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FABRICATION OF MICROFLUIDIC CHANNEL USING MICRO END MILLING AND MICRO ELECTRICAL DISCHARGE MILLING

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ABSTRACT

This paper discusses the fabrication of microfluidic channels using micro end milling and micro electrical discharge (ED) milling on metals and polymers. The width of the microchannels fabricated by micro end milling was 100-800 µm with 1-2 aspect ratio. The average surface roughness values were 100-200 nm and 80-120 nm on metals and polymers respectively. The end milling was found to form more burrs on metallic surface. Micro ED milling, on the other hand, was capable to produce high aspect ratio microchannels on metallic materials without forming any burrs. Using this micro ED milling process, microchannels of 120 µm width and 8-9 aspect ratio were machined with 40-50 nm average surface roughness. Micro swiss-roll combustor mold cavity was machined by using micro ED milling.

Keywords: Microfluidic channel, micro end milling, micro ED milling, micro EDM, micro/meso mechanical manufacturing, M^4 technology, Bio-MEMS

1. INTRODUCTION

A microfluidic device has one or more channels with at least one dimension less than 1 mm. The fluid flow through a microfluidic channel is completely laminar as characterized by the Reynolds number in the range of 1-100 (Yager, 2008). A large number of biomedical applications need to manipulate fluids moving through a small channel which is known as microfluidic. This new field stimulated mainly two research areas: (1) development and fabrication of functional microfluidic channels and devices, and (2) fundamental research on microfluidic behaviour in small channels and sophisticated fluid handling capabilities. The use of microfluidic devices has a number of significant advantages. The volume of fluids used in microfluidic channel is very small, usually in the range of sub-millilitre to several nanolitres. It requires very small amount of reagents which is extremely significant especially for expensive reagents. As a result, the ultimate objective of microfluidic research is to develop lab-on-a-chip (LOC) to integrate laboratory functions in one chip with the handling of very small amount of liquid in the range of nanolitre or picolitres. It is a sub-set of micro-electro-mechanical systems (MEMS) and often called micro total analysis system (µTAS). It can perform multiple tasks such as mixing, separation, detection, etc. The advantage of LOC includes low cost, high accuracy, less contamination, faster analysis with a very small amount of fluid, etc. (Jung *et al.*, 2007). Micro swiss-roll is also a microfluidic device for energy supply at micro level. It re-circulates fuels through microfluidic channels to generate high density energy within a tiny region (Kim *et al*, 2007; Ashman and Kandlikar, 2006). Microchannels of thin walls and low thermal conductivity provide higher efficiency of the combustor. It has the potential to substitute lithium-ion batteries widely used in cell phone, laptop, etc. (Ahn *et al*., 2004; Ronney, 2003). For the development of functional fluidic devices the main concerns are the materials and fabrication processes. Microfluidic devices can be fabricated from a variety of materials such as silicon, metals, ceramics, glass, polymers, etc. However, silicon has been used extensively to create microfluidic devices for the last decades. One of the fundamental requirements of materials for microfluidics is the biocompatibility as most of them are used for biological analysis. The typical fabrication techniques are lithography, wet etching, LIGA (Lithography, Electroforming, and Molding), microreplication, etc. The micro/meso mechanical manufacturing (M^4) techniques such as micromilling, micro electrical discharge machining (EDM), etc. are also used to directly fabricate microfluidic channel on metals and plastics (Mateusz *et al.*, 2007). Microfluidic chips were also fabricated using LIGA-similar processes where the metal mold masters were machined with M^4 technologies (Ribeiro *et al.*, 2005). This paper presents and compares two M^4 technologies namely micro end milling and micro electrical discharge (ED) milling for the fabrication of microfluidic channels and chips on metals and polymers.

2. MICROFLUDIC CHANNEL FABRICATION

The selection of M^4 techniques for the fabrication of microfluidic channel depends on the channel size, aspect ratio, surface roughness, etc. In many cases, it requires initial experiments and investigations before selecting a process for a particular substrate material. In the following sub-sections micro end milling and micro ED milling are discussed for the fabrication of microchannel directly or microchannel master mold for replication in the second stage. Integrated multi-process micromachining tool (DT-110: Mikrotools Inc. Singapore) was used for the experiments. This machine integrates several M^4 techniques such as micromilling, microturning, micro EDM, etc. The surface roughness of the fabricated microchannels was measured using a surface profiler (Surftest SV-500, Mitutoyo, Japan and WYKO NT9100, Veeco Instrument Inc., USA). The machined surface was inspected by scanning electron microscope (SEM) (JSM-5600, JEOL, Japan).

2.1 Micro End Milling

Among the M^4 techniques, micro end milling has shown great potentials in the fabrication of microfeatures. The motivation comes from the translation of the knowledge obtained from the conventional process to the micro level. Its specialty includes the ability of fabricating microfeatures from wide varieties of materials with complex three dimensional geometries. The master micromold produced by micro end milling can be used economically in microreplication. However, several macro rules are not directly applicable when machining in the micro/meso scale due to the size effect (Ahn *et al.*, 2005; Ahn and Ronney, 2005). In this research, two-flute tungsten-carbide end milling tools were used for machining microchannels of different dimensions on beryllium copper alloy (Protherm, % wt: Be = 0.4, Ni = 1.8, and Cu = 97.8) and polymethylmethacrylate (PMMA) plastic. Simple straight microfluidic channels of 500 µm width and 100 µm depth were machined on Be-Cu alloy as shown in Figure 1.

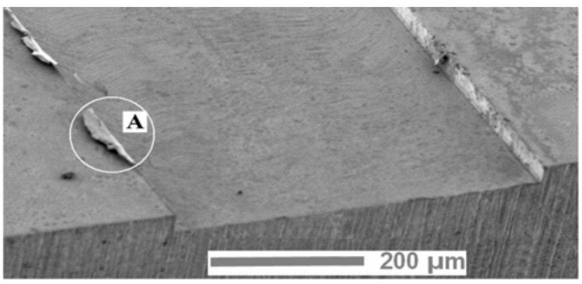

Figure 1. SEM micrograph of straight microfluidic channel produced by micro end milling on Be-Cu alloy. Window A shows the burrs that form during machining.

The process parameters are listed in Table 1. The average surface roughness of the channels was 180 nm. The formation of burrs, as shown in Figure 1, is a critical issue of this process. A complex microfluidic system was machined on PMMA using the concept of an existing design (Jung *et al.*, 2007) as shown in Figure 2a. The process parameters for the fabrication of these complex channels are listed in Table 1. The machined microchannels' width is 500 µm with different aspect ratio in the range of 1-2. Various complex parts such as sharp corner, V-angle, small curvature of the microchannel are shown in Figure 2b and Figure 2c. These microstructures on PMMA produced average surface roughness of 100 nm with less burrs.

Table 1. Experimental condition and results of micro end milling.

Parameters	**Be-Cu**	**PMMA**
Tool diameter (µm)	500, 800	500, 800
Feed rate (µm.tooth^{-1})	0.3-4	10
Depth of cut (µm)	70-100	200
Spindle speed (rpm)	3000	1500
Results:		
Average surface roughness (nm)	100-200	80-120
Dimensional accuracy (µm)	< 1	< 1

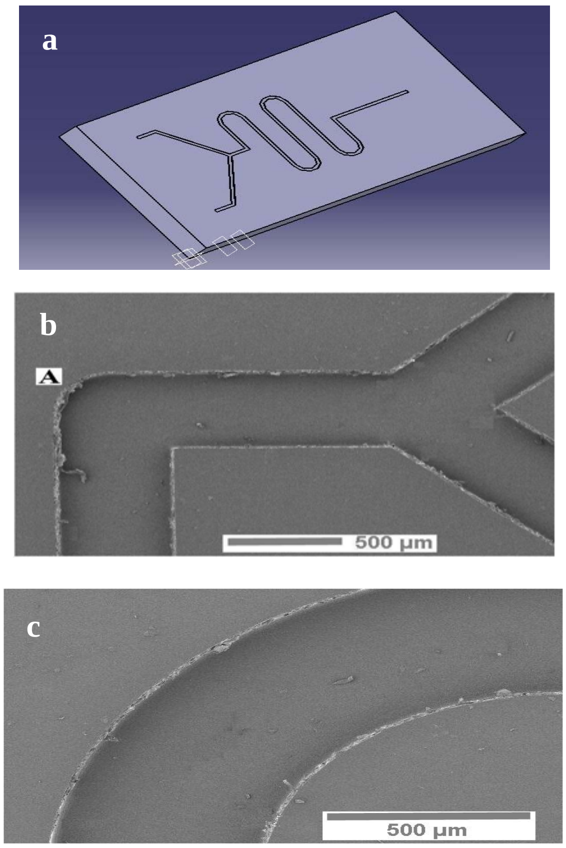

Figure 2. Complex microfluidic systems produced by micro end milling on PMMA based on an existing design (Jung *et al.*, 2007) (a) computer model, (b) SEM micrograph of a selected part of the channel, and (c) zoom-in view of a curvilinear corner of the channel marked by "A".

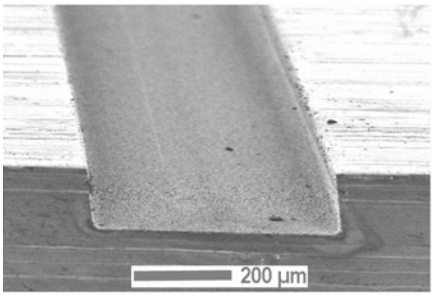

Figure 3. SEM micrograph of straight microfluidic channel produced by micro ED milling on Be-Cu alloy.

2.2 Micro Electrical Discharge Milling

Micro ED milling is a promising technique for machining microchannels on metallic materials with almost no burrs as shown in Figure 3. This process is usually used for fabricating master micromold which will be used for replication of microfluidic channels on plastic mainly by hot embossing. In this sub-section, the machining of micro swiss-roll mold cavity is discussed. The design of the micro swiss-roll combustor mold cavity, as shown in Figure 4, is the inverse of an existing design of micro swiss-roll combustor (Ahn and Ronney, 2005). Beryllium-copper alloy was selected as the mold material because of its high thermal conductivity, high heat and corrosion resistance. Tungsten carbide tool-electrode was selected because of its high stiffness and lower wear rate in micro ED milling (Mehfuz, 2008). The CNC code of the designed structure was generated by using CATIA V.5 R14 computer aided drafting software.

Cylindrical tungsten electrode of 300 µm diameter was reduced to 100 µm, as shown in Figure 5a, by micro wire electrical discharge grinding (WEDG) and used to fabricate microchannels of micro swiss-roll using the micro ED milling process parameters as listed in Table 2. The width and depth of the channels are 120 µm and 1 mm respectively (i.e., aspect ratio > 8). The optical and SEM image of the machined swiss-roll are shown in Figure 5b and Figure 5c respectively. The measured R_a surface roughness of the micro swiss-roll combustor cavity was found to be 40 nm.

3. DISCUSSIONS

The microfluidic channels produced on metallic and plastic materials using micro end milling and micro ED milling were investigated based on width, depth (aspect ratio = depth ÷ width), burrs, and surface roughness. Microchannels on metallic materials were fabricated using both of the milling techniques. It was found that higher aspect ratio and surface finish could be achieved on plastic substrate compared to metallic one. Moreover, formation of burr was a critical issue in micro end milling which requires a deburring process.

The micro end milling was more prone to form burr on metallic substrate.

Table 2. Experimental condition and results of micro ED milling for micro swiss-roll combustor mold cavity.

Parameters	**Value/description**
Feed rate (µm .s^{-1})	4.8
Capacitance (nF)	0.1
Voltage (volts)	80
Threshold (volts)	30
Tool electrode diameter (µm)	100
Spindle speed (rpm)	2000
Dielectric medium	EDM-3 synthetic oil
Depth per pass (µm)	200
Machining length per tool dressing (µm)	500
Results:	
Average surface roughness (nm)	40
Dimensional accuracy (µm)	< 1
Aspect ratio	8

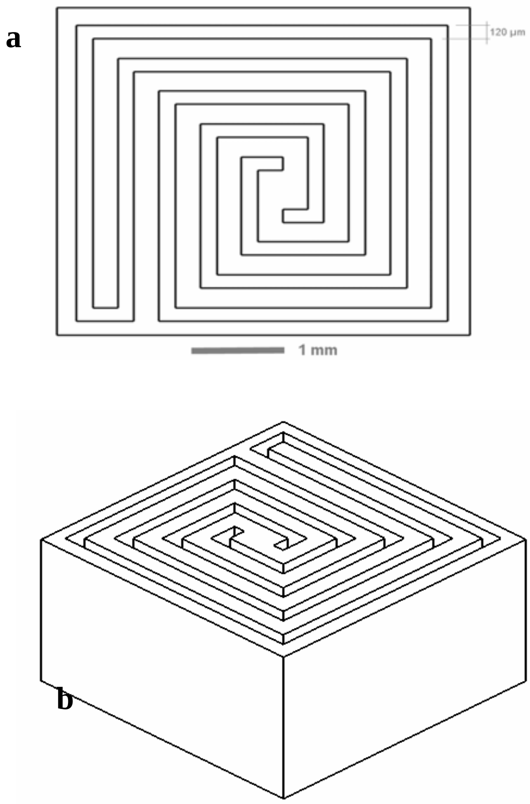

Figure 4. Design of micro swiss-roll combustor mold cavity of 120 µm channel width (a) top view, and (b) isometric view (Ahn and Ronney, 2005).

The integrated microchannel (Fig. 2) on PMMA shows fewer burrs compared to the channels on metallic materials (Fig. 1).

Alternatively, micro ED milling is a burr free process for fabricating microchannels on conductive metallic materials. This process is not applicable for machining of polymeric materials. However, it is usually used for fabricating master micromold cavity for the replication of microchannels on polymer and ceramic substrates. The size of the structures produced by micro end milling are in the range of 500-800 µm, where as micro ED milling has been applied to produce microchannels as small as 100 µm with very high aspect ratio of more than 8 (Fig. 5b). Very high surface finish (40 nm R_a) was achieved on the mold cavity which will result easy demolding and high surface finish on replicated polymer microfluidic channels. Higher aspect ratio and few tens of nanometer surface roughness are difficult to achieve by micro end milling. For the machining of micro swiss-roll mold cavity, layer by layer material removal approach was used to produce deeper channel with high dimensional accuracy. The thickness of each layer was 100-200 µm. The gap between two microchannels (i.e., wall thickness) was 380 µm. After machining each 500 µm, the tool-electrode was dressed by micro WEDG to achieve higher shape and dimensional accuracy.

4. CONCLUSIONS

This paper describes and compares the fabrication of microfluidic channel using micro end milling and micro ED milling which are extensively used in micro/meso scale fabrication. Microchannels on metals and polymers were fabricated. Micro swiss-roll mold cavity of aspect ratio 8 was fabricated using micro ED milling. The following conclusions can be made from this experimental research.

1. Although, micro end milling can be used for metals and non-metals, it forms more burrs on metallic channels compared to that of plastic microchannels. As a result micro end milling is recommended for direct fabrication of microchannels on polymeric materials.
2. The micro ED milling process is not directly applicable for machining microchannels on polymeric materials. However, this process is used to fabricate master mold to replicate microfluidic channels on polymer by micro hot embossing which is a cheaper and reproducible mass production technique.
3. It is possible to produce high aspect ratio (8-10) microchannel using micro ED milling, whereas only 1-3 aspect ratio can be achieved by micro end milling. The surface roughness produced by micro ED milling (40-50 nm R_a) is much lower than that of micro end milling (100-200 nm R_a). Micro ED milling produces no burr.
4. The prospect of fabrication of microchannel using micro end milling and micro ED milling is very promising with high level of interest for the later. It is possible to produce commercial microfluidic device using the combination of several M^4 processes.

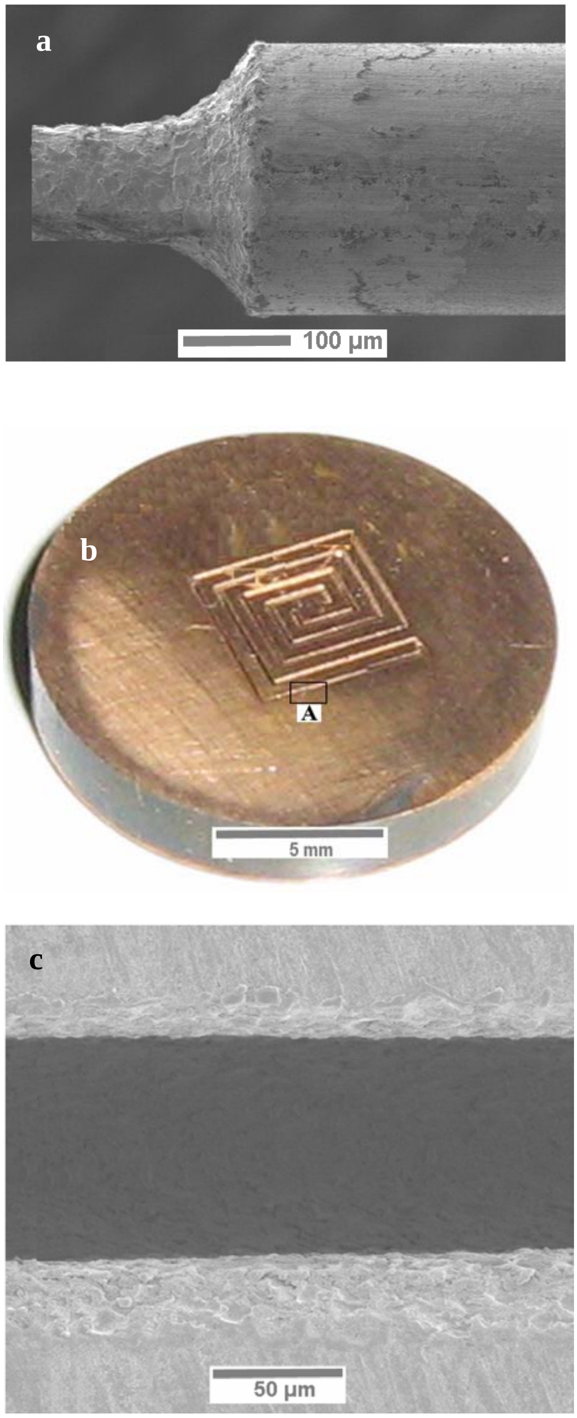

Figure 5. Fabrication of micro swiss-roll combustor mold cavity by micro ED milling (a) SEM micrograph of dressed tool electrode produced by micro WEDM, (b) optical image of fabricated micro swiss-roll combustor mold cavity, and (c) magnified SEM micrographs of a part of microchannel (window "A" in Figure 5b).

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REFERENCES

Ahn, J., Eastwood, C., Sitzki, L., Ronney, P.D., 2004. Gasphase and catalytic combustion in heat re-circulating burners. *Proc. Combustion Institute*, 30.

Ahn, J., Ronney, P.D., 2005. Plastic mesocombustors, Combustion Institute, http://carambola.usc.edu/Research/MicroFIRE/PlasticMesoCombustors.pdf.

Ashman, S., Kandlikar, S.G., 2006. A review of manufacturing processes for microchannel heat exchanger fabrication, *Proc. Fourth International Conference on Nanochannels, Microchannels and Minichannels*, ICNMM2006-96121, June 19-21, Limerick, Ireland.

Jung, W.-C., Heo, Y.-M., Yoon, G.-S., Shin, K.-H., Chang, S.-H., Kim, G.-H., Cho, M.-W., 2007. Micro machining of injection mold inserts for fluidic channel of polymeric biochips, *Sensors*, Volume 7, pp 1643-1654.

Kim, N.I., Yokomori, T., Fujimori, T., Maruta, K., 2007. Development and scale effects of small swiss-roll combustors. *Proc. Combustion Institute*, doi:10.1016/j.proci.2006.08.043.

Mateusz, L., Hupert, W., Guy, W.J., Llopis, S.D. Shadpour, S., Rani, S., Nikitopoulos, D.E., Soper, S.A., 2007. Evaluation of micromilled metal mold masters for the replication of microchip electrophoresis, *Microfluid Nanofluid*, Springer, Volume 3, pp 1-11.

Mehfuz, R., 2008. Micro electro discharge milling for microfabrication, MEng. Thesis, Department of Manufacturing and Materials Engineering, International Islamic University Malaysia.

Ribeiro, J.C., Minas, G., Turmezei, P., Wolffenbuttel, R.F., Correia, J.H., 2005. A SU-8 fluidic microsystem for biological fluids analysis, *Sensors and Actuators A*, Volume 123-124, pp 77-81.

Ronney, P.D., 2003. Analysis of non-adiabatic heat re-circulating combustors, *Combustion and Flame*, Volume 135, 421-439.

Yager, P., 2008. Basic Microfluidic Concepts, http://faculty.washington.edu/yagerp/microfluidicstutorial/basicconcepts/basicconcepts.htm.