The Bi-phasic Numerical Simulation of Metal Co-injection Molding

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ABSTRACT: Based on the previous works on bi-phasic explicit algorithms, a new bi-phasic modeling for Metal Co-injection Molding is proposed. The matched algorithm is developed for simulation. When two sorts of feedstocks mixed with metallic powder and plastic binder are co-injected into the mold, their different properties are assigned in simulation, such as the viscous behaviors for the flows of powder and binder phase, densities and powder/binder volume fractions. The filling front, the interface between two types of the feedstock and the powder segregation in each injected feedstock can be predicted. Some simulation results are shown to validate this new algorithm.

Key words: Numerical simulation, Metal Co-injection Molding, Segregation, Interface shape

1 INTRODUCTION

Metal Co-injection Molding (MCM) is a new technology for manufacturing components with two metallic materials. It can be used to produce for example magnetic–nonmagnetic components [1] or components with surface layer material and core material [2]. The co-injection process parameters and the viscosities of the feedstocks well determine the shape of the interface between the two materials in the co-injected component. Similar to MIM process, powder segregation in each injected feedstock should be taken into account in MCM. Based on the previous works on bi-phase explicit algorithms [3,4,5], a new bi-phasic model for MCM is discussed and the relevant algorithm is developed. Generally the two types of feedstocks present different properties, such as viscous behavior, density and powder/binder volume fraction. They should be assigned distinctly in simulation in order to evaluate their influence on the filling process and the interface between the two materials. Some simulation results are shown to validate the new algorithm.

2 BI-PHASIC MODELLING OF MCM

2.1 Filling state

In MCM process, two types of feedstocks are injected into the same mould cavity one after the other by the same inlets. Feedstock A is firstly feeded into the mould from instant $t=0$ to $t=t_1$. Then feedstock B will be injected by the same inlet from $t=t_1$ until the mould cavity is entirely filled. During the injection process, the spaces occupied by the two types of feedstock, as well as the unfilled portion occupied in fact by air, should be well described and distinguished to assign the different material properties.

The co-injection filling problem is defined by Eulerian description. Let t be a time step during the filling in the entire period: $t \in [0,\ t_{fn}]$. The cavity Ω consists of a filled portion $\Omega^F(t)$ and a void portion $\Omega^V(t)$. The filled domain $\Omega^F(t)$ is composed of two different subsets: the portion filled actually by feedstock A and the portion in which the filled feedstock A is replaced by feedstock B. The second subset occupied by feedstock B is expressed by $\Omega^R(t)$. Obviously $\Omega^R(t) \subset \Omega^F(t)$.

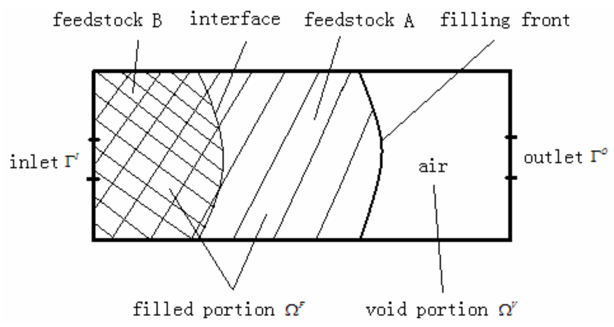

Fig. 1. Geometrical definition

Γ^I indicates inlets of the mold. Γ^O represents the outlets where the air originally in mold gets escaped during injection (Figure 1).

Two field variables $F(\mathbf{X},t)$ and $R(\mathbf{X},t)$ are defined to describe the filling state of the two types feedstock in the mold cavity at instant t. $F(\mathbf{X},t)$ takes value 1 to indicate the filled state at position $\mathbf{X}$ and value 0 for the unfilled state. This field variable describes where it is filled in the mold, whatever by feedstock A or B. $R(\mathbf{X},t)$ is used to indicate the sort of feedstock in the filled portion. If value 0 is assigned to $R(\mathbf{X},t)$, the portion is filled by feedstock A. When $R(\mathbf{X},t)$ takes value 1, the portion is filled by feedstock B.

From $t=0$ to $t=t_1$, only $F(\mathbf{X},t)$ is solved. $R(\mathbf{X},t)$ is set to 0. Starting from $t=t_1$, the mould begins to be filled by feedstock B, instead of feedstock A. The solution of variable $R(\mathbf{X},t)$ begins, while the solution of variable $F(\mathbf{X},t)$ continues. The space filled previously by feedstock A is progressively by feedstock B, driven by the advance of the flow front. The state of filling inside the mould cavity can be well distinguished as shown in table 1:

Table1. Regions of different material properties

Region	F	R	Material
$\{\Omega^F(t)-\Omega^R(t)\}$	1	0	feedstock A
$\Omega^R(t)$	1	1	feedstock B
$\Omega^V(t)$	0	0	air

In the portion filled by feedstock A and feedstock B, one consider the flow of two distinct phases: the metallic powder phase and the plastic binder phase. The volume fraction of powder and binder phase are defined as ϕ^s and ϕ^f, which takes the following values for the two types of feedstock respectively:

$$\begin{aligned}&\forall t,\ \mathbf{X}\in\{\Omega^F(t)-\Omega^R(t)\},\ \phi^s=\phi^s_A\ and\ \phi^f=\phi^f_A\\&\forall t,\ X\in\Omega^R(t),\ \phi^s=\phi^s_B,\ \phi^f=\phi^f_B\end{aligned} \qquad (1)$$

where ϕ^s_A, ϕ^f_A are the powder and binder volume fraction for feedstock A, ϕ^s_B, ϕ^f_B are the powder and binder volume fraction for feedstock B.

The velocities of the two different phases are defined as:

$$\begin{aligned}&\forall t,\ \mathbf{X}\in\{\Omega^F(t)-\Omega^R(t)\},\ \mathbf{V}^s=\mathbf{V}^s_A,\ \mathbf{V}^f=\mathbf{V}^f_A\\&\forall t,\ \mathbf{X}\in\Omega^R(t),\ \mathbf{V}^s=\mathbf{V}^s_B,\ \mathbf{V}^f=\mathbf{V}^f_B\end{aligned} \qquad (2)$$

where $\mathbf{V}^s_A$, $\mathbf{V}^f_A$ are the velocities of powder and binder phase of feedstock A, ϕ^s_B, ϕ^f_B are the velocities of powder and binder phase of feedstock B.

For the void portion, two fictive phases are assigned for uniqueness of the solution algorithm, but the results are not of interest.

The filling state variable $F(\mathbf{X},t)$ is governed by an advection equation, expressed as:

$$\frac{\partial F}{\partial t}+\nabla\bullet(\mathbf{V}^{ef}F)=0 \qquad (3)$$

in which $\mathbf{V}^{ef}$ is the effective velocity of feedstock, defined as:

$$\forall\ \mathbf{X}\in\Omega^F(t),\ \mathbf{V}^{ef}=\phi^s\mathbf{V}^s+\phi^f\mathbf{V}^f \qquad (4)$$

The filling state variable $F(\mathbf{X},t)$ is solved during all the injection process from $t=0$ to $t=t_{fn}$. For the boundary conditions, it takes the value $F=1$ on the inlet Γ^I.

The field variable $R(\mathbf{X},t)$ is governed by an advection equation, too. It is expressed as:

$$\frac{\partial R}{\partial t}+\nabla\bullet(\mathbf{V}^{ef}R)=0 \qquad (5)$$

2.2 *Volume fraction*

The flows of the two phases for feedstock A and B should satisfy the saturation conditions at each space position:

$$\forall \mathbf{X} \in \Omega^F(t), \phi^s + \phi^f = 1 \; and \; \frac{\partial \phi^s}{\partial t} + \frac{\partial \phi^f}{\partial t} = 0 \qquad (6)$$

The densities of each phase are respectively denoted ρ^{s_0} and ρ^{f_0}. Their values depend on the filling of feedstock A and B respectively. The two phases are intrinsically incompressible while their volume fraction can change during the injection process. The apparent densities of each phase in the mixture, denoted by ρ^s and ρ^f, are related to their volume fraction by the following relationships:

$$\rho^s = \phi^s \rho^{s_0} \text{ and } \rho^f = \phi^f \rho^{f_0} \qquad (7)$$

The mass conservation associated to the flow of each phase is expressed as:

$$\forall \mathbf{X} \in \Omega^F(t), \quad p \in \{s, f\}, \frac{\partial \rho^P}{\partial t} + \nabla \bullet (\rho^P \mathbf{V}^P) = 0 \qquad (8)$$

As the densities are constant, mass conservation of each phase can be written as:

$$\forall \mathbf{X} \in \Omega^F(t), \quad p \in \{s, f\}, \frac{\partial \phi^P}{\partial t} + \nabla \bullet (\phi^P \mathbf{V}^P) = 0 \qquad (9)$$

2.3 *Momentum conservation*

The mass conservation for each phase and the saturation condition of the mixture result in incompressibility of the mixture flow:

$$\forall \mathbf{X} \in \Omega^F(t), \quad \nabla \bullet \mathbf{V}^{ef} = 0 \qquad (10)$$

When the Reynolds number is small, the momentum conservations of the two distinct phases are expressed by two coupled Stokes equations. These equations for the filled part of the mould cavity are:

$$\forall \mathbf{X} \in \Omega^F(t), \; p \in \{s, f\}, \quad \rho^P \frac{\partial \mathbf{V}^P}{\partial t} = -\nabla(\phi^P P) + \nabla \bullet (\mu_P \dot{\boldsymbol{\varepsilon}}_P) + \rho^P \mathbf{g} + \mathbf{m}^P \qquad (11)$$

where P stands for the pressure. μ_s and μ_f are viscosities of powder and binder phase in filled part, depending on the filling by feedstock A and B. $\dot{\boldsymbol{\varepsilon}}_s$ and $\dot{\boldsymbol{\varepsilon}}_f$ are the rate of strain for the two phases. ρ^s and ρ^f are respectively the apparent densities of the two phases, $\mathbf{g}$ is the gravitational acceleration vector. At each position, the coupling terms $\mathbf{m}^s$ and $\mathbf{m}^f$ associated to momentum exchange are proportional to the velocity differences between the two phases:

$$\mathbf{m}^s = k(\mathbf{V}^f - \mathbf{V}^s), \; \mathbf{m}^f = k(\mathbf{V}^s - \mathbf{V}^f) \qquad (12)$$

where k is an interaction coefficient determined by relevant experiments, which may have different values for the flow region of feedstock A and B.

The explicit algorithm for bi-phasic MCM modeling is based on the same principle as the previous work for MIM simulation [6], but two kinds of feedstocks with different properties should be taken into account. This part of the work is not described in the paper.

3 SIMULATION RESULTS

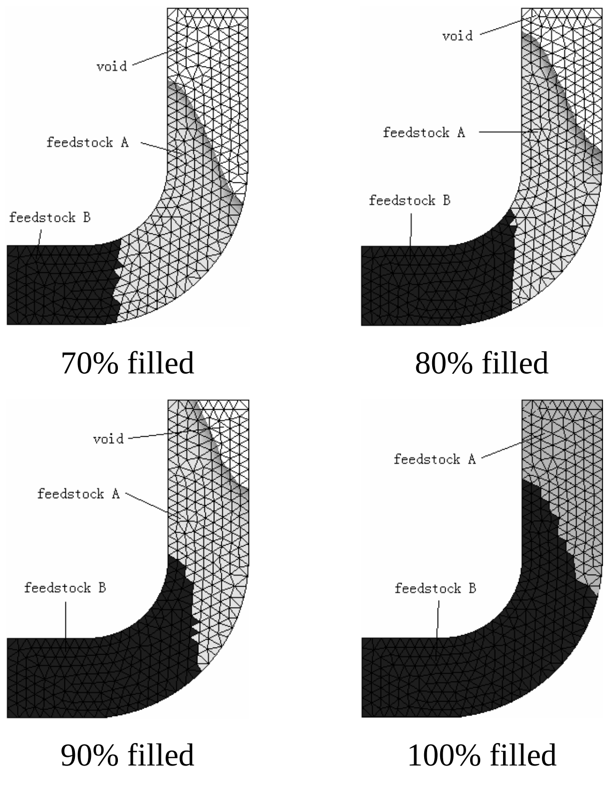

Fig. 2. Co-injection filling state

The feedstock A is injected into the mould cavity until 40% volume of the cavity is filled, then feedstock B replaces feedstock A at injection inlet and continues the injection step. The filling fronts and interfaces between two feedstocks are shown in figure 2, when 70%, 80%, 90% and 100% of the mould cavity is filled. If the mesh is refined, the interface shape would be smoother. The powder volume fraction at the end of the filling stage is shown in figure 3. It can be observed an obvious segregation phenomenon in feedstock B happens in the domain inner radius. The segregation effect is not obvious in the domain filled by feedstock A. The geometrical effect is the main factor which induces the segregation in the elbow part.

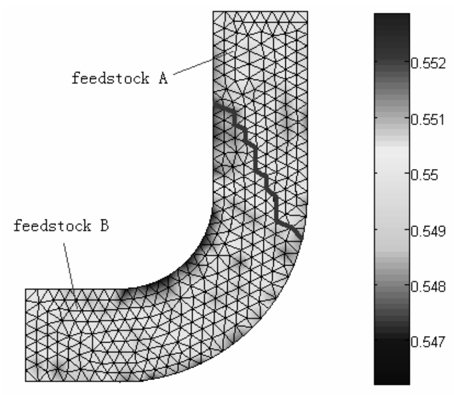

Fig. 3. Powder volume fractions

4 CONCLUSIONS

Metal Co-injection Molding (MCM) is a new technology for manufacturing components with two different metallic materials. The co-injection parameters and the viscosities of the two types of feedstocks influence the shape of the interface between two materials in the co-injected component. Furthermore, powder segregation in each injected feedstock should be taken into account in MCM. In the paper, a bi-phasic MCM modeling is discussed. The filling injection front, the interface between the two feedstocks and the powder segregation in the two filled feedstocks can be predicted.

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