COMPARISON OF EMBOSSING PROPERTIES OF POLYCARBONATE AND POLYSTYRENE FOR DEEP MICROSTRUCTURES

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ABSTRACT

Low cost and high-volume production has been identified as the successful route for commercialisation of many Micro Electromechanical system (MEMS) devices. Hot embossing, being a simple and cost effective method of replication of many micro-components in polymeric substrates, has been recognised as the most viable process using laser machining and consequent electroforming. Recently, Polycarbonate (PC) and Polystyrene (PS) are increasingly used for polymer microreplication mainly because of their suitable material properties such as Glass transition temperature (Tg), mechanical stability at high operating temperature and pressure conditions, bondability with other materials especially in the fabrication of multi-layered structures. Hence, in this paper, we present the results of our investigations on the effect of pressure and temperature during microembossing of different features into Polycarbonate and Polystyrene. The hot embossing experiments were carried out on specially designed home made equipment. These experiments demonstrated that polystyrene with lower Tg (~100ºC) is more suitable for the replication of relatively finer features. The higher glass transition temperature of PC (~150ºC) necessitates extra heating time, thus extending the replication process time and increasing thermally induced stresses in the embossed material. The effect of variation of temperature and pressure on the replication of similar features in the polycarbonate and polystyrene is discussed in detail.

1. INTRODUCTION

Hot embossing is a simple method used for quality and precision replication of microstructures. It is the most effective way to achieve low-cost production and high replication accuracy of MEMS components as the demand for these devices has been growing rapidly. A schematic representation of the hot embossing system is depicted in Figure 1.

An embossing tool, also referred to as a master or shim, is a negative copy of a required microstructure and can be fabricated in various ways. Traditionally CNC machining of stainless steel has been employed to achieve features >100 µm with no sharp corners or right angles. Smaller features however, require lithographic methods to deliver the desired accuracy. In this case, laser machined PC sheet was used as a mold to grow the nickel shim by electroforming.

The whole embossing process is performed under vacuum to prevent the formation of air bubbles and also to avoid the detrimental influence of evaporated water on the shim. The mold and substrate are heated just above the glass transition temperature Tg of the substrate to ease imprint via change of the material properties of the substrate. After completion of embossing the mold and substrate are cooled down while vacuum and pressure are still applied to maintain the embossed structure in the solidified substrate. This thermal cycle, the difference between the working and de-embossing temperatures, results in small, thermally induced stresses. According to this cycle the recommended temperature range can be between 25 and 40 °C, or as small as possible. The last step is the separation of the shim and substrate, also known as de-embossing. The substrate with replicated structure can further be machined if required.

The process described above is an isothermal embossing (both substrate and shim heated above Tg). Non-isothermal embossing is employed when the heat effect on the process is to be investigated, and in such a case only one of them, the shim or substrate, is heated to the embossing temperature. The embossing temperatures, pressures and times recommended in the literature differ significantly. These process parameters can be optimised depending on the feature size, geometry and shape of the pattern and finally the shim and substrate contact area.

This paper presents results of our investigations on the evaluation of shims and the polycarbonate and polystyrene substrates after the embossing. Nickel shim’s with simple experimental structure was used for embossing on these substrates. Results of replication quality, at different working pressures, during various
embossing runs were evaluated using confocal and optical microscopy.

2. EXPERIMENTAL

The manufacturing process of the master mold comprised laser machining of polycarbonate and subsequent nickel electrodeposition. As the result of UV-laser ablation, two different polycarbonate molds were machined. A 248 nm KrF excimer laser micromachining system (Exitech Ltd, S8000, UK) was used to produce polymer molds to obtain the features used for embossing on PS. This system works by illuminating a chrome-on-quartz mask, and the image is demagnified by x10 to ablate the workpiece. Its schematic representation is depicted in Figure 2.

**Figure 2.** Schematic representation of excimer laser system

For creation of features for embossing on PC a 355 nm frequency tripled Nd:YAG laser system was employed (LaserTec, The Netherlands). In this system (Figure 3), the path of the laser beam directed onto the workpiece is controlled by two galvo-scanners before passing through the lens.

**Figure 3.** Schematic representation of frequency tripled Nd:YAG laser system

Electroforming into the machined PC features using a nickel sulfamate bath, produced master embossing shims. As a result of these two processes Ni master molds with dimensions 25mm x 75mm and 300µm thickness were produced using this process. Microstructures on the master molds included structures that can be described as inverse channels (Figure 4) with variable height and width as detailed in Table 1.

**Table 1.** The dimensions of experimental features

<table>
<thead>
<tr>
<th>Feature</th>
<th>PC</th>
<th>PS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height [H] (µm)</td>
<td>130</td>
<td>200</td>
</tr>
<tr>
<td>Width bottom [WB] (µm)</td>
<td>70</td>
<td>170</td>
</tr>
<tr>
<td>Width top [WT] (µm)</td>
<td>30</td>
<td>30</td>
</tr>
</tbody>
</table>

A single line mold was used for PS and the parallel two lines were used for embossing of PC.

An isothermal hot embossing process was performed, using a home made embossing tool depicted in Figure 5 for all embossing experiments.

This tool consists of top and bottom stages. The top stage can slide in vertical direction on four guiding posts, while the bottom stage is fixed. The top and bottom parts of the embossing tool have three 400-watt heating elements in each of them. Cooling is achieved by circulating compressed air. Also, there is a vacuum pump connected to the top part of the embossing tool, in order to prevent the formation of air bubbles and also to avoid the detrimental influence of evaporated water on the shim during the embossing process.

**Figure 5.** Schematic representation of the hot embossing tool used in experiments

In this embossing process master mold and polymer substrate are placed into the embossing chamber. The chamber is closed by lowering the upper stage of the tool and evacuated. When the temperature of the substrate and the mold are equal and reach the preset level, pressure is applied for a certain period of time. The next stage of the process is cooling the substrate and mold sandwich under the same embossing pressure while vacuum is still applied. The final step is separation of the master mold and substrate.
PC and PS substrates were embossed under four different pressure values at a temperature above the glass transition temperature ($T_g$) region, which was 150 and 100°C respectively. The pressures used during embossing varied with the material. For example, the pressure in the embossing of PC varied up to as high as 190 bars compared with that used in PS, which was a maximum of 161 bars. The embossing time was fixed at 5 minutes in both cases. The effect of very high/low values of pressure and temperature combinations on the embossed structures was studied in this process, especially using low pressure/high temperature for PC and high pressure/low temperature for PS.

The quality of the embossed microstructures was examined using a laser scanning confocal microscope (Olympus Pty. Ltd., OLS1100). This microscope allows non-contact measurement of 3D profiles of the microstructures with high resolution (0.01µm), due to its very short depth of field. It can be used as a common microscope to obtain 2D images of the surface. The advantage of a confocal microscope in comparison with other 3D information systems, such as interferometers or fringe projections, is the possibility of obtaining quantitative information of roughness and aspect ratio. Filtering and levelling operations were provided to post process generated image data.

### 3. RESULTS

Evacuating the embossing chamber causes only atmospheric pressure to act on the tool, which is insufficient to transfer a feature onto the substrate’s surface even when the temperature is above $T_g$. Not surprisingly, by increasing the pressure the embossing quality improves from poor (Figure 6) to good as the substrate material is forced to fill all the corners with respective to the embossing tool (Figure 7). Thus a higher pressure influences the embossing quality positively.

However, Figure 8 shows that an excessive increase in pressure causes the tool features to bend aside creating an elevated lip on the substrate. This might be due to the plastic flow of the substrate material sideways due to increased pressure. Thermal expansion of the substrate material during embossing seems to have minimal contribution to the substrate flow. Additionally, this time-consuming replication process cannot be accelerated via reducing the temperature and increasing the pressure as the quality of the replicated feature deteriorates.

**Figure 8. Poor feature transfer in PC**

Tables 2 and 3 summarize the results for embossing of PC and PS substrates.

#### Table 2. Embossing results for PC at 150°C

<table>
<thead>
<tr>
<th>Embossing pressure (bars)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>153</td>
<td>Feature transfer without problems</td>
</tr>
<tr>
<td>165</td>
<td>Feature of good quality, although some defects occur</td>
</tr>
<tr>
<td>177</td>
<td>Lips on edges of the feature, bending of the master due to high pressure</td>
</tr>
<tr>
<td>190</td>
<td>Lips of up to 40 µm, feature transfer poor due to the flow as a result of high pressure-related damage (Fig. 6)</td>
</tr>
</tbody>
</table>

#### Table 3. Embossing results for PS at 100°C

<table>
<thead>
<tr>
<th>Embossing pressure (bars)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Feature of poor quality, corners not filled (Fig. 8)</td>
</tr>
<tr>
<td>50</td>
<td>Feature of poor quality, corners not filled</td>
</tr>
<tr>
<td>85</td>
<td>Feature transfer without problems (Fig. 7)</td>
</tr>
<tr>
<td>105</td>
<td>Feature of good quality, although some defects occur</td>
</tr>
</tbody>
</table>
It is also interesting to note that at a very low pressure (1 bar) and at the temperature of 165 °C (which is above $T_g$) no feature transfer in PC is observed, as the pressure is not substantial enough. At the other extreme of values with pressure maintained at 161 bars at low temperature of 90 °C (under $T_g$) the replicated features are of poor quality due to low plasticity at this temperature (Figure 9).

Figure 9. Cracked surface of PS substrate due to low plasticity of material at low temperature under high pressure.

4. CONCLUSIONS

This study mainly concentrated on identifying the important parametric effects during the microembossing runs, which could affect the quality of replication of a given sample. Results clearly showed that the pressure, temperature and embossing time are the three important parameters, which together decide the quality of replicated feature with respect to the master.

Based on the results, the optimal conditions for embossing microstructures into Polystyrene are 85 bar pressure applied on the sample for 5 minutes at a temperature of 100°C. For Polycarbonate, the optimal conditions are 150°C temperature and the pressure of 150 bar with a heating time of 5 minutes.

These results also indicated that the pressures above approximately 150 bar for PC and 100 bar for PS respectively are not recommended, as this appears to lead to a poor feature transfer or even structural damage due to the substrate flow effects.

These experiments also indicate that polystyrene with lower $T_g$ (~100°C) is more suitable for the replication of relatively finer features. The higher glass transition temperature of PC (~150°C) necessitates extra heating time, thus extending the replication time and increasing thermally induced stresses in the embossed material.

Moreover, the results show that employing Nd:YAG laser machining as a mold fabrication method is very useful for sharp, thin and high features that can be used for example as a cutting tool. On the other hand, excimer laser provides more opportunity to control shape, surface quality and dimensions of the features and consequently, to ensure desired quality in replication.

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REFERENCES