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Numerical simulation of industrial die filling using the discrete element method

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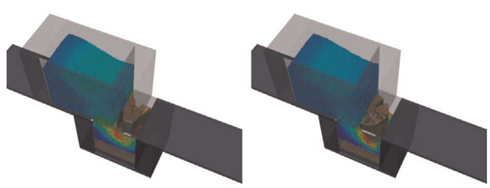
HIGHLIGHTS

- The signed distance function (SDF) model was employed to the DEM simulation.
- In this study, the DEM/SDF model is newly applied to arbitrarily shaped dies.
- The macroscopic flow in the simulation corresponds to that in the experiment.
- Adequacy of the DEM/SDF model is validated in the case of a die filling system.
- The DEM/SDF model is shown to be effective to industrial die filling systems.

GRAPHICAL ABSTRACT



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ABSTRACT

Die filling is an important aspect of powder molding in chemical engineering. The discrete element method (DEM) has been applied to simulations of die filling systems in the literature. In these simulations, the die has been modeled by simple shapes such as cylinders and cuboids. However, industries require modeling of complex die shapes in the computations. In addition, the existing DEM is problematic from the viewpoint of industrial applications, since complexly shaped dies might not be modeled by existing technologies. To solve this problem, the signed distance function (SDF) model is applied to the DEM simulation (DEM/SDF) and the DEM/SDF approach is validated for arbitrarily shaped dies. Focusing on macroscopic powder flow, simulation results are compared with experimental results, and good agreement is confirmed for the spatial distribution of velocity, the projection areas of the shoe, and the final mass of filling particles. Therefore, the adequacy of the DEM/SDF model is newly demonstrated in the die filling system; i.e., the DEM/SDF method is shown to be an effective method for the numerical simulation of particle flow into arbitrarily shaped dies.

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1. Introduction

Die filling is a process carried out in powder molding, and is widely employed in the field of powder metallurgy and in the ceramic, pharmaceutical and food industries (Rowe et al., 2005; Schneider et al., 2007). In these applications, the filling state of the

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powder in the die determines the quality of product. To achieve an appropriate filling state, raw powders should be uniformly poured into the die. Powder filling is strongly affected by the apparatus of filling systems, specifically, the shapes of the dies. In fact, the shapes of the dies are empirically determined and created by trial and error. Because these processes are financially expensive and time consuming, there is a need for numerical simulation as an alternative. The die filling process has thus been viewed by industry as an important subject.

Numerical simulation is a promising approach of investigating various phenomena. The discrete element method (DEM) (Cundall and Strack, 1979) is an effective method of determining discontinuous granular flows by computing interactions between particles. In the DEM, the behavior of each particle is calculated using Newton's second law of motion. It is thus easy not only to calculate the contact force of particles but also to add additional physics models such as that for the cohesive force. There are models available for the calculation of the contact force. In particular, the simple linear contact model has been commonly used in previous DEM simulations of industrial applications such as a fluidized bed (Jajcevic et al., 2013; L. Lu et al., 2014; Sakai et al., 2014, 2012b, 2010), conveyor transport (Sakai and Koshizuka, 2009; Shigeto and Sakai, 2011) and mixing/milling (Govender et al., 2013; Gui et al., 2013; Sakai et al., 2012a; Sun et al., 2014, 2013).

The DEM has been applied to the die filling system in an investigation of the powder flow behavior during die filling, revealing the essential features of powder flow into box-shaped dies (Guo et al., 2009). The segregation behaviors of binary mixtures or non-spherical particles during die filling have also been investigated (Bierwisch et al., 2009; Guo et al., 2011). However, these simulation studies were almost completely limited to simple box-shaped dies rather than dies with complex shapes like those used in industrial applications. Hence, applicability of the DEM simulation to die filling was not demonstrated in previous studies. Indeed, the modeling of a complexly shaped die is a difficult challenge in DEM simulations. Accordingly, there is little knowledge or information on arbitrarily shaped die systems, though an arbitrarily shaped die is often required by industry.

In previous DEM simulations, the calculation domain, namely the wall boundary, has been modeled using meshes (Cleary et al., 2003; Shigeto and Sakai, 2011). Although the meshes are applicable to an arbitrarily shaped wall, the detection of collisions between particles and wall boundaries is difficult. In other words, the procedures of the collision detection requires make multiple detections such as on particle-vertex, particle-edge, or particle-surface, and depends on the complexity of mesh boundaries. In addition, the algorithm of the moving-boundary calculation using a mesh boundary might become extremely complex. Consequently, DEM simulations using a mesh boundary have rarely been employed by researchers at universities or institutes. To solve problems relating to the wall boundary, a new boundary model was recently proposed (Shigeto and Sakai, 2013). In this model, the wall boundaries are created using a scalar field based on the signed distance function (SDF) in the DEM (DEM/SDF). This DEM/SDF model can simulate not only arbitrarily shaped systems but also a moving wall boundary by means of a simple algorithm. Additionally, the DEM/SDF model can easily evolve to simulate a solid–fluid coupling problem without using adaptive mesh methods or other special methods. Although the SDF model has an advantage over the mesh model, the adequacy of the SDF model has only been verified by comparison with a mesh model. The SDF model has not been previously validated for arbitrarily shaped systems such as those of die filling. Validation of the DEM/SDF model is expected to benefit the design of dies for industrial use. Thus, there is a need to validate the DEM/SDF model for arbitrarily shaped die filling systems.

In the field of powder metallurgy, metal injection molding is employed to produce geometrically complex metal parts. In the current study, we focus on powder metallurgy, where particles having relatively high density, such as glass beads, are used. Although the wall boundary has been modeled by the mesh model in previous DEM simulations, the SDF model is introduced into the die filling simulation by means of the DEM. The DEM/SDF model is an approach differing from previously used models in the simulation of die filling. In previous studies, the die shape was quite simple, and hence the applicability of the DEM to geometrically complex die filling system was not demonstrated. Accordingly, the challenge is to demonstrate the application of the DEM/SDF to a geometrically complex die filling system from the viewpoint of industrial applications.

From the above background, in this study, the DEM/SDF model is newly applied to arbitrarily shaped dies. Adequacy of the DEM/SDF model is validated in the case of a die filling system for the first time. In addition, applicability of the simple linear spring model is demonstrated for the die filling systems. Indeed, it is important to model the complexly shaped die and to apply the simple contact model, which is commonly used in simulations, when applying the DEM simulation to die filling. Powder flow simulations are conducted for four differently shaped dies. The shapes and the calculation domain are modeled using the SDF model. In the validation tests of the DEM/SDF model, the simulation results are compared with experimental results. In addition, particle image velocimetry (PIV) is employed to perform more accurate validation tests. The macroscopic powder flow obtained from the DEM/SDF model is shown to qualitatively agree with that of experimental systems, specifically, the mass of filling particles and the frontal projected area of the shoe. Hence, the DEM/SDF model is newly validated for a die filling system. These results indicate that the use of the DEM/SDF model is an effective approach of modeling real and complex die shapes in numerical simulation. The DEM/SDF model thus opens a door for numerical simulation in the design of die filling.

2. Numerical modeling

2.1. Modeling of solid particles

In the DEM, modeling of the solid particle is based on Newton's second law of motion. The governing equations of the translation and rotation of the solid particle are

$$m\frac{d\boldsymbol{v}}{dt}=\sum \boldsymbol{F}^C+\boldsymbol{F}^G, \tag{1}$$

$$I\frac{d\boldsymbol{\omega}}{dt}=\boldsymbol{T}, \tag{2}$$

where m is the mass of the solid particle, $\boldsymbol{F}^C$ and $\boldsymbol{F}^G$ are respectively the contact force and gravitational force acting on the solid particle, I is the particle inertia, $\boldsymbol{T}$ is torque, and $\boldsymbol{v}$ and $\boldsymbol{\omega}$ are the translational and rotational velocities of the solid particle. In this study, the solid particle is assumed to be spherical. The particle–particle and particle–wall contact forces are modeled using the Voigt model, which comprises of a spring, dashpot and friction slider (Cundall and Strack, 1979). In this model, the contact force is divided into normal and tangential components:

$$\boldsymbol{F}^C=\boldsymbol{F}_n^C+\boldsymbol{F}_t^C, \tag{3}$$

where the subscripts n and t indicate the normal and tangential directions, respectively. The normal component is calculated from the overlap and relative velocity. This is given by

$$\boldsymbol{F}_n^C=-k\boldsymbol{\delta}_n-\eta\boldsymbol{v}_n, \tag{4}$$

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