Modeling of Hot Embossing Process for the Fabrication of Microlens Array

WCMNM 2021

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Abstract

Micro Hot Embossing is a versatile technique to fabricate micro-scale components and features. It has various advantages over other manufacturing methods, such as low material flow, low internal stresses, high precision, and good surface finish. For materials like polymers and metallic glasses, hot embossing is proven to be one of the most suitable fabrication techniques enabling mass production of components such as micro-lens arrays, and micro-fluidic devices and channels. In hot embossing, the final product quality is highly dependent on process parameters such as temperature, load pressure/force, pressing time, strain rate, and stamp displacement. This research aims to develop a computational model of the micro-hot embossing process to fabricate microlens arrays on a PMMA workpiece. Simulation experiments are run to investigate the effect of two load control configurations, i.e., force-controlled and displacement-controlled motion of the embossing stamp, on the quality of the lens arrays in terms of filling time, internal stresses developed, and the reaction force on the stamp. In the force-controlled loading, a gradually applied external force is subjected to the stamp, while in the displacement control, a defined vertical displacement is given to the stamp. The model predicts that a displacement-controlled configuration is preferred as it leads to faster filling of the material and low reaction forces on the stamp, making the process time-efficient and prolonging the life of the stamp.

Keywords: micro hot embossing, microlens array, computational model, PMMA.

1. Introduction

Hot embossing is a popular process used to fabricate parts with materials such as thermoplastic polymers and metallic glasses. In this process, the material is heated slightly above its glass transition temperature (T_g) to allow the material to flow. An external load is then applied to the material using a stamp for a given amount of time. The newly formed structure is cooled down by decreasing the temperature, which gives the final product. The hot embossing process is shown to yield low material flow, low internal stresses, high precision, and good surface finish and can be easily adapted for the fabrication of micro-scale components. The high repeatability and short production time of the process also make it ideal for mass fabrication. However, the choice of process parameters that can lead to minimum replication errors, faster processing time, and low tool degradation remains challenging.

In hot embossing, the workpiece material needs to flow and fill the stamp cavities to ensure optimal replication. At the same time, the forces and internal stresses on the stamp and the workpiece need to be low to prevent tool degradation and increase process repeatability. Longer fill time could lead to the initiation of recrystallization in the material. Multiple studies have been conducted to analyze the effects of process parameters on the hot embossing of thermoplastic polymers. Becker and Heim [1] observed that the quality of the product during hot embossing of high aspect ratio features on polymers is determined by four key variables, i.e., the sidewall roughness of the stamp, the side walls angle with the vertical, chemical interface between the stamp and the workpiece, and the thermal expansion coefficient of the material. Juang, Lee, and Koelling [2] concluded that for isothermal embossing, it is necessary to balance embossing conditions with cycle time to produce the most effective and cost-efficient embossing method. Z.W. Zhong et al. [3] observed that replication accuracy depends on the density of feature size or pitch of the featured size. The structures having greater pitch, i.e., 200 μm to 300 μm showed better replication as compared to pitch size of the 50 μm to 100 μm which exhibited poor accuracy. Lin et al. [4] have shown that the replication accuracy is highly dependent on the molding force, process temperature, and hold time. High temperatures generally produce better replicas but increase the cycle time. In addition, very high temperatures, near the material's crystallization temperature, may lead to quick recrystallization. Increasing the load can also increase replication accuracy and care must be taken to exceed the critical force (equilibrium stress of the material, based on the Viscoplastic Overstress Model) or recovery can occur. Two popular load configurations are used to control the motion of the stamp during the process, i.e., force-controlled and displacement-controlled loading. In the force-controlled setup, a defined force is gradually applied and then held constant on the stamp to press it into the material, whereas, in displacement control, the stamp is pushed into the substrate by a pre-decided distance. Post the application of the load, the stamp is held in place for the holding stage. This stage is important as it allows the material to flow and fill the stamp, while its internal stresses relax and reach equilibrium. Therefore, hold time, temperature, and loading configuration are the most critical out of many process parameters that affect the quality of the finished product in the isothermal hot embossing process.

This research aims to develop a finite element model to study the effect of key process parameters – load configuration, load magnitude, loading time and hold time. The material model for PMMA is calibrated against experimental data. Two load configurations, namely – force controlled and displacement controlled, are studied and compared. For each configuration, 3 cases of loads are simulated and the variation in filling time, the internal stresses in the product and the force on the stamp are evaluated. Based on these results the loading configurations are compared.

2. Material model for Polymethyl Methacrylate

Polymethyl methacrylate (PMMA) is an amorphous polymer widely used to manufacture microlens arrays due to its transparent nature and highly suitable thermo-mechanical properties [5-7]. To model the material behavior of PMMA, the Overstress Model (VBO) [8] is utilized. In the VBO model, the stress has to overcome the equilibrium stress before any inelastic deformation is possible. The viscoplastic strain rate is a function of the difference between the stress and the equilibrium stress, known as the overstress. The two-layer viscoplasticity model on ABAQUS/Standard is used with material parameters obtained by fitting the model against the experimental data. The experimental data used here is obtained from the relaxation test by Cheng et al.[9] conducted on PMMA at a temperature of T_g+20°C.

In a relaxation test, the strain remains constant while the stress decreases. Therefore, the plastic strain rate as well as the total strain rate is zero. A schematic diagram representing the material behavior, as described by the VBO model, is shown in **Figure 1.** The total strain rate is given in equation (1):

$$\dot{\varepsilon}^{to} = \dot{\varepsilon}^{el} + \dot{\varepsilon}^{pl} + \dot{\varepsilon}^{vp} \quad (1)$$

where $\dot{\varepsilon}^{to}$, $\dot{\varepsilon}^{el}$, $\dot{\varepsilon}^{pl}$ and $\dot{\varepsilon}^{vp}$ are the true total, elastic, plastic and viscoplastic strain rates respectively.

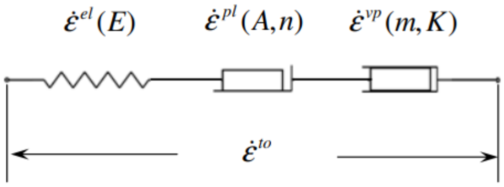

Figure 1: Schematic representation of the elastic-viscoplastic network by Cheng et al. [9]

$$\dot{\varepsilon}^{el} = \frac{\dot{\sigma}}{E} \quad (2)$$

$$\dot{\varepsilon}^{pl} = \begin{cases} A_{pl} m \sigma^{m-1} \dot{\sigma} & if\ \dot{\sigma} > 0 \\ 0\ if\ \dot{\sigma} \leq 0 \end{cases} \quad (3)$$

$$\dot{\varepsilon}^{vp} = \begin{cases} A_{vp} (\sigma - g)^n & if\ \sigma > g \\ 0\ if\ \sigma \leq g \end{cases} \quad (4)$$

where $\dot{\sigma}$ is the stress rate, g is equilibrium stress, (σ-g) is overstress, A_{pl}, A_{vp}, m & n are material constants.

The fit of the modelled data with the experiment data is shown in **Figure 2**. The values of material constants calculated is given in the **Table 1**.

Table 1 : PMMA Overstress material model parameters for the temperature T_g+20°C

A_{pl}	A_{vp}	m	n
6.629E-06	2.741E-09	0.8381	1.17

3. Model development for Hot Embossing

The aim of the model is to characterise the filling time and internal stresses during hot embossing of a microlens array for two load control configurations: force-controlled and displacement-controlled. In force control, the stamp is pressed into the workpiece with a pre-determined force, while in the displacement control, the stamp is subjected to a pre-defined displacement. The model was developed using ABAQUS. The VBO model was implemented to describe the behavior of the PMMA specimen at a temperature of T_g+20°C. The entire isothermal embossing process is divided into four distinct stages:

1. Pressing Stage: Here the stamp is pressed into the PMMA by ramping the load gradually
2. Holding/Filling Stage: The stamp is held in position after being pushed into the workpiece (PMMA), while the material flows and fills into the cavities.
3. Cooling Stage: This involves cooling the PMMA to a temperature much below T_g to cause hardening.
4. Retraction: The stamp is retracted and the final molded product is obtained.

In this research, only the first two stages are modeled. This is because the filling time and filling efficiency, which is our main focus, is solely dependent on the first two stages. The last two stages mainly deal with material hardening and contraction. The force and displacement-controlled load configurations are studied and analysed.

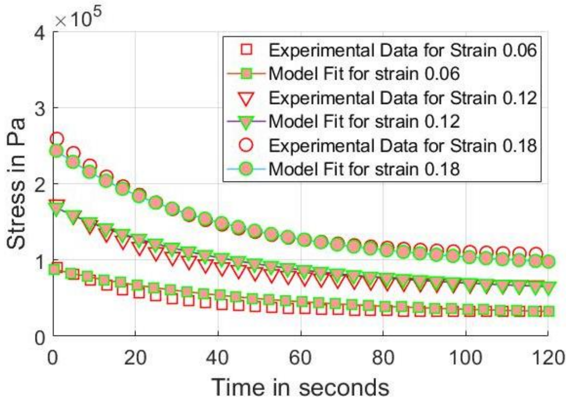

Figure 2: Experimental data (Cheng et al.[9]) vs Model Fit for Relaxation Test on PMMA specimen at temperature T_g+20°C

3.1. Domain and Process Parameters

The fabrication of a hexagonally packed microlens array designed by SUSS Micro-optics[10] is simulated. The pitch of the array is 250 µm, with the radius of curvature and diameter of a single lens in the array being 350 µm and 240 µm respectively. A schematic of a microlens and the array is shown in **Figure 3**.

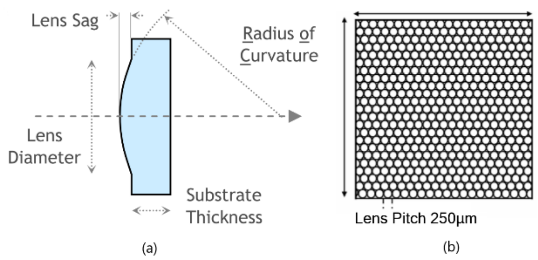

Figure 3: (a) Schematic of a typical microlens (b) Schematic of a hexagonally packed microlens array

For the model, a 3D finite element model of a single symmetrical unit of the lens is created on ABAQUS. The stamp is defined as a rigid body. The workpiece is defined as a solid homogeneous body. A 43340-element mesh generated using Hexagonal 3D Stress elements (C3D8H), with the finest mesh size being 25 µm, was chosen post a mesh-independence study. The solver used was ABAQUS/Standard, with the embossing step defined as Dynamic, Implicit. The pressing stage is set to be of 5s & the filling stage of 120s. Since a symmetrical unit is chosen, a zero-displacement boundary condition is specified normal to the planes of symmetry and a no-slip condition on the base of the substrate.

Friction was not taken into account since the effect of friction in the pressing and holding stage is minimal, as verified by the agreement between the experimental and simulation results by J. A. Gomez et al [11] and Cheng et al.[9]. Moreover, the friction is highly dependent on the choice of stamp and its surface roughness and the exact value needs to be determined experimentally for a given pair of surfaces. Furthermore, simulations were conducted, to verify the assumption, for three cases of friction (μ = 0, 0.15, and 0.3) for the displacement-controlled configuration with a load of 55 µm. There was no observable effect on the filling time and filling efficiency, while the maximum internal stress showed a minimal variation of ≈ 0.5 %, as shown in **Figure 5.**

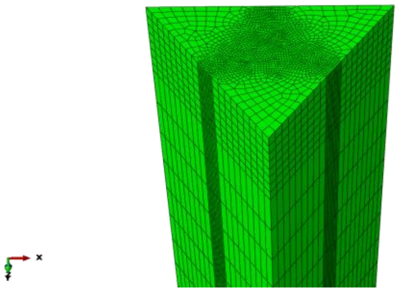

Figure 4: Meshing of a basic symmetrical unit for the microlens array

4. Results and Discussion

The hot embossing process simulated comprises two steps: loading and holding. The loading lasts for 5 s, while the holding is of 120 s. The external load is gradually applied as its magnitude ramps linearly from 0% at t=0 s, to 100% at t=5 s during the loading stage. In the holding stage, the load is held constant and the material is allowed to relax and flow into the stamp. **Figure 6** shows the material flow and the stress during hot embossing using displacement-controlled loading, with a load of 55 µm. A cross-sectional view along the diameter of a single lens is shown, along with a 3D view of the lens at different step times. The first three images, from step time 0 s-5 s, show the material flow in the loading stage, while the last three images illustrate the holding stage.

For analysing the two load configurations, simulations were performed for three cases for each of the configurations. The mold filling time, filling efficiency, internal stresses in the workpiece, and the stamp's reaction force were studied.

4.1. Model Predictions for Force Control

The model is simulated for 3 different forces on the stamp: **6 mN**, **8 mN** & **10 mN**. The workpiece is able to fill the stamp cavity 100% for each of these cases. As the force increases, the filling time substantially decreases, with a simultaneous increase in the internal stresses. shows the key results.

Table 2: Key results for Force Controlled loading results

Force (mN)	100% Filling Time (s)	Max Stamp Displacement (µm)	Maximum Internal stress in the workpiece (MPa)
6.00	48.85	39.691	0.1463
8.00	18.85	49.672	0.1464
10.00	6.50	59.281	0.1492

4.2. Model Predictions for Displacement Control

The simulation is performed for 3 values of stamp displacement: **35 µm, 45 µm** and **55 µm**. The workpiece is able to fill the stamp cavity 100% for each of these cases as well. As the displacement increases, the filling time decreases, with a simultaneous increase in the stresses.**Table 3** shows the key results.

Table 3: Results for displacement-controlled loading

Displacement (µm)	100% Filling Time (s)	Equilibrium Reaction force on stamp (mN)	Maximum Internal stress in the workpiece (MPa)
35.00	73.37	4.2	0.144
45.00	19.28	6.5	0.1453
55.00	7.82	8.69	0.147

4.3. Comparison and Discussion

The results for both the simulated load configurations are analysed. Our primary aim is to minimise the filling time. However, we also need to ensure that the internal stresses in the workpiece and the reaction force on the stamp are minimum. A low reaction force will help increase the tool life.

In **Figure 7(a),** we compare the variation in the maximum stress developed inside the workpiece with the filling time for both the force and displacement-controlled loadings. We see that for any given filling time, the stress developed in the displacement, as well as force-controlled set-up, is almost the same, with displacement control having slightly lower stresses.

Figure 7(b) shows the variation in filling time with the reaction force experienced by the stamp for both the load control configurations. We see that for a certain filling time, the equilibrium reaction force experienced by the stamp is lower in the case of displacement-control. A lower force means less tool damage and increased tool life. Hence displacement-controlled loading should be preferred.

The material behavior during the displacement-controlled loading resembles that of a stress-relaxation test since the strain is held constant here. On the other hand, the force-controlled configuration resembles a creep test since the force is kept constant while the strain increases. This may be the reason why the displacement control configuration gives a lower equilibrium reaction force. For example, in the case of **45 µm** and **8 mN** loadings, the filling time is almost equal (≈19 s), however, the equilibrium reaction force on the stamp is **25%** higher for the force-controlled setup. Here, for both the loading configurations, the force on the stamp ramps during the pressing stage to a maximum value of 8 mN up to which ≈95% of the filling is completed. During the holding stage, which lasts for 120 s, the material relaxes during the displacement control configuration and fills the remaining cavity while decreasing the stress on the stamp. In the force-control configuration, however, due to the constant force load on the stamp, the reaction force does not reduce and the material fills the remaining cavities while undergoing creep behaviour.

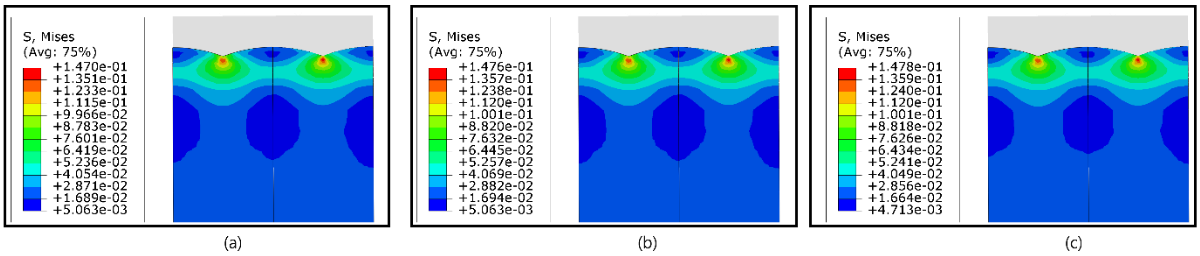

Figure 5: Stress distribution at the end of the holding stage for a displacement controlled hot embossing with load of 55 µm with the co-efficient of friction (a) µ = 0 (b) µ = 0.15 (c) µ = 0.3

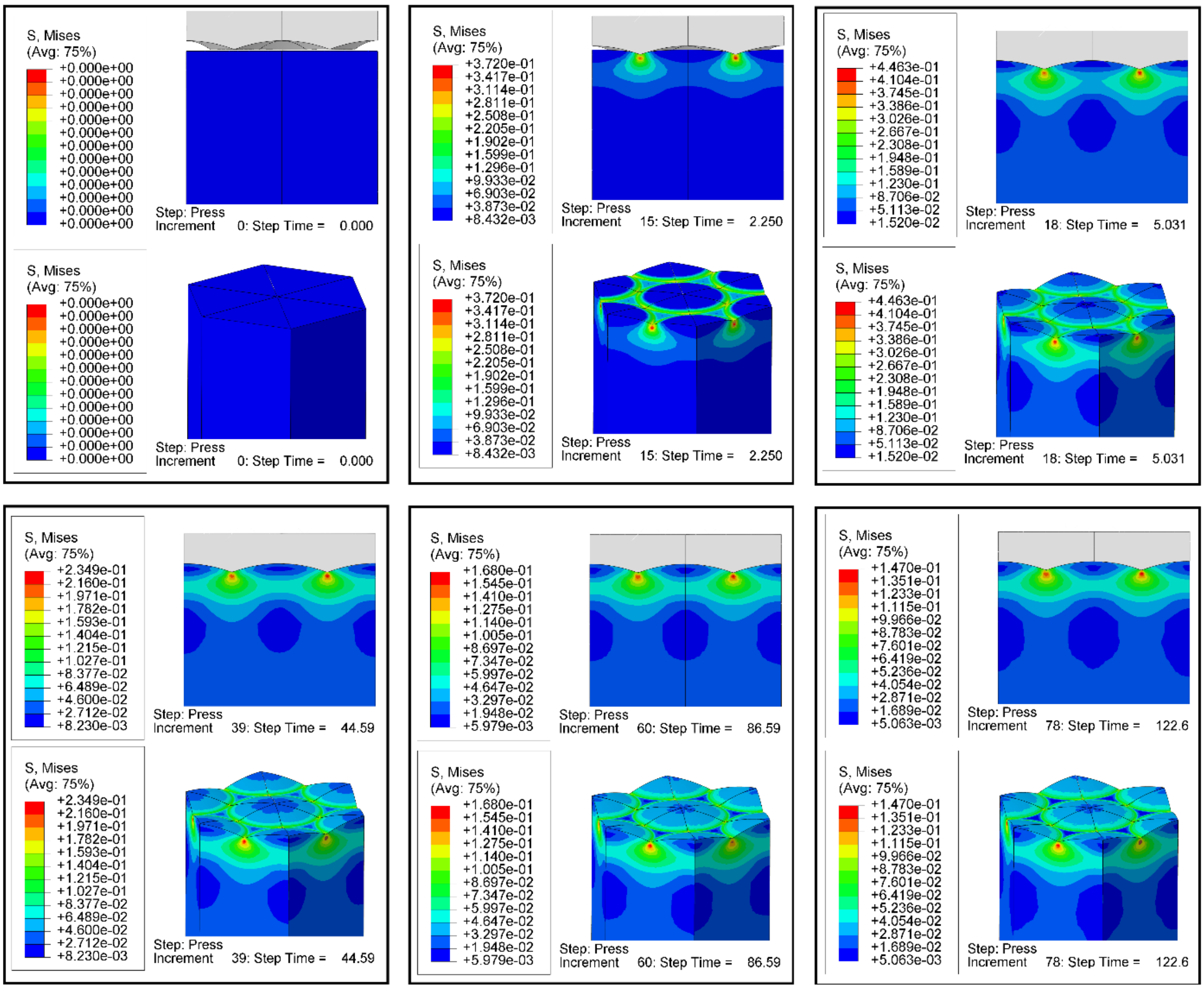

Figure 6: Cross-sectional and 3-dimensional view of the stress distribution and deformation in a single lens of the microlens array during the pressing and holding stage of Hot Embossing.

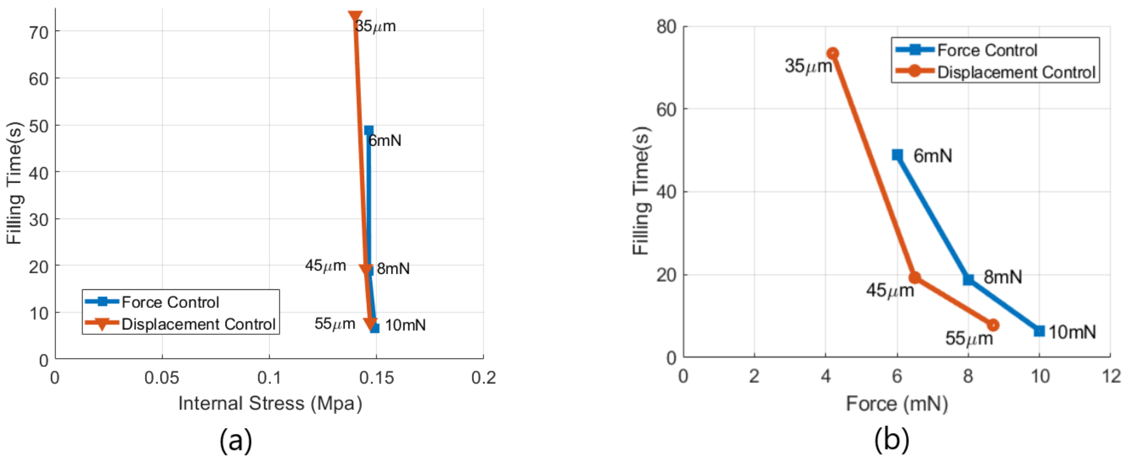

Figure 7: (a) Filling time vs Maximum Internal Stress and (b) Filling time vs equilibrium reaction force on stamp for the force and displacement-controlled loading configurations

5. Conclusions

Using the Viscoplasticity-based overstress (VBO) material model, a Finite Element Model for the hot embossing of a PMMA specimen is developed. The parameters for the model are determined by fitting it against experimental data of the relaxation test by Cheng et al. [9]. The isothermal hot embossing of a microlens array at a temperature of Tg+20°C (T_g is the glass transition temperature of PMMA) is simulated for two different configurations, i.e., force and displacement controlled. In the force-controlled configuration, the PMMA workpiece is pressed with constant stress throughout the embossing process which leads to an increasing creep strain and hence filling up of cavities. In the displacement configuration, the stamp is pushed by a given distance and the PMMA workpiece is compressed. Then the stamp is held stationary, while the stress in the workpiece relaxes, and the material fills the cavities. The filling time, internal stresses, and reaction force experienced by the stamp are compared for both cases

The model predicts that displacement control proves to be the better load configuration. Whereas there is not much difference between the loading configurations in the internal stress developed during the process, for a particular filling time, the reaction force observed by the stamp is much lesser for the displacement control configuration. The lower reaction forces can be attributed to the fact that the material exhibits relaxation behavior during the displacement control configuration. A lesser reaction force is preferred since it increases the tool life of the stamp and hence the repeatability of the process.

This model helps to analyze product quality and the effect of process parameters while minimizing the need for time and resources for physical experiments. On the basis of these studies, a hot-embossing process to fabricate mircolens arrays using bulk metallic glass (BMG) as the tool material would be designed. This would enable single-step mass production with lower costs and higher efficiency while producing quality lenses with a very low surface roughness of 50-100nm [13].

Future work shall involve simulation experiments, using the developed model, to study the effect of other process parameters such as strain rate, hold time, and embossing temperature. Further, the model would be developed to include the cooling stage and stamp retraction stage as well. These stages are important to account for the material shrinkage, material recovery and distortion

References

[1] Holger Becker and Ulf Heim. Hot embossing as a method for the fabrication of polymer high aspect ratio structures. *Sensors and Actuators A: Physical*, 2000, 83(1-3):130–135

[2] Yi-Je Juang, LJ Lee, and KW Koelling. Hot embossing in microfabrication. part i: experimental, polymer. *Eng Sci*, 2002, 42:539–550.

[3] Zhong, Z. W., et al. "Hot roller embossing of multi-dimensional microstructures using elastomeric molds." *Microsystem Technologies* 24.3 (2018): 1443-1452.

[4] Ming-Chung Lin, Jung-Peng Yeh, Shia-Chung Chen, Rean-Der Chien, and Cheng-Li Hsu. Study on the replication accuracy of polymer hot embossed microchannels. *International Communications in Heat and Mass Transfer*, 2013, 42:55–61.

[5] Kamakshi Singh. *Material characterization, constitutive modeling and finite element simulation of polymethyl methacrylate (PMMA) for applications in hot embossing*. PhD thesis, The Ohio State University, 2011.

[6] Danielle Samone Mathiesen. *Experiments, Constitutive Modeling, and Multi-Scale Simulations of Large Strain Thermomechanical Behavior of Poly (methylmethacrylate)(PMMA)*. PhD thesis, The Ohio State University, 2014.

[7] JR McLoughlin and AV Tobolsky. The viscoelastic behavior of polymethylmethacrylate. *Journal of Colloid Science*, 1952, 7(6):555–568.

[8] I Nishiguchi, T-L Sham, and E Krempl. A finite deformation theory of viscoplasticity based on overstress: part i—constitutive equations. 1990.

[9] Gang Cheng and Thierry Barriere. Effect of viscoplasticity on microfluidic cavity filling efficiency of a thermoplastic polymer in hot-embossing process. *The International Journal of Advanced Manufacturing Technology*, 2019, 103(1-4):549–565.

[10] SUSS MicroOptics SA. Microlens arrays: Suss microoptics catalogue.

[11] Gomez, Juan & Conner, Glenn & Chun, Du & Kim, Yoo-Jae & Song, In-Hyouk & You, Byoung Hee. (2014). *Mold Filling Analysis of an Alignment Structure in Micro Hot Embossing. Fibers and Polymers*. 15. 1197-1201. 10.1007/s12221-014-1197-5.

[12] Deshmukh, Swarup S., and Arjyajyoti Goswami. "Hot Embossing of polymers–A review." *Materials Today: Proceedings* 26 (2020): 405-414.

[13] Liwei Lin, Y-T Cheng, and C-J Chiu. Comparative study of hot embossed micro structures fabricated by laboratory and commercial environments. Microsystem Technologies, 4(3):113–116, 1998