pressuring parameters and other parameters such as capillary pressure, static pressure, pressure of separating out gas among dendrites, and so on are same, its extrusion and infiltration ability at X location among dendrites mainly depends on the pressure difference and time of grade-pressuring.

In general, the bigger the grade-pressure difference, the greater the solidification feeding pressure among dendrites, and the stronger the extrusion and infiltration ability, so the molten metal can flow more smoothly toward feeding area through the narrow channels of the solidified dendrites, leading to improved feeding ability. Furthermore, even if the dendrites form continuous skeleton and isolated liquid area during extrusion and infiltration process, they will be plastically deformed, even rushed and broken by the molten metal flow when their strength is lower than the feeding pressure caused by grade-pressuring, resulting in the increase of dissociated grains, the refinement of

grains and the density increasing of microstructure^[6, 19]. On the other hand, the grade-pressuring time is determined by the solidification time and liquid volume fraction. Previous research^[13] showed that the melt is at the stage of gap-type feeding when the solid volume fraction of aluminum alloy is less than 0.65, and the capillary feeding stage began when the solid volume fraction of the aluminum alloy reaches about 0.65. At the gap-type feeding stage, the feeding pressure loss among dendrites is smaller, therefore, the primary solidification pressure can be satisfied with the feeding requirement. But at the capillary feeding stage, the feeding pressure among dendrites is decreased rapidly with the increase of solidification time, which results in the extrusion and infiltration effect and feeding capacity to reduce sharply. Therefore, the optimal beginning time of grade-pressuring is the solidification time when the solid volume fraction of aluminum alloy reaches about 0.65, that is to say, the liquid volume fraction is about 0.35, which can exert the ability of grade-pressuring solidification feeding of vacuum counter-pressure casting and obtain the optimal feeding effect.

3 Conclusions

- (1) With the increase of the pressure difference in grade-pressuring, the density of all the aluminum alloy samples increases. Meanwhile, the density of the samples first decreases gradually and then increases from the pouring gate to the top location.
- (2) In obtaining maximum density, the optimal grade-pressuring time is different for samples with different wall thicknesses, and the solidification time when the solid volume fraction of aluminum alloy reaches about 0.65 is the optimal beginning time of grade-pressuring.
- (3) The grade-pressuring solidification feeding model of vacuum counter-pressure casting is established, and its extrusion and infiltration ability at X location among dendrites is obtained, which indicates the grade-pressuring solidification feeding ability mainly depends on pressure difference and time of grade-pressuring.

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