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Maskless writing of microfluidics: Rapid prototyping of 3D microfluidics using scratch on a polymer substrate

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ABSTRACT

We present a new rapid prototyping method designed for simple fabrication of 3D microfluidics using a maskless direct writing technique on polymer substrates. The entire process is enabled by a commercial cutter plotter with 10 μm resolution precision and high speed. A CAD design of top and bottom microstructures is directly written on a polymer substrate using a cutter plotter after setting up the suitable force. The smallest channel width of 20 μm was obtained with the minimum force and 100 μm from the maximum. Also the written depth increased linearly with force from 30 to 130 μm. Several 3D microfluidic devices are demonstrated using a maskless writing technique. The entire fabrication process from CAD layout to a final 3D device can be completed in 30 min outside the clean room facilities.

1. Introduction

Microfluidics is the technology of systems that process or manipulate tiny volume of fluids, using channels with dimensions in the order of micrometers [1]. The technology has grown rapidly over the past two decades, and its advances are revolutionizing multidisciplinary fields intersecting engineering, physics, chemistry, microtechnology, and biotechnology.

Early microfluidic devices were mostly made with fabrication methods developed in the microelectronics field and involved materials like glass, quartz, or silicon. However, these relatively complicated fabrication processes and the demand for disposable devices such as point-of-care diagnostic testing devices motivated the use of polymer fabrication techniques as alternative fabrication methods and for rapid prototyping processes.

Current commercial rapid prototyping methods for microfluidic devices include: casting of polydimethylsiloxane (PDMS) [2–9], laser ablation [10–14], stereolithography [15], micropowder blasting [10], hot embossing [4,16], micromilling [17], and lamination [18,19]. Due to its simplicity and short replication time, casting of PDMS, also often referred to as soft lithography, has become the most common prototyping process in the laboratory environment [2,3,6]. More recently a number of creative ways have been demonstrated to reduce the cost and time for fabricating mold masters for casting PDMS microfluidic devices [20–23].

Lamination of polymeric films is another fast prototyping process for thermoplastic-based microfluidic devices. It is mostly performed by laser cutting and lamination of thin layers of plastic [12,24]. Laser cutting generally requires expensive equipment (in thousands of dollars) and high maintenance costs [18–19]. As plotter technology has significantly improved, commercially available cutter plotters (a plotter fit with a knife blade) can now achieve precise control in the range of 10 μm resolution with high speed at a quite low cost set up (in hundreds of dollars). Bartholomeusz et al., [18] demonstrated an inexpensive prototyping method exploiting a cutter plotter and a pressure sensitive adhesive (PSA) film.

There are many microfluidic components that utilize relatively small (less than 100 μm) microchannel structures on either the bottom or top layer of the device (e.g. a chaotic mixer with herringbone structure [25]). Although a cutter plotter is able to perform a fast and low-cost prototyping, the minimum feature width usually increases with the film thickness used due to a blade thickness making it challenging to achieve a clean cut for 100 μm width on 50 μm thick PSA film [19].

We adopted and modified a fast prototyping method using a cutter plotter, and present rapid prototyping method of 3D microfluidics using scratch writing on a polymer substrate (Fig. 1) [18].

2. Experimental

2.1. Equipment

A cutter plotter is similar to an ink plotter, it cuts films or materials like vinyl with a knife blade instead of plotting onto it.

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It has been used in the graphic arts industry to make large retail signs. We purchased a desktop digital cutter plotter (Craft ROBO Pro, CE5000-40-CRP, Graphtec America, Inc., Santa Ana, CA, USA) because it has a programmable resolution of 10 μm while most plotters achieve only 25 μm, and a repeatable resolution of 0.1 mm per 2 m. It also cuts materials up to 0.25 mm thick with a force up to 2.9 N.

It comes with standalone software (ROBO Master Pro®) which supports the DXF file format and a Cutting Master 2® plug-in for use with Adobe Illustrator® and CorelDraw®. A layout file of microfluidic device design can be generated in any software supporting DXF file like AutoCAD® (Autodesk, Inc., San Rafael, CA, USA) and then imported onto the ROBO Master Pro® for cutting. Adobe Illustrator® and CorelDraw® can be used directly for cutting after editing.

2.2. Characterization of scratches

The major factors that determine the size of scratches are tension in the substrate material, blade sharpness, cutting speed, and substrate material properties such as Young's modulus and Poisson's ratio. Test patterns of three 5 mm long lines at each applied force were drawn in a CAD program and imported into ROBO Master Pro®. These patterns were cut on 1 mm thick cyclic olefin polymer (COP, Young's modulus: 2600–3500 MPa, Poisson's ratio: 0.41) sheet (Zeon Chemicals, Louisville, KY) at a cutting speed of 10 cm/s. The blade used is CB09 UA with a width of 0.9 mm. Characterization of written micropatterns on polymer substrates was performed by observing width and depth achieved with different force setups using measurements from a surface profiler (KLA Tencor, Alpha-Step 500, Milpitas, CA), and from SEM images analyzed with ImageJ (http://rsb.info.nih.gov/ij). The cutter plotter employed in this work allows for the application of nominal forces between 1 and 30 (0.2–2.9 N).

A cross-section of the written microchannel has triangular shape resulting from the wedge of the cutter blade (Fig. 2). The smallest channel width of 20 μm was obtained with the minimum nominal applied force (0.2 N) and 100 μm from maximum (2.8 N). The channel width increases linearly as force increases. The written depth increases linearly with force from 30 to 130 μm (Fig. 3).

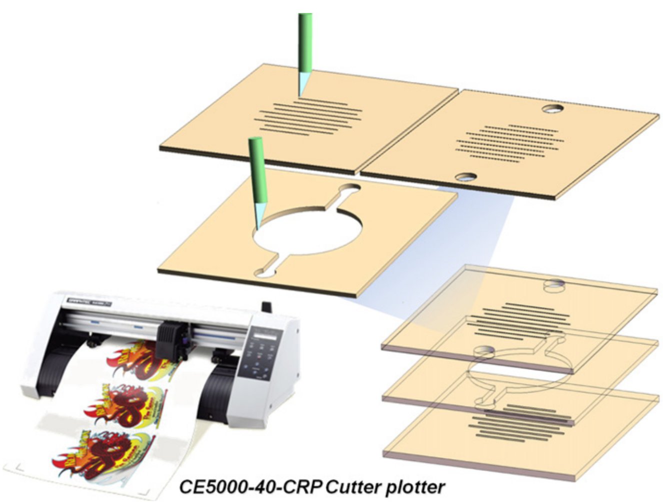

Fig. 1. Fabrication process of writing microfludics using a cutter plotter showing both a through cut layer and scratched microfluidic patterned layers bonded to form a complete 3D microfludic channel.

3. Device examples

Various 3D microfluidic devices are demonstrated using a maskless writing technique. A CAD design of the top and bottom microstructures and the alignment mark of inlet and outlet holes are directly written on a COP sheet using a cutter plotter after setting up suitable force and cutting speed depending on the design of each device. After peeling off COP sheet from a cutting mat, inlet and outlet holes are drilled in the top layer.

A main channel is made by cutting completely through a polymer film with desired thickness. In order to create a deeper microfluidic device, multiple layers of film can be stacked. Main channel designs for each of the microfluidic devices were drawn and loaded onto the cutter software. The cutter plotter cuts the main channel design out of a 188 μm thick COP film (ZF-188, Zeon Chemicals, Louisville, KY) covered with 50 μm thick plastic protective layers that were adhered onto a reusable cutting mat. Next, the cut layer was peeled away from the reusable cutting mat carefully not to cause any damage to thin cut film. The prepared

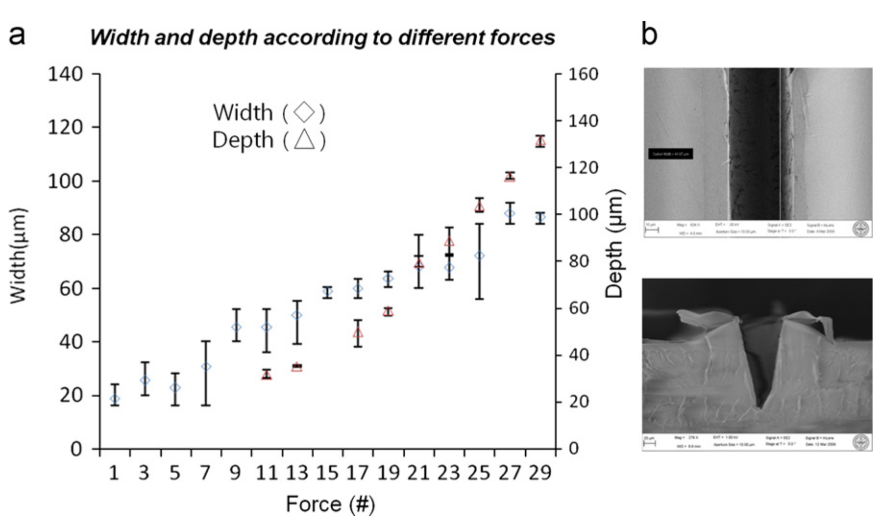

Fig. 2. (a) Plot for the width and the depth of channels fabricated using different nominal forces and (b) SEM pictures of a typical written microchannel on a COP substrate; cross-sectional view (top), and top view (bottom).

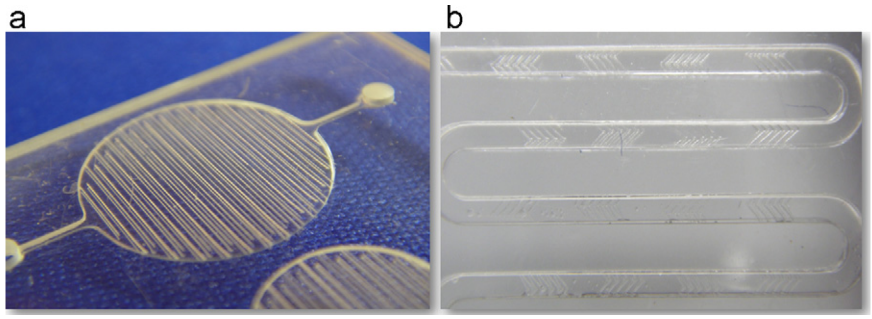

Fig. 3. Examples of fabricated microfluidic devices using the rapid prototyping technique; (a) a device for bubble free filling of a low aspect ratio microfluidic chamber using surface tension flow guide and (b) a chaotic micromixer featuring raised features within a continuous flow channel.

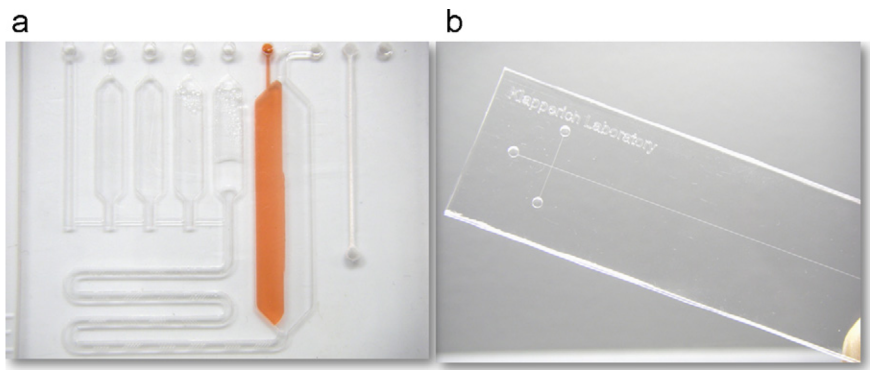

Fig. 4. More examples: (a) a recombiner using a surface tension barrier before a passive micromixer and (b) a disposable capillary electrophoresis chip.

three layers are cleaned in acetone, methanol, and DI water and dried with nitrogen before thermal bonding. After proper alignment using a right angle corner, three layers are thermally bonded in a hot press (Heated Press 4386, Carver, Wabash, IN) at 125 °C for 5 min with 0.5 T following 5 min curing at 137 °C without any pressure. The entire turnaround time from CAD design to a complete prototype of 3D microfluidic device is less than 30 min.

The first example demonstrated is a bubble free filling device of a low aspect ratio (188 μm deep and 2 cm in diameter) microfluidic chamber using surface tension flow guide [26] (Fig. 3(a)). Bubble trapping is one of the common issues encountered in microfludic devices with low aspect ratios. A flow guide (interdigitated lines, 60 μm wide, and 500 μm apart each other) simply written on a top and a bottom surface solves this issue without adding complex structures to the design. The second example is a chaotic micromixer (Fig. 3(b)). A traditional planar microfabrication method for this device requires multi-layered photolithography steps to realize the raised 3D structures (herringbone structures of 60 μm width and 100 μm gap) inside the channels (700 μm wide). This laborious multiple photolithography process inevitably takes days to make a prototype device even combined with a soft lithography technique well known for its fast replication ability. In Fig. 4(a), a microfluidic recombiner is shown. It recombines two small liquid plugs prior to entering micromixer. A preloaded liquid plug is confined in a selected region due to the increased surface tension of the written pattern (60 μm wide) on a chamber (376 μm deep) surface. As the final demonstration, a polymer capillary electrophoresis chip is fabricated by thermally bonding a capillary channel (100 μm wide) with a blank cover layer (Fig. 4(b)).

4. Conclusion

These results demonstrate maskless fabrication of 3D microfluidic devices with controlled microstructure patterning suitable for many polymer substrates. The method is capable of fabricating microfludic devices with microchannels as small as 20 μm wide and 30 μm deep in less than 30 min. Furthermore, a maskless direct writing technique enables researchers without clean room facilities to test the feasibility and design of 3D microfluidic devices before high throughput techniques such as injection molding are used.

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