A novel method for producing a polymer microfluidic device

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Abstract

Microfluidics is an interdisciplinary field of technology which refers to the research and development of micro-scale devices. The devices are built for detection of chemicals from small volumes of fluid. By downsizing the chemical reactions the sensitivity, speed and resolution of the detection improves. Microfludic devices manufacturing require understanding of chemistry, physics, engineering, molecular geology and medicine. From manufacturing perspective the functionality, geometrical elements to be made and material selection of microfluidic device often dictate the use of certain fabrication methods. Most of the manufacturing techniques of microfluidics rely on the photolithography based MEMS fabrication and replication processes. The lithographical manufacturing processes has a disadvantage of requiring multiple steps prior the mass replication process is feasible. The more steps in the process the more errors there will be in the part produced. The use of ultraprecision machining for patterning of microfluidics elements shortens this manufacturing process from tooling to replication.

In this paper a novel method of combining ultraprecision machining with UV-moulding for producing a polymer microfluidic device is introduced. The focus of this study was to generate a production path for plastic microfluidics devices combining ultraprecision machining and UV-replicating processes. A five axis Moore 350FG ultraprecision machine tool with a diamond tool and a 50 µm carbide milling tool was used to machine a boss insert from the microfluidic device. The micro milled electroless nickel insert was then replicated with UV-cure moulding material and the UV-part produced was measured with SEM-images and laser interferometer.

The microfluidic device constructed in this study contains two fluid inlet aperture areas, two primary micro-channels in opposite directions and a reaction area. Two fluids can be inserted to the opposing sides of the device and the reaction takes place in the middle of the device in a separate mixing area. The dimensions for the primary channels were designed so that the flow could be capillary driven. The dimensions in the primary channels were also set so that the flow of fluid would be laminar in case external pumping instead of capillary action is needed. In the reaction area the two fluids are pushed through smaller channels to enhance the chemical mixing between them.

1 Introduction

Microfluidics devices need to be precisely made to be able to handle small volumes of liquid. Typical volumes are in the order of nanoliters. Manufacturing of microfluidic devices often require the use of multiple micro and nanostructuring methods. A broad variety of manufacturing techniques such as photolithography, micro-milling, diamond machining, laser ablation, micro EDM and etching techniques are used for pattern generation. Replication of microfluidics devices depend on the substrate material. For high volume applications the use of polymers such as PMMA, PC, PP and PDMS is desirable and the use of injection moulding or embossing techniques are well suited [1]. Normally the replicated patterns still require surface manipulation with laser, electromagnetic radiation exposure, plasma treatment, plasma deposition, metallic coating or biomarker deposition to provide functionality to the surfaces [2]. The surface chemistry and the materials used play an important role in microfluidics devices. Since microfluidic devices are often made from two parts these two surfaces need to be bonded together properly without destroying the channels at the same time. The leakage between bonded surfaces often occurs while flowing material is being fed into the device. Widths of micro-channels vary from hundreds of microns to hundreds of nanometers, depending on the application. Liquid flow handling in the channels might also require means to actuate valves and drive fluids in the channels with electro-osmotic force, magnetohydrodynamic force and mechanical pumping.

The miniaturization of chemical and biological detection through microfluidics has several benefits:

- Possibility to integrate microfluidics operations such as sampling, pre-treatment, separation and detection on a single chip
- Sensors and electronic components may be integrated on the chip
- The speed of chemical reactions gets faster and more efficient in micro scale
- Consumption of sample and reagent materials is reduced

Thus the ability to pattern nano and micro sized structures for the detection of chemical components becomes essential for the manufacturing of microfluidic

devices. The detection of chemicals can often be applied as an on-chip detection utilizing the following methods: UV-visible spectroscopy, infrared light, Raman spectroscopy, refractive index variation, fluorescence, light scattering, luminescence, electrochemical reaction and thermal conductivity [3]. As an alternative to lithography based manufacturing techniques direct machining of microfluidics patterns on metallic or plastic inserts offer a shorter manufacturing process. In MEMS process several working steps are required prior the insert made can be replicated in numbers [4]. Figure 2 shows the novel manufacturing path for microfluidics investigated in this study. The blue boxes in the figure are optional working steps. The results from surface modification and mass replication are not included in this article.

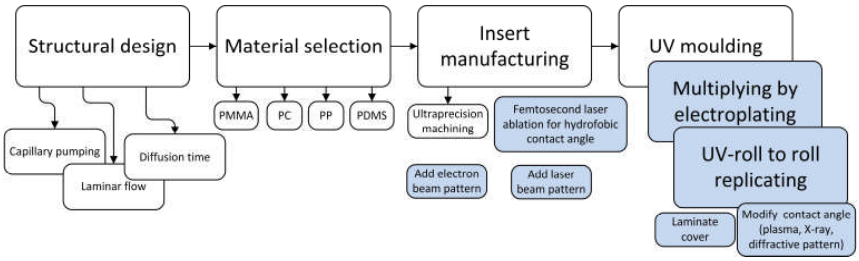


Figure 2: Manufacturing path for roll-to-roll polymer replication of microfluidics

Direct machining offers following advantages on the manufacturing path of microfluidic devices:

- Multi-axis machining can be used for making 3D micro-channels
- Submicron features can be patterned by ruling, fly-cutting and micro chiseling
- In a single set-up light guides, prisms and micro-lenses can be incorporated in to the fabricated patterning tool
- Various materials can be machined
- Speed of patterning is higher than in lithographical processes
- Shorted process path from design to working part
- Other mechanical features can be incorporated into the part (locators, guides, cover structures, etc.)

The disadvantages for direct machining are:

- Limited capabilities in making tightly spaced post or hexagonal patterns due to tool sizes
- Submicron features are difficult to make in a larger area (machine stability, tool life)
- Aspect ratios have tooling limitations
- Small diamond tools and carbide tools are expensive
- Material limitations and high tool wear

The use of multiple manufacturing techniques is quite often a must for making a functional fluidic device. In example for plastic materials capillary flow in narrow laminated channels require separate micro-channel surface tension and contact angle modification towards hydrophilic behavior [5]. This calls for separate physical modification of the channel surfaces by coating/plasma techniques or by micro/nanostructuring (femtosecond lasering or diffractive patterning) [6,7].

2 Methods

2.1 Designing microfluidic device

The design of the microfluidic device depends on the material selection and manufacturing technologies. Material selection is determined by mechanical, chemical and optical properties and has its impact on fabrication technologies. The use of polymers is well suited for fluidic devices but for liquid handling the surface contact angle usually needs to be altered from hydrophobic to hydrophilic [8]. This change enables the use of capillary pumping and no external pumping is needed. The fluidic device made in this case study was designed so that external pumping is required incase no contact angle modification is made for the micro-channel surfaces. By treating the micro-channels with plasma, electromagnetic radiation or diffractive pattern the device turns into capillary driven and no external pumping is needed [9]. The microfluidic device designed in this study contains two fluid inlet aperture areas, two primary microchannels in opposite directions and a reaction area.

To evaluate the design of the microchannel in capillary pumping method a numerical analysis with water as the passing fluid was done. To make the device work a cover needs naturally to be laminated above the microchannels to create a duct where the fluid flows. The primary channels were designed by using Hagen–Poiseuille law that assumes the fluid passing through the channels is viscous, incompressible, the flow is laminar and cross-section of the channel is longer than wider. The velocity of fluid v in the primary channel (equation 1) is relative to driving pressure ΔP, channel depth d and viscosity μ of the fluid used. The driving pressure in a sealed micro-channel (equation 2) can be written as a function of hydrophilic contact angle θ and surface tension between the channel walls and the fluid used. To check that the flow in the primary channel is laminar Reynolds number R_e (equation 3) was calculated based on the cross sectional area A and perimeter Pi of the channel. Figure 1 shows equations 1-3 used for calculating fluid velocity, driving pressure and Reynolds number. Properties of water and its interaction between hydrophilic PMMA were used for calculations [4,5].

$$v = \frac{\Delta P d^2}{\mu L S} \quad (1)$$

$$\Delta P = (2\gamma \cos\theta)/d \quad (2)$$

$$R_e = \frac{\rho(4A/Pi)v}{\mu} \quad (3)$$

For water on PMMA:
μ *viscosity* $1.0 \times 10^{-3}\ Ns/m^2$
L *length of half channel* $0.011\ m$
S *channel geometric constant* 60
d *depth of channel* $16 \times 10^{-6}\ m$
γ *surface tension between the channel surfaces and the fluid* $7.2 \times 10^{-2}\ kgm/s^2$
$\cos\theta$ *contact angle for moving fluid on PMMA* 60°
ρ *the density of fluid* 998.2 kg/m³
A *the cross sectional area* $4.8 \times 10^{-9} m$
Pi *the perimeter of the channel* $632 \times 10^{-6} m$

Figure 1: Calculations for velocity, driving pressure and Reynolds number

Based on the numerical design, manufacturing techniques and literature review the dimensions of the primary device were set. A Pro/Engineering part file was created containing five identical patterns of the microfluidic device. Figure 2 shows five identical boss shapes with their dimensions to be ultraprecision machined on an electroless nickel stamper. The reaction area was designed so that it could be machined with a small micro-milling tool. To see how small features can be replicated small one µm rounded edges were added to the top of channel and mixing area grooves.

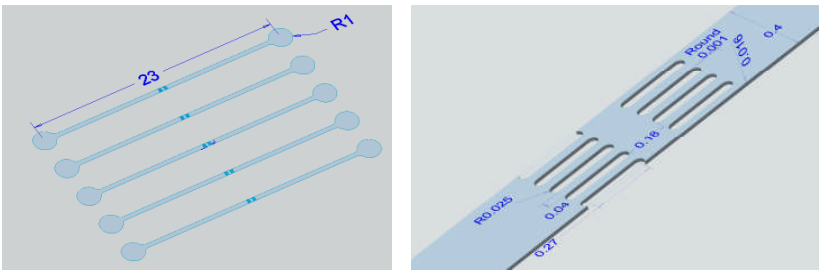
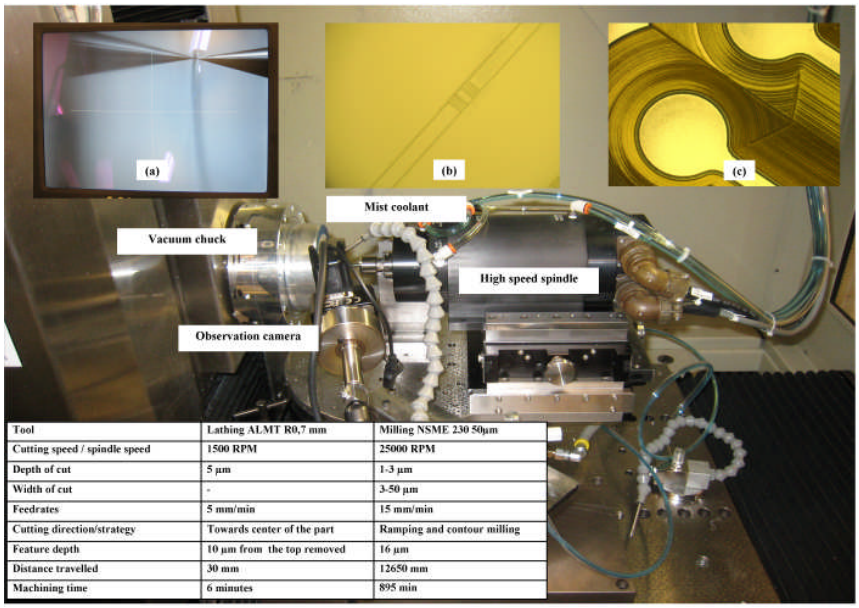


Figure 2: (a) Primary dimensions, (b) mixing area dimensions (units in mm)

2.2 Manufacturing of the electroless nickel mould and UV moulding

A rectangular 50X50X25 mm copper slab coated with 300 µm thickness high phosphorous electroless nickel was pre-machined with Mikron XSM400 high speed milling machine. The boss shapes without the mixing area grooves were micro-milled to 10 µm work allowance. The part was then transferred to a five axis Moore Nanotechsys 350FG ultraprecision machine tool and cut straight by turning with a 0.7 mm radius diamond lathing tool. The turned surface was measured with Fisba µPhase2 laser interferometer and an RMS 22 nm was achieved. The boss shapes for the device were finished by micro-milling using a 60 000 rpm high speed spindle in the Moore machine with a square NSME230 50µm diameter carbide milling tool from NS-Tool Co. The micro-milling tool was balanced to 20 nm with a Sigma balancer and the tool run out was adjusted down to 0.2 µm. Tool path programming was done in Pro/Engineering program.

The XYZ tool path programming accuracy was set to 0.1 µm accuracy although this is known to slow down the ultraprecision machine tools tool path following speed. Cutting strategies consisted of ramping and contour milling. Thermal stabilization of the machine was monitored during micro-milling by measuring the temperature of the part, mist coolant, high speed spindle head and machine enclosure. By dry-running the cutting program for 6 hours the temperature fluctuation of various points were stabilized within ±0.1 C. Figure 3 shows the overall machining set-up, observation camera view, microscopic images from the machined part. The cutting data is also represented in the same figure.



Tool	Lathing ALMT R0,7 mm	Milling NSME 230 50µm
Cutting speed / spindle speed	1500 RPM	25000 RPM
Depth of cut	5 µm	1-3 µm
Width of cut	-	3-50 µm
Feedrates	5 mm/min	15 mm/min
Cutting direction/strategy	Towards center of the part	Ramping and contour milling
Feature depth	10 µm from the top removed	16 µm
Distance travelled	30 mm	12650 mm
Machining time	6 minutes	895 min

Figure 3: Machining set-up: observation camera view (a), in-machine tool micro-scope views (b-c) and cutting values

3 Results

After the machining of the nickel mould a set of molded sheet parts were made from UV-curable silicate-based inorganic–organic hybrid polymer ORMOCER-material, ORMOCOMP US-S4. ORMOCER adheres very well on most substrates such as: metallized silicon wafers, inorganic glasses and polymers. The thermal stability of the material is high (decomposition temperature 270 ºC) and it has good long-term environmental stability and reliability. ORMOCER can be used in optical application requiring RMS values of 2-4 nm. ORMOCER electrical and optical properties can be tailored as well and the material is widely used in devices containing light guides, prisms and micro lenses. For further processing moulded structures from UV-curable material can be replicated into Ni-shims by electroforming [10,11].

SEM images were taken with Carl Zeiss NTS GmbH, SUPRA™ 55VP Scanning electron microscope from one moulded part. The thickness of the moulded sheet parts was 300 µm. Figure 4 is showing a top view SEM image from the mixing area (a) and an inlet area (b).

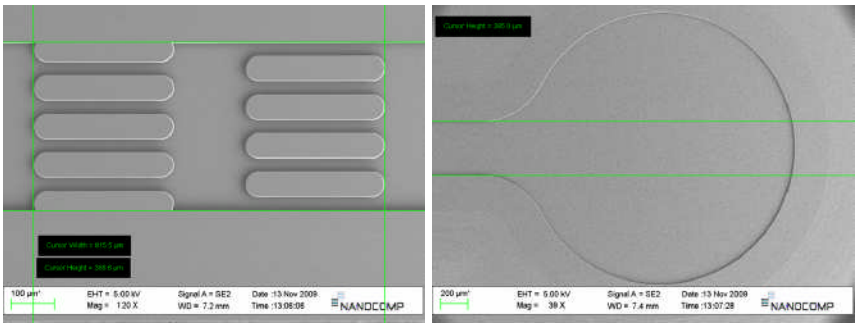


Figure 4: (a) SEM images from UV-mould: mixing area (a), inlet area (b)

Figure 5 show a side view close up of the primary channel wall (a) and cross section view from the primary channel (b). The microchannel was cut in half by freezing the UV-part with liquid nitrogen and then breaking it in an arbitrary position.

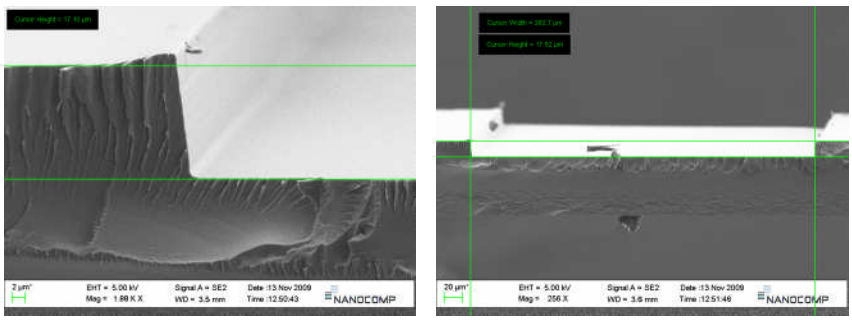


Figure 5: (a) Primary channel wall with small radius (a), cross section view (b)

According to figures 3 and 4 the nominal width of the primary channel was replicated with ± 5 µm tolerance and the nominal depth of the primary channel was replicated within ± 0.6 µm tolerances. The NS-tool micro-milling carbide tool used has a form accuracy tolerance within ±2 µm and this will have an effect on the width dimensions achieved. Also adding slightly to form error are the run out error for high speed spindle and the high speed spindle balancing error. It must be noted that dimensional measurements were done from a thin plastic sheet part which bends rather easily. Setting the part perpendicular to the SEM measurement scales is not very easy leading to higher uncertainty of this dimensional measurement. It was estimated that the uncertainty of SEM dimensional measurements from a cross section of the thin film UV replicated

part is U = ± 0.5 + L/200 µm. The smaller details are replicated very well in the ORMOCER material, figure 5 a shows nicely the 1 µm radius at the bottom of UV-mould that was machined on the nickel insert. The used 50 µm carbide milling tool was inspected with 1000X magnification Keyence VHX600 microscopic camera. The tool was slightly worn from the tip but it did survive the entire 15 hours cut and distance of 12.5 meters without breaking.

Surface roughness and surface topography of the UV-moulded part was measured from one sheet part with Fisba µPhase2 Twyman-Green laser interferometer. The sheet part was coated with 20 nm sputtered gold layer and vacuum chucked to a straight aluminum plate. Five different inlet locations were measured and the diameter of each inlet area measured was 800 µm. The measurement results from inlet areas are shown on figure 6.

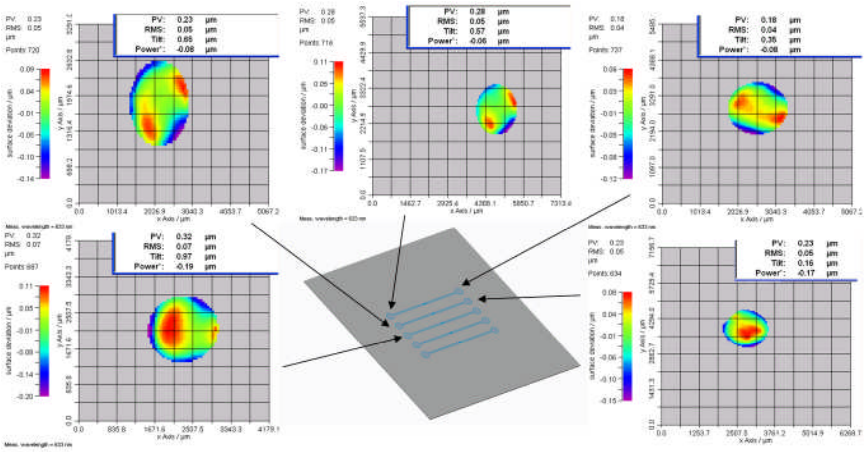


Figure 6: Laser interferometer images from five inlet areas

According to laser interferometer measurements the five inlet areas had an average PV of 0.25 µm and RMS of 0.05 µm. Once again the bending of the thin plastic UV-moulded part can be seen from the tilt values on figure 6.

4 Conclusions

In this study a novel method of combining ultraprecision machining with UV-moulding for producing a polymer microfluidic device was introduced. An ultraprecision machine tool was used to machine a microfluidic pattern on an electroless nickel insert. UV-moulded replicated part was then made from the nickel insert. UV-part produced was then measured with SEM images and laser interferometer. According to interferometer results the 22 nm RMS values of the diamond cut insert turned into an average of 50 nm on the UV moulded part. The small micro-machined details were also replicated very well according to

the SEM images. The 50 µm carbide milling tool survived the entire 15 hours cut with little wear.

In conclusion direct machining of microfluidics patterns offers in some cases a more straight forward manufacturing process in comparison to lithography based manufacturing techniques. Micro-milling is most suited for making microchannels and reaction areas directly on metallic inserts. Direct machining is governed by the fact that smallest micro-milling tools have a diameter of 10 µm. In reality milling tools with a diameter from 30 µm are usable having acceptable tool life. In the same machining set-up light guides, prisms and micro-lenses can be incorporated in to the fabricated mould insert. Additional micro and nano features may be added to the insert by laser ablation or metallic coating. These inserts can then be replicated by UV-moulding, hot embossing or injection moulding. In reality direct machining will make certain manufacturing steps of microfluidics devices more straight forward but combination of other feature patterning techniques is often required to make working fluidics devices.

5 Acknowledgements

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References

[1] Pamme N., "Principles and Applications of Microfluidics in Life Sciences", Lab-on-a-Chip European Congress, Dublin, (2010).
[2] Wootton R., "Microfluidic Design Basic concepts and techniques", MicrofluidicsWorkshop Lancaster University, (2010).
[3] Desmulliez M., "Some microsystems fabrication processes", MicrofluidicsWorkshop Lancaster University, (2010).
[4] Jean Berthier J., Silberzan P., "Microfluidics for Biotechnology (2nd Edition) ", Artech House, ISBN: 978-1-59693-443-6, (2009)
[5] Tesar V., "Pressure-Driven Microfluidics", Artech House, ISBN: 978-1-59693-134-3, (2007).
[6] Kim S., Huh P., "E-Beam Graft Polymerization of Hydrophilic PEG-Methacrylate on the Surface of PMMA", Journal of Surface Engineered Materials and Advanced Technology, Vol. 2, p. 264-270, (2012).
[7] Martines E., Seunarine K., Morgan H., Gadegaard N., Wilkinson C., Riehle M., "Superhydrophobicity and Superhydrophilicity of Regular Nanopatterns" Nano Letters, Vol. 5, No. 10, p.2097-2103, (2005).
[8] Lin R., Burns M., "Surface-modified polyolefin microfluidic devices for liquid handling", Journal of Micromechanics and Microengineering, Vol.15, Number 11, (2005).
[9] Zimmermann M., Hunziker P., Delamarche E., "Capillary pumps for autonomous capillary systems" Lab on a Chip,Vol.7, p.119-125 (2007).

[10] Houbertz R., Domann G., Cronauera C., Schmitt A., Martin H. , Park J.-U., Fröhlich L., Buestrich R., Popall M., Streppelc U., Dannber P., Wächter C., Brauer A., "Inorganic–organic hybrid materials for application in optical devices", Thin Solid Films Vol. 442, p.194–200, (2003).
[11] Pietarinen J., Siitonen S., Tossavainen N., Laukkanen J., Kuittinen M., "Fabrication of Ni-shims using UV-moulding as an intermediate step", Microelectronic Engineering Vol. 83, p. 492–498, (2006).