Simulation and Fabrication of a PMMA Micro-Suction Tool for a Capsular Endoscope

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Abstract

This paper presents a simulation and fabrication of a PMMA (Poly (methyl methacrylate)) micro-suction tool for a capsular endoscope using a solid chemical propellant, AIBN (azobisisobutyronitrile). A capsular endoscope integrated with a micro-suction tool can gather gastro-intestinal juice for medical diagnosis. Our previous PDMS (polydimethylsiloxane) micro-suction tool has a fabrication problem: the PDMS Venturi-tube body and the glass substrate become detached during suction operation. In this study, PMMA is used as a material for enhancing the bonding strength. Additionally, PMMA has a lower contact angle than does PDMS, which results in an improved suction efficiency. The proposed PMMA micro-suction tool consists of an AIBN chamber, a micro-heater, a Venturi-tube, and a liquid reservoir. The PMMA Venturi-tube body is fabricated using X-ray lithography. The suction mechanism is as follows: The AIBN is decomposed into by-product and inert nitrogen gas by the heat generated by the micro-heater. The generated nitrogen gas is accelerated through the vena contracta section of the Venturi-tube. The accelerated nitrogen gas induces a negative pressure, so that the negative pressure pumps the target gastro-intestinal juice. The bonding strength of the PMMA and PDMS micro-suction tool are measured to be 1.6 N/m and 0.3 N/m, respectively. The PMMA micro-suction tool starts to pump the diluted ink when the generated negative pressure is 0.11 kPa. This value is approximately three times lower than the pressure of the PDMS micro-suction tool. The capsular endoscope integrated with the PMMA micro-suction tool is expected to improve the diagnosis achievable with the intended pathological research.

Keywords: PMMA micro-suction tool, Venturi-tube, Capsular endoscope, AIBN (Azobisisobutyronitrile)

1. Introduction

After the commercialization of the capsular endoscope, the capsular endoscope has gradually replaced the conventional wired-endoscope [1]. The capsular endoscope can transfer images in all regions of the digestive tract and cause little discomfort to patients. In contrast, a conventional wired-endoscope has a limited diagnostic scope and causes continuous discomfort to patients during inspection. In order to facilitate the complete replacement of the wired-endoscope, there have been many studies performed to develop the potentially versatile functions of capsular endoscopes such as active locomotion, drug delivery, and biopsy [2, 3, 4, 5].

The gastrointestinal juice is one of the biomarkers used to diagnose disease including gastric cancer, ulcer and duodenal ulcer [6, 7]. Fluidic sample pumping function enables the capsular endoscope to diagnose gastro-intestinal disease.

Figure 1 shows the conceptual schematic of the capsular endoscope integrated with the proposed micro-suction tool. The camera module of the capsular endoscope searches for gastro-intestinal juice. Then, the capsular endoscope approaches the target juice. Finally the integrated suction tool gathers it.

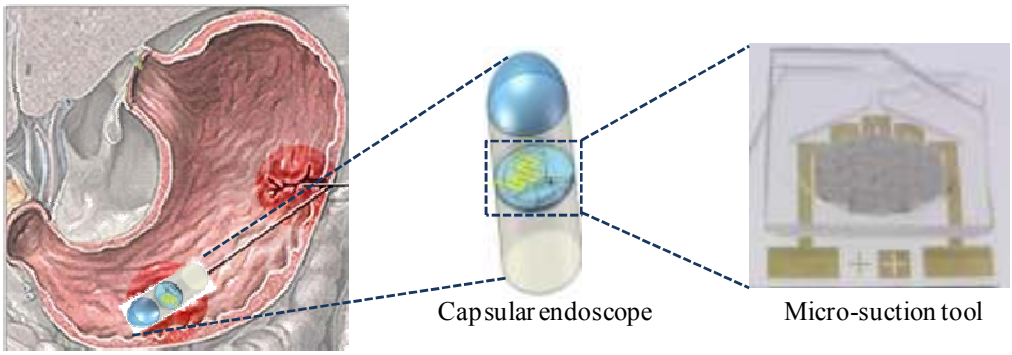


Figure 1. The conceptual schematic of the integrated capsular endoscope

Our research group reported a PDMS (polydimethylsiloxane) micro-suction tool in 2007 [8]. However, the previous PDMS micro-suction tool has fabrication problems. The PDMS Venturi-tube body is bonded with the glass substrate using a stamping method. However, the bonding strength is not enough to endure heat and pressure during the suction operation. Approximately 40 % of the fabricated PDMS micro-suction tool is detached unintentionally. Figure 2 shows that the generated N_2 gas leaks in unexpected directions.

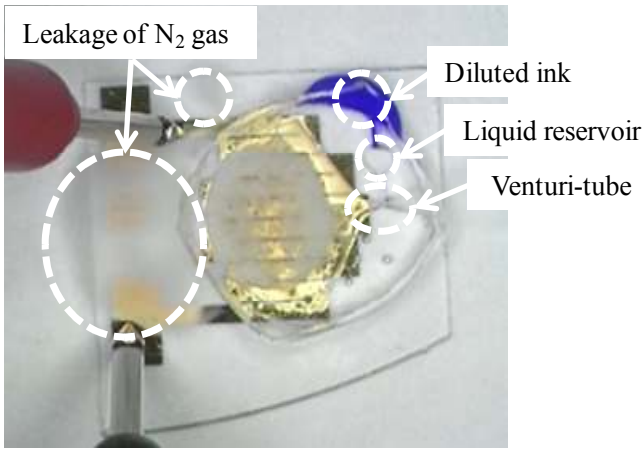


Figure 2. The N_2 gas leakage during suction operation

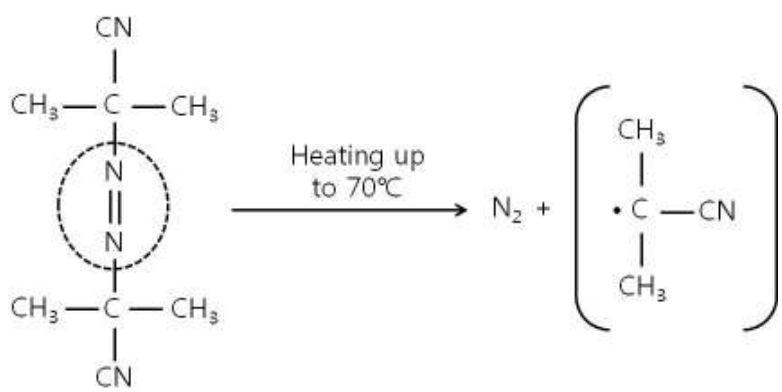
In this paper, an advanced PMMA (Poly (methyl methacrylate)) micro-suction tool is presented. Before the AIBN (azobisisobutyronitrile) ignition test, a preliminary study is performed to measure the bonding strength and the required negative pressure for suction. In order to improve fabrication precision, X-ray synchrotron lithography is used for the fabrication of the PMMA Venturi-tube body. Then, the MMA (methyl methacrylate) is used

to obtain strong bonding between the glass substrate and the PMMA Venturi-tube body. The relationship between the input pressure and the contact angle is also studied.

2. Material and Design

2.1. Ignition source (AIBN)

The AIBN is decomposed by heat. Its decomposition system has two stages. First, at around 70°C, the AIBN is decomposed into N_2 and by-product. At the second stage, the AIBN is oxidized at over 105°C. The first stage of the AIBN decomposition is shown in Fig. 3 [9, 10]. In this research, the AIBN is controlled to generate N_2 gas.



(3)

Figure 3. The AIBN decomposition mechanism

2.2. Micro-heater design

A thin film micro-heater is designed and fabricated for the AIBN ignition. The micro-heater is designed with a length of 57.2 mm and a width of 1.4 mm was adopted for the Ti/Au thin film. The thickness of the Au layer is 750 Å and that of the Ti layer is 500 Å. The resistance of the thin film micro-heater is designed to be 21.7 Ω from Ohm's Law:

$$\frac{1}{R_{total}} = \frac{1}{R_{Au}} + \frac{1}{R_{Ti}} \tag{1}$$

where R_{total} is the total resistance of the micro-heater, R_{Au} is the Au film resistance and R_{Ti} is the Ti film resistance. The measured value of the resistance of the fabricated micro-heater is 25.2 Ω.

2.3. Venturi-tube design

A PMMA micro-suction tool is designed using a Venturi-tube [11]. Figure 4 shows the basic design of the proposed suction tool. In a Venturi-tube, negative pressure is induced when an incompressible fluid is accelerated at the vena contracta section. An equation for the pressure drop due to the Venturi effect is derived from Bernoulli's principle (Eq. 2).

$$\mathrm{V}P = P_1 - P_2 = \frac{1}{2}\rho v_1^2 \left(\frac{A_1^2}{A_2^2} - 1 \right) \tag{2}$$

where P_1, P_2 are pressures, ρ is the density, v_1 is the fluid velocity, and A_1, A_2 are the channel areas. In order to compensate for the pressure drop, suction fluid flow is generated in the vena contracta section. The proposed suction tool is designed to maximize the negative pressure at the intersection of the vena contracta and suction channel.

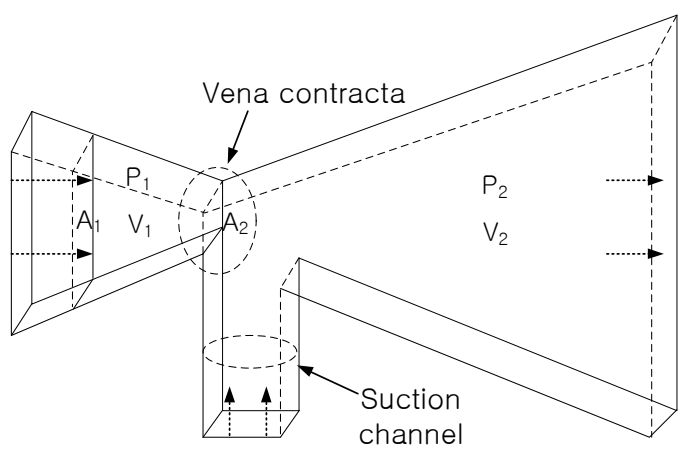


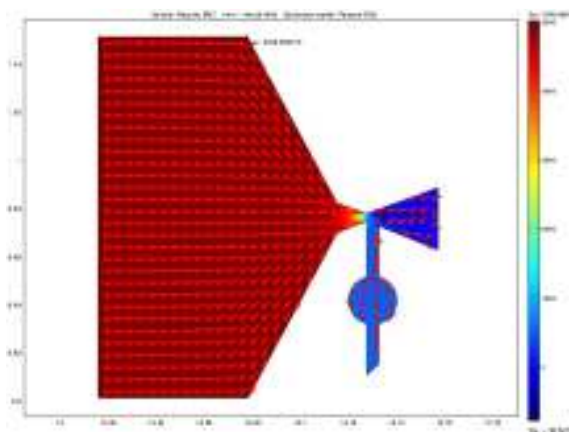
Figure 4. The basic design of the micro-suction tool

2.4. Simulation model of Venturi-tube design

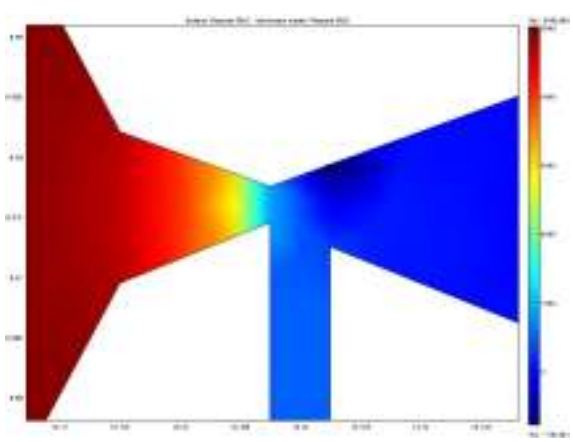
FEMLAB™ 3.2 (Comsol, U.S.A.) software is used to find the section which has the maximum negative pressure. The designed Venturi-tube generates a maximum negative pressure at the vena contracta section. The governing equation of the simulation model is the Navier-Strokes equation:

$$\rho(\frac{\partial \overline{v}}{\partial t} + \overline{v} \cdot \nabla \overline{v}) = -\nabla P + \mu \nabla^2 \overline{v} + \rho \overline{g} \tag{3}$$

where ρ is the density, $\boldsymbol{\upsilon}$ is the velocity vector, P is the pressure, μ is the dynamic viscosity, and $\boldsymbol{g}$ is the gravity vector. The width of the vena contracta section is 300 um, the width of the suction area is 500 um and the volume of the liquid reservoir is 1.57 mm^3. Figure 5(a) shows the simulation result. The AIBN chamber in the simulation model is represented by a rectangular shape instead of a half circular shape so as to reduce the computational burden. Figure 5(b) shows the generated maximum negative pressure to be approximately 0.8 kPa at the intersection of the vena contracta and the suction channel, when the inlet pressure is 5 kPa.



(a)



(b)

Figure 5. The simulation model and the result of the Venturi-tube design (a) Simulation result for the Venturi-tube design (b) Expanded view of the area which has maximum negative pressure

3. Fabrication

A PMMA micro-suction tool consists of a micro-heater, AIBN chamber, Venturi-tube and liquid reservoir. The fabrication process for the PMMA micro-suction tool is shown in Fig. 6 and 7.

3.1. Fabrication process of PMMA Venturi-tube body

The fabrication process for the PMMA Venturi-tube body is shown in Fig. 6. A 250 um thick polyimide film (Leomid, Kolon, Korea) is used as the X-ray mask substrate because of its good mechanical and optical transmission properties. A polyimide film is attached to the Si wafer using a dry photoresist (Accuimage, Kolon, Korea) as shown in Fig. 6(a). A thin Cr/Au (300Å/1500 Å) layer is sputtered on the polyimide film to serve as a seed layer for Au electroplating (Fig. 6(b)). Thick photoresist (P-LA 900PM, Tokyo Ohka Kogyo, Japan) is uniformly spin-coated on the deposited seed layer with a thickness of 25 um, and the wafer is exposed using an aligner (MA-6, Karl-suss America, inc., USA) with an energy of 3750 mW·sec/cm^2 (Fig. 6(c)). The thick photoresist is developed sequentially using a developer (P-7G, Tokyo Ohka Kogyo, Japan) as shown in Fig. 6(d). then next, a 15 um thick Au electroplating process is performed in order to make the X-ray mask (Fig. 6(e)). After the detachment of the polyimide film from the substrate wafer, the thick photoresist is finally removed with a stripper (502A, Tokyo Ohka Kogyo, Japan) as shown in Fig. 6(f). In order to prepare the substrate for X-ray irradiation, a 500 um thick PMMA (Goodfellow, USA) sheet is attached to a titanium sheet of thickness 2 mm (Fig. 6(g)). Subsequently the PMMA Venturi-tube body is fabricated using X-ray irradiation at 2.5GeV with an electron current between 110 and 190 mA (Fig. 6(h)). The irradiated PMMA is subsequently developed to form a PMMA Venturi-tube body with a specific organic developer, commonly known as GG developer (2-(2-butoxy-ethox) ethanol 60 %, Morpholine 20 %, Ethanolamine 5 %, DI water 15 %) at 35°C with a stirring speed 50 rpm.

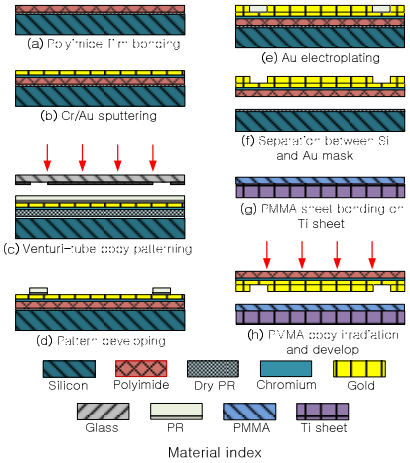


Figure 6. The fabrication process of the PMMA micro-suction tool

3.2. Fabrication process of the PMMA micro-suction tool

Figure 7 shows the fabrication process of the PMMA micro-suction tool. In order to fabricate a micro-heater, a thin Ti/Au (500Å/750 Å) is sputtered on a glass wafer (Fig. 7 (a)). Photoresist (AZ1512, Microchem, USA) is uniformly spin-coated with a thickness of 0.9 um, and the wafer is exposed using an aligner (MA-6, Karl-suss America, inc., USA) with an energy of 3750 mW·sec/cm^2 (Fig. 7 (b)). The micro-heater is successively developed and wet etched using aqua regia and hydrofluoric acid (Fig. 7 (c)). Then, liquid PMMA (950 PMMA C 9, MicroChem, America) is spin-coated and baked for three hours to form an adhesion layer (Fig. 7 (d)). The PMMA is cut manually for use as a cover-plate for the micro-suction tool. After each component is fabricated, the PMMA Venturi-tube body, the PMMA cover-plate and the Ti/Au micro-heater are bonded using an MMA interlayer. Then next, a pressure of approximately 100 kPa is applied for three hours to obtain bonding (Fig. 7 (e)).

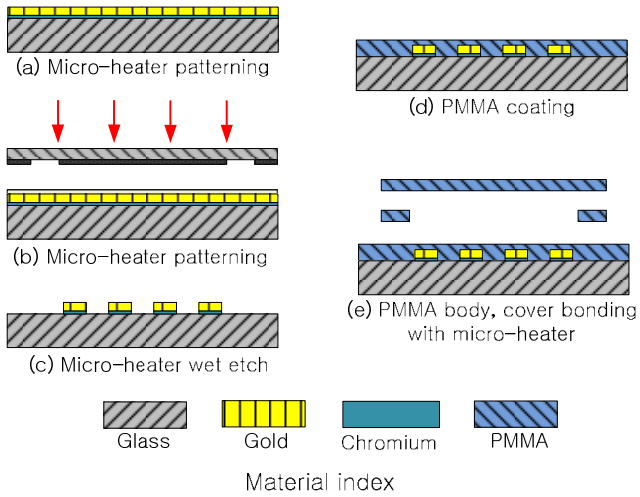


Figure 7. The fabrication process of the PMMA micro-suction tool

The PMMA Venturi-tube body and the micro-heater are shown in Fig. 8 (a) and Fig. 8 (b), respectively. The bonding result of implemented PMMA micro-suction tool is shown in Fig 8 (c).

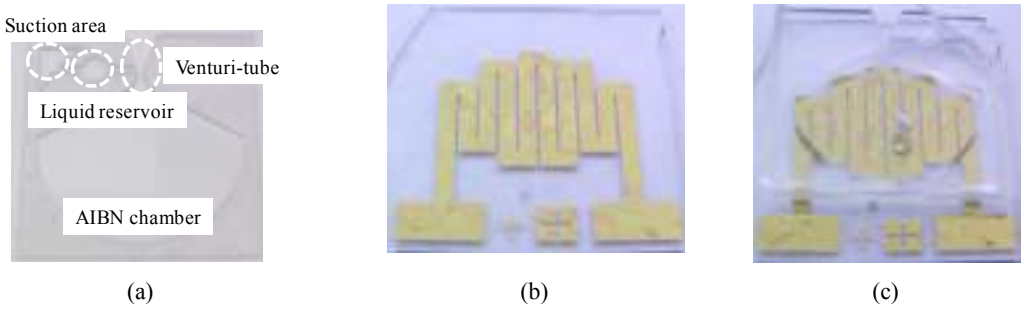
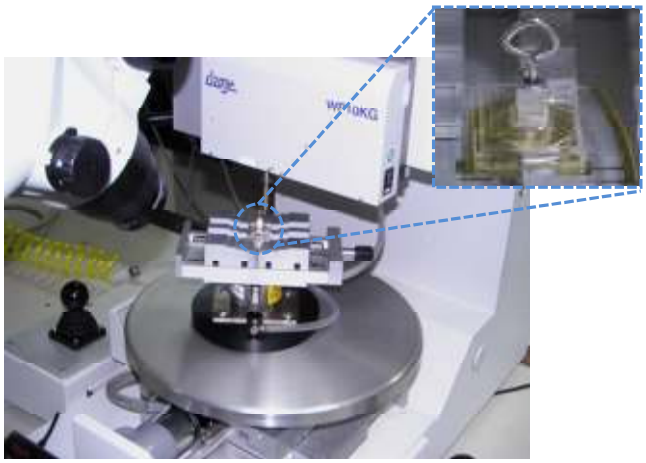


Figure 8. The fabrication results of the PMMA micro-suction tool (a) PMMA Venturi-tube body (b) Micro-heater (c) Bonded PMMA micro-suction tool

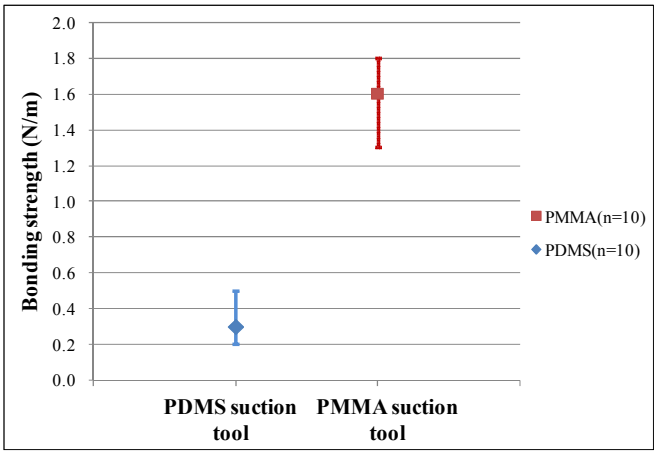
4. Experiment

4.1. Measurement of bonding strength

The bonding strength between the Venturi-tube body and the glass substrate is measured using a bond tester (DAGE 4000, DAGE, United Kingdom) as shown in Fig. 9 (a). The PMMA and the PDMS micro-suction tool are bonded with a linker using an epoxy adhesive. After waiting 10 minutes for the bonding to reach maximum strength, the linker is connected to the bond tester.



(a)



(b)

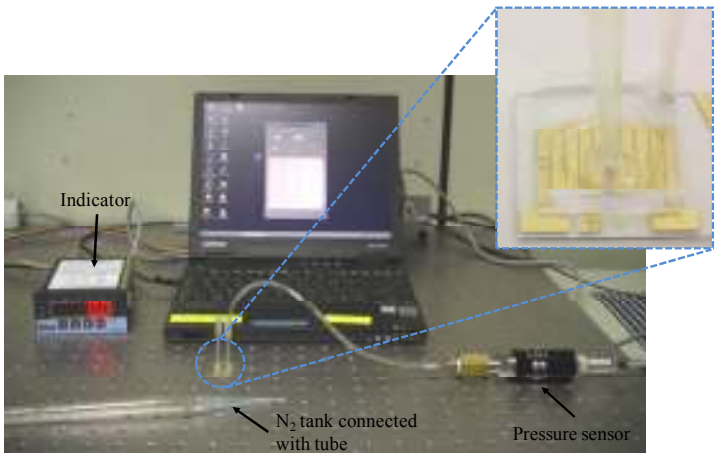
Figure 9. The bonding strength measurement of the PMMA and PDMS micro-suction tool (a) Measurement setup (b) Measurement result of the bonding strength

The PMMA Venturi-tube body is detached from the glass substrate at 1.6 N/m, and the PDMS Venturi-tube body is detached from the glass substrate at 0.3 N/m, as shown

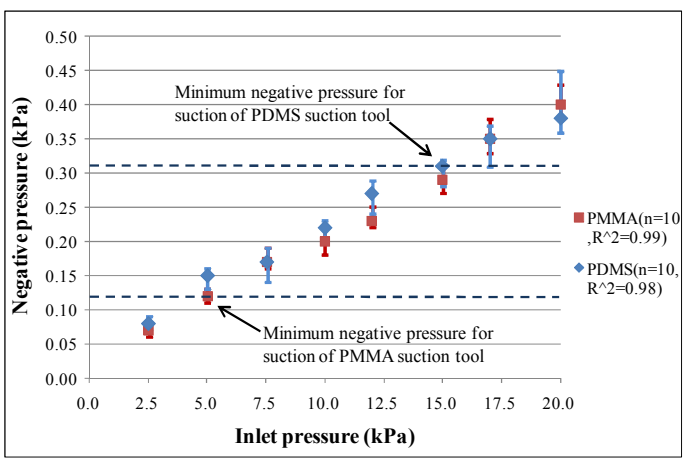
in Fig. 9 (b). The bonding strength of the PMMA micro-suction tool is about five times stronger than that of the PDMS micro-suction tool.

4.2. Measurement of minimum negative pressure for suction

In order to measure the minimum negative pressure for suction of the PMMA and the PDMS micro-suction tool, N_2 gas tank is used as an input source, instead of the AIBN matrix (Fig. 10 (a)). The fluid inlet of the punctured cover-plate is connected to an N_2 gas tank using a tube and a regulator. The negative pressure is measured with respect to the N_2 gas pressure from the inlet using a pressure sensor (PSHK-760HAAG, SETech, Korea) connected to the suction area with a tube.



(a)



(b)

Figure 10. The negative pressure measurement of the PMMA and PDMS micro-suction tool (a) Measurement setup (b) Measurement result of the negative pressure

Figure 10 (b) shows that the generated negative pressures of the PMMA and PDMS micro-suction tool are approximately linearly related to the increment of N_2 gas

pressure. The PMMA micro-suction tool starts to pump the diluted ink. The negative pressure is 0.11 kPa, and the inlet pressure is 5.0 kPa. The PDMS micro-suction tool starts to pump the diluted ink. The negative pressure is 0.31 kPa, and the inlet pressure is 15.0 kPa. The minimum negative pressure of the PMMA micro-suction tool is approximately three times lower than that of the PDMS micro-suction tool because the contact angle between PMMA and diluted ink is less than that of PDMS. This indicates that the PMMA micro-suction tool can operate with less amount of AIBN.

5. Conclusion

An advanced PMMA micro-suction tool is developed. Before the AIBN ignition test, a preliminary study is performed. The bonding strength and minimum negative pressure for suction are measured to evaluate the performance of the PDMS and PMMA micro-suction tool. In the bonding strength experiment, the PMMA Venturi-tube body is detached from the glass substrate at 1.6 N/m. The measured value is five times larger than that of the PDMS micro-suction tool. The PMMA micro-suction tool starts to pump the diluted ink when the negative pressure is 0.11 kPa. The minimum negative pressure for suction of the PMMA micro-suction tool is approximately three times lower than that of the PDMS micro-suction tool. The capsular endoscope integrated with the PMMA micro-suction tool is expected to improve the diagnosis of the pathological research.

6. Acknowledgements

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7. References

[1] M. E. Karagozler, E. Cheung, J. Kwon, and M. Sitti, “Miniature Endoscopic Capsule Robot using Biomimetic Micro-Patterned Adhesives”, Biomedical Robotics and Biomechatronics, Pisa, Italy, 2006, pp. 105-111,

[2] M. Andrea, M. Arianna, O.S. Marc, and D. Paolo, “Wireless capsule endoscopy: from diagnostic devices to multipurpose robotic systems”, J. Biomed Microdevices, 9, 2007, pp.235-243

[3] C. Cavallotti, M. Piccigallo, E. Susiloa, P. Valdastri, A. Menciassia, and D. Paolo, “An integrated vision system with autofocus for wireless capsular endoscopy”, Sensors and Actuators A: Physical, 2009

[4] D. J. Laser, and J. G. Santiago, “A review of micropumps”, J. Micromech. Microeng, 14, 2004, pp. R35-R64

[5] S. k. Park, K. I. Koo, S. M. Bang, J. Y. Park, S. Y. Song, and D. I. Cho, “A novel microactuator for microbiopsy in capsular endoscopes”, J. Micromech. Microeng. 18, 2008, pp.25-32

[6] T. C. Freeman, R. J. Playford, C. Quinn, K. Beardshall, L. Poulter, J. Young, and J. Calam, “Pancreatic secretory trypsin inhibitor in gastrointestinal mucosa and gastric juice”, International journal of gastroenterology and hepatology, 31, 2000, pp. 1318-1323

[7] S. Fujimoto, U. Kitsukawa, and K. Itoh, "Carcinoembryonic Antigen (CEA) in Gastric Juice or Feces as an Aid in the Diagnosis of Gastrointestinal Cancer", Ann Surg, 189(1) , 1978, pp34–38

[8] K. I. Koo, S. K. Park, J. W. Ban, and D. I. Cho, "A Novel Fluid Suction Tool For Capsular Endoscope", The 14th International Conference on Solid-State Sensors, Actuators and Microsystems, vol. 1, Lyon, France, 2007, pp. 1335-1336

[9] M. T. Tabka, J.M. Chenal, and J.M. Widmaier, "Effect of Stannous Octoate on the Thermal Decomposition of 2,2A-azobis(isobutyronitrile), Polymer Int., 2000, 49, 412

[10] C. C. Hong, S. Murugesan, S. H. Kim, G. Beaucage, J. W. Choi, and C. H. Ahn, "A Functional On-Chip Pressure Generator Using Solid Chemical Propellant for Disposable Lab-on-a-Chip", Lab-on-a-Chip, 3, 2003, pp 281-286

[11] K. I. Koo, M. J. Jeong, S. K. Park, H. M. Choi, K. S. Kim, J. H. Park, and D. I. Cho., "Valveless, Venturi-tube Micro Suction Pump Using Solid Chemical Propellant", World Congress 2006, seoul, korea, 2006, pp. 306-309

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