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Prediction of density variation in powder injection moulding-filling process by using granular modelling with interstitial power-law fluid

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ABSTRACT

In the present study, granular modelling with an interstitial power-law fluid was used to simulate the filling process in powder injection moulding (PIM). The granular model enables direct prediction of the density distribution. The feedstock, consisting of stainless steel powder and a multicomponent binder system, was injected in two moulds with designed features to verify the simulation results. The effects of the moulding parameters on the homogeneity of the powder particle distribution were investigated. The experimental results agreed well with the predictions. The results indicated that the granular model presented herein could be used for mould design and the determination of injection parameters.

1. Introduction

Density variation is an inherent problem in the injection-moulding process of metallic and ceramic powders [1,2]. It is desirable to maintain a uniform powder packing density in the feedstock to eliminate any sources of distortion in the subsequent sintering process [3–5]. To save the cost of materials, numerical simulation is employed to predict the density variation in the mould-filling process [6–11]. There are three types of models used: continuum model, bi-phase model and granular model. The continuum model assumes that the feedstock maintains a constant density during moulding, and thus it cannot predict the density variation.

To remedy this problem, some researchers recommend using the mixture theory for modelling the PIM, where the bi-phase model is the most frequently used theory [12–15]. In the literature, the bi-phase model is usually used to simulate the powder–binder-phase separation. Barriere et al. achieved good results simulating the powder–binder separation [16]. Greiner et al. established a bi-phase model to explain the yield stress and shear-induced powder migration in the micro-PIM process [17]. Wang et al. used the bi-phase model to explain the boundary layer effect [18]. However, the bi-phase model treats the flow of feedstock as the addition of two distinct but coupled flows characterised by the viscosities of the binder and powder. As well as the binder, the viscous behaviour of the rigid powder phase must be provided to simulate the flow of feedstock; however, the viscosity of powder in the binder cannot be measured directly. Hence, additional work and more simulation time are required to obtain the viscous behaviour of the powder. Moreover, powder particles are theoretically incapable of being treated as a continuous phase. Thus, the bi-phase model suffers both practical and theoretical flaws.

As an alternative to the above continuum mechanics approach, a discrete model might be a better choice for describing mutual interparticle interactions, even locally [19]. Aizawa and Iwai developed a granular model to simulate the mould-filling process of electropackaging materials [20,21]. The model considers the movement and trace of each granular element, which is composed of a powder and a thin surrounding binder layer. The prediction of density variations allows for direct process simulations for investigating the formation of defects such as pores and density variations. However, their model treats the internal contact force between two granular elements as the sum of the elastic and damping forces. This assumption fails to consider the fact that the actual contact force during moulding is a viscous force for most wax-based binder systems.

Further work needs be carried out on modelling the contact force. The thermoplastic binder is power-law fluid. The powder injection-moulding process can be regarded as a process of squeeze flowing of a power-law fluid between rigid spheres, an idea that has been employed in the simulation of many real industrial problems, including the classical lubrication of engineering bearings, the press moulding of composite materials, and powder granulation [22–26]. However, there is no research focusing on the simulation of powder injection moulding using this idea.

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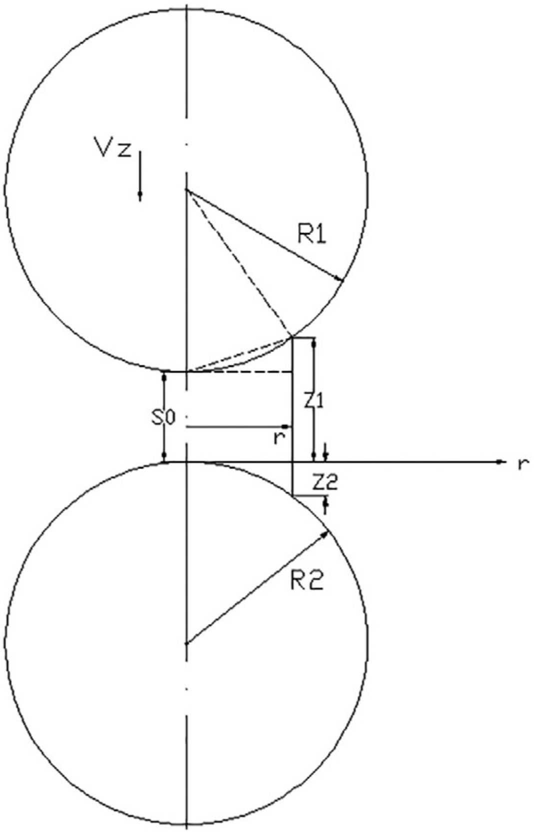

Fig. 1. Schematic of normal motion of two particles.

In this work, a granular model with an interstitial power-law fluid is proposed to simulate the powder injection-moulding process. The density variation is predicted and validated by comparison with experiments. This model can provide not only alternative solutions in understanding die filling and powder transfer mechanisms, it also establishes an improved numerical tool for mould design and injection parameter optimising.

2. Theoretical model

In this work, we use the derivation of the leading-order lubrication term for the axisymmetrical squeeze flow of a power-law fluid between two rigid spherical particles under a no-slip boundary condition. The particles are assumed to be completely immersed in the fluid of binder and to have the same radii, R. The effects of particle shape and particle size are ignored. It is considered that every particle approaches every other particle along their common axis. As shown in Fig. 1, it is assumed that one particle is stationary and the other has a velocity v; thus, the problem is formulated using cylindrical coordinates.

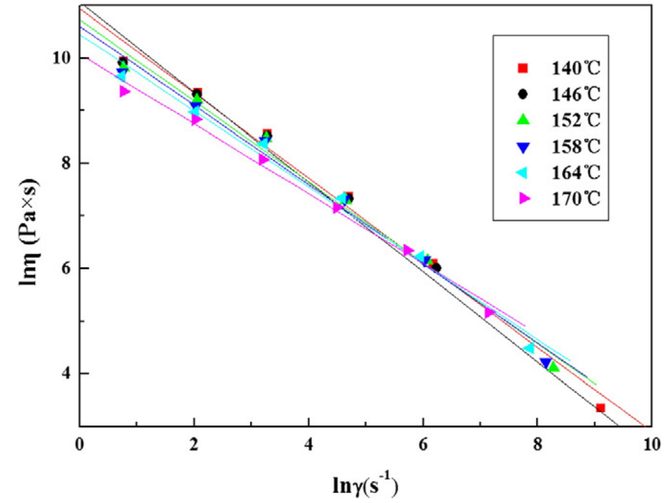

Fig. 3. lnη vs. ln$\dot{\gamma}$ rate at different temperatures for the binder.

Table 1
Moulding parameters for simulation and experimental works.

Parameters	Values
Injection temperature (°C)	150, 160, 170
Injection pressure (MPa)	90, 180
Injection velocity (m/s)	6, 9, 12
Holding pressure (MPa)	40
Cooling time (s)	40

The governing equations of the granular model are expressed as follows [22–26]:

(1) Under the lubrication assumption, the momentum equation reduces to the following expression:

$$\frac{\partial p}{\partial r}=\frac{\partial \tau_{rz}}{\partial z} \tag{1}$$

where p is the pressure and τ_{rz} is the shear stress.

(2) The continuity equation for the symmetric radial flow of the fluid between the particles can be expressed as

$$\frac{1}{r}\frac{\partial (r v_r)}{\partial r}+\frac{1}{r}\frac{\partial v_\theta}{\partial \theta}+\frac{\partial v_z}{\partial z}=0 \tag{2}$$

where v_r and v_z are the radial and axial velocities, respectively.

(3) The constitutive equation for a power-law fluid can be expressed as

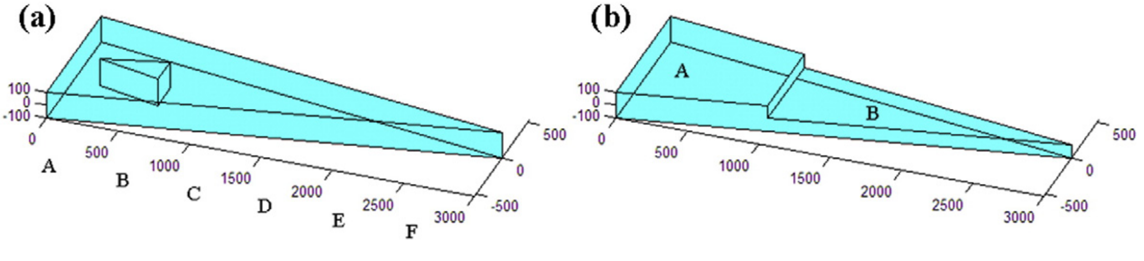

Fig. 2. Schematics of moulds for simulation and verification work: (a) Obstacle mould and (b) step mould (unit: μm).