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Modified method for simulation of the filling states at the end of injection molding process

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Abstract: In order to improve the accuracy of numerical simulation for injection molding process, a modified method for outlet condition was introduced. As the feedstock is regarded as incompressible fluid, the filling ratio should be a linear one with respect to time. But there remains a persistent trouble in previous researches that the linearity is not respected when the filling front approaches near the outlet boundary. The problem is caused by lack of adequate treatment on the outlet boundary. To remedy this defect, the present paper deals with the modeling and realization of suitable condition on outlet boundary for solution of the whole filling process. A simple straight channel mold was taken as an example to prove the proposed simulation method. The result shows that this modified method can suppress the distortion phenomenon and can be valid to realize the correct simulation for the filling of incompressible viscous flow at the ending stage. This long-term filling problem was finally solved.

Introduction

Metal Injection Molding (MIM) is a near net shape technology for the manufacture of small intricate parts in 3D shapes^[1]. It represents a strong importance in the field of automotive, aerospace and microelectronics industries^[2]. The MIM technology includes four main stages^[3]: 1) Mixture of feedstock. 2) Injection molding to get the green parts. 3) Debinding stage to remove the binder. 4) Final sintering stage to get the condensed part in pure metallic material.

As a new manufacturing technology, numerical simulation plays an important role in its efficient applications. The analysis of injection molding was started by Spencer and Gilmore^[4] in the early 1950s. Ballman et al^[5] investigated one-dimensional rectangular flow in 1959. Analytical solutions for two-dimensional flow in a rectangular cavity were presented since the late 1970s^[6-9]. Then large amounts of research works were done in detail on fountain flow^[10-12]. The implicit finite element method for simulation of the filling process was firstly tried by some authors^[13-15]. It was found that the main barrier for filling flow model^[16] is the tremendous computational time due to the application of 3D finite element or finite difference method. Therefore, the explicit algorithms for improving the efficiency of simulation for injection flow model were studied and realized by Lewis and Gao, using MINI elements in 2D casting problems^[17-19]. The explicit algorithms with MINI element are much faster than the implicit ones and their validity was proven by the experiments^[20, 21]. For the sake of further reduced computational cost, a new explicit algorithm with fully vectorial operations was proposed by Liu^[22]. The full development is carried out by the research work of Cheng^[23, 24]. By eliminating global solution in the previous explicit algorithm, it made successfully the computational cost to be about linearly proportional to the degree of freedom number.

However, there remains a persistent trouble in simulation of the filling states at the end of injection molding. It happens in the simulations of filling process with imposed constant velocity on inlet. As the feedstock is regarded as incompressible fluid, the filling ratio should be a linear one with respect to time. But the linearity is not respected when the filling front approaches near the outlet boundary.

The cause is indicated in the Ph.D. thesis of T. Barriere ^[25] in 2000, but none of the references is involved to its solution in the retrieving of available sources. In fact, there is a lack of the integration on the outlet boundary. This integration is negligible when the filling front is far way the outlet, but it becomes significant when the front of feedstock approaches. To remedy this defect, the modeling is formulated again. An integration term on the outlet boundary is realized in solution of the advection equation for filling state. The problem in solution of the filling process at the ending stage is finally solved. The examples prove well validity of the proposed method. Stability of the in-house solvers for solution of the volume fractions is improved.

1. Mechanical modeling

1.1 General Definition

As usual, Eulerian description is used for simulation of the mold filling problems, which avoids the remeshing procedures in high expense with Lagrangian description. So general definition of the mold filling problems is expressed as followings:

Let $t \in [0, t_i]$ be an instant in the injection course, in which t_i is the last moment for the fully filled state. The sum of space position X in the whole model is defined as set Ω . The model of injection molding consists of two different portions at each instant, the portion filled by feedstock Ω_F and the remained void portion Ω_V . A field variable $F(x, t)$ is defined to represent filling state of the model at different instants. This field variable takes value 1 to indicate the portion filled by feedstock and value 0 for the remained void portion, which contains in fact the atmosphere. Their physical and geometrical meanings are shown in Fig. 1 In which Γ_I indicates inlet of the mold, Γ_O represents the outlet through that the air originally in the mold may get escaped during the injection. Γ_S stands for intersection of subsets Ω_F and Ω_V , which is in fact the filling front of the injection flow. V_I is the injected velocity on inlet boundary. P_O is the pressure on outlet boundary, which is set to be 0 in present work.

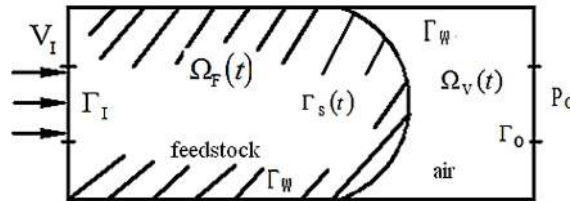


Fig. 1 Filling model based on Eulerian description

1.2 Governing equation for filling state

To keep uniqueness of the solution strategy and simplicity of the software structure, incorporating with the Eulerian description, the governing equation for filling state is the same for filled and void portion of the injection model, except that the parameters are chosen differently for these two domains.

The front position of filled domain is represented by the predefined filling state variable $F(x, t)$. Some authors call it as the variable of pseudo concentration or fictive concentration ^[26, 27]. This variable is dominated by an advection equation, driven by the velocity field.

$$\frac{\partial F}{\partial t} + \nabla \cdot (V F) = 0 \quad (1)$$

The filling flow is intrinsically incompressible, according to mass conservation, the flow should satisfy incompressible condition $\nabla \cdot V = 0$, so Eq. 1 can be written as:

$$\frac{\partial F}{\partial t} + V \cdot \nabla F = 0 \quad (2)$$

The boundary condition is $F = 1$ on inlet of the mold. Its initial condition is $F = 0$ everywhere in the mold except for the inlet surface.

1.3 Determination of the filling states

The filling state variable $F(x,t)$ is determined by the advection Eq. 2. To ensure its stability, the solution is performed by a Taylor-Galerkin method^[28]. The time differential of variable $F(x,t)$ in discretised form can be expressed by a Taylor series development:

$$\frac{(F_{n+1} - F_n)}{\Delta t} = \frac{\partial F_n}{\partial t} + \frac{\Delta t}{2} \frac{\partial^2 F_n}{\partial t^2} + O(\Delta t)^2 \quad (3)$$

where F_n and F_{n+1} represent the filling state at time step t_{n+1} and t_n , Δt stands for the time increment. The same notation is used for velocity variable V . The governing Eq. 3 can lead to the follow relationship by an approximation $\partial V / \partial t = (V_{n+1} - V_n) / \Delta t$:

$$\frac{\partial F_n}{\partial t} = -V_n \cdot \nabla F_n, \quad \frac{\partial^2 F_n}{\partial t^2} = V_n \cdot \nabla (V_n \cdot \nabla F_n) - \frac{(V_{n+1} - V_n)}{\Delta t} \cdot \nabla F_n \quad (4)$$

The weak form of Eq. 3 can be then written as

$$\int_{\Omega} f^* \frac{(F_{n+1} - F_n)}{\Delta t} d\Omega = - \int_{\Omega} f^* V_{n+1/2} \cdot \nabla F_n d\Omega + \frac{\Delta t}{2} \int_{\Omega} f^* V_n \cdot \nabla (V_n \cdot \nabla F_n) d\Omega \quad (5)$$

where $V_{n+1/2} = (V_{n+1} + V_n) / 2$, f^* is a kinematically admissible field associated to variable F . As the velocity V_n is an incompressible field, known that $\nabla \cdot (a\vec{b}) = a \nabla \cdot \vec{b} + \vec{b} \cdot \nabla a$, the second term in right side of above equation can be written as

$$\frac{\Delta t}{2} \int_{\Omega} \nabla \cdot [f^* V_n \cdot (V_n \cdot \nabla F_n)] d\Omega - \frac{\Delta t}{2} \int_{\Omega} (V_n \cdot \nabla F_n) \cdot (V_n \cdot \nabla f^*) d\Omega \quad (6)$$

By virtue of the divergence theorem, the first term can be transformed to a surface integration:

$$\frac{\Delta t}{2} \int_{\Omega} \nabla \cdot [f^* V_n \cdot (V_n \cdot \nabla F_n)] d\Omega = \frac{\Delta t}{2} \oint_{\Gamma} f^* V_n \cdot (V_n \cdot \nabla F_n) \cdot \vec{n} dS \quad (7)$$

2. The inexact result at the end of filling process

Because of incompressibility of the injection flow, the filling ratio should behave linearly versus time when constant velocity is imposed on inlet. But it did not at the ending stage of filling process, when the modeling and simulation in laboratory is applied. There remains a persistent trouble for simulation of the final stage of injection process, when the filling front approaches to the outlet boundary, as shown in Fig. 2.

The results reproduced accurately the real nature until the filling ratio reached to 90%, when the filling front gets near to the outlet boundary. Then the filling of remained void portion becomes slower than the true fact. The cause of such a trouble was indicated in the Ph.D. thesis of T. Barriere

[25]. For Eq. 7, the integration was supposed to take value zero all around the boundary, while it is not true when the filling front approaches to the outlet boundary $X \in \Gamma_o$. It takes indeed value zero when the filling front represents the distance to outlet boundary, when the filling ratio is smaller than 90%. But for the last moment in injection course, this term must be taken into account to simulate correctly the filling pass through the outlet.

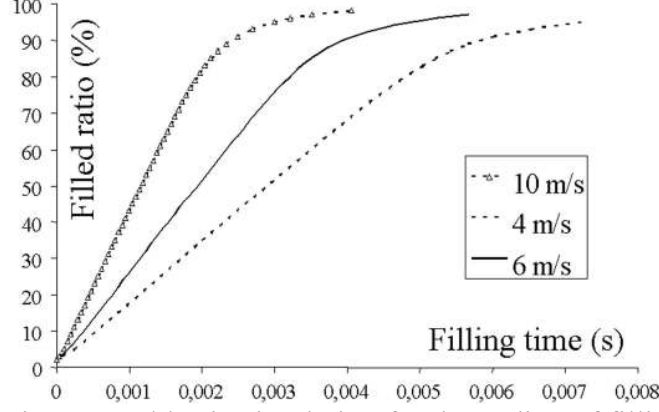


Fig. 2 Persistent troubles in simulation for the ending of filling process

3. Modification of the outlet boundary condition

To remedy the problem mentioned in section 3, an additional integration term should be taken into account on outlet boundary for the last stage in injection course. The following procedure is proposed to realize the adequate integration on outlet boundary.

The discretized form of Eq. 5 by finite element method should be written as:

$$\mathbf{M} \frac{\mathbf{F}_{n+1} - \mathbf{F}_n}{\Delta t} = -[\mathbf{K}^{\text{ad}}(\mathbf{V}_{n+1/2}) + \mathbf{K}^{\text{df}}(\mathbf{V}_n)] \mathbf{F}_n + \mathbf{K}^{\text{O}}(\mathbf{V}_n) \mathbf{F}_n \quad (8)$$

where \mathbf{M} is a lumped pseudo matrix constructed in a specific manner, $\mathbf{K}^{\text{ad}}(\mathbf{V})$ is a stiffness matrix represents the advection effect while $\mathbf{K}^{\text{df}}(\mathbf{V})$ is a stiffness matrix stands for diffusion effect. $\mathbf{K}^{\text{O}}(\mathbf{V}_n)$ is the operator for outlet surface integration term.

$$\begin{aligned} \mathbf{M} &= A \int_{\Omega^e} \mathbf{N}^T \mathbf{N} d\Omega \\ \mathbf{K}^{\text{ad}}(\mathbf{V}_{n+1/2}) &= A \int_{\Omega^e} \mathbf{N}^T \mathbf{V}_{n+1/2}^T \mathbf{G} d\Omega \\ \mathbf{K}^{\text{df}}(\mathbf{V}_n) &= \frac{\Delta t}{2} A \int_{\Omega^e} \mathbf{G}^T \mathbf{V}_n^T \mathbf{V}_n \mathbf{G} d\Omega \end{aligned} \quad (9)$$

where A represents the assembling operation in finite element method. \mathbf{N} is the matrix of interpolation functions in each element for filling state variables F , \mathbf{G} is a gradient operator constructed by derivatives of these interpolation functions. $\mathbf{V}_{n+1/2}$ and \mathbf{V}_n are the values obtained at each Gauss points.

Note N_{out} the nodes associated to outlet surface. Ω_{out}^e represents the elements associated to node N_{out} , defined as:

$$\Omega_{out}^e = \{ \Omega^e \mid N_{out} \subset \Omega^e \} \quad (10)$$

Let Γ_{out}^e represent the edge or side of element Ω_{out}^e on outlet boundary. A unit vector \vec{n}_{out} is defined for each element Ω_{out}^e . This vector is normal to its edge or side Γ_{out}^e .

The term $\mathbf{K}^0(\mathbf{V}_n)$ in Eq. 8 takes the following forms:

$$\mathbf{K}^0(\mathbf{V}_n) = \frac{\Delta t}{2} A \int_{\Gamma_{out}^e} N^T (\mathbf{V}_n^e)^T \mathbf{V}_n^e \cdot \vec{n}_{out}^T \mathbf{G} d\Omega \quad (11)$$

where \mathbf{V}_n^e represents the velocity vector in the element associated to Γ_{out}^e .

By investigation of the flow pattern at outlet of the mold cavity, it is realized that the velocity vector \mathbf{V} and outer normal \vec{n} take the same direction, whereas the gradient of variable F should exhibit the direction opposite to \mathbf{V} and \vec{n} . So on the integration of Eq. 7 can be simplified.

Taking into account the above mentioned features, the integration of Eq. 7 can be written as

$$\frac{\Delta t}{2} \oint_{\Gamma} \mathbf{V}_n \cdot (\mathbf{V}_n \cdot \nabla F_n) \cdot \vec{n} dS = \frac{\Delta t}{2} \int_{\Gamma^o} \|\mathbf{V}_n\| \mathbf{V}_n \cdot \nabla F dS \quad (12)$$

in which $\|\mathbf{V}_n\|$ is the norm of velocity vector, it represents the value $\|\mathbf{V}_n\| = \sqrt{\mathbf{V}_n \cdot \mathbf{V}_n}$.

Then the term $\mathbf{K}^0(\mathbf{V}_n)$ in Eq. 8 takes the following forms:

$$\mathbf{K}^0(\mathbf{V}_n) = \frac{\Delta t}{2} A \int_{\Gamma_{out}^e} N^T \|\mathbf{V}_n^e\| \cdot (\mathbf{V}_n^e)^T \mathbf{G} d\Omega \quad (13)$$

where \mathbf{V}_n^e represents the velocity vector in the element associated to Γ_{out}^e .

This solution scheme consists of only the local and explicit operations, so the prediction is very efficient.

4. Validation of the modified algorithm

The modified integration term on outlet boundary in section 4 was realized on a platform of the Matlab to focus the effort on its development and validation. As this work is based on the previous work on explicit algorithm in laboratory [23, 25], some technical issues were taken directly from the previous work. A simplest filling mold in shape of straight channel was chosen to do the simulation, which was often used as the validation evidence of a newly developed algorithm. It was meshed with triangle elements as shown in Fig. 3 The density of feedstock is 7000 kg/m³, the viscosity takes a value 100 Pa · s, and the velocity value imposed on inlet along the axial direction is 4 m/s, 6 m/s and 10 m/s respectively. These material properties and boundary conditions are assigned just for the purpose to validate the software. They do not mean the real values calibrated by experiments.

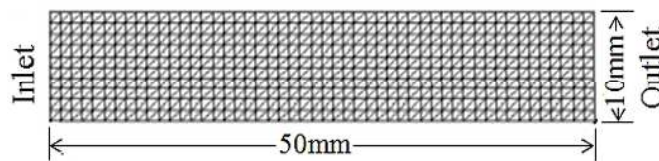


Fig. 3 Meshes of straight channel model

Comparison on evolution of the filling ratio versus time, obtained by previous and modified algorithm, is shown in Fig. 4 It shows that the results obtained by two methods are globally the same until the filling ratio reaches to 90%. Then the results issued of previous algorithm show the filling rates slower than the true ones. While the filling ratio of modified algorithm keeps nearly proportional

all over whole time, including the ending stage. Although it presents a little deviation to the real fact when it fills up to 98%, the fully filled pattern is soon achieved. For the approach and simulation by computation, it represents no more a significant problem.

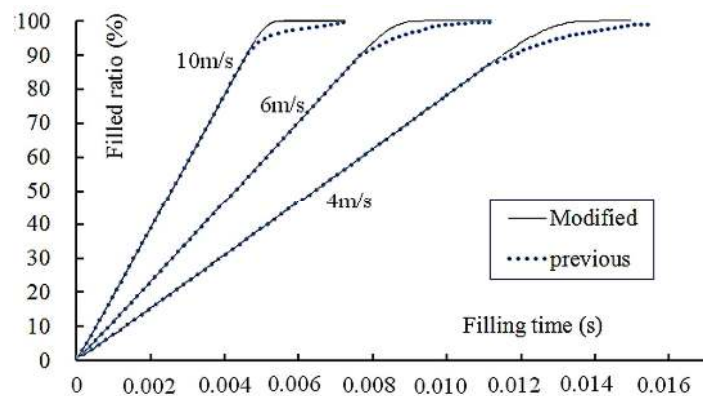


Fig. 4 Comparison on evolution of the filling ratio versus time

5. Conclusion

The modeling of injection molding is modified to simulate correctly the ending stage of filling process. The incorporated implementation is realized in the developed solver. The examples with constant injection velocity on inlet are provided to validate the proposed method. Based on the validations, one can conclude that:

- (1) The modified boundary condition represents a true effect that should be taken into account. Incompressibility of the filling flow can hence be well respected at the last stage of filling process.
- (2) The filing problems in simulation happened in the work of Dutilly^[13] and Barriere^[25] can be solved by modification of the boundary condition on outlet. The opinion of Barriere^[25] was correct. Lack of the integration term on outlet boundary was the true cause for such a problem.
- (3) The persistent problem is solved successfully. The simulation of filling process is made more reliable. Furthermore, the stability for solution of the volume fractions was improved. The in-house solver for simulation of the injection molding was optimized.

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