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Fabrication of metallic micromolds by laser and electro-discharge micromachining

P. P. Shiu[1], G. K. Knopf[1], and M. Ostojic[2]

[1] *Department of Mechanical and Materials Engineering, The University of Western Ontario, London, Ontario, Canada N6A 5B9*

[2] *Industrial Materials Institute, National Research Council Canada, London, Ontario, Canada N6G 4X8*

E-mail: gknopf@eng.uwo.ca

Abstract A method of creating metallic micromolds with features that have high-aspect ratios is described in this paper. The proposed manufacturing process utilizes laser micromachining to cut the negative two-dimensional profiles of the desired microfeatures and fluidic network patterns on a 100μm thick brass sheet. The positive relief of the cut pattern is then created by using electro-discharge micromachining (micro-EDM) die-sinking the metallic mask onto a brass substrate. The final substrate with the desired relief pattern becomes the molding tool used for either elastomer casting or thermoplastic hot embossing. To validate the proposed fabrication methodology and evaluate the quality of surface finishes, a brass mold master of a T-channel micromixer (50μm width, 25μm height) is developed and multiple replicate devices are cast on this mold using poly-di-methyl-siloxane (PDMS). The surface finish of both the original micromold master and final molded channels on PDMS are measured using an optical profiler and found to have a roughness of approximately 400nm Ra. The ability of the proposed fabrication technique to create accurate features with high-aspect ratios is illustrated by manufacturing a Y-channel micromixer with an aspect ratio of 4. Experimental results are discussed and suggestions for improvement are presented.

Keywords - microfluidics; micromold fabrication; laser micromachining; microEDM

1 Introduction

Over the past decade miniaturized microfluidic platforms, lab-on-a-chip (LOC), and micro-total analysis systems (μTAS) have emerged as the dominant technologies for real-time chemical or biomolecular analysis. The key benefits of these microsystems include increased speed of analysis, high level of system integration, portability, and lower operating cost due to the small amount of reagents consumed during the analysis process. To avoid sample contamination it is also important that these microsystems be used only once. It is essential, therefore, that cost-effective and flexible manufacturing methods be developed to support the mass production of disposable units.

Several manufacturing methods have been explored in the past for the high volume production of disposable polymer microfluidic devices including thermoplastic hot embossing (Becker and Heim 2000; Heckele et al. 1998) and micro-injection molding (Piotter et al. 1997; Larsson et al. 1997). Each of these manufacturing methods requires the design and construction of very costly high-strength micromolds. To meet the desired design specifications, surface finish quality, and microfeature aspect ratios it is often necessary to adjust the mold master parameters through a timely trail-and-error exercise. During product manufacturing the hardened tool will also experience surface wear and damages due to the large number of molding cycles. It may be, therefore, necessary to periodically repair or replace these mold masters while maintaining dimensional accuracy and reproducibility between the successive production runs.

One famous technique for producing high-resolution mold masters is the LIGA method which involves three stages: lithography, galvanoforming, and plastic molding. The method utilizes X-ray lithography to transfer fluidic network patterns onto poly-methyl-methacrylate (PMMA) resists. The PMMA microstructures are then electroplated using nickel (Ni) or nickel based alloys (NiCo, NiFe). The metal master is finally released from the PMMA resists by dissolving it in chemicals such as a mixture of tetrahydro-1, 4-oxazine and 2-aminoethanol-1. These metallic mold masters can be used for either hot embossing or injection molding plastic replicates. The primary advantage of LIGA is that a master with a high aspect ratio can be produced. Unfortunately, the cost of fabrication and the difficulty in accessing the LIGA equipment is often a major detriment by industry in exploiting this technology (Becker et al. 1986; Abgrall and Gue 2007).

Soft-lithography is another widely used method for rapidly prototyping microfluidic devices (Duffy et al. 1998; McDonald et al. 2000; Whitesides et al 2001; Becker and Locascio 2002; Nguyen and Wereley 2002; McDonald and Whitesides 2002). The method is based on the ultra-violet (UV)-LIGA process with the elimination of the electroplating stage. The mold masters in soft-lithography are made from

SU-8 photoresist polymer and the fabrication method requires a number of steps to create the positive relief mold master (McDonald et al. 2000).

Recently, some researchers have reported an alternative method of fabricating metallic micromold masters via laser micromachining and welding (Shiu et al. 2007). This method, termed LCWM, employs a high-power laser to initially cut the desired microchannel features on thin 75μm thick stainless steel sheets and then precision weld the channel features onto a metal substrate using a high-power laser to form the completed micromold master. The advantage of the method is that it involves only a few processing steps. These same researchers proposed another method that also uses laser micromachining called the LHEM method (Laser micromachining, Hot Embossing, and Molding). In this application, the laser is used to micro-machine the negative relief of the desired microchannel structure on a thin sheet to form the mask. A heated polymer is then intruded into the finished mask by hot embossing to form the positive microreliefs of the channel features. The advantage of the method is that the surface finish of the extruded microfeatures is near optical quality (Shiu et al. 2008). The LCWM and LHEM methods are both non-lithography micro-fabrication processes.

Electro-discharge machining (EDM), or spark eroding, has also been proposed as a method of cutting features in micro-scale. Van Ossenbruggen (Van Ossenbruggen 1969) first reported a microEDM process in the late 1960's to drill 15 to 300μm holes for ink-jet printer nozzles (Sato et al. 1985). More recently Masuzawa et al. (Masuzawa et al. 1989) described how high aspect ratio (10:1) microholes could be drilled using an EDM with a 50μm diameter electrode. The authors further developed the process of microEDM machining where a wire electrode was moved through a contour tool path to fabricate 3D features (Masuzawa et al. 1994). J. Flescher et al. (Fleischer et al. 2006) introduced a technique for combining both the electric discharge machining and laser ablation to fabricate micro-scaled structures. The authors also report an increase in productivity by first machining a large volume block of material via EDM and then performing laser ablation for creating the fine microfeatures.

A new method of manufacturing micromold masters that combines the advantages of laser micromachining and the microEDM is presented in this paper. In contrast to the LHEM method previously reported (Shiu et al. 2008), the hot embossing step this case is replaced with a die sinking microEDM process. This innovation enables hardened metallic micromold masters to be fabricated directly without introducing additional steps that may cause dimensional inaccuracies. The method is described in Section 2 and the experiments undertaken to evaluate the fabrication of the micromold and polymer replicates for a T-micromixer are summarized in Section 3. Two additional prototypes are briefly presented in Section 4 to illustrate high aspect ratio microfeatures and the ability to fabricate molds with complex channel designs. The experimental results are further discussed in Section 5. Finally, concluding statements are provided Section 6.

Fabrication of Micromold Masters

The construction of the metallic micromolds requires the two basic steps as shown in Fig. 1. First, a two-dimensional mask is created by laser cutting the negative relief of the microchannel profiles on a thin brass sheet. The positive microchannel structure is then imprinted on a metallic (brass) substrate by a microEDM die sinking process. Once completed, the substrate with the patterned relief is used in a poly-di-methyl-siloxane (PDMS) casting process by pouring the PDMS polymer over the micromold master and allowing the material to cure. Once cured the replicated part is demolded and assembled with the other microsystem components to form the final device. The proposed fabrication method of the mold master is abbreviated as LEDM^2 (Laser micromachining, micro-EDM die-sinking, and Molding).

Comments about the Micromold Construction

The EDM process provides several key advantages for creating a micromold master for large production run. As the individual features and overall patterned networks imprinted on the mold masters became smaller, increasing the demand for microstructures with high strength substrate material is needed. Unfortunately, hardened tool steels are very difficult to machine using conventional material removal processes. Micro-electro-discharge machining (microEDM) is capable of accurately machining any electrically conductive material regardless of its hardness and strength. The material removal mechanism of the microEDM is based on spark-erosion. The spark erosion effect is created by separating positive and negative electrodes with a small gap and then applying high voltage. The spark generated by the discharge can produce a temperature of nearly 8000 to 12,000°C which causes the targeted material to be removed through melting and sublimation. Micromold inserts and features can be created using a very small electrode with a typical length of 50μm and diameter of 5 to 50μm. Although photolithography techniques can produce smaller sized features, the microEDM approach does permit the creation of dimensional sizes that are sufficient for many practical applications in health and environmental sciences which usually in the dimensions of 10 to 100μm width microchannels.

From a design perspective, it may be necessary to rapidly modify mold parameters during the preproduction phase. The geometric dimensions of the patterned metallic mask can also change dramatically after the EDM die-sinking process and, therefore, it cannot be reused because of electrode tool wear. It is important to remember that the same spark that creates the mold will also erode the tool electrodes significantly but at a different rate (Guitrau 1997). Laser micromachining is, therefore, selected to minimize the cost of fabricating the metallic masks because it is fast, requires simple tool paths, and consistently produces accurate 2D cuts on the thin metallic sheets.

Another very attractive feature of the proposed $LEDM^2$ method is that the material of the final master is a harden metal that can be used in injection molding or hot embossing of thermoplastics directly, thus making the $LEDM^2$ suitable for mass production of microfluidic devices. Unlike the LIGA method where multiple steps are required to produce Nickel based masters, the $LEDM^2$ process can fabricate masters for any type of electrical conductive material.

Fabrication of an Experimental Prototype

Prototype Design

Lab-on-chip devices are comprised of several different components such as micropumps, micromixers, separators, filters, reaction chambers, and liquid reservoirs. The microfluidic mixer is particularly important in analytical systems because it permits the controlled mixing of chemicals and bio-reagents. To validate the proposed manufacturing method a brass master for molding a microfluidic T-mixer device, shown in Fig. 2, is first produced. The brass master is then used to produce a replicate T-mixing device from PDMS elastomer.

The suitability of the proposed fabrication method was evaluated by examining the geometric accuracy of the microfeatures and quality of surface finish for both the brass micromold master and the sample device. All the channels of the T-mixer chip in Fig. 2 are about 50μm wide and interconnect to three reservoirs: two input reservoirs, and an output reservoir. All the reservoirs are 1.5mm in diameter.

Fabrication Methodology

The masks with the microfeatures associated with the channels and reservoirs were initially cut on a 100μm thick brass sheet using the AVIA UV laser from Coherent Inc., USA. The laser has 3.0 Watts of power at 20 kHz. For fabrication purposes the pulse duration of the laser was set to less than 40 nanoseconds. The laser cutting was conducted under atmospheric pressure and done with air-assistance. 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 of the mask were within +/-5μm. The sides of the microchannels were reasonably smooth and within the limits of what can be achieved by nanosecond laser micromachining.

The microEDM die-sinking step of the proposed method was conducted using the MG-NC82 Micro-ElectroDischarge Machining (EDM) system from Panasonic. The voltage was set at 80V with a capacitor of 220pf. The speed of Z-axis die-sinking was set at 1μm/sec. To prepare for the machining process, the mask was immersed in the dielectric oil stage tank, and clamped down. A brass rod of 4mm diameter was mounted on the rotating shaft and, the brass rod substrate was micro-EDM die-sunken on a flat brass sheet to prepare a flat surface on the brass rod substrate for subsequent process. After the flatten brass rod was prepared, the brass rod was microEDM die-sinking to create the final mold master. The die-sinking process took about two day without technician intervention. The substrate was then removed from the system. The ultrasonic bath was then used to clean up the debris deposited on the mold master during die-sinking.

Results and Validation

The metallic mold masters were completed in about 48 hours, without any significant intervention by a technician. Fig 3 shows an SEM view of the T-channel micromixer metallic mold master fabricated via the proposed method. The measured width was about 50μm which is very close to the dimensions of the originally designed mask. The T-intersection of microchannels appears to replicate the sharp corner of the mask fairly well. The SEM view also shows the edges of positive reliefs and that the electro-discharge machined surfaces display no evidence of extreme spark erosion. The debris that was weakly deposited on machined surface was largely removed in the ultrasonic bath. Since the debris was easily removed by the ultrasonic bath it can be concluded that this debris was only weakly deposited during the die-sinking process. Further cleaning would be completed after a few molding cycles.

Fig. 4 shows the measurement of the micromold master captured and generated by Wyko optical surface profiler where the scale of Z-coordinates has been enlarged. The results show the average surface roughness for the finished feature to be about 400nm Ra. These measurements indicate that the electro-discharge machined walls of the microchannel are slightly inclined which appears to be caused by the electrode wear of the tool mask during the die-sinking process. The inclined microchannel walls also suggest that the level of spark erosion across the positive relief and the rate of wear are reasonably stable. This observation is consistent with the type of surface roughness found in other similarly machined surfaces. One advantage, from a manufacturing perspective, is that the inclined microchannel walls will assist the demolding process by reducing friction between molded polymer and mold master.

The cross-sectional views of the mold master, with a 25μm machined height, in the X and Y directions are provided in Fig. 5. The corners at the peak of the positive microchannel feature are observed to be slightly sharper than at the bottom ones. This was expected because as the die-sinking process continues the tool electrode will wear resulting in a wider opening. This figure also shows that the top surface of microchannel is relatively parallel to the bottom surface.

A three-dimensional representation of the measured surface finish is provided in Fig. 6. The surface measurement by the optical profiler shows that a master with a good quality surface finish can be achieved by the proposed $LEDM^2$ method. Since optical quality surface finishes are not possible with this method, the replicated microfluidic devices created in this manner are more suitable to applications that use electrical or chemical detection methods. The experimental measurement also demonstrates that the spark erosion arising from the electro discharging process was largely uniform across the brass surface.

Once the metallic master was completed and cleaned with ultrasonic bath, a premixed and degassed PDMS elastomer was poured over it. The PDMS was left to cure at room temperature for 24 hours and then demolded by a peeling action. Due to the trapezoidal cross-section of the microchannel positive reliefs, demolding was unhindered and no damage the microfeatures were observed in the molded microchannels or the metallic master. The microscopic view of the molded PDMS T-mixer is shown in Fig. 7. Some weakly deposited debris that attached to the metallic master, during the die-sinking process, was transferred to the molded PDMS channels. Figs. 8 and 9 provide measurements of the PDMS T-mixer device's microchannels via Wyko optical profiler. The depth of the molded PDMS microchannels was slightly less than the height of master, about 5μm less.

The surface finish of the molded T-mixer is nearly identical to the surface quality of the mold master. Experimental measurements, Fig. 10, confirm that the molded part has a similar surface finish to the master with a surface roughness (Ra) around 350 to 400nm.

Fabrication of Microstructures with High Aspect Ratios

To explore the capability and flexibility of the LEDM2 fabrication method in producing microstructures with high aspect ratios micromold masters, a Y-micromixer and a more complicated microfluidic network were created. Due to the high degree of laminarity of the fluid flow in microchannels the proper mixing of different fluids is often difficult to achieve in short microchannels (Whitesides 2006). For a simple Y-micromixer, molecular diffusion is the primary mechanism and its rate of diffusion, or efficiency, depends on size of the interface area between the two mixing fluids. Therefore, high-aspect ratio microchannels provide a large interfacial area that is desirable for micro-mixing applications.

Fig. 11 shows an SEM view of the Y-channel micromixer mold master with aspect ratio of about 4. Fig 12 shows SEM views of a more complicated fluidic network micromold master. The smallest width of the microfeatures produced using this method was 10 to 20μm. Any microstructures smaller than 10μm were found to be damaged by the debris igniting an irregular pattern of spark erosion. Observations also supported the higher aspect ratio microstructures could be produced by optimizing flushing debris during die-sinking.

General Observations and Discussion

Although the quality of the surface finish for both the metallic master and replicated PDMS T-mixer microchannel layer is noticeably less than optical grade, it remains adequate for many fluidic applications where a surface finish of 300 to 400nm Ra is acceptable. It may be possible to improve the quality of surface finishes through different combinations of tool electrode and substrate materials, and selecting optimal process parameters of microEDM die-sinking. However, this requires further investigation and detail study.

Furthermore, it is essential that a quick and cost-effective solution be found to fabricate the electrode mask because these electrodes experience excessive wear during the micro-EDM die-sinking process and must be replaced after a single use. To reduce the machining time as much as possible, the LEDM2 approach presented in this paper uses a high-power laser to cut the contour of microfluidic network on a planar brass sheet. The T-mixer electrode tool was cut in less than 20 minutes. For certain types of microfluidic network designs that require masks with deep channels and reservoirs, it may be difficult to accurately cut through the thick substrate material without distorting the template channel walls. In these applications an electrode tool milled directly on a block of conductive substrate by a laser may create the desired geometry but the machining time and fabrication costs will significantly increase because of the laser milling operation is a sequential process. In addition, the cut through technique presented in this paper for machining the electrode mask assisted the process of removing, or flushing, debris from the cut-through openings during die-sinking. In contrast, a fully laser machined 3D electrode tool would require more debris flushing of the holes and microstructures than the proposed method.

To lower the unit cost of a single microfluidic device, the mold masters should be built to sustain an extensive number of molding cycles before a replacement is needed. With this method various conductive metals can be used as the substrate material. Tool steels that can be machined via microEDM process are particularly attractive. Not only can mold masters from higher strength metals be fabricated using this method but also lower cost off-the-shelf metals can be easily purchased and used. Brass sheets and substrates were selected in this study to demonstrate this economical aspect of the LEDM2 method. Furthermore, the resultant metallic mold master has sufficiently high strength that it can be used for either hot embossing or micro-injection molding. Hot embossing and injection molding are common techniques for mass production and, therefore, contribute to the reduction in cost per replicated microfluidic devices. The proposed method is also relatively environmental friendly due to the minimal use of chemicals in the process except dielectric oil. From a product life-cycle perspective, the cost of disposing chemicals used in manufacturing is minimal.

One disadvantage of using the die-sinking process to fabricate the mold master is that it requires about 24 to 48 hours. However, unlike the more common electroplating process to produce metallic mold master, the LEDM^2 method has only a few operational steps. Another concern about the proposed methodology is that surface wear on the electrode tool mask resulted in significant dimensional variations, as measured from the peak-to-bottom, in microfeatures with high aspect ratios. This suggests the aspect ratio is limited by a combination of the electrode and work piece materials. If high aspect ratio microstructures are desirable then a thicker electrode mask should be employed.

Conclusions

A new method of fabricating metallic mold masters, for replicating polymeric microfluidic devices, via laser micromachining and microEDM die-sinking was introduced and experimentally demonstrated. This method enables the manufacturer to use a variety of conductive metals as the micromold master substrate. More conventional methods of producing metallic mold masters through electroplating are limited to a small selection of substrate materials. Hard to machine high strength materials, such as tool steels, may be used for fabricating micromold masters using the proposed $LEDM^2$ process. Consequently, mold masters will require less frequent replacement or repair during medium and large production runs, which may significantly reduce production downtime and cost per unit device.

Microstructures with aspect ratios from 0.5 to about 4 were explored and demonstrated. The surface finishes of the mold masters were around 400nm average roughness (Ra). Surface finishes of final mold masters may be improved by optimizing the process parameters of EDM die-sinking or introducing a post polishing step.

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(Please note that only the figure captions will be submitted in this text document and figures will be submitted separately. The attached figures here are for the easy of editing reason.)

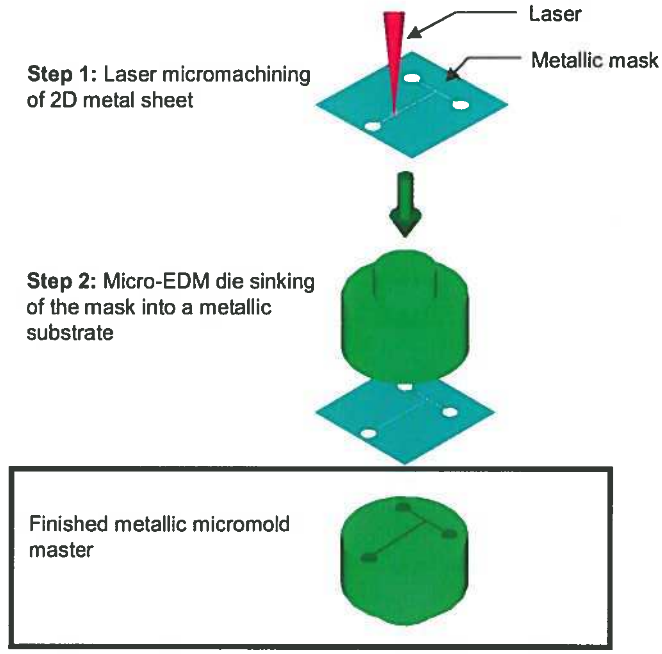

Fig. 1 The two basic steps used to create a metallic micromold using laser and microEDM machining.

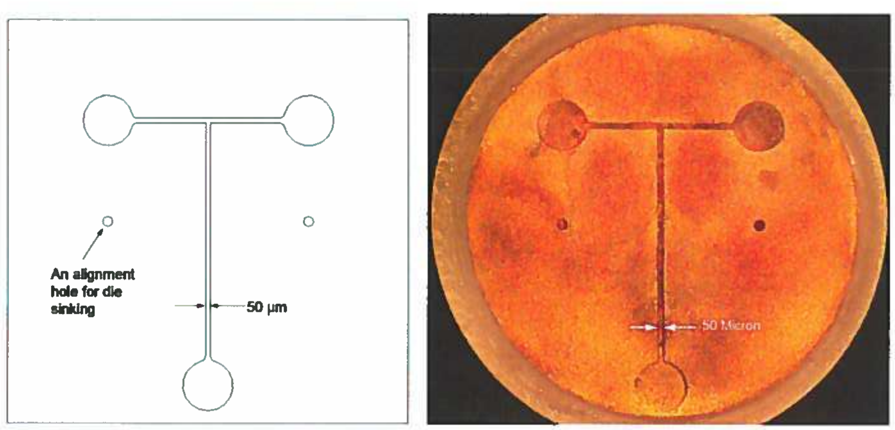

Fig. 2 The design pattern for the mask of T-channel microfluidic mixer and a microscopic view of the fabricated brass micromold master.

Fig. 3 An SEM view of the brass mold master of T-micromixer fabricated via the LEDM^2 method.

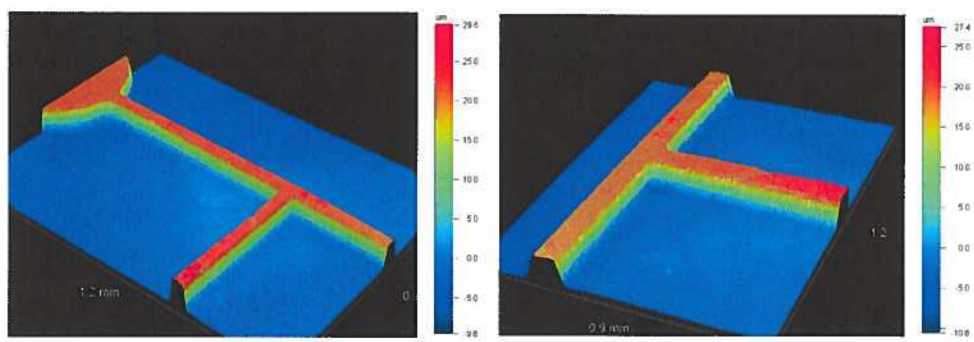

Fig. 4 Three-dimensional measurements of the T-micromixer mold master taken by Wyko optical surface profiler.

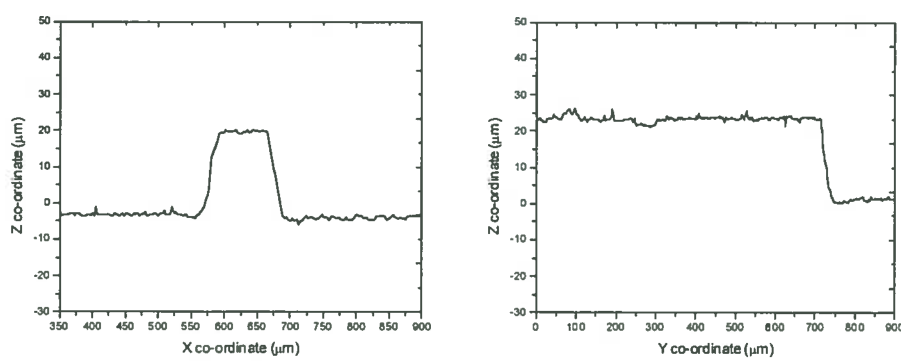

Fig. 5 Cross-sectional profiles of the brass micromold master along the X-axis and Y-axis, measured by the optical profiler.

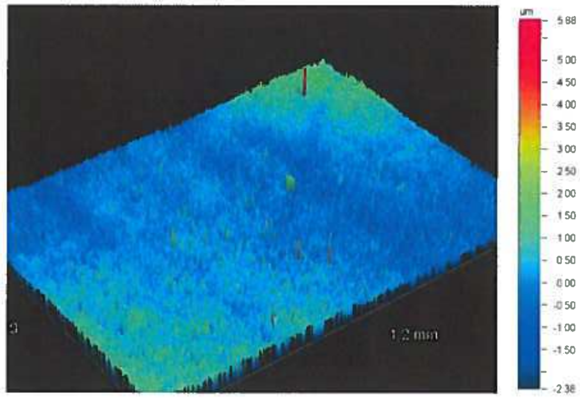

Fig. 6 Surface finish, about 400nm Ra, after the process of microEDM die sinking.

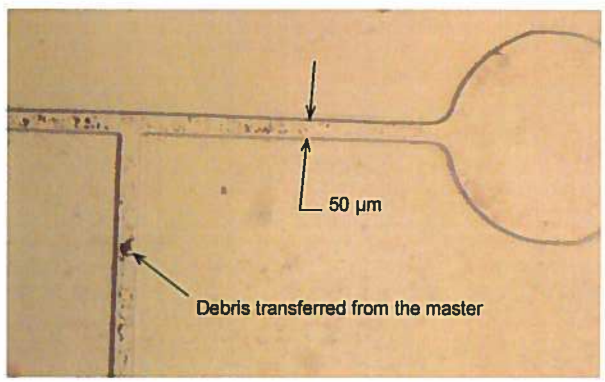

Fig. 7 The molded PDMS T-micromixer fabricated via the LEDM[2].

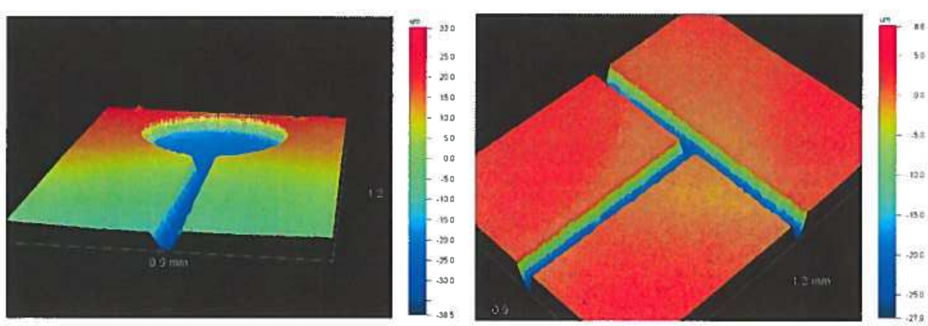

Fig. 8 Computer generated 3D views of the molded PDMS T-micromixer measured by optical profiler.

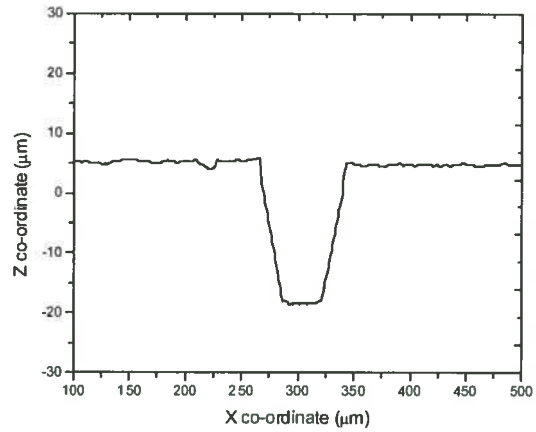

Fig. 9 Cross-sectional profile of the molded T-mixer along the Y-axis, measured by the optical profiler.

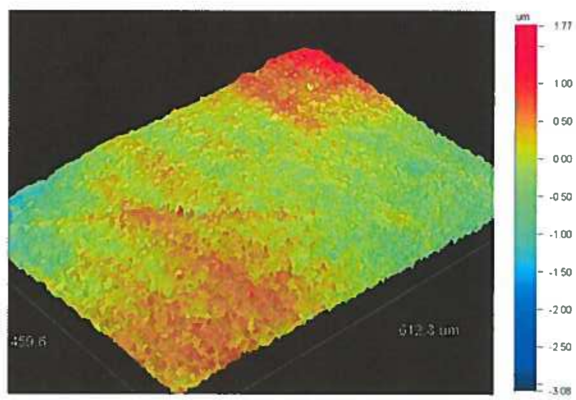

Fig. 10 Surface finish of the molded T-mixer as measured by the optical profiler (350-400 nm Ra).

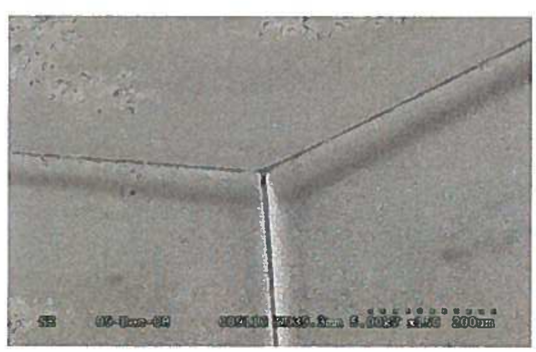

Fig. 11 An SEM view of a Y-channel micromixer mold master with an aspect ratio about 4.

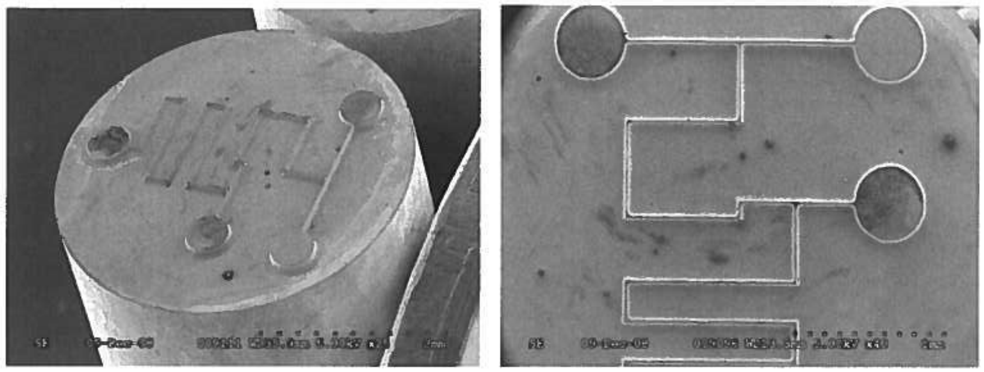

Fig. 12 SEM views of a mold master with a more complex microchannel network.