Warpage Characterization of Microchannels Fabricated by Injection Molding

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Mass-production of microfluidic devices is important for biomedical applications in which disposable devices are widely used. Injection molding is a well-known process for the production of devices on a mass scale at low-cost. In this study, the injection molding process is adapted for the fabrication of a microfluidic device with a single microchannel. To increase the product quality, high-precision mechanical machining is utilized for the manufacturing of the mold of the microfluidic device. A conventional injection molding machine is implemented in the process. Injection molding was performed at different mold temperatures. The warpage of the injected pieces was characterized by measuring the part deformation. The effect of the mold temperature on the quality of the final device was assessed in terms of the part deformation and bonding quality. From the experimental results, one-to-one correspondence between the warpage and the bonding quality of the molded pieces was observed. It was found that as the warpage of the pieces decreases, the bonding quality increases. A maximum point for the breaking pressure of the bonding and the minimum point for the warpage were found at the same mold temperature. This mold temperature was named as the optimum temperature for the designed microfluidic device. It was observed that the produced microfluidic devices at the mold temperature of 45 °C were able to withstand pressures up to 74 bar. [DOI: 10.1115/1.4029841]

1 Introduction

Micro- and nano-scale fabrication of microfluidic devices is a popular topic for both academic research and industry. Repeatable, efficient, mass-scale production of microfluidic devices is vital for biomedical applications in which disposable devices are widely used. When the fabrication of the microfluidic devices is concerned, there are basically two common approaches: direct substrate manufacturing and mold-based techniques. Direct substrate manufacturing includes etching, laser ablation, and mechanical machining. On the other hand, mold-based techniques include soft-lithography, hot embossing, and injection molding. Although the fabrication of the mold may be complicated; once the mold is fabricated, the mold may well be used for several times. After the completion of the mold, the rest of the fabrication procedure is simple and highly reproducible (i.e., low-cost replication), which makes mold-based techniques very suitable for mass production.

Among the mold-based techniques, injection molding is a well-established manufacturing processes for macroscale (dimensions larger than millimeter) in which the melted material is injected into a mold to get the desired shape. Materials used are generally plastics though ceramics and metals can also be molded with plastic binders. During the process, the material is supplied into a heated barrel, mixed, and forced into a mold cavity where it cools and solidifies in accordance with the shape of the cavity [1]. Once a mold has been manufactured, several thousand parts can be molded with little or no extra effort. The products have good dimensional tolerance and the process requires almost no finishing operation on the final product. Considering these aspects, injection molding is a popular manufacturing process for fabricating parts on mass scale and is widely used in many areas such as aerospace, automotive, medical, toys, and optics [2]. However, the process is usually not a preferred method of manufacturing for short production runs or prototyping due to the tool/operation cost.

The injection molding process has a complex nature, as it is transient and involves several heat transfer mechanisms, a phase change and time varying boundary conditions in the mold. While these challenges are substantive, the process becomes more complicated by the material properties and the geometry of the product [3]. Injection molding can also transfer micrometer or even submicrometer features of molds to a product [4]. Injection molding has been utilized for the fabrication of various microscale devices and their components [4–10] as well as nanofluidic channels [11]. For a good product quality, the mold needs to be manufactured so as to yield the desired features with desired accuracy. The mold material can be polymer-based or metal-based depending on the replication process. However, metallic materials are more suitable for injection molding and hot embossing due to their strength against both high pressures and large temperature variations in mass production [5]. Considering the fabrication of the metal-based molds, soft-lithography followed by electroplating [5] or mechanical machining techniques like electro-discharge machining and/or micromilling [9] can be utilized. In particular, mechanical machining techniques allow the fabrication of a mold material of a wide variety with a desired accuracy for a microfluidic channel. Moreover, they do not require any clean-room facility. Micromilling have been utilized for the fabrication of aluminum molds for hot embossing [12–14] and for polydimethylsiloxane (PDMS) molding [15,16], fabrication of nonstandard mold insert sizes or shapes in the range of 20–500 μm with different aspect ratios ranging between three and 20 [12].

Typically, high pressures are not involved in the microfluidic processes. However, there are some certain applications like high performance liquid chromatography (HPLC) which requires high back-pressures within the device. The bonding quality of the microfluidic devices is an important parameter to prevent the failure (breakage and/or leakage) of a microfluidic device due to high back-pressures. The maximum allowable back-pressure (burst pressure) for PDMS based (which is the common material for soft-lithography based fabrication of microfluidic devices) microfluidic devices is between 5 and 10 bar. However, the use of the different thermoplastic materials (such as PMMA and cyclic olefin copolymer) together with thermal bonding may result in higher

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allowable pressure up to 15 MPa [6]. The burst pressure is an important parameter which can be enhanced with the optimization of the molding and bonding conditions. One important parameter which affects the bonding quality is the warpage of the surface of the injected parts. However, characterization of warpage of the injected parts is a problematic task due to the complexity associated with the nature of the injection molding process and has not been standardized. Several different methods for warpage characterization have been proposed previously for the injection molded parts at macroscale [17]. However, there are few studies regarding the characterization of the warpage of a part with microfeatures [18].

In this study, the injection molding process was adapted for the fabrication of a microfluidic device with a single microchannel. A conventional injection molding machine was utilized for the injection molding process; however, to obtain the desired product quality, the mold was manufactured by using high-precision mechanical machining. For the injected products, the warpage characterization was performed using an optical measurement via a microscope. Injection molding was performed at different mold temperatures, and the effect of the mold temperature on the quality of the final device was assessed in terms of the part deformation which is related to the warpage of the products and the bonding quality. To the best of our knowledge, this study is one of the few in terms of the characterization of the warpage of a product with microfeatures and the only study which relates the warpage of the products with microfeatures and the bonding quality.

2 Design of the Mold and Material Selection

There are certain critical design rules to be followed while designing a mold for injection molding. Elimination of sharp corners in the part is essential since they result in stress peaks in the product which may lead to cracks. In injection molding, most problems are caused not by the filling of the mold cavity but by the demolding process. If the mold is not designed properly or if inappropriate molding parameters are used, structures with microfeatures may crack, be torn apart, be deformed, or be destroyed during the demolding process [19]. The demolding process can also cause wear of mold inserts and may damage the delicate portions of the mold insert even after a single cycle. Introduction of a draft angle of just 2 deg–5 deg for the vertical (side) walls of a part reduces the demolding forces significantly and allows the ejection of a microstructure with relative ease. This issue is vital and even more important than the roughness of the side walls for the products with microfeatures [19]. Another important issue in demolding is the shrinkage of the material which occurs during the cooling of the part between the filling and demolding stages [20]. As a result, the demolding forces become function of the orientation of microstructures relative to the direction of shrinkage and the location of critical microfeatures relative to the center of shrinkage [19]. Delicate microstructures, like pins with high aspect ratios, can be protected against shear forces resulting from the shrinkage by the inclusion of neighboring auxiliary structures which are stable enough to resist these shear forces [19].

The mold was designed by considering the aforementioned issues. The rendered image of the computer-aided design (CAD) drawing of the mold can be seen in Fig. 1. The mold has two different microchannel features (one of the microchannel structure is highlighted by an ellipse at the top left). Lengths of the microchannels were 10 mm and 20 mm and each had a width and a depth of 200 μm. Such a microfluidic device is suitable for HPLC applications. The mold consisted of top and bottom plates. The inlet and outlet reservoir openings (2 mm in diameter) were included at the bottom plate (highlighted by black in Fig. 1), and the microchannel is included at the top plate. For the ease of demolding, a 5 deg draft angle was introduced at the side walls of the microchannels and the mold cavity. To avoid turnabout (reverse flow of the melted material which causes additional flow resistance) of the melted material, v-shaped runners were included in the

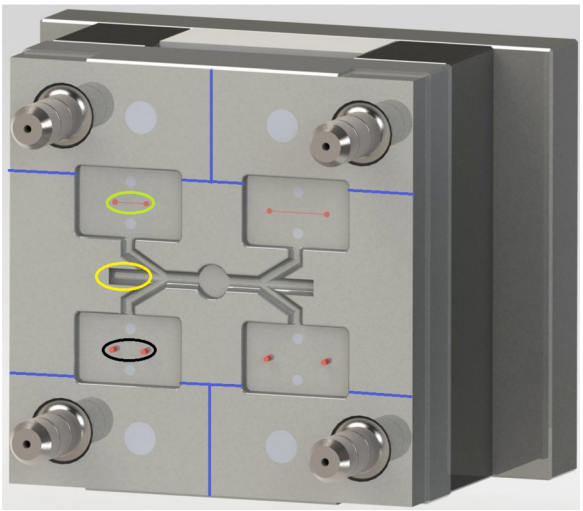


Fig. 1 Rendered image of the CAD drawing of the mold

design. Additional cavities as cold slug wells were also included (highlighted by an ellipse at the midsection in Fig. 1) in the mold to ensure the use of the mold for multiple device production without any contamination problems. To ensure easy and smooth filling, air vents (shown by blue lines in Fig. 1) were also introduced in the design. For demolding, housing for pushing pins was included in the mold (can be seen as gray circles in Fig. 1). The depth of the mold cavity was chosen as 3 mm which was the thickness of the product (the details of the design can be found elsewhere [21]).

Selection of a suitable polymer for the injection molding of microfluidic components is a delicate task in the design process for microfluidic applications since considerations such as the effect of polymer on achievable product tolerances and satisfying the material property requirements have to be taken into account [4]. For microfluidic applications, it is important that the device material is chemically inert (to avoid any interaction with the chemicals within a buffer solution), biocompatible (to avoid any interaction with the bioparticles), transparent (for visual access during the biological process/experiment), and cheap (to allow disposable devices). Considering all these aspects, Evonik plexiglas 6N (PMMA—Acrylics, Evonik Industries AG, Essen, Germany) was selected for this study.

3 Fabrication

During fabrication of a mold, the negative or inverse of the desired product pattern or geometry was machined on the mold material. Precision of the mold significantly determines the quality of the end product such as any surface defect on the mold is replicated in the polymer product. Moreover, the lifetime of the mold depends strongly on the surface quality of the mold. The smoother the mold surface is, the lower the frictional forces are during demolding [22]. For reliable high-quality replication, roughness of the mold is advised to be less than 100 nm root mean square [23]. Surface morphology, adhesion properties to the molded materials, lifetime, feature sizes, and costs are the critical factors to be considered for the manufacturing of the mold [22]. High-precision mechanical machining (micromilling) method was used to manufacture the mold. The mold was fabricated out of blank (unmachined) mold system by using the high-precision computer-numerical control system (Deckhel Maho DMU 50) at the Bilkent University Micro System Design and Manufacturing Center. The mold material was chosen as the stainless mold steel CK-50 AISI 1.1050. In the machining process, four-tooth coated carbide tools were preferred. For the machining of the mold, the required G-codes were generated in SOLIDCAM software. Since the mold geometry includes side walls with a draft angle, ball shaped

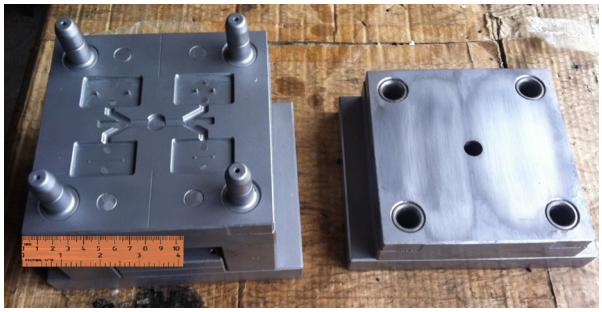


Fig. 2 Photograph of the mold after machining

runner, and gate, three-dimensional (3D) CAM was utilized. The machining of the mold took nearly 4 hr. The machined mold can be seen in Fig. 2 (the details of the fabrication of the mold can be found elsewhere [21]).

The mold produces two microfluidic devices with different microchannel lengths at a single cycle. The cavities for the top and bottom plates of each microfluidic device were in the left mold plate. The injected polymer was distributed to the four cavities through the runners and enters each cavity through a single gate. After the machining of the mold, in order to increase the surface quality, a surface finish operation was performed by using a grinding machine and a grinding paste. To check the accuracy of the machining, the dimensions of the microchannel structures within the mold were measured using optical measurement microscope (Hawk 200, Vision Engineering, Surrey, UK). The accuracy of the dimensions was found to be within ± 5 μm.

3.1 Injection Molding of the Parts. Following the manufacturing of the mold, the injection molding of the microchannels was performed. The injection was performed in Modern Teknik Plastik San. Tic. Company (OSTİM, Ankara, Turkey). Plastic injection molding machine with a maximum injection pressure of 90 MPa was used. The machine had two heaters: one for melting the injection material and the other for adjusting the mold temperature. Injection molding is performed with six different mold temperatures: 35 °C, 45 °C, 55 °C, 65 °C, 75 °C, and 85 °C. The melting temperature of the plexiglas (245 °C) and the injection pressure (90 MPa) were kept constant during the injection experiments. Only the mold temperature was varied during the injection. In order to monitor the mold temperature precisely, an external thermocouple was installed. To install the thermocouple (can be seen in Fig. 3), a hole was drilled as close as possible to the mold cavity. Then, the thermocouple was inserted into the hole. During the injection experiment, only the mold temperature was monitored.

Prior to molding, polymer material (Plexiglas 6N) was placed in an oven and kept at 90 °C for 120 min to remove humidity (if the injected material is not dry, the end product is likely to have low surface quality along with bubbles becoming trapped inside the product). The molding experiments were conducted beginning with the molding cycles at the highest mold temperature (85 °C) and moving toward the lowest mold temperature (35 °C). For production of the highest-mold temperature parts, internal heater for the mold was adjusted to 85 °C and the flame gun was on to prolong the steady-state condition at the desired mold temperature for the molding of the parts. When the injection was first started, the thermocouple reads the mold temperature at about 90 °C. The mold temperature dropped further with continuing molding cycles until a quasi-steady-state condition was reached at 84.2 °C (± 0.4 °C). Since a single injection cycle consists of injection/cooling/ejection stages, the temperature still exhibited an oscillatory nature at steady-state even though the mean temperature value was constant. One injection cycle took about 22 s at this temperature. The molded parts produced during the steady-state phase were collected for characterization. At the nominal mold temperature of 85 °C, nine samples were able to be collected as the steady-state mold temperature could not be maintained for a long time at 84.2 °C. Upon ejection, the product was observed to have cooled sufficiently to attain rigidity although the sprue and runners were hot and pliable after the demolding. The production experiments were repeated at other mold temperatures following the same procedure. The attained steady-state temperatures, the number of collected samples, and the respective cycle times are tabulated in Table 1. For experiments at low mold temperatures, the actual steady-state mold temperatures were slightly over the nominal (desired) mold temperatures. At the lowest (35 °C) mold temperature experiment (as in the highest temperature case), the steady-state conditions were not able to be sustained for long. For 45 °C and 55 °C mold temperatures, the heater of the injection molding machine was able to sustain the steady-state condition, and more samples could be collected at these temperatures.

Table 1 Number of samples collected and cycle times for different mold temperatures

Mold temperature (°C)	Actual temperature (°C)	Number of samples	Average cycle time (s)
35	36.2 ($\pm$0.5)	15	12
45	45.6 ($\pm$0.5)	30	13
55	55.4 ($\pm$0.5)	30	15
65	64.7 ($\pm$0.4)	18	18
75	74.7 ($\pm$0.4)	12	20
85	84.2 ($\pm$0.4)	9	22

For the ease of ejection of the molded part from the mold, sometimes it is necessary to use release agents. These agents are typically introduced into the injection mixture or applied to the mold cavity [24]. In this study, it was observed that there is no need for any release agent. This was important especially for biomedical applications. Contamination of the microchannel structure may have a negative effect on the chemical or biological process which will take place within the microchannel.

3.2 Bonding of the Microfluidic Device. Following the production of the microchannels by injection molding, in order to transform the microchannels into a microfluidic device, the two molded components (one containing the microchannel and the

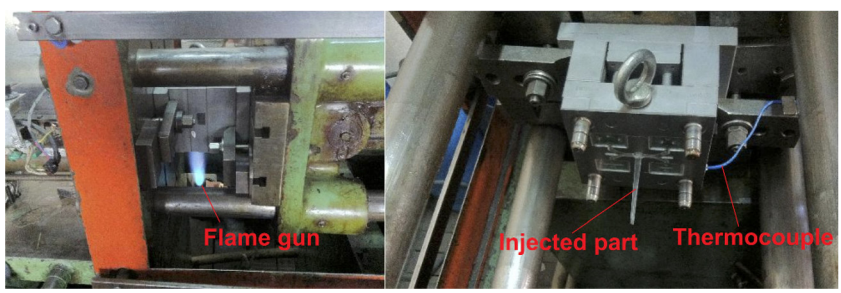


Fig. 3 Photograph of the experiment

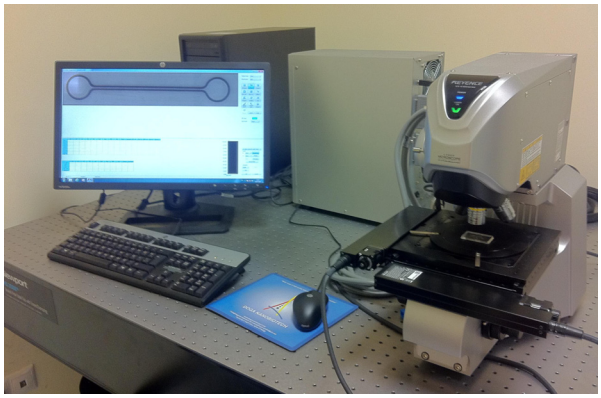


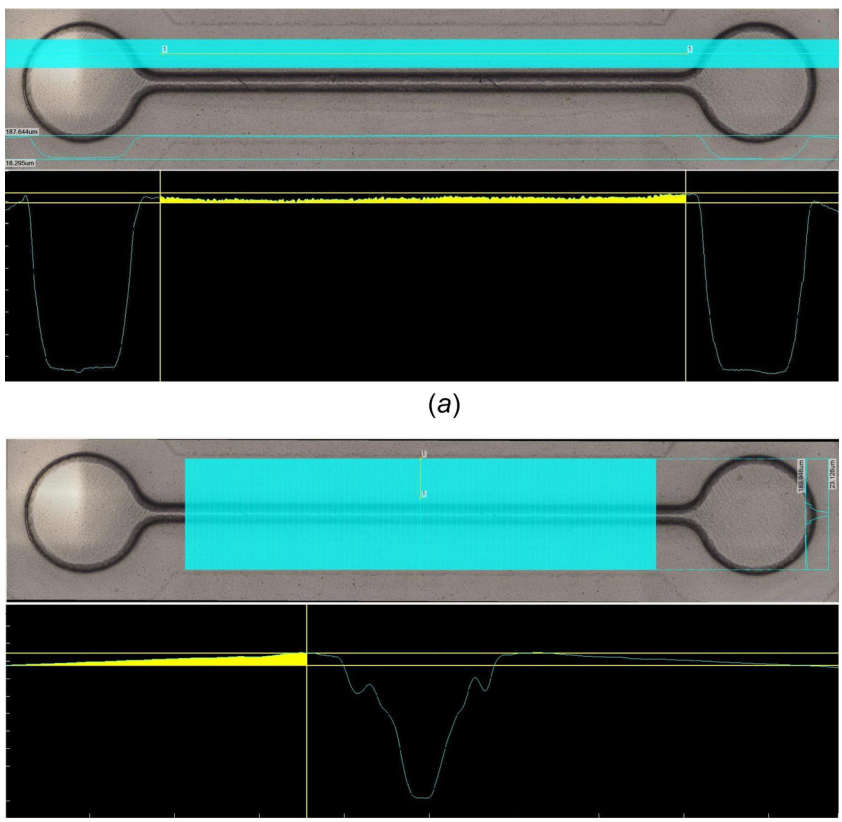
Fig. 4 VK-X100 3D laser microscope

other containing the reservoirs which will be aligned with the microchannels) were to be assembled by bonding. Direct bonding technique was applied to bond two substrates of the same material. Direct bonding, also called fusion bonding, bonds materials of the same kind under high temperature. The advantage of this technique is the lack of thermal stresses due to the perfect matching of the thermal expansion coefficient of the two substrates. Many polymers can also be directly bonded/sealed at temperatures which are above their glass transition temperatures (T_g) [25]. In the direct bonding method, it was very critical to align microchannels on reservoirs. For this purpose, a lock mechanism was designed. Moreover, a lock mechanism also supplied the pressure to help bonding. Direct bonding occurs above the glass transition temperature of the polymer which is 110 °C for plexiglas. Direct bonding was achieved by keeping the products at 140 °C for 15 min.

4 Results and Discussion

The injection molding of the microdevice components was performed at six different mold temperatures: 35 °C, 45 °C, 55 °C, 65 °C, 75 °C, and 85 °C. The molded components were to be assembled through bonding, and any warpage on bonding surfaces might adversely affect the bonding quality. To characterize the warpage in the molded components, optical measurements were performed using Keyence VK-X100 3D laser microscope seen in Fig. 4. Six randomly selected specimens among those molded at each mold temperature were characterized for warpage. The characterization was focused near the microchannel region on each specimen as the microchannel was the "irregularity" within the overall component structure, and more warpage was expected in this region. This region was also critical for preventing leakage from the microchannels, once the device was assembled through bonding. A standard method for characterization of warpage could not be found in the few studies in literature involving warpage characterization [17,18]. To characterize the warpage through optical means, the following procedure was followed for each sample:

(1) A scan window in the vicinity of the microchannel structure is defined as an input parameter to the software (a typical scan window can be seen in Fig. 5, colored in gray (cyan in online version).
(2) The surface area within the scan window was scanned, and the surface profile was digitized for the postprocessing by the software of the microscope (which takes approximately 40 min).
(3) For the warpage measurement, several lines parallel to each other were generated by the software. The location of these lines was selected in accordance with the area where the measurements were wanted to be taken (these lines can be seen as blue areas in Fig. 5, actually these gray areas (cyan



(*a*)

(*b*)

Fig. 5 Measured area for the upper side: (*a*) *x*-direction and (*b*) *y*-direction

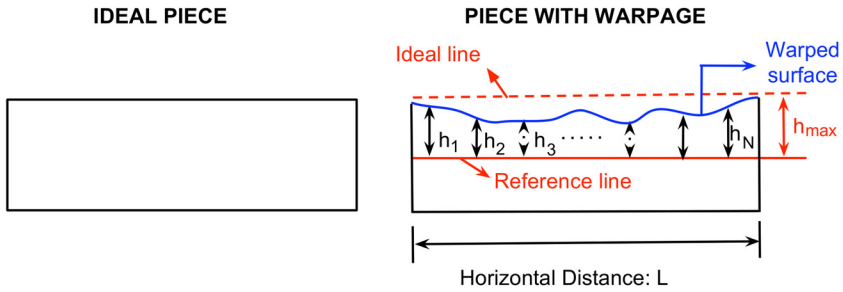


Fig. 6 Schematic drawing to show the parameters in the characterization of the warpage. (*a*) Ideal piece and (*b*) piece with warpage.

in online version) are composed of several lines). Seventy and 1000 lines were generated parallel to the *x*- and *y*-directions, respectively.

(4) To restrict the measurements at the upper and the lower sides of the microchannel, a line needs to be defined at the upper and the lower side of the microchannel. The defined lines for the measurements in *x*- and *y*-directions for the upper side of the microchannel can be seen as a yellow line on Figs. 5(*a*) and 5(*b*), respectively.

(5) The software determines the average profile of the generated lines. The white area (yellow in online version) shows the shaded area between the line indicating the average profile of the surface and a reference line (arbitrary selected, see the schematic drawing in Fig. 6).

(6) The software calculates the area of the yellow area which depends on the selection of the reference line (which is the area between the blue line and the solid red line in Fig. 6).

(7) The average height of the white area (yellow in online version) (h_{avg}) was calculated by dividing the yellow area by the horizontal distance, L which can be seen in Fig. 6.

(8) h_{max}, which is indicated in Fig. 6, is defined as the difference between the ideal line (line correspondence to zero warpage) and the reference line. To characterize the warpage, a parameter called *part deformation* was defined as the difference between h_{max} and the h_{avg}.

The average part deformations about the microchannels for the characterized samples produced at different mold temperatures are presented in Table 2. To characterize the overall warpage of the samples, the mean of the average values at the upper and lower sides along *x*- and *y*-directions was calculated and is presented in Fig. 7. Smaller deformation (warpage) should yield a better bonding with the remaining component of the microdevice. The results show that the minimum part deformation is 4.96 μm which occurs in the samples produced at the mold temperature of 45 °C.

The bonding quality in microfluidic devices assembled through direct bonding was characterized through a series of tests. Water was injected into the microchannels at different pressures and the breaking pressure of the microfluidic device was used as the indicator of the bonding quality. A capillary tube connected to the pump was inserted into the reservoirs of the microchannel and sealed with epoxy. The water within the microchannel was pressurized by means of a micropump (LC-10ATVP, Shimadzu Corporation, Kyoto, Japan). The experimental setup is presented in Fig. 8. In these experiments, three samples produced at each mold-temperature were used. Flow rate of the micropump was increased step by step using the controllers on the device until the bonding was broken. Once the microchannel was broken, the pressure in the system dropped to near atmospheric pressure, which could be monitored over the display of the micropump. The possible leak from the capillaries and connection points was also checked by visual inspection during the experiments, and no

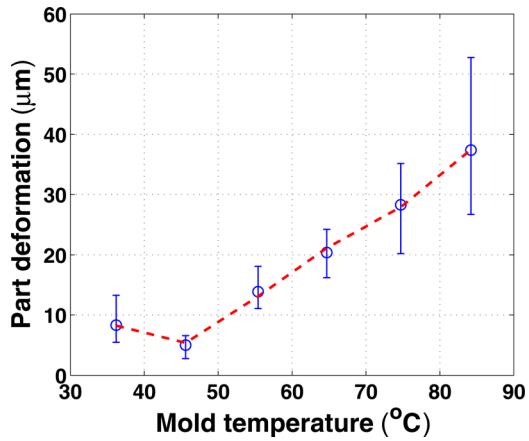


Fig. 7 Overall part deformation

Table 2 Part deformation of the microchannel

Mold temperature (°C)	M1 average[a] (μm)	M2 average[b] (μm)	M3 average[c] (μm)	M4 average[d] (μm)
36.2 (±0.5)	8.51	6.57	8.82	9.30
45.6 (±0.5)	4.41	4.93	5.29	5.20
55.4 (±0.5)	13.46	12.99	14.04	15.00
64.7 (±0.4)	19.95	18.85	21.25	21.47
74.7 (±0.4)	29.26	25.16	31.36	27.29
84.2 (±0.4)	34.43	34.85	44.54	35.73

[a]M1: *x*-direction (upper side of the microchannel).
[b]M2: *x*-direction (lower side of the microchannel).
[c]M3: *y*-direction (upper side of the microchannel).
[d]M4: *y*-direction (lower side of the microchannel).

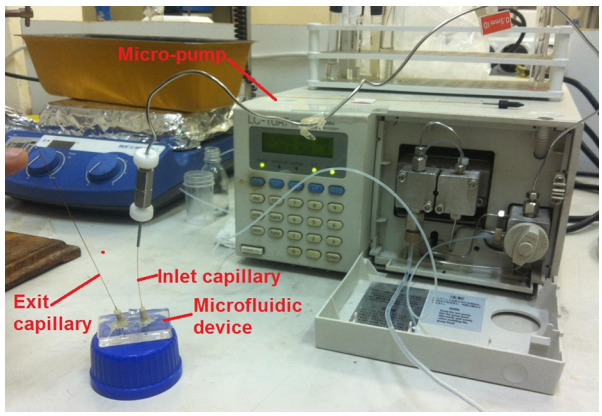


Fig. 8 Experimental setup

Table 3 Bonding quality experiment results

Mold temperature (°C)	S#1 (bar)	S#2 (bar)	S#3 (bar)	Average (bar)
36.2 (±0.5)	32	32	33	32.3
45.6 (±0.5)	70	74	45	63.0
55.4 (±0.5)	23	24	22	23.0
64.7 (±0.4)	17	24	18	19.7
74.7 (±0.4)	4	4	6	4.7
84.2 (±0.4)	1	3	1	1.7

leakage was observed for each sample prior to the breakage of the bonding. Breaking pressure for each sample and the average value for the samples produced at the same mold-temperature are listed in Table 3 and plotted in Fig. 9.

The results show that the strongest bonding is achieved for the microdevice whose components were produced at a mold temperature of 45 °C. According to the warpage measurements (Fig. 7), the minimum part deformation was found to be for specimens produced at the same mold temperature. The trends of breaking pressure (of the microfluidic device) and part deformation (of the components that are assembled through bonding to form the microfluidic device) are consistent with each other. As the part deformation decreases (and the bonding quality increases), the microchannel is able to withstand higher pressures without breaking and vice versa. A maximum breaking pressure of 74 bar was achieved for the microfluidic device out of plexiglas molded at a mold temperature of 45 °C. Considering the bonding between PDMS and glass/PDMS, which is a common material for microfluidic applications and can withstand up to 5–15 bar [25], the current results are quite promising especially when the HPLC applications are considered in which flow pressures around 50 bar are generated. The capability to withstand leakage during flow for the microfluidic device which could withstand the highest flow pressure of 74 bar (whose components were molded at the mold temperature 45 °C) was investigated with further experiments. The flow rate of the micropump was adjusted to a value of 2 ml/min, which was less than the flow rate that yields the breaking pressure. At this flow rate, the flow pressure is steady at 70 bar, and water was allowed to flow in the microchannel at this pressure for a few minutes. After this flow was stopped, and blue ink was injected into the microchannel by a syringe so that the flow pattern could be visualized. The microchannel was inspected for possible leakage and none was observed.

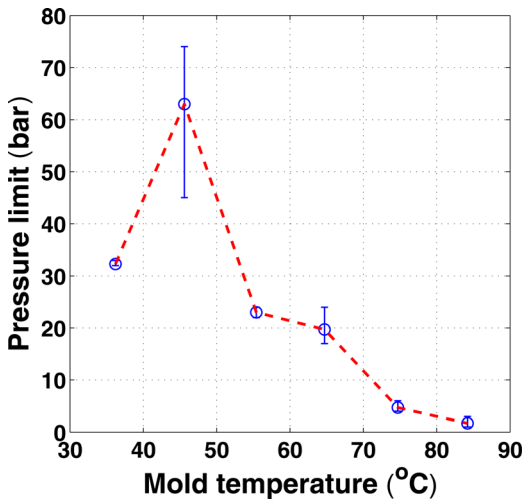


Fig. 9 Breaking pressure of the bonding for different mold temperatures

5 Concluding Remarks and Outlook

The ultimate goal of the microfluidics technology is to develop disposable devices which can accomplish biomedical analyses at much lower manufacturing and operational cost compared to its room-sized or benchtop-sized counterparts. Injection molding of structures with microfeatures is a developing process with great potential for the mass-production of microscale devices at low-cost. The major focus of this study was to develop a technique for repeatable, productive, and accurate fabrication of microfluidic devices on a mass production scale. To achieve this, the injection molding process was adapted for the fabrication of a microfluidic device which composed of a single microchannel.

A proper mold for the injection molding was designed and manufactured using high-precision mechanical machining. The microfluidic device was fabricated out of Plexiglas 6N. To analyze the effect of the mold temperature, the injection molding of the microfluidic device has been performed at different mold temperatures. The bonding of the microfluidic device was performed by direct bonding and adhesive bonding. The practical aspects of two bonding techniques were assessed, and it has been concluded that direct bonding is more feasible than adhesive bonding. The warpage and the bonding quality of the final products were characterized for different mold temperatures. It was found that there exists one-to-one correspondence between the warpage and the bonding quality of the molded pieces. As the warpage of the pieces decreases, the bonding quality increases. A maximum point for the breaking pressure (which is the parameter used for the characterization of the bond quality) and the minimum point for the warpage were observed at the same mold temperature of 45 °C. This mold temperature was named as the optimum mold temperature for a better quality. The ideal injection molding parameters depend on the injection molding machine, environmental conditions, and complete mold geometry (not only mold cavity), which have considerably effects on the pieces with microfeatured parts compared to macrosized parts. For the optimum mold temperature of 45 °C, samples obtained could withstand pressure up to 74 bar which is much higher pressure than that of PDMS-based microfluidic devices.

The production of a single microfluidic device set (two piece) was performed in approximately 15 s (depending on the mold temperature). However, the machining of the mold takes approximately 4 hr. For the bonding of the microfluidic device another half an hour was required. However, considering that the mold was manufactured for one time, and the bonding process can be automated, the fabrication of the polymeric microfluidic devices can be performed very fast with the injection method presented. Therefore, injection molding is a very promising method for the production of microfluidic device on a mass scale (about 10,000 pieces/day with a single injection machine, by the use of a larger mold or a larger machine this number may go up without any problem). The investigation of process parameters for the fabrication of more complicated microfluidic device structures rather than a single microchannel will be one of our future research directions.

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