PROCESS-INTEGRATED PRINTING TECHNOLOGY FOR PLASTIC PARTS DURING INJECTION MOLDING

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Abstract

In-Mold technologies, such as In-Mold Labeling or In-Mold Decoration, have been used for several years for the process integrated decoration of plastic surfaces. The additional handling and transport processes cause considerable costs and are a big disadvantage. The new in-mold printing, a process integrated printing technology offers an alternative and enables the decoration of plastic parts during injection molding. Here, the image is pad printed onto the surface of the mold and then transferred to the surface of the plastic part during injection molding. The feasibility of this method is demonstrated on PP and a process related phenomena of the ink transfer and the ink adhesion are identified. The mold temperature is considered to be particularly critical. This is due to the fact that the temperature of the ink is affected by the mold temperature and liquid ink is necessary for a transfer of the ink to the polymer surface. In this study the thermal situation at the ink-plastic interface as well as the microscopic structure of the ink-plastic-interface are investigated. The goal of this paper is to show the influence of process parameters and conditions and their influence on the ink adhesion of printed motives.

Introduction

Nowadays the end-users are setting higher standards for the plastic parts and their surface properties. Thereby the requirements to achieve more effective printing, painting or coating of plastic parts are increasing. The printing of finished parts is a very popular way to increase the visual esthetics of the part for a relatively low cost. But often, except In-Mold Decoration or In-Mold Labelling [1, 2], printing of polymer parts takes place as an additional process. Because of the hydrophobic character of plastic parts, a pretreatment for activation of polymer surfaces is needed. This is currently achieved through flame, plasma or corona treatment. The functionalities introduced by oxidation improved bondability results from increased wettability, due to increased surface energy and interfacial diffusivity, caused by chain scission [3]. This surface treatment must occur immediately before plastic part will be printed. These types of surface functionalization represent an additional step and cause higher costs for time, energy and equipment (handling, logistic).

The current study has been triggered by the need to reduce the number of process steps and surface functionalization during injection molding. Hättig et al. [4] and Kalinowska et. al [5, 6] developed in-mold printing, where the entire decoration process is integrated into the injection molding cycle. The image is pad printed directly onto the surface of the injection mold, then the plastic melt is injected into the mold and during solidification, the ink is transferred from the mold surface to the plastic part. Figure 1 shows a schematic sketch of the in-mold printing process.

It is therefore aimed to investigate possibilities and limits of a processing window. In view of the decoration mechanism that takes place during the injection molding, the variable process parameters were chosen. Furthermore, the scientific background of an innovative approach of process integrated surface decoration during injection molding is investigated and its potential is explored.

Figure 1. Principle of in-mold printing process

Experimental

For the in-mold printing experiments polypropylene (PP Moplen 501 H, LyondellBasell Industries AF S.C.A) was used as thermoplastic material and PP plates (60 × 60 × 2 mm³) were produced by injection molding with Arburg Allrounder 320 S injection molding machine (model: 500-150/60, Arburg GmbH & Co. KG). The injection molding machine was operated at various melt and mold temperatures. In this study the influence of injection molding parameters on ink transfer to the plastic part was examined and occurring phenomena were characterized. The influence of process parameter and conditions and their influence on the ink adhesion of printed motives are also investigated. The commercially available ink Nori-Prop N 948 (Pröll KG, Weißenburg i. Bay.) with 25 wt.-
% thinner was used. NoriProp N 948 is an one-component ink suitable for untreated and pre-treated polypropylene. The experiments were also carried out with a self-developed pad printing machine. The employed cliché was an etched photo-polymer with a gravure depth of 25 µm.

After injection molding the in-mold decorated PP-plates were examined by means of polarizing microscope (Type: BX51, Olympus) and atomic force microscope (Type: NanoWizard II, JPK Instruments AG) to estimate a structure of surface layer of polypropylene. Also the structure of polypropylene under the ink layer and at the marginal side of the ink layer were investigated.

In addition to microstructural features of in-mold decorated samples the mechanical performance determined. Mechanical properties of in-mold decorated polypropylene samples were investigated by means of chemo-mechanical hand-abrasion test in accordance to DIN EN 60068-2-70 and to BMW Group Standard GS97034-1 [7, 8]. In this test the continuous damage to a decorated surface by the human hand is simulated. To permit realistic chemo-mechanical testing the samples were moistened with testing fluid (artificial sweat according to DBL 7384). The testing parameters are shown in Appendix (Table 2).

Results

The temperature of the melt has enormous influence on the ink transfer, as shown in figure 2. The temperature of the mold was increased continually. The specimens produced at standard injection molding parameters ($T_{mold} = 230^\circ C$, $T_{mold} = 30^\circ C$, $p = 350$ bar) show that no ink transfer from the mold to polypropylene parts took place. First the temperature increase caused an ink transfer. At mold temperature of 100°C almost complete ink transfer with high replication of printed pattern took place. Only a thin layer of the contours remained on the mold wall (Fig. 2h). This contours of the printed image dry on the fastest and contain less solvent than inside of the ink layer. The investigations show that this area of the dried paint adheres better to the mold so that these contours are not transferred to the plastic component and remain on the mold.

For the thermal properties of the ink, the same parameters as for polypropylene were taken. The ink is an unknown composition of polychlorinated polyolefins with different additives, but the thermal properties are in the same range as the properties for polypropylene [9]. The FEM was carried out in MATLAB 2007a PDE Toolbox. A simple model of heat transfer in equation 1 was used:

$$\rho C \frac{\partial T}{\partial t} - \nabla \cdot (k \nabla T) = 0$$

The determined melting temperature of the ink $T_{ink} = 80^\circ C$ and the melting temperature of polypropylene $T_{app} = 183^\circ C$ [11] are marked in the diagrams with dashed lines. The core temperature of the polymer $T_{MAX}$, the ink temperature at the interface between the ink and the plastic melt $T_{inkMAX}$ and the ink temperature at the in-

Table 1. Parameters for the FEM-simulation [9]

<table>
<thead>
<tr>
<th>Characteristic value</th>
<th>Mold</th>
<th>Polypropylene/Ink</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density $\rho$ [kg/m³]</td>
<td>7854</td>
<td>905</td>
</tr>
<tr>
<td>Heat capacity $C$ [J/kgK]</td>
<td>434</td>
<td>1930</td>
</tr>
<tr>
<td>Coefficient of heat conduction $k$ [W/Km]</td>
<td>60</td>
<td>0,24</td>
</tr>
<tr>
<td>Melting range of PP [°C]</td>
<td>-</td>
<td>165-175</td>
</tr>
<tr>
<td>Process parameters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Melt temperature of PP $T_m$ [°C]</td>
<td>-</td>
<td>230</td>
</tr>
<tr>
<td>Mold temperature $T_{wz}$ [°C]</td>
<td>30, 100</td>
<td>-</td>
</tr>
</tbody>
</table>

For the thermal properties of the ink, the same parameters as for polypropylene were taken. The ink is an unknown composition of polychlorinated polyolefins with different additives, but the thermal properties are in the same range as the properties for polypropylene [9]. The FEM was carried out in MATLAB 2007a PDE Toolbox. A simple model of heat transfer in equation 1 was used:

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The determined melting temperature of the ink $T_{ink} = 80^\circ C$ and the melting temperature of polypropylene $T_{app} = 183^\circ C$ [11] are marked in the diagrams with dashed lines. The core temperature of the polymer $T_{MAX}$, the ink temperature at the interface between the ink and the plastic melt $T_{inkMAX}$ and the ink temperature at the in-
interface between the ink and the mold $T_{\text{inkMIN}}$ are plotted for the different time steps in figure 3e and 3f.

Figure 3. Results of the FEM-simulation of the temperature distribution between plastic melt and the mold for different time’s after injection molding. Left: the mold temperature was set to 30°C and the mold walls were hold on 30°C. Right: the mold temperature was set to 100°C and the boards were also hold on 30°C.

For both initial temperature of the mold, the core temperatures $T_{\text{MAX}}$ reaches the melting point of polypropylene after 3 seconds and the thermoplastic become solid. The melt cools down in the same way, so we conclude that the melt temperature is not the key parameter for a satisfying ink transfer. At a mold temperature of $T_{\text{mold}} = 30^\circ\text{C}$, the temperature $T_{\text{inkMAX}}$ on the ink-melt-interface is after 0.03 seconds under the melting point of the ink. At the mold-ink-interface, the temperature $T_{\text{inkMIN}}$ are always lower than 37°C. This has no influence on the nanomechanical properties (as shown in figure 1b-Appendix). The heat is faster transferred through the ink and the steel mold that the hot melt cannot heat up the ink over the melting point. With a starting mold temperature of $T_{\text{mold}} = 100^\circ\text{C}$, the ink is at the injection of the melt above its melting point. The ink solidifies after 0.3 seconds and after 1 second, the ink and the thermoplastic have the same temperatures as with the lower starting temperature. The ink has to transfer from the mold to the melt before one second is over. The adhesion between melt and ink have to be greater in the liquid state than the adhesion between mold and ink. That the temperature of the ink is for short times higher than the mold temperature could be an explanation for the observed beginning ink transfer at 60°C mold temperature in figure 2h.

Morphological Characterization

In the present work sections of in-mold decorated samples of PP were examined by means of polarizing microscope. This arrangement has been visualized for both systems, where the ink was backmolded in wet and dried condition. In dried samples, microscopic investigations show a variance of optical properties of the surface layer (Fig. 4). The ink layer is situated at the polymer surface. At the same time (during cooling phase by injection molding) this ink layer stopped a formation of amorphous frozen layer. It can be concluded that the ink layer has a function of thermal isolator. This ink layer originate, that the thermal energy from the plastic melt cannot be easily led away. In the effect the polymer under the ink layer cools slower as polymer at marginal side of ink layer, where the amorphous layer can be observed.

Figure 4. Surface layer of in-mold decorated polypropylene. Ink layer backmolded in dried condition. Research in transmitted and polarized light.

Backmolding with rapid cooling system of freshly printed ink layer leads to another result, shown in Fig. 5. In-mold printed ink layer is completely enclosed in the surface layer of polymer. Ink layer is well recognizably. The surface layer of polymer remains in the same state, marginal surface layer and decorated surface layer are the same.

Figure 5. Surface layer of in-mold decorated polypropylene. Ink layer backmolded in wet condition. Research in transmitted and polarized light.

Moreover, the thin section of the interface between the ink and plastic in the cross section by means of scanning force microscopy was studied. The microstructure of the interface between ink and plastic (Fig. 6) shows dark domains (ink retention) in the polypropylene approxi-
mately 100 nm. This indicates that at this interface deformation of the ink through flowing melt takes place and the ink components diffuse inside the plastic. It also can be clearly seen that there is a segregation of ink and plastic melt. The shape of the interface is not flat or smooth, which is a further indication that the ink melts and deforms when it comes in contact with the plastic melt. The diffusion of components of ink in the polypropylene as well as the expansion and integration of the interface between ink and plastic is an important contribution for the good ink adhesion by in-mold decorated samples.

**Mechanical Properties**

Figure 7 shows the results of hand-abrasion test. For the first test the in-mold decorated specimens with previously dried ink patterns were used. After 60 cycles on the fabric and a sample were no traces visible. First visible traces and a discoloration on the fabric were visible after 2,000 cycles. After 4,000 cycles the test was canceled due to the clear abrasion of the ink from polypropylene.

Remarkable is the fact that all of the samples passed the chemo-mechanical abrasion test with testing fluid. There were no disruptive artefacts in the ink layer. After all tests (after 60; 2,000 and 4,000 cycles) the specimens were functional and no traces were visible. The structure of the specimens after the test was still unchanged.

**Discussion**

The adhesion between ink and the polymer is the key property for a satisfying ink transfer. The most important process parameter is the temperature of the mold surface. The mold temperature has influence on the ink transfer, whether it is incomplete, where only the shape of the ink is molded into the polymer, a complete ink transfer but with the contours of the image, or a complete transfer of the ink together with an undisturbed image. Between 80°C and 100°C of mold wall, promising results were achieved.

The adhesion between the ink and the polymer is not the problem, if the ink is heated, but the adhesion between the ink and the injection mold appears to be too strong. To improve the in-mold printing process, this adhesion has to be smaller.

Finally, the experiments show that the ink layer have an influence on the morphological structure of polymer directly under the ink layer. A surface layer under the ink is different as a surface at the marginal side of the ink layer. A special process control during in-mold printing enables fully embedding of the ink layer in the polymer. Such complete encapsulation of the ink induced at the same time higher mechanical properties of the decorated parts.

In-mold decorated polypropylene parts fulfilled the industrial standards for functional and non-functional decorated plastic strips. This new decoration technique can be an alternative solution for industrial applications.

**Conclusions**

In-Mold Printing is a new manufacturing technique which enables decoration of plastic parts already during injection molding. This method does not need post-processing steps for industrial applications. First the image is printed onto the mold surface and then transferred to the surface of the produced part during injection molding. The present research focuses on identifying, investigating and
tailoring the technological as well as physico-chemical processes during ink transfer.

An application of in-mold printing to nonpolar polyolefins was currently investigated and the results are presented. The printed image was successfully transferred to polypropylene parts during injection molding. The temperature of the injection mold seems to be a key parameter for satisfying ink transfer. This is due to the fact that the temperature of the ink is affected by the mold temperature and liquid ink is necessary for a good transfer of the ink to the polymer surface. Furthermore, backmolding of directly printed ink pattern allows the complete ink transfer as well. At the same time better mechanical properties of decorated areas are guaranteed.

The phenomena of in-mold printing were investigated with surface analysis methods like optical microscopy and atomic force microscopy as well as mechanical properties to define the adhesion of the ink on polymer substrate.

With the knowledge of the process control and resulting properties of the parts we improved the in-mold printing process for polypropylene, which is an important polymer for industrial applications.

Acknowledgements

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References

Appendix

Figure 1. Young’s modulus and work of adhesion of the ink at different temperatures: (top) An example of one force-distance-curve for a mold temperature of 80°C. The red curve is the fit for the young’s modulus with DMT-contact-model. Young’s modulus of the ink on the mold surface at different mold temperatures. Error bars represent the standard deviation of the distribution of the young’s moduli. (bottom) Mean force-distance-curve for a mold temperature of 80°C. Work of adhesion at different mold temperatures.

Table 2. Testing parameters for hand-abrasion test according to GS 97034-1:2012-02

<table>
<thead>
<tr>
<th>Plastic part</th>
<th>Test travel</th>
<th>Test speed</th>
<th>Fabric feed</th>
<th>Testing fluid</th>
<th>Test force</th>
<th>Number of strokes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instrument panel</td>
<td>40</td>
<td>60</td>
<td>None</td>
<td>dry</td>
<td>10</td>
<td>60</td>
</tr>
<tr>
<td>Non-functional decorative strips (Cockpit, door)</td>
<td>10</td>
<td>60</td>
<td>none</td>
<td>dry</td>
<td>10</td>
<td>60</td>
</tr>
<tr>
<td>Functional decorative strips (door pull handle)</td>
<td>10</td>
<td>60</td>
<td>0.3/1000</td>
<td>dry</td>
<td>10</td>
<td>4,000</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>60</td>
<td>0.3/1000</td>
<td>artificial sweat</td>
<td>10</td>
<td>1,000</td>
</tr>
</tbody>
</table>