

Epoxy resins as stamps for hot embossing of microstructures and microfluidic channels

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Abstract

Fabrication of micro total analysis systems using plastic substrates has become more prevalent in the recent literature with the driving force being the development of inexpensive disposable analytical devices. Hot embossing is one polymer micro-fabrication method that has shown significant promise in this area because identical polymeric devices can be produced using a master to repeatedly stamp an image into a number of plastic substrates/materials. One major disadvantage of hot embossing in a research setting is the time and expense needed to produce a stamping tool able to withstand the temperature and stress of the embossing process. This paper describes a method of producing an epoxy stamp that is relatively inexpensive, rapid to produce and durable enough to withstand multiple embossing cycles ($n > 50$). The epoxy-stamping tool can be micro-molded from either a positive or a negative imaged master and is compatible with a number of materials including SU-8 resist on silicon, PDMS or glass. The low viscosity of the pre-cured epoxy permits the reproduction of microstructures with dimensions below $1\ \mu\text{m}$ in size and allows for the transfer of these small structures to PMMA by hot embossing without loss in detail. The stamp fabrication process can be performed in less than 4 h. When the process is combined with rapid device prototyping capabilities of SU-8/silicon micro-fabrication the entire process of microchip fabrication process (design to device) may be completed in 24–48 h.

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1. Introduction

Miniaturized electrophoretic analytical devices that employ micro-machined channels for separation were introduced in the early 1990s [1–3] and since then have expanded into the rapidly growing field of miniaturized total analysis systems (μTAS) [4,5]. Due to their small dimensions microfluidic devices use smaller amounts of sample and provide shorter analysis times compared with conventional analytical systems and have generated great interest for both analytical and bioanalytical applications. First generation microfluidic devices were constructed of glass mainly due to fabrication protocols borrowed from the microelectronics industry and

the utility of electrokinetic pumping [6,7]. Glass devices however are relatively expensive because of the photolithography and wet chemical etching protocols required to produce each micro-device. In addition, the manufacturing process does not lend itself to rapid modification of the device design. Polymeric materials are seen as a promising alternative to conventional glass [8] because of both the diversity of the materials available, which provides a wide range of surface/material properties, and the various methods available for device fabrication, including casting [8], embossing [9–11], injection molding [12], thermoforming [13] and laser ablation [11,14].

Micro-fabrication in polymeric materials using hot embossing has garnered much interest due to its ability to imprint structures in polymeric materials using a preformed master or tool. The material is heated to its glass transition temperature (T_g) followed by imprinting with a micro-machined stamp

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utilizing several kiloNewtons of embossing force. The key to this process is the development of a robust stamp that is both able to withstand multiple temperature cycles, as well as the significant *embossing forces*. Several fabrication techniques have been employed for stamp fabrication including electroplating of nickel or nickel alloys [15], deep reactive ion etching (DRIE) in silicon, KOH wet etching in silicon [16] and soft lithography [17–19]. Electroplating with nickel produces a very durable but expensive master (>US\$ 3000) due to required complex manufacturing processes, and as a direct result, does not allow for rapid device design modifications. Soft photolithography processes (e.g. SU-8) as well as photolithography combined with KOH etching processes and silicon wafers, allow for more rapid production and modification of the embossing master. However, these masters have a limited life (<5 cycles in some cases) in the embosser [16], due to cracking and warping from the high stress and temperature cycles involved in the embossing process.

A methodology that would enable the facile creation of a robust master that is easily customizable would be of significant benefit to those developing polymeric microfluidic systems. In this paper we discuss an alternative method for producing a master tool using a high temperature compatible epoxy that, when micro-molded from a PDMS template, can be used for embossing polymeric materials such as polymethylmethacrylate (PMMA) to produce microstructures and microfluidic devices of varying types. The method can be utilized with either positive or negative imaged masters and should be amenable to other materials that possess a glass transition temperature below the temperature limit of the epoxy stamp (180 °C).

2. Experimental

2.1. Chemical reagents

Sylgard 184 silicone elastomer and curing agent were obtained as a kit from Dow Corning Corporation (Midland, MI, USA) and used without modification. Conapoxy® FR-1080 high temperature epoxy was purchased as a kit including resin, glycidyl phenol/formaldehyde polymer, and hardener (nadic methyl anhydride, 2,4,6 tris(dimethylaminomethyl)phenol, Bis[(dimethylamino)methyl]phenol, from Cytec Industries Inc. (Olean, NY, USA). PMMA sheets (150 mm × 150 mm × 3 mm) were acquired from Warehoused Plastic Sales Inc. (Toronto, Ont., Canada) and cut to the desired dimensions before embossing. Cy-5® monofunctional reactive dye was purchased from Amersham Pharmacia Biotech UK (Buckinghamshire, UK). Phosphate buffer (5 mM, pH 8.0) used for electrophoresis experiments was prepared using potassium phosphate (Sigma–Aldrich) and adjusted to the proper pH with 0.1 M NaOH (Solid NaOH, Sigma–Aldrich).

2.2. Fabrication of the epoxy stamp (from a positive image master)

A positive image master can be fabricated utilizing soft lithographic processes described by others [16]. In this work a commercially available AFM grating standard (Test Grating TGT1, NT-MDT, Nano Technology Instruments, The Netherlands) as well as an SU-8 patterned silicon master was obtained with a variety of micro-fabricated structures to test the efficacy of the stamp fabrication and embossing process. Epoxy stamp fabrication was accomplished utilizing a two-step micro-molding protocol. In the first step, PDMS (30 g total weight) was mixed in a 10:1 mass ratio of silicone elastomer to curing agent and poured over the silicon or SU-8 master. After curing for 4 h at 65 °C the PDMS was peeled off the master resulting in a negative image, which was then used as a mold for the high temperature epoxy. The final step involved pouring the Conapoxy® FR-1080 high temperature epoxy resin/hardener mixture into the PDMS mold followed by curing the epoxy at 180 °C for 2 h. After cooling, the epoxy was removed from the PDMS mold and used as a stamp for the embossing process.

2.3. Fabrication of the epoxy stamp (from a negative image master)

This was accomplished in a manner similar to molding from a positive master image with the addition of another molding step. A glass substrate (100 mm × 100 mm) containing an array of six separate etched electrophoretic devices was acquired from Micralyne (Edmonton, Alta., Canada) and used as a negative image master for the three-step micro-molding stamp fabrication procedure. In the first step a PDMS positive replica was produced in a manner similar to that in the previous section. After the PDMS had cured the edges of the PDMS were marked with a mold release material (Berkley, Akron, PA, USA), which allowed for the facile identification of the master/substrate interface and a second amount of PDMS (45 g) was poured over the positive PDMS image. After sufficient curing time (1 h at 65 °C) the final PDMS mold was obtained by carefully cutting and peeling away the positive image of the mold resulting in the fabrication of a PDMS clone of the original glass mold. This PDMS mold was then used to manufacture the epoxy stamp in the final fabrication step. This was accomplished by pouring the Conapoxy® FR-1080 high temperature epoxy resin/hardener mixture into the PDMS mold and curing the epoxy following the manufacturer recommended protocol.

2.4. Microchip fabrication

PMMA sheets were embossed with the Conapoxy® FR-1080 epoxy master using a HEX 01 hot embossing system (Jenoptik Microtechnik, Jena, Germany). In a typical experiment the epoxy master and the pre-cut PMMA substrate were mounted on heating plates in the embosser and a predefined

macro that controls the temperature, pressure, and time of the embossing protocol was initiated. The substrate and the tool was heated to 45 °C, the chamber was closed and a touch force of 250 N was applied for 30 s, the chamber was evacuated and the temperature was brought to 115 °C (T_g for PMMA is 106 °C) [20] and a force of 2500 N was applied for 5 min. Following, the temperature of the tool and substrate are lowered to 45 °C and the chamber is brought to atmospheric pressure. The embossing force was then removed and the PMMA chip is de-molded from the epoxy stamp by hand. The embossed PMMA chip was cut to size and then cleaned in an ultrasonic bath of ethanol for 5 min to prepare it for attachment to the cover plate. The cover plate was prepared from pre-cut PMMA sheets with holes drilled in predefined locations to act as sample reservoirs in the final device.

2.5. Measurement of cover plate adhesion force

The strength of the bond between the modified cover plate and the embossed microchip was determined using an Instron 3369 tensile tester (Instron, Toronto, Ont., Canada). In a typical experiment two pieces of PMMA were subjected to the same bonding protocol used in the manufacture of the microchips producing a known cross sectional area of bonding. These samples were then clamped into the tensile tester and brought to the point of adhesion failure resulting in a peak load failure. The results were divided by the cross sectional area to obtain the strength of adhesion. These experiments were repeated for at least five samples per area and at least two different cross sectional areas were performed.

2.6. Microchip electrophoresis

The separation efficiency of the fabricated microchip was determined by multiple injections of a fluorescent dye (Cy-5) using a microfluidic Tool Kit (Micralyne, Edmonton, Alta., Canada). The kit consists of a high-voltage (HV) power supply coupled with a laser-induced fluorescence (LIF) detection system (635 nm diode laser with 670 nm band pass filter for detection of Cy-5 fluorescence). The fabricated microchip has a double “T” design with an injection volume of approximately 150 pl (Fig. 1). The channels and reservoirs of the micro-device were filled with operating buffer (5 mM phosphate, pH 8.0) and the device was fitted into the instrument.

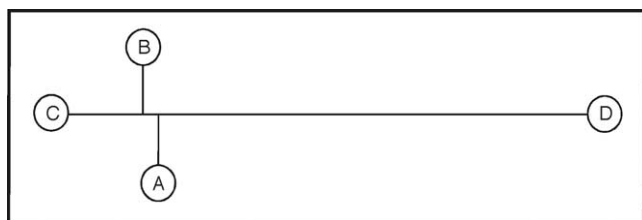


Fig. 1. Schematic representation of the microfluidic chip used in determining the separation performance of the embossed device. The dimensions between sample reservoir (A) and (B) are not to scale and have been enlarged for clarity.

The buffer solution in reservoir (A) was then replaced with a solution of Cy-5 dye (30 μ M) and the electrodes were lowered into the buffer reservoirs. Sample injection was accomplished by applying voltages to reservoirs A (+2.0 kV), B (ground), C (float) and D (float). The separation step consisted of applying a voltage of +2.5 kV to reservoir C while grounding reservoir D. A pushback voltage +2.08 kV was applied to reservoirs A and B to limit sample leakage. The duration of the injection program and the separation program were both 50 s each.

3. Results and discussion

3.1. Fabrication of epoxy stamp from a silicon or SU-8 positive image master

Hot embossing has been shown to be an effective procedure for rapidly producing multiple copies of microfluidic devices in polymeric materials [9–11]. The method is simple, and essentially involves stamping out micro-devices near the glass transition temperature of the polymer using a stamp or master. This is an attractive fabrication method because multiple micro-devices can be fabricated from one master device resulting in a low cost fabrication alternative to those required for glass. In addition, different surface/material properties can be obtained by simply embossing a different material or polymer type. Although hot embossing is very effective for repeated micro-fabrication it has limited capability for rapid modifications in the micro-fabrication process due to the time and expense needed to produce the master. Nickel masters [15] are durable, but time consuming and costly to produce, while masters made from silicon or SU-8 can be produced more rapidly, and are less expensive, but have a limited life in the embosser due to their fragile nature [16]. SU-8/silicon processing has been utilized to rapidly prototype of microfluidic devices [8]. SU-8 negative photo resist is patterned on silicon and developed to yield a micro (positive image) mold that can be used to cast PDMS devices. In this manner devices can be designed and ultimately fabricated in only 24 h. However the process can only be used with materials that are readily cast and do not significantly adhere to either the silicon or SU-8 material. Utilization of an epoxy stamp molded from an SU-8 master provides an inexpensive method for rapid modification and production of a cost effective durable stamping tool. The SU-8/silicon master is never used within the embosser and may be used to continuously manufacture epoxy stamps. To produce the epoxy tool, we first created a mold of the SU-8 negative image using PDMS (Fig. 2). This mold was created because of the low adhesion of PDMS to the SU-8 and epoxy surfaces. This would not have been the case if epoxy were used directly with an SU-8 master due to the adhesion of the epoxy to the surface. The epoxy used in this study was Conapox[®] FR-1080, a high temperature epoxy resin/hardener composite. This epoxy, developed commercially for high temperature electronic applications, was used for its significant hardness/shore even at elevated

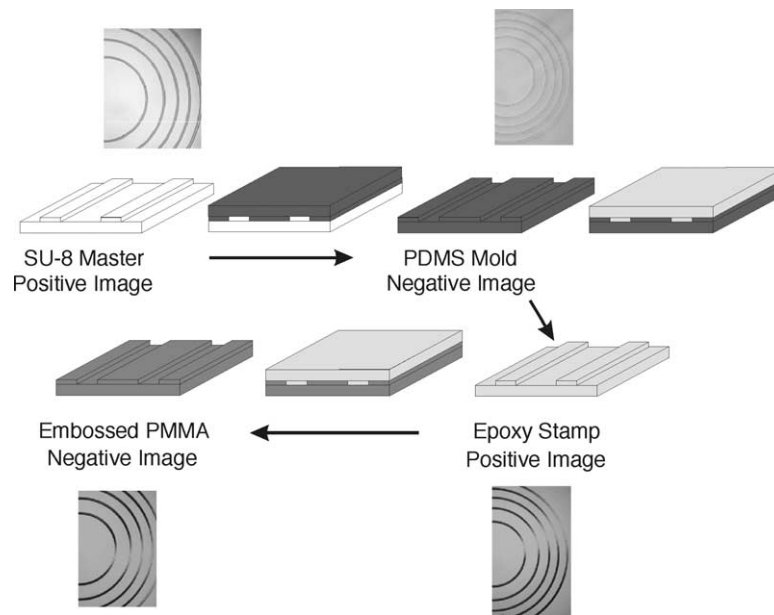


Fig. 2. Schematic representing the process to create an epoxy clone of an SU-8 master positive image, which can then be used as a stamping tool to emboss PMMA. The insert images are photomicrographs of the microstructures at different stages of the fabrication process. The diameter of the smallest circle is $950\ \mu\text{m}$ and the ring is $25\ \mu\text{m}$ wide.

temperatures (180°C), that would allow for embossing of a number of commonly utilized substrates with glass transition temperatures below 180°C . In addition, the epoxy has a low initial mixed viscosity (2500 cps) and low shrinkage (1.42%) that is required to replicate fine details during the molding and stamp fabrication steps. The epoxy stamp is prepared by simply pouring the epoxy into the PDMS replica mold and then following the manufactures recommended protocol to cure the epoxy. After cooling and removing the epoxy stamp from the PDMS mold it could be tooled and mounted in the embosser and used to emboss microstructures in PMMA by a standard protocol (Fig. 3). Photomicrographs of annular ring test structures (smallest ring $950\ \mu\text{m}$ diameter with $25\ \mu\text{m}$ thickness) are shown at each of the molding and embossing

stages (Fig. 2). Visual and microscopic inspection of the test structures show that the process yields excellent replication of the original SU-8 master. Other structures of similar size and dimension such as closely spaced lines were also replicated with the same high exactitude yielding a functional epoxy-stamping tool. It should also be noted that de-molding of the epoxy stamp from the PMMA is accomplished without the need of surface releasing agents.

To examine the ability of the stamp fabrication and embossing process to replicate even smaller features an atomic force microscope calibration grating was molded and embossed. Given in Fig. 4 are the scanning electron microscope (SEM) photomicrographs for an epoxy stamp, created from a silicon master (Test Grating TGT1), and the embossed PMMA negative image. The spikes on the original master are $3\ \mu\text{m}$ apart and $300\text{--}500\ \text{nm}$ high and show that the low mixed viscosity of the epoxy is able to clone even small details with high exactitude. These SEM photomicrographs (Fig. 4), taken following 10 embossing cycles, show that the stamp is quite durable and suitable for the fabrication of embossed microstructures with low copy number. No visible warping or deterioration in the stamps were noticed for <50 replications. To determine the point at which the epoxy stamp fails we subjected a tool to the maximum pressure and (20 kN) and temperature (200°C , above the 180°C limit recommended by the manufacturer) allowed by our instrument. Under these conditions some visible warping of the epoxy was observed after five replications resulting in distorted embossed features. However, if severe embossing conditions are warranted and the epoxy-stamping tool becomes damaged, a replacement can be fabricated from the original master with little time and expense. In addition, this method allows the possi-

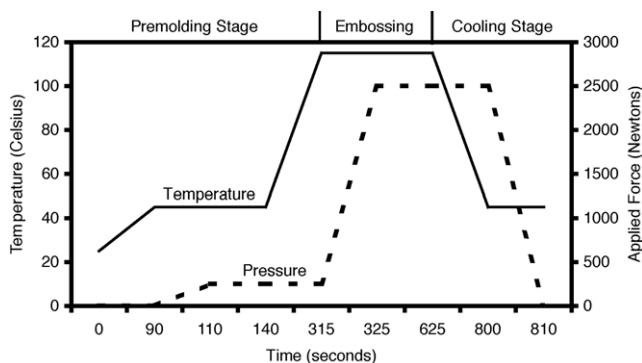


Fig. 3. Graphical representation of the force and temperature program used to emboss structures in PMMA with an epoxy stamp. The solid line represents the temperature as a function of time while the dotted line is the applied force. The time scale is not linear and reflects times where an instrumental parameter was changed.

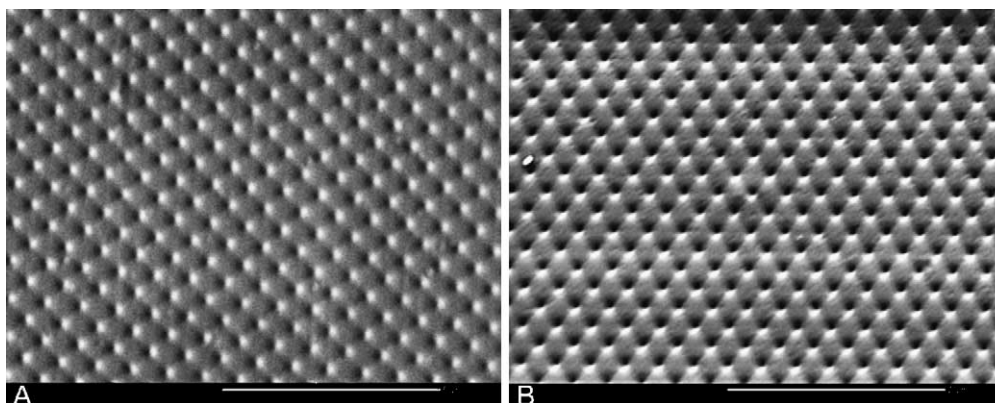


Fig. 4. SEM photomicrographs (2500 \times) of spikes in the epoxy positive image fabricated from the TGT1 atomic force microscope calibration grating (A) and the results of embossing in PMMA creating the corresponding negative image (B). The spikes on the original master are 3.0 μm apart with a height of 300–500 nm. The image shown in (A) was taken after the epoxy stamp had been used for 10 complete embossing cycles.

bility of rapid device production from design to SU-8 master through to epoxy stamp in 1 or 2 days.

3.2. Fabrication of epoxy stamp from a glass negative image master

To determine the effectiveness of this method in producing a working microfluidic device we fabricated an electrophoresis device with a double T-shaped injector. The fabrication process is similar to that of the SU-8 positive image master replication with one additional micro-molding step. In this case the original master was a glass negative image of an array of six individual micro-devices (Fig. 5). From this master we made a PDMS positive image, followed by a PDMS negative image, and finally an epoxy stamp that was used to produce the micro-device in PMMA. The SEM photomicrographs of a channel intersection in the double T region of the micro-device (Fig. 6) demonstrate that the technique can replicate fine structure very well. In fact, the SEM clearly shows that artifacts from the original glass etching process are still visible even after multiple molding and embossing steps.

In addition, these pictures were taken from a piece of PMMA that had been embossed with an epoxy stamp that

had been used more than 25 times. A major advantage of this process over others is the ability to fabricate devices from either a positive or negative image. This flexibility would allow fabrication of devices from either a negative or a positive image which ever is more inexpensive or facile to manufacture.

3.3. Microchip fabrication

The microchip is completed by sealing the channels with a PMMA cover plate that had been predrilled with holes to act as reservoirs for buffer and sample. Bonding is an extremely important part of polymeric microfluidic chip fabrication. The most common method of bonding two pieces of polymer together is by thermal annealing [21,22]. This has been shown to be a useful method for bonding PMMA micro-devices with deep channels, but we have found that the results were somewhat unpredictable for 20 μm deep channels where the channel structures would often fill in and disappear. Another method of bonding two pieces of PMMA is oxidation of the surface with oxygen plasma before bonding of the PMMA sheets [23]. This technique likely oxidizes groups of the surface of the polymer to set a hydrogen bonded network between groups on the surface of the two pieces of PMMA

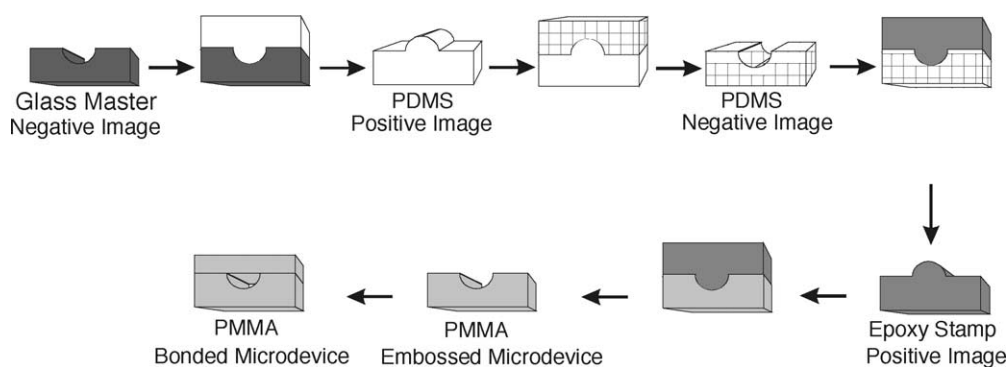


Fig. 5. Schematic diagram representing the process to create an epoxy stamp from a glass negative image, which is then used as a stamping tool to emboss PMMA. After embossing the microstructures in the PMMA, a chemically modified cover plate is bonded to create a micro-device for capillary electrophoretic separations.

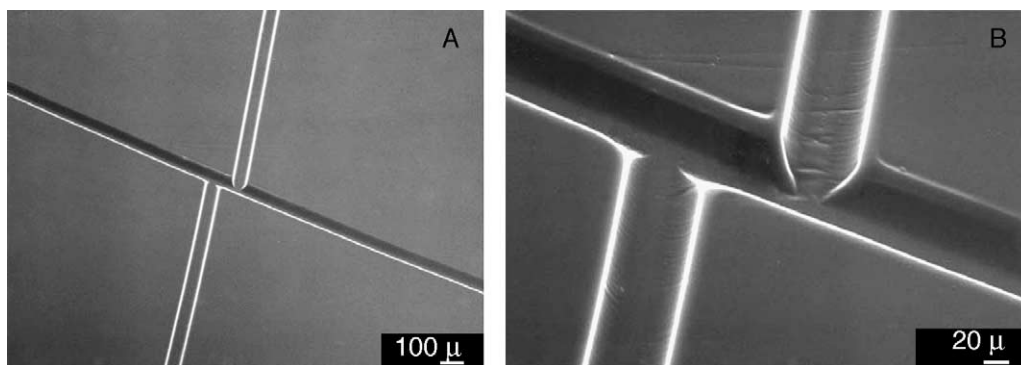


Fig. 6. SEM photomicrographs of the injector region of a microfluidic device embossed in PMMA using an epoxy stamp prepared from a glass negative image master (Fig. 5). The channel dimensions are 50 μm wide and 20 μm deep.

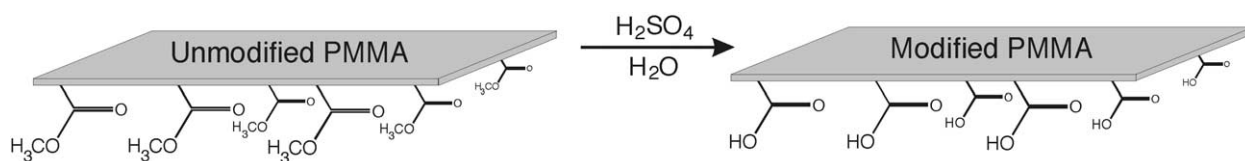


Fig. 7. Schematic representation of the hydrolysis of surface ester groups to a carboxylic acid to enhance bonding of the cover plate to the embossed micro-device.

and would be similar to what is observed for bonding oxidized PDMS [24] and glass. We have found that soaking the PMMA cover plate in an aqueous sulfuric acid solution was enough to provide adequate surface modification of the ester groups, determined by chemical force microscopy (CFM) [25], to provide good bonding of the cover plate to the micro-device. The surface modifications obtained from the exposure of the PMMA to strong aqueous acid solution results in the conversion of the surface ester groups to carboxylic acid groups (Fig. 7). Given this modification the bonding between the two pieces of PMMA, once in conformal contact, is either due to hydrogen bonding between the surface ester groups on the unmodified device and the acid groups on the modified cover plate, or anhydride formation. We prefer the latter explanation because surface modification of both the device and the cover plate resulted in a much weaker bonding between the two pieces of PMMA than in cases when only one of the pieces was treated. Once the surface modification was complete the two pieces of PMMA were bonded in the embosser at a temperature well below the glass transition of PMMA (Fig. 8). The strength of the adhesion forces between the micro-device and the cover plate were determined using tensile strength measurements. This was accomplished by bonding two pieces of PMMA with varying cross sectional areas using the above protocol and then recording the force needed to break the adhesion forces holding the two pieces of PMMA together. The results of the load at adhesion failure given in Table 1 were then divided by the cross sectional area to get the tensile stress at adhesion failure. The results obtained for the bonding are in good agreement between the two different cross sectional areas with the average stress force being 1484 kN/m² or 1.5 MPa. These results compare favorably with those in the literature for similar systems [21,26].

3.4. Microchip electrophoresis

The easiest way to test the efficacy of our embossing and bonding regime is to determine how the microchips function as analytical devices. The separation efficiency of the fabricated microchip was determined by multiple injections of a fluorescent dye (Cy-5). The relative fluorescent intensity for the multiple injections was then plotted versus time to determine the reproducibility of the injections, which is dependent on the bonding of the fabrication of the micro-device. The micro-device is filled with operating buffer (5 mM phosphate, pH 8.0), fitted into the detector and a program is used to inject the sample and then run the electrophoretic separation. This is accomplished by first applying a voltage and ground to reservoirs (A) and (B), respectively (Fig. 1). This resulted in the formation of a plug of sample in the channel between

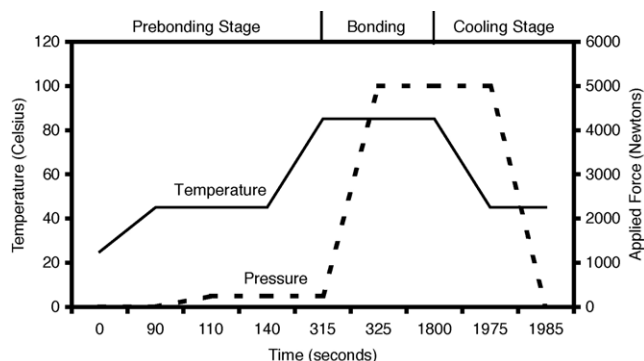


Fig. 8. Graphical representation of the force and temperature program used to bond the cover plate to the embossed micro-device. The solid line represents the temperature as a function of time while the dotted line is the applied force.

Table 1
The results of tensile strength measurements

Cross sectional area (2 cm ²)		Cross sectional area (4 cm ²)	
Load at adhesion failure (kN)	Tensile stress (kN/m ²)	Load at adhesion failure (kN)	Tensile stress (kN/m ²)
0.4016	2008	0.4037	1009
0.2930	1465	0.6046	1512
0.3548	1774	0.5144	1286
0.2888	1444	0.4617	1154
		0.6050	1513

Average stress: 1484 ± 243 kN/m².

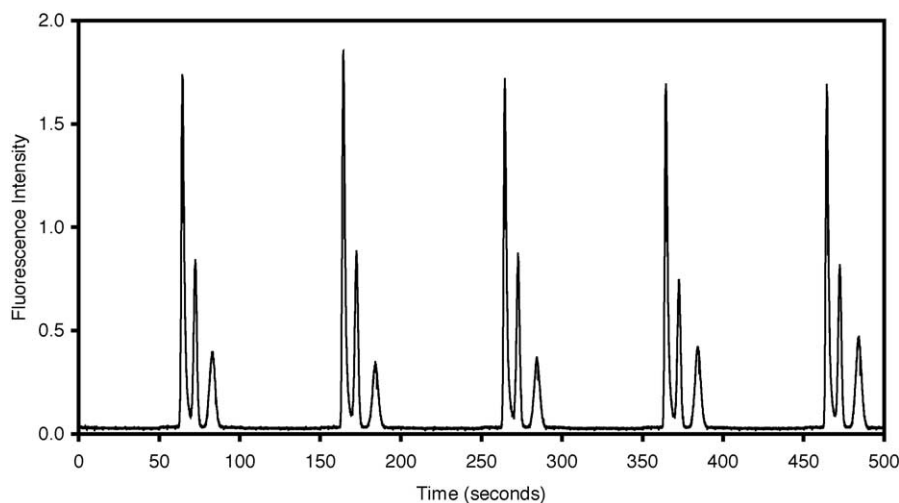


Fig. 9. Electropherogram of the relative fluorescence intensity vs. time of five replicate injections of mono-functional Cy-5 dye demonstrating the reproducibility and separation efficiency of the embossed micro-device.

(C) and (D) (Fig. 1). The separation voltage then directed this plug of Cy-5 dye towards the detector and is accomplished by applying high voltage to reservoir (C), ground for reservoir (D) and push back voltages to reservoirs (A) and (B) (Fig. 1). The results of five multiple injections can be seen in Fig. 9 with each set of three peaks representing a 50 s injection and 50 s run time resulting in 100 s total analysis time. The peaks in the electropherogram represent the Cy-5 dye and its associated impurities [27]. The area under the most intense peak in each set was averaged in order to obtain an indication of the reproducibility of the injection (3.5% error). The device shows good separation efficiency with plate numbers for the major peak being $\approx 33,000$. These values demonstrate that fabrication procedures utilized in the microchip fabrication process (i.e. embossing and bonding) produce a functioning device capable of electrophoretic separations with good separation efficiencies.

4. Conclusion

The use of hot embossing in the fabrication of micro-devices has definite advantages over the methods used to produce similar devices from glass. Unfortunately, the stamps previously used were either costly (nickel) or fragile (silicon based). We have developed a method to manufacture

embossing stamps from high temperature epoxy that can reproduce fine detail accurately, are robust enough to remain unchanged through multiple fabrication cycles and are inexpensive to fabricate. The stamp production process is flexible and can be adapted to either positive or negative image masters and is compatible with a wide variety of commonly used micro-fabrication materials such as silicon, glass or PDMS. This study has utilized silicon/SU-8, glass and PDMS as masters from which we mold an epoxy-stamping tool that is used in the embossing process. The micro-fabricated master is not used directly as the embossing tool and remains unaffected by thermal cycling and pressures associated with embossing. When combined with soft photolithography a very inexpensive and rapidly modifiable embossing manufacturing process is created. We show that the embossing process combined with a suitable bonding protocol, such as surface modification followed by heat/pressure is excellent for the production of capillary electrophoretic microfluidic devices in PMMA.

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