Fractionation and Mold Filling of Semisolid Slurries I: Isothermal Condition

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The fractionation and mold filling of semisolid slurries were numerically investigated for a range of mold geometry, inflow velocity, nozzle diameter, and fraction solid. The slurry was assumed to be a shear-thinning, non-Newtonian fluid. Fractionation was determined from the trajectories of isothermal particles injected into the slurry. The results indicate fractionation is reduced with a tapered mold, high-inflow velocity, large nozzle diameter relative to mold, and low fraction solid.

Keywords casting, fractionation, mathematical analysis, non-Newtonian fluid, slurry

1. Introduction

Semisolid slurry processing is widely employed for producing dispersion-strengthened, metal-matrix composites of near net shapes. The properties of the composite products are strongly dependent on the slurry rheology and mold-filling characteristics. Slurry rheology is quite complex, being shear dependent and thixotropic. The mold filling of slurry is further complicated by the occurrence of phase segregation or fractionation, depending on the operating conditions. This paper examines this problem during mold filling of slurries at high-fraction solid.

The experimental works of Suery (Ref 1), Suery and Flemings (Ref 2), and Flemings (Ref 3), on semisolid, tin-lead alloys have demonstrated the effect of shear stress on mechanical behavior and phase segregation in the solidified composite. The numerical model of Ohnaka (Ref 4), on solidification of semisolid slurries has been used for the design of castings of complex shapes for industrial production.

Relatively few studies, however, have addressed the problem of fractionation of semisolid slurries. Secordel and Valette (Ref 5) provided some experimental data on semisolid steels, showing a direct correlation between inflow velocity and liquid rejection during extrusion. This study was, however, limited to steady state behavior. Kennedy and Clyne (Ref 6) performed a quasi-one-dimensional analysis of particle migration during solidification processing of metal-matrix composites. The dynamics of isolated particles was considered, and there was no evidence the results could be applicable to highly loaded slurries of practical interest.

This paper addresses phase segregation during mold filling of semisolid slurries under assumed isothermal condition. Fractionation was determined from the trajectories of isolated particles introduced with the slurry at the inlet. The particles were allowed to exchange momentum with the slurry. A range of operating parameters was investigated, including inflow rate, fraction solid, nozzle diameter, and mold geometry.

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2. Formulation

Figure 1 illustrates the systems considered, a cylindrical and a tapered mold. The mold diameter at the inlet is 2.54 cm, and the nozzle diameter ranges are from 1.27 to 2.03 cm. A semisolid slurry of Sn-15%Pb alloy was injected from the bottom of each mold. The objective was to use an appropriate constitutive model of slurry rheology to represent the mold filling process as well as possible phase segregation (or fractionation). A mathematical representation of this process under isothermal condition required solution of the equations governing the conservation of mass and momentum as well as representation of the slurry rheology, particle dynamics, and free surface.

The slurry was assumed to behave as a non-Newtonian incompressible fluid with a power-law dependence of the viscosity on the shear rate (Ref 7, 8). This simple power-law model has been demonstrated to adequately reproduce the essential shear-thinning characteristics of semisolid slurries (Ref 7, 8).

The governing equations can thus be expressed as the following:

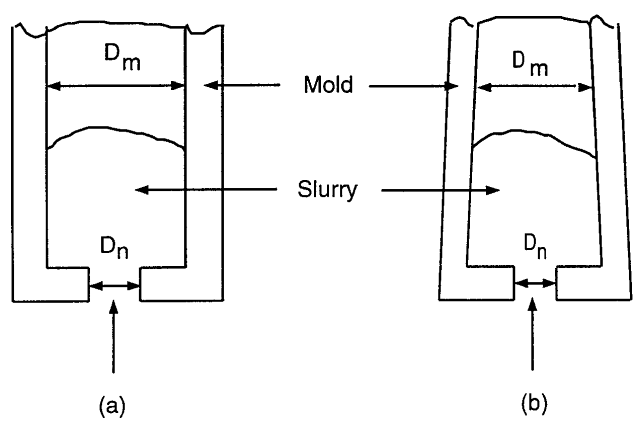

Fig. 1 Schematic sketch of mold filling operation (a) cylindrical mold and (b) tapered mold

For mass conservation:

$$\nabla \cdot \bar{u} = 0 \qquad \text{(Eq 1)}$$

For momentum conservation:

$$\rho \frac{\partial}{\partial t}(\bar{u}) + \rho \nabla \cdot (\overline{uu}) = -\nabla p + \nabla \cdot \tau \qquad \text{(Eq 2)}$$

where p is the static pressure, $\bar{u}$ is the velocity vector, and τ is the shear stress tensor related to slurry viscosity, μ, thus:

$$\tau = \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \qquad \text{(Eq 3)}$$

To determine μ, the slurry was assumed to be a non-Newtonian fluid with a power-law rheology, thus (Ref 9):

$$\mu = m\left|\frac{1}{2}(\Delta : \Delta)^{1/2}\right|^{n-1} \qquad \text{(Eq 4)}$$

where Δ is the rate of deformation tensor, $(\Delta : \Delta)$ is the dyadic product of Δ, and m and n are empirical coefficients defined as (Ref 9, 10):

$$m = \exp(9.783 f_s + 1.435) \qquad \text{(Eq 5)}$$

$$n = 0.1055 + 0.41 f_s \qquad f_s < 0.30$$
$$n = -0.308 + 1.78 f_s \qquad f_s \geq 0.30 \qquad \text{(Eq 6)}$$

Although the relations in Eq 5 and 6 were originally derived from the data on a semisolid tin-lead alloy (Ref 9, 10), Ilegbusi and Szekely (Ref 7, 8) have demonstrated their validity for other alloy systems.

3. Determination of Fractionation

A quasi-multiphase approach was used to quantify fractionation. Specifically, a known number of particles was injected into the mold with the slurry, and the dynamics and trajectories of these particles were investigated. The particles were allowed to exchange momentum with the continuous phase. A particle was assumed to be removed from the domain if it either hit the wall or got trapped in a recirculation zone.

The amount of particles remaining in the slurry at various sections of the mold were then numerically counted to determine the extent of segregation. Fractionation is defined here as:

$$F_r = 1 - \frac{\Sigma n_z}{n_o} \qquad \text{(Eq 7)}$$

where n_o is the total number of particles introduced at the inlet and Σn_z is the predicted sum of all particles across the mold that remain in the slurry at height, z, above the nozzle.

4. Numerical Method

The governing equations (Eq 1, 2) were solved numerically with a fully implicit, finite-domain scheme embodied in the PHOENICS code (Concentration, Heat and Momentum, Ltd. [CHAM], Wimbledon, England) (Ref 11). The velocity-pressure coupling was handled using the SIMPLE algorithm (Ref 12).

The mold filling process involved the interaction of two distinct media (slurry and air) at the free surface. This sharp property interface was handled with a scalar-equation numerical method (Ref 11), which used the Van Leer scheme (Ref 13). A 30 by 50 grid structure coupled with a time step of 0.001 s was employed for complete mold filling in all computations.

5. Results

Calculations were performed to investigate the effects on fractionation and mold filling of mold geometry, inflow rate, nozzle diameter relative to mold, and fraction solid. Only one-half of the mold was considered in each case due to symmetry.

Figure 2 shows an intermediate stage of the mold filling process at 0.5 s after injection. Both systems exhibited a jetting characteristic with high velocity at the axis due to slurry thixotropy. The jet penetration and hence, free surface deflection, were lower in the tapered mold than in the cylindrical mold due to the larger adverse pressure gradient. In addition, the high

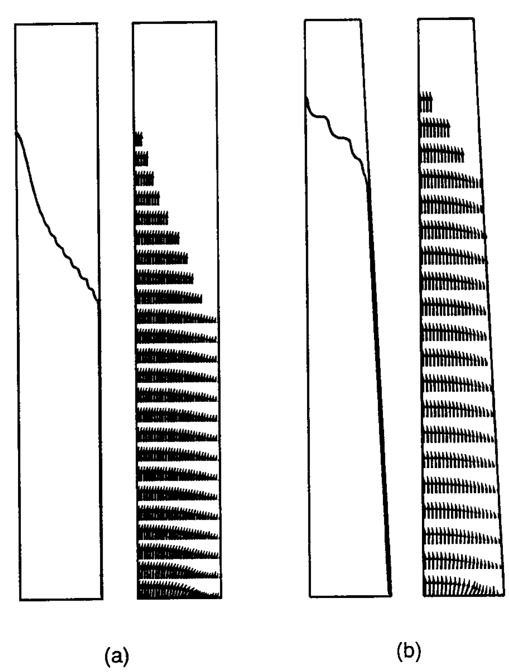

Fig. 2 Advance of slurry and velocity field after 0.5 s for (a) cylindrical and (b) tapered mold (V = 0.4 m/s, f_s = 0.6, D_n = 0.6 D_m)

shear rate generated in the tapered mold enhanced the shear thinning and flowability of the slurry and suppressed free-surface waves.

This result is significant because one of the primary reasons for employing bottom pouring in practice is the expectation that the free-surface disturbances will be reduced compared to top pouring arrangement. While such a trend is generally true for mold filling of pure melts, the result obtained here indicates a somewhat different behavior and underlines the complexity of semisolid slurry rheology. Apparently, free-surface disturbance can be suppressed by use of a tapered mold.

Figure 3 presents the effect of inflow velocity on fractionation in the molds. Fractionation generally decreased with the inflow rate as the residence time of slurry in the mold decreased and interphase drag forces increased. While the fractionation levels were essentially the same for both molds at high velocity, they were much smaller for the tapered mold at low flow rate. This trend is consistent with the flow pattern presented in Fig. 2 and the larger drag forces in the tapered mold.

Figure 4 presents the effect of nozzle diameter (D_n) at the inlet on fractionation. Fractionation decreased as the nozzle diameter increased due to the reduced size of the recirculating flow between the nozzle and the wall, as the nozzle diameter increased relative to the mold (D_m). The recirculation zone enhanced the retention of particles and hence, the fractionation rate. The change in fractionation was considerably larger for the tapered mold because of the smaller recirculation zone for the same nozzle diameter, compared to the cylindrical mold.

Figure 5 shows the response of the fractionation rate with changes in the fraction solid, f_s, of the slurry. The observed reduction in fractionation at high-fraction solid resulted from the enhanced flow resistance.

6. Conclusions

Fractionation during mold filling of semisolid slurries was studied for cylindrical and tapered mold configurations. The systems were investigated under a range of injection velocity, nozzle area, and fraction solid. Fractionation was estimated by solving transport equations for isothermal particles injected with the slurry and determining the proportion of particles remaining in the system at various axial sections of the mold.

The major finding of the study is that fractionation is strongly dependent on the processing conditions and mold geometry. It is reduced at high-inflow velocity, large nozzle area relative to mold at the inlet, and low fraction solid of slurry. The fractionation rate is generally lower in the tapered mold than the cylindrical mold. Both mold filling processes are characterized by jetting of the slurry. The degrees of jetting and free-surface distortion are reduced in the tapered mold.

These results have major practical implication. Specifically, in order to successfully cast slurries of high-solid fraction as required for advanced engineering components with minimal phase segregation, rapid mold filling with large nozzle diameter relative to the mold is required. The results also indicate that

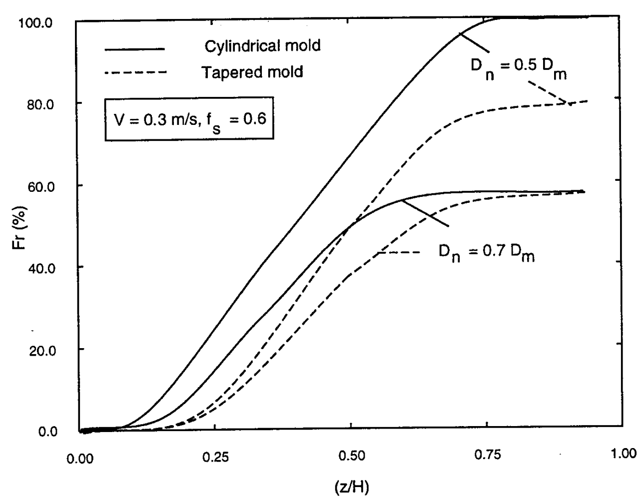

Fig. 4 Effect of nozzle diameter on axial variation of fractionation at complete filling

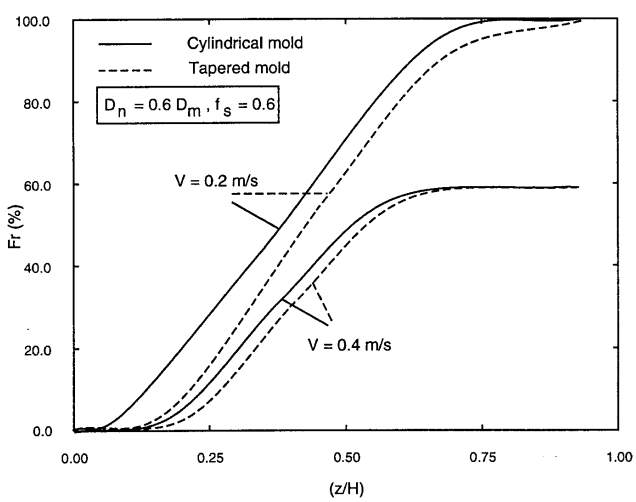

Fig. 3 Effect of inlet velocity on variation of fractionation at complete filling

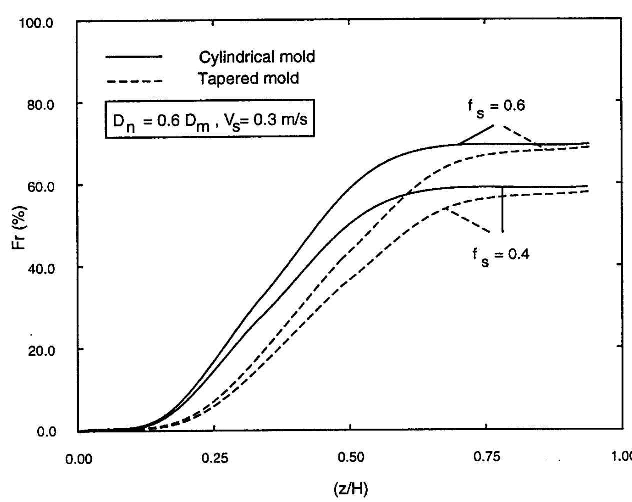

Fig. 5 Effect of fraction solid on axial variation of fractionation at complete filling

the large drag force created by reduced mold section improves flowability (or shear-thinning characteristics) and decreases phase segregation in the slurry.

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