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Non-lithographic fabrication of metallic micro-mold masters by laser machining and welding

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Abstract: A non-lithographic process of rapidly fabricating metallic micro-mold masters for the manufacture of disposable polymer microfluidic devices is presented in this paper. The developed technique exploits the precision material removal capabilities of industrial lasers to cut accurate profiles of microfeatures (e.g. liquid flow microchannels, reservoirs, passive micro-mixers) from thin metallic sheets. The machined micropatterns are then laser welded onto a metal substrate to form the final functional mold master. Multiple versions of the functional device are replicated from the assembled master by either soft-molding polydimethyl-siloxane (PDMS) or hot-embossing polymethyl-methacrylate (PMMA). Several metallic micromold masters and polymer replicas are tested for dimensional accuracy and surface roughness to verify the developed microfabrication process.

Keywords – Lab-on-a-chip; microfluidics; mold masters, microfabrication; laser machining; microwelding; soft molding; hot embossing

1. Introduction

Commercialization of *micro-electromechanical systems* (MEMS) has exploded in recent years because these low-cost versatile devices have provided compact solutions for a variety of products used in household, automotive, aerospace, environmental science, telecommunication, and medical applications. One area where MEMS technology has completely revolutionized product design is in the development of efficient *micro-Total Analysis Systems* (µTAS), *Lab-on-a-Chip* (LOC), and microfluidic devices [1]. These microfluidic systems are based on the notion that conventional laboratory analysis of biological or chemical samples can be performed more effectively on a miniaturized platform [2,3] that supports passive and active microfluidic components including liquid flow microchannels, micro-valves [4,5], micro-pumps [6], and micro-mixers [7,8]. In addition, these miniature analytical systems often contain signal detection elements such as electrical, chemical, and optical sensors [9,10].

Microsystems have become an important tool in modern diagnostics because these microfluidic devices permit precision delivery of small quantities of liquid to specified locations on the chip. The sophisticated fluidic networks are commonly used for analyzing DNA and RNA, medical screening, monitoring airborne toxins and contaminants in the environment, or performing chemical analysis to identify dangerous substances [11]. The potential benefits of using miniaturized microfluidic systems in life and environmental sciences include a significant reduction in the time to perform the experiment, ability to perform multiple tests simultaneously, and the requirement for only low quantities of bio-samples and reagents. The small size of the microfluidic system reduces the need for large quantities of expensive reagents and enables the entire laboratory analysis to be portable for on-site field applications.

Early microfluidic systems were created using the same silicon based *Integrated Circuit* (IC) microfabrication techniques used to manufacture electronic microprocessors. However, a number of problems emerged with these silicon microfluidic devices. For example, optical detection methods commonly used in life science are difficult to incorporate into the device because the silicon substrates used in microelectronics are often opaque to both visible and ultraviolet regions of the spectrum. Optically clear glass substrates and relatively expensive chemical etching processes were then used to address this problem but these materials were found unsuitable for handling certain biological samples [2]. LOC devices also require a larger surface area than conventional microelectronic chips to house a number of passive features (reservoirs, mixers) and complex fluidic network patterns resulting in a significant increase in overall silicon fabrication costs. Furthermore, as applications require thinner and thinner substrates, brittle silicon and glass becomes more difficult to manipulate without breakage during system assembly and, consequently, more expensive to embed within the integrated analysis system.

To reduce the manufacturing and assembly costs associated with silicon-based microfluidic devices, a number of researchers have begun to explore other materials and microfabrication technologies. Becker et al. [12] was one of the first to suggest polymer processing technologies because there is a large selection of bio-compatible polymers and the well established macro scale manufacturing techniques that are both low cost and for high volume production. Nguyen and Wereley [13] estimated the substrate cost of using silicon or glass (boron-float glass and boron-silicate glass) for creating a microfluidic device to be 10 to 100 times more expensive than an equally compatible polymer material. A number of well-established polymer manufacturing technologies have been exploited such as hot embossing [12, 14] and microinjection molding [15, 16].

Polymer based replication methods often use metallic micromold masters to produce high volumes of identical devices. LIGA (X-ray lithography, galvanoforming - elctroplating and plastic molding) is one of the methods for fabricating high-resolution and high aspect ratio micromold masters [17,18]. The method uses X-ray lithography to transfer patterns onto polymethyl-methacrylate (PMMA) resists. The PMMA microstructures are then electroplated using nickel or nickel based alloys (NiCo, NiFe). The metal master is finally released by dissolving the PMMA resists in chemicals such as a mixture of tetrahydro-1, 4-oxazine and 2-aminoethanol-1. The resultant mold masters can be used for either injection molding, soft-molding or hot embossing plastic replicates. The primary advantage of this method is that high aspect ratio masters can be produced. However, the disadvantages of the LIGA method include the relatively high cost of the X-ray lithographic process [17,18].

The electroplating step of the LIGA process usually requires lengthy process times, lasting hours or days, for depositing the desired plating material thickness. Furthermore, post processing is often needed to flatten the back of the plated metal because of the varied deposited thicknesses of metal layer created by the deposition process. Shortening the fabrication time and reducing the number of processing steps involved in the fabrication of micromold masters are, therefore, one of the essential factor to lowering total production costs for replicating LOC devices in high volume.

Alternative fabrication methods that are simpler and require lower cost equipment have also been investigated. Researchers at Harvard University [19] developed a soft-lithography technique to rapidly fabricating polymer microfluidic devices [20-24]. In general, soft-lithography is based on the UV-LIGA process without the electroplating stage [21]. The mold masters are made from SU-8 photoresist by first using a high-resolution printer to create a low cost mask, or template, with the desired microchannel pattern [25]. SU-8 photoresist is then spun coated on a silicon wafer, or glass substrate, and soft-baked. After this step the printed mask is aligned with the SU-8 coated wafer and exposed to UV light, hard baked and chemically developed by dissolving the non-crosslinked SU-8. An elastomer such as polydimethylsiloxane (PDMS) is finally cast over these SU-8 molds to replicate a microfluidic device with the desired channel pattern and cured. The curing process can be either at an elevated temperature for short time duration [24] or at room temperature for 24 to 48 hours. Once it is cured, the PDMS layer is peeled off and bonded with another PDMS, glass, or silicon substrate layer. Without electroplating process, the fabrication cost of these micromold masters is significantly lower than those created using the LIGA approach. Furthermore, the simplicity of the process makes it the most popular method for fabricating microfluidic prototypes in academic research laboratories.

Recently, Shiu et al. [26] reported an alternative non-lithographic approach to rapidly manufacturing metallic mold masters by utilizing a laser to cut the positive reliefs of the microchannel patterns from metallic thin sheets and directly welding the cut-out pattern onto another metallic substrate to form the final micromold master. The PDMS elastomer is then poured over the mold and allowed to cure forming the final replicated microfluidic part.

This paper expands upon the developed methodology and describes how laser cutting, micro-welding and soft molding can be used to create functional polymer microfluidic chips. The steps used to fabricate the metallic micromolds and final replicated polymer devices are summarized in Section 2. Section 3 describes several experiments that had been performed to validate the proposed micro-manufacturing process. Studies involving PDMS soft-molding and PMMA hot-embossing are presented. The selection of appropriate process parameters are discussed in Section 4. Finally, concluding remarks are provided in Section 5.

2. LCWM Micro-fabrication Process

The LCWM (Laser Cutting, Welding and Molding) method is based on the observation that most passive microfluidic components (eg. channels, mixers, reservoirs) are planar and the micromolds needed to create more sophisticated 3D network designs can, therefore, be manufactured by stacking and assembling multiple 2D micro-patterns. The key benefit of the proposed LCWM fabrication process is that the engineers who design and build the mold can micromachine multiple 2D microfeatures as separate mold reliefs and then fuse them together on the substrate material by a suitable joining technique. The basic steps of the LCWM fabrication method, as illustrated in Figure 1, involves laser micromachining the desired patterns and then microwelding the cut relief patterns onto the metallic mold substrate to form the completed mold master. The sequence can be repeated if the design goal is to create a more complicated multi-level microchannel master. Furthermore, the same proposed method can be used to fabricate metallic masters for either casting soft elastomers or hot embossing thermal plastic sheets. In general, the simple two step process makes the LCWM method easy to implement and very cost-effective. An additional advantage of the non-lithographic technique is that if the mold master becomes damaged during the actual part production then it can be easily repaired or rapidly replaced to minimize the expensive production downtime.

Laser micromachining is used to fabricate the 2D imprint features because it enables the precise machining of microfeatures on various materials such as polymers, metals, composites, and ceramics [27,28]. In addition, laser micromachining is a non-contact machining process where tool distortion does not occur during material removal. Laser microwelding technology is selected to fuse the machined patterns onto the substrate because it permits joining of dissimilar materials. Under optimal process parameters, the weld pool can be made as small as 50 to 100μm in diameter with relatively smooth surface finishes. The non-contact nature of laser welding also makes it a viable joining technique for producing parts with fine features. Although flexible, laser micromachining is a sequential process that may limit the number of produced units at a time. However, this low volume constraint does not impact the suitability of this proposed fabrication technology for creating multi-use metallic mold masters.

An example of a positive micro-relief pattern cut from the low carbon steel sheet is illustrated in Figure 2(a). The relief pattern is then micro-welded onto the substrate to form the completed mold master, Figure 2(b). To assist with the alignment of the metallic imprint pattern onto the substrate during the welding operation, the alignment sheet, microfluidic pattern, and the master substrate were all cut from the same 50μm thick low-carbon steel sheet. This reduced the manufacturing time because it would not be necessary to change materials during the process. Finally, the master is then placed in a mold fixture as shown in Figure 2(c).

3. Experimental Results

3.1 Fabrication of Metallic Micro-mold Masters

Several metallic mold masters were produced to experimentally validate the LCWM microfabrication process. The microfluidic mixers were originally designed using Mastercam CAD/CAM software. The desired pattern of the microfluidic channels were first cut from a 50μm thick sheet of low-carbon steel using a laser micromachining station, Figure 3, equipped with an AVIA UV laser from Coherent Inc., USA. The laser has 3.0 Watts of power at 20 kHz with a pulse duration of less than 40 nanosecond at 60kHz. Laser micromachining was conducted under atmospheric pressure and done with air-assistance. Appropriate controller software was used to synchronize the laser cutting and work piece movement. For this study, the laser microwelder was a Starwelder 6002 model from Rofin-Basssel Inc., Germany.

The selection of suitable process parameters for laser cutting positive relief patterns is critical for producing accurate micro-molds. Thermal distortions often occur in laser micromachining because of the high laser pulse energy used to vaporize materials is essentially a thermal cutting process. To reduce the heat conduction that causes the thermal distortion of mold master dimensions, it is essential to use the minimum possible laser input energy per pulse in cutting. Typically, a lower level of pulse energy produces a higher quality of laser cut edges. The dimensional distortions and surface roughness caused by thermal effects of laser cutting can be reduced by using a minimal power density and the increased number of cutting passes.

High quality cut edges are essential because the smooth surface finishes of the microfeatures determine the smoothness of the final replicated polymer parts. The surface quality of the metallic sheet determines the surface quality of certain features such as the bottom of a microchannel. The surface quality of laser cut edges determines the microchannel wall surface finishes. Therefore, low carbon steel sheets or stainless steel sheets were selected and used as the substrate because it provides good surface finish, good ability to be laser welded, and it's easy to be laser cut. Using low carbon steel welding to stainless steel further reduces problems as those found in joining dissimilar materials, such as material segregation or cracking due to the difference in shrinkage factor after cooling.

The laser microwelding process parameters (pulse profile, pulse duration, power level, and spot size) must also be optimized to produce a smooth surface finish at the weld pool. The laser only takes a few milliseconds to weld the microrelief patterns onto the substrate. It is necessary, however, that only a small welding gap exist between the metallic materials. Theoretically, the weld gap should be no more than 5% of the thickness of the thinnest of two materials being welded together [27]. The requirement of a minimum weld gap in microwelding is more critical than welding parts in the macroworld due to the scaling effect. For example, the low carbon steel sheet used in this study is 50μm thick and, therefore, the theoretical maximum weld gap is 2.5μm.

To assist with the micro-welding process a permanent magnet was placed under the stainless steel sheet to provide a magnetic force to hold the Y-channel component tightly to the substrate surface to reduce the welding gap. Argon gas, at 20 Psi pressure, was supplied into the welding chamber to reduce the impurities formed in the weld pool. Figure 4 shows the optical profiler measurements of the weld pool at the reservoir location of the microfluidic network pattern. The process parameters were: 309J/cm^2 pulse density, shielding gas Argon, 0.66J pulse energy, 1.3ms pulse length, spot welding, and level-and-decline pulse shape.

For experimental verification and testing purposes, a metallic micromold of a Y-channel micromixer was designed and constructed as shown in Figure 5(a). The width of the microchannel is 200 to 500μm. It took approximately 25 minutes to laser-cut the Y-channel relief, with 15 passes at 50mm/min cutting speed. A number of laser cutting tests were conducted to find optimal parameters for best cut edge quality [26]. Equipment settings were as follows: UV wavelength laser, air assisted cutting, 10X beam expander, focusing objective that delivers the beam diameter to about 10-15µm at focus. The relief pattern was then ultrasonically cleaned to remove debris and the ferrous oxide created during the laser cutting process. An optical profiler measurement of a feature on the microrelief pattern of the mold master is given in Figure 5(b).

3.2 Replicating Polymer Microfluidic Devices

3.2.1 Soft-Molding PDMS

The metallic micro-mold of the Y-channel micromixer, Figure 5, was used to create a polymer microfluidic device through casting polydimethyl-siloxane (PDMS). Detailed views of the prototype and replicated features are provided in Figure 6. The molded PDMS part is shown Figure 6(a) with the white squares indicating the locations of the optical profiler measurements given by Figures 6(c) and 6(d), respectively. Figure 6(b) is an optical close-up image of the molded PDMS microchannel. The top image of Figure 6(c) shows the surface measurement of a mold master near the Y-channel taken using the Wyko NT1100 optical profiling system from Veeco Instruments Inc., NY, USA.

The sidewalls of the channel pattern were nearly vertical with the average surface roughness Ra much coarser than the top surface of the microchannel pattern. The surface finishes of top surface of microchannels, surfaces that are parallel to the substrate, was similar to the metallic sheet material, about 300 to 500nm Ra. The rougher surface finishes of the side walls of the microchannels are the typical surface finishes of laser cut walls. The bottom graph of Figure 6(c) shows the A-A cross-sectional measurement of the molded surface created from the mold feature. Finally, Figure 6(d) shows the measurements taken from an optical profiler of a two-level PDMS molded microchannel. For the multi-level mold master, the difficulty of alignment of second level to the first level increases significantly.

3.2.2 Hot-Embossing PMMA

The use of thermoplastics as the substrate for microfluidic devices has a number of advantages including that the availability of a wide range of low-cost biocompatible polymers for various different applications and the ability to form rigid structures. In addition, thermoplastics can be easily formed over short processing cycles in injection molding process. If the LCWM micromold can be effectively used for hot embossing, then the developed technique will be sufficiently robust to replicate a broad range of microfluidic devices used in the applications of environmental monitoring and medical diagnostics where the biocompatibility and high volume production are necessary.

To demonstrate how the LCWM metallic mold master can be used for hot embossing (HE) processes, a metallic mold master was created for preliminary testing. Hot embossing was conducted using the Multi-purpose Press from GEO Knight & Co. Inc. The press is capable of applying a pressure from 140 to 550kPa (20 to 80Psi) with temperatures from 66 to 220^{0}C. The LCWM mold master was placed onto a 1.5mm thick PMMA substrate. Process parameters were determined empirically. The process parameters included HE temperature about 130°C, HE pressure about 207 kPa (30 Psi) and HE time about ten minutes and de-embossing temperature at 90°C. The metal substrate was about 150μm thick, slightly thicker than the substrate used in casting PDMS to improve the structural support during the thermal cycle of HE.

The microchannels with various widths are shown in Figures 7(a) and 7(b). The molded corners were slightly rounded which are similar to the results found in the previously published literature. The surface quality was observed to be about 300 to 400nm Ra, which is slightly better than the PDMS molded microchannels. The higher quality surface finish of the PMMA mold microchannels may be the result of the release of residual stresses in the softened polymer after the removal of molding pressure. Consequently, the small forces may smooth out the surface roughness of the soften polymer, at a nano-scale, by driving the material to an equilibrium state.

Figure 7(c) show the measurements of the HE PMMA microchannels as captured by Wyko optical profiler. The hot-embossed microchannels exhibit a draft angle and the channel bottoms were not as flat as the previously soft-molded PDMS microchannels. This appears to be the heat and force factors that were distorting the mold master during the hot embossing process. It can be concluded, therefore, that a higher strength material should be used to fabricate the mold master. Subsequently, the microchannel size, thickness and the number of welding spots were increased to strengthen the mold masters. The experimental results demonstrated that the damages to masters during hot embossing were reduced by design changes. Figure 8 shows the SEM view of the HE replicated microchannels that has near vertical walls, however, the sidewalls of these HE microchannels were rough due to the soften PMMA was replicating the rough laser cut edges.

The metallic micromold shown in Figure 5 was also used to create a polymer PMMA microfluidic chip using the hot embossing process. A SEM photograph of the reservoir region for the replicate device is shown in Figure 9. The microchannel entrance to the reservoir shows rounded wall corners which are characteristic of the hot embossing process. As well, the replicated weld spot in the center of the image appears to have a smooth surface finish and its shape can be compared with the optical profiler measurement of the weld pool on the micro-mold, Figure 4.

Finally, a metallic mold master with a sophisticated fluidic channel pattern and multiple reservoirs was created using the LCWM process, Figure 10. This example clearly illustrated the capability of hot embossing thermal plastics, such as PMMA, with a metallic micromold master created by using the LCWM process.

4. Discussion

The experimental results provided in the previous section demonstrate that the LCWM mold masters can be successfully used to produce polymer LOC devices from casting PDMS elastomers and hot embossing thermal plastics. However, the LCWM method appears limited for multi-level microstructures because of the difficulties that arise in aligning the second level. This problem may be minimized by using post-process, such as micromilling or microEDM (Electro Discharge Machining) to correct the final dimensions of the mold master. In general, the cost of producing the LCWM master is relatively low in terms of both the material cost and the expensive skilled-labor hours; therefore, a number of masters can be fabricated as the back-up masters for production.

Each of the molding process tested with the LCWM master in this paper has its advantages and disadvantages. Producing a polymer microfluidic device by casting PDMS is simple and straightforward, without the need of complicated or expensive manufacturing equipment. It only requires a vacuum chamber for degassing the PDMS after the base and curing agents are mixed. In this study, PDMS micromixers were replicated by pouring the PDMS over the mold and curing it for 48 hours. The speed of curing PDMS can be increased by elevating the temperature. The demolding of the PDMS parts were not difficult but care must be taken because the PDMS elastomer can be torn easily.

In hot embossing, the PMMA microchannels were successfully replicated using the LCWM mold master with larger microchannel sizes because these enlarged features reduce damage caused by the shearing forces along the walls during part demolding. The damage appears to have been caused by the excessive filling of PMMA which increased the surface friction between the molded polymer and mold structures. Although the slightly inclined sidewalls of the micromold would appear to assist the demolding exercise, the experiments prove otherwise. It was necessary, therefore, to reduce the hot embossing pressure to lower the quantity of material packed into the cavities. Consequently, the lower embossing pressure created microchannels with tapered cross-sections rather than the sharp rectangular shapes found through casting the parts in PDMS. In addition, a single production cycle of the hot embossing process required approximately 30 minute to complete. The longest step in the process was cooling the material prior to de-molding the polymer replicate. Rapid cooling was not possible because this would result in thermal stresses that significantly distort the microfeatures after the mold was released.

Both the PDMS and PMMA replicated microchannels exhibited similar surface roughness characteristics, around 300 to 500 nm Ra, because the molded surfaces were the direct copies of the metallic sheets used to create the micromold. It is important to note that this assessment was based only on the non-laser welded locations of the mold. Ideally, increasing the number of welding spots enhances the master durability under the hot embossing process. However, each weld spot also increases the surface roughness. For producing highly accurate geometric features, casting PDMS is recommended over the HE PMMA process. In contrast, if a short production cycle time is the critical factor then hot embossing thermoplastics may provide a satisfactory solution. Finally, there exists a wide range of low-cost biocompatible thermoplastics making the HE technique very appealing for medical and environmental monitoring applications.

5. Conclusions

A non-lithographic fabrication technique to manufacture metallic micromold masters, for medium to high volume production of polymeric microfluidic devices, was introduced. The LCWM (**L**aser **C**utting, **W**elding and **M**olding) method is based on the observation that sophisticated microfluidic network designs can be manufactured by stacking and assembling multiple 2D micro-relief patterns. The fabricated metallic masters can be employed for either casting PDMS elastomers or hot embossing thermoplastic sheets.

In general, the LCWM process is a simple two-step process that is easy to implement and relatively cost-effective. The use of low-cost materials for creating the LCWM mold master also reduces total fabrication cost. An additional advantage of the LCWM method is that if the mold master becomes damaged during the part production then the masters can be easily repaired or rapidly replaced to minimize the costly production downtime.

Although an effective microfabrication technique, the width of the structures produced by the LCWM micromold is limited to about 75 to 500μm. To explore the versatility of the process for manufacturing polymer LOC devices, the LCWM masters were used to produce several micromixer by casting elastomers - polydimethyl-siloxane (PDMS) and hot embossing thermal plastics - poly(methyl methacrylate) PMMA. Both thermal set and thermal plastic polymer materials were successfully used to accurately replicate microchannels in a fluidic network.

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List of Figure Captions

Fig. 1 LCWM fabrication process for creating polymer microfluidic devices. The basic steps include (a) laser machining of the microrelief pattern, (b) laser microwelding the cut pattern onto the substrate to form the (c) metallic mold master. Once the mold master has been fabricated, the master can be used for either (d) hot embossing (HE) with a PMMA sheet or (e) casting an elastomer (PDMS). Finally, the replicated microfluidic device with desired features and dimensional accuracy is produced (f).

Fig. 2 Microfabrication of a metallic micro-mold master using the LCWM process. (a) Laser cut positive relief of desired microfluidic pattern, (b) relief pattern welded onto the substrate material to form the master mold, and (c) insertion of the master into a mold fixture for casting the part in PDMS.

Fig. 3 Laser micromachining station used to produce the experimental prototypes for this study. Key features include focusing optics to accurately deliver the laser beam to the work piece (low carbon steel), concentric gas nozzle to protect the optical system from particles and gasses, and a precision motion stage to translate the work piece during microfabrication.

Fig. 4 Weld pool at the reservoir location with an average surface roughness of Ra 4.79μm.

Fig. 5 (a) Experimental LCWM metallic mold master with a surface roughness, about 300 to 500nm Ra, and (b) an optical profiler measurement of a microfeature on the relief pattern.

Fig. 6 (a) Molded PDMS part from LCWM metallic mold master, (b) a close-up optical microscopic view of the Y-channel, (c) A-A sectional view of the PDMS microchannel, and (d) optical profiler generated view of the multi-level molded microchannel.

Fig. 7 The HE PMMA microchannels, about 300nm Ra, HE temperature at 155°C, de-embossing temperature 100°C, HE pressure at 40Psi, 10 minutes. (a) optical microscopic view of the mold master and (b) the 3D view generated by Wyko optical profiler. (c) Cross-sectional view of the PMMA HE microchannels taken by Wyko optical profiler. Note that some of the HE molded microchannel bottoms were slightly tilted.

Fig. 8 (a) SEM view of the hot embossed PMMA microchannels with relatively rectangular cross-sections. (b) A close up of a single microchannel showing a rough vertical sidewall.

Fig. 9 SEM close-up view of the reservoir region on the hot embossed PMMA device produced from the LCWM metallic mold master shown in Fig. 5. The entrance of the microchannel shows rounded corners and the replicated weld spot appears to have a smooth surface finish (compare to Fig. 4).

Fig. 10 Optical images of the (a) LCWM metallic mold master and (b) hot-embossed PMMA device for a more sophisticated fluidic network pattern. The enlarged images show a liquid reservoir and the Y-channel feature. The shadow effects in (b) occur because PMMA is optically transparent.

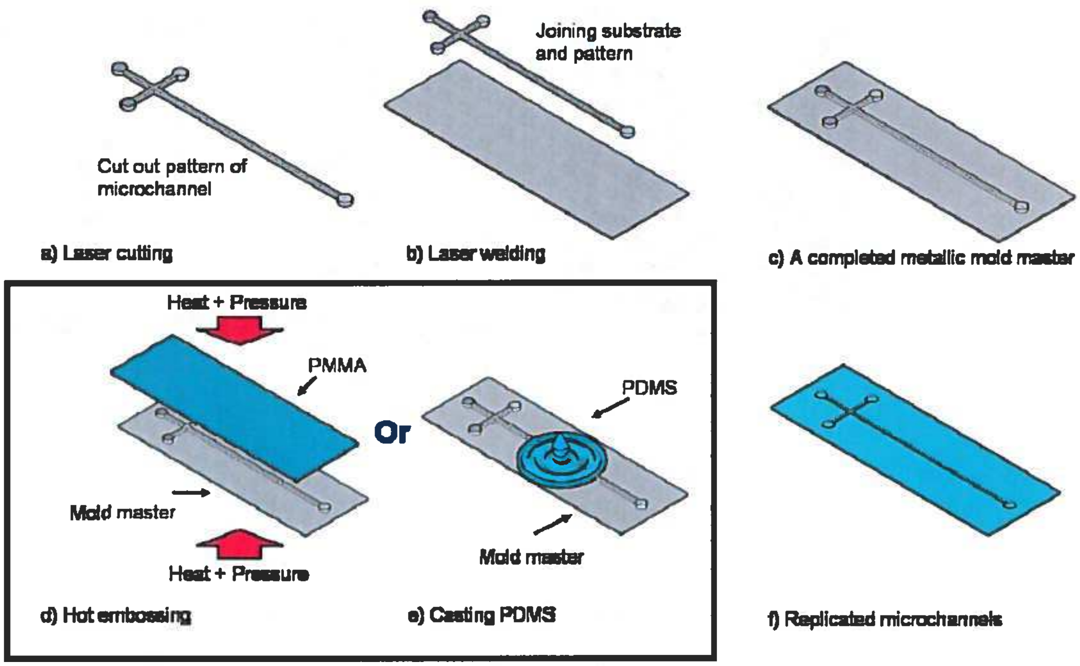


Fig. 1 LCWM fabrication process for creating polymer microfluidic devices. The basic steps include (a) laser machining of the microrelief pattern, (b) laser microwelding the cut pattern onto the substrate to form the (c) metallic mold master. Once the mold master has been fabricated, the master can be used for either (d) hot embossing (HE) with a PMMA sheet or (e) casting an elastomer (PDMS). Finally, the replicated microfluidic device with desired features and dimensional accuracy is produced (f).

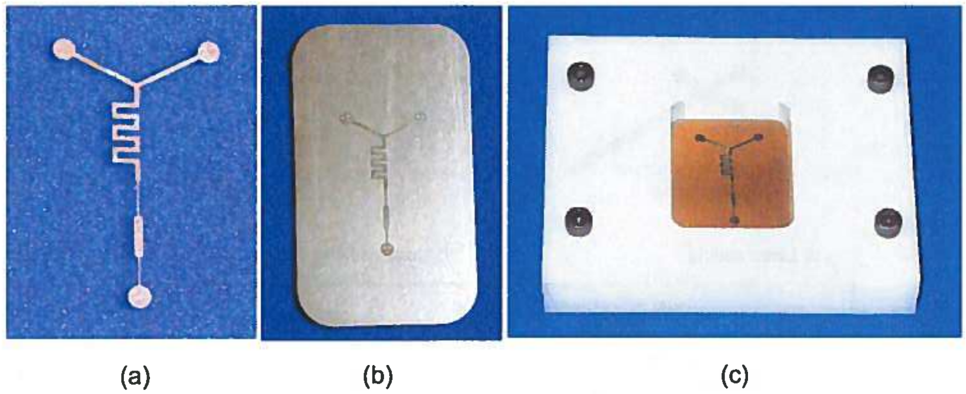


Fig. 2 Microfabrication of a metallic micro-mold master using the LCWM process. (a) Laser cut positive relief of desired microfluidic pattern, (b) relief pattern welded onto the substrate material to form the master mold, and (c) insertion of the master into a mold fixture for casting the part in PDMS.

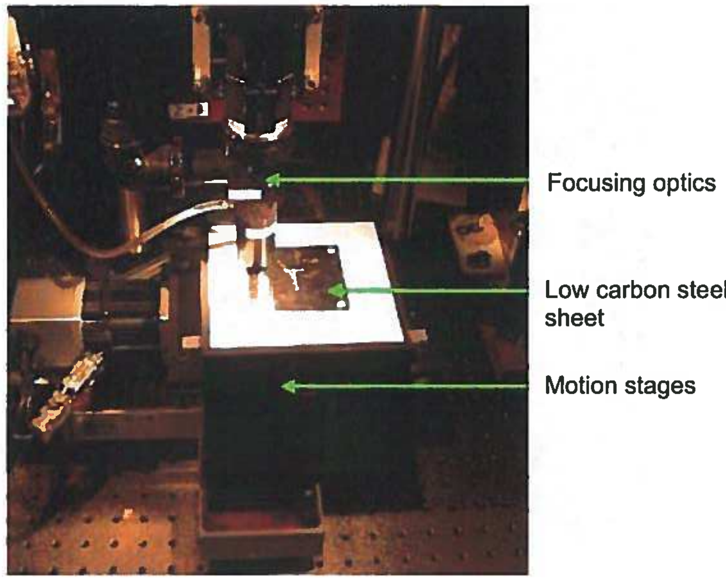


Fig. 3 Laser micromachining station used to produce the experimental prototypes for this study. Key features include focusing optics to accurately deliver the laser beam to the work piece (low carbon steel), concentric gas nozzle to protect the optical system from particles and gasses, and a precision motion stage to translate the work piece during microfabrication.

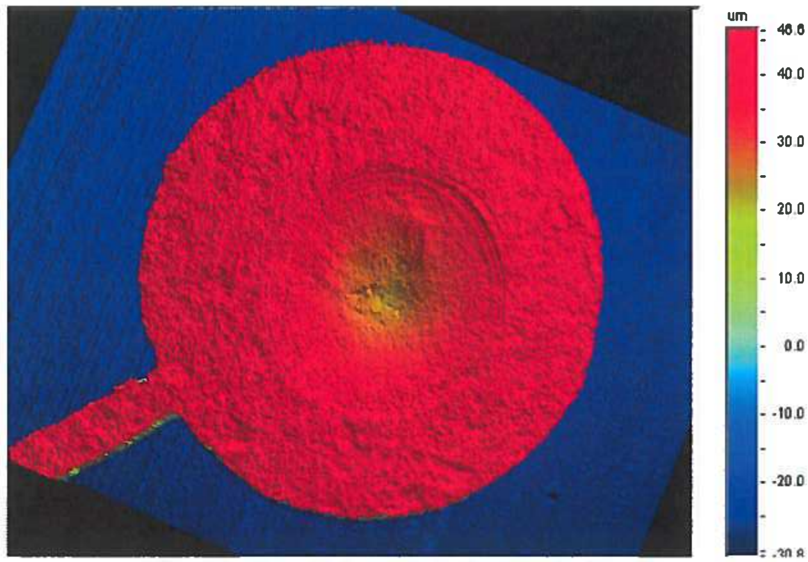
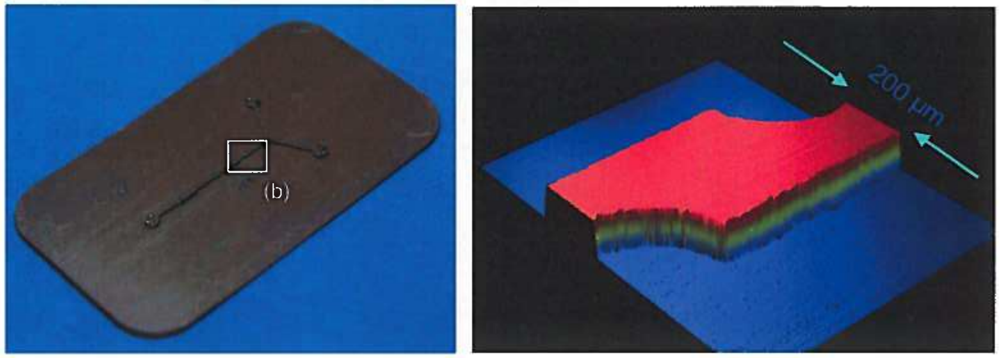


Fig. 4 Weld pool at the reservoir location with an average surface roughness of Ra 4.79μm.



(a) (b)

Fig. 5 (a) Experimental LCWM metallic mold master with a surface roughness, about 300 to 500nm Ra, and (b) an optical profiler measurement of a microfeature on the relief pattern.

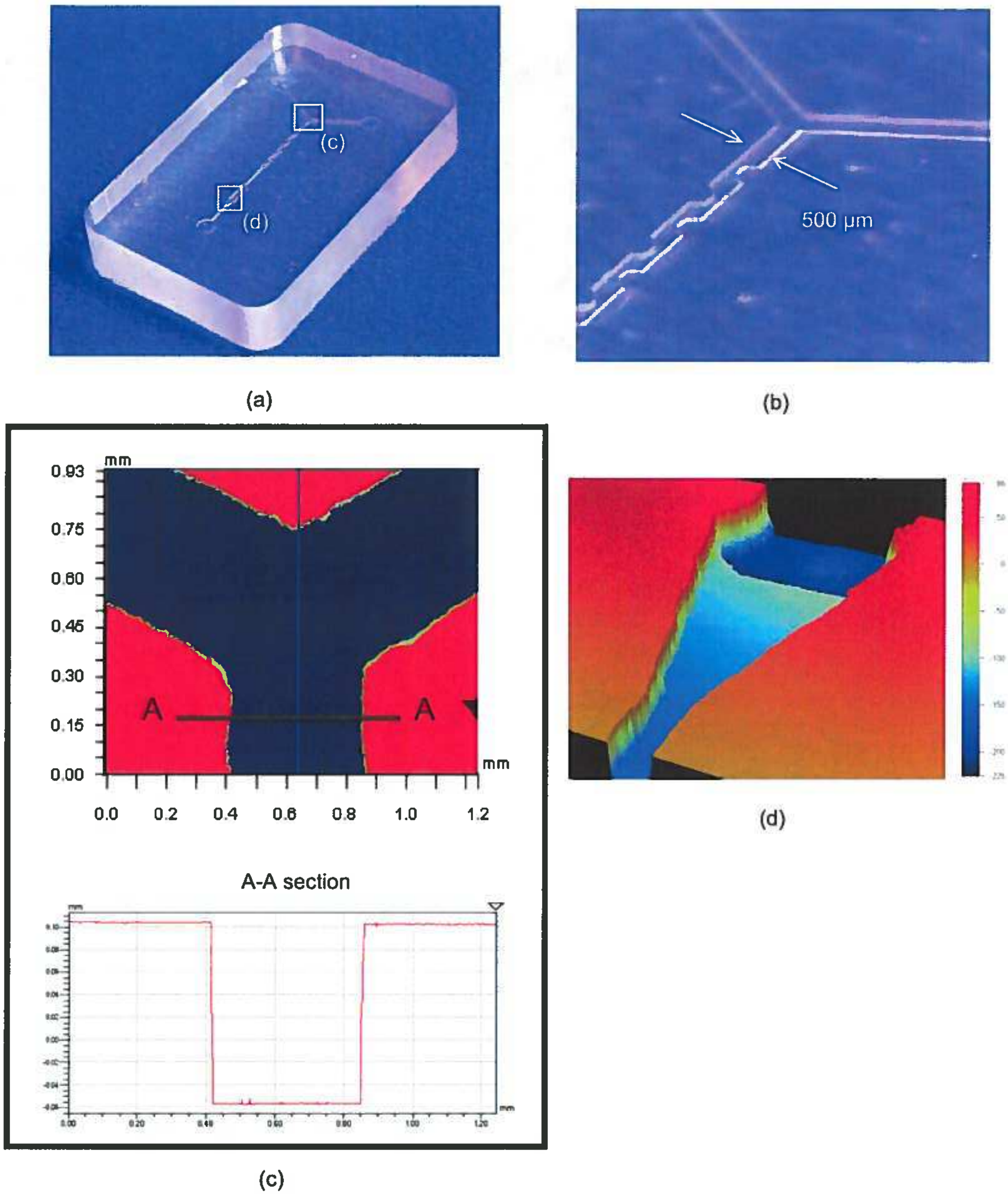


Fig. 6 (a) Molded PDMS part from LCWM metallic mold master, (b) a close-up optical microscopic view of the Y-channel, (c) A-A sectional view of the PDMS microchannel, and (d) optical profiler generated view of the multi-level molded microchannel.

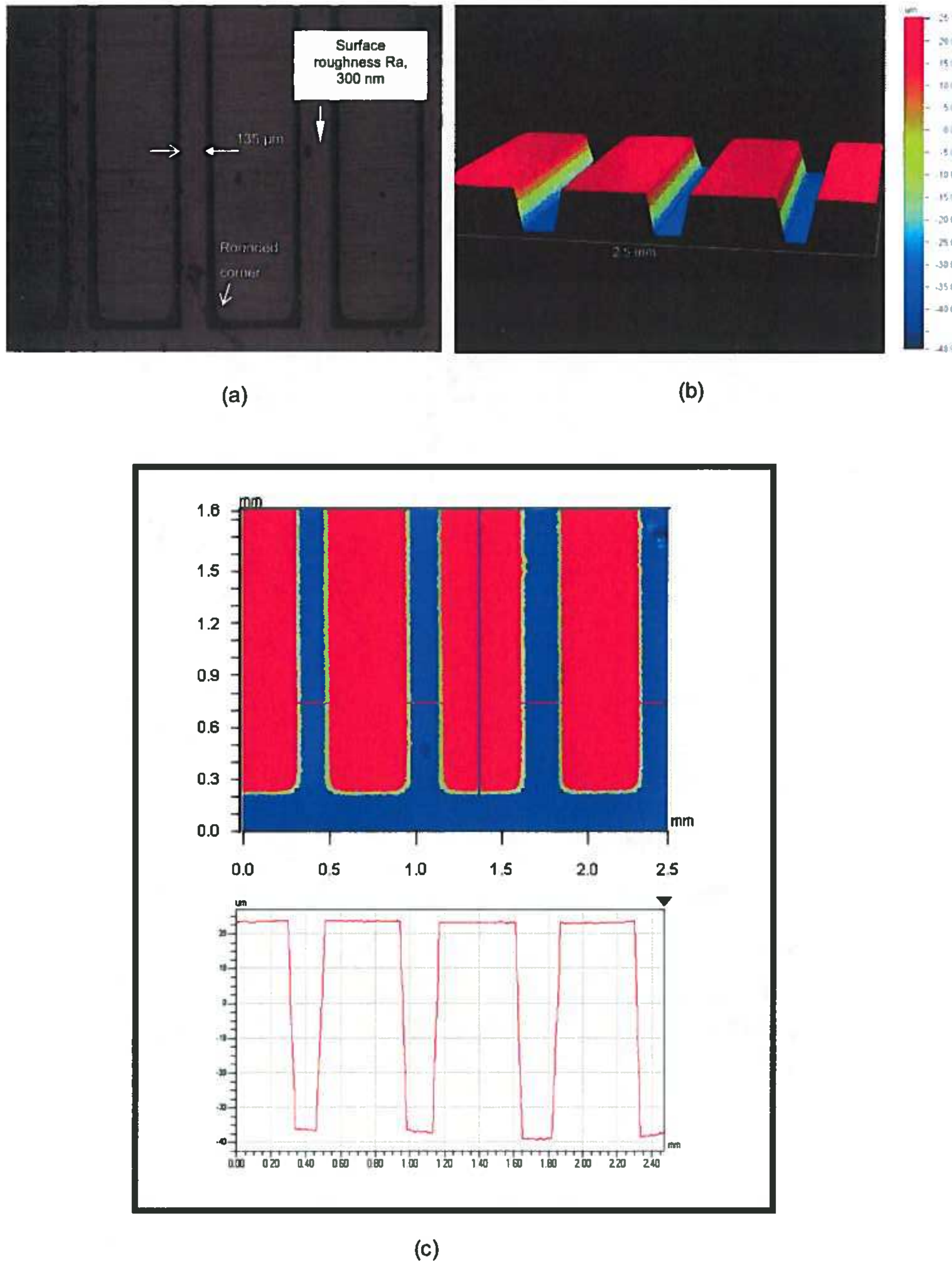
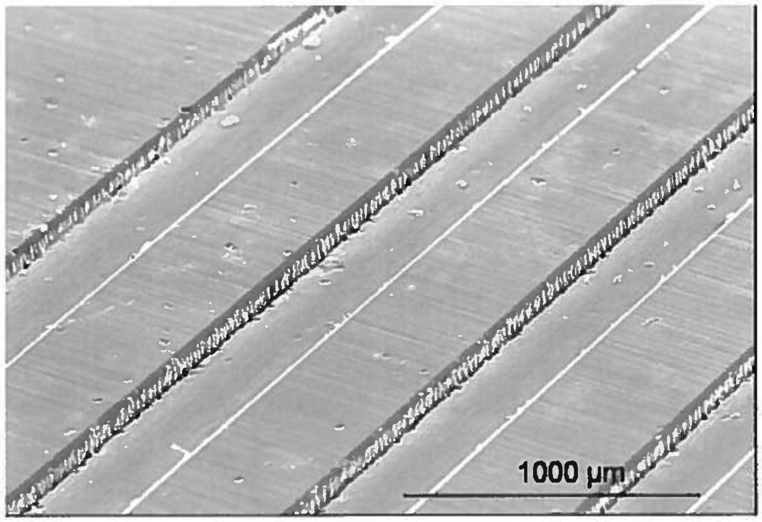
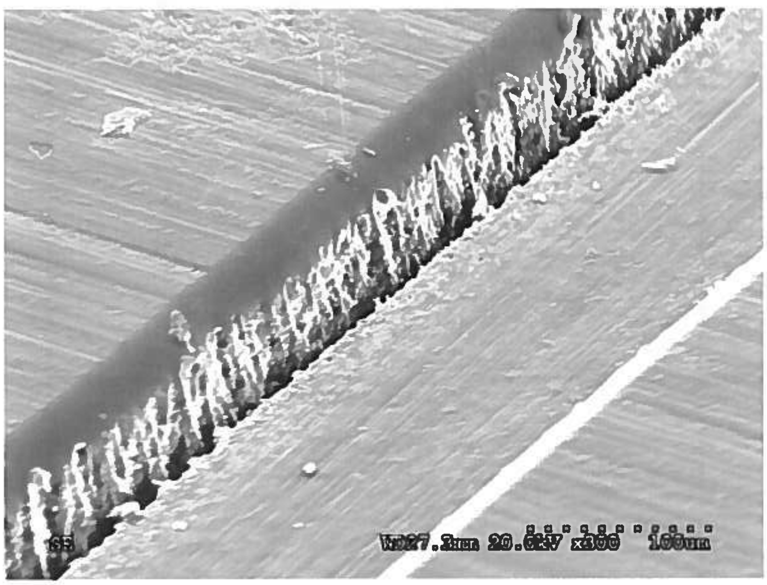


Fig. 7 The HE PMMA microchannels, about 300nm Ra, HE temperature at 155°C, de-embossing temperature 100°C, HE pressure at 40Psi, 10 minutes. (a) optical microscopic view of the mold master and (b) the 3D view generated by Wyko optical profiler. (c) Cross-sectional view of the PMMA HE microchannels taken by Wyko optical profiler. Note that some of the HE molded microchannel bottoms were slightly tilted.



(a)



(b)

Fig. 8 (a) SEM view of the hot embossed PMMA microchannels with relatively rectangular cross-sections. (b) A close up of a single microchannel showing a rough vertical sidewall.

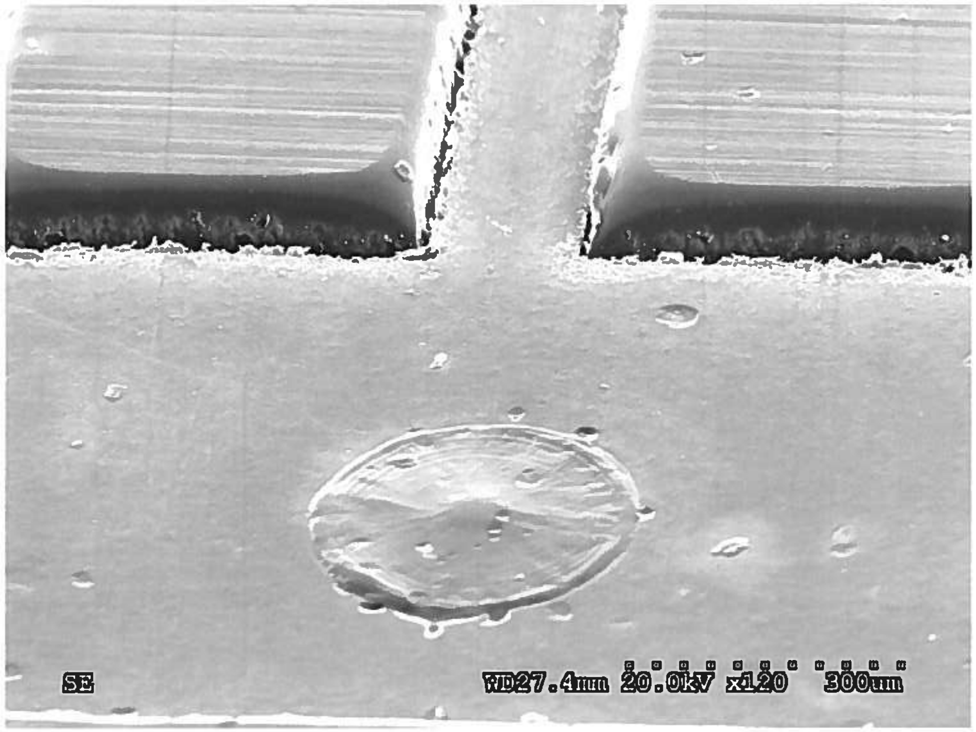


Fig. 9 SEM close-up view of the reservoir region on the hot embossed PMMA device produced from the LCWM metallic mold master shown in Fig. 5. The entrance of the microchannel shows rounded corners and the replicated weld spot appears to have a smooth surface finish (compare to Fig. 4).

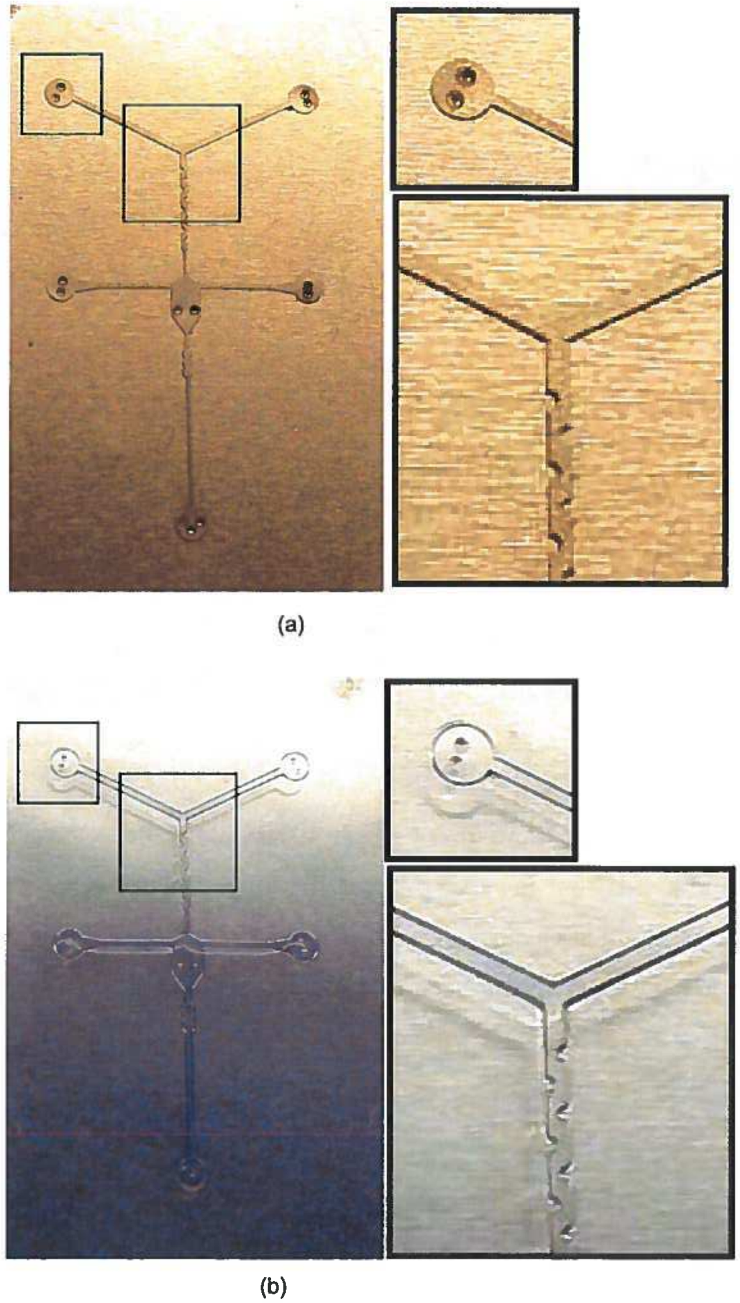


Fig. 10 Optical images of the (a) LCWM metallic mold master and (b) hot-embossed PMMA device for a more sophisticated fluidic network pattern. The enlarged images show a liquid reservoir and the Y-channel feature. The shadow effects in (b) occur because PMMA is optically transparent.