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Development of fluid-based heating and pressing systems for micro hot embossing

J.-H. Chang, S.-Y. Yang

Abstract This paper reports three innovative methods of rapid heating and uniform pressing for micro hot embossing. Fluids were used as heating and pressing media. With these three systems, the temperature of substrate rises rapidly and uniform pressure is exerted over the whole substrate. The working fluids used in this experiment included steam, gas, and oil. In addition, rapid heating through far infrared radiation (FIR) was also implemented with a gas pressurized hot embossing process. It was found that a 0.2 millimeter-thick PVC substrate can be heated from 25°C to 130°C in 30 seconds using steam heating, in only 25 seconds using FIR heating, and in 3.5 minutes using oil heating. The heating speeds of all three methods are much faster than those using conventional hot-plate heating, which takes more than 10 minutes. Successful replications of micro-features onto substrates have been achieved.

1 Introduction

Hot embossing is a method of production that involves replicating precise micro-features onto plastic substrates. It has become a popular process since LIGA and MEMS technologies have made the creation of master molds with microstructures relatively easy [1]. With a single master or stamp, identical structures can be reproduced onto substrates. This technique has been widely used for microstructure fabrication with applications in optical sensors and biochips. Before embossing, the substrate must be heated above its glass transition temperature (Tg). In the conventional hot embossing process, heating is usually accomplished with hot plates. The hot plates, which are heated by internal heating coils, heat up the substrate and stamper by means of conduction. After the embossing temperature is reached, the plates are pressed against the stamper–substrate stack. The pattern in the stamper is fully transferred onto the substrate after a certain amount of contact time. The system is then cooled down. Finally, the substrate is separated from the stamper after the temperature falls below the substrate's Tg. The entire cycle usually takes more than ten minutes. Hot embossing is rather time consuming for mass production and it is an energy-costly process as well.

In order to reduce the cycle time, recent research efforts have been focused on developing efficient and cost-effective heating–cooling systems for the hot embossing process. Ultrasonic vibrations have been employed to generate heat in hot embossing operations [2]. Ultrasonic heating can heat the surface layer to the embossing temperature in fewer than 10 seconds, but vibration-based heating is not suitable for micro-features with a concave-structures. Also, the size of the replication area is limited by the size of the ultrasonic horn. A radiation heating system was also implemented in a traditional hot embossing press [3]. It was found that radiation heating slightly reduced birefringence. The cycle time was also drastically reduced. Grewell [4] et al. studied the feasibility of three fast surface heating hot embossing methods: ultrasonic, infrared radiation (IR) heating and hot gas heating. The results showed the cycle times using ultrasonic and IR can be reduced to within 10 seconds.

However, the above-mentioned research efforts focused on hot embossing using a press. When performing hot embossing with a press, both the area and the accuracy of replication are limited due to the inherent non-uniform pressure distribution. Moreover, brittle materials can not be used as a mold; silicon wafers are easily broken if embossing is carried out using hot plates. Recently, Chang and Yang [5] have proposed an innovative method for hot embossing: gas was used as the pressure media. This paper extends the authors' research on gas to fluids. Working fluids are used to press the substrate and mold. The working fluid is also used to heat the substrate and mold. With this system, the temperature of the stamper–substrate stack can be raised rapidly while the pressure exerted on the entire area remains uniform. The working fluids used in this study include steam, oil and gas. In addition to using working fluids to heat the substrate and stamper, a far infrared radiation (FIR) heating system was also implemented and tested.

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2
Experimental procedure and setup

2.1
The fluid-based heating and pressing process

As illustrated in Figure 1, the fluid-based heating and pressing process consists of five steps: (a) placing the plastic substrate onto the mold to form a substrate–mold stack, which is then placed above the plate; (b) covering the substrate–mold stack with a seal film and enclosing the stack in the chamber; (c) introducing the working fluid into the chamber to heat and press the stack; (d) cooling the stack; (e) exhausting the fluid and finally opening the chamber to retrieve the embossed substrate. The seal film can be a plastic film or aluminum foil.

Note that the system is capable of double-sided embossing as long as the upper mold–substrate–lower mold stack is arranged as shown in Fig. 1, a configuration described in a previous paper by the authors [5]. This system can also be used for nanoimprinting. The resist can be first spin coated onto the wafer, and then the mold–resist–wafer stack arranged.

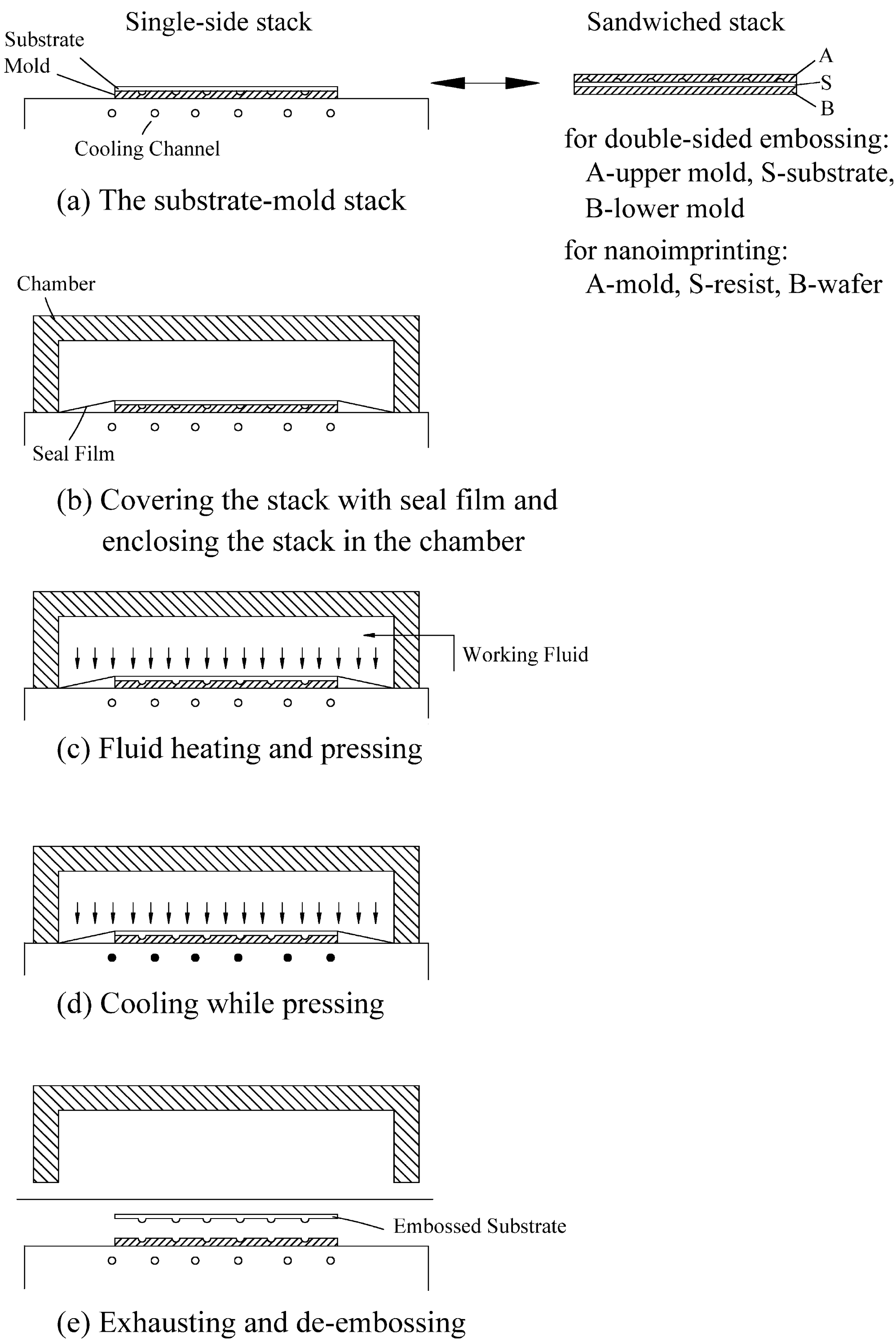


Fig. 1a–e. Schematics showing the steps of the fluid-based heating and pressing hot embossing process. (The thicknesses of the mold and substrate are not drawn to scale)

2.2
Mold, substrate and temperature measurements

The micro-features of a Fresnel lens on a 120 × 120 mm electroplated nickel stamper was to be transcribed onto thermoplastic substrates using the fluid heating embossing process. Figure 2 shows the photo and the dimensions of the electroplated nickel stamper. The substrate used was thermoplastic polyvinyl chloride (PVC) film (Nan Ya Plastics, Taiwan). The film was 0.2 mm thick.

The micro-features of the Fresnel lens on stamper and embossed substrates were measured using a surface profiler (Alpha-Step 500, Tencor, U.S.A.). Images were also taken using a scanning electronic microscope (Jeol Model 5410, Japan).

Temperatures at five points, as shown in Figure 2, were measured to investigate the thermal responses and temperature distribution of the substrate during the fluid-based heating process with all three systems tested. Five J-type thermocouples were taped onto the surface of the substrate. A computer-aided data acquisition system (Daq System, IOtech, U.S.A.) was used to record the temperatures.

3
The micro-embossing experiments with three fluid-based hot embossing systems

3.1
The steam-heating gas-pressing system

A steam-heating hot embossing system is shown in Figure 3 (a). The substrate–mold stack, covered by a seal

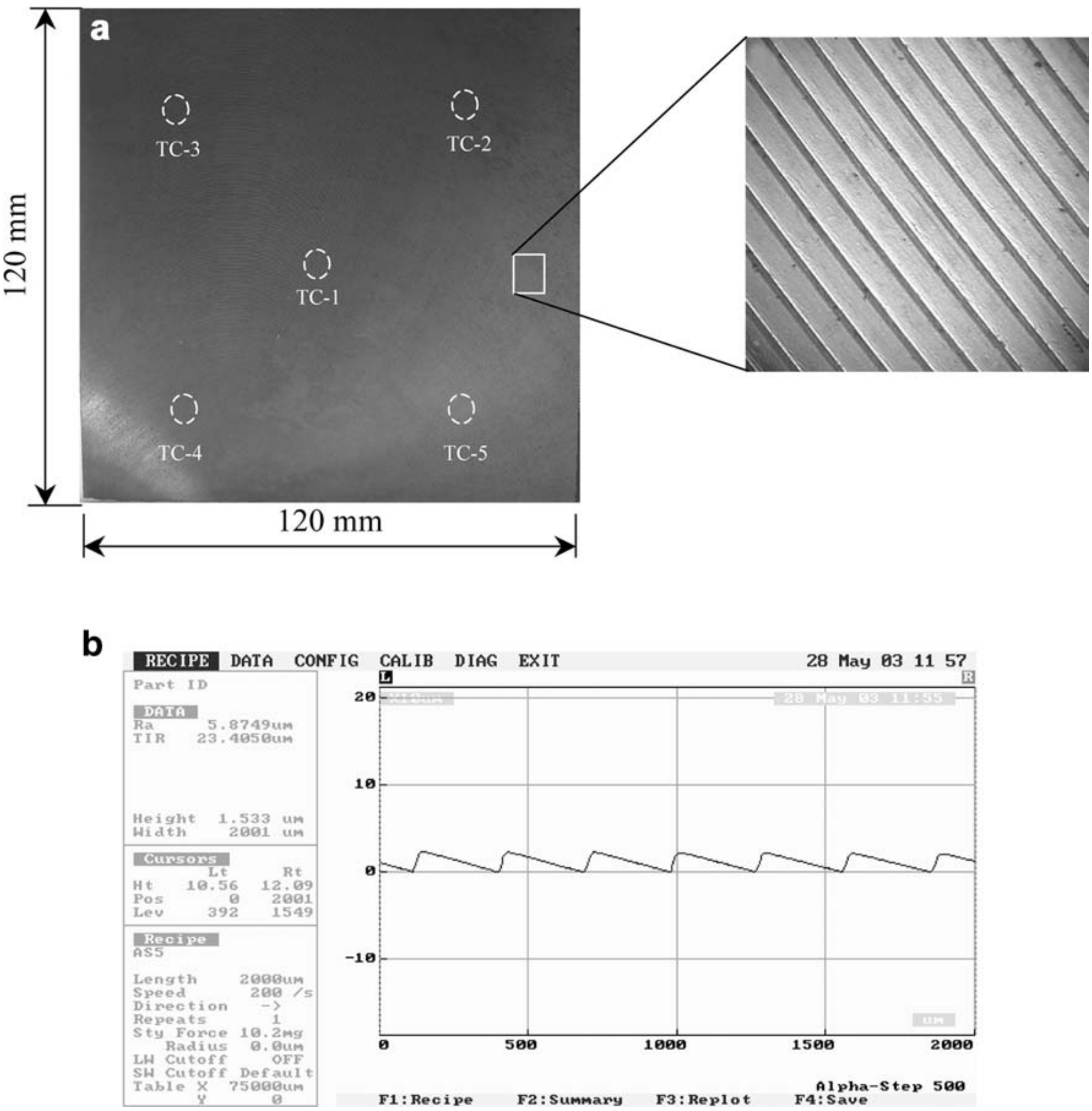


Fig. 2. **a** Photo and dimensions of the electroplated nickel stamper. The locations of the temperature measurements are indicated with dashed-line circles; **b** The measured surface profile of the micro-features on the mold of the Fresnel lens

film, was placed inside the chamber. The seal film was a double-layer PC film (Lexan-8010, GE, U.S.A.). The film was 0.178 mm thick. Heated steam with a pressure of 500 kPa was blown into the chamber to heat the substrate–mold stack directly. Steam was generated from an electric steam boiler with a maximum pressure of 700 kPa and an equivalent evaporation of 15 kg/h. After steam heating, nitrogen gas—highly pressurized at 3000 kPa—was blown into the chamber to press the substrate–mold stack. After the gas-pressurized embossing, cooling water was circulated inside the bottom plate to cool the substrate and mold.

A typical thermal response of the steam-heated substrate is shown in Figure 3 (b). As can be seen, the substrate was heated from 25°C to 130°C in 30 s. The heating is fast and the process is clean. After steam heating, gas-pressurized embossing was then carried out at an embossing temperature of 130°C and a gas pressure of 3000 kPa. It was found that with such a steam-heating gas-pressurizing water-cooling process, microstructures can be replicated from mold to substrate successfully with a cycle time of about 2 minutes.

It should be noted that the temperature of the steam cannot be controlled directly. The steam temperature is a function of the pressure; the steam temperature can only be adjusted by adjusting the steam pressure. It is not straight-forward to control. Nevertheless, the hot embossing system for amorphous-type thermoplastics has a large operation window [6]. Embossing can be easily made over a wide range of temperatures.

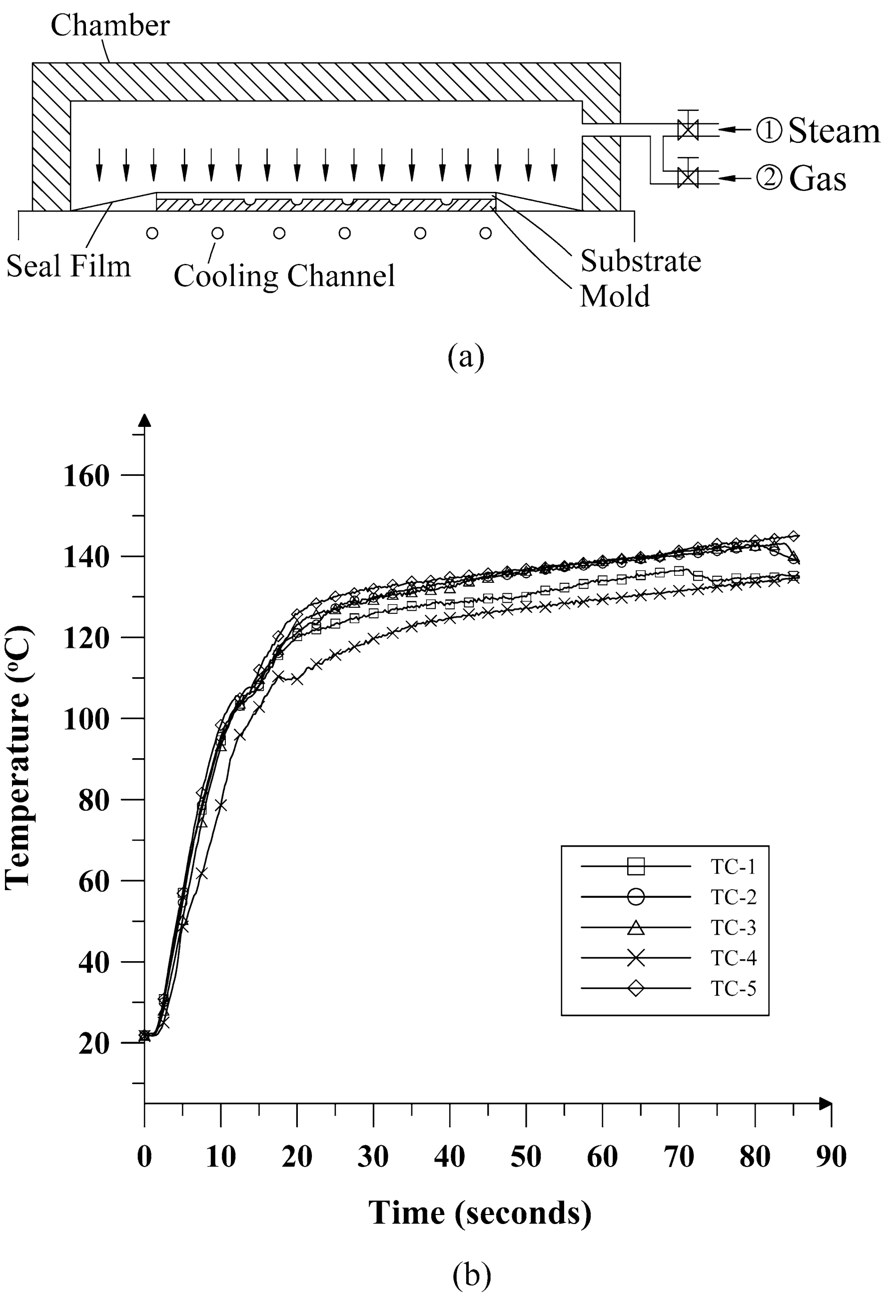


Fig. 3. **a** Schematic showing the steam-heating gas-pressing system. The steam is introduced into the chamber to heat the substrate and mold. Then, high pressure gas is blown in to press the stack; **b** The measured temperature responses at five different locations of the substrate using the steam-heating hot embossing system

3.2
The oil-heating and pressing system and process

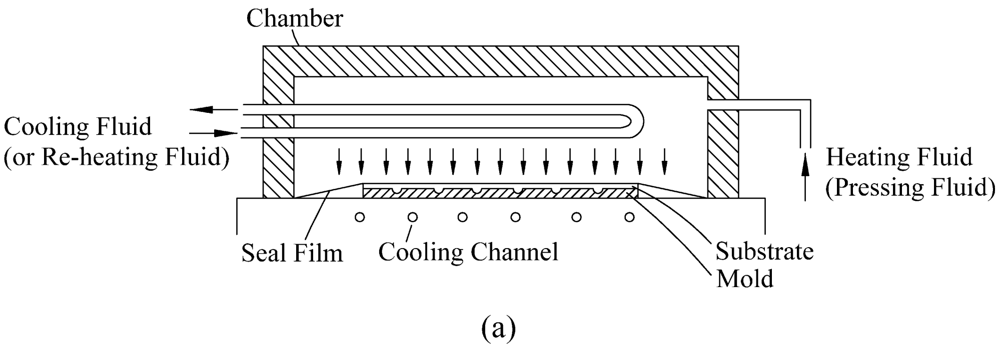
An oil-heating hot embossing system is shown in Figure 4 (a). Note that cooling channels were placed both inside the bottom plates and in the chamber. Both types of cooling channels can be used for heating as well. Silicone oil (Calflo AF, Canada) at a temperature of 150°C was pumped into the sealed chamber. The heat was transferred from the heated oil to the substrate–mold stack. At the same time, the oil pressurized the stack, forcing the micro-features to be transcribed from the mold to the substrate. The oil pressure can be regulated throughout the process with a manual pump. During the cooling stage, water was circulated through tubes in the bottom plate. Additional cooling water was circulated in the chamber space. The embossing temperature can be independently adjusted even as the embossing pressure is applied. In this oil-based system, two major embossing parameters, i.e., the temperature and pressure, can be controlled independently.

The embossing experiments were carried out with an inlet oil temperature of 150°C. Figure 4(b) shows the temperature responses at five different locations. The substrate temperature rose from 25°C to 130°C in 3.5 minutes. It was found that heating with oil took a little more time than heating with steam, but the smaller standard deviation in the temperature indicates there is a more uniform heat distribution over the embossed area in this process.

It was verified that the micro-features in the mold can be successfully replicated onto the substrates using the oil-heating and pressing system. Compared with conventional hot-plate heating, the oil-heating hot embossing system has a much shorter cycle time.

3.3
The FIR-heating gas-pressing system

A FIR-heating hot embossing system is shown in Figure 5 (a). A far infrared radiant heater (T-FSF, Elstein,



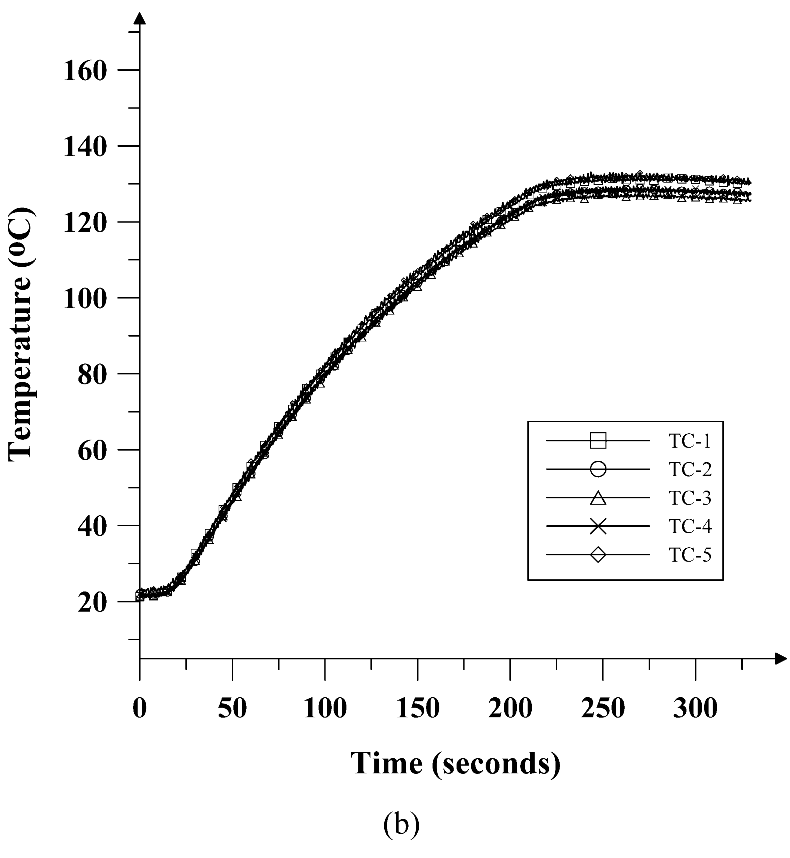
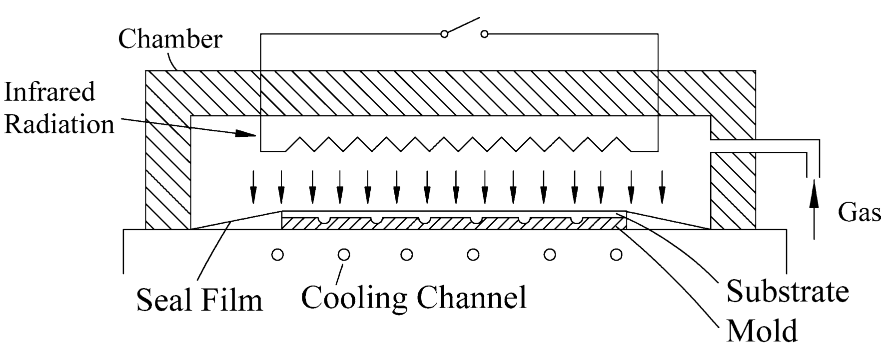


Fig. 4. **a** Schematic showing the oil-heating and pressing system; **b** The measured temperature responses at five different locations of the substrate using the oil-heating hot embossing system

Germany) mounted in the chamber is used to heat the substrate and mold. Its maximum power was 1000 W. After 25 s of heating, gas—highly pressurized at 3000 kPa—was blown into the chamber to press the heated stack. With this process, the substrates can be heated rapidly by means of radiation; there is no contact between the heating element and the stamper–substrate stack. To prevent heat dissipation during heating, a thin insulation layer was placed between the mold and the cooling plate. During the cooling stage, water was forced to circulate through the cooling channels in the cooling plate.

Note that the seal film used here was a double-layer PET film (Teijin, 188S, Japan). The film is 0.188 mm thick. The PET does not absorb the infrared radiation and is therefore well suited for the system. If the sandwiched stack is used, the surface of the stamper facing the radiation source should be painted black to improve the absorption of the radiation.

The heating and cooling responses of the FIR-heating hot embossing process are shown in Figure 5(b). The heating time using the FIR heating process is extremely short: the temperature rose from room temperature to 130 °C in 25 s. The temperature can cool to 65 °C in 90 seconds. The overall process took only about 2 minutes per run. The temperature deviation is a little larger than it is with the oil-heating hot embossing process. Also, the control of the temperature is not as straightforward as it is with oil heating. It is found that the micro-features can be successfully transcripted from the



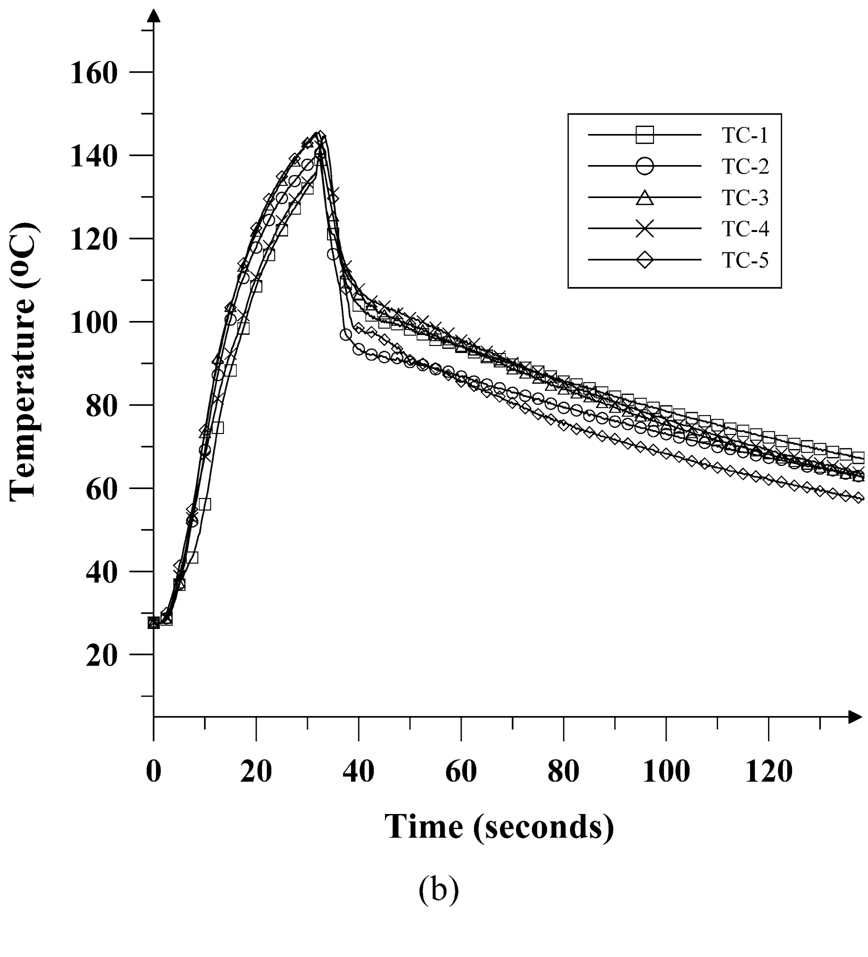


Fig. 5. **a** Schematic showing the FIR-heating hot embossing system; **b** The measured temperature responses at five different locations of the substrate using the FIR-heating hot embossing system. The total cycle time is about 2 min

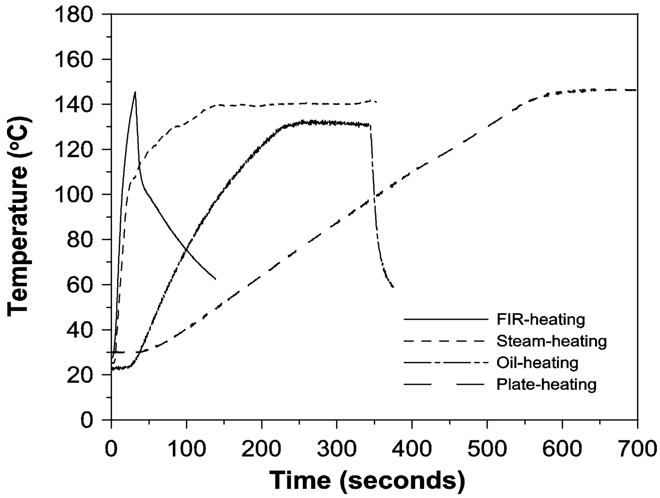


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Fig. 6. Comparison of the heating times of the FIR, steam, oil and conventional hot-plate heating processes

mold onto PVC substrates using the FIR-heating gas-pressing system.

4 Results and discussions

4.1 Temperature response and distribution using three systems

The heating speeds of all three methods described here are much faster than those methods using conventional hot-plate heating. Figure 6 shows a comparison of the response times of steam heating, oil heating, FIR heating and traditional plate heating. Among them, the FIR-heat-

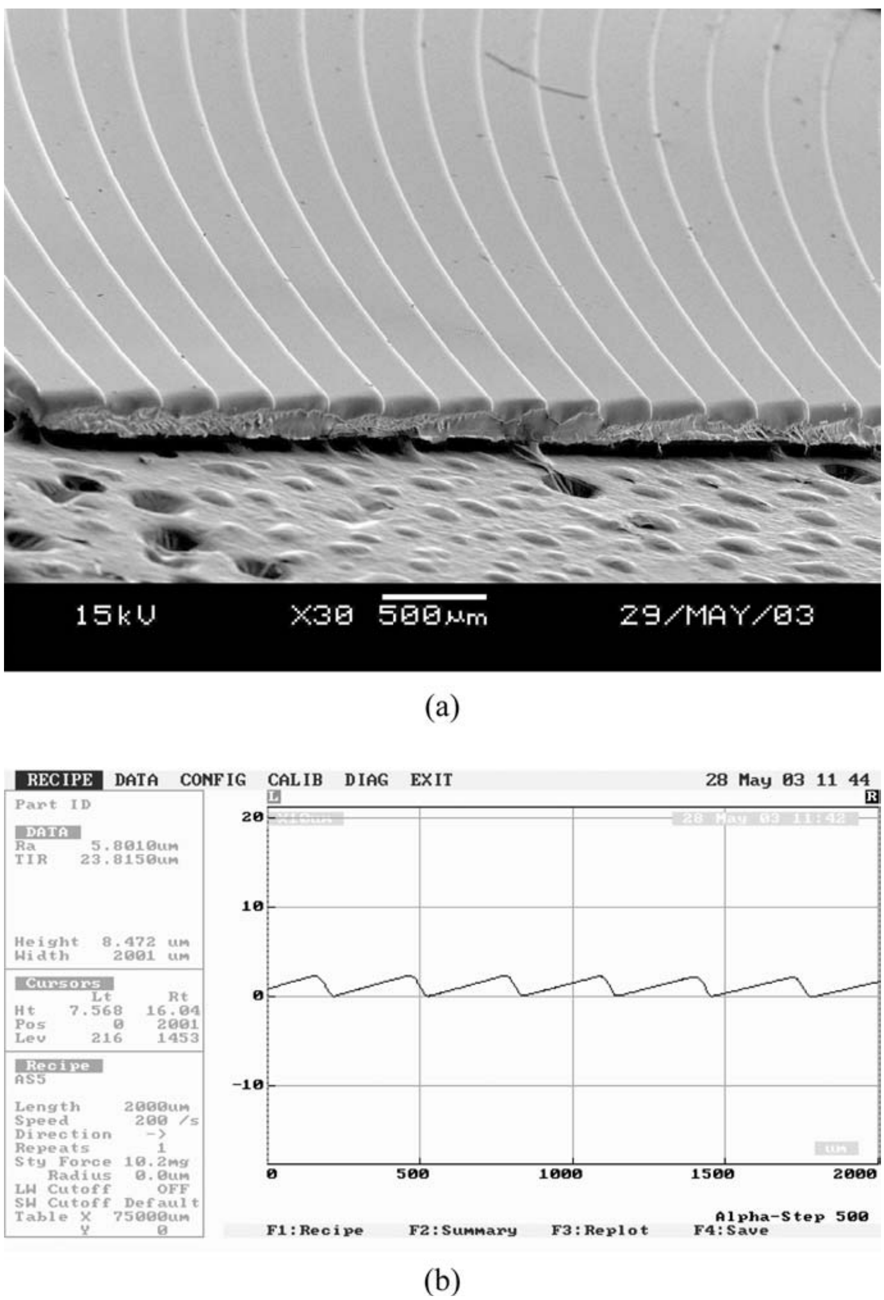

Fig. 7. A typical SEM micrograph **a** and surface profile **b** showing the hot embossed PVC substrate fabricated using the fluid-based hot embossing system

ing system had the shortest cycle time. The steam-heating system had the next-shortest cycle time. The oil-heating system had the longest cycle time, but the temperature distribution is the most uniform and the temperature can be directly controlled. All three hot embossing processes using fluid-based heating and pressing systems had cycle times that were far shorter than those using the conventional plate heating and pressing systems.

4.2
Replication results using three systems

Successful replications of micro-features onto substrates have been achieved using all three systems. A typical SEM microphoto and the surface profile of the replicated micro Fresnel lens using the fluid-based hot embossing processes is shown in Figure 7. It can be seen that the microstructures were precisely replicated onto the PVC substrate.

5
Summary

This paper has extended the authors' previous work on gas-pressurized hot embossing to include fluid-based hot embossing. Three innovative fluid-based heating and pressurizing methods were implemented and tested. The working fluids used in the experiments included steam, gas, and oil. Among the heating systems, the FIR-heating system had the shortest cycle time. The steam-heating system had the next-shortest cycle time. Though the oil-heating system had the longest cycle time, the temperature distribution was the most uniform and the temperature can be directly controlled. All three systems had cycle times that were far shorter than that of the conventional plate heating and pressurized hot embossing process. Successful replications of micro-features onto substrates have been achieved with each of the systems tested.

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