Fabrication of Glass Serpentine Microchannels using Rotary Ultrasonic Milling

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by

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July, 2017

CERTIFICATE

I hereby declare that the thesis entitled **"Fabrication of Glass Serpentine Microchannels using Rotary Ultrasonic Milling"** is an authentic record of my work carried out as requirements for the award of the degree of **Master of Engineering** in **Production Engineering** at **Thapar University, Patiala** under the supervision of **Dr. Vivek Jain** and **Dr. Dheeraj Gupta**, Associate Professor, Mechanical Engineering Department, Thapar University, Patiala during July, 2015 to July, 2017. No part of the matter embodied in this report has been submitted to any other university or institute for the award of any degree.

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Dedicated to:

My parents

Mr. Ambrish Jain & Mrs. Archna Jain

Acknowledgement

Words are often less to reveals one's deep regards with an understanding that work like this can never be the outcome of a single person. I take this opportunity to express my profound sense of gratitude and respect to all those who directly or indirectly helped me through the duration of this work.

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Abstract

Microchannel is the basic structure in any microfluidic device to control, deliver, manipulate and store the liquid. These microchannels are typically made of silicon, metal, or glass and often feature circular, rectangular or trapezoidal cross sections, ranging in terms of the hydraulic diameter from 1 µm to 1000 µm. Various lithographic micromachining techniques are widely used to fabricate the microchannels on such type of substrates. Additive manufacturing is one of the silicon micromachining techniques of producing parts by successive deposition of layers of material as in the case with rapid prototyping.

A new technique for creating serpentine microchannels has been produced on soda lime glass with the help of Rotary Ultrasonic Milling (RUM). Microchannels are the basic structure for any microfluidic device to handle, deliver, operate and to collect the liquid. There are various technologies by which these microchannels are being fabricated but they are more time consuming. With RUM any type of complex profile can be easily made in lesser time and that too with good precision. In this paper serpentine microchannels have been fabricated characterized by scanning electron microscope and profile projector.

The various output parameters were observed from the fabrication of the serpentine microchannels like tool wear, surface roughness and edge chipping. The best results which were obtained by the input variables were spindle speed 4500 rpm, feed rate 3 mm/min and amplitude 20 µm.

Key words: Microchannels; Glass; Micromachining; Rotary Ultrasonic Milling.

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Chapter 1

Introduction

Microchannels are characterized as the channels with measurements under 1 millimeter and more than 1 micron. Design and fabrication of microchannels have become an important aspect with respect to the evolution of microfluidic devices. For the unique type of materials and applications, various types of fabrication techniques have been evolved and adopted. Microchannels can be created with two different techniques which are given as under:

1. Miniaturized Traditional Technique
2. Modern Technique

Traditional technique consists of conventional machining which is miniaturized to use them in micro regime e.g. Micro EDM, Stereo lithographic fabrication, electroforming, molding, ultrasonic and water jet machining, electroforming are key processes of this type.

Modern Technique mainly contains Focused Ion Beam, Laser Machining, Isotropic and anisotropic wet chemical etching are some examples of silicon-based fabrication. LIGA (Lithography, Galvan forming, Electroplating, and Molding) is a fabrication process based on lost wax molding technique. It is used for micro-structures fabrication of high aspect ratio with compromising to their surface finish and quality. Hybrid fabrication e.g. wafer bonding in which different etched shaped wafers are bonded together to form micro-channels.

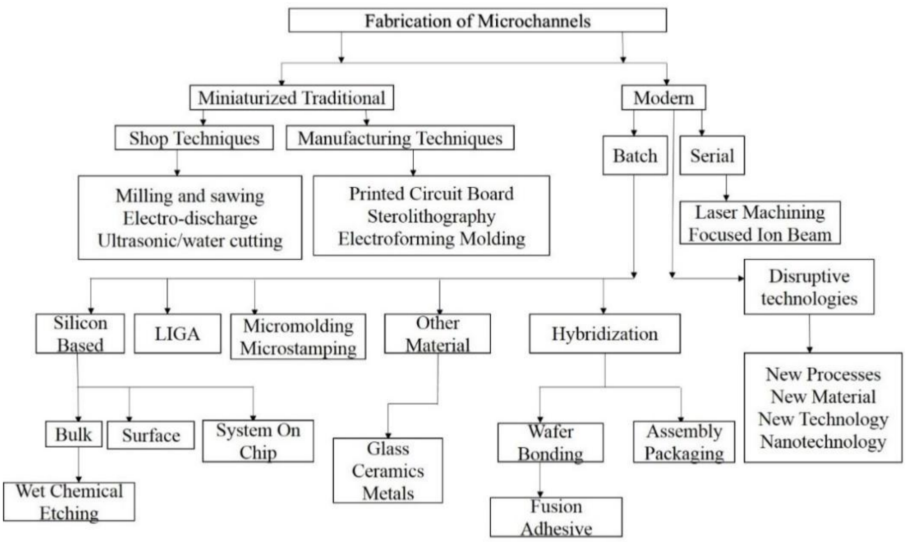


Figure 1.1: Different fabrication techniques (Young et al. 1992)

Microchannels are having advantages because of their small volumes and their high surface to volume ratio. The enormous surface-to-volume proportion prompts high rate of heat and mass transfer, making miniaturized scale devices phenomenal devices for compact heat exchangers. The introduction of the term microchannel is very necessary before we proceed with flow and heat transfer of microchannel. The extent of the term is among the subjects of open deliberation between analysts in the field. The following characterization based on manufacturing techniques required to acquire different scopes of channel dimensions (CD), is the smallest channel dimension:

1 μm < CD < 100 μm: Microchannels

100 μm < CD <1 mm: Minichannels

1 mm < CD < 6 mm: Compact passages

6 mm < CD: Conventional passages

Microchannels are the only way for the flow of liquid in any microfluidic device. They handle, deliver, operate and are also used to collect the liquid. In the literature, many types of microchannels is fabricated of different materials depending on the applications. Conventional technologies such as photolithography, pattern transfer techniques, additive and subtractive techniques are used to fabricate the microchannels with the channel dimension of few microns which are being used in quartz or silicon substrates. For the development of IC and MEMS, these technologies have become the biggest branches for about three decades. Microchannels are the principle parts of an immense class of micro total analysis systems (μ-TAS) and biochip devices which are fabricated for rapid and effective examination of nano litre volumes of chemical reagents and natural species.

The form, dimensions and structure changes with the different type of applications. Many microfluidic channels have involvement of high aspect ratio, low aspect ratio channels are additionally normal in applications for example molecule detachment devices. Fabrication also plays a very important role. Fabrication of the microchannels with various cross sections is going on from many years. The basic cross sections include square, rectangular, circular, half circular and U-shaped microchannels.

Many practical applications have come into notice of microchannel structure when compared to conventional channels, namely;

1. Bioengineering,

2. Bio-technology,

3. Include Analysis (of DNA and proteins)

4. Sorting (of cells)

5. Chemical reactions

6. Transfers of small volumes (1 to 100 nl)

7. Aerospace and

8. Mini-heat exchangers.

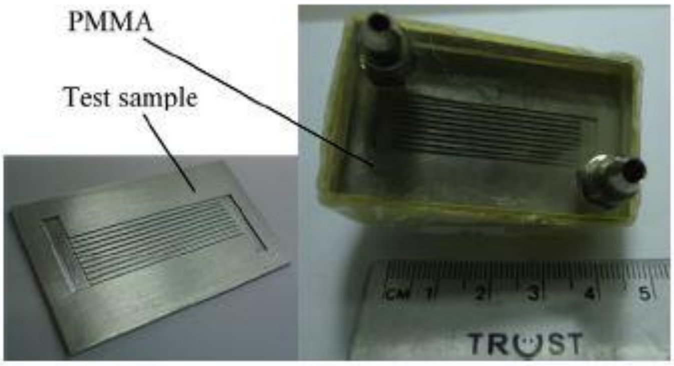


Figure 1.2: Microchannel Heat Exchanger (Dhang et al. 2010)

1.1 Motivation

Nowadays, microfluidic systems have become very important. Microfluidic devices has many applications which makes our lives comfortable. There are three main examples which plays an important role in the application of microfluidics which are as follows:

1. Lab on a chip systems: Bigger machines are replaced at hospitals, which affects the standards of human being.

2. MEMS: Micro Electro Mechanical Systems (MEMS) is a wide spread research on heat transfer and fluid flow at the micro scale. Some past logical and exploratory outcomes for the flow and heat transfer characteristics in microchannels are amazingly not the same as those for traditional channels, like the variation of the friction factor, the heat transfer coefficient and the early transition from laminar to turbulent flow.

3. Microchannel heat exchangers: Their use can be in achieving high thermal efficiency, high heat transfer coefficients and a lower required fluid mass flow rate. For Automobile air conditioning they have a great use in condensers and are also used in evaporators and domestic air conditioning.

(a) (b)

Figure 1.3: (a) Automotive industries (b) Electronic cooling

1.2 Liquid flows in microchannels

Generally, microchannels are the channels with dimensions less than 1mm and greater than 1µm. Over 1µm the flow shows behavior that is same as macroscopic flows. Beneath 1µm the flow is described as nanoscopic. Recently, most microchannels come quite close 30 to 300µm. Fabrication of microchannels should be possible by numerous materials - glass, polymers, silicon metals utilizing different procedures including surface micromachining, bulk micro-machining, molding, embossing and traditional machining with small scale cutters.

Microchannels are used because of their high surface-to-volume proportion and their little volumes. For the use of compact heat exchangers, microdevices have proved to be excellent tools because of the big surface to volume proportion which leads to a high rate of heat and mass transfer. For instance, the device in Fig 1.4 is a cross-flow heat exchanger produced using a store of 50 14mm-14mm foils and contains 34 200µm wide x 100µm profound channels machined into the 200 µm thick stainless steel foils by the procedure of direct high precision mechanical micromachining [1,2]. The heading of the stream in adjoining foils is rotated 90º, and the foils are appended by the methods of diffusion bonding to make a pile of cross-flow heat exchangers fit for exchanging 10kW at a temperature distinction of 80K using water flowing at 750kg/hr. The impressive large of heat transfer is accomplished mainly by the large surface zone secured by the inside of the microchannel: roughly 3600mm^2 stuffed into a 14mm cube.

Another case of the microchannels is in the field of microelectromechanical systems (MEMS) devices for biological and chemical examinations. It is a decent match for the biological structures and potential for placing various functions for chemical analysis, microscale devices have played a great role.

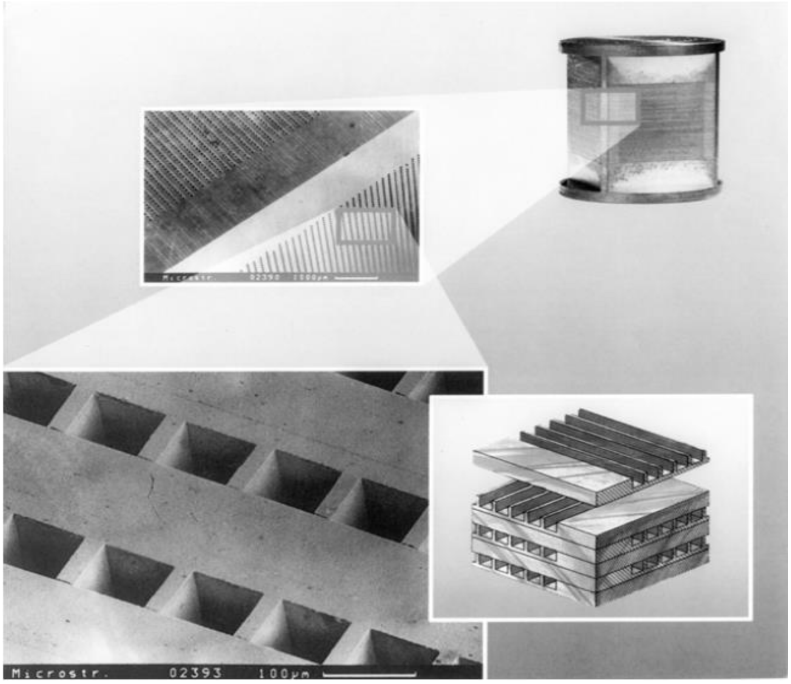


Figure 1.4: Micro heat exchanger constructed from rectangular channels machined in metal. (The MEMS Handbook (2002))

Microchannels are used for the transportation of biological materials like (in order of size) proteins, DNA, cells and embryos and even to transport chemical samples. Flow in biological devices and chemical analysis micro devices are usually much slower than those in heat transfer and chemical reactor micro devices.

Figure 1.5: Blood sample cartridge using microfluidic channels (The MEMS Handbook 2002)

1.3 Need for glass slides in microchannels

Based upon the potential to revolutionize analytical measurements a great interest has been generated in microfabricated devices for the applications mainly in the areas of microfluidics, micro optics, biochemistry and micromechanics [3] [4]. The use of these devices is in micro analytical systems which include capillary electrophoresis for Deoxyribonucleic acid (DNA) and for the separation of proteins, as biochemical reactors, sensors and application which includes biology and tissue engineering [3]. Microfluidics can benefit from such three-dimensional (3D) complex structures by affecting the hydrodynamics of fluid flowing inside microchannels which can generate vortices at low Reynolds numbers. For the transportation of fluids, microfluidic devices are made up of microchannel network so that the reactions, separation and analysis can be performed very quickly with little consumption of reagents. Generally, the dimensions of the microchannel range from 10-100 µm resulting in low Reynolds number which makes the flow laminar. Under laminar conditions, mixing is dominated by diffusion which is a very slow process [4]. The substrate which is used effects on the speed of the process and use of hydrophobic molecules requires robust and stable surface. So, for these processes glass substrate is considered to be the best and also for many biomedical applications [5] [3].

There are many materials which are used for the fabrication of microfluidic system but among them, glass is preferred material for the biochemical applications because of some interesting properties like:

1) High resistance to chemical,
2) Transmission of light is good which permits direct perception of cell or reactions of chemicals
3) It has high resistance to thermal and electrical allowing the utilization of high voltage for the division of electrophoretic,
4) It also has the great mechanical strength that allows high hydraulic pressure which is required to transport liquids inside the microchannels.

The surface of the glass can be functionalized with biomolecules because it has chemical inertness, its surface can be functionalized with biomolecules.

1.4 Fabrication of microchannels

Primarily, the use of microchannels is in microfluidic applications and biomedical devices. Various type of methods is used for fabrication of microchannels. Both conventional and non-conventional techniques are used for the fabrication like lithography, micro milling, embossing processes and laser ablation processing. Mainly, the fabrication of microchannels is done on polymeric, glass, silicon, and on the substrates of metals. The use of polymeric and glass substrates is mostly in biomedical and chemical devices.

1.4.1 Methods to fabricate microchannels

The capacity to persuade a large variety of materials into considerably smaller devices depends on advancement in micromachining and other manufacturing strategies. For various sorts of materials and applications, various different type of methods has been researched throughout the world. In this section, some mostly used fabrication processes have been discussed.

Lithography:

It is one of the chief fabrication techniques which is utilized to fabricate microchannels. It allows to create various sorts of topography that are difficult to be fabricated with different types of techniques. Photo-lithography is the most extremely used form of lithography. In industries, the fabrication of microchannels the transfer of pattern via a mask on the thin films is mostly done with the help of photolithography. Abdelgawad et al. [6] adopted the simple approach of lithography for the fabrication of circular microchannels on Polydimethylsiloxane (PDMS) which ranges between 5 to 200 μm in diameter. Pal and Sato [7] used one-step lithography for the fabrication of different designs of microstructures and microfluidic channels. For creating microchannels on PDMS soft lithography has been used. Curing of PDMS is done on a designed photoresist on the silicon wafer surface. After that, the removal of cured PDMS is done which is joined to a glass surface for creating closed microchannels. A notable benefit of applying this manufacturing technique is, the polymers are attached with one other easily. Disadvantage of using soft lithography while using PDMS is as follows: 1) while cutting shrinkage is above 1% and swelling likewise happens because toluene and hexane which are nonpolar solvents in nature, (2) there is deformation in the soft elastomeric stamps and (3) substrate material being soft is the constraint for achieving aspect ratio via sagging.

Materials, geometry, aspect ratio, dimensions, shape, the precision of microstructures and number of parts are major requirements of Microchannel-based devices which are not satisfied by standard machining processes. LIGA (German abbreviation for Lithography, Galvanoformung (electroplating) and Abformung (Molding) permits the accurate manufacturing of high aspect ratio microchannels which have ranged from 100–1000mm. LIGA have all the benefits of X-ray lithography. It comprises high-energy X-rays and galvanizing techniques to fill the mold with a metal. LIGA empowers materials for new building and dynamic scope of dimensions and shapes is also wide.

Wet and Dry Etching:

It is the process which is broadly used as a subtractive method for micromachining. It can be explained as pattern shift by the chemical/physical expulsion of material from a substrate, frequently in a pattern defined by a protective mask layer like resist or an oxide [8]. In dry etching, the etching on the surface is done either in gaseous or vapor stage, actually it is done by the ion bombardment and chemically it is done by the chemical reactions by a reactive species on the surface or by the combination of chemical and physical mechanisms. Non-parallel walls on glass surface are generated by wet etching technique and as the channel goes on etching deeper it etches the walls also. In comparison to wet etching techniques, dry etching techniques like powder blasting, plasma and deep reactive ion etching are more successful techniques. In the fabrication of microchannels, etching is also utilized as a secondary process.

Metallic substrates react well with chemicals so chemical etching has established with suitable results. For glass and polymer based materials dry etching has been mainly used because of the need of lower reactive energy [8].

Micro Ultrasonic Abrasive Machining:

It is one of the well-organized material removal processes which is suitable for the micromachining of brittle and hard materials. The principle of this machining process involves certain steps that include keeping the workpiece on the worktable that vibrates at an ultrasonic frequency. An abrasive slurry that is a mixture of abrasive particles and water/oil is then introduced on the crest of the work material. The rotating tool strikes the abrasive particles in the slurry which in succession hit the workpiece and the material is chipped away from the workpiece.

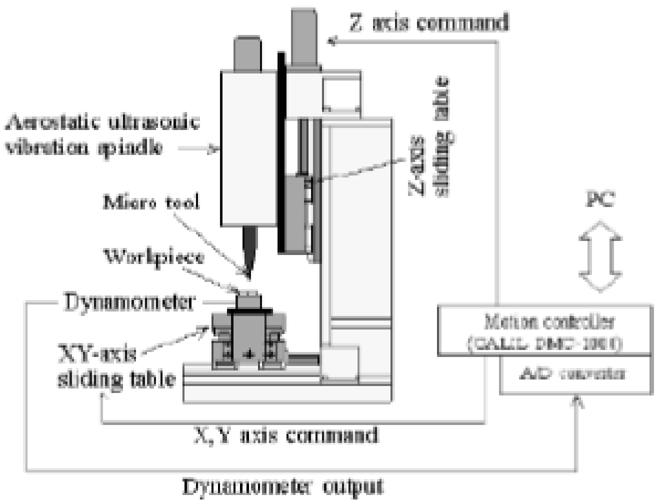


Figure 1.6: Sample micro ultrasonic machining system [9]

Laser evolved microchanneling:

Since process complication is worried, laser related microchannel fabrication processes are the most uncomplicated having potential of creating every form of microchannels. It being a very flexible process, takes less amount of time which makes it usable for all amount of substrate material. Usually, the material removal process is dependent on heat, for achieving the best possible outcome the processing should be optimized. This process for creating microchannels has been developed lately and is studied by many researchers. Mainly laser fabrication process requires not more than two steps and there is no requirement of room cleanliness. There is no need to prepare mask like in photolithographic or etching process. This process has many advantages over other processes like they are environmentally clean, do not produce scrap and based on simple to operate techniques. By using the exact type of laser any kind of material like metals, ceramic and non-ceramic can be easily cut into any shapes.

It has always been an interesting job for laser machining to create channels with smooth surface and also free of micro cracks and edge chipping because laser mostly induces thermal stress. Researchers have done many studies with selected laser sources to lower the thermal induced cracking issue. Basically, material removal phenomena begin when the surface is stroked by the laser beam. According to the wavelength of the laser, there is a variation in the energy of photons. Since the higher amount of energy is contained by the photons of shorter wavelength laser, lower volume of energy is contained by the photons of a higher wavelength. Because of this reason, there is a great use of shorter wavelength in comparison to higher wavelength laser beam since transparent materials like quartz and glass can be cut. The shorter UV wavelength (193, 266, 355 nm) laser beams are found to be more suitable for removal of Si or SiO_2 than longer infrared (IR) wavelength (usually 1064 nm) laser beams by the study of the absorption coefficient of these materials. However, thin SiO_2 films also possess a good degree of absorption at a 10mm wavelength and had been studied by various authors [10].

IR laser microchanneling:

In this list the most widely used lasers are Nd: YAG, fiber lasers and CO_2 lasers. Mostly, the original wavelength of Nd: YAG laser is 1064 nm in range of IR while CO_2 lies in the class of mid-IR value whose wavelength is of 10640 nm. ND: YAG and fiber lasers are appropriate for metallic substrates and semiconductors. Whereas the use of CO_2 laser has mostly been found in polymers and organic materials as it gets easily absorbed with such type of materials.

Lim et al. [11] fabricated microchannel which had a flat wall and herringbone ridges on 660 µm thick silicon. Fabrication of multiple level microchannels was done which had a continuous penetration of 125 µm and various sizes of 250, 200, 160 and 125 µm with the use of a high brightness diode-pumped Nd: YAG laser. Hong et al. [12] fabricated PMMA based microfluidic devices which used high-speed CO_2 laser built for scribing purpose and used an unfocused laser beam as shown in figure 1.7.

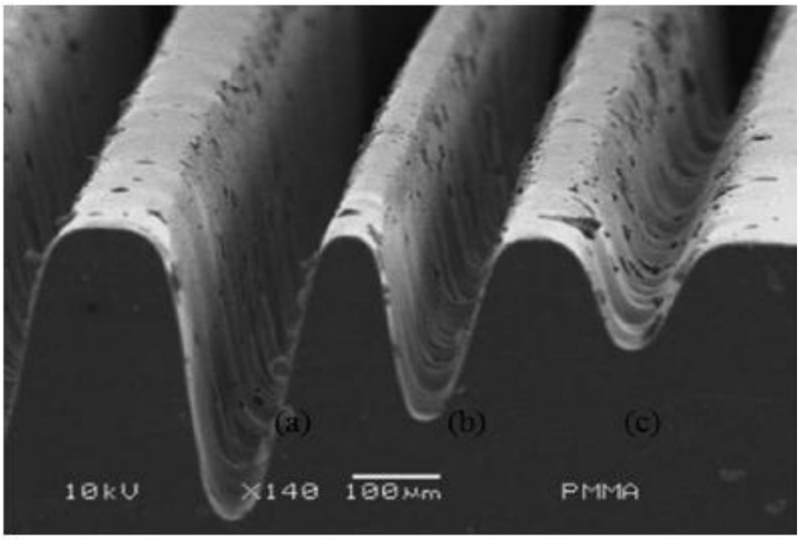


Figure 1.7: Scanning Electron Microscopy picture of PMMA substrate with channels of dissimilar pits which are formed with the help of unfocused laser beam [12]

Powder Blasting:

The phenomena of erosion can be observed in many applications of thermodynamics. The severe loss is generated to entities which come in touch with the eroding particles which exist in the atmosphere or liquid flux. Some studies are done on the mechanisms of erosion for the brittle materials like glass and ceramic with the collision of firm & sharp-edged eroding materials. When a particle approaches the workpiece with some velocity and also have energy more than the fracture threshold, it persuades a local material distortion in the form of cracks ensuring in the removal of some parts from the source material. This process of separating material from a target by bombarding it with particles is called powder blasting [13].

With the help of this technique difficult & precise contours of the eroded structure could be obtained. Powder blasting process is very suitable for fast and complex 3D micro-structuring because the rate of erosion for this process ranges in hundreds of micrometers per minute, which is quite high above with the results obtained by a wet or dry etching process. A method like powder blasting is used to create structures with the help of 3D topography in glass utilizing masks of elastomeric. The relation between the mask opening width and the erosion depth is broken to fabricate microstructures with varying depth in a single micro patterning step [14].

Powder blasting technology contains few steps that result in the 3-D microchannel in the glass. Firstly a mask is prepared of photoresist, photopolymers or metals which are basically the negative of the microchannel required in the glass. Depending on the material of the mask, the process of mass machining can be CNC machining to vapor deposition or it can also be made by laser machining [15].

Generally, elastomers and photosensitive materials are used as masks because of their good resistance to powder blasting. Because of their photosensitive nature, photolithography can be utilized in fabricating the mask straight on the glass substrate, making it easy for obtaining different features with high resolution. As soon as the glass is ready with the photoresist it is placed in front of the powder blasting nozzle from a certain distance. The piece is kept constant, allowing the nozzle to move in different directions in a zigzag path limiting the scanning area to that of the glass slide, once it begins operating it results microchannels in glass [15].

On through holes, a taper angle is produced by the powder blasting process which leads to a larger entry hole than the bottom or the exit hole leading in both the dimensions different. Because of this limitation, an accurately dimensioned micro-channel cannot be produced. It results in higher surface roughness in comparison to other processes. These are few limitations of this process which gives other an advantage because they can create higher aspect ratio straight wall channels.

Electro Chemical Discharge Machining (ECDM):

ECDM is a hybrid machining process which is utilized in machining hard and brittle materials which are non-conducting in nature. It is a hybrid process of electric discharge machining (EDM) and electro-chemical machining (ECM) method which is generally used for machining firm and brittle non-conductive materials like glass, ceramic, refractory bricks, quartz and composite materials. It is an intricate physical-chemical method where the removal of the material from the workpiece is done by material anodic dissolution and also by electrical sparks which occur in the middle of the working surface of the electrode piece and electrode tool. The energy and the electrical discharges which are produced from the sparks ensure a chain of micro explosions on the surface which raise the local spot temperature to a very high value so that it gets melted and vaporize the material, accompanied by partial chemical etching which results in the material removal in micro quantities [16] [17]. Figure 1.8 shows the representation of ECDM arrangement.

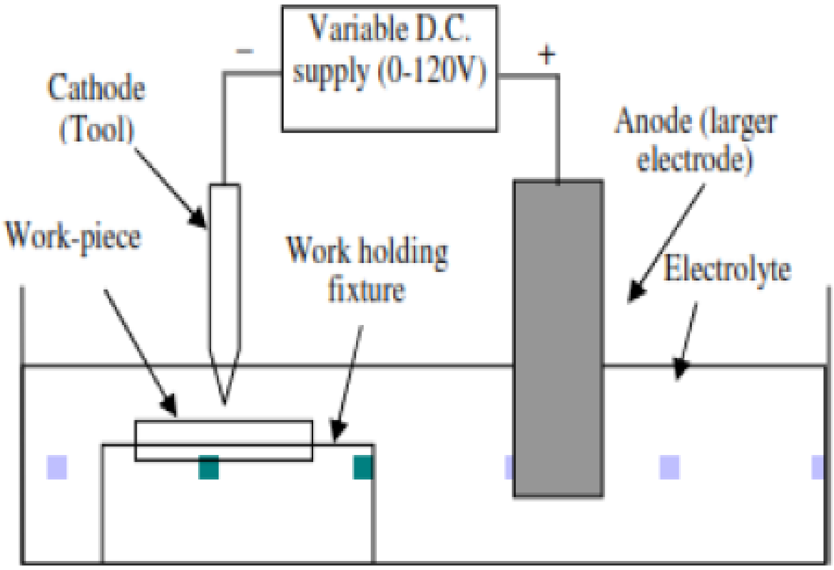


Figure 1.8: Schematic of Electro Chemical Discharge Machining [16]

Table 1.1: Summary of fabrication of microchannel methods with their pros and cons [Prakash and Kumar 2014]

Techniques of fabrication	Application area	Materials	References	Pros / Cons
Micro-mechanical cutting	Metallic micro parts	Acceptable for metals	Pan et al. [18], Liow et al. [19], Qin [20]	Individual component, not appropriate for mass/batch production, cutting tool gets wear off, generation of crack, surface finish is good, burr formation occurs at the ends
Lithography	Analysis of DNA, synthesis of protein, applications in engineering	Silicon, polymers	Yao et al. [21], Pal and sato [7]	It is able to create most intricate topography, do not require facility for cleanliness, large lead time, human resources should be skilled, able to machine very high aspect ratio microchannels
Wet and dry etching	Biomechanical applications	Mainly metals and reactive materials only	Belloy et al. [22], Park et al. [23], Maselli et al. [24]	Selective material removal, Non-parallel walls, exact control of dimensions is impossible

Embossing and Imprinting	Chemical and biomechanical applications	Silicon, polymers	Martynova et al. [25], Lin et al. [27], Michel et al. [26]	Usually wishes higher degree of temperature, large lead time, lower surface finish, suitable for individual needs
Injection molding	DNA elongation, Electrochemistry and cell trapping	Metals, polymers and silicon	Whiteside et al. , Thomas et al., Tosello et al. , Matteucci et al. ,	Very small size of microstructure can be formed, low strength

1.5 Rotary Ultrasonic Milling (RUM)

1.5.1 Background and Introduction of RUM

New materials are the result of continuous research and development, which face difficulty in machining e.g. materials which are super hard like tungsten and titanium carbides, rubies, diamonds, magnetic alloys and hard steels. There are some other groups of materials which have difficulty in machining due to more hardness and brittleness e.g. ferrites, germanium, silicon, ceramics, sapphire, glass, quartz, corundum and some composites. The requirements of machining these type of materials have led to arise of non-conventional machining techniques like ultrasonic machining (USM).

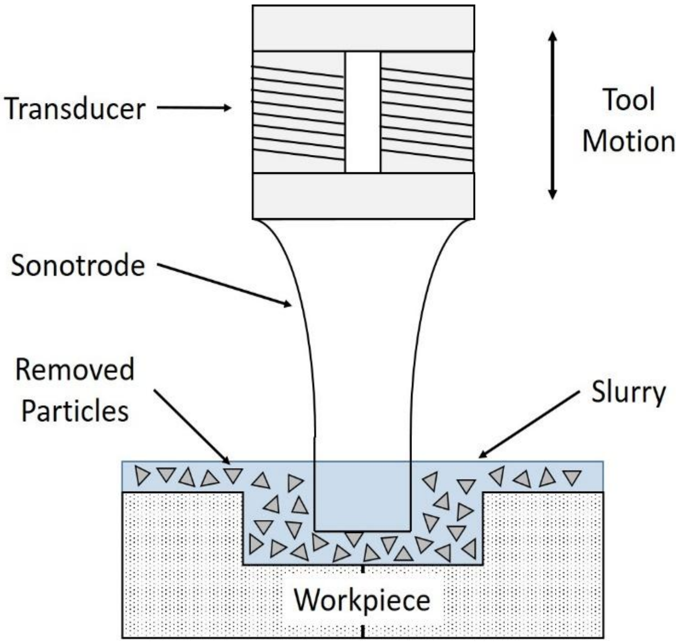


Figure 1.9: Schematic diagram of Ultrasonic Machine

Figure 1.9 shows drawing of the ultrasonic machine (USM). The tool oscillates at a high frequency greater than 20 KHz and is fed towards the workpiece. The abrasive slurry is supplied between the tip of the tool and workpiece which consist of tiny abrasive particles and water. Material removal is in the shape of small particles due to the continuous striking of the abrasive particles onto the work surface. But USM has some disadvantage also its material removal rate and accuracy of is low.

One alteration of USM to deal with their disadvantage is RUM. It is a hybrid machining method which combines the material elimination process of traditional diamond grinding and static USM which results in the more MRR than that achieved by either USM or diamond grinding. This process is defined as the hybrid machining method where USM and traditional grinding happen at the same time for removing material from the work surface by the grinding action of the abrasives and micro chipping [28].

In this method, a rotary core drill on which the abrasives of diamond are infused is vibrated ultrasonically and is continuous fed towards the workpiece. Swarf is washed away by pumping the coolant through the core of the drill. Coolant keeps the machine cool and also prevents the jamming of the drill that keeps the processing of the RUM smooth and continuous as illustrated in figure 1.10.

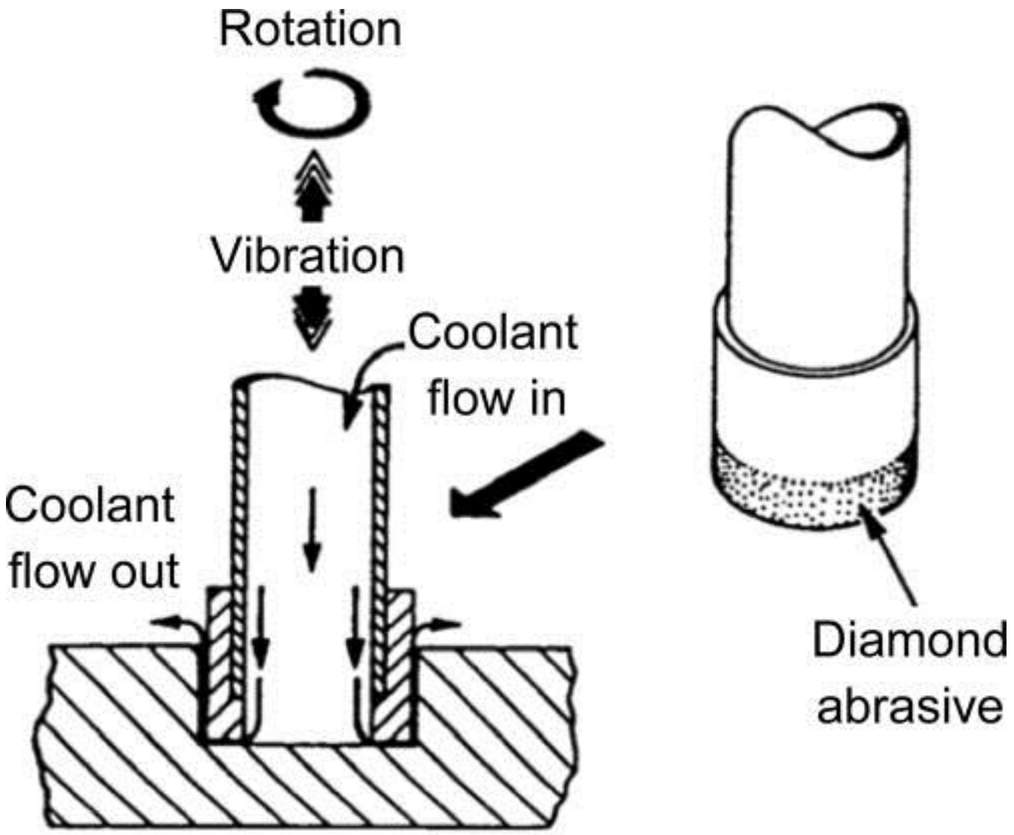


Figure 1.10: Illustration of Rotary Ultrasonic Milling [29]

There are some snag of the USM method like little MRR and inaccurate hole (oversized hole, out of roundness) which are overcome by RUM. It becomes very difficult to achieve close tolerances because the occurrence of abrasive slurry causes eroding of machining hole particles during flushing. For better results diamond was impregnated on the tool which gave an improved accuracy of the hole. By impregnation of abrasive slurry on the tool tip, the RUM process can also be discovered for a massive range of applications in industries.

Rotary Ultrasonic Milling is one of the profitable and atmosphere agreeable machining process existing for the machining of advanced engineering materials which refine the accuracy of the hole, higher MRR, finer surface finish and high tight tolerances.

1.5.2 Working Principle

The setup of rotary ultrasonic milling consists basically a system with the ultrasonic spindle, a coolant supplying arrangement and a data acquisition arrangement as its principal features. The assembly comprised of an ultrasonic spindle, a power supply unit, a transducer and an electric motor. The power supply unit makes use of high power sine wave generator which is used for the conversion of low frequency (50-60 Hz) electrical signal into high frequency up to 20 kHz electrical signals. A piezoelectric transducer receives this high energy and converts it into linear mechanical vibrations of high frequency. Basically, in the ultrasonic based machining process, the preference is given to piezoelectric transducer because it bestows improved performance with high electromechanical alteration efficiency (up to 96%) which too requires less cooling of the transducer in comparison to a magnetostrictive transducer which has lower efficiency (up to 20-35%). As magnetostrictive transducer converts electrical signals into mechanical vibrations into two steps, it leads to loss of energy in the form of heat. For the same output lesser amount of power is consumed by the piezoelectric transducer which also makes little noise levels making the working circumstances more relaxed for the worker. These ultrasonic vibrations are further amplified and then transferred to the diamond abrasive coated tool that finally causes the tool for vibrating it at an ultrasonic frequency.

The alteration in the vibration amplitude can be achieved by regulating the speed of output control of the power supply. Rotational motion of the cutting tool is achieved by engaging an electric motor which is attached at the top of the ultrasonic spindle. The speed of the motor can be controlled by the knob which is present there on the control unit.

1.5.3 Mechanisms of Material Removal

The RUM process is a combination of the material removal mechanisms of conventional grinding and static USM. There are three types of mechanisms involved which are mainly hammering, extraction and abrasion actions.

1) Indentation and crumpling of the sample below the contact of ultrasonic vibration results in the removal of material by “hammering action”.
2) As in conventional grinding removal of the material is done through the cutting tool. The motion of the cutting tool is rotary and the action is called “abrasion action”.
3) The concurrent activity of rotational motion and vibration movement of the tool causes the material expulsion by “extraction action”.

All the above-described mechanisms are clearly described in figure 1.11.

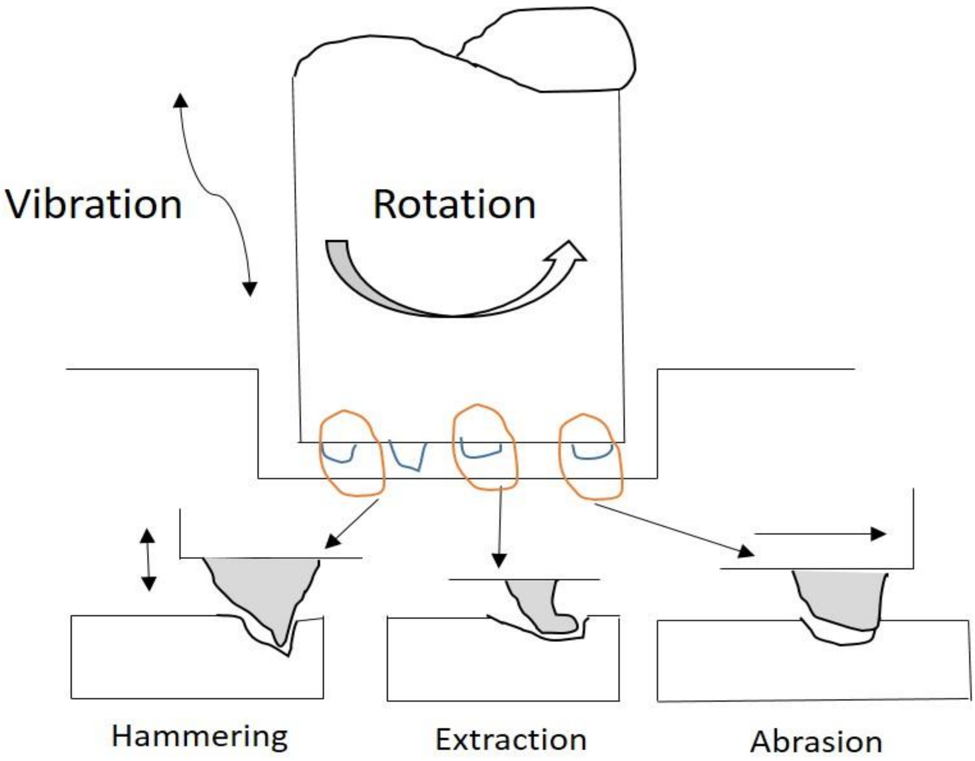


Figure 1.11: Material removal mechanism in RUM

For studying the mechanisms which are complicated in the material removal, many researchers have studied the machined surface topography. The main reason for the material removal of the work surface was observed as the brittle fracture. This presiding style of material removal was caused because of the mixture of hammering, abrasion and extraction arrangements which occurred with the rotational motion and tool vibration. The hammering action of the diamond grits was disclosed to be a superior aspect for removal of material towards the tip of the tool, whereas for the milled part abrasion action was found majorly close to the walls. The actions of both i.e. hammering and abrasion resulted in the formation of debris formation and then mixing them with the pressurized coolant fluid was responsible for the removal of the walls of the milled surface.

1.6 Dissertation organization

Chapter 1: It represents the necessity of microchannel and also what is the use of fabricating glass microchannels. This chapter also includes the various other processes by which microchannels can be fabricated.

Chapter 2: It contains the literature study on the various fabrication processes and the effect of process parameters on the various inputs. Finally, the literature gap and analysis has been devised based on the gaps identified from the past work. This chapter extends the problem formulation, the aims of the present study and the design of present methodology.

Chapter 3: This chapter contains the fabrication of the fixture setup and also included the experimental setup and input and output parameters. The experiments planned according to the design of experiments are discussed in this chapter.

Chapter 4: This chapter includes brainstorming discussion on the effect of input variables on the tool wear, surface roughness and edge chipping size. The SEM characterization of the tool and the edge quality is further discussed in this chapter.

Chapter 5: Conclusions are explained along the groundwork of the present work in this chapter. Further, future scope in the field of microchannels that how to improve the properties and how to use the efficiency of this machine is suggested in this chapter.

Chapter 2

Literature Review

Experimental investigations have been done by various techniques to fabricate microchannels by various researchers. Each and every technique has some pros and cons with them. Both conventional and non-conventional techniques have been researched. The previous work also includes mixing of the fluids, surface finish, tool wear, chipping size, power rating and much more. Here in this chapter are discussed some papers regarding the techniques as well as the results of the process parameters performed by the researchers.

2.1 Fabrication techniques of the microchannels

Belloy et al. (2000) reported powder blasting as a capable innovation for the three-dimensional structuring of brittle materials. The impact of different parameters on the etching rate was studied by the authors, for example powder velocity and the mask feature size, which actuates geometrical effects to the erosion process. The erosion rate of the powder blasting procedure is commonly several hundreds of micrometers per minute, which is substantially higher than what is attained by standard wet or dry etching processes. This makes the powder blasting technology exceptionally suitable for quick and complex three-dimensional micro structuring without any geometrical size upper limits. Experiments were performed by the authors and gave a few applications in light of powder blasting process. A distance “d” kept on increasing there was a decrease in the particle velocity. This is shown with the help of graph in fig 2.1. Powder blasting has been exceptionally encouraging technique because of the high etching rate and the good control of eroded profile slopes [30].

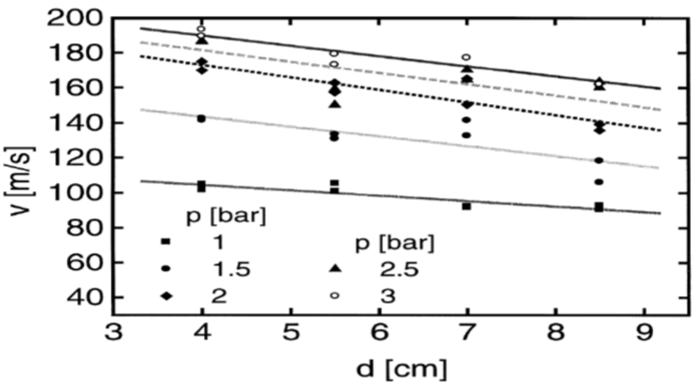


Figure 2.1: Effect of the distance between the nozzle and the substrate on the particle velocities for different air pressures [30]

Nieto et al. (2014) developed a novel method for fabrication of microchannels for the uses of microfluidics on soda lime glass. They used a mixture of laser direct write technologies and then used the thermal treatment which was useful in reshaping and in the improvement of the morphological properties of the fabricated microchannels. With the help of this technique, the authors were able to obtain the least diameter of 8 µm in depth. After applying thermal treatment they were able to decrease roughness by two orders of magnitude by reaching the values of the order of the unprocessed glass [31].

Cao et al. (2009) studied the potential of the ECDM machine, fabricated and studied the microstructure of glass less than 100 µm. The research on this topic was necessary because of the limitations of USM includes severe wear of tool and mechanical cracks on both, the surface as well as inside the structures. With the help of this process machining on the non-conductive materials can be done. Since, microstructures which are having a size less than 100 µm are still a challenge with good surface quality because of controlling the material removal rate, surface roughness and machining resolutions. But in this paper authors have tried to obtain better surface quality with the help of ECDM.

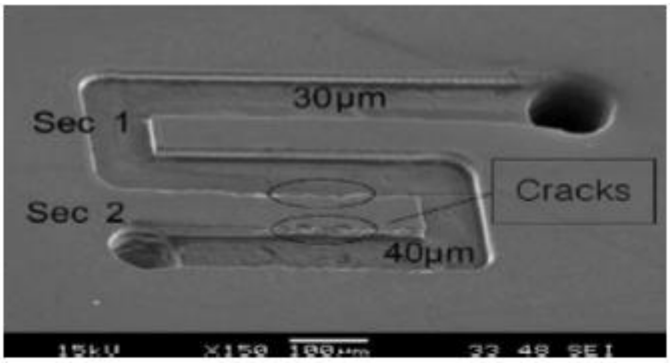


Figure 2.2: Mechanical cracks resulting from mechanical contact [32]

As shown in Fig 2.2, mechanical cracks seemed at the edge of the channel in Section 2 because the tool was in contact with the work surface while serving. There was no existence of the cracks at a depth of 30µm. It is said that the depth of the machining layer can be 30µm or less [32].

Choi et al. (2007) studied chemical assisted ultrasonic machining which overcame the drawbacks of ultrasonic machining like low MRR and low surface quality. For this, in abrasive slurry hydrofluoric acid was added in low concentration. For obtaining the optimal conditions the authors investigated the machining mechanisms and they also carried out several experiments. From the different experiments and analysis, the authors concluded that there was an improvement in the surface roughness and the MRR by 40% at micro-drilling and 200% at macro-drilling.

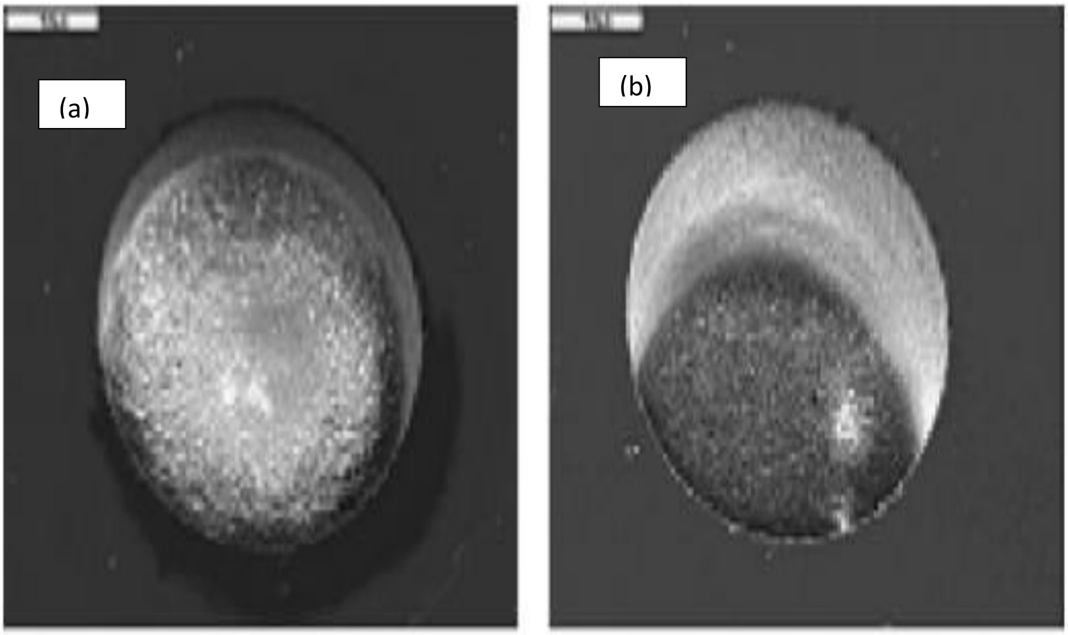


Figure 2.3: Evaluation of Material Removal Rate (d = 1.5 mm) (a) USM (550 m) (b) CUSM (950 m) [33]

Also, the load of the machining was severely lowered and can be maintained stably as shown in figure 2.4. However, the size of the machined hole is enlarged by CUSM to a certain degree, therefore it is suggested to utilize somewhat low concentration i.e. below 5% HF.

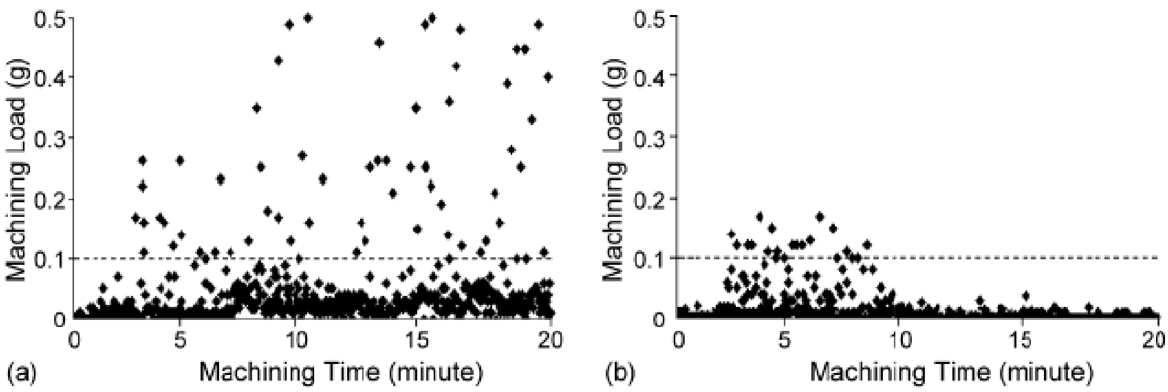


Figure 2.4: Difference between machining load with (a) USM and (b) CUSM [33]

Bulushev et al. (2016) studied the processing of femtosecond laser on the BK7 glass with a high speed of 50 kHz so that they could fabricate the microchannels and could eliminate the micro-cracks and edge chipping**.** The authors obtained regression model for fabricating the microchannels with a predetermined depth of 1-30 µm. The authors were able to fabricate the crack free microfluidic structures with high quality with the help of femtosecond laser without post-processing at the productivity higher than 0.3 mm^3/min [34].

Prakash et al. (2013) studied the Nd: YAG laser processing for the fabrication of microchannels on poly methyl methacrylate which was carried out underwater so that the heat affected zone, micro cracking and burr formation can be minimized. The authors used response surface methodology to conduct their experiments and by varying various parameters the authors concluded that all the output parameters like HAZ, burr formation they depend on the processing parameters of laser [35].

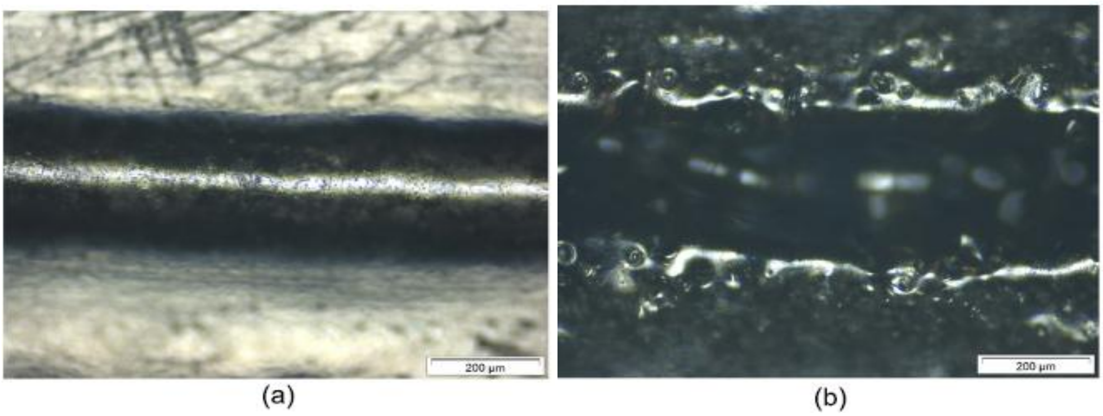


Figure 2.5: Microscopic observation of microchannels (a) underwater processing; (b) open air processing [35]

Maselli et al. (2006) reported the use of femtosecond laser irradiation for the manufacturing of microfluidic channel in fused silica which was further processed by chemical etching. The authors used an astigmatically shaped beam for achieving the microchannels which have circular cross sections and dimension of 1.5 mm [36].

Sugioka et al. (2005) performed micromachining of glass using a femtosecond laser to manufacture lab on a chip. The authors fabricated the microfluidic components which were Y-branched microchannel embedded in a photosensitive glass. Authors concluded that the feasibility of genuine 3D micromachining in the photosensitive glass by utilization of an fs laser worked at a near-IR wavelength for applications of lab-on-a-chip. Mechanism of Photoreaction uncovered that free electrons were produced in the glass for precipitation of Ag atoms by inter-band excitation through flaw levels with a process of six-photon. The photochemical reaction utilizing the six-photon process would perform high throughput processing with high spatial resolution. For optical investigation of reactants, the researchers on the glass chip created micro lasers and micro optical components [37].

Jain et al. (2014) fabricated and designed microchannels for MEMS. The authors highlighted the fabrication of less price microchannel network on a substrate of glass by utilizing micro ultrasonic machining. Micro USM is a cost saving technique in comparison to the other techniques which are existing for the fabrication of complex structures. It being a non-conventional technique process is very ideal for the firm and brittle that is tough to the machine by other techniques. In the micro USM process, the material removal process takes place by the impact forces which are produced on the particles of abrasive with the help of a vibrating tool. The authors have fabricated various sorts of microchannels on the glass substrates which are shown in figure 2.6. The authors also reported that as there is a decrease in the size of the channel to the order of few microns, the result of the surface roughness on the flow of liquid via microchannels becomes important [38].

Figure 2.6: Different types of microchannels on glass (a) V- type (b) H- type (c) I- type [38]

Cheema et al. (2014) studied the fabrication of 3D stepped microchannel with the help of ultrasonic machining. The authors considered power rating, abrasive concentration and feed rate as the process parameters for the study of tool wear and surface roughness in the fabrication of different microchannels. The authors graphically represented the effect of power rating, higher power ratings will result in abrasive particles striking with higher energy. Because of this high energy, there is more damage inside the workpiece which further forms larger sized craters. The authors contributed that with the decrease in power rating there is an improvement in the surface finish as depicted in figure 2.7. The size of the craters which is formed on the lower power rating decreases which result in the better surface finish. In the same manner, there was a reduction in the tool wear (longitudinal wear) which was observed by the authors at the higher power ratings as shown in fig 2.7. Authors defined feed as the relative motion between the tool and workpiece with respect to time. In this case, the workpiece was given a feed of 10, 20 and 30 mm/min. feed rate decided the interaction time between tool abrasives and workpiece [39].

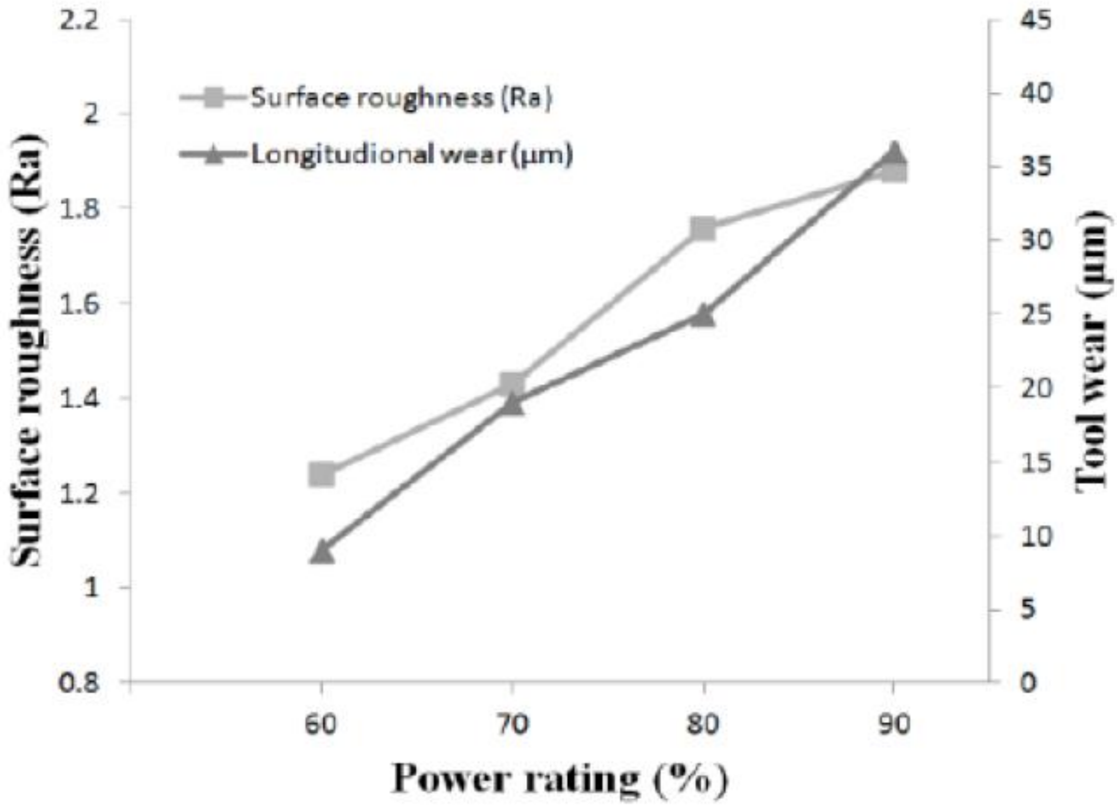


Figure 2.7: Effect of power rating on surface roughness and power rating [39]

Jain et al. (2012) studied fabrication of microchannels using micro ultrasonic machining. The authors conducted the experiment on borosilicate glass of 2 mm thickness and a <1 1 1> p-type single crystal silicon wafer with 0.5 mm thickness was employed as workpiece material for the experimentation. After the machining authors concluded that because of the movement of the Table (back and forth) the channel cannot sustain the straightness and observe some extent of out of straightness (OOS). At some position, the width of the channel is more than other locations. The width of a channel is not constant but is narrow at the base than at the top. The authors observed OOS with the help of SEM micrographs. After observing the results it is concluded that the relative contact between the abrasive and side edge of a solid cylindrical tool gives rise to the taper of walls and results in a V-type microchannel. As the lateral edge of the tool is also involved in cutting, the tool wear is more in this technique. The channels have poor form accuracy in terms of straightness and a low aspect ratio but, same can be improved by maintaining the precision of the equipment.

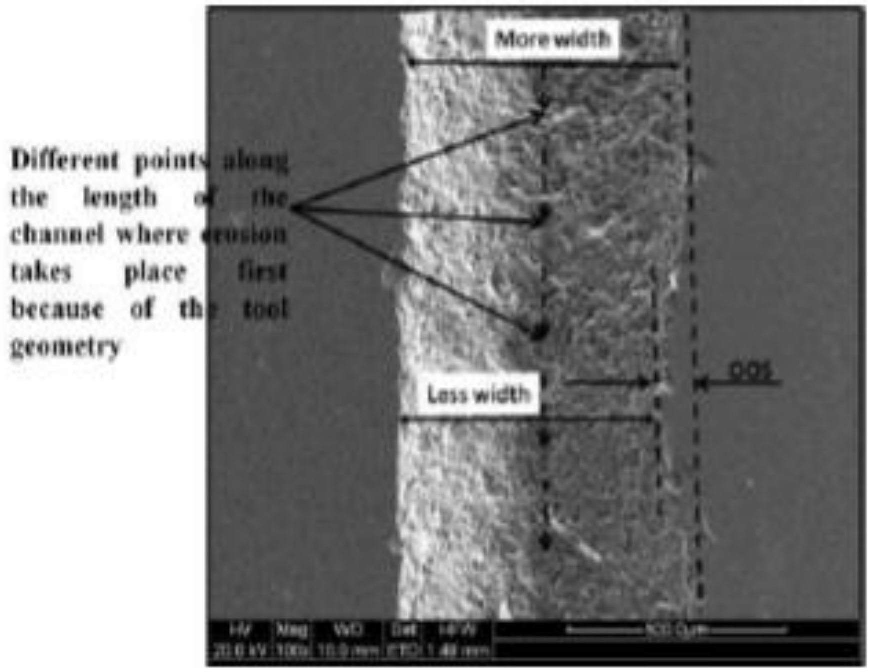


Figure 2.8: A Glass Microchannel Fabricated using micro USM [40]

Kuo (2008) studied the glass milling by the use of rotary ultrasonic machining. With the increase in the use of the hard brittle material in recent years, it has become challenging to a part such type of materials. On the other hand, if ultrasonic energy is connected to the milling process and combined with the use of hard diamond grits, the hard brittle material can be successfully evacuated [41].

Lin et al. (2001) reported a method by which microfluidic microchannels can be fabricated on the soda lime glass with less cost and fast prototyping process. In this particular process, the authors did not use costly polysilicon nitride layer as an etch mask but used AZ4620 positive photoresist which avoided the problem of peeling. The microfluidic channel having a depth of 35.95 ± 0.39 µm was formed after 40 min buffered oxide etching (BOE) in an ultrasonic bath. The channel which was formed had an even profile with a surface roughness of not more than 45.95 ± 7.96 Å [42].

Papautsky et al. (1998) fabricated microchannels of various different dimensions above the silicon and glass substrates. The length of these microchannels varied from 0.5 mm to 12.75 mm whereas width from 20 µm to 1.5 mm. The height of these microchannels ranged from 5 to 100 µm. At this low temperature less than 110 ºC, IC compatible process for fabrication of metallic microchannels uses electroformed metals. This process has the involvement of spin coating of the molding wall in addition to standard lithography technique [43].

Yao et al. (2005) showed an easy lithography technique to create microchannels using simple processing steps as spin coating, baking, exposing and development. The authors generated precise microchannels of various cross sections having dimensions of 10 μm x 7 μm x 200 μm and 4 μm x 1.8 μm x 1200 μm. The authors also extended the primary approach to the fabrication of multilevel microchannels and microchannel components. The authors demonstrated this concept by fabricating an orthogonal three-channel system and also a bundle of six channels, that holds promise for many microfluidic applications [21].

Santana et al. (2013) stated cost effective and simple method for the fabrication of glass microchannels with the help of wet etching using masks which are made by xurography in vinyl adhesive films. The authors concluded that when the urban technologies like photolithography are unavailable then this new method with speed, low cost, simplicity and reliability make it interesting for large production of glass microfluidic devices [44].

Atkin et al. (2002) reported their work on Poly ethylene terephthalate (PET) by using direct-write Neodymium Yttrium Aluminium Garnet (Nd: YAG) method for fabricating microfluidic devices mainly for the purpose of bio chip for DNA diagnostic. Observing the need for disposable diagnostic sensors in the industry of health care leads to the evolution of low-cost microfluidic devices. The authors worked on PET because of the limitations of the polymer materials and it also does not own the wanted properties for biochip operations like their poor electro osmotic flow characteristic and their high non-specific binding. With the help of this technique, complex geometry shapes can be fabricated of around 10 μm [45].

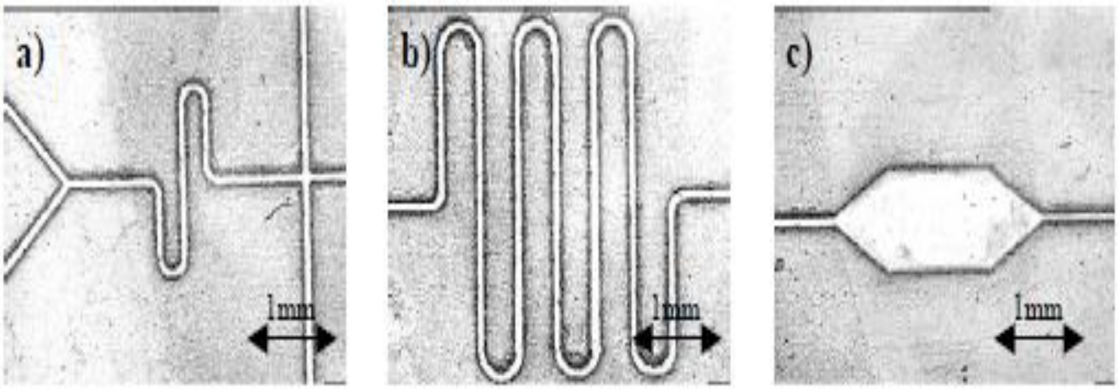


Figure 2.9: Images of the three main sections of the fluidic network after thermal bonding a) inlet and injection channels b) diffusion mixer c) micro chamber [45]

Abdelgawad et al. (2011) reported a method for the fabrication of polydimethylsiloxane (PDMS) in the form of circular microchannels. The authors fabricated the circular microchannels which ranged from few micrometers to few hundreds of micrometers along the diameter. The authors applied PDMS coating to the square microchannels which were fabricated with the help of soft lithography. It is used for forming small diameters having microchannels. Rapid prototyping with limited resolution can also be used in coating large channels [46].

2.2 Study of process parameters in rotary ultrasonic machining (RUM)

Zhang et al. (2011) reported the study on rotary ultrasonic face milling (RUFM). The authors machined the flat surfaces of K9 glass, because of its mechanical properties K9 glass is considered to be one of the most difficult materials to be machined. In the study the authors reported the impact of process variables like spindle speed, cutting width, depth and feed rate while showing their effect on surface roughness and cutting force by performing single factor experiments. They authors in their research also included the difference between RUFM and diamond milling. In their study, they concluded that cutting force is remarkably reduced by the process of RUFM, which further concluded that there will be less tool wear resulting in the longer tool life. In the results, the authors also showed that the surface roughness of K9 glass is little higher than which was obtained with the diamond milling [47].

Zhang et al. (2014) reported their study on the optical K9 glass which has various applications in various sectors like electronics, optics, thermodynamics and fluidics. In Rotary ultrasonic machining cutting fluid is used successfully for the machining of various brittle materials like sapphire, optical K9 glass and ceramics. Considering the safety of the environment dry machining has been employed successfully for machining some materials. The authors for the first time reported their study for machining optical K9 glass with the help of compressed air as a coolant. The authors made their investigation on the input parameters like feed rate, ultrasonic power and spindle speed and showed their results on the output parameters like surface roughness, edge chipping size and ultrasonic power consumption. The authors concluded that by the use of compressed air as a coolant the drilling of a hole in the workpiece like optical K9 glass can be done by using RUM but will face difficulty while producing it by diamond drilling [48].

Zhao et al. (2013) made a comparison between conventional grinding and rotary ultrasonic machining of cutting force by the machining of K9 glass. The authors in their study found that force generated through the rotary ultrasonic machine is lesser than the traditional diamond face grinding, drilling and side grinding. The maximum cutting force increases with increase in the feed rate [49].

Zhen et al. (2016) reported their research on rotary ultrasonic face milling on ceramic matrix composite which has great importance in various fields of industry, mainly in aerospace. The rotary ultrasonic machine being a high productivity handling technology was used by the authors for these advanced materials. The authors discussed the material removal mechanism by the brittle fracture of C/SiC. The authors also developed a simulation software for cutting force which was based on the brittle fracture cutting force model. The authors in their study also optimized the cutting parameters which resulted in the reduction of the cutting force. Then a set of RUFM experiments were also conducted which resulted that the surface quality was improved in comparison to the conventional milling [50].

Jiao et al. (2005) reported their experimental work on the ceramic material which is 92% alumina through rotary ultrasonic machining. Furthermore, the authors have reported on the effects of process parameters like surface roughness and material removal. The authors used the diamond grit tool of mesh size 140. The authors concluded that MRR was only affected by the feed rate. Surface roughness was significantly affected by the grit size, feed rate and the spindle speed [51].

Kuo and Tsao (2012) reported their study on ultrasonic milling. The authors started their study with the improvement in the tool design. The authors used their designed tool with the rotary ultrasonic machine and conducted their experiments on considering glass as their workpiece. The authors mainly studied the surface roughness with various parameters. The authors concluded that there is an increase in the surface roughness with the increase in the depth of cut and feed rate as shown in figure 2.10. The authors observed that when there is an increase in the depth of cut and feed because of the increase in resistance, which tends to accelerate the tool wear [52].

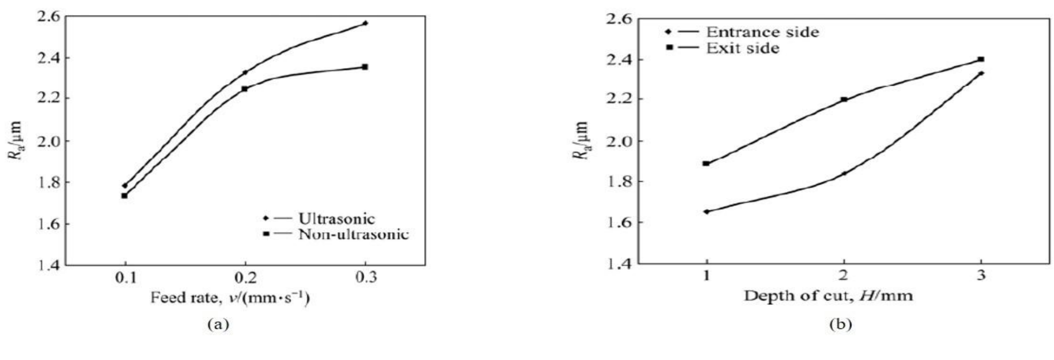


Figure 2.10: (a) Comparison of feed in ultrasonic and non-ultrasonic (b) depth of cut at entrance and exit [52]

Cheema et al. (2015) reported their study on the wear of tool while fabricating microchannels in ultrasonic machining. The authors had a great concern about the form accuracy of the machined component, it depends on the form stability of the tool. The authors have discussed the effect of the material of the tool, abrasive size and the step feed for the machining of microchannels with the help of ultrasonic machine on borosilicate glass. They observed that there was a better form accuracy with the tungsten carbide tool in comparison to the stainless steel tool. The authors concluded that the width of the channel was increased with the use of larger abrasive tools whereas depth was dependent on the step feed [53].

Cheema et al. (2016) studied the mathematical model of the tool wear which was measured in two dimensions and further converted into three-dimensional wear model. The authors then verified the effectiveness of the model with the help of machining data on the glass with the tungsten tool. The results that came into conclusion were that the depth of the microchannel is affected by longitudinal wear whereas taper shape on the microchannel is induced because of lateral wear. The form accuracy is influenced by the abrasive size [54].

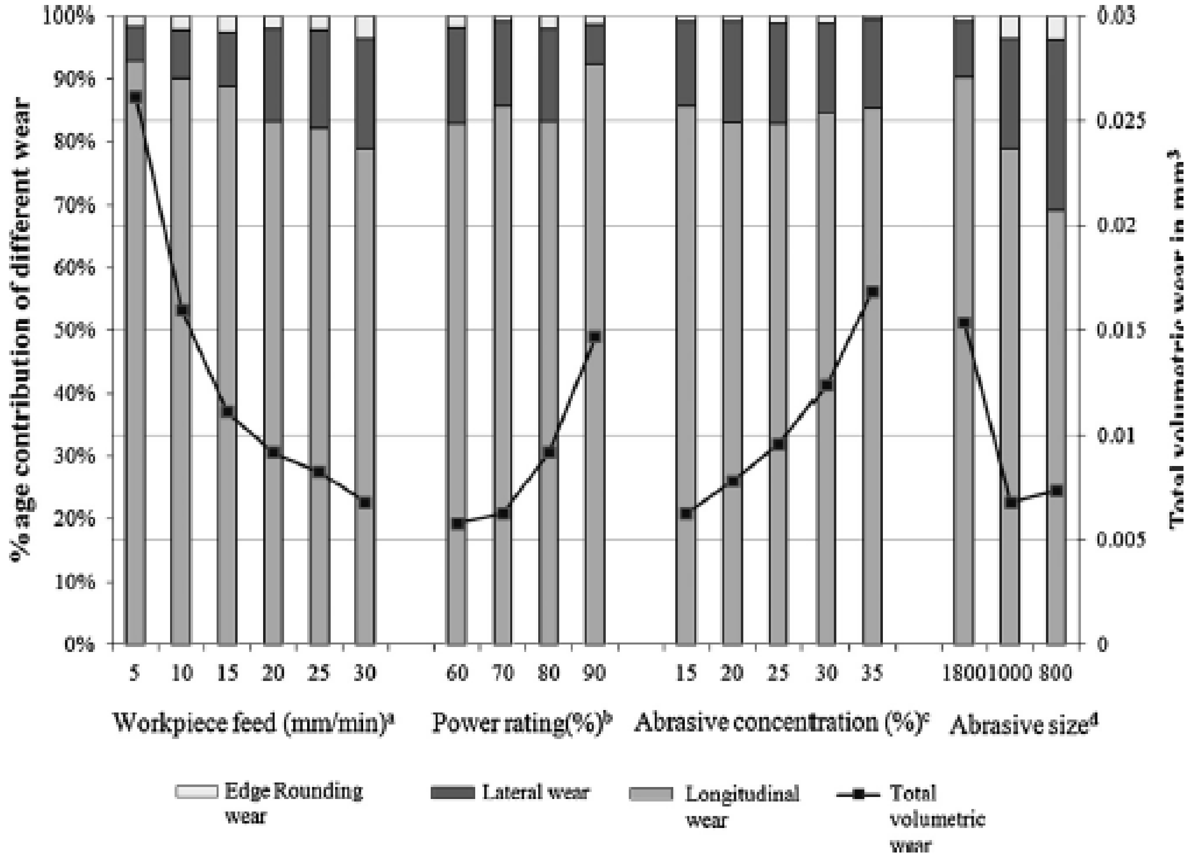


Figure 2.11: Effect of various parameters [54]

2.3 Literature Gap

From the previous literature, it has been seen that most of the fabrication process for the microchannels is done on various materials (polymers, silicon) except glass. The machining methods which have been adopted are lithography, laser, wet and dry etching etc. Rotary ultrasonic milling has been used but it is done for the drilling purpose only.

1) Machining of glass is difficult because of its hard and brittle nature.
2) UV laser micromachining cannot be used because it requires high initial investment and mostly it is suitable for mass production.
3) None of the researchers has reported the fabrication of serpentine microchannels with the help of rotary ultrasonic milling.
4) Various designs of the microchannels by Rotary Ultrasonic Milling can be explored so that the best design could be achieved for micromixing and could be helpful for bioengineers.

2.4 Problem formulation

Rotary ultrasonic milling can be a high potential candidate for machining the glass which is very hard and brittle in nature and many low-cost parts can be fabricated which can be used in different industries for various applications.

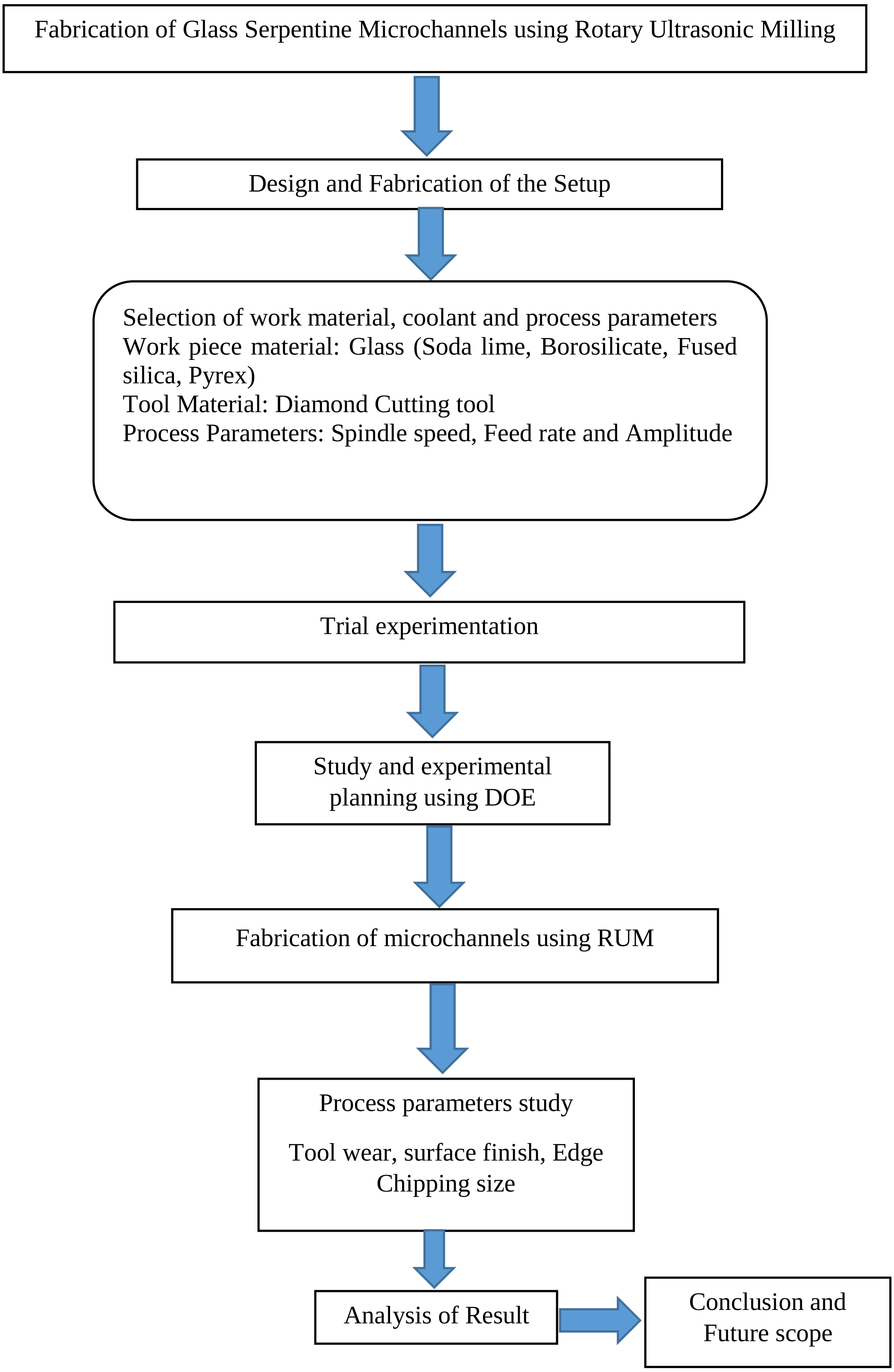
Thus, in the present study all the shortcomings of the previous work has been identified from a comprehensive literature survey and an attempt has been made for **"Fabrication of glass serpentine microchannels using Rotary Ultrasonic Milling".**

2.5 Objectives

The main objectives of this study are:

1) To fabricate and investigate glass serpentine microchannels using Rotary Ultrasonic Milling.
2) To analyze and optimize the effects of various process parameters on performance characteristics of the RUM process.
3) To characterize the samples using SEM, EDS and Talysurf.

2.6 Proposed Methodology



Chapter 3

Experimentation

Rotary ultrasonic milling is a potential candidate for the fabrication of microchannels. The experiments are carried out with the help 3-axis CNC RUM setup. The complete explanation of the machine tool, tool holder, tool type, the workpiece and the measuring instruments used for this research are discussed in this following chapter.

3.1 Description of Machining Setup

3.1.1 CNC vertical milling machine

The experiments were conducted on BFW Chandra + machine situated in Thapar University Patiala. The machine consists of several systems like the ultrasonic system, drive system and feed control system. The machine has inbuilt CPU for feed and controlling of the motor. Fig 3.1 shows the experimental setup for fabrication of the serpentine microchannels. For the conversion of line voltage to 20 kHz of electrical energy, a generator was used. A piezoelectric transducer receives this high energy and converts it into linear mechanical vibrations of high frequency. For the high electromechanical conversion efficiency, a piezoelectric transducer is recommended for the processes like ultrasonic machining i.e. likely 96 % and in comparison with magnetostrictive transducer less cooling is required.

Figure 3.1: Experimental Setup

The maximum consumption of the machine is 22.4 kW with a maximum of 8100 rpm and its coolant capacity is 208 L. The length and the width of the machine are 1219 mm high and 457 mm respectively. The maximum diameter of the tool that can be held in the tool holder is 89 mm. Full technical specification for the machine is given in Table 3.1.

Table 3.1: Specification of CNC vertical milling machine

Specification	Units	Parameters
Table (width*length)	mm	315*1060
Stroke (X/Y/Z)	mm	1016/508/635
Power	kW	22.4
Spindle speed	rpm	60-8100
Feed rate	mm/min	1-5000
Current	Ampere	26
Voltage	V (DC)	24
Coolant capacity	L	208

3.1.2 Tool holder

To fabricate the serpentine microchannels using RUM, the rotary ultrasonic tool was fabricated as shown in figure 3.2. A transducer with a frequency of 20 kHz and 800 W was connected to the housing from one side and another side of the housing diamond abrasive coated tool is mounted.

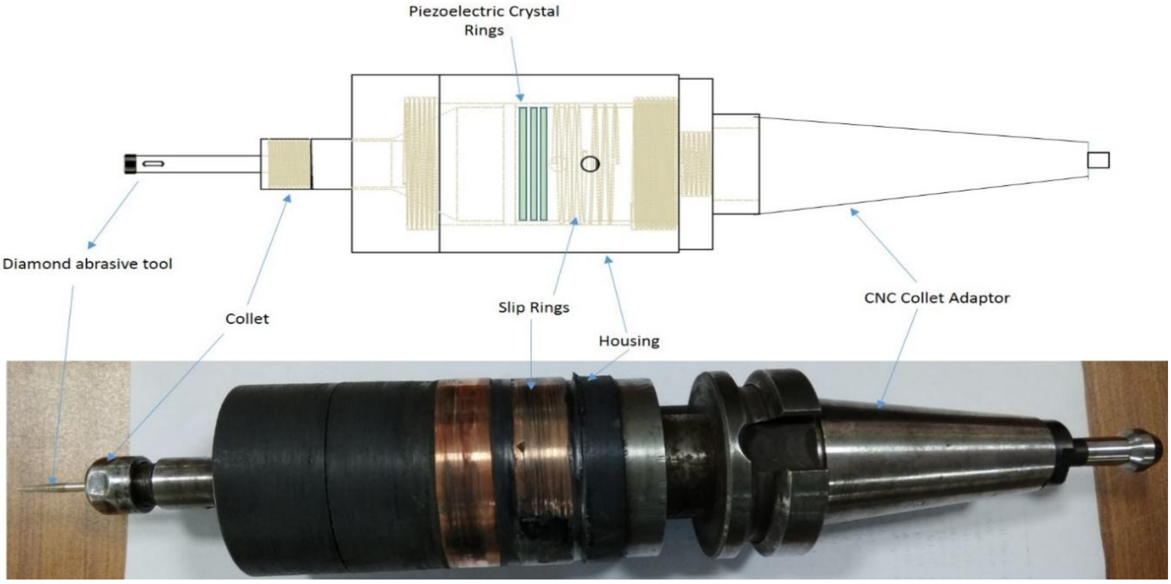


Figure 3.2: Rotary ultrasonic tool

To provide the electrical signal input, slip rings were provided on the housing. Then the full designed assembly was fastened on then CNC milling machine. Rotation of the tool, motion of the Table in x and y-direction and feed was controlled by the controller unit of the machine.

3.1.3 Tool

The glass being brittle in nature makes difficulty in performing milling with the common cutting tool. A commercially available diamond abrasive coated tools were used for the fabrication of serpentine microchannels as shown in figure 3.3. The diameter of the tool was 0.6 mm. and length varied from 12-16 mm. The mesh size of the abrasives was 90-140. The chemical composition of the tool was observed with Energy Dispersive Spectroscopy (EDS) at Thapar University, Patiala as shown in Table 3.2 and figure 3.4.

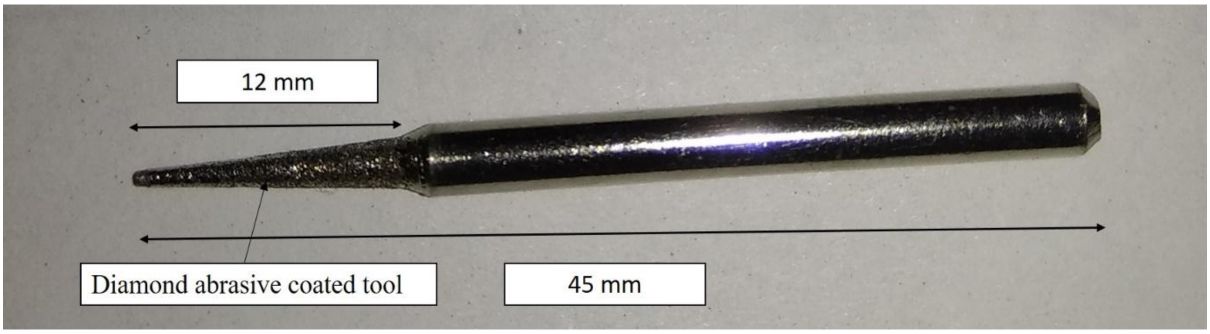


Figure 3.3: Tool used for the fabrication of microchannels

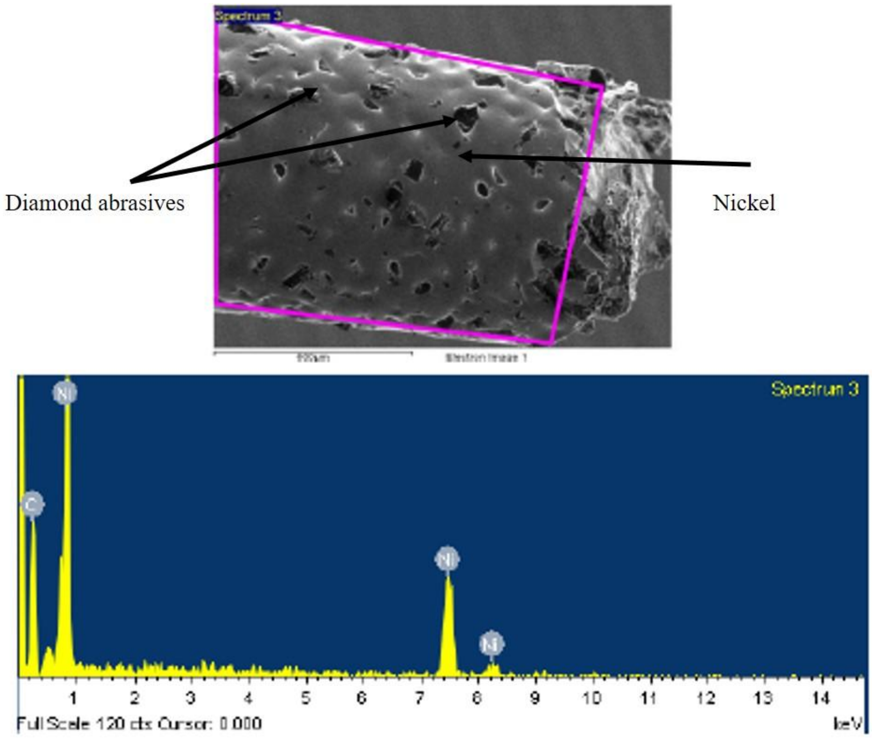


Figure 3.4: EDS report of diamond abrasive coated tool (Performed at Thapar University)

Table 3.2: Chemical composition of tool

Element	Weight %	Atomic %
C	41.60	77.69
Ni	58.40	22.31
Total	100	

3.1.4 Selection of material

A glass workpiece was considered for the fabrication of serpentine microchannel because in biochemical applications it owes some fascinating properties like 1) high resistance to chemical, 2)) transmission of light is good which permits direct perception of cell or reactions of chemicals, 3) it has high resistance to thermal and electrical allowing the utilization of high voltage for the division of electrophoretic and 4) it also has great mechanical strength that allows the use of high hydraulic pressure which is required for the transportation of liquids inside the microchannels The surface of the glass can be functionalized with biomolecules because it has chemical inertness, its surface can be functionalized with biomolecules. The chemical composition of the soda lime glass which was characterized with the help of Energy Dispersive Spectroscopy (EDS) is given in Table 3.3 followed by the image given shown in figure 3.5.

Table 3.3: Chemical composition of soda lime glass

Element	Weight %	Atomic %	Compound %	Formula
Na	13.17	11.8	17.75	Na_2O
Al	0.21	0.16	0.4	Al_2O_3
Si	34.66	25.41	74.14	SiO_2
K	0.1	0.05	0.12	K_2O
Ca	5.42	2.79	7.58	CaO
O	46.44	59.78		
Total	100			

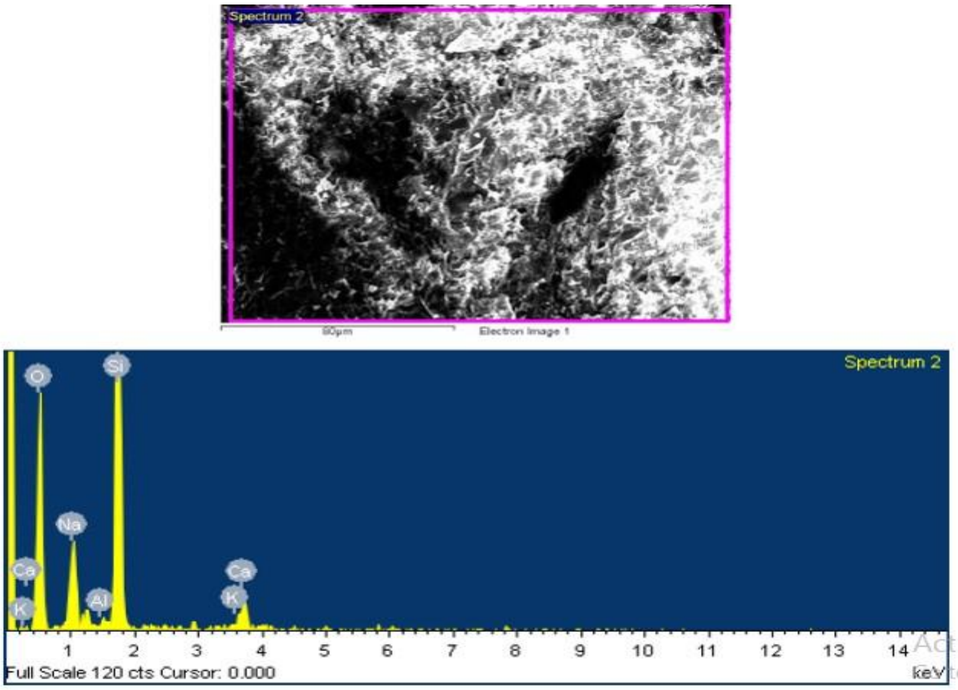


Figure 3.5: EDS report of soda lime glass (Performed at Thapar University)

3.1.5 Fabrication of the fixture

After finalizing the workpiece design and material, the fixture is designed and fabricated to clamp the workpiece. The fixture is fabricated from the aluminum block by milling to get the required shape. In order to rigidly clamp the workpiece and sustain the forces acting during the material removal, a clamping nut is provided as shown in Fig. 3.6. To properly hold the workpiece fixture on the machine bed two holding screws are provided on both sides of the fixture.

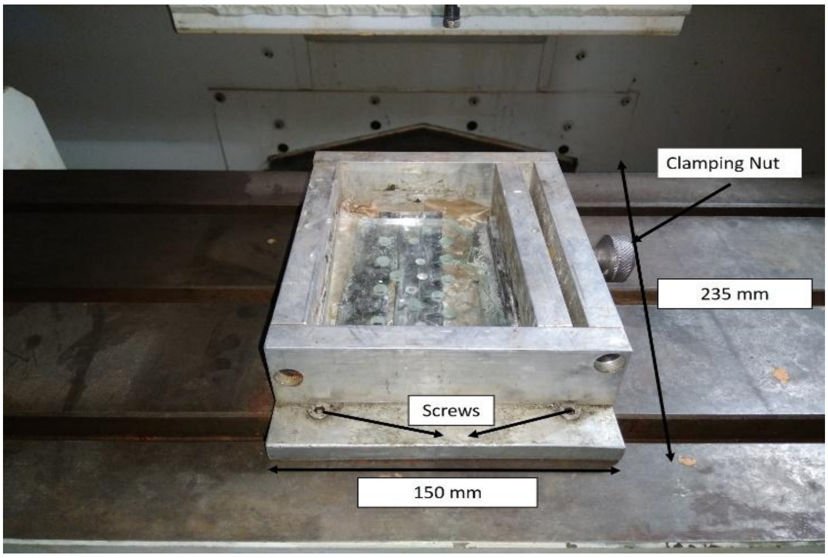


Figure 3.6: Fixture used for machining

3.2 Design of Experiment

It is a method of gathering the experimental knowledge and that knowledge based on the experimental details and not on the theoretical model. It is really helpful in determining the significant parameters inducing the quality features of interest. It is scientifically varying the administrable input aspects in the process and finding the effects of these attributes on the output product parameters.

The design of experiments has certain benefits which are summed up as follows:

- The number of trials are basically decreased.
- Important decision variables are identified, which control and improve the execution of the process or the product.
- Optimal setting of the parameters can be discovered.
- Experimental error can be determined.
- Inference with respect to the impact of parameters on the attributes of the process can be made.

In the accompanying segments, the examination methodology for the technique 'Taguchi method ' utilized as a part of the present research work is exhibited.

3.2.1 Taguchi Experimental Design Strategy

Dr. Genichi Taguchi of Nippon Telephones and Telegraph Company Japan has built up a strategy for conducting design of experiments. This technique utilizes an exceptional arrangement of exhibits which is known as an orthogonal array. Tests led by utilizing orthogonal array give tremendously lessened "variance" for the try different things with "ideal settings" of control parameters.

The conventional full-factorial designs need trial information for all the conceivable combinations of the variables required in the work; therefore there is a need to perform countless number of trials. Along these lines, the experiments that generally included more number of variables, just a little division of combination of variables are chosen that produces the greater part of the data to diminish test exertion. This tactic is known as fractional-factorial design of experiment. The investigation of results in this approach is intricate because of non-accessibility of for the most part acknowledged rules [Ryan (1988)]. The Taguchi technique gives an answer for this issue. Taguchi strategy rearranges and institutionalizes the fragmentary factorial plan by presenting orthogonal array (OA) for developing or laying out the outline of trials. It additionally recommends a standard technique for the investigation of results.

Taguchi recommends two unique courses to complete the examination of the trials. In the principal approach, the consequences of a solitary run or the normal of monotonous runs are prepared through fundamental impact and ANOVA examination (Raw information investigation). The second approach is for multiple runs where signal to noise ratio (S/N ratio) is utilized.

3.2.2 Assumptions of Taguchi method

Since the impact of each variable might be linear, quadratic or of higher order, yet the Taguchi method expect that associations of individual element i.e. their cross product are not accessible. This suggests the impact of one autonomous variable does not rely on another independent parameter with their diverse levels and the other way around. If any of this case, this assumption is pillaged then it changes the additivity of primary effects and interaction occur between the factors.

3.2.3 Selection of OA

In choosing a proper OA, the given essentials are required:

1) Selection of process parameters as well as their interaction to be assessed.
2) Selection of a number of levels for the chosen parameters.

Brainstorming, flow charting, cause-effect diagrams are a portion of the techniques for the choice of parameters to be incorporated into the experiment. Two levels for every parameter are prescribed to limit the measure of investigation. In any case, if higher request polynomial connection between parameters is expected, no less than three levels are required [Barker (1990)]. Expanding a number of levels for parameters increases the degree of freedom (DOF) in the experiment and subsequently the quantity of trials. The essential sort of OA created by Taguchi [Taguchi and Wu (1980)] is either two-level arrays (L4, L8, L12, L16, L32) or three level arrays (L9, L18, L27). The subscript in the array designation demonstrates the quantity of trials in that array.

At the point when a specific OA is chosen for an analysis, the accompanying disparity ought to be fulfilled.

3.2.4 Analysis of Results

Signal to Noise Ratio

S/N ratio is utilized as an objective function for parameter optimization. Control factors can be adjusted effectively and their values are defined by us. Quality characteristic mainly depends on these control factors. Noise factors like temperature, humidity, weather etc. are difficult or impossible to control. The ratio of the mean (signal) with the standard deviation (noise) is termed as the S/N ratio. For analysis purpose, Taguchi gave three type of S/N ratio which are portrayed beneath-

(1) SMALLER-THE-BETTER:

N= -10 $\log_{10}$ (mean sum of square of experimental data)

This is mainly selected for all unwanted characteristics whom we want minimum like defects etc. Also, it is used to find the difference between the standard or ideal value of any data to its measured value (like in case of measuring surface roughness of any material, if required value is 0.02 µm and experimental value are in some finite rate then the difference between the standard data and experimental data is required to minimum. Then formula for calculating S/N ratio is,

N= -10 $\log_{10}$ [mean sum of square of (experimental data – ideal data)]

(2) THE-LARGER-THE-BETTER:

N = -10 $\log_{10}$ [mean sum of squares of reciprocal of experimental data].

This is required for maximizing any data. This is generally used for desired results, as they require to be maximum as possible like material removal rate.

(3) THE-NOMINAL-THE-BEST:

This case is used for achieving a required value. It was used when a certain value is desirable and neither higher nor small value from that value is required.

$$n = \frac{mean\ sum\ of\ square\ of\ data}{variance\ of\ data}$$

3.3 Experimental details

3.3.1 Material Preparation

A glass sheet of 4 mm was bought from the market and then was cut into the dimensions of 88.9 x 139.7 mm so that it can fit into the fixture. The image of the initial specimen is shown in figure 3.7.

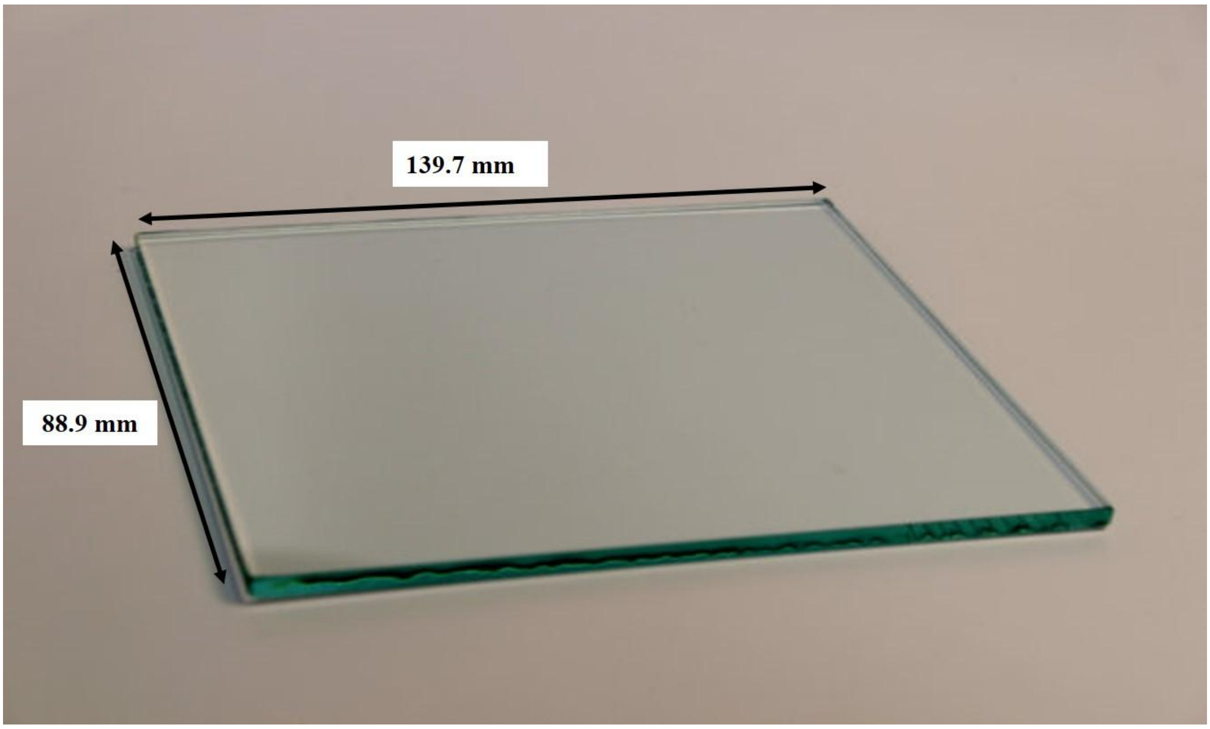


Figure 3.7: Initial image of specimen

3.3.2 Clamping Methodology

To clamp the workpiece on the fixture an adjustable nut was provided on the fixture which could be moved if there is any change in the dimensions of the workpiece. Glass being brittle in nature breaks easily if a large amount of forces are applied to it or it is provided with a high amount of vibrations. The glass workpiece was to be kept in an aluminium fixture so for absorbing the shocks the glass workpiece was kept on the rubber support as shown in figure 3.8.

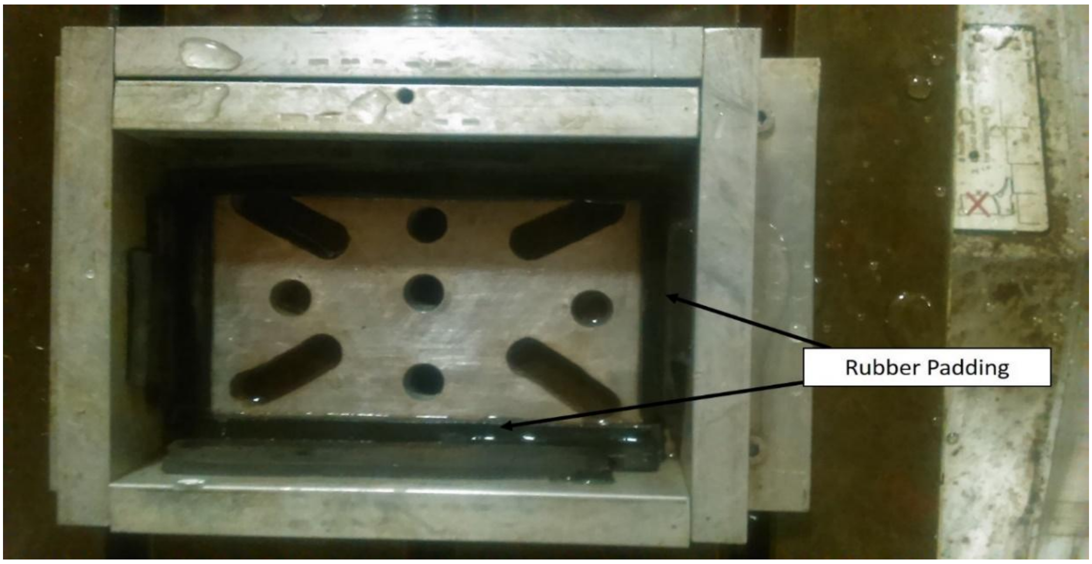


Figure 3.8: Support to the workpiece

After the clamping of the workpiece, the programming was fed to the controller unit of the machine. For cooling the workpiece and the tool, water was used a coolant which was supplied from outside with the made arrangement.

3.4 Rotary Ultrasonic Milling of microchannels

The experimentation was completed in two stages as given underneath:

1) The beginning stage included the trial experiments to recognize the imperative processing parameters for the study and to remove the undesirable parameters from the study.

2) The second phase involved carrying out actual milling operation using the milling parameters identified for the study.

3.4.1 Trial Experiment

The trial experiments were performed by various process parameters over a scope of values and after that concentrating their impact on the face milling process. Machining parameters which fluctuated were cutting speed, axial depth of cut, vibration frequency and amplitude. The process parameters that were used are Speed 2500-5000 rpm, Feed 3-10 mm/min and Amplitude 0-20 µm. Straight channels were fabricated with these parameters (figure 3.10) so that the difference between conventional and RUM can be categorized and proper selection of the parameters can be done for the DOE. The experiments were also performed on the work pieces of 1.3 mm but the glass was unable to sustain the vibrational forces and broke down into pieces as shown in figure 3.11. The serpentine microchannel was fabricated and firstly it was found the dimensional inaccuracy because of inaccurate clamping of the workpiece and uneven rubber padding as shown in figure 3.9.

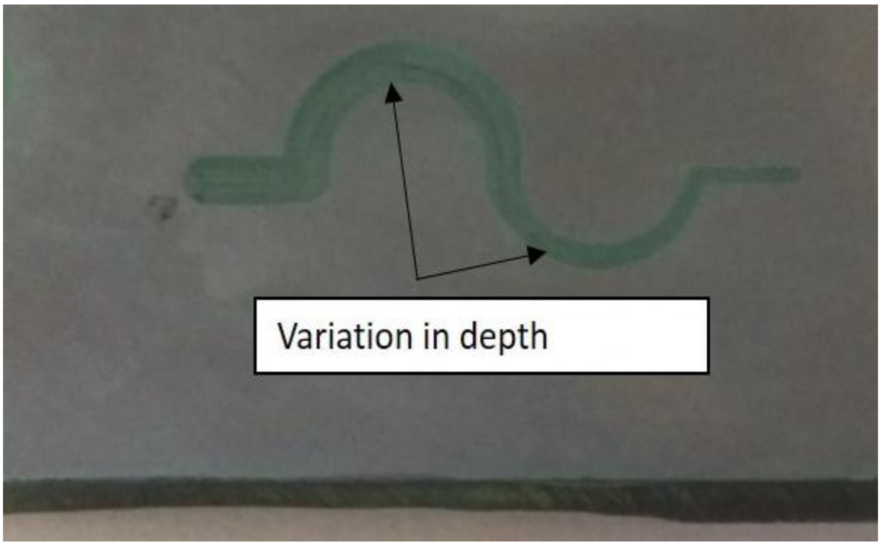


Figure 3.9: Trial experiment of serpentine microchannel

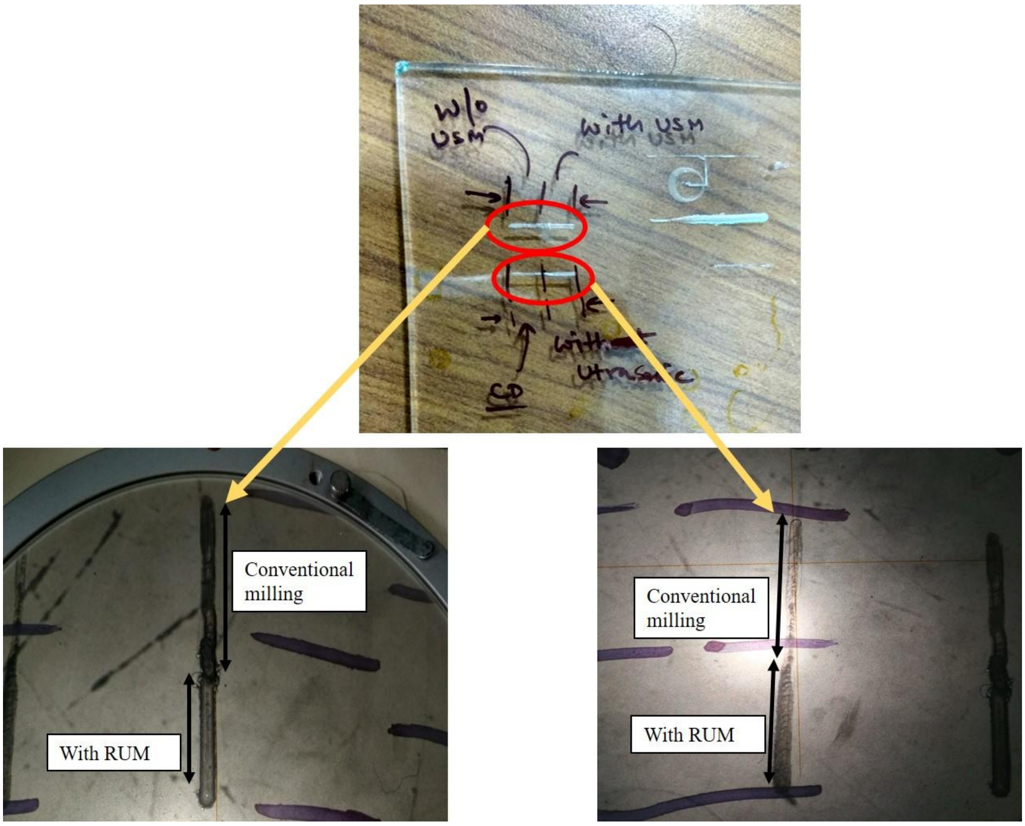


Figure 3.10: Trial Experiment with RUM and conventional

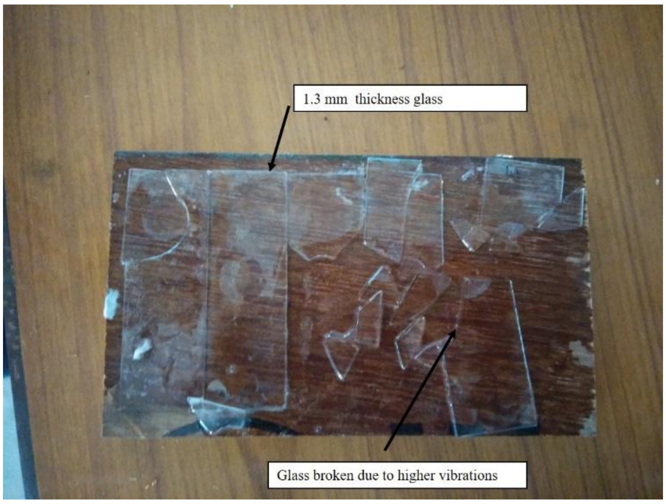


Figure 3.11: Broken glass of thickness 1.3 mm

3.4.2 Experimentation

After the preliminary experiments, the fabrication of the microchannel was done with some constant parameters with both the machining processes i.e. RUM and conventional technique. The parameters which were selected are mentioned in Table 3.4. The difference in the images can be easily seen in figure 3.12 which were taken with the help of profile projector (Nikon V 10A).

Table 3.4: Factors for fabricating microchannels

Sr. No.	Factors	Conventional	Rotary ultrasonic milling
1.	Speed (rpm)	3000	3000
2.	Feed (mm/min)	3	3
3.	Amplitude (μm)	NA	20

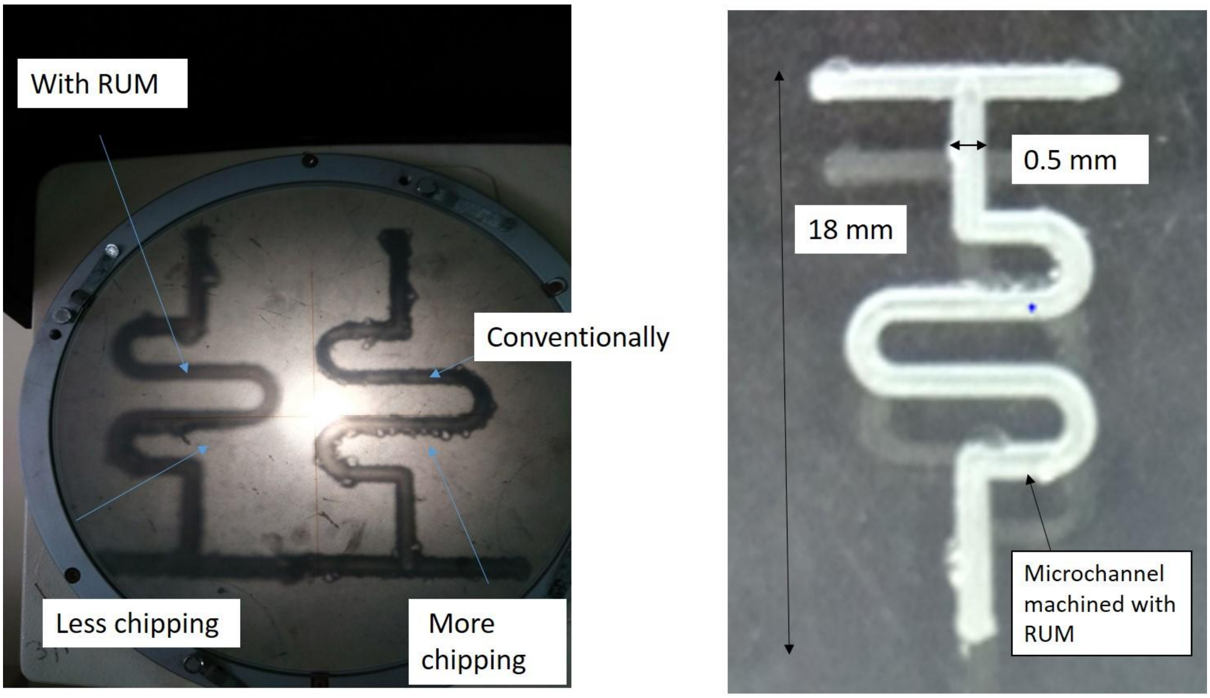


Figure 3.12: Machined by RUM and conventionally

As it was observed from the experiments that RUM has the potential to fabricate the microchannels more precisely than the conventional method so further DOE was used to know much about the output parameters which are described in the further sections.

3.4.3 Parameter Selection

From the performed screening tests, machining limitations and working constraints recognized processing parameters were-

1) Speed
2) Feed Rate
3) Amplitude

These parameters were chosen for further study. While different parameters, for example, material thickness, depth of cut and coolant pressure were kept consistent. Coolant was given around the tool and the surface of the workpiece. There are substantial theoretical relations that interface the parameters that were chosen for the study and the parameters that were eliminated in the screening phase.

The levels of every parameter were settled in view of the screening tests done at first and the theoretical estimations based on the relations accessible.

The lists of factors studied with their levels are given in Table 3.5.

Table 3.5: Control variables and their levels

Sr No.	Factor	Level 1	Level 2	Level 3
1	Speed (rpm)	2500	3500	4500
2	Feed (mm/min)	3	4	5
3	Amplitude (µm)	5	10	20

The effect of process parameters was measured on the following performance characteristics:

1) Tool wear.
2) Surface roughness.
3) Chipping size.

3.4.4 Measurement of the tool wear

Measurement of the tool wear was done manually with the help of profile projector (Nikon V 10A) which is situated in Thapar University as shown in figure 3.15. Firstly the initial reading of each tool was recorded before the machining process. Then after the machining process, the readings of both, the lateral as well as longitudinal wear were noted down.

3.4.5 Measurement of surface roughness

The surface roughness of the machined channel was measured with the help of Mitutoyo Sufjet sj 301 in Maharishi Markandeshwar University, Mullana University Road, Mullana, Ambala. The surface roughness of the machined glass serpentine microchannel was measured inside the depth.

Figure 3.13: Nikon Profilometer used to measure tool wear

3.4.6 Measurement of chipping size

Chipping size was measured with the help of profile projector manually at Thapar University as shown in figure 3.16. On the fabricated channel, different points were selected where the readings were noted and then an overall average was calculated for the measurement of chipping size.

Figure 3.14: Profilometer to measure chipping size

3.4.7 Selection of appropriate orthogonal array:

Out of the standard orthogonal array available in Taguchi design, L9 orthogonal array has been chosen for the experiments. Each of the array is implied for a particular number of autonomous plan factors and levels. The L9 orthogonal array is implied for understanding the effect of 4 independent factors each having 3-factor level values. In addition, there is no loss in the orthogonality of the array if more than one column is not used. L9 array is presented in Table 3.6.

Table 3.6: L9 array in Taguchi

Experiment No.	A	B	C
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

3.4.8 Actual fabrication process:

Rotary ultrasonic milling for the fabrication of serpentine microchannels was carried out as per the L9 orthogonal array shown in Table 3.6. A total of 9 experiments were conducted. Parameters for each experiment are listed in Table 3.7. The images were observed with the help of profilometer at Thapar University. In the images, the chipping can be easily distinguished as shown in figure 3.14 (a-i).

Figure 3.15: Rotary ultrasonic milling of microchannels

Table 3.7: Factors considered for fabricating serpentine microchannels

Experiment No.	Spindle speed (rpm)	Feed rate (mm/min)	Amplitude (µm)
1	2500	3	5
2	2500	4	10
3	2500	5	20
4	3500	3	10
5	3500	4	20
6	3500	5	5
7	4500	3	20
8	4500	4	5
9	4500	5	10

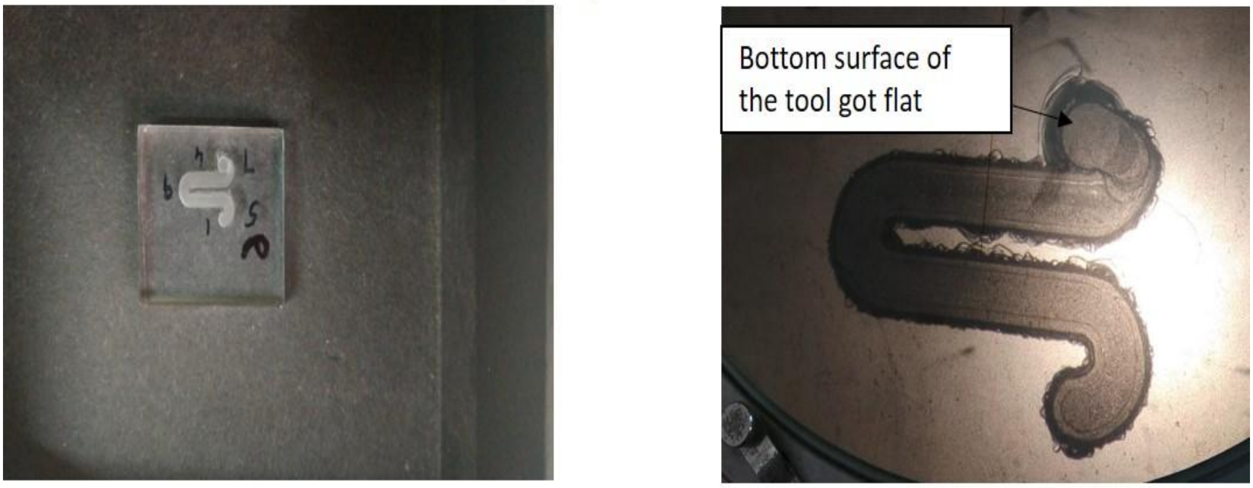
(a) Experiment 1

(b) Experiment 2

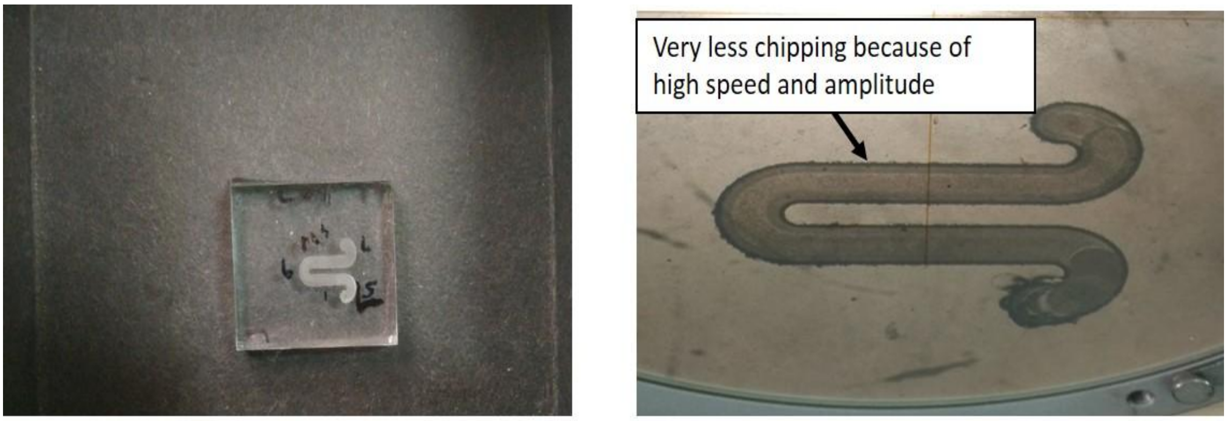
(c) Experiment 3

(d) Experiment 4

(e) Experiment 5

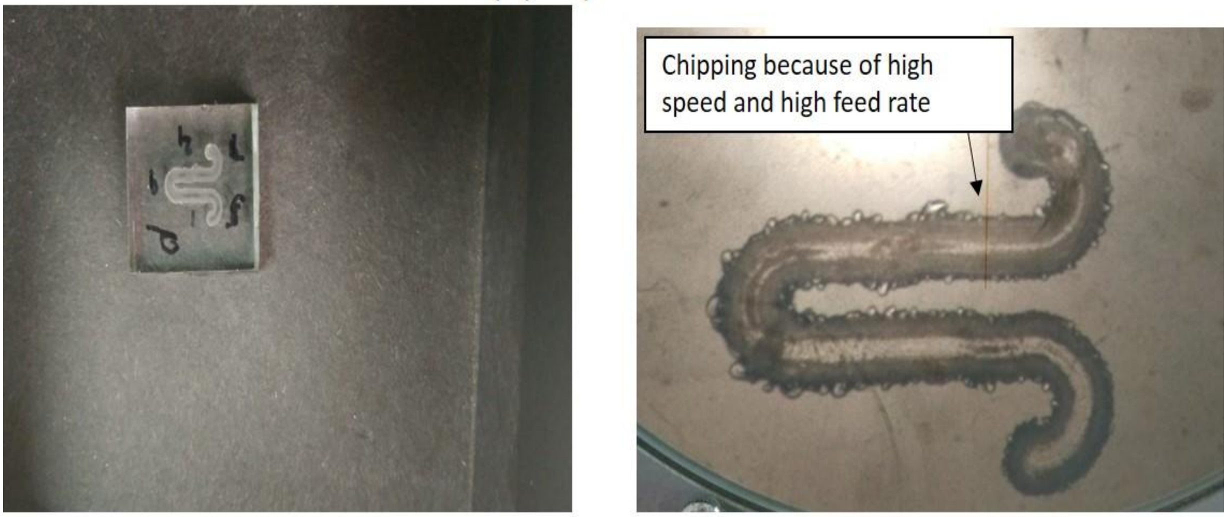


(f) Experiment 6



(g) Experiment 7

(h) Experiment 8



(i) Experiment 9

Figure 3.16: (a- i) Profilometer images of microchannels fabricated with different parameters

Chapter 4

Results and Discussions

After performing the experiments the values have been collected and has been analyzed by 'Minitab 17' software. This chapter contributes the experimental results analysis and discussions of the experiments. The critical analysis is done to find the trend and effect of input parameters on output parameters. The effect of each input parameters like speed, feed rate and amplitude on the tool wear, surface roughness and edge chipping has been discussed.

4.1 Results

The values obtained after every experiment for several output parameters have been registered in several Tables, i.e. Table 4.1 (Tool wear), Table 4.2 (Surface roughness) and Table 4.3 (Chipping size).

Table 4.1: Results for Tool Wear

Experiment No.	**Speed (rpm)**	**Feed rate (mm/min)**	**Amplitude (µm)**	**Tool wear (mm) 1**	**Tool wear (mm) 2**	**Tool wear (mm) 3**	**Average Tool wear (mm)**	**SN Ratio for Tool wear**
1	2500	3	5	0.56	0.63	0.7	0.63	4.0132
2	2500	4	10	0.65	0.73	0.77	0.71	2.9748
3	2500	5	20	0.95	1.5	0.98	1.1	-0.8279
4	3500	3	10	0.58	0.65	0.72	0.65	3.7417
5	3500	4	20	0.93	0.75	0.99	0.86	1.3100
6	3500	5	5	0.61	0.55	0.65	0.6	4.4370
7	4500	3	20	0.24	0.3	0.41	0.32	9.8970
8	4500	4	5	0.09	0.11	0.15	0.11	19.1721
9	4500	5	10	0.13	0.25	0.17	0.18	14.8945

Table 4.2: Results for Surface Roughness

Experiment No.	Speed (rpm)	Feed rate (mm/min)	Amplitude (μm)	Surface roughness (μm) 1	Surface roughness (μm) 2	Surface roughness (μm) 3	Average Surface roughness (μm)	SN Ratio for Tool wear
1	2500	3	5	0.56	0.84	0.63	0.68	3.34
2	2500	4	10	0.79	0.89	0.97	0.89	1.01
3	2500	5	20	1.1	0.99	1.6	1.3	-2.3
4	3500	3	10	0.69	0.78	0.66	0.72	2.85
5	3500	4	20	0.9	0.65	0.8	0.78	2.15
6	3500	5	5	0.65	0.83	0.63	0.7	3.09
7	4500	3	20	0.34	0.54	0.43	0.44	7.13
8	4500	4	5	0.64	0.54	0.43	0.54	5.35
9	4500	5	10	0.37	0.47	0.65	0.5	6.02

Table 4.3: Results for Chipping Size

Experiment No.	Speed (rpm)	Feed (mm/min)	Amplitude (μm)	Chipping size (mm) 1	Chipping size (mm) 2	Chipping size (mm) 3	Aver-age chipping size (mm)	SN ration for chipping size
1	2500	3	5	0.25	0.37	0.35	0.32	9.897
2	2500	4	10	0.33	0.41	0.39	0.37	8.636
3	2500	5	20	0.43	0.35	0.4	0.39	8.1787
4	3500	3	10	0.2	0.25	0.23	0.21	13.5556
5	3500	4	20	0.15	0.225	0.19	0.2	13.9794
6	3500	5	5	0.4	0.28	0.39	0.35	9.1186
7	4500	3	20	0.09	0.15	0.11	0.12	18.4164
8	4500	4	5	0.19	0.11	0.14	0.15	16.4782
9	4500	5	10	0.15	0.28	0.17	0.2	13.9794

4.2 Effect of process parameters on tool wear

It is found that tool wear during the milling of the serpentine microchannels is dependent on the input variables. Experimental results are represented in Table 4.1. The average values of mean and S/N ratio are plotted in figure 4.1 and 4.2 respectively. The quality characteristics is 'smaller is better' type.

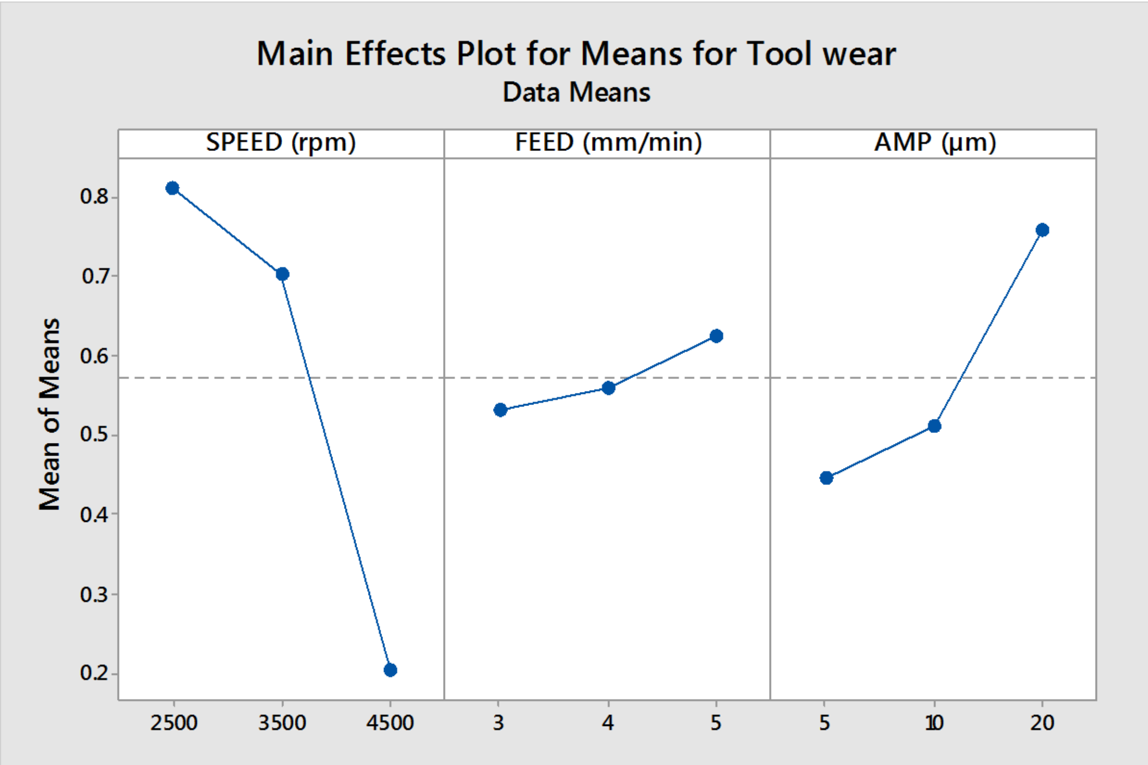


Figure 4.1: Main effect graph for tool wear

From the above graphs, it can be seen that as the spindle speed is going on increasing there is a continuous decrease in the tool wear. There is maximum tool wear at 2500 rpm and minimum tool wear at 4500 rpm.

As the feed rate is increasing there is a rapid increase in the tool wear. From the figure 4.1 it can be observed that at 3 mm/min there is least tool wear but as the feed rate is at 5 mm/min the value is maximum. The reason behind this is that at high feed rate the tool strikes the workpiece with a high velocity which further shear off the tool more frequently.

From the main effect diagram for amplitude with respect to tool wear as the amplitude is increasing the graph for tool wear is also going up. The tool wear is seen to be maximum at 20 µm and minimum at 5 µm. The reason is that in RUM the tool oscillates in vertical direction so as the vibrations keep on increasing the tool also starts striking the workpiece with higher velocity. Therefore the tool gets worn off in longitudinal and lateral direction.

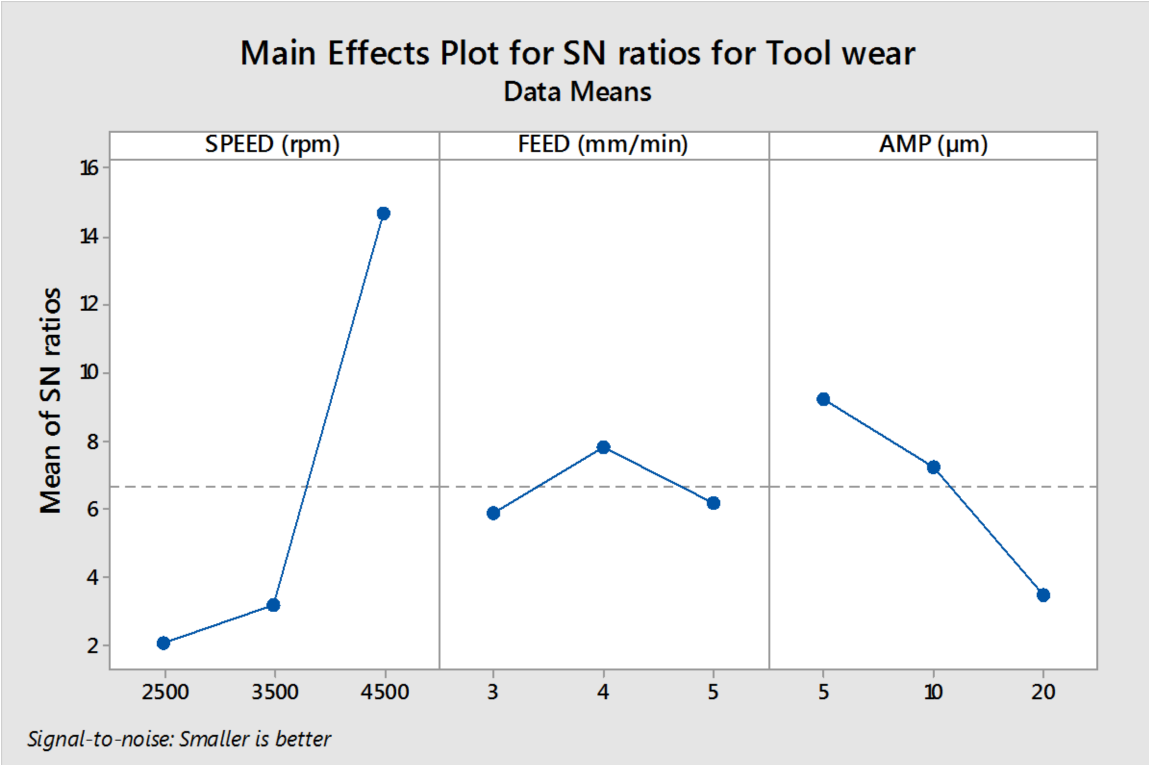


Figure 4.2: Main effect graph for S/N ratio of tool wear

Table 4.4 shows the response Table for tool wear. From this Table it can be observed that how much the input parameters affect the tool wear. Here, according to the rank the effect of variables on tool wear are speed, amplitude and feed. It means that speed plays the major role in tool wear whereas the feed has the least effect in comparison to the taken parameters. It is also represented by pie chart shown in figure 4.3.

Table 4.4: Response Table of means for tool wear

Level	**Speed (rpm)**	**Feed (mm/min)**	**Amplitude (μm)**
1	0.8133	0.5333	0.4467
2	0.7033	0.56	5133
3	0.2033	0.6267	0.76
Delta	0.61	0.0933	0.3133
Rank	1	3	2

Table 4.5, represent all the significant variables and their present contribution on tool wear in ANOVA for 95% confidence level. It is observed that speed 77.19%, Amplitude 19.8% and feed 1.688% of contribution on the tool wear.

Table 4.5: ANOVA for mean of tool wear

Source	DOF	Seq SS	Adj MS	F	P	% contribution
Speed (rpm)	2	0.6342	0.3171	63	0.016	77.19
Feed (mm/min)	2	0.01387	0.006933	1.38	0.421	1.688
Amp (µm)	2	0.16347	0.081733	16.24	0.058	19.8
Residual error	2	0.01007	0.005033			1.22
Total	8	0.8216				

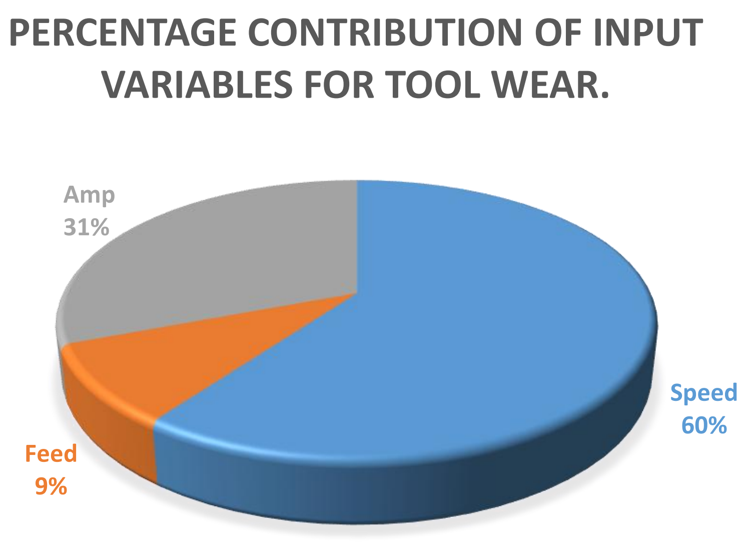


Figure 4.3: Representation of percentage contribution of response table for tool wear

4.3 Effect of process parameters on surface roughness

The main effect plot for surface roughness with S/N ratio is plotted in figure 4.4 and 4.5 respectively. The quality characteristics is of ‘smaller is better’ type.

It is clear from the graph 4.4 that as the speed is increasing there is a decrease in the surface roughness because with the higher speed the material below the tool gets eroded very smoothly and gives better surface quality. As the feed rate and amplitude are increasing there is also an increase in the surface roughness because there are longitudinal vibrations in the rotary ultrasonic milling. In milling with RUM, the direction of motion of the tool is perpendicular. The cause for the increase in surface roughness can also be that the tool gets somewhat worn off from the bottom surface to it creates an uneven path the glass workpiece.

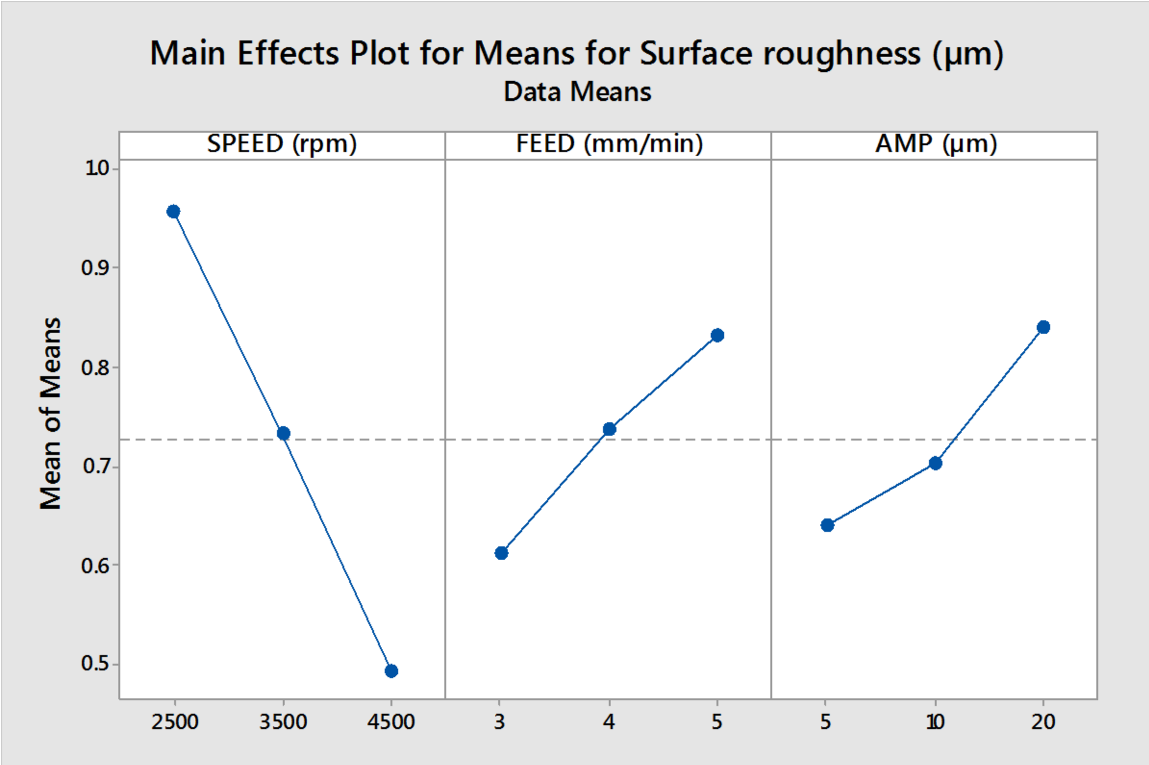


Figure 4.4: Main effect graph for surface roughness

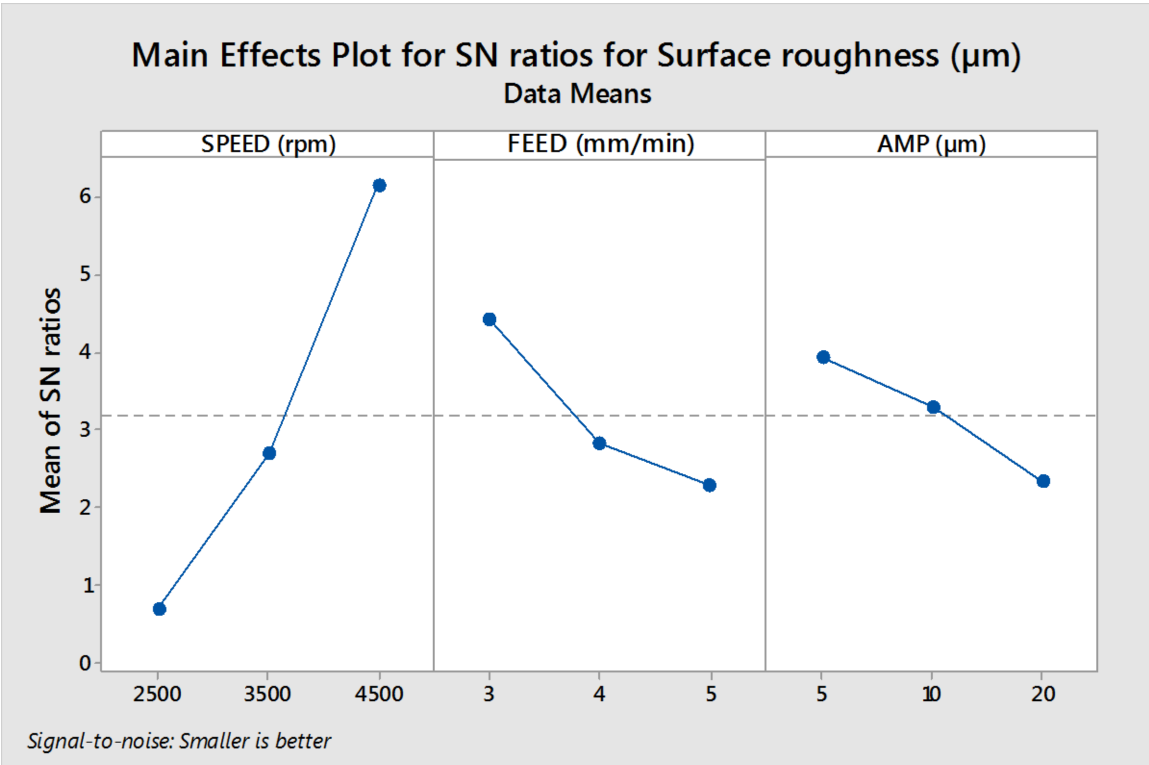


Figure 4.5: Main effect graph for S/N ratio of surface roughness

Table 4.6 shows the response Table for surface roughness where the rank of the parameters can be seen. Change in surface roughness is largely dependent on the spindle speed than the feed rate and amplitude. It is also shown with the help of pie chart as shown in figure 4.6.

Table 4.6: Response Table of means for surface roughness

Level	Speed (rpm)	Feed (mm/min)	Amplitude (µm)
1	0.9567	0.6133	0.64
2	0.7333	0.7367	0.7033
3	0.4933	0.8333	0.84
Delta	0.4633	0.22	0.2
Rank	1	2	3

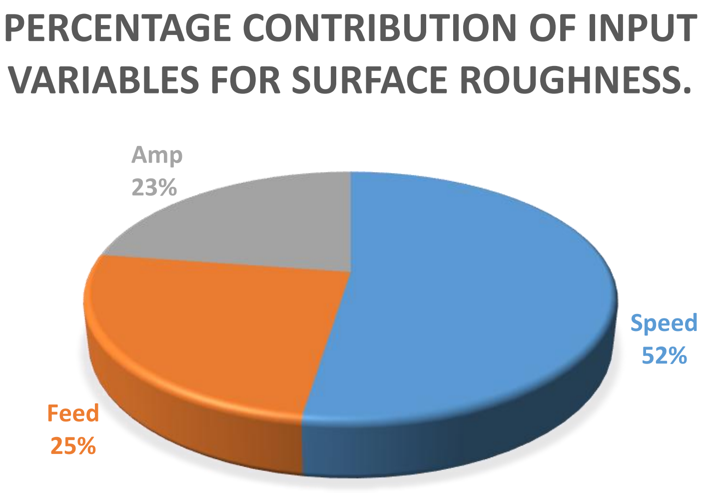


Figure 4.6: Representation of percentage contribution of response table for surface roughness

Table 4.7, represent all the significant variables and their present contribution on surface roughness in ANOVA for 95% confidence level. It is observed that speed 60.8%, Amplitude 13.7% and feed 11.8% of contribution on the surface roughness. Hence maximum surface roughness was found at 2500 rpm, feed 5 mm/min and amplitude 20 µm.

Table 4.7: ANOVA for mean of surface roughness

Source	DOF	Seq SS	Adj MS	F	% contribution
Speed (rpm)	2	0.32216	0.16108	4.49	60.8
Feed (mm/min)	2	0.07296	0.03648	1.02	13.7
Amp (µm)	2	0.06269	0.03134	0.87	11.8
Residual error	2	0.07176	0.03588		13.5
Total	8	0.52956			

4.4 Effect of process parameters for edge chipping size

It is observed that chipping size during fabrication of serpentine channels on glass depends upon the input variables. Experimental results are represented in Table 4.3. The average value of main effect of chipping size and S/N ratio are plotted in figure 4.7 and 4.8 respectively. The quality characteristics is ‘smaller the better type’.

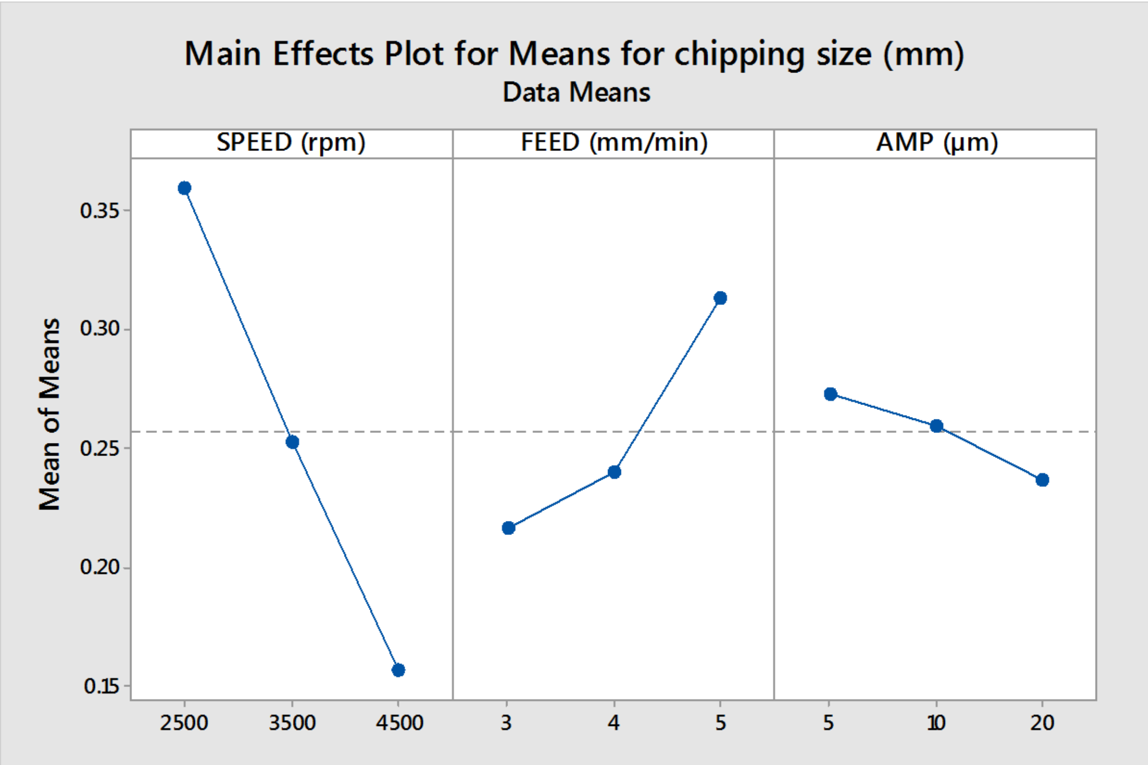


Figure 4.7: Main effect graph for chipping size

From the graph, it is observed that the chipping value decreases with the increase in speed. At 4500 rpm there is minimum chipping observed whereas at 2500 maximum chipping has been observed. The reason behind this is that at low speed the abrasives of the tool get in touch with the walls of the workpiece for more time than in the case of higher speed.

The increase in the feed rate results in the increase of the chipping size because with the feed rate there is cutting force also which is acting directly proportional on the workpiece.

As the amplitude is increasing the chipping size gets reduced. At higher amplitude i.e. 20 µm, there is less chipping as from the readings of Table 4.3 and the same can be observed in figure 3.17. The observation is consistent with the observation of Wang et al. [55].

Table 4.6 shows the response Table for surface roughness where the rank of the parameters can be seen. Change in surface roughness is largely dependent on the spindle speed than the feed rate and amplitude. It is also shown with the help of pie chart as shown in figure 4.6.

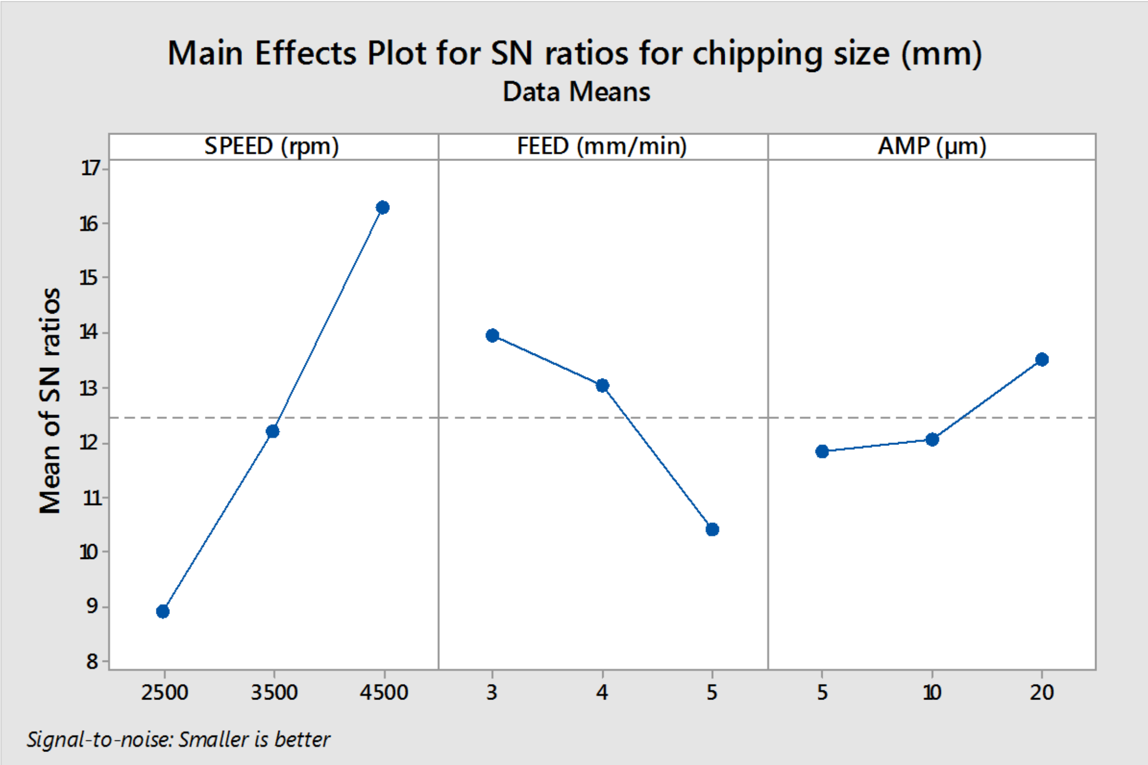


Figure 4.8: Main effect graph for S/N ratio of chipping size

Table 4.8 shows the response Table for edge chipping size where the rank of the parameters can be seen. Change in chipping size is largely dependent on the spindle speed than the feed rate and amplitude. Amplitude plays the least role in edge chipping size this has been explained with the help of modeling by Wang et al. [55]. It is also shown with the help of pie chart as shown in figure 4.9.

Table 4.8: Response Table of means for edge chipping size

Level	**Speed (rpm)**	**Feed (mm/min)**	**Amplitude (µm)**
1	0.36	0.2167	0.2733
2	0.2533	0.24	0.26
3	0.1567	0.3133	0.2367
Delta	0.2033	0.0967	0.0367
Rank	1	2	3

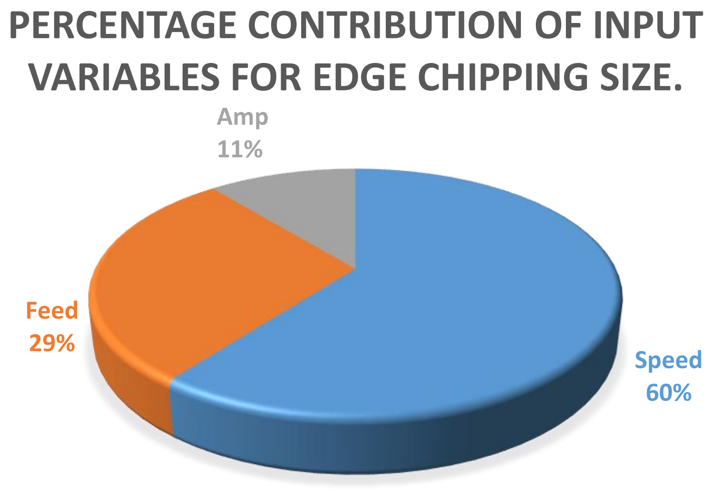


Figure 4.9: Representation of percentage contribution of response table for edge chipping size

The above pie chart shows the percentage contribution of each variable which shows its effect on the edge chipping. The chart shows that 60% of the credit goes to the spindle speed, then 29% of the credit belongs to the feed and the remaining is of amplitude. Table 4.9, represent all the significant variables and their present contribution on chipping in ANOVA for 95% confidence level. It is observed that speed 75.69%, Amplitude 18.6% and feed 2.52% of contribution on the surface roughness. Hence maximum surface roughness was found at 2500 rpm, feed 5 mm/min and amplitude 20 µm.

Table 4.9: ANOVA for mean of edge chipping size

Source	DOF	Seq SS	Adj MS	F	% contribution
Speed (rpm)	2	0.062067	0.031033	23.87	75.69
Feed (mm/min)	2	0.015267	0.007633	5.87	18.6
Amp (µm)	2	0.002067	0.001033	0.79	2.52
Residual error	2	0.0026	0.0013		3.17
Total	8	0.082			

4.5 SEM Characterization

4.5.1 Tool wear

Tool wear is found to be a significant parameter which results in the form accuracy of the machined part. On the other hand, form accuracy clears that to how much extent dimensions of the tool has been replicated on the working surface. To maintain the form accuracy it becomes very important to keep the shape and size of the tool unchanged which can be done by choosing the appropriate material of the tool. There are two types of tool wear namely: lateral and longitudinal wear. Lateral wear is responsible for tool diameter reduction as shown in figure 4.10 (a and b), where fig 4.10 (a) is the schematic view to tool reduction in diameter and fig 4.10 (b) is the image of the original tool which has been captured with the help of Nikon profile projector. Figure 4.10 (b) shows one of the tools by which machining of the glass serpentine microchannel has been done. The shapes of the tool slightly kept on increasing with respect to the bottom face of the tool. In figure 4.10 it can be seen that the on the upper side of the tool the diameter is more i.e. 0.698 mm and after reduction in diameter from the tip it went to 0.598 mm.

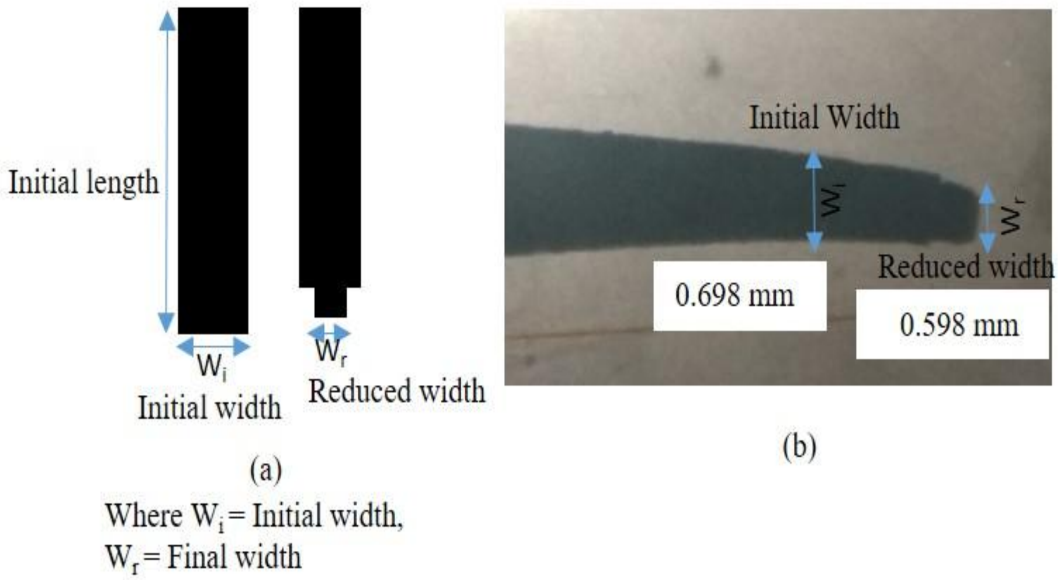


Figure 4.10: (a) Illustrative view of the tool; (b) Lateral reduction of the tool

The lateral wear occurred at the edges of the tool is because of rubbing of the abrasives between the walls of the workpiece and the tool. Whereas longitudinal wear was responsible for tool length reduction which was occurred because of micro chipping and cavitation phenomena. The schematic view, the fresh tool and the tool after longitudinal wear are shown in figure 4.11 whose images were observed with SEM. Fig 4.11 (b) shows the fresh tool whose initial length is 15.766 mm and in fig 4.11 (c) the length of the tool is reduced to 15.107 mm and the bottom of the tool is also worn off. In figure 4.11 (c) the tool wear is observed in the case of RUM and the working conditions were speed = 2500 rpm, feed = 3 mm/min and amplitude = 5 µm.

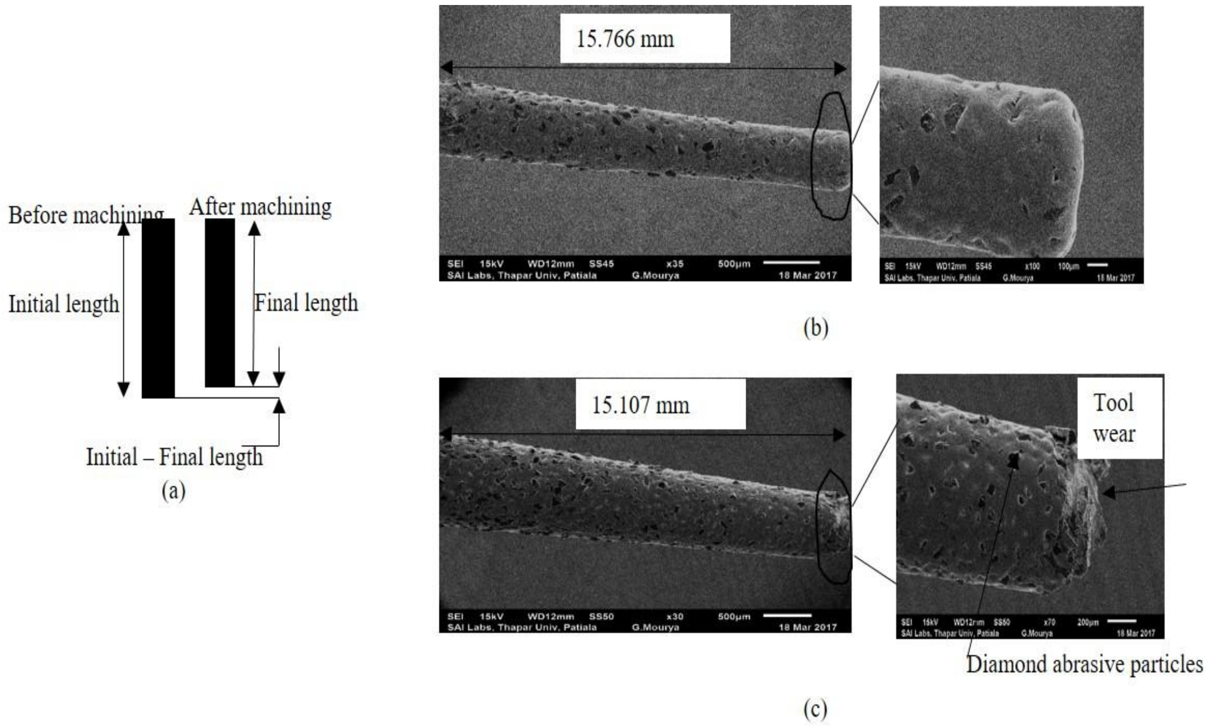


Figure 4.11: (a) Illustrative view of longitudinal wear; (b) Fresh tool; (c) Tool after machining the channel

4.5.2 Edge quality

SEM images have been taken of the glass workpiece after performing various experiments with their respective variables. Here the images show the edge quality that how much chipping is occurring at the walls of the workpiece.

Figure 4.12 shows the image of experiment 1 which was fabricated with parameters i.e. speed 2500 rpm, feed rate 5 mm/min and amplitude 5 µm. The image clearly shows that how much the chipping is going outside the edges of the walls of the fabricated serpentine microchannel. This is due to slow speed and high feed because of which there is great impact force on the glass substrate.

Figure 4.13 shows the image of experiment 4 in which ductile streak can be visualized which were the result of tool wear from the tip leaving its profile on the glass workpiece. Figure 4.14 shows the image of the best fabricated serpentine channel with the least chipping because of the parameters which were spindle speed 4500 rpm, feed rate 3 mm/min and amplitude 20 µm. Figure 4.15 is also near to the previous experiment only a little more edge chipping occurred during its fabrication. A crack can be observed that occurred due to the solid tool. Since, pointed edge of the tool and fatigue loading is included such sort of issue can be anticipated. Though, this type of crack was seen in this case only.

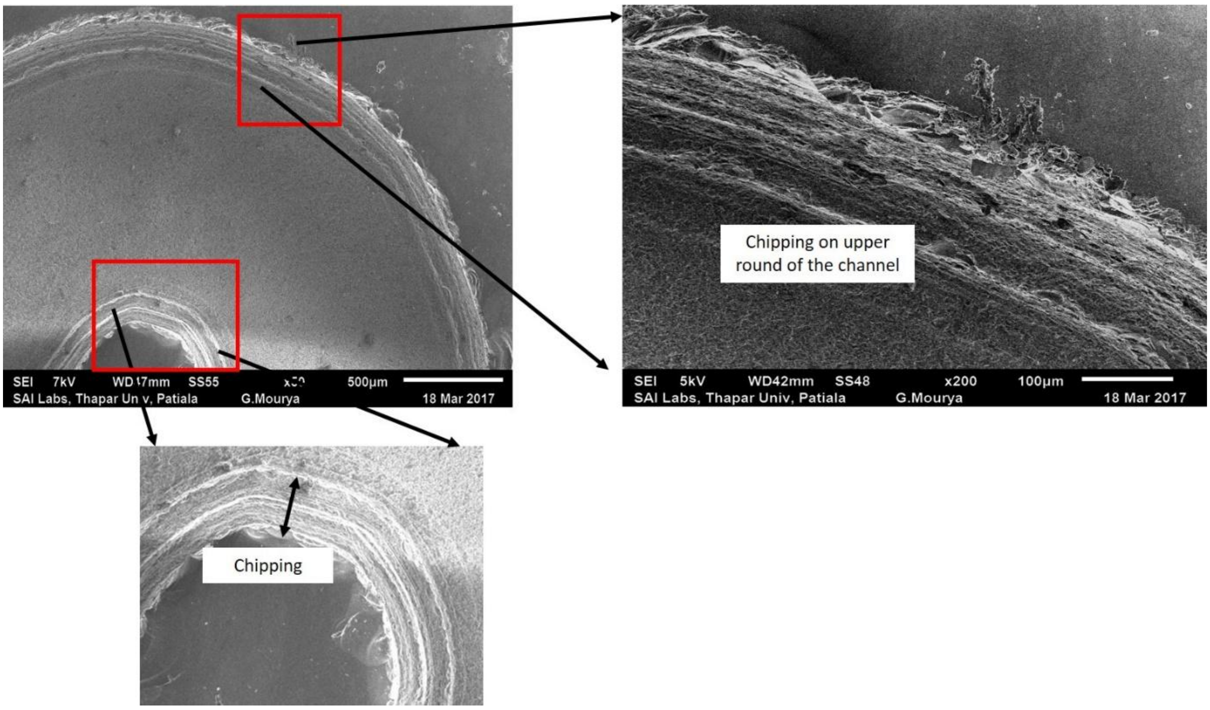


Figure 4.12: SEM image of experiment 1

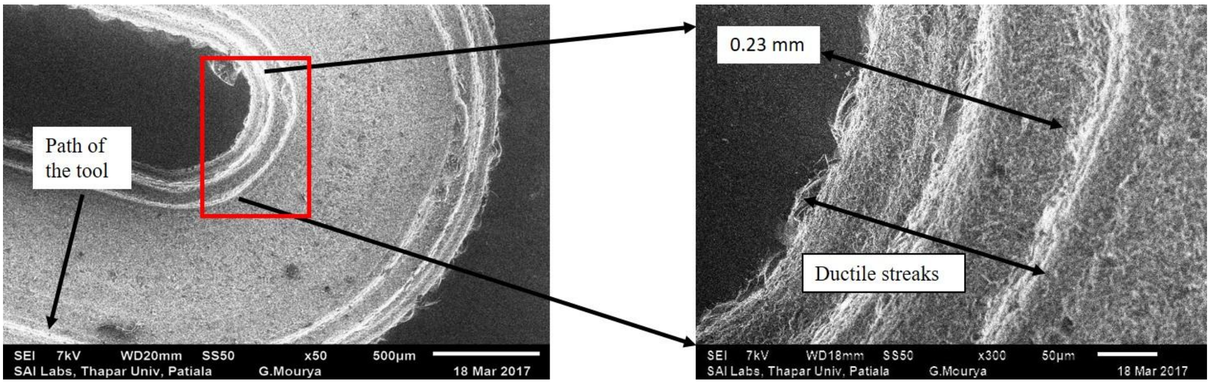


Figure 4.13: SEM image of experiment 4

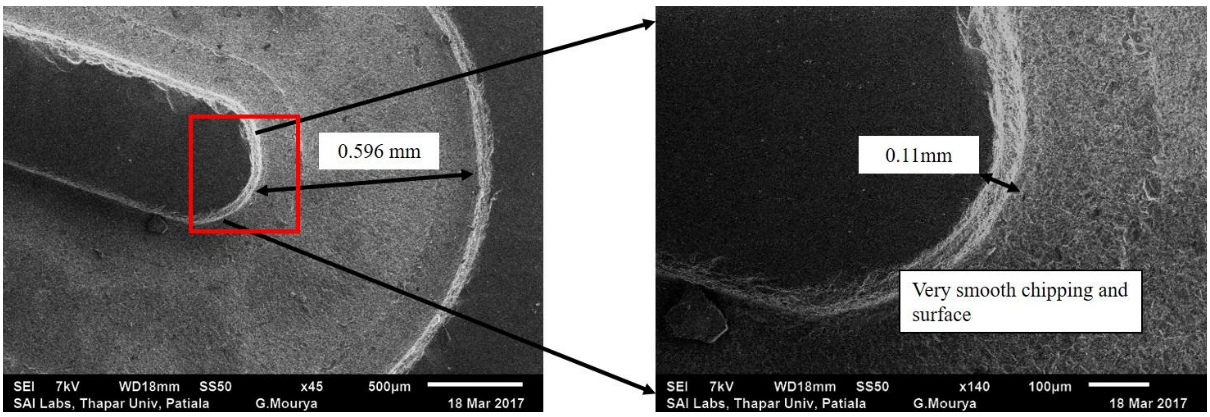


Figure 4.14: SEM image of experiment 7

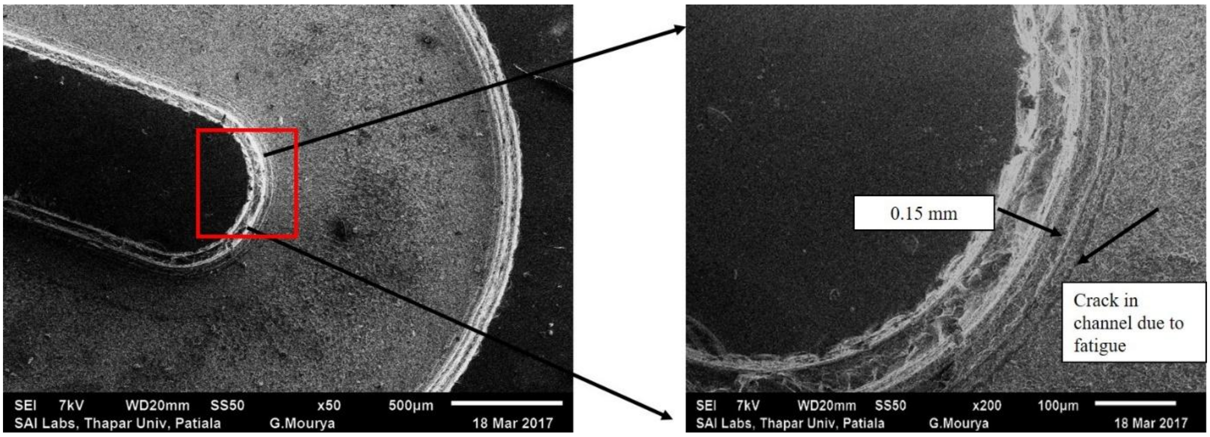


Figure 4.15: SEM image of experiment 8

Figure 4.16 shows the channel which was fabricated with conventional milling. The SEM image shows that there is stray cutting on the edges of the serpentine channel surface. These stray cutting can arise due to the deflection in the vibrating tool and also because of the deflected abrasive particles.

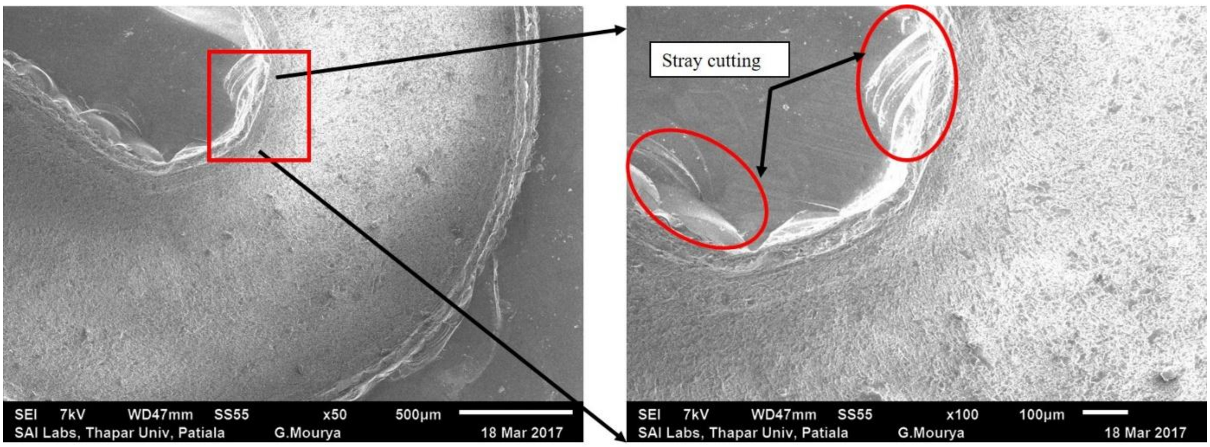


Figure 4.16: SEM image of channel fabricated with conventional milling

Chapter 5

Conclusion and Future Scope

5.1 Conclusion

After studying the effect of input parameters such as spindle speed, feed rate and amplitude exerted on tool wear, surface roughness and edge quality of the soda lime glass for the fabrication of serpentine microchannels with the help of rotary ultrasonic milling, the following conclusions are made:

1) Surface finish can be increased immensely by using the more precise abrasive size of the diamonds and by improving the material quality of the tool so that it may not get worn off easily.
2) The tool wear decreased with the increase in speed and increased as there was an increase in the feed rate and the amplitude.
3) The surface roughness also decreased as the speed increased and an increase was seen in the results as the values of feed rate and amplitude kept on increasing.
4) The edge quality decreased as the speed as well as the amplitude increased and the increase can be seen when the feed rate was increased.
5) Because of the longitudinal and lateral wear of the tool, there is a dimensional inaccuracy.
6) Spindle speed played the major role in all the output parameters which was followed by feed rate and amplitude in the case of surface roughness and edge quality. Whereas, in the case of tool wear after the spindle speed the next role was of amplitude than of feed rate.
7) The utilization of above proposed strategy will reduce the complex procedure of optimization of the glass milling and will support the resarchers to perform such experiments more precisely.

5.2 Future scope

Although present study considers rotary ultrasonic milling of serpentine microchannels but there is still a scope in the future investigation considering the vast potential of this technique. The following suggestions can be useful for the future work:

1) There can be drastic improvement in the surface finish with the use of exact abrasive size and ultrasonic power. Further, by adjusting these settings there can be an improvement in the tool wear and stray cutting will also get reduced.
2) For the improvement in the morphological properties the microchannels can be given heat treatment.
3) The vast majority of the microfluidics applications utilizes the well to hold the medium. Including well manufacturing into the process is a potential future opportunity for the research.
4) In the future study more process parameters can be taken for the study like cutting force and ultrasonic power.
5) Different materials can be machined with the rotary ultrasonic machine so that the other areas of engineering can also get benefit.

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