SOCIETY OF PLASTICS ENGINEERS
Plastics Research Online
10.2417/spepro.006967

High-efficiency hot embossing for polypropylene

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A new plate-to-plate isothermal hot embossing method with a low cycle time enables highly uniform microstructures to be introduced in semicrystalline polymers for use in practical devices.

Hot embossing is one of the most promising methods for the fabrication of high-precision and high-quality micro- and nanoscale structures in thermoplastic polymer substrates.[1] In the hot embossing process, the temperature of a polymer is increased until its glass-transition temperature (T_g) is just exceeded, thus softening the material. A pattern is then stamped into the polymer surface. The polymer is subsequently cooled, causing the embossed pattern to set within the material.

The first form of micro hot embossing was proposed by Ulrich and coworkers in the early 1970s.[2] In this approach, the researchers introduced microgrooves on poly(methyl methacrylate) (PMMA) substrates using glass fibers as a mold. The hot-embossing process was later advanced by S. Y. Chou and coworkers,[3] who introduced 'vias' and trenches with a minimum size of 25nm on thermoplastic polymer substrates. This research extended the use of hot embossing from the micro- to the nanoscale. A problem inherent in all such conventional micro hot embossing processes, however, is their long cycle time, which is mainly attributed to the high thermal inertia of the embossing mold. The process requires that the mold first be heated (to enable embossing) and then cooled (to set the material), resulting in a cycle time of more than 10 minutes.[4] Because of the higher costs and lower efficiencies thus incurred, hot embossing has not been considered attractive for mass production compared with common processing methods (e.g., microinjection molding). In conventional hot embossing, the amount of time spent heating and cooling the sample can comprise up to 90% of the overall cycle time:[5] see Figure 1(a). Many researchers are therefore seeking to develop rapid heating and cooling systems[6] to make hot embossing a viable alternative to traditional molding techniques.

We have proposed a new plate-to-plate isothermal hot embossing (P2P IHE) method to achieve free heating and cooling of the embossing mold (i.e., that is not limited by thermal inertia), and to thereby increase the efficiency of hot embossing. In our previous work,[7,8] we focused on

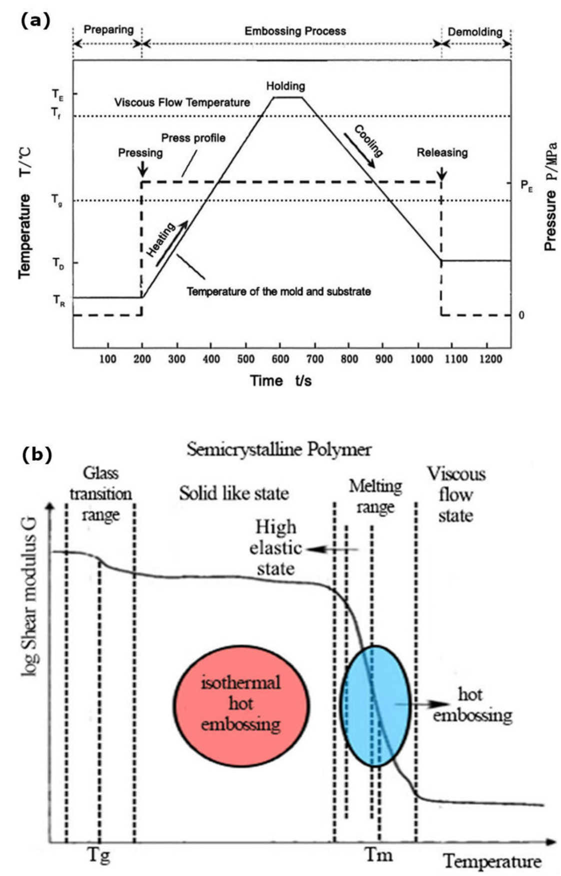

Figure 1. *(a) Schematic view of the conventional micro hot embossing process. T_R: Room temperature. T_E: Embossing temperature. T_D: Demolding temperature. P_E: Embossing pressure. T_g: Glass-transition temperature. (b) Molding windows of conventional micro hot embossing (blue) and our plate-to-plate isothermal hot embossing (P2P IHE) method (red) for semicrystalline polymers. T_m: Melting temperature.*

the forming process and the mechanism behind isothermal hot embossing for PMMA (a typical kind of amorphous polymer). Semicrystalline polymers show great potential for use in functional microstructure

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devices and systems, but few publications have paid attention to their microfabrication process. Therefore, in this work, we chose polypropylene (PP) as an example with which to explore the feasibility of the P2P IHE process for semicrystalline polymers. The processing windows for conventional micro hot embossing and our P2P IHE method for semicrystalline polymers are shown in Figure 1(b).

In our P2P IHE process, we use a thermocoupled mold temperature controller (monitored by a programmable logic controller system) to maintain the mold temperature at a set value for the whole embossing cycle. For semicrystalline polymers, we chose the region above the T_g and below the melting temperature (T_m) as the molding window. The polymeric substrate can be placed in the embossing mold under ambient temperature (i.e., without preheating). The substrate is then heated up rapidly—from ambient temperature to the molding temperature—during the embossing period, and pressure is applied to impress a pattern on its surface. After the molding process is finished, demolding can be carried out straight away. Furthermore, because no heating or cooling of the mold itself is required, another embossing cycle can begin immediately.

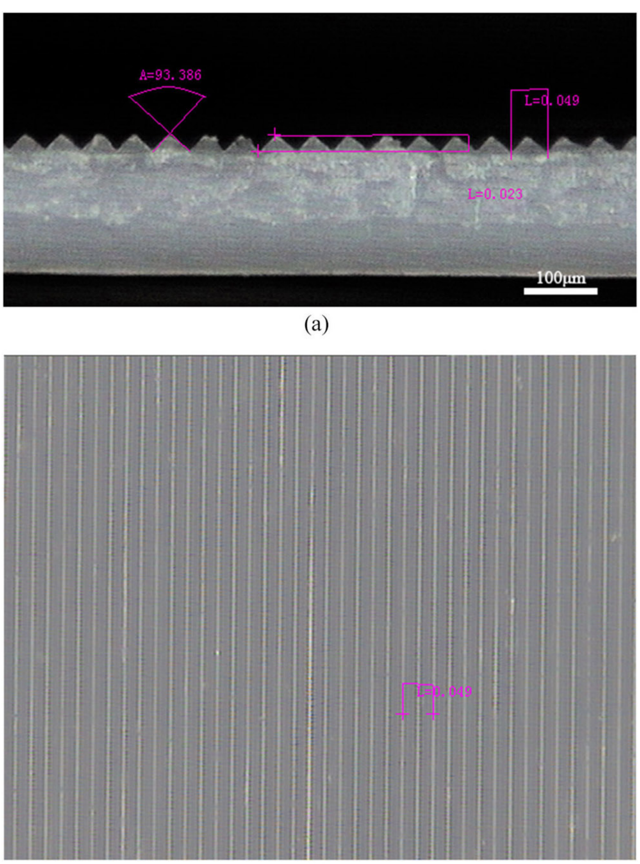

Figure 2. Scanning electron microscope images show the structure introduced to the polypropylene (PP) surface using P2P IHE. (a) Sectional view and (b) overhead view, showing the high replication precision. A: Angle. L: Length.

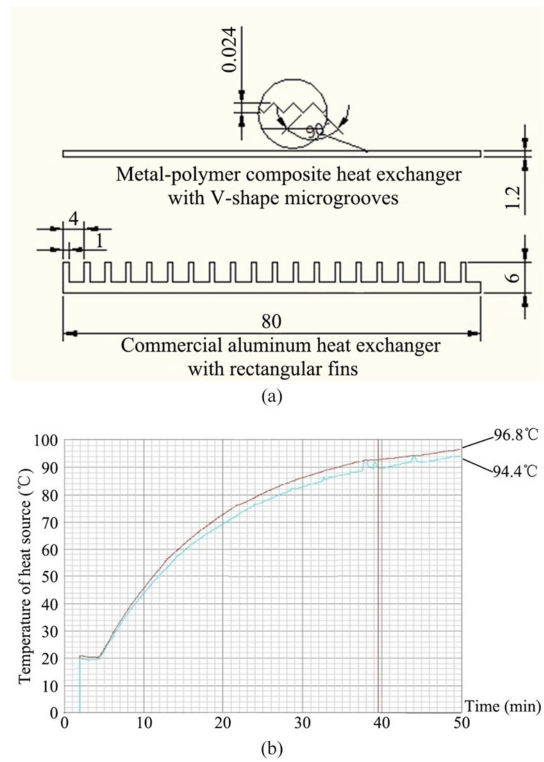

Figure 3. Comparison of the performance of a metal-polymer-composite heat exchanger (i.e., based on the PP substrate shown in Figure 2) and a traditional aluminum heat exchanger. (a) Schematic views of the devices. (b) Results of heat-source temperature tests for the aluminum (red) and metal-polymer (blue) heat exchangers.

To investigate the influence of mold temperature, pressure, and holding time on the replication precision of our P2P IHE method, we fabricated PP samples with V-cut microstructures under a range of different conditions. We then assessed the results by looking at scanning electron micrograph (SEM) images. We found that the best results were achieved with a combination of parameters: a mold temperature of between 110 and 115°C; a pressure of higher than 5MPa; and a holding time of more than 20 seconds. That is, the most precise features were achieved in samples processed for a relatively short embossing cycle time of 20 seconds and held at a constant, low mold temperature (i.e., 40–60°C below T_m) for the whole embossing cycle. Moreover, the excellent uniformity of the V-cut microstructures on the PP substrate

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showed that our method can be used to achieve high replication precision. Sectional and overhead SEM images of the PP sample fabricated under these conditions are shown in Figure 2.

Another important part of our research was evaluating the viability of our technique for the development of microstructured devices. We therefore fabricated and tested the performance of a micropart in a real-life application—a metal-polymer composite heat exchanger—and compared its performance to that of a traditional aluminum-based device. Our system comprised a metal thermal-conductive element and a polymer thermal-dissipation unit (fabricated by P2P IHE). A comparison of our device and a commercial aluminum heat exchanger is shown in Figure 3. Because the microstructured PP increases the specific surface area of a heat exchanger, we expected the micropart to enable the thermal dissipation performance to be enhanced within a limited space.[9]

To determine the efficacy of each device, we placed both heat exchangers on heat sources with the same heating power and then carried out thermal-dissipation-performance tests. By comparing the real-time data of the heat-source temperature for each device, we found that the heat-source temperature of the aluminum and metal-polymer-composite heat exchangers came into balance at 96.8 and 94.4°C, respectively. These results show that the thermal-dissipation performance was almost the same for both devices. Considering the space that each system occupied, our metal-polymer-composite exchanger—see Figure 3(a)—achieved a much stronger thermal dissipation performance per unit volume than the aluminum one.

In summary, we have proposed a new, simple plate-to-plate method for the hot embossing of semicrystalline polymers (P2P IHE) that succeeds in significantly reducing cycle time (down to 20 seconds). Furthermore, we fabricated a PP sample using our approach to test the part's performance in a metal-polymer composite heat exchanger. The heat exchanger achieved perfect thermal dissipation performance, suggesting that our hot embossing approach is well-suited to fabricating microparts for use in microdevices. In the next stage of our work, we will fabricate PP samples with different microstructures (e.g., rectangular) to further demonstrate the capabilities of P2P IHE. In addition, we will continue our investigations into the use of P2P IHE for the fabrication of functional microdevices.

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References

1. H. Becker and U. Heim, *Hot embossing as a method for the fabrication of polymer high aspect ratio structures*, **Sens. Actuators A: Phys. 83**, pp. 130–135, 2000.
2. R. Ulrich, H. P. Weber, E. A. Chandross, W. J. Tomlinson, and E. A. Franke, *Embossed optical waveguides*, **Appl. Phys. Lett. 20**, pp. 213–215, 1972.
3. S. Y. Chou, P. R. Krauss, and P. J. Renstrom, *Imprint of sub-25nm vias and trenches in polymers*, **Appl. Phys. Lett. 67**, pp. 3114–3116, 1995.
4. M. Worgull, **Hot Embossing: Theory and Technology of Microreplication**, 1st ed., William Andrew, 2009.
5. L. Peng, Y. Deng, P. Yi, and X. Lai, *Micro hot embossing of thermoplastic polymers: a review*, **J. Micromech. Microeng. 24**, p. 013001, 2014.
6. P. Xie, P. He, Y.-C. Yen, K. J. Kwak, D. Gallego-Perez, L. Chang, W.-C. Liao, A. Yi, and J. Lee, *Rapid hot embossing of polymer microstructures using carbide-bonded graphene coating on silicon stampers*, **Surf. Coat. Technol. 258**, pp. 174–180, 2014.
7. D. Wu, J. Sun, Y. Liu, Z. Yang, H. Xu, X. Zheng, and P. Gou, *Rapid fabrication of microstructure on PMMA substrate by the plate to plate transition-spanning isothermal hot embossing method nearby glass transition temperature*, **Polym. Eng. Sci. 57**, pp. 268–274, 2016.
8. J. Sun, D. Wu, Y. Liu, L. Dai, and C. Jiang, *Numerical simulation and experimental study of filling process of micro prism by isothermal hot embossing in solid-like state*, **Adv. Polym. Technol.**, 2017. doi:10.1002/adv.21815
9. J. Sun, J. Zhuang, H. Jiang, Y. Huang, X. Zheng, Y. Liu, and D. Wu, *Thermal dissipation performance of metal-polymer composite heat exchanger with V-shape microgrooves: a numerical and experimental study*, **Appl. Therm. Eng. 121**, pp. 492–500, 2017.