Ink-wash and Warpage Defect Prediction from the In-Mold Decoration Process Simulation

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Abstract

We introduced in this paper a simulation tool designed to predict the most common defects related to the in-mold decoration process. Ink-wash is the most obvious aesthetic problem caused by high temperature or high shear from the incoming melt. Warpage is another dimensional uncertainty defect due to the poor heat conduction of the film. Overcoming these problems often requires mold fixing including critical gate location change. Mold filling simulation could help identify these potential problems in the early mold design stage. However, conventional simulation techniques require tedious work of thin layer mesh making of the decoration film. It is therefore essential to develop a quick pre-process tool without losing simulation accuracy.

Introduction

IMD (In-mold decoration) process is now widely used to manufacture graphical, textured, or even personalized products. For all the plastic manufacturing processes, IMD is the most promising technology to produce diversified products for small quantities. The graphic design on demand could quickly alter the appearance and texture on the identical product shape. With the growing trend of Industry 4.0 toward customized manufacturing experience, IMD technique will see more applications in the future.

Among the variations of IMD processes, the most important ones are in-mold film (IMF) and in-mold roll (IMR). The difference lies in whether the ink carrier film is left on the final product as a protection of the underneath ink. IMF product uses a PET or PC film with a thickness of 100-200μm. For the IMR process, the ink carrier film is peeled off during the demolding process with only the ink left on the product surface. IMR can easily transfer the pattern on to a curved product surface but prone to scratch due to the lack of surface protection film.

Several differences distinguishing the IMD from a general injection molding process requires attention while designing the process. First, since there is an ink-film attached to only one side of the mold during filling, temperature distribution across the part while cooling is not symmetrical. Second, the adhesion between the ink/film and the resin may not withstand the harsh environment during injection. Therefore the simulation tool should consider the interplay between the resin and the film according to their properties and also the filling conditions including the pressure, shear force and temperature. Failure to address these design/processing aspects often lead to defects. Among them the most unwanted defects are
ink-wash and warpage of the part. The rest include ink cracking, film cracking, and wrinkle. Therefore, we discuss in this paper the prediction of ink-wash and part warpage based on the molding parameters along with validation studies.

Ink-wash is caused by the high shear stress between the stationery ink/film and the moving melt. The ink is screen-printed on the film. If the shear stress is higher than the adhesion between the ink and the film, there is a greater chance for the ink to be removed from the film. Unfortunately, since there are so many variations of film and ink materials, it is difficult to characterize the critical adhesive strength for film/ink separation. An ink-wash index was used in the simulation tool to estimate the likelihood of ink-wash. Usually, the high ink-wash index area is near the gate region or the area with drastic thickness variation. For part optimization, ink-wash can be avoided by optimizing the gate location, gate design, and part thickness distribution. They can also be improved by optimizing the molding parameters including the melt temperature and injection speed.

A special technique introduced in this study is the use of a 2.5D solid mesh representing the film insert. Because the nature of thin film, it is not suitable to create a 3D mesh because the aspect ratio of element will be too high for a good quality mesh. A 2D mesh however can be conveniently created but the asymmetric property through thickness is ignored. Combining both the advantage of 2D and 3D meshing of the film insert, high computational speed can be achieved without compromising the temperature and stress gradient across the thickness direction.

**Numerical Method**

The conventional injection molding (CIM) process can be divided into three stages, including filling/packing, cooling and warpage. Different from CIM process, the ink-carrier film needs to be considered in the IMD process simulation. For filling/packing process, the polymer melt is assumed to behave as Generalized Newtonian Fluid. Hence the non-isothermal 3D flow can be described by the following equations:

\[
\frac{\partial p}{\partial t} + \nabla \cdot \rho \mathbf{u} = 0
\]

\[
\frac{\partial}{\partial t} \left[ \rho \mathbf{u} \right] + \nabla \cdot (\rho \mathbf{u} \mathbf{u} - \sigma) = -\nabla p + \rho \mathbf{g}
\]

\[
\sigma = -\eta \left( \nabla \mathbf{u} + \nabla \mathbf{u}^T \right)
\]

\[
\rho C_p \left( \frac{\partial T}{\partial t} + \mathbf{u} \nabla \cdot T \right) = \nabla \cdot (k \nabla T) + \eta \dot{\gamma}^2
\]

where \( \mathbf{u} \) is the velocity vector, \( T \) is the temperature, \( t \) is the time, \( p \) is the pressure, \( \sigma \) is the total stress tensor \( \rho \) is the density, \( \eta \) is the viscosity, \( k \) is the thermal conductivity, \( C_p \) is the specific heat and \( \dot{\gamma} \) is the shear rate. In this work, the modified-Cross model with Arrhenius temperature dependence is used to describe the viscosity of polymer melt:
\[ \eta(T, \dot{\gamma}) = \frac{\eta_0}{1 + (\eta_0 \dot{\gamma}/\tau^*)^{\nu}} \]

(5)

with

\[ \eta_0 = B \exp\left(\frac{T_b}{T}\right) \]

(6)

where \( n \) is the power law index, \( \eta_0 \) is the zero shear viscosity, \( \tau^* \) is the parameter that describes the transition region of the viscosity curve.

The finite volume method (FVM) due to its robustness and efficiency is employed to solve the transient flow field in a three-dimensional geometry with complex[3-4]. In order to track the evolution of the melt, a transport equation which describes the advancement of fluid over time is presented as the following equation:

\[ \frac{\partial f}{\partial t} + \nabla \cdot \rho \vec{f} = 0 \]

(7)

Here, \( f \) is the volume fraction function, \( f=0 \) is defined as the air phase, \( f=1 \) is defined as the polymer melt phase, and the melt front is located within cells with \( 0 < f < 1 \).

During the cooling phase, a three-dimensional cyclic, transient heat conduction with convection boundary condition on the cooling channel and mold component surface is involved. The heat conduction during cooling process is governed by a three-dimensional Poisson equation:

\[ \rho C_p \left( \frac{\partial T}{\partial t} + \vec{u} \cdot \nabla T \right) = k \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) \]

(8)

where \( x, y \) and \( z \) are the Cartesian coordinates. Equation (8) holds for part, ink-carrier film and mold components despite their different thermal properties.

After the ejection, the IMD part experiences a free shrinkage due to the temperature and pressure change. The warpage analysis assumes that the mechanical properties are linear-elastic. The stress-strain equations enable us to solve the shrinkage.

\[ \nabla \cdot \vec{\sigma} = 0 \]

(9)

\[ \vec{\sigma} = C(\varepsilon - \varepsilon_0) \]

(10)

\[ \varepsilon = \frac{1}{2} \left( \nabla \vec{u} + \nabla \vec{u}^T \right) \]

(11)

Where \( \vec{\sigma} \) is the stress, \( C \) is a 4th order tensor related to the material mechanical properties, \( \varepsilon \) is the strain tensor, \( \varepsilon_0 \) is the initial strain caused by the PVT relationship, and \( \vec{u} \) is the displacement.

In IMD process, ink-carrier film is umuch thinner than the part. Generally the thickness of ink-carrier film is around 0.1 to 0.2 mm. Due to this characteristic of film, a 2.5D approach is developed for ink-carrier film and is integrated with the Moldex3D injection module. Figure 1 shows the setup procedure for IMD films. Note that the film thickness can be defined. Its effect on the asymmetric temperature distribution and warpage could all be considered.

**Results and Discussion**

**Ink-wash**

An ink-wash study considering the effects of part thickness, injection speed and melt-temperature was referred to validate the accuracy of this simulation tool. There was a
significant difference on the ink-wash radius using the polycarbonate material Makrolon LQ 2647 compared to other materials in the study. It was thus used also in this simulation to test the sensitivity by changing the processing factors.

Part thickness
Part thickness relates directly to shear rate when the filling time remains the same (same linear velocity). The wash-off radius increased from 14 mm to 22 mm with a decrease of the thickness from 3 mm to 2 mm. The simulation result is shown in Figure 2. A higher wash-off index could indeed be seen at the gate entry region for the 2mm-part.

Injection speed
As the speed increases, the shear rate/stress also increases adding the chances of ink-washing. An increase of the injection speed from 15 mm/s to 25 mm/s also increases the ink wash-off radius for about 3 mm. The simulation result is shown in Figure 3. The 25mm/s part shows a larger wash-off radius near the center gate region.

Melt temperature
There is strong asymmetric temperature distribution between the cavity side and the core side of the part due to the inserted film. The film causes heat hesitation so the interface between the film and the bottom side of the part remains high at 200 °C. Compared to the top side where the resin contacts directly to the mold, the bottom side has a higher temperature because the heat is more difficult to dissipate through the film. (Figure 4 and 5)

The ink-wash off radius also related to the melt temperature as the resin soften more easily the underneath film causing deformation or slip. For the high melt-temp sample from the experimental study, the ink-wash radius was 15 mm compared to the lower temperature (270°C) one of less than 10 mm. The simulation results in Figure shows the same trend of the melt temperature effect as the experiment. (Figure 6)

Warpage
By adding the decoration film, the part becomes easier to trap heat between the film side and the mold. The simulation result has shown earlier that the temperature near the film side is higher compared to the other. This asymmetric temperature distribution is the main reason causing the part to deflect toward the film side. A previous study with a U-shaped product showed a deflection of the part with a shrinkage between the two ends of the part. [4] In the study, a part with a mold temperature of 55°C and a corner angle of 90°C has a measured in-ward angle of 1.54°. The same processing condition is applied for simulation and the warpage result is shown in Figure 7. The tip displacement in the X-direction of the left arm is 0.537mm, which is also a deflection angle of 1.53°. This matches closely to the experimental 1.54° and is even better than the 1.43° calculated from the prior simulation technique. Figure 8 shows the asymmetric temperature distribution leading to this warpage. Considering the film effect on the heat
Conduction of the part proves to be essential in achieving high accuracy of dimension prediction.

**Conclusions**

We have seen in this paper that the interplay between the film and the part leads to defects of ink-wash and warpage. While less shear and heat can help relieve the ink-wash, warpage may require tedious mold fixing to achieve the desired dimension. The amount of warpage to be corrected showed a good correlation between simulation and experiment. More important is that the simulation took no more time than a regular run without considering the film, which is vital in the short design review cycle.

**References**

Figure 1. Designate IMD film boundary condition on the surface of IMD parts and assign thickness of IMD films through Moldex3D Designer user-interface.

Figure 2. When the part thickness increases from 2 to 3 mm, the wash-off radius decreases according to simulation.

Figure 3. When the injection speed decreases from 25 to 15 mm/s, the wash-off radius decreases according to simulation.

Figure 4. Across the thickness direction, highest temperature occurred at the thickness center. The part/film/mold interface has a higher temperature than the part/mold interface.
Figure 5. Difference of part surface temperature caused by the difference of heat conduction between the mold and the part with IMD film.

Figure 6. When the melt temperature decreases from 310 to 270°C, the wash-off radius decreases according to simulation.

Figure 7. Part warpage with a deflection angle of 1.43° based on its 0.53-mm tip displacement from its one of the two 20-mm arms.

Figure 8. The asymmetric temperature distribution of the U-shaped part through its thickness direction parting at the center line. The high temperature core moved toward the film side (top) causing the part to bend more obvious toward inside.