Abstract

With the rapid growth of the miniaturization of electronic devices, the heat dissipation from these miniaturized electronic devices becomes the major challenge in the current scenario. If this heat dissipation is not done effectively, then this will affect the life of the device and other electronic devices adversely which will result in decreased efficiency. Micro-channel is one of the best options for removing heat from electronic devices, due to its compact size and higher thermal efficiency. There are Conventional and Non-Conventional processes of machining a micro element. But however Conventional processes pose certain problems. Microchannels are primarily used in biomedical devices and microfluidic applications. Fabrication of microchannels has always been a tough task using conventional manufacturing technologies. Various types of materials are in use for fabricating microchannels in different types of applications including metals, polymers and ceramics. A number of methods are in use for fabricating different types of microchannels. This report reveals a broad spectrum of different processes used for fabricating microchannels and best processes which can be used. Currently, Micro-EDM is a good option for fabricating microchannels. In this article, material selection is done which can withstand high temperature ranges in the industries to fabricate the micro channels and it has been fabricated with the help of EDM using minimum tool diameter. The effect of the same on the surface roughness of the workpiece is also discussed.

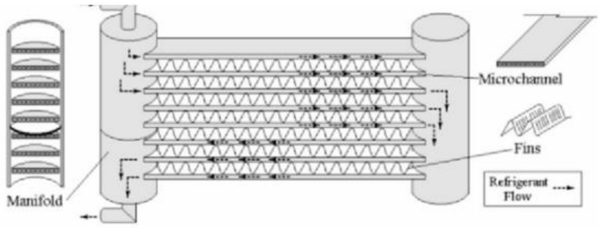
1. Introduction

Fabrication of microchannels is an important aspect in the context of development of microfluidic devices. A number of fabrication techniques have been developed and adopted during the years for different types of applications and materials. These processes include conventional time-consuming technologies such as photolithography, etching and ultrafast laser processing. Depending on the applications of microchannel-based devices, different types of materials are preferred. The ever-increasing demand of these microchannel-based devices has also led to the development of several other hybrid techniques to manufacture microchannels in an efficient and effective way. Basically, microchannels are created on polymeric, glass, silicon as well as on metallic substrates. While most of the polymeric and glass substrates are used in biomedical and chemical devices, the silicon-based substrates and metallic substrates are used for electronics and mechanical engineering related applications. However, fabricating these microchannels on such substrates in large numbers has always been a difficult task for manufacturers because of the precision required in such products. Lack of suitable technologies for fabricating these devices has hindered the further development of microchannel-based devices. New methods for faster and cheaper production of these devices must be explored for sustainable development in this area.

1.1 Micro channels

The concept of the microchannel was proposed for the first time by researchers Tuckerman and Pease of Stanford Electronics Laboratories in 1981. The microchannel features an innovative design where cooling is intensified due to fast heat removal. In most cases when cooling requirements are over 100 W/cm^2, they cannot be easily met either by simple air-cooling or water-cooling systems. Then microchannels are used for the same. Microchannel is a channel with a hydraulic-dimension below 1 mm.

In microchannels there is a development of heat sinks directly embedded back of the heat source for uniform heat flux removal. This heat sink is usually made out of silicon, with a silicon dioxide layer to keep the component electrically insulated. Very narrow rectangular channels are formed with fins in the micrometer range that ensure uniform heat flux removal by circulating cold fluid through the rectangular microchannels.



Courtesy: Next generation micro-channel heat exchangers

1.2 Fabrication Methods of Micro channels

1. **Micro-Mechanical cutting** - With the advent of high-precision machining, mechanical micro--cutting has emerged as a key technology for creating microchannels. The mechanical micro-cutting process is particularly suitable for fabricating individual personalized components rather than large batch size, which is largely indispensable for the current market situations. With a high level of machining accuracy of ultra-precision machine tools, good surface finish and form accuracy can be achieved. The high machining speed of micro-cutting is another advantage over micro manufacturing technologies. Moreover, it can fabricate a large number of materials, such as steel, aluminum, brass, plastics and polymers. Unlike micro-laser beam machining and lithographic techniques, it does not require a very expensive setup, which enables the fabrication of miniatures at an economically reasonable cost. Micro-milling and micro turning are the two most used mechanical cutting processes. Recently, multi-cutter based micro-milling processes have been studied and found to be more economic and faster when compared to other contemporary micro-machining processes. In this process, a composite cutting tool has been used and the depths of the microchannels were found to have inconsistency in depth. Also, it has been observed that the corners were not sharp instead curved which may result in creating void during sealing or bonding process. Microchannels have also been slotted on stainless steel using thin slotting cutters and top burr height was found to be predominantly controlled by feed and cutting speed, and the top burr width was strongly influenced by cutting depth, feed and cutting speed. The significant disadvantages of mechanical cutting processes are wear of cutting tools, generation of cracks due to mechanical stress and long processing time.

2. **Wet and dry etching** - Etching is the most widely used subtractive technique for micromachining. Etching can be described as pattern transfer by chemical/physical removal of material from a substrate, often in a pattern defined by a protective mask layer such as a resist or an oxide. In dry etching, the surface is etched in the gas or vapor phase, physically by ion bombardment, chemically by a chemical reaction through a reactive species at the surface or by combined physical or chemical mechanisms. Sometimes a combination of wet and dry etching has also been used as a tool for micromachining. Wet etching technique results in non-parallel walls on glass

surface and as the channel etches deeper, the walls are also etched. Electrochemical etching in any acid/solution is dependent on etchant concentration as well as etching time. Alternatively, dry etching techniques such as powder blasting and plasma or deep reactive ion etching have been proved to be much more effective than wet etching. Synchrotron radiation stimulated etching has been performed on a PDMS base material to etch patterns having lateral dimensions as precise as 21–24mm and 32–35mm by varying pattern mask sizes. Etching is also used as a secondary process in various microchannel fabrication methods. Wet chemical etching has been found to be suitable for metallic substrates that react well with chemicals. Dry etching has been mostly utilized for glass and polymer base materials due to requirements of lower reactive energy.

3. **Lithography** - Lithography is one of the major fabrication techniques used to fabricate microchannels. Lithography enables the fabrication of many different types of topography which is hard to be generated using other fabrication techniques. Yao et al demonstrated a simple lithography technique to fabricate microchannels using simple processing steps as spin coating, baking, exposing and development. The most widely used form of lithography is photolithography. In the microchannel fabricating industries, pattern transfer from mask onto thin films is done majorly by photolithography. Lithography-based simple approach has been adopted by Abdelgawad et al for fabricating circular microchannels on PDMS of various diameters ranging from 5 to 200mm in diameter. Pal and Sato developed and demonstrated a fabrication method for various shapes of microfluidic channels and microstructures in one-step photolithography. Soft lithography has been used to create microchannels on PDMS. In this process, PDMS is cured over a patterned photoresist on the surface of a silicon wafer. The cured PDMS is then removed and then joined to a glass surface to create closed microchannels. A significant benefit of using this fabrication technique is that the polymers can be easily bonded to each other or to glass or plastic substrate using conformal contact. Disadvantages using soft lithography based on PDMS include the following: (1) shrinkage during cutting ranges to more than 1% and swelling also takes place due to nonpolar solvents such as toluene and hexane, (2) softness of the substrate material limits the achievable aspect ratio through sagging and (3) deformation of the soft elastomeric stamps. In recent times, X-ray lithography has also been used to create polymer microchannels. In contrast with ion-beam lithography and

electron beam lithography, X-ray lithography does not require the presence of vacuum and clean room facilities, which makes this process cheaper and faster. The majority of PDMS based microchannels have been widely fabricated using this process. PMMA absorbs most of the X-rays and is therefore best suited to be manufactured using this method. This process can produce high aspect ratio microchannels in PMMA.

4. **Embossing and imprinting** - For the first time, the embossing technique for replicating microstructures was applied in the Institute for Microstructure technology of Forschungszentrum Karlsruhe during the 1990s as a secondary process of LIGA. In the course of due time, this technique has been developed to be an independent technique for micro feature fabrication. The embossing technology that is particularly useful in the replication process generally involves a high degree of temperature equivalent to polymer molding temperature and therefore called hot embossing. For imprinting on plastic substrates, wires are also used. In recent studies, silicon stamps have been found to be a better imprinting tool for the fabrication of microchannel-based devices. A drawing of the channels using a computer-aided design (CAD) tool is replicated to a photomask for fabricating silicon stamps. If the required features have sizes more than 20mm, a high contrast resolution transparency is used instead of photomask. A silicon micromachined wafer can also be used to create stamps out of metal. A metal electroform, made of nickel, is produced using micromachined silicon wafer as the master. The first electroform will be a mirror image of the master, while the second electroform will be a replica of the original master. To fabricate a microchannel by using either embossing or imprinting, generally a cleaned plastic material is dried and placed over the silicon stamp or metal stamp. The embossing load, temperature and embossing time significantly affect the accuracy of microchannel width and depth. The plastic material along with the stamp is then placed in a hydraulic press and a force is applied for sometime typically less than 10 min. Imprinting can also be carried out at room temperature and very high mechanical pressure or vice versa, that is, at high temperature and low mechanical pressure. Imprinting at very high pressure significantly reduces the fabrication time and also increases the life of substrate material. However, when imprinting at very high pressure, the microchannel characteristics are dependent on parameters such as pressure, contact time and room temperature. Many common plastics have been successfully imprinted or hot embossed

with excellent device-to-device reproducibility. These include PS, PETG, PMMA, PVC and PC.

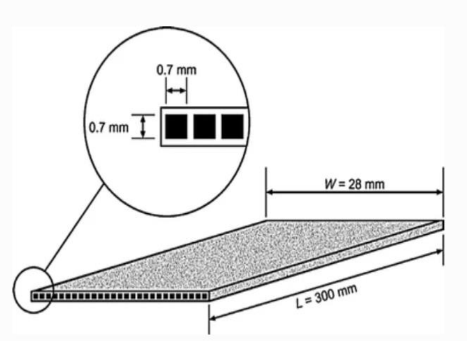
5. **Injection molding** - Injection molding as a technique for fabricating microstructures was developed due to the low fabrication cost and the associated molding technique is called micro-molding technique. Micro-molding technique is also called precision molding technique because of its high precision output. The injection unit of micro injection molding machine consists of various sub-devices such as heater, injection piston, shut-off valve, extrusion screw, dosing sleeve, nozzles and sprues. Injection molding, which was developed for the fabrication of macro-, medium- and large-scale fabrication, has been adopted for the necessities of micro component fabrication by different researchers. Researchers at ACLARA (ACLARA Biosciences Inc, CA, USA) were the first to use injection molding techniques for fabricating microchannels. In the injection process, the chosen polymer is required to have low viscosity and good contact with the mold walls to produce well-defined features. The parameters that affect the quality of microchannels in the injection molding process include mold temperature and relaxation of polymer after release. By suitably adjusting and optimizing the processing time, temperature and relaxation behavior of polymer, the microchannel parts can be produced with high precision. Injection molding has been used to produce microchannels out of different polymers such as PC75 and PMMA. The major disadvantage of injection molding is the presence of weld lines in the fabrication of complex parts. Weld lines occur as the mold gets filled. The presence of a weld line causes reduction in strength of macro as well as micro parts. The foremost advantage of using injection molding process when compared to imprinting or hot embossing is that performance elements can be embedded into plastic during the process. Matteucci et al utilized the method for fabricating multi-level microfluidic chips by means of silicon dry etching, electroplating and injection molding for applications in the fields of electrochemistry, cell trapping and DNA elongation. The chips ranged in sizes of channel depths between 100 nm and 100mm and depth-to-width aspect ratios ranged between 1/200 and 2.

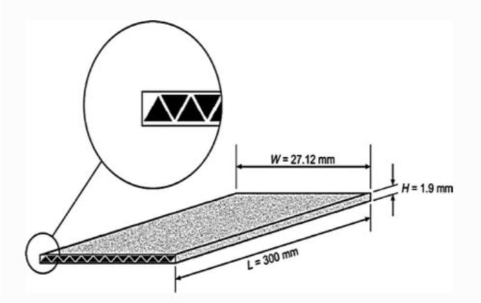
1.3 Application of Micro channels

Microchannel heat exchangers have applications in several important and diverse fields including: aerospace; automotive; bioengineering; cooling of gas turbine blades, power and process industries; refrigeration and air conditioning; infrared detectors and powerful laser mirrors and superconductors; microelectronics; and thermal control of film deposition. The advantages of microchannel heat exchangers include high volumetric heat flux, compactness for space-critical applications, robust design, effective flow distribution, and modest pressure drops. This chapter will cover selected industrial examples for microchannel heat exchangers, microchannel heat pipes, and microchannel heat plates.

1. Automotive and Aerospace

Microchannel heat exchangers have at least one fluid flow passage with typical dimensions between 1 μm and 1 mm and have great potential in process intensification of various industrial areas (Fan and Luo 2008). There are many possible channel geometries for microchannel heat exchangers, two types of which are the most widely used in compact heat exchanger designs for automotive and aerospace applications. High-temperature and compact micro heat exchangers can be manufactured using ceramic tape technology (Schmitt et al. 2005), which uses fused ceramic layers to create channels with dimensions below 1 mm (Ponyavin et al. 2008). Metal-based microchannel heat exchangers are also of current interest because of the combination of high heat transfer performance and improved mechanical integrity (Mei et al. 2008). Figure shows a manufactured, flat extruded multi channel aluminum heat exchanger With the aim of reducing size and cost, microchannel heat exchangers are now able to achieve performances for surface area per unit volume as high as 1500 m2/m3. Their fin geometry is rather complex, as they are specially designed to augment the heat transfer level on both the liquid and air sides with a balanced resistance between the two sides. Several experimental correlations for compact heat exchangers are available, but their current technical limitations may not allow for the practical design and optimization of new microchannel heat exchangers. In recent years major progress in microchannel heat exchangers has been made by the automotive, aerospace, chemical reactor, and cryogenic industries. Thermal duty and energy efficiency requirements have increased during this period, while space constraints have become more restrictive. The trend has been toward greater heat transfer rates per unit volume. The hot side of the evaporators in these applications is generally air, gas, or a condensing vapor. With advances in the air-side fin geometry, heat transfer coefficients have increased, as have surface area densities. As the air-side heat transfer resistance has decreased, more aggressive heat transfer designs have been sought on the evaporating side, resulting in the use of microchannel flow passages on the liquid side (evaporating or condensing or single-phase regimes). The major changes in recent evaporator and condenser designs for automotive and other compact heat exchanger applications involve the use of individual, small-hydraulic-diameter flow passages arranged in a multichannel configuration on the liquid side. The ability to efficiently transfer heat between fluids using lightweight, compact heat exchangers is important in a variety of applications, such as automobile radiators, air conditioning, and aerospace applications. Microchannel heat exchangers are well suited to these applications due to the microchannels' compactness, lightness, and high heat transfer performance.Car radiators employ a cross flow design that allows a sufficient mass flow rate of air through the radiator while using only the stagnation pressure associated with the motion of the automobile. The common measure of performance for car radiators is the heat transfer/frontal area normalized by the difference in inlet temperatures of the coolant (water–glycol) and the air. For conventional car radiators, 0.31 W/Kcm2 of heat transfer/frontal area can be obtained between the air and the coolant (Webb and Farrell 1990; Parrino et al. 1994). However, these radiators are extremely thick (1–2 cm) compared with the thickness of the micro heat exchanger described here (0.1–0.2 cm). Harris et al. (2000) designed and fabricated a cross flow micro heat exchanger that transfers heat from coolant (water–glycol) to air. They used a manufacturing process that combines LIGA micromachining, traditional precision micromachining, and bonding. They compared the thermal performances of plastic, ceramic, and aluminum microchannel heat exchangers with those of conventional car radiators. The cross flow microchannel heat exchanger can transfer more heat/volume or mass than existing conventional heat exchangers within the design constraints. This can be important in a wide range of applications (automotive, home heating, and aerospace). Figure shows a plate-fin evaporator geometry commonly seen in compact refrigerant evaporators for automotive and aerospace applications. As seen in the figure, fins are placed between microchannel flow slabs, and the arrangement is brazed together in a special oven. Figure shows a manufactured aluminum microchannel heat exchanger.





courtesy : https://www.steeltubesindia.net/

2. Chemical Reactors

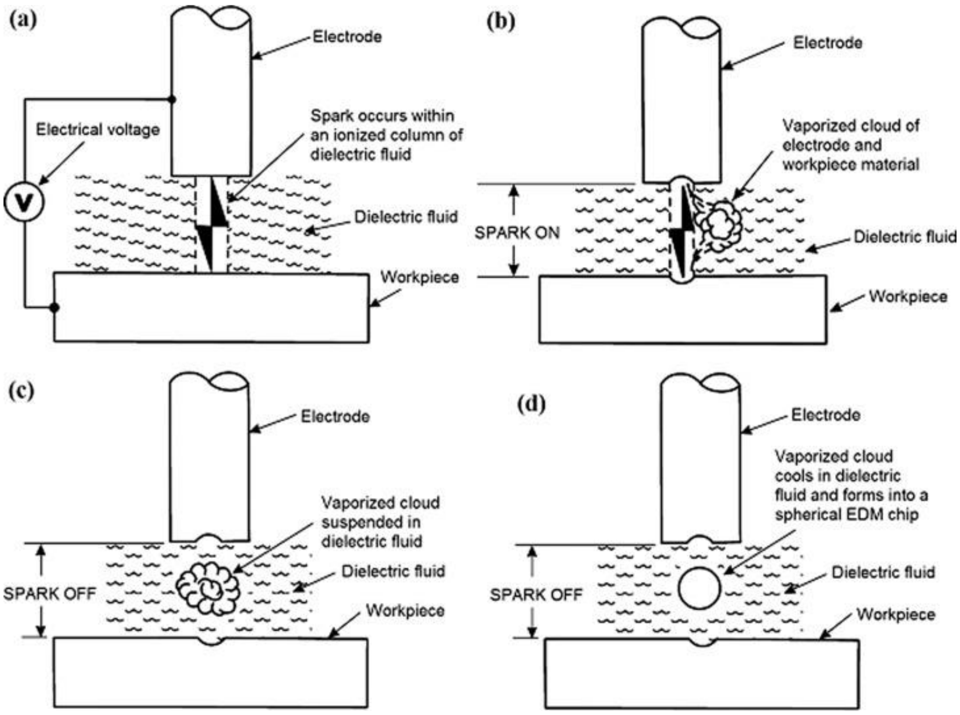
Microchannel chemical processing technology is an emerging field with applications in most industrial processes due to its excellent mixing capabilities, controlled reaction environment, and energy efficiency. This technology offers improvements in existing processes and will enable new processes to become cost effective. The basic microchannel reactor design is based on the flow between parallel platelets coated with a catalyst. The large aspect ratio of the channel provides extensive surface area in a small volume. Microchannel reactors have been developed based on ceramic substrates as well as metal substrates. In both types of reactors, multiple layers coated with catalytic material are bonded, forming a monolithic structure. An added benefit of a layered pattern is the ability to easily scale up or down by adjusting the number of layers. This provides great flexibility in the design, since if the production capacity needs to be changed, there is no need to redesign the reactor.

3. Microchannel heat pipes

Because advanced electronic equipment is decreasing in size, the circuit integration per unit area must increase, which in turn contributes to a rapid increase of heat generation rates. As a consequence, the operating temperatures of electronic components may exceed the desired temperature level, and if heat is not sufficiently removed, the failure rate of the equipment will cause an accelerated system failure. Due to the compactness of most modern electronic components, cooling devices also need to be small but highly effective in heat transport. Wicked heat pipes (or capillary-force-driven heat pipes) evaporate and condense the working fluid and include complicated wick structures to circulate the working fluid. Although wicked heat pipes are prominent passive heat transfer devices, their performances decrease significantly as the thickness decreases below a certain limit—for instance, 2–3 mm. This is because there is a noticeable temperature drop across the flow direction when the vapor space volume is limited. Hence, microchannel technology has been applied to the fabrication of micro heat pipes. Many experiments have been conducted on microchannel heat pipes. Cotter (1984) first introduced the concept of a micro heat pipe that did not include a complicated wick structure.

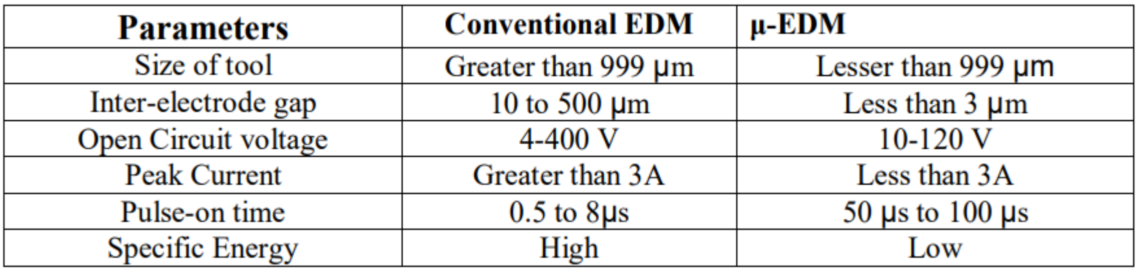
1.4 Introduction to Micro EDM Process

Electro Discharge Machining (EDM) is an electrothermal non-traditional no physical cutting force between the tool and the workpiece where material is removed using thermal energy by generating a spark between two opposite polarities to erode the work-piece. The material is removed by a series of rapidly recurring spark discharges between the two electrodes under the presence of dielectric fluid which results in high temperature of order of 8,000 0C to 12,000 0C. With the advancement in material science which have led to new engineering metallic materials, composite materials and high tech ceramics having good mechanical properties, Edm has proved to be a very effective process to machine metals irrespective of their hardness and different mechanical properties. Change in thermal properties has very little effect on the process. μ-EDM capability to machine microstructures of varying complexity levels on difficult to cut metals and alloys. The term micro-machining defines the processes that have machine dimensions in the range of 1 μm to 999 μm. μ- EDM has gained importance because of its ability to produce stress free micro sized cavities of desired shapes on conducting and semiconducting materials. Even the principle of EDM and μ- EDM are same but there are differences due to scaling effect Table 1 shows the major differences between the conventional EDM and μ-EDM.



courtesy: https://www.sciencedirect.com/topics/materials-science/electrical-discharge-machining

1.4.1 Major differences between EDM and micro EDM



Parameters	**Conventional EDM**	**µ-EDM**
Size of tool	Greater than 999 µm	Lesser than 999 µm
Inter-electrode gap	10 to 500 µm	Less than 3 µm
Open Circuit voltage	4-400 V	10-120 V
Peak Current	Greater than 3A	Less than 3A
Pulse-on time	0.5 to 8µs	50 µs to 100 µs
Specific Energy	High	Low

Basic principle:

The basic principle followed is the conversion of electrical energy into thermal energy through a series of recurring spark discharges between the two electrodes. During this process two electrodes are kept at a certain distance and ignition voltage of 200V is given and breakdown of dielectric medium occurs which results in electric spark and increases the temperature ,the increased temperature creates thermal erosion and hence material is removed.

Components of EDM:

1. Work-piece-almost all the conductive material can be worked by EDM.

2. Tool Electrode-depended on the shape of the cavity.

3. Dielectric fluid- Electrode & workpiece submersed into the dielectric fluid.

4. Servo system-The servo system is commanded by signals from the gap voltage sensor system in the power supply and controls the feed of electrode & work-piece to precisely match the rate of material removal.

5. Power supply-The power supply is an important part of any EDM system. It transforms the alternating current from the main utility supply into the pulse direct current (DC) required to produce the spark discharge at the machining gap.

6. DC pulse generator- The DC pulse generator is responsible for supplying pulses at a certain voltage and current for a specific amount of time.

EDM Machine

1.4.2 Micro EDM Process Parameters

1. **Pulse On Time:** The time interval during which the spark (electron discharge) occurs between electrode (wire) and the workpiece once the breakdown voltage of the dielectric is reached causing its ionization.
2. **Pulse-off time or pulse interval:** The time duration between consecutive sparks during which there is no current supply to the electrodes and deionization of dielectric takes place.
3. **Peak current** is the maximum current available for each pulse from the power supply/generator.
4. **Discharge Voltage:** the voltage supplied is approximately 50 to 300 volts because higher voltage is not suitable for high precision machining. Therefore, the EDM discharge gap is about 0.005 - 1.0mm.

2.0 Literature Survey

Extensive literature survey was done by going through many papers and the findings are tabulated for easy understanding as below

SL No.	Title of the Paper	Author and Affiliation	Highlights of the paper
1	Optimization of Nd:YAG laser for microchannels fabrication in alumina ceramic (2019)	Muneer Khan Mohammed, Usama Umera Abdulrahman Al-Ahmari	● Microchannels are fabricated in alumina ceramic using Nd:YAG direct laser writing ● Microchannels having width of 200µm and different depths are machined by varying three parameters viz. intensity of laser beam, pulse overlap and scan strategy
2	Effect of a protective coating on the surface integrity of a microchannel produced by micro ultrasonic machining (2021)	JunZhao, Jin feng Huang, Yong chao Xiang, Rui Wang, Xinqiang Xu, ShimingJi, Wei Hang	● In micro-ultrasonic machining (µUSM), slight lateral vibration at the end of the tool inevitably occurs due to tool manufacturing installation errors and mechanical system vibrations ● These vibrations cause overcutting and edge breakage, creating undesirable effects on heat transfer and flow deflection ● By changing the slurry viscosity and feed rate, the lateral amplitude of the WC tool can be effectively suppressed to improve the over-cutting phenomenon.

3	Analysis of micro-scale EDM process (2005)	Z. Katz · C.J. Tibbles	● It makes use of dimensionless groups related and relevant to micro electro discharges and their effect on metal removal during the process. ● The dielectric forms a channelof partially ionized gas. ● The discharge duration is between 250 ns and 10 µs. ● The results show that the size of the electrode does have an effect on the discharge process. ● This is mainly due to the change in the electric field intensity influenced by the electrode sizes at the micro EDM level.
4	Accuracy Improvement and Precision Measurement on Micro-EDM (2020)	Amit Kumar Singh, Siddhartha Kar and Promod Kumar Patowari	● Tool wear cannot be diminished entirely in µEDM, but measures can be taken to minimize it. ● The first and foremost necessity is the selection of processing parameters of µEDM such that tool wear is minimum without impacting machining efficiency and surface quality.

2.0 Literature Survey (contd.)

SL No.	Title of the Paper	Author and Affiliation	Highlights of the paper
5	Experimental Study on Micro-deburring of Micro-grooves by Micro-EDM (2019)	Elumalai Boominathan and S. Gowri in affiliation with Easwari Engineering CollegeChennaiIndia, College of Engineering, AU Chennai India	● This This article describes the experiments conducted to remove top burrs in micro-channels produced by micro-milling. ● The correlation between burr size and feed rate is studied. The burr formation in the down-milling side always tends to be higher than that on the up-milled side. ● Moderate feed rate (1.25 μm/tooth) produces better surface quality and less top burrs.
6	Micro-EDM Drilling (2019)	S. N. B. Oliaei Muhammad P. Jahan and Asma Perveen in affiliation with Department of Mechanical Engineering Atilim University,Ankara,Turkey Department of Mechanical and Manufacturing Engineering,Miami University,Oxford,USA	● This chapter provides a concise overview of the micro-EDM drilling process. ● It presents working principle of the micro-EDM drilling as well as both operating and performance parameters ● Micro-EDM drilling provides comparative advantages over conventional process ● This chapter also covers micro-EDM drilling for difficult-to-cut materials such as steel alloys, Ti alloys and Ni alloys.

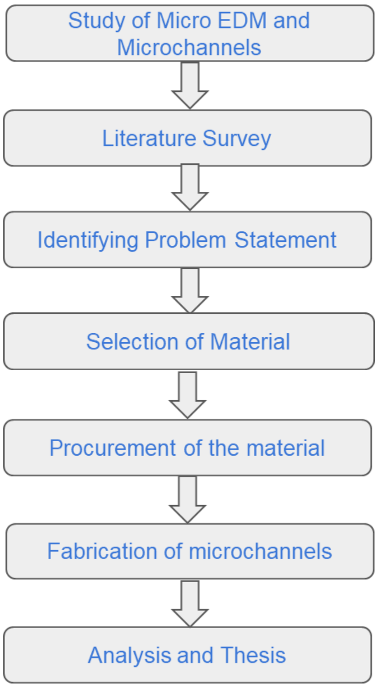
SL No.	Title of the Paper	Author and Affiliation	Highlights of the paper
7	Micro-electro-Discharge Machining (2019)	Francesco Modica, Valeria Marrocco Irene Fassi in affiliation with Institute of Industrial Technology and Automation,Consiglio Nazionale delle Ricerche,Milan,Italy	● This chapter provides a concise overview of micro-EDM process, principle and different application of the same. ● Fundamental issues related to micro-EDM are addressed and some common strategies for the evaluation of machining performance are presented. ● It is a contactless technology for the manufacturing of materials featuring electro-conductivity, high hardness and strength. The functioning principle is based on a series of discrete electrical discharges occurring in between two electrodes, the tool and the workpiece.

3.1 Objective

The aim of the project is to generate the micro channels using Micro EDM process or using Micro Tool in EDM and to conduct experiments to find the effect of surface roughness.

3.2 Methodology

The below methodology was followed along the course of the project.



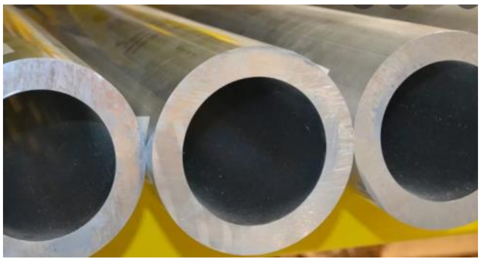
4.1 Inconel 625

The material for the fabrication of microchannels was selected to be Inconel 625. Inconel Alloy 625 is a nickel-based superalloy that possesses high strength properties and resistance to elevated temperatures. It also demonstrates remarkable protection against corrosion and oxidation. Its ability to withstand high stress and a wide range of temperatures, both in and out of water, as well as being able to resist corrosion while being exposed to highly acidic environments makes it a fitting choice for nuclear and marine applications.

Inconel 625 was developed in the 1960s with the purpose of creating a material that could be used for steam-line piping. Some modifications were made to its original composition that have enabled it to be even more creep-resistant and weldable. Because of this, the uses of Inconel 625 have expanded into a wide range of industries such as the chemical processing industry, and for marine and nuclear applications to make pumps and valves and other high pressure equipment.

Because of the metal's high Niobium (Nb) levels as well as its exposure to harsh environments and high temperatures, there was concern about the weldability of Inconel 625. Studies were therefore conducted to test the metal's weldability, tensile strength and creep resistance, and Inconel 625 was found to be an ideal choice for welding. Other well known names for Inconel 625 are Haynes 625, Nickelvac 625, Nicrofer 6020, Altemp 625 and Chronic 625

Inconel 625 is an alloy of nickel containing chromium and iron, resistant to corrosion at high temperatures. This superalloy is composed mainly of nickel (58% min.) followed by chromium, and molybdenum, niobium, iron, tantalum, cobalt, and trace amounts of manganese, silicon, aluminum, and titanium.



courtesy: https://www.specialmetals.com/

4.2 Properties of Inconel 625

- **Exceptional material strength :** The strength of Inconel 625 lies not only in its nickel-chromium base but also in the hardening mechanism of niobium and molybdenum. The alloy matrix is strengthened by the interaction of niobium with molybdenum that offers high strength without the need for precipitation-hardening treatment. The tensile strength of this superalloy is 690 MPa, while its yield strength measures 275 MPa.

- **High temperature resistance :** With a melting point of about 1300°C and a thermal expansion coefficient of 1.28 x 10^{-5} 1/K (at 20°C), Inconel 625 resists a wide range of temperature extremes from cryogenic to extremely high.

  At high temperatures in the presence of oxidizing agents, the titanium and niobium compositions of the oxide film on Inconel 625 increase drastically to form a natural protective layer in the material.

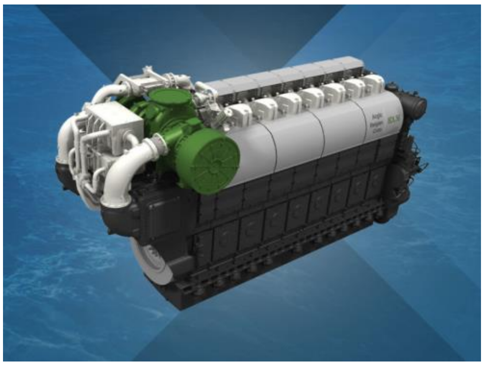
- **Corrosion resistance :** The unique combination of its components makes Inconel 625 highly resistant to corrosive substances. This is the reason why this superalloy works excellently under high saline seawater, and more so in milder environments such as fresh water and standard atmospheric conditions.

- **High level of fabricability :** Inconel 625 was designed to have better weldability than earlier alloys, with no signs of cracking when exposed to strain and temperature changes post-welding. Its high creep resistance and yield strength make this superalloy a good choice for tubes, piping, and plant equipment that require welding.

Basically, Inconel is an ideal material whenever extreme temperature and chemical resistance are a must, and for any process where temperature highs would normally degrade the oxidation resistance of other metals.

4.3 Applications of Inconel 625

- **Marine applications** - Owing to its high corrosion resistance especially pitting and crevice resistance, Inconel 625 is an ideal for high saline, underwater applications. The material is used as propeller blades for boats, mooring lines to secure ships and similar vessels, accessories and fixtures for submarines, and parts for oceanographic equipment.



(Main Propulsion Unit)

courtesy : https://www.abc-engines.com/

- **Aerospace equipment** - The superalloy has also found its way into the aircraft industry, particularly for exhaust equipment, fuel lines, heat exchanger casings, and rocket components. This is because Inconel 625 works well even in extreme temperatures under high stress.

courtesy: https://avionalloys.com/inconel/

- **Nuclear technology** - Its strength as well as its resistance to corrosion and stress make Inconel 625 a suitable component of nuclear reactors, particularly in the control rod and reactor core. Nuclear systems also generally involve high temperatures beyond 650°C, in which the strength of Inconel 625 can withstand.

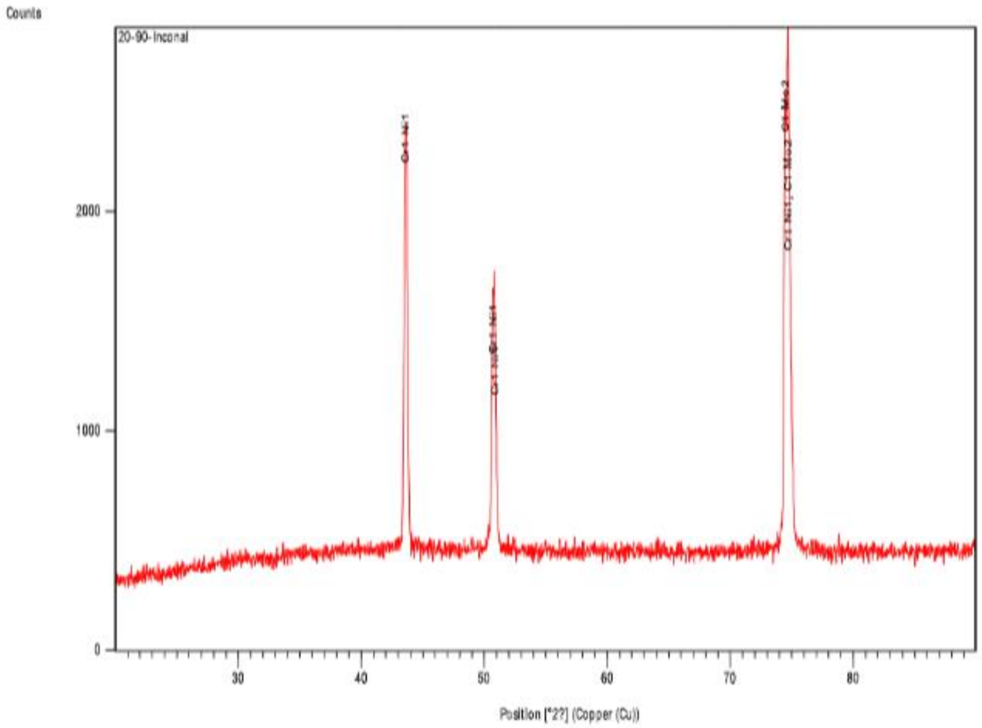
courtesy: https://upload.wikimedia.org

- **Industrial processing** - Because the alloy is conveniently fabricable and resistant to heat and corrosion, it is a useful ingredient in the production of manufacturing equipment such as vessels, heat exchangers, valves, and fluid distribution systems. Its excellent weldability also makes it a suitable component for pipes and tubes used in manufacturing plants.

courtesy: https://www.aesteiron.com/

5.1 XRD Analysis

X-Ray diffraction analysis (XRD) is a nondestructive technique that provides detailed information about the crystallographic structure, chemical composition, and physical properties of a material. It is based on the constructive interference of monochromatic X-rays and a crystalline sample. X-rays are shorter wavelength electromagnetic radiation that are generated when electrically charged particles with sufficient energy are decelerated. In XRD, the generated X-rays are collimated and directed to a nanomaterial sample, where the interaction of the incident rays with the sample produces a diffracted ray, which is then detected, processed, and counted. The intensity of the diffracted rays scattered at different angles of material are plotted to display a diffraction pattern. The peaks of the XRD pattern play a vital role in the identification of the phases as well as the properties of the nanoparticles. In this case, the width of the peak would reveal the average crystalline size of a nanoparticle where sharp peaks indicate a large size of crystallites, whereas broad peaks indicate smaller crystallites.



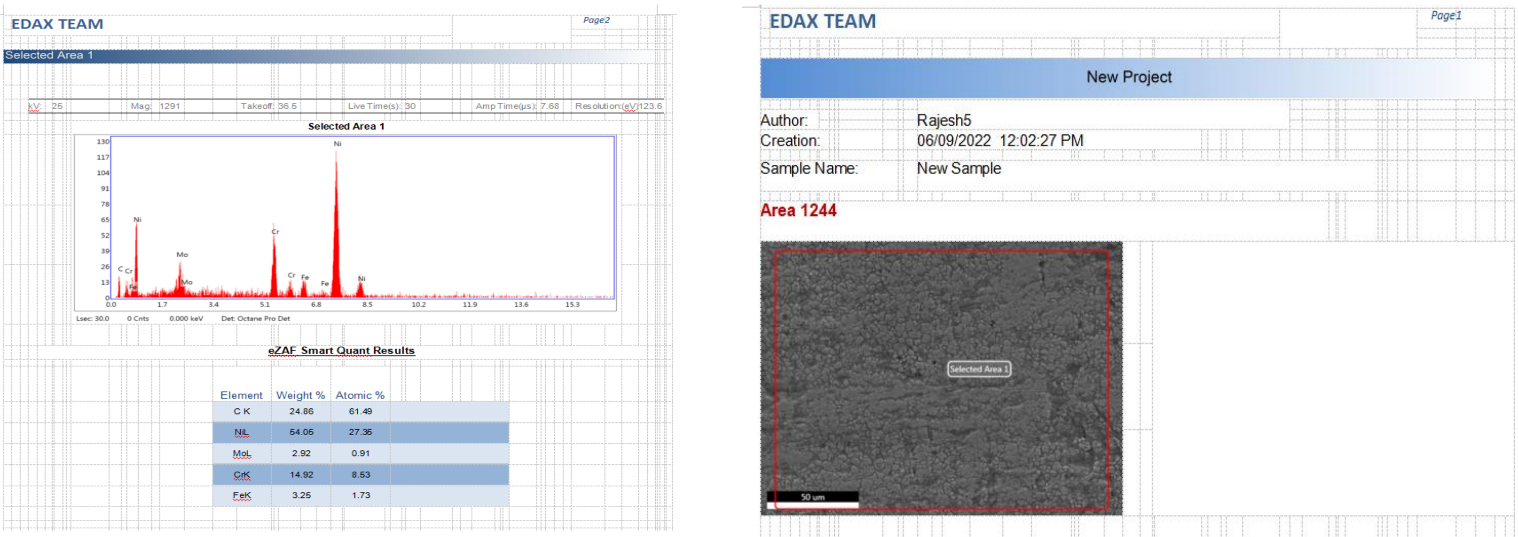
XRD Analysis Graph

The below image gives the result of the test conducted. From the above test, the type of crystal structure along with the composition is obtained. The test also indicates the intensity (count/sec) of the crystals present in the material.

5.2 EDAX Analysis

Energy-dispersive X-ray spectroscopy (EDS, EDX, EDXS or XEDS), sometimes called energy dispersive X-ray analysis (EDXA or EDAX) or energy dispersive X-ray microanalysis (EDXMA), is an analytical technique used for the elemental analysis or chemical characterization of a sample. It relies on an interaction of some source of X-ray excitation and a sample. Its characterization capabilities are due in large part to the fundamental principle that each element has a unique atomic structure allowing a unique set of peaks on its electromagnetic emission spectrum (which is the main principle of spectroscopy). The peak positions are predicted by Moseley's law with accuracy much better than the experimental resolution of a typical EDX instrument.

To stimulate the emission of characteristic X-rays from a specimen a beam of electrons is focused into the sample being studied. At rest, an atom within the sample contains ground state (or unexcited) electrons in discrete energy levels or electron shells bound to the nucleus. The incident beam may excite an electron in an inner shell, ejecting it from the shell while creating an electron hole where the electron was. An electron from an outer, higher-energy shell then fills the hole, and the difference in energy between the higher-energy shell and the lower energy shell may be released in the form of an X-ray. The number and energy of the X-rays emitted from a specimen can be measured by an energy-dispersive spectrometer. As the energies of the X-rays are characteristic of the difference in energy between the two shells and of the atomic structure of the emitting element, EDS allows the elemental composition of the specimen to be measured. The results of the tests are shown below.



EDAX TEAM Page2

Selected Area 1

kV: 25 Mag: 1291 Takeoff: 36.5 Live Time(s): 30 Amp Time(µs): 7.68 Resolution:(eV)123.6

Selected Area 1

Lsec: 30.0 0 Cnts 0.000 keV Det: Octane Pro Det

eZAF Smart Quant Results

Element	Weight %	Atomic %
C K	24.86	61.49
NiL	54.05	27.35
MoL	2.92	0.91
CrK	14.92	8.53
FeK	3.25	1.73

EDAX TEAM Page1

New Project

Author: Rajesh5
Creation: 06/09/2022 12:02:27 PM
Sample Name: New Sample

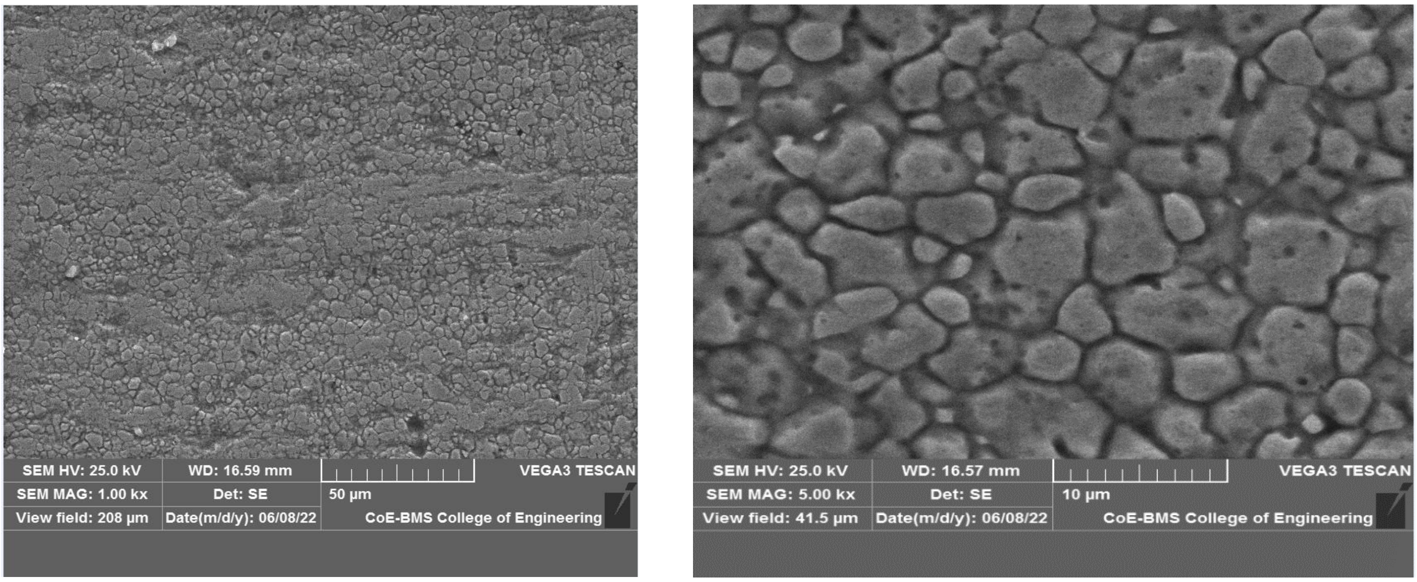
Area 1244

EDAX Analysis Graph

From the above test that was conducted, the composition of the material was obtained and from the results of the test it was concluded that the material is Inconel 625.

5.3 SEM Analysis

Scanning Electron Microscopy (SEM) is a test process that scans a sample with an electron beam to produce a magnified image for analysis. The method is also known as SEM analysis and SEM microscopy, and is used very effectively in microanalysis and failure analysis of solid inorganic materials. Electron microscopy is performed at high magnifications, generates high-resolution images and precisely measures very small features and objects.

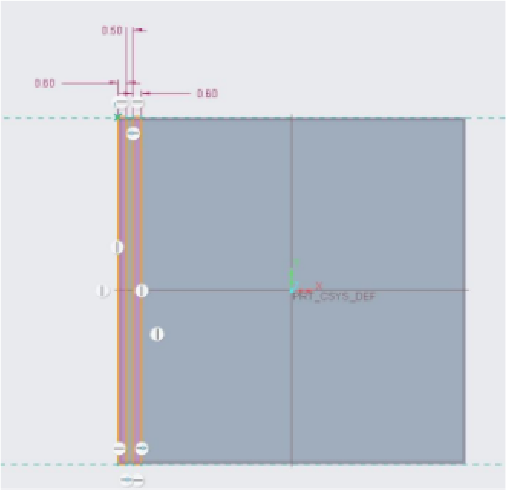


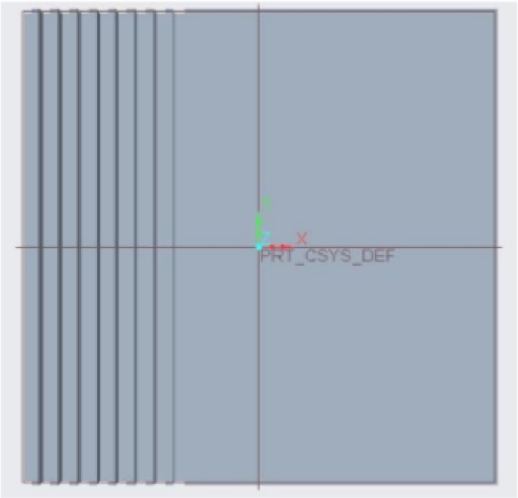
SEM Analysis

From the above test, the magnified view of the surface of the sample was used to investigate the microstructures and it was concluded that there were no abnormalities/irregularities or cracks, dents on the surface of the sample.

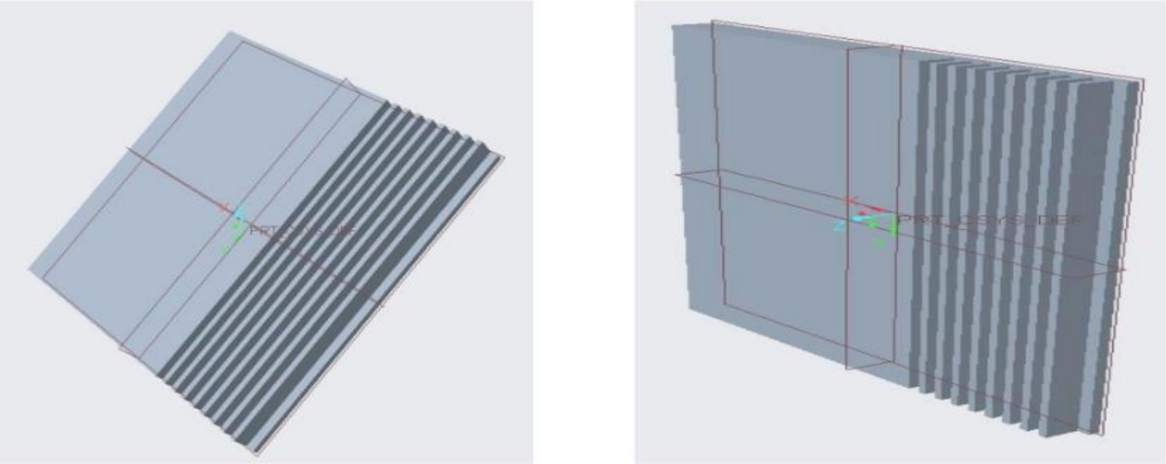
6.0 CAD Model

The CAD model of the micro-channel along with the dimensions are given below:

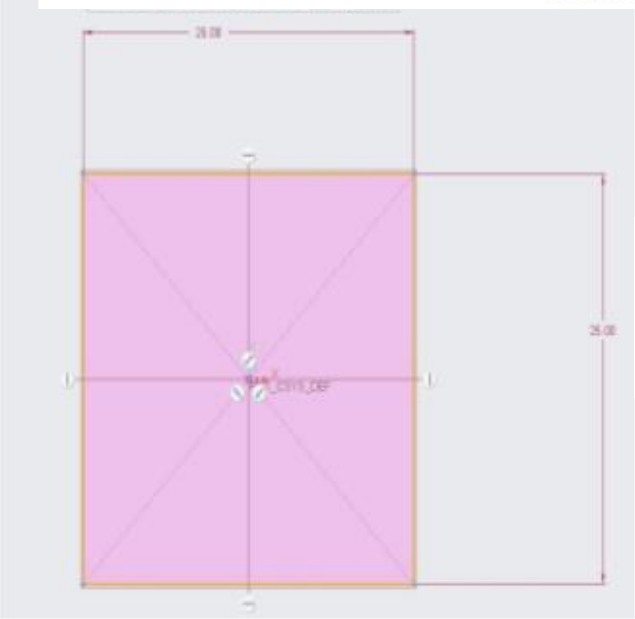


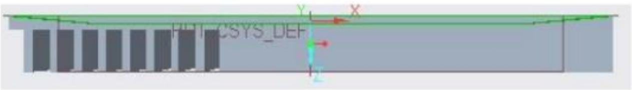


Top View



isometric views

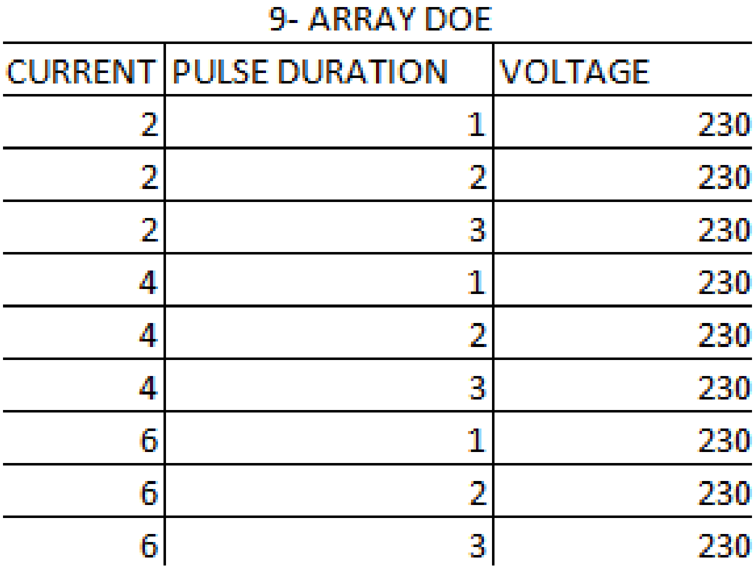




Front View

7.0 Design of Experiments

Design of experiments (DOE) is defined as a branch of applied statistics that deals with planning, conducting, analyzing, and interpreting controlled tests to evaluate the factors that control the value of a parameter or group of parameters. DOE is a powerful data collection and analysis tool that can be used in a variety of experimental situations. It allows for multiple input factors to be manipulated, determining their effect on a desired output (response). By manipulating multiple inputs at the same time, DOE can identify important interactions that may be missed when experimenting with one factor at a time. All possible combinations can be investigated (full factorial) or only a portion of the possible combinations (fractional factorial). A strategically planned and executed experiment may provide a great deal of information about the effect on a response variable due to one or more factors. DOE was obtained by following Taguchi method with the help of MiniTab software. Taguchi method is a broadly accepted method of DOE, which has proven in producing high-quality products at subsequently low cost.



9- ARRAY DOE

CURRENT	PULSE DURATION	VOLTAGE
2	1	230
2	2	230
2	3	230
4	1	230
4	2	230
4	3	230
6	1	230
6	2	230
6	3	230

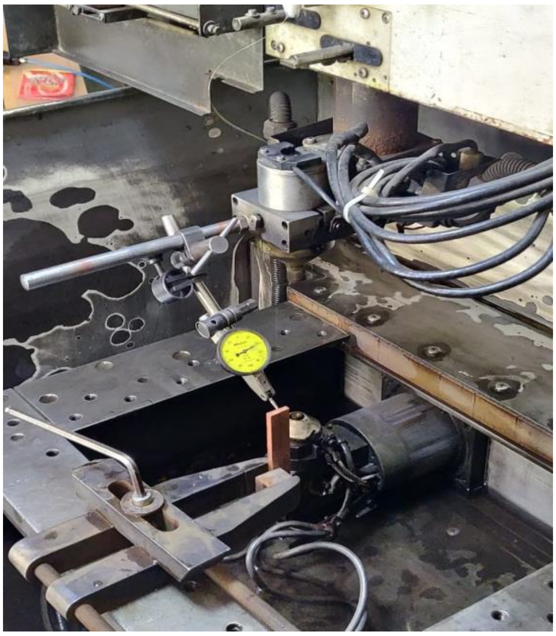
8.1 Experimental Details

A sheet piece of (25 mm x 25 mm x 2 mm) of Inconel 625 has been used as a workpiece material for the current experiment which was cut to desired dimension using an abrasive water jet.

Percentage chemical composition of workpiece is as follow:

Elements wt%	**Inconel 625 plate**
C	**0.058**
Si	**0.283**
Mn	**0.36**
P	**0.008**
S	**0.011**
Fe	**4.451**
Mo	**8.195**
W	**0.1**
Al	**0.005**
Co	**0.114**
Nb	**3.4**
Ti	**0.22**
V	**0.005**
Cr	**21.407**
Ni	**bal.**

8.2 Experiment using EDM

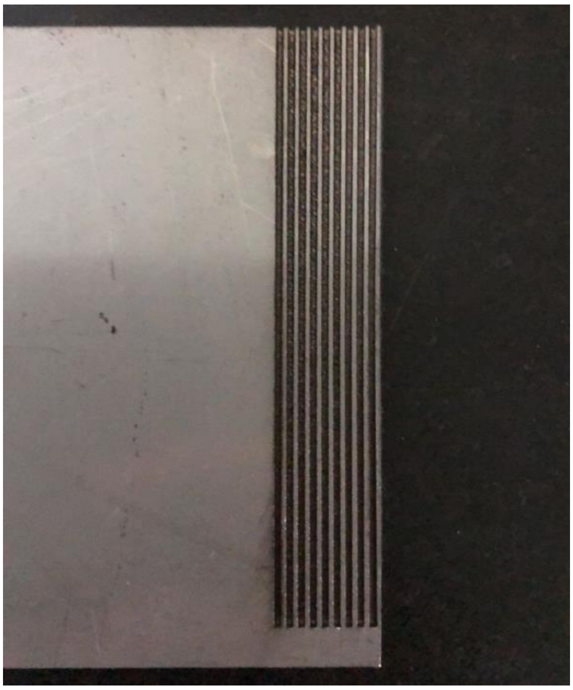


Constants during the experiment were :

1. Workpiece polarity: Anode i.e positive
2. Dielectric fluid: Ipol 450
3. Capacitance: 300 pf
4. Voltage: 230 volts

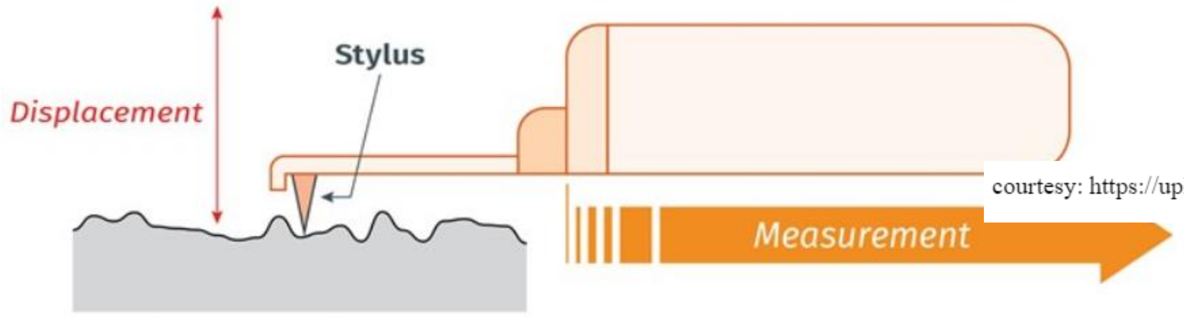
Variables are Current and Pulse Duration from the DOE Array.

8.3 The Machined Product

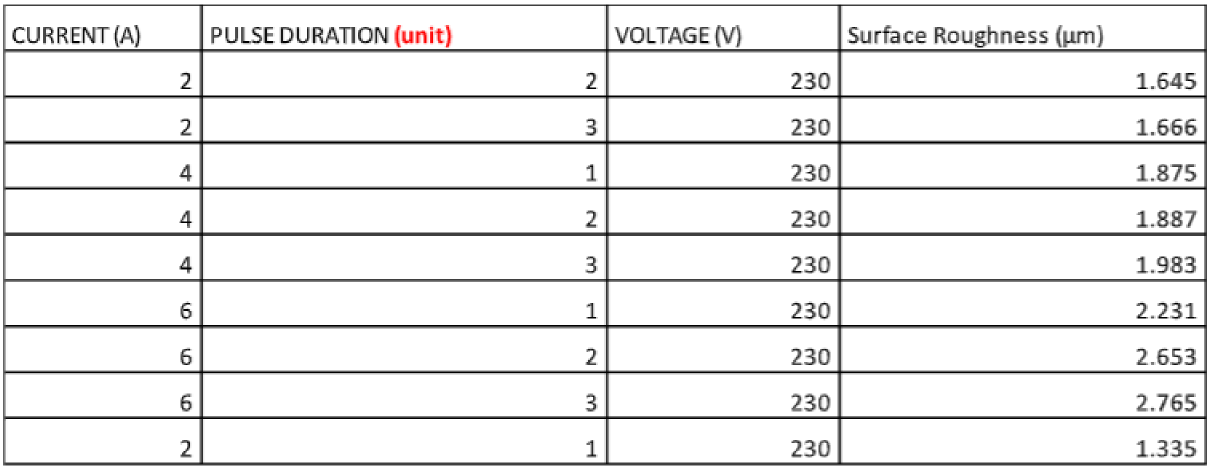


9.0 Surface Roughness Test using Optical Profilometer

Profilometry is a technique used to extract topographical data from a surface. This can be a single point, a line scan or even a full three dimensional scan. The purpose of profilometry is to get surface morphology, step heights and surface roughness. This can be done using a physical probe or by using light. Optical profilometry uses light instead of a physical probe. This can be done a number of ways. The key component to this technique is directing the light in a way that it can detect the surface in 3D. A profilometer/roughness gauge is a measuring device used to capture 2D or 3D data on the surface of a sample in order to measure roughness, flatness, or other critical 2D and 3D dimensions. These instruments are placed on the workpiece to be measured, and the stylus is traversed automatically at rates somewhere around 1 millimeter per second. Tip radius for handheld profilometers can be as small as a few micrometers, and they can accurately measure Ra down to 0.005 µm and Rz down to 0.02 µm.

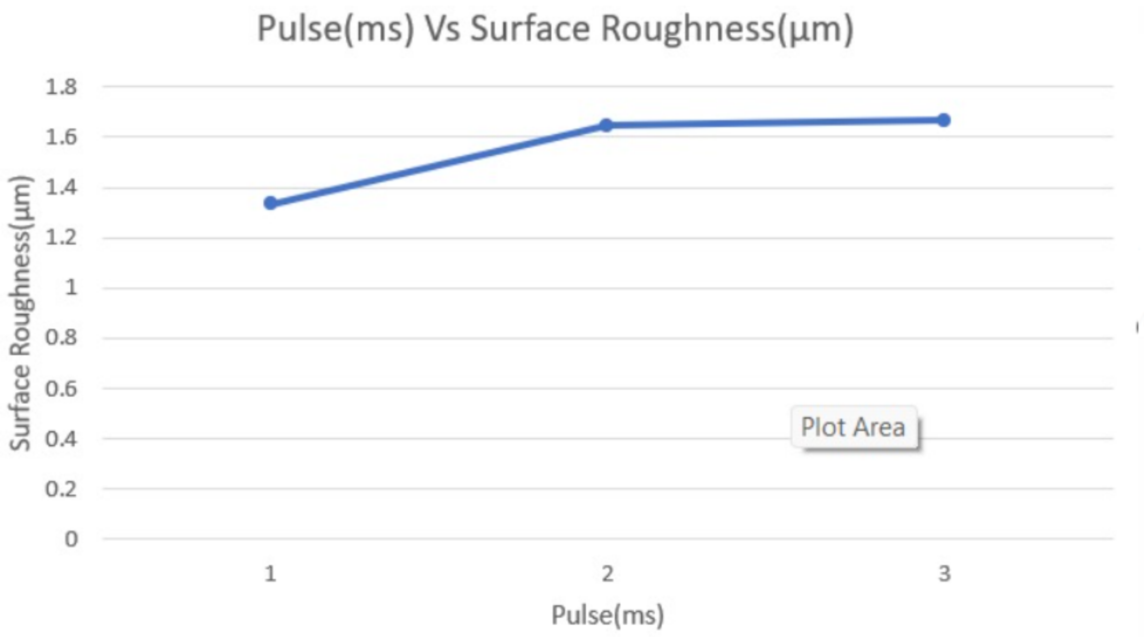


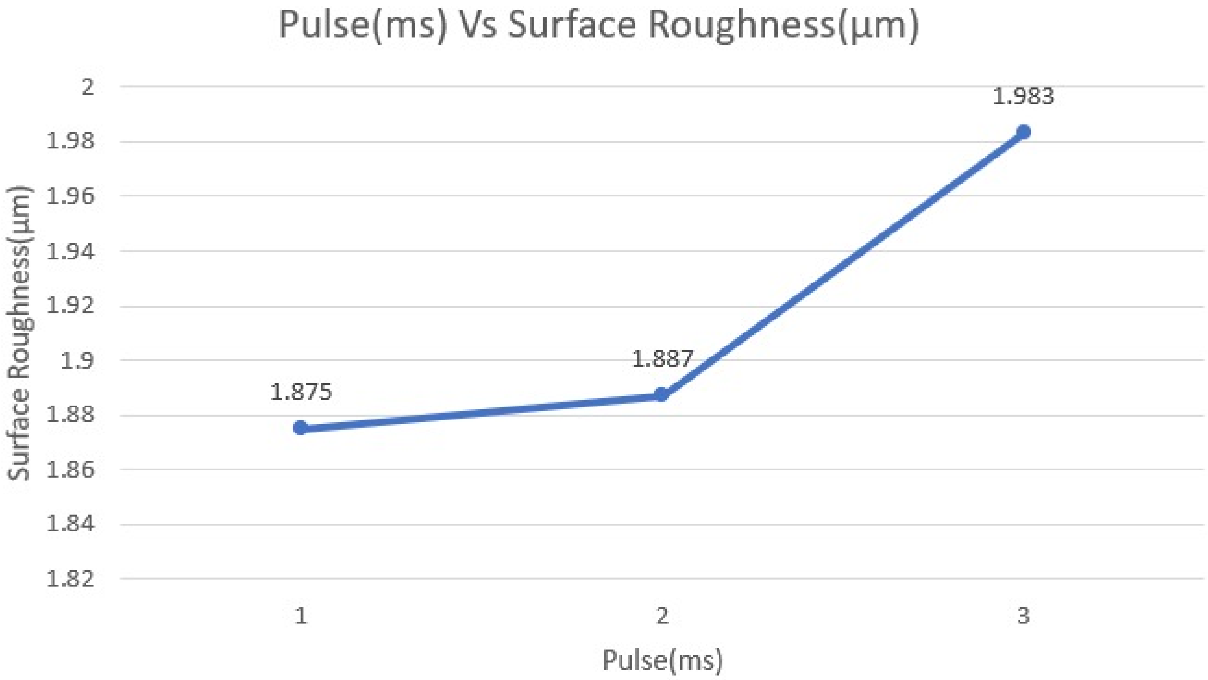
courtesy: https://upload.wikimedia.org

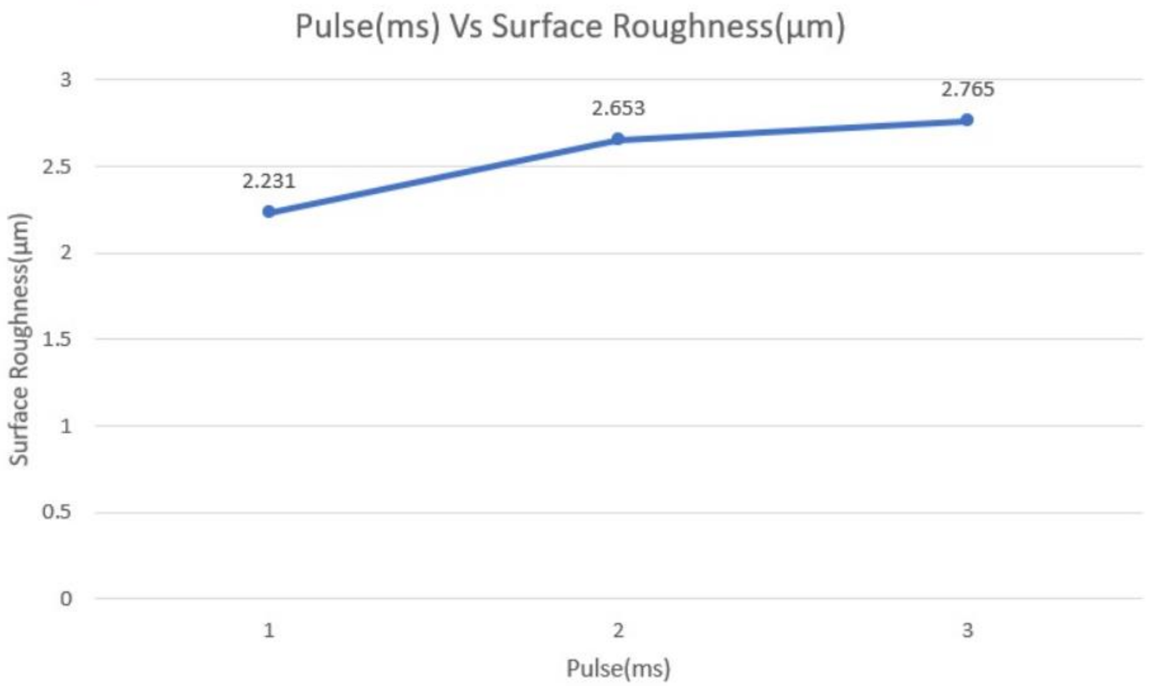


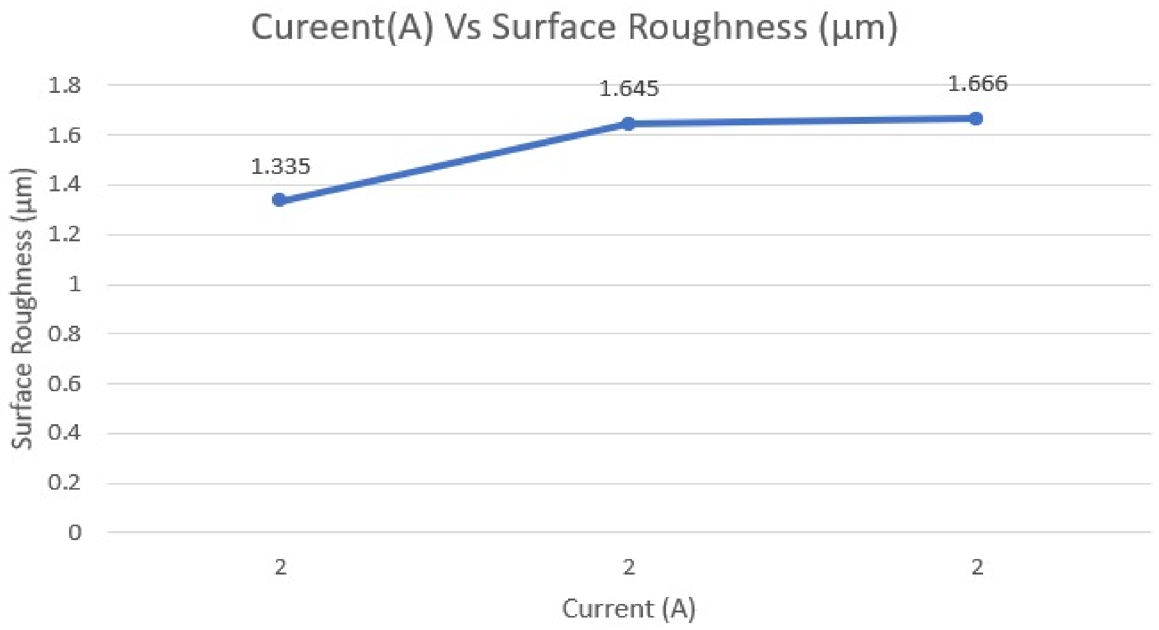
CURRENT (A)	PULSE DURATION (unit)	VOLTAGE (V)	Surface Roughness (µm)
2	2	230	1.645
2	3	230	1.666
4	1	230	1.875
4	2	230	1.887
4	3	230	1.983
6	1	230	2.231
6	2	230	2.653
6	3	230	2.765
2	1	230	1.335

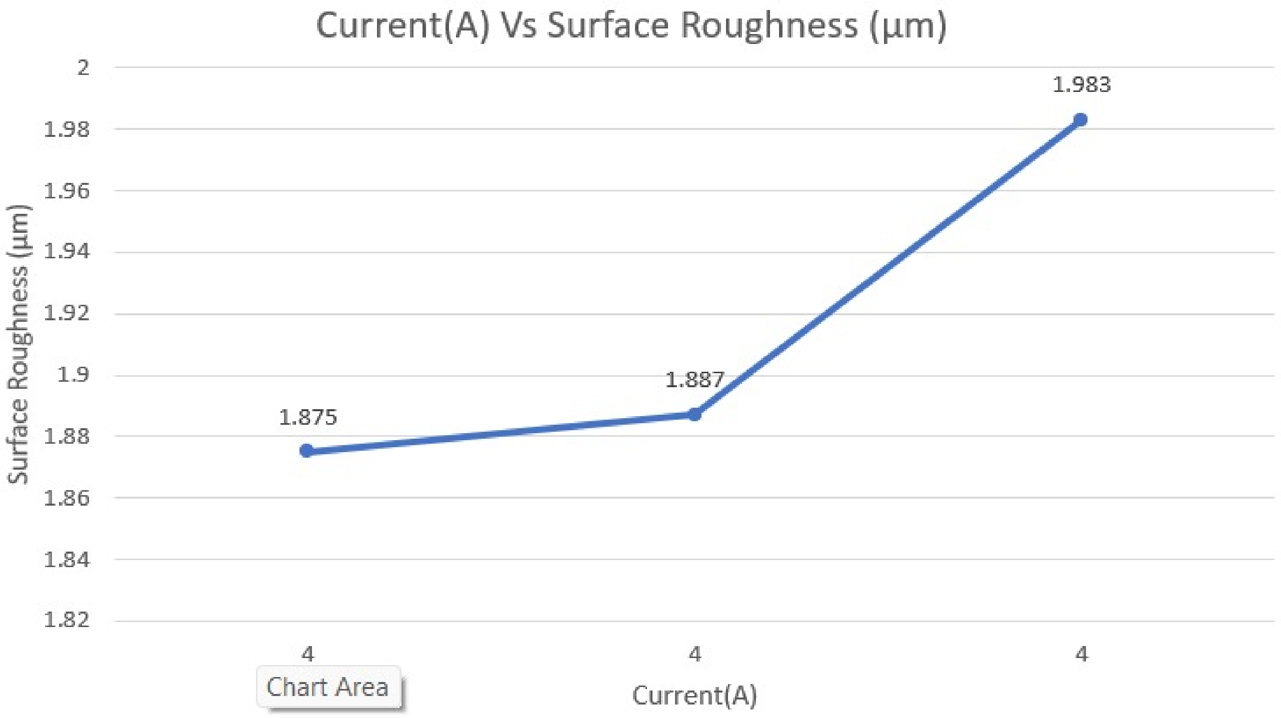
10.2 Graphs on Results:

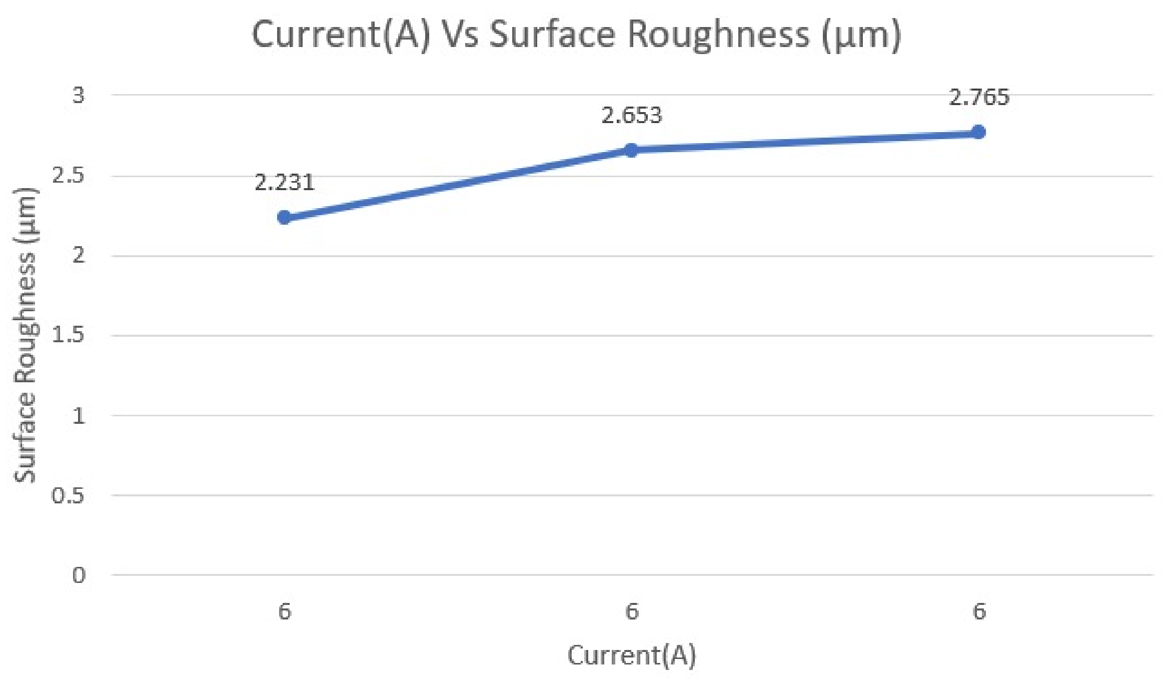


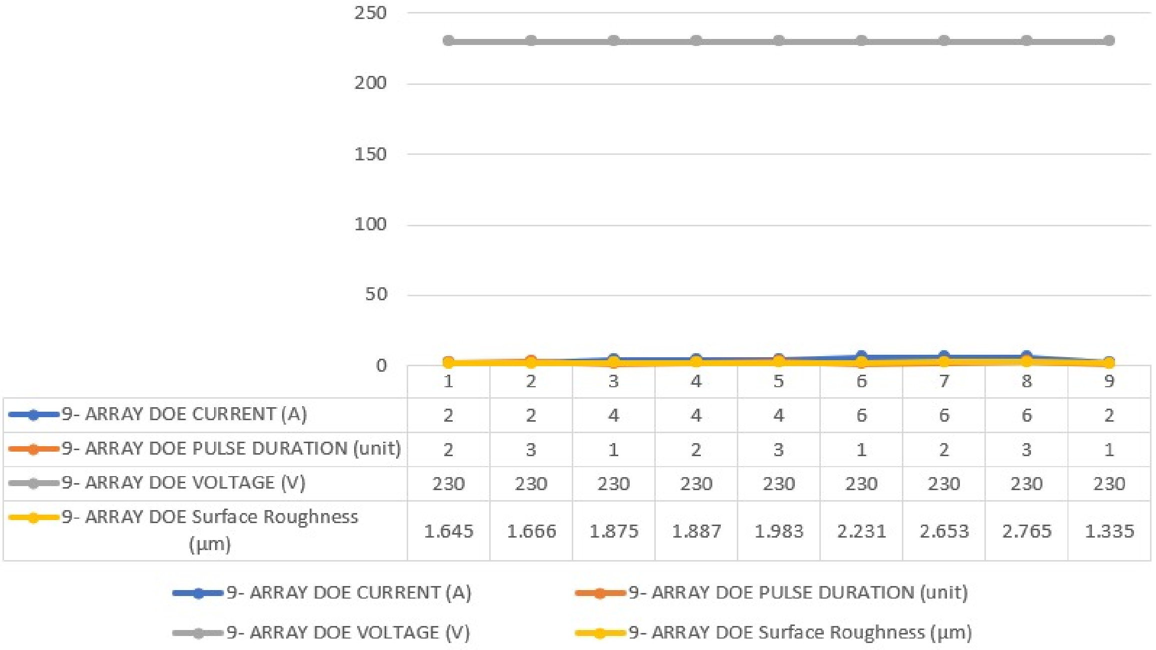

Pulse(ms) Vs Surface Roughness(µm)
Surface Roughness(µm)
2
1.98
1.96
1.94
1.92
1.9
1.88
1.86
1.84
1.82
1.875
1.887
1.983
1
2
3
Pulse(ms)


Pulse(ms) Vs Surface Roughness(µm)
Surface Roughness(µm)
3
2.5
2
1.5
1
0.5
0
2.231
2.653
2.765
1
2
3
Pulse(ms)


Cureent(A) Vs Surface Roughness (µm)
Surface Roughness (µm)
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1.335
1.645
1.666
2
2
2
Current (A)


Current(A) Vs Surface Roughness (µm)
Surface Roughness (µm)
2
1.98
1.96
1.94
1.92
1.9
1.88
1.86
1.84
1.82
1.875
1.887
1.983
4
4
4
Chart Area
Current(A)





	1	2	3	4	5	6	7	8	9
9- ARRAY DOE CURRENT (A)	2	2	4	4	4	6	6	6	2
9- ARRAY DOE PULSE DURATION (unit)	2	3	1	2	3	1	2	3	1
9- ARRAY DOE VOLTAGE (V)	230	230	230	230	230	230	230	230	230
9- ARRAY DOE Surface Roughness (µm)	1.645	1.666	1.875	1.887	1.983	2.231	2.653	2.765	1.335

10.3 Conclusion on the Results:

The increase in the surface roughness of the microchannel will increase the overall flow resistance and Nusselt number. However, increasing surface roughness not only increases the heat transfer performance, but also introduces a large flow resistance, which makes the friction coefficient rise sharply. From the graphs that have been obtained, the result that can be concluded is that the surface finish increases drastically with increase in the current (Ampere). It was also observed that when current is kept constant and the pulse duration is varied, then the surface finish also increases along with the increase of pulse duration.

11.0 References

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