The numerical simulation and experiment on extrusion roller embossing of light diffusion plate with micro-structure

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Abstract: Extrusion roller embossing process has demonstrated the ability to produce polymer film with micro-structure. However the influence of various parameters on the forming quality has not been understood clearly. In this paper, a light diffusion plate with semi cylindrical micro-structure array as the research object, the influence of the main processing parameters such as roller speed, pressing distance and polymer film temperature to the rolling quality was investigated in detail by simulation and experimental methods. The results show that the thickness of the light diffusion plate and the micro-structure fitting diameter increases with the increasing of the roll speed and the polymer film temperature, and decreases with the increasing of the pressing distance. Besides, the simulation results conformed well to the experimental results.

1. Introduction
With the development and application of polymer micro-devices in optics, biology and other fields, micro-nanometer manufacturing technology has gradually become the research focus of related scholars[1]. In 2007, Jiang et al.[2] proposed a novel fabrication method which is based on the traditional micro-hot embossing technology. The film extrusion equipment and R2R hot embossing device were used, and the material is fully warmed and then embossed. This method has the advantages of low forming pressure, high efficiency and continuous production.

Extrusion roller embossing has attracted the interest of scholars since it was proposed. Yeo et al. [3] explored and discussed the effects of the process parameters, such as embossing pressure, substrate preheating, roller temperature and roller speed, on the embossed channel depth, with the goal of achieving process optimisation. Raymond Frenkel et al.[4]designed a variotherm extrusion roller imprinting system. The extruded polymer film was embossed between the belt mold with micro-structure and the pressure roller. Due to the variotherm capability, it was beneficial to reduce the springback of polymer micro-structure after demoulding. Wenlong Liu et al.[5]introduced a new production process. In this process, the thickness of the polymer film was planished and adjusted after it was extruded from the extruder to ensure the thickness and uniformity of the film. In addition. Some people focus on simulation studies. M. Sahli et al.[6] used LSDYNA software to investigate the filling of micro cavities with COC polymer during the roll embossing process and analyse the polymer deformation. Deng Y, et al.[7] established a 3D numerical model of the R2R hot embossing process based on the viscoelastic of PVC polymer to analyse the flow behaviors of the polymer in the filling stage and the demoulding stage.
Although extrusion roller embossing has demonstrated great commercial potential and application prospect in many fields, it still faces many challenges in forming theory, forming process and other aspects. In addition, due to the viscoelasticity of the polymer material, the microstructure on the roller cannot be completely imprinted onto the polymer film. So how to control the extrusion process parameters to obtain the desired size of the product, and the influence of various parameters on the forming quality has not been studied clearly, these problems need to be resolved in order to achieve industrial production.

In this paper, a light diffusion plate with semi cylindrical micro-structure array as the research object, the heat curable material PMMA was employed. Single-factor analysis was adopted to analyze the data. The thickness of the light diffusion plate and the fitting diameter of the micro-structure were taken as the evaluation criterions. Detailed analysis was made to investigate the influence of the main processing parameters such as roller speed,pressuring distance (between substrate roller and drive roller) and polymer film temperature to the rolling quality by the ABAQUS software and the independent building experiment platform. Finally, comparisons made between the experiment and simulation results, and approve the forecast capability of FEM simulation for extrusion roller embossing process.

2. Numerical simulation and experiment

2.1 Experiment

The main process of the roll embossing is illustrated in Figure 1. The semi-circle micro-structure with a radius of 0.5mm is evenly distributed on the substrate roller surface, and the diameter of the two rollers is 65mm. The thickness of PMMA film is 1mm. The material employed in the experiment is Polymethylmethacrylate (VH001) of Japan Mitsubishi Company. Firstly, the PMMA film is extruded from the coat-hanger die. Secondly, it is cooled to a certain temperature, and fed into the rolling device. In this stage, the PMMA film is embossing at a high distance between substrate roller and drive roller, after the embossing process is stable, the parameters are adjusted to the experiment of setting value and begin the experiment.

![Figure 1. Schematic diagram of the extrusion roller embossing](Image)

2.2 Numerical simulation

The viscoelastic model is utilized to simulate the properties of PMMA material. The Wiechert model is adopted to describe the stress relaxation and creep of PMMA, which can be expressed as [8]:

\[
E(t) = E_\infty + \sum_{i=1}^{n} E_i \alpha \left( 1 - \frac{t}{\tau_i} \right)
\]

where \(E_\infty\) is the equilibrium modulus; \(n\) is the number of Maxwell units, \(E_i\) and \(\lambda_i\) are material constants. And the parameters of the Wiechert model are obtained by uniaxial tensile stress relaxation. Table 1 shows the relaxation modulus and the corresponding relaxation time constant of PMMA material at 105°C. Another the Williams–Landel–Ferry(WLF) equation is used to describe the temperature-dependent modulus of the PMMA material, which can be expressed as[9]:

\[
\log_{10} \alpha(T) = -\frac{C_1(T - T_0)}{C_2 + (T - T_0)}
\]

where \(\alpha(T)\) is the shift factor at temperature \(T\); \(T_0\) is the reference temperature \((T_0=105°C)\); \(C_1\) and \(C_2\) are material constants \((C_1=17.6, C_2=65.5)\). The material parameters used in the simulation are listed in
table 2.

### Table 1. Parameters of PMMA Wiechert model

| \( n \) | \( E_i \) | \( \lambda_i \) |
|---|---|---|
| 0 | 24.495 | — |
| 1 | 20.432 | 1.039 |
| 2 | 10.685 | 10.561 |
| 3 | 2.194 | 94.613 |

### Table 2. Mechanical and thermal parameters of PMMA

| Properties | PMMA |
|---|---|
| Density (g cm\(^{-3}\)) | 1.19 |
| Elastic modulus (MPa) | 3300 |
| Poisson's ratio | 0.39 |
| Specific heat capacity (J g\(^{-1}\)K\(^{-1}\)) | 1.47 |
| Thermal expansion coefficient (K\(^{-1}\)) | 6e\(^{-5}\) |
| Thermal conductivity (W m\(^{-1}\)K\(^{-1}\)) | 0.19 |

The simplified 2D model of extrusion roll embossing was established as shown in Figure 2, and the 1/4 model was selected. Several assumptions were proposed to describe boundary conditions. At first, the bottom of the PMMA film was fixed and the substrate roller was allowed to move downward to pressure the PMMA film. And then, the substrate roller was constrained to move in the -x direction and has a constant rotational velocity about the z direction. Moreover, one considers that the polymer material exhibits the viscoelastic behaviour. The coupled temperature-displacement analysis was considered in the FE model. The roller was treated as an analytical rigid body. The PMMA film was treated as a deformable body and meshed with temperature-displacement coupled elements (CPE4RT) analyzed in plane strain case.

![Figure 2. FE model of the extrusion roller embossing process](image)

3. Results and discussions

3.1 Effects of roller speed

The experiment and simulation were conducted at five different roller speeds (1.5rpm, 1.6rpm, 1.7rpm, 1.8rpm and 1.9 rpm), with a 1mm film thickness, pressing distance of 0.7mm and film temperature of 140°C. The light diffusion plate section under the processing conditions of \( V_{Roll} = 1.8 \) rpm is given in Figure 3 (In order to observe, film section of experiment results were blackened. The \( U_2 \) in the simulation result is the \( Y \) directional displacement).
The effect of the roller speed on the thickness of the light diffusion plate and the microstructural fitting diameter is shown in Figure 4. According to the Figure 4, with the increasing of the roller speed, the thickness of the light diffusion plate raises gradually, the width and height of micro-structure also raise gradually, so does the fitting diameter. Because if the strain value is constant, the stress will decline with increasing time, which will transform part of the elastic deformation into viscosity deformation, the larger the forming time is, the better the transition is. And the elastic recovery of the micro-structure will be smaller after demoulding. Therefore, when the roller speed increases, the contact time between the roller and the film becomes shorter, resulting in poor replication accuracy and incomplete filling the mold cavity. Again the elastic recovery becomes larger, and the thickness of the light diffusing plate and the fitting diameter of the micro-structure increase.

### 3.2 Effects of pressing distance

The experiment and simulation were performed with five different pressing distances ranging from 0.6 to 0.8mm, with a 1mm film thickness, roller speed of 1.7rpm and film temperature of 140°C. The light diffusion plate section under the processing conditions of L=0.65mm is given in Figure 5.

- **Figure 3.** The light diffusion plate section under the processing conditions of \( V_\text{Roll} = 1.8 \text{rpm} \): (a) simulation result; (b) experiment result

- **Figure 4.** Effect of roller speed on the quality: (a) thickness of light diffusion plate; (b) micro-structure fitting diameter

- **Figure 5.** The light diffusion plate section under the processing conditions of L=0.65mm: (a) simulation result; (b) experiment result

- **Figure 6.** Microstructural fitting diameter also decreases little by little. As the increase in pressing distance is equivalent to increasing the forming pressure, the polymer filling rate gradually increases, mold cavity is very sufficiently filled, and the elastic recovery of the micro-structure is smaller after demoulding. But if the pressure was too high, it
will generate residual stress in the products after rolling, and the uneven distribution of the pressure will lead to a poor replication precision.

**Figure 6.** Effect of pressuring distance on the quality: (a) thickness of light diffusion plate; (b) micro-structure fitting diameter

### 3.3 Effects of film temperature

The experiment and simulation were designed at five different film temperatures (130°C, 135°C, 140°C, 145°C, 150°C) to investigate the forming quality. The pressing distance of 0.7mm and film temperature of 140°C with a 1mm film thickness was used to study the film temperature effects. The light diffusion plate section under the processing conditions of T = 145°C is given in Figure 7.

**Figure 7.** The light diffusion plate section under the processing conditions of T = 145°C: (a) simulation result; (b) experience result

The effect of the film temperature on the thickness of the light diffusion plate and the micro-structural fitting diameter is shown in Figure 8. From Figure 8, the thickness of the light diffusion plate gradually increases with the increasing of the film temperature, the fitting of the microstructure also gradually increases. That is because the film temperature has a significant impact on the flow ability of the polymer material. The higher the polymer film temperature is, the better the flow ability is, and the more easier the mold cavity is filled. But if the temperature of the polymer film is too high, the stability of the polymer structure can be destroyed, thus generating many defects on the micro-structure, it also causes residual stress in the final products.
4. Conclusions
In this work, a light diffusion plate was fabricated by extrusion roller embossing process. By means of numerical simulation and experimental investigation, the influence of critical parameters such as roller speed, pressuring distance and polymer film temperature during the extrusion roller embossing process on the thickness of the light diffusion plate and the micro-structure fitting diameter were analyzed. Besides, we compared the simulation and experimental results and well summarized the influence rules of the process parameters. Based on the simulation and experimental results, some preliminary conclusions can be drawn:

(1) The thickness of the light diffusion plate and the micro-structure fitting diameter increases with the increasing of the roll speed and the polymer film temperature, and decreases with the increasing of the pressing distance.

(2) Comparing the simulation and experimental results, the relative errors of the thickness of the light diffusion plate is within 3.2%, and the relative errors of the fitting diameter of microstructure is within 9.2%. The simulation results are satisfactory agreement with the experiment results.

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