Numerical study on porosity distribution in casting under micro-amplitude vibration condition

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Abstract. Combining with Pequet’s porosity model, this paper coupled vibration effect into the heat transfer models based on the turbulent heat transfer theory, on this basis porosity distribution of alloys under micro-amplitude vibration conditions can be analyzed. The simulated porosity results of ZL201 alloy show that appropriate vibration frequency (10Hz~30Hz) promoted the mass feeding and capillary feeding by increasing the Dendrite Arm Spacing (SDAS) and heat transfer specific surface area of mass liquid channel, thus efficiently decreasing porosity distribution in casting. However, too high vibration intensity (40Hz~50Hz) may deteriorate porosity distribution in casting due to insufficient feeding capacity. The vibration model provides a theoretical basis for the study on effect of mechanical vibration on casting, which is significant for the optimization of vibration parameters and porosity prevention in casting technology.

1. Introduction
Porosity is one of the major defects in castings, which results in a decrease of the mechanical properties. Convection caused by vibration can shorten the solidification time of hot spot, break up dendrites and expand the feeding channel [1, 2], thus decreasing porosity in casting. But unreasonable vibration parameters may lead to serious segregation, hot cracks and so on.

Numerical method is convenient for investigating the solidified structure of alloys. However, few numerical studies combine mechanical vibration with porosity formation. The random distribution of nucleation and growth of voids should be considered during the solidification process. Ch. Pequet [3] et al developed a porosity model for micro-porosity, macro-porosity formation during the solidification of alloys using a mushy-zone refinement method, which superimposes fine and regular finite volume grids onto the finite-element mesh used for the heat-flow computations, and solves the governing equations of micro-porosity with appropriate boundary conditions. The porosity model has been widely used in shrinkage porosity simulation.

The influence of vibration on casting has been widely discussed [4, 5]. Turbulence caused by vibration can accelerate the heat transfer, which will affect the porosity distribution. This paper established a theoretical model of vibration casting connecting with Pequet’s model, which is significant for porosity prediction and optimization of vibration parameters in vibration casting.

2. Mathematical models
2.1. Heat transfer equation
Under micro-vibration amplitude condition, the Reynolds number in the molten pool is very small, so the heat transfer in the molten pool is mainly in the way of heat conduction. The dominant equation is shown as:
\[ \rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \lambda \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( \lambda \frac{\partial T}{\partial z} \right) + Q_v. \]  

(1)

Where \( \rho \) is the density; \( c_p \) is the specific heat; \( T \) is the temperature; \( t \) is the time; \( \lambda \) is the thermal conductivity; \( Q_v \) is the energy input by vibration. The convection of liquid melt can be reflected by increasing the thermal conductivity, which is also called effective thermal conductivity \( \lambda_e \):

\[ \lambda = \lambda_m + \lambda_t \quad \lambda_t = \frac{1}{\rho_r^2} \rho C_p \frac{\kappa^2}{\varepsilon}. \]

(2)

Where \( \lambda_m \) is the static thermal conductivity of the metal pool, \( \lambda_t \) is turbulent thermal conductivity generated by convection[6]; \( \varepsilon \) is the turbulent flow dissipation rate, \( \kappa \) is the pulsating kinetic energy. \( C_p \) is the experimental constant and usually take 0.09 in engineering. For micro-vibration amplitude, liquid motion in molten pool is disorderly, to weaken the effect of vibration direction, three-dimensional vibration energy \( Q_v \) is exerted on the casting mould during solidification. The same frequency \( f \) and amplitude \( A \) are exerted at each orthogonal coordinate direction, and the difference of phase angle between each two coordinate axis is 120degrees.

For the vibration energy \( Q_v \), it can be expressed as:

\[ Q_v = 3Q_{vi}: \quad Q_{vi} = 8\pi^2 \rho A^2 f^3, \quad i = x, y \text{ and } z. \]  

(3)

In semi-solid metals, a solid-phase network is formed when the solid fraction \( g_s \) exceeds 0.4, which interrupts the liquid phase [7, 8], thus \( Q_v = 0 \) and \( \lambda_t = 0 \) in this condition.

2.2. Porosity nucleation and growth model

2.2.1. Mass conservation with porosity

The mass conservation is a continuity equation as follow:

\[ \text{div}(\rho_l g_l v_l) - \rho_l \frac{\partial g_p}{\partial t} = - \frac{\partial}{\partial t} \langle \rho \rangle \frac{\partial T}{\partial t}. \]

(4)

where \( \langle \rho \rangle = \left( \rho_s g_s + \rho_l (1 - g_s) \right) \) and \( g_l = 1 - g_s - g_p \), \( \rho_s \) is the specific mass of the solid, \( g_s \) is the solid fraction, \( \rho_l \) is the density of the liquid, and \( v_l \) is the velocity of the liquid in solid skeleton.

2.2.2. Porosity nucleation criterion

In the absence of gas dissolved in the liquid metal: pore will nucleate if decreasing liquid pressure reaches minus of the overpressure due to capillarity effect:

\[ p_{nuc} = -\Delta p_r; \quad \Delta p_r = \frac{2\sigma_{lw}}{r}. \]

(5)

Where \( \Delta p_r \) is the overpressure of nucleation; \( \sigma_{lw} \) is the interfacial tension between the liquid and the pore, and \( r \) is the radius of curvature of the pore.

2.2.3. Porosity growth model

Three cases are considered as follow (Figure 1 (b)):

1. Case 1: A region where solid fraction is lower than the "mass feeding limit": liquid contraction and solidification shrinkage are compensated by liquid from the top of critical region.

2. Case 2: A region is higher than “mass feeding limit”, but lower than the inter-dendrite "gravity draining limit": Liquid contraction and solidification shrinkage are compensated by liquid with solid fraction lower than “gravity draining limit”, which can be solved by Darcy’s flow:
\[ g_lv_l = -\frac{K}{\mu} (\nabla p_l - \rho_l g); \quad K(g_s, \lambda_2) = \frac{(1-g_s)^3 \lambda_2^2}{g_s^2 180}. \] (6)

Where \( p_l \) is local pressure in liquid; \( K \) is the permeability of the solid skeleton; \( \lambda_2 \) is the secondary dendrite arm spacing; \( v_l \) is the dynamic viscosity and \( g \) is the gravity vector.

(3) Case 3: Solid fraction is above "gravity draining limit": liquid contraction and solidification shrinkage are compensated by distributed inter-dendrite micro-shrinkage increment.

2.3. Model and calculation of parameters
Three-dimensional finite element model with a cylindrical shape has been established ((figure.1(a))). Standard ZL201 aluminum alloy is used. The mould material is H13 and the insulation material is High alumina brick. The pouring temperature is 710°C. Both the initial temperature of mould and insulation is 20°C. The interfacial heat transfer coefficients of mould/ingot, insulation/ingot and mould/insulation are 2300, 500 and 1000 W/m\(^2\)-K, respectively.

![Figure 1](image)

Figure 1. The casting system (a) and three cases of porosity model (b).

3. Results
3.1. Solidification distribution
In this section, casting without vibration and casting with vibration frequencies from 10Hz to 50Hz were simulated. It can be seen from figure.2 (upper part) that lower temperature gradient formed in all castings with vibration than that of casting without vibration, which is the same as results reported in reference [9]. Here the solid fraction in scale of 0–40% is supposed to be lower than the "mass feeding limit" and solid fraction in scale of 40–60% is supposed to be higher than the "mass feeding limit" but lower than inter-dendrite "gravity draining limit".
Figure 2. Solidification at 60% of solid fraction and final porosity distribution.

It can be seen that the depth of mass liquid feeding (0–40%) channel in all castings with vibration were shallower than that in casting without vibration at the same solid fraction, and the depth of mass liquid feeding became shallower gradually with increasing vibration frequency. The area of capillary feeding channel (40–60%) in all castings with vibration is broader than that of casting without vibration, and the area of capillary feeding channel became boarder gradually with the increasing frequency.

3.2. Porosity distribution

Figure 2 (lower part) shows porosity distribution of all castings with and without vibration, it can be seen porosity was mainly located at the top and central part of castings. Because the top position is the last solidification position, thus only small ratio of porosity was formed. Gradually decreasing porosity ratio and area was formed for castings with vibration when the frequency increasing from 10Hz to 30Hz, showing better casting quality than casting without vibration. However, bigger porosity ratio and area was formed both at the top and the central part for castings with vibration frequency of 40Hz and 50Hz than that of casting without vibration, which indicated inadequate feeding ability. This trend is the same as the conclusion of some experimental results in reference [10, 11].

4. Discussion

Porosity is mainly affected by combination effects of mass feeding and capillary feeding. Figure 3 (a) shows the aspect of mass feeding channel of all castings. Higher aspect symbols lower specific surface area of mass feeding channel. With the increasing vibration frequency from 10Hz to 30 Hz, the mass liquid channel became broader, which promoted compensation of mass feeding. But when the vibration frequency was above 40 Hz, porosity distribution area became enlarged, which can’t be explained only by the aspect of mass feeding channel.

Figure 3. Length-width ration of mass feeding zone (a) and SDAS of capillary feeding (b).
According to Darcy's Flow, larger \( \lambda_2 \) may symbolize stronger capillary feeding ability. Figure 3 (b) shows that \( \lambda_2 \) at the center line of all castings, it can be seen increasing \( \lambda_2 \) were formed in castings with vibration than casting without vibration, indicating higher capillary feeding ability in castings with vibration (10–30Hz) than casting without vibration. However, when the solid fraction of 40–60% is too board (40Hz and 50Hz), Mush zone may solidify completely before capillary feeding is achieved (or not adequate feeding liquid). Thus, bigger porosity area is easily accumulated in castings with frequency of 40Hz and 50Hz than that of casting without vibration. In addition, high vibration frequency increases the internal energy of liquid melt, which slows down the cooling rates of solidification front and increases porosity ratio in casting.

5. Conclusion

Based on turbulent heat transfer theory, this paper inserts the effect of mechanical vibration into heat transfer model, on this basis porosity distribution of alloys under micro-amplitude vibration condition can be analyzed combining Pequet’s refined porosity model. The simulated results of ZL201 alloy showed that enhancing vibration frequency from 10Hz to 30Hz increasingly promoted the mass gravity draining feeding and capillary feeding in casting, thus reducing the porosity distribution. However, when vibration frequency was above 40Hz, porosity distribution in casting was deteriorated due to the increase of capillary complementary area and vibration energy. The vibration model provides a theoretical basis for predicting porosity distribution in casting under vibration conditions and is significant for the improvement of vibration parameters in casting technology.

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Acknowledgments

We are grateful for grants from the National Natural Science Foundation of China (No. 51775167), and the Qing Lan Project of Jiangsu province.