EFFECTS OF PROCESSING PARAMETERS ON THE SURFACE STRUCTURE OF INJECTION MOLDED PARTS: APPLICATION OF IMAGE ANALYSIS FOR THE INVESTIGATION OF 2D CAVERN STRUCTURES WITH RESPECT TO ELECTROPLATING QUALITY REQUIREMENTS

Jens P. Siepmann and Johannes Wortberg, University of Duisburg-Essen, Institute of Product Engineering (ipe), Germany
Felix A. Heinzler, BLA Kunststoff- und Galvanotechnik GmbH & Co KG, Solingen, Germany

Abstract

For the production of injection molded parts with a subsequent electroplated coating, technical polymers like acrylonitrile butadiene styrene or polycarbonate/acrylonitrile butadiene styrene blends are used. The quality of these parts is affected by both the electroplating parameters and the properties of the surface and subsurface structures of the injection molded part. Processing parameters influence these structures during injection molding and hence are responsible for the adhesion of the polymer and the metal [1],[2].

The effects on the resulting caverns in polymer surfaces (after etching) caused by changing injection molding parameters are investigated. For this purpose, relevant processing parameters affecting the surface structure are examined. Furthermore, image analysis is applied as an objective evaluation method to quantify the two-dimensional shape of caverns. This analysis is based on electron microscope (SEM) images of chemical etched polymer part surfaces (ABS, PC/ABS). Meaningful key figures, such as roundness, degree of orientation, caverns/µm², and area of caverns, are emerged to quantify the surface structure. An ABS and PC/ABS material is tested and compared, and coherences between the shape of the caverns, processing parameters, material properties, and geometry influences are elaborated.

Introduction

The two main requirements of attractive products in the automotive industry are technical innovations and design elements. While electroplated parts are sparsely applied in the exterior of a car, especially in the interior design appealing genuine metal surfaces are used. These design elements suggest a feeling of high quality and safety to the customer. By electroplating injection molded plastic parts, hybrid composite parts can be produced. These parts combine advantages of polymer parts, such as lightweight, flexible design, and low material costs, with high quality impressions. However, the production of such parts often goes along with high reject rates compared to conventional processing techniques. These high reject rates are often caused by the insufficient adhesion of the metal layer and the surface of the injection molded part. These defects can first be detected in climate change tests after the electroplating process. Even small defects on the surface of the injection molded part (micro/nanoscale structures) before electroplating result in failures of the completely electroplated parts. In order to meet the requirements of the automotive industry, not only a perfect setup of the injection molding and electroplating process but also a better understanding of the emerging part surface structure properties is required [3],[4].

Electroplating of Plastics

In general, electroplating of polymers is similar to the electroplating of metals. Nevertheless, the non-conducting properties of polymers require some special pre-treatment of the part before it can be conventionally processed. Hence, the electroplating of plastics can be divided in an electroless pre-treatment and an electrolytic reinforcement [5]. The electroless pre-treatment, which consists of three stages, is one of the key factors for products to meet the high quality requirements regarding the metal layer [6]. First, butadiene is dissolved out of the surface and subsurface layer of the part through chemical roughening. The subsequent stages are the seeding within the emerged caverns and the electroless metallization of the first layer. As depicted in Figure 1, the impact of the individual processing stages on the adhesion between the polymer and the metal is decreasing along the process chain.

![Figure 1. Impact on the adhesion between polymer and metal layer during electroplating processing steps [7, extended representation.](image-url)](image-url)

Seeding and electroless metallization provide a first layer of chemical nickel with a thickness of 1 µm. The other layers are applied by electroplating. The common layer structure with one idealized schematic cavern can be...
seen in Figure 2. The different layers determine the properties of the part, e.g., the glossy/tarnished nickel layer defines the optical appearance of the part.

\[
\begin{align*}
\text{Chrome} & = 0.3 \,–\, 0.8 \,\mu m \\
\text{glossy/tarnished nickel} & = 15 \,–\, 20 \,\mu m \\
\text{Acid copper} & = 20 \,–\, 30 \,\mu m \\
\text{”Pre”nickel} & = 2 \,\mu m \\
\text{Chemical nickel} & = 1 \,\mu m
\end{align*}
\]

Figure 2. Schematic layer structure of an electroplated polymer part.

**Image Analysis Algorithm and Key Figures**

The developed procedure presented in [8] is shown in Figure 3. The original SEM image of the part surface, captured with the lower secondary electron image mode (LEI) with a JEOL JSM-7500F, is edited by applying contrast optimization, binarization, noise filter, segmentation, and ellipse fitting using ImageJ.

![Image Analysis Algorithm](image)

Figure 3. Procedure of the image analysis algorithm.

The ellipse fitting results as well as the original structure are shown in Figure 4 as an excerpt of the SEM image in Figure 3. The fitting results are evaluated regarding the orientation angle \( \alpha \) (Figure 4) between the ellipse’s major axis and x axis, which is orthogonal to flow direction (y axis), the roundness as the ratio of major and minor axis with a value of 1 for ideal roundness, the cavern area, and the number of caverns per \( \mu m^2 \).

![Ellipse fitting results compared to original image](image)

Figure 4. Ellipse fitting results compared to original image and illustration of the meaning of the orientation angle \( \alpha \).

**Experimental Setup**

In order to analyze the effects of processing parameters on the two-dimensional shape of caverns, a 2³+1 experimental design is established. The processing parameters, which essentially affect the formation of the surface and subsurface layer, are the screw advance speed (Factor A), the cooling temperature (Factor B), and the barrel temperature (Factor C). As shown in Table 1, these parameters are varied for an ABS (Table 1, a)) as well as a PC/ABS (Table 1, b)). The Center Point for both materials is Setup No. 9. The materials used are an ABS (Novodur P2MC, INEOS Styrolution Group GmbH, Frankfurt on the Main, Germany), and a PC/ABS (Bayblend T45 PG, Covestro AG, Leverkusen, Germany). For the range of the factor levels, material data sheets as well as experiments are considered.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>2</td>
<td>–</td>
<td>+</td>
<td>–</td>
</tr>
<tr>
<td>3</td>
<td>+</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>4</td>
<td>+</td>
<td>+</td>
<td>–</td>
</tr>
<tr>
<td>5</td>
<td>–</td>
<td>–</td>
<td>+</td>
</tr>
<tr>
<td>6</td>
<td>+</td>
<td>–</td>
<td>+</td>
</tr>
<tr>
<td>7</td>
<td>–</td>
<td>+</td>
<td>–</td>
</tr>
<tr>
<td>8</td>
<td>+</td>
<td>+</td>
<td>–</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>A [mm/s]</th>
<th>B [°C]</th>
<th>C [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) 30</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>b) 30</td>
<td>20</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 1. The ellipse fitting results as well as the original structure are shown in Figure 4 as an excerpt of the SEM image in Figure 3. The fitting results are evaluated regarding the orientation angle \( \alpha \) (Figure 4) between the ellipse’s major axis and x axis, which is orthogonal to flow direction (y axis), the roundness as the ratio of major and minor axis with a value of 1 for ideal roundness, the cavern area, and the number of caverns per \( \mu m^2 \).

Besides varying the material, two different positions on the part are investigated (Figure 5) in order to demonstrate the variation of effects throughout the surface layer of the part with constant injection parameters. With the focus on realistic effects, rheological material properties were measured and implemented to the simulation.

![Experimental Setup](image)
The selected positions on the part differ by the material’s shear load during filling and were selected based on the results of a 3D injection molding simulation with varying screw advance speed (Figure 6). It is supposed that the shearing rate during filling has a very pronounced effect on the deformation and deviation of the butadiene particle and therefore leads to increasing differences in geometry effects.

At position 1, the general shear rate level is higher and the shear rate also increases stronger by increasing screw advance speed than at position 2.

Results: Influence of Processing Parameters

Due to the large amount of data, only an extract of results regarding the effects for different positions and for the materials ABS and PC/ABS is shown subsequently.

ABS

At first, the effect of the cooling temperature on the two key indicators number of caverns and cavern area at position 1 processed at different barrel temperatures is presented (Figure 7). For a low barrel temperature of 230 °C, higher cooling temperatures lead to an increasing number of caverns per µm². Opposite results are obtained for higher barrel temperatures. For parts processed at 250 °C, the number of caverns decreases with higher cooling temperatures. At the same time, the cavern area increases for high barrel temperatures and higher cooling temperatures.

Figure 7. Cavern area and number of caverns at position 1 on the part depending on cooling temperature and barrel temperature for ABS.

For the degree of orientation, different effects can be detected for position 1 and 2 (Figure 8). At position 1, the degree of orientation increases with increasing screw advance speed. At position 2, where lower shear rates occur, the degree of orientation is nearly unaffected by the screw advance speed. Here, the importance of the mold geometry is clearly visible. The distance between position 1 and 2 is only 5 mm but the surface properties caused by the variation of the processing parameter screw advance speed are clearly different.

Figure 8. Degree of Orientation depending on screw advance speed for Position 1 and 2 for ABS.

The results for the roundness of the caverns are shown in Figure 9. Again, a difference can be detected for the two positions on the part. For all nine parameter setups of the DoE, the roundness of the caverns at position 2 is higher than at position 1. The roundness differs from 0.58 % (experiment 1) to 7.26 % (experiment 6). It is shown that especially the experiments with the high screw advance speed (experiments 2, 4, 6, 8) lead to a difference in roundness results.
Figure 9. Comparison of roundness at position 1 and 2 for all nine setups of the DoE.

The data implies that the geometry of the caverns at position 1 and 2 is influenced by different processing parameters. Whereas screw advance speed most strongly impacts the degree of orientation at position 1, barrel temperature has the most pronounced effect at position 2.

PC-ABS

In the following, the results of the DoE for PC-ABS are presented. Figure 10 shows the degree of orientation depending on the screw advance speed and barrel temperatures at position 1. For 250 °C, the degree of orientation increases with increasing screw advance speed. For 260 °C, only a slight increase from 1.75 to 2% can be observed, whereas a decreasing degree of orientation is detected for 270 °C. The interaction between the increasing screw advance speed and temperature is caused by the different reactions of PC and ABS viscosity to shearing rate and temperature.

The results imply that the roundness of the caverns is higher at position 2 than at position 1 (Figure 11). For a screw advance speed of 10 mm/s (experiments 1, 3, 5, 7), the difference between the positions is smaller than at the setups with 30 mm/s. In experiment 7, the roundness at position 1 is even higher than at position 2. This may be caused by a high cooling as well as a high barrel temperature.

Figure 11. Comparison of roundness at position 1 and 2 for all experimental setups.

The degree of orientation also shows a strong difference between position 1 and 2, especially for the high screw advance speed experiments (2, 4, 6). In combination with high cooling and barrel temperature, the differences disappear in experiment 8 (Figure 12).

Figure 12. Degree of orientation at position 1 and 2 for all experimental setups.

Practical Implications and Part Quality

The experiments reveal a direct relationship between the orientation and the processing parameters. Especially in the boundary layers, orientations strongly influence the adhesion of electroplated surfaces. The higher the orientation, the higher the resulting tension, which may reduce the adhesion and therefore lead to quality defects. Part areas with high tension due to high shear rates may delaminate during climate change tests.

To analyze the practical implications of the shown effects on the orientations for part quality in series production, a design of experiment has been performed under series conditions at BIA Kunststoff- & Galvanotechnik GmbH & Co. KG, Solingen, Germany. Processing parameters have been varied and a product
relevant quality criteria (delamination effect after climate change test) was investigated. Figure 13 shows an example for delamination after the climate change test.

The processing parameters screw advance speed (Factor A) and barrel temperature (Factor B) were used in a design of experiment as shown in the following table.

Table 3. $2^2+1$ DoE to reference quality criteria.

<table>
<thead>
<tr>
<th>No.</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>4</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

The results of the climate change test (PV 2005 [9]) are shown in Figure 14. As already indicated by the presented investigation, the orientation of the butadiene is influenced by the screw advance speed and the barrel temperature. The higher the screw advance speed and the lower the barrel temperature are, the more the orientation and tension increase, which reduce the adhesion of the layer system. Hence, the reject rates of experiment 1 and 2 are very high. After just 14 cycles in the climate change test, first delamination effects occur. The best results were achieved by reducing the screw advance speed and increasing the barrel temperature (experiment 4). Up to 40 climate change cycles have been passed in this experiment.

The influence of screw advance speed and barrel temperature is cross-linked and should be discussed for different part geometries. Also, the venting of the mold is important. The boundary conditions are given by the geometry and the viscosity of the polymer. At the end, a complete filling is required and the temperatures have to stay within the processing window to avoid thermal degradation and discoloration. However, as shown in the investigation, it is possible to analyze the morphology of the parts after injections molding and etching and to derive process optimizations to increase the part quality.

**Conclusion and Outlook**

This research shows that the developed method is applicable to the analysis of the surface morphology since it detects differences of the surface layer due to changes of the injection molding process parameters. Hence, it is possible to quantify structures and to detect potential problems before the electroplating and quality tests are performed. The results show that a complex interaction of the processing parameters screw advance speed, barrel temperature, and cooling temperature exists. Clear morphology differences can be measured at different positions on the part. The performed climate change tests with series production parts at BIA Kunststoff- & Galvanotechnik GmbH & Co. KG demonstrate the advantages of a low screw advance speed in combination with high barrel temperatures.

Further work will concentrate on morphology measurements of the depth of caverns and will therefore enhance the two-dimensional information gathered so far. Additionally, 3D injection molding simulation will be used to explain the different effects of the processing parameters depending on the geometry of the part at different positions in detail.

**References**