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PAPER

Fabrication of thermoplastics chips through lamination based techniques

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In this work, we propose a novel strategy for the fabrication of flexible thermoplastic microdevices entirely based on lamination processes. The same low-cost laminator apparatus can be used from master fabrication to microchannel sealing. This process is appropriate for rapid prototyping at laboratory scale, but it can also be easily upscaled to industrial manufacturing. For demonstration, we used here Cycloolefin Copolymer (COC), a thermoplastic polymer that is extensively used for microfluidic applications. COC is a thermoplastic polymer with good chemical resistance to common chemicals used in microfluidics such as acids, bases and most polar solvents. Its optical quality and mechanical resistance make this material suitable for a large range of applications in chemistry or biology. As an example, the electrokinetic separation of pollutants is proposed in the present study.

1 Introduction

For lab-on-chips to find their way into routine clinical analysis, microfluidic chips must be inexpensive, disposable and amenable to mass production. In most applications, the choice of the appropriate chip material is fundamental. This involves a complex optimization and selection tree, which must take into account a number of issues, from operational performance to protocol development and industrial cost. The machinability of the device material and, quite often, manufacturing processes lead to compromises regarding the material choice. Thus, both manufacturers and research laboratories are in search of plastic materials able to take advantage of simple and fast processing methods issued from several years of technical developments in industry. Polymers are increasingly replacing traditional microfabrication substrates like silicon and glass and standard microlithography is giving way to "soft lithography" or replication-based methods.[1] PDMS remains one of the most popular materials for fast prototyping. Nevertheless, this elastomeric material is poorly adapted to mass production requirements and its mechanical softness, surface treatment instability and gas permeability strongly limit its applicability for many biological or chemical purposes.[2]

The proportion of thermoplastic and thermoset materials in microfluidic applications has been increasing very quickly during the last few years. In addition to their large range of physical–chemical properties, thermoplastic materials benefit from a large variety of already existing industrial fabrication processes. In particular, latest developments in this field emphasize the role of replication based techniques such as *hot embossing* and *injection molding*.

Hot embossing is probably one of the simplest and most straightforward methods to replicate microfluidic channels in thermoplastic substrates.[1,3–8] Despite its low throughput, this technique can be implemented on low cost press systems and is a method of choice for the production of microfluidic devices in a laboratory environment.[9] *Injection molding*, in contrast, was developed for the industrial manufacturing of large series of devices. Even if some examples were reported at the academic level,[10–12] this technique is poorly exploited because of its price and global initial investment. Typically, depending on its complexity, the "entry cost" (cost to be spent before having the first device) of this technology lies between twenty and several hundred thousand dollars. Bridging the gap between this large scale production and hot embossing, with processes that are flexible enough to be compatible with academic research constraints, is still a challenge. Lamination based techniques offer a strong potential in this respect.

In particular, roll to roll embossing is an attractive alternative to hot embossing.[13] This method is based on a replication between two rotating rolls instead of fixed plates. It was initially developed in the context of nanostructures replication[14–16] and was more recently extended to microfluidic device fabrication.[17–19] Several variants of the process include double sided patterning of foils,[20] extrusion embossing,[21] ultraviolet embossing[15] and hot roller embossing.[17,22] Roller embossing or roll-to-roll embossing is a well known variant of the hot embossing process. Using rolls instead of plates, roller embossing is a continuous process in which heat is supplied to the embossing interface through the rolls while a clamping pressure is applied between the two rollers. This feature ensures a uniform

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combination of contact time and contact pressure even over large substrates (width up to 2 m on industrial machines), and on arbitrary lengths. Roller embossing requires simple and low cost equipment and thus is well adapted for rapid prototyping. Contrary to hot embossing it provides continuous molding capabilities and thus compensates for limitations regarding throughput. It offers a better replication uniformity and reduces constraints regarding sample size limitations and opens the way to flexible devices manufacturing also referred to as lab on foils. Finally roller embossing provides fast production and is easily amenable to industrial manufacturing[13] being compatible with a large range of roll-based integration technologies (*e.g.* screen printing, laser ablation, laser bonding…).[13,22] More generally, roll-based technologies can borrow technologies from the printing industry and achieve development shortcuts, getting *e.g.* inspiration from the explosive development of "printed electronics".

In this work, we used the advantages of roll-to roll embossing to develop a complete fabrication toolbox for thermoplastic microfluidic devices (Fig. 1) adapted to rapid prototyping (<2 h from master fabrication to final device integration) and compatible with the production of short series of samples (>20 copies with the same master). We used Cyclo-Olefin Copolymer (COC) as a demonstrator material for chip fabrication.

We first investigated a process for master fabrication. We developed here a method that offers very short fabrication time and leads to robust flexible masters with a lifetime compatible with 30 successive replications. We studied the evolution of the dimensions of the replicated structures as functions of parameters such as the rollers temperature, embossing pressure and rotation speed. Finally, in order to seal the channels, we developed a simple and reliable solvent assisted bonding method that was performed using the same roll-lamination setup. The method is compatible with both flexible and rigid microfluidic chip fabrication.

2 Experimental

Materials

COC films (Topas® 8007, T_g = 80 °C, 135 μm thick) were purchased from Topas Advanced Polymers. Flexible copper boards were obtained from CIF (France). They consist of 55 μm polyimide films covered with a 35 μm copper layer. Dry film resist (Ordyl AM 100) was purchased from Elga Europe (Italy). Developer solution was prepared by dissolving Na_2CO_3 (VWR) in Milli-Q water with a concentration of 0.85% (w/v). Anthracene-9-carboxylic acid, 2-(fluoranthene-8-carbonyl)-benzoic acid, hexadecane and acetonitrile were purchased from Sigma-Aldrich (France).

Equipment

Lamination, roll to roll embossing and microchannel sealing were all performed on a RLM 419 laminator (Bungard Elektronik GmbH & Co.KG, Germany).

Photopatterning was done using a 5 cm collimated UV light source (model 66808, Oriel Instruments). During exposure, samples were mounted on a 30 cm long translation stage that was withdrawn at a constant velocity. This simple and low cost setup allows for the production of 30 cm × 5 cm samples. The appropriate exposure dose was chosen by adjusting the stage velocity. Characterization of the replicated structures was performed through SEM observation (Hitachi, S3600). 3D profiles

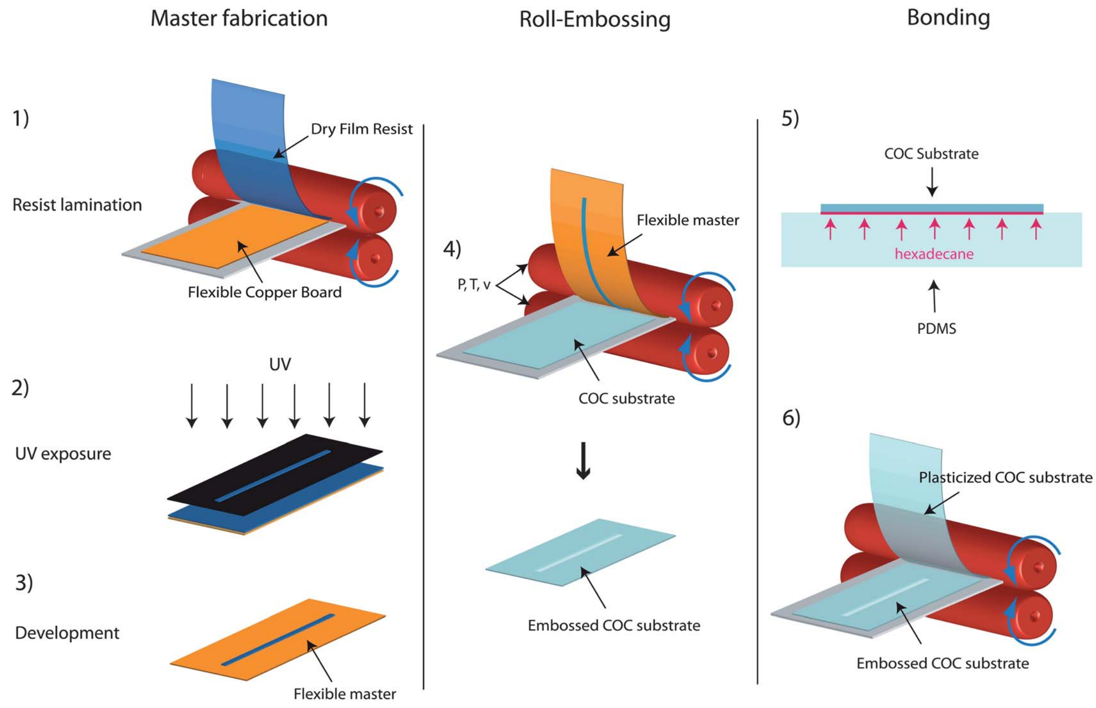

Fig. 1 Schematic representation of the lamination-based processes: (1) lamination of the dry film resist on the substrate, (2) and (3) photolithography steps, (4) replication by roll-embossing, (5) and (6) bonding steps.

were obtained through optical profilometry (Wyko NT1100 Optical Profiling System, Veeco).

Flexible master fabrication

The fabrication process is summarized in Fig. 1. Flexible Copper Boards (FCB) were first deoxidized in a diluted solution of orthophosphoric acid (20/80; v/v in deionised water), rinsed in water and then dried in a nitrogen stream. A dehydration bake was then performed at 120 °C for 15 min on a hot plate to improve resist adhesion. AM negative dry film resist was laminated on copper substrates at 90 °C with a speed of 0.3 m min^{-1}. In order to produce large features without the expense of a large mask aligner, resist exposure was performed on a homemade photolithography system composed of a UV lamp and a translation stage. The samples were translated together with a photomask to perform exposure. This method allows us to prepare masters with a width up to 2 inches, and an arbitrary length (up to 30 cm) using a conventional and low cost illumination device. The stage velocity is directly related to the exposure time, and was adapted to resist thickness (30 µm: 2 s, 50 µm: 5 s, 100 µm: 10 s, 200 µm: 15 s). Resist development was performed in an aqueous Na_2CO_3 solution (0.85%, w/v) at 30 °C. Samples were finally rinsed with DI water and dried in a nitrogen stream.

Roll-embossing of COC with flexible masters

Fig. 1 illustrates the process used for the structuration of flexible COC chips. A Topas 8007 film (T_g, 85 °C, 135 µm) was cut at the desired size, cleaned with isopropanol and dried with a nitrogen stream. The COC films were inserted together with masters between the laminator rolls. Lamination experiments were performed at temperatures ranging from 90 °C to 190 °C and speed ranging from 0.3 to 0.55 m min^{-1}. Once out of the laminator, the COC films were peeled off at room temperature. Access holes were punched with a card puncher.

Microdevice bonding

Enclosing of the devices was done by bonding the embossed COC film to a second flat COC substrate. We developed an inkpad-and-solvent-assisted bonding process. First, a slab of PDMS was prepared by replication molding on a flat surface (*e.g.* polystyrene Petri dish or silanized silicon wafer). This slab was used as an inkpad. It was first immersed in a solution of hexadecane for 1 hour. After immersion, the excess of hexadecane was removed from the inkpad surface using a gas stream (*e.g.* nitrogen or argon). COC substrates were placed in contact with the flat inkpad surface for 4 minutes as shown in Fig. 1 (5). The originally patterned film and the plasticized one were then laminated together at 80 °C (below the T_g). Cross-sectional cuts of the sealed channel were obtained using a razor blade. Examples of final flexible chips and cross-sections of the channels are given in Fig. 2a–c. All these steps were done in a laminar flow hood to limit contamination with dust particles.

Chip holder

In a first approach, 1 mm diameter access holes were punched in the embossed COC films before bonding using a card puncher. Commercial microfluidic adapters (NanoPort Upchurch Scientific) were then mounted and sealed using UV-curable adhesive (Norland Optical Adhesive 61).

In another approach, a home-made stainless steel adapter was used as a chip holder and as an interface for external fluidic connexions. Fluid injection was done using a PMMA manifold. Leak-free connexion was ensured by inserting o-rings. Fluidic connexion was performed using luer-lock connectors (Value Plastics Inc.).

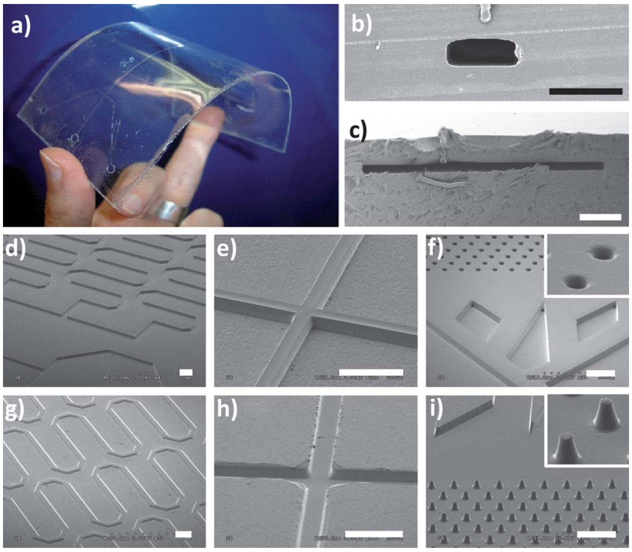

Fig. 2 (a) Flexible chip with a long separation channel (15 cm); SEM images of the cross-section of the sealed chip with 20 × 50 µm (b) and 30 × 200 µm (c); SEM images of masters (d–f) and COC replicas (g–i) after metallization. Bars 200 µm.

Electrokinetic separation of charged compounds

As an application, we performed microchip electrophoresis experiments which were carried out on the stage of an inverted fluorescence microscope (Nikon Eclipse Ti) with a simple cross-chip with 50 µm depth, 50 µm width and 6 cm length.

Voltage control was performed by inserting platinum wires (10 µm diameter) in the chip reservoirs. A HVS488 high voltage sequencer (LabSmith, Livermore, USA) was used to apply voltage from −3000 V to 3000 V.

The two model compounds used for electrophoresis were anthracene-9-carboxylic acid (A) and 2-(fluoranthene-8-carbonyl)-benzoic acid (B). The background electrolyte (BGE) was prepared with 80% of acetonitrile and 20% of borate buffer solution (ionic strength 8.75 mM and pH 9.2). The sample consisted of a mixture of A and B with [A] = 2.7 mg mL^{-1} and [B] = 3.7 mg mL^{-1} in BGE. Electrolytes were prepared by using 18.2 MΩ deionised water filtered through a Milli-Q purification pack (Millipore, Bedford, MA, USA).

The pinched injection was performed by applying 550 V in A, 900 V in B, −790 V in C and 650 V in D. Separations were performed by applying −1000 V in A and C, +1500 V in B and −3000 V in D. The detection was performed at 1 cm away from the injection cross.

3 Results and discussion

As for most replication-based techniques, the question of the transfer of high aspect ratio structures remains critical. Some studies related to hot roller embossing can be found in the literature, but most of the results reported until now are mainly devoted to the replication of nano structures.[23] Several groups have demonstrated the potential of this technique to achieve very high production rates (in excess of 1 m s^{-1} for plastic foil of up to 2 m width) but the fabrication of micron sized features with deep relief (typically >10 μm) such as those required for microfluidic applications is not yet an established mass-production process.[24] The main difficulties in transferring such structures come from the large volumes of polymers that must be displaced during replication, combined with its high viscoelastic constants. Thus, in contrast with *e.g.* PDMS replication, in which replication difficulty increases with decreasing size, in thermoplastic embossing, increasing both the size and the aspect ratio of structures induces higher processing times for complete replication, requires a global increase of the temperature and/or pressure budget, and generally speaking makes the optimization of operational parameters more difficult.

This also provides additional constraints on masters, which must have enough rigidity, robustness and life expectancy in operating conditions involving high temperatures and high stresses. Moreover, whereas flat, rigid masters are usually used in hot embossing or injection molding, hot roller embossing typically requires flexible masters (or, for industrial scale, cylindrical ones, as in the printing industry). Classical molds employed in hot embossing or hot roller embossing are nickel shims, usually obtained through electroplating.[17,25,26] Although such molds are mechanically resistant and likely to withstand hundreds of replications, their manufacturing is expensive and time consuming and thus poorly adapted for fast prototyping. Other solutions relying on flexible polymer molds were also proposed.[27] In most cases, these approaches imply first the fabrication of a master using photolithography[28] and eventually additional transfer steps.[29] This first master is then transferred through replication to yield a flexible master. This approach, however, increases the global development time.

We propose here a solution based on hybrid polymer–metal masters, which provides both a better master robustness and faster prototyping. Copper laminated polyimide foils were used as the base support while dry film resist was used to define the structures to be embossed[30] (Fig. 1). Dry film resist (DFR) has several advantages; it provides high aspect ratio structures with thicknesses ranging from 20 to 500 μm; this resist can be laminated on substrates using the same lamination system as used for roll embossing. It provides a good thickness uniformity and strong adhesion to metal layers, even on large scales. DFR can be patterned through photolithography in a single step process and does not require any baking procedure. In this study we used a collimated UV light source to perform exposure. Compared to a conventional mask aligner this system provides a cheap and flexible way of producing resist patterns. Moreover, the light source was coupled to a translation stage which extends the exposure area and makes possible the production of channels up to 30 cm. For example, a significant limitation of microchip electrophoresis, as compared to capillary electrophoresis, is the microchannel length, which in turn influences resolution. Thanks to our setup, we can easily prepare flexible microfluidic devices with straight and long channels as shown in Fig. 2a.

Regarding the substrate, polyimide provides the flexibility and robustness necessary for roll processing while the metal laminate improves mechanical robustness, adhesion with the master structures and heat transfer during the embossing step. These films are flexible and can be easily wrapped around a roll. Approaches involving copper substrates were already reported in literature[30,31] but either they do not lead to flexible masters or do not provide resolution better than 100 μm.

Fig. 2d–f shows SEM images of flexible masters prepared according to the described method. Dry film features were transferred by photolithography in a 55 μm thick film. The minimum feature dimension we tested was 20 μm yielding an aspect ratio close to 1 : 3. The amplitude of the feature edge roughness was <5 μm. Structures with higher aspect ratios could be obtained but experiments revealed their limited mechanical stability upon embossing. Thus, we restrict this technology to thickness to width aspect ratios up to 3 only. Fig. 2g–i shows SEM images of the corresponding structures after replication at 190 °C and 0.3 m min^{-1}.

Influence of the rolling speed and roller temperature on the replication depth

Optimization of heat transfer between master and substrate is a critical issue in roll embossing. Indeed the actual contact time between the master and the polymer substrate is very short (typically in the order of a few seconds) and heat transfer from the master thus limits polymer flow. Using low-cost polymer based or hybrid masters suitable for fast prototyping, thermal transfer has to be carefully optimized to provide homogeneous and accurate replication while preserving the master from mechanical or thermal stress that could critically impede its lifetime. This is quite different from hot embossing where the sample is given a long time to heat up and contact times can be increased indefinitely to perform the transfer. Furthermore pressure can be applied continuously during cooling and demolding occurs at low temperature, typically below polymer's T_g.

Preheating can be a solution for softening the polymer prior to embossing,[17] but this feature is in general not available on low-cost lamination machines. In our approach, we compensate for this limitation by increasing the roll temperature to well above the T_g of the polymer material. For instance, in the experiments dedicated to Topas 8007 materials (T_g = 80–85 °C), we investigated temperatures ranging from 90 °C up to 200 °C.

In order to evaluate the embossing accuracy and dimensional stability after several replications, the following parameters were monitored during the successive embossing steps: the depth of the channel (H), the width at the bottom (l) and the width at the top of the channel (L). The roller velocity was set to 0.3 m min^{-1}. For a continuous process, this speed would allow a throughput between 100 and 500 chips per hour, depending on chip size. Such a throughput comfortably exceeds the needs of fast prototyping applications.

Fig. 3a shows a first illustration of the influence of rolling temperature on the quality of replication using a master of 50 μm width and depth. All measurements were repeated 3 times.

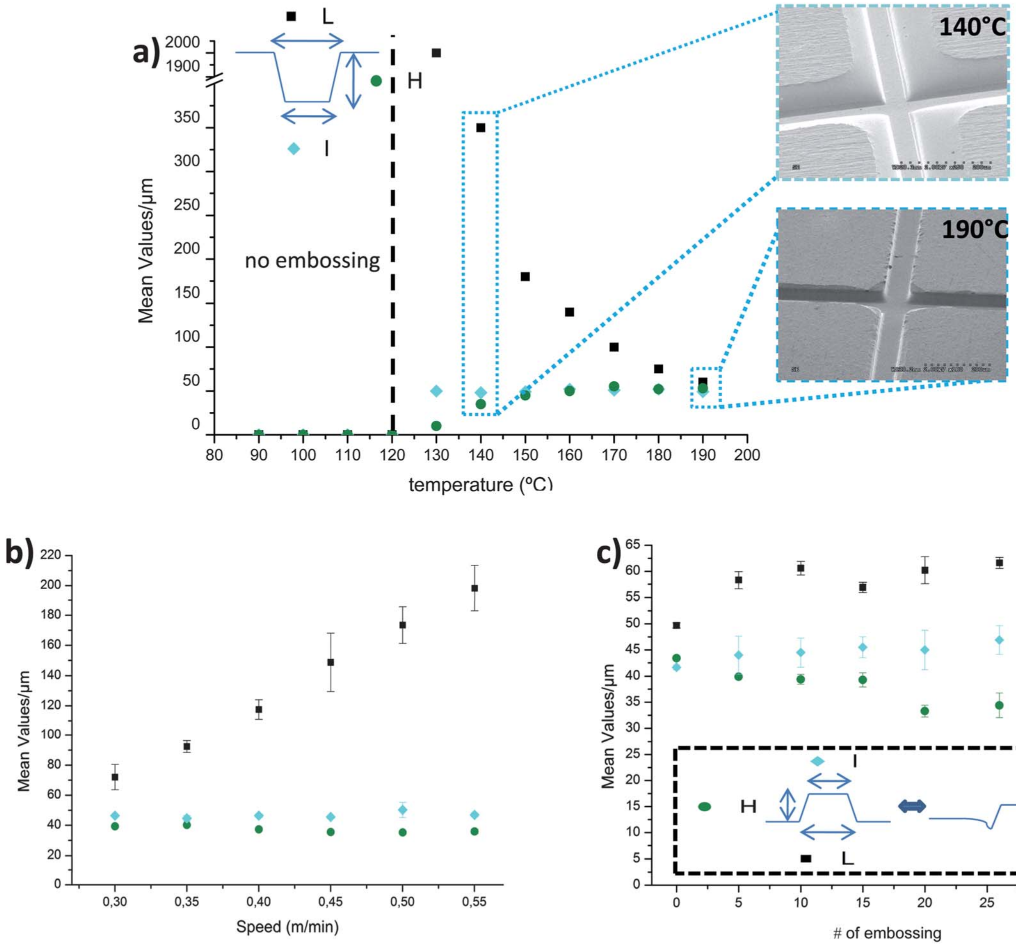

Fig. 3 Influence of (a) the rolling temperature on the dimension of a replica from a 55 × 55 μm square channel master; (b) the rolling speed; (c) the number of embossing on the shape of the master. (Black squares, width at top; green circles, depth; blue lozenges).

L, *l* and *H* parameters were monitored as a function of *T*. At a 0.3 m min^{-1} velocity, we found the optimum replication temperature (*i.e.* the minimum value resulting in a homogeneous transfer of the structures *H*, *l* and *L* matching the expected dimensions) was around 180–190 °C. This set of parameters was used for the replication of the structures shown in Fig. 2g–i.

At lower temperatures, we observed a clear decrease of the structure depth *H* (from 40 μm down to 30 μm) associated with an increase of the *L* parameter. These results suggest that in this temperature range the polymer viscoelastic flow becomes limiting and results in an incomplete replication. As the mold penetration is limited by polymer viscosity, the resulting mechanical stress is distributed around the contact areas, leading to a large deformation around the structure edges that appears as a structure enlargement on the graph. It is interesting to notice that below 120 °C, no transfer is observed. This result suggests that just below this threshold value, the effective temperature at the master/sample interface becomes lower than polymer's T_g.

In another set of experiments described in Fig. 3b, the temperature of the roller was kept constant (190 °C) while the roller speed was increased from 0.3 m min^{-1} up to 0.55 m min^{-1}. As discussed above, increasing the roller speed leads to a shorter contact time and to a partial transfer of the master features into the COC substrate (both *L* and *H* parameters deviate from expected values). These experiments show once again the impact of insufficient heat transfer to overcome the viscoelastic behaviour of the polymer material.

Ageing and lifetime of the flexible masters

The robustness and lifetime of the hybrid masters were then studied. We first investigated the ageing of the master by monitoring the evolution of the structure dimensions through repetitive imprints, using the optimum process parameters found before (190 °C, 0.3 m min^{-1}). Fig. 3c shows typical results obtained after more than 30 replications using the same template. Whereas both *L* and *l* parameters stay within the ±5% tolerance, it is clear from this figure that the depth of the embossed structures decreases over the number of replications. Indeed after 15 replications we observe a clear decrease of the height of the master from 40–45 μm to 30–35 μm. A first intuitive explanation for this result would be to consider a possible collapse of the master features. This hypothesis was ruled out, as profilometry scans of the masters showed no significant deformation of the master structures. However, larger scans of the back of the master surface revealed a long-range deformation of the polyimide substrate (Fig. 3c). We think that this observation can be associated with the elastomeric behaviour of the roller, combined with the compliance of the polymer film used as a basis for the substrate. Indeed, roll lamination is performed through silicone heating rollers. The deformability of the rollers upon pressure provides a reliable and uniform contact between the master and the substrate. However, the deformation of the rollers during replication induces, in the contact areas, a mechanical stress and deformation of both master and substrate. Even though this mechanism does not affect significantly the dimensions of the embossed features, we believe this causes an accelerated ageing of the master. A solution to this problem might lie in the replacement of the polyimide basis of the embossing film by a harder material. Alternately, a harder material could be used for the rolls.

In this set of experiments, the process was stopped after 32 embossings, the last experiment causing damage to the dry film structures. Whereas we observed no issue concerning polymer adhesion, it seems however that the successive heating and pressure cycles cause an accelerated ageing of the polymer material. This lifetime is significantly smaller than that of Nickel or Silicon masters, which can withstand hundreds of replications. Nevertheless, considering the quick master fabrication process (less than 1 hour), the low cost of the starting material, and the low embossing time (few seconds) we believe that this approach offers a reliable route for short series manufacturing (typically 20 devices) and is particularly well adapted to rapid prototyping.

Channel sealing

The sealing of the channels is a critical step in the fabrication process of thermoplastic chips. Typically it consists of bonding a capping layer to the microchannel substrate, in order to create enclosed fluidic paths. Several considerations have to be taken into account to select the appropriate bonding method. The bond strength will control the robustness of the devices and is critical, especially when dealing with *e.g.* high pressure flow or applications such as PCR, requiring repeated cycling between high and low temperatures. The sealed interface must also provide chemical and solvent compatibility with the targeted application. Finally, the bonding method must prevent channel deformation and preserve the dimensions, shape and surface chemistry of the channels.

In this respect, thermoplastics materials are advantageous: they offer the possibility to fabricate monolithic devices, and the variety of available materials solves most of the issues related to surface chemistry. In the most straightforward approach, enclosed devices are obtained by direct thermal bonding, *i.e.* by heating the surfaces to be assembled above their T_g. The combined effect of pressure and temperature generates flow of the polymer at the interface to achieve intimate contact, inter-diffusion and ultimately entanglement of polymer chains between the surfaces. A critical issue in this method is to prevent excessive deformation of the channel cross-sections by properly controlling temperature, time and pressure. Even with a well characterized bonding system, the limitation of channel collapse remains a critical step.[32] Notably, microchannels with a very low aspect ratio (*i.e.* wide and flat channels) are difficult to achieve.

Decreasing the T_g of the material surface is an advantageous method to solve the above problem as it provides local bonding while limiting the bulk material deformation. This can be achieved either by depositing a low T_g material on the surface[33] or by using a solvent. As compared to glue-assisted bonding, this latter approach retains the monolithic character of the device. This method is simple and readily scalable from rapid prototyping to high throughput mass production. Solvents can be applied either in liquid or vapor phase.[19,34] Vapor phase deposition is a simple and effective method but unfortunately this process is rather slow and requires a precise control of experimental conditions.[34] We have already reported a method based on a mixture of solvents (IPA/hexadecane) to perform COC chip bonding.[19] Whereas this method provides an improved control of solvent absorption, it requires many precautions to control the homogeneity of the solvent mixture deposition. Here, we propose a novel strategy using a PDMS inkpad to control the amount of solvent deposited on the surfaces to be treated. The inkpad is first saturated with hexadecane by immersion. The polymer substrate is then placed in contact with the inkpad. When in contact, the solvent diffuses towards the COC substrate through the PDMS elastomeric network. This approach provides a better control of the exposure time compared to a method involving direct immersion of the substrates. The elastomeric behavior of PDMS ensures a uniform contact and thus a homogeneous surface treatment. Furthermore, this method is compatible with the treatment of patterned substrate. While the inkpad supplies solvent to the surface to be bonded, the recessed structures (*e.g.* microchannels) are preserved, and they will resist deformation during the bonding process. This method is thus perfectly adapted to multilevel microfluidic chip fabrication. Finally, it can be directly upscaled to mass production and integrated in lamination-based techniques, for instance using an elastomeric roller as the inkpad for continuous surface treatment prior to bonding, a process adapted to roll embossing.

Bonding was finally achieved by placing the treated substrate in contact with the embossed microchannel substrate and by performing a "warm lamination" at 80 °C, *i.e.* below the T_g of the chip material. Both temperature and pressure applied during lamination promote intimate contact and help the inter-diffusion of polymer chains at the interface and lead to a uniform bonding as shown in Fig. 2b and c. Thanks to this method, microfluidic channels with aspect ratios (width/thickness) up to 25 were successfully sealed without deformations as shown in Fig. 2c. To our knowledge, such aspect ratios are extremely difficult to achieve with conventional techniques.

In ideal conditions, the bond strength resulting from solvent bonding can reach the cohesive strength of the bulk material. Experiments performed in COC chips showed a pressure resistance up to at least 10 bars without any damage (experiments at higher pressures could not be performed due to limitations in our connectors). This pressure is typically one order of magnitude higher than that affordable in PDMS chips, and suitable for many classical microfluidic experiments, for instance for the introduction of viscous sieving matrices for microchip electrophoresis,[35] or for imposing high flow rates in relatively long microchannels.

Electrokinetic separation of charged compounds

To demonstrate the potential of our thermoplastic devices for analytical purposes, we investigated the electrokinetic separation of non-hydrosoluble polycyclic aromatic hydrocarbons (anthracene-9-carboxylic acid and 2-(fluoranthene-8-carbonyl)-benzoic acid). These chemicals are known as pollutants and have been identified as carcinogenic and mutagenic. Due to their low solubility in water, organic solvents are thus required. From a general point of view, organic solvents have been used, either pure or in mixture, to improve the resolution of electrokinetic separations.[36–38] In addition to the analysis of non-hydrosoluble compounds, organic or hydro-organic solvent systems can be used to change the solvation or the charge of the analytes in order to improve separation performance. As compared to other thermoplastic materials (*e.g.* PMMA, PC, *etc.*) or PDMS, COC is chemically inert as it is only affected by highly oxidizing treatment such as, for instance, plasma or electrochemical.[39] COC thus appears as very appealing for the development of such separations.

We took advantage of the high chemical resistance of COC towards solvents to perform the separation of PAHs using an electrolyte consisting of acetonitrile (MeCN) and borate buffer. As expected, the PAHs are negatively charged using this hydro-organic electrolyte. Fig. 4 presents the separation of the two PAHs using an electrolyte containing 80% of MeCN in the COC microdevice. The COC microchip electrophoresis provides baseline-resolved peaks with a resolution of 1.6. The efficiencies achieved for anthracene-9-carboxylic acid (A) and 2-(fluoranthene-8-carbonyl)-benzoic acid (B) are rather high (13577 and 23378 pl m^{-1} respectively). To investigate the influence of hydro-organic electrolytes on COC chips, the separations were repeated 5 times using the same microdevice. The relative standard deviations (RSD) obtained for separation times were 2.1% for A and 2.6% for B. These values of reproducibility and efficiency were comparable to those obtained with glass chips. These results demonstrate the reproducibility of the separation even when using a high solvent content, and thus indicate that there was no significant adsorption of the analytes on the COC surface. Furthermore the device has withstood more than 10 experiments in hard conditions such as the use of hydro-organic solvents.

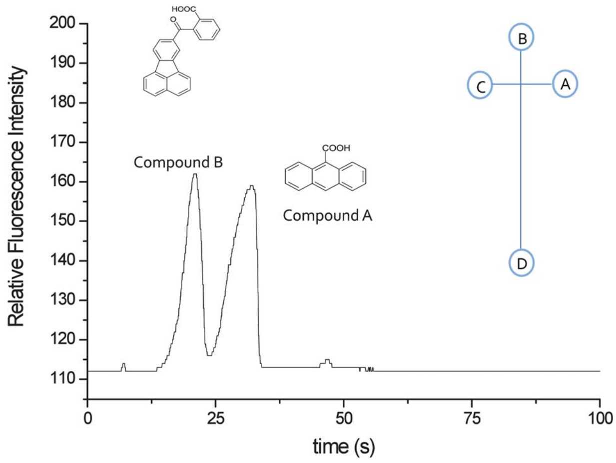

Fig. 4 PAHs separation on COC microchip under 550 V cm^{-1}. Electrolyte: acetonitrile in borate buffer (I = 8.75 mM; pH = 9.2) (80/20, v/v): PAH concentration: [A] = 2.7 mg mL^{-1}; [B] = 3.7 mg mL^{-1}: distance from injection to detection: 1 cm: Well A: sample, wells B, C and D: running buffer.

4 Conclusions

In conclusion, we have demonstrated a rapid and very simple prototyping method for the preparation of thermoplastic microdevices, and applied it here to the preparation of COC microfluidic chips. The complete process based on lamination has been successfully developed for fast prototyping of short series (around 20). By using a simple office laminator we were able to perform all the procedures needed to create a robust microsystem withstanding at least 1 MPa (10× atmospheric pressure). This process involves the use of hybrid polymer–metal masters, prepared from low-cost initial films, and an original stamp-and-solvent-assisted bonding. Microchannels with a wide range of sizes (from 20 to 500 μm) and width to thickness aspect ratios (from 1/3 to 25) could be achieved with low deformation. This process could be used at laboratory scale but, as compared to PDMS and soft lithography, it offers a much more direct route towards upscaling and industrial production, and the democratization of microfluidic chips for chemical and biomedical applications. For that, the flexible "hybrid" masters used here should be replaced by metal based masters (either flexible micropatterned metal films, or cylindrical masters). Metal masters would also allow the use of higher embossing pressures, and a significant acceleration of the embossing speed, as compared to the current fast prototyping strategy. Finally, the chemical inertness and mechanical resistance of COC also expand the range of potential applications to high pressure flows and "harsh" fluids, notably including most organic or hydro-organic solvents.

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