Design, development, and experimental investigation of induction-aided hot embossing process

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Presented in International Conference on Precision, Micro, Meso and Nano Engineering (COPEN - 12: 2022)
December 8 - 10, 2022 IIT Kanpur, India

ABSTRACT

KEYWORDS

Induction-Aided Hot Embossing,
Polymer,
PET,
Performance Analysis,
Replication Accuracy.

Hot embossing (HE) is a microfabrication technique employed to develop micron-scaled patterned polymer substrate. This process has long cycle time which affects productivity. To overcome this, induction-assisted hot embossing (IHE) setup was developed in-house by altering the traditional–HE setup. From the results of a performance study, it is clear that the IHE arrangement has a much shorter total cycle time than the conventional-HE setup. The overall cycle time in conventional-HE setup is 27.18 minutes, while for IHE setup it is 11.38 minutes. The percentile decrement in overall cycle time is 58.13%. It is observed that embossing-temperature mainly influences the % replication-accuracy of an embossed microchannel. From a parametric study was observed that the % replication-accuracy improved from 44.01% to 97.79% as embossing-temperature rise from 90°C-110°C. The max % replication-accuracy was obtained at embossing-temperature = 110°C, embossing-pressure = 20 Kg/cm^2, embossing-time = 240 seconds and deembossing-temperature = 60 °C.

1. Introduction

Due to the ever-increasing need for micro-components, it is now more important than ever to find a way to mass-produce these parts quickly and cheaply. The micro-replication techniques like micro-injection molding, hot embossing is worth looking into as an alternative approach to soft lithography for creating micro-structure. However, hot embossing offers several benefits, such as lower production costs and utilization of the same mold for many runs. The hot embossing (HE) process is simple to perform and yields precise results. Hot embossing results in much lower component stress than other processes. In hot embossing, the polymer (work material) is stretched locally over a shorter distance than the polymer substrate as a whole. Hot embossing has a narrower temperature window of operation than other production methods therefore the shrinkage and frictional forces experienced during chilling and deembossing are mitigated. Polymers such as polymethyl methacrylate (PMMA), polycarbonate (PC), etc., are often utilized as the working substrates in hot embossing. These replicated micro-patterns have various applications in different domains like optical (micro-lens array, micro-fresnel lens array, optical waveguide), biomedical (micro-fluidic chip, micro-needles), and MEMS domains (micro-mixers, micro-reactor, biosensor). In traditional-HE, the workpiece is positioned over the hot plate and heated above the glass transition temperature (T_g) of the polymer workpiece. A cartridge heater is fitted inside the lower hot plate for heating. The mold has micro-patterns placed over the polymer substrate, and pressure is applied over the mold through a pressure system (Becker & Heim, 2000). The schematic of a conventional-HE setup is depicted in Fig. 1(a).

At the start, pre-pressure was applied over the mold to correctly position the working material between the mold and the lower hot plate. Pre-pressure was raised to embossing pressure after the workpiece temperature reached T_g, and it was kept constant for a particular time interval. The duration during which this pressure is maintained is known as the holding period. After this period has elapsed, the polymer substrate is cooled by circulating water through the hot plate's cooling channels. The mold was

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https://doi.org/10.58368/MTT.22.6.2023.20-27

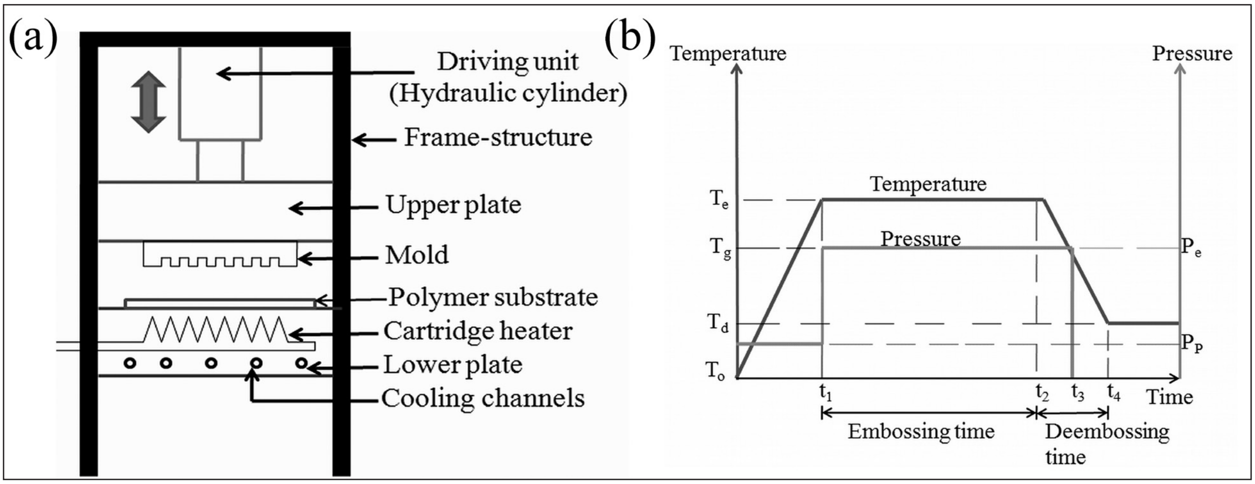

Fig. 1. (a) Schematic of conventional-HE setup, (b) Temperature and pressure variation throughout the process.

released from the polymer workpiece when the temperature dropped to about 35-40°C below T_g. In such a manner, micro-patterns over the mold are transferred over the polymer specimen. The temperature and pressure variation throughout the process is depicted in Fig. 1(b) (Deshmukh & Goswami, 2020, 2021; Li et al., 2008).

Chang & Yang (2003) developed a gas-pressurized-HE setup to overcome the non-uniform pressure distribution issue that arises in the traditional-HE. In this setup, a brittle material mold (Si-wafer) was used to fabricate the micro-channel over the PMMA substrate, which is impossible in the traditional-HE setup. Due to uniform pressure distribution during the embossing stage, good replication accuracy was achieved. With the help of this setup, Hocheng et al. (2008) successfully fabricated a 300 X300 micro-lens array on the polycarbonate substrate. Kimerling et al. (2006) insulated the mold and provided tiny air pockets over the mold for minimization of the overall cycle time. The cycle time was reduced from a few minutes to a few seconds. With the help of this mold, various shapes like circular, hexagonal, and sinusoidal micro-patterns were successfully embossed over the PMMA substrate. A thermal fatigue test was performed to check the sustainability of the mold due to rapid heating and cooling. This mold withstands 10,000 thermal cycles without cracking. Chang & Yang (2005) developed the fluid-based HE setup to reduce the overall cycle time. The heating of the substrate was done by passing the steam and heated oil through the bottom hot plate. In addition to this, the results were also compared with heating through infrared radiation. The PVC substrate of 200 µm thickness was heated from 25°C to 130°C. Infrared heating takes less time than others, but uniform heating was observed in the case of oil heating. Due to uniform substrate heating, the best replication accuracy was achieved in oil heating. Yang et al. (2008) used CO_2 gas in the gas-pressurized HE setup instead of the pressurized air to apply pressure over the substrate. This CO_2 gas acts as a plasticizer that minimizes the T_g of the polymer substrate. So the embossing takes place at less than T_g and at lower pressure which leads to lesser thermal stresses in the embossed part. It is noted that dissolving pressure also has a significant impact on replication accuracy. The maximum replication accuracy was achieved at higher T_e and low dissolving pressure. The same setup has been used for the fabrication of the micro-lens array (Huang et al., 2009; Wu et al., 2010).

Kurita et al. (2018) developed a laser-assisted HE setup to fabricate micro-patterns over glass substrate. Continuous and pulsed laser beam was used for the heating purpose. The glass substrate was heated by heating the mold through a laser beam, and the temperature was controlled by regulating the power of the laser beam. The maximum depth and less percentile error in circularity of embossed micro-pattern were observed in the case of pulse laser heating. He et al. (2015) developed a low-force HE setup using the lever-type mechanism to investigate the HE process thoroughly. The load was employed by simply attaching the dead weight to the lever mechanism. This mechanism is kept in a vacuum oven for heating. The experimentation was performed as per orthogonal array by considering embossing-temperature (T_e), pressure (P_e), and time (t_e) as operating parameters. The best replication ratio was achieved at T_e=150°C, P_e=300N, and t_e=30minutes. Recently, Chen et al. (2014) designed a far-infrared assisted-HE setup for the minimization the cycle time of the HE

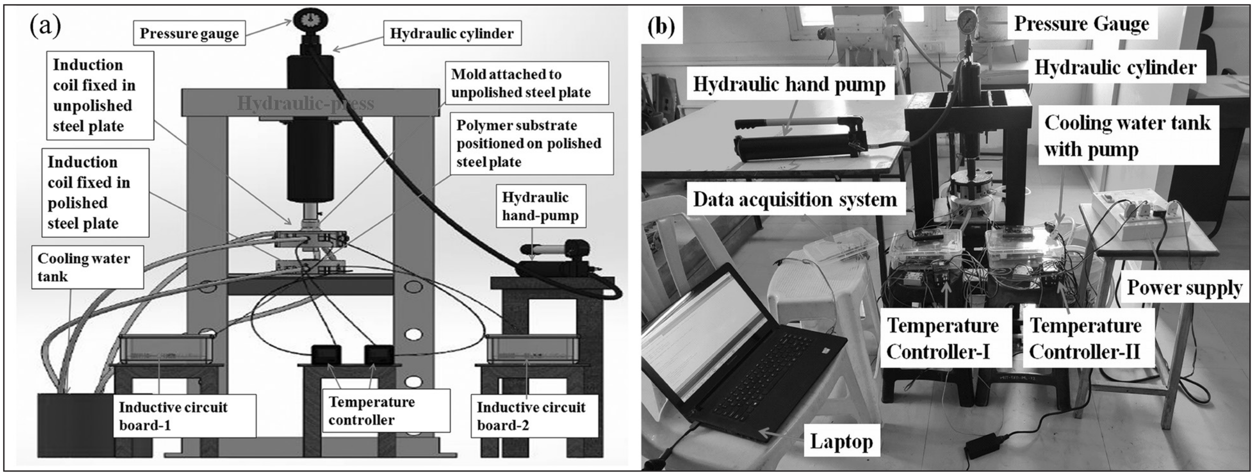

Fig. 2. (a) Schematic of IHE setup, (b) Actual IHE setup.

process. A spring drive press device that worked on Hook's law was developed to apply the pressure over the mold during the embossing, and this device was kept in an iron box. Two 250-watt infrared bulbs were fitted in the iron box for the heating purpose. It is observed that the PMMA substrate was heated from room temperature to 130°C within 5 minutes. With the help of this setup micro-fluidic chip was successfully fabricated over the PMMA substrate.

In the present work, an induction-aided-HE setup was designed and developed in-house over the hydraulic press. Its performance was compared with the traditional-HE setup. The impact of operating parameters of IHE on the $R_{accuracy}$ of embossed micro-channel was also investigated.

2. Development of Induction-Aided Hot Embossing System

Fig. 2 (a) and 2(b) show the schematic and actual photograph of the setup.

This setup is designed over the hydraulic press system of 5-ton capacity. This setup consists of a hydraulic cylinder, hydraulic hand pump, pressure gauge to monitor the applied pressure, and two steel plates; one is diamond-polished, another is unpolished. The polished plate is positioned at the bottom side on the base plate of the hydraulic press. On the polished plate, the polymer substrate is put for heating purposes. The unpolished steel plate is linked to the hydraulic cylinder. The patterned mold is attached to the unpolished steel plate at the central position. Both steel plates (polished and unpolished) are heated through the induction heating mechanism. The induction heating mechanism consists of two-induction coils, two-induction circuit boards (ICB), K-type thermocouples, and two-temperature controllers. These inductive coils were fitted inside the cavity of both steel plates and connected to the ICB separately. These ICB's were connected to the temperature controller, which monitors and controls the temperature of both steel plates. ICB's power supply switches off when the temperature exceeds the set value. As a result, the temperature of both plates was maintained at the set value. Two additional K-type thermocouples were fitted inside the steel plates and were connected to the data acquisition (DAQ) system developed using Arduino-mega 2560 microcontroller and max-6675 thermocouple module. This DAQ is connected to the laptop to store the temperature data with respect to time. For the cooling of the polymer substrate and mold, cooling channels were provided in both steel plates. Two submersible pumps were used to pump the cooling water from the cooling tank to the steel plates to cool down polymer substrate and mold from T_e to T_{de} during the deembossing stage. The detailed specifications of the hydraulic press system, heating mechanism, DAQ, and cooling mechanism are depicted in Table 1.

3. Results and Discussion

3.1. Comparison of performance analysis of traditional-HE and induction-aided-HE

In this work, PET substrate was used as a workpiece positioned on a polished steel plate. To evaluate its exact T_g, DSC (Differential scanning calorimetry) test was performed. The T_g of this substrate was found to be 74.47 °C. The cartridge heater was fitted inside the diamond polished

Table 1
Detailed specifications of IHE setup.

Sr. No.	Parts of IHE	Dimension/Specification
1.	Hydraulic Press system	Type: Manual, Working base size = 300X280 mm, Column height =780 mm, Stroke of hydraulic cylinder =125mm. Steel plates (polished and unpolished) size = 175 mm diameter and 50 mm thickness.
2.	Heating mechanism	Type: Induction heating, Two-induction coils of 1800 watt of size 155 mm diameter, Two-induction circuit boards of 1800 watt 220 volts, 2-K-type thermocouples, Two-temperature controller- Selec TC544B.
3.	Data acquisition System	Arduino mega-2560 microcontroller, Max-6675 module (12 bit analogue-to-digital converter), 2-K-type thermocouples (range: 0-1024 ºC, Precision:± 1.5°C).
4.	Cooling system	Two submersible 18-watt pumps [power supply: 180-240 Volt], Cooling water tank.

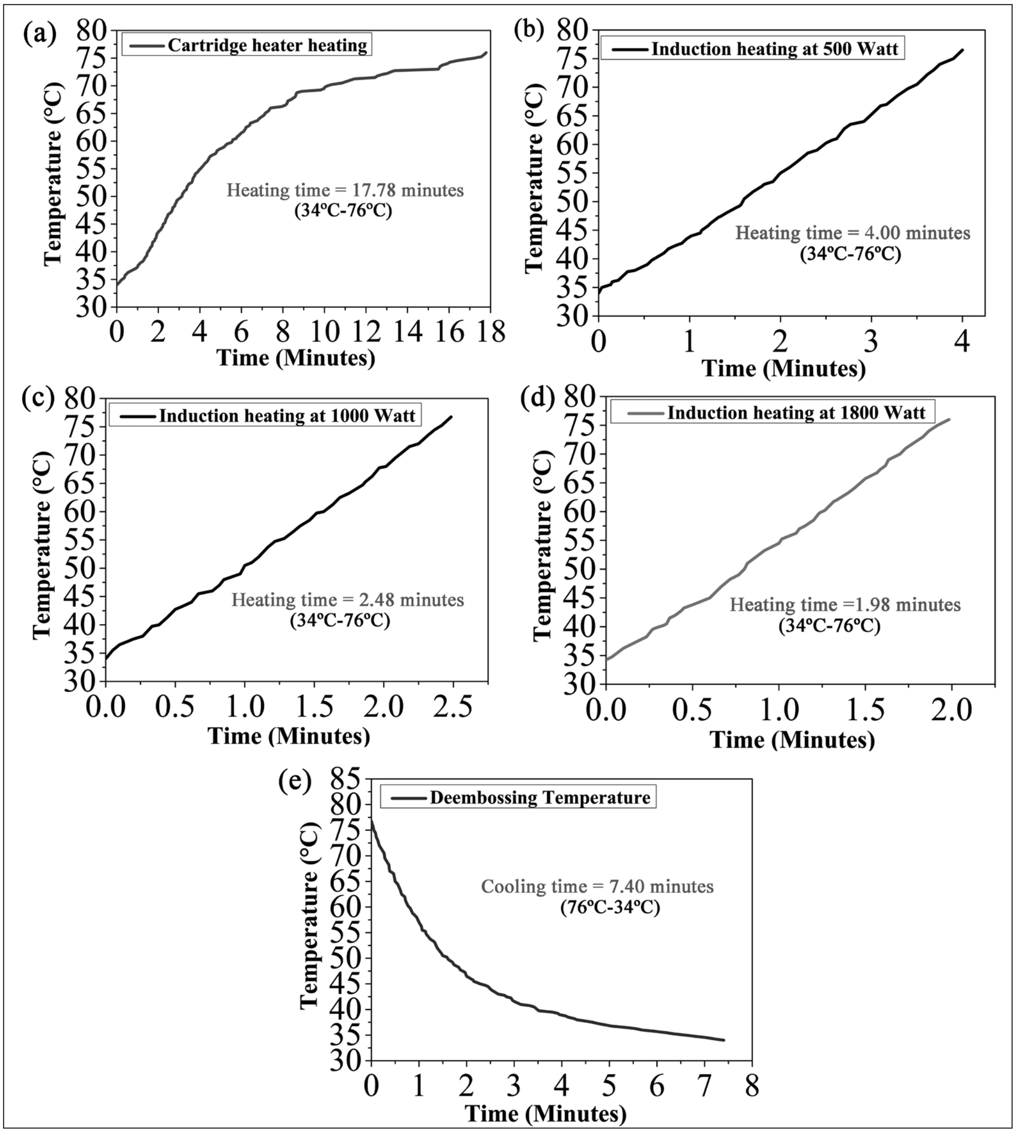

Fig. 3. Results of (a) cartridge heater heating, results of induction heating at (b) 500 watt, (c) 1000 watt, (d) 1800 watt, (e) cooling stage.

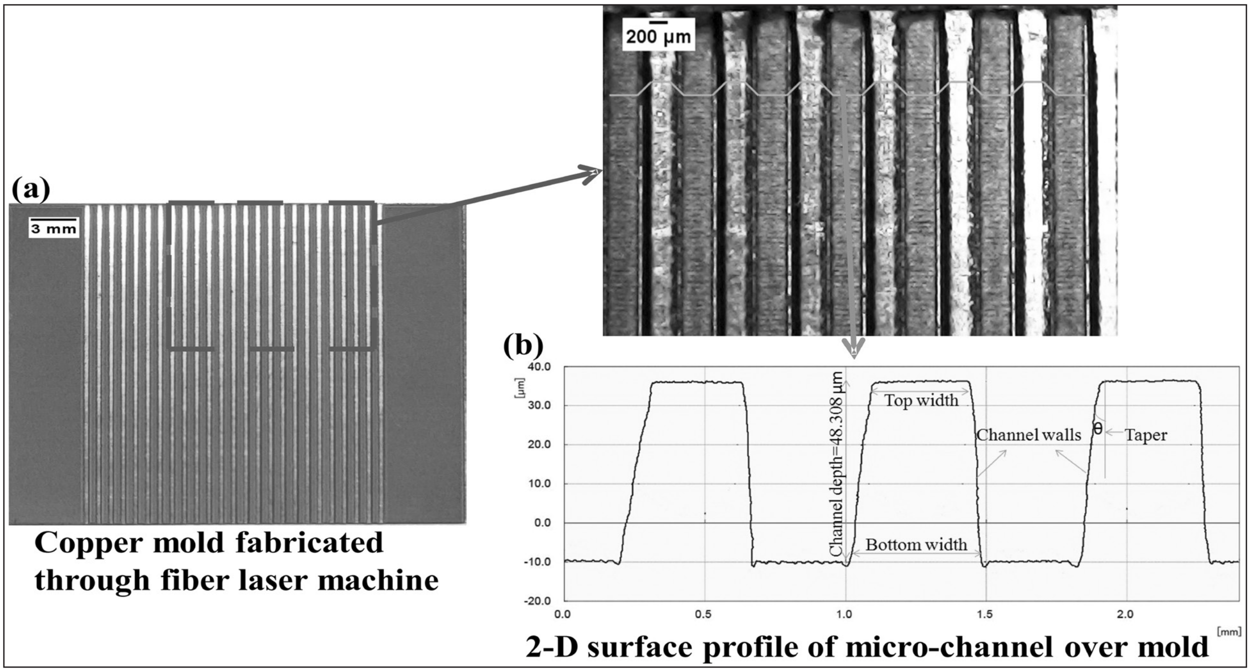

Fig. 4. (a) Copper mold fabricated through fiber laser machine, (b) 2-D surface profile of microchannel (Deshmukh et al., 2022).

steel plate at the initial phase of the experimentation. The substrate was heated from room temperature (34°C) to 76°C, i.e., above the Tg, and the cartridge heater took 17.78 minutes to achieve this temperature. In the next step, the induction coil was fitted inside the cavity of the polished steel plate, and the polymer substrate was positioned over it. The substrate was heated from 34°C to 76°C by setting induction power at 500 watts. In this case, the substrate takes 4.00 minutes to reach this temperature. The induction coil was operated at 1000 watts for the same heating; it took 2.48 minutes. Finally, the coil operated at its maximum capacity, i.e., 1800 watts; in this case substrate was heated in 1.98 minutes. Finally, the cooling was performed by passing water (at room temperature ≈ 30-32°C) through the cooling channel of the polished steel plate and substrate cool from 76°C to 34°C. The cooling stage is completed in 7.40 minutes. This result shows that in the case of traditional HE (cartridge heating), the overall cycle time (heating + cooling +loading and unloading sample (2min)) is equal to ≈ 27.18 minutes. While in the case of induction -HE setup, when it's operated at 1800 watts, the overall cycle time is ≈ 11.38 minutes. The percentile decrement in overall cycle time is 58.13%. Definitely this IHE setup helps to enhance productivity. In the future, the overall cycle time of IHE setup will be further reduced by passing chill water with temperatures between 5-15°C. The results of cartridge heater heating and induction heating at 500, 1000, and 1800 watt is shown in Fig. 3(a), 3(b), 3(c), and 3(d), respectively. The outcome of the cooling stage is shown in Fig. 3(e).

3.2. Effect of process parameters of IHE on replication accuracy ($R_{accuracy}$)

The mold required for the HE process was fabricated through a fiber laser machine. The copper plate having the dimension of 5mmX5mmX1mm thickness was used as a workpiece. The detailed fabrication procedure of the mold is given in our previous published work (Deshmukh et al., 2022). The depth of micro-channels over the mold was evaluated through a surface roughness tester (Mitutoyo-SJ-500) and found to be 48.30 µm. Fig. 4(a) and 4(b) show the fabricated mold and its surface profile.

The replication accuracy is calculated as follows:

$$\% R_{accuracy} = \frac{depth\ of\ embossed\ microchannel}{depth\ of\ microchannel\ on\ mold} X100 \quad ..(1)$$

The effect on $R_{accuracy}$ was evaluated by varying the operating parameters one at a time by keeping others at the central value of the varying range. The T_e is changed from 90-110°C (15-20°C, above the T_g), P_e from 10-30 Kg/cm^2, t_e from 120-360

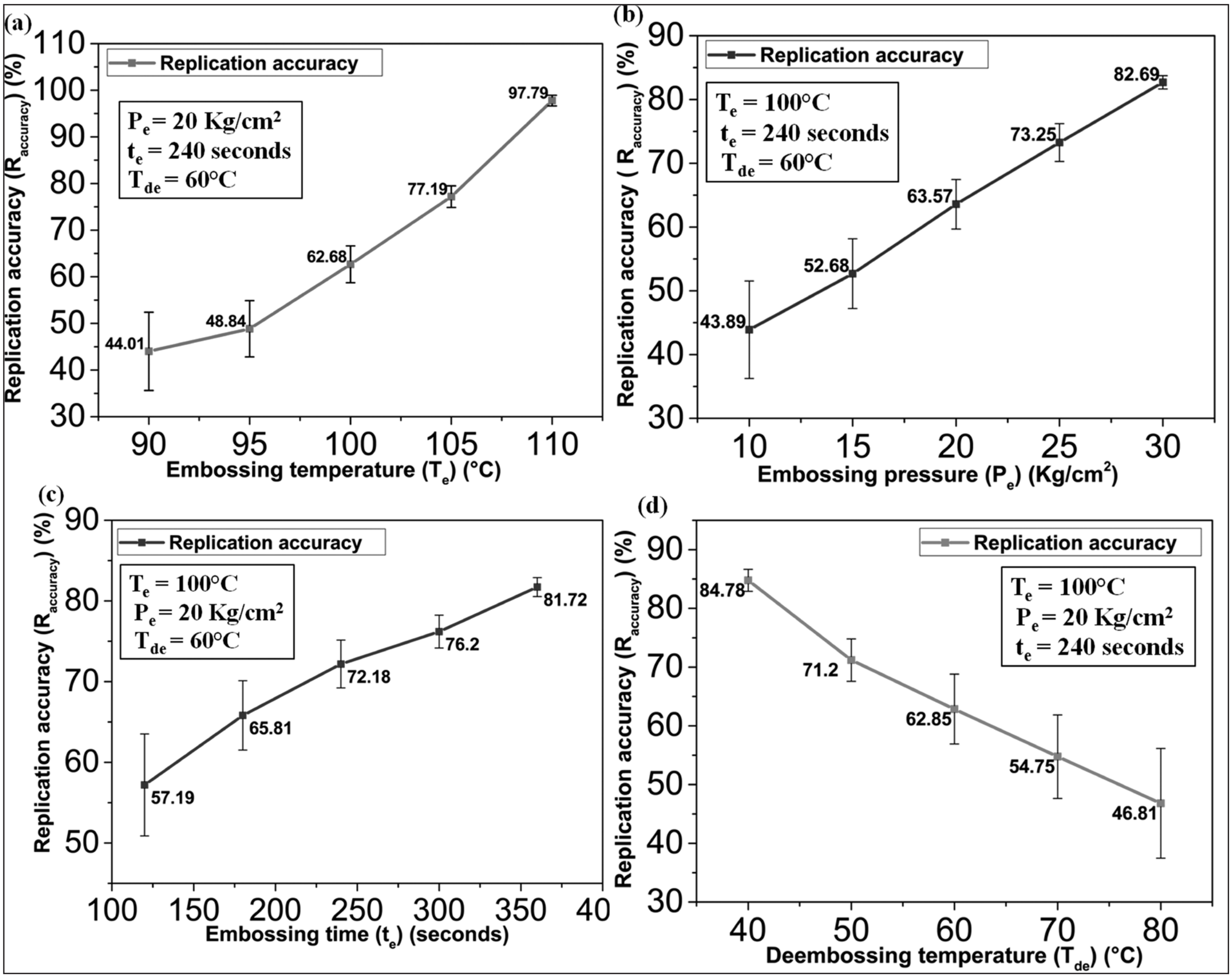

Fig. 5. Effect of (a) T_e, (b) P_e, (c) t_e, (d) T_{de} on % R accuracy.

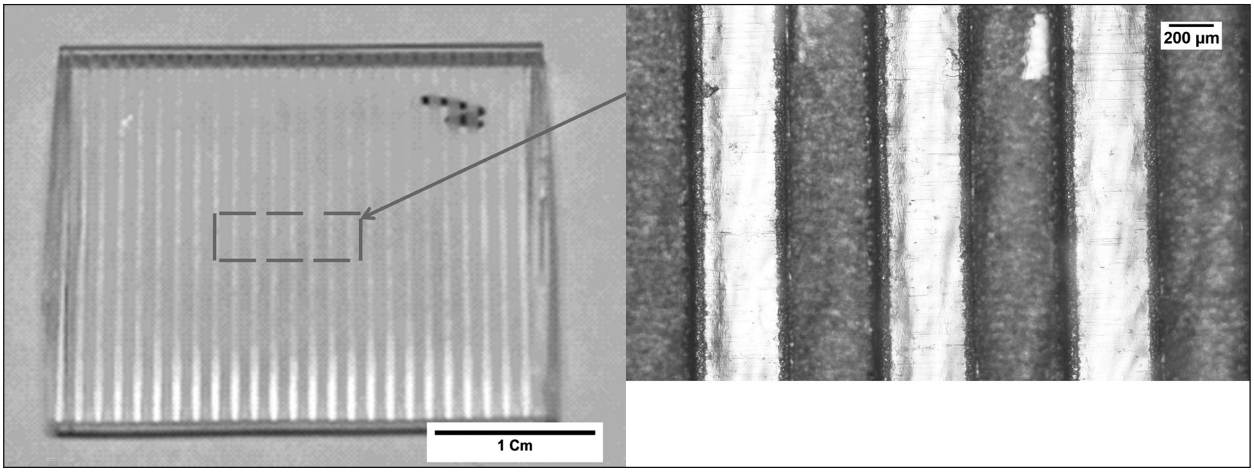

Fig. 6. Embossed microchannels fabricated by IHE setup.

seconds, and T_{de} from 40-80°C. The $R_{accuracy}$ increased from 44.01% to 97.79% as T_e rose from 90°C to 110°C by keeping P_e at 20 Kg/cm², t_e at 240 seconds, and T_{de} at 60°C. Increment in % $R_{accuracy}$ due to the higher T_e is because the polymer gets more viscous, and the cavity over the mold was filled easily. In the case of P_e, % $R_{accuracy}$ increased from 43.89% to 82.69% as P_e rose from 10-30 Kg/cm² by keeping T_e at 100°C, t_e at 240 seconds, and T_{de} at 60°C. It is noted that at the more significant value of P_e, a viscous polymer is adequately pressed into the cavity over the mold; as a result, % $R_{accuracy}$ increases. The same pattern was observed; in this case it was noted that % $R_{accuracy}$ improved from 57.19% to 81.72% as t_e was raised from 120 to 360 seconds. In the case of T_{de}, % $R_{accuracy}$ dropped from 84.78% to 46.81% as T_{de} rose from 40 °C to 80 °C. It was observed that at the higher value of the T_{de}, embossed specimen does not get cooled adequately; as a result, viscoelastic recovery takes place, which affects % $R_{accuracy}$. All these results are shown in Fig. 5(a), 5(b), 5(c), and 5(d), respectively.

The maximum % $R_{accuracy}$ achieved at T_e= 110°C, P_e = 20 Kg/cm^2, t_e = 240 seconds and T_{de} = 60°C. The embossed substrate and optical microscope image of the embossed microchannels are shown in Fig. 6.

4. Conclusion

In this work, the induction-HE setup was designed and developed in-house. The performance of this setup was compared with the Traditional-HE setup by evaluating the overall cycle time of the process. The effect of process parameters on % $R_{accuracy}$ is also investigated. The main conclusions of this work are as follows:

1. The traditional-HE setup takes 17.78 minutes to heat the PET polymer substrate above the T_g, i.e., (74.47 °C) from the room temperature (34 °C).
2. The overall cycle time (heating + cooling + loading/unloading of the sample) in the case of a traditional-HE setup is 27.18 minutes.
3. Induction-HE setup heats the PET substrate above its T_g only in 1.98 minutes when it is operated at 1800 watts.
4. The overall cycle time in the case of induction-HE setup is 11.38 minutes. The percentile decrement in overall cycle time is 58.13% compared to the traditional-HE setup. Definitely, this IHE setup helps to enhance productivity. In the future, the productivity of the IHE setup will be increased by passing the ice-chilled water through the cooling channel of the polished steel plate.
5. The embossing temperature mainly influences the % Raccuracy. It is noted that % $R_{accuracy}$ improved from 44.01% to 97.79% as T_e was raised from 90°C to 110°C by setting P_e at 20Kg/cm^2, t_e at 240 seconds, and T_{de} at 60°C.

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