THREE-DIMENSIONAL SIMULATION OF MULTI-SHOT SEQUENTIAL MOLDING

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Abstract

For the recent years, multi-shot sequential molding is widely applied in various industries. It is a process that uses two or more molds to produce a multi-material component. In principle, the first material is injected into the first mold by standard single-material molding technique and then moved to the next mold where the next material can be injected to combine with it. This complex process is difficult to identify and study correctly by the traditional 2.5D model. In this paper, a three-dimensional numerical approach is developed to simulate the filling, packing and cooling stages in multi-shot sequential molding, as well as the part warpage after ejection. Several cases are reported to indicate the success of the present model.

Introduction

For the recent years, the multi-shot sequential molding in injection molding has been very popular. It is a process that uses two or more molds to produce a multi-material component. In principle, the first material is injected into the first mold by standard single-material molding technique and then moved to the next mold where the next material can be injected to combine with it. This molding process is an efficient technology for injection-molded products. However, the material of previous shot will have a significant effect on the molding phenomena of later shots. It is like the plastic insert decrease the performance of drawing heat from the cavity. On the other hand, it reduces the cooling efficiency. Besides, the interaction and constraint between different molded parts also affects the behavior of warpage.

Conventional 2.5D CAE analysis technology adopts the "Mid-plane Model". The basic principal is to create the Mid-plane of the geometry model. After a long-time development, this technology is quite mature and stable. Now it is also good at the analytic speed and efficiency. Besides, it helps to obtain accurate results for most of the plastic parts, especially for the thin shell parts. Therefore, the 2.5D analysis technology is widely used and becomes the main stream of the injection molding analysis. Since the mid-plane model is quite approved, lots of defects still exist that may affect the accuracy and the efficiency. Especially for the thick parts and multi-component parts, the 3D solid effects are absolutely obvious and cannot be precisely analyzed by the conventional methods. This paper develops a three-dimensional numerical approach to simulating the multi-shot sequential molding in injection-molded part of complex geometry.

Theory

The injection molding simulation has 3 main processes, includes filling/packing, cooling and warpage. For the filling/packing process, the polymer melt is assumed to behave as Generalized Newtonian Fluid (GNF). Hence the non-isothermal 3D flow motion can be mathematically described by the followings.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{u} = 0 \qquad (1)$$

$$\frac{\partial}{\partial t}(\rho \mathbf{u}) + \nabla \cdot (\rho \mathbf{u}\mathbf{u} - \boldsymbol{\sigma}) = \rho \mathbf{g} \qquad (2)$$

$$\boldsymbol{\sigma} = -p\mathbf{I} + \eta(\nabla \mathbf{u} + \nabla \mathbf{u}^T) \qquad (3)$$

$$\rho C_P \left(\frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T \right) = \nabla(\mathbf{k}\nabla T) + \eta \dot{\gamma}^2 \qquad (4)$$

where $\mathbf{u}$ is the velocity vector, T the temperature, t the time, p the pressure, σ the total stress tensor, ρ the density, η the viscosity, k the thermal conductivity, C_p the specific heat and $\dot{\gamma}$ the shear rate. The FVM due to its robustness and efficiency is employed in this study to solve the transient flow field in complex three-dimensional geometry.

During the molding cooling process, a three-dimensional, cyclic, transient heat conduction problem with convective boundary conditions on the cooling channel and mold component surfaces is involved. The overall heat transfer phenomenon is governed by a three-dimensional Poisson equation.

$$\rho C_P \frac{\partial T}{\partial t} = k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) \quad for \quad \vec{r} \in \Omega \qquad (5)$$

where T is the temperature, t is the time, x, y, and z are the Cartesian coordinates, ρ is the density, C_P is the specific heat, k is the thermal conductivity. Equation

(5) holds for both mold components and part components with modification on thermal properties. The previous molded parts will be set as mold inserts and considered into overall cooling analysis with themselves thermal properties. Besides, we assume there is a cycle-averaged mold temperature that is invariant with time.

After the part is ejected from the mold, a free thermal shrinkage happens due to the temperature and pressure difference. The warpage analysis assumes the mechanical properties are elastic. The stress-strain equilibrium equations enable us to solve the problems.

$$\sigma = \mathbf{C}(\varepsilon - \varepsilon^0 - \alpha \Delta T) \quad (6)$$

$$\varepsilon = \frac{1}{2}(\nabla \mathbf{u} + \nabla \mathbf{u}^T) \quad (7)$$

where σ is the stress tensor, $\mathbf{C}$ is a 4th tensor related to the material mechanical properties, ε is the strain tensor, α is CLET tensor and $\mathbf{u}$ is the displace tensor. All molded parts in the multi-shot sequential molding will be taken into account with themselves mechanical properties.

Results and discussions

Fig. 1 shows the multi-component consumer product studied in this paper. It is made by two-shot sequential molding process. The injected part of first shot is like a semi-sphere solid, and the injected part of second shot is like a ladle, as shown in Fig 2(a) and Fig 2(b). They are combined smoothly through the mechanism of geometry constraint.

In the first shot, the gate is put at the center of flat side, as shown in Fig 3. The used resin is ABS. The melt temperature is 230^{o}C, and the mold temperature is 70^{o}C. The filling time is about 0.20 second. The eject temperature is 120^{o}C. The cooling time is 40 sec. Fig 4(a) illustrates the predicted melt front distribution on the cavity surface. To further demonstrate how the cavity is filled, the iso-surfaces of melt front are plotted in Fig 4(b). The cavity temperature from filling analysis is plotted in Fig 5. The final cavity temperature after several cooling-filling-packing-cooling iterations is shown in Fig 6.

The first molded plastic part is transferred from first mold to second mold after the molding process of first shot. The combined model and mold design are shown in Fig. 7. The used resin of second shot is PS. The melt temperature is 230^{o}C, and the mold temperature is 50^{o}C. The gate is located in the center of flat side. The filling time is about 0.75 second. The packing time is 3.0 sec. The packing pressure is stepwise from 10.0 MPa to 50.0 MPa. The cooling time is 35 sec. Fig 8 illustrates the predicted melt front distribution. Fig 9 illustrates the temperature distribution after packing analysis. The side of first plastic part has higher temperature due to poor heat transmission. Hence the volumetric shrinkage is also larger over there as shown in Fig 10. Fig 11 shows the temperature distribution after cooling analysis. The predicted temperature in the interface of two plastic parts is higher than the other side due to the relatively poor heat removal performance around the first plastic part. This agrees with the experimental observations. Finally, the predicted deformation of combined part from warpage analysis is shown in Fig 12.

Conclusions

In the past, due to the poor hardware demands, it is difficult to simulate an entire injection-molded part using 3D models. With the hardware progress, anyway it is not a dream to simulate full 3D analysis. At present we can effectively simulate the 3D multi-shot sequential molding process. These results are in good agreement with real world. This developed approach is proved from numerical experiments to be a cost-effective tool to analyze and further optimize the multi-shot sequential molding process.

Acknowledgements

The authors would like to thank the National Science Council of the R.O.C. for partially supporting this research under Contact No. NSC93-2216-E-007-023.

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Key Words

Multi-shot sequential molding, three-dimensional analysis, multi-component molding

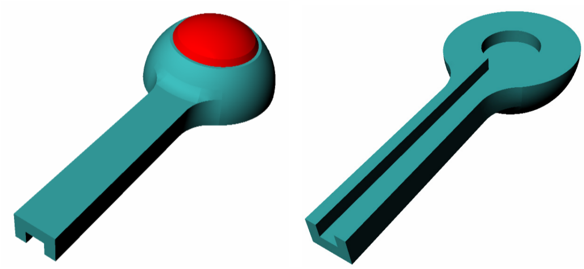
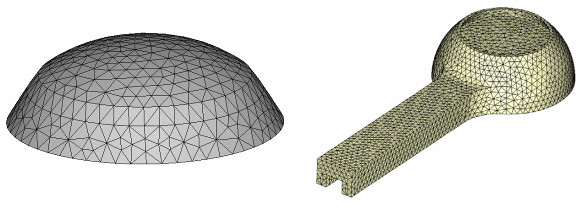


Figure 1. Multi-component consumer product



(a) (b)

Figure 2. Model geometry and mesh: (a) first shot (b) second shot

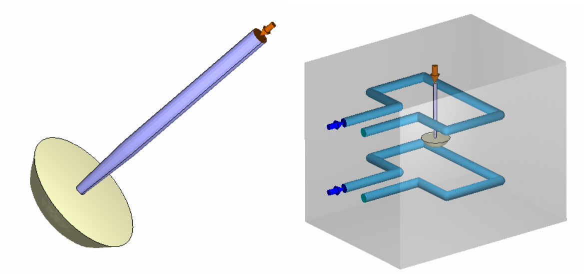
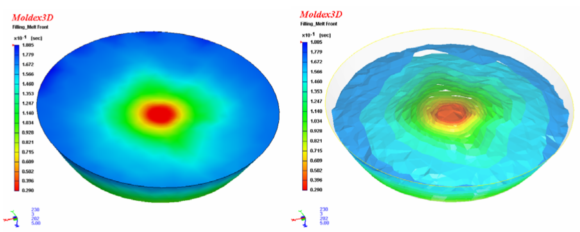
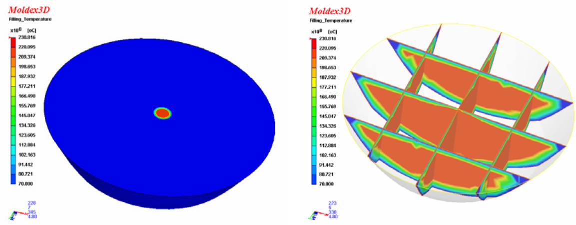


Figure 3. First shot cavity and its mold design



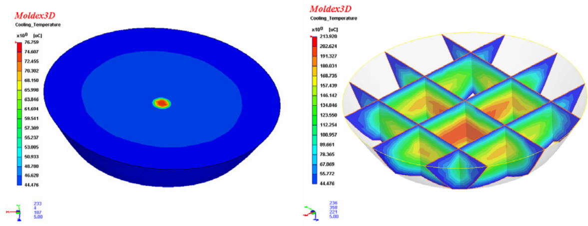
(a) (b)

Figure 4. (a) Predicted melt front distribution on the cavity surface (b) Iso-surface plot of melt fronts.



(a) (b)

Figure 5.cavity temperature distributions from filling analysis (a) surface (b) interior



(a) (b)

Figure 6.cavity temperature distributions from cooling analysis (a) surface (b) interior

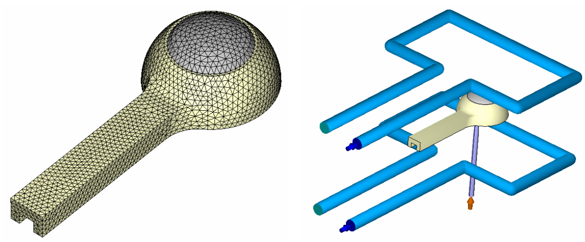
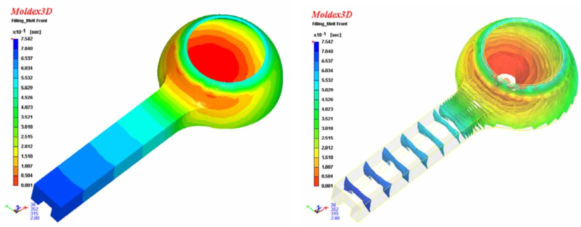
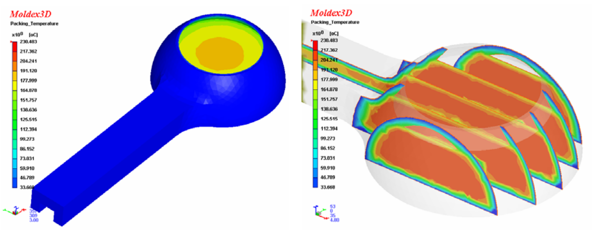


Figure 7. Combined model mesh and its mold design



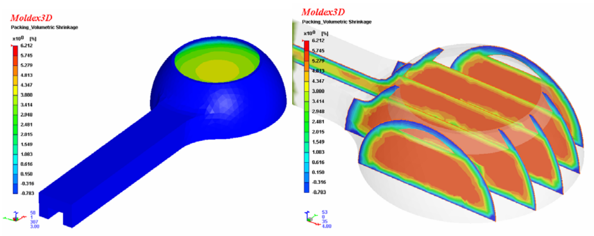
(a) (b)

Figure 8. (a) Predicted melt front distribution on the cavity surface (b) Iso-surface plot of melt fronts.



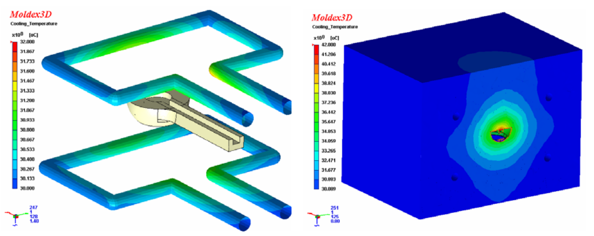
(a) (b)

Figure 9. cavity temperature distributions after packing analysis (a) surface (b) interior

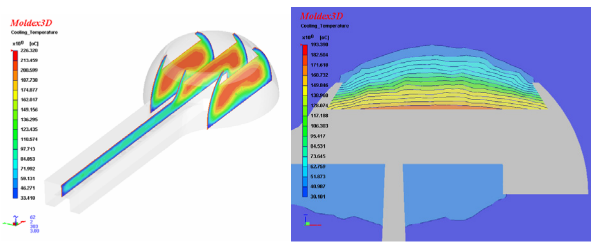


(a) (b)

Figure 10. volumetric shrinkage distributions from packing analysis (a) surface (b) interior

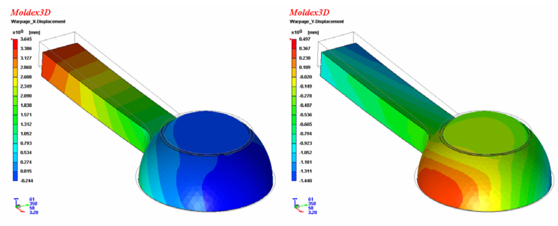


(a) (b)

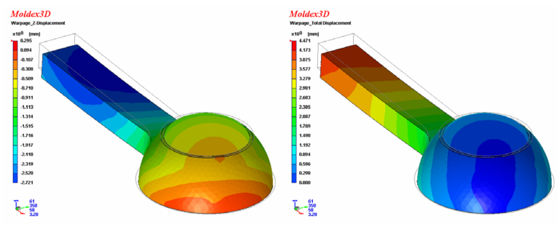


(c) (d)

Figure 11. temperature distributions from cooling analysis (a) cooling channels (b) moldbase (c) second shot part (d) first shot part



(a) (b)



(c) (d)

Figure 12. Warpage analysis result (a) x-displacement (b) y-displacement (c) z-displacement (d) deformation shape