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Fabrication of thermoset polyester microfluidic devices and embossing masters using rapid prototyped polydimethylsiloxane molds

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Plastics are increasingly being used for the fabrication of Lab-on-a-Chip devices due to the variety of beneficial material properties, affordable cost, and straightforward fabrication methods available from a range of different types of plastics. Rapid prototyping of polydimethylsiloxane (PDMS) devices has become a well-known process for the quick and easy fabrication of microfluidic devices in the research laboratory; however, PDMS is not always an appropriate material for every application. This paper describes the fabrication of thermoset polyester microfluidic devices and masters for hot embossing using replica molding techniques. Rapid prototyped PDMS molds are conveniently used for the production of non-PDMS polymeric devices. The recessed features in the cast polyester can be bonded to a second polyester piece to form an enclosed microchannel. Thermoset polyester can withstand moderate amounts of pressure and elevated temperature; therefore, the cast polyester piece also can be used as a master for embossing polymethylmethacrylate (PMMA) microfluidic systems. Examples of enclosed polyester and PMMA microchannels are presented, and we discuss the electroosmotic properties of both types of channels, which are important for analytical applications such as capillary electrophoresis.

Introduction

A variety of materials and methods have been introduced for the fabrication of microfluidic devices.¹ Original devices were typically made in glass or silicon using the techniques of wet etching and micromachining.^{2,3} More recently, polymeric devices, comprised of polymers such as polymethylmethacrylate (PMMA), polycarbonate (PC), cyclic olefin copolymer (COC), and polydimethylsiloxane (PDMS), have been made by replication techniques, including injection molding, embossing, and replica molding, using a patterned silicon or metal master.^{4–7}

Injection molding, and to a lesser extent embossing, have been commonly used for the large-volume high-throughput production of disposable devices due to the low cost of the raw material and the nature of the fabrication process. Several techniques are commonly used to fabricate the masters used in injection molding and embossing, including conventional machining, silicon and glass micromachining, and electroplating.^{5,6,8} Conventional machining (*e.g.* milling) can be used to produce masters with features of the order of a few tens of micrometers in a variety of materials.^{5,9} To create smaller features, silicon micromachining, such as anisotropic wet or dry etching, can be used to create patterns on a silicon wafer.^{10–12} In addition to subtractive techniques as exemplified by the etching of silicon, additive methods such as electroplating are commonly used for the fabrication of metal masters for embossing. Nickel or nickel alloy electroforms can be produced from various templates, including etched silicon wafers,¹³ photoresist patterned on a substrate, or X-ray patterned PMMA as in the LIGA process (German acronym for lithography, electroplating, and molding).¹⁴ These techniques can require significant time and capital investment; however, once the master has been created the production of large numbers of replicas is rapid and economical.

For small-scale production, polydimethylsiloxane (PDMS) has become the material of choice for the rapid prototyping of

microfluidic systems.^{15–23} PDMS devices are usually fabricated by molding the PDMS elastomer against the bas-relief features of a negative photoresist that were lithographically patterned on a silicon wafer.¹⁵ The technique of molding, also called casting, has several advantages in the laboratory over traditional microfabrication methods, including increased speed of production and decreased cost. In addition, molding can be used for replicating complex multilayer structures in one step,^{18,19,23} a feat that may be difficult to achieve with other methods of replication.

Despite the advantages of PDMS in rapid prototyping, PDMS is not an appropriate material for all applications. In particular, hydrophobic molecules tend to leach into PDMS, while the presence of organic solvents will swell PDMS. Also, PDMS has a high oxygen permeability, thus PDMS micro-devices may not be suitable for use with oxygen sensitive applications. Because of these incompatibilities, PDMS is typically limited to aqueous-based applications. In addition, the surface properties of PDMS are not stable over periods of hours, possibly due to the exchange of PDMS molecules on the surface with those in the bulk. Surface-sensitive applications, such as capillary electrophoresis, will thus require careful monitoring of the surface characteristics of PDMS.

To address these limitations of PDMS while retaining the advantages of PDMS rapid prototyping, this paper describes two strategies for the small-scale production of polyester and PMMA microfluidic systems using PDMS molds. One approach replicates features in polyester resin using PDMS molds (Fig. 1A), while the other method uses molded polyester as a master for embossing PMMA channels (Fig. 1B). The thermoset polyester resin used in this work yields itself easily to replica molding of micro-devices since the resin has a low viscosity prior to curing. Also, thermoset polyester is rigid when cured and can withstand moderate amounts of pressure and temperature; therefore, it can be used as masters for embossing as an alternative to metal masters. Although this paper focuses on the rapid prototyping of polyester and PMMA microchannels,

the two strategies outlined here should be applicable to other polymer materials of interest.

Experimental

Materials

Silicon wafers were purchased from Montco Silicon Technologies, INC (Royersford, PA, USA); SU-8 50 from Microchem (Newton, MA, USA); propylene glycol methyl ether acetate (PGMEA) and styrene from Aldrich (Milwaukee, WI, USA); tridecafluoro-1,1,2,2-tetrahydrooctyl-1-trichlorosilane from United Chemical Technologies (Bristol, PA, USA); PDMS (Sylgard 184) from Dow Corning (Midland, MI, USA); polyester resin (Clear-Lite Casting Resin), Cab-O-Sil, and methyl ethyl ketone peroxide (MEKP) catalyst from Tap Plastics (Stockton, CA, USA); PMMA sheet (2.5 mm) from Plaskolite (Columbus, OH, USA); 2-propanol from Fisher

Scientific (Pittsburgh, PA, USA); sodium dodecylsulfate from Sigma (St. Louis, MO, USA); sodium tetraborate decahydrate from J.T. Baker (Phillipsburg, NJ, USA). Polyester and PMMA samples were sputter coated with gold (SPI Supplies, Westchester, PA, USA) prior to imaging on a FEI Sirion scanning electron microscope (Hillsboro, OR, USA). A Carver (Wabash, IN, USA) Model C press with heating platens was used for embossing, and a Stanford Research Systems (Sunnyvale, CA, USA) high voltage power supply (Model PS350) was used for the measurement of electroosmotic flow in microchannels.

Fabrication of silicon master

Silicon masters were fabricated using photolithography as described elsewhere.¹⁵ Briefly, negative photoresist, SU-8 50, was coated on 3-inch silicon wafers to the desired thickness. A transparency with the printed design was used as a mask, and the coated wafers were exposed to ultraviolet light. Following exposure, the wafers were developed with PGMEA yielding a patterned silicon master. The patterned silicon master was silanized with tridecafluoro-1,1,2,2-tetrahydrooctyl-1-trichlorosilane prior to use.

A negative photoresist is rendered insoluble when exposed to ultraviolet light, and consequently raised or recessed features can be obtained depending upon the mask used. In this paper we will use the terms “light field image” or “dark field image” to describe the polarity of the mask.²⁴ In a light field image, the desired pattern is opaque and the remaining area, *i.e.* the field, is transparent. For a dark field image, the pattern is transparent and the field is opaque. A dark field image yields raised features, while a light field image yields recessed features in negative photoresist.

Casting PDMS molds and modification of PDMS

PDMS was prepared by mixing the prepolymer base and curing agent in a 10:1 weight ratio and then degassed. The PDMS was then poured onto the silanized wafers and cured in a 60 °C oven for 2 h. Once cured, the PDMS mold was cut using a scalpel blade and peeled away from the master. To slightly strengthen the PDMS molds, a common hardening additive, Cab-O-Sil (fumed silica), was added to the PDMS prepolymer prior to curing. Approximately 2 g of Cab-O-Sil was used per 25 g of prepolymer. The mixture was then degassed. Due to the fine particle size of the additive, a fume hood, particle mask, and goggles were used during the addition of Cab-O-Sil.

Casting polyester resin on PDMS

The non-patterned sides of the hardened-PDMS (PDMS containing fumed silica additive) molds were sealed to glass microscope slides to secure the mold to a solid surface. A flat, non-patterned piece of cured PDMS was cut to form a mold surround. The PDMS surround was conformally sealed to the patterned mold leaving the patterned area clear for casting of the polyester resin and the edges of the surround in place to prevent polyester resin from spilling off the patterned mold.

Polyester resin was prepared by mixing the resin with additional styrene crosslinker and MEKP catalyst. Approximately 0.4–0.5 g of styrene monomer was added to 20 g of resin and mixed. Five drops of catalyst (0.15 g) were then added to the resin/styrene mix and stirred and then degassed to remove air bubbles. The polyester resin was then poured into the PDMS surround and onto the patterned mold. To obtain a level polyester cast for embossing, a microscope slide was placed on top of the resin, making contact with opposite edges of the PDMS surround (Fig. 2A). The polyester resin was cured in

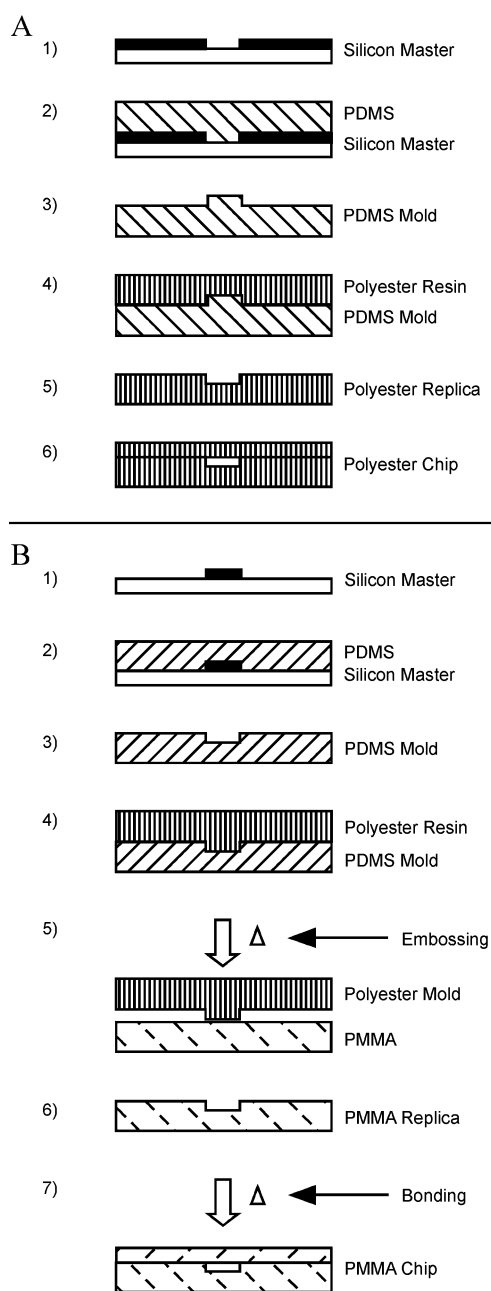


Fig. 1 Schematic illustrating the procedure for fabricating polyester microfluidic systems (A) and the procedure for fabricating PMMA chips using polyester embossing masters (B).

several stages. The resin-filled molds were left at room temperature for a specified time, followed by treatment at 60 °C and 120 °C. The specific times used for each stage of the curing are different for the preparation of polyester chips and for the preparation of polyester embossing masters and are stated in the respective sections below.

Fabrication of polyester chips

Fig. 1A illustrates the process used for the fabrication of polyester chips. Light field masks were used to produce recessed features in the SU-8 photoresist on silicon wafers. Following silanization of the silicon master, hardened-PDMS was cast on the silicon master and cured as described above. The hardened-PDMS mold was then conformally sealed to a microscope slide and a PDMS surround was conformally sealed onto the PDMS mold. Posts were placed on the pattern in selected locations to provide access holes for the final device. Stainless steel needles were used for the posts. The tapered ends were filed until flat, and then the needles were pushed into the PDMS for stability during pouring and curing of the resin. Polyester resin mix, with a composition of 20 g resin, 0.4 g styrene, and 5 drops catalyst (0.15 g), was prepared and poured into the mold.

In addition to the patterned PDMS mold, a non-patterned PDMS mold was also prepared and filled with polyester resin. The two polyester molds, one patterned and one non-patterned, were allowed to cure at room temperature for 1.5 h, followed by 15 min at 60 °C, and then allowed to cool for 15 min at room temperature. The posts and surround were removed, and the two polyester molds were removed from the PDMS molds and brought into contact with one another. The combined polyester pieces were then cured at room temperature for 1 h, cured at 60 °C for 10 min, and then cured at 120 °C for 1 h. The resulting

chip was allowed to cool at room temperature for 30 min, followed by cleaning with deionized water prior to use.

Fabrication of PMMA chips using polyester embossing masters

Fig. 1B illustrates the process used for embossing with polyester masters. Dark field masks were used to yield raised features on the silicon master. Flat polyester molds of the desired pattern were then prepared as described above. Briefly, polyester resin mix, with a composition of 20 g resin, 0.5 g styrene, and 5 drops catalyst (0.15 g), was prepared and poured into a mold. The polyester resin was allowed to cure in the mold at room temperature for 2.5 h, followed by 30 min at 60 °C and 1.5 h at 120 °C.

PMMA sheet was cut into 25 mm by 50 mm pieces by scoring with a plastic knife and cracking or by using a scroll saw. The PMMA pieces were then cleaned with 2-propanol and dried with nitrogen. Immediately prior to embossing, the PMMA pieces were placed on microscope slides and put into a small furnace. The temperature was raised to 140 °C and maintained for a minimum of 20 min to allow the PMMA pieces to reach 140 °C. In the meantime, a laboratory hydraulic press with heating platens was brought to the desired temperature. The bottom heating platen was heated to 145 °C, while the top platen was maintained at room temperature. Once the heating platen reached the set temperature, the microscope slide and heated PMMA piece were transferred to the press. The polyester mold was aligned and placed on top of the PMMA piece. A glass microscope slide was also placed on top of the polyester mold. The press was then used to apply approximately 1.7 MPa of pressure. The temperature was maintained at 145–155 °C during the embossing procedure. After an embossing time of 30 min, the pressure was released and the embossing assembly was removed from the press. The embossing assembly was allowed to cool for 3 min and then the embossed PMMA piece was manually separated from the polyester stamp.

The embossed piece of PMMA was cleaned with 2-propanol and dried with nitrogen. Access holes were drilled in a second piece of PMMA, and the piece was cleaned with 2-propanol and dried with nitrogen. The two PMMA pieces were then aligned with one another and placed between two glass microscope slides. The heating platens of the press were heated to approximately 107 °C, the reported glass transition temperature of the PMMA. The PMMA and glass slide assembly was placed in the press and approximately 0.7 MPa was applied for 10 min, during which time the temperature of both platens was maintained at 105–110 °C.

Measurement of electroosmotic flow

Electroosmotic flow in fabricated channels was determined by the current monitoring method.²⁵ PMMA channels were 50 μm by 50 μm and were approximately 3 cm in length. Channels were filled with 10 mM sodium borate solution by the application of vacuum, then solution was removed from one of the reservoirs and replaced with 100 mM sodium borate. Platinum electrodes were placed in both of the wells, and a high-voltage power supply was turned on with the polarity of the power supply set to produce electroosmotic flow in a direction to displace the 10 mM borate buffer in the channel with the higher concentration buffer. The current was recorded as a function of time for each selected voltage applied, and the time required to reach a steady current was equivalent to the time necessary to displace the volume of 10 mM borate buffer over the length of the channel. To calculate v_{eof} , the linear velocity of the electroosmotic flow, the length of the channel was divided by the time needed to achieve steady current, $v_{eof} = l/t$.

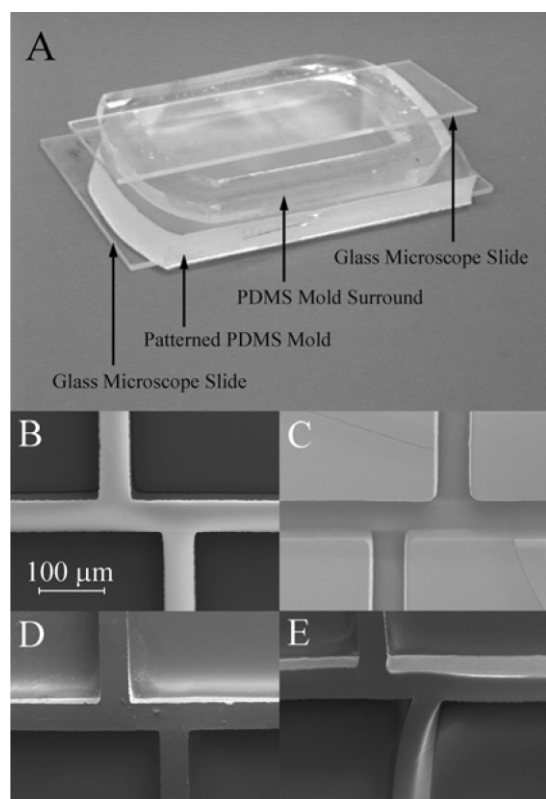


Fig. 2 (A) Photograph of a molding assembly. SEM images of (B) silicon master with SU-8 patterned 50 μm-wide double-T channel, (C) hardened-PDMS mold of the silicon master, and (D) polyester replica of the PDMS mold. (E) SEM image of a warped polyester replica using improper curing conditions. Scale bar in (B) also applies to (C)–(E).

Results and discussion

Composition, casting, and curing of polyester resin

The polyester used for this work is an unsaturated polyester resin. The cured polyester is a firm, set material and is considered a thermoset. As such, the thermoset polyester cannot be reshaped by reheating once it is cured due to the extensive crosslinking that occurs during the curing procedure.²⁶ This characteristic contrasts with the ability of thermoplastics, such as the PMMA used for embossing, to be reshaped when heated above the glass transition temperature. The unsaturated polyester resin used here contains already polymerized chains formed by condensation polymerization, and the chains contain sites of unsaturation that crosslink with styrene through free radical polymerization of the vinyl groups, which are activated by the methyl ether ketone peroxide (MEKP) catalyst.

Although some styrene is present in the resin to begin with, additional styrene may be added to the resin to improve specific properties, such as viscosity of the resin prior to curing and the strength of the final product. Styrene acts as a solvent, thus thinning the solution and lowering the viscosity of the polymer mixture, which provides for a longer working time before the resin starts to set. Additional styrene also increases the mechanical strength of the material by providing additional crosslinks between polymer chains, which is useful for creating a strong, rigid polyester embossing master.

Just as the amount of styrene affects the final properties of the thermoset polyester, the amount of MEKP catalyst and the curing conditions also affect the properties of the resin. The MEKP catalyst produces a free radical that is transferred to the vinyl groups present in the polyester polymer chains and to the styrene monomers. As such, the amount of catalyst used determines the rate at which the crosslinking occurs and can affect the final mechanical properties of the polyester chip. A fast rate of curing can yield distorted features due to stress. A carefully controlled curing rate and the use of hardened-PDMS molds (fumed silica filler added to PDMS to produce slightly stronger molds) produces excellent replication of features. Fig. 2 shows a series of SEM images, starting with an image of the original master consisting of SU-8 photoresist patterned on a silicon wafer (Fig. 2B), moving to the hardened-PDMS mold (Fig. 2C) obtained from the silicon master, then to the resulting polyester cast (Fig. 2D) replicated from the hardened-PDMS mold. In contrast, Fig. 2E shows the results of casting polyester under less desirable conditions, specifically the use of twice the amount of MEKP catalyst (0.3 g vs. 0.15 g per 20 g resin), a shorter curing time (1.5 h vs. 2.5 h at RT), and the use of a standard PDMS mold instead of a hardened-PDMS mold. The combined effects of a fast, high stress cure in flexible elastomeric molds produce twisted and distorted features in the polyester, an outcome clearly unacceptable for fabrication of micro-devices.

Fabrication of polyester microchannels

Fig. 3A shows an SEM image of a polyester chip, which displays excellent fidelity in reproducing the silicon master *via* the hardened-PDMS mold. Fig. 3B is an SEM image showing the cross-section of the polyester channel, in which the walls of the channels are parallel and the base is quite smooth. The irregularities of the side walls originate from the pixels present in the original transparency photomask, and demonstrate the high fidelity by which features in the original silicon master is being replicated in the polyester cast. The debris at the front of the image is an artifact and was produced during the cutting of the chip for taking SEM.

To enclose the microchannel, the surface containing the cast polyester channel was bonded to a flat surface of a second

polyester piece by placing the two surfaces in contact with each other prior to complete curing of the individual pieces. This process requires removing the polyester chips from the molds before completion of polymerization, and the curing of the material must be timed to achieve this. The polyester resin must be cured enough to maintain the channel dimensions during transfer of the piece, yet the polyester pieces must be able to complete the polymerization in conjunction to produce a bonded chip. An initial 1.5 h curing period at room temperature, followed by a short interval of low heat (60 °C), was sufficient to set the polyester resin pieces and to maintain channel dimensions during handling and transfer of the pieces. Once the two pieces were placed together, the combined pieces were allowed to rest for an hour at room temperature to ensure thorough contact and to continue the polymerization process. After this point, the pieces were introduced to high heat (120 °C) for an hour to accelerate and finish the curing process, yielding a bonded polyester chip.

Fig. 3C shows an SEM image of a cross-section of a sealed polyester channel. The sealed channel maintained its original dimensions except for a curvature at the interface between the flat piece and the molded channel. This curvature is caused by the creeping of the uncured polyester into the channel due to capillary action. This effect is most prominent for channels with small dimensions (< 50 μm), such as the one shown in Fig. 3C. Low aspect ratio (depth/width) channels also do not show such prominent curvatures. The interface of bonding between the two pieces cannot be seen because polymerization was completed only after the two pieces were brought into contact and further cured (for reference, the dashed line in Fig. 3C denotes the location of the interface).

Embossing PMMA with polyester masters

A thermoset, such as the polyester resin we used, can withstand reasonable temperatures and pressures without changing shape. To increase the strength of the thermoset polyester even further, we added ~7% additional styrene monomer to the resin for crosslinking. Traditional embossing techniques, in which metal embossing masters are heated, were not used with the polyester masters. Instead, we heated the PMMA well beyond its glass

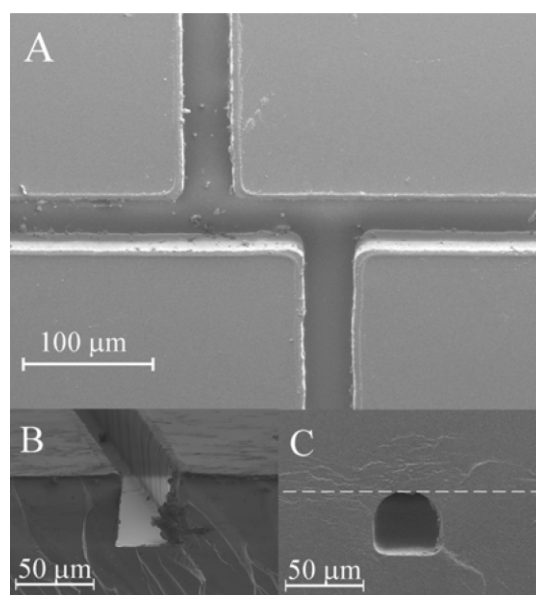


Fig. 3 SEM images of a cast polyester channel. (A) Top view of the intersection of a 50 μm double-T channel, (B) Cross-section of a 50 μm channel, and (C) Cross-section of a 50 μm polyester channel bonded to a second flat polyester piece (dashed line denotes bonding interface).

transition temperature both before and during the embossing procedure.

We found pre-heating the PMMA in a furnace prior to embossing to be beneficial. The optimal temperature for the furnace was determined to be 140 °C. At temperatures above 140 °C, the PMMA would blister and curl due to the high temperature. In addition to pre-heating the PMMA, we also used the bottom heating platen of the press, which is in contact with the PMMA piece, to maintain the elevated temperature of the PMMA during the embossing procedure. The bottom heating platen was maintained within the range of 145 to 155 °C, a slightly higher temperature than the temperature of the furnace, to compensate for any temperature gradient across the heating platen.

Fig. 4A shows the intersection of an embossed 50 µm double-T PMMA chip, while Fig. 4B shows a cross-section of an embossed 50 µm channel (with a bonded top piece). There is slight curvature at the top edges of the channel, which corresponds to the base of the feature on the polyester embossing master. When the embossing master is brought into contact with the hot PMMA piece and pressure is applied, the feature of the embossing master presses into the PMMA surface. The contact between the surface of the feature and the PMMA is very good at this point, resulting in a well-embossed channel floor and bottom edges. After the initial pressure is applied, the PMMA needs to remain at the embossing temperature for a period of time to allow for PMMA to flow to the sides and top corners of the feature. During the embossing time of 30 min, the PMMA does flow to the sides of the feature, but does not completely flow to the top corners. This incomplete contact at the top corners causes the top of the PMMA channel to curve and not form straight square edges. The lines of contact can be seen in the SEM image of the PMMA chip (Fig. 4A); the curved shadows on the four plateaus above the channel feature indicate where incomplete contact was made between the embossing master and the PMMA. Longer embossing times and higher temperatures may improve the curvature, but at the cost of processing time and possible damage to the polyester master. For most applications in which rapid prototyping of plastic microfluidic devices is used to test a fluidic design, however, slightly curved top edges is usually not an issue.

The bonding of plastic chips has been described previously.^{5,6,10} Most often PMMA pieces are clamped together

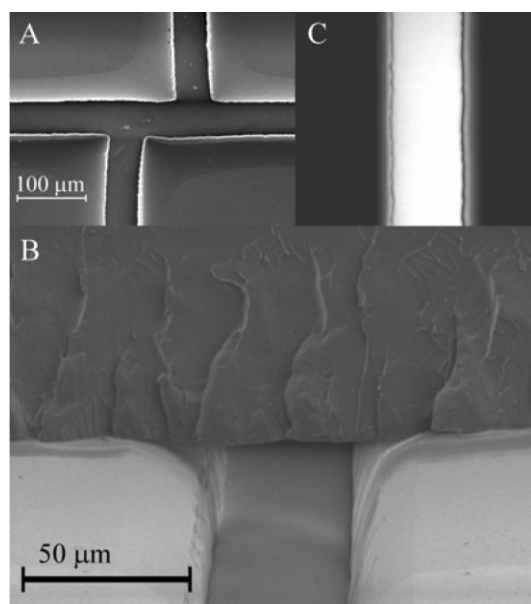


Fig. 4 Images of a PMMA channel embossed with a cast polyester master. (A) SEM image of the top view of the intersection of a 50 µm-wide double-T channel, (B) Cross-section of a bonded 50 µm channel, and (C) A bonded 50 µm PMMA channel filled with 25 µM fluorescein.

and placed in an oven at a temperature near 107 °C (glass transition temperature of PMMA) for approximately 10 min. In our procedure, we used a heated press to provide both the pressure and temperature needed for bonding to occur. Application of 0.7 MPa was sufficient to create contact between the PMMA pieces. Increased pressure caused the pieces to squeeze together too much, thus distorting the channel and sometimes even blocking the channel completely. Fig. 4B shows the results of bonding two pieces of PMMA, one of which was embossed to obtain a channel feature. Due to the limited strength of PMMA bonding, a bonded chip could not be diced for SEM without causing separation of the pieces; therefore, the pieces were diced and then bonded, resulting in edges that were offset slightly. The curvature of the channels does not affect the yield in bonding; also, the channel feature was not distorted from the bonding procedure as the curved top edges of the channel remain, and the resulting channel is therefore slightly wider at the top. The bonded channel was sealed, which permits the 50 µm channel to be filled with a 25 µM fluorescein solution (Fig. 4C). The fluorescence is confined to the channel and no leakage can be seen.

Electroosmotic flow in PMMA and polyester channels

PMMA exhibits a negative surface charge and therefore the direction of electroosmotic flow (EOF) in PMMA is similar to that of fused silica or PDMS,²⁷ although the magnitude of EOF differs in these three substrates. Fig. 5 shows the dependence of the electroosmotic flow rate, v_{eof} , on the applied electric field strength, E , up to 400 V cm⁻¹ for PMMA. The flow rates are linearly dependent upon the electric field strength throughout this range, indicating that there is sufficient heat dissipation in PMMA chips within this range. Adequate heat dissipation through a microchannel is an important consideration for electrophoretic separations because increased temperatures change the viscosity of the buffer, thereby changing electroosmotic mobilities and thus causing band broadening. The average electroosmotic mobility, μ_{eof} , is defined as v_{eof}/E , and can be determined from the slope of the line in Fig. 5 to be 2.4×10^{-4} cm² V⁻¹ s⁻¹ for the embossed PMMA channel and is similar to previously reported values.²⁷ In comparison to an μ_{eof} of 6.2×10^{-4} cm² V⁻¹ s⁻¹ for a 50 µm inner diameter fused silica capillary and an μ_{eof} of 8.2×10^{-4} cm² V⁻¹ s⁻¹ for a freshly oxidized 50 × 50 µm PDMS channel (100 mM Tris, 20 mM boric acid, pH 9),¹⁵ the μ_{eof} of 2.4×10^{-4} cm² V⁻¹ s⁻¹ in a 50 × 50 µm PMMA channel is approximately a factor of three times lower than the μ_{eof} observed in fused silica and PDMS.

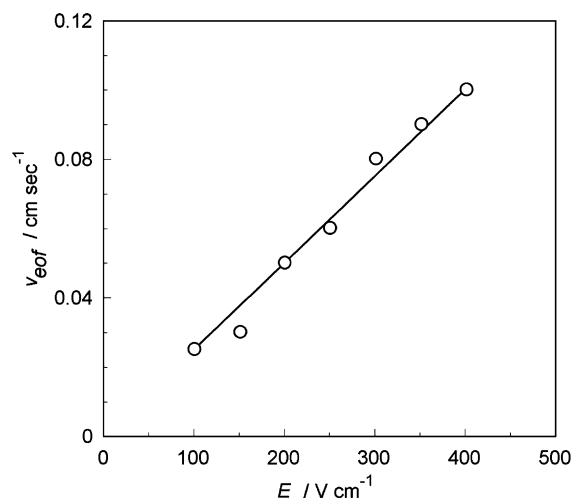


Fig. 5 Electroosmotic velocity, v_{eof} , as a function of applied electric field strength, E , for an embossed PMMA channel.

In contrast to PMMA, the surfaces of unsaturated polyester resin are hydrophobic, which makes difficult the filling of the polyester channels with aqueous solutions. Previous work with unsaturated polyester has shown that the addition of 10 mM SDS, a surfactant, to aqueous solutions aids in filling the hydrophobic polyester channels for EOF measurements.²⁸ With 10 mM SDS present in the electrolyte solutions, we measured in the polyester channels an μ_{eof} of $2.2 \times 10^{-4} \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ with an electric field strength between 150 and 300 V cm^{-1} . As an alternative to the use of SDS in the electrolyte solutions, surface modification is another option for making the polyester chips compatible with aqueous solutions. Polyester chips, however, may be well suited for non-aqueous applications because thermosets in general have good chemical resistance.

Conclusions

Although the two methods described here are capable of producing non-PDMS based polymeric microdevices, the core of the methods exploits the rapid prototyping capabilities of PDMS. These fabrication techniques should find applications in which rapid prototyping is desired but PDMS-based devices are unsuitable, such as for experiments in which organic molecules are involved or when the stability of surface properties is required. This molding approach should also find use in the replication of fragile microstructures, in which the harsh conditions of embossing or injection molding cannot be used.

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