Numerical study on effect of micro-amplitude vibration on the grains morphology of alloys

Lei Rao*, Kai You, Xue Bai and Tianyu Miao
College of Mechanics and materials, Hohai University, Nanjing 211100, China
*corresponding author: raol@hhu.edu.cn

Abstract. Combining with CAFE model, this paper introduced a modified heat transfer model which interfere the effect of mechanical vibration based on turbulent heat transfer theory, on this basis the grains morphology of alloys under micro-amplitude vibration can be analyzed. Based on this model, the results of ZL201 alloys showed that vibration can promote columnar-to-equiaxed transition (CET) and grain refinement, and improve homogeneity of grains distribution. The optimum vibration frequency in current study is 40Hz. The method used in this paper provides a reference for study on the theory of vibration casting and is beneficial for parameters optimization of mechanical vibration in foundry field.

1. Introduction
Grain refinement for metallic materials is a very efficient way to obtain outstanding performance including high strength, excellent bend-ability and high ductility. The application of sonic, ultrasonic and mechanical vibration can promote grain refinement and change the distribution form of second phase [1, 2]. Among above methods, application of mechanical vibrations attracts much attention because of a simple system [3].

The formation of microstructure of castings results from the nucleation and growth of grains. Nucleation and growth of grains depend on the state of under-cooling liquid melt, which is determined by the solidification rate and temperature gradient of dendrite tip. Cellular automaton-finite element (CAFE) model has been successfully used to simulate the solidification microstructure under various casting conditions in recent years [4, 8]. However, the method has rarely been used in vibration casting. Combining with CAFE model, a modified heat transfer model was established in this paper which considered the effect of mechanical vibration on casting. On this basis grains morphology of alloys can be analyzed, which provides a reference for parameters optimization of vibration casting.

2. Mathematical model
2.1. Heat transfer equations
Under micro-vibration amplitude condition, the Reynolds number in the molten pool is very small, so heat transfer in the melt is mainly in the way of heat conduction, which can be expressed 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; \( Q_V \) is the energy input by vibration; \( \lambda \) is effective thermal conductivity, which can be expressed by:
\[ \lambda = \lambda_m + \lambda_t : \quad \lambda_t = \frac{1}{Pr_t} \rho C_p C_\mu \frac{\kappa^2}{\varepsilon}, \]  

(2)

Where \( \lambda_m \) is static thermal conductivity, \( \lambda_t \) is turbulent thermal conductivity [5]. \( \varepsilon \) is turbulent flow dissipation rate, \( \kappa \) is pulsating kinetic energy. \( C_\mu \) is experimental constant and takes 0.09. Considering the disorder of liquid motion under micro-amplitude vibration condition, three-dimensional vibration energy \( Q_V \) is exerted on casting mould to weaken the effect of vibration direction. 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 120 degrees.

The total vibration energy \( Q_V \) can be expressed as:

\[ Q_V = 3 Q_{V'i} : \quad Q_{V'i} = 8 \pi^2 p A^2 f^3, \quad i = x, y \text{ and } z. \]  

(3)

Liquid flow in the bulk melt is a blocked state when the solid fraction \( g_S \) is higher than 0.4 [6-7], in this case \( Q_V = 0 \) and \( \lambda_t = 0 \).

2.2. CAFE model

2.2.1. Nucleation equations

It is assumed that nucleation become active when the under-cooling increases to an active value. In present work, continuous nucleation model proposed by Rappaz and Gandin [4] is applied. The relationship between nucleation density and under-cooling is given by:

\[ \frac{dn}{d(\Delta T)} = \frac{n_{max}}{\sqrt{2\pi} \Delta T_\sigma} \exp \left[ -\frac{(\Delta T - \Delta T_{max})^2}{2\Delta T^2} \right]. \]  

(4)

The grain density can be calculated by equation:

\[ n(\Delta T) = \int_0^{\Delta T} \frac{dn}{d(\Delta T)} d(\Delta T). \]  

(5)

Where \( n \) is the grain density, \( \Delta T \) is the under-cooling, \( n_{max} \) is the maximum nucleation density, \( \Delta T_\sigma \) is the deviation standard of the nucleation under-cooling, and \( \Delta T_{max} \) is the maximum nucleation under-cooling.

2.2.2. Dendrite growth equations

The total under-cooling of the dendrite tip \( \Delta T \) is the sum of four contributions [8-9]:

\[ \Delta T = \Delta T_c + \Delta T_t + \Delta T_k + \Delta T_r. \]  

(6)

Where \( \Delta T_c \), \( \Delta T_t \), \( \Delta T_k \) and \( \Delta T_r \) are the under-cooling value of solute diffusion, thermal diffusion, attachment kinetics, and solid/liquid interface curvature, respectively. For most metallic alloys, the last three under-cooling are very small and can be ignored, thus a simplified calculation function is introduced based on the KGT model. The dendrite tip growth kinetics in the casting will be calculated by:

\[ \nu = a_2 \Delta T^2 + a_3 \Delta T^3. \]  

(7)

Where \( a_2 \) and \( a_3 \) are coefficients of the growth velocity of the dendrite tips, which were 3.12e-007 and 7.56e-008 in this paper, respectively.

2.3. Model and calculation of parameters
Finite element models of cylindrical ingot (with radius of 25mm and height of 140mm) and casting mould (with thickness of 10mm) were established. Standard ZL201 aluminum alloy and H13 were respectively assigned to the ingot and casting mould. The initial temperature of mould and the pouring temperature were 80 °C and 710 °C, respectively. And the heat transfer coefficient of ingot/mould was 2000 W/m^2-K.

3. Results and discussion

3.1. Temperature field and grain morphology

The simulated results of temperature field of castings without and with vibration (10 Hz, 0.2mm) are coupled in figure 1. Temperature fields corresponding to solid fraction of 30% and 60% were selected for both castings. It can be seen that positive temperature gradient was established towards the inner melt during the solidification. Lower temperature gradient was formed in the casting with vibration than that of casting without vibration, which suggests the enhancement of heat transfer in liquid melt.

Figure 1. Temperature field of casting without ((a), (b)) and with vibration ((c), (d)). (a) $g_S = 30\%$; (b) $g_S = 60\%$; (c) $g_S = 30\%$; (d) $g_S = 60\%$.

The solidified structure of casting depends critically on the temperature distribution in the molten pool [10, 11]. Figure 2 (left part) shows the grains morphology of the ZL201 alloy castings with and without vibration. As for casting without vibration, wide grains zone near the side wall showed obvious tendency of columnar shape which faced the axis of the cylinder casting. While for the casting with vibration, grains morphology became more disordered and the columnar grain zone was compressed to a very narrow width near the side wall.

The grains morphology mainly depends on the $G/R$ ratio [12-13], where $R$ is solidification rate and $G$ is temperature gradient. High $G/R$ ratio promotes formation of columnar grains, while Low $G/R$ ratio favors formation of equiaxed grains. Figure 2 (right part) shows the $G/R$ ratio of castings with and without vibration. The width of high $G/R$ zone in casting with vibration was narrower than that of casting without vibration, thus columnar grain zone of casting with vibration was thinner. The results indicate that vibration can effectively restrain the growth of columnar grains zone.

Figure 2. Grain morphology (left part) and $G/R$ ratio (right part) of casting.
The homogeneity and compactness degree can be respectively evaluated by variance of grain size and the average radius of grains. Lower variance of grain size represents good homogeneity and smaller radius of grains means higher compactness degree. The distribution of grains radius of the two castings was shown in figure 3. The average grain size of casting with vibration is slightly smaller than that of casting without vibration, showing an improved compactness degree. The grains size mainly depends on the $N/K$ ratio [13], where $N$ is the nucleation density, and $K$ is grain growth rate. With solidification processing, the under-cooling zone are enlarged by vibration, which resulted in a rise of nucleation quantity in under-cooling zone, thus decreasing the grains size of casting. In addition, the variance of grain size in casting with vibration was only 2/3 of that of casting without vibration, which exhibited a higher homogeneity. The improved grain homogeneity may be attributed to lower temperature gradient of under-cooling zone under vibration condition.

**Figure 3.** Grain size distribution and statistics of casting with and without vibration.

### 3.2. Effect of vibration frequency

Figure 4 displays the grains size and variance of castings with different vibration frequency. The average grains radius decreased from 0.036 to 0.0345 cm when vibration frequency increased from 10 to 40 Hz, which owned to the increasing vibration effect on heat transfer. But when the vibration frequency rose to 50 Hz, the average grain size increased to 0.0356 cm, which may caused by the excessive vibration energy. The trend of grain size change is similar to experiment results in reference [14]. Besides, the uniformity of grains become better gradually with increasing vibration frequency, which was attributed to improved uniformity of temperature field in under-cooling zone.

**Figure 4.** Simulated grain size and deviation of casting with different vibration frequency.

It can be seen that appropriate vibration frequency is beneficial for both grain refinement and uniformity of microstructure, which in turn affect the mechanical properties such as strength and ductility. Highly similar to the conclusion in reference [3], all castings with vibration showed better homogeneity and smaller grain size than casting without vibration, which suggested enhanced mechanical properties.

### 4. Conclusion

This paper established a modified heat transfer model which considered the micro-amplitude vibration effect on solidification of alloys based on turbulent heat transfer theory. On this basis the grain
morphology of alloys can be analyzed combining CAFE model. The simulated results of ZL201 alloys showed that vibration promotes CET and grain refinement, the best vibration frequency is 40Hz. Besides, with increasing vibration frequency, the homogeneity of grain distribution was improved gradually. The improvement of grain morphology was determined by the combined action of temperature gradient, solidification rate and nucleation density, which was influenced by redistribution of temperature field under mechanical vibration condition. The model is significant for research on theory of vibration casting and optimization of vibration parameters in casting.

5. References
[1] Rasgado M T A and Davey K. The effect of vibration on surface finish for semisolid and cast components[J]. Journal of Materials Processing Tech 2002, 125–126(13) 543-548.
[2] Kocatepe K. Effect of low frequency vibration on porosity of LM25 and LM6 alloys[J]. Materials & Design 2007, 28(6) 1767-75.
[3] Taghavi F, Saghafeian H and Kharrazi Y H K. Study on the effect of prolonged mechanical vibration on the grain refinement and density of A356 aluminum alloy[J]. Materials & Design 2009 30(5) 1604-11.
[4] Gandin C A, Desbiolles J L, Rappaz M, et al. A three-dimensional cellular automation-finite element model for the prediction of solidification grain structures[J]. Metallurgical & Materials Transactions A, 1999, 30(12) 3153-65.
[5] Macro-and Microstructure Evolution of 5CrNiMo Steel Ingots during Electroslag Remelting Process[J]. Journal of Iron and Steel Research, International 2014, 21(7) 644-652.
[6] Lashkari O, and Ghomashchi R The implication of rheology in semi-solid metal processes: An overview[J]. Journal of Materials Processing Technology 2007, 182(1-3) 229-240.
[7] Kirkwood, D H Semisolid metal processing[J]. International Materials Reviews 1994, 39(5):173-189.
[8] Trivedi R and Kurz W. Theory of Microstructural Development During Rapid Solidification[J]. Acta Metallurgica 1986, 34(5) 823-830.
[9] Lipton J, Glicksman M E and Kurz W. Dendritic growth into undercooled alloy metals[J]. Materials Science & Engineering 1984, 75(1) 57-63.
[10] Wu M, Ludwig A, Bührig-Polaczek A, et al. Influence of convection and grain movement on globular equiaxed solidification [J]. International Journal of Heat & Mass Transfer 2003, 46(15) 2819-2832.
[11] Sobczak J J, Drenchev L and Asthana R. Effect of pressure on solidification of metallic materials [J]. Cast Metals 2013, 25(1) 1-14.
[12] Spittle J A. Columnar to equiaxed grain transition in as solidified alloys[J]. Metallurgical Reviews 2006 51(4) 247-269.
[13] Martorano M A, and Biscuola V B. Predicting the columnar-to-equiaxed transition for a distribution of nucleation under-cooling [J]. Acta Materialia 2009, 57(2) 607-615.
[14] Effects of vibration frequency on microstructure, mechanical properties, and fracture behavior of A356 aluminum alloy obtained by expendable pattern shell casting [J]. The International Journal of Advanced Manufacturing Technology 2016, 83(1-4) 167-175.

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