Process Parameters Affecting the Quality of Functionalized In-Mold Decoration Injection Molded Composites

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ABSTRACT

This report studies the fundamental parameters affecting the wash-off and the warpage of parts manufactured in in-mold decoration process (IMD). The purpose is to derive a process model for describing the wash-off and the warpage of the parts as a function of the main influencing parameters based on a dimensional analysis. In order to investigate the influence of the materials and various processing conditions, a test mold was created for experiments and simulations were carried out. First of all the main influencing factors have been identified. To quantify the influence of each factor, a full factorial design was used. A DOE of process parameters including injection speed, injection pressure, melt temperature, mold temperature, post-injection pressure and the material were designed and executed. Based on the DOE specimens with a 250 µm and 375 µm thick PC film and a part thickness of 2 mm and 3 mm made from different thermoplastics were produced. In addition, the results of the experiment were compared with the simulation.

Index Terms – in-mold decoration injection molding, warpage, ink wash-off

1. INTRODUCTION

The in-mold decoration process (IMD) is an injection molding method to manufacture parts with printed and high gloss surfaces. It is also possible to integrate indicating and adjustment elements on the surface. The IMD process is divided into consecutive steps. At first a decor and/ or conductive paths are printed onto a sheet or film, then the semi-product gets shaped to fit the mold cavity and finally, the film is inserted into the mold cavity and is being backside overmolded with molten plastic, shown in Figure *1*. [1]

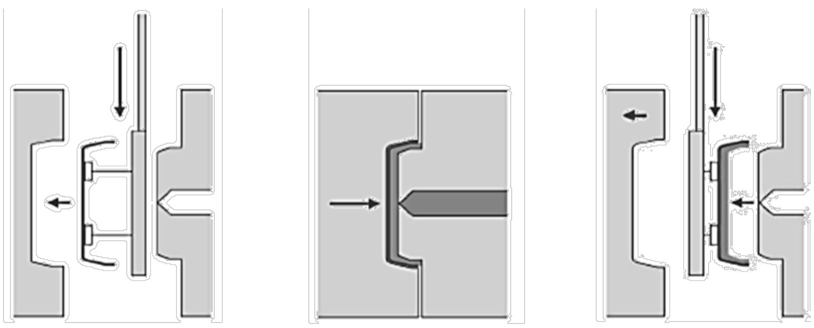

Figure 1: Schematically, the in mold decoration injection molding process [2]

The integration of displays and capacitive sensors into in-mold decoration (IMD) injection molded parts is becoming more important for the automotive industry and other applications. The objective is to produce one part that contains multiple interaction and control elements. The advantage is a reduction of manufacturing cost and weight. Additionally it opens a new opportunity in design freedom.

A problem in IMD molding is a typically high scrap rate due to sensitive processing conditions, film quality and material patterns, especially relative to the connection between film and substrate. Challenges lie in high warpage and ink wash-off during back-overmolding. Deformation and wash-off of printed conductor paths on the film create additional challenges for the process and achievable part properties.

The warpage of the whole part results from the residual stresses of film and substrate and local differences in the shrinkage. [3] The poor thermal conductivity of the film is a barrier for the heat flow and leads to an asymmetrical temperature distribution. [4]According to this, the shrinkage is also asymmetrical and the part warped in the direction of the highest temperatures, as shown in Figure *2*. [8] Beside the asymmetrical temperature profile, there is flow-induced residual stress [9]. During the injection, a thin plastic layer solidifies on the printed film and the melt stretches the film.

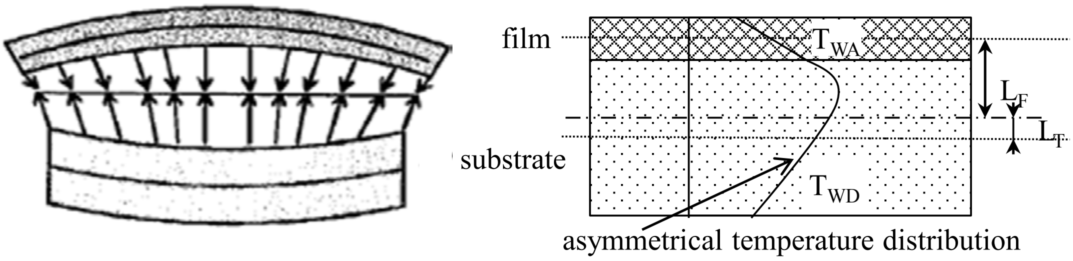

Figure 2: warpage of the film and substrate because of the asymmetrical temperature distribution

The ink wash-off appears on the printed film below the gate and is due to the influence of the hot flowing melt. On the one hand, the ink washes away by the polymer melt, on the other hand, the high temperature damages the ink.

In conclusion, the ink wash-off and the warpage depend on many different process and material parameters. This report investigates the main influencing parameters and compares the simulations with the experiments. The purpose is to derive a process model for describing the wash-off and the warpage of the parts as a function of the main influencing parameters based on a dimensional analysis.

2. EXPERIMENT AND SIMULATION

2.1 Materials and Experimental Setup

The IMD specimen has a rectangular shape with 190 mm in length and 80 mm in width. The thickness can be changed between 2 mm and 3 mm. All specimens were molded on a Klöckner-Ferromatik FM 60 injection molding machine. The film was a 250 µm and a 375 µm thick Makrofol DE 1-1 by Bayer. To examine the influence of the ink wash-off, a 250 µm thick XtraForm polycarbonate film by MacDermit was used. These films were printed with NORIPHAN by PRÖLL, a special IMD color system. Two different Makrolon polycarbonate grades, a Makrolon 2405 with a melt flow index (MFI) of 19 g/10 min at 300 °C and a Makrolon LQ2647 with a MFI of 11 g/10 min, were used as substrate material.

2.2 Molding Parameters and DOE

Because of the use of two different materials and different thicknesses of the part it was necessary to find parameter ranges at which the part could be molded. The melt temperature for the Makrolon 2405 was maintained at 260 °C and 300 °C, for Makrolon LQ2647 at 270 °C and 310 °C. The post injection pressure was kept at 31,2 MPa or 43,7 MPa for Makrolon 2405 and at 25 MPa or 37,5 MPa for Makrolon LQ 2647. To analyse the influence of the

mold temperature on the warpage, 40 °C and 80 °C were tested. To investigate the ink wash-off, the mold temperature was kept constant at 60 °C. Two different injection speeds of 15 and 25 mm/s were tested. For all experiments the cooling time was 10 seconds.
The statistic Design of Experiments (DOE) method was used to investigate the influence of the different process parameters. [6] A DOE of parameters including injection speed, injection pressure, melt temperature, mold temperature, post-injection pressure and the material, thickness of the part and thickness of the film was designed and executed. The effect chart shows the relationship between the process parameters and warpage or ink wash-off. The magnitude and the importance of the effects can be determined in a Pareto chart. This chart shows a standardized effect to compare the significance of each factor.

2.3 Numerical Simulation

The warpage and the ink wash-off were simulated with the software Moldex3D. A 3D-model was built in Rhinoceros3D. The substrate and the film were separated meshed with triangular elements. Then, a separate mesh for the boundary surface between the film and the substrate was created. After creating the gate it was necessary to implement the cooling ducts and the injection mold. The computer model is shown in Figure *3*.

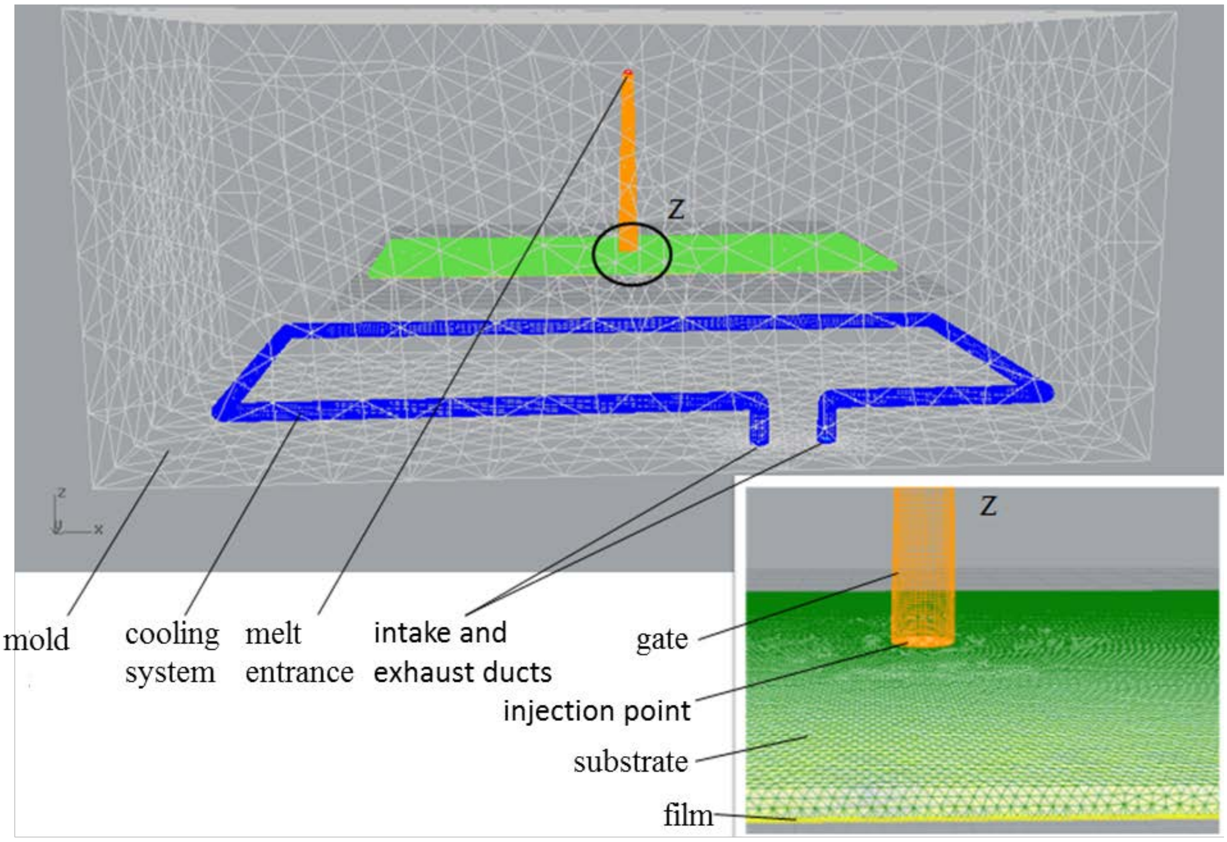

Figure 3: Computer model used to simulate the warpage and ink wash-off

The process parameters in the simulation coincide with the parameters in the experiment. The material properties of the substrate are available in the material database of the program. To model the film, the following parameters were used: transition temperature of 140 °C, conductivity of 0,2 W/(mK), heating capacity: 1,17 kJ/(kgK), Coefficient of linear thermal expansion: 70*10^-6/K, density: 1,2g/(cm^3), modulus of elasticity: 2200 MPa, Poisson number: 0,4.

3. RESULTS AND DISCUSSION

3.1 The Warpage in In-mold Decoration of Injection molded Parts

The test specimens are rectangular parts. A curvature of this regular form, shown in Figure *2* is warpage. There are positive and negative warpage. Positive warpage is the deformation in direction of the film and negative warpage is the deformation in direction of the gate. The warpage was measured at the outer edge with a dial gauge. In Figure *4* the influence of the melt temperature, the mold temperature, the thickness of the film and the post-injection pressure on a 2 mm thick part made of Makrolon 2405 is shown.

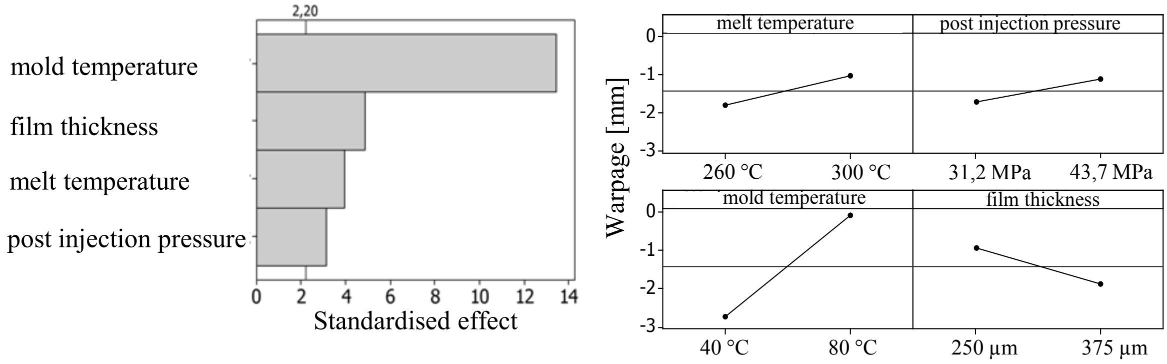

Figure 4: Parameters influencing the warpage of parts made of Makrolon 2405

The Pareto chart shows, that all observed parameters have a significant influence on the warpage. The most influencing parameter is the mold temperature with a standardized effect about 13, followed by the thickness of the film, the temperature of the melt and the post injection pressure. That means if an increase of the mold temperature about 40 °C occurs, a deformation in direction of the film about 3 mm takes place. An increase of the film thickness decreases the heat removal in the mold cavity. This leads to an asymmetrical temperature profile. The maximum of the temperature moved to the boundary layer and the contraction of the part in direction of the film increases. [5] Another effect becoming visible mentioned in [5]. With an increasing film thickness at a constant part thickness, the distance of the film to the neutral fiber is becoming larger. As a result, the mechanical moment of the film on the whole part increases. Also the deformation in direction of the film increases with a rise of the melt temperature. The asymmetrical temperature profile gets higher and so the contraction of the part towards the hotter side, the film side. This leads to higher shrinkages [3] A contrary effect is caused by the post injection pressure. As the post injection pressure rises the warpage decrease because the contraction of the part is lowered. Due to the high influence of the mold temperature, a second test series to investigate the influence of the warpage was carried out, shown in Figure *5*.

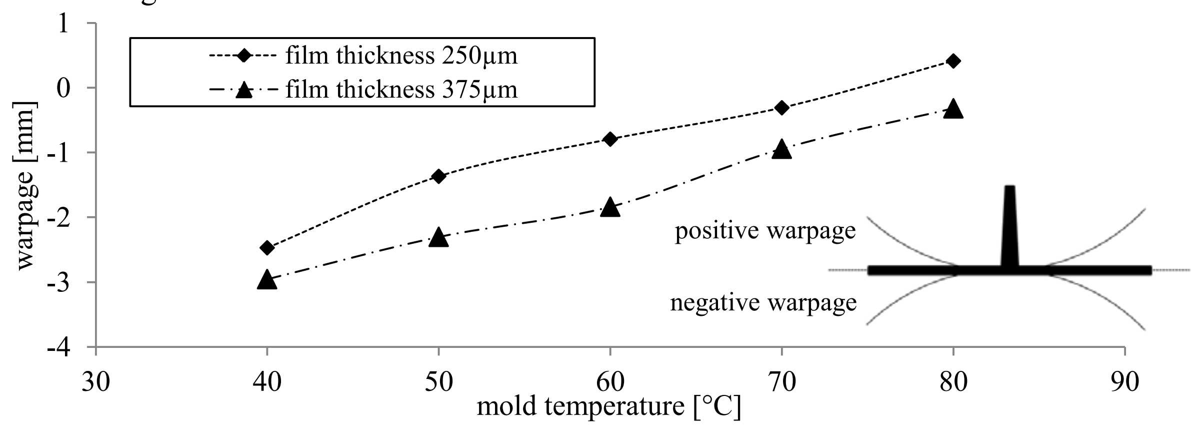

Figure 5: Experimental results on warpage of 2 mm thick IMD parts

The mold temperature was increased in steps of 10 degrees Celsius from 40 °C up to 80 °C. In addition to the mold temperature, the film thickness varied between 250 µm and 375 µm. Increasing mold temperature delayed the cooling of the hot plastic and reduced the temperature gradient in the part. This leads to less warpage with an increase of the mold temperature due to the reduced temperature gradient. Moreover Figure *5* shows the influence of the film too. A thick film increases the distance to the neutral fiber. This leads to a higher moment of the film on the whole part in negative direction, shown in Figure *2*.

A first approximation to predict the warpage of a part in dependence of the most influencing factors was made. The target is to calculate the warpage s. The parameters of the equation are: the thickness d of the part, the thickness D of the film, the mold temperature T_w, the melt temperature T and the post injection pressure p. To get a dimensionless property the injection time t and the mass m of the part are taken into the equation too. The aim is to calculate the warpage as a function of:

$$s = f(d, D, T, T_w, p, t, m) \qquad (1)$$

From a dimensional analysis follows

$$\pi_1 = \frac{d}{s},\ \pi_2 = \frac{D}{s},\ \pi_3 = \frac{T}{T_W}, \quad \pi_4 = \frac{pst^2}{m} \qquad (2)$$

The dimensionless parameters are summarized to:

$$\pi_{dT} = \pi_1 \cdot \pi_2^{-1} \cdot \pi_3 = \frac{d \cdot T}{D \cdot T_w} \qquad (3)$$

Now, the warpage can be calculated as

$$\frac{pst^2}{m} = f(\frac{d \cdot T}{D \cdot T_w}) \qquad (4)$$

The functional correlation between these two parameters follows from the test results shown in **Figure *6***. The warpage can be calculated in the following way:

$$\pi_4 = 1{,}8075e^{0{,}0058\pi_{dT}} \qquad (5)$$

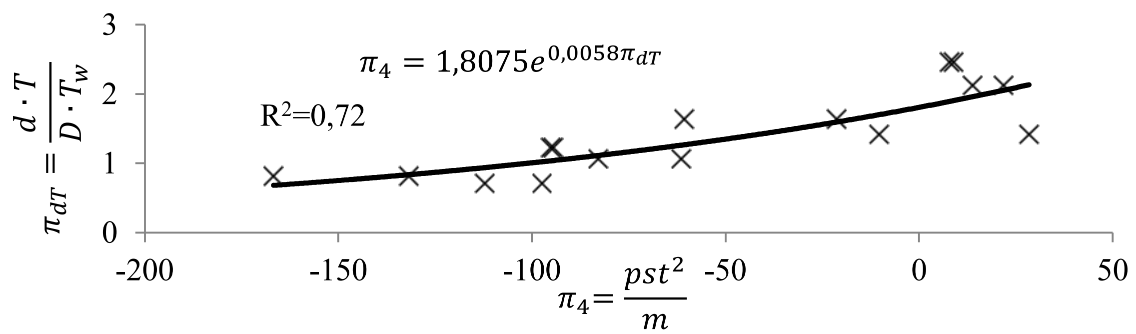

Figure 6: Equation to approximate the warpage of IMD parts

With a coefficient of determination of 0.72, the model delivers good results.

3.2 The Ink Wash-off in In-mold Decoration of Injection molded Parts

The ink wash-off is the radius of the washed-out ink on the film under the injection point. A high stress on the ink leads to a large wash-off radius. In Figure *7* and Figure *8* the influence of the melt temperature, the post injection pressure, the injection speed and the thickness of the part on the ink wash-off are shown. All observed parameters in the DOE have no significant influence on parts made of Makrolon LQ2647. A very low ink wash-off was observed with the material Makrolon 2405. Due to the different MFI between Makrolon 2405 with 20 g/10 min and Makrolon LQ 2647 with 11 g/10 min, the flowability has a large influence.

Without taking effect to the material, the main influencing parameters are the thickness of the part and the melt temperature, shown in Figure *7* and Figure *8*.

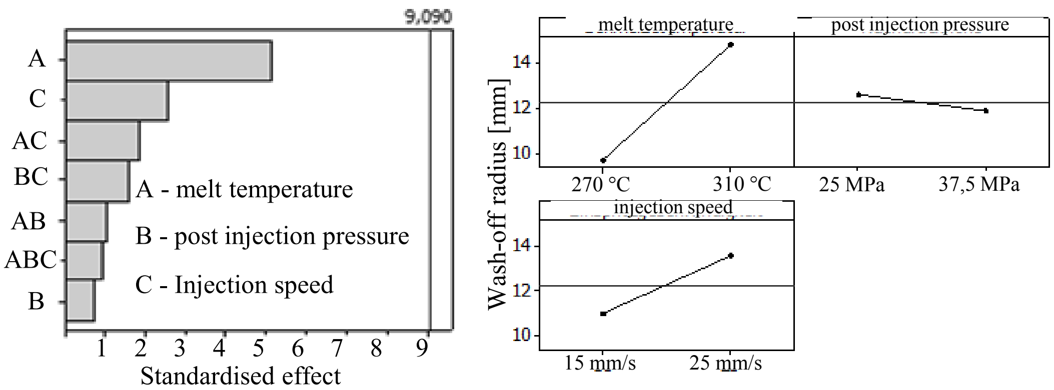

Figure 7: Pareto and main effect diagram for the ink wash-off of 2 mm thick party made of LQ2647

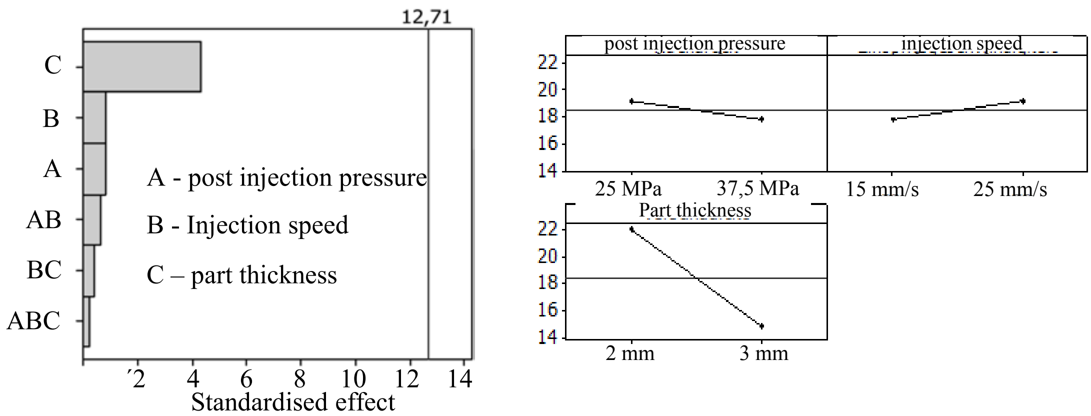

Figure 8: Pareto and main effect diagram for the ink wash-off of parts made of LQ2647

The wash-off radius decreases with an increase of the thickness from 2 mm to 3 mm from 22 mm to 14 mm. An increase of the injection speed from 15 mm/s to 25 mm/s also increases the ink wash-off about 3 mm. The post injection pressure has no influence. An increase of the temperature also increase the ink wash-off. Despite the fact, that an increasing temperatur rises the viscosity and the shear stress, an other mechanismen mentioned in[7] is the key. During the filling process the melt solified on the film. The thickness of this layer depends on the temperature. With an incresase of the temperature, the solified melt layer on the surface of the film gets thinner. This solified melt layer is connected to the ink, gets stretched by the flowing melt and leads to a delamination of the ink. In conclusion the ink wash-off depends mainly on the shear stress. A thick part or a low-viscosity melt decreases the shear stress on the ink. As described in the previous chapter, an approximation to predict the ink wash-off was made. The target is to calculate the radius of ink wash-off r. In the equation the main influencing parameters are integrated: the thickness D of the part, the melt temperature T and the injection speed v. To get a dimensionless property the injection time t and the mold temperature T_w are taken into the equation. The aim is to calculate the ink wash-off r as a function of:

$$r = f(D, T, T_w, v, t) \tag{6}$$

From a dimensional analysis follows:

$$\pi_1 = \frac{vt}{D}, \ \pi_2 = \frac{T}{T_W}, \ \ \pi_3 = \frac{r}{D} \tag{7}$$

The dimensionless factors 1 and 2 are summarized to:

$$\pi_4 = \pi_1 \cdot \pi_2 = \frac{v \cdot t \cdot T}{D \cdot T_w} \tag{8}$$

Now, the ink wash-off can be calculated as:

$$\frac{r}{D} = f(\frac{T}{T_w}, \frac{vtT}{DT_w}) \tag{9}$$

The functional correlation between these parameters follows from the test results shown in Figure *9*. The warpage can calculated in the following way:

$$\pi_4 = 19{,}3\pi_1 + 31{,}2 \tag{10}$$

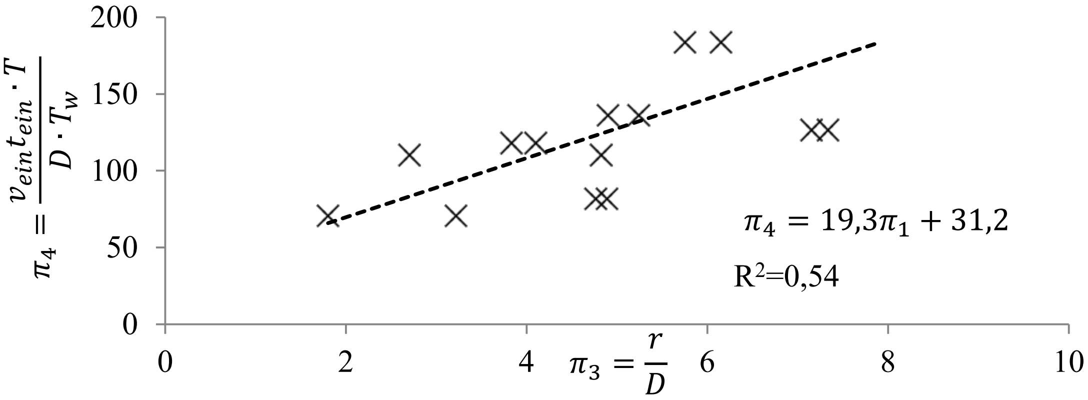

Figure 9: Equation to approximate the ink wash-off of IMD parts

With a coefficient of determination of 0.52, the model is developable.

3.3 Comparison of simulation and experiments

In Figure *10* the results of the simulated and measured warpage are shown. On the abscissa the simulated and on the ordinate axis the results of the experiment are pointed. Five different parameter configurations are tested with Makrolon 2405 and Makrolon LQ2647 from 2 mm and 3 mm thick parts. Additionally a variation of the injection speed and the mold temperature were observed.

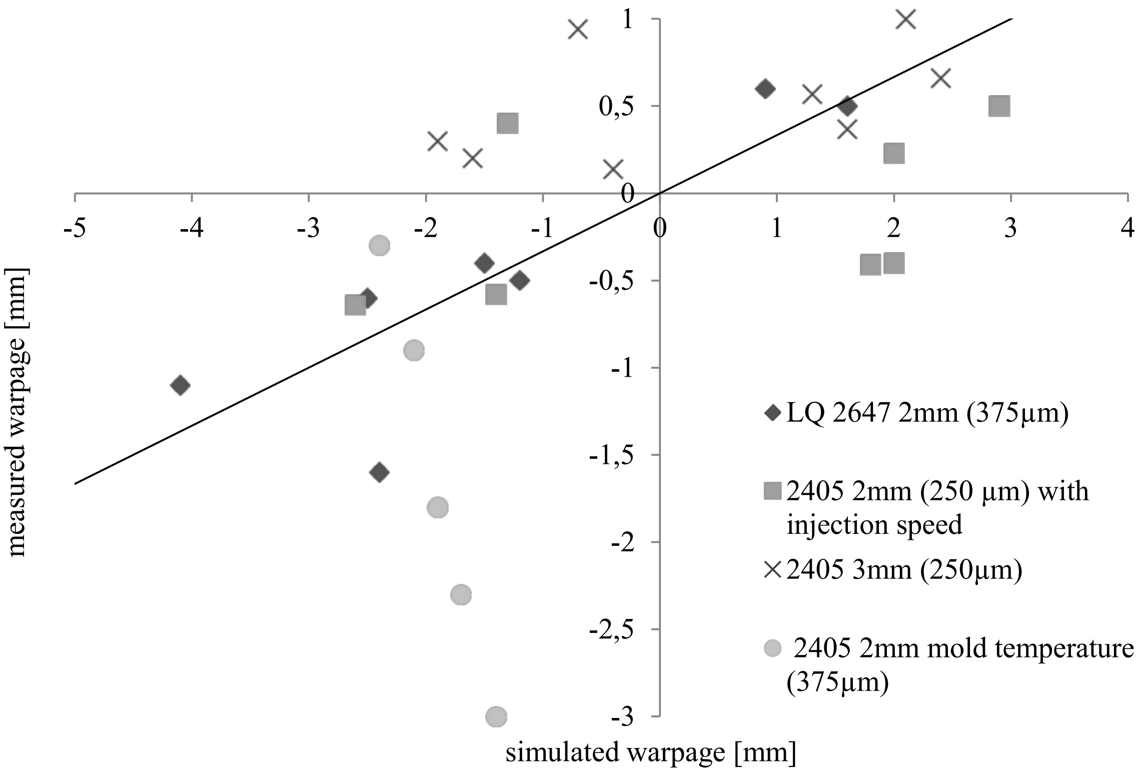

Figure 10: comparison between simulated and measured warpage

A qualitatively good agreement between the experiment and the simulation could be established for the diamond-shaped points. The simulated warpage is about the three fold increase of the measured warpage. In contrast to the most influencing parameters observed in the experiment, the post injection pressure has the most influence on the simulation with Makrolon LQ2647. Moreover, the post pressure on parts made of Makrolon 2405 has only a small impact. The quantitative comparison between experiment and simulation showed depending on the material larger deviations by specimens made of Makrolon 2405. Generally, the direction of the warpage in dependence of the influence of the parameters is up to the influence of the material the same. The thickness of the film and the mold temperature have a lager influence on the warpage in the experiment than in the simulation.

4. CONCLUSION

This study has examined the parameters influencing the ink wash-off and warpage of IMD parts. The main parameter affecting the warpage are the mold temperature. Moreover, the thickness of the film, the melt temperature and the post injection pressure also influence the warpage. The ink wash-off depends mainly on the shear stress. A comparison between simulation and experiment shows a qualitative good agreement for the material Makrolon LQ2647. However, the influence of the film and the mold temperature in comparison to the experiment is small. The equation for the calculation of the warpage delivers good results. A first approach to calculate the ink wash-off was found. With a coefficient of determination of 0.52 the model is developable. Considering the material in both equations is the next step to improve the predictive accuracy.

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