Effect of vibration on seepage feeding during low-pressure casting of ZL205A alloy

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Abstract: Appropriate vibration can promote the feeding capacity of gravity casting, but the effect of vibration on the feeding of low-pressure casting is not clear. The effect of vibration on the seepage feeding of ZL205A alloy was investigated by vibration casting experiment and physical simulation. The aqueous solution of sodium carboxymethyl cellulose (CMC) with the same rheological characteristic of metal melt was used. The results show that vibration can improve the feeding capacity and reduce shrinkage defects of ZL205A alloy in low-pressure casting. The orthogonal physical simulation experiments indicate that vibration with low frequency and great exerted force can significantly improve the seepage velocity of non-Newtonian fluid with solid particles in porous medium. The seepage phenomenon in CMC solution shows that vibration can change the structure of accumulated particles at the seepage entrance, and thus open the blocked feeding channel. The numerical simulation of one-dimensional semisolid fluid seepage reveals that vibration can form a wave field in the porous medium, which can reduce the adhesion force between fluid and capillary wall and destroy the boundary layer of fluid, and thus promote the seepage velocity.

Key words: mechanical vibration; physical simulation; seepage; ZL205A alloy

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Shrinkage porosity is one of the typical and most common defects in castings, which can dramatically affect the properties of the casting. It is very difficult to eliminate shrinkage porosity through subsequent thermo-mechanical treatments^[1] or forging process^[2], especially in the near-net shape casting process. Research has been done to prolong the service life of castings by reducing the shrinkage porosity^[3-7]. It is found that shrinkage porosity in the casting is usually caused by obstruction of the feeding channel or insufficient feeding pressure of the alloy melt^[8-11]. Low-pressure casting is an effective way to improve the feeding capacity and eliminate shrinkage defects in castings^[12]. However, for the ZL205A alloy, which has been widely used in aviation, aerospace and military industries^[13, 14], there are still many shrinkage porosities even if produced by low-pressure die casting^[15]. Considerable studies indicate that vibration can improve the casting quality since Chernov first successfully refined grains of steel castings by gentle mould vibration^[16, 17]. Therefore, we creatively combine the vibration technology with low-pressure

casting technology to improve the feeding capacity of ZL205A alloy castings. Mould vibration^[16] is one of the most convenient methods to improve the casting quality by vibration. Thus, mould vibration is introduced into the low-pressure casting process to reduce shrinkage porosity. For the high temperature of molten metal and the opacity of low-pressure casting process, physical simulation experiments are applied to explore the effect of vibration on the seepage feeding during the low-pressure casting of ZL205A alloy.

1 Experimental procedure

1.1 Vibration low-pressure casting of ZL205A alloy

Vibration low-pressure casting is a new technology which combines the vibration process with low-pressure casting to improve feeding capacity. During the vibration low-pressure casting process, the metal melt fills the mould in low-pressure casting mode and then solidifies under vibration. As shown in Fig. 1, the vibration was transmitted to the mould through a #45 steel rod, and formed a point vibration source which can concentrate the energy in the narrow feeding channel. The size of the casting is shown in Fig. 2. The pouring temperature of the melt was 700 °C and the holding pressure was 0.1 MPa. The vibration

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Fig. 1: Principle of vibration low-pressure casting

Fig. 2: Size of ZL205A aluminum alloy casting

amplitude was 0.2 mm, and the vibration frequency was 25 Hz. The temperature at the start of vibration was 650 °C. For comparison, the castings without vibration were also prepared under the same conditions.

1.2 Physical simulation

In order to study the effect of vibration on molten metal, the transparent CMC aqueous solution with the same rheological characteristic of the melt [18, 19] was selected as the experimental material, and acrylonitrile butadiene styrene resin (ABS) particles with similar density of CMC aqueous solution were added as the solidified equiaxed grains. The movement of ABS particles can also indicate the flow pattern of fluid under vibration. As shown in Fig. 3, the closely connected steel balls with a diameter of 2 mm were used to simulate the equiaxed grains of ZL205A alloy, and a mesh screen was used to prevent the drop of steel balls. The CMC aqueous solution with concentration of 4.5% and the steel balls were all packed in a cavity with thickness of 10 mm. The front surface of the device was sealed with plexiglass, thus the fluid flow under vibration/non-vibration can be observed by digital industrial photogrammetry. Electromagnetic vibrators were set on both sides of the mould to vibrate the mould. The exerted force and frequency of vibration were regulated by an adjustable frequency converter. The fluid expelled from the top of the device under different processing parameters were weighed and converted into volume. The seepage velocity to estimate

the seepage capacity was calculated through the seepage volume divided by seepage sectional area and seepage time. The physical simulation experiments were performed at 18 °C. The orthogonal experimental scheme of three factors (holding pressure, frequency and exerted force) and three levels was designed, as shown in Table 1.

Fig. 3: Sectional diagram of physical simulation device

Table 1: Factors and levels of experiments

Levels	Factors		
	A Holding pressure (MPa)	B Frequency (Hz)	C Exerted force (N)
1	0.1	10	8
2	0.13	20	10
3	0.16	30	12

2 Results and discussion

2.1 Effect of vibration on feeding capacity

The castings were cut along the axis, and the area of shrinkage cavity in the castings was used to estimate the effect of vibration. As shown in Fig. 4, there is a large shrinkage cavity in the center of the casting solidified under non-vibration, while there is almost no shrinkage under vibration. Drainage method was used to measure the density of castings. The density of the casting without vibration is 2.7967 g·cm⁻³, lower than that of the casting with vibration at 2.8038 g·cm⁻³. The results indicate that vibration can improve the feeding capacity and reduce shrinkage defects in low-pressure casting.

2.2 Seepage phenomenon

The dimensional size of ABS particles used in this experiment is between 40–60 mesh. Therefore, some of the particles can pass the gaps between the densely packed steel balls, and the remaining particles will accumulate at the seepage entrance and lead to higher resistance of seepage. The above seepage phenomenon is similar to that in the mushy solidified alloys (e.g.

Fig. 4: Cross section of castings under non-vibration (a) and vibration (b)

ZL205A alloy), in which the solidifying equiaxed grains easily accumulate at the feeding entrance and increase the feeding resistance. A tiny vibration on the ABS particles can change the structure of the accumulated particles and reduce the resistance of semisolid seepage.

2.3 Effect of vibration parameters on seepage

As shown in Fig. 5, the seepage velocity of a semisolid fluid in a porous medium increases with the increment of holding pressure under non-vibration. Appropriate vibration can greatly improve the seepage velocity (e.g., when the frequency is 30 Hz, the exerted force is 10 N and the holding pressure is 0.16 MPa), whereas it will decrease under inappropriate vibration. The effects of vibration on the seepage are different under different holding pressures. The seepage velocity under the proper vibration (10 Hz, 10 N) is twice that under non-vibration when the holding pressure is intermediate value, 0.13 MPa. However, vibration has little influence on the seepage velocity when the holding pressure is of relatively great value, 0.16 MPa.

Table 2 shows the results of the orthogonal test. It can be concluded from the analysis of range (R) in Table 2 that holding

Fig. 5: Effect of vibration on seepage flow

pressure influences seepage velocity the most, exerted force influences less and frequency influences the least. The optimized parameters to obtain the seepage velocity are the greatest holding pressure and the vibration with great exerted force and low frequency. As shown in Fig. 6, the seepage velocity increases with the increment of holding pressure and exerted force but decreases with the increase of vibration frequency. This is because the pressure gradient increases with the increase of holding pressure when the pressure of the seepage outlet is equal to that of the atmosphere. According to Darcy's law, the seepage velocity becomes faster with a higher pressure gradient. However, in the practical low-pressure casting process, the seepage velocity cannot increase any more even if the holding pressure continually increases once the feeding channel is blocked. Therefore, the unimpeded feeding channel is a prerequisite condition to improve seepage velocity by increasing holding pressure. In terms of the above seepage phenomenon in the semisolid fluid under vibration, the vibration can change the structure of accumulated particles. The greater the exerted force is, the more easily the blocked structure is destroyed, and consequently, the seepage velocity becomes faster.

On the other hand, according to the equation of vibration acceleration of particle:

$$a = 4\pi^2 A f^2 \quad (1)$$

where a is the vibration acceleration of particle, A is the vibration amplitude and f is the vibration frequency. When the exerted force is constant, the amplitude becomes smaller with higher frequency, and therefore, the accumulated structure changes very little, and consequently, the seepage velocity becomes slower. Meanwhile, mechanical vibration propagates in the castings in the form of wave, and its amplitude decreases with the increase of the propagation distance. The higher the vibration frequency is, the more serious the attenuation of the mechanical vibration. Therefore, the low-frequency mechanical vibration is more suitable for decreasing the shrinkage porosity during low-pressure casting compared with the high-frequency mechanical vibration.

2.4 Calculation of seepage flow in porous medium during low-pressure casting with vibration

The pressure equation of a semisolid fluid in a one-dimensional porous medium under vibration and low-pressure is obtained by coupling the continuity equation with the momentum equation based on the assumption that solid particles are incompressible, the semisolid fluid is weakly compressible, the viscosity of the fluid is constant, and the seepage velocity and seepage pressure gradient satisfy Darcy's law^[20].

$$\left. \begin{aligned} \frac{\partial^2 p}{\partial x^2} &= \frac{1}{\eta} \frac{\partial p}{\partial t} \\ p(0, t) &= p_w + p_0 \sin \omega t \\ p(L, t) &= p_e \\ p(x, 0) &= p_w + \frac{P_e - P_w}{L} x \end{aligned} \right\} \quad (2)$$

where p_w is the stable pressure at the entrance of seepage, Pa;

Table 2: Results and analysis of $L_9(3^3)$ orthogonal test

No.	Levels and factors			Results
	A (MPa)	B (Hz)	C (N)	Seepage velocity ($\text{mm}\cdot\text{s}^{-1}$)
1	1	1	1	0.555
2	1	2	2	0.592
3	1	3	3	0.692
4	2	1	2	0.890
5	2	2	3	0.845
6	2	3	1	0.560
7	3	1	3	0.872
8	3	2	1	0.868
9	3	3	2	0.785
K_1	1.838	2.317	1.985	
K_2	2.295	2.307	2.268	
K_3	2.527	2.037	2.407	
k_1	0.613	0.772	0.662	
k_2	0.765	0.768	0.757	
k_3	0.842	0.678	0.802	
R	0.230	0.093	0.142	
Sequence of factors			A>C>B	
Optimization level	A3	B1	C3	
Excellent combination			A3B1C3

Fig. 6: Seepage velocity with different factors and levels

p_0 is the additional pressure of vibration, Pa; p_e is the stable pressure at the outlet of seepage, Pa; L is the length of porous medium, m; ω is the angular frequency of vibration, $\text{rad}\cdot\text{s}^{-1}$; and η is the pressure transmitting coefficient, $\text{m}^2\cdot\text{s}^{-1}$. And η can be expressed by the following equation:

$$\eta = \frac{K}{\phi\mu C} \quad (3)$$

where K is the permeability of porous medium, m^2 ; ϕ is the porosity ratio of porous medium; μ is the viscosity of fluid, $\text{Pa}\cdot\text{s}$; C is the comprehensive compression coefficient which can be calculated by the sum of compressibility of fluid and porous medium, Pa^{-1} .

Under the vibration, the additional pressure satisfies the following equation:

$$p_0 = \frac{F}{S} \quad (4)$$

where F is exerted force of vibration, N; and S is the action area of exerted force, m^2 .

In this study, the length of porous medium increases continually due to the accumulation of solid particles in the semisolid liquid during the seepage progress. According to the volume conservation of solid particles, the relationship between the volume of seepage discharge and the length of porous medium can be obtained by the following equation,

$$\frac{1}{6}\pi d^3 \rho_n \int_0^t q dt = S \Delta L (1 - \phi) \quad (5)$$

where q is the seepage discharge, $\text{m}^3 \cdot \text{s}^{-1}$; d is the equivalent diameter of solid particles, m ; ρ_n is the particle concentration of semisolid fluid, m^{-3} ; and ΔL is the increment of length of

porous medium due to the accumulation effect of particles, m .

The finite difference method was used to solve Eq. (2) and (5). The calculation parameters are shown in Table 3.

Table 3: Parameters of seepage calculation

Parameter	P_w (MPa)	P_0 (MPa)	P_c (MPa)	L (mm)	d (mm)	C (Pa^{-1})	K (m^2)	ϕ	μ ($\text{Pa} \cdot \text{s}$)	ω ($\text{rad} \cdot \text{s}^{-1}$)
Value	0.2	0.02	0.1	50	2	4.76×10^{-10}	9.3×10^{-5}	0.264	1.28×10^5	20π

Figure 7 shows the distribution and evolution of seepage pressure in the porous medium by solving Eqs. (1) and (4) numerically. As shown in Fig. 7, the pressure in the seepage process is changing like a wave under vibration, and the changing pressure can make the flow velocity of fluid in capillary channels of porous medium change periodically, which means vibration forms an elastic wave field in a porous medium. The pressure transmitting coefficient Eq. (1) is calculated as $5.6 \text{ m}^2 \cdot \text{s}^{-1}$. Thus, the seepage pressure can rapidly achieve an equilibrium state, which results in the linear pressure gradient in the porous medium. Therefore, the pressure gradient along the porous medium changes in sinusoidal since the pressure of vibration source is sinusoidal. The vibration of the fluid in the boundary layer formed because the adhesion force between the semisolid liquid and the capillary wall can reduce the adhesion force, so that the elastic wave field can significantly reduce the influence of capillary force on seepage flow and increase the movement of fluid through the porous medium [20]. Meanwhile, mechanical vibration can also destroy the boundary layer [21]. Consequently, the effective size of the capillary can be increased.

Fig. 7: Distribution and evolution of seepage pressure in porous medium

In addition, the 4.5% CMC aqueous solution has viscoelastic rheological characteristics, and the solution can only flow when the pressure gradient of the porous medium is greater than the critical pressure. The critical pressure of fluid decreases with increasing the size of the capillary under the same pressure gradient [18]. The fluid in some small capillaries in the porous medium cannot flow under the pressure which is smaller than the critical pressure, as shown in Fig. 8(a). Part of the capillary which cannot flow starts to move when the

Fig. 8: Effect of vibration on capillary flow in porous medium

pressure is greater than the critical pressure due to the additional pressure of vibration. Consequently, the permeability of the porous medium increases, as shown in Fig. 8(b).

The propagation of vibration could produce tensile and shear stress in the melt [22]. The apparent viscosity of the melt reduces with increasing of shear rate [23], as shown in Eq. (6) [24].

$$\frac{\eta - \eta_{\infty}}{\eta_0 - \eta_{\infty}} = \frac{1}{1 + k \dot{\gamma}} \quad (6)$$

where η is the melt viscosity; η_0 and η_{∞} are the asymptotic viscosity values at zero and infinite shear rates, respectively; k is the parameters related to time; and $\dot{\gamma}$ is the shear strain velocity.

In addition, the shear stress caused by vibration will consume the vibration energy in the form of internal friction. Therefore, the local temperature of the fluid will increase. According to theory [25], the viscosity of the fluid decreases with the increase of temperature. Hence, apparent viscosity of the melt can also be reduced by thermal effect of vibration, which will promote the flow velocity of fluid. The thermal effect and the shear rate become greater with the increase of the amplitude and frequency, thus, vibration can reduce the viscosity of the fluid more obviously according to Eq. (6). However, the velocity and direction of the fluid particle are constantly changing under vibration, which makes the fluid particle move from one layer to another and produces additional resistance to the flow of the fluid. The turbulence degree of fluid and the additional resistance caused by turbulence will increase by increasing the vibration amplitude and frequency. Vibration will reduce the seepage velocity when the obstructing effect is greater than the promoting effect.

3 Conclusions

(1) Vibration can improve the feeding capacity and reduce

shrinkage defects of ZL205A alloy in low-pressure casting.

(2) Vibration can change the structure of accumulated particles at the seepage entrance, thus open the blocked feeding channel. Meanwhile, vibration can form a wave field in the porous medium, which can reduce the adhesion force between fluid and the capillary wall and destroy the boundary layer of fluid, and thus promote the seepage velocity.

(3) Holding pressure influences seepage velocity the most, exerted force influences less and frequency influences the least. The vibration with low frequency and great exerted force (e.g., when the frequency is 10 Hz, the exerted force is 12 N and the holding pressure is 0.16 MPa) can significantly improve the seepage feeding of semi-solid fluid in porous medium, however, if the obstructing effect of turbulence induced by vibration is greater than the promoting effect, the vibration will reduce the seepage velocity.

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