Sensors **2007**, *7*, 1643-1654

sensors
ISSN 1424-8220

www.mdpi.org/sensors

Full Research Paper

Micro Machining of Injection Mold Inserts for Fluidic Channel of Polymeric Biochips

Woo-Chul Jung [1], Young-Moo Heo [1], Gil-Sang Yoon [1], Kwang-Ho Shin [1], Sung-Ho Chang [1], Gun-Hee Kim [2] and Myeong-Woo Cho [2,*]

1 Precision Molds & Dies Team, Incheon R&D Center, KITECH, Incheon 406-840, Korea
E-mail: bogus2@ kitech.re.kr; ymheo@kitech.re.kr; seviaygs@kitech.re.kr; ppori@kitech.re.kr; shchang@kitech.re.kr
2 Department of Mechanical Engineering, Inha University, Incheon 402-751, Korea
E-mail: venkey@empal.com; chomwnet@inha.ac.kr

* Author to whom correspondence should be addressed.

Received: 11 June 2007 / Accepted: 24 August 2007 / Published: 27 August 2007

Abstract: Recently, the polymeric micro-fluidic biochip, often called LOC (lab-on-a-chip), has been focused as a cheap, rapid and simplified method to replace the existing biochemical laboratory works. It becomes possible to form miniaturized lab functionalities on a chip with the development of MEMS technologies. The micro-fluidic chips contain many micro-channels for the flow of sample and reagents, mixing, and detection tasks. Typical substrate materials for the chip are glass and polymers. Typical techniques for micro-fluidic chip fabrication are utilizing various micro pattern forming methods, such as wet-etching, micro-contact printing, and hot-embossing, micro injection molding, LIGA, and micro powder blasting processes, etc. In this study, to establish the basis of the micro pattern fabrication and mass production of polymeric micro-fluidic chips using injection molding process, micro machining method was applied to form micro-channels on the LOC molds. In the research, a series of machining experiments using micro end-mills were performed to determine optimum machining conditions to improve surface roughness and shape accuracy of designed simplified micro-channels. Obtained conditions were used to machine required mold inserts for micro-channels using micro end-mills. Test injection processes using machined molds and COC polymer were performed, and then the results were investigated.

Keywords: Biochip; lab-on-a-chip; micro machining; injection molding; mold inserts.

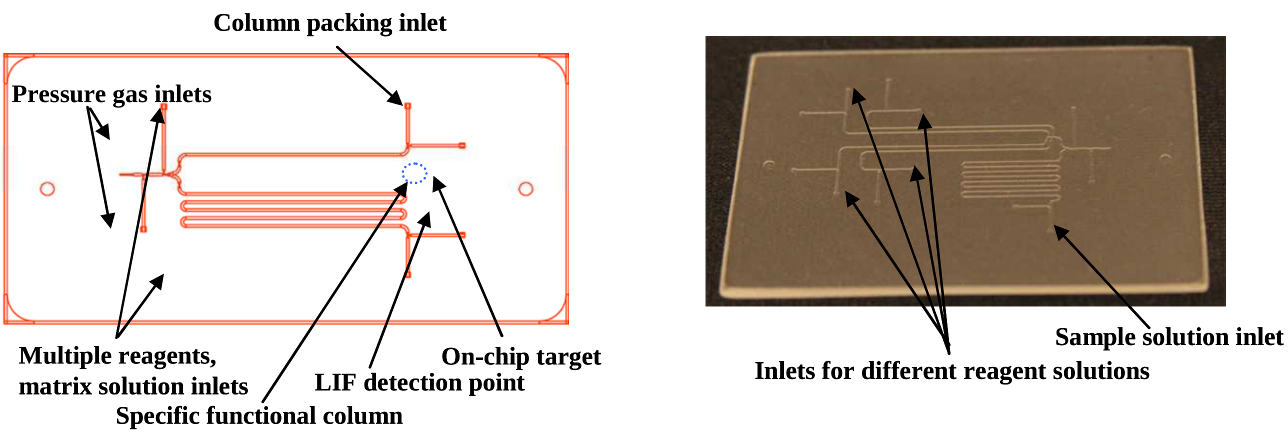
1. Introduction

Recently, with the development of MEMS (micro electro-mechanical system) technologies, conventional biotechnological analytical processes can be rapidly performed using miniaturized biochips. Typical biochips can be categorized into two groups; micro-array and micro-fluidic chips. The micro-array has an array of miniaturized test sites on a chip. The number of micro-arrays varies from a hundred to a few thousand; and the typical size of the test sites ranges from 10 to 500μm. Because the micro-fluidic chip can perform multiple tasks in a typical biochemical analysis laboratory, such as mixing, reaction, separation, and detection, etc., it is often called as LOC (lab-on-a-chip) or μTAS (micro total analysis system).[1,2] Advantages of the LOC are; (1) required time for analysis is much shorter, (2) very small amount of specimen and reagent are required, (3) low cost, high analysis accuracy, low contamination, and easy to use, etc. Thus, the micro-fluidic chips have been focused as a leading technology in related fields.[3-6] Unlike the micro-array, the micro-fluidic chip contains many micro-channels to connect the unit tasks for consecutive processing steps.[1] The continuous flow of input test samples and reagents through the micro-channels can make the analytical process to be performed on a chip by minimizing sample contamination and processing time. Typical substrate materials for micro-fluidic chip fabrication are glasses (such as fused silica glass, etc.) or polymers (such as PDMS (polydimethyl siloxane), PMMA (polymethyl metacrylate), COC (cyclic olefin copolymer) etc.). The substrates for micro-fluidic chips should be biocompatible since most of they are used for biological analysis. Besides, various material properties such as mechanical strength, porosity, and hydrophobicity, etc., are required for real application. Fabrication procedures of such substrate depend on the used material and complexity of the chip. Typical technique for micro-fluidic chip fabrication is based on the soft lithography, such as wet-etching, micro-contact printing, and hot-embossing, micro injection molding, etc.[2-5] Also, LIGA and micro powder blasting processes are applied to form required micro-channels on the biochips.[7] Several studies were performed to replicate microchips using metal mold masters which were prepared by CNC micro-milling processes.[8-11] In the studies, brass [7] and aluminum masters [9-11] with micro-channels were machined to replicate PMMA and thermosetting resin by hot embossing.

In this study, to establish the basis of the micro pattern fabrication and mass production of polymeric micro-fluidic chips using injection molding process, micro machining method was applied to form micro-channels on the LOC molds. As a first step, simplified micro-channels were designed based on existing research results. Then, a series of machining experiments using micro end-mills were performed to determine optimum machining conditions to improve better surface roughness and shape accuracy. Obtained conditions were used to machine required mold inserts for micro-channels using micro end-mills of 400μm diameter. Finally, test injection processes using machined molds and COC polymer were performed, and the results were investigated. As the results, it can be observed that the required micro-fluidic chips can be obtained using injection molding process.

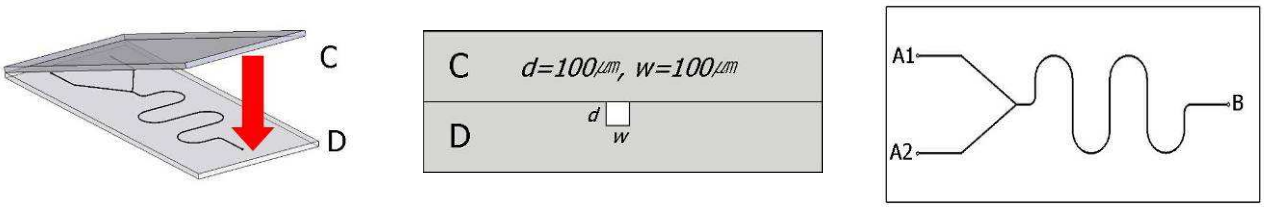
2. Design of a Sample Biochip with Micro-channels

Figure 1 shows a sample of the LOC designed by the MicroSystems and BioMEMS Lab at University of Cincinnati.[3] As can be seen in the figure, there are many micro-channels for the required biochemical processes. Thus, for the experiments of this research, a simplified biochip with micro-channels was designed based on the existing research results as illustrated in Figure 2. The designed biochip is composed of an upper plate C and a bottom plate D (Figure 2(a)). By closing the upper plate, square-type micro channels (width=100μm and depth=100μm) can be formed between the plates (Figure 2(b)). As shown in the Figure 2(c), A1 and A2 are the inlet ports for the reagent and test sample; B is the sensing port of the reaction result. The micro-channel is formed between the ports A and B for sufficient mixing of the reagent and test sample. It is designed to have 90mm of total flow distance and 70mm of detection length for 700nl resolution.



(a) Conceptual drawing. (b) Photograph.

Figure 1. A disposable lab-on-a-chip device with a specific bead packed column for MALDI-MS.[3]



(a) Biochip. (b) Cross-sectional view. (c) Top view.

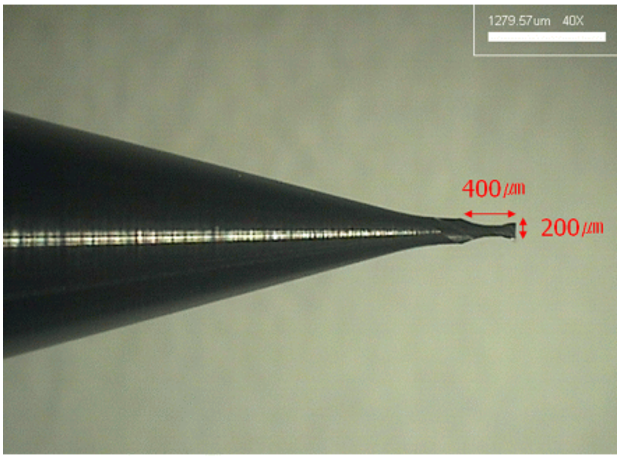
Figure 2. Designed simplified micro-fluidic channels for experiments.

3. Machining Experiments Using Micro End-mills

3.1. Experimental Setup

Experimental setup for the micro-channel machining is shown in Figure 3. Figure 3(a) shows the 3-axis micro stage; resolution of each linear carriage is 0.1μm, and maximum rotational speed of main spindle is 100,000rpm. Generally, the micro end-milling process requires much higher specific energy than the traditional cutting processes since the tool diameter is very small. In many cases, such high specific cutting energy consumption causes higher cutting heat, shorter tool life and serious burr formation, etc. Thus, an oil mist supplier and a suction unit are attached to the system for more effective machining of micro-channel with higher accuracy and better surface roughness. One of the used micro end-mill is shown in Figure 3(b); its diameter=200µm, length of cutter=400µm and helix angle=15degree. Generally, micro end-mills are made with WC (tungsten carbide), and have lower aspect ratio than traditional end-mill to compensate its low rigidity. Also, NAK80, which is a precipitation or age-hardened mold steel with a uniform through hardness of approximately 40 HRC, was chosen as the test workpiece material.

(a) 3-axis micro machining stage.



(b) Micro end-mill (diameter=200µm).

Figure 3. Experimental setup for the micro machining of mold inserts.

3.2. Experiments for Surface Roughness Improvement

Surface roughness of the machined micro-channel is an important factor to determine the liquid fluidity in the channel. Since the conventional finishing processes, such as polishing, lapping, etc., are almost impossible for micro-channel fabrication, it is very important to decide optimum machining conditions based on the required experimental results. Thus, as a first step of this research, the relationship between the machining condition and surface roughness was investigated through a series of experiments.

Since the micro-channels for the biochips have straight and curved regions, a test specimen was designed to have both regions with same curvature as shown in Figure 4. The specimen was cut by two methods at constant spindle speed of 17,000rpm and by changing the feed-rates as follows; (a) 1 pass cutting, depth-of-cut was 100µm, (b) 10 times of step cutting, depth-of-cut for each step was 10µm. Measured results of the surface roughness are shown in Figure 5(a) and (b) for straight and curved region, respectively. The best results were observed when the depth-of-cut was 100µm and feed-rate was 50mm/min for both of the straight (Ra=31nm) and curved (Ra=44nm) regions.

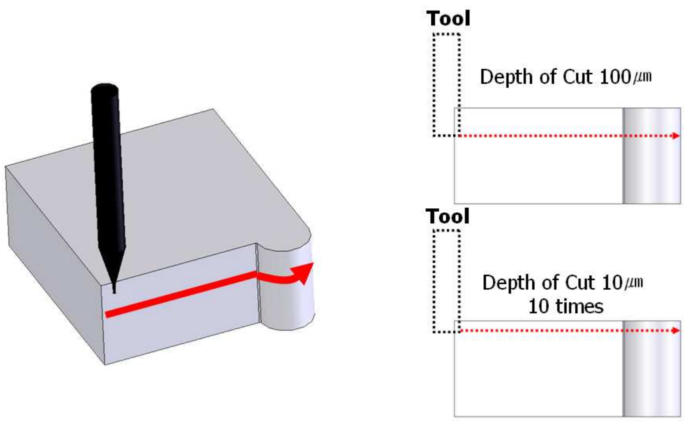
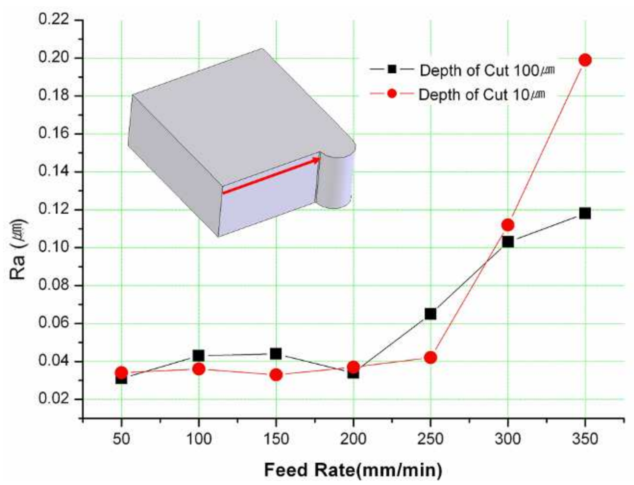


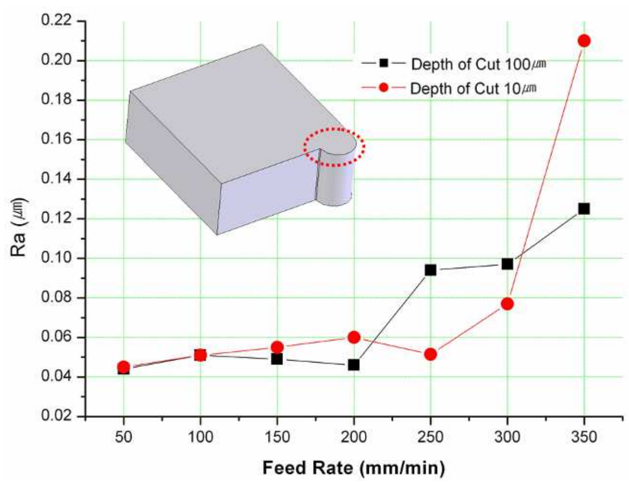
Figure 4. Cutting methods for experiments.

3.3. Experiments for Shape Accuracy Improvement

As a next step, a series of experiments were performed to investigate the influence of tool diameter variation on the shape accuracy of machined micro-channel. For the experiments, micro tools of 200µm and 400µm diameter were used, and the results were analyzed. Depth-of-cut was set to 100µm and feed-rate was set to 50mm/min according to the previous experimental results. Measured results of the machined micro channels and 3D profiles of straight and curved regions are shown in Figure 6 (tool diameter=200µm) and 7(tool diameter=400µm). From the figures, it can be seen that the micro end-mill of 400µm diameter gives better shape accuracy at same machining conditions.

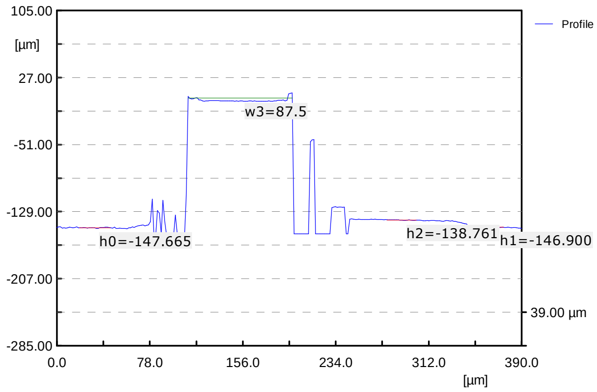


(a) Straight region.

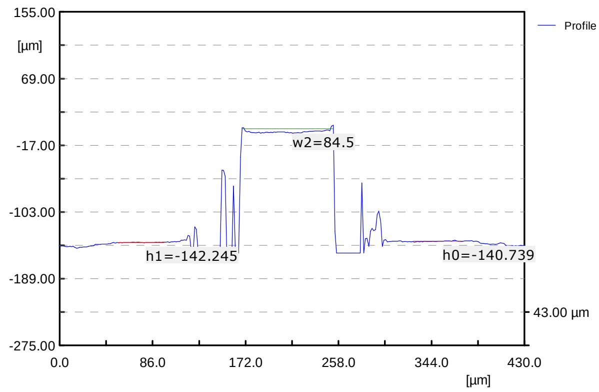


(b) Curved region.

Figure 5. Measured surface roughness.



(a) Straight region.



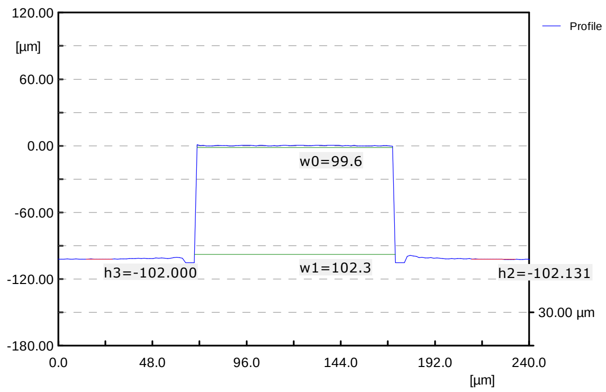
(b) Curved region.

Figure 6. Measured profiles of micro channels machined using 200µm micro end-mill.

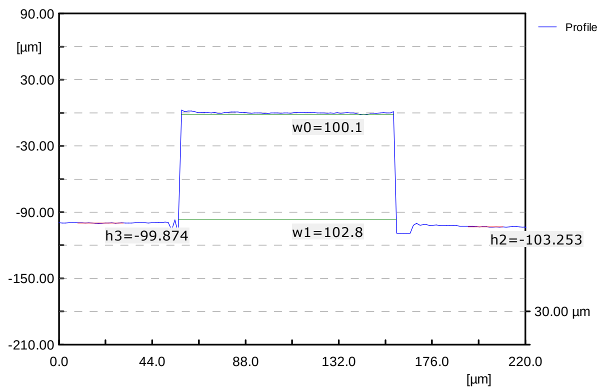
4. Fabrication of Mold Inserts and Test Injection Experiments

4.1. Mold design

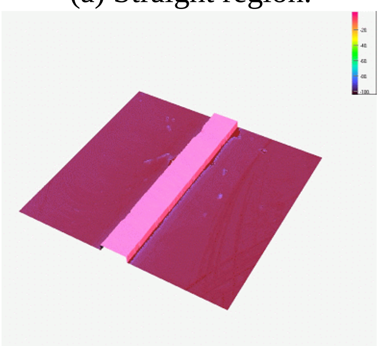
In this research, a required injection mold set for biochip production was designed as shown in Figure 8. It has simple mold base structure for easy alignment and manufacture. The mold has 4 cavities, which is surrounded by isolation plates to prevent heat loss, and to maintain the inside temperature constant during injection process. Using the mold, the upper and bottom plates of the biochips can be formed at a time by one process.



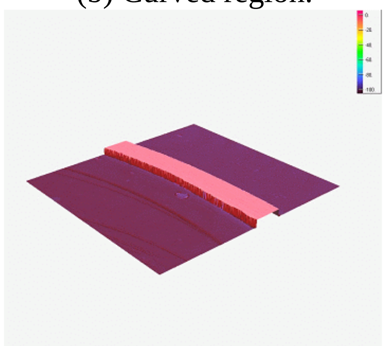
(a) Straight region.



(b) Curved region.

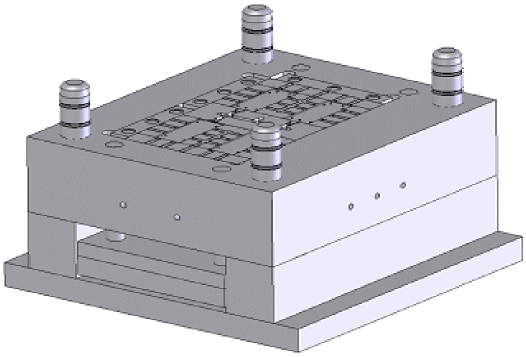


(c) Straight region-3D.

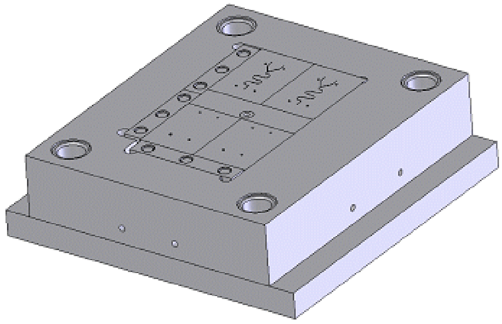


(d) Curved region-3D.

Figure 7. Measured profiles of micro channels machined using 400µm micro end-mill.



(a) Bottom part.



(b) Upper part.

Figure 8. Designed injection mold set.

Table 1. Applied conditions for core machining.

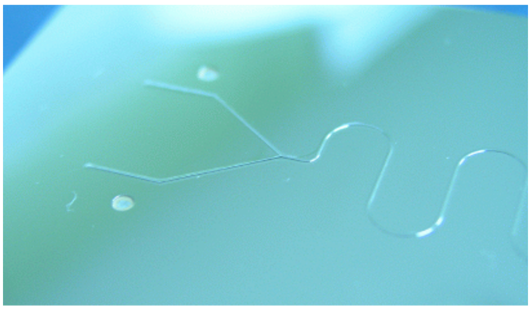
Feed-rate	50mm/min	RPM	17,000
Depth-of-cut	100µm	Tool	Union 400µm
Side depth-of-cut	10µm	Machine	DMU 100T

4.2. Mold Fabrication for Biochips

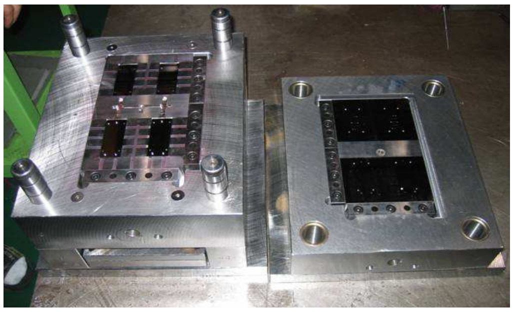
Based on the previous experimental results, the optimum conditions for core machining to form micro channel were determined as shown in Table 1. SKD11 was used for inject pin and guide bush manufacture; and NAK80 was used for mold cavity and cores for micro channel forming. Figure 9(a) shows the mirror-finished bottom plate core for micro-channel machining. Figure 9(b) and (c) show the machined core, and (d) shows the assembled mold set for the test injection experiments. As shown in figure, 4 cavities are assembled in a mold set.

(a) Bottom plate core after mirror-finishing.

(b) Machined core by micro end-milling.



(c) Micro-fluidic channel on the core.



(d) Assembled mold set for test injection.

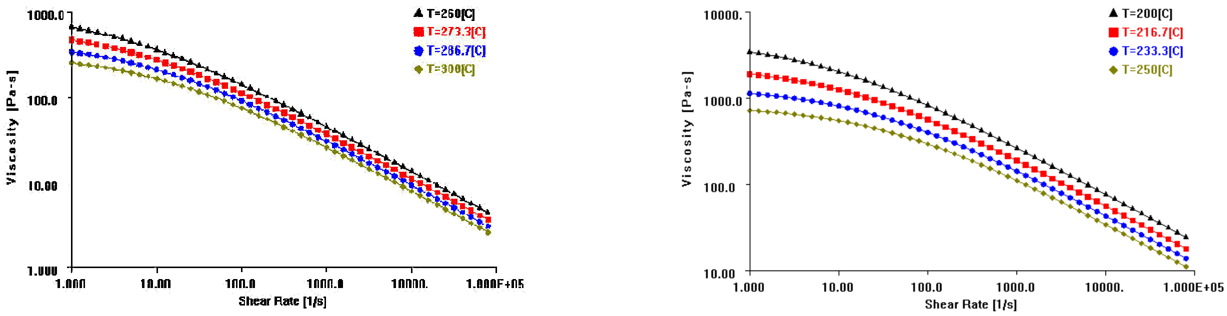
Figure 9. Manufactured core and injection mold.

4.3. Injection Molding Characteristics of COC

The materials used for test injection process were COC (cyclic olefin copolymer), which have good material properties, such as high transparency, low double refraction, low absorptive property, and biocompatibility, etc. To investigate the injection characteristics using the developed molds, two types of COC resins (Topas 5013S-04 and 8007S-04) were used. Thermal properties of COC and their viscosity characteristics are shown in Table 2 and Figure 10.

Table 2. Thermal properties of COC

COC	5013S-04	8007S-04
Melt temperature	260°C	230°C
Glass transition temperature	136°C	80°C
Viscosity index (MPI data)	VI(260)0058	VI(260)0091



(a) Topas5013S-04 (b) Topas8007S-04

Figure 10. Viscosity characteristics of COC resins.

Table 3. Injection conditions for test injection.

<table>
<tr><th rowspan="2">No.</th><th colspan="2">Polymer Temp.(°C)</th><th rowspan="2">Injection Pressure (kgf/㎠)</th><th rowspan="2">Flow Rate (㎤/sec)</th><th rowspan="2">No.</th><th colspan="2">Polymer Temp.(°C)</th><th rowspan="2">Injection Pressure (kgf/㎠)</th><th rowspan="2">Flow Rate (㎤/sec)</th></tr>
<tr><th>5013S-04</th><th>8007S-04</th><th>5013S-04</th><th>8007S-04</th></tr>
<tr><td>1</td><td rowspan="9">270</td><td rowspan="9">250</td><td rowspan="3">1263</td><td>23</td><td>15</td><td rowspan="4">280</td><td rowspan="4">260</td><td>1768</td><td>41.4</td></tr>
<tr><td>2</td><td>33.2</td><td>16</td><td rowspan="3">2273</td><td>23</td></tr>
<tr><td>3</td><td>41.4</td><td>17</td><td>33.2</td></tr>
<tr><td>4</td><td rowspan="3">1768</td><td>23</td><td>18</td><td>41.4</td></tr>
<tr><td>5</td><td>33.2</td><td>19</td><td rowspan="9">290</td><td rowspan="9">270</td><td rowspan="3">1263</td><td>23</td></tr>
<tr><td>6</td><td>41.4</td><td>20</td><td>33.2</td></tr>
<tr><td>7</td><td rowspan="3">2273</td><td>23</td><td>21</td><td>41.4</td></tr>
<tr><td>8</td><td>33.2</td><td>22</td><td rowspan="3">1768</td><td>23</td></tr>
<tr><td>9</td><td>41.4</td><td>23</td><td>33.2</td></tr>
<tr><td>10</td><td rowspan="5">280</td><td rowspan="5">260</td><td rowspan="3">1263</td><td>23</td><td>24</td><td>41.4</td></tr>
<tr><td>11</td><td>33.2</td><td>25</td><td rowspan="3">2273</td><td>23</td></tr>
<tr><td>12</td><td>41.4</td><td>26</td><td>33.2</td></tr>
<tr><td>13</td><td rowspan="2">1768</td><td>23</td><td>27</td><td>41.4</td></tr>
<tr><td>14</td><td>33.2</td><td colspan="5"></td></tr>
</table>

To investigate the filling characteristics of the polymers into the micro channels in injection processes, a micro rib feature was designed and machined as shown in Figure 11. Applied injection conditions are listed in Table 3, and the results are shown in Figure 12 and 13. Figure 14 and 15 show the measured results of the micro rib filling experiments.

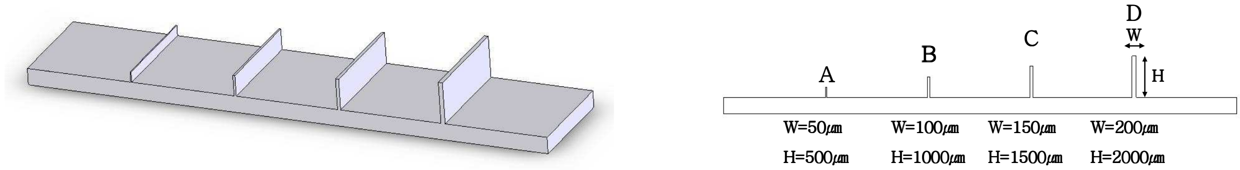
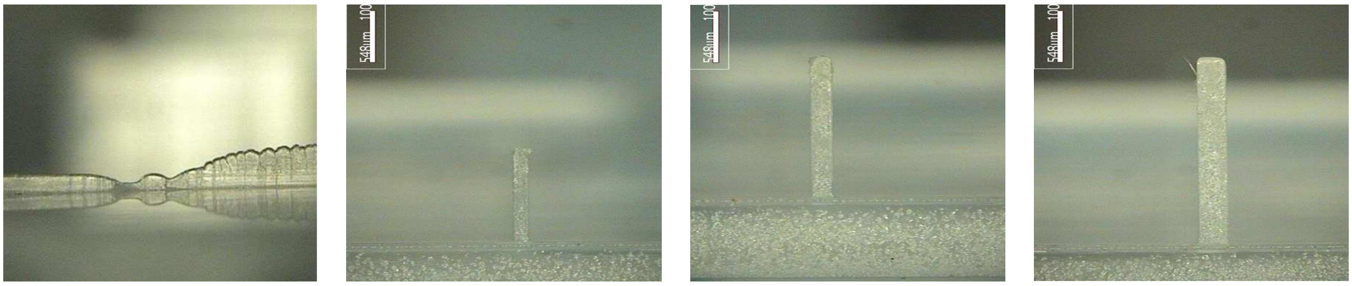
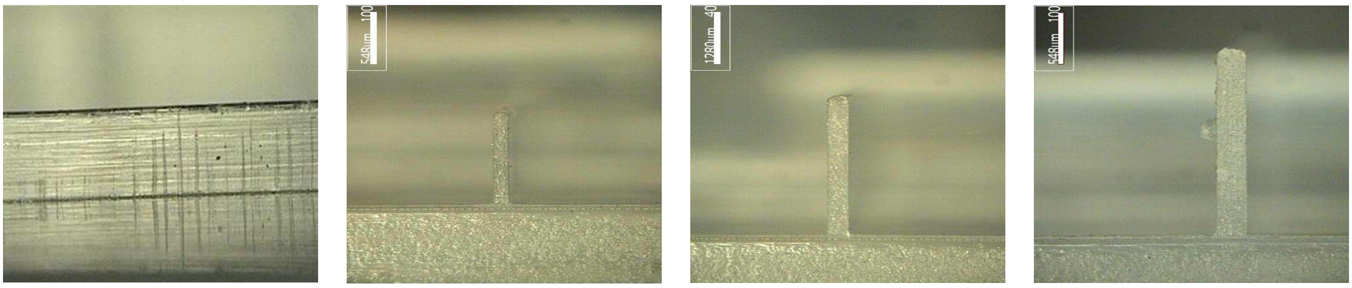


Figure 11. Micro rib feature for test injection experiments.



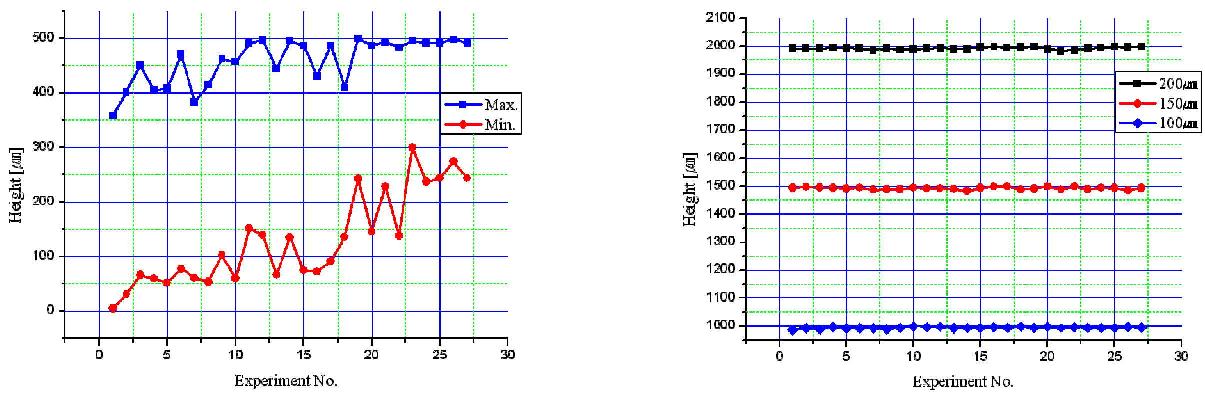
(a) W=50µm (b) W=100µm (c) W=150µm (d) W=200µm

Figure 12. Test injection results using Topas5013S-04.



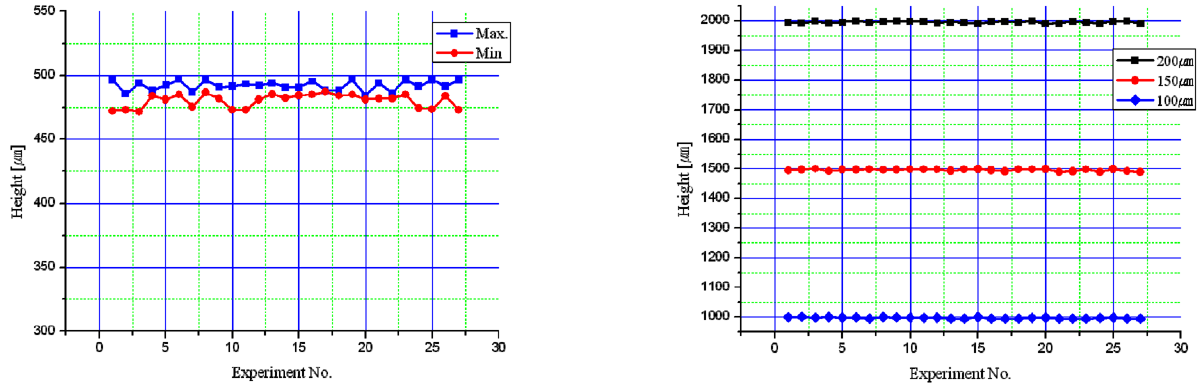
(a) W=50µm (b) W=100µm (c) W=150µm (d) W=200µm

Figure 13. Test injection results using Topas8007S-04.



(a) W=50µm (b) W=100, 150, 200µm

Figure 14. Measured results of the filling experiments for Topas5013S-04.



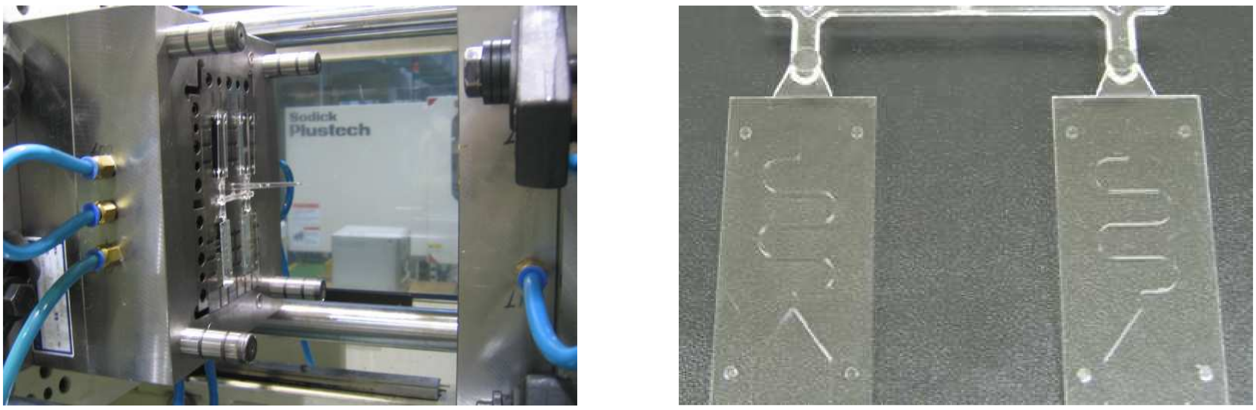
(a) W=50µm (b) W=100, 150, 200µm

Figure 15. Measured results of the filling experiment for Topas8007S-04.

From the figures, it can be observed that Topas8007S-04 has better micro filling characteristics, especially when W=50µm, than Topas5013S-04.

4.4. Test Injection of Sample Bipchips

Test injection process using the fabricated mold set is shown in Figure 16(a), and the injected samples of biochip are shown in Figure 16(b). From the figures, it can be seen that the micro-channels are formed on the polymer plates successfully.



(a) Mold set for test injection. (b) Test injected biochips.

Figure 16. Test injection process and samples of polymeric LOC.

5. Conclusions

In this study, injection mold inserts for micro-channel forming on the biochip were manufactured using micro end-mills. Micro rib filling experiments were performed to evaluate the characteristics of polymers. And, test injection process was performed using the fabricated inserts and mold set. From the results of this study, it can be shown that the method can be applied for the mass production of biochips. The results of this study can be summarized as follows:

(1) In micro end-milling process, the best surface roughness could be obtained at depth-of-cut was 100µm and feed-rate was 50m/min. Under the condition, surface roughness of Ra=31nm was obtained for the straight regions, and Ra=44nm for curved regions.

(2) When tool diameter was 400μm, better shape accuracy of the micro-channel could be obtained than the 200μm diameter tool.
(3) The mold inserts for micro-channel forming was machined based on the experimental data.
(4) In micro rib filling experiments, Topas8007S-04 showed better filling characteristics than Topas5013S-04.
(5) Test injection process was performed successfully. Thus, it can be shown that the applied method can be a way for the mass production of biochips.
(6) To form more precise micro channel patterns using injection molding process for biochip production, more extended studied such as tool deflection compensation, micro-fluidics analysis for the given polymers, etc. are needed as the future works.

Acknowledgements

This research was supported by 2010 Renovation Plan of Fundamental Manufacturing Technology (Strategic Project) from Korea Institute of Industrial Technology.

References and Notes

1. Song, S.; Lee, K.Y. Polymers for Microfluidic Chips. *Macromolecular Research* **2006**, *14*, 121-128.
2. Reyes, D. R.; Iossifidis, D.; Auroux, P.A.; Manz, A. Micro Total Analysis System. 1. Introduction, Theory and Technology. *Analytical Chemistry* **2002**, *74*, 2623-2636.
3. Ahn, C.H. Appication of Micro Molding Technology to BioMEMS Components and Systems **2006**, University of Cincinnati, *Internal technical report to KITECH*, Korea,
4. Blattert C. Separation of Blood Cells and Plasma in Microchannel Bend Structures. *Proceedings of μTAS* **2004**, *1*, 483–485.
5. Michael, J. H. DNA Micro Array Technology: Devices, Systems and Applications. *Annual Review of Biomedical Engineering* **2002**, *4*, 129-153.
6. Kurian, K. M.; Watson, C. J.; Wylie, A. H. DNA Chip Technology. *Journal of Pathology* **1999**, *187*, 267-271.
7. Jakeway, S. C.; de Mello, A. J.; Russell, E. L. Miniaturized Total Analysis Systems for Biological Analysis. *Analytical Chemistry* **2000**, *66*, 525-539.
8. Hupert, M.L.; Guy, W.J.; Llopis, S.D.; Shadpour, H.; Rani, S.; Nikitopoulos, D.E.; Soper, S.A. Evaluation of micromilled metal mold masters for the replication of microchip electrophoresis devices. *Microfluidics and Nanofluidics* **2007**, *3*, 1-11.
9. Mecomber, J.S.; Stalcup, A.M.; Hurd, D.; Halsall, H.B.; Heineman, W.R.; Seliskar, C.J.; Wehmeyer, K.R.; Limbach, P.A., Analytical Performance of Polymer-Based Microfluidic Devices Fabricated By Computer Numerical Controlled Machining. *Analytical Chemistry* **2006**, *78*, 936-941.
10. Mecomber, J.S.; Hurd, D.; Limbach, P.A., Enhanced machining of micro-scale features in microchip molding masters by CNC milling. *Int. J. of Machine Tools and Manufacture* **2005**, *45*, 1542-1550.

11. Zhao, D.S.; Roy, B.; McCormick, M.T.; Kuhr, W.G.; Brazill, S.A. Rapid fabrication of a poly(dimethylsiloxane) microfluidic capillary gel electrophoresis system utilizing high precision machining, *Lab on a Chip* **2003**, *3*, 93-99.