



Plasticizer-assisted bonding of poly(methyl methacrylate) microfluidic chips at low temperature

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ABSTRACT

As an important phthalate plasticizer, dibutyl phthalate (DBP) was employed to decrease the bonding temperature of poly(methyl methacrylate) (PMMA) microfluidic chips in this work based on the fact that it can lower the glass transition temperature of PMMA. The channel plates of the PMMA microchips were fabricated by the UV-initiated polymerization of prepolymerized methyl methacrylate between a silicon template and a PMMA plate. Prior to bonding, DBP solution in isopropanol was coated on PMMA covers. When isopropanol in the coating was allowed to evaporate in air, DBP was left on the PMMA covers. Subsequently, the DBP-coated covers were bonded to the PMMA channel plates at 90 °C for 10 min under pressure. The channels in the complete microchips had been examined by optical microscope and scanning electron microscope. The results indicated that high quality bonding was achieved below the glass transition temperature of PMMA (~105 °C). The performance of the PMMA microfluidic chips sealed by plasticizer-assisted bonding has been demonstrated by separating and detecting ionic species by capillary electrophoresis in connection with contactless conductivity detection.

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1. Introduction

Microfluidic chips are of considerable recent interest owing to their high degree of integration, portability, minimal reagent consumption, high performance and speed [1–3] since the pioneering work of Manz and Harrison [4,5]. They hold considerable promise for biomedical and pharmaceutical analysis, clinical diagnostics, environmental monitoring, forensic investigations, etc.

Most microfluidic chips in the earliest reports were fabricated using glass or silicon materials in connection with standard photolithographic techniques [6]. However, their application was limited because of high cost, harmful and complicated fabrication procedures, and the limitation on the geometric modification of the chip channel [7]. Polymers are less expensive and are becoming the most promising materials for fabricating microfluidic devices with mass-replication technologies, such as injection molding and hot embossing [7,8]. A wide variety of polymer materials have been evaluated for fabricating microchips instead of glass, including poly(dimethylsiloxane) (PDMS), poly(methyl methacrylate) (PMMA), polycarbonate (PC), polyester, polystyrene, poly(ethylene terephthalate glycol), and polyolefins [6,7]. PMMA

has been one of the most commonly used polymers for microfluidics. It is particularly useful for microfluidic chips with the features of attractive chemical properties, low price, excellent optic transparency, ease of fabrication, biocompatibility, and excellent electric and mechanical properties [8–10]. Because PMMA can decompose into methyl methacrylate (MMA) at a high temperature and can be reused, it is an ideal material for preparing “green microchips”. In addition, its unique chemical and physical properties offer great promise for the fabrication of microdevices with useful functionalities.

The microchannels that are open after the fabrication steps have to be closed without clogging the channels, changing their physical parameters or altering their dimension [7]. Recently, Tsao et al. published a review that summarized the strategies for the bonding of thermoplastic polymer microfluidic chips [11]. A variety of techniques have been developed for bonding PMMA microchips, including thermal bonding [12–15], solvent bonding [16–23], in situ polymerization bonding [24], microwave bonding [25,26], glue bonding [27], thermal lamination [28], etc. Among them, solvent bonding is usually less satisfactory due to the possible blocking of the microchannels [2]. To solve the problem, various approaches have been developed to improve the quality of solvent bonding. Woolley and Tennico employed wax and ice as sacrificial layers to protect the PMMA channels from the solvents that might dissolve the PMMA substrates [29,30]. However, the bonding procedures were complicated and time-consuming. Recently, Remcho's group sealed PMMA microfluidic chips by vaporized

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organic solvent bonding [31]. A blank PMMA cover plate softened by chloroform was successfully bonded to a channel plate at a low temperature. In addition, some solvents in which the solubility of PMMA was low were successfully employed in the bonding of PMMA microdevices at room temperature, including isopentylacetate [17], azeotropic solvent composed of ethanol and 1,2-dichloroethane [18], acetonitrile [19], etc. Various low molecular weight aliphatic alcohols (such as methanol [20,21], ethanol [20,22], and isopropanol [20,23]) have also been employed in the bonding of PMMA microfluidic chips. The alcohols sandwiched between channel plates and covers could dissolve the surface layers of the PMMA substrates at higher temperatures (60–100 °C) to realize satisfactory bonding although PMMA does not dissolve easily in these alcohols at room temperature. The bonding time was in the range from 5 to 90 min [20–23]. Various thermal bonding techniques are preferable as they allow the formation of microchannels with uniform surfaces composed entirely of the same polymeric materials [2,11–15]. Prior to sealing, the PMMA substrates were heated to the temperature above the glass transition temperature (T_g , 105 °C) of PMMA and positive pressures were applied on the channel plate and the cover [2]. However, slight variance of the pressures and temperature may cause microchannel deformation and affect the reproducibility and yield because of the higher bonding temperature employed. It is of high importance to decrease the bonding temperature below the T_g of PMMA. Recently, Wooley et al. demonstrated that PMMA substrates could be bonded together to form microfluidic devices by clamping a blank cover to a channel plate and heating the assembly in a boiling water bath. Rapid and high-resolution capillary electrophoresis (CE) separations of derivitized amino acids were successfully carried out to demonstrate the performance of the prepared microchips [32]. Other sealing approaches unavoidably introduce other materials to form microchannels with non-homogeneous internal surfaces, which leads to undesired effect on the electroosmotic flow (EOF) and may reduce the separation efficiency [33,34].

A plasticizer is a substance or material incorporated in a polymer to increase its flexibility, workability, and extensibility. It can reduce the cohesive intermolecular forces along the polymer chains. The chains can then move more freely so that the stiffness, the melt viscosity, and the T_g of the polymer decrease significantly [35]. Plasticizers are usually inert organic materials with high boiling points and low vapor pressures. Phthalates are the most dominant class of plasticizers in the entire plasticizer industry [36]. As an important phthalate plasticizer, dibutyl phthalate

(DBP) is the most commonly used plasticizer in manufacturing cast PMMA products [37]. Because DBP can decrease the T_g of PMMA [36,37], it may find application in the low temperature bonding of PMMA microfluidic chips. However, we are not aware of early reports on the plasticizer-assisted bonding of polymer microfluidic chips.

In this work, a novel plasticizer-assisted bonding strategy was developed for the rapid fabrication PMMA microfluidic chips (Fig. 1). The channel plates of the microchips were fabricated by ultraviolet (UV)-initiated polymerization of prepolymerized MMA between a silicon template and a PMMA plate at room temperature. Subsequently, the PMMA channel plates and the blank PMMA covers were bonded together at a lower temperature (90 °C) below the T_g of PMMA with the aid of DBP coated on the covers. The ease, simplicity, versatility, and low cost of the plasticizer-assisted bonding approach thus make it extremely attractive for the mass production of PMMA microfluidic chips. The feasibility and performance of the obtained microchip have been demonstrated by separating and detecting ionic species by CE in connection with contactless conductivity detection (CCD).

2. Experimental

2.1. Reagents and solutions

MMA, benzoin ethyl ether (BEE), 2,2'-azo-bis-isobutyronitrile (AIBN), DBP, dioctyl phthalate (DOP), dimethyl phthalate (DMP), and diethyl phthalate (DEP), isopropanol, potassium chloride, sodium chloride, lithium chloride, boric acid, and tris(hydroxymethyl)aminomethane (TRIS) were all purchased from Shanghai Chemical Reagent Company (SinoPharm, Shanghai, China). Appropriate amounts of potassium chloride, sodium chloride, and lithium chloride were dissolved in doubly distilled water to reach the final concentration of 100 mM. Other chemicals were all analytical grade. The running buffer for the microchip CE separation was a boric acid–TRIS buffer (20 mM each, pH 8.0). Sample solutions were prepared by diluting the stock solutions in the running buffer. Microscopic glass slides (76.2 mm × 25.4 mm × 1 mm) were obtained from Shanghai Jinglun Industrial Glass Co. Ltd. (Shanghai, China).

2.2. Apparatus

Scanning electron microscopy (SEM) images of the channels in the PMMA microfluidic chips were obtained with a PHILIPS XL

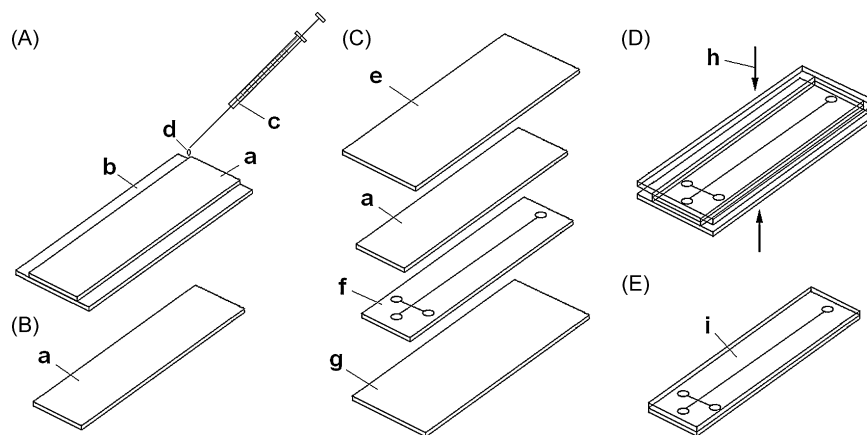


Fig. 1. Schematic diagram showing the process of plasticizer-assisted bonding. (A) Covering PMMA cover (a) on a piece of PMMA plate (b) and applying an accurate amount of DBP solution (d) in isopropanol between (a) and (b) using a syringe (c); (B) exposing the coated surface of (a) in air to allow isopropanol to evaporate; (C) sandwiching (a) and a channel plate (f) between two microscope slides served as upper (e) and lower (g) pressure pads; (D) bonding (a) and (f) between (e) and (g) under pressure (h) at 90 °C for 10 min and (E) removing the complete microchip (i) from the bonding device.

30 scanning electron microscope (Netherlands). The microchip CE-CCD system used has been described previously [38–40]. It consisted of a high-voltage dc power supply, a contactless conductivity detector, and a simple-cross PMMA microchip bonded by present method. A homemade +3000 V high-voltage dc power supply provided a voltage for the electrophoretic separation and the electrokinetic sample introduction. The circuit of the contactless conductivity detector contained a RC filter (time constant, 0.01 s), followed by a voltage follower (LF 356) to the circuit output, and allowed convenient data reading. A VC 2002 function generator (Shenzhen Victor Electronics Co. Ltd., Shenzhen, China) was used to generate a sinusoidal signal with a frequency of 300 kHz with peak-to-peak amplitude of 5 V that was applied to movable CCD electrode pairs on the cover sheet (100- μm thick) of the PMMA electrophoresis microchip. A N2000 chromatographic workstation (Zhejiang University Star Information Technology Co. Ltd., China) connected to a computer was used to record electropherograms.

Details of the movable CCD electrodes have been reported previously [38–40]. Briefly, rectangular-shaped electrodes (0.8 mm \times 10 mm) were made from two 10 μm thick copper-foil strips. The electrodes were glued to a piece of PMMA plate (22 mm \times 11 mm \times 1 mm) using chloroform, with a distance of 0.8 mm between them. The electrodes were placed in an “anti-parallel” orientation to reduce the stray coupling. The detector plate was then equipped by two PMMA “clip-like” open-rectangular holders from both shorter ends of the PMMA plate to hold the microchip. The position of the detection electrodes could be changed by sliding manually the microchip through the detector holder along the microchip. In this work, the effective length of the separation channel (from the injection cross to the detection point) was adjusted to be 5.5 cm. Two pieces of copper wires (75 μm diameter) were attached to the electrodes on the top of the detector plate using a conducting epoxy (Chemtronics, Kennesaw, GA, USA) and were linked to the detector electronics.

2.3. Fabrication of silicon template

Photolithographic positive mask bearing the channel network of microchips was designed using a computer-aided design software (Adobe Illustrator CS3, Adobe), and transferred onto a transparency film at a local photo shop using a commercial high-resolution printer with 3600 dpi resolution. Simple-cross microchip and microchip with pre-column reactor and post-column channel have been designed. The channel network was represented by 40 μm wide black lines on a transparent background. Silicon wafers (*p*-type, (100) orientation, 500 μm thick, 4-inch diameter, Wafer Works, Shanghai, China) were used to fabricate the molding template using standard photolithography and wet etching. The fabrication details of the silicon templates can be found in our previous reports [38,40].

2.4. Fabrication of channel plates

The simple-cross PMMA chip (16 mm \times 75 mm \times 1.3 mm, Fig. 2A) had simple-cross layouts, with a four-way injection cross connected to the three reservoirs and the separation channel. It consisted of a 60 mm-long separation channel (between the injection cross and the detection reservoir) and a 5 mm-long injection channel. The two channels crossed each other halfway between the sample and the unused reservoirs, at 5 mm from the running buffer reservoir. Besides the simple-cross PMMA microfluidic chip, PMMA microchip with pre-column reactors and post-column channel were also fabricated (Fig. 2B). The length of the main channel (the longest channel) in the microchip was 65 cm. The 45 mm-long post-column channel was linked to the

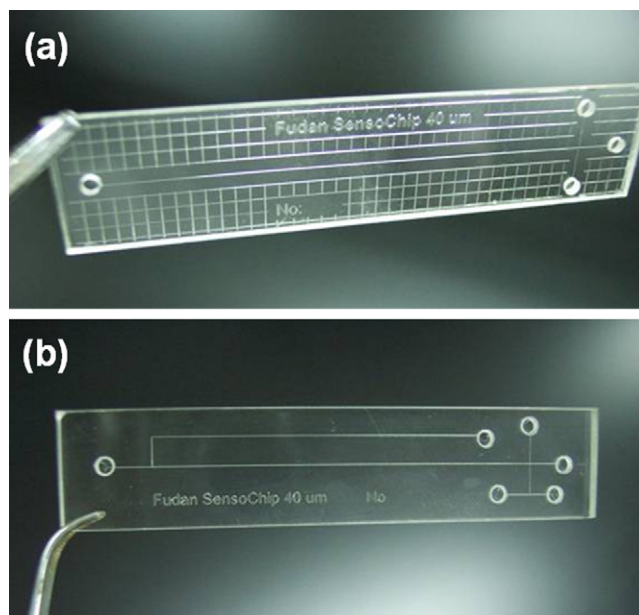


Fig. 2. Photographs of (a) a simple-cross PMMA microchip and (b) a PMMA microchip with pre-column reactor and post-column channel sealed by DBP-assisted bonding. Dimensions: 75 mm \times 16 mm.

end of the main channel via a 4 mm-long channel. The 5 mm-long channel between the cross and the “T” shape junction served as pre-column bioreactor. All channels had a trapezoidal cross section with a top width of $\sim 100 \mu\text{m}$, bottom width of $\sim 40 \mu\text{m}$, and depth of $\sim 33 \mu\text{m}$. The channel plate of PMMA microchip was fabricated by the UV-initiated polymerization of the prepolymerized MMA between a silicon template and a commercially available PMMA plate (75 mm \times 16 mm \times 1.0 mm) [24].

To fabricate the PMMA channel plate, MMA containing AIBN (0.2% w/v, a thermal initiator) and BEE (0.2% w/v, a UV initiator) in a conical flask was allowed to prepolymerize in an 85 $^{\circ}\text{C}$ water bath for ~ 15 min to generate a dense prepolymer molding solution. Adequate amount of the molding solution (about 2 mL) was cast directly on the silicon template of a microchip along its midline from one side to another side. Subsequently, a PMMA plate (75 mm \times 16 mm \times 1 mm) was carefully covered on the molding solution and pressed slightly. The solution spread in the interspace between them. The pressure was left until the interspace was fully filled by the molding solution. The excess solution could flow out and agglomerated along the edge of the PMMA plate on the silicon template and could prevent the ingress of air bubbles as a result of the shrinkage during the polymerization. Subsequently, the molding solution sandwiched between the PMMA plate and the silicon template was exposed to an UV light (365 nm lamp, 20 W, Shanghai Jinguan Lamp Co. Ltd., Shanghai, China) through the PMMA plate. Complete polymerization of the solution under the UV light could be accomplished within 30 min at 25 $^{\circ}\text{C}$. The images of the raised microstructures on the silicon template were precisely replicated into the synthesized PMMA layer on the PMMA plate. The obtained PMMA channel plate could be demolded from the template by sonicating in a 40 $^{\circ}\text{C}$ water bath for 10 min.

To fabricate PMMA cover sheet, about 2 mL of the molding solution mentioned above was cast on a piece of glass plate (100 mm \times 40 mm \times 2 mm) along the midline from one side to another side. A piece of glass slide (76.2 mm \times 25.4 mm \times 1.0 mm) was then put on the molding solution and squeezed until a film was formed between the two glass plates. Subsequently, the sandwiched molding solution was exposed to UV light for 30 min to obtain the PMMA cover sheet. Note that 100- μm thick plastic film

spacers needed to be sandwiched between the two plates to define the thickness.

2.5. Plasticizer-assisted thermal bonding

Fig. 1 illustrates the process of plasticizer-assisted bonding. Prior to sealing, 2-mm-diameter access holes were drilled at the ends of channels on the channel plate or the corresponding sites of a 1-mm thick PMMA cover plate to create reservoir ports. The channel plate (75 mm × 16 mm × 1.2 mm, Fig. 1f) and the cover (75 mm × 16 mm, area, 12 cm², Fig. 1a) were cleaned by sonicating in water and isopropanol for 1 min each and were dried under a stream of compressed air. Subsequently, the PMMA cover was covered on a piece of PMMA plate (77 mm × 25 mm × 1 mm, Fig. 1b). An accurate amount (60 μL, i.e. 5 μL cm⁻² cover) of 5% (w/v) DBP solution in isopropanol (Fig. 1d) was applied to the interspace between them via a microliter syringe. The bonding solution can spread very fast to form a liquid film between them. And then, the cover was pulled away in the parallel direction to the PMMA plate (Fig. 1b) and the coating on the cover was exposed in the air for at least 2 min at room temperature, allowing isopropanol to evaporate. This so-called “sandwich coating” provided a simple and convenient way to form a layer of uniform DBP coating on the PMMA cover without a spin-coater. Because the cover (Fig. 1a) and the plate for sandwiching coating (Fig. 1b) was both made from PMMA, approximately half amount of the applied coating solution (Fig. 1d) was coated on the cover. Finally, the channel plate and the cover were put together with the coated surface of cover and the channel-bearing surface of the channel plate touched face-to-face and sandwiched between two glass slides (76.2 mm × 25.4 mm × 1 mm). After they were clamped together between the upper and lower indenters of a laboratory-built hot press, a pressure of 0.6 MPa was applied on them at 90 °C for 10 min. The bonded chip was then allowed to cool slowly to the room temperature and was removed from the glass slides. The crude microchips after bonding were polished with emery sand papers to acquire the final chips with uniform edges. For comparison, the PMMA microfluidic chips were also bonded with the assistance of the same amount of DBP-free isopropanol (5 μL cm⁻² cover). The fabrication and bonding details are the same as those mentioned above.

2.6. Electrophoresis procedure

The channels of the prepared simple-cross PMMA microchip were treated before use by rinsing with water for 10 min. The sample reservoir was filled with a sample solution while the other three reservoirs were all filled with running buffer. The injections were performed by applying a voltage of +1000 V between the sample-containing and the grounded-detection reservoirs for 2 s while all other reservoirs were kept floating. Separations were performed by applying a voltage of +1000 V between the two reservoirs at the ends of the separation channels and all other reservoirs were floating.

3. Results and discussion

In order to form capillaries in microchips, the microchannels fabricated on the channel plates have to be bonded to a cover, without clogging the channels and changing their dimension. This often represents a big challenge for the fabrication of microchips [7]. Thermal bonding techniques are commonly used for PMMA microchips, because homogeneous internal surfaces can be obtained. PMMA substrates are usually heated above its T_g (105 °C) and pressures are applied on them for bonding. The higher bonding temperature (for example, 108 °C [13]) employed

may cause microchannel deformation and affect the yield. It is a challenging task to lower the bonding temperature below the T_g of PMMA substrate to alleviate the microchannel deformation. As a class of important external plasticizers, various phthalate plasticizers have been widely used in manufacturing plastic products as important additives because they can lower the T_g of polymers and reduce crystallinity by disrupting physical interactions between the polymer chains. DBP is the most commonly used plasticizer in cast PMMA products [37]. In this work, it was employed to decrease the bonding temperature below the T_g of PMMA.

Fig. 1 shows the process of plasticizer-assisted bonding. To lower the bonding temperature, DBP was coated on the inner surface of the PMMA cover (75 mm × 16 mm, 12 cm²). If it was coated on the structure-bearing surface of the channel plate, the microchannel would deform during the subsequent thermal bonding. Because only a little amount of DBP needed to be coated on the PMMA cover, 5% (w/v) DBP solution in isopropanol was used instead of pure DBP. Isopropanol is an inert solvent towards PMMA and is usually employed to rinse PMMA covers and channel plates in microfabrication [41]. To control the amount of the coated DBP, an accurate amount (60 μL, i.e. 5 μL cm⁻² cover) of the solution was sandwiched between the PMMA cover and the PMMA plate (Fig. 1b). Because the physical and chemical properties of their surfaces were the same, about half amount of the applied coating solution could leave on the PMMA cover. After the isopropanol in the coating evaporated in the air, a very thin layer of DBP was coated on the surface of the cover. The weight change of the PMMA cover indicated that approximately half amount of the DBP in the applied coating solution (Fig. 1d) was left and the isopropanol evaporated almost completely after the coating on the cover was exposed in air at room temperature for 2 min. When the DBP-coated surface was allowed to touch the surface of the channel plate at 90 °C under pressure, DBP would migrate towards the bulks of both PMMA substrates. Because a little amount of DBP was applied, only the T_g of the very thin DBP-permeated layers on the surfaces of the PMMA cover and channel plate was decreased to some extent, allowing a low bonding temperature (90 °C) below the T_g of PMMA (105 °C). More importantly, the surfaces of the channels in the channel plates did not touch the DBP-coated surfaces of the PMMA covers so that their T_g did not decrease during bonding. Because the DBP-assisted bonding was carried at 90 °C that was much lower than the T_g of PMMA, the deformation of the channels in the PMMA substrate was minimized so that a higher yield of 94% ($n=100$) could be achieved for the production of the complete microchips in comparison with the glue bonding (60%) [27]. Recently, Chen et al. demonstrated PMMA channel plates and covers could be sealed by vacuum-assisted thermal bonding with high yield up to 90% [42]. The bonding was performed in a vacuum-heating oven for 60 min at 112 °C. The bonding yield in our study is comparable to Chen's work [42], while both the time (10 min) and temperature (90 °C) for bonding were significantly reduced.

Fig. 2 illustrates the photographs of a simple-cross PMMA microchip bonded with a 100-μm thick PMMA cover sheet and a PMMA microchip with pre-column reactor and post-column channel that was bonded with a 1-mm thick PMMA cover plate. High quality PMMA microchips can be fabricated by using the present DBP-assisted bonding approach with no observable interspace along with the absence of the air bubbles in them. Because PMMA chips are transparent, optical microscope was used to check their bonding quality. Fig. 3 illustrates the microscopic photographs of the injection cross section of a PMMA channel plate before and after it was bonded with a PMMA cover. The replication quality of the injection cross section in the PMMA substrate was satisfactory. Fig. 3b indicates that the main channel body and cross section were

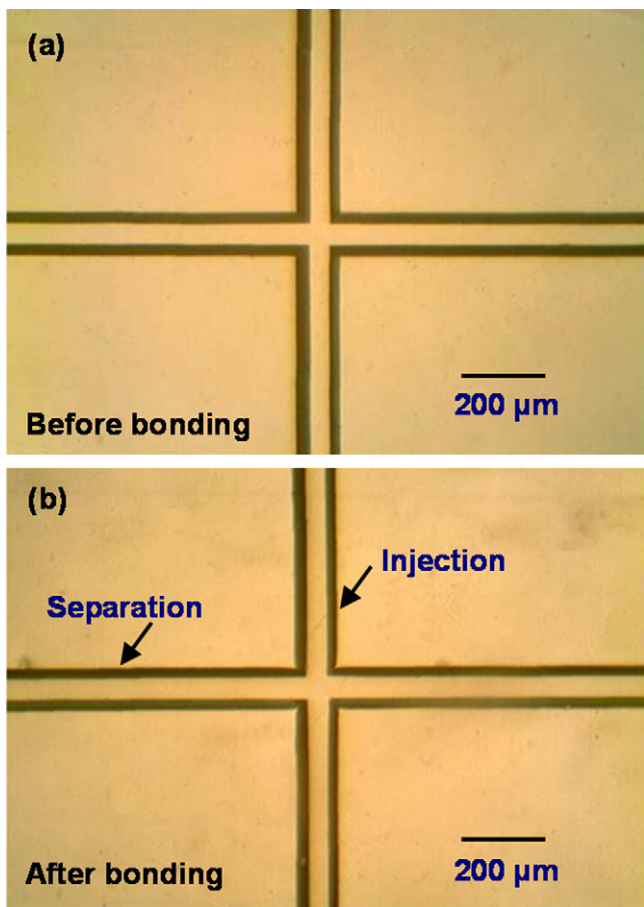


Fig. 3. Microscopic photographs of the injection cross section of a PMMA channel plate before (a) and after (b) bonding. Magnification: 100 \times .

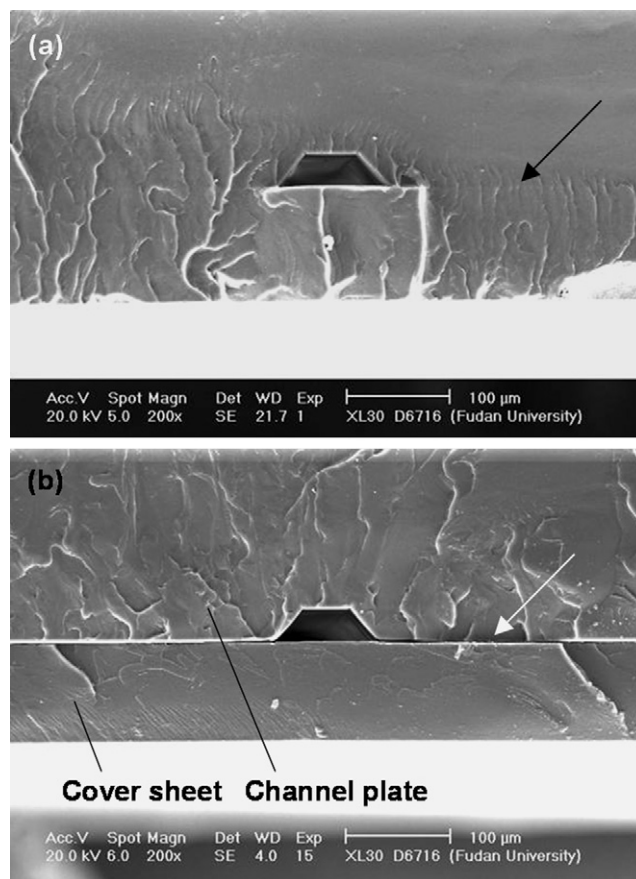


Fig. 4. Scanning electron microscopy (SEM) images illustrating the cross section of channel in PMMA microchips that were bonded with (a) and without (b) the assistance of DBP at 90 °C. Accelerating voltage: 20 kV and magnification: 200 \times .

complete and intact after the bonding process. Such a bonding process provided no changes and voids between the covers and the channel plates.

Fig. 4 illustrates the SEM images of the cross sections of the channels in PMMA microchips that were bonded with and without the assistance of DBP. The continuous furrows on the cross section shown in Fig. 4a indicated that the PMMA cover and the PMMA channel plate merged during the bonding process. No boundary between them was observed, indicating a high quality bonding. In addition, it was found that the bonding of the PMMA microchips with the assistance of DBP was fairly strong, allowing the microchips to be sawed, scraped, polished, filed, and broken without debonding. During the plasticizer-assisted thermal bonding, DBP in the thin DBP-permeated surface layers on the PMMA channel plate and cover caused a reduction in the cohesive intermolecular forces along the polymer chains at 90 °C. The chains could then move more freely relative to one another to achieve entanglement of polymer chains across the interface of the two contacting surfaces. When the temperature was decreased to room temperature, the polymer chains on the contacting surfaces lost their mobility, resulting in exceptionally strong bonding. In contrast, the bonding between the cover and the channel plate was poor in the absence of DBP (Fig. 4b). Boundaries and interspaces can be observed in the SEM image of the channel cross section in the obtained PMMA microchip. The EOF properties of the PMMA microchips were evaluated using the well-established baseline monitoring technique of Huang et al. [43]. The EOF mobility (μ_{eo}) at pH 8.0 measured at a field strength of 200 V/cm was $2.18 \times 10^{-4} \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ that was well in agreement with the liter-

ature values of pristine PMMA chips ($1.2\text{--}2.6 \times 10^{-4} \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$) [9].

Temperature is a key parameter for the DBP-assisted bonding of PMMA microfluidic chips. It was found that satisfactory bonding could be achieved over the temperature range of 85–95 °C. Upon raising the temperature above 105 °C, the microchannel readily tends to be blocked due to the deformation of the PMMA substrates. In addition, the bonding was poor at temperatures below 85 °C.

The earlier solvent bonding works could be performed at room temperature or under heat. If strong solvents (such as chloroform, 1,2-dichloroethane, acetone, acetonitrile) for PMMA were used, the bonding was usually performed at room temperature based on the fact that these solvents could dissolve the PMMA substrates and resulted in strong bond [11]. When methanol [20], ethanol [20,22], and isopropanol [20,23] were employed to bond PMMA microfluidic chips, the bonding had to be performed under heat because PMMA can dissolve in these alcohols at high temperature. All solvents used in the existing strategies for solvent bonding owned low boiling points and high vapor pressures. They might evaporate during bonding and affect the yields of bonding. In most cases, solvents were directly sandwiched between the channel plates and the covers. The solvents might result in the deformation and blocking of the microchannels. In the plasticizer-assisted bonding technique, DBP was employed to assist the thermal bonding of PMMA microfluidic chips at a low bonding temperature because it can decrease the T_g of PMMA [36,37]. The bonding mechanism was different from that of conventional solvent bonding. In solvent bonding, the employed solvents dissolved the surfaces of the channel plates and the covers. When the solvents evaporated, the touched surfaces would

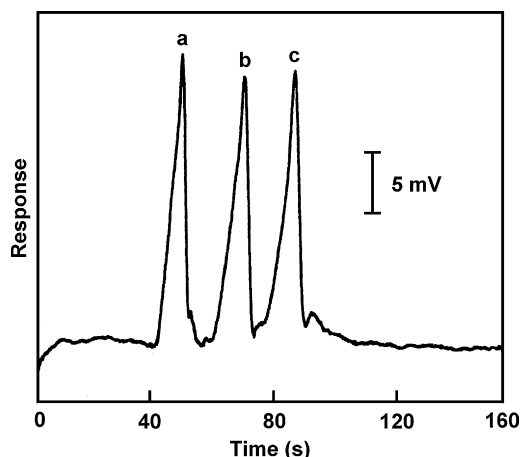


Fig. 5. Electropherogram of a mixture containing (a) potassium, (b) sodium, and (c) lithium (1 mM each). Operation conditions: separation and injection voltage, +1000 V; injection time, 2 s; running buffer, 20 mM boric acid–20 mM TRIS (pH 8.0); sinus waveform with a frequency of 300 kHz and a peak-to-peak voltage of 5 V; electrode distance: 0.8 mm; and electrode width: 0.8 mm.

solidify to form strong bond. In the case of plasticizer-assisted bonding, plasticizer only diffused into the thin surface layers of the PMMA substrates resulting in the decreased T_g and low bonding temperature. In comparison with the existing solvent bonding approaches, DBP used in this work would not evaporate during bonding because of its high boiling point (340 °C at 101.325 kPa) [44] and low vapor pressure (0.032 kPa at 90 °C and 101.325 kPa) [44], offering great promise for the high quality thermal bonding. During the plasticizer-assisted bonding, the inner surfaces of the open channels in the channel plates did not touch the plasticizer coated on the PMMA covers so that the deformation of the channels was minimized. In addition, the present bonding approach is more environmental friendly because the amount of DBP used for bonding was very limited (3 mg per microchip) and the plasticizer was left in the bulk of the microchips rather than in the atmosphere.

The analytical performance of the obtained simple-cross PMMA microchip was demonstrated by the CE separation of three cations coupled to CCD. Fig. 5 illustrates the typical electropherogram of a mixture containing potassium, sodium, and lithium (1 mM each). The PMMA electrophoresis microchip provides baseline-resolved peak shape and high plate numbers (12316, 20988 and 43641 plates/m for potassium, sodium and lithium, respectively) under the selected conditions. The half peak widths of potassium, sodium, and lithium are 4.5, 5.0, and 4.3 s, respectively, with the corresponding sensitivities of 23.61, 21.25, and 20.69 mV/mM. Based on a signal-to-noise ratio of 3, the detection limits of potassium, sodium, and lithium were estimated to be 31.7, 35.3, and 36.2 μ M, respectively. The precision was evaluated based on a 7 repetitive measurements of a sample mixture containing 1 mM potassium, 1 mM sodium, and 1 mM lithium. Reproducible signals were obtained with RSDs of 3.2% (potassium), 2.9% (sodium), and 3.7% (lithium) for the peak heights.

Although only the performance of DBP in the thermal bonding of PMMA microfluidic chips has been intensively investigated in this work, other phthalate plasticizers, such as dioctyl phthalate (DOP), dimethyl phthalate (DMP), and diethyl phthalate (DEP), can also be employed in the plasticizer-assisted bonding of PMMA microfluidic chips at low temperature. They are all transparent liquids with high vapor boiling point and low vapor pressure. In our preliminary experiments, DOP, DEP, and DMP had been successfully applied to decrease the bonding temperature of PMMA microchips because they could lower the T_g of PMMA. The bonding procedures and parameters were the same as those we used in the DBP-assisted

bonding of PMMA microchips in this work because the properties of these plasticizers are very similar.

4. Conclusions

In summary, it was demonstrated a novel bonding approach was successfully developed for the fabrication of PMMA microchips based on the fact that plasticizer can decrease the T_g of PMMA. The bonding temperature was significantly decreased from 108 to 90 °C that was far below the T_g of PMMA (105 °C). Because DBP was coated on the surface of the PMMA cover and did not touch the channel surfaces in the channel plates during bonding, the T_g of the channels would not change so that the deformation of channels was minimized, resulting in a higher yield for the enclosure of PMMA microchannels. No observable boundary was found in the SEM images of the channel cross sections in the prepared PMMA microchips, indicated that the two parts of the microchips merged during the bonding. The plasticizer-assisted bonding of PMMA microchips was almost permanent, allowing the chips to be sawed, scraped, polished, filed, and broken without observable debonding. This flexible and simple bonding methodology offers great promise for the rapid and simple fabrication of PMMA microchips. In addition, the present bonding approach may also find more application in the fabrication of other polymer microfluidic chips.

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