Simulation and Experimental Study of the Effects of Process Factors on the Uniformity of the Residual Layer Thickness in Hot Embossing

Hot embossing replica are characterized by the quality of the molded structures and the uniformity of the residual layer. In particular, the even distribution of the residual layer thickness (RLT) is an important issue in hot embossing and the related process of thermal nanoimprint lithography, as variations in the RLT may affect the functionality or further processing of replicated parts. In this context, the paper presents an experimental and simulation study on the influence of three process factors, namely the molding temperature, the embossing force, and the holding time, on the residual layer homogeneity achieved when processing 2 mm thick PMMA sheets with hot embossing. The uniformity of the RLT was assessed for different experimental conditions by calculating the standard deviation of thickness measurements at different set locations over the surface of each embossed sample. It was observed that the selected values of the studied parameters have an effect on the resulting RLT of the PMMA replica. In particular, the difference between the largest and lowest RLT standard deviation between samples was 18 μm, which was higher than the accuracy of the instrument used to carry out the thickness measurements. In addition, the comparison between the obtained experimental and simulation results suggests that approximately 12% of the RLT uniformity was affected by the local deflections of the mold. Besides, polymer expansion after release of the embossing load was estimated to contribute to 8% of the RLT nonuniformity. It is essential to understand the effects of the process parameters on the resulting homogeneity of the residual layer in hot embossing. In this research, the best RLT uniformity could be reached by using the highest considered settings for the temperature and holding time and the lowest studied value of embossing force. Finally, the analysis of the obtained results also shows that, across the range of processing values studied, the considered three parameters have a relatively equal influence on the RLT distribution. However, when examining narrower ranges of processing values, it is apparent that the most influential process parameter depends on the levels considered. In particular, the holding time had the most effect on the RLT uniformity when embossing with the lower values of process parameters while, with higher processing settings, the molding temperature became the most influential factor.

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1 Introduction

There is a growing demand for the high volume production of parts with micro and nanoscale features in today’s industrial applications. Consequently, micro and nanofabrication technologies have developed rapidly, and a large number of research studies have been published on this topic in the last decade. Some of the current micro and nano manufacturing methods include Lithographie Galvanik and Abformung (LIGA) [1], micromechanical machining [2], laser machining [3], injection molding (IM) [4], hot embossing (HE) [5], and UV nanoimprinting lithography (UV-NIL) [6]. The latter three methods are applicable for large series production as they enable the replication of polymers parts with micro and nanoscale structures from a master mold.

Among these molding techniques, hot embossing is a process, which relies on raising the temperature of a sheet of polymer just above its glass transition temperature and on pressing a heated master plate into the polymer for triggering a local flow of the material to fill the cavities to be replicated. This technique has attracted increased attention in recent years in particular due to the relatively simple setup and low cost associated with its implementation in comparison to other replication techniques [7–9]. However, due to the fact that the cycle time of the hot embossing process is in the order of minutes and thus significantly longer than that for microinjection molding, this technology is best suited for proof-of-concept development projects and for the production of small to medium scale series. Relatively high aspect ratio features can be replicated with hot embossing in a wide range of structure sizes, from several hundred micrometers down to several nanometers [10,11].

Due to the principle on which the process relies, which is illustrated in Fig. 1, hot embossed parts are characterized by the formation of a residual layer underneath the replicated structures. For some applications, the existence of a residual layer is beneficial and it can be used for housing purposes. This is the case when replicating microfluidic channels, for instance. This layer can also be removed or etched, which is typical for thermal nanoimprint lithography, a process that shares similarities with hot
embossing. In particular, heating, molding, cooling, and demolding are the fundamental steps for both processes (see Fig. 1). However, thermal nanoimprint lithography is typically conducted for molding nanoscale structures on thin spin-coated polymer films, which are then further used as etching masks. Nevertheless, hot embossing and thermal nanoimprinting can be implemented with the same machine. The uniformity of the residual layer thickness is an important issue for both processes as variations in its distribution may affect the functionality or further processing of replicated parts. For example, an inconsistent RLT will result in adjacent micro or nanostructures being oriented at different angles. This can be detrimental for optical applications, for instance, as it could affect the functionality of devices such as benches or wave guides. In addition, a constant RLT distribution is essential for further etching of parts replicated with thermal NIL to avoid removing functional structures during the etching process.

The influence of the machine, the mold, the polymer, and the process parameters on the uniformity of the RLT is complex and has to be investigated systematically. In this context, the paper presents a study on the effect of three process factors, namely the molding temperature, the embossing force, and the holding time, on the residual layer homogeneity achieved with hot embossing. Using a design of experiments approach performed on both experimental and simulation data, the relation between process parameters and the resulting residual layer thickness is established.

The paper is organized as follows. Section 2 discusses different factors which influence the homogeneity of the RLT. Then, the experimental and simulation setup, the mold, the selected material, and the RLT measurement technique used in this research are described. The design of experiments together with the approach adopted to perform the trials and analyze the data are also presented. Finally, the results obtained are reported and the relationship between the process settings and the RLT achieved in hot embossing are discussed.

2 Factors Affecting the Homogeneity of the Residual Layer

2.1 Hot Embossing Machine. To achieve a high replication quality, stiff construction concepts for the axes and support elements of the hot embossing machine have to be adopted. In particular, the stiffness of the construction should be large enough to prevent bending under embossing loads as elastic bending of the whole assembly may result in nonuniform embossed parts. In typical implementations of the process, the mold and the polymer are pressed against each other as a result of the relative vertical motion of the hot plates of the machine (see Fig. 2).

When manufacturing and assembling the plates and mold inserts, their roughness and flatness deviation should be minimized as these will be a source of RLT nonuniformity as illustrated in Figs. 3(a) and 3(b). Using grinding and lapping, the possible achievable roughness and flatness of the plates and the back side of the mold can be as low as 10 nm Ra and 500 nm, respectively, depending on the processed thickness, surface area, and material [12]. Another challenge is to achieve a high degree of parallelism between both plates as this will not only increase the nonuniformity of the residual layer, but it could also generate high pressure in small areas causing damages to the mold or the substrate (see Fig. 3(c)). With some commercial hot embossing machines, it is possible to compensate the nonparallelism of the plates or the mold through the
motion of two wedge-shaped disks that can be rotated relative to each other.

To improve the uniformity of the RLT, Chang and Yang conducted gas-assisted hot embossing, where a polymer film is pressed against the mold by gas pressure rather than a solid plate, and reported that this technique significantly improved the uniformity of the applied pressure [13]. Hocheng and Wen investigated a similar gas-assisted hot embossing setup although it is questionable whether the results described provide a suitable comparison between both traditional and gas-assisted hot embossing given that a clear gradient in one direction for the pressure distribution should also be ensured to prevent anisotropic shrinkage over the whole molded part will result in a nonuniform melt flow into the cavities to be filled. In turn, this may induce variations in the thickness of the residual layer. During cooling, a uniform temperature distribution during molding and, thus, the uniformity of the RLT.

In this study, the experiments were conducted with the HEX03 hot embossing machine from Jenoptik Mikrotechnik. Table 1 holds times on the RLT uniformity achieved with hot embossing. Variations in the processing temperature directly impact the polymer behavior. Thus, ensuring a homogenous temperature distribution in the mold and substrate plate is also essential for successful replications, especially when large microstructured areas are processed. Hence, the heating system of the machine has to guarantee a homogenous and stable molding and demolding temperature over the replicated area. In particular, during heating, an inhomogeneous temperature distribution will lead to variations in the polymer viscosity, which may result in a nonuniform melt flow into the cavities to be filled. In turn, this may induce variations in the thickness of the residual layer. During cooling, a uniform temperature distribution should also be ensured to prevent anisotropic shrinkage and inhomogeneous solidification of the polymer.

2.2 Mold Insert and Polymer Material. During the hot embossing process, the mold is subjected to mechanical stress in structured and nonstructured areas. This stress is a function of the mold design, the applied force on the backside of the mold, and the opposing forces due to the viscoelastic behavior of polymers. This stress can result in undesirable deformations across the mold, which will contribute to the nonuniformity of the residual layer. In addition, gaps left between the mold insert and the master plate during their integration can also contribute to the bending of the mold under load, which will result in a gradient in the RLT. Reported studies for thermal NIL provide experimental evidence that the density of the structures to be replicated also has an important influence on the residual layer uniformity [16,17]. In particular, the mold deformation was observed to be higher in areas where structures are denser as a result of higher opposite forces generated by the polymer melt. It was also reported that the RLT decreases towards the edges of the mold due to the abrupt decrease in structure density. In particular, mold deformation in such areas can be significant and lead to damaging thin structures at the periphery of the mold as demonstrated in Ref. [16]. The importance of the mold thickness on the RLT was also investigated in the case of thermal NIL by Merino et al. [18]. These authors studied the influence of the thickness for silicon and nickel molds, the filling factors, and the patterned area sizes on the residual layer homogeneity. The imprinted parts were scratched using a mechanical profiler to measure the RLT. It was concluded that the thickness of Si molds had an important influence on the RLT, while this effect was not so pronounced in the case of Ni. In addition, a larger bending was experienced by the thinner 400 µm thick Si mold utilized, which resulted in an increased flow of polymer to the nonpatterned area.

During the molding of a polymer above its glass transition temperature, the compression force induced by pressing the mold plate onto the polymer sheet causes a nonuniform pressure distribution in the melt. It was reported that the typical pressure distribution is parabolic during embossing, with the maximum in the center of the mold [19,20]. Such a pressure variation can lead to the bending of thin molds. However, this bending could be negligible if the mold is supported by a rigid plate, as this is the case in a typical hot embossing setup and, thus, only localized mold deflections could be an issue. Once the polymer reaches its demolding temperature, the mold plate is lifted up. Following this unloading, the polymer will expand to some extent due to its elastic behavior [5,21]. Polymer elastic or compression modulus at demolding temperature may have an influence on the RLT uniformity. More specifically, a higher molding pressure applied in the central area of the mold will induce larger changes in polymer expansion after the release of the embossing force compared to areas at the edges. The polymer macromolecular arrangement also has an effect on the uniformity of the residual layer as amorphous polymers are typically characterized by isotropic shrinkage, while semicrystalline polymers exhibit anisotropic behavior. Nonuniform shrinkage over the whole molded part will result in a nonuniform residual layer distribution [22].

Worgull [5] presented a method relying on integrating additional structures in the margin region of the substrate plate or the mold as shown in Fig. 4 in order to improve the homogeneity of the pressure distribution during molding and, thus, the uniformity of the RLT. The additional role of these structures was to absorb the majority of the stress and thus to protect the main features on the mold.

To summarize, it can be said that in order to achieve a high level of RLT uniformity, different factors linked to the machine, the mold design, and the process parameters should be considered. Previous studies that investigated the homogeneity of the RLT mostly focused on the influence of factors linked to the hot embossing machine, the mold design, and the polymer processed. None of these investigations studied whether the process parameters also had an effect on the RLT uniformity by employing a systematic design of experiments approach. Thus, the main objective of this research is to study the influence of three process parameters, namely the molding temperature, the embossing force, and the holding time on the RLT uniformity achieved with hot embossing.

3 Experimental Setup

In this study, the experiments were conducted with the HEX03 hot embossing machine from Jenoptik Mikrotechnik. Table 1
shows the technical specifications of this system as provided by
the manufacturer [23]. The following subsections describe the
design and the manufacture of the mold used in this research as
well as the characteristics of the polymer material processed, the
experimental design adopted, and the measurement technique car-
ried out to assess the thickness of the residual layer. The mold
design, the polymer properties, and the planning of the experi-
ments were also used as input for the conducted simulation study
in order to compare theoretical and experimental results. The par-
ticular simulation tool utilized in this research was the Simprint
Core simulation software [24].

### 3.1 Mold Design and Manufacture

In this research, a 170 µm thick nickel mold with overall lateral dimensions of 32 mm × 32 mm was used. The structured area of this mold was 28 mm × 28 mm and consisted of 16 × 16 arrays of transistor gate electrodes with different sizes. The depth of the gates was 500 nm, and the width varied between 500 nm, 1 µm, and 2 µm. The fabrication of the nickel mold was carried out using a process chain developed in previous studies [25–27]. This process chain, which is illustrated in Fig. 5, consists of three main steps: (1) template fabrication, (2) replication with UV nanoimprint lithography using a step and repeat approach, and (3) electroforming.

Initially, a fused silica template was prepared to be utilized as a master for the UV nanoimprint lithography step. The fabrication of the 28 mm × 28 mm structured area on the surface of the template was done in two stages: (1) micro structuring with photolithography and (2) nanopatterning with focused ion beam (FIB). Using conventional photolithography, a Microposit S1813 resist was spin-coated on the template at 4000 rpm and then baked at 97 °C for 2 min. A mask aligner was then used to expose the resist for 3 s with UV light. The template was then dipped in a developer solution for 15 s to remove unwanted resist. Next, the template was rinsed in de-ionized water and dried with N₂ gas. The following step was to transfer the pattern into the fused silica surface using reactive ion etching. An example of microstructures created with this photolithography process is shown in Fig. 6.

The nanostructuring step was then performed with a Carl Zeiss XB 1540 FIB/SEM cross beam system to add the features on the template, which had widths comprised between 1 µm and 500 nm as shown in Fig. 7. To achieve this, a 20 nm thick chromium layer was first sputter coated on the template surface to avoid any charging effects during the FIB machining. Despite the low removal rates and, consequently, the long machining time associated with FIB milling, the process exhibits high resolution and high surface quality, which are important characteristics when producing nanoscale features on master molds/templates [28]. Following the completion of the FIB nanostructuring step, the chromium layer was etched away and the fused silica template was loaded into a UV-NIL system for replication. Figure 8 shows a selected area of imprinted structures. The imprinting was performed on a double-sided polished silicon wafer.

Finally, a commercial electroforming system was utilized to produce the 170 µm thick nickel mold. The micro and nano
features were replicated by growing Ni on top of the imprinted wafer. This processing step allows the precise replication of micro and nano features in Ni shim form [39]. Figure 9 shows an example of some of the features replicated in Ni.

3.2 Test Material. Two millimeter thick poly(methylmethacrylate) (PMMA) sheets were used for the hot embossing experiments. PMMA is an amorphous polymer and one of the common choices for hot embossing [30,31]. It is one of the hardest polymers, glass clear with glossy finish and has good weather resistance. It has found many applications such as in optics, automotive, electrical engineering, medicine, and office equipment. The mechanical properties of PMMA are shown in Table 2 [32].

3.3 Planning of Experiments. The parameters considered in this study were the molding temperature \((T_m)\), the embossing force \((F)\), and the holding time \((t_h)\). Three levels were used for each of the selected three factors. Table 3 shows the 11 trials that were designed where a full factorial approach was employed for \(T_m\) and \(t_h\). Two additional experiments were also conducted in which \(F\) was varied to provide an indication of its influence. The chosen range of parameters levels was determined based on material properties, initial simulation results, literature data [33–36], and preliminary experiments in order to ensure complete filling of the mold cavities and stable behavior of the replication setup throughout the experiments. For each of the designed trials, three repetitions were performed. The combinations of the parameters’ values for the selected three factors are provided in Table 3.

The Simprint Core software used for the simulation study was developed by Taylor and is based on the contact mechanics theory [37]. This software enables the prediction of elastic stamp deflections and the formation of arbitrarily thin residual layers. It is capable of modeling linear viscoelastic resists as well as simply Newtonian ones. The accuracy of the simulation in hot embossing is critically dependent on the viscosity of the polymer material studied. In this research, the typical viscosity values of PMMA depending on the shear rate and the temperature are taken from those given in Ref. [5] and illustrated in Fig. 10.

3.4 Residual Layer Thickness Measurement. An optical coordinate measuring machine (OCMM) was employed to measure the residual layer thickness of the embossed samples. In particular, this was achieved by autofocusing the optical head of the OCMM on the top and the bottom surface of the samples to record the height difference between two corresponding measured points on these surfaces. The accuracy of the OCMM when performing height measurements is stated to be \(3 \mu m\) by the manufacturer of the system [38]. For each embossed sample, 13 thickness values were obtained in this way from points distributed equally all over the surface of the PMMA replica including the edges and the middle area as shown in Fig. 11. In order to ensure that the thickness values were consistently obtained from the same locations on each replica, measurement marks were engraved by laser.
machining on the nickel mold. To minimize measurement errors, the maximum magnification allowed by the instrument (×212) was used to assess the height of the selected points.

4 Results and Discussion

4.1 Residual Layer Uniformity. Figure 12 shows an SEM image of a sample area of a replica. All the experimental trials exhibited a complete embossing of the mold structures. The RLT values obtained from the simulation and experiments are presented in Table 4. The uniformity of the RLT was assessed by calculating the ± one standard deviation of the measured data for each trial. Thus, an increased standard deviation value from one experimental trial to another implies a larger nonuniformity. By comparing the experimental results shown in Table 4, it can be observed that the selected values of the studied parameters have an effect on the resulting RLT of the embossed samples. In particular, the difference between the largest and lowest RLT standard deviation is 18 μm, which is higher than the accuracy of the OCMM used to carry out the measurements. The experimental results show that the highest measured RLT standard deviation was for trial 1, while the lowest was for trial 9, which respectively correspond to the trials with the lower and higher settings for \( T_m \) and \( t_h \).

The experimental and simulation data show a relatively good agreement for the mean RLT as the average percentage difference between both sets of results is 14%. However, the simulation results do not predict an important RLT nonuniformity, as the difference between the largest and lowest simulated RLT standard deviation is 2.2 μm, which is only 12% of its experimental counterpart, 18 μm. The highest and smallest simulated standard deviations occur for trials 10 and 11, respectively. These correspond to the experiments with the lower (trial 10) and higher (trial 11) settings for the embossing force \( F \). This important difference between the predicted and experimental data can be explained with the fact that the simulated results reflect only local mold deflections. In practice, the following factors also contribute to the nonuniformity of the RLT:

- The roughness and flatness errors of the mold insert, the top plate, and the bottom plate. In this study, through the application of grinding and lapping, the achieved values of roughness and flatness of the plates used were 0.5 μm Ra and 4 μm, respectively.
- The parallelism errors between the plates due to the machine setup.
- The elastic deformation of the polymer during demolding due to the release of the compression force applied by the mold. In particular, given the nonuniformity of the pressure distribution during embossing, this deformation can be inhomogeneous across the surface of the molded polymer.

The experimental RLT standard deviation results for the different considered values of temperature \( (T_m) \) and embossing time \( (t_h) \) are presented in Fig. 13. This figure clearly shows that an increase of \( T_m \) results in an improved RLT uniformity. This is an expected result given that the viscosity of a polymer is directly dependent on its processing temperature and thus reducing its viscosity value through an increase of its temperature will improve its flow behavior. In particular, an increase in the temperature reduces the polymer internal stress and decreases its strength, which in turn eases the polymer flow during processing. This will lead to a
reduced filling time of the mold cavities and also will be beneficial to achieve a better uniformity of the RLT.

For both the predicted and experimental data obtained, the comparison between the results for the trials 5, 10, and 11, in which the molding temperature and the holding time are constant parameters, show that the RLT uniformity reduces when the embossing force becomes larger. This can be explained by the fact that an increased embossing force results in a higher pressure gradient in the polymer and also in a larger deformation of the mold. The simulation results reported in Fig. 14 show the increase in contact pressure distribution from an embossing force of 5 kN to 15 kN at a fixed processing temperature of 150°C and for an embossing time of 5 min, which are the conditions corresponding to trials 5, 10, and 11. Some initial simulation tests also showed that augmenting the embossing force always resulted in an increase of the RLT nonuniformity regardless of the different temperature or holding time values considered.

As mentioned earlier, due to its elastic behavior, a polymer under compression tends to expand after releasing the load to which it is subjected at demolding temperature. This results in variations in the RLT after demolding, which will be more pronounced in the central area of the processed polymer sheet where the applied pressure is the highest and negligible at the edges where the pressure is very low. In this work, the contribution of this shape change after demolding is also assessed. To achieve this, the compression modulus $K$ of the polymer can be calculated at demolding temperature taking into account its temperature-dependent Poisson’s ratio value $\mu$ and Young’s modulus $E$ \[5\]:

$$K(t, T) = \frac{E(t, T)}{3(1 - 2\mu(T))}$$  \[1\]

In the conducted experiments, demolding was carried out at 90°C and in this case, the Young’s modulus of PMMA is $E = 2.4$ GPa and its Poisson’s ratio value is $\mu = 0.33$. Thus, the compression modulus the processed polymer is calculated to be $K = 2.35$ GPa during demolding. Given that demolding takes place below the glass transition temperature $T_g$ of the polymer and that the range of embossing force considered in this work is too low to induce plastic deformation below $T_g$, it is assumed that a full elastic recovery will take place following release of the embossing load. The change of the thickness $dl$ for an isotropic material can be determined as a function of the pressure variation to which it is subjected \[39\]:

$$K = V - \frac{dP}{dV} = \frac{-l}{dl/dP}$$  \[2\]

Where $dl$ is the value of the RLT variation due to compression. In this case, it is taken as the difference in the RLT before and after the release of the embossing force. $dP$ is the difference between the pressure just before demolding and the atmospheric pressure, and $l$ is considered to be the RLT after demolding. The experimental and simulated results across the surface of the polymer and the simulated pressure distribution were employed to calculate $dl$. In this way, it was possible to estimate that the maximum percentage contribution of $dl$ to the RLT standard deviation is 8% for the experiments and 45% for the simulation. The simulated pressure and RLT distributions at the end of embossing for the trial number 2 are shown in Figs. 15(a) and 15(b), respectively. In addition, based on Eq. (2) above, the calculated RLT distribution taking into account polymer expansion after demolding is provided in Fig. 15(c) and in this case, the predicted RLT standard deviation increases from 2.2 µm to 4 µm.

To assess the impact of the holding time on the RLT uniformity, three different values (1, 5, and 10 min) were used for each temperature range. From the results shown in Fig. 13, it can be
said that increasing the holding time improved the RLT uniformity. This can be explained by the viscoelastic creeping behavior of polymers. In particular, as creep is a time-dependent phenomenon, the polymer deformation will increase and the pressure gradient will decrease when extending the time during which the embossing load is applied (see Fig. 6.10 in Ref. [5]).

4.2 Main Effects and Response Table. Figure 16 and Table 5 present, respectively, the main effect plot and the response table of the process parameters on the RLT standard deviation. It is observed from this figure that an increase of $T_m$ and $t_h$ improves the RLT uniformity, while an increase of $F$ has the opposite effect. From the response table provided, it is apparent that the most influential process parameter is different based on the levels considered. In particular, the temperature was the least important factor when it is increased from 120 °C to 150 °C, while it became the most influential parameter between 150 °C and 180 °C. The applied force was the second most influential factor in all cases. Finally, increasing the holding time from 1 to 5 min had the highest impact on the RLT uniformity when comparing parameters between levels 1 and 2, while this effect was not so pronounced when its value varied between 5 and 10 min. When comparing results between levels 1 and 3, i.e. across the whole range of processing values studied, it can be observed that the considered three parameters have a relatively equal influence on the RLT distribution.

Finally, the theoretical optimum set of parameter levels to achieve the lowest RLT standard deviation for this experimental setup was determined based on the results provided in Fig. 16 and corresponds to 180 °C, 5 kN, and 10 min for $T_m$, $F$, and $t_h$, respectively. A verification experiment was further conducted with this theoretical best combination of parameters and resulted in a RLT standard deviation of 10.6 μm. By comparing this result with those reported in Table 4, in which the lowest standard deviation is 14 μm, this experiment confirmed that the identified parameters were the optimum combination with respect to the RLT uniformity.

Table 5  Response table for the RLT standard deviation

<table>
<thead>
<tr>
<th></th>
<th>$T_m$</th>
<th>$F$</th>
<th>$t_h$</th>
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<tr>
<td>Levels</td>
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<td>18.2</td>
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<td></td>
<td>Level 2 (μm)</td>
<td>23.6</td>
<td>22.8</td>
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<td></td>
<td>Level 3 (μm)</td>
<td>17.9</td>
<td>27.0</td>
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<tr>
<td>Comparison between levels 1 and 2</td>
<td>Difference (μm)</td>
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<td>4.6</td>
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<td>Difference (%)</td>
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<td>20</td>
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<td>2</td>
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<td>Comparison between levels 2 and 3</td>
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5 Conclusions

In addition to the quality of the molded structures, the achieved RLT uniformity is an important process output in hot embossing. The analysis of the literature on this subject revealed that the influence of the process parameters on the homogeneity of the RLT has not been systematically studied. In this context, using simulation and experimental studies, this work investigated the relationship between the residual layer uniformity and three process parameters when processing PMMA sheets. In particular, the characteristics of the RLT of embossed parts were analyzed as a function of the molding temperature, embossing force, and the holding time. The results of the conducted experimental and simulation studies were analyzed to identify potential ways for improving the hot embossing process. In particular, the following conclusions can be made based on the reported research:

(1) Increasing the molding temperature resulted in a reduction on the average residual layer thickness and on its nonuniformity. This is directly related to the fact that polymer flow is improved at elevated temperature.

(2) An increase in the embossing force led to a decrease in the homogeneity of the residual layer. It is expected that this is caused by the increased pressure gradient at higher compression forces, which can result in mold deformation and a more pronounced polymer recovery between the central and boundary area of the processed sheet.

(3) An improvement of the RLT uniformity was also observed when embossing with a longer holding time. This should be the result of the polymer creep effect under load.

(4) The comparison between the obtained experimental and simulation results suggest that approximately 12% of the RLT uniformity is affected by the local deflections of the mold.

(5) For the studied setup, it was calculated that polymer expansion after release of the embossing load contributes to 8% of the RLT nonuniformity. This value is calculated to be 45% for the ideal conditions where the plates and the mold are completely flat, parallel, and uniform.

(6) Generally, it can be concluded that a better uniformity of the RLT could be achieved by using the highest selected settings for the temperature and holding time and the lowest value of embossing force.

(7) Finally, the analysis of the obtained results also shows that, across the range of processing values studied, the considered three parameters have a relatively equal influence on the RLT distribution. However, when examining narrower ranges of processing values, it is apparent that the most influential process parameter depends on the levels considered. In particular, the holding time had the most effect on the RLT uniformity when embossing with the lower values of process parameters while, with higher processing settings, the molding temperature became the most influential factor.

Further studies should focus on investigating the effect of additional factors such as the flatness error of the mold and plates on the influence of the process parameters studied.

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