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Rapid Fabrication of Micromolds for Polymeric Microfluidic Devices

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***Abstract*—Lab-on-a-chip (LOC) and other microfluidic devices for medical applications need to be mass produced at a low fabrication cost because the disposable device is destroyed after a single use to avoid sample contamination. In this paper, a new method for rapidly fabricating metallic micromold masters for manufacturing large volumes of polymeric microfluidic devices is presented. Polymers are preferred over silicon as the device material due to their better compatibility with biological and chemical substances. The manufacturing method involves laser micromachining of the desired imprint features from thin metallic sheets and then microwelding them onto a substrate to form the final mold master. The polydimethylsiloxane (PDMS) elastomer is then poured over the mold and cured to produce the microfluidic device. The proposed method involves fewer processing steps than the soft lithography, electroplating and molding (LIGA) process. To verify the method, a metallic mold for a passive Y-channel microfluidic mixer was fabricated. The mold master was made from low-cost steel and the mold manufacturing process can be completed within an hour. PDMS elastomer is then poured over the mold and cured to produce the mixer. The channels of the mixer were 75 micrometers wide and 50 micrometers high. The mixer created from the mold was tested by mixing two streams of colored water in it. The maximum flow rate achieved by the prototype was 6.4 microlitres per minute. The experimental results confirm that a viable metallic mold master for microfluidic devices can be created by combining laser micromachining and microwelding processes. Finally, the limitations of the proposed rapid fabrication method are discussed.**

Keywords - microfluidics; micromold fabrication; laser micromachining; microwelding

I. Introduction

Microfluidic devices play an important role in many applications such as analytical microsystems for cell biology, and chemical synthesis. Most of these devices are disposable and used only once to avoid sample contamination, and therefore methods for low-cost mass production of these devices are critical. Various methods for mass production of microfluidic systems have been explored in the past, such as hot embossing [1], [2], and microinjection molding [3], [4]. These methods require a mold master which is usually costly to fabricate. Furthermore, numerous trials and adjustments of the mold are needed in the initial stages of the design and production to determine the optimal molding process parameters. Thus, the ability to rapid-prototype mold masters is desirable because it can reduce the concept-to-market product development cycle. Soft lithography as a rapid prototyping fabrication method for microfluidic device has been reported in [5]-[7], [10]. The mold masters in this work are made of SU-8 photoresists and the fabrication methodology requires a number of steps to create the positive relief mold masters [5].

In this paper we present a new method for rapid fabrication of metallic micromolds, one that combines laser micromachining and laser microwelding processes. Compared with the soft lithography method, the proposed method involves fewer fabrication steps yet achieves adequate quality of the manufactured mold master.

The proposed fabrication method is summarized in Section II. Section III describes the experimental validation and evaluation of the method. The fabrication and testing of a molded microfluidic device is presented in Section IV. Key challenges are discussed in Section V. The conclusions are drawn in Section VI.

II. PROPOSED FABRICATION METHOD

The primary motivation for this research is that most polymeric microfluidic devices require 2D mold masters. Thus, the idea behind the proposed fabrication method is to produce the 2D imprint features (that is, the relief of the mold) separately from the substrate of the mold, and then fuse the relief to the substrate by a suitable joining technique.

In this work laser micromachining is used to fabricate the 2D imprint features because it enables precise machining of small features, at the micrometer scale, with a high quality surface finish. Furthermore, laser micromachining has several advantages when machining a variety of materials such as polymers, metals, composites, and ceramics [11], [12]. It is a non-contact machining process that does not distort the material like traditional mechanical material removal processes. This is because the heat-affected-zones in the processed material are very small. One disadvantage is that, as a sequential process, laser micromachining has a limited productivity.

For fusing the laser-cut 2D relief to the substrate of the mold, we propose the use of laser microwelding technology. Laser microwelding has a major advantage of being able to join dissimilar metals and plastics. Under optimal process parameters, the weld pool can be made very small (in the micrometer range) and having a smooth surface. The non-contact property of the laser welding also makes it a viable joining technique for parts with fine features.

Figure 1 depicts the five steps of the proposed fabrication method. The process involves laser machining of the desired relief, cleaning the relief in an ultrasonic bath, laser microwelding the relief onto the mold substrate (to form the mold master), depositing and curing of the elastomer, and finally demolding the polymeric device from the mold.

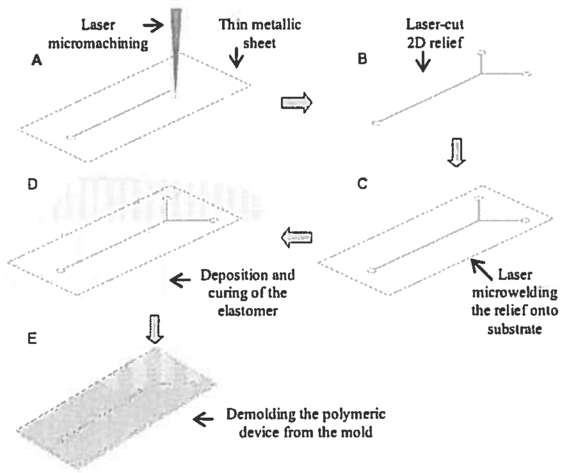

Figure 1. Micro-mold fabrication for a microfluidic device: (A) Laser micro machining, (B) Cleaning, (C) Laser microwelding, (D) Elastomer deposition and curing, (E) Demolding (peeling off) the part from the mold.

The proposed technique has several advantages. First, the mold master can be fabricated quickly. Second, it takes only three steps to create the micromold master: material cutting, cleaning, and welding. Third, it involves direct fabrication of a metallic mold. In comparison, the conventional SU-8 soft-lithography process involves additional processing steps: spin coating, soft baking, exposure, hard baking, and developing.

III. EXPERIMENTAL VALIDATION AND EVALUATION OF THE METHOD

To validate the proposed method and evaluate its performance, a metallic mold for a passive Y-channel microfluidic mixer was produced. The Y-channel micromixer design was selected for testing because a number of microfluidic devices that analyze biological samples use it for mixing two or more liquids.

The mixer was designed in the Mastercam CAD/CAM software. Its channels are 75μm in width and 50μm in depth. The stock material was a 50μm thick sheet of low-carbon steel. It took approximately 25 minutes to laser-cut the Y-channel relief, with 15 passes at 50 mm/min cutting speed. The relief was then ultrasonically cleaned to remove debris and the ferrous oxide created during the laser cutting process.

The Y-channel micromold was produced in the Precision Fabrication Laboratory of the Integrated Manufacturing Technologies Institute of the National Research Council of Canada. Laser micromachining was done using the AVIA UV laser from Coherent Inc., USA. The laser has 3.0 Watts of power at 20 kHz, pulse duration of less than 40 nanoseconds at 60 kHz. The laser microwelder used was a Starwelder 6002 model from Rofin-Basssel Inc., Germany.

A number of tests were conducted to determine optimal parameters for laser micromachining (Table 1). Equipment settings were as follows: UV wavelength laser, air assisted cutting, 10X beam expander, focusing objective, and 10-15μm beam diameter at focus.

TABLE I

LASER MICRO-MACHINING PROCESS PARAMETERS, 15 PASSES

Power density [W]	Feed rate [mm/min]	Pulse frequency [kHz]	Observed edge quality
0.24	25	1	rough
1.38	25	10	smooth
0.60	40	10	smooth
0.60	50	10	excellent

The produced Y-channel relief was laser welded onto a 37.5μm thick stainless steel metal sheet. The process parameters were: 309 J/cm^2 pulse density, shielding gas Argon, 0.66 J pulse energy, 1.3 ms pulse length, spot welding, and level-and-decline pulse shape. The average surface roughness (Ra) was found to be about 0.5μm.

A permanent magnet was placed under the stainless steel sheet to provide magnetic force to hold the Y-channel in place while Argon gas, at 20 psi pressure, was supplied into the welding chamber. This prevented the Y-channel being blown away when the shielding gas is applied.

Figures 2, 3 and 4, created by the Wyko Surface Profilometer, illustrate the quality of the final mold master. The weld pool had average surface roughness of 4.79μm at the inlets and outlet. The average surface roughness of 0.59μm was measured at the channel.

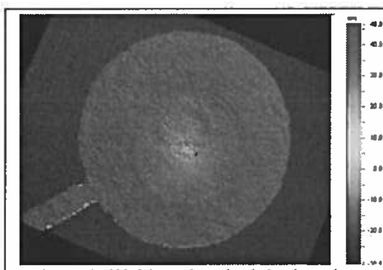

Figure 2 Weld pool at the inlet location, Ra 4.79 μm.

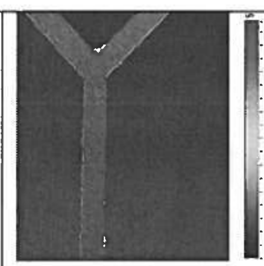

Figure 3 Y channel mold, positive relief, Ra 0.59 μm.

IV. MICROMOLDING THE POLYMERIC (PDMS) MICROFLUIDIC DEVICE AND ITS TESTING

The polymeric Y-channel mixer was molded using the fabricated mold master and PDMS from Slygard 184 elastomer kit (Dow Corning). The material is degassed and then poured on the mold master to cure at room temperature. The PDMS chip can be peeled off (demolded) after 24 hours and requires another 24 hours for full curing under the room temperature.

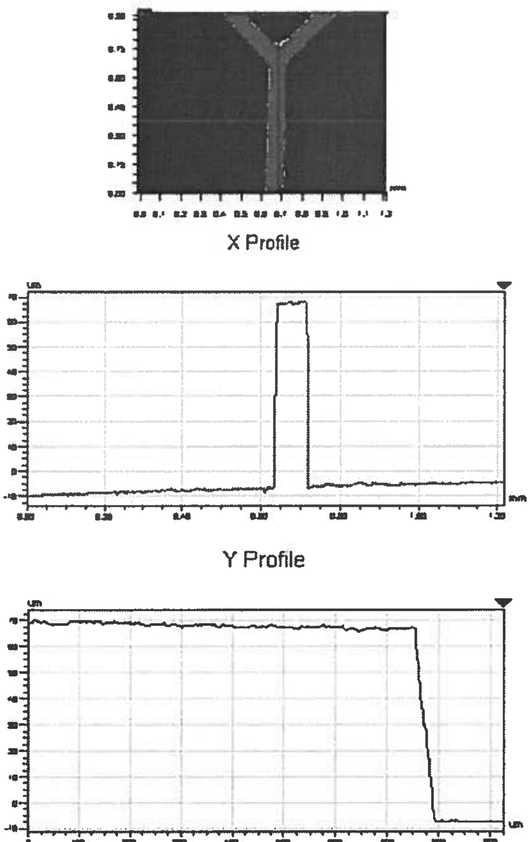

Figure 4 Diagrams from the Wyko optical surface profilometer show that the mold has nearly straight walls.

After curing, the PDMS chip was placed on a supporting plate made from 2.85 mm thick acrylic material. Three holes were drilled in the supporting plate to connect the micro-channels to the fluid supplying tubes. The tubes were glued to the supporting plate by a five-minute epoxy from Lepage.

Figure 5 shows the experimental setup. A silicone based adhesive tape was placed over the PDMS chip to ensure proper sealing.

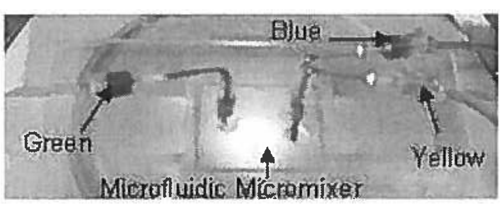

Figure 5. The experimental setup

The Y-mixer was tested with two-syringe pump providing steady streams of colored waters, blue and yellow, to its channels. As the result of mixing, green-colored water appears at the outlet. Figure 6 shows the Y-channel with colored water flowing through it, with flow rate of 6.4μL/min. Another Y-mixer design, part of which is shown in Figure 7, was fabricated for further experimentation with microfluidic mixers. This mixer was tested with flow rate from 0.2 to 10μL/min.

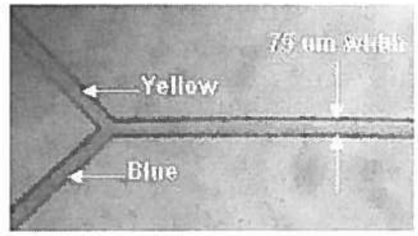

Figure 6. A simple Y-channel mixer, 75 μm width 50 μm height.

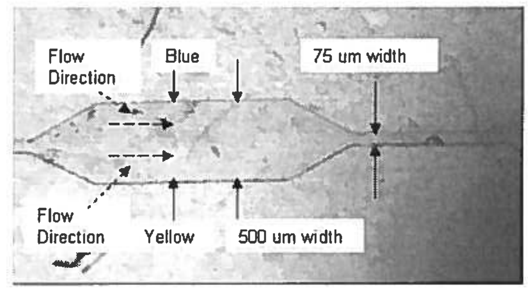

Figure 7 A different design of microchannel to show the laser mold fabrication for LOC devices.

V. Discussion

Most microfluidic devices feature high length-to-width ratio of their channels. In the Y-channel presented in this paper, this ratio is about 280:1. Two issues arise because of the large ratio: first, thermal input can distort the channel features during cutting and, second, excessive oxidation occurs during the laser cutting of oxygen-reactive materials, which results in rough surface of the channel walls.

Thermal distortion induced by the laser cutting can be reduced by using minimal power density and increasing the number of passes. The reduced power density lowers the heat input per pulse, and consequently, the heat-affected-zone is reduced. Furthermore, increasing the speed of laser-cutting of oxygen reactive materials can prevent excessive oxidation of the material and thus increasing the quality of the channel walls. For this reason, reducing the airflow rate to protect the focusing component of the laser material processing system is essential.

A small welding gap is critical in laser microwelding of metallic materials: the weld gap should be about 5% of the thinnest of the two materials being welded. This requirement is further emphasized in microwelding conditions. For example, the low carbon steel sheet is 50μm thick and, therefore, the maximum weld gap is 2.5μm. To avoid having a large weld gap, a low carbon steel was used in our experiments due to its magnetic property. A permanent magnet was used to hold down the Y-channel part for welding.

The laser welding pulse duration is 1 to 2 ms. On the other hand, the laser cutting pulse duration is 10 to 30 ns. Therefore, the laser microwelding process induces greater thermal distortion of the material due to its longer pulse duration and longer time for heat conduction. The high ratio and small material volume of this Y-channel part, the thermal distortion increased dramatically in welding. A larger amount of material is at the inlet and outlet compared to channels; therefore, we selected it as the suitable welding locations.

The surface quality of the metal sheet used for fabrication of the relief determines the quality of the channel surface at the bottom. The roughness of cutting edges, then, determines the surface quality of channel walls. Therefore, a stainless steel sheet was used in our experiments as it provides both good surface finish and good weldability to other steel materials, such as low carbon steel. Using low carbon steel welding to stainless steel reduces problems that arise in the process of joining dissimilar materials, such as cracking, material segregation during cooling period, or the difference in shrinkage.

VI. Conclusions

This paper presents a method for rapid fabrication of metallic mold masters for manufacturing large volumes of microfluidic devices from elastomers such as polydimethylsiloxane (PDMS). The method involves laser micromachining to create the desired relief of the mold, and laser microwelding to join and integrate components into the final mold master. Then, the elastomer is poured over the mold and cured to fabricate the microfluidic device. Compared to conventional soft lithography process, the proposed method is simpler and involves fewer processing steps.

To evaluate the practicality of the proposed method, it was used to fabricate a passive Y-channel microfluidic mixer from polydimethylsiloxane (PDMS). The quality of the fabricated mold master was found to be adequate for microfluidic applications. Mixing of two streams of colored water, flow rate of 0.2 to 10μL/min, was successfully achieved in the fabricated device.

There are several benefits to this approach in micromold master fabrication for microfluidic systems. First, the mold master can be fabricated in short time. Second, this is a maskless micromold fabrication approach that is simpler (involves fewer processing steps) then LIGA and UV-LIGA methods. Third, the use of a low-cost material as the substrate for the mold master reduces the total fabrication cost, relative to the conventional SU-8 soft lithography method.

A limitation of the proposed method is that the microfluidic devices need to be based on 2D features. The channel length and width ratio is limited as the longer the channel length reduces the strength in the middle of two welding points, in results, some defection may occurs during demolding.

Future work on this method will concentrate on exploring different joining methods as potentially lower-cost alternatives to the laser microwelding proposed in this paper.

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