The effects of filling patterns on the powder–binder separation in powder injection molding

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ABSTRACT

The powder–binder separation is a common difficulty during injection molding, which leads to the inhomogeneity in the debinding and sintering stages. Previous studies focus on the relationship between "final results" and "initial conditions", while the dynamic filling process of feedstock and the evolution of powder–binder separation were ignored. This work investigated the effects of filling patterns on the powder–binder separation during powder injection molding. The mold filling model of PIM has been developed, based on the multiphase fluid theory and the viscosity model of feedstock. Parameters of the viscosity model were modified by the experimental data. Numerical simulations were compared with experiments with the same process parameters. The powder–binder separation phenomena in green bodies were detected by X-Ray computed tomography (CT). The experimental phenomena were explained clearly by the evolution of powder–binder separation obtained with numerical simulation method. A typical compacting filling pattern of PIM and filling mobility variable of the feedstock were proposed. A proper filling pattern was helpful to ensure the mobility of feedstock and the homogeneity of green body.

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1. Introduction

Powder injection molding (PIM) is a net-shape-forming technology that provides advantages when making complex-shape parts with high-performance of engineering materials. Typically, there are four stages involved in PIM process, namely mixing, injection molding, debinding and sintering, among which molding is a critical stage for forming a desired shape. The study of the rheological behavior of feedstock is very important to understand the molding process. The feedstock exhibits pseudoplastic or shear thinning flow behaviors, and the properties of feedstock are generally closer to a polymer [1]. A systematic analysis for the effect of binder and powder system on rheological properties was done by Ahn [2], and the results showed that the power law index of viscosity model was more sensitive in binder selection than powder selection. The effects of other factors on rheological properties of feedstock during molding process, such as molding dimensions [3], particle size distribution [4], powder loading [5,6] and process parameters [7,8] were widely reported in the technical literature.

The separation of powder and binder is a common difficulty during injection molding, which may lead to the inhomogeneity in the debinding and sintering stages. The phase separation phenomena could be detected by X-Ray CT [9,10]. Increasing powder content

was available to alleviate separation effects [11]. The effect of mold on powder accumulation regions and binder rich regions was discussed by Karatas [12]. Shivashankar [13] proposed a predictor of powder–binder separation, which is based on particle size, particle volume fraction and maximum particle content. The powder–binder separation has been widely investigated, but these studies mentioned in the literature [9,13] were focused on the relationship between "final results" and "initial conditions", sometimes, conflicting conclusions were obtained [11,13]. The dynamic filling process of feedstock and the evolution of powder–binder separation were ignored.

The evolution of powder–binder separation during injection molding is difficult to be detected with experimental method, especially, in the early stage of molding. Numerical calculation method has the advantage in the understanding of material feature evolution during preparation process. Multiphase fluid model has been developed to study the injection molding stage with numerical simulations [14,17]. The modified viscosity model of feedstock based on the experimental data had good effect on the simulations [18,19]. Simulations of powder–binder separation have been done by Kim [15] and Samanta [17], but there was a lack of evolution of powder–binder separation and corresponding systematic analysis.

The purpose of this study was to investigate the influence of filling patterns on the powder–binder separation in powder injection molding. The mold filling model of PIM has been developed, coupling the multiphase fluid theory with viscosity model of feedstock. The viscosity

model of feedstock was modified by the measured experimental data. In order to compare the obtained experimental data with numerical simulation results, the same process parameters were used. The powder–binder separation in the green body was detected by X-Ray CT. The experimental phenomena were explained clearly by the evolution of powder–binder separation obtained by numerical simulation. A compacting filling pattern of PIM and filling variable of feedstock were proposed, and the corresponding quantitative analysis was performed.

2. Model of mold filling

2.1. Powder–binder two-phase model

In PIM, a high powder loading is required, and particles almost touch with each other. Therefore, in this study the powders were hypothesized to be a pseudo-liquid phase that had properties very similar to that of real solid particles. The binder was treated as another liquid phase. The powder pseudo-liquid phase and binder liquid phase follow the continuity equations for mass, momentum and energy.

The mass conservation equation is:

$$\frac{\partial}{\partial t}(\phi_k \rho_k) + \nabla \cdot (\phi_k \rho_k \mathbf{v_k}) = 0. \tag{1}$$

The momentum conservation equation is:

$$\frac{\partial}{\partial t}(\phi_k \rho_k \mathbf{v}_k) + \nabla \cdot (\phi_k \rho_k \mathbf{v_k} \mathbf{v_k}) = -\phi_k \nabla p_k + \nabla \cdot (\phi_k \boldsymbol{\tau}_k) + \phi_k \rho_k \mathbf{g} + \mathbf{F}_k. \tag{2}$$

The energy conservation equation is:

$$\frac{\partial}{\partial t}\left[\phi_k \rho_k \left(e_k + \frac{1}{2}\mathbf{v_k^2}\right)\right] + \nabla \cdot \left[\phi_k \rho_k \mathbf{v_k}\left(e_k + \frac{1}{2}\mathbf{v_k^2}\right)\right] = -\nabla \cdot (\phi_k p_k \mathbf{v_k}) \\ + \nabla \cdot (\phi_k \boldsymbol{\tau}_k \cdot \mathbf{v_k}) - \nabla \cdot (\phi_k q_k) + \phi_k \rho_k \mathbf{g} \cdot \mathbf{v_k} + E_k \tag{3}$$

where k represents either the powder phase or the binder phase and ϕ_k, ρ_k, $\mathbf{v_k}$ and $\mathbf{q}_k$ are the volume fraction, density, velocity and heat flow flux of phase k, respectively.

$\mathbf{F}_k$ is the drag force that results from momentum exchange between both phases. E_k is the source term in the energy equation that takes care energy exchange between the phases.

2.2. Viscosity model of feedstock

Using the appropriate model is helpful to get reliable results of numerical simulation. Koszkul [20] discussed several viscosity models, and the difference mainly concentrated upon viscosities at the very low shear rate range. In this study, the power law model was used to describe the viscosity of feedstock.

$$\eta_f = \eta_b K_{\phi D}\dot{\gamma}^{n-1} \tag{4}$$

where η_f and η_b are the viscosities of feedstock and binder system; $\dot{\gamma}$ is the shear rate and n is the power law index, for polymer melts, $0 < n < 1$. $K_{\phi D}$ is a factor based on the powder loading, particle size and shape. In this study, the powder loading and particle are fixed, and $K_{\phi D}$ is a constant decided by the viscosity experimental data.

The viscosity of each component of the binder is:

$$\eta_{bx} = \eta_{0x} \exp\left[\left(\frac{E_x}{R}\right)\left(\frac{1}{T_b} - \frac{1}{T_{0x}}\right)\right] \tag{5}$$

where η_{bx} and η_{0x} are the viscosities of each component at the binder temperature T_b and T_{0x}. R is the gas constant and E_x is the viscous flow activation energy of each component [21], as shown in Table 1. The influence of temperature on the viscosity of feedstock is mainly reflected in the viscosity of binder.

Table 1
Viscosity properties of components of the binder.

Components	T_{0x}/K	$\eta_{0x}/Pa\cdot s$	$E_x/J\cdot mol^{-1}$
PW	373	0.009	4400
HDPE	463	300	26,300
SA	383	0.007	0

The viscosity of the binder system can be calculated by the superposition principle [22,23]:

$$\ln(\eta_b) = \sum_{i=1}^{n} W_i \ln(\eta_{bi}) \tag{6}$$

where W_i is the weight fraction of each component.

Study by Manninen [24] showed that the viscosity of binder and powder agreed with the additive principle:

$$\eta_f = \phi_b \eta_b + \phi_p \eta_p \tag{7}$$

where η_p is the powder viscosity. According to Eqs. (4)–(7), the powder viscosity can be obtained.

2.3. Powder–binder drag force

In the two-phase model, the drag force [25,26] between binder and powder is defined as:

$$\mathbf{F_{bp}} = \frac{1}{2}C_D A_p \rho_{bp}\left|\boldsymbol{v_p} - \boldsymbol{v_b}\right|\left(\boldsymbol{v_p} - \boldsymbol{v_b}\right) \tag{8}$$

where C_D is the drag coefficient, A_p is the area of a single particle projected in the flow direction, $A_p = \frac{\pi d_p^2}{4}$, d_p is the particle mean diameter, ρ_{bp} is the mixture density, and $\rho_{bp} = \phi_b \rho_b + \phi_p \rho_p$.

The drag coefficient [25,26] is defined as:

$$C_D = \frac{24}{Re_p}\left(1 + 0.15Re_p^{0.687}\right) + \frac{0.42}{1 + 42500Re_p^{-1.16}} \quad \text{for } Re_p < 2 \times 10^5. \tag{9}$$

The magnitude of drag force is primarily dictated by the particle Reynolds number [26], defined as:

$$Re_p = \frac{\rho_{pb} d_p \left|\mathbf{w_{pb}}\right|}{\eta_f} \tag{10}$$

where $\mathbf{w_{pb}}$ is the relative velocity between powder and binder, and $|\mathbf{w_{pb}}| = |\boldsymbol{v_p} - \boldsymbol{v_b}|$.

When the viscosity of feedstock is influenced by the feedstock temperature and the shear strain rate, Re_p changes, resulting in the change of drag force between powder and binder. Furthermore, the different velocities of binder and powder will be obtained with numerical calculation of the continuity equations, leading to the powder–binder separation.

2.4. Energy exchange between the phases

In the two-phase model, energy exchange between the phases is made mainly of interphase heat transfer. The rate of interphase heat transfer between binder and powder Q_{bp} is defined as:

$$Q_{bp} = h_{bp} A_p \left|T_p - T_b\right| \tag{11}$$

where T_p is the temperature of phase powder, and h_{bp} is an overall heat transfer coefficient, defined as:

$$h_{bp} = \frac{\left(\phi_b \lambda_b + \phi_p \lambda_p\right)N_u}{d_p} \tag{12}$$