The Particle Distribution in Liquid Metal with Ceramic Particles Mould Filling Process

Qi Dong, Shu-ming Xing
School of Mechanical, Electronic and Control Engineering, Beijing Jiaotong University, Beijing 100080, China
E-mail: 15116360@bjtu.edu.cn

Abstract. Adding ceramic particles in the plate hammer is an effective method to increase the wear resistance of the hammer. The liquid phase method is based on the "with the flow of mixed liquid forging composite preparation of ZTA ceramic particle reinforced high chromium cast iron hammer. Preparation method for this system is using CFD simulation analysis the particles distribution of flow mixing and filling process. Taking the 30% volume fraction of ZTA ceramic composite of high chromium cast iron hammer as example, by changing the speed of liquid metal viscosity to control and make reasonable predictions of particles distribution before solidification.

1. Introduction
Adding ceramic particles (radius=1mm) in high chromium cast iron can effectively enhance the performance of wear parts to improve the wear resistance of the plate hammer [1-3]. Kaihong Zheng [4] used the infiltration method to prepare matrix composite of ZTA ceramic particles (1~3 mm) with high chromium cast iron. After heat treatment the composite abrasive wear performance is 5.9 times of Cr20 high chromium cast iron.

2. Particles distribution model
The establishment of the theoretical model of particles distribution in a two-phase mixture during the filling process. The parameters influence the particles distribution in the two-phase flow of granular particles and metal melt [5]:

\[ \frac{6\sqrt{2}\nu_p \varphi}{d_p} = \frac{\rho_f}{\rho_p} \left( \frac{18\nu_f}{d_p^2} + \frac{2.7\nu_f^{0.313} \nu_l^{0.687}}{d_p^{1.313}} \right) \]  

With the particle volume concentration increasing, the interaction frequency between particles increasing too, the particles are prone to collisions and agglomeration. When the fluid and particle density difference is small, the ability of the particle following fluid pulsation will be enhanced, the agglomeration of particles will be decreased. With the increase of particle diameter, it is not conducive to the interaction between fluid and particles, the aggregation easy to happen. In addition, with the grain terminal (fluid flow) increasing, agglomeration and separation will be destroyed in hydrodynamic shear.

3. Filling simulation
The convective mixing filling process involving liquid metal, particles and air phase. The calculation using Eulerian multiphase flow model, because of the particles volume ratio is greater than 10% in the field of wide distribution. The particles as discrete systems for processing, it needs to be as quasi
continuous medium particles or quasi fluid.

3.1 Volume fraction

The ZTA ceramic particle was selected as the reinforced phase and the physical parameters are shown in Table 1. The particles will be simplified for spherical particles in the simulation process.

Table 1. Physical parameters of ZTA ceramic particles.

| Ceramic Particles | Particle diameter (mm) | density (g·cm⁻³) | porosity (λ) |
|-------------------|------------------------|------------------|--------------|
| Zr40(40%ZrO₂)     | 2-4                    | 4.2-4.6          | 0.3-0.5      |

The matrix of plate hammer selection of high chromium cast iron, which has characteristics of low thermal conductivity, wide range of crystallization temperature, alloy liquid viscosity, flow resistance. The physical parameters see Table 2:

Table 2. Physical parameters of Cr20.

| temperature /K | density /Kg/m³ | liquidus temperature /K | solidus temperature /K | kinetic viscosity /Pa·s | surface tension /N/m |
|----------------|----------------|-------------------------|------------------------|------------------------|----------------------|
| 1573           | 7620           | 1563                    | 1493                   | 0.006                  | 1.88                 |
| 1623           | 7620           | 1563                    | 1493                   | 0.005                  | 1.88                 |

3.2 Volume fraction

\[ V_q = \int_V \alpha_q \, dV \]  
\[ \sum_{q=1}^{n} \alpha_q = 1 \]

3.3 Fundamental equations

3.3.1 The conservation equations of continuity equation \[ Q \]

\[ \frac{\partial}{\partial t} (\alpha_q \rho_i \tilde{v}_i) + \nabla \cdot (\alpha_q \rho_i \tilde{v}_i \tilde{v}_i) = -\alpha_i \nabla p + \nabla \cdot \tilde{t}_i + \alpha_i \rho_i \tilde{g} + \alpha_i \rho_i (\tilde{F}_i + \tilde{F}_{lift} \text{ $i$ } + \tilde{F}_{vm, $i$}) + \sum_{p=1}^{n} [K_{pi}(\tilde{v}_p - \tilde{v}_i) + m_{pi}\tilde{v}_{pi}] \]  

Momentum conservation equation of particle phase:
\[
\frac{\partial}{\partial t} (\alpha_s \rho_s \vec{v}_s) + \nabla \cdot (\alpha_s \rho_s \vec{v}_s) \\
= -\alpha_s \nabla p - \nabla \cdot \vec{f}_s + \alpha_s \rho_s \vec{g} + \alpha_s \rho_s (\vec{F}_s + \vec{f}_{lift} + \vec{f}_{vm.s}) \\
+ \sum_{p=1}^{n} [K_{ps} (\vec{v}_p - \vec{v}_s) + m_{ps} \vec{v}_{ps}]
\]

(6)

Momentum conservation equation of gas:
\[
\frac{\partial}{\partial t} (\alpha_g \rho_g \vec{v}_g) + \nabla \cdot (\alpha_g \rho_g \vec{v}_g) \\
= -\alpha_g \nabla p - \nabla \cdot \vec{f}_g + \alpha_g \rho_g \vec{g} + \alpha_g \rho_g (\vec{F}_g + \vec{f}_{lift} + \vec{f}_{vm.g}) \\
+ \sum_{p=1}^{n} [K_{pg} (\vec{v}_p - \vec{v}_g) + m_{pg} \vec{v}_{pg}]
\]

(7)

3.3.2 Turbulence model\(^{[9]}\). In the standard k-\(\varepsilon\) turbulence model, the relationship between turbulent kinetic energy \(K\), dissipation rate \(\varepsilon\) and turbulent viscosity \(\mu\) expressed as:
\[
\mu = \rho C_\mu \frac{k^2}{\varepsilon}
\]

(8)

The turbulent kinetic energy equation \(K\):
\[
\rho \frac{\partial k}{\partial t} + \rho \mu \frac{\partial k}{\partial x} = \frac{\partial}{\partial x} \left[ \left( \mu + \frac{\mu}{\sigma} \right) \frac{\partial k}{\partial x} \right] + \psi - \rho \varepsilon
\]

(9)

Equation of turbulent kinetic energy dissipation rate \(\varepsilon\):
\[
\rho \frac{\partial \varepsilon}{\partial t} + \rho \mu \frac{\partial \varepsilon}{\partial x} = \frac{\partial}{\partial x} \left[ \left( \mu + \frac{\mu}{\sigma} \right) \frac{\partial \varepsilon}{\partial x} \right] + \frac{\varepsilon}{k} (c_1 \psi - c_2 \rho \varepsilon)
\]

(10)

The turbulent phase:
\[
\psi = \mu \left( \frac{\partial \mu}{\partial x} + \frac{\partial \mu}{\partial x} \right)
\]

(11)

\(C_v=0.09, \ c_1=1.44, \ c_2=1.92, \ \sigma_k=1, \ \sigma_{\varepsilon}=1.3\)

4. Results and discussion

The distribution of particles in the straight runner and the cavity of the workpiece have been found after simulation, and the particle distribution expressed by volume fraction. The particles distribution on the centre line of the model are shown in the figures to the below:
Figure 1. Distribution of particle volume fraction along the centre of hammer when the molten metal with a velocity of 0.5 m/s

Figure 2. Distribution of particle volume fraction along the centre of hammer when the molten metal with a velocity of 1 m/s
According to the particle volume fraction set of 30%, make curve $y=0.3$ linear, the curve and straight line to form uniform area to characterize the degree of particle distribution. The greater area shows that the volume fraction of the particles deviates from the set value is greater, the distribution of particles are uneven. The smaller particle volume fraction means that the distribution is close to the set value, the particle distribution are uniform. By calculation, the molten metal with a velocity of 2m/s was obtained particle distribution more uniform than other groups.

The influences of liquid metal speed on the particle distribution include: when the speed is 0.5 m/s, 1 m/s, 2 m/s, the time needed for the workpiece cavity filled with respectively 3.58s, 1.79s, 0.89s. In the different viscosity, when the filling time long, will be easy to cause the particles float. In simulation results, the particle volume fraction is very low at the bottom of the hammer. When the filling time is short, the floating particles is not obvious. The greater liquid metal flow velocity lead to large flow shear stress relatively, it can be promote particle dispersion to reducing the particle gathered. The bottom of the plate hammer is the turning point of the workpiece cavity, and the side the wall have no arc, rectangular region on both sides were the primary causes of liquid metal flow slow. The particle retention in the workpiece at the bottom lead to particle volume fraction significantly larger is the result of slow molten metal velocity.

5. Conclusions
(1) At a certain speed in the two-phase mixing and flow process, the possibility of particles aggregation can be reduced;
(2) The uniform particle distribution was obtained when the liquid metal flow velocity is 2m/s;
(3) Through the analysis of the simulation results, it is concluded that the greater the flow velocity of metal liquid is the greater shearing force of fluid flow. The high-speed is the promotion of particle phase dispersion. This result is similar with the forecast of the mathematical model.

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