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Feasibility of Double-Layer Microchannel Fabrication at Low Speed Micro End-Mill and Wire-Cut EDM Machines

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ABSTRACT

This study compares micron-scale features of double layer-microchannel heat sink (DL-MC) fabrication.Massive theoretical researches investigated DL-MC and its advantages over single-layer. However, micro-machining of DL-MC is still immature area. Here, Two advanced machining technologies, namely: Micro end-mill and wire-cut EDM are utilized to fabricate a DL-MC. Investigation on burr formation, surface roughness and shape configuration that influence heat transfer mechanism is done through a series of machining runs. Manipulating machine parameters such as: spindle speed, feed rate and tool dimension shown that low speed micro end-mill is capable of creating sufficient DL-MC quality. Also, scanning electron microscope (SEM) micrographs and roughness measurement reveal that wire-cutEDM is better in machining time and stability of surface roughness.

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INTRODUCTION

Advanced technology enables a notable development in MEMS and electronic semiconductor. This development is always related with an increase in heat generation that needs a compact and efficient cooling system to remove the heat and avoid electronic devices damage. Limited capabilities of traditional air heat sink to remove heat pushed researchers to adapt a higher thermal capacity liquid coolant in cooling systems. Liquids such as water, oil and most recently nano-fluid are being circulated through a closed loop passing a small size heat exchanger to overtake generated heat. In 1981,Tuckerman(1981) found that utilization of micro-scale grooves for heat exchanger (Microchannel)provides higher surface to volume ratio leading to better heat transfer rate. Microchannel is high efficient, small in size and compact in structure however Non-uniformity in temperature distribution across microchannel causes a malfunction of the electronic element. A double-layer microchannel design is suggested by Vafai and Zhu (1999)where two layers of micro-groove are stacked one atop the other to overcome this challenge. Then, a series of detailed numerical and theoretical investigations are doneto evaluate the DL-MC thermal and hydrodynamic performance showing the effect of geometrical shape, coolant type, pumping power, substrate materials and dimensions on overall heat transfer performance.Chong, Ooi *et al*. (2002), Hung, Yan *et al*. (2012), Hung, Yan *et al.* (2012), Xie, Chen *et al*. (2013), Wu, Zhao *et al*. (2014) It is concluded that the preferences of DL-MC in overall thermal performance over a single-layer and giving the light to DL-MC to be the tool of futuristic electronic -cooling system**.**

However, at the experimental and manufacturing level, few studies concentrated on DL-MCHS fabrication specially the metallic-based one. One potential reason behind a remarkable few experimental studies of DL-MC is thedifficulty in fabrication although there are various possible techniques to fabricate a microchannel. Micro-fabrication processes can be grouped into conventional process which is an extend to the macro-manufacturing concept like computer numerical controlled (CNC) machining , and non-conventional process that depend on chemical reactions such as X-ray lithography, deep reactive ion etching, deep UV lithography, electrical discharge machining (EDM) and laser machining,Madou (2002) .Wei, Joshi *et al*. (2007)experimentally studied a silicon stacked microchannel heat sink using deep reactive ion etching (DRIE) focusing on flow direction in the DL-MC. Unfortunately, this unique work is not investigating the effect of micro-processing on thermal

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behavior of the DL-MC even though DRIE technology employs an inductively coupled plasma machine that creates a reentrant geometry Ayon, Bayt *et al*. (2001).

Asad, Masaki *et al*. (2007) Conducted several tests on micro-EDM, micro-ECM, micro-WEDG, micro-WEDM, micro-Turning and micro-Milling, and reported that conventional (tool-based) micro-machining has advantages over a lithography technology in terms of cost effectiveness, efficiency and productivity. Fabrication time of a 20 µm -diameter hole on stainless steel takes less than 100 s, but to fabricate a 15 µm –diameter tool electrode of 0.5 length takes 3-4 h. Length of the electrode produced in EDM- machines is always smaller than the targeted length due to the groove created on the surface of the block electrode. Thus, non-conventional techniques have not proved themselves yet in DL-MC fabrication and it still faces an extreme challenge specially in metallic micro-structure such as physico-mechanical properties of metals (copper, steel and aluminum).

Moreover, different fabrication techniques produce specific geometrical shapes (rectangular, triangular, rounded-corner and ect.) those influence the overall thermal performance and pressure drop. Raj, Lisik *et al*. (2011) compared couples manufacturing techniques used in MEMS and single layer microchnnel showing the cooling abilities of each resulted structure , and found that wire-cutEDM technology and End-mill machining are the only two available methods to manufacture microchannel with given dimensions and chosen material . Rounded-corner shape resulted from wire-cut EDM provides more heat transfer rate than the sharp-corner resulted from micro end-mill .Review for surface integrity shows that although no strong impact of surface roughness in conventional macrochannel flow, but this influence cannot be neglected in microsystems because of the large surface-to-volume ratio in these systems .

14 Found experimentally that the surface roughness affects the values of the friction factors even in the laminar flow in the trapezoidal silicon/glass microchannels. For pressure drop, Weilin, Mala *et al*. (2000) explained the higher pressure drops and lower Nusselt numbers in microchannel to the surface roughness in trapezoidal silicon microchannels, and proposed a debatable model stating that" an increase in wall roughness caused the decrease in Nusselt number" . This roughness-viscosity model is contradicting with Wu and Cheng (2003) findings .

Wu and Cheng (2003)Experimentally found that Nusselt number and apparent friction constant depend greatly on geometric shape of microchannel. The laminar Nusselt number and apparent friction constant increase with the increase of surface roughness and surface hydrophilic property which lead to enhance convective heat transfer. Although it is concluded that the geometric parameters of microchannel have more influence on the overall performance than the surface roughness and surface hydrophilic property, but this result was for silicon-based microchannel microchannel manufactured by chemical wet etching. Whereas metallic micro-process creates a different surfaces .

Despite the extensive work in characterizing the micro-machining techniques, it has found that few (if not) research done in the field of metallic DL-MCHS. A clear picture of wire-cut EDM and low speed Micro End-Mill processes are needed to be addressed for DL-MC machining in two main domains: (1) geometry variation and (2) surface integrity and burr formation .The effect of both domains in overall thermal performance and pressure drop are demonstrated.

2.0 Experimental Equipment And Methods:

Manufacturing process investigation was held in tool and die and CIM laboratories at International Islamic university Malaysia. Two machines were used in experiment utilizing two different concepts of machining, namely non-conventional and conventional machining.

2.1 Machines:

2.1.1 Multi-Purpose Miniature Machine:

A multi-purpose miniature machine (MPMM), with a travel ranges of (210 mm X 110mm X 110 mm) in (X, Y, Z) respectively, is used to fabricate DL-MC microchannel by End-milling process Lim, Wong *et al*. (2003).see fig 1 . MPMM guarantees a high accuracy by adapting a full closed feedback control system and an optical linear scale with 0.1 micro resolution. This machine serves as non-conventional machine represented by micro-EDM and conventional machine represented by micro-end mill.

2.1.2 Wire cut EDM machine:

Wire-cut EDM machine (FX-K series) made by Mitsubishi Electric Corporation is used. Wire-cut EDM machine utilizes the concept of electro-discharge machining. It provides variety of controllable machining conditions like wire speed and surface finish with an approximate $\pm 0.025\ mm$accuracy. A 25x25mm^2 DL-MCHS takes (13 min) to completely fabricate a semicircular-corner shape with 30 slots. A minimum 100 µm wire diameter (that represents slot width) is considered as a main limitation involved in microchannel constructions. However, available wire dimensions are still widely acceptable for many MEMS and

Microchannel dimensions. It is essential here to specify the microchannel length (25 mm) as a workpiece thickness in wire-cut EDM programming.

Fig. 1: A multi-purpose miniature machine.

2.2 Burr formulation and surface roughness measurements:

A comparative study of burr formation for several machining conditions is conducted for both wire-cut EDM and multi-purpose miniature machines. Scanning electron microscope (SEM) is employed to analysis the burr formation throughout a series of images that show top, bottom and entrance views of upper and lower layer microchannel.

Although the primarily result shows top burr is the largest in size, However, the entrance and bottom burr formation have higher influence in DL-MC hydrothermal performance.

For surface properties, Surface roughness measuring machine (WYK$WYCO^{@}NT1100$) is utilized to measure the value of surface roughness Ra. A non-contact optical profiler system allows an accurate measurement and wide ranges o surface conditions. A super-clean reference surface is required to reduce potential errors. Also. Four measurement points are taken at the centerline of created slot to represent an average roughness point because preliminary fabrication indicates variation in roughness along the microchannel .

2.3 Micro-tool and micro-channel substrate material:

Micro End-mill uses a tungsten carbide micro-tool (provided from ATP company, UK) . Tungsten carbide tools with d= 200 , 300, 400, 500 µm were used in Micro-end mill .For wire-cut EDM machine , 100, 200 and 300 µm diameter wire made from brass were used . Fig 2 .

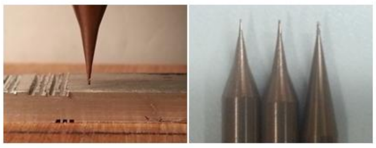

Fig. 2: Different micro-diameter end mill.

Commercial al 6061-T6- Aluminium is chosen for its high thermal performance .Then the wire-cut EDMand MPMM are used to make the channel groves with variety of experiment conditions as shown in table 1 and 2. It is essential to mention that depth and width of the micro-slot cut are ranged from 200 µm micro to 500 µm that represent previous recommendation investigationsSakanova, Yin *et al*. (2014), Hung, Yan *et al*. (2012), Hung, Yan *et al*. (2012).

Table 1: Machining condition in micro End-Mill machine:

Cutting speed	spindle speed	width of cut (tool diameter)	depth of cut
0.5 mm/min	1000 rpm	200 µm	100 µm
1 mm /min	1500 rpm	300 µm	200 µm
2 mm /min	2000 rpm	400 µm	300 µm
3 mm /min	2500 rpm	500 µm	400 µm
4 mm /min	3000 rpm		500 µm

RESULAT AND DISCUSSION

Several points can be concluded in producing metallic microchannel by micro-machining process in terms of time, cost, and complexity of machine usage. While EDM wire cut requires (10 -15 min) to fabricate one micro-slot regardless of the slot length, machining time for low speed micro end- mill is a function of the slot length and the maximum cutting speed is (4 mm/ min) .Increasing the cutting speed beyond 4mm/min causes a tool breakage for 200 and 300 µm tool-diameter and dramatically increases the burr formation .However, this section focuses on variation in machinability characteristics with spindle or wire speed , tool or wire diameter and cutting speed .

Table 2: Machining conditions in EDM wire cut.

Rate feed cutting	Wire feed rate speed
2 mm/min	10 mm/s
4 mm/min	12 mm/s
6 mm/min	14mm/s
8 mm/min	
10 mm/min	
12 mm/min	
14 mm/min	

3.1 Burr formation:

It is observed that top of the michrochnnel faces the largest burr formation regardless of tool-diameter or cutting speed .Images from SEM show burr size and shape from top and entrance views . Generally, increasing cutting speed with fixing spindle speed and tool diameter (cutting width) increases the burr formation amount and chips size in both top and entrance sides.Fig3.a The entrance and side wall of microchannel encountered a less sever burr formation .

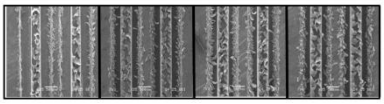

Fig. 3: A From lift , top burr formation for (0.5, 1,2 and 3 mm/min) cutting speed at 3000 rpm and 400 µm tool diameter.

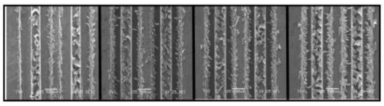

Fig. 3.b: From lift, top burr formation for (3000, 2500, 2000 and 1500 rpm) spindle speed at 1 mm/min speed and 400 µm tool diameter.

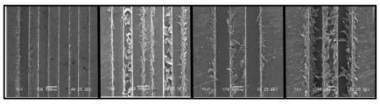

Fig. 3.c: From lift , top burr formation for (500,400,300 and 200 µm) tool diameter at 1 mm/min cutting speed and 3000 µm spindle speed.

Even through spindle speed controls the amount of vibration in work piece which leads to larger burr formation, however, burr size seems not strongly affected by decreasing spindle speed due to a relatively small change in spindle speed (3000-1000 rpm). Fig 3.b. shows a small increase in a wavy -chips size by decreasing spindle speed. At higher spindle speed, shearing takes place more than ploughing mechanism leading to fewer burrs. It is observed that 1000 rpm spindle speed is very dangerous for tool at which the possibility of breakage may occur. Thus, it is impossible to lower down the speed less than 1500 rpm.

Effect of tool diameter (microchannel width) on generating burrs is illustrated in fig3.c . It is obvious that increasing the tool diameter influence the size and shape of burrs. However, this increase is not following specific pattern or shape because cutting speed is kept constant. At 1 mm/min cutting speed, 500 µm tool diameters produces no burrs whereas 400 µm tool has big chips burr indicating that each microchannel dimension must be treated uniquely in terms of cutting and spindle speed. Same behaviour is applied to burr formation mechanism for 300 and 200 µm tool diameters. One worthy observation was the dramatically increase in burr formation once the tool wears, especially for soft materials (copper) ,that adds another obstacle for micro end-mill. Thus, to avoid any effect of tool wear on analysis, a new tool is replaced for each run because tool wear impact is beyond this paper objective.

The optimum condition of burr formation at entrance or tip of a microchannel can be obtained by increasing the cutting speed as shown fig. 4.a Increasing cutting speed seems not a strong parameter to eliminate burrs as it does in Up-milling and down milling where varying cutting speed influences chip size in both sides wall. Fig4.b shows almost no relation between varying spindle speed and burr formation. Burr at the entrance of microchannel has a strong influence on DL-MC thermal performance since the fluid flowing velocity are a function of inlet and outlet shape. Larger chips size may block or change the flow behavior inside the microchannel .

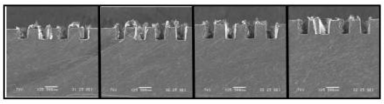

Fig. 5.a: From lift, entrance burr formation for (0.5, 1,2 and 3 mm/min) cutting speed at 3000 rpm and 400 µm tool diameter.

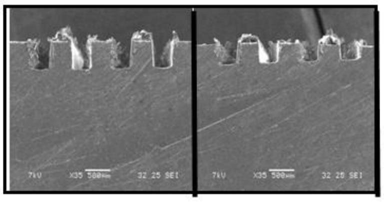

Fig. 5.b: From lift, top burr formation for (3000 and 2000 rpm) spindle speed at 1 mm/min speed and 400 µm tool diameter.

Generally, the burr formation indicates a negative impact on DL-MC surface quality .Wide range of techniques are developed to remove chips burr such as ultra-sonic cleaner .Fig 5.c shows a sample before and after burr cleaning using tradition sand paper which reveals the possibility to enhance channel surface .

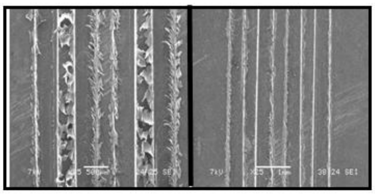

Fig. 5.c: Microchannel sample before and after cleaning using tradition sand paper.

EDM-wire cut machining mechanisms behave differently from End-milling resulting in fewer burrs and a more stable surface. The continuous wire feeding in wire-cut EDM machine eliminates the unstable burr formation and reduces generating vibration in the work piece.see Fig 6.

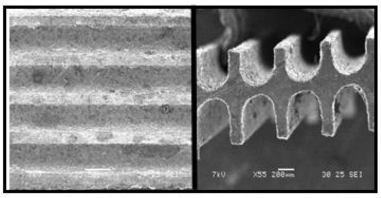

Fig. 6: Top and side view of DL-MC fabricated by wire-cut EDM.

3.2 Surface integrity:

As shown in literature, surface quality plays a significant role in overall heat transfer of the micro-channel and pressure drop. For micro End-mill, Changing the cutting speed, spindle speed or using of coolants cause a massive variation in surface roughness (Ra) Fig 7a, b and c. The minimum roughness Ra measured is obtained by increasing spindle speed and decreasing cutting speed. At relatively high spindle speed (3000 rpm), Ra values return to increase due to the associated vibration in the tool fig 7.b. Width of the slot is determined by tool diameter. An acceptable tolerance Ra (0.03 µm) is measured for (200, 300, 400 and 500 µm). However, there is an obvious variation in roughness Ra between these widths fig 7.c .It is likely that varying cutting speed is required and each tool diameter has different appropriate cutting speed.

In General, wire-cut EDM machine provides a higher controllability for surface finish and better surface integrity. The maximum surface roughness Ra is 3.4 µm .Fig 8. Illustrates that increasing feed cutting rate causes a slightly increase in measured Ra for relatively small wire diameter (100 and 200 µm). Reducing feed cutting speed in thick wires (250 or 300 µm) lead to less burr and Ra. No remarkable observation is recorded for wire speed variation effect in surface roughness Ra, however higher wire speed enhances the possibility of wire breakage.

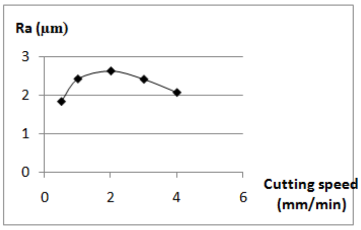

Fig. 7.a: Ra with Cutting speed variation.

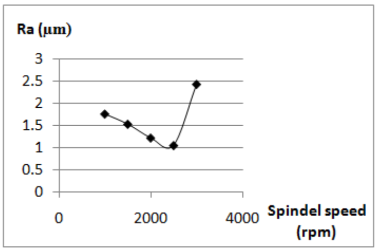

Fig. 7.b: Ra with spindle speed variation.

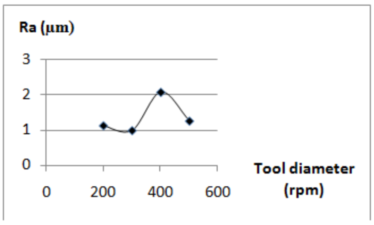

Fig. 7.c: Ra with tool diameter variation.

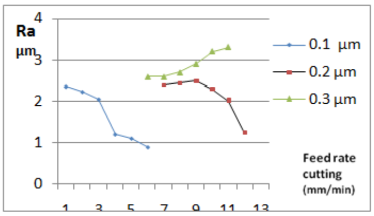

Fig. 8: Measured surface roughness Ra for wire-cut EDM process as a function of feed rate cutting and wire diameter. .

3.3 Geometry Configuration:

Fig.9 schematically shows clear picture of the difference between micro end-mill and wire-cut EDM. A rectangular and rounded-corner cross-section are obtained for micro end-mill and wire-cut EDM respectively. The influence of microchannel shape can be examined numerically or experimentally by investigating the total heat flux overtaken from the microchaneel structure determining the heat transfer coefficient , However the authors not discussed it here.

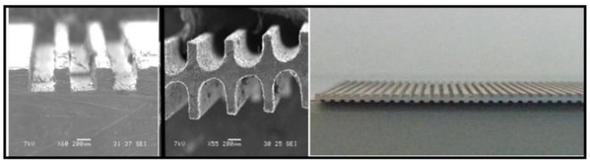

Fig. 9: Rectangular and rounded corners geometry.

4.0 Conclusion:

Based on experimental data obtained from Wire-cut EDM and micro end –mill machines samples with a help of SEM and roughness measurement machining, correlations are concluded as:

- A low-speed end-mill machine is capable of creating A DL-MC with an acceptable tolerance, surface roughness and burr formation.
- The analysis of low-speed end-mill machine conditions show that increasing the spindle speed and decreasing the cutting speed are critical parameters to obtain a less burr formation .Burr formation is concentrated on the top of the microchannel which has a less influence on internal flow.
- Roughness of the surfaces can be controlled by varying cutting speed and spindle speed. Specifically, middle cutting speed (2 mm/min) produces high value of measured roughness whiles middle spindle speed(2000 rpm) produces less roughness .
- Wire-cut EDM produces high uniform surfaces with almost no chips on the top, side wall or entrance of microchannel .However, the roughness Ra values is higher than end-mill process.
- Impact of burr formation on microchannel performance is limited since the burr chips are mostly generated outer side of microchannel .
- Wire-cut EDM creates only semicircular-corner geometry while Micro End-mill has more geometrical options like triangular or rectangular shape.
- Unlike macro-scale, surface roughness influences heat transfer mechanism in DL-MC by increasing heat transfer at the expenses of pressure drop. However, a sophisticated model in describing the roughness effect is required as well as experimental research.

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