Development of CNC Micro-milled Leaf-Pattern Micro-channel Heat Sink (LP-MCHS) and Testing Using Nanofluids

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Abstract. Micro-channel heat sinks (MCHS) have attracted the attention of researchers because of their compact design and wide range of applications. MCHS is mostly used to dissipate heat where large amount of heat is generated in a confined space. In this work, leaf pattern MCHS is fabricated on pure copper block by micro-milling on CNC machining center and is tested for its thermal performance and fluid flow behaviour using pure water as well as various nanofluids such as Copper Oxide(CuO), Aluminium Oxide(Al2O3)and Silicon Oxide(SiO2). The volume concentration of nanofluids was kept constant, i.e., 0.3% volume fraction and the experiments were carried out for heat flux ranging from 65 W/cm² to 200 W/cm² and flow rate from 100 ml/min to 900 ml/min. The results of experiments indicate that these nanofluids, as a working fluid, enhance the heat transfer by 35% and Nusselt Number by up to 37%, however, increases the pressure drop by 18% which increases the pumping power. From the performance evaluation analysis, it was found that the SiO2 nanofluid with leaf pattern MCHS gives optimal performance.

Keywords: Micro-channel Heat Sink (MCHS), Leaf pattern micro-channel heat sink (LP-MCHS), Reynolds number (Re), Nusselt Number (Nu), Deionized water (DI), Performance Evaluation Criterion (PEC), Nanofluid (nf), Base fluid (bf), Pressure drop (ΔP).

1. Introduction

The fabrication method of micro-channel is most essential aspect in the development of microfluidic devices. Depending upon the application of micro-channel-based device, different types of fabrication methods and materials of micro-channel are preferred. The rising demand of micro-channel devices has led to the development of many other new hybrid technologies that makes micro-channel more efficient and cost-effective. Basically, micro-channels are mostly created on glass, polymeric, metallic and silicon substrate. While polymeric, glass and silicon substrate are mostly used in chemical and biomedical devices, metallic and silicon substrate are used for electronic and mechanical engineering applications. However, fabrication of these micro-channels on such substrate in large number has always been a difficult task for manufacturers due to the precision and cost required for the products.

Development in the electronic industries is associated with the increase in the heat flux. Hence, to improve the performance and life of electronic devices, it is very essential to remove heat from the confined space and maintain the efficient working temperature. By using MCHS the main goals in

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electronic cooling can be achieve i.e. reduction of maximum temperature and minimization of temperature gradient on the surface of the devices. One of the ways to enhance the heat transfer is the application of additives to the working fluid. The basic idea is to improve the heat transfer for changing the properties of working fluid such as nanofluids where solid nanoparticles are added to base fluid to increase the thermal conductivity of working fluid. Nanofluids, consists of the base fluid such as water or ethylene glycol, and the nano sized particles of metal or non-metal. Group at the Argonne National Laboratory, USA first introduced the term nanofluid, about decade ago. In recent years, the nanofluids have gained much attention due to their potential advantages including higher thermal conductivity than pure base fluids, excellent stability and little increase in pressure drop.

The idea of using micro-channel heat sink (MCHS) for electronic cooling was introduced in 1981 [1]. Experimental results show that the MCHS have the capability to dissipate heat flux rate of 790 W/cm². Increasing the area wetted by the heat transfer fluid and decreasing the width of heat sink channels would improve the convective heat transfer for single phase flows. Nanofluids have greater potential for heat transfer enhancement because of their higher thermal conductivity [2], [3], [4], [5].

Traditional working fluids are used to dispersed nanoparticles uniformly for the preparation of Nanofluids. Traditional working fluids used for dispersion are water, alcohol, oil etc. [6]. Experimental investigation was done to measure the convective heat transfer and pressure drop for nanofluids in tube flow [7], [8]. Their result shows that heat transfer coefficient was highly enhanced, and it depends on particle volume fraction, Reynolds Number and the particle size and shape. And nanoparticles did not cause an excessive pressure drop was founded.

Together increasing the nanoparticle volume fraction and decreasing the nanoparticles diameter enhances the Nusselt number value and SiO₂ nanofluid has the highest heat transfer rate compared to CuO, Al₂O₃, and ZnO nanofluids which are made with water as base fluid [9]. It was also found that the heat transfer coefficient increased by increasing the nanoparticles concentration in different MCHS shapes with various nanofluids and various volume fraction when studied for the fluid flow and heat transfer characteristics [10], [11], [12].

In this work the LP-MCHS is fabricated and then it is tested for the heat transfer enhancement for its performance. Heat transfer behaviour was also tested with different nanofluids. Micro-channel and different applications of micro-channel in industries are discussed in the next section.

1.1. Micro-channel and their application

Different types of applications require different shapes, sizes, and structures of micro-channels. While most microfluidic channels involve a high form ratio, the micro-channels having a low aspect ratio also have a very great application in particle separation devices. Channels with dimensions between 1 and 999 μm are considered as micro-channels. The manufacturing method shows more importance in the performance of micro-channels. Micro-channels are mainly (except micro-grinding) manufactured by unconventional methods. Over the decade different types of micro-channels are manufactured. Commonly used microchannels cross sections includes circular, square, semi-circular, rectangular, U-shaped and Gaussian bundle micro-channel. Almost all types of micro-channels are manufactured on base material except circular cross section. Since on circular cross section, a thickness of few microns is usually left over along the length for optical and visual transparency, hence those are manufactured inside the material mostly [16].

Researchers has been attracted towards micro-channel heat sink because of its highly efficient heat exchange component and unique characteristics like compact design, operational safety, high efficiency and low volume along with its vast range of applications like chemical industry, aerospace industry, electronic communication, biomedical devices and so on. Microchannel applications are divided into the three types such as (1) biological application, (2) electronic and mechanical application, (3) chemical engineering applications.

For most microfluidic applications, the properties of the materials that matter are surface charge, molecular adsorption, electrical and thermal conductivity, machinability, optical properties, mobility of electroosmotic flows and many others. The most developed microchannel based devices are inkjet printers in microfluidics, which is possible due to the introduction of miniaturized gas chromatographs and nozzles. Some of the geometrically simplest micro-channels can be used in the manufacture of fuel cells comprising single or dual T-junctions. Different materials used to fabricate micro-channels are listed in next section.
1.2. Materials
Various types of materials have been used for different micro-channel devices. These various types of materials can be divided into three main categories according to their properties.

- Polymeric and glass substrates
- Metallic substrates
- Semiconductors, ceramics and composites

In this case copper is selected as the substrate material for engraving LP-MCHS. Copper has high thermal conductivity which is important with respect to heat transfer. Also, it is ductile, has good machinability and available everywhere at low cost. In mechanical milling process the base material should be thicker so that it can sustain the cutting forces and vibrations.

Table 1: Composition of Copper block

| Cu   | Zn | Pb | Sn | P  | Mn | Fe |
|------|----|----|----|----|----|----|
| 99.6 | 0.0885 | 0.005 | 0.005 | 0.01 | 0.01 | 0.06 |
| Ni   | Si | Al | S  | As | Bi | Se |
| 0.01 | 0.005 | 0.02 | 0.037 | 0.07 | 0.01 | 0.01 |

Fabrication method used for fabrication of micro-channel is discussed in next section. The fabrication method is selected according to the requirement of surface finish, geometrical and dimensional tolerances, precision, accuracy, surface quality, thermal and mechanical deformations etc.

2. Micro-mechanical cutting
With the advancement in high-precision machining, micro-mechanical cutting has become a key technology for the creation of micro-channels. Micro-mechanical cutting process is mainly suitable for manufacturing individual customized components rather than for large batches. It can manufacture many materials, such as Aluminium, brass, plastic, steel and polymers. It doesn’t require a expensive configuration, which allows the manufacture of miniatures at an economically reasonable cost [19]. With a high level of precision machining of ultra-precise machine tools, it is possible to obtain a good surface finish and precision of shape. The high machining speed of micro-cutting is another advantage over micro-manufacturing technologies. Most commonly used mechanical cutting processes are micro-milling and micro-turning. Recently, the multi-knife micro-milling process has been studied [17] and has proved more economical and faster compared to other contemporary micro-machining processes.

Composite cutting tool was used in this process of fabricating MCHS, and the depths of the micro-channels were taken inconsistent. In addition, it was observed that the corners were not sharp but curved, which could create a vacuum during the sealing process or bonding. Micro-channels were also slotted on stainless steel using thin groove cutters and the height of the upper cutter was mainly controlled by feed rate and cutting speed. In mechanical cutting processes, main disadvantages are the generation of cracks due to mechanical stresses, wear of the cutting tool and the long processing time. The challenges come in the fabrication process are discussed in next section.

2.1 Fabrication Challenges
In above geometry, the dimensions are in micron so fabrication of such a heat sink comes under the category of microfabrication. In conventional symmetric MCHS the primary channel is running along the length of the heat sink having taper cross section. The secondary veins are branching out from primary vein having width of 500 um and secondary channels are required to fabricate at an angle to primary vein. Because of these complicated and very fine geometry it is difficult to fabricate. Again, maintaining the depth, width and surface finish is challenging which require precision and accuracy. Unavailability of the probes of CMM below 1 mm makes it difficult for dimensional inspection. So, it is necessary to do modification in traditional instruments. There are number of methods like micro-EDM, etching, laser machining, lithography, molding, micro-machining, etc. In this work the
component is fabricated using CNC micro-milling process. The fabrication process and the specification of cutter and milling machine used is discussed in the next section.

2.2. Fabrication

Manufacturing of micro sized component, i.e., (1 to 999 µm) is called as microfabrication. In this work, metallic substrate is used for fabricating micro-channels. The copper is selected as metallic substrate because of its high thermal conductivity which mainly affects the heat transfer rate. Along with this benefit, copper is ductile hence shows good machinability and it is easily available at low cost. In mechanical machining process it is necessary that the substrate should be thicker component so that it should withstand the forces and vibrations generated during cutting action. First the CNC machining program is tested on aluminium block to check the correctness of the program. From the testing it is found that the corresponding carbide milling cutter can be used for the final fabrication.

Micro-milling is one of the subtractive manufacturing technologies. It is characterised by mechanical interaction of sharp tool with the workpiece material causing shearing of material along the defined path to get the specified geometry. The phenomenon of size effect comes in picture and it is defined as the specific energy generally increases with the decreasing depth of cut, this is because the effective rake angle increases as the depth of cut decreases, and the larger the rake angle, greater the specific energy.

In case of micro cutting the depth of cut is very small. The workpiece is mainly process by the cutting edge and compression. Hence it becomes dominant in the deformation of the workpiece material. This results in larger frictional force at the tool-chip interface and consequently in a greater cutting ratio.

The program was made to make one set of leaf pattern micro-channel and then the program was repeated for the 8 times to make complete set of micro-channels. Table 2 shows cutting tools Parameters used for fabrication and figure 1 shows the magnified image of cutting tool.

Table 2. Specification of cutting tool

| Tool Material         | Tungsten Carbide | Tungsten Carbide |
|-----------------------|------------------|------------------|
| Tool diameter (mm)    | 0.5              | 0.3              |
| Cutting length (mm)   | 2                | 2                |
| Tool length (mm)      | 38               | 38               |

Figure 1. Solid carbide end mill cutter under Zeiss Microscope at DKTE, Ichalkaranji (a) Two flute Carbide milling tool (b) Enlarged view of end mill cutter

The sequence of operation are as follows: Inlet well - Outlet well – primary veins – secondary veins.

The geometrical dimensions of LP-MCHS is shown and discussed in next section.

2.3 Geometry of micro-channel

The Figure 2 shows the geometry of the micro-channel model. This microchannel model consists of primary veins extending along the heat sink and secondary veins branching from primary veins. The primary channels are convergent or divergent. All secondary channels are convergent in nature, which helps to improve the rate of heat transfer and requires less pumping power. To ensure adequate supply of coolant by the secondary veins in a set of three main channels, the outlet of the central main channel is blocked. The central main channel is connected by main channels.
Table 4 presents the geometric dimensions of conventional micro-channel heat sinks and sheet patterns. The micro-channel test section comprises of 24 parallel rectangular micro-channels of width 0.5 mm, depth of 0.9 mm, length of 25 mm. The aspect ratio of micro-channel is 1.8. The fluid enters and distributes into the channels with the help of inlet well. Micro-channel is covered with transparent acrylic sheet of 6mm. The thermocouples are attached from the top of micro-channel such as one thermocouple at inlet section, and three thermocouples at outlet section. And four thermocouples attached at the bottom of the micro-channel for surface temperature measurement.

**Table 3. Geometrical Dimensions of micro-channel**

| Characteristic                        | Straight micro-channel | Leaf pattern micro-channel |
|---------------------------------------|------------------------|---------------------------|
| Material                              | Copper                 | Copper                    |
| Footprint width length (mm x mm)      | 25 x 25                | 25 x 25                   |
| Main channel width W\(_{ch}\) (µm)   | 500                    | 500                       |
| Channel Depth H\(_{ch}\) (µm)        | 900                    | 900                       |
| Aspect ratio                          | 1.8                    | 1.8                       |

Figure 3 shows the details of one set of micro-channels. Eight such sets are clubbed together to form the required design. Fabrication of the enhanced micro-channel design cannot be done using saw blade cutter as the inclined channels of 0.3 mm width are to be cut to create the leaf venation pattern. After studying the various alternatives of machining, it was decided to fabricate the micro-channels using end mill cutter. Figure 4 shows the actual fabricated leaf pattern MCHS. The methodology used for testing thermal performance of LP-MCHS is discussed in next section.
2.4 Methodology

The micro-channel are carved on the pure copper block because of its higher thermal conductivity. The fabrication of the micro-channel is carried out on 5 axis CNC machining centres. Then the leaf pattern MCHS was tested with Deionised (DI) water followed by the different nanofluids with 0.3 vol% and the particle size of 30-50 nm dispersed in DI water. The temperature readings for different heat fluxes ranging from 65 W/cm² to 200 W/cm² are taken with the varying flow rate of 100 ml/min to 900 ml/min. Surface temperature of the MCHS was taken with the K-type thermocouples. The inlet and outlet temperature were also taken with the K-type thermocouples. Flow rate was maintained and varied by the peristaltic pump. The outlet temp was also taken with the thermal camera for the cross verification. Nanofluid can enhance the heat transfer rate, but increases the pressure drop. Hence micro-channel further evaluated for performance evaluation analysis for the feasibility of use of nanofluid [14].

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PEC = \left( \frac{\frac{Nu(nf)}{Nu(bf)}}{\left( \frac{\Delta P(nf)}{\Delta P(bf)} \right)^{\frac{3}{2}} \right}
\]

The experimental setup used for the investigation of thermal performance of LP-MCHS is discussed in following section.

3. Experimental setup

A schematic view of the experimental setup which shows main components including a peristaltic pump (Masterflex L/S, Cole-Parmer make, variable speed digital driver.), micro-channel test section,
The data acquisition system (DEWE-Soft Data Acquisition System), Manometer for Differential Pressure, and a collecting tank is shown in figure 5.

Figure 5. The schematic of micro-channel test section

The DI water and Nanofluids is pumped through the experimental by the peristaltic pump. The flow rate can be measured and controlled from the pump control panel itself. Fluid will pass through the peristaltic pump followed by micro-channel. The U tube manometer is attached to the micro-channel in parallel connection. The thermocouples are used to measure surface temperature and fluid inlet and outlet temperature. They attached to the channel connected to the DAQ system and DAQ is connected to computer. The temperature readings are recorded in DEWE-Soft X3 software. Differential pressure readings are taken manually. The results of the experimental work is discussed in the next section.

4. Results and Discussion
4.1 Dimensional Inspection

After fabrication of LP-MCHS the dimensions are measured with the help of CMM. The dimensional inspection of micro-channel is shown in table 4.

Table 4. Dimensions by CMM

| Sr no | Part                          | Desired Dimensions (mm) | Actual Dimension (mm) | % Error |
|-------|-------------------------------|-------------------------|-----------------------|---------|
| 1     | Hole Diameter (Left)          | 14                      | 14.05                 | 0.35    |
| 2     | Hole Diameter (Right)         | 14                      | 14.08                 | 0.57    |
| 3     | Depth of hole (Left)          | 50                      | 50                    | 0       |
| 4     | Depth of hole (Right)         | 50                      | 52                    | 4       |
| 5     | Well depth                    | 2.5                     | 2.38                  | 4.8     |
| 6     | Well width (Closed end)       | 6.5                     | 6.34                  | 2.46    |
| 7     | Well width (open end)         | 6                       | 6.05                  | 0.83    |
Aspect ratio for the fabricated LP-MCHS is presented in next section.

4.2 Aspect Ratio

As aspect ratio increases, surface area available for heat transfer increases too which improves the heat transfer performance of micro-channel, so, it is desirable to produce high aspect ratio micro-channel to improve heat transfer performance. Table 6 shows the aspect of the fabricated LP-MCHS.

| Feature            | Depth (µm) | Width (µm) | Aspect Ratio |
|--------------------|------------|------------|--------------|
| LP-MCHS            | 900        | 500        | 1.8          |

The MRR of micro end milling is discussed in next section.

4.3 MRR

Micro end milling possesses higher MRR (0.6 mm³/min) which is higher than other fabrication processes such as EDM, chemical etching. MRR is directly related to the time required for fabrication of component. As MRR increases, the number of units produced increases. The material compatibility of micro end milling is discussed in next section.

4.4 Material Compatibility

In micro end milling process, material is removed by shearing and ploughing phenomenon. So soft and ductile materials can be effectively processed by micro end milling process, e.g. copper, aluminium, mild steel. Micro end milling is not suitable for machining of hard materials. The surface temperature variation in LP-MCHS is discussed in next section.

4.5 Surface Temp

The main objective of using micro-channels is to maintain the lower surface temperature. And from the results it is clearly observed that the leaf pattern MCHS is able to maintain the lower surface temperature for the same heat flux and flow rate when compared to conventional MCHS. The surface temperature decreases due to increase in flow rate, Reynolds number and the turbulence caused in micro-channel. Keblinski et al proposed the four possible mechanisms for heat transfer enhancement with nanofluids which are Brownian motion, ballistic phonon transport, liquid layering/ particle interference and nanoparticle clustering [18]. The heat transfer coefficient is discussed in next section.
4.6 Heat transfer coefficient

From the measured micro-channel wall temperatures, heat absorbed by the fluid and fluid bulk temperature, the local heat transfer coefficient was calculated. Then we have calculated the Reynolds number and Nusselt number. After comparing the ratio of Re and Nu, it was found that the leaf pattern MCHS shows greater ratio which is better for the better performance of MCHS. It is shown in graph 2. Here it was observed that the leaf pattern MCHS shows average enhancement of 17% in Reynolds number and 37% in Nusselt Number. The performance evaluation analysis is discussed in next section.

4.7 Performance Evaluation Analysis

From the experimental result it is clearly seen that the nanofluids enhances the heat transfer but tends to increase pressure drop. Thus, to analyse that, the nanofluid performance in terms of heat transfer enhancement was studied. Hence in this study the PEC values were considered in the comparison of the heat transfer characteristics of the nanofluids and water under equal pressure drops. Specifically, the
sample is good to use for the application if PEC>1, then the sample is regarded as unsuitable if PEC<1. PEC values for LP-MCHS at different heat flux is shown in graph 3.

![PEC for Leaf and Parallel Pattern Microchannel](image)

**Graph 3. Reynolds No Vs PEC values**

The PEC values were plotted as a function of Re. The leaf pattern MCHS achieved PEC>1 for almost all heat fluxes and flow rates. Hence, it was concluded that the leaf pattern MCHS is convenient to use and have more effectiveness than conventional MCHS. PEC values for LP-MCHS with SiO$_2$ nanofluid for different heat flux is shown in graph 4.

![0.3% SiO$_2$ (30-50 nm)](image)

**Graph 4. Reynolds No Vs PEC value for SiO2 nanofluid**

The SiO$_2$ nanofluid with leaf Pattern MCHS have achieved the PEC>1, hence the SiO$_2$ nanofluid was found suitable to use and having more effectiveness. For higher heat fluxes and flow rates, the PEC value is getting increased. For Al$_2$O$_3$ and CuO nanofluids the PEC<1, hence these nanofluids were not suitable to use with leaf pattern MCHS. The pressure drop developed in micro-channel is discussed in next section.

**4.8 Pressure Drop**

For the same Reynolds number, the leaf pattern MCHS shows the lower pressure drop. For all heat flux and flow rates, the pressure drop was less in case of leaf pattern MCHS when compared with
conventional pattern. The variation of the pressure drop was found to be increasing with the increase in Re which is shown in the graph 5. LP-MCHS shows 18% increase in pressure drop.

![Graph 5. Pressure drop variation with Reynolds no for Leaf and Parallel MCHS](image)

From the graph 6, it was found that the CuO and SiO$_2$ nanofluids shows very little variation in the pressure drop compared to the DI water. This little variation is because of the surfactant used while preparing the nanofluid. Al$_2$O$_3$ nanofluid shows very large difference in pressure drop.

![Graph 6. Pressure drop variation in LP-MCHS with nanofluids](image)

Al$_2$O$_3$ nanofluid have larger viscosity than the CuO and SiO$_2$ nanofluid for the same concentration and same particle size hence the pressure drop is larger in case of Al$_2$O$_3$ nanofluid than the other nanofluids [15]. The thermal conductivity is discussed in next section.

### 4.9 Thermal Conductivity

The variation of thermal conductivity and flow rate is shown in graph 7 and graph 8. Thermal conductivity is seen to be increasing with the increase in flow rate. Increase in flow rate increases the contact of more nanoparticles and due to higher thermal conductivity of nanoparticles the nanofluid is able to carry out more amount of heat compared to DI water. Also increase in flow rate increases the Re, and the increase in Re indirectly increases the thermal conductivity.
Graph 7. Variation of thermal conductivity of DI water with the variation of flow rate for Leaf and Parallel MCHS

Graph 8. Variation of thermal conductivity of nanofluids with the variation in flow rate

The thermal conductivity shows significant increase above the flow rate of 500 ml/min for nanofluids. Conclusion is presented in the next section.

5. Conclusion

• In micro end milling process, material is removed by shearing and ploughing phenomenon, hence only soft and ductile materials can be processed by micro-milling. It is not suitable for hard materials.
• Micro end milling is recommended for fabrication of MCHS up to 100 µm due to limitation on the size of tool.
• Micro end milling results in good surface finish, i.e., 5 to 6 µm Rt value.
• Higher aspect ratio increases the heat transfer area. Micro end milling results in moderate aspect ratio i.e., 2 to 3.
• The production cost increases linearly with number of components, hence best suited for job production.
• Following conclusions are drawn based on the thermal experimentation results
  • Leaf pattern MCHS able to maintain lower surface temperature due to the high Reynolds number, and increased Brownian motion.
  • Due to the availability of higher area and the higher aspect ratio of MCHS, it shows higher heat transfer coefficient with average enhancement of 17% in Reynolds number and 37% in Nusselt number.
  • For the same Reynolds number, the leaf pattern MCHS shows lower pressure drop. But for same flow rate LP-MCHS shows average 18% increase in pressure drop.
  • Presence of higher thermal conductivity nanoparticles shows enhancement in thermal conductivity of nanofluids.
  • SiO2 nanofluid shows lower pressure drop, higher thermal conductivity and higher PEC value, which indicates the suitability of SiO2 nanofluid for application.

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