Investigation of deviation in width of embossed micro-structure by hot embossing

S S Deshmukh and A Goswami*
Department of Mechanical Engineering, National Institute of Technology Durgapur, 713209
West Bengal, India
Email: *arjyajyoti.goswami@me.nitdgp.ac.in

Abstract: In today’s scenario every manufacturing industry tries to achieve maximum productivity and profit. Manufacturing large number of components within less time helps in increasing the productivity and profit. Hot Embossing is a manufacturing process chiefly used for development of micro-structures on polymer. The parameters considered in this study are the embossing temperature, applied load, embossing time, and de-embossing temperature. The optimization has been carried out with help of Taguchi method for reduction of deviation in width of embossed micro-structures. The Taguchi L9 orthogonal array has been used for collection of data and ANOVA has been performed to find out the percentage contribution of each process parameter of Hot Embossing. ANOVA result reveals that embossing temperature has major contribution of 45.92% as compared to other process parameters. After optimization the working values for different process parameters are embossing temperature = 115°C, applied load = 1.5 tonne, embossing time = 8 minute and de-embossing temperature = 40°C. At an optimum level deviation in width of embossed micro-structure from dimension of mold is only 1.72 μm which is less than the value obtained in each experimental run.

Keywords: Hot Embossing, Poly methyl methacrylate, Laser engraved mold, Taguchi method, ANOVA.

1. INTRODUCTION

Micro-structured film has numerous applications in the area of optics, light guided plates, micro lenses, brightness enhancement in case of LCD, anti-reflection films etc. Micro-structured film also has applications in the area of the Micro Electro Mechanical Systems (MEMS) like micro reactors, micro pumps, micro sensors etc. Micro-structured film was also utilized for generating hydrophilic or hydrophobic surfaces for self-cleaning applications [1]. There are various methods for fabricating the micro-structured film like lithography, micro EDM, micro ECM, deep reactive ion etching, laser ablation, micro injection molding and Hot Embossing. Amongst the different processes Hot Embossing process has less running cost and large productivity [2]. In case of Hot Embossing most of the work has been done in the area of improving the productivity and quality of the replicated micro-structure. Hot Embossing is the process in which polymer is heated above the glass transition temperature and a mold containing the micro-structure is placed above the polymer followed by application of load on the mold. When the mold is separated from the heated polymer the structures form the mold is transferred on to the polymer. The Hot Embossing and graph of temperature and pressure variation in Hot Embossing is shown in Figure 1 and Figure 2 respectively. During the process the polymer is heated from room temperature to its glass transition temperature. Simultaneously the preload condition is applied for proper setting of polymer. When the glass transition temperature is reached the load is suddenly increased from preload value to the embossing
load value. This load is maintained constant during the duration of embossing and in the demolding stage when temperature goes below 30-40°C of the glass transition temperature, the load is suddenly removed [3].

![Figure 1. Conventional Hot Embossing [4]](image)

![Figure 2. Temperature and pressure variation in Hot Embossing [4]](image)

Sean Moore et al. [5] manufactured the micro lenses array on PMMA sheet by partial filling method. The mold was developed through micro milling on brass material. Through partial filling technique good surface finish of micro lenses can be obtained which reduces the scattering of incident light. In this study Taguchi L9 orthogonal array was used to analyse the radius of curvature (ROC) and focal length of replicated micro lenses. Embossing temperature, pressure and time were considered as process parameters for the study. Embossing temperature was found to have maximum effect compared to other process parameters. Yong He et al. [6] developed low pressure hot embossing setup. The micro machining operation was performed on Aluminium sheet for fabricating the mold. This work focused on improvement in replication quality. For analysis purpose molds having different height and width were manufactured. Taguchi L9 orthogonal array was used for optimization by varying the process parameters like Embossing temperature, time, pressure and width of mold. Micro
linear array was developed on conductive polymer which resulted in four folds improvement in the
resistance of the conducting polymer.
Bong Kee Lee et al. [7] fabricated the embossing mold through X-ray lithography and Ni
electroplating. The different width of micro-structures replicated on PMMA sheet was analyzed by
varying the process parameters. Taguchi L4 orthogonal array was used for analyzing the relative error
in depth of embossed micro-structure. Compared to other process parameters embossing temperature
was found to play a vital role in the relative error in depth of embossed micro-structure.

J. M. Li et al. [8] used PMMA sheet of 1mm thickness and used Ni mold fabricated by UV
lithography. This study was performed by varying the process parameters according to Taguchi L16
array and analyzed flow behaviour of polymer with the help of stereo vision system. The measurement
of replication accuracy of depth, width and shape of embossed micro-channel was carried out with the help
of SEM. The embossing temperature and time contribute more in replication accuracy.

Rean-Der Chien et al. [9] manufactured the micro-channels on PMMA substrate and fabricated mold
by UV lithography. These micro-channels were implemented in biomedical field. In this
experimentation major focus was on the replication accuracy of width, depth, and sidewall angle by
influencing the embossing force, temperature, and time. The 3D laser microscope was utilized for
measurement of dimension of the replicated micro-structure. Maximum replication accuracy was
obtained at embossing temperature = 200°C, embossing load = 20KN, embossing time = 5min.

Harutaka Mekaru et al. [10] developed the ultrasonic Hot Embossing setup and utilized polycarbonate
sheet was used as a substrate. The Ni mold was fabricated by the reactive ion etching and
electroforming technique. On a mold there are 7 types of pattern and each type contain 8 different
patterns of different sizes i.e. total 56 patterns are present on mold. The length and depth of these 56
patterns were analyzed at with and without ultrasonic vibration condition. During this condition
embossing temperature and force was varied by maintaining the embossing time as constant i.e. equal
to 5 minute. The molding rate was calculated for embossed structure. From the analysis it is clear that
higher molding rate was obtained at ultrasonic vibration condition.

From the previous literature it is observed that embossing temperature, applied load, embossing time
and de-embossing temperature are important process parameters for hot embossing. In the present
work these parameters have been optimized using L9 orthogonal array.

2. EXPERIMENTAL SETUP

The prototype of hot embossing setup is developed on the manual hydraulic press shown in Figure
3. The circular copper plate of 120 mm diameter and 25 mm thickness is used as bottom plate inside
which a cartridge heater is fitted for heating purpose.

For measurement of temperature K-type thermocouple is fitted inside the copper block. The
temperature during the process is controlled through a temperature controller. For reducing the overall
cycle time, stage cooling was achieved with the help of cooling system during demolding. For
circulation of water small pump is used in cooling tank and water is continuously circulated until the
demolding temperature is reached. The close-up view of hot embossing setup is shown in the Figure
4. The force is applied on the mold with the help of manual hydraulic press. Mirror finished copper
block of 25 mm diameter and 50 mm thickness is used as mold material. The copper mold is shown in
Figure 5. The micro slots of 84 μm width and 250μm length is engraved on the copper block with the
help of laser engraving machine.
Figure 3. Hot Embossing setup

Figure 4. Close-up view of Hot Embossing setup.

The setup of laser engraving system which is shown in Figure 6. The poly methyl methacrylate sheet of 2mm thickness is used as the substrate. To avoid the heat conduction between the bottom plate of Hot Embossing setup and hydraulic press, two asbestos sheet of 2mm thickness is placed between them. In this experimentation embossing temperature (°C), applied load (Tonne), embossing time (minute) and de-embossing temperature (°C) are considered process parameters. The deviation in replicated width of micro-structure is measured as output. In this study major focus is on the reduction of the deviation in width of embossed micro-structure. Each process parameters are varied in 3 levels as per Taguchi L$_9$ orthogonal array. The embossing temperature is varied from the 125°C to 135 °C, applied load is varied from the 1 tonne to 2 tonne, embossing time is varied from 5 min to 10 min and de-embossing temperature varied from 40 °C to 80 °C. The Hot Embossing process parameters and its level are shown in table 1 and Taguchi L$_9$ orthogonal array is shown in table 2. The analysis and measurement of the fabricated micro-structure on PMMA substrate is carried out on the inverted microscope is shown in Figure 7.
Figure 5. Mirror finished copper mold of 25mm diameter consist of engraved micro-structure.

Figure 6. Laser engraving system

Figure 7. Inverted microscope

Table 1. Hot Embossing process parameters and its levels

| Levels | Embossing Temperature (°C) | Applied Load (Tonne) | Embossing Time (Minute) | Deembossing Temperature (°C) |
|--------|---------------------------|----------------------|--------------------------|-------------------------------|
| 1      | 115                       | 1                    | 5                        | 40                            |
| 2      | 125                       | 1.5                  | 8                        | 60                            |
| 3      | 135                       | 2                    | 10                       | 80                            |

Table 2. Taguchi L9 orthogonal array

| Experiment No. | Embossing Temperature (°C) | Applied Load (Tonne) | Embossing Time (Minute) | Deembossing Temperature (°C) |
|----------------|---------------------------|----------------------|--------------------------|-------------------------------|
| 1              | 115                       | 1                    | 5                        | 40                            |
| 2              | 115                       | 1.5                  | 8                        | 60                            |
| 3              | 115                       | 2                    | 10                       | 80                            |
| 4              | 125                       | 1                    | 8                        | 80                            |
| 5              | 125                       | 1.5                  | 10                       | 60                            |
| 6              | 125                       | 2                    | 5                        | 40                            |
| 7              | 135                       | 1                    | 10                       | 60                            |
| 8              | 135                       | 1.5                  | 5                        | 80                            |
| 9              | 135                       | 2                    | 8                        | 40                            |
3. RESULTS AND DISCUSSION

This work deals with the reduction of deviation in width of the embossed micro-structure, by setting the process parameters of hot embossing at an optimum level. The data is collected through the Taguchi L9 orthogonal array. The results of the deviation in width of embossed micro-structure are shown in the table 3 and response table for S/N ratio of deviation is shown in table 4. As deviation of width micro-structure is required to be minimum therefore it is included in the lower the better type category. The S/N ratio for deviation in width of micro-structures is calculated by the following equation 1.

\[
S/N \text{ ratio} = -10 \log \left( \frac{1}{n} \sum_{i=1}^{n} y_i^2 \right)
\]  

(1)

| Embossing Temperature (°C) | Applied Load (Tonne) | Embossing Time (Minute) | Deembossing Temperature (°C) | Width of Embossed micro-structure (μm) | Deviation in width (μm) | S/N ratio |
|---------------------------|----------------------|--------------------------|-----------------------------|---------------------------------------|------------------------|-----------|
| 115                       | 1                    | 5                        | 40                          | 76.89                                 | 6.93                   | -16.8237  |
| 115                       | 1.5                  | 8                        | 60                          | 81.17                                 | 2.66                   | -8.51557  |
| 115                       | 2                    | 10                       | 80                          | 79.53                                 | 4.30                   | -12.671   |
| 125                       | 1                    | 8                        | 80                          | 75.66                                 | 8.17                   | -18.2508  |
| 125                       | 1.5                  | 10                       | 40                          | 79.65                                 | 4.18                   | -12.4352  |
| 125                       | 2                    | 5                        | 60                          | 73.70                                 | 10.12                  | -20.1111  |
| 135                       | 1                    | 10                       | 60                          | 74.56                                 | 9.27                   | -19.3436  |
| 135                       | 1.5                  | 5                        | 80                          | 72.48                                 | 11.34                  | -21.0976  |
| 135                       | 2                    | 8                        | 40                          | 76.90                                 | 6.93                   | -16.8209  |

Tool/Mold= Width of engraved structure= 83.83μm

The size of micro slot on mold is shown in Figure 8. The results for minimum and maximum deviation in width of micro-structure i.e. experiment run no 2 and experiment run no 8 is shown in Figure 9 and Figure 10 respectively. It is necessary to set the process parameters at an optimum level to achieve maximum accuracy of the embossed micro-structure. As embossing temperature, embossing load and embossing time values exceeds the particular limit the distortion in embossed micro-structure i.e. distortion near the edges of slot increases as observed from the inverted microscope images.

| Level | Embossing Temperature | Applied Load | Embossing Time | Deembossing Temperature |
|-------|-----------------------|--------------|----------------|-------------------------|
| 1     | 12.67*                | -18.14       | -19.34         | -15.36*                 |
| 2     | -16.93                | -14.02*      | -14.53*        | -15.99                  |
| 3     | -19.09                | -16.53       | -14.82         | -17.34                  |
| Delta | 6.42                  | 4.12         | 4.82           | 1.98                    |
| Rank  | 1                     | 3            | 2              | 4                       |
Figure 8. Size of micro slot on mold

| LINE  | Width (µm) |
|-------|------------|
| LINE1 | 87.911     |
| LINE2 | 86.895     |
| LINE3 | 80.814     |
| LINE4 | 78.771     |
| LINE5 | 77.696     |
| AVERAGE | 83.8366   |

Figure 9. Minimum deviation in width of embossed micro-structure (Experiment run no.2).

Figure 10. Maximum deviation in width of embossed micro-structure (Experiment run no.8).
Due to the distortion near the edges of micro slot, when the average width of the micro slot is calculated it deviates from the actual dimensions of mold. From the main effect plot of S/N ratio which is shown in Figure 11, it is clear that if demolding temperature is not set at particular level then recovery of polymer will take place due to improper cooling. Maximum accuracy in width of micro-structure can be obtained when demolding temperature is at 40°C as compared to 60°C and 80°C. Similarly when embossing time and applied load is set at low level i.e. 5 minute and 1 tonne respectively then large deviation in the width of micro-structure can be observed due to the improper replication of micro-structure on polymer. The main reason behind it is insufficient embossing time and the applied load during the embossing process. But as embossing temperature increases above the glass transition temperature the polymer goes into a viscoelastic state. When the temperature is higher than the glass transition temperature the polymer becomes softer due to which greater deviation in the embossed micro-structure takes place.

![Figure 11. Main effect plot for S/N ratios](image)

From the main effect plot it is clear that for reduction of deviation in width of embossed micro-structure it is necessary to set process parameters at an optimum level. The optimum level of process parameters is embossing temperature = 115 °C, applied load = 1.5 tonne, embossing time = 8 minute, de-embossing temperature = 40 °C.

| Process parameters        | DOF | SS      | MS    | F-Value | % Contribution |
|---------------------------|-----|---------|-------|---------|----------------|
| Embossing Temperature     | 2   | 31.746  | 15.873| *       | 45.92%         |
| Applied Load              | 2   | 6.381   | 3.191 | *       | 9.23%          |
| Embossing Time            | 2   | 25.183  | 12.592| *       | 36.43%         |
| Deembossing Temperature   | 2   | 5.823   | 2.911 | *       | 8.42%          |
| Error                     | 0   | *       | *     | *       |                |
| Total                     | 8   | 69.133  |       |         | 100.00%        |

| Table 5. Analysis of variance for deviation in width of embossed micro-structure |

| Process Parameters        | DOF | SS      | MS    | F-Value | % Contribution |
|---------------------------|-----|---------|-------|---------|----------------|
| Embossing Temperature     | 2   | 31.746  | 15.873| 5.45    | 45.92%         |
| Applied Load              | 2   | 6.381   | 3.191 | 1.10    | 9.23%          |
| Embossing Time            | 2   | 25.183  | 12.592| 4.33    | 36.43%         |
| Deembossing Temperature   | (2) | Pooled  | -     | -       |                |
| Error                     | 2   | 5.823   | 2.911 |         | 8.42%          |
| Total                     | 8   | 69.133  |       |         | 100.00%        |

| Table 6. Pooled analysis of variance for deviation in width of embossed micro-structure |
Analysis of variance has been calculated to find out percentage contribution of each parameter. From ANOVA it becomes evident that percentage contribution of embossing temperature is more compared to other process parameters. The percentage contribution of embossing temperature is equal to 45.92% followed by embossing time equal to 36.43%, applied load equal to 9.23% and error obtained is 8.42%. In the initial analysis of ANOVA DOF of residual error and percentage contribution of error is zero, to overcome this pooled ANOVA has been calculated by neglecting the less contributed parameter i.e. deembossing temperature in the initial stage. The results of ANOVA and pooled ANOVA are given in the table 5 and table 6 respectively. The percentage contribution of each process parameter is shown in Figure 12.

4. CONCLUSION

- The results of Hot Embossing reveals that embossing temperature plays very crucial role for deviation in width of the embossed micro-structure as compared to other process parameter.
- The contribution of embossing temperature is near about the 45.92%.
- It is necessary to set process parameters at an optimum level for getting less deviation in width of the embossed micro-structure.
- When the de-embossing temperature is set at a higher value, due to improper cooling recovery in the polymer will take place which is responsible for the deviation in the width of the embossed micro-structure.
- When the embossing time and applied load exceeds the particular limit it causes more distortion at the edges of the micro-slot due to this greater deviation in the width of micro slot takes place.
- When the embossing temperature is set above glass transition temperature then the polymer goes into viscoelastic state, which results in higher softening of polymer and causes greater deviation in width of embossed micro structure.
- The optimum level of process parameters are embossing temperature= 115 °C, applied load = 1.5 tonne, embossing time = 8 minute and de-embossing temperature = 40 °C.
- After setting process parameters at an optimum level the deviation in width of embossed micro-structure is only 1.72 μm which is less than the value of deviation getting in the orthogonal array.
ACKNOWLEDGMENTS

Authors acknowledge the Metallurgical and Materials Engineering Department of National Institute of Technology Durgapur for their help in carrying out this work.

REFERENCES

[1] Patil D, Sharma A, Aravindan S and Rao P V 2019 Development of hot embossing setup and fabrication of ordered nanostructures on large area of polymer surface for antibiofouling application Micro Nano Lett. 14 191–5
[2] Kuo C C and Chiang T S 2017 Development of a precision hot embossing tool with microstructures for microfabrication–Main source paper Int. J. Adv. Manuf. Technol. 91 1321–6
[3] Deshmukh S S and Goswami A 2020 Hot Embossing of polymers – A review Mater. Today Proc. https://doi.org/10.1016/j.matpr.2019.12.067
[4] Chang J H and Yang S Y 2003 Gas pressurized hot embossing for transcription of micro-features Microsyst. Technol. 10 76–80
[5] Moore S, Gomez J, Lek D, You B H, Kim N and Song I H 2016 Experimental study of polymer microlens fabrication using partial-filling hot embossing technique–Main sorce paper Microelectron. Eng. 162 57–62
[6] He Y, Wu W, Zhang T and Fu J 2015 Micro structure fabrication with a simplified hot embossing method RSC Adv. 5 39138–44
[7] Lee B K, Kim J H, Kim D S, Chang S S and Kwon T H 2010 Microfabrication of a nickel mold insert by a modified deep X-ray lithography process and its application to hot embossing Microelectron. Eng. 87 2449–55
[8] Li J M, Liu C and Peng J 2008 Effect of hot embossing process parameters on polymer flow and microchannel accuracy produced without vacuum J. Mater. Process. Technol. 207 163–71
[9] Chien R D 2006 Hot embossing of microfluidic platform Int. Commun. Heat Mass Transf. 33 645–53
[10] Mekaru H, Goto H and Takahashi M 2007 Development of ultrasonic micro hot embossing technology Microelectron. Eng. 84 1282–7