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Abstract:

Many parameters influence the warpage developing at the corners of injection molded plastic parts. One of the main causes of this deformation is the asymmetrical cooling of the injection mold. This study presents an injection molding analysis of the heat flow developing in injection molds. The analysis shows that significant temperature difference appeared between the two sides of the mold after the hot polymer melt had filled the cavity. It was highlighted that the unevenness of the cooling should be considered during the mold design in order to avoid the warpage of the parts.

Keywords: simulation, injection molding, corner effect, cooling, simulation

Nomenclature

a_{eff} effective thermal diffusivity

B viscosity coefficient

$\vec{g}$ gravity vector

k thermal conductivity

m flow index

n normal direction

p pressure

p_{in} inlet pressure

s thickness of the part

t time

T temperature

T_b reference temperature

$T_{ejection}$ ejection temperature

T_m freezing temperature

T_{melt} melt temperature

T_w mold temperature

$t_{cooling}$ cooling time

$\vec{u}$ velocity vector

x,y,z is the Cartesian coordinate

Greek symbols

$\dot{\gamma}$ shear rate

∇ Laplace operation vector

η viscosity

η_0 reference viscosity

ρ density

τ^* reference stress.

1. Introduction

The injection molding process is a high speed, automated process used to produce plastic parts with complex geometries and fairly tight dimensional tolerance requirements. The quality of the product is determined by the process parameters and several defects can occur because of improper mold design or incorrect machine setup [1, 2]. One of the main errors is shrinkage which derives from the decreasing volume of the injection molded part during the cooling phase of the process. Shrinkage causes warpage as it appears unequally throughout the geometry. The warpage is strongly influenced by non-uniform cooling, differential shrinkage and orientation effect [3-5]. Differential shrinkage is caused by variation in crystalline content and volumetric shrinkage. Orientation effect is the result of the ratio between the in-flow shrinkage and the cross-flow shrinkage. Unfilled polymers shrink more in the flow direction (in-flow shrinkage) compared to the direction perpendicular to flow (cross-flow shrinkage); on the other hand reinforced plastics shrink more in the cross-flow direction than in the direction of flow. This difference in shrinkage causes the orientation effect. Non-uniform cooling can cause significant differences in shrinkage through the thickness of the part as it cools from process temperature to room temperature. Non-uniform cooling creates a more significant problem in areas such as corners, where there are differences in the sizes of the core and cavity mold volumes required to be cooled down. The cooling becomes asymmetric as the core side can be difficult to cool effectively compared to the cavity side of the mold. Hotter surfaces of the plastic part shrink more than cooler surfaces and therefore, due to stresses introduced during this cooling phase, the corner angle of the part becomes smaller than the nominal mold one after ejection from the mold. This phenomenon is known to be the main cause of corner warpage in injection molding of thermoplastics [5, 6].

The use of injection molding simulation provides a method to analyze this effect. Not only part models, but also injection mold designs, can be examined and optimized with simulation [2, 7, 8]. Because of the high demand of productivity it is nowadays essential to control the effectiveness of cooling system designs. To get accurate simulation results, it is necessary to use the mathematical model of heat transfer in three-dimensional flows [9, 10]. Most injection molding simulation software uses the boundary element method to analyze the heat transfer which is similar to the boundary integral formulation [11, 12]. In this study an injection molding analysis is presented showing the heat flow ruling in an injection mold particularly at the corner geometry.

2. Experimental

2.1. Mathematical model

The mass, momentum and energy conversation governing equations for the non-isothermal, generalized Newtonian fluid are given by Equation 1-10.:

Continuity Equation:

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

Momentum Equation:

$$\rho\left(\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \nabla \vec{u}\right) = -\nabla p + \eta \nabla^2 \vec{u} + \rho \vec{g}. \qquad (2)$$

Energy Equation:

$$\rho\left(\frac{\partial T}{\partial t} + \vec{u} \cdot \nabla T\right) = k(\nabla^2 T) + \eta \cdot \dot{\gamma}^2. \qquad (3)$$

The viscosity model of fluid:

$$\eta(\dot{\gamma}, T, p) = \frac{\eta_0(T, p)}{1 + \left(\frac{\eta_0(T, p)\dot{\gamma}}{\tau^*}\right)^{1-m}}. \qquad (4)$$

$$\eta(T, p) = B \exp\left(\frac{T_b}{T}\right) \exp(\quad p). \qquad (5)$$

Then

$$\dot{\gamma} = \sqrt{\nabla^2 u}. \qquad (6)$$

Boundary and initial conditions:

$$\vec{u} = 0; \ T = T_w; \ \frac{\partial p}{\partial n} = 0 \quad \text{on mold wall} \qquad (7)$$

$$\frac{\partial \vec{u}}{\partial z} = \frac{\partial T}{\partial z} = 0 \quad \text{on center line} \qquad (8)$$

$$p = 0 \quad \text{on flow front} \qquad (9)$$

$$p = p_{in}(x, y, z, t); \ T = T_m \quad \text{at inlet.} \qquad (10)$$

In this study the control volume finite element method was used to solve the equations above [13].

2.2. Part and mold design

To measure the effect of the process conditions on the part quality at corners of injection molded parts a special specimen was designed (Fig.1.). The dimensions of the V-top specimen are 65 mm x 75 mm x 2 mm. The sides of the part create an angle of 90°, and the deformation caused by technological parameters and material properties can be quantified by the change of this angle.

To enable examination of the warpage of different mold design and mold cooling cases, an injection mold was constructed with changeable and variable inserts (Fig.2.). The gate types can be changed with the use of gate inserts in the mold. Both unidirectional and bidirectional cavity filling can also be achieved with the use of rotatable inserts in the mold. This makes it possible to analyze weld lines at the corners.

The cavity pressure can be measured at the gate and at the end of the flow with the two mounted sensors, allowing the processes in the cavity to be followed and controlled.

Warpage is basically influenced by cooling and it is very significant at corners, therefore to investigate the effect of different mold temperature, an efficient cooling system design was required. In order to control the cooling, sensors are implemented to measure the core and cavity temperatures in the mold.

2.3. Simulation analysis

Autodesk Moldflow Insight 2011 injection molding simulation software was used to run the cooling analysis on the model assembly of the V-top specimen, and the mold cavity inserts, to investigate the heat transfer during injection molding (Fig. 2.). The model consists of one single cavity using the geometry of the injection mold. 3D mesh type was used to represent the model, filling the volume with four-node and tetrahedral elements. The material used was Daplen HD120MO (Borealis). The temperature of the mold insert was 40°C and the polymer melt temperature was 230°C.

The temperature at the mold surface should be as uniform as possible at the different points to reduce the warpage to a minimum. The results showed that the temperature distribution in the mold inserts was uniformly 40°C at the moment of filling (Fig. 3/a.). The contact between the hot polymer melt and the mold increased the mold wall temperature near the cavity (Fig. 3/b. and 3/c.). After approximately 7 seconds the heat from the injected melt caused a temperature increase of 2°C in a narrow range round the cavity in the cavity plate of the mold. The temperature of the core plate of the mold also increased but in this instance to 46°C, creating a difference of 4°C between the two sides of the mold. As a result of the mold cooling circuits, approximately 21 seconds after the cavity filling took place, the temperature of the stationary side of the mold was generally at 40°C, with only a relatively small area close to the part surface indicating a temperature slightly above 40°C (Fig. 3/d.). In contrast , the temperature of the moving side of the mold was still seen to be increasing. After 33 seconds the temperature of the entire stationary half of the mold was cooled uniformly towards 40°C but the moving side of the mold still continued to show an increase in temperature (Fig. 3/e.). After 50 seconds the moving side of the mold reached a temperature of 47.5°C, resulting in a differential of 7.5°C between the two mold inserts (Fig.3/f, and Fig. 4.).

The time required to reach the required ejection temperature of 93°C through the entire thickness of the part was studied in 3 positions: A, B and C (Fig.1.). At all 3 positions an asymmetrical change of the required cooling time was observable (Fig. 5.). At the corner of the part (position A), a time difference of 2 seconds was observed (at a distance of 0.33mm or 16.67% in from the side surfaces). At position B, the largest difference was 1 second (0.67mm or 33.33% from the walls). The largest difference in the time needed to reach ejection temperature was at position C where a time of 4 seconds was seen (0.33mm or 16.67% from the walls).

The asymmetry can be observed in the cooling of the cross section of the part (Fig.6.). It can be seen that whilst both outer surfaces of the part cooled rapidly towards the initial mold temeprature of 40°C, the centre of the part cooled at a slower rate. The cooling effect of the core half of the mold is less than that of the cavity due to the smaller surface area available, resulting in a less efficient heat transfer. This in turn results in an increase in the temperature of the core surface of the part as the heat cannot escape as rapidly as on the cavity side.

After 33 seconds, comparing the temperature through the cross section of the part, it can be seen that the average temperature was highest at position A and lowest at position C (Fig.7). Moreover the temperature distribution through the thickness became more symmetrical away from the corner. At position A a temperature difference of approximately 10°C throughout the cross-section of the part is observable. At position C this difference fell off to 6°C. This non-uniform change led to different shrinkage and thus to the deformation of the part.

The cooling time can be determined for a plate-like part after Equation 11. [14]:

$$t_{cooling} = \frac{s^2}{\pi^2 \cdot a_{eff}} \cdot \ln\left(\frac{4}{\pi} \cdot \frac{T_{melt} - T_w}{T_{ejection} - T_w}\right) = 10.25\ s \quad (11)$$

Comparing the simulation results and the analytical result it can be seen that the analytical method gives only an average value for the required cooling time. In contrast, the simulation results showed that the corners actually required a longer cooling period before ejection should take place.

4. Conclusion

In this study the temperature distribution ruling in injection molds, especially at corners was analyzed with Autodesk Moldflow Insight 2011 injection molding simulation software. The analysis showed that significant temperature difference appeared between the two sides of the mold. Moreover the cooling of the injected part became asymmetrical. This uneven cooling caused anisotropic shrinkage in the part which is the main cause of corner deformation.

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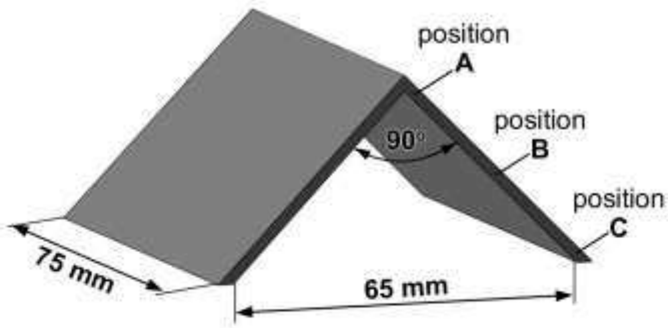

Fig.1. V-top specimen

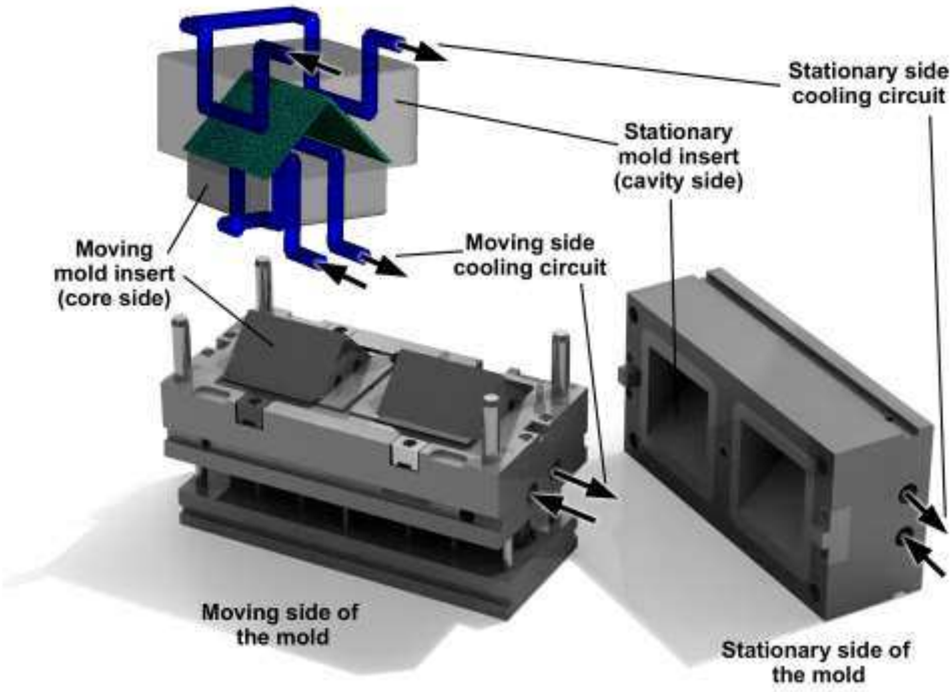

Fig.2. The injection mold with the model for the numerical simulation

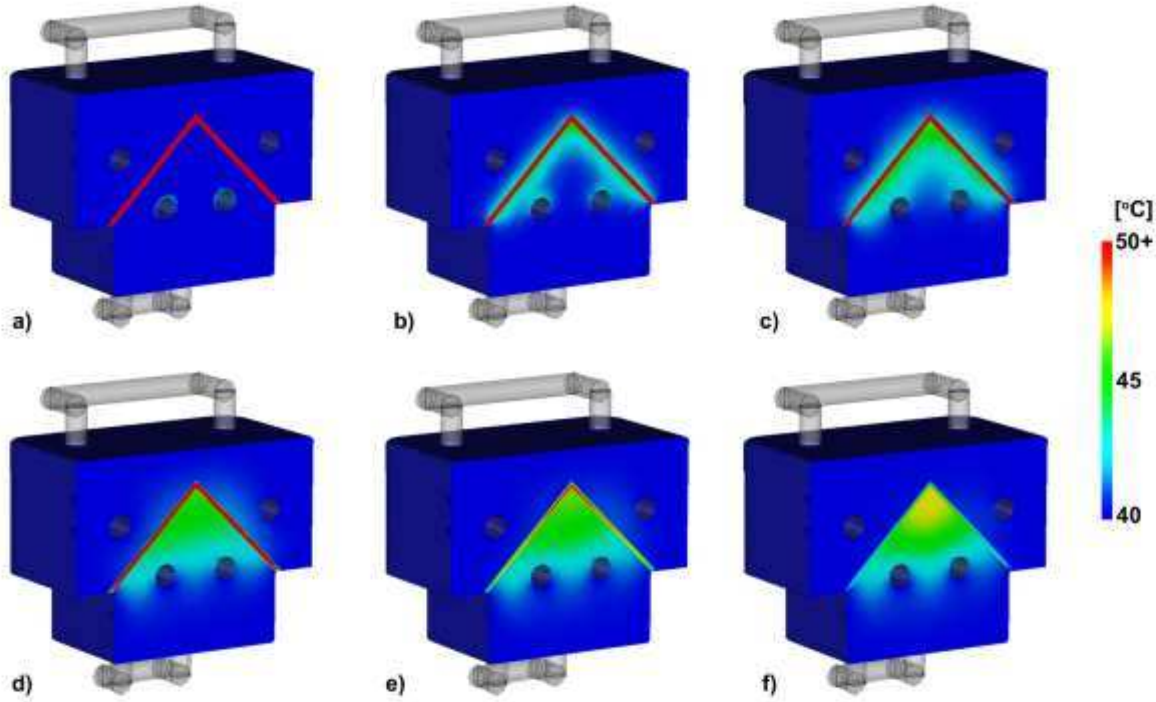

Fig.3. Temperature gradient through the injection molded part and the mold
a) at the end of filling, b) 3 seconds after filling, c) 7 seconds after filling, d) 21 seconds after filling, e) 33 seconds after filling, f) 50 seconds after filling

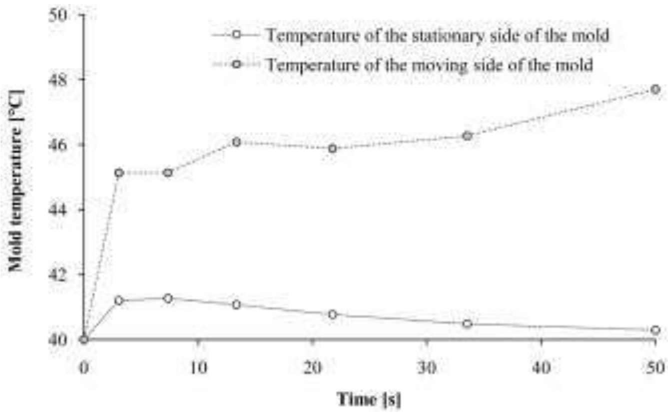

Fig.4. Mold temperature change at the corner as a function of time

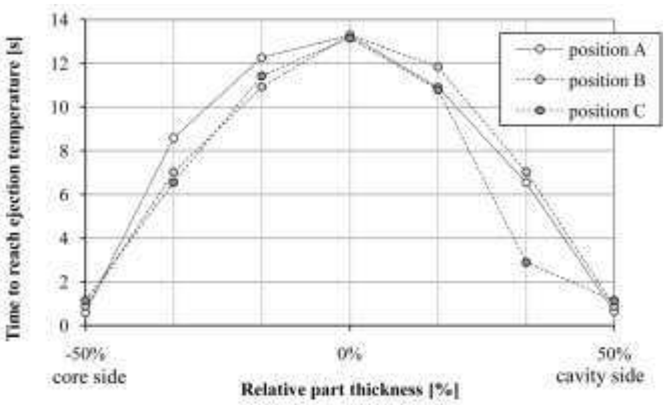

Fig.5. Time to reach ejection temperature at the corner along part thickness

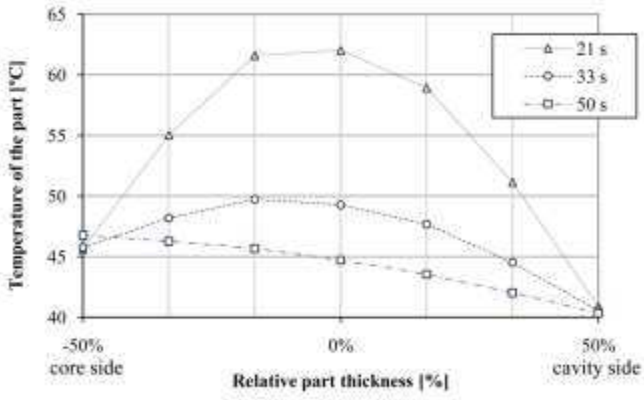

Fig.6. Temperature of the part at position A through the cross section

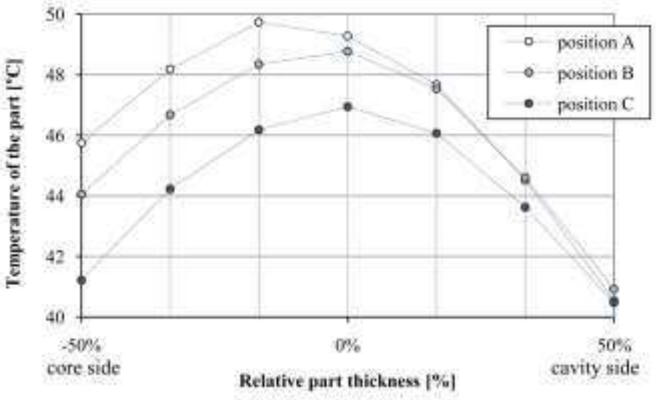

Fig.7. Temperature of the part 33 seconds after cavity filling