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Warpage prediction of the injection-molded strip-like plastic parts☆

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ABSTRACT

For most strip-like plastic injection molded parts, whose cross section size is much smaller than their length, the traditional Hele-Shaw model and three-dimensional model do not work well in the prediction of the warpage because of their special shape. A new solution was suggested in this work. The strip-like plastic part was regarded as a little-curved beam macroscopically, and was divided into a few one-dimensional elements. On the section of each elemental node location, two-dimensional thermal finite element analysis was made to obtain the non-uniform thermal stress caused by the time difference of the solidification of the plastic melt in the mold. The stress relaxation, or equivalently, strain creep was dealt with by using a special computing model. On the bases of in-mold elastic stress, the final bending moment to the beam was obtained and the warpage was predicted in good agreement with practical cases.

1. Introduction

Injection molding is a widely used plastic processing method and plays an important role in plastic industry due to its high production rate, economical efficiency and ability to produce complex articles with high precision [1–3]. In recent years, traditional method of the mold design and injection molding practices based on past experience is no longer adequate [4]. Numerical simulation techniques have now become helpful tools for mold designers and process engineers in injection molding [5–9]. During the last decade, various authors studied the numerical simulation of injection molding, and some related CAE software have also been developed, such as Moldflow, Moldex, HSCAE and Z-mold, which helped engineers to design part and mold, select parameters of injection molding, and so on [10–12].

CAE software is becoming indispensable tool for the engineers to design the mold for injection-molded parts. However, it does not work well for some parts with special shape. The strip-like part is a common one of them. The decorative/reinforced strips in cars and the boundary frames of solar panels are some examples. Unfortunately, general commercial CAE tools cannot work well for strip-like parts due to their insufficient accuracy. For most parts with shell-like geometry, the well-known 2.5 dimensional (2.5D) model, namely Hele-Shaw model, can provide very good solution [13]. Based on the 2.5D model and shell theory, Zhou *et al.* [14,15] predicted the warpage of the shield plate of air-conditioners. Ozcelik *et al.* [16] and Zhao *et al.* [17] used Moldflow software to simulate the warpage of the cell phone cover and the LCD TV front shell. The representative thickness for these parts is 2 to 3 mm and the ratio of part surface size to thickness is above 10. Although the strip-like part is not thick, its cross section has only low ratio of height/width to thickness, so the advantage of Hele-Shaw model cannot be taken.

In addition to the Hele-Shaw model, three-dimensional (3D) model [18–22] is also often used to simulate plastic injection molding process. Yan *et al.* [23] investigated the 3D computational model and successfully predicted the warpage of the blower cover. Hakimian and Sulong [24] simulated the warpage of injection-molded micro gears by using Autodesk Moldflow Insight. However, we still have to face some difficulty if 3D model is employed to deal with the strip-like part. In the Hele-Shaw model, the thickness is usually divided into 20 layers. This means that the elemental size in 3D model should be about 0.1–0.2 mm if the accuracy same as the Hele-Shaw model is expected. Because the strip-like part is so long, around 10^8 to 10^9 elements, or even more, are needed, which is beyond the capacity of general PCs. Of course, coarse mesh and some simplification in computing that the current commercial software might use allow the simulation executed, but the error is unavoidable, and not acceptable to the strip-like parts.

A new solution to predict the warpage of the strip-like injection-molded parts was suggested, which was composed of two steps. Firstly, the part was macroscopically considered as a beam with smoothly changed cross section and this beam then was divided into a few one-dimensional (1D) elements. Next, at each 1D elemental node, the thermal and strain analysis of the cross section of the part was made using 2D finite element method (FEM); after these calculations, the curvatures at all beam nodes were obtained, and the part warpage prediction became very simple. In this way, the time-consuming 3D finite element analysis (FEA) was turned into several 2D FEA and a 1D FEA, so that the warpage of the strip-like injection-molded part was reasonably

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estimated. The numerical examples showed that the predicted result was in good agreement with practical cases.

2. Basic Idea

A typical example of the strip-like plastic part is shown in Fig. 1. No matter what kind of cross section it might be, its size is much smaller in comparison with its length. Therefore, it is generally a little-curved beam macroscopically. To predict the final deformation of the part, the beam theory is employed to calculate the moment and curvature firstly. The moment here refers to the one that the part is subjected to when it is still in the mold. When the part is ejected, it is liberated from the mold, the moment is released, and resulted in partial deformation. It is obvious that the crucial work is the calculation of the in-mold moment or curvature. So long as it is done, the left job is straightforward.

(a) CAD model (b) Cross section

Fig. 1. Chafing strip of car.

It is well known that the in-mold stress has two sources, *i.e.*, thermal and flow-induced. In fact, although there is shear stress during the filling stage, it disappears when the mold is filled up. The so-called flow-induced stress more refers to the one caused by the flow-induced material property change. As it is common knowledge that the flow-induced stress is much smaller than the thermal one [25], the former will be neglected in our discussion. There are three determinant factors in the stress development. The first one is packing induced. When the melt cools down to a certain degree, the packing pressure will be solidified in the part. The second factor is temperature variation. When the temperature becomes lower, the thermal stress appears. When the stress is larger than packing-induced stress (the reverse case not considered here), the part tends to shrink. However, the mold prohibits this shrinkage, so that the in-mold stress appears which will produce the strain to balance the thermal strain. The last factor is stress relaxation, or equivalently, strain creep. Because of non-uniform temperature distribution, different areas in the part have different time-points of solidification. On the other hand, except for final residual stress, all stresses located at different areas will be released at same time in demolding, which causes the different stress relaxation periods. Generally speaking, the area with longer relaxation period tends to have less stress, *vice versa*. It is the fundamental reason of the part warpage.

The modeling will be done on the basis of the above discussion. To realize our purpose, the following assumptions are specified:

- The part must be long enough so beam theory can be used.
- The geometry of the cross section does not change too much along the axial (x) direction. In the analysis, the part will be cut into several elements. This means that the curvature in the element can be interpolated.
- The heat does not transfer along the x-direction, but only on the cross section of the part.
- Nowhere there is part movement in the mold, *i.e.*, the strain being zero everywhere before the ejection.
- Only the packing pressure and thermal stress are considered, and flow-induced stress is neglected.
- The material is isotropic, *i.e.*, the crystal or fiber orientation is not taken into consideration.
- The twist of the part is not considered.

On the basis of the above assumptions, the procedure to simulate the deformation of the injection-molded strip-like part is as follows. (1) The part is considered as a beam and will be cut into a few elements connected by nodes along the x-direction. The element length is about 5 times the part width, depending on the section shape. If the section varies less, the element is chosen longer. (2) At each node position, the cross section perpendicular to x-axis is taken and the finite element mesh is drawn on it, as shown in Fig. 2. Different sections have their own mesh. (3) The thermal analysis is made on all sections. (4) According to the cooling history of each section, the in-mold elastic strain is calculated on the nodal bases, which is further used to get curvature of the beam node. (5) Finally, curvature distribution in each beam element is interpolated and the deflection can be integrated based on the beam theory.

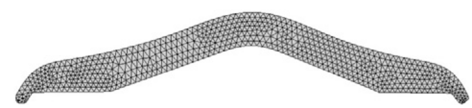

Fig. 2. Sample of finite element mesh of a cross section.

3. Temperature Field

According to the assumption, the heat conduction along x-direction is neglected. So the heat transfers only on the y–z plane. Please note that the 1D analysis as in the Hele-Shaw model is not acceptable because the ratio of dimension of the section to the part thickness is not large enough. The end time of the filling stage is taken as starting time of the temperature analysis for all sections. The standard FEM is used in this study.

In our study, there exists no internal heat source and material property is isotropic, thus the 2D heat conduction equation can be simply [26,27]

$$\rho c\frac{\partial T}{\partial t}=k\left(\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right) \tag{1}$$

with initial condition

$$T(0)=T_{\mathrm{melt}} \tag{2}$$

and the third boundary condition

$$\begin{cases} k\dfrac{\partial T}{\partial \boldsymbol{n}}=h_{\mathrm{in}}(T_{\mathrm{mold}}-T) & t\le \text{mold open time} \\ k\dfrac{\partial T}{\partial \boldsymbol{n}}=h_{\mathrm{out}}(T_{\mathrm{air}}-T) & t>\text{mold open time} \end{cases} \tag{3}$$

where ρ is density, c specific heat, k heat conductivity, h_{in} heat transfer coefficient between melt and mold, h_{out} heat transfer coefficient between part and air, T_{melt} initial melt temperature, T_{mold} mold temperature and T_{air} room temperature.

With the standard FEM formulation [28], the system of equations that gives the discrete solution of Eqs. (1)–(3) can easily be derived:

$$\boldsymbol{KT}+\boldsymbol{M}\dot{\boldsymbol{T}}=\boldsymbol{q} \tag{4}$$

in which $\boldsymbol{K}$ is stiffness matrix, $\boldsymbol{M}$ the mass matrix and $\boldsymbol{q}$ heat loading coming from the third boundary condition. The detail of derivation can be found in any reference about heat transfer FEM and will not be repeated here.