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Rapid fabrication of tooling for microfluidic devices via laser micromachining and hot embossing

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Abstract

This paper presents a new method for rapid fabrication of polymeric micromold masters for the manufacture of polymer microfluidic devices. The manufacturing method involves laser micromachining of the desired structure of microfluidic channels in a thin metallic sheet and then hot embossing the channel structure onto Poly(methyl methacrylate) PMMA substrate to form the mold master. The channeled layer of the microfluidic device is then produced by pouring the polydimethylsiloxane (PDMS) elastomer over the mold and curing it. Polymers like PDMS are preferred over silicon as the material for building microfluidic devices because of their biocompatibility properties as well as because of their lower cost. The proposed manufacturing method involves fewer processing steps than the conventional soft lithography process and enables manufacture of non-rectangular channels in microfluidic devices. To test the method, a mold for a micro capillary electrophoresis microfluidic chip was fabricated. The experimental results confirmed that high quality (Ra 10 to 100 nm) molds can be fabricated quickly and inexpensively. Advantages and limitations of the proposed method are discussed in the concluding section of the paper.

(Some figures in this article are in colour only in the electronic version)

Keywords - microfluidics; micromold fabrication; laser micromachining; hot embossing

1. Introduction

Microfluidic devices play an important role in applications such as analytical microsystems for cell biology, environment monitoring, medical screening and chemical analysis. These devices are often disposable and used only once to avoid sample contamination and therefore practical methods for their mass production are essential for cost-effective manufacturing.

Various methods for mass production of microfluidic devices have been explored in the past, such as hot embossing [1, 2], and microinjection molding [3, 4]. These methods require mold masters and those are usually costly to fabricate. Numerous trials and adjustments of the mold are often needed in the initial stages of its development to meet the requirements of the final microfluidic product. Therefore, the ability to rapidly fabricate micromold masters is desirable in

reducing the concept-to-market product development cycle.

LIGA method (lithography, galvanofforming and plastic molding) produces high-resolution mold masters. The method uses X-ray lithography to transfer patterns onto PMMA resists. The PMMA microstructures are electroplated using nickel or nickel based alloys (NiCo, NiFe). Then the metal master is released by dissolving the PMMA resists. Finally, these masters can be used either for hot embossing or injection molding for plastic replicates. The advantage of this method is that high aspect ratio masters can be produced, but its limitation is the high-cost of the process [5, 6].

Soft-lithography is a well-known method for rapid prototyping of microfluidic devices [7-12]. The method is based on the UV-LIGA process, without the electroplating stage. The mold masters in soft-lithography are made from SU-8 photoresist and the

fabrication method requires a number of steps to create the positive relief mold master [8].

In the method proposed in [13] the positive microchannel relief is cut out from a metallic sheet directly by laser micromachining, and then laser-welded onto a metal substrate. The advantage of the method is that it involves a smaller number of processing steps than the conventional soft-lithography.

In this paper, we present another method that is based on laser micromachining but, unlike in [13], laser micromachining is used to produce the negative relief of the microchannel structure. The method combines laser micromachining with the hot embossing process and, as described in the following sections of the paper, has several advantages over the current state-of-the-art.

The proposed method is illustrated in Section 2. Section 3 describes the experiments undertaken to evaluate the method, and the experimental results are discussed in Section 4. Concluding remarks and directions for further research are in Section 5.

2. Proposed fabrication method

The basic idea behind the proposed method is based on the fact that most microfluidic devices are either planar (two-dimensional) or made as a stack of 2D layers to produce a device with three-dimensional (3D) structure of channels. Thus, fabrication of both 2D and 3D devices can be achieved using 2D mold masters.

In this paper, we propose a method for rapid fabrication of 2D mold masters using a “mask”: a negative of the microchannel relief cut out in a metallic sheet. The use of the mask enables quick and cost-effective fabrication of a number of micromold masters by pressing the mask onto a suitable substrate.

The complete fabrication process involves only two major steps (figure 1):

- 1) Fabrication of the mask by laser micromachining (cut-through) the desired channel structure in a thin metallic sheet,
- 2) Hot embossing the microchannel structure by pressing the mask onto a Poly(methylmethacrylate) PMMA substrate.

The PMMA substrate with the relief produced in Step 2 is then used as a micromold master for molding the microchannel structure in suitable materials, such as the polydimethylsiloxane (PDMS) elastomer.

The process of molding a microfluidic device from PDMS elastomer involves pouring the material over the micromold master, then curing and demolding it. The

fabricated microchanneled part is then assembled with other parts of the components forming the final device.

a) Laser micromachining of the mask

b) Hot embossing

c) Completed mold master

Figure 1. Rapid fabrication of micromold master via laser cutting and hot-embossing: a) laser micromachining of the mask, b) hot embossing the channel structure onto the PMMA substrate, c) PMMA master with the extruded microchannel structure.

Figure 2 shows another view of the proposed fabrication method, along with the steps of fabricating a microfluidic device. As seen in the figure 2, the cross section of the extruded relief on the micromold master is non-rectangular. The non-rectangular shape is a result of the hot embossing process using the mask – the relief is extruded during the process without contacting the walls

of the mask and its shape is determined by the physical process of the free flow of the softened material into the negative channel relief of the mask. Non-rectangular shape of microchannels is a desirable feature in many applications [14, 15].

Figure 2. Cross sectional view of the fabrication processes: (a) laser micromachining the mask from a thin metallic sheet, b) preparing all parts for hot embossing, c) hot embossing process, d) a view of the completed mold master with non-rectangular profile of the microchannel relief, e) PDMS elastomer poured over the mold master, f) two PDMS layers with molded channels bonded together to form a complete fluidic device with non-rectangular channels.

As seen above, the complete process of producing the mold master is rather simple and involves only two major steps: laser micromachining and hot embossing. This simplicity makes the method easy to implement and potentially very cost-effective.

Another very attractive feature of the method is that a single mask can be used to produce several mold masters, thus making the mask suitable for producing a large number of mold masters, and thus microfluidic devices.

Finally, because the microchannel relief of the PMMA master is formed by the free flow of softened material

into the negative relief of the metallic mask (without touching its walls), surface finish of the created microchannel relief is very high.

It should be noted that the mold master can be produced from materials other than PMMA; the only requirement of this method is that the material has to be suitable for (hot) embossing. Furthermore, the mold master can be used for molding microfluidic devices from materials other than PDMS, as long as the mold master material can sustain the process temperature without deforming.

3. Experimental validation

To validate the proposed method, we used it to produce a PMMA master for molding a double-T shape micro capillary electrophoresis (CE) device shown in figure 3. CE devices are commonly used in bio-analytical systems for DNA analysis [16, 17]. Our purpose was to fabricate a PMMA master and use it to mold a sample CE device from PDMS elastomer. Then, the suitability of the proposed method for fabrication of micromold masters was judged on the basis of the geometric accuracy and surface finish quality of both the PMMA master and the sample device.

Figure 3. Micro capillary electrophoresis (CE) device.

All the channels of the CE chip in figure 3 are $140\ \mu\text{m}$ wide and they interconnect to four reservoirs: a sample reservoir, buffer reservoir, injection reservoir, and waste reservoir. All the reservoirs are 2 mm in diameter.

First, we fabricated the mask by laser cutting the channels and reservoirs structure of the CE device in a $100\ \mu\text{m}$ thick sheet of low-carbon steel. Laser cutting 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 nanosecond at 60 kHz. The laser cutting was done with air-assisted condition and conducted under atmospheric pressure. The air-assisted condition of laser cutting was used primarily to provide protection to the laser optics.

After laser cutting, the mask was cleaned in an ultrasonic bath to remove the debris and oxides from the part. The geometric accuracy of the channels and the reservoirs structure of the mask were within 2 to 3 micrometers. The sides of the microchannels were very smooth, within the limits of what can be achieved by nanosecond laser micromachining. The actual surface finish quality of the sides was not measured as it is not critical for the proposed method (the sides of the microchannel structure of the mask do not get into contact with the PMMA material during the hot embossing process).

The hot embossing step of the proposed method was conducted using the Multi-purpose Press from GEO Knight & Co. Inc. The press is capable of applying a pressure from 20 to 80 Psi (1.4 to 5.5 bar) with temperatures from 66 °C to 220 °C.

The mask was placed onto a 1 millimeter thick PMMA substrate. The parameters of the press were set to 125 °C temperature and 30 Psi (2 bar) pressure. The press was preheated to the target temperature before placing the mask onto the PMMA substrate. After the target temperature was reached, the sample was placed in the press. The pressure was applied and held on for 10 minutes. Then the heater was turned off, while still applying the pressure and fan-assisted cooling was conducted for 20 minutes. After that, the mask and the substrate were removed from the substrate. Further cooling to the room temperature was aided by placing a flat steel bar on top of the assembly. Cooling to the room temperature was completed in about 5 minutes. Then the mask was removed from the substrate and the mold master was completed.

Figure 4 shows a detail (intersection of the channels) of the fabricated mold master. It is notable that the surface finish quality of the relief is very high. This is attributed to the fact that the relief is formed by extrusion during the hot embossing process, without contacting with the sides of the cut-through slots of the mask. Thus, the free flow of the softened material flowed into the slots of the mask and the surface tension of the material result in a very smooth surface of the relief.

Figure 5 shows the cross-sectional profile of the relief of the PMMA master. The profile was measured using the Dektak³ST surface profile measuring system from Veeco, Sloan Technology. The actual width of the extruded channel relief was slightly (10-12 μm) smaller than the width of the slots in the mask. This non-rectangular profile of the relief indicates that there was no contact between the sides of the mask slots and the softened material during the hot-embossing process.

To measure the surface finish (average roughness, Ra) of the PMMA master, we used the Wyko NT1100 optical profiling system from Veeco Instruments Inc., NY, USA. Figure 6 to 8 show measurements using the optical profiler of the PMMA master. The results show the proposed method produced surface finish of 010 nm Ra of the extruded channel relief. Furthermore, few measurements were taken in different locations at the PMMA master, it shows the Ra is around 10 to 100 nm, optical quality. The optical profiler inherits a limitation, which cannot capture data when the angle of the surface being measured is too steep (not enough of light reflection from the measuring surface). This limitation was shown in Figure 6 from the black colour area (no data was captured). However, the measurement of the optical profiler shows good surface finish of the master can be achieved by the proposed method.

Figure 4. Detail of the PMMA master fabricated via the proposed method.

Figure 5. Cross-sectional profile of the PMMA master.

Figure 6. The image of PMMA master measured by the optical profiler.

Figure 7. The cross-sectional measurement of PMMA master along the X-axis measured by the optical profiler.

Figure 8. The surface roughness of PMMA master along the Y-axis of PMMA master measured by the optical profiler.

Once the PMMA master was completed, we fabricated a sample microfluidic CE device as follows. The PMMA master was placed on a horizontal surface and the PDMS elastomer poured over it (The PDMS elastomer was degassed prior to that). The material was left to cure at room temperature for 24 hours, and then demolded (peeled off). Due to the non-rectangular profile of the microchannel relief, demolding was easy

and without damages both the molded microchannels in the device and the PMMA master. The resulting PDMS part was then bonded onto a flat piece of PDMS material to complete the CE device.

Figure 9 and 10 show a couple of microscope views of the CE device's microchannels, and figure 11 shows a smooth transition from a microchannel to a reservoir of the device. Further, figure 12 presents a measured cross-sectional profile of one of the channels.

Figure 13 to 15 show the measurement of the CE device's microchannel by the Wyko optical profiler. The results show good surface finish and Ra is around 40 nm Ra.

Figure 9. Microscope view of a microchannel of the CE device.

Figure 10. A close-up microscope view of one of the microchannels, showing high quality of its surface finish.

Figure 11. Smooth transition from the microchannel to the reservoir of the CE device.

Figure 12. Cross-sectional profile of the CE device's microchannel.

Figure 13. The image of CE device measured by optical profiler.

Figure 14. The cross-sectional data of CE device along the X-axis, measured with the optical profiler.

Figure 15. The surface roughness of CE device along the Y-axis, measured by the optical profiler.

4. Discussion

The observed quality of both the PMMA master and the fabricated CE device indicates that the proposed method for fabrication of the mold master is adequate for intended applications. The quality of the surface finish of the fabricated microchannels is notably very high, yet it is simply a beneficial side-effect of the proposed method.

The experiments also confirmed that the complete process of fabricating a mold master and the desired fluidic device is quick and inexpensive. The most time-consuming step of the process is the PDMS curing (24 hours under the room temperature in our experiments). This can be significantly reduced if curing was under an elevated temperature.

A limitation of the proposed method is that the mold master can only be made from materials suitable for hot embossing. Furthermore, the mold master can only be used with the molding materials that the processing temperature is well below the temperature of the master's glass transition temperature. Even with these limitations, the proposed method appears to be a high-quality yet cost-effective solution for a wide range of applications.

To make the method more readily usable, a practical method is needed for choosing suitable process parameters (primarily the hot embossing parameters) for a given design of the microfluidic device. This will be a key topic of our further research.

5. Conclusions

This paper presents a new method for rapid fabrication of mold masters for manufacturing of microfluidic devices based on elastomers such as polydimethylsiloxane (PDMS). The method involves only two major steps: laser micromachining to create a metallic mask, and hot embossing the microchannel features onto a PMMA substrate. Then, fabrication of microfluidic devices involves pouring the PDMS elastomer over the PMMA mold and curing it at a suitable temperature.

The main advantages of the proposed method are:

- 1) Quick and inexpensive fabrication of the metallic mask, and the mask can be used to fabricate a large number of micromold masters,
- 2) High quality surface finish of the micromold relief and the molded microchannels,
- 3) Non-rectangular profile of the microchannels,
- 4) Low cost and biocompatibility of the mold master material (PMMA).

The limitations of the method can be summarized as:

- 1) The material used for the mold master has to be suitable for (hot) embossing,
- 2) The mold master can be used only in applications where the molding temperature is lower than its glass transition temperature,
- 3) It would be difficult to fabricate rectangular microchannels via this method.

Even with these limitations, the proposed method appears to be a high-quality yet cost-effective solution for the intended applications.

Our future work will concentrate on devising a practical method for optimization of process parameters, especially the hot-embossing parameters.

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