FABRICATION AND EXPERIMENTAL CHARACTERIZATION OF A THERMOPLASTIC MICROPUMP WITH RECTANGULAR CHANNEL CROSS-SECTION FOR BIOMEDICAL APPLICATION

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Abstract

In this study, a peristaltic thermoplastic micropump was designed and fabricated for a biomedical application. Extended experiments were performed on the fabricated micropump in order to obtain its operational characteristics including maximum flow rate and head. The micropump are pneumatic which is fabricated by sandwiching multi layers of poly methyl methacrylate (PMMA) and thermoplastic polyurethane (TPU) film as a membrane. A computer numerical control (CNC) micromilling method is used to make a rectangular channel on PMMA sheet. The use of rectangular cross-section in the channel makes the manufacturing process more effective in terms of cost and time. A thermal fusion bonding method is served to bond the TPU film to the PMMA layers in a single step. The fluid flow rate through the micropump as a function of pneumatic gas pressure and frequency of microvalves wass obtained. The fluid flow is increased by increasing the frequency with a maximum at a frequency of 15 Hz. The maximum flow rate that can be generated using the fabricated micropump is about 350 µL/min. The introduced micropump in this study was shown to be reliable with low-cost production that can be used in lab-on-a-chip devices.

Key words: Micropump, Fabrication, Microfluidics, Biomedical

1. Introduction

Recently, the fabrication and development of thermoplastic actuators have been increased dramatically. Thermoplastic materials are known to be appropriate substitutes for polydimethylsiloxane (PDMS) that are used in microfluidic systems [1 ،2]. This originates

from the fact that thermoplastic materials possess some advantages including viability [3], recyclability [4], mass production features [5-8].

Thermoplastic materials in contrast to other plastic materials can be fabricated in various methods such as: hot embossing, micromilling, injection molding, laser ablation and sterolithography. Fabrication methods such as hot embossing, and injection molding require pre-fabricated masters to transfer patterns to thermoplastic. In particular, the fabrication of master molds for multi-layer microfluidic patterns is time-consuming and increases the prototyping costs. For this purpose, different studies have been conducted towards the development of rapid prototyping methods for the manufacturing of thermoplastic microfluidics by using CO2 laser ablation [9]. After using laser ablation, however, some post processing procedures are required. As an example, chemical surface treatment must be applied on created features to improve the surface quality, which makes this method expensive and time-consuming. Furthermore, the shape of cross-section in this fabrication method is restricted to near Gaussian shape. On the other hand, the micromilling fabrication method can make any shape of cross-section in channels without requirement of any chemical surface treatment.

The microvalves and micropumps are key components in microfluidic systems used to manipulate and induce fluid flow. One of the most applicable microfluidic valves is the external-pneumatic membrane valve which consists of a control chamber, a liquid chamber and a thin layer membrane as a fluid actuator. In this microvalve, by regulating the actuation gas pressure, fluid flow can be controlled [10]. Owing to the rigidity of most thermoplastic materials, the membrane of microvavels are made of different materials such as PDMS [11 ، 12], Viton® [13], Teflon [14], poly(methyl methacrylate) (PMMA) [15], cyclic olefin polymer (COP) [16]. Due to the viability and hyperelasticity of thermoplastic poly urethane (TPU), it has been recently used as membrane in some microfluidic devices [17 ،18].

In this study, we describe design and fabrication of a thermoplastic microvalve and micropump which are made of PMMA and TPU. The fabricated actuators are multi layers made using computer numerical control (CNC) micromilling without any surface chemical treatment. The components are then assembled using thermal fusion bonding method. The surface quality of micro-machined channels is measured using atomic force microscopic (AFM). The fabricated microvalve which is similar to a push-up Quake valve has a rectangular channel which differentiates it from those available in the literature. Next, we introduce a peristaltic pump that consists of five serial interconnected Quake valves. The performance of the microvalve and micropump under various operational conditions are examined.

2. Material and apparatus

PMMA sheets (Calvin, Vietnam) in different thickness (1-2mm) are used to fabricate the microvalve and micropump. A commercial CNC micro milling (DSP, China) with an X-Y platform and adjustable Z-axis are used for micromachining of the PMMA sheets. The SOLIDWORKS® software (Version 2016) is first used to draw the desired geometry. Next, the MASTERCAM® software (Version 2017) converts the SOLIDWORK drawing into a series of G-code to control the CNC micromachining. A TPU film (PT9200US NAT 1.0 mil, Covestro LLC, MA, USA) with a thickness of 25μm is used to fabricate thin flexible membranes implemented in the microvalves and micropumps. Due to its biocompatibility, proper mechanical properties and hyper elasticity, the TPU film is an adequate material in

biomedical applications [19 ،20]. A laboratory vacuum oven (AFE200LV-60DH, ATRA, IRA) is used for thermal treatment and bonding of the PMMA sheets to the TPU film. A custom made valve controller system is used to actuate fabricated microvalves and micropumps. The system includes FESTO® pneumatic valves (MH1-24V DC) which are controlled by the WAGO® controller system. A software interface is developed in the CODESYS® for communication with the controller system to control the actuation of microvalves and micropumps using compressed nitrogen gas. A pressure regulator with units of kPa is used to control the gas pressure. The deionized water is selected as the fluid mixed with a red food dye with a certain volume ratio in order to measure the flow rate.

3. Fabrication
3.1 Design and fabrication of layers

All layers are designed in the SOLIDWORK® software. The laser ablation and CNC micromilling are two rapid prototyping methods mainly used by researchers to make a microchannel in rigid thermoplastic materials such as PMMA sheets [5]. The shape of channel cross-sections, created by the laser ablation, depends on the beam power, and the distance between the PMMA sheet and laser lens [9 ،21]. The shape created using this method is mainly near Gaussian shape; this is the main limitation of this method in creating various cross sectional shapes. On the other hand, the use of micromilling makes it possible to fabricate different geometrical shapes with no limitation. In this study, the desired channels are created by micromilling using cutting tools that remove the bulk material. The end mill has a key role in the micromilling technique. Depending on the type of application, the surface quality is important. In laser ablation method, post processing or chemical surface treatment is required. The micromillng method, however, does not need the post processing depending on the type of application. In this study, channels with rectangular cross-sections are investigated. To determine the channels surface quality, the surface roughness is measured using the AFM method in various locations inside the channel. In rectangular channels, the maximum average roughness (Ra) is measured to be 11.43 nm which is considered appropriate for microfluidic applications (**Fig. 1**).
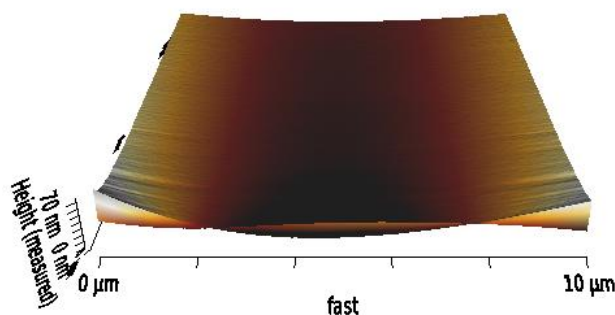

Figure 1. The surface topography image of channel

3.2 Thermal bonding method

To obtain a high quality bonding with least deformation, some parameters including temperature, pressure and bonding time must be controlled accurately. First, all layers (except

TPU membrane) are washed with water-soap and ethanol (**Fig. 2 a-1**) and then thermally treated in a vacuum oven at 90 °C and −80 kPa (gauge pressure) for at least 8 hours and cooled down afterwards in room temperature (**Fig. 2 a-2**). This step is necessary for releasing the dissolved gases entrapped within the bulk PMMA specimens. In the next step, the PMMA layers and TPU membrane are aligned and sandwiched between two clamps with a width of 30 mm. The assembly is then kept in the vacuum oven at 142 °C and −80 kPa for 60 min followed by a gradual cooling down process to 50 °C in 50 min (**Fig. 2 a-3**). The above bonding steps along with their corresponding temperatures, pressures and times are selected based on the reported literature for the PMMA material [9].
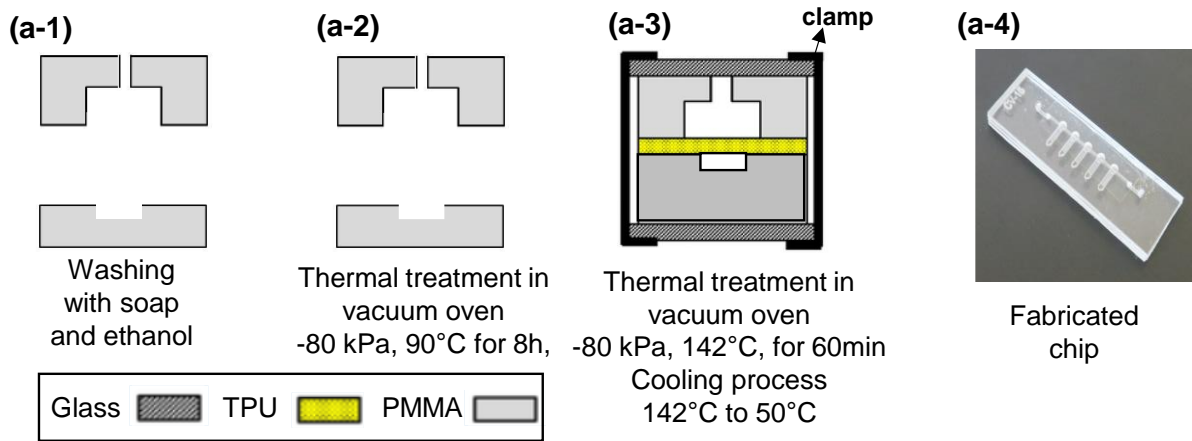
(a-1) Washing with soap and ethanol

(a-2) Thermal treatment in vacuum oven -80 kPa, 90°C for 8h,

(a-3) clamp Thermal treatment in vacuum oven -80 kPa, 142°C, for 60min Cooling process 142°C to 50°C

(a-4) Fabricated chip

Glass   TPU   PMMA

Figure 2. Bonding protocol.

3.3 Microvalve and Micropump Fabrication

The microvalve is a pneumatic-actuated valve which is normal open fabricated using the above-mentioned procedure by sandwiching multi layers of PMMA and a TPU film as a membrane (**Fig. 3a**). The microvalve, which has two status of open and close, includes a control chamber, a liquid channel and a membrane (**Fig. 3b**). The flow of liquid is controlled by passing the compressed nitrogen gas through the control chamber, thereby applying pressure to the TPU membrane (**Fig. 3b-2**). The fabricated peristaltic micropump consists of five serial interconnected microvalves, which works based on the differences in the actuation time of microvalves relative to each other.
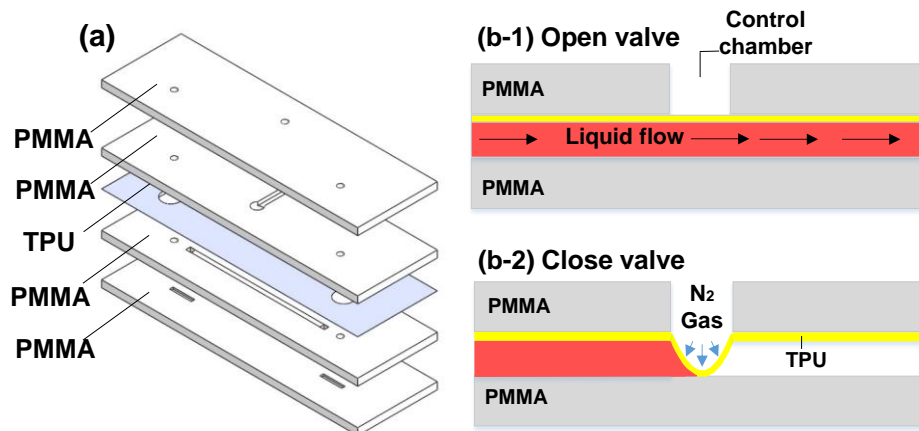
(a) PMMA PMMA TPU PMMA PMMA

(b-1) Open valve Control chamber PMMA Liquid flow PMMA

(b-2) Close valve PMMA N_2 Gas TPU PMMA

Figure 3. Fabrication and operation of microvalve. (a) 3d architecture of different layers of microvalve; (b) operation design of microvalve.

4. Result and Discussion

4.1 Experimental setup of the microvalve

A custom-made valve controller system is used to control and characterize the fabricated microfluidic components. The system consists of solenoid pneumatic valves controlled by a programmable WAGO controller. A software interface is written in the CODESYS software as a medium between the WAGO controller and solenoid valves. A nitrogen gas tank is connected to the solenoid valves whose outlets are connected to the fabricated chips by using the Tygon® tubing. A regulator with unit of kPa (**Fig. 4**, regulator 1) is used to control the gas pressure on the chips. A reservoir with water-mixed red food dye with a certain volume ratio is used to provide the liquid flow through the microvalve. To generate a flow with a specific pressure, the reservoir is connected to the nitrogen gas tank. By controlling the pressure gauge connected to the reservoir (**Fig. 4**, regulator 2), the liquid pressure is adjusted. The flow rate through the microvalve is measured by the time it takes for the exiting liquid to fill a certain volume of a Tygon® tube with a specific inner diameter (**Fig. 4**).
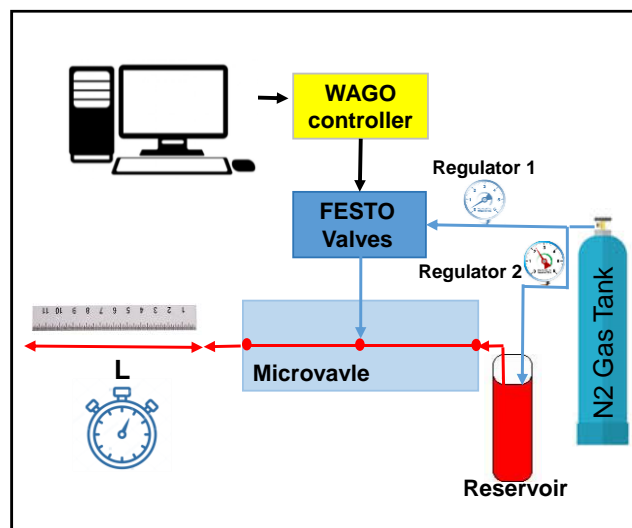

Figure 4. Schematic illustration of the microvalve test

4.2 Characterization of Microvalve

The bonding strength of the microvalve is investigated first. The microvalve is found capable of resisting a gas pressure more than 500 kPa with no burst failure. **Fig. 5** shows the microvalve volume flow rate versus actuation gas pressure at fluid inlet pressures of 18 kPa, which can generate a flow rate of 2.82 ml/min. The result, as shown in the figure, indicate that when the actuation gas pressure is increased, the liquid flow is decreased. In the liquid pressure of 18 kPa, as the actuation gas pressure of 360 kPa is applied, the flow rate reduces to negligible leakage of 215 nL/min, respectively. By applying the actuation gas pressure more than the above values, no decrease is detected in the leakage flow rate. The microvalve can be used for liquid flow regulation, in terms of its ability to provide low flow rates suitable for Lab-on-a-chip applications.
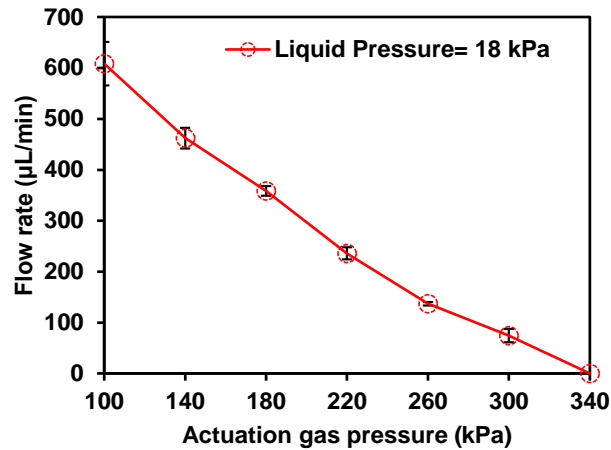
Figure 5. Characterization of the microvalve leakage rate versus applied nitrogen gas.

4.3 Experimental setup of the micropump

All components of the micropump and microvalve test are similar except for the FESTO® valve and the reservoir. In the micropump experimental setup, the reservoir is in contact with air to create atmospheric pressure at the pump inlet (**Fig. 6**). The fabricated peristaltic micropump consists of five serial interconnected microvalves which works based on the differences in the actuation time of microvalves relative to each other. To pump the flow, a certain pattern written by the CODESYS software is applied to open and close the FESTO® pneumatic valves relative to each other.
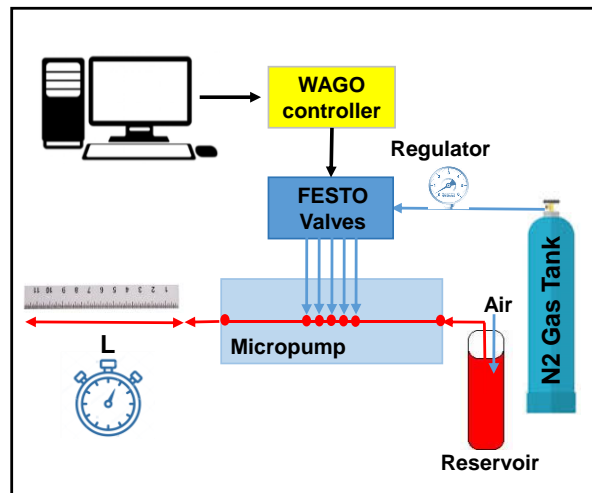

Figure 6. Schematic illustration of the micropump test

4.4 Characterization of the micropump

As shown in **Fig. 7a**, the micropump flow rate is illustrated as a function of frequency in three different actuation gas pressures of 100, 160, 220 kPa. It is observed that with increasing the pressure from 160 to 220 kPa, the maximum flow rate occurred in a frequency of 15 Hz, decreases from 345.29±10 μL/min to 325.99±10 μL/min, respectively.

The effects of downstream pressure on the pumping flow rate is also investigated. For this purpose, a liquid column with an adjustable height is used at the outlet port of the micropump, while the inlet port is connected to a liquid reservoir maintained at the atmospheric pressure.

The downstream pressure is altered by varying the height of the liquid column (H) at the outlet port. Experiments are performed using actuation gas pressure of 200 kPa at a frequency of 2 Hz. The experiment is conducted for a height (H) greater than 20mm for which a maximum flow rate of 66 ±5 µL/min is measured. As shown in Fig. 7b, the pumping flow rate is decreased to 12.05 ± 1.75 µL/min as the downstream pressure at the outlet port is increased to 0.6 kPa which corresponds to a liquid height of 60 mm. The key feature of the micropump fabricated in this paper is the rectangular cross-section design. In this micropump, the necessity for having round channels in the architecture of the corresponding microvalves [22] is eliminated.
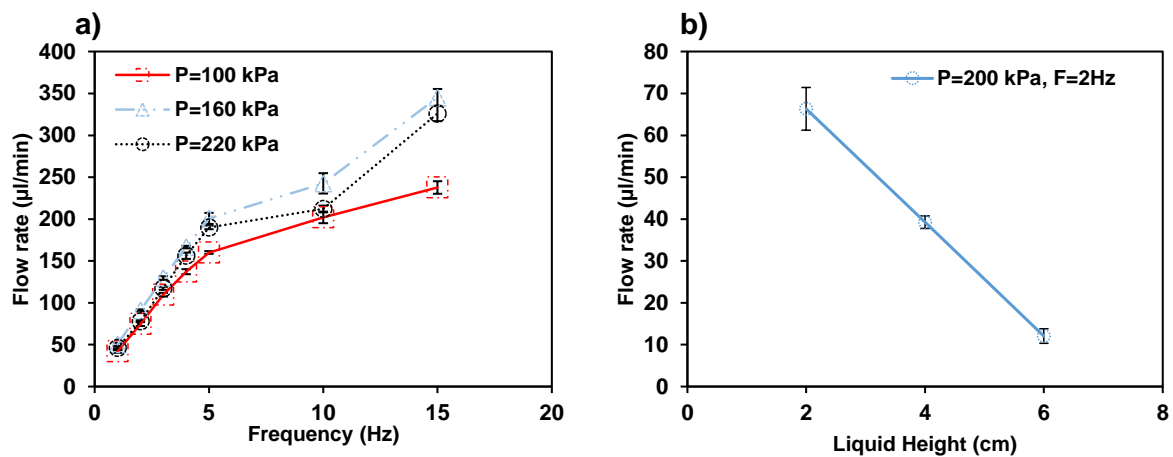

Figure 7. a) Effect of gas actuation pressure and the frequency of actuation on pumping flow rate in micropump; **b)** Effect of backpressure on pumping flow rate in the micropump; pressure difference between inlet and outlet ports of the micropump was produced by increasing the height of the outlet port.

5. Conclusion

In this article, a simple, fast prototyping method is presented in order to fabricate a thermoplastic microfluidic microvalve and a micropump from the PMMA with an elastomeric TPU. The micromilling fabrication method without any surface chemical treatment is used to fabricate rectangular microchannels in PMMA, while the TPU film is used as an elastomeric membrane to close the fluid channel required for on-chip flow manipulations. A high-strength thermal fusion bonding method is used to bond the TPU film to PMMA layers to fabricate micropump and microvalves. The fabricated microvalves can close the channel in a liquid pressures of 18 kPa, with negligible leakage of 218nL/min, respectively. The fabricated micropump can generate a maximum flow rate of about 350 µL/min at an actuation gas pressure of 160 kPa. In the presented valve design, the requirement for having curved channels in the architecture of the valve, which is common for normally open valves, is eliminated. Furthermore, the use of rectangular channels for the microfluidic actuators fabricated in this paper, is rare in the literature. The fabrication method introduced in this study is more effective compared to available methods in terms of time and cost. Therefore, it can be used for making various microfluidic actuators in a research laboratory for biomedical applications

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