EXPERIMENTAL INVESTIGATIONS INTO ULTRASONIC MACHINING PROCESS FOR MICROMACHINING APPLICATIONS

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Award: Nil

PROFORMA – 1

"Statement of Originality"

I Santosh Kumar registered on 17th August 2016 do hereby declare that this thesis entitled "EXPERIMENTAL INVESTIGATIONS INTO ULTRASONIC MACHINING PROCESS FOR MICROMACHINING APPLICATIONS" contains literature survey and original research work done by the undersigned candidate as part of Doctoral studies.

All information in this thesis have been obtained and presented in accordance with existing academic rules and ethical conduct. I declare that, as required by these rules and conduct, I have fully cited and referred all materials and results that are not original to this work.

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This is to certify that the thesis entitled "**EXPERIMENTAL INVESTIGATIONS INTO ULTRASONIC MACHINING PROCESS FOR MICROMACHINING APPLICATIONS**" submitted by Mr. **SANTOSH KUMAR**, who got his name registered on 17th August 2016 for the award of Ph.D. (Engg.) degree of Jadavpur University, is absolutely based upon his own work under the supervision of **PROF. BISWANATH DOLOI and PROF. BIJOY BHATTACHARYYA** and neither his thesis nor any part of the thesis has been submitted for any degree/diploma or any other academic award anywhere before.

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PREFACE

Innovations in the fields of biomedical devices, aerospace, automobiles, energy, optics, semiconductors, electronics and communications have led to miniaturization of the parts and devices. Small sized devices and their component parts are desirable to keep things compact and portable. Thus, material and energy required for manufacturing reduces drastically. As a result the cost of production and environmental pollution is reduced. Small parts have lower inertia because of which production process needs lesser time. Consequently, the productivity increases.

Production of small parts requires different processes and systems capable of machining at micro scale. To manufacture functional micro parts and devices, tighter tolerances, higher accuracy and precision, superior surface integrity, improved repeatability and reliability are desirable constantly. These capabilities are limited by the existing technology. Consequently, constant advancement of the micro machining techniques is essential for fabrication of the micro parts and devices.

Micro machining refers to the capacity to create micro features with dimensions ranging from 1 µm to 999 µm, while the removal of material occurs at the micron level [3]. However, as defined by the Scientific Technical Committee of the Physical and Chemical Machining Processes of CIRP, acceptable dimension range for micro machining is 1 to 500 µm.

Ultrasonic machining (USM) is a non-conventional mechanical type material removal process in which material is removed by repetitive impact of abrasive particles carried in liquid medium on the work surface, by a shaped tool, vibrating at ultrasonic frequency. The application of ultrasonic energy for machining of engineering materials was first reported by Wood and Loomis in 1927. However, American engineer Lewis Balamuth invented the USM process in 1945. USM has been variously termed as ultrasonic drilling; ultrasonic cutting; ultrasonic dimensional machining; ultrasonic abrasive machining and slurry machining. From 1950s it has been commonly known as ultrasonic impact grinding or USM. In ultrasonic machining process, the converter transforms electrical energy into high frequency mechanical vibrations. The process parameters of USM includes the static pressure, vibration amplitude, vibration frequency, rotational speed of tool for rotary USM (RUM), diamond grit concentration, grit size, diamond and bond type, slurry concentration and coolant etc.

The basic principle of ultrasonic micromachining (USMM) is similar to USM but the micro-tool is used in USMM for micro machining applications. The USMM uses the mechanical vibration at ultrasonic frequency about 20 kHz to 40 kHz and some times more than 40 kHz. The micro-tool is mechanically vibrated with ultrasonic frequency and amplitude. The mixture of irregular shaped abrasive particles with liquid medium is supplied into the gap between the tool and workpiece. As the vibrating tool tip strikes the free abrasives in the slurry, these particles attain momentum and impact upon the target workpiece. Material is removed from the impact zone due to continue hammering and micro-chipping by the mechanical abrasion of the hard micro abrasive particles. Further, collapsing of the gas bubbles, also called cavitations, can play a key role in material removal at micro level. Water is usually preferred as the liquid medium. The chemical impurities present in the slurry medium can cause immediate degradation of the work material resulting in loss of material. A continuous supply of abrasive slurry between workpiece and tool keeps away the debris from the machining zone and refills the gap with fresh slurry.

Various research works have been reported on USMM process. The above discussions clearly reflect that development of micro shapes through USMM is a promising field for micro features and micro structure development scenario and has more to offer in near future. Moreover, fabrication of micro tool, micro hole, micro feature with high aspect ratio with USMM are more challenging and to get further insight, some reviews have been presented in this section to depict the current research trends in USMM and related areas.

Research on ultrasonic machining at the macro level has been already reported in various fields of industrial applications. However, downscaling of USM to micro level is essential to produce miniature features on parts of hard and brittle materials. Although some research work activities have already been carried out on ultrasonic micromachining process, in-depth studies and experimental investigation into ultrasonic micromachining of various engineering materials are very much demanded. Extensive research and technical improvement are needed to transform this USM technology into a capable and well-received technology for the successful adoptability of this process in fulfilling the needs of the modern micro-manufacturing industries. Keeping the above considerations in view, the objectives of the present research work have been moduled as follows:-

(a) To study in depth ultrasonic micro machining setup for carrying out experimental investigation. To develop and modify micro tool holding and work holding unit of the existing USM setup which can be capable of performing investigation in the micro domain for micro machining of different ceramics.

(b) To develop cylindrical micro tools, multi tips micro tool and array of square micro tool for fabrication of micro holes, multiple micro channels and array of square micro holes by using USMM.

(c) To perform the experiments utilizing developed micro tools on micro-USM setup for generating micro holes on quartz. Experimental results will be further analyzed to study the influences of ultrasonic micromachining (USMM) process parameters on various responses.

(d) To develop empirical models for different responses, e.g. material removal rate (MRR), overcut and taper angle of micro holes on quartz during ultrasonic micromachining (USMM) based on Response Surface Methodology (RSM) utilizing experimental results and to analyse the influences of process parameters on the responses through response surface plots and contour plots based on developed empirical models.

(e) To perform single objective as well as multi objective optimization of response characteristics for determining optimal machining parametric combination in order to obtain the desired micromachining performance characteristics of ultrasonic micromachining (USMM) for generating micro holes.

(f) To perform the experiments utilizing developed multi tips micro tool on micro-USM to produce multiple micro channels on quartz as well as zirconia and also to analyze the influences of ultrasonic micromachining (USMM) process parameters on responses and also to analyse various defects of machined surface through observation of micrographs.

(g) To perform experiments utilizing developed array of micro tool on micro-USM to produce array of square micro holes on quartz and also to analyze the influences of ultrasonic micromachining (USMM) process parameters on responses and also to study various faults of machined surface through observation of micrographs.

The thesis is structured in a well-organized manner into eight chapters. A brief outline of each chapter is provided as below:

Chapter 1 outlines an overview of micromachining processes, need of micro machining, types of non-traditional micro machining processes, ultrasonic micromachining process. Literature review of previous work done including recent developments of ultrasonic machining and recent reports from researches in the areas of micro ultrasonic machining processes, role of USMM process parameters and their influence on the machining performance.

Chapter 2 outlines about the details of ultrasonic micromachining setup and components of ultrasonic micro machining setup. It also highlights the development of micro tool for ultrasonic micro machining for fabricating different micro features on quartz and zirconia.

Chapter 3 highlights the experimental investigation into USMM on quartz. Influences of process parameters on responses of ultrasonic micro machining on quartz have also been discussed.

Chapter 4 highlights the development of empirical model based on response surface methodology and parametric analysis for achieving better ultrasonic micro-machining characteristics based on response surface plots. The results of parametric optimization of ultrasonic micro machining for generating micro hole on quartz have also been included. The single objectives as well as multi objective optimization of responses have been performed to find the optimal USMM process parameters for achieving maximum MRR, minimum overcut and minimum taper angle of through micro hole on quartz.

Chapter 5 includes the results of experimental investigation into ultrasonic micro-machining (USMM) process for producing micro channel on quartz using developed multi tips micro tool. Influences of process parameters on responses of ultrasonic micro machining for generation of multiple channel on quartz have been also discussed through experimental results, graphs, and SEM micrograph.

Chapter 6 represents the discussion on experimental investigation into ultrasonic micro-machining (USMM) process for producing micro channel on zirconia using developed multi tips micro tool. Influences of process parameter on responses of ultrasonic micro machining for generation of multiple channel on zirconia have been also presented through experimental results, graphs, and SEM micrograph.

Chapter 7 includes the experimental analysis on ultrasonic micro-machining process for producing array of micro hole on quartz using developed multi tips tool. Influences of process parameter on responses of ultrasonic micro machining for generating array of micro hole on quartz have been also discussed through experimental results, graphs, and SEM micrograph.

Chapter 8 provides conclusions on the results and discussion found from various experiments. Recommendation for the future work is also outlined in this chapter.

The author has made contributions to present the research work by investigating the machining of quartz and zirconia for producing micro holes, micro channels, and array of micro holes on quartz as well as zirconia utilizing cylindrical shaped and multiple tips micro tools. Researchers, scientists, and engineers who are working on ultrasonic machining in the micro domain with various hard and brittle materials can greatly benefit from this experimental investigation and debate. Additionally, it can serve as guidance for the making of microtools for ultrasonic machining for industrial uses in the micro domain for the fabrication of various complex microfeatures with various hard and brittle materials, which have potential uses in biomedical science, microfuel cells, the cooling of MEMS components, optical interconnection, inkjet printers, aerostatic air bearing systems, etc.

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VITA

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Dedicated to almighty, my parents, teachers, wife and well wishers for their endless support and love

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INTRODUCTION

1.1 Introduction

Innovations in the fields of biomedical devices, aerospace, automobiles, energy, optics, semiconductors, electronics and communications have spurred a remarkable trend towards miniaturization. This transformative process has resulted in the creation of smaller, more compact and portable devices and components. The drive for small-sized innovations has yielded significant benefit, particularly in the realm of material and energy consumption during manufacturing.

As a consequence, there has been a drastic reduction in the material and energy required for the production of these devices. This, in turn, has led to a notable decrease in the overall cost of manufacturing and operation, while also contributing to a reduction in environmental pollution. The adoption of small parts has the added advantage of lowering inertia in the production process, resulting in more efficient manufacturing and shorter production times. Consequently, this boost in productivity has become a hallmark of these advancements in various industries.

The desirability of small-sized devices and their components lies in their ability to maintain compactness and portability. This inherent characteristic leads to a significant reduction in the material and energy needed for manufacturing. As a direct consequence, the overall cost of production, operation, and environmental impact experiences a substantial decrease. Moreover, the use of smaller parts results in lower inertia during the production process, effectively reducing manufacturing time and ultimately enhancing productivity.

The production of small parts necessitates specialized processes and systems capable of micro-scale machining [1]. Achieving functional micro parts and devices requires strict adherence to tighter tolerances, higher accuracy, precision, superior surface integrity, and improved repeatability and reliability consistently. However, the existing technology has its limitations in providing these capabilities. Therefore, it becomes imperative to continually advance micro machining techniques to meet the demands of fabricating micro parts and devices successfully. Since the requirement for realising micromachining is as straightforward as the one just explained, a variety of machining techniques can be used [2].

Micro machining refers to the capacity to create micro features with dimensions ranging from 1 µm to 999 µm, while the removal of material occurs at the micron level [3]. However, as defined by the Scientific Technical Committee of the Physical and Chemical Machining Processes of CIRP, acceptable dimension range for micro machining is 1 to 500 µm.

Research in micro-manufacturing focuses on developing techniques for machining materials including electrical discharge machining (EDM), electrochemical machining (ECM), laser beam machining (LBM), ultrasonic machining. The machinability of the materials used for making the devices and parts depend on their characteristic properties. Some materials such as glass, quartz, silicon, ceramics, titanium alloys are difficult to machine by the traditional machining techniques because of their high hardness, brittleness and toughness. Non-traditional machining techniques including ultrasonic machining can be used to machine such hard and brittle materials. Satisfactory surface finish with close tolerances and dimensions can be achieved by ultrasonic micro machining (USMM) on hard and brittle materials [4]. Every hard and brittle material can be machined using ultrasonic micro machining process [5]. Some of the applications of typically used hard and brittle materials are listed in the Table 1.1.

In the realm of micro-manufacturing research, the focus lies in developing machining techniques for various materials, such as electrical discharge machining (EDM), electrochemical machining (ECM), laser beam machining (LBM), and ultrasonic machining. The machinability of these materials depends on their specific properties. Certain materials like glass, quartz, silicon, ceramics, and titanium alloys pose challenges for traditional machining techniques due to their high hardness, brittleness, and toughness.

To overcome these challenges, non-traditional machining techniques, including ultrasonic machining, come into play for machining such hard and brittle materials. Ultrasonic micro machining (USMM) proves effective in achieving satisfactory surface finish with close tolerances and dimensions on these materials [4]. Every hard and brittle material can be machined using ultrasonic micro machining process [5]. Table 1.1 illustrates some of the typical applications of these hard and brittle materials.

Table 1.1 Typical applications of hard and brittle materials [6]

Materials	**Applications**
Glass	Micro-fluidic systems, monolithic grid structure, lab-on- chip, accelerometers, membrane in fuel cell, micro device for blood analysis
Quartz crystal	Pressure sensor, accelerometers, optical chopper, filter and sensor
Lead Zirconate Titanate (PZT)	Medical imaging transducers, Actuators and transducers
Silicon Carbide	Vibration sensor, high temperature pressure sensor, micro gas turbine engine
Silicon Nitride	Solid immersion lens, biaxial pointing mirrors
Alumina	Vacuum windows, Micro gimbal, bilayer lipid membrane sensor

1.2 Need of micro machining

The terminology "micromachining" describes process used to create 3D structures on a micrometre size. Recent years the needs of micro products for societies motivate us to introduce more and more micro parts/products which are used in variety of industries. Considerably lowering an item's size and weight can significantly increase its value and convenience. The trend towards the miniaturization, micromachining becomes extremely important to manufacture micro parts/products. Semiconductor devices, electrical circuits, integrated circuit packages, fuel injection nozzles for automobiles, biotechnology, biomedical equipments, surgery tools, optics, aeronautics, micro-fluidic systems, lab-on- chip, micro sensors, actuators and transducers etc are some examples of micro products. Micro machining is one of the main technologies that can make it possible to realise all of the aforementioned needs for microproducts, and industries with such requirements are increasing rapidly.

Through the miniaturization of medical instruments, painless diagnosis and surgery are now achievable in the medical profession. The design and construction of tools, tool holders, cutting tools, and electrodes are needed for machining these miniature parts. Through a study of micromachining processes, it becomes evident that micro cutting techniques are not merely a miniature version of conventional cutting technology. Instead, they demand a complete readjustment of the entire machining process and setup. Miniaturization technologies are considered as potentially important future technologies that will result in fundamentally new methods for machines and humans to interact with the physical environment.

In the industrial realm, the interest in microscopic scale manufacturing is experiencing exponential growth, driven by the need to meet the increasing demands of societies. To fulfil the demand of micro products give the greater importance to improve the micro machining technologies to obtain more precise micro parts/products.

1.3 Non-traditional micro machining

The parts or component produced by primary manufacturing process (casting and forging) are needed to further operation to fulfilment the requirements of dimensional accuracy, tolerance and surface finish for engineering applications. The further operation is named as machining which involved the removal of materials from the work surface in order to produce accurate geometry and surface quality.

In the 20th century machining operation was performed by different machine tools to remove specific amount of materials from workpiece utilizing specific tool to produce with accurate dimension and surface finish. The kind of tools, tool materials, energy source, and kinematic structure of machine tools are the primary factors that affect both the precision and the cost of machining. With the development of society, need of advanced equipment more and more to the society. To meet the requirements of society by using newer tool materials and newer machining techniques, fresh machining obstacles were faced and overcome. With the development of advanced materials which are high hardness, high strength, and high toughness are not able to machined by these machine tools. To overcome this problem various non-traditional machining processes are developed by scientists where tool is not in contact with workpiece. Non-traditional machining processes are used for machine these materials with high precision and surface quality. Non-traditional machining processes utilize different form of energy by different process.

Non-traditional micro machining is a process in which materials is removed from the work surface in micron and sub micron range [7]. Micro-machining is not easy for traditional machining processes due to direct contact of tool and workpiece. Non-traditional micro machining processes are very much capable of removed materials in micro and sub micro range with desired accuracy and surface finish. Non-traditional micro machining process is broadly classified based on the basic requirement, mechanism, types of energy required and energy transfer medium which is illustrated in fig. 1.1.

Non-traditional micro machining process has got importance over traditional machining process due to in micromachining application because of extremely precise machining and controlled material removal from the workpiece to produce real 3D sculptured complex components. Other important advantage of non-traditional micromachining process is no physical contact between tool and workpiece. Some of the typical processes are ultrasonic micromachining (USMM), Chemical micromachining (CMM), electrochemical micromachining (EMM), Electron beam micromachining (EBMM), Electro discharge micromachining (EDMM), Laser beam micromachining (LBMM), Ion beam micromachining (IBMM) etc.

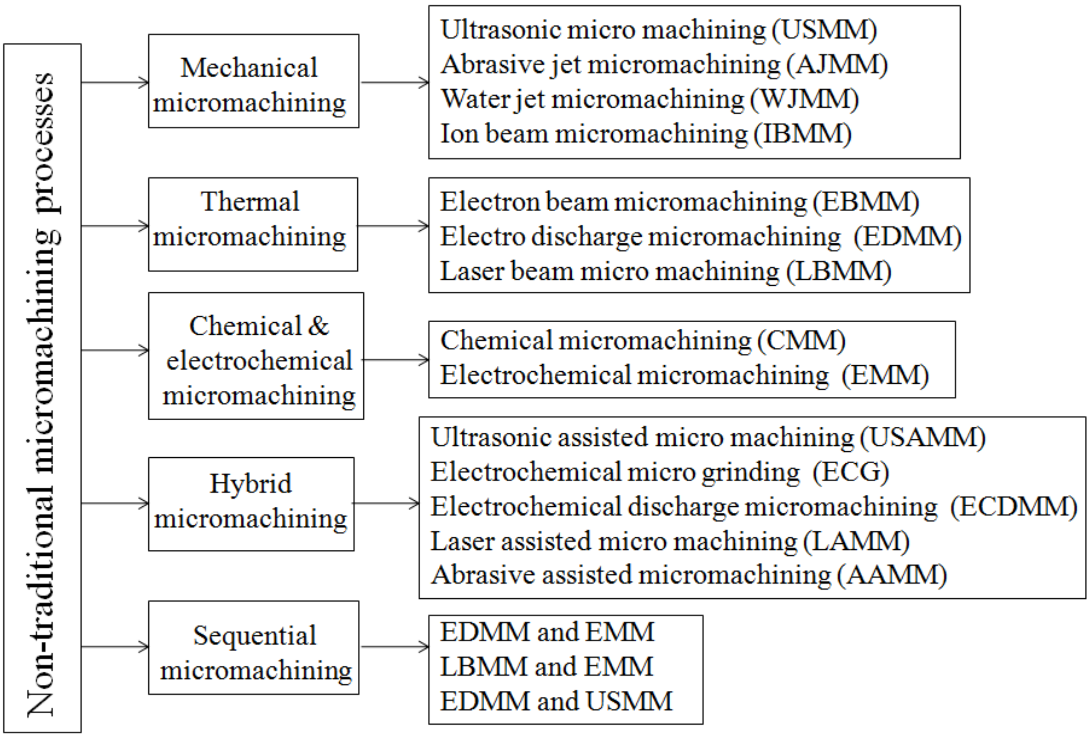


Figure 1.1 Classification of non-traditional micro machining process

Solid state lasers (e.g. Nd:YAG laser, fiber laser and diode laser), CO_2-laser and excimer laser etc is used in laser beam machining for micromachining applications [8]. Till, this process has certain issues like heat affected zone (HAZ), thermal stresses in micro machined part etc need to be solved. Electro discharge micromachining is normally used to produce micro-holes on workpieces, using simple-shaped micro-tools [9, 10]. Electro chemical micromachining is used to machine conductive materials like stainless steel, copper alloys, super alloys, titanium, and titanium alloy etc which are extensively utilized in biomedical, electronic, and MEMS applications [11]. But, EMM is limited to only for conductive materials. In Electron beam machining (EBM) high energy electron beam of high power density in the order of 1.55 $MWmm^{-2}$ [12] is focused on workpiece material. Material is removed by evaporation, causes thermal effects around the machining zone restricts the aspect ratio of micro features. Focused Ion Beam (FIB) machining presents an innovative approach to create intricate structures with exceptional precision. The process involves directing ions emitted from a plasma source onto the surface, effectively sputtering away material [13]. By employing this technique, it becomes possible to fabricate intricate 3D structures. Notably, reported spot sizes in the range of 10-50 nm further underscore the remarkable precision achieved [14]. The machining rates in this process are relatively low, typically in the order of pm^3/s. It involves utilizing ions of inert gas, such as argon, which possess high kinematic energy, typically around 10 KeV. These high-energy ions bombard the workpiece surface, causing elastic collisions that result in the ejection of atoms from the surface [15]. However, FIB is highly expensive and complex process. Chemical micromachining (CMM) is a process that relies on one or more chemical reactions to oxidize a substrate workpiece, leading to the formation of reaction products. These products are then carried away from the surface by the surrounding medium. Generally, CMM involves oxidation-reduction or complexation reactions. In CMM, both anodic and cathodic reactions occur on the reactive surface without the need for external current, ensuring that the rate of material removal (oxidation) is balanced by the rate of reduction of the etchant species. However, the CMM process does face some challenges, including a relatively lower machining rate, the use of highly corrosive electrolytes leading to ecological and safety concerns, and the inability to machine chemically resistive materials. Despite these limitations, CMM is successfully employed in the fabrication of micro-devices such as semiconductor devices and integrated circuits [16].

1.4 Fundamentals of ultrasonic micro-machining

Ultrasonic micro-machining (USMM) is a unique non-traditional machining process for generation of micro-features on parts of hard and brittle materials such as glass, quartz, ceramics, silicon, etc. USMM can be used to machine both conductive and nonconductive materials. USMM does not cause any thermal or chemical damage to the workpiece machined surface. Table 1.2 provides a comprehensive comparison of various micromachining processes. Upon examination of the table, it becomes evident that the USMM process shares similarities with nearly all other micromachining methods. In particular, USMM exhibits a notable advantage over the highly competitive LIGA (Lithographie, Galvanoformung, Abformung) process when it comes to achieving 3D profile machining. Additionally, USMM shows versatility by being applicable to a wide range of work materials, as a micromachining technique.

Table 1.2 Comprehensive comparison of various micromachining processes [17, 18, 19]

Features	Micromachining techniques						
	Bulk-surface	LIGA	Laser	Micro-EDM	Micro-ECM	Micromilling	Micro-USM
Minimum Dimension	+	++	++	++	+	+	++
Accuracy	+	++	±	+	+	±	+
Aspect ratio	−	++	±	±	±	±	±
MRR	Depends upon process	Depends upon process	+	++	+	+	+
Thermal damage to the surface	No	No	Yes	Yes	Yes	Yes	No
Geometrical freedom	2D	2D	3D	3D	3D	3D	3D
Material	Very limited material suite	Very limited material suite	Metal, polymers, ceramics	Only conductive materials	Only conductive materials	Metal, polymer	Conductive, nonconductive, hard, and brittle materials

++ Very good; + good; ± fair.

Ultrasonic machining (USM) represents a non-conventional mechanical material removal technique, where material is eliminated through repetitive impacts of abrasive particles suspended in a liquid medium upon the work surface. These impacts are generated by a specially shaped tool vibrating at ultrasonic frequencies. The concept of using ultrasonic energy for machining engineering materials was first documented by Wood and Loomis in 1927. However, it was the American engineer Lewis Balamuth who invented the USM process in 1945. USM has been referred to by different names over time, such as ultrasonic drilling, ultrasonic abrasive machining, ultrasonic cutting and ultrasonic dimensional machining. From the 1950s onward, it has commonly been known as ultrasonic impact grinding or USM. In the USM process, an electrical converter transforms electrical energy into high-frequency mechanical vibrations. Several important process parameters influence USM, including static pressure, vibration amplitude, vibration frequency, rotational speed (for rotary USM or RUM), diamond grit concentration, grit size, diamond and bond type, slurry concentration, and coolant selection, among others. These parameters play a crucial role in determining the efficiency and effectiveness of the ultrasonic machining process.

Ultrasonic machining (USM) offers numerous advantages, making it a valuable process in advanced manufacturing. Some of these benefits include high accuracy and excellent surface finish, as well as the absence of heat generation during machining. USM demonstrates the capability to drill both circular and non-circular holes in extremely hard materials. Furthermore, it exhibits no thermal effects on the machined workpiece and possesses the ability to machine both electrical conductive and non-conductive materials. Ultrasonic machining is capable of machining advanced ceramic materials such as alumina, zirconia, silicon carbide, silicon nitride, boron carbide, boron nitride, and others. Given the ever-increasing demand for ultrasonic machining and its vast potential in advanced manufacturing, a detailed parametric analysis of the USM process is highly sought after. Such analysis aims to improve machining performance, especially when generating non-circular hole geometries in advanced engineering materials like ceramics.

Ultrasonic machining has achieved a well-established place in manufacturing technology and is steadily gaining traction in diverse industries, such as aerospace, optics, and automotive. The initial USM tools were primarily integrated into drilling and milling machines and were developed around 1953-1954. As the technology evolved, independent USM tools of different types were commercialized by 1960 and began regular production for diverse applications [20]. With the continuous requirement of micro product and micro component a variation of USM has been explore for the application of micro machining named as ultrasonic micro machining. USM is first attempted for micro-machining application by Masuzawa of Tokyo University in year 1997 [21]. The USMM is used for machining hard and brittle materials including glass, silicon, and alumina. USMM shares a set of process parameters akin to USM. However, when applied to micromachining applications, USM necessitates a micro tool, micro-sized abrasives and low amplitude in order to achieve the best possible outcomes. Comparison between ultrasonic micromachining (USMM) and ultrasonic machining (USM) parameters are listed in Table 1.3.

Table 1.3 Comparison between USMM and USM parameters

Parameters	**USMM**	**USM**
Power	200-600 W	200-1000 W
Vibration frequency	> 20 kHz	≥ 20 kHz
Vibration amplitude	0.1-25μm	15-100 μm
Vibrating part	Tool or workpiece	Tool
Abrasive size	0.5-64, μm	14-300, μm
Tool tip dimension	1-500 μm	>1 mm
Static load	gf	kgf

Ultrasonic micromachining (USMM) follows a fundamental principle similar to USM, but it employs a micro-tool to carry out precise micro-machining operation. Figure 1.2 illustrates a basic principle of an ultrasonic micromachining process. The USMM uses the mechanical vibration at ultrasonic frequency about 20 kHz to 40 kHz and some times more than 40 kHz. The micro-tool is mechanically vibrated with ultrasonic frequency and amplitude. The mixture of irregular shaped abrasive particles with liquid medium is supplied into the gap between the tool and workpiece. During USM, the vibrating tool tip comes into contact with the free abrasives present in the slurry. As a result, these abrasive particles gain momentum and forcefully impact the surface of the target workpiece. In the impact zone, material removal occurs through sustained hammering and micro-chipping caused by the mechanical abrasion of the small, hard micro abrasive particles. Additionally, cavitation, which refers to the collapse of gas bubbles, plays a crucial role in removing material at the micro level. Water is typically the preferred liquid medium in this process. However, it is essential to be cautious of chemical impurities in the slurry as they can lead to immediate degradation of the work material, resulting in material loss. To facilitate the machining process, a continuous supply of abrasive slurry is provided between the workpiece and the tool, serving two main purposes: firstly, it helps to clear debris from the machining zone, and secondly, it ensures the gap is replenished with fresh slurry, maintaining the effectiveness of the process.

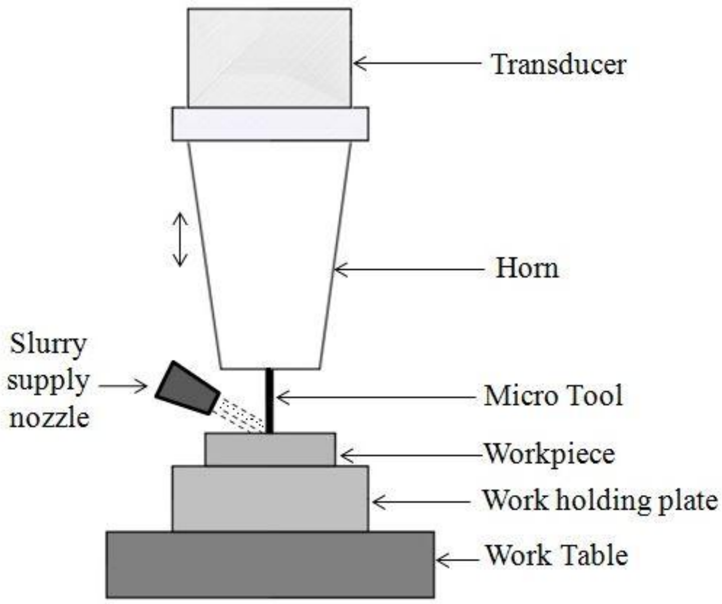


Figure 1.2 Principle of ultrasonic micromachining (USMM)

Based on the research on USM, the mechanisms contributing to USMM can be identified as follows:

(i) Micro chipping occurs due to the impact of the moving abrasive particles,
(ii) Mechanical abrasion takes place as the abrasive particles interact with the workpiece surface,
(iii) The cavitation effect arises from the agitation of the liquid caused by ultrasonic vibrations,
(iv) Chemical actions are associated with the specific liquid employed in the process.

These mechanisms together play essential roles in the ultrasonic micromachining process, allowing for precise and controlled material removal on micro-scale.

Ultrasonic micromachining can be categorized into two main types: stationary ultrasonic micro machining and rotary ultrasonic micro machining. Additionally, there is a hybrid machining process known as ultrasonic-assisted micro machining. Figure 1.3 illustrates the various possibilities of classifying ultrasonic micromachining processes.

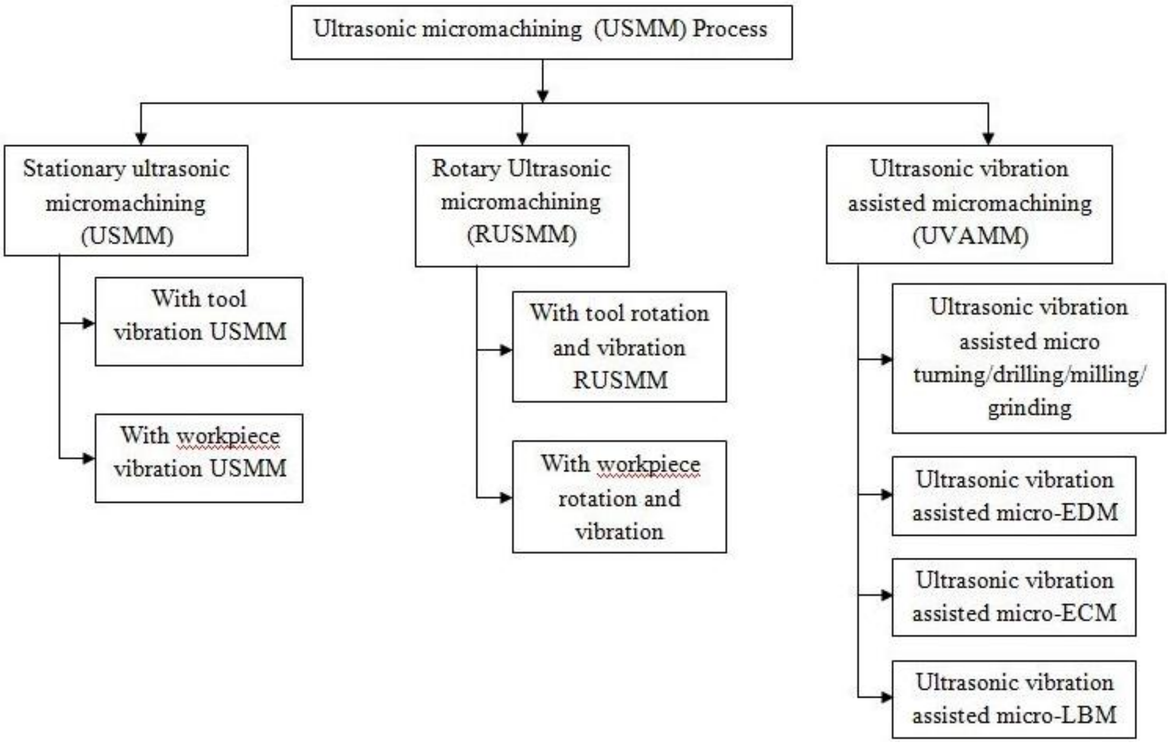


Figure 1.3 Classification of ultrasonic micromachining (USMM) process

The main objective for improving the performance of USMM is to achieve economical machining while maintaining surface integrity, superior surface finish, high dimensional accuracy, and the capability to fabricate intricate 3D micro features. However, achieving these objectives is challenging due to the complexity of the parametric relationship in USMM. Numerous factors and associated parameters influence the performance outputs, making it essential to consider various variables to optimize the process. Figure 1.4 depicts the input-output model of USMM.

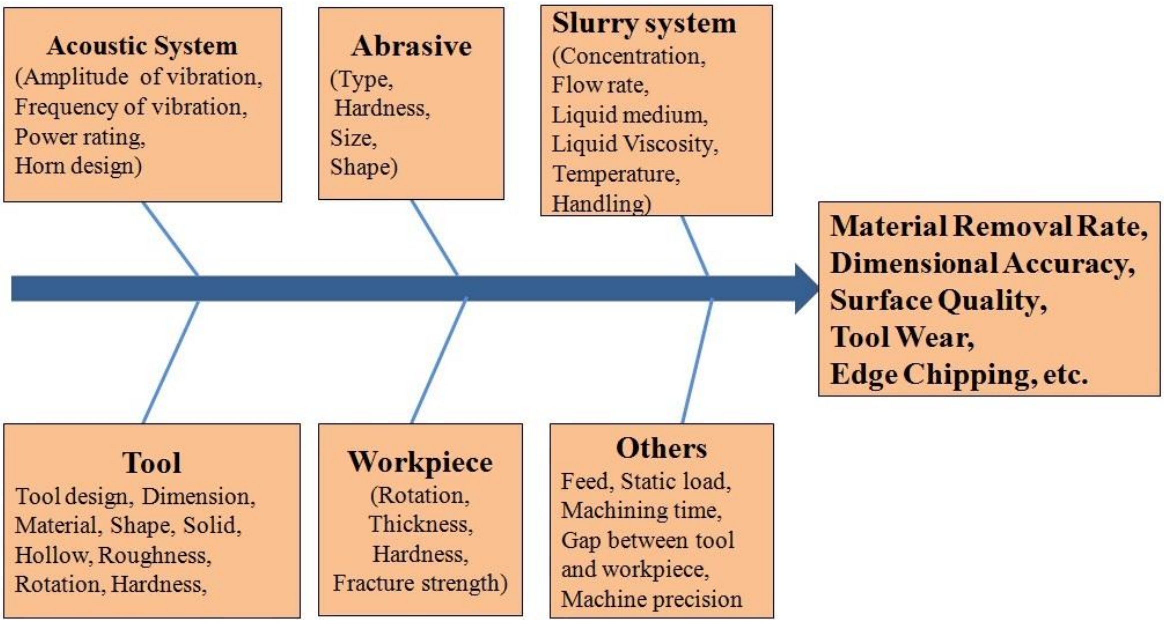


Figure 1.4 Associated parameters in input-output model of USMM

1.5 Review of past research

The use of ultrasonic energy in manufacturing industry was first given by R. W. Wood and A. L. Loomis in 1927. Approx two decade later in 1945, Lewis Balamuth (an American engineer) granted patent for ultrasonic machining. The discovery of USM brought rapid benefits to the industry, leading to the commencement of USM-tool production in the 1950s. By 1953-1954, the first ultrasonic machine tools had been developed, primarily for drilling and milling application. This innovative technique demonstrated its effectiveness in machining a variety of materials, particularly hard materials like tungsten and titanium carbides, as well as brittle materials like silicon, ferrites, ceramics, glass, and quartz. The ability to machine such materials effectively expanded the possibilities for various industries, making USM a significant advancement in manufacturing technology. In the mid of 90's ultrasonic machining was first employed for micro machining application by Masuzawa of Tokyo university. The USMM is used for machining hard and brittle materials including glass, silicon, and alumina. Gradually its utilization for micro machining application was increased.

Various research works have been reported on USMM process. The above discussions clearly reflect that development of micro shapes through USMM is a promising field for micro features and micro structures development scenario and has more to offer in near future. Moreover, fabrication of micro tool, micro hole, micro feature with high aspect ratio utilizing USMM are more challenging which needs more investigation to get further insight. Some literature reviews have been presented in this section which depicts the current research trends in various aspects of ultrasonic micro machining and related areas.

(i) Fundamentals and process capabilities of USMM,
(ii) Ultrasonic micro machining setup development,
(iii) Mathematical modelling, simulation and optimization, and
(iv) Parametric influence on machining performance of USMM.

(i) Fundamentals and process capabilities of USMM

In order to understand the fundamental concepts of ultrasonic micromachining (USMM) process, in depth review of various research articles in the area of ultrasonic machining has been studied and presented in the following discussion. Comprehensive study of on process capabilities is also an equal importance before executing experiments.

Komaraiah et al. [22] investigated the influence of fracture toughness and hardness of workpiece materials such as glass, ferrite, porcelain (hard), alumina (pure) and tungsten carbide (K20) in ultrasonic machining. Fracture toughness identified as a significant parameter, emerged from research. Tests were carried out using both USM and RUM with silicon carbide grit of mesh size 220. Experimental results showed that material removal rate was decreased when hardness of workpiece was increased in both conventional and rotary ultrasonic machining. The experimental observation also exhibits that material removal rate increases when static load increases. The machining performance in RUM was found to be significantly superior compared to the USM

Wiercigroch et al. [23] proposed that primary mechanism responsible for the improvement in material removal rate during ultrasonic machining. The researchers acknowledged that the impact process involved in ultrasonic machining is characterized by inherent nonlinearity, which means that the relationship between the forces and their effects is not a simple linear one. To gain a deeper understanding of this nonlinearity, the researchers developed a model to simulate the discontinuous impact process. This model represents a significant advancement in the field, as it allows for a better understanding of the experimental observations related to the material removal rate. One notable finding from their research was that at higher static forces, the material removal rate actually decreases. A dynamic model of rotary ultrasonic drilling supported by relevant mathematical formulation was proposed for determining the material removal rate.

Guzzo et al. [24] investigated during ultrasonic machining of quartz under diverse ultrasonic abrasion conditions. Abrasive particle size and crystallographic orientation are equally responsible for MRR and roughness of machined surface. Experimentation was done in a stationary USM using boron carbide (B_4C) and silicon carbide (SiC) abrasive with different size. They reported that machining rate was primarily controlled by brittle microcracking and drastically increased by increasing the size of SiC particles. The roughness value was also depend on abrasive grit size and noticed that roughness value increased when abrasive size increased from 15 to 25 µm. The machining rate was also depend on machining depth, especially when solid cross-sections tools were used. It was also observed the clear influence of crystal anisotropy on fracture toughness. The machining rate also depends on the crystallographic orientation of quartz crystals.

Singh et al. [25] presented a review on basic principles of stationary USM, mechanisms of material removal and effect of machining parameters on MRR, tool wear rate and machined surface finish of titanium and its alloys for industrial application. It was observed that the ideal vibration amplitude must be the same to the average grit size of abrasive used in machining. Summarized advantages of USM process were burr-less, distortion-less, and no thermal and chemical effects. It was also possible to create hole on titanium with no surface damage, especially cracking. Ultrasonically drilling holes in titanium was successfully accomplished without causing significant surface integrity damage, particularly avoiding cracking, using ultrasonic-assisted drilling. The selection of operating parameters at appropriate levels proved crucial in achieving satisfactory productivity. Notably, no major fatigue issues arose with the high-speed steel tool, with any instances of chipping or fracture usually attributed to tool/hole misalignment during the fabrication process. Through experimentation, the optimum static load for achieving the highest machining rate was found to depend on various factors, including the tool configuration (e.g., cross-sectional area and shape), as well as the amplitude and mean grit size used in the process.

Liao et al. [26] studied on ultrasonic vibration assisted drilling of Inconel 718 super alloy. Experimental results showed that the chip size was reduced, and the variation of torque in drilling became smaller. It was also found that there was little improvement in drilling performance when the frequency of the ultrasonic vibration was varied. Vibration amplitude as compared with vibration frequency was proved to have a larger effect on tool life. According to the study, smaller amplitude and a higher frequency were more appropriate for ultrasonic vibration assisted drilling of Inconel-718. It was also found that the application of ultrasonic vibration in drilling could prolong tool life.

Kumar et al. [27] presented a review on the problems encountered in machining titanium and application of USM in machining titanium and its alloys. The effect of three factors, i.e. tool material, grit size of the abrasive slurry and power rating of ultrasonic machine on machining characteristics of titanium (ASTM Grade I) was studied using full factorial approach for design and analysis of experiments. It was concluded that all factors have significant effect on material removal rate, tool wear rate and surface roughness of the machined surface. The levels for each factor that contribute the most to the variation in machining performance of USM of titanium have also been established. It was also concluded that titanium is fairly machinable with USM process. All three parameters were observed to be significant to have effect on material removal rate and tool wear rate. Two way interactions among tool and power rating, tool and grit size and grit size-power rating were also significant for material removal rate, tool wear rate. For surface roughness, grit size of the abrasive slurry was the only factor found significant. None of the two-factor interactions were observed to have any significance for surface roughness.

Majeed et al. [28] carried out experiments on ultrasonic drilling of $Al_2O_3/LaPO_4$ composites with hollow and solid low carbon steel tools in order to evaluate response to machining. Drilling of holes was carried out on LEHELDT-DIATRONIC, ultrasonic drilling machine with frequency of 18-22 kHz. X-ray diffraction was employed to study the phase content: Ultra scan inspection was carried out to check any internal defects on the workpiece. Experimental results illustrate the significance of $LaPO_4$ addition on machinability of $Al_2O_3/LaPO_4$ composites in terms of MRR, acoustic emission response and hole geometry related with defects. In all cases with hollow tool, appreciable enhancement of MRR was observed.

Rajurkar et al. [29] suggested that USM is an effective and cost-efficient method for precision machining of Al_2O_3 ceramic. However, despite its benefits, there was limited understanding of the mechanics involved, particularly regarding crack initiation, crack propagation, and stress development in the subsurface of the Al_2O_3 ceramic. To address this knowledge gap, the authors conducted experimental simulations to analyze the mechanism of material removal during Al_2O_3 ceramic machining. The results revealed that applying low-impact force caused structural disintegration and particle dislocation, while high impact force led to the formation of cone cracks and successive surface damage.

Lee et al. [30] explained the fundamental mechanism behind ultrasonic machining of ceramic composites. They developed and verified models to understand the impact force and material removal rate during the process. The principles of USM were also described. The researchers conducted experiments to measure and discuss the effects of MRR and surface roughness while changing size of the abrasive, tool tip amplitude and applied static load. The study concluded that increasing applied energy to the machined ceramics, through higher amplitude of the tool tip, greater static load, and larger abrasive size, resulted in an increased MRR and lead to poor surface finish.

Nath et al. [31] investigated the fundamental material removal mechanism in USM) of ceramics and glass. They observed that rapid mechanical indentations by abrasive grits led to micro-chipping via micro-cracks. The study focused on drilling holes in various ceramic such as alumina, zirconia and silicon carbide. The research revealed that material removal occurred in the "lateral gap" between tool periphery and the hole wall. Entrance chipping, wall roughness, and subsurface damage were identified as adverse effects of this inherent removal phenomenon. Radial and lateral cracks were formed due to adjacent abrasives under the tool face, leading to entrance chipping. In the lateral gap, material removal was influenced by sliding (abrasion) and rolling mechanisms involving larger abrasives. However, the formation of micro-cracks in the radial direction resulted in surface and subsurface damages, leading to higher wall-surface roughness. The study found that the size of micro-cracks in brittle materials depended on the grit size of the abrasive. Consequently, minimizing the adverse effects on hole integrity during USM required employing smaller grit sizes, but complete elimination of such effects was not achievable.

Ichida et al. [32] proposed a novel non-contact ultrasonic abrasive machining (NUAM) technique that utilizes free abrasives energized in a liquid medium by ultrasonic generator. They explored the suitability of this method for precision machining. The researchers used frequency of 28 kHz and amplitude of 20 μm at the end of tool. They mixed fluids with Al_2O_3 abrasive grains with a mean diameter of 1 μm, and conducted experiments on aluminum alloy to investigate the basic mechanisms of NUAM. Three distinct processing modes were observed in NUAM: (a) Mode-A: Material removal occurred based on the erosion caused by the collapse of liquid cavitation, generating an impact force known as cavitation erosion. (b) Mode-B: Material removal was a result of abrasive grains colliding or sliding on the workpiece surface, accelerated by the impact force due to cavitation collapse. (c) Mode-C: Small-scale material removal took place due to the action of the abrasive grains energized by ultrasonic energy. Material removal efficiency decreased in the form of mode A to C. By utilizing the NUAM technique in Mode-C, it was possible to create a high-quality surface finish with nanoscale range.

Lalchhuanvela et al. [33] investigated the potential for improving the accuracy of job profiles produce by USM through control of process parameters. They studied the effects of various USM process parameters, including slurry concentration, tool feed rate, power rating, slurry flow rate, size of abrasive on corner angles deviations and dimensional deviations across flat surfaces and corners of hole profile of hexagone. Through the analysis of these parametric influences and various test results, they identified the best combination of parameters for achieving better profile accuracy during the machining of alumina ceramics. The optimal parametric combination was found to be a grit number of 600, slurry concentration of 30%, power rating of 500W, and feed rate of 1.08 mm/min. Moreover, the study revealed that abrasive grit, slurry concentration, and tool feed rate were the primary controlling factors for achieving improved hole profile quality.

Lalchnuanvela et al. [34] performed experimental investigation into ultrasonic machining of high alumina ceramics based on central composite second-order rotatable design. RSM was utilized to develop empirical models, and the researchers analyzed the machining performance of USM for drilling operation based on these models. The study considered abrasive particle size, power rating, tool feed rate, slurry flow rate and slurry concentration as the process parameters for ultrasonic machining. The researchers evaluated the performance of the USM process in terms of machined surface on the workpiece material. They used Analysis of Variance (ANOVA) to assess the effects of the process parameters on machined surface. Through multi-objective optimization, they determined the optimum combination of process parameters that minimized the surface roughness values.

Choi et al. [35] proposed a novel process called chemical-assisted ultrasonic machining (CUSM) aimed at enhancing both the material removal rate and the quality of the machined surface. In CUSM, a low concentration hydrofluoric acid solution was added to the alumina slurry to induce chemical effects during the machining process. Through extensive experimentation and comparison with conventional methods, the researchers confirmed the superiority of the CUSM method. The novel approach not only increased the MRR by up two times but also resulted in enhanced surface quality and significantly reduced machining load.

Pie et al. [36] studied on micro USM to generate micro features in ceramic materials. The paper focused on understanding the relationship between the machined surface profile and various machining parameters, such as amplitude of ultrasonic vibration, tool dimension and abrasive size. In µ-USM, the material was removed by impacting abrasive particles onto the workpiece, resulting in the chipping away of material. The abrasive particles were randomly circulated within the machining area. The researchers performed experiments to examine how the presence and distribution of abrasive particles influenced the profile of machined surface during micro USM. The study revealed that the machined surface profiles could take the form of either convex or concave shapes. The specific profile shape was affected by several factors, including the hole depth, cross-sectional area of the tool and amplitude of vibration used during µ-USM.

Soundararajan et al. [37] proposed the utilization of USM to process hard and brittle materials. Although the removal mechanism was intricate, it was widely accepted that, for non-porous materials, two essential processes contribute significantly to the material removal: high velocity impact of free moving abrasive particles and direct hammering of abrasives particles. To carry out their experiments, the researchers used a mild steel tool and boron carbide abrasive. They machined various materials, including glass, high-speed steel and tungsten carbide. The experimental design allowed the isolation of the two processes, and it was observed that material removal predominantly occurred through the hammering process.

Deng et al. [38] investigated the impact of the properties and microstructure of alumina-based ceramic composites on the Material Removal Rate (MRR) during ultrasonic machining. Additionally, they evaluated the surface integrity by analyzing the distribution of strength in the ultrasonically machined specimens. The results of the study indicated that the fracture toughness of the ceramic composite played a crucial role in determining the MRR. In other words, the MRR was influenced by the material's ability to withstand fracturing or crack propagation during the machining process. In the specific case of USM of composites, the MRR was found to be dependent on the orientation of the whiskers within the material. This suggests that the arrangement of the reinforcing whiskers affects the machining efficiency and material removal. The flexural strength of the composites was found to vary narrowly around the mean value. Moreover, composites with high fracture toughness exhibited higher Weibull modulus values.

Pei et al. [39] conducted a study revealing that rotary ultrasonic machining (RUM) involves not only brittle fracture but also plastic flow as material removal modes in machining ceramic materials. The experimental evidence demonstrated the existence of both brittle fracture and plastic flow in the material removal process during RUM. Depending on specific machining conditions, either brittle fracture or plastic flow could dominate. The study indicated that by adjusting the process input variables, such as vibration amplitude, rotational speed, diamond grit size, and others, different ratios of brittle fracture to plastic flow could be achieved.

Yu et al. [40] presented experimental results of micro hole drilling and 3D micro-shape machining utilizing micro-ultrasonic machining. During the micro hole drilling experiments, they observed significant tool wear, which had a detrimental effect on the accuracy of the machined parts. To address this issue and enable the generation of 3D micro cavities, the researchers employed a newly developed technique called the uniform wear method, which was integrated with CAD/CAM software. The uniform wear method served the purpose of compensating for the tool wear that occurred during the machining process. By doing so, it helped in maintaining the original tool shape, thus improving the accuracy of the machining outcome. This approach was especially useful in cases where high precision was required for micro cavities. Additionally, the researchers aimed to develop a theoretical model based on the material removal mechanism.

Zhang et al. [41] proposed micro ultrasonic assisted lapping for create microstructures in brittle materials with high aspect ratios, exceeding even five. To achieve this, they introduced a number of innovative strategies into the lapping process. One of the key strategies was the use of a rotated tool, which allowed for more precise machining and enabled the creation of intricate microstructures. Additionally, they employed on-machine tool preparation; vibration was applied to the workpiece, allowing the fabrication of holes as small as 5 µm in diameter in materials like quartz glass and silicon. Moreover, they successfully machined complex structures, such as spiral trenches, by utilizing a path-controlled scanning mode. However, despite these achievements, the researchers acknowledged that the current knowledge on micro ultrasonic assisted lapping was still limited, particularly in three critical areas: subsurface damage control, tool wear, and reasonably coarse surface roughness. To overcome these limitations, proposed conducting further investigations, including the implementation of Acoustic Emission (AE) based sensing and monitoring. AE sensing can provide valuable real-time information about the machining process, helping to detect tool wear and potential subsurface damage.

Hu et al. [42] described about the micro ultrasonic machining (micro-USM) principle, theoretical and experimental analysis for mechanism and process parameters of hard and brittle material. To produce micro-scale features in brittle and hard materials including silicon, quartz, glass, and ceramics, USM has been reduced in size to micron level. Micro-holes, micro-slots, and three-dimensional features have all been machined using micro-USM. They were also discussed about experimental system design. Recent experimental results were presented for the material removal rate, tool wear, and surface roughness in micro USM. The need for future research has been highlighted to advancement of this unique micromachining technique.

James and Panchal [43] reported that micro ultrasonic machining process was successfully used to machine hybrid composite stacks with precise and good surface finish. The hybrid composite stack is made of titanium (Ti) and carbon fibre reinforced polymer (CFRP). In this study finite element simulation method was used to study the material removal mechanism in micro-USM. Tool material, amplitude of vibration and feed rate are used as process parameters to study the cavity depth, cutting force and equivalent stress distribution of micro-USM. The material removes from the CFRP substrate is more than Ti substrate during micro-USM of hybrid composite stack. The cavities produced on Ti is uneven compared that of CFRP. The cutting force acting on Ti substrate is higher than that on CFRP substrate. The observed peak stresses on Ti substrate are significantly higher compared to those on the CFRP substrate. For both experimental and simulation result indicates that the WC tool removes more material than the Cu tool.

Klopfstein et al. [44] performed experiments on the micro-ultrasonic machining by a 0.1 mm radius cylindrical tool with diamond abrasive slurries. The workpiece used for this experiment was silicon (100) and tool as cemented carbide. It was found that the average surface roughness of the machined surface was varied from 5 to 15 nm. The roughness of machined surface was depended on the depth of cut. The obtained low surface roughness was attributed to two main factors: the small depth of cut and the fine size of the abrasive particles present in the slurries used during the machining process. The combination of a low depth of cut and the use of fine abrasive particles led to the achievement of low surface roughness. The Confocal Raman microscopy analysis revealed the presence of amorphous silicon and the diamond cubic phase in the cut surfaces, with the amorphous phase being more prevalent in the cuts made with the 0.25mm abrasive, aligning with previous findings in silicon indentations.

Tsuboi et al. [45] applied two ultrasonic-assisted micromachining techniques to enhance tool life and improve machining efficiency when working with hard and brittle materials. The first method they employed was USV (Ultrasonic Vibration) drilling, where ultrasonic vibration was applied in the axial direction to the tool. The second method was cavitation machining, which involved utilizing ultrasonic vibration of the cutting fluid during the machining process. The application of ultrasonic-assisted micromachining, particularly through USV drilling and cavitation machining, proved beneficial for achieving longer tool life, reducing tool wear, improving accuracy, and preventing chipping in the micro-drilling of SiC and similar hard and brittle materials.

Zarepour and Yeo [46] developed a method based on the impingement of a single abrasive particle as a fundamental way to identify the material removal modes of ductile and brittle during the micro-ultrasonic machining process. In micro-USM, controlling the process conditions and parameters allows for the management of material removal, leading to improved productivity and surface quality. To investigate the morphology of craters formed by single particle impact, various vibration amplitudes and particle sizes were studied using confocal imaging profiler, field emission SEM, and AFM. This approach serves as a benchmark for identifying conditions that result in either brittle or ductile material removal under different process parameters. Through single particle impingement, a purely ductile material removal mode was achieved using a particle size of 0.37 μm at vibration amplitude of 3 μm. On the other hand, employing particles with a size of 3 μm and vibration amplitude of 4 μm resulted in a purely brittle mode of material removal, characterized by radial/median and lateral cracks. The findings of this study have practical implications. By controlling the material removal mode through the manipulation of process parameters and machining conditions, the surface quality of micro-features can be enhanced, and the MRR in micro-USM can be optimized.

Liu et al. [47] developed and implemented an ultrasonic micromachining system that incorporated a wet-etch smoothing process which was employed to fabricate micro-fluidic chips on glass substrates. This system allowed for the creation of high-aspect-ratio microstructures, including microchannels, microchambers, and microholes, in glass workpiece in a shorter timeframe. To prevent surface scratches and cracks at the exit of the through holes, a thin adhesive film and a sacrificing glass sheet were attached to the sample surfaces during the machining process. To improve the surface morphology of the microstructures, an ultrasonic-assisted chemical etching process was implemented using hydrofluoric (HF) acid solutions. This smoothing process further enhanced the quality and precision of the micro-fluidic chip fabrication. Using this integrated method, the researchers successfully fabricated micro-fluidic chips suitable for capillary electrophoresis (CE) and solo-chamber chips.

Schorderet et al. [48] described ultrasonic process for drilling micro holes in ceramics and experimentally evaluate the tool type influence on productivity (MRR). They used two types of tools: a cylindrical tool and a twist drill with two different diameters (100 and 200 μm). The study highlighted the importance of tool selection in micro-drilling. Twist drills were beneficial in maintaining a higher mean drilling speed, while cylindrical tools initially provided a higher speed but with a drop-off in speed at deeper drilling depths. The research demonstrated that the drilling speed in deep micro-drilling of glass was influenced by the depth of drilling and the type of tool utilized. This knowledge can aid in optimizing drilling processes and selecting the most suitable tool for specific micro-drilling applications.

Pei et al. [49] explored the relationship between the machined surface profile and the distribution of abrasive particles supplied through slurry during micro-machining. They observed that the movement of abrasive particles during vibration tended to concentrate them towards the center of the machining area. However, the accumulation of debris at the center blocked the movement of abrasive particles, resulting in the formation of either a convex or concave bottom shape in a micro hole. During the initial stages of machining, the accumulation of debris hindered the abrasive particles from reaching the center, leading to convex surface profiles. As the particle size increased under the same conditions, it became easier to generate a concave bottom shape. Increasing the vibration amplitude also accelerated the particle movement, further promoting concave bottom shapes. Additionally, the choice of tool diameter also played a role in determining the shape of the bottom surface. Using a smaller diameter tool allowed particles to reach the center faster, resulting in concave bottom shapes, while larger diameter tools delayed this process. Furthermore, when drilling deep holes, the extended machining time provided sufficient duration for the particles to move, leading to variations in the bottom shape.

Li et al. [50] presented the material removal mode in the micro ultrasonic machining (micro-USM) to produce micro features on quartz. it was discovered that two modes of material removal, namely brittle and ductile, coexisted. To investigate this phenomenon, extensive experiments were conducted using specially developed micro USM equipment. One key finding was that the surface roughness parameter, Rpk, proved to be a valuable indicator for identifying the material removal modes of quartz in micro USM. Specifically, if the machined surface exhibited a relatively smooth roughness value (Rpk < 350 nm), it indicated a ductile machining mode. On the other hand, if the machined surface displayed sharp tips and cracks, it indicated a brittle machining mode.

Kuriakosea et al. [51] reported about the machinability of Zr-Cu-Ti metallic glass. For this investigation micro hole drilling was performed using micro-USM. The machinability of metallic glass was evaluated using various performance measures, including overcut, edge deviation, hole taper, MRR, and tool wear rate (TWR). To investigate this, the input machining parameters such as feed rate, abrasive grit size, and concentration of the abrasive slurry were considered. In-depth analysis of the drilled hole edges in metallic glass was carried out using scanning electron microscopy (SEM) and energy-dispersive spectroscopy (EDS) to study any microstructural changes caused by micro ultrasonic machining (micro-USM). The SEM and EDS analysis confirmed that the amorphous structure of the metallic glass remained unaffected during the micro-USM machining process. By employing the multi-objective optimization based on the ratio analysis (MOORA) method, a specific range of optimal feed rates, abrasive grit sizes, and slurry concentrations was identified for micro-USM drilling in metallic glass

(ii) Ultrasonic micro machining setup development

Ultrasonic sonic machining emerged as a promising advanced machining process for micromachining applications. However, an effective and efficient USMM set up is essential for using this process to its full potential. Without the proper setup and tools, USMM cannot perform at its full potential. Therefore, the development of a comprehensive USMM setup and micro tool that can produce microfeatures with the desired accuracy and precision is urgently needed. In this regard, several researchers have made significant efforts to develop a range of USMM experimental setups and micro tools which have been used for the corresponding research findings. This section presents an in-depth assessment of the developed USMM experimental setups and microtools.

Oliaeia and Karpat [52] fabricated PCD planarization tools having micro-pyramid lattice structure by using combination of micro-WEDM and micro-EDM process. A tungsten wire having 30 µm diameters was used as tool electrode for tool fabrication in micro-WEDM. The performance of micro-scale grinding tools was evaluated by conducting grinding experiments on silicon. The researchers identified and determined the appropriate machining parameters that led to ductile regime machining of silicon. By utilizing these tools, the researchers were able to enhance the surface quality of silicon and eliminate any detrimental subsurface damage. This post-processing technique is valuable in micro fabrication applications where precise and smooth surfaces are essential.

Sun et al. [53] developed a new setup by combining wire electro discharge grinding (WEDG), electro discharge machining (EDM) and ultrasonic machining (USM) system. The grouping of WEDG and EDM was applied for fabricating co-axial micro- tools and hence utilizing this micro tool, USM operation was performed to generate micro hole on brittle materials. For the first time, micro holes of 15 µm diameter and various complicated geometries, including inclined holes, square holes, and 3D chambers, have been made. Some quality and cost factors for micro-ultrasonic machining were also investigated. The tool wear was increased with a decrease in tool diameter. The micromachining speeds range of 2-6 μm/min was achieved at optimal condition. The sidewall roughness, out-of-roundness and taper ratio of micro holes were 0.2 μm, 1.0 μm and 5%, respectively. On the developed setup, a 3D micro air turbine with three layers was successfully built. The test findings demonstrated that the center-pin bearing micro air turbine was operated successfully and a maximum rotational speed of 11,000 rpm, was achieved.

Egashira and Masuzawa [54] developed a micro-USM setup with the aid of ultrasonic vibration on workpiece. In the micro-USM setup, also incorporated spindle mechanism which permits highly precise tool rotation. Micro-holes of 5 μm diameter on quartz glass and on silicon were produced by micro-USM. Experimental investigations were carried out to elucidate the machining characteristics within the diameter range of approximately 10 μm. To address the issue of high tool wear ratio, sintered diamond (SD) was adopted as the tool material. The introduction of SD tools significantly enhanced wear resistance and substantially improved tool life. Consequently, it was demonstrated that multiple holes could be machined using a single tool, and high-aspect-ratio micro holes could be successfully fabricated. Moreover, the use of SD tools led to an overall improvement in the machining rate.

Egashira et al. [55] fabricated micro-tool by using wire electro discharge grinding. Cutting was performed in the ductile regime at a depth of cut of 0.05 μm. No fractures or cracks were detected around the rim of the hole, regardless of whether the workpiece was subjected to vibration or not. The cutting force measured by an electronic balance revealed a remarkable reduction of 60-70% when the vibration amplitude was set to 0.8 μm compared to the cutting process without vibration. This reduction in cutting force contributed to a substantial increase in tool life, resulting in enhanced machining rate and machining depth. Additionally, the examination of the machined surfaces through scanning electron microscopy (SEM) demonstrated that the surfaces produced with vibration were notably smooth.

Yang and Li [56] produced micro parts in brittle materials, especially ceramics using micro ultrasonic Machining (MUSM) by utilizing appropriate micro metallic dies. The fabrication efficiency can be greatly improved by employing the LIGA process to create micro nickel dies, which also double as microelectrodes in Die-sinking Electrical Discharge Machining (EDM) to generate micro tungsten tools for MUSM. Utilizing these micro metallic dies, it becomes possible to fabricate micro ceramic components with precision.

Egashira et al. [57] developed a multi-tool comprising 16 circular cross-sectional tools in a square array for Micro MUSM. They applied this multi-tool configuration to perform MUSM on soda-lime glass, using tungsten carbide abrasive with a grain size of 0.6μm. The experimentation involved varying oscillation amplitudes between 0.4 to 1.6μm, machining loads from 0.025 to 0.2N, and an oscillation frequency of 40 kHz. The results showed successful drilling of arrays of micro holes, with only a few holes exhibiting chippings around their entrances. The researchers also investigated the drilling speed and tool wear ratio during the process. With the use of cemented carbide tools, the drilling speed increased with higher machining loads, similar to that observed for a single tool. However, the drilling speed decreased as the oscillation amplitude increased. Regarding the tool wear ratio, it exhibited considerable variability and did not exhibit clear relationships with either the machining load or the oscillation amplitude. On the other hand, polycrystalline diamond tools displayed excellent wear resistance but were susceptible to breakage under high machining loads.

Li and Gianchandani [58] developed a new setup called (LEEDUS). It is a combination of lithography, electroplating, batch mode EDM and batch mode USM. This innovative setup enables die-scale pattern transfer onto ceramics, including piezo ceramics like PZT and PMN-PT. Additionally; they proposed a related process called SEDUS, which is designed for rapid prototyping of simple patterns. SEDUS utilizes serial micro-EDM and omits the lithography step, making it suitable for faster prototyping of basic patterns. In the experiments, LEEDUS setup is used to define a die-scale pattern with minimum feature sizes of 25 μm on a mask. They then transferred this pattern onto Macro ceramic workpieces using microtools made of stainless steel and WC/Co with a machining speed of 18 m/min. As a demonstration of their process, they fabricated octagonal and circular spiral-shaped in-plane actuators from bulk PZT-5H plates. The octagonal spirals had a footprint of 450 μm x 420 μm and a beam width of 50 μm, while the circular version had an outer diameter of 500 μm and a beam width of 80 μm. The experimental results showed that the actuators' displacement was 6–8 times larger than the calculated transverse displacement from a straight beam actuator with the same equivalent length. This indicated that practical devices with enhanced displacement characteristics could be manufactured using this process.

Park et al. [59] developed micro-diamond tools using the process of electroless Ni-P composite plating. Micro-USM Ultrasonic machining process performed on silicon utilizing the micro-tool for tool life investigation. In this investigation, the researchers explored the impact of different plating parameters and diamond grit sizes on the fabrication process of the micro-diamond tools. The key plating parameters under scrutiny included the composite plating time, solution stirring speed, embedding time and the rotational speed of the substrate. The substrate material chosen for the micro-tools was cemented carbide, and the tool's tip had a cylindrical shape with dimensions of 100 µm in diameter and 500 µm in length. Three different types of diamond grits in the diameters of 0.5-2µm, 2-4 µm, and 5-10 µm were used to make micro-tools. The fabricated micro-diamond tools had a diameter of approximately 115–120 µm for each diamond size. The researchers also investigated the tool life while conducting micro-grooving on silicon. Their findings revealed that the tool's lifespan increased with larger diamond grit sizes. When the grinding speed was set at 11.3 m/min and the feed rate at 2.4 mm/min, the 5-10 µm grit tools enabled micro-grooving with a groove depth of 100 µm over a length exceeding 550 mm. Moreover, these developed micro-tools were employed in the production of micro-devices, creating various types of micro-channels that could serve as components in micro-devices. During this process, no chipping occurred, and the sharp edges of each channel were well-preserved. Although, the major focus of this work was on micro-grooving technology to examine tool performance. However, it becomes visible that our instruments be capable of used for micro-drilling operation, and expects their range of use for micro-devices to increase.

Boy et al. [60] developed new micro-ultrasonic machining setup at FEMTO-ST (A research unit of French National Centre for Scientific Research). The development concern about the designing and manufacturing and assemble of a complete acoustic system for ultra precision machining. The focus is on microstructure production, especially in piezoelectric materials, carried out at the FEMTO-ST institute. To achieve the desired results, various factors are taken into consideration. Finite element modelling is employed to determine the appropriate material choice and dimensions for the acoustic transducer. Additionally, several parameters influencing the machining process are experimentally investigated. These parameters include the static load of the tool, abrasive material, abrasive size, vibration amplitude and characteristics of the workpiece. The goal is to enhance machining quality by improving surface state and precision while minimizing tool wear.

Zarepour et al. [61] presented a new method in micro-ultrasonic machining process. The method was used to measured static force and workpiece clamping in micro-ultrasonic machining process. In this study, a high-precision force measurement system, incorporated with a precise actuator and z-axis stage, was developed to control small forces during micro-USM processes. To ensure stability, a vacuum clamping system was implemented, firmly holding the workpiece onto the ultrasonic vibrating horn during entire machining duration. To evaluate the effectiveness of the setup, actual amplitude and frequency of vibration of the workpiece were measured using a laser scanning vibrometer. The results indicated that the amplitude variation across the workpiece ranged from 5.2% to 8%, while the mean and standard deviation of the vibration frequency were measured at 49.74 and 0.08 Hz, respectively, with respect to the nominal frequency of 50 kHz. These findings demonstrated that the proposed vacuum chuck efficiently transmitted ultrasonic vibrations to the workpiece. To validate the overall functionality of the force measurement and workpiece clamp arrangement, experiments were conducted using a tungsten micro-tool with a diameter of 150 μm to machine micro-holes on a silicon workpiece. Remarkably, the depth of the generated holes reached 350 μm, and each hole was machined in 25 minutes, resulting in a machining speed of 14 μm/min.

Viswanath et al. [62] introduced a high-resolution micro ultrasonic machining (HR-μUSM) process designed for the post-fabrication trimming of 3-D microstructures, particularly those made from glass and other materials. This process demonstrated impressive capabilities, achieving machining rates of ≤10 nm/sec on flat fused silica substrates, with an average surface roughness (Sa) of ≤30 nm over a 1 minute period. The efficacy of the HR-μUSM process was further confirmed through the successful trimming of hemispherical 3-D shells made from glass. The process efficiently formed cavities on the thin shell rims, allowing for controlled depths and machining rates. These experimental results showed great promise for future enhancements and refinements, indicating that the HR-μUSM process holds significant potential for further improvements in microstructure trimming applications.

Turner et al. [63] described a method for tool detection using acoustic emission sensor joined with work surface. Detection of the precise standoff distance of a micro-tool when oscillating at ultrasonic frequencies posed a challenge at the micron-scale. Analyzing the amplitude of the AE data in the time domain provided limited information, particularly when the tool tip was within 10 µm of the surface, the critical region where material removal occurred by exciting loose abrasives against the target surface. However, the researchers found a viable solution by examining the acoustic emission data in the frequency domain using Fast Fourier Transform (FFT). This approach enabled the detection of the relative distance between the tool tip and the workpiece surface. While the power of the fundamental frequency (40 kHz) remained relatively constant in non-contact positions, the 2nd (80 kHz) and 3rd (120 kHz) harmonics exhibited a sharp increase as the tool tip approached the surface. This indicated an escalating coupling between the tool and the workpiece through the stand-off air-gap. By monitoring the power of these harmonics, they could position the ultrasonically oscillating tool within 5 µm of the surface without requiring physical contact. This non-contact detection method helped prevent potential damage to the workpiece surface caused by the oscillating tool tip, providing an effective means to achieve accurate standoff control during micro-tool machining processes.

(iii) Mathematical modelling, simulation and optimization

Mathematical modelling, simulation and optimizations are another important area of ultrasonic micro machining. The development of several mathematical models, simulation, and optimisation of USMM process parameters, all of which are related to predicting and analysing data obtained from actual experiments. It helps in building a frame work with proper idea of outcomes when a standard process is repeated or changed without performing further experimentations. Some mathematical models, simulations and optimizations, those are prominent in the area of ultrasonic machining for micro machining applications have described in this section.

Jadoun et al. [64] conducted a comprehensive investigation on the impact of various process parameters on the tool wear rate (TWR) during ultrasonic drilling of alumina based ceramics, utilizing SiC abrasive. The parameters under study included the tool material, workpiece material, power rating, abrasive size, and slurry concentration. To determine the optimal combination of these parameters, the researchers employed the Taguchi method to plan and execute systematic experiments. This approach allowed them to identify the settings that resulted in the most favourable TWR during the ultrasonic drilling process. By exploring the effects of these process parameters, the study aimed to enhance the efficiency and effectiveness of ultrasonic drilling on alumina-based ceramics, paving the way for improved machining processes in various applications. Notably, the TWR increased with higher alumina content in the workpiece. Among the tested tools, the TWR ranked in descending order as follows: HCS (High-Speed Steel) > HSS (High-Speed Steel) > TC (Tungsten Carbide). Additionally, the TWR exhibited a nearly linear increase with larger grain sizes. While the TWR only marginally increased with higher power ratings and slurry concentrations, there were notable interactions observed between various factors, such as tool and workpiece, workpiece and grit size, and tool and grit size. Based on ANOVA results, it was clear that the entire individual factors except slurry concentration had a significant effect on TWR. The optimal parameter settings for achieving minimum TWR were determined as follows: workpiece material: 50% alumina, tool: tungsten carbide, grit size: 500, power rating: 40%, slurry concentration: 30%. By understanding and optimizing these process parameters, the study aimed to enhance the efficiency and precision of ultrasonic drilling on alumina-based ceramics, opening up potential advancements in various applications.

Jain et al. [65] worked on optimizing four mechanical types of advanced machining processes: ultrasonic machining, abrasive jet machining, water jet machining, and abrasive-water jet machining. They used genetic algorithms for the optimization. The authors reported the details of their optimization models, including the formulation of these models, the solution methodology used, and the optimization results. They based their material removal model on one proposed by Shaw, as it is a simple and easy-to-optimize model that can be applied to all types of materials. The developments of empirical and mathematical formulations for determining the material removal during ultrasonic machining were thoroughly discussed. The optimization model includes decision variables i.e. amplitude, frequency of tool, abrasive grit size, slurry concentration and tool feed force; objective functions were for maximizing material removal rate; surface roughness constraint; variable bounds were formulated based on the survey of range of values of decision variables. The objective functions of the optimization model were focused on maximizing the material removal rate, while ensuring acceptable surface roughness levels. Additionally, the authors formulated variable bounds based on a survey of the range of values for the decision variables.

Rao et al. [66] focused on the optimization aspects of ultrasonic machining, an important advanced machining process. Their main objective was to maximize the material removal rate while also considering the constraint of surface roughness. The process variables they considered for optimization were vibration frequency, amplitude of ultrasonic vibration, static feed force, abrasive particles size and volumetric concentration of abrasive particles. To achieve optimization, the researchers utilized three non-traditional optimization algorithms: Artificial Bee Colony (ABC), Harmony Search (HS), and Particle Swarm Optimization (PSO). The results of their study showed that the ABC, HS, and PSO algorithms performed better than the traditional Genetic Algorithm (GA). These three non-traditional algorithms exhibited a considerable improvement over GA in terms of their optimization capabilities for ultrasonic machining. Furthermore, they suggested that the ABC, HS, and PSO algorithms they presented could be easily adapted and applied to optimize the process parameters of other advanced machining processes. These could include electric discharge machining, electrochemical machining, laser beam machining, and others.

Singh and Gill [67] introduced a fuzzy logic-based model designed to simulate the material removal rate in ultrasonic drilling of porcelain ceramic. The model was built on two input signals: the depth of penetration and the time for penetration. To create the model, they utilized the Adaptive Neuro-Fuzzy Inference System (ANFIS) technique, which is a fuzzy-based system used for modelling and simulating complex systems. The focus of their research was to apply fuzzy logic in predicting the material removal rate during ultrasonic drilling of porcelain ceramic. The results of the study supported the effectiveness of the fuzzy logic technique as a viable alternative to conducting actual experiments for analysis. By using fuzzy logic, they were able to achieve accurate predictions without the need for extensive experimental trials. One of the notable advantages of the fuzzy logic system they employed was its flexibility and ease of comprehension. This made it well-suited for providing subjective solutions, and it offered an accessible and user-friendly approach to analyzing and understanding the material removal rate during ultrasonic drilling of porcelain ceramic.

Yu et al. [68] proposed a theoretical model to estimate the tool wear rate of micro ultrasonic machining (USM). They identified that the dominant factor leading to tool wear in micro USM was low cycle fatigue of the tool material. To validate their theoretical model, the researchers conducted experiments using tungsten and stainless steel 316L as tool materials. The experimental results demonstrated a good agreement between the predicted theoretical values and the actual measurements obtained during the experiments. However, during their investigation, they also discovered an important limitation related to tool diameter and abrasive particle size. Specifically, when using small diameter tools and large-sized abrasive particles, significant errors were observed due to the variance of particle numbers in the working area. Similarly, when using large diameter tools in micro USM, errors were easily generated due to the measurement error of tool wear length. On the other hand, the researchers found that tool rotation had an insignificant influence on the tool wear in micro USM.

(iv) Parametric influence on machining performance of USMM

The process parameters of ultrasonic micro machining (USMM) play a major role in achieving highly effective and precise machining on the scale of microns. This part of the literature review presents discussion on the contributions of various researchers in the area of USM process parameters for improving accuracy of micro features machined by USM.

Chen and Lin [69] proposed a novel combined process that integrated EDM and USM to investigate the machining performance and surface modification on Al–Zn–Mg alloy. During the experiment, they introduced TiC particles into the dielectric medium to study the effects of the combined process on various parameters like MRR, electrode wear ratio, surface roughness, machined hole accuracy. To further analyze the modifications induced by the combined process, the researchers quantitatively determined the elemental distributions of titanium and carbon on the cross-section using an electron probe micro-analyzer. Additionally, they conducted micro-hardness and wear resistance tests to evaluate the changes in the machined surface. Based on the experimental results, Chen and Lin reported that the combined process showed improved machining performance compared to individual EDM or USM processes. The integration of EDM with USM resulted in the formation of an alloyed layer on the machined surface. This alloyed layer exhibited enhanced hardness and wear resistance, which can be beneficial for applications requiring improved mechanical properties in Al-Zn-Mg alloy components.

Baek et al. [70] introduced a novel fabrication method that allowed for precision hole machining by adding a coating layer on glass substrate during ultrasonic machining (USM). The process involved depositing a hard wax coating onto the glass substrate, after which holes were precisely fabricated in the coated glass using USM. Following the machining, a cleaning process was employed to remove the wax coating. The key advantage of this method was that the wax coating acted as a protective layer for the glass surface during the machining process. As a result, any cracks generated during the process occurred in the sacrificial wax coating rather than on the glass surface itself. To evaluate the surface accuracy of the glass substrate at the hole entrance, the researchers varied the thickness of the wax coating. They measured the entrance diameters of the machined holes and the machining forces at the beginning of cutting as a function of the coating's thickness. Their findings showed that the entrance cracks and out-of-roundness of the machined holes were generated in the sacrificial wax coating on the glass substrate. This resulted in an enhancement of the surface quality of the glass holes drilled by USM.

Sagar et al. [71] conducted a comprehensive review of the effect of process parameters on MRR and tool wear rate during the finishing of glass, ceramics, and titanium surfaces. These materials are known for their hardness and brittleness, making those poor conductors of electricity and suitable for machining only through mechanical processes. USM was chosen for this purpose due to its high-frequency vibrating tools with mechanical motion. The paper focused on summarizing the recent progress made in the field, particularly in the context of machining glass, titanium, or ceramics using USM. These materials exhibit low coefficients of thermal expansion and high levels of hardness, which pose challenges for conventional machining techniques. The review discussed the selection of process parameters that influence material removal rate, tool wear rate, and surface finishing during the machining of glass, ceramics, and titanium. Understanding and optimizing these parameters are essential for achieving efficient and effective machining outcomes in these challenging materials. Furthermore, the paper also explored potential further applications of USM in the manufacturing industry. Given the unique capabilities of USM in handling hard and brittle materials, its implementation in various manufacturing processes was discussed, highlighting its potential benefits and advantages in specific manufacturing applications.

Zhang et al. [72] analyzed the stress distribution during the ultrasonic drilling on ceramics. During the final stage of ultrasonic drilling, researchers noticed that the stress exerted on the hole exit's periphery reached its peak, leading to fractures in engineering ceramics. To address this issue, a viable solution was introduced to prevent such fractures. When the maximum stress was more, fracture would take place. The experimental findings established that with the application of an opposing uniformly distributed force to the workpiece the back surface it could be avoided fracture in the terminal period of ultrasonic drilling.

Khairy [73] extensively explored the mechanisms responsible for the micro-chipping action in ultrasonic machining, identifying localized hammering and free impact by abrasive grains in the slurry as the main factors. These effects were found to manifest randomly in terms of their strength and location on the work surface. To enhance observation of the hammering and striking modes of material removal in high-speed steel and glass materials, a specially designed ultrasonic tool was introduced. Additionally, computer-aided sampling, modeling, and surface roughness analysis were employed to quantitatively assess the relative contributions of these underlying mechanisms in the material removal process.

Azghandia et al. [74] conducted a study to explore the impact of applying ultrasonic vibration during conventional drilling. A comparison was made between conventional drilling (CD) and ultrasonic-assisted drilling (UAD) by analyzing the cutting forces. The researchers employed numerical calculations and analytical software (ANSYS) to design the test structure and the horn used for vibration imposition. The vibratory behaviour of the components was predicted, revealing longitudinal mode vibrations occurring in the direction of the tool feed and peaking at the tool tip. The findings demonstrated a significant improvement in the drilling process and chip removal mechanism with ultrasonic-assisted drilling. Notably, the average drilling thrust force along the tool axis noticeably decreased during the ultrasonic-assisted drilling, indicating enhanced drilling efficiency and reduced forces required for the process.

Bhosale et al. [75] conducted experimental investigations and analyzed material removal rate (MRR), tool wear rate, and surface roughness in ultrasonic machining of alumina-zirconia ceramic composite. The experiments were designed using a full factorial Design of Experiments (DOE) method with an orthogonal array. The analysis of the results revealed that the amplitude of ultrasonic vibrations had a significant effect on both the MRR and surface roughness. Increasing the amplitude led to higher MRR and surface roughness. Furthermore, the choice of abrasives played a crucial role in the machining process. Pure SiC (silicon carbide) abrasives resulted in a better surface finish, while the use of mixed abrasives led to higher tool wear and MRR. These findings provided valuable insights into optimizing the machining parameters for achieving desired material removal rates and surface quality when working with alumina-zirconia ceramic composites in ultrasonic machining.

Yu et al. [76] successfully applied micro ultrasonic machining (USM) process for generating micro features on silicon. Experimental results showed that machining speed was decreased after a certain value of static load, which was similar to macro USM. The researchers identified the dominant reason for this decrease as debris accumulation, which caused a portion of the static load to be consumed in impacting the debris instead of the abrasive particles. To explain this observation qualitatively, the researchers developed a model to calculate the number of impacts. A larger number of impacts indicated more time for debris removal from the gap. The calculated number of impacts decreased with an increase in static load, consistent with the experimental findings showing reduced machining speed at higher static loads. Moreover, the calculated results demonstrated that the number of impacts was lower when using small-sized particles and applying a large static load as machining conditions. Additionally, the experimental results revealed that the particle size was the dominant factor influencing the surface roughness during micro ultrasonic machining. These findings shed light on the critical factors affecting the efficiency and quality of microfeatures generation using ultrasonic machining on silicon

Cherku et al. [77] conducted experiments on micro-(USM with oil-based abrasive slurry. They utilized a custom-built experimental setup to perform designed experiments and investigated the influence of various process parameters on the performance of micro USM, focusing on MRR and Surface finish. The experimental study revealed that machining with water-based slurry was suitable primarily for finer particle sizes with higher concentration, medium particle sizes with medium concentration, or coarser particle sizes with lower concentration. On the other hand, machining with oil-based slurry proved to be suitable for all particle sizes with low concentration, offering greater versatility in the process. Additionally, the study demonstrated that machining with oil-based slurry consistently produced better surface finish compared to water-based slurry. The best surface finish was achieved when machining with finer particles, while using coarse grains resulted in poorer surface finish. These findings provided valuable insights into the performance characteristics of micro USM when using different slurry types and particle sizes, offering guidance on optimizing the process parameters to achieve desired material removal rates and surface quality.

Fan et al. [78] studied about the surface integrity of machined surface of glass using micro-ultrasonic machining (USM) process. While USM has been utilized for producing patterns and drilling holes on brittle materials, the surfaces generated by this process often exhibited roughness and were covered by deep cracks. The research aimed to improve the surface integrity of the USM-ed surface and devised a method to minimize the occurrence of scattered cracks, thus achieving a high-quality surface finish. The team systematically investigated various machining parameters, including the type and concentration of abrasive particles, grit size, and feed rate, to understand their influence on the machined surface. Through their research, they developed a "multi-stage" micro-USM process, which led to a significant improvement in surface quality. As a result, they achieved a remarkable Ra value of 0.2 μm using the proposed process. This study not only sheds light on enhancing the surface quality of glass materials through micro-ultrasonic machining but also paves the way for producing intricate patterns and precise holes on brittle materials with improved surface integrity.

Sundaram et al. [79] conducted experiments on micro ultrasonic machining using both water and oil based abrasive slurry. Their findings revealed a significant influence of process variables, such as slurry medium, slurry concentration, and abrasive particle size, on the performance of micro USM. The study indicated that a three-body material removal mechanism was predominant when using oil-based slurry in micro USM. Generally, the material removal rate increased with an increase in abrasive particle size for both water-based and oil-based abrasive slurries. However, consistently higher material removal rates were observed for experiments conducted with aqueous abrasive slurry medium. On the other hand, the oil-based slurry medium provided better surface finish compared to the aqueous slurry medium. Additionally, smaller abrasive grains contributed to better surface finish for both aqueous and oil-based abrasive slurries. The role of slurry concentration was found to be ambiguous, as no clear trend of its effect on process performance was evident in the available experimental results. Overall, the study highlighted the importance of selecting the appropriate slurry medium and abrasive particle size to achieve desired material removal rates and surface finish in micro ultrasonic machining processes.

Jain et al. [80] discussed about issue of tool wear in micro-ultrasonic machining. The strength was somewhat low due to the tool's small size in the micro domain, which led to increased tool wear. Usually, tool wear was measured offline after machining by removing the tool from the machine. However, this process was cumbersome and impractical to perform frequently. To overcome this challenge, the researchers introduced a simple technique known as the 'Reference Point' method to assess linear tool wear directly on the machine itself. This approach allowed them to monitor tool wear continuously without the need for repeated removal and reinstallation of the tool. In their study, a comparative analysis of tool wear was conducted between solid and hollow tools while drilling silicon. The static load was considered as a process parameter affecting tool wear. Additionally, the researchers discussed surface topography and fracture mechanisms using SEM micrographs, providing insights into the tool wear behaviour during micro-USM operations.

Cheema et al. [81] discussed on tool wear in fabrication of micro-channels in borosilicate glassusing ultrasonic micromachining. The study aimed to investigate the impact of several process parameters, including tool material, abrasive size, and feed, on tool wear and the resulting accuracy of the micro-channels. The experiment involved comparing two different tool materials: tungsten carbide and stainless steel. After conducting the machining process with both materials, the researchers analyzed the form accuracy of the micro-channels produced. The results indicated that the micro-channels machined using the tungsten carbide tool exhibited better form accuracy compared to those machined with the stainless steel tool. To understand the wear process, the researchers utilized scanning electron micrographs of the tools as evidence. These micrographs likely provided insights into the wear patterns and damages sustained by the tools during the machining process.

Lin et al. [82] created microfuidic channels on quartz using different manufacturing technologies like micro-USM, micro-LBM and ultra-precision machining. Each technique was utilized to fabricate specific types of microfluidic channels with varying dimensions and shapes. Ultra-precision machining was employed to manufacture cross-junction channels with a three-dimensional triangle cross-section. These channels had a size of 14 µm in width and 28 µm in depth. The results of ultra-precision machining were particularly impressive, as it achieved high surface quality with a roughness value (R_a) below 0.27 µm. The microfluidic channel surfaces produced through this technique were exceptionally smooth, devoid of any chipping or cracks. For micro laser machining, the researchers created U-shaped and ц-shaped microfluidic channels on the quartz substrate. Micro ultrasonic machining, on the other hand, was employed to fabricate deep holes (aspect ratio, 25) and microfluidic channels with a high slenderness ratio, which refers to the ratio of the width to the depth of the channels. To reduce chipping during micro ultrasonic machining, the researchers found that increasing the rotational speed and size of the abrasive grains was effective.

Suganthi et al. [83] discussed about the various strategies for accuracy improvement of micro features, particularly in micro-hole dimensioning and shape. They discussed various micromachining processes, including both contact and non-contact methods, each with its own advantages and disadvantages. Microstructures such as micro-holes play a crucial role in highly sensitive products like automotive fuel injection nozzles, watches, medical devices, electronics, and camera parts. For these applications, achieving a high degree of accuracy in the profile parameters of micro-holes is essential. Among the various micromachining processes, micro-drilling was highlighted as the most ultimate technique for generating micro-holes. Micro-drilling offers several benefits, including the ability to create deeper holes with improved straightness, better roundness, and smoother surfaces compared to other methods. The study provided a review of accuracy-related micro-drilling operations to emphasize the importance of precision in micro-hole production. By understanding the need for accuracy and exploring different micro-drilling techniques, the researchers aimed to identify how technology advancements and research efforts have contributed to enhancing accuracy in micro-hole manufacturing.

Cheema et al. [84] presented a method for quantification of wear measurement for micro ultrasonic machining. They introduced a mathematical model that allowed them to quantify wear in two dimensions and then convert it into three-dimensional wear data. To verify the efficiency of the model, the researchers utilized machining data from micro ultrasonic machining of glass with tungsten carbide tools. The obtained tool wear values from the model were then correlated with the form accuracy of the machined micro-channels. The results demonstrated a reasonable correlation between tool wear and form accuracy, suggesting that the wear of the tool significantly influences the quality of the fabricated micro-channels. The study also investigated the effects of various process parameters on tool wear behaviour during micro ultrasonic machining. These parameters included abrasive size, slurry concentration, power rating, and workpiece feed. The researchers found that higher power ratings and slurry concentrations were associated with increased tool wear and subsequently led to higher form inaccuracy in the machined micro-channels. Moreover, the size of the abrasives played a role in form accuracy as well. Coarse abrasives were linked to higher form inaccuracy in the micro-channels. The study revealed that different types of wear led to distinct deformations in the micro-channels. Longitudinal wear, for example, resulted in decreased micro-channel depth, while lateral wear caused tapered micro-channel walls. Edge rounding wear led to rounded corners in the fabricated micro-channels.

Sreehari and Sharma [85] fabricated micro channel on silicon wafer substrate using micro-USM. The micro-channel was used in the heat removal application in various microelectronic components. To enhance the precision and quality of the fabricated silicon micro-channels, the researchers investigated the use of viscous fluids with different viscosities in combination with other machining conditions. The goal was to optimize surface roughness, overcut, and stray cut in the machined micro-channels. The experimental investigation revealed some important findings. When low viscous fluids were used, the surface roughness of the fabricated micro-channels improved compared to when high viscous fluids were used. On the other hand, the overcut and stray cuts were minimized when high viscous fluids were employed. This indicated a trade-off between surface roughness and overcut/stray cut, depending on the choice of fluid viscosity. Another important factor influencing the machining results was the feed rate. Higher feed rates led to improved surface roughness, overcut, and stray cut, regardless of the abrasive concentration percentage. The researchers also delved into the interactions between the tool, abrasive, and workpiece in the machining zone.

Jain and Pandey [86] focused on investigating tool wear in μ-RUM during micro drilling operations on borosilicate glass. The study utilized two sets of experiments, employing an electroplated hollow diamond tool and borosilicate glass as the workpiece, to evaluate the effects of various μ-RUM parameters on tool wear. In the first set of experiments, the researchers studied the impact of tool-based parameters, such as grit size and thickness of the hollow tool, using a full factorial design. Through this analysis, they were able to determine the optimum tool design for minimizing tool wear. In the second set of experiments, the focus shifted to process-related parameters, including spindle speed, distance traverse in each stroke, table feed rate, vibration amplitude, and vibration frequency. A central rotatable composite design was employed, using the optimum tool design from the first step. This allowed the researchers to investigate the effects of these process parameters on tool wear. To analyze the data and understand the significance of the μ-RUM factors on tool wear, the researchers used the analysis of variance (ANOVA) technique. Based on their investigation and data analysis, concluded that, hollow diamond tool thickness and grain size had an inverse effect on tool wear. A tool with 100 μm thicknesses and 30 μm grain sizes was found to be the best condition for achieving minimum tool wear. Process parameters, such as traverse in each stroke, vibration amplitude, vibration frequency, and spindle speed, also affected tool wear. Among these, vibration frequency had the most significant influence on tool wear. Improper selection of vibration frequency could lead to rapid tool wear.

1.6 Research gap identification

The need for miniaturisation is rising rapidly throughout almost all industries, which encourages researchers and engineers to investigate the possibilities of different micromachining processes of materials in order to represent innovative technologies for micro engineering applications. Advanced ceramic materials will have a greater influence on the functional properties of microstructures when they are included into the micro domain.

Advanced ceramic materials like quartz and zirconia have greater scope of applications due to their exceptional properties. These materials possess unique characteristics, including high hardness, high corrosion resistance and high strength. As a result, they have found widespread use in diverse industries and applications worldwide. In the field of electronics, advanced ceramics like quartz are extensively employed in various electronic devices and components. Quartz crystals are widely used for their precise frequency control in oscillators, resonators, and filters, making them essential for accurate timekeeping in electronic devices. The application in other includes automotive industry, biomedical sector, optical applications etc. The strict design requirements in these industries necessitate materials with exceptional properties to meet the demanding standards of modern technology and manufacturing. Therefore, it needs to manufacture various components having micro features with high aspect ratio on hard and brittle materials. However, machining of these materials is very challenging by traditional as well as non-traditional machining technologies due to their hardness and brittleness.

Ultrasonic micromachining (USMM) is one of the excellent techniques for quartz and zirconia machining in micro-domain. Ultrasonic micromachining has emerged as an extremely promising technology for various reasons. It offers several advantages that permit machining nonconductive materials, precise machining, and no thermal or electrical phenomena occur during machining and also not require a clean room environment. Various efforts have been taken by researchers for micro-machining on different materials like silicon, glass by tungsten carbide tool, and diamond abrasive powder which is very expensive.

However, very few experimental studies have been reported for fabrication of micro tools, and generation of micro feature such as through hole, micro channel, and array of micro holes on quartz as well as zirconia by ultrasonic micro machining technique. These issues need to be addressed to bridge this gap so as to explore the potential use of micro tool development to successfully use in ultrasonic machining for micro machining applications. The utilization of developed micro tools, ultrasonic micromachining for quartz as well as zirconia to fulfil the emerging trend of micro machining applications. More research is needed in the area of micro tool design and development as well as selection of micro tool material and abrasive materials e.g. silicon carbide and aluminium oxide which is economical and easily available. More research is also needed for reduction in machining time and improvement in productivity by generating multi channel or multi hole of different shape and size utilizing various multi tips micro tool on hard and brittle materials like quartz and zirconia etc. Hence, this motivates the author towards investigation into development of micro tools and their effective utilization for ultrasonic micro machining applications.

1.7 Objectives of the present research

Research on ultrasonic machining at the macro level has been already reported in various fields of industrial applications. Nevertheless, it is crucial to downscale USM to the micro level to enable the production of miniature features on components made from hard and brittle materials. Although some research work activities have already been carried out on ultrasonic micromachining process, in-depth studies and experimental investigation into ultrasonic micromachining of various engineering materials are very much demanded. Significant research and technical advancements are necessary to refine and enhance USM technology, making it a reliable and widely accepted method for meeting the demands of modern micro-manufacturing industries. With these considerations in mind, the objectives of the present research work are structured as follows:

(a) To perform in depth study on ultrasonic micro machining (USMM) process and its setup for carrying out experimental investigation. To develop and modify micro tool holding and work holding unit of the existing USM setup which can be capable of performing investigation in the micro domain for micro machining of different ceramics.

(b) To develop cylindrical micro tools, multi tips micro tool and array of square micro tool for fabrication of micro holes, multiple micro channels and array of square micro holes by using USMM.

(c) To perform the experiments utilizing developed micro tools on micro-USM setup for generating micro holes on quartz. Experimental results will be further analyzed to study the influences of ultrasonic micromachining (USMM) process parameters on various responses.

(d) To develop empirical models for different responses, e.g. material removal rate (MRR), overcut and taper angle of micro holes on quartz during ultrasonic micromachining (USMM) based on Response Surface Methodology (RSM) utilizing experimental results and to analyse the influences of process parameters on the responses through response surface plots and contour plots based on developed empirical models.

(e) To perform single objective as well as multi objective optimization of response characteristics for determining optimal machining parametric combination in order to obtain the desired micromachining performance characteristics of ultrasonic micromachining (USMM) for generating micro holes.

(f) To perform the experiments utilizing developed multi tips micro tool on micro-USM to produce multiple micro channels on quartz as well as zirconia and also to analyze the influences of ultrasonic micromachining (USMM) process parameters on responses and also to analyse various characteristics of machined surface through observation of micrographs.

(g) To perform experiments utilizing developed array of micro tool on micro-USM to produce array of square micro holes on quartz and also to analyze the influences of ultrasonic micromachining (USMM) process parameters on responses and also to study on machined surface topography through observation of micrographs.

The primary goal of this research is to achieve a comprehensive understanding of the micro-USM process. By gaining this fundamental knowledge, it is anticipated that the research will lead to more informed process design and aid in determining the optimal ultrasonic micro-machining conditions for various micro-machining applications. The use of developed micro tools and multi tips micro tools helps to carry out experiments for generating micro hole, micro channels and array of micro holes to analyse the influence of process parameters on machining criteria. With the effective use of multi tip micro tools, machining time can be reduced and hence productivity increases for micromachining applications.

SETUP DETAILS AND MICRO TOOL DEVELOPMEMT FOR ULTRASONIC MICRO-MACHINING (USMM) EXPERIMENTATION

2.1 Introduction

Ultrasonic micro-machining experiments were performed by using “AP-1000” (made: Sonic mill). The ultrasonic frequency (20 kHz) and amplitude of ultrasonic vibration (25 μm) was fixed for ‘AP-1000’. The power rating, abrasive slurry concentration, tool feed rate and slurry flow rate are process parameters in USMM set-up. Abrasive slurry is incessantly supplied into the gap between the ultrasonically vibrated tool and fixed workpiece. The water-based abrasive particles are forcefully driven by the tool, impacting the workpiece surface and effectively wearing it down to mirror the shape of the tool. As a result, the workpiece takes on a corresponding pattern that matches the form of the tool. The details depiction of the each components of USMM setup has been discussed here. Figure 2.1 shows the schematic view of ultrasonic micro-machining setup. All the subunits of USMM setup as shown in fig. 2.1 have been described in details here under.

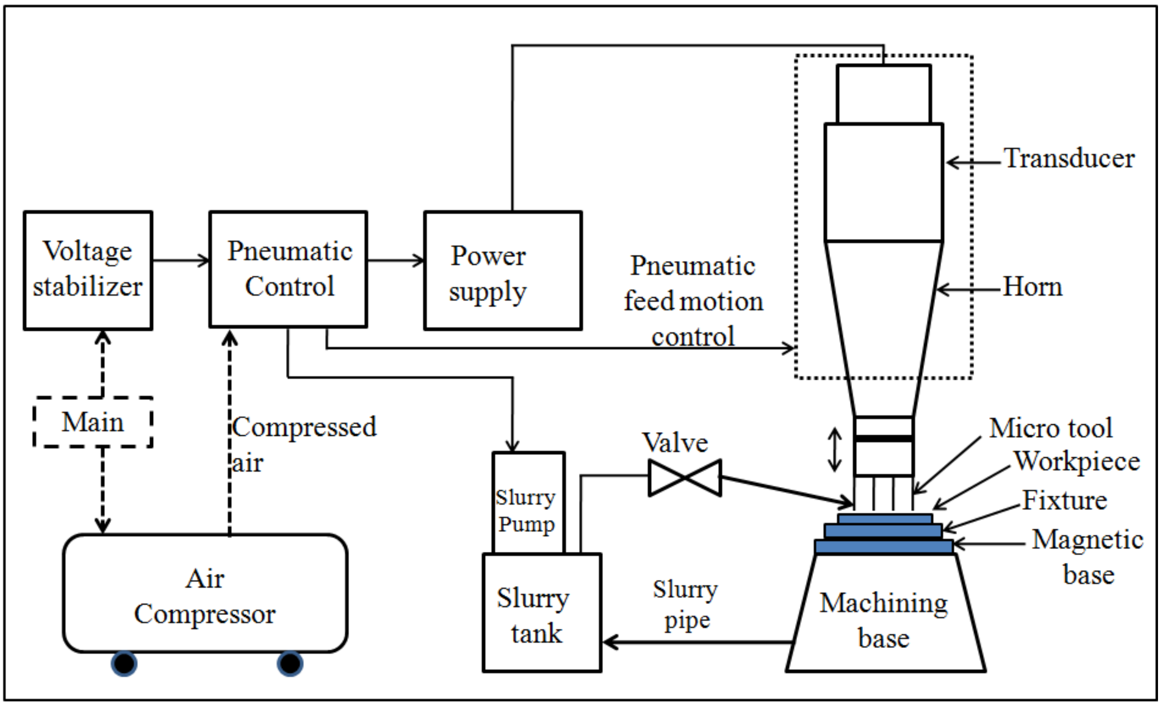


Figure 2.1 Schematic view of ultrasonic micro-machining setup

2.2 Components of ultrasonic micro-machining setup

Ultrasonic micro-machining setup has various components, which are represented in fig. 2.2 such as power supply unit, controlling unit, abrasive slurry supply unit and vibration unit, etc. The details descriptions of various component of USMM set-up are discussed in this following subsection.

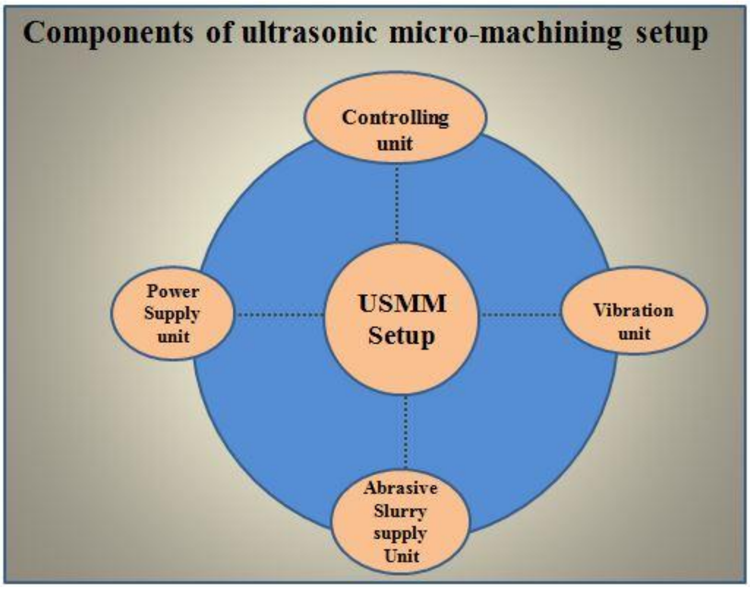


Figure 2.2 Components of ultrasonic micro-machining setup

2.2.1 Power supply unit

The power supply unit of an ultrasonic machine is comprised of a high-power sine wave generator, responsible for generating the desired frequency and power of the signal. It features a solid-state, variable output power supply with options for internal or external power control. This power supply unit is designed to handle continuous duty in industrial operations. To ensure optimal efficiency, the unit is equipped with automatic frequency control and automatic load compensation. These features allow it to maintain constant output amplitude at the desired setting, meeting the diverse energy requirements encountered during the machine's operating cycle. This combination of capabilities ensures smooth and precise operation for various applications in industrial settings. The power supply unit designed with safety features which protect system from, tool failure or overloading. If an overload condition occurs, the control system shuts off the ultrasonic machine and activates the front panel overload indicator lamp. Figure 2.3 shows the photographic view of power supply unit of USMM. The power supply starts with 20% onwards up to 1000 watts at 208 - 240 volt single Phase system.

Figure 2.3 Power supply of ultrasonic micro-machining setup

2.2.2 Control unit

The electro-pneumatic control unit (Autopac IIb) is shown in fig. 2.4. The control unit has various functions which are listed below:

(i) It offers accurate depth control, enabling precise machining depths during the Sonic-Mill process.

(ii) The unit monitors and regulates air pressure, which is vital for positioning the tool in the Z-axis, ensuring precise and consistent movements.

(iii) A tool lift system is incorporated, allowing the slurry to flow beneath the tool, enhancing the machining process.

(iv) The power supply unit controls the electrical timing for major functions, such as activating or deactivating slurry flow, sonics, and tool movement.

(v) Manual controls are provided, enabling operators to manage individual functions during setup and testing processes.

(vi) The unit facilitates control over the optional magnetic worktable, adding versatility to the machining setup.

(vii) An LCD readout timer is integrated into the unit, allowing operators to monitor the cutting time precisely.

(viii) The unit also oversees the control of the slurry circulation system, ensuring a continuous and consistent supply during operations.

(ix) An optional LCD readout feature is available, which enables monitoring of the power supply frequency, providing additional insights for optimization and fine-tuning.

By encompassing these functionalities, the control unit plays a crucial role in the effective and reliable operation of the Sonic-Mill process, meeting the demands of various industrial applications.

Figure 2.4 Control unit of ultrasonic micro-machining setup

Air-compressor as shown in fig. 2.5 is installed to supply necessary compressed air for the feeding unit at pressure 0.41MPa. The electro-pneumatic control unit manages the air pressure for both raising the tool from the workpiece (via the "Up air" output) and operating the clutch for tool lift (via the "Forced release" output). The control unit allows for adjusting the air pressure, which directly influences the tools up and down movements. To ensure the ultrasonic machine operates smoothly, an appropriate amount of air must be stored in an air tank to meet the demands of the tool's movements.

Figure 2.5 Air compressor

2.2.3 Abrasive slurry supply unit

An abrasive slurry pump is utilized as sub components of the abrasive slurry supply unit to circulate abrasive slurry solution. The abrasive particles are the actual cutting tools in USMM. The abrasive slurry solution used in the USMM is composed of micro-sized abrasive particles combined with water, serving the dual purpose of cooling the tool and workpiece. The flow rate of the abrasive slurry is adjusted through a control valve, which is connected to the mill-module. The power supply for the abrasive slurry pump is regulated by the main control unit. The success of machining operations is heavily reliant on several factors related to the slurry. These include the slurry concentration, slurry flow rate, and the efficiency of the cooling system. A higher concentration of abrasive slurry may result in a greater material removal rate, but for optimal functioning of the slurry pump, a lower concentration is preferred. Finding the right balance in these factors is crucial for achieving the desired machining performance and ensuring the overall effectiveness of the USMM.

Various abrasives are available in different grain sizes for USMM operation. When choosing an abrasive for a specific application, various factors are taken into account, such as hardness, grit size, usable life, and cost. The abrasive particles should be harder than the workpiece material. The hardness of various abrasive particles commonly used in ultrasonic micro machining are listed in Table 2.1. After the appropriate abrasive is chosen and combined with water, the resulting mixture is stored in a slurry tank and is pumped to the tool-work interface by the re-circulating pumps. Figure 2.6 shows the photographic view of abrasive slurry supply unit.

Table: 2.1 Abrasive particles commonly used in USMM

Abrasive	Knoop Hardness
Aluminium oxide	1850-1920
Silicon carbide	2480-2500
Boron carbide	2800
Cubic boron nitride	4700
Diamond	6500-7000

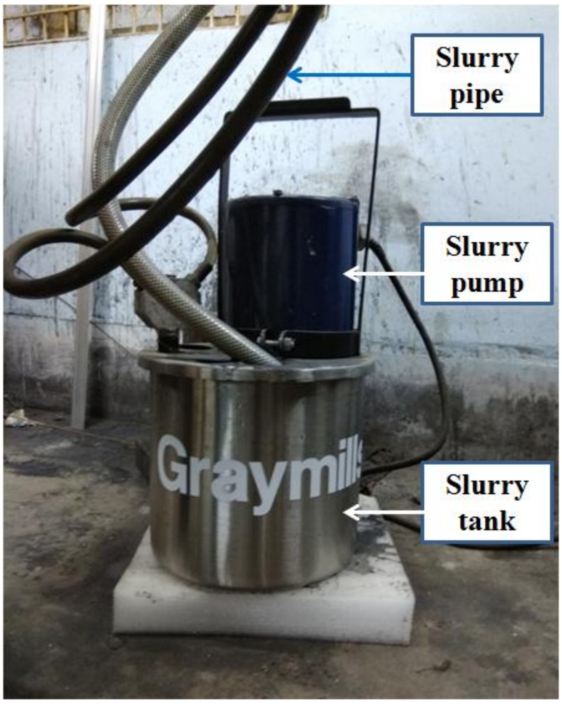


Figure 2.6 Photographic view of abrasive slurry supply unit

2.2.4 Vibration unit

In ultrasonic micromachining (USMM) setup vibration unit is one of the main and very sensitive units which are shown in fig. 2.7.

In this unit, the elements are as follows:

I. Transducer

II. Coupler

III. Horn

IV. Micro tool and tool holding unit

I. Transducer

The Ultrasonic transducer, also known as a converter, serves as a crucial component in the ultrasonic micro-machining process, responsible for transforming energy from one form to another. Specifically, it converts a 50 Hz electrical signal from the power supply into a high-frequency 20 kHz electrical energy signal. This 20 kHz electrical energy is then directed to the transducer element, where it undergoes a conversion into ultrasonic mechanical vibrations. In USMM, two distinct types of transducers are utilized, each based on different working principles.

A. Magnetostrictive transducer,
B. Piezoelectric transducer,

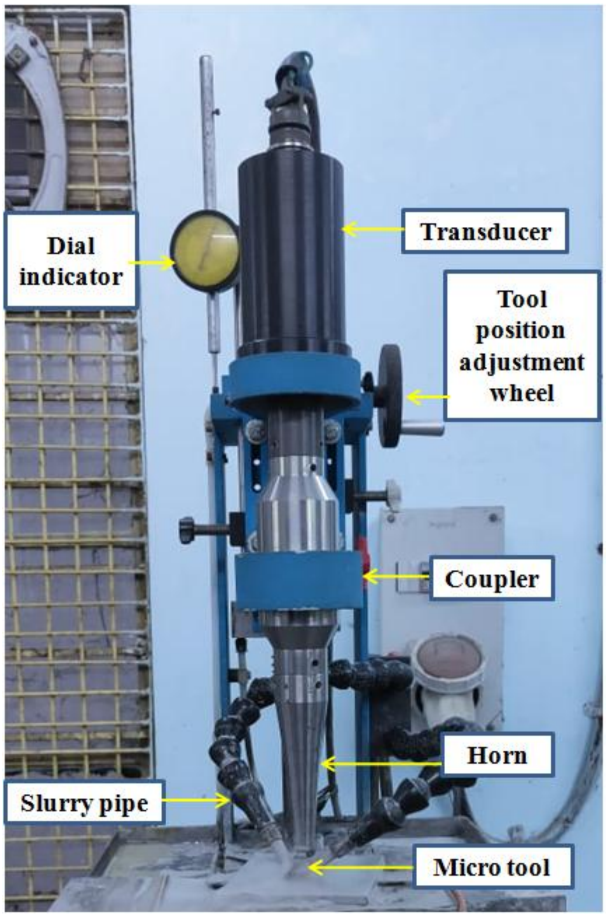


Figure 2.7 Photographic view of vibration unit

A. Magnetostrictive transducer

The magnetostriction effect was first discovered by Joule in 1874. This effect refers to the phenomenon where the length of ferromagnetic metals and alloys changes when subjected to a strong applied magnetic field. The resulting deformation can be either positive or negative, leading to dimensional changes in the material. In practical applications, an electric signal of ultrasonic frequency is introduced into a coil wound around a stack of magnetostrictive material. The transducer created through this setup is primarily constructed using nickel or nickel alloy sheets. These transducers exhibit a conversion efficiency of approximately 20-30%. They are available in power ratings of up to 2000 W, making them suitable for various applications. The maximum achievable change in length using this magnetostriction effect is around 50 microns. To optimize this effect, it's necessary to superimpose a high-frequency AC current on an appropriate DC pre-magnetizing current. This combination of currents helps achieve the maximum magnetostriction effect, enhancing the efficiency of the transducer. However, there is a notable concern associated with magnetostrictive transducers. These transducers experience electrical losses in the form of heat, which not only reduces their overall efficiency but also necessitates the inclusion of cooling systems. The added electrical losses, in turn, lead to extra costs and an increase in the weight of the cooling system needed to manage the generated heat.

B. Piezoelectric transducer

This transducer is used for USMM to generate mechanical vibration through the piezoelectric effect by which a certain materials (quartz or lead zirconate titanate), which generate a minor electric current when subjected to compression. Conversely, the application of an electric current leads to a slight expansion of the material. Upon removing the current, the material promptly reverts to its original shape. Piezoelectric transducer, by nature, exhibits extremely high electro-mechanical conversion efficiency (90-97%), negating the necessity for water cooling. Piezoelectric transducer is used in USM machine. These transducers can handle power levels of up to 900W. Piezoelectric transducers are resistant to thermal failure and easy to construct.

II. Coupler

The coupler serves as a bridge connecting the transducer and the horn. This configuration enables the transducer, coupler, and horn assembly to be clamped together, presenting a range of amplitude options suitable for diverse applications. As depicted in fig 2.8, the couplers are meticulously engineered to resonate at the identical frequency as the converter they are intended for. They are typically positioned at a nodal point along the axial motion to minimize energy loss and prevent the transmission of sound into the supporting column.

Figure 2.8 Coupler

III. Horn

The ultrasonic horn is known by various names, such as an acoustic coupler, tool holder, concentrator, or sonotrode. Given the relatively lower amplitude of ultrasonic vibration at the transducer's end face (ranging from 0.001 to 0.1 μm), the horn is integrated into the vibration unit to amplify these ultrasonic vibrations. Exponential shaped horn was used to carry out all experiments. A horn material must possess several key attributes, including favourable soldering and brazing properties, excellent acoustic characteristics, and high fatigue resistance at elevated oscillation amplitudes. Additionally, it should exhibit corrosion resistance, high wear resistance, good elastic and fatigue strength, and elevated values of toughness and hardness. Commonly used materials for horns include titanium alloy, monel, stainless steel (AISI 304), polycrystalline diamond (PCD), aluminum, and aluminum bronze.

The horn can be affixed to the machining tool using diverse techniques like soldering, brazing, or screw thread fitting. In accordance with specific needs, the horn can even undergo machining to attain the precise tool shape and dimensions. While threading expedites the horn-tool attachment process, these connections can be vulnerable to concerns like self-loosening, fatigue failure, and diminished acoustic power transmission. The iterative high-frequency vibro-impact mode introduces distinct characteristics and enhancements into the metal cutting process, reshaping the interaction between the workpiece and the cutting tool into a micro vibro-impact procedure.

However, the purpose of the horn is to transfer ultrasonic vibrations from the transducer to the tool. It assumes the role of a resonator, significantly amplifying these vibrations. The horn's shape plays a pivotal role in modifying the gain factor, which represents the ratio of output amplitude to input amplitude. Typically, these horns find application in tools with diameters exceeding 1 inch (25.4 mm) or ½ inch (12.7 mm), as illustrated in fig. 2.9. Tips are affixed to horns, with a variety of head thicknesses to ensure weight proportions are maintained with the horn, accommodating different tool weights and lengths. This meticulous adjustment enables the horn/tip/tool ensemble to function optimally at the desired frequency.

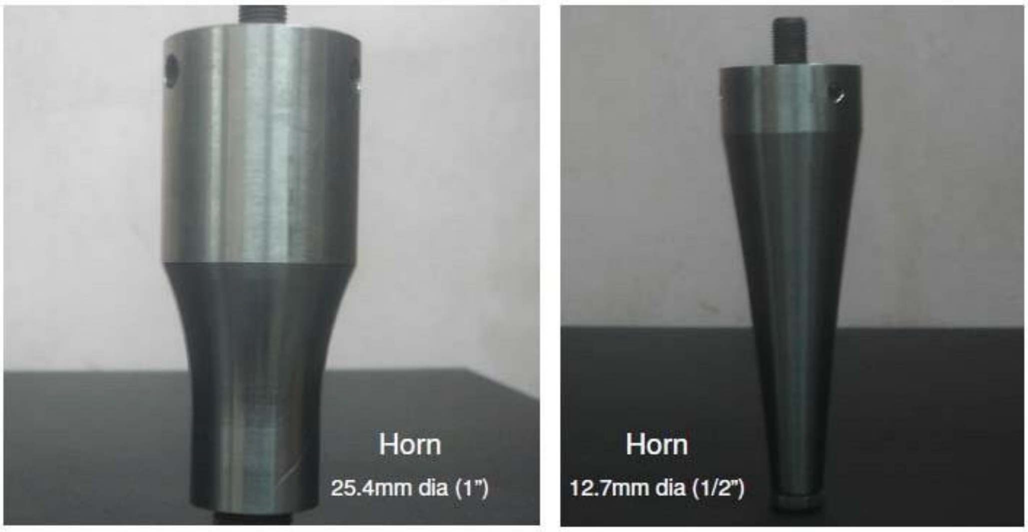


Figure 2.9 Horn used in AP-1000 Sonic-Mill machine

There are mainly three geometrical shapes of horn design as shown in figure 2.10 which are used in ultrasonic micromachining.

(i) Linear taper horn: Simple to make but its potential magnification is limited.

(ii) Exponential taper horn: This configuration presents greater magnification factors compared to the linear taper horn. Although its shape introduces manufacturing complexities, its extended length combined with a small diameter at the working end renders this design exceptionally suitable for micro-scale applications.

(iii) Stepped horn: In this design, the magnification factor is determined by the ratio of the end areas. The achievable magnification is constrained solely by the dynamic tensile strength of the horn material. This design is characterized by its simplicity and ease of manufacturing.

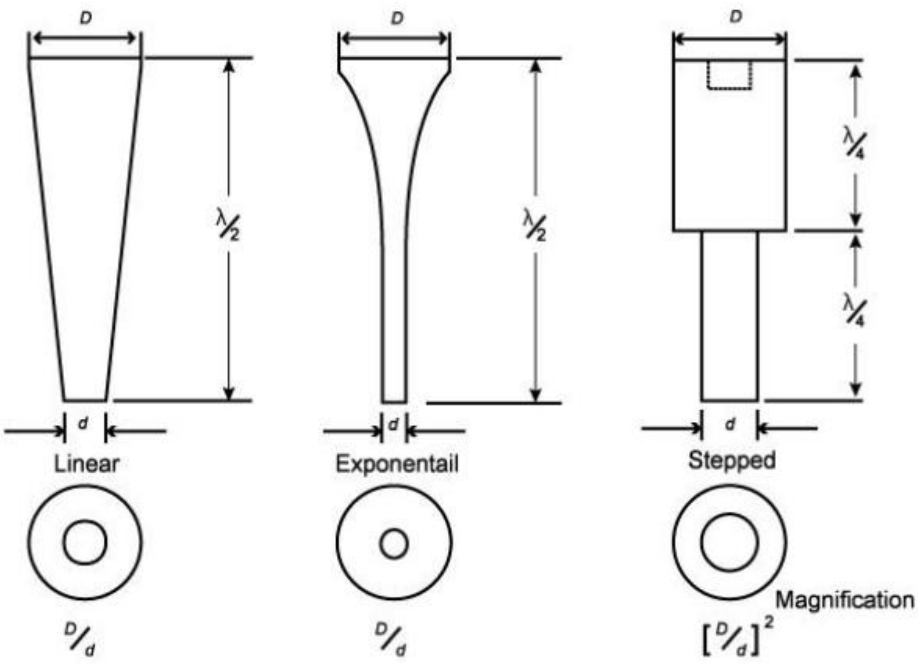


Figure 2.10 Geometrical shapes of horn design

IV. Micro tool and tool holding unit

The tools are made of tough, ductile material with high wear resistance and good fatigue strength. Stainless steel (SS304) is used as tool material. Tools are normally silver brazed to tool holder and finally fitted with horn by Screw fitting. Figure 2.11 shows schematic view of micro tool holder made of stainless steel. Otherwise, the physical tool configuration can be fabricated onto the tip of the horn. The tool is designed such that it can generate the highest vibration amplitude at the free end, for at a specific frequency. As tool is held against by a static load exerted via pneumatic feed system. To get optimum results, a uniform working force must be maintained during machining, with a sensitivity level that effectively counters the resistance arising from the cutting process. Typical static load values range from approximately 0.1 to 30 N.

The workpiece holding unit is composed of a magnetic-based worktable and a workpiece holding plate, both designed to facilitate machining operations on the workpiece. The magnetic base worktable is constructed with a steel plate, measuring 100 mm x 100 mm in cross-section and 8 mm in thickness. This worktable serves the purpose of securely positioning the workpiece holding plate directly beneath the tool's centre. To ensure proper functionality, the worktable is supported by four die springs, with two located at each of its ends. The entire assembly is positioned above the slurry bowl, indicating a specific operational context. For machining operations, work samples are affixed onto the workpiece holding plate using wax. Subsequently, the workpiece holding plate, along with the attached work samples, is magnetized and positioned on the worktable in a suitable configuration for the machining processes to be carried out. This arrangement optimizes precision and stability during the machining procedures.

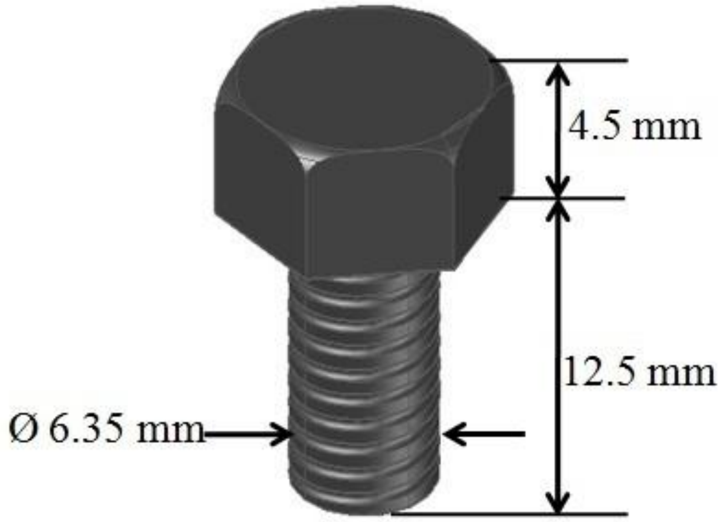


Figure 2.11 Schematic view of tool holder

The workpiece holding plate, measuring 100 x 100 mm in square dimensions and having a thickness of 10 mm, is crafted from mild steel with a particular focus on its construction. It features a specialized design incorporating a central cavity with a diameter of 10 mm and a depth of 5 mm. This cavity serves the purpose of creating a through hole in ceramic workpieces. The same is also made without cavity for generating channels and blind hole generation on the workpiece. To facilitate the machining tasks designated for these plates, they are securely attached and magnetized onto the worktable within the mill module. The design of the fabricated work holding plate is visually represented in fig. 2.12, providing a schematic illustration of its structure. As part of the preparation process, the workpieces holding plate is subjected to a temperature of 70°C on a hot plate. This elevated temperature assists in affixing the workpieces onto the plate with wax, ensuring they are firmly positioned above the central cavity or other designated areas for machining operations.

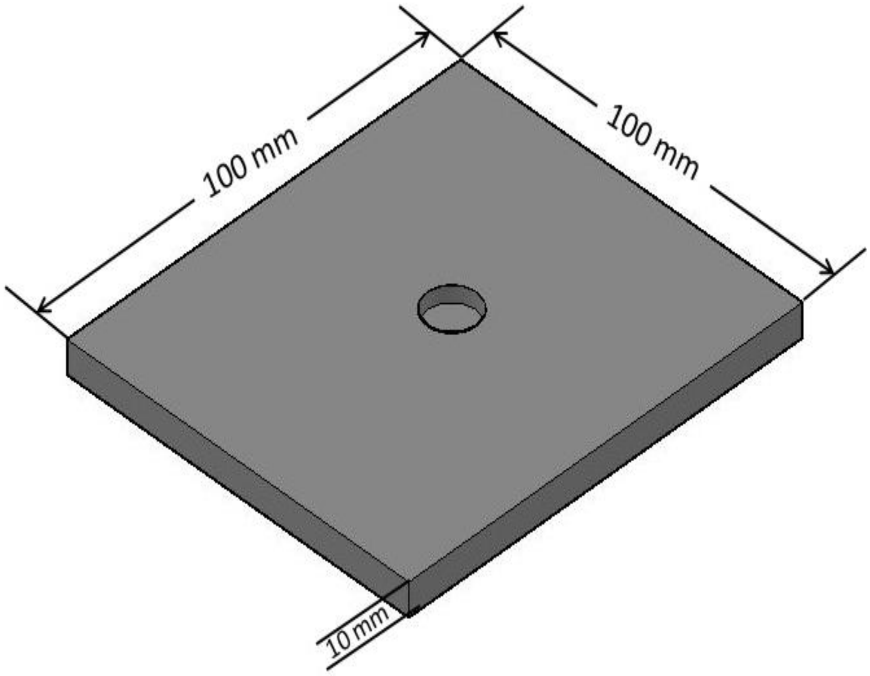


Figure 2.12 Schematic view of work holding plate

2.3 Development of micro tools for ultrasonic micro-machining operation

The cutting tool is always an integral part for machining operations. The importance of this machining component is reflected in the increasing need for new micro-tool development which is fundamental to the progress of modern manufacturing.

Within the realm of tool-based micro fabrication methods, mechanical micromachining holds a significant position. This technique employs micro-tools within dimensions range from 1 to 999 μm, enabling the creation of intricate 3D micro-features with precise dimensional and geometrical tolerances while maintaining relatively efficient material removal rates. Within the realm of mechanical micromachining processes, the micro tools themselves constitute the adaptable element within the micro-machining setup. The intricate micro-features produced in these machining processes are the result of a dynamic interplay between the micro-tool and the workpiece. Consequently, the quality and precision of the machined features are profoundly affected by the micro tools' strength, dimensional accuracy, and surface quality. Notably, the substantial impact of micro tool tolerances and inherent process uncertainties stand as primary contributors to the challenges in accurately predicting outcomes in micromachining endeavours. Furthermore, a deep understanding of the capabilities, attributes, advantages, and constraints inherent to various fabrication methods is essential. When opting for a fabrication approach suited for large-scale usage, factors beyond design requisites come into play. Both the dependability and economic viability of the chosen process must be taken into account.

Micro-tool design and development for ultrasonic micro-machining is one of the main key challenges for generation of micro features on hard and brittle materials. Design of micro-tool is very important for USMM. Tool design means shape of micro-tool, which will suit in ultrasonic machining and produce a desired feature with accurate dimensions and accuracy. At first, a cylindrical rod composed of grade 304 stainless steel was chosen as the starting material for the fabrication of the cylindrical micro tool. Next stainless steel rod was machined with the help of CNC lathe as per design in 3D CAD model as shown in fig. 2.13. Following steps were performed for cylindrical micro tool fabrication.

(i) Tooling layout preparation for the given work piece (cylindrical rod).
(ii) Set the cutting tool in their respective position of the tool post.
(iii) Next the work piece is chucked and checked for the rotation.
(iv) Switch on the motor after selecting the proper speed.
(v) Next by moving the cross slide facing operation is done.
(vi) After shortening the height of the work piece turning operation is completed.
(vii) Make the step turning operation as per required dimension.
(viii) Next chamfer the corners and check the dimensions.

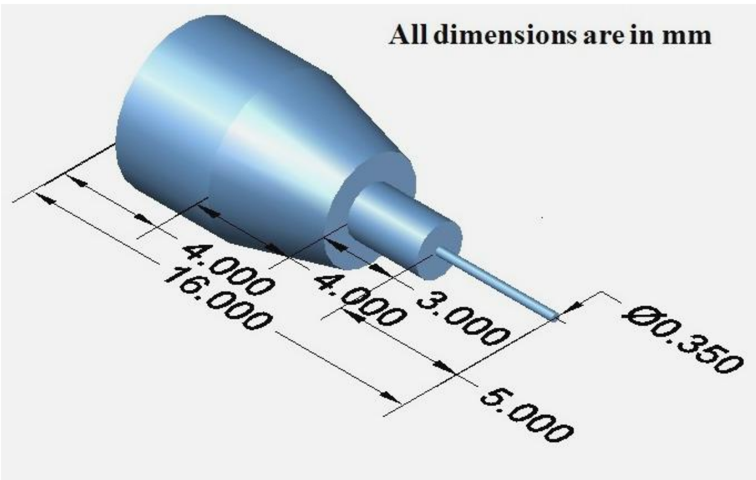
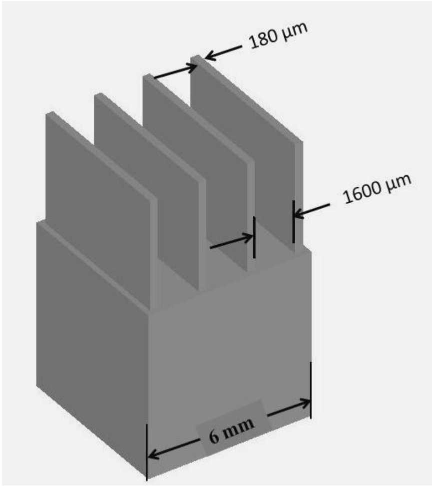


Figure 2.13 Design of micro tool in 3D CAD model

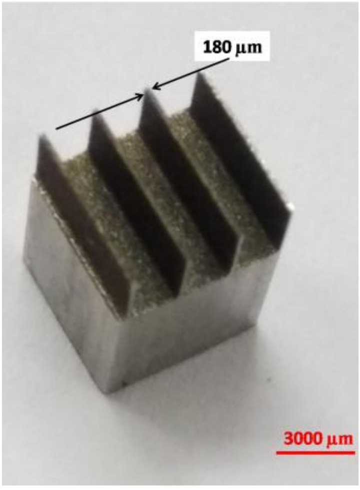
Figure 2.14 shows the photographic view of developed micro-tool. Subsequently, the tool holder, in the form of a hexagonal bolt, and the underside of the fabricated tool were appropriately cleansed. Following the cleaning process, the tool holder and the tool were united through the application of silver brazing. Silver brazing is a technique wherein a nonferrous filler metal alloy is heated to a melting point exceeding 800°C. This process can be carried out using flame heat sources. Specifically, silver filler metal is employed in silver brazing. To facilitate the brazing procedure, the use of flux becomes essential. Flux serves the purpose of eliminating and preventing the reformation of surface oxides on the base metals, thus promoting effective bonding. Proper brazing is very much essential for good joint design.

Figure 2.14 Photographic view of micro tool

By using of cylindrical tip micro tool only micro hole can be generated. So, for generation of micro channel; multi tip micro tool is developed. The multi tip micro tool is developed by wire electro discharge machining (W-EDM) process. Copper wire with zinc coated having diameter 250 µm is utilized as an electrode for wire-EDM. The 3D CAD model and photographic view of multi tips micro tool is shown in fig. 2.15 (a) and (b). The height of the tips are 4 mm and total height of tool is 10 mm. the width of each tool tip is 180 µm and length is 6 mm. the gap between two tips is 1600 µm. The aspect ratio of multi tips micro tool is obtained as 16.



(a)



(b)

Figure 2.15 Multi tip micro tool (a) 3D CAD model and (b) photographic view

Another micro tool i.e. array of micro-tool comprises 4 X 4 square micro tips array is also developed by wire EDM process. The corresponding dimensions lay out are shown in fig. 2.16 and schematic view of micro array tool is shown in fig. 2.17.

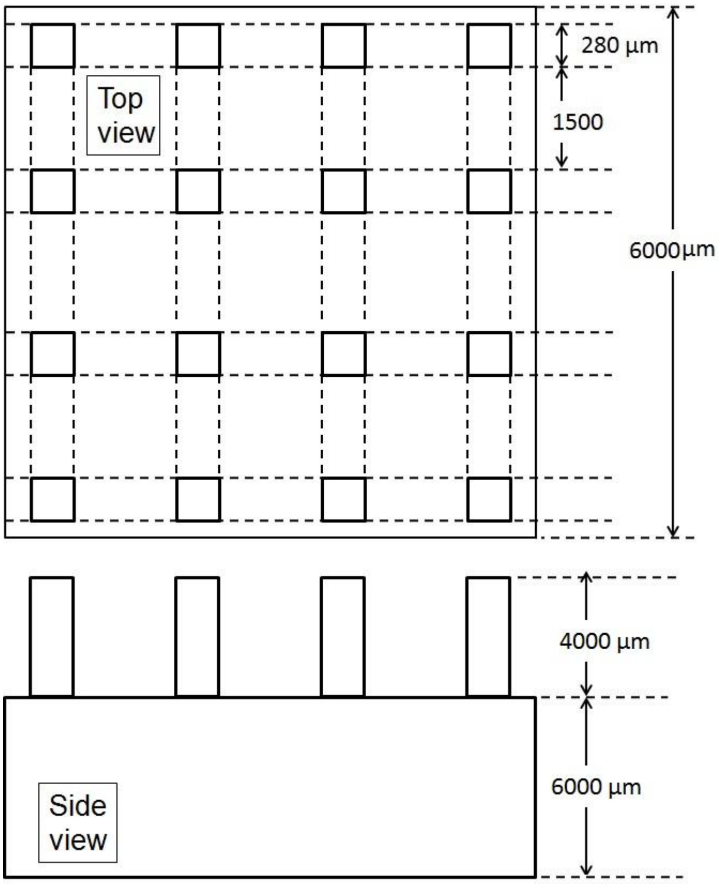


Figure 2.16 Tool dimension layout of array micro tool

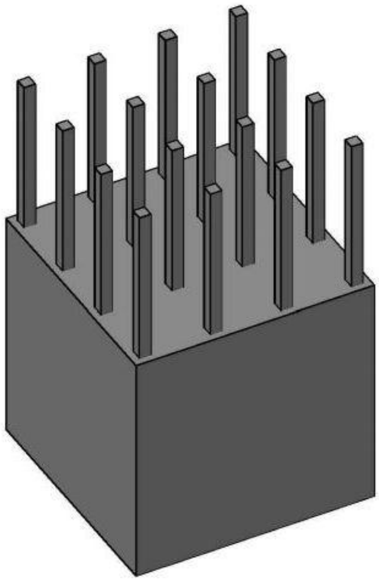


Fig. 2.17 Schematic view of micro array tool

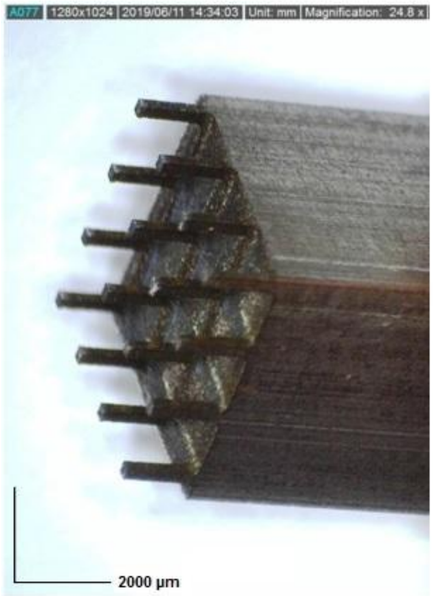


Figure 2.18 Microscopic view of array of micro tool

The micro tool consist of total 16 micro square tips of size 280 X 280 µm and 4 mm height with 10 mm total height. The microscopic view of array of micro tool is shown in fig. 2.18.

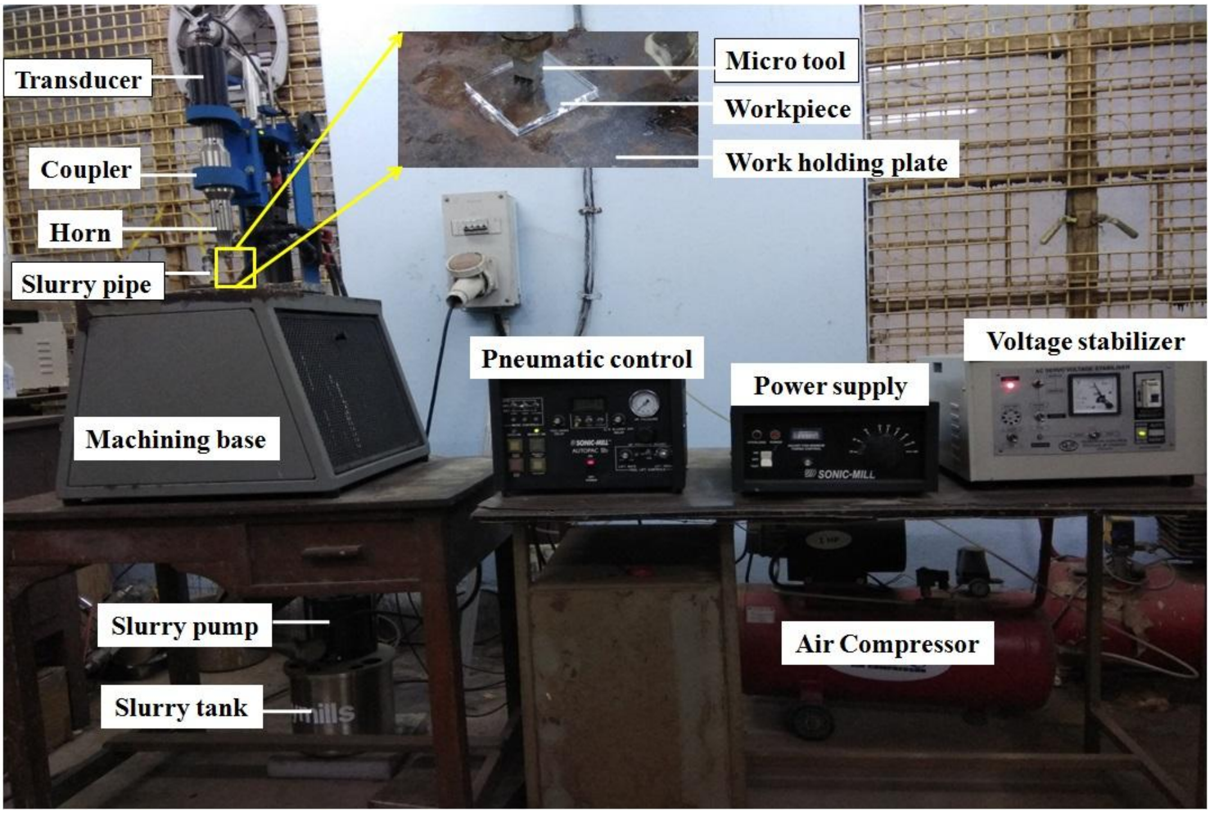


Figure 2.19 Photographic view of ultrasonic micro-machining setup

Table 2.2 Typical range of process parameters for USM machine [87]

Parameters	**Typical values**
Power	200- 1000 W
Tool feed rate	0.05 to 2.5 mm/min
Abrasive slurry concentration	5-60 %
Frequency of Vibration	20 kHz
Amplitude of Vibration	25 µm

The photographic view of ultrasonic micromachining setup, which consists of all the sub components including the power supply unit, pneumatic control unit, tool vibration unit, workpiece holding arrangement, abrasive slurry system unit, etc., is shown in fig. 2.19. Table 2.2 listed the typical range of process parameters available in "AP 1000" sonic mill machine. The experimentation has been planned utilizing the USMM setup for conducting all the experimentation to select process parameters and their range and derive useful research findings during ultrasonic machining for micro machining application.

EXPERIMENTAL INVESTIGATION INTO ULTRASONIC MICRO-MACHINING PROCESS FOR MICRO HOLE GENERATION ON QUARTZ EMPLOYING DEVELOPED MICRO TOOL

3.1 Introduction

In contemporary times, there is a significant demand for miniaturized components and products due to their exceptional advantages. These advantages encompass reduced space requirements, lowered energy and material consumption, ease of transportation and handling, and cost-effectiveness. The expansion of micro electro mechanical systems (MEMS) and the corresponding research across various industries including electronics, optics, medical, biotechnology, automotive, communications, and avionics can be primarily attributed to the presence and significance of these micro components. Lots of micromachining technologies have been developed to fabricate MEMS components and devices. There is a continuous and growing demand for micro-structures, micro-parts, and micro-products across various sectors such as electronics, optics, medical equipment, automotive, and communications. In the production of these items, hard and brittle materials like quartz are utilized due to their exceptional attributes. These include a high strength-to-weight ratio, resistance to heat and corrosion, capability to withstand shocks, and resistance to erosion. Keep in mind for micro machining applications, micro tool have been developed for micro hole drilling on quartz using USMM. Micro hole on quartz have been generated by selecting the process parameters by literature and pilot experiments. The influence of process parameters, including abrasive slurry concentration, power rating and tool feed rate on response of micro hole on quartz like MRR, overcut and taper have been investigated.

3.2 Experimental planning

The experiments were carried out in stationary Sonic Mill USM machine (Model: AP-1000) as discussed in previous chapter with the frequency of vibration of the ultrasonic machine about 20 kHz. The square shaped flat quartz workpiece of 1 mm thickness fixed on the work holding plate made of mild steel. The details properties of quartz have been given in Table 3.1. Abrasive slurry is prepared using B_4C abrasive with a grain size of 14 µm, which is mixed with water at room temperature. Then, developed micro tool of diameter 350 μm and 16 mm long was used for micro hole drilling on quartz. Figure 3.1 exhibit the schematic view of micro tool and workpiece combination. Figure 3.2 shows microscopic views of the entry and exit side of micro hole generated on quartz produced by USMM.

Table 3.2 represents the experimental conditions for generating micro hole on quartz by ultrasonic micromachining process. A rough edge of the hole surface at entry side was observed due to scattered chipping and large penetrated cracks when large size abrasives are applied. Hole surface finish can be improved by using finer abrasives. Too high concentration of abrasive slurry would normally result in a poor surface finish because the circulation and of abrasives are not proper and abrasives are concentrated at the machining zone. From a manufacturing perspective, achieving a high Material Removal Rate (MRR) is desirable. However, it is important to note that significant overcut and large taper angles are not acceptable outcomes in this context. Considering the above points based on pilot experiments and the previous research work, the range of process parameters has been selected for experimentation. Abrasive slurry concentration varies from 20% to 40% by weight. Power rating varies from 200 W to 400 W during experimentation. Tool feed rate varies from 0.8 mm/min to 1.2 mm/min during experimentation.

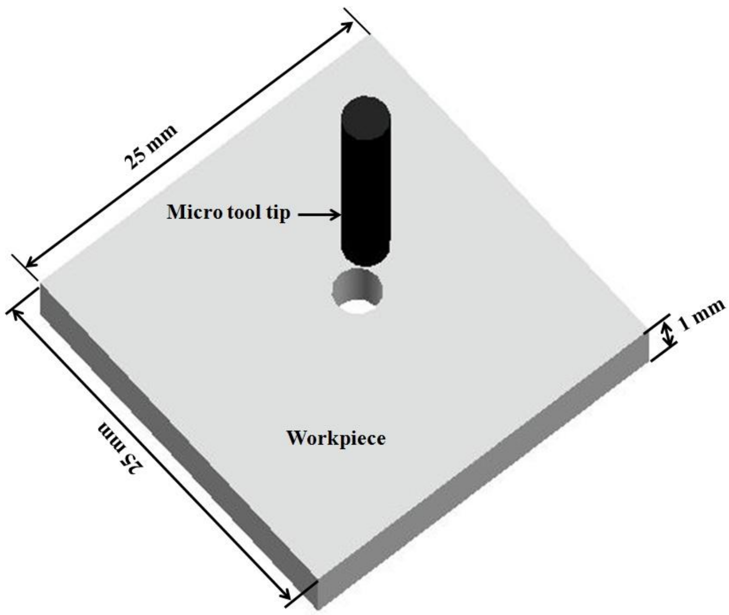


Figure 3.1 Schematic views of micro tool and workpiece

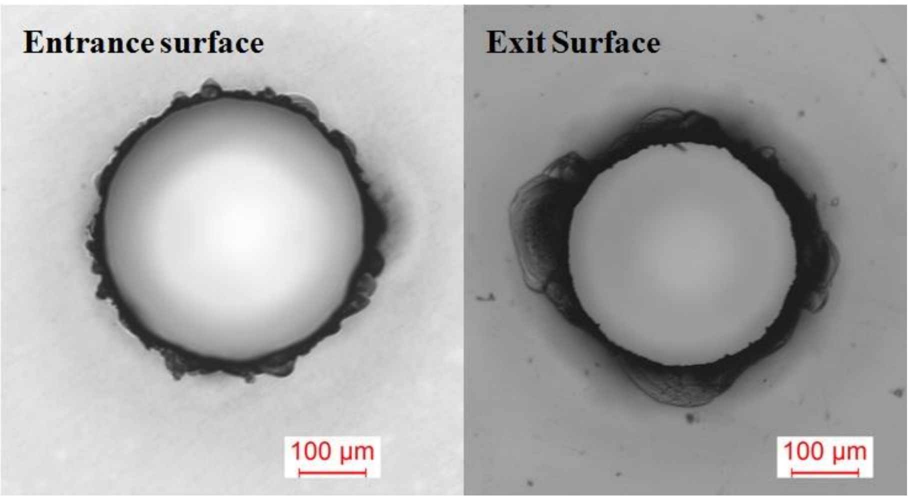


Figure 3.2 Microscopic view of micro hole on quartz

Table 3.1 Detailed properties of quartz

Parameters	**Description**
Chemical composition	SiO_2
Compressive strength (Pa)	1.9×10^{9}
Tensile strength (Pa)	4.8×10^{7}
Density (kg/m^3)	2.2×10^{3}
Young's modulus (Pa)	7.2×10^{10}
Bulk Modulus (Pa)	3.7×10^{10}
Hardness (Mohs Scale)	5.5 - 6.5
Poisson's ratio	0.17
Coefficient of thermal expansion (at 20 - 320° C):	5.5×10^{-7}
Thermal conductivity (W/m° C)	1.4
Specific heat at 20°C (J/kg °C)	670
Softening point (° C)	1683
Annealing point (° C)	1215
Melting point (° C)	1713
Electrical resistivity (350° C) Ω m	7×10^{17}
Index of refraction	1.4585

Table 3.2 Experimental Condition for micro USM on quartz

Work condition	**Description**
Work material	Quartz of size 25 mm x 25 mm x 1 mm
Tool material	SS-304
Tool geometry and diameter	Cylindrical, 350 µm
Abrasive used	Boron carbide (B_4C)
Frequency of vibration	20 kHz
Amplitude of vibration	25 µm
Slurry concentration	20-40 % by weight
Power rating	200-400 W
Feed rate	0.8-1.2 mm/min
Slurry media and temperature	Water & 27^0C (Ambient room temperature)

3.3 Measurement of responses

The measurement procedure and calculations of responses such as MRR, overcut and taper angle are discussed in the subsequent sections.

3.3.1. Measurement of material removal rate (MRR)

At first the diameter of hole was measured after machining and then calculates the volume of the material removed. Subsequently, this value was divided by the total machining time. The calculation of volumetric material removal rate was conducted for each experimental scenario using equation 3.1.

$$MRR = \frac{V}{T} \quad (mm^3/min) \tag{3.1}$$

Where, V= Volume of the material removed (mm^3)

T= Total machining time (min)

The volume of the micro hole has been calculated with the help of following equation (3.2) assuming the shape of micro hole as a frustum of a cone which is illustrated in fig 3.3.

$$V = \frac{\pi t}{3} \left(R_1^2 + R_1 R_2 + R_2^2\right) \tag{3.2}$$

Where, R_1= Radius of micro hole at entrance,

R_2= Radius of micro hole at exit and

t = Thickness of workpiece.

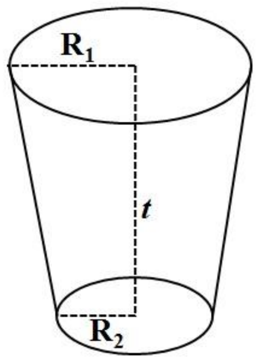


Figure 3.3 Micro-hole indicating as frustum of cone

3.3.2. Measurement of overcut

The diameter of tool was measured by measuring microscope (Leica DM 2500, Germany) before machining. Then the diameter of hole on workpiece was measured by same measuring microscope. Next difference between hole diameter of workpiece and tool was calculated. In this way diametrical overcut (OC) was calculated for each experiment as in equation (3.3).

$$OC = D_h - D_t \tag{3.3}$$

Where, $D_h = D$iameter of micro hole (μm) and

$D_t = D$iameter of micro tool (μm)

3.3.3. Measurement of taper angle

The workpiece was cleaned by acetone carefully. Entrance diameter and exit diameter of micro hole on workpiece was measured by measuring microscope ((Leica DM 2500, Germany). The equation (3.4) is used to calculate the half taper angle of micro hole on quartz.

$$Half\ taper\ angle\ (\alpha) = \tan^{-1} \frac{D_{entry} - D_{exit}}{2t} \tag{3.4}$$

Where, $D_{entry} = D$iameter of micro hole

$D_{exit} = D$iameter of micro tool

t = Thickness of workpiece

3.4 Influence of process parameters on performance criteria of USMM

Influence of process parameters such as abrasive slurry concentration, power rating and tool feed rate on MRR, overcut and taper angle are investigated and discussed in the following sub-section.

3.4.1 Influence of abrasive slurry concentration on MRR

In ultrasonic micro machining process the abrasive slurry concentration is one of the important process parameters. The effects of abrasive slurry concentration on MRR, overcut and taper angle have been observed, presented through various figures and analyzed in the following discussions.

Figure 3.4 shows the influence of abrasive slurry concentration on MRR while power rating and tool feed rate is kept constant at middle level. From the fig. it is clear that as abrasive slurry concentration is increasing, the MRR is increasing gradually. Because there will be a significant numbers of abrasive grains under the tool and the condition for circulation of abrasive in the machining zone are satisfactory. When the concentration of abrasive slurry is lower, the quantity of abrasive grains present within the machining zone becomes limited. Hence, the penetration rate will also be less. Thus due to less number of active abrasive grains taking part in the material removal, the MRR is less. When the abrasive slurry concentration is 20 % (200 g/l) then the MRR is very less and when concentration is 40 % (400 g/l) MRR is more as shown in fig. 3.4.

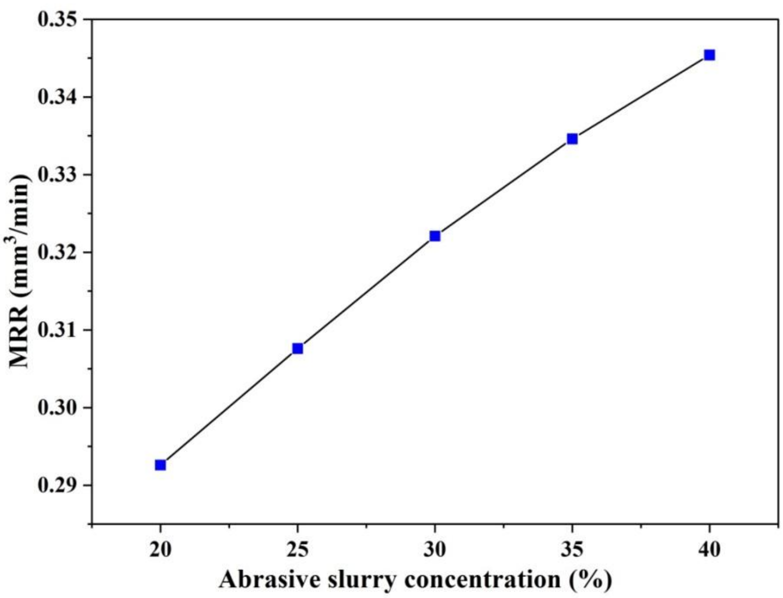


Figure 3.4 Influence of abrasive slurry concentration on MRR

3.4.2 Influence of power rating on MRR

Power rating is also one of the key parameter in USMM process. The effects of power rating on MRR have been observed and analyzed through graphs. Figure 3.5 shows power rating Vs MRR while abrasive slurry concentration and tool feed rate is kept constant at middle level. When the power rating is comparatively high i.e. 400 W for micro-drilling then the MRR is high. In general, low power rating offers the low MRR. Actually if the power increases then MRR also increases because of additional applied energy. Abrasive particle in slurry were striking with more momentum and kinetic energy hence more materials are eroded. At lower power rating, abrasive particles in slurry are striking with low momentum and kinetic energy hence, material removal rate also decreases.

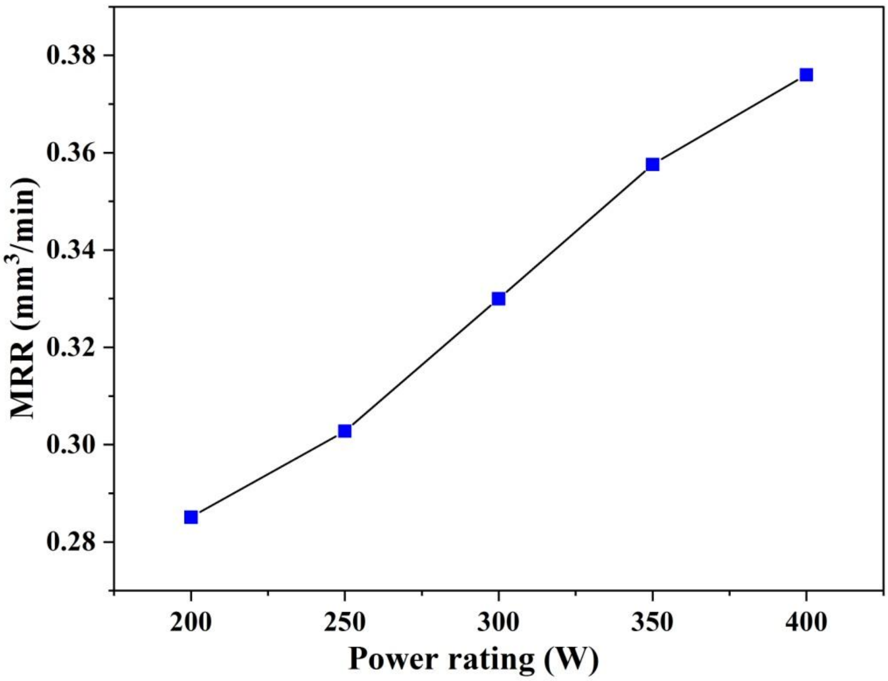


Figure 3.5 Influence of power rating on MRR

3.4.3. Influence of tool feed rate on MRR

Tool feed rate is also one of the important parameter of USM process. The effect of tool feed rate on MRR explained in the subsequent discussion. Figure 3.6 shows that the effect of the tool feed rate on MRR while abrasive slurry concentration and power rating is kept constant at middle level. It shows that when tool feed rate is increasing the MRR increases gradually. It reached at higher value at tool feed rate 1.2 mm/min. When tool feed rate is low, MRR is also low because abrasive particles are striking at small force on work piece. When tool feed rate increases abrasive particles are striking with larger force on workface, hence MRR also increases.

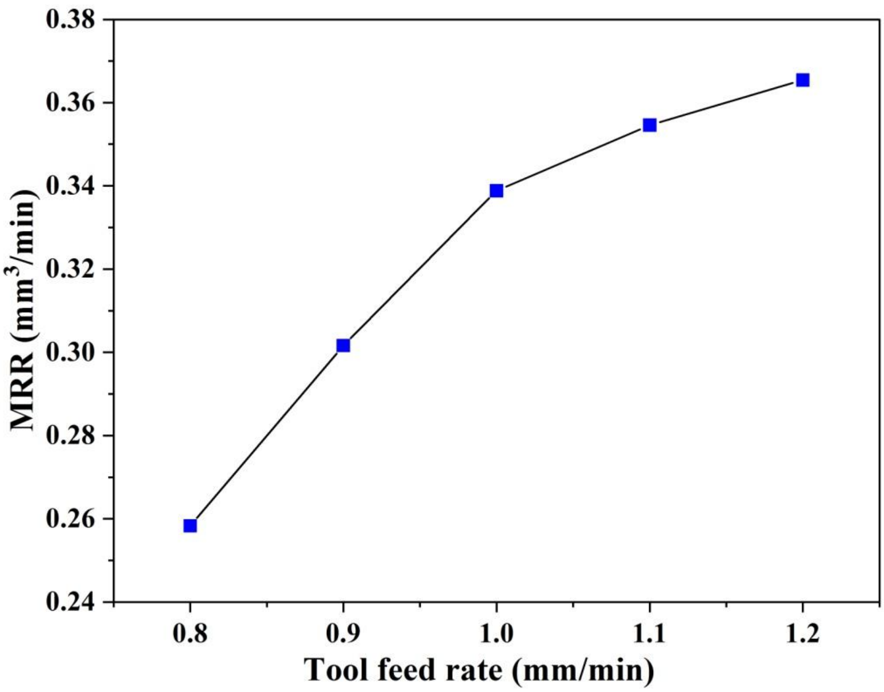


Figure 3.6 Influence of tool feed rate on MRR

3.4.4. Influence of abrasive slurry concentration on overcut

Figure 3.7 shows influence of abrasive slurry concentration on overcut; at the same time power rating and tool feed rate is kept constant at middle level. From figure 3.7 it is observed that overcut is less when abrasive slurry concentration is 20 % and it is slowly increasing up to 25 % and after that overcut steadily increases up to 40 %. When abrasive slurry concentration is less overcut is less because less number of abrasive particles is available. When abrasive slurry concentration increases more number of abrasive particles are active to remove the material from the side edge of the tool, as a result overcut is more.

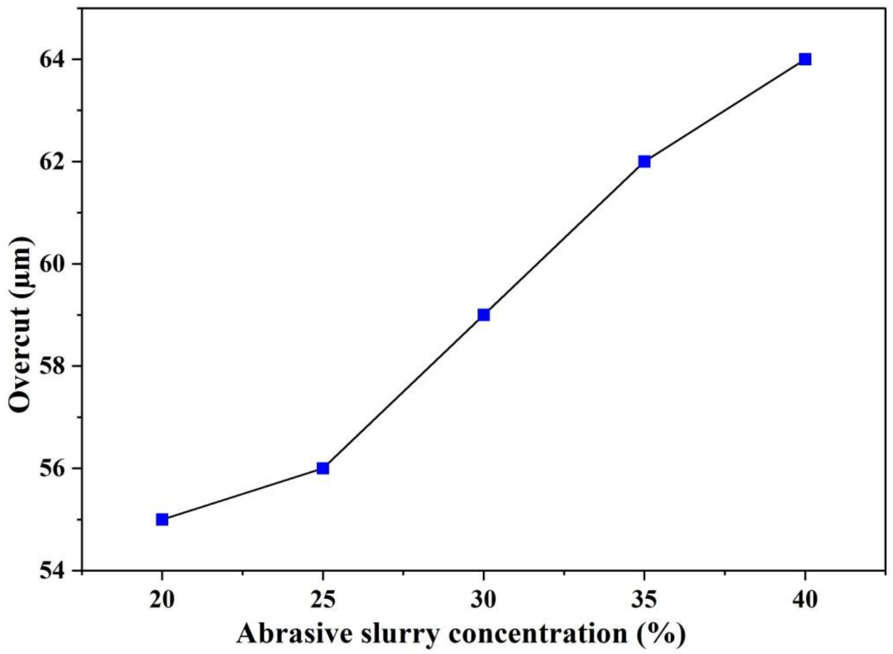


Figure 3.7 Influence of abrasive slurry concentration on overcut

3.4.5. Influence of power rating on overcut

Figure 3.8 shows that influence of power rating on overcut; at the same time abrasive slurry concentration and tool feed rate is kept constant at middle level. From figure it is observed that as power rating is increasing the overcut is also steadily increasing. When power rating is low the overcut is low because at low power rating abrasive particle is striking workpiece at low momentum and kinetic energy. When power rating increases, there is the striking of abrasive particle present in slurry with more momentum and kinetic energy so deduction of material is more. With fixed feed rate of tool as more materials are removed, the diameter of the hole increases. As a result overcut will increases.

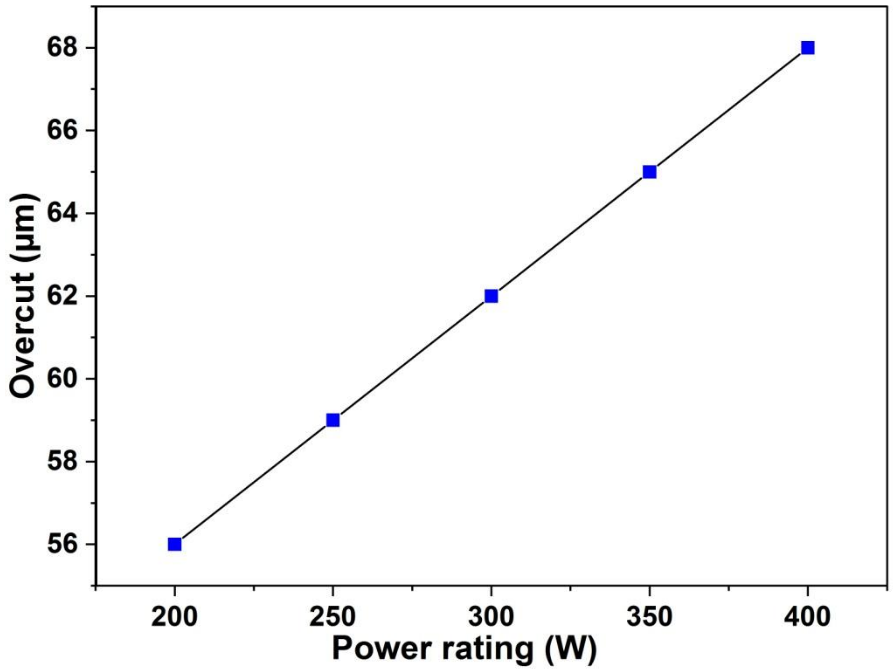


Figure 3.8 Influence of power rating on overcut

3.4.6 Influence of tool feed rate on overcut

Figure 3.9 illustrate that the effect of the tool feed rate on overcut whereas abrasive slurry concentration and power rating is kept constant at middle level. Figure 3.9 shows that when tool feed rate is increasing, overcut is increasing. At low tool feed rate abrasive particle striking at small force hence diametrical deviation is low. When tool feed rate increases, striking force of abrasive particle also increases and hence overcut increases. Overcut is larger at higher value of tool feed rate.

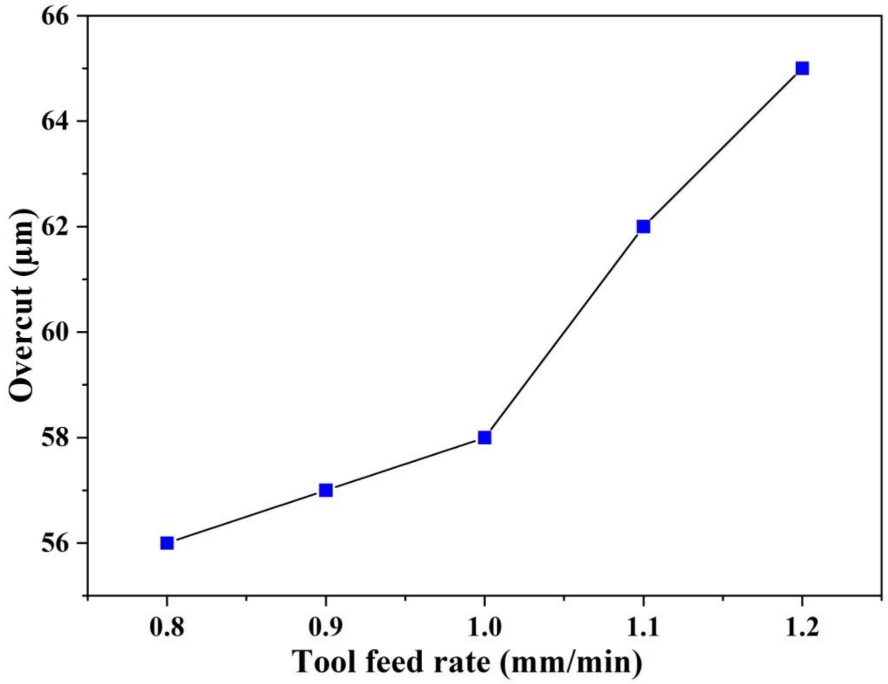


Figure 3.9 Influence of tool feed rate on overcut

3.4.7 Influence of abrasive slurry concentration on taper angle

Figure 3.10 shows influence of abrasive slurry concentration on taper angle; at the same time power rating and tool feed rate is kept constant at middle level. From figure it is clear that taper angle is less when abrasive slurry concentration is low (20 %) and then it is being slowly increased when concentration is 35 %. When abrasive slurry concentration is less, machining rate is uniform therefore taper angle is less. Variation in taper angle is more with higher value of abrasive slurry concentration. The concentration of abrasive slurry significantly affects the non-uniform distribution of abrasive particles in the slurry. Higher concentrations might result in more abrasive particles impacting the workpiece, potentially leading to a larger taper angle due to increased material removal from the top surface.

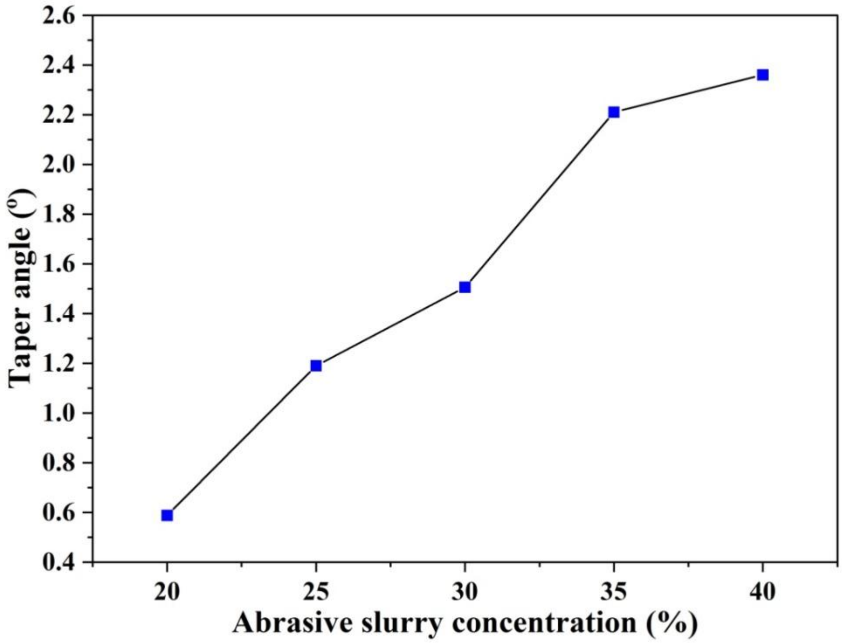


Figure 3.10 Influence of abrasive slurry concentration on taper angle

3.4.8 Influence of power rating on taper angle

Figure 3.11 shows the influence of power rating on the taper angles; at the same time abrasive slurry concentration and tool feed rate is kept constant at middle level. From figure it is clearly shown that increase of power rating results in decrease of taper angles. When power rating is increased, the impact power of the abrasive particles increase that lead to a high momentum transfer of the abrasive particles and the cutting rate is high. Uniform material removal occurs at the bottom side of hole. Therefore, the difference in top and bottom diameter is small. So, the taper angle value is less. For achieving lesser taper angle, high value of power rating is preferred.

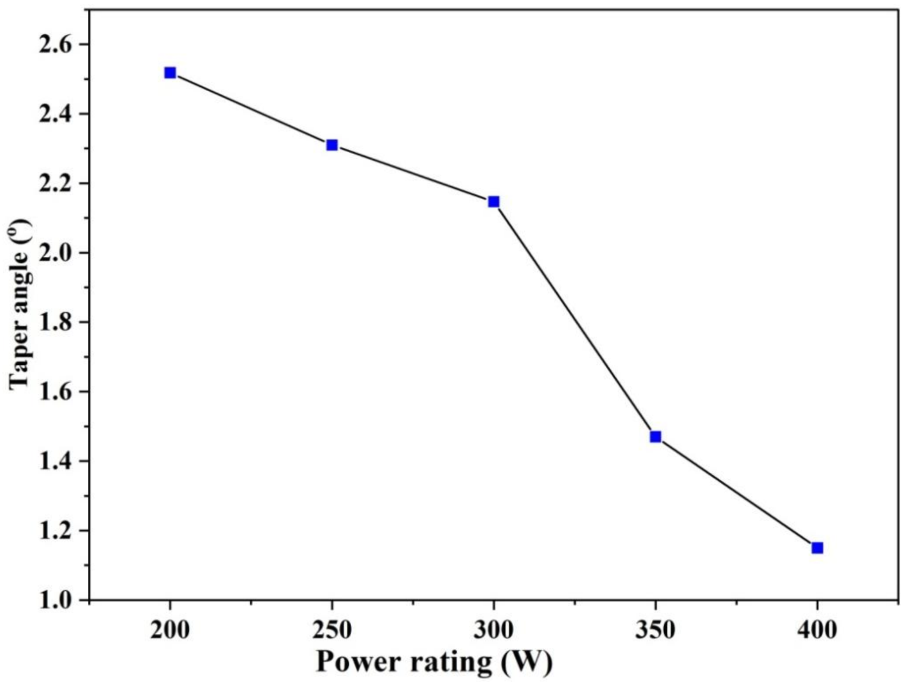


Figure 3.11 Influence of power rating on taper angle

3.4.9 Influence of tool feed rate on taper angle

Figure 3.12 shows the effect of tool feed rate on taper angle while abrasive slurry concentration and power rating is kept constant at middle level. At low tool feed rate, taper angle is less. When tool feed rate is increasing the taper angle also increasing because with increase in tool feed rate, striking force is higher. After increasing tool feed rate, taper angle is observed as large because at higher tool feed rate, impact force on work surface increases. Material removed from the top portion of micro hole is more since more abrasive particles are available for machining surrounding the micro tool at upper portion of micro hole.

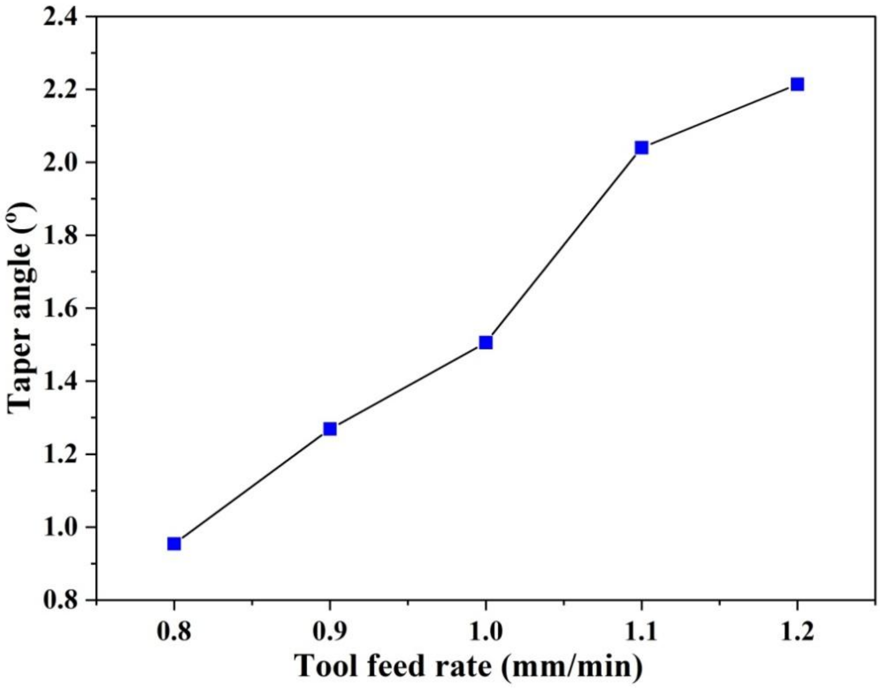


Figure 3.12 Influence of tool feed rate on taper angle

3.5 Outcomes of the present research

Ultrasonic micromachining process has been applied for generation of micro hole on quartz using the fabricated micro tool. Based on the study of parametric influences, it has been summarized that performance of ultrasonic micro machining is very much influenced by abrasive slurry concentration compared to power rating and tool feed rate. For achieving higher MRR, higher power rating, higher abrasive slurry concentration and higher tool feed rate are to be set during USM micro drilling on quartz. Higher MRR i.e. 0.376 mm^3/min is obtained at 400 W power rating because of the fact that abrasive particles striking with higher energy erode the workpiece material at a faster rate. For achieving lesser overcut i.e. 55 µm and taper angle i.e. 0.588^0 of micro hole low value of abrasive slurry concentration, set during USM for micro drilling on quartz. For generation of micro hole on quartz with better quality lesser overcut as well as lesser taper angle is desirable. This present experimental investigation and analysis are very much effective for better control and setting of process parameters in order to achieve higher machining rate and accuracy during USM for micro drilling on quartz. However, development of empirical models is needed for correlating various parameters of USMM with different responses considering above mentioned range of parameter setting. At this stage, it is also necessitated to search out optimum parameter combination for achieving best level of responses for USMM.

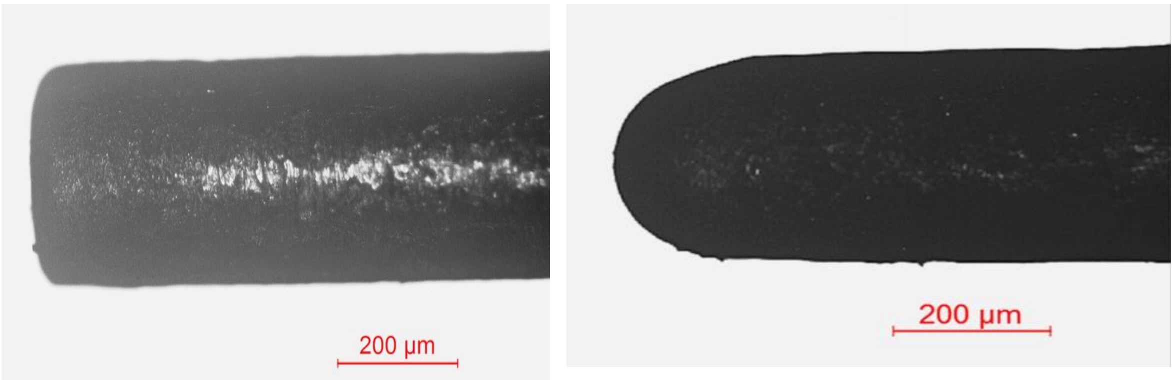
DEVELOPMENT OF EMPIRICAL MODELS AND OPTIMIZATION OF ULTRASONIC MICRO-MACHINING PROCESS PARAMETERS BASED ON RSM

4.1 Introduction

The basic experiments for generating micro hole on quartz was described in previous chapter. In this chapter, ultrasonic micro machining of quartz have been performed according to experimental plan based on response surface methodology (RSM) for determining optimal parametric combination for generating micro hole on quartz. Empirical models were created based on the experimental findings to establish connections between response variables like MRR, overcut, and taper angle, and the process parameters of USMM. These constructed models underwent validation through analysis of variance (ANOVA). The effects of parameters on the responses are examined using response surface plots. The single objectives as well as multi objective optimization of responses have been execute to find the optimal USMM process parameters for achieving maximum MRR, minimum overcut and minimum taper angle of through micro hole on quartz.

4.2 Experimental planning based on RSM

Response Surface Methodology is the technique of design of experiments that find the optimal combination of factors using the plots of response surfaces in which the feasible levels of each factor are continuous. In response surface methodology the optimal combination of factor levels is found in most efficient way. Response surface methodology has two main phases. The initial phase involves identifying the region encompassing the optimal point, while the subsequent phase involves refining the search within that region to pinpoint the optimal point with greater precision. An initial set of factor levels or treatment combinations is selected with the help of expert’s knowledge. During the initial phase of experiments, it is common to make the assumption that the experimental region forms a plane, with a consistent slope in all directions. This assumption of a planar surface is generally reasonable, as any sufficiently small area of a response surface can be effectively approximated by a plane according to mathematical principles. But at a position near the optimal surface, a plane is not adequate to describe a curve surface. In practical terms, achieving statistically significant results in an experiment doesn't occur close to the optimal point. Instead, it's deduced from the data that the experiment hasn't reached the peak of the curved surface. The presumption is that any upward incline observed on the plane, regardless of its statistical significance, is likely to lead towards an optimal point. This is why this series of procedures is commonly referred to as the 'Method of Steepest Ascent'. Once a region is found in the first phase of experiment that fails the test of “reasonableness of the assumption of a plane”, it can be concluded that very high proximity to the optimum value has been achieved. Then the second phase starts in order to probe the surface in greater details allowing the interaction term and quadratic terms. It requires considering a second order model. The second phase is called the “Method of Local Exploration”. The combinations of input parameters are set into the ultrasonic micromachining as per the design from RSM in which central composite design (CCD) is chosen for three factors. In this study, abrasive slurry concentration, power rating and tool feed rate were considered as three factors and varied at five levels as shown in Table 4.1. Micro holes on quartz were produced by the ultrasonic micromachining setup for different levels of machining parameters. Performance criteria for each and every micro hole were analyzed and their experimental results are given in Table 4.2. Figure 4.1 shows the micro tool used for drilling operation before machining and after machining on quartz by ultrasonic micromachining process.



(a) (b)

Figure 4.1 Micro tool tip (a) before machining and (b) after machining

Table 4.1 Actual and Coded values of ultrasonic micromachining process parameters

Factor	Unit	Symbol	Level				
			-2	-1	0	1	2
Abrasive slurry concentration	%	A	20	25	30	35	40
Power rating	W	B	200	250	300	350	400
Tool feed rate	mm/min	C	0.8	0.9	1	1.1	1.2

"RSM was employed to forecast the machining outcomes of the USMM process, encompassing material removal rate (MRR), overcut, and taper angle, based on input process parameters. The optimal parameter values were derived through systematic planning and analysis within the RSM framework. A highly effective approach for modeling USMM within RSM is the utilization of central composite design (CCD). The polynomial equation derived from RSM was utilized to articulate the machining performance of the USMM process, as depicted in equation (4.1). In this experimental study, the machining performance metrics of MRR, overcut, and taper angle were expressed as functions of process parameters, including abrasive slurry concentration, power rating, and tool feed rate."

The general second-order polynomial response surface equation, employed to assess the effects of parameters on different response criteria, is presented as follows:

$$Y_u = \beta_o + \sum_{i=1}^{n} \beta_i x_{iu} + \sum_{i=1}^{n} \beta_{ii} x_{iu}^2 + \sum\sum_{i<j=2}^{n} \beta_{ij} x_i x_j + \epsilon_u \quad (4.1)$$

"In the equation above, Y_u represents the associated response. X_{iu} denotes the coded values of the i_{th} machining process parameters. The coefficients β_0, β_i, β_{ii} and β_{ij} are regression coefficients, while the residual term ϵ_u accounts for the experimental error of the u_{th} observations. The selection of process parameter ranges was guided by a review of existing literature as well as insights gained from preliminary pilot experiments.

For calculations of MRR, overcut and taper angle equations (3.1) to (3.4) are used, which are discussed in chapter 3.

Table 4.2 Actual values of USMM process parameters and observed responses

	USMM Processes parameters			**Responses**		
Exp. No.	Abrasive slurry concentration (%)	Power rating (W)	Tool feed rate (mm/min)	MRR (mm^3/min)	Overcut (μm)	Taper angle (^{0})
1	25	250	1.1	0.3661	62.30	1.2864
2	35	250	1.1	0.3673	63.01	1.3000
3	20	300	1.0	0.4931	66.91	2.5200
4	30	300	1.0	0.1912	54.00	0.7540
5	30	300	1.0	0.2111	58.00	1.0100
6	30	300	1.0	0.3156	54.00	1.2070
7	30	300	0.8	0.4543	64.09	2.0400
8	30	300	1.0	0.3661	62.00	1.3020
9	30	200	1.0	0.6436	66.19	2.8190
10	25	250	0.9	0.1977	55.00	0.7540
11	35	350	1.1	0.2127	52.00	1.0000
12	30	400	1.0	0.3881	62.00	1.2200
13	35	350	0.9	0.3690	62.00	0.9000
14	35	250	0.9	0.1511	51.00	0.6640
15	30	300	1.2	0.4739	66.00	2.6909
16	25	350	1.1	0.3673	62.78	0.9200
17	30	300	1.0	0.3661	62.98	1.2520
18	25	350	0.9	0.3432	66.03	1.3200
19	30	300	1	0.3002	64.16	1.1890
20	40	300	1	0.3517	67.99	1.8862

4.3 Development of empirical model based on response surface methodology

Three distinct independent variables, namely abrasive slurry concentration (A), power rating (B), and tool feed rate (C), are under observation. Each of these variables encompasses main factors, interactions, and pure quadratic terms that collectively impact the quality of micro hole on quartz during the USMM. Second-order polynomial equations are employed to establish relationships between the material removal rate

(Y_{MRR}), overcut (Y_{OC}), and taper angle (Y_{TA}) of the ultrasonic micromachining process, and the input factors: abrasive slurry concentration (A), power rating (B), and tool feed rate (C). These relationships are defined by equations (4.2), (4.3), and (4.4) respectively. The derived mathematical models are utilized for predicting material removal rate, overcut, and taper angle using Minitab software, with a standardized unit as outlined below:

The equation corresponding to Material Removal Rate (Y_{MRR}) is as follows:

$$\mathbf{Y_{MRR}} = 0.359999 + 0.040065\ A + 0.092684\ B + 0.058961\ C - 0.011284\ A^2 + 0.004091\ B^2 - 0.009714\ C^2 + 0.007618\ A\ B + 0.009332\ A\ C - 0.005557\ B\ C \quad (4.2)$$

The equation corresponding to overcut (Y_{OC}):

$$\mathbf{Y_{OC}} = 62.6051 + 1.3681\ A + 3.8956\ B + 1.6281\ C - 0.4556\ A^2 - 0.9319\ B^2 - 0.4669\ C^2 + 1.0260\ A\ B - 2.0035\ A\ C - 2.0110\ B\ C \quad (4.3)$$

The equation corresponding to taper angle (Y_{TA}):

$$\mathbf{Y_{TA}} = 1.12257 + 0.33050\ A + 0.39814\ B + 0.24824\ C + 0.12185\ A^2 + 0.12661\ B^2 + 0.10048\ C^2 + 0.16977\ A\ B + 0.03273\ A\ C - 0.04152\ B\ C \quad (4.4)$$

4.4 Analysis of variance for the developed models

To validate the fitness of the empirical models devised to describe the material removal rate, overcut and taper angle responses in the micro ultrasonic machining process for generating micro hole on quartz plate, analysis of variance (ANOVA) test has been conducted.

Table 4.3 represents the results of analysis-of-variance for material removal rate. The p-value of all the process parameters is less than 0.05. The lack-of-fit F-value is 1.59, which is below the tabulated value of 4.77. This insignificance of the lack-of-fit implies a significant fit. Additionally, the p-values corresponding to the linear effects of the three process parameters, for the material removal rate (MRR), are all below 0.05 at a 95% confidence level. This outcome signifies that the empirical model for MRR, as formulated in equation 4.2, holds statistical significance and is appropriate at the 95% confidence level.

Table 4.3 ANOVA table for MRR

Source	DOF	Seq SS	Adj SS	Adj MS	F	p
Regression	9	0.226417	0.226417	0.025157	6.40	0.004
Linear	3	0.218751	0.218751	0.072917	18.55	0.000
A	1	29.947	29.947	29.947	2.80	0.025
B	1	242.811	242.811	242.811	22.67	0.001
C	1	242.811	242.811	242.811	22.67	0.001
Square	3	24.900	24.900	8.300	0.78	0.534
A*A	1	1.186	5.219	5.219	0.49	0.501
B*B	1	18.234	21.833	21.833	2.04	0.184
C*C	1	5.480	5.480	5.480	0.51	0.491
Interaction	3	72.883	72.883	24.294	2.27	0.143
A*B	1	8.421	8.421	8.421	0.79	0.396
A*C	1	32.111	32.111	32.111	3.00	0.114
B*C	1	32.352	32.352	32.352	3.02	0.113
Residual Error	10	107.089	107.089	10.709		
Lack-of-Fit	5	105.979	105.979	21.196	1.47	0.910
Pure Error	5	1.110	1.110	0.222		
Total	19	520.045				
S 0.0007663	R-sq 99.24%	R-sq(adj) 98.57%	R-sq(pred) 96.26%			

Upon reviewing ANOVA Table 4.4, it becomes evident that the lack-of-fit F-value for the overcut of micro hole is 1.47, falling below the tabulated value of 4.77. The resulting lack-of-fit insignificance implies the model's meaningfulness. Furthermore, the associated p-value for the linear effect and all four process parameters pertaining to overcut are below 0.05. This outcome underscores the statistical significance and adequacy of the developed empirical model for overcut, as defined by equation 4.3, at the 95% confidence level.

Table 4.4 ANOVA Table for overcut

Source	DOF	Seq SS	Adj SS	Adj MS	F	p
Regression	9	412.956	412.956	45.884	4.28	0.016
Linear	3	315.173	315.173	105.058	9.81	0.003
A	1	29.947	29.947	29.947	2.80	0.025
B	1	242.811	242.811	242.811	22.67	0.001
C	1	42.414	42.414	42.414	3.96	0.035
Square	3	24.900	24.900	8.300	0.78	0.534
A*A	1	1.186	5.219	5.219	0.49	0.501
B*B	1	18.234	21.833	21.833	2.04	0.184
C*C	1	5.480	5.480	5.480	0.51	0.491
Interaction	3	72.883	72.883	24.294	2.27	0.143
A*B	1	8.421	8.421	8.421	0.79	0.396
A*C	1	32.111	32.111	32.111	3.00	0.114
B*C	1	32.352	32.352	32.352	3.02	0.113
Residual Error	10	107.089	107.089	10.709		
Lack-of-Fit	5	105.979	105.979	21.196	1.47	0.910
Pure Error	5	1.110	1.110	0.222		
Total	19	520.045				
S 0.0032245	R-sq 99.96%	R-sq(adj) 97.92%	R-sq(pred) 98.79%			

From ANOVA Table 4.5, it is revealed that for taper angle, the lack-of-fit F-value stands at 2.84, which is below the tabulated value of 4.77. This insignificance of the lack-of-fit is evident due to the calculated F-value falling short of the tabulated benchmark. Additionally, the p-values corresponding to the linear effect and all four process parameters associated with taper angle are below 0.05. This underscores the high significance and adequacy of the developed empirical model for taper angle, as outlined in equation 4.4. This model effectively represents the relationship between overcut of smaller diameter of a stepped hole and the USM process parameters with a confidence level of 95%."

Table 4.5 ANOVA Table for taper angle

Source	DOF	Seq SS	Adj SS	Adj MS	F	P
Regression	9	6.24957	6.24957	0.69440	4.15	0.018
Linear	3	5.26990	5.26990	1.75663	10.49	0.002
A	1	1.74767	1.74767	1.74767	10.44	0.009
B	1	2.53626	2.53626	2.53626	15.14	0.003
C	1	0.98596	0.98596	0.98596	5.89	0.036
Square	3	0.72673	0.72673	0.24224	1.45	0.287
A*A	1	0.18187	0.37329	0.37329	2.23	0.166
B*B	1	0.29100	0.40307	0.40307	2.41	0.152
C*C	1	0.25387	0.25387	0.25387	1.52	0.246
Interaction	3	0.25294	0.25294	0.08431	0.50	0.688
A*B	1	0.23058	0.23058	0.23058	1.38	0.268
A*C	1	0.00857	0.00857	0.00857	0.05	0.826
B*C	1	0.01379	0.01379	0.01379	0.08	0.780
Residual Error	10	1.67466	1.67466	0.16747		
Lack-of-Fit	5	1.48525	1.48525	0.29705	2.84	0.821
Pure Error	5	0.18941	0.18941	0.03788		
Total	19	7.92423				
S 0.0033250	R-sq 98.95%	R-sq(adj) 96.90%	R-sq(pred) 96.77%			

4.5 Parametric analysis for achieving better ultrasonic micro machining characteristics based on response surface plots

The impact of various process parameters in USMM, such as abrasive slurry concentration, power rating, and tool feed rate, on outcomes like material removal rate, overcut, and taper angle during the machining of a quartz plate has been investigated through the use of response surface plots.

4.5.1. Parametric effects on material removal rate (MRR)

Abrasive slurry concentration stands as a crucial parameter impacting machining characteristics significantly. The response surface plot depicted in fig. 4.2 showcases the interplay between abrasive slurry concentration and power rating concerning material removal rate, while maintaining a constant tool feed rate of 1 mm/min. Enhanced material removal rates are achievable with increased abrasive slurry concentration and power rating values. This effect arises from the greater material removal facilitated by higher abrasive slurry concentration in micro ultrasonic machining. Higher power ratings result in abrasive particles impacting the workpiece with greater force, consequently leading to heightened material removal rates under elevated abrasive slurry concentration and power rating conditions."

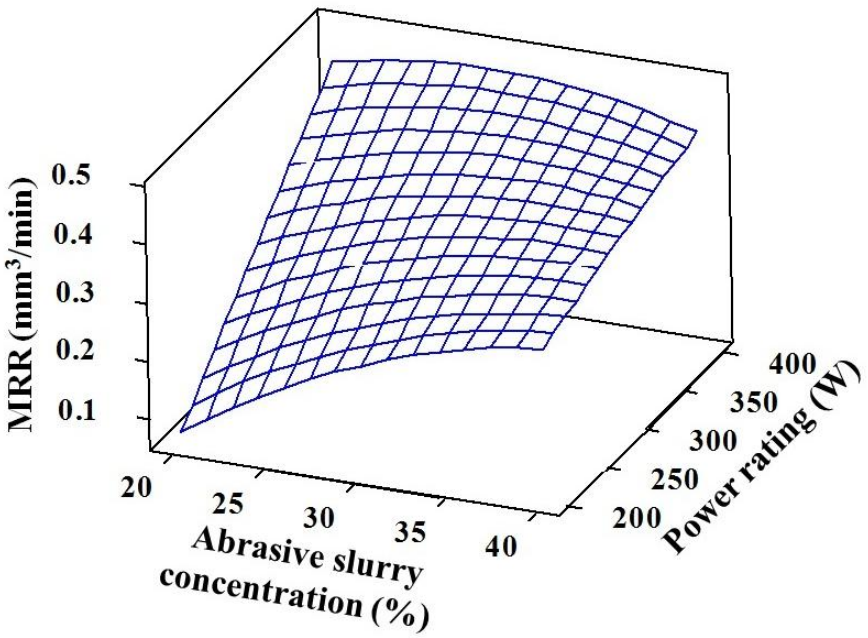


Figure 4.2 Influences of abrasive slurry concentration and power rating on MRR

Figure 4.3 visually presents the effects of power rating and tool feed rate on material removal rate (MRR), while maintaining a constant preset value of abrasive slurry concentration (30%). The figure illustrates that MRR displays an upward trend in response to increments in both power rating and tool feed rate. This behaviour can be attributed to the enhanced momentum of abrasive particles, resulting in increased MRR as the tool feed rate rises.

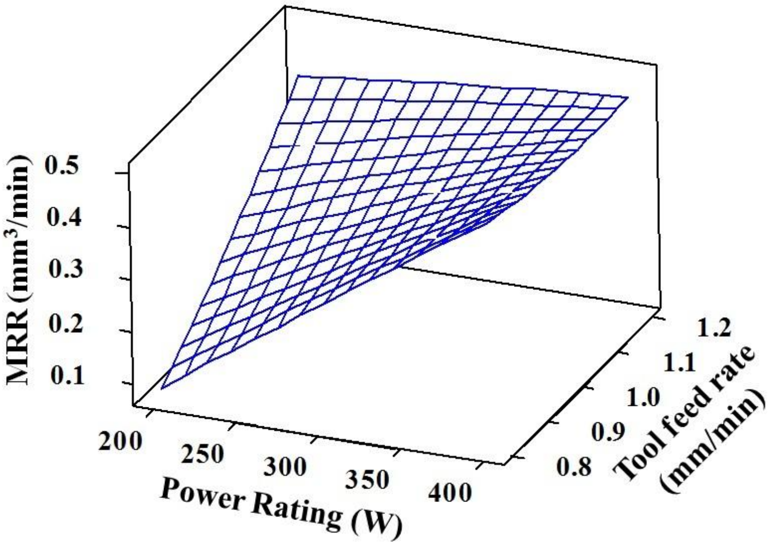


Figure 4.3 Influences of power rating and tool feed rate on MRR

4.5.2 Parametric effects on overcut

Figure 4.4 visually depicts the impact of abrasive slurry concentration and power rating on the overcut of a hole, while maintaining a constant preset tool feed rate of 1 mm/min. The graph highlights that the smallest overcut value is observed when abrasive slurry concentration and power rating are at their lowest values. As abrasive slurry concentration increases, the overcut also tends to increase, while it changes gradually with abrasive slurry concentration and power rating both.

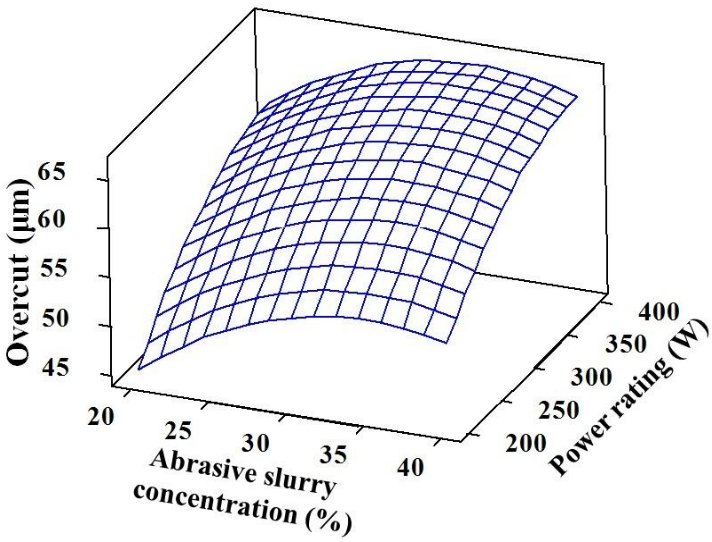


Figure 4.4 Influences of abrasive slurry concentration and power rating on overcut

Figure 4.5 visually represents the effects of power rating and tool feed rate on the overcut of a hole, while maintaining a constant preset abrasive slurry concentration of 30%. The graph reveals that the smallest overcut value occurs when both tool feed rate and power rating are at their lowest values. Overcut increases slowly with increase in power rating at small feed tool rate and it is also increased with increase in power rating with high tool feed rate.

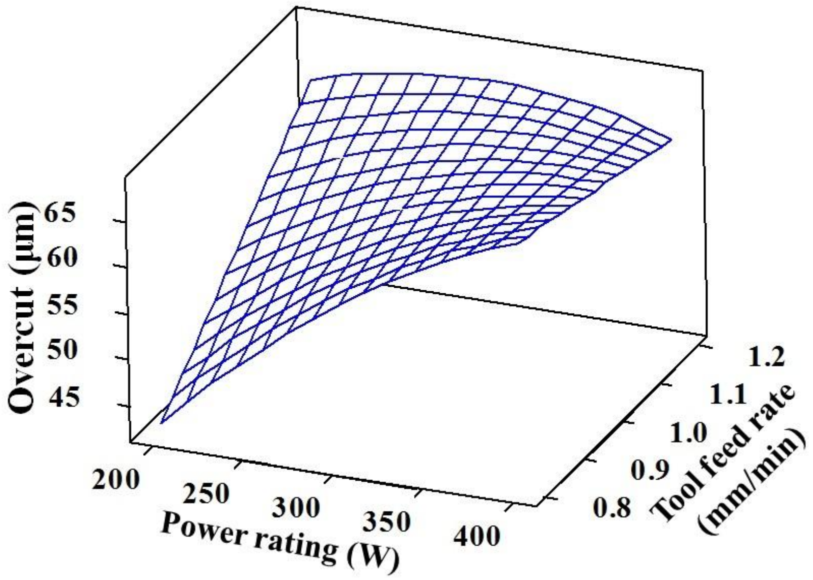


Figure 4.5 Influences of power rating and tool feed rate on overcut

4.5.3 Parametric effects on taper angle

Figure 4.6 visually showcases the impact of abrasive slurry concentration and power rating on taper angle, while maintaining a constant preset tool feed rate of 1 mm/min. The graph demonstrates that lower taper angles are attainable when both abrasive slurry concentration and power rating are at their lowest values.

Figure 4.7 visually presents the impact of power rating and tool feed rate on the taper angle of the generated hole, while maintaining a constant preset abrasive slurry concentration of 30%. The graph reveals that lower taper angles are observed when both tool feed rate and power rating are at their lowest values. As the tool feed rate increases, the taper angle of the generated hole experiences a sharp increase, especially under higher power rating conditions.

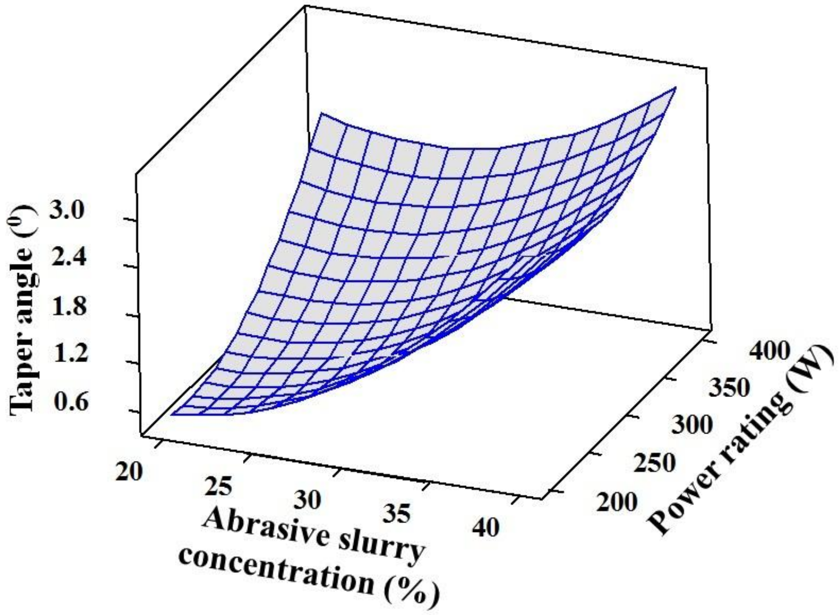


Figure 4.6 Influences of abrasive slurry concentration and power rating on taper angle

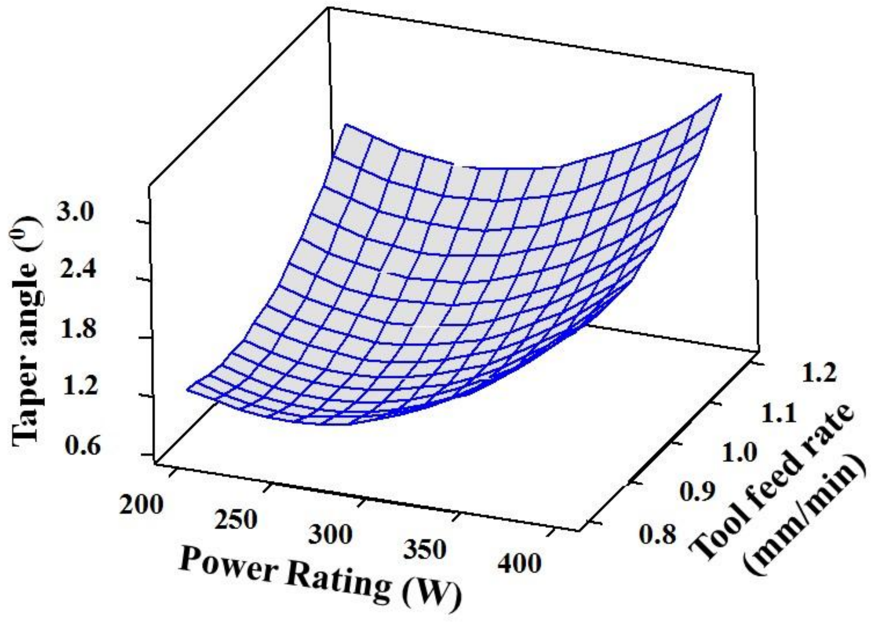


Figure 4.7 Influences of Power rating and Tool feed rate on taper angle

4.6 Optimization of ultrasonic micro machining of quartz

Single objective optimizations as well as multi objective optimization of USMM process parameters to produce micro hole in quartz plate have been executed using MINITAB software. The responses of ultrasonic machining process such as the material removal rate, overcut and taper angle are considered.

4.6.1 Single objective optimization of ultrasonic micro machining characteristics

Figure 4.8 exhibits the results of optimization and optimal values of the ultrasonic micro machining parameters for achieving maximum material removal rate during machining of quartz. In this optimization, it can be observed that MRR is maximum at medium value of abrasive slurry concentration (A), high value of power rating (B) and middle value of tool feed rate(C). For achieving maximum MRR, the optimal combination of process parameter are obtained as slurry concentration of 31.71 %, power rating of 400 W and tool feed rate of 1.03 mm/min. The maximum material removal rate is obtained as 0.4631mm^3/min. The value of composite desirability (d) is considered as 1.

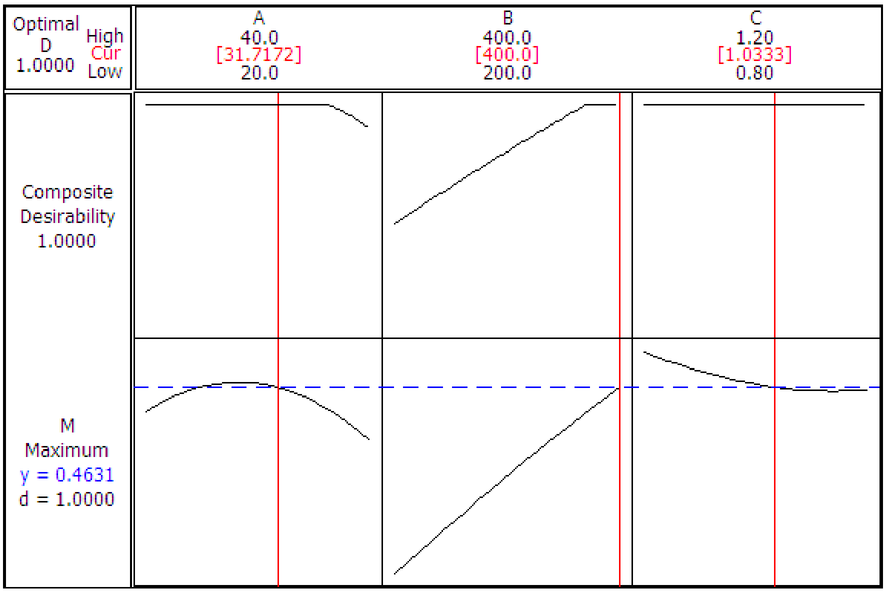


Figure 4.8 Single objective optimization of material removal rate

Figure 4.9 represents optimized values of the micro ultrasonic machining parameters for achieving minimum overcut during drilling of quartz plate. In this optimization, it can be observed that the overcut is minimum at lowest value of abrasive slurry concentration, lowest value of power rating and lowest value of tool feed rate. For achieving minimum overcut the optimal combination of process parameter are obtained as abrasive slurry concentration of 20 %, power rating of 200 W and tool feed rate of 0.8 mm/min. The minimum overcut is obtained as 30.1671 µm. The value of composite desirability (d) is considered as 1.

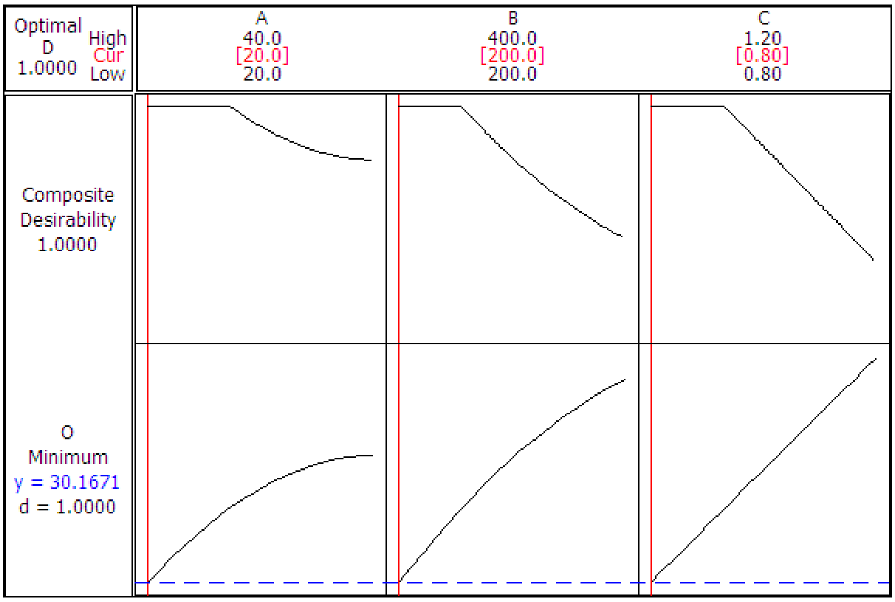


Figure 4.9 Single objective optimization of overcut of drilled hole

Figure 4.10 shows optimized values of the ultrasonic micro machining parameters for achieving minimum half taper angle during machining of quartz plate. In this optimization, it can be observed that the taper angle is minimum at lowest value of abrasive slurry concentration, low value of power rating and lowest value of tool feed rate. For achieving minimum overcut the optimal combination of process parameter are obtained as abrasive slurry concentration of 20 %, power rating of 220.20 W and tool feed rate of 0.9010 mm/min. The minimum half taper angle is obtained as 0.3371^0. The value of composite desirability (d) is considered as 1.

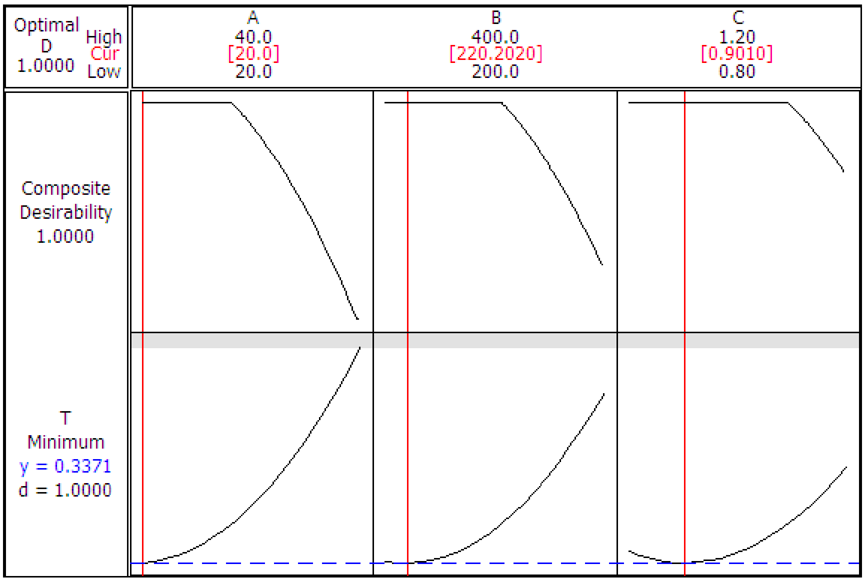


Figure 4.10 Single objective optimization of taper angle

Table 4.6 shows the results of single objective optimization and compare predicted values with actual values and also percent of errors. The percentage of error in single objective optimization for all three responses is well below 5%. Therefore prediction of results is acceptable

Table 4.6 Percentage of error for single objective optimization

Responses	Optimal parametric combination	Predicted value	Actual value	Percentage of error
Material removal rate (mm^3/min)	Abrasive slurry concentration 31.71 %, Power rating 400 W and Tool feed rate 1.0 mm/min	0.4631	0.4502	2.78%
Overcut (µm)	Abrasive slurry concentration 20 %, Power rating 200 W and Tool feed rate 0.8 mm/min	30.1671	31.01	2.79%
Taper angle (^{0})	Abrasive slurry concentration 20 %, Power rating 220 W and Tool feed rate 0.90 mm/min	0.3371	0.3425	1.6%

4.6.2 Multi objective optimization of ultrasonic micro machining characteristics

The multi-objective optimization process was executed to determine the optimal combination of process parameters that would yield the maximum material removal rate, minimum overcut, and minimum taper angle. The outcome of the multi-objective optimization, depicted in fig 4.11, showcases the optimized results for material removal rate, overcut, and taper angle. The optimized parameter values are determined as follows: an abrasive slurry concentration of 23.43%, power rating of 290.84 W, and a tool feed rate of 0.80 mm/min. The achieved results from multi-objective optimization are a maximum material removal rate of 0.2008 mm^3/min, a minimum overcut of 50.29 µm, and a minimum half taper angle of 0.7880^0. The value of overall composite desirability (d) is considered as 1.

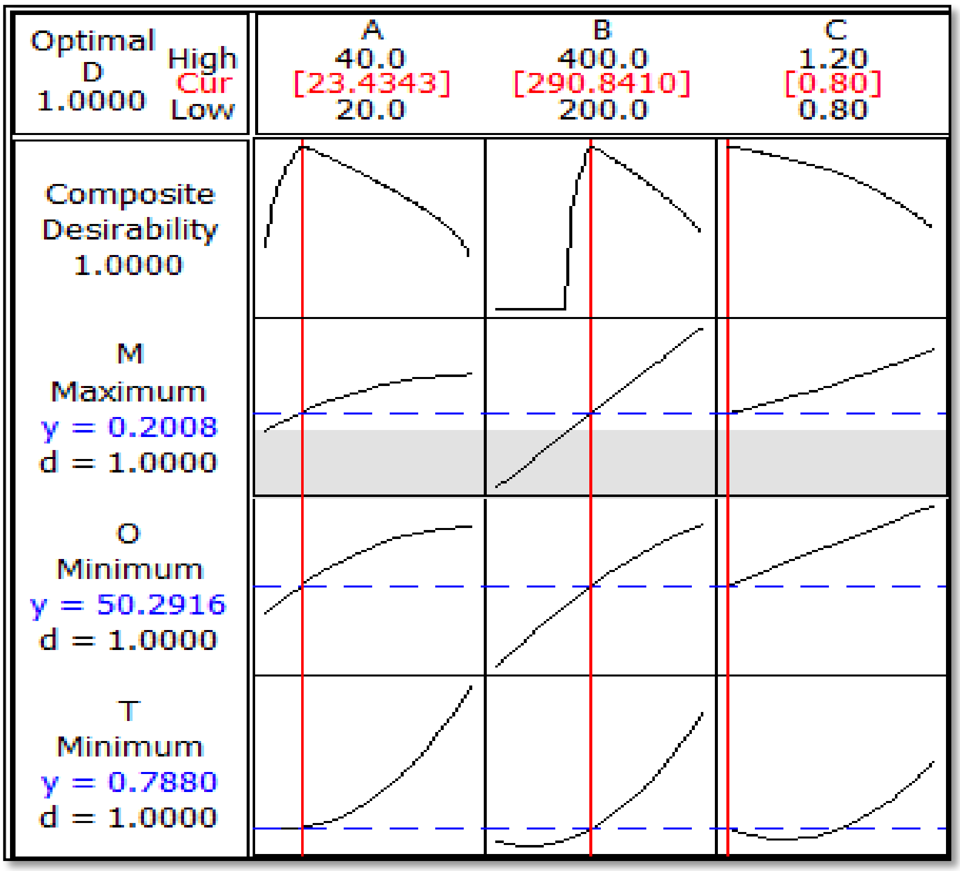


Figure 4.11 Multi objective optimization of material removal rate, overcut, and taper angle during micro ultrasonic machining of quartz

With the optimal parameter setting as obtained by multi objective optimization, optimal value of MRR is low but it is good that overcut is also low and taper angle is very low. It also indicates that almost low values of abrasive slurry concentration and tool feed rate and middle value of power rating gives the optimal parametric condition. It may also indicate that abrasive slurry concentration is more significant than quantity of slurry flow under normal working conditions whereas lower tool feed rate may even affect more overcut as there is more chance of slurry movement across the tool and the surface of the workpiece. Lower abrasive slurry concentration is recommended for larger tool areas of cross section. The experiments were conducted using the optimal parameter combination, and the actual responses were observed and measured. Table 4.7 shows the result of multi objective optimization and comparison with predicted and actual value and also the calculated percent of errors. It is found that the percentage of errors for all the responses is within 5%. The photographic view of machined workpiece is shown in fig. 4.12 and microscopic view of micro hole machined on quartz at optimum parametric condition is shown in fig. 4.13.

Table 4.7 Percentage of error for multi objective optimization

Optimal parametric combination	Multi responses	Predicted value	Actual value	Percentage of error
abrasive slurry concentration 23.43 %, power rating 290.84 W and tool feed rate 0.80 mm/min	MRR(mm^3/min)	0.2008	0.1976	1.59%
	Overcut (µm)	50.2916	49.0236	2.52%
	Half taper Angle (^{0})	0.7880	0.752	4.56%

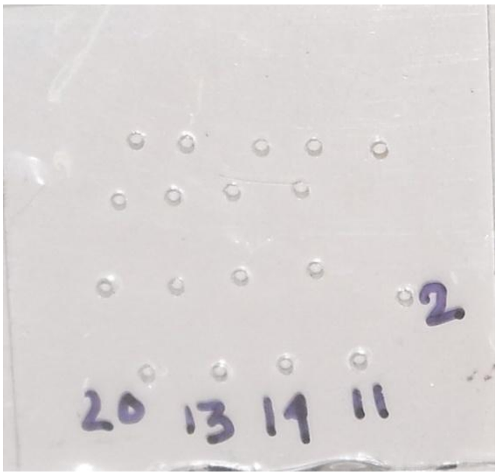


Figure 4.12 Photographic view of the machined workpiece

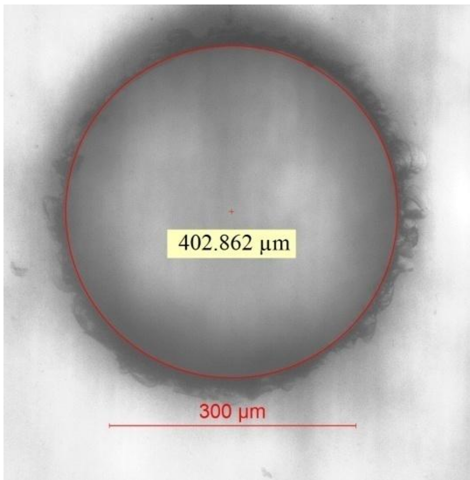


Figure 4.13 Microscopic view of micro drill on quartz at optimal parametric setting

4.7 Outcomes of the present research

This chapter deals with the development of empirical models, parametric analysis, and optimization of USMM process for micro hole drilling on quartz workpiece. From ANOVA, developed empirical models, response surface plots and single as well as multi-objective optimization based on RSM, the following outcomes are obtained.

The established mathematical models for material removal rate (MRR), overcut, and taper angle have been determined to be suitable for assessing the impacts of process parameters on the response characteristics of micro holes generated on quartz using USMM process. From the response surface graphs based on RSM models, it is observed that MRR increases with increases in abrasive slurry concentration with little variation in values of power rating. Lower overcut has been achieved with a combination of medium power rating and higher value of slurry concentration. The taper angle has been found to be minimized when employing a medium tool feed rate and medium abrasive slurry concentration. For achieving maximum MRR, the optimal combination of process parameters obtained as abrasive slurry concentrations of 31.71 %, power rating of 400 W, and tool feed rate of 1.03 mm/min. The maximum MRR is obtained as 0.4631 mm^3/min. For achieving minimum overcut the optimal combination of process parameters obtained as abrasive slurry concentrations of 20 %, power rating of 200 W, and tool feed rate of 0.8 mm/min. The minimum overcut is obtained as 30.16 µm. For achieving minimum half taper angle the optimal combination of process parameters obtained as abrasive slurry concentrations of 30 %, power rating of 220.20 W and tool feed rate of 0.90 mm/min. The minimum half taper angle is obtained as 0.3371^0. Multi-objective optimization was executed to obtain the optimal combination of process parameters, aiming for maximum material removal rate, minimum overcut, and minimum taper angle. The optimal parameter combination comprises an abrasive slurry concentration of 23.43%, a power rating of 290 W, and a tool feed rate of 0.80 mm/min. Consequently, the achieved outcomes from this optimization effort include a maximum material removal rate of 0.2008 mm^3/min, a minimum overcut value of 50.29 µm, and a minimum taper angle value of 0.7880^0.

The experiments are conducted at optimal process parametric settings and the percentage of errors based on the results of actual and predicted values of responses for single objective as well as multi objective optimization lie within 5%. Therefore, the results and analysis is quit adequate and acceptable. Further, to investigate the influence of USMM process parameters on responses during micro channel generation, it is also necessary to perform experiments for machining micro channels on quartz by ultrasonic micromachining. Multi tips micro tools as developed can be utilized during experiments for generation of multi channels on quartz by USMM.

EXPERIMENTAL INVESTIGATION INTO ULTRASONIC MICRO MACHINING PROCESS FOR MICRO CHANNEL GENERATION ON QUARTZ EMPLOYING DEVELOPED MULTI TIPS MICRO TOOL

5.1 Introduction

Micro channels are used to hold as well as transmit liquids through passage which have been applied in various areas like biomedical science, micro fuel cell and cooling of components of micro electronics. Thus, fabrication of micro channels is the essential part for developing micro devices. Various processes are used to developed micro channels on various engineering materials to fulfil the requirement. Because of extreme brittleness and hardness of quartz, generation of micro channel is a difficult task. Among different materials quartz is attractive material for research interest because it is employed in various chemical and medical applications. Quartz is also used in bioscience, since it has good thermal and chemical stability, high resistant to heat, cost effectiveness etc. Multi tips micro tool has been developed and utilizing this tool, multi channel is generated on quartz. The influence of various major process parameters of USMM, i.e. power rating, abrasive slurry concentration, tool feed rate and slurry flow rate on width overcut, MRR, taper angle and surface roughness of micro channel have also been investigated in this chapter.

5.2 Experimental planning

When micro channels fabricated by using single tip micro tool of circular cross section by travelling the micro tool with the application of CNC, it hampers the accuracy of micro features by repetition of same tool during successive machining and also time consuming. To solve this problem multi tips micro tool has been designed and developed by wire-EDM process as discussed in chapter 2. The schematic as well as photographic views of multi tips micro tool are shown in figure 2.13 (a) and (b) respectively. Figure 5.1 shows the SEM image of multi tips micro tool used during USMM operation for micro channels generation on quartz.

All the experiments were performed on micro-USM setup ‘AP sonic Mill 1000’. After the development of multi tips micro tool it is joined with tool holder, by silver brazing process. Then micro tool holder mounted to horn with screw fitting. Quartz was taken as workpiece having size 25 X 25 X 2 mm^3. The workpiece is fixed with work holding plate by using wax. The work holding plate made of mild steel having size 100 X 100 X 10 mm^3. The magnetic base is used to hold the work holding plate. SiC was taken as abrasive slurry particle to investigate effectiveness of SiC during USMM operattion. The average size of SiC abrasive particle is 4 μm. Water is used as liquid media and mixed with abrasive to form slurry. Abrasive slurry is continuously supplied between workpiece and tool. It works as coolant for tool, horn and workpiece and also removes the debris particles from the machining zone. The gap between workpiece and tool is set by micro meter. By utilizing this developed multi tips micro tool, multi channels have been fabricated at a time using ultrasonic micro machining process. Figure 5.2 shows the optical image of micro channels produced on quartz by ultrasonic micro machining process utilizing multi tips micro tool.

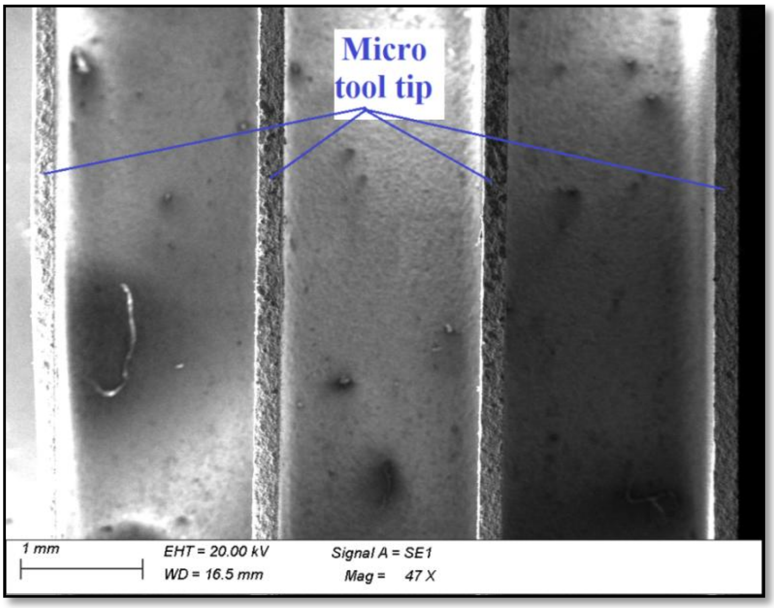


Figure 5.1 SEM image of multi tips micro tool

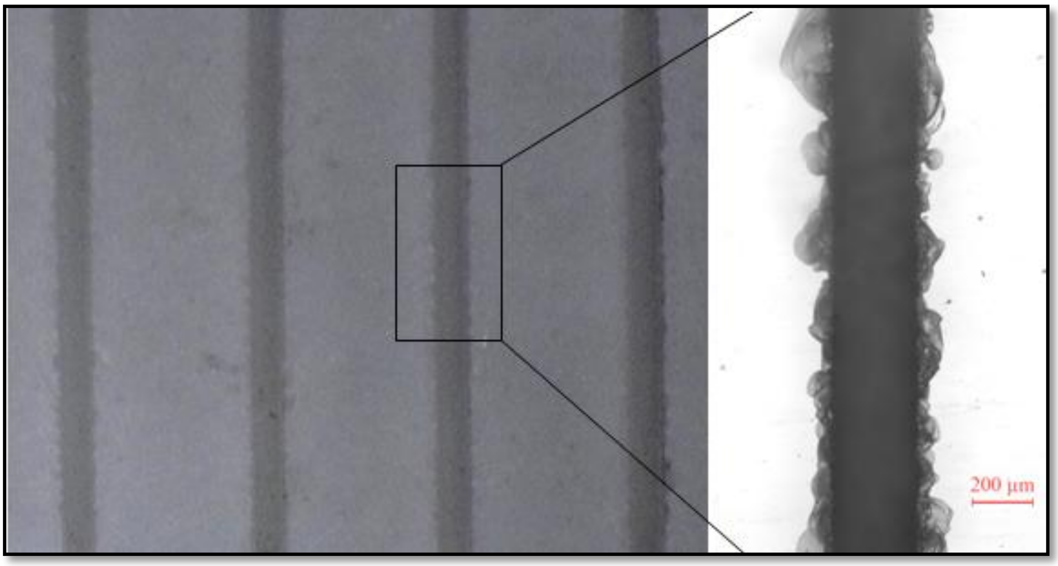


Figure 5.2 Optical image of micro channel on quartz utilizing multi tips micro tool

5.3 Measurement of responses

The measurement procedure and calculations of responses such as MRR, width overcut, taper angle and surface roughness are described in the subsequent subsections.

5.3.1 Measurement of material removal rate (MRR)

The average width at top surface and bottom surface of micro channel is measured by measuring microscope (made: Leica *DM 2500 M*). The width at four places of a single micro channel is measured and average value of it is determined. The material removal rate (MRR) is calculated by:

$$MRR = \frac{4\, W_e * l * d}{t} \quad (5.1)$$

Where, W_e, l, and d are the width, length, and depth of micro channel respectively which are illustrated through the diagram as shown in fig. 5.3 and t is the time taken for machining.

5.3.2 Measurement of width overcut

After the measurement of average width at entrance surface of micro channel and average width of micro tool tip, width overcut (WOC) is calculated by using equation (5.2).

The width overcut (WOC) of micro channel is given by:

$$Width\ overcut\ (WOC) = W_e - W_t \quad (5.2)$$

Where, W_e average width of micro channel at entrance and W_t is the average width of micro-tool tip.

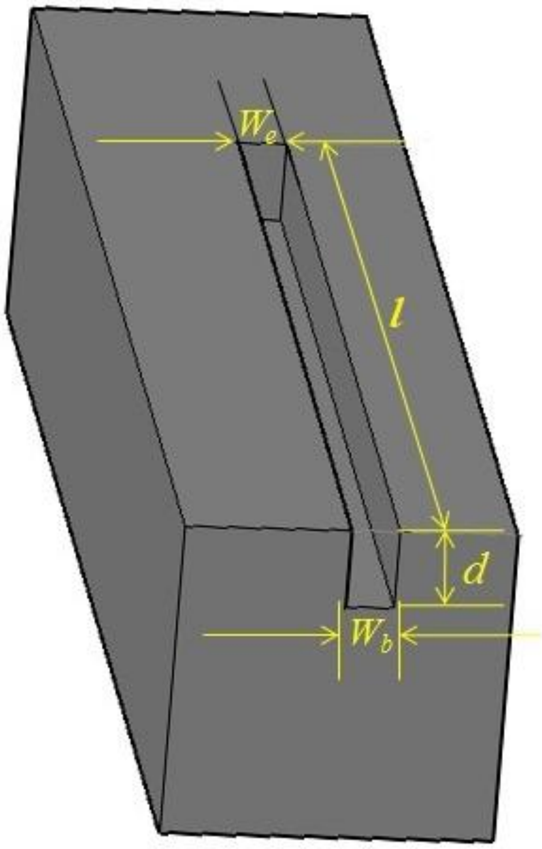


Figure 5.3 Schematic view of micro channel

5.3.3 Measurement of surface roughness

The length of the micro channel is 6000 μm and depth of the micro channel is 500 μm. The surface roughness of micro channel is measured by Surface Roughness Testers (Surftest SV-3200 Series 178) made by mitutoyo. Surface roughness (R_a) is measured at three different positions for a single channel and average value is considered.

5.3.4 Measurement of taper angle

After the measurement of average width at entrance and bottom surfaces of micro channels, the taper angle is calculated as per equation (5.3).

The taper angle is calculated as follows:

$$\text{Taper angle } (\alpha) = \tan^{-1} \frac{W_e - W_b}{2d} \quad (5.3)$$

Where, W_e is the width of micro channel at entrance, W_b is the width of micro channel at bottom surface and d is the depth of micro channel.

5.4 Influences of power rating on MRR, width overcut, taper angle and surface roughness

Power rating is a significant process parameter which controls the impact energy of abrasive particles striking on the workpiece. Power rating varies from 200W to 400 W. The abrasive concentration of abrasive slurry, feed rate of tool and flow rate of slurry were fixed at 15 %, 1 mm/min and 50 ml/sec respectively. Figure 5.4 shows the effect of power rating on material removal rate (MRR) of micro channel. At lower value of power rating, MRR is 4.26 mm^3/min and up to 350 W, MRR increases slowly. But at 400 W power rating, MRR suddenly increased to 5.48 mm^3/min. When power rating increases the impact energy of the abrasive particles also increases. So more material is eroded from the work and hence material removal rate is more.

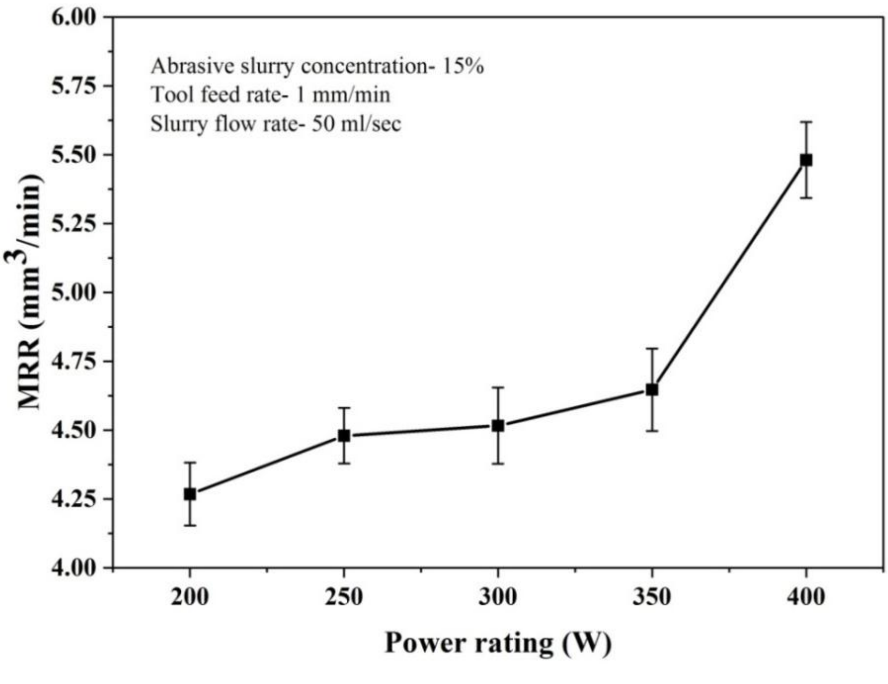


Figure 5.4 Influences of power rating on MRR

Figure 5.5 demonstrates the influence of power rating on width overcut of micro channel. At lower value of power rating, the striking energy of the abrasive particle is less. At higher value of power rating, more is the striking energy of the abrasive particles. Due to higher striking energy, larger size of indentation is formed. So, more materials are removed not only from the work bottom but also from the side wall surface. Hence, width overcut is more at higher power rating. At power rating of 200 W, the average width overcut is 42 µm and at 400W, the average width overcut of 96 µm is obtained.

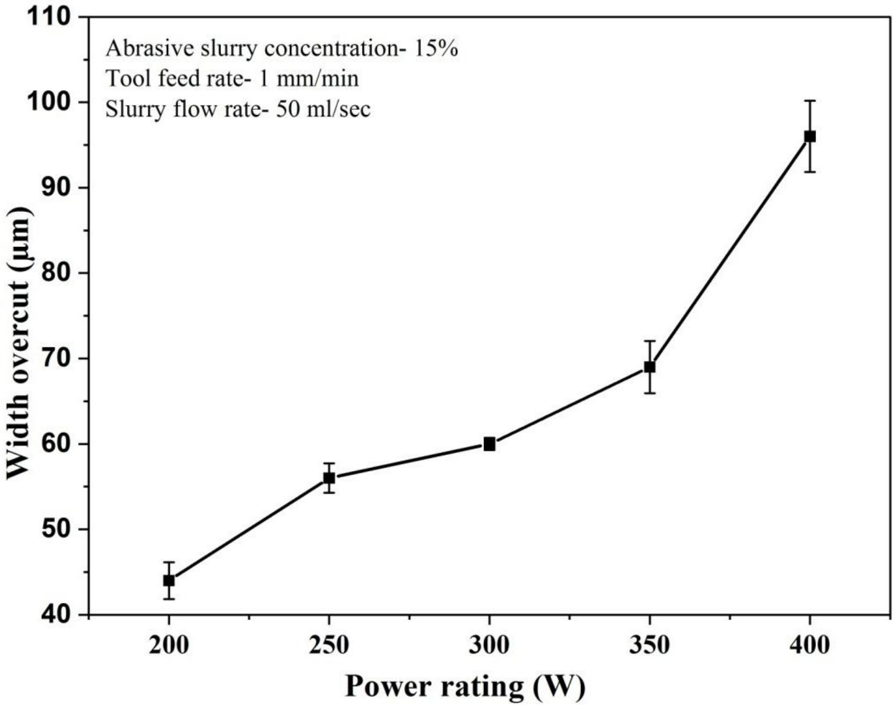


Figure 5.5 Influences of power rating on width overcut

Figure 5.6 represents the effect of power rating on taper angle of micro channel fabricated by micro USM. Taper angle decreases with the rise in power rating. Due to increase in power rating, kinetic energy of abrasive particles increases so cutting rate is high. Materials are removed uniformly from the bottom part of the micro channel. Hence taper angle is less at high power rating. At power rating 200 W the taper angle is 2.7^o and at 400 W taper angles 1.6^o is obtained.

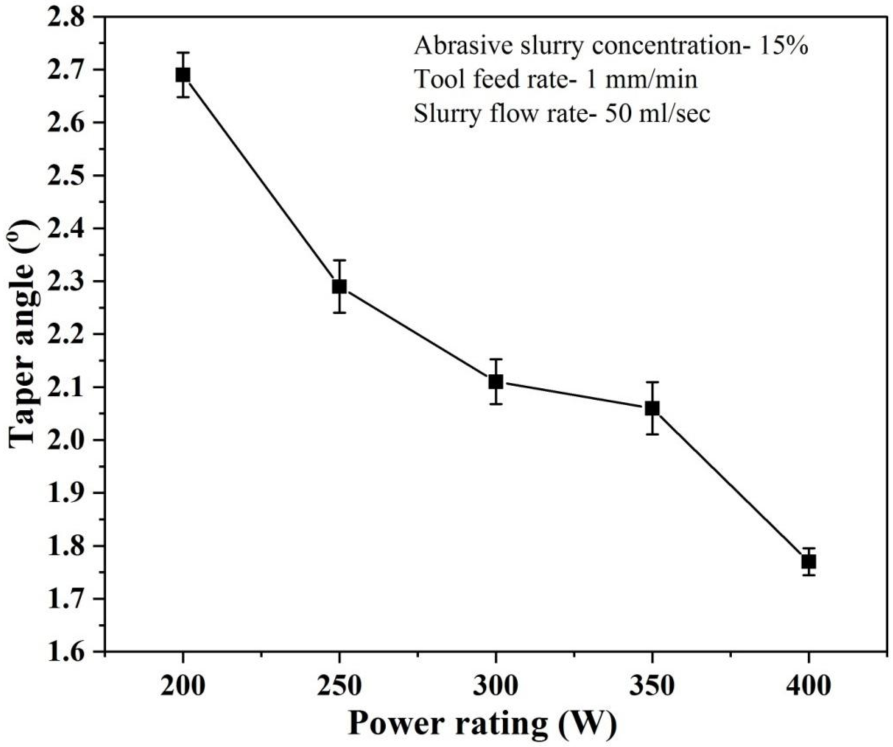


Figure 5.6 Influences of power rating on taper angle

The effects of power rating on surface roughness R_a value of machined surface of micro channel are exhibited in fig. 5.7. At low power rating, surface roughness is low. If power rating increases surface roughness also increases, because abrasive particles strike the work surface with higher energy. This higher energy of abrasive particles results in large indentation on the workpiece surface. So, Surface roughness increases with the rise in power rating. The surface roughness (R_a) is obtained as 4.268 µm at 200 W and 5.181 µm at 400 W.

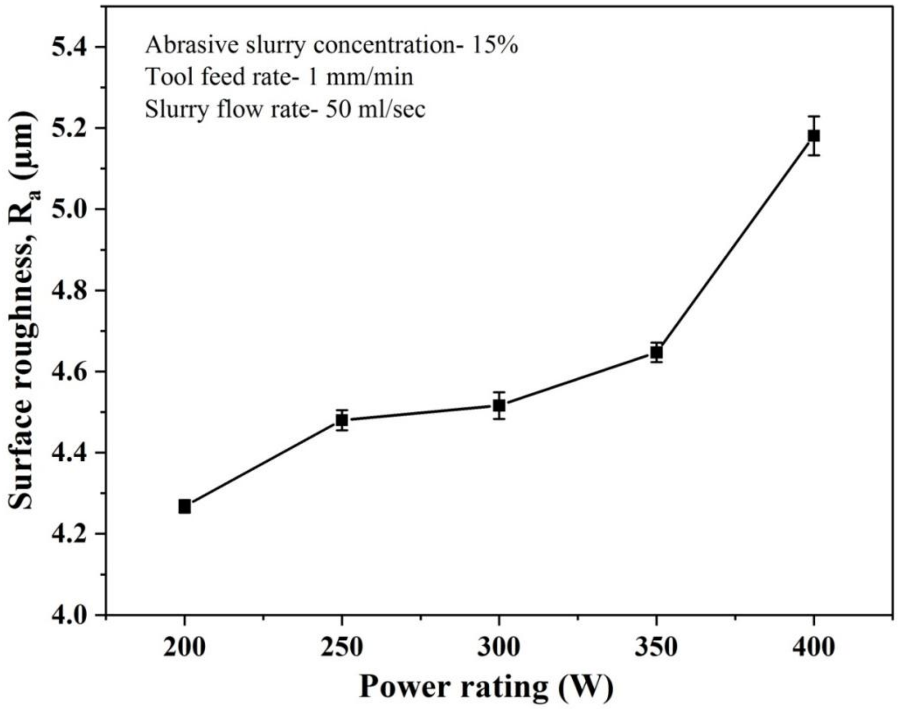


Figure 5.7 Influences of power rating on surface roughness

5.5 Influences of abrasive slurry concentration on MRR, width overcut, taper angle and surface roughness

Figure 5.8 shows the effect of abrasive slurry concentration on MRR. Abrasive slurry concentration is an influential process parameter. Other process parameters like power rating, tool feed rate and slurry flow rate are kept constant at 300W, 1 mm/min and 50 ml/sec respectively. Abrasive slurry concentration is an important process parameter for ultrasonic machining. At 5% slurry concentration, MRR of 3.64 mm^3/min is obtained. After increasing the slurry concentration more number of abrasive particles is present at bottom face of micro tool. Due to this, numbers of impact are more and hence more material is removed. At 25% slurry concentration MRR of 5.64 mm^3/min is achieved during micro channel generation on quartz by micro ultrasonic machining.

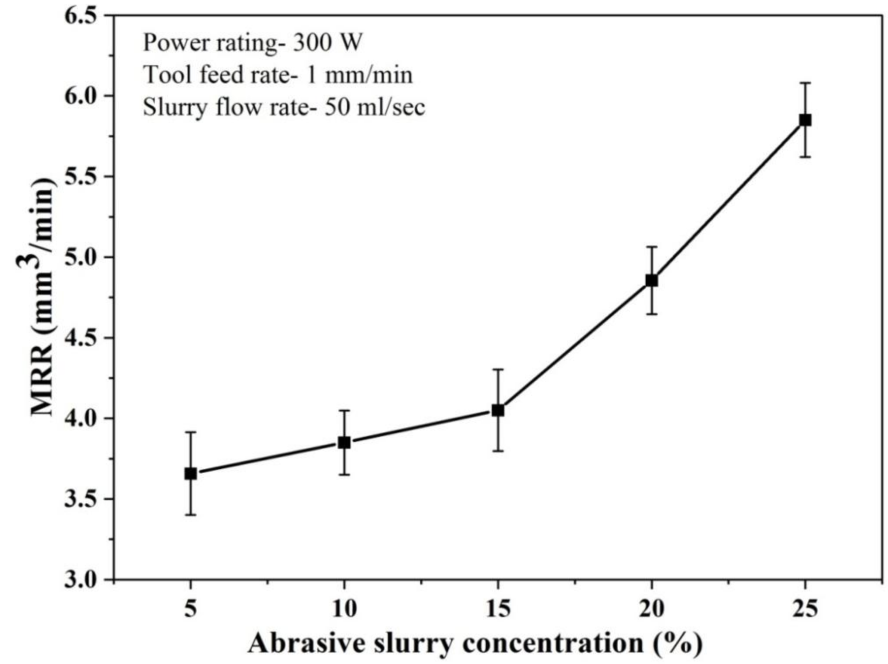


Figure 5.8 Influences of abrasive slurry concentration on MRR

The width overcut of micro channel on quartz is affected by abrasive slurry concentration as shown in fig. 5.9. At 5% slurry concentration the width overcut of 73 μm is obtained. After increasing the slurry concentration, more abrasive particles participates in machining and also these are present near the side wall of the channel. So from the side wall of channel, more materials are also removed. Hence, width overcut of micro channel becomes large. At 25% slurry concentration the width overcut is 90 μm.

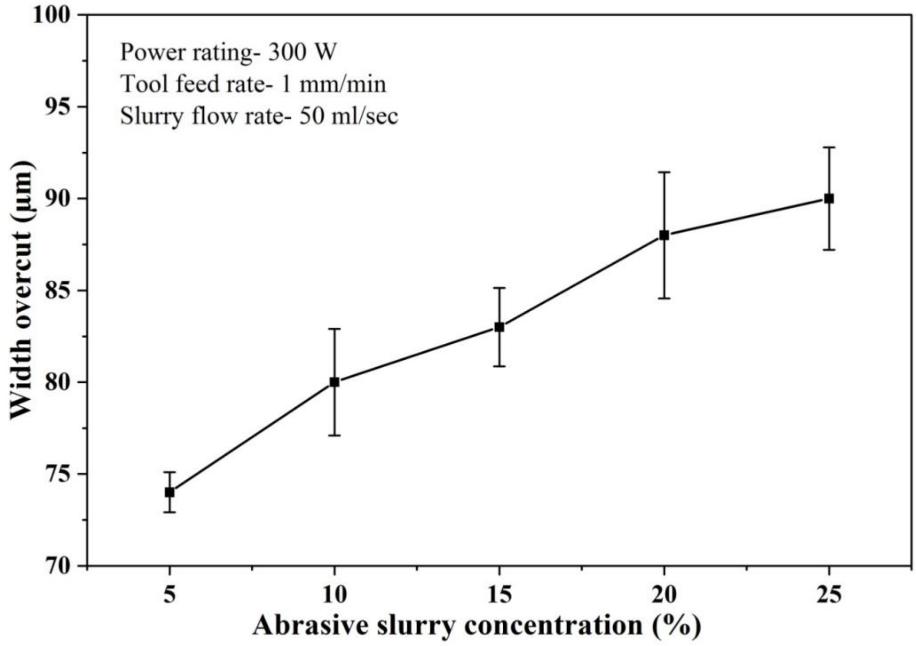


Figure 5.9 Influences of abrasive slurry concentration on width overcut

Figure 5.10 shows the effect of abrasive slurry concentration on taper angle of micro channel on quartz. At 5 % abrasive slurry concentration by weight taper angle of 3.331^o is obtained. With the increase in abrasive slurry concentration, taper angle increases gradually but after 20% abrasive slurry concentration taper angle increases slowly. As abrasive slurry concentration increases, more abrasive particles are available at upper surface of micro tool as well as side wall of micro channel. So, more materials come out from the upper/top part of the micro channel. Hence taper angle increases as abrasive slurry concentration increases. Taper angle at 25 % abrasive slurry concentration is obtained as 3.802^o.

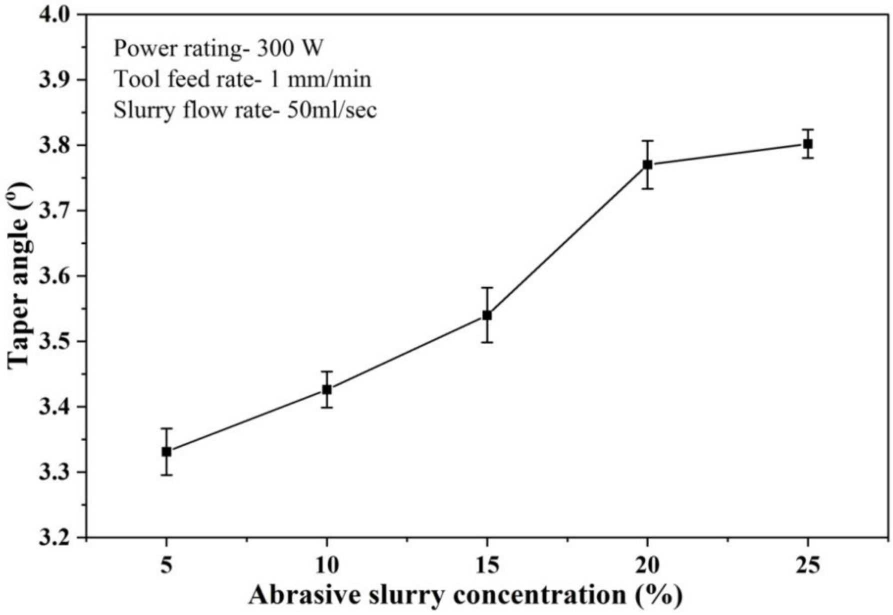


Figure 5.10 Influences of abrasive slurry concentration on taper angle

Figure 5.11 shows the effect of abrasive slurry concentration on surface roughness. The better surface finish is achieved at 5% (by weight) abrasive slurry concentration. At 5% abrasive slurry concentration, surface roughness, R_a value is obtained as 3.657 μm. With the increase in slurry concentration surface roughness also increases. At 25% abrasive slurry concentration, surface roughness, R_a value is obtained as 5.652 μm. With the increase in slurry concentration, more abrasives are present to interact with work surface which results in more number of indentations with large crater depth on the bottom surface of the workpiece, which produce rougher surfaces.

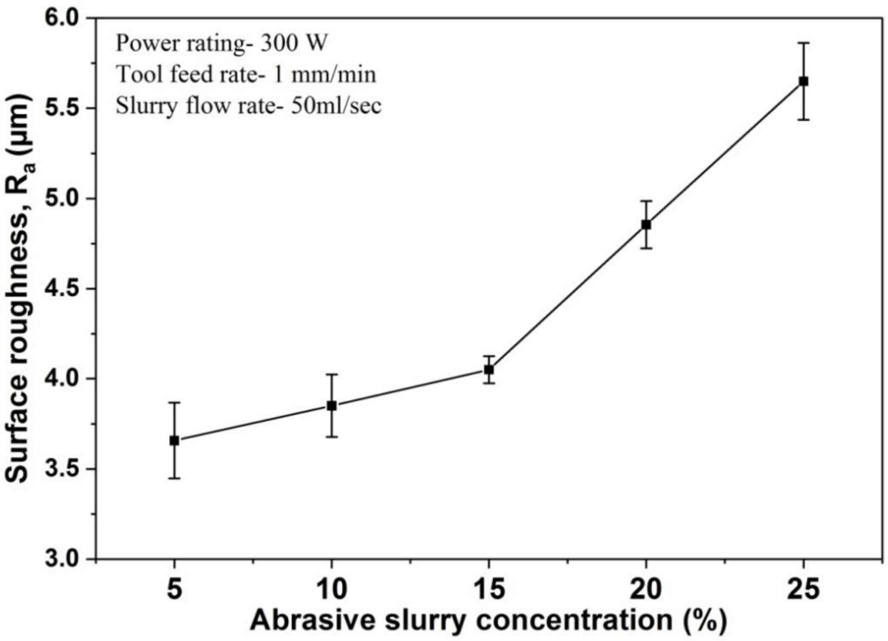


Figure 5.11 Influences of abrasive slurry concentration on surface roughness

5.6 Influences of tool feed rate on MRR, width overcut, taper angle and surface roughness

Figure 5.12 show the effect of tool feed rate on MRR. Tool feed rate is crucial process parameter for micro ultrasonic machining. The tool feed rate is varied from 0.8 mm/min to 1.2 mm/min. At the same time other process parameters such as power rating, abrasive slurry concentration and slurry flow rate are kept at 300 W, 15 % and 50 ml/sec respectively. At tool feed rate of 0.8 mm/min, MRR is 3.293 mm^3/min. With the increase in tool feed rate MRR increases slowly up to 1.1 mm/min after that it increase suddenly. If the tool feed rate increases the impact force of micro tool on the abrasive particles is more, so crater depth of indentation is more and as a result MRR increases. At 1.2 mm/min tool feed rate MRR is observed as 4.032 mm^3/min.

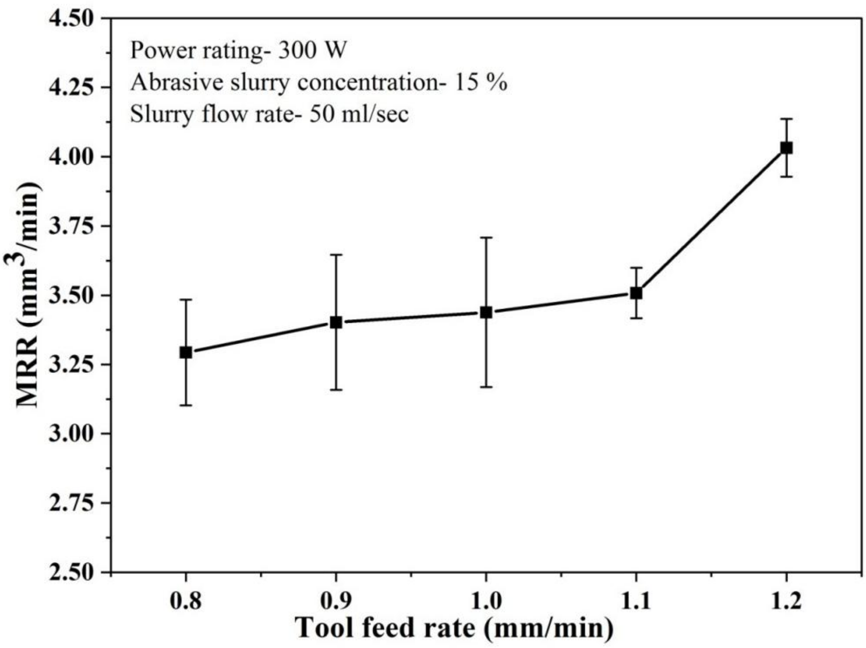


Figure 5.12 Influences of tool feed rate on MRR

Figure 5.13 shows the results of variation of tool feed rate on width overcut. Tool feed rate means the rate at which the tool moves towards workpiece. Width overcut of 35 μm is obtained at 0.8 mm/min tool feed rate. With the increase in the tool feed rate, width overcut increases gradually. Impact force on the work surface is more by increasing the tool feed rate hence crater size of indentation is large. Hence, more material is removed from side wall of micro channel at large tool feed rate, so width overcut is large. Width overcut of 81 μm is obtained at 1.2 mm/min tool feed rate.

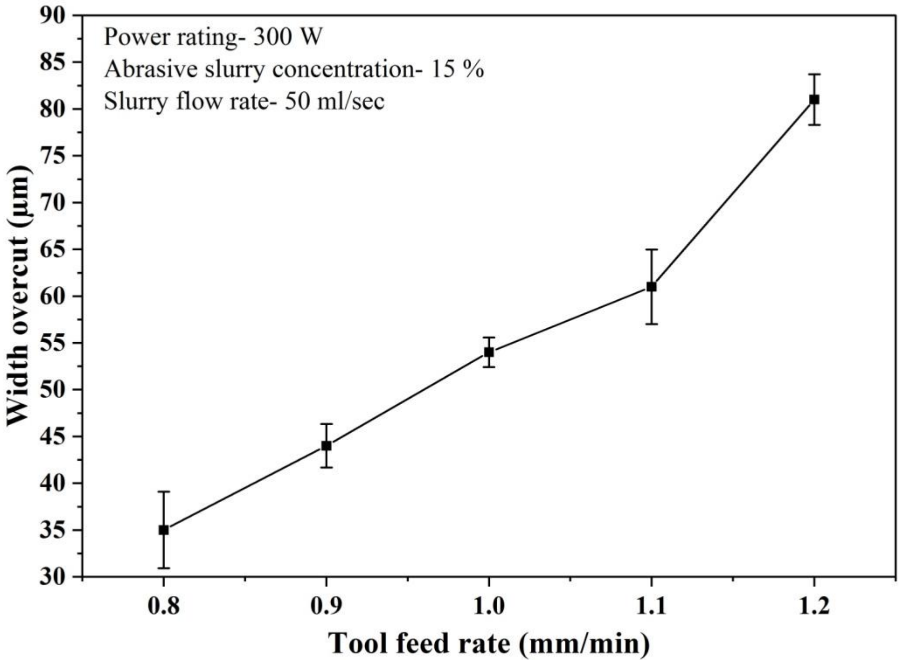


Figure 5.13 Influences of tool feed rate on width overcut

Tool feed rate also affects the taper angle which is illustrated in fig. 5.14. At tool feed rate of 0.8 mm/min, micro channel has less taper angle i.e. 1.31^0. After increasing tool feed rate, taper angle is observed as large because at higher tool feed rate, impact force on work surface increases. Material removed from the top portion of micro channel is more since more abrasive particles are available for machining from both side wall of micro channel. Due to this, top width of cut is more than that of bottom surface of the micro channel, so taper angle increases. Less taper angle can be achieved at lower tool feed rate setting. Taper angle of 2.57^0 is obtained at 1.2 mm/min tool feed rate.

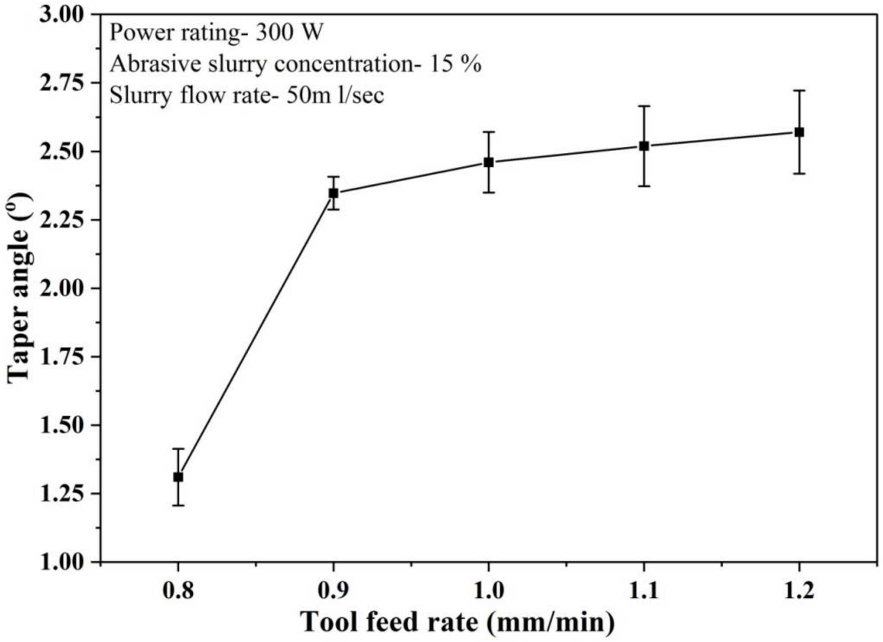


Figure 5.14 Influences of tool feed rate on taper angle

Figure 5.15 shows the effect of tool feed rate on surface roughness. From figure it is clear that surface roughness increases as tool feed rate increases. The lower surface roughness i.e. 3.833 μm is obtained at 0.8 mm/min tool feed rate. With the increase in tool feed rate, impact force increases and larger size craters are formed at bottom surface of micro channel which results in large surface roughness, R_a value. Surface roughness of 6.606 μm is obtained at 1.2 mm/min tool feed rate

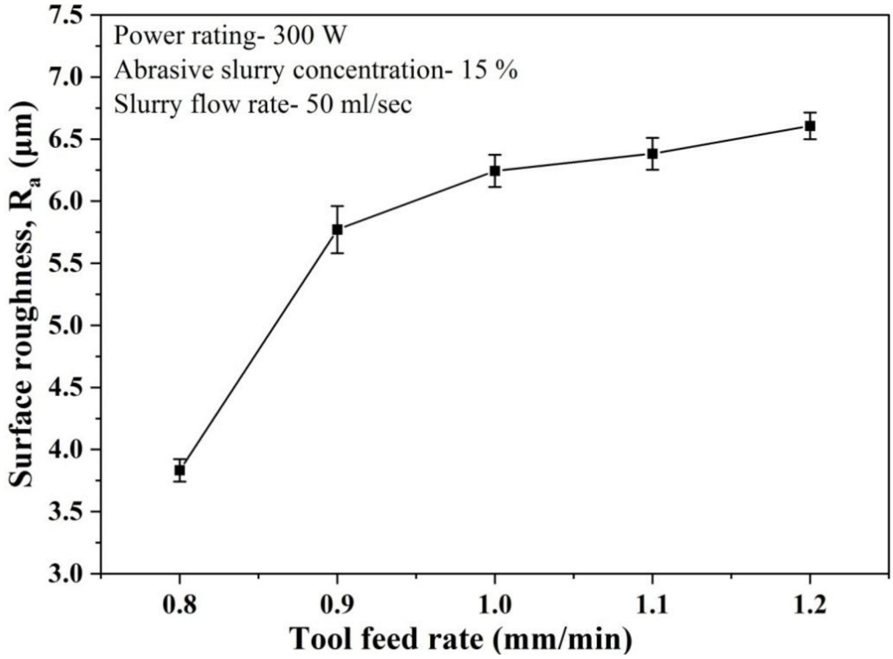


Figure 5.15 Influences of tool feed rate on surface roughness

5.7 Influences of slurry flow rate on MRR, width overcut, taper angle and surface roughness

Figure 5.16 shows the effect of slurry flow rate on MRR during micro channel fabrication. Slurry flow rate is varied from 40 ml/sec to 60 ml/sec. At the same time other process parameters such as power rating, abrasive slurry concentration and tool feed rate are kept at 300 W, 15 % and 1 mm/min respectively. At low slurry flow rate (40 ml/sec) the MRR is obtained 3.78 mm^3/min. As the slurry flow rate increases, MRR also increases. Due to increasing slurry flow rate, availability of fresh abrasive particles at tool work interface is higher. Due to fresh abrasive particles present at tool-work interface, penetration into work is more. Hence, MRR increases with the increase in abrasive slurry flow rate. At higher slurry flow rate i.e. 40 ml/sec, the MRR is obtained 5.64 mm^3/min.

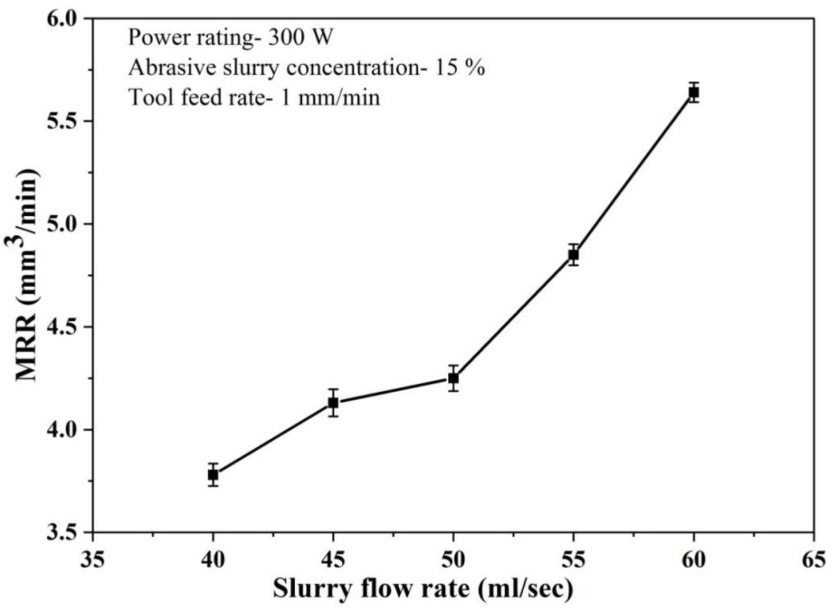


Figure 5.16 Influences of slurry flow rate on MRR

Slurry flow rate also affects the width of micro channel as shown in fig. 5.17. At low abrasive slurry flow rate (40 ml/sec), width overcut is large i.e. 64 µm. With higher slurry flow rate (60 ml/sec), width overcut becomes less i.e. 16 µm. At low abrasive slurry flow rate, width overcut is small. With higher slurry flow rate, width overcut becomes more. With increase in slurry flow rate, availability of fresh abrasives during machining is more in gap between workpiece and micro tool. Hence more materials are removed from side wall of micro channels. So width overcut of micro channel increases.

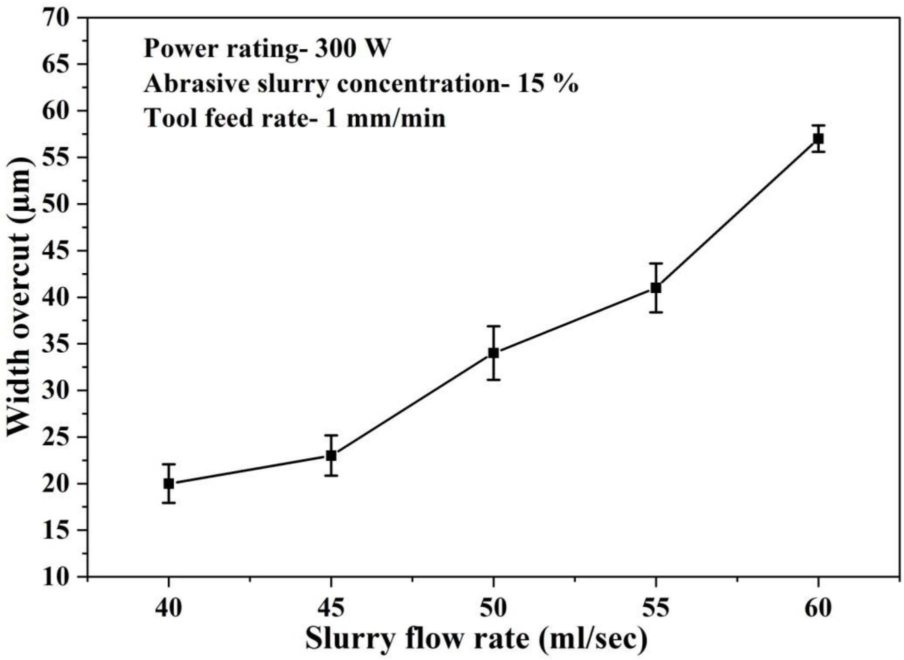


Figure 5.17 Influences of slurry flow rate on width overcut

The taper angle of micro channel is also influenced by slurry flow rate. The variation is shown in fig. 5.18. At 40 ml/sec slurry flow rate, taper angle is observed as 1.66^0. Taper angle increases as slurry flow rate increases. At 60 ml/sec slurry flow rate, taper angle is observed as 2.91^0.

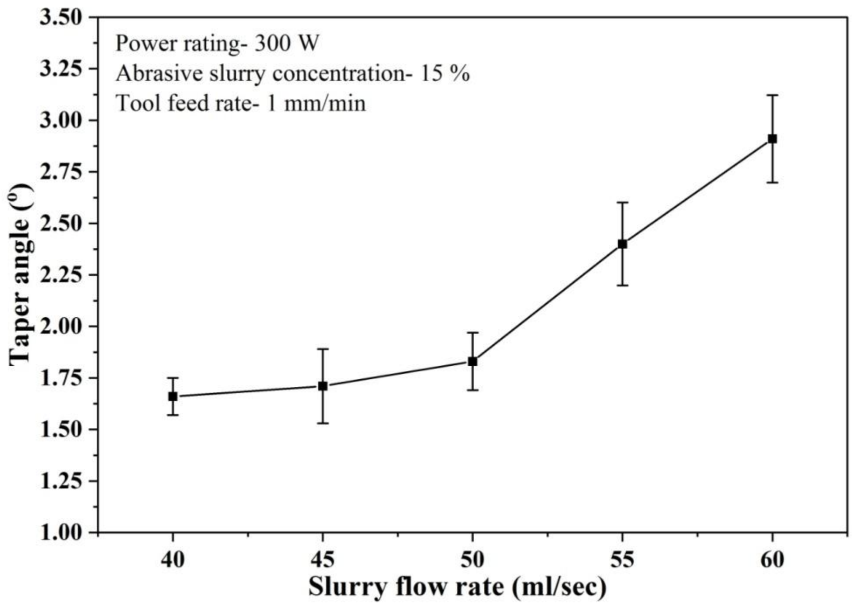


Figure 5.18 Influences of slurry flow rate on taper angle

Figure 5.19 shows the effect of slurry flow rate on surface roughness of micro channel formed on quartz by micro USM. At 40 ml/sec slurry flow rate, surface roughness, R_a value is observed as 4.917 µm. Surface roughness increases as slurry flow rate increases. At 60 ml/sec slurry flow rate, roughness value R_a is obtained as 6.51 µm.

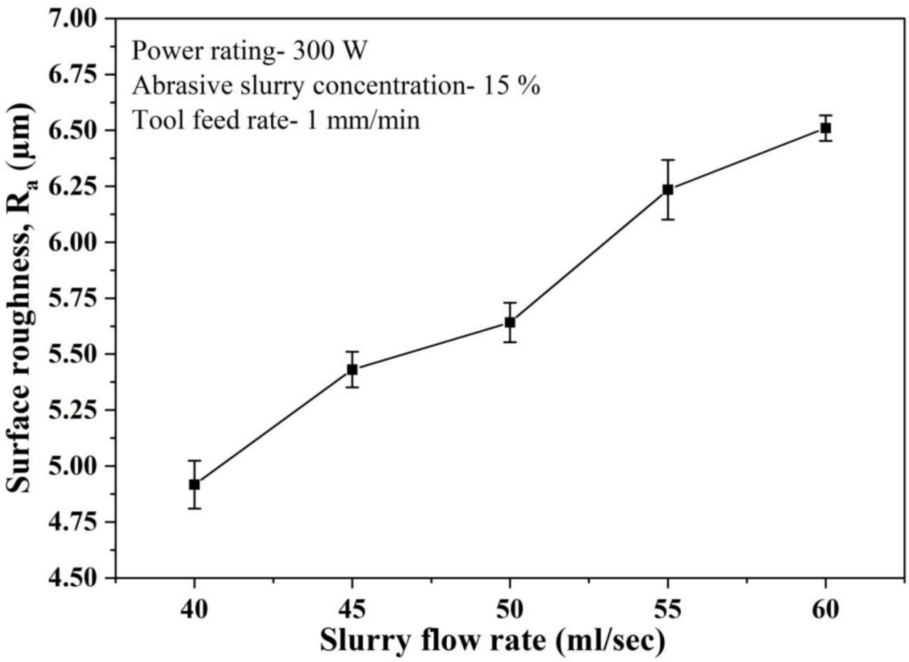
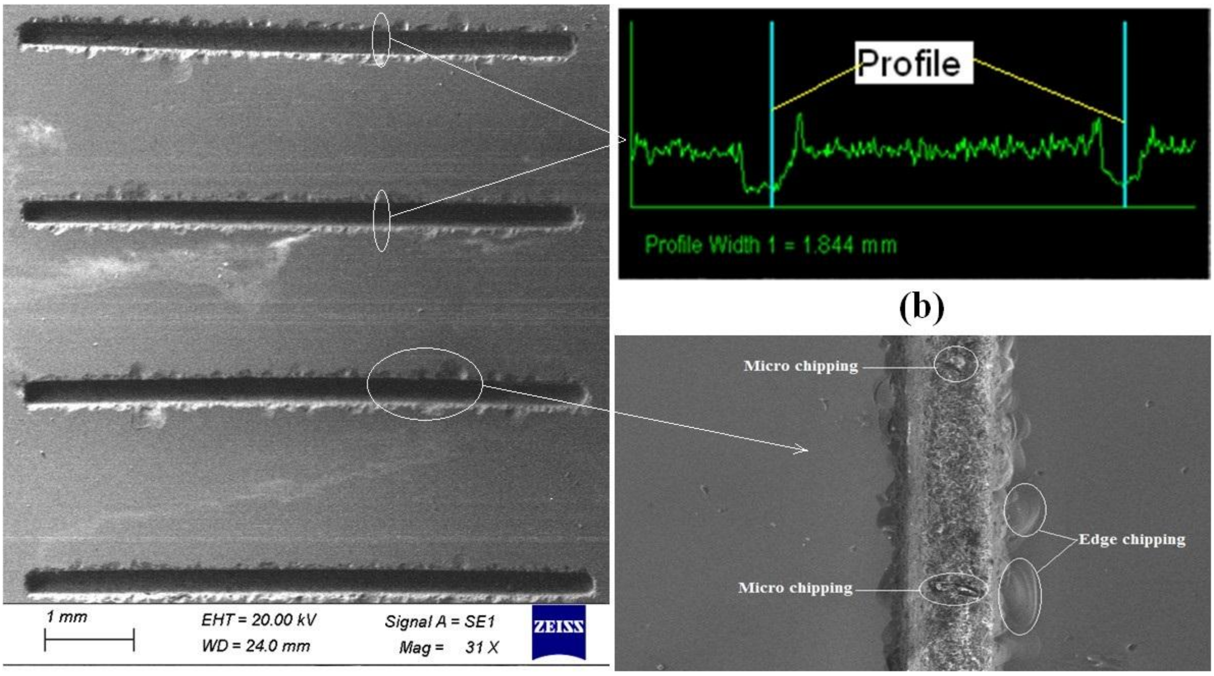


Figure 5.19 Influences of slurry flow rate on surface roughness

Figure 5.20 (a) shows the SEM micrograph of the multiple micro channels fabricated on quartz using multiple tips micro tool utilizing micro USM process. The average width of micro channels was obtained as 254 µm and depth of micro channel was obtained as 500 µm. The micro channels fabricated by multiple tips micro tool are of rectangular shape. Figure 5.20 (b) shows the profile of micro channels which is approx mirror image of tool except overcut. Micro chipping is observed on the bottom surface of micro channel due to fatigue failure. Some edges chipping were also observed nearby on both sides of the machined micro channel at entrance surface due to deflection of abrasive particle on the workpiece surface. Figure 5.20 (c) represents the scanning electron micrograph showing micro chipping and edge chipping formed in micro channel on quartz.



(a) (b) (c)

Figure 5.20 (a) SEM image of top view of multiple micro channels fabricated on quartz and (b) Micro channel profile on quartz after channel fabrication, (c) micro chipping and edge chipping formed on micro channel

5.8 Outcomes of the present research

In this chapter, multi tips micro tool is designed and fabricated by wire EDM and utilizing this developed multi tips micro tool, micro channels on quartz have been produced by ultrasonic micromachining process. The average width of each tip is 180 μm and the width between two tips is 1600 μm. The aspect ratio of developed micro tool tip is 16. Micro-channels have been successfully fabricated on quartz by micro ultrasonic machining process. Micro USM process parameters have a significant effect on MRR, width overcut, taper angle and surface roughness. The aspect ratio of micro channel has been obtained as 3. The best width overcut of micro channel is obtained as 16 μm at slurry flow rate of 60 ml/sec. The lesser value of taper angle obtained is obtained as 1.31^0 at lower tool feed rate. The lower value of surface roughness, R_a is obtained as 3.657 μm at lower abrasive slurry concentration. The surface roughness, R_a is large because quartz is extremely brittle. So, machining of quartz is very difficult due to its brittleness. It can be improved by setting all process parameters at lower values. The micro channels fabricated by multi tips tool are of rectangular shape. It is also observed that micro channel profile fabricated on quartz is approximately the mirror image of tool tip. Edge chipping is also observed on both sides of the machined micro channel at entrance surface. The micro channels on quartz have wide range of application in biomedical science, micro fuel cell and cooling of components of micro electronics etc. So, fabrication of multiple micro channels on quartz at a single operation will be very much useful employing multiple tips micro tool by ultrasonic micro machining process to improve productivity and good accuracy. Moreover, multiple micro channels generation are also necessitated for other ceramic materials for micro engineering applications. Hence, at this stage developed multi tips micro tools can also be utilized for generation of multi micro channels on zirconia ceramics to investigate the influence of process parameters of USMM during micro machining applications.

EXPERIMENTAL INVESTIGATION INTO ULTRASONIC MICRO MACHINING PROCESS FOR MICRO CHANNEL GENERATION ON ZIRCONIA EMPLOYING DEVELOPED MULTI TIPS MICRO TOOL

6.1 Introduction

Zirconia is an advanced engineering ceramic material that has a wide range of applications in semiconductor, electronics, aerospace, and biomedical industries. It is used in above mentioned industries owing to its exceptional attributes like high hardness and strength at elevated temperatures, chemical inertness, superior wear resistance, low thermal conductivity, impressive strength-to-weight ratio, corrosion resistance, and resistance to oxidation, among others. However, zirconia is difficult to machine by conventional machining processes. However, zirconia can be successfully machine by some nonconventional machining processes. Ultrasonic machining is one of the most successful machining processes for machining zirconia due to its above mentioned properties especially brittle in nature. In this present work micro channels are fabricated on zirconia by utilising ultrasonic micromachining process. The impact of process parameters, including power rating, abrasive slurry concentration, tool feed rate and slurry flow rate on machining performances have also been investigated during USMM of zirconia.

6.2 Experimental planning

Each experiment was performed on AP sonic Mill 1000. The square flat zirconia plate (size 20 mm X 20 mm X 5 mm) is fixed on work holding plate. The physical properties of zirconia are listed in Table 6.1. The multi tips micro tool has been developed by wire-EDM process as discussed in chapter 2. The developed multi tips micro tool is silver brazed with hexagonal bolt. The schematic view of multi tips micro tool after the silver brazing with hexagonal bolt is shown in fig. 6.1. Figure 6.2 shows the Schematic view of workpiece and multi tips micro tool after machining. The magnetic base is used to hold the work holding plate. SiC was taken as abrasive slurry particle. The average size of SiC abrasive particle is 4 μm. Water is used as liquid media and mixed with abrasive to form slurry. It continuously supply between workpiece and tool. The range of process parameters for experimentation was determined based on prior research and the outcomes of preliminary pilot experiments. Abrasive slurry concentration varies from 5 % to 25 % by weight. Power rating varies from 200 W to 400 W during experimentation. Tool feed rate varies from 0.8 mm/min to 1.2 mm/min during experimentation. Slurry flow rate varies from 40 to 60 ml/sec. Table 6.2 represents the experimental conditions of ultrasonic micromachining for micro channel generation on zirconia. The optical view of the micro channel generated on zirconia utilizing developed multi tips micro tool is shown in fig. 6.3.

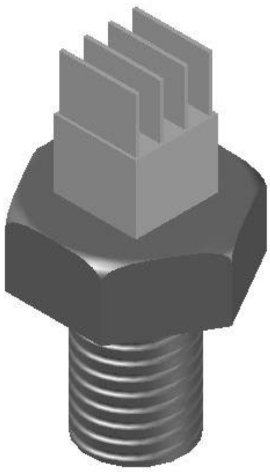


Figure 6.1 Schematic view of multi tips micro tool joined with tool holder

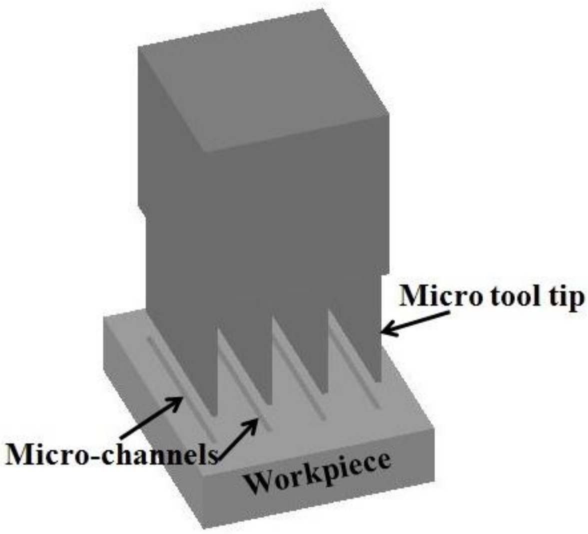


Figure 6.2 Schematic view of workpiece and multi tips micro tool

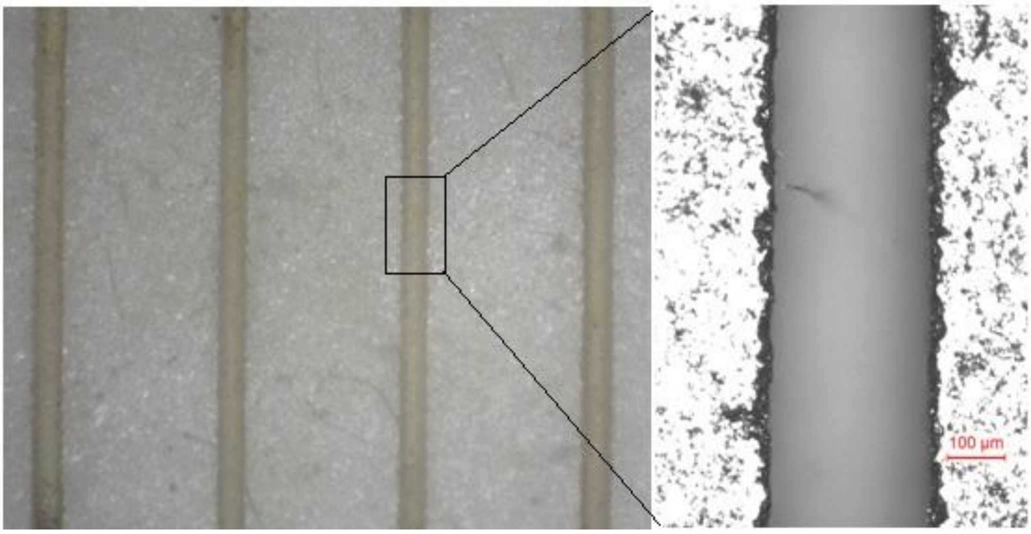


Figure 6.3 Optical image of micro channel utilizing developed multi tips micro tool

Table 6.1 The physical properties of zirconia [88]

Property	**Value**	**Units**
Density	6.15	g/cm^3
Hardness	1200	HV
Bend strength	900-1200	MPa
Compressive strength	2000	MPa
Fracture toughness	7-10	MPa $m^{1/2}$
Young‘s modulus	210	GPa
Thermal expansion coefficient	5.89 $x10^{-6}$	K^{-1}
Melting point	1852	^0C
Poisson’s ratio	0.23-0.31	-

Table 6.2 Experimental conditions of ultrasonic micromachining for micro channel generation on zirconia

Experimental condition	**Value**
Frequency of vibration, kHz	20
Amplitude of vibration, µm	25
Abrasive	SiC
Abrasive slurry concentration, % (by weight)	5-25
Power rating, W	200-400
Tool feed rate, mm/min	0.8-1.2
Slurry flow rate, ml/sec	40-60

All the measurements and calculation of responses have been done similarly as mentioned in sub-section 5.3.1 to 5.3.4.

6.3 Influences of power rating on MRR, width overcut, taper angle and surface roughness

The experiments have been carried out with varying power rating from 200 W to 400 W. At the same time concentration of abrasive slurry, feed rate of tool and flow rate of slurry were fixed at 15 %, 1 mm/min and 50 ml/sec respectively. The influence of power rating on MRR is shown in fig. 6.4. At 200 W power rating, MRR is obtained as 1.130 mm^3/min and MRR increases slowly with power rating up to 300 W. But after 300 W power rating, MRR rapidly increases and at 400 W, MRR reached to 2.343 mm^3/min. When power rating increases, the impact energy of the abrasive particles also increases and more material is eroded from the workpiece.

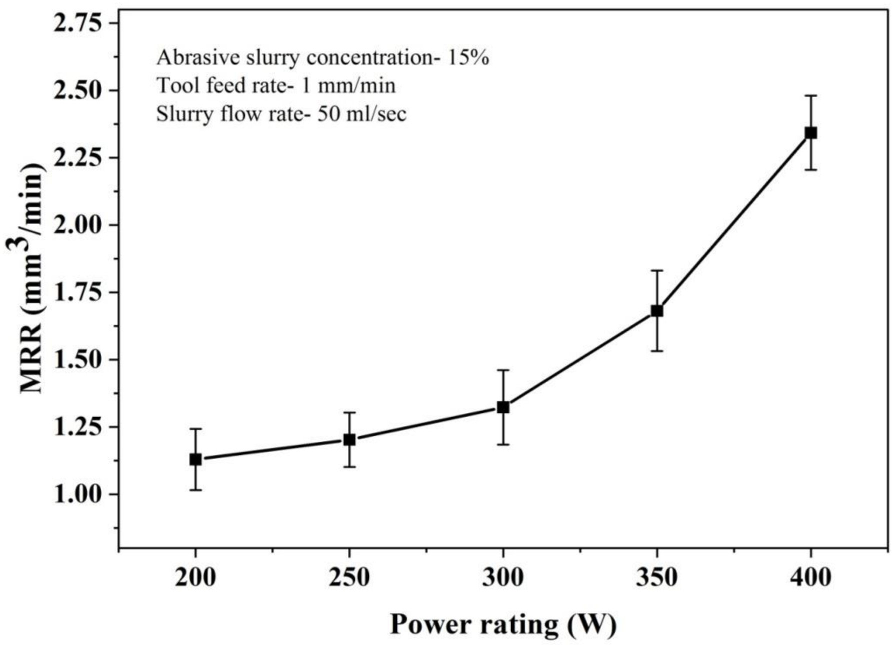


Figure 6.4 Influences of power rating on MRR

Figure 6.5 show the influence of power rating on width overcut of micro channel fabricated on zirconia. Power rating is a significant process parameter which controls the impact energy of abrasive particles striking on the workpiece. At low value of power rating, the striking energy of the abrasive particle is less. Due to higher striking energy, larger size of indentation is formed. So, more materials are removed from the work surface which in turn increases width overcut. Hence, width overcut is more at higher power rating. At 200 W power rating and 400 W power rating, width overcut is obtained as 44 μm and 96 μm respectively.

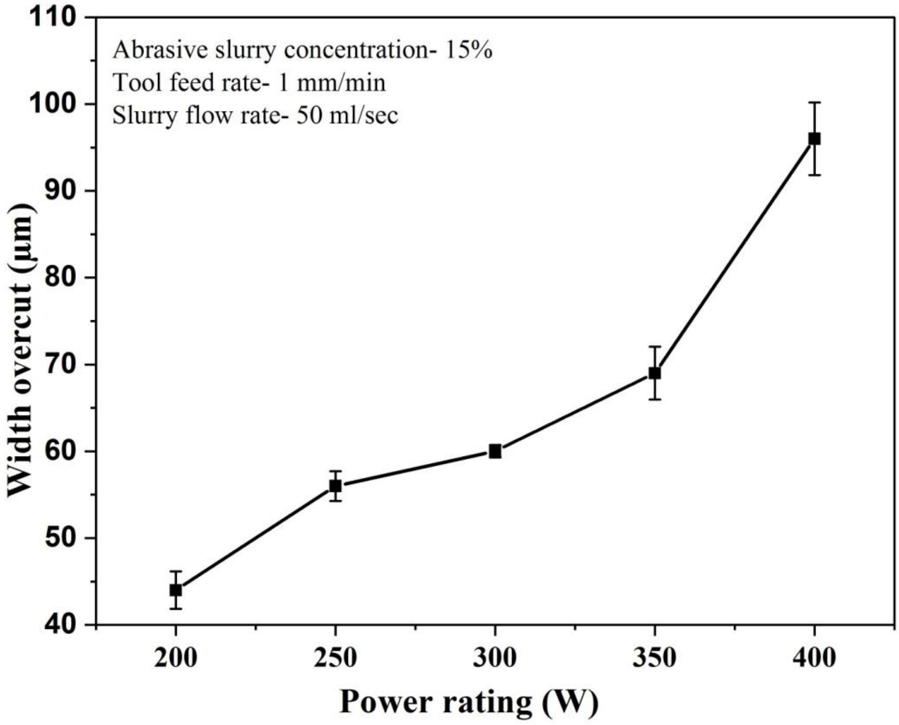


Figure 6.5 Influences of power rating on width overcut

Figure 6.6 demonstrate the effect of power rating on taper angle of micro channel fabricated by micro USM. Taper angle decreases with the rise in power rating. Due to increase in power rating, kinetic energy of abrasive particles increases so cutting rate is high. Materials are removed uniformly from the bottom part of the micro channel. Hence taper angle is less at high power rating. At power rating 200 W and 400 W the taper angle are obtained as 2.35^o and 1.37^o respectively.

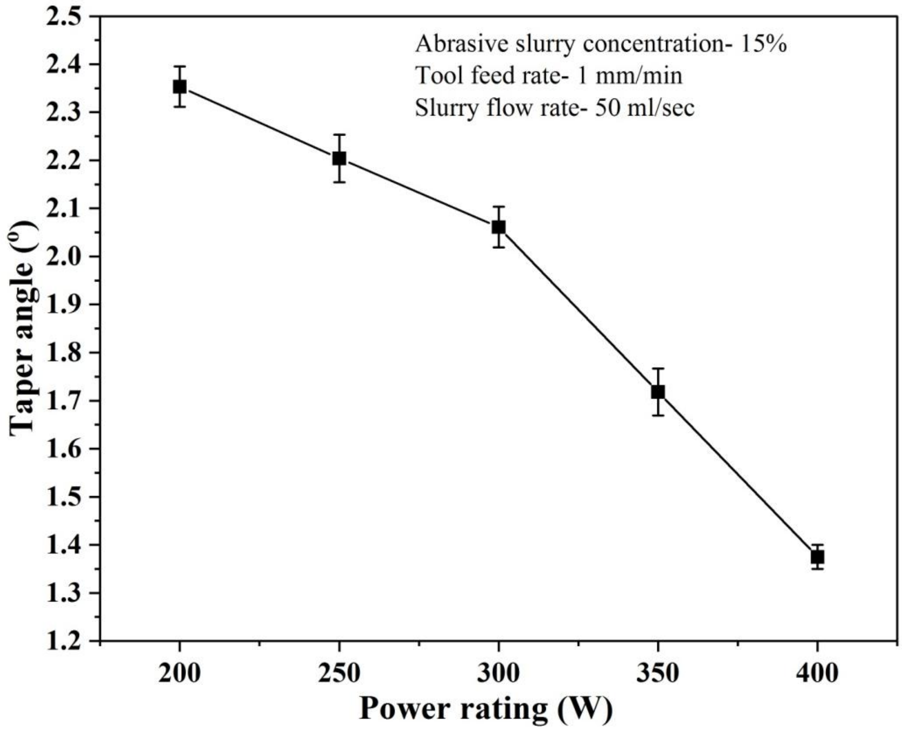


Figure 6.6 Influences of power rating on taper angle

The influence of power rating on surface roughness, R_a value of machined surface of micro channel is shown in fig. 6.7. At low power rating, surface roughness is low. If power rating increases surface roughness also increases, because abrasive particles strike the work surface with higher energy. This higher energy of abrasive particles results in large indentation on the workpiece bottom surface. So, Surface roughness increases with the increase in power rating. The surface roughness (R_a) is obtained as 4.035 μm at 200 W and 5.310 μm at 400 W power rating.

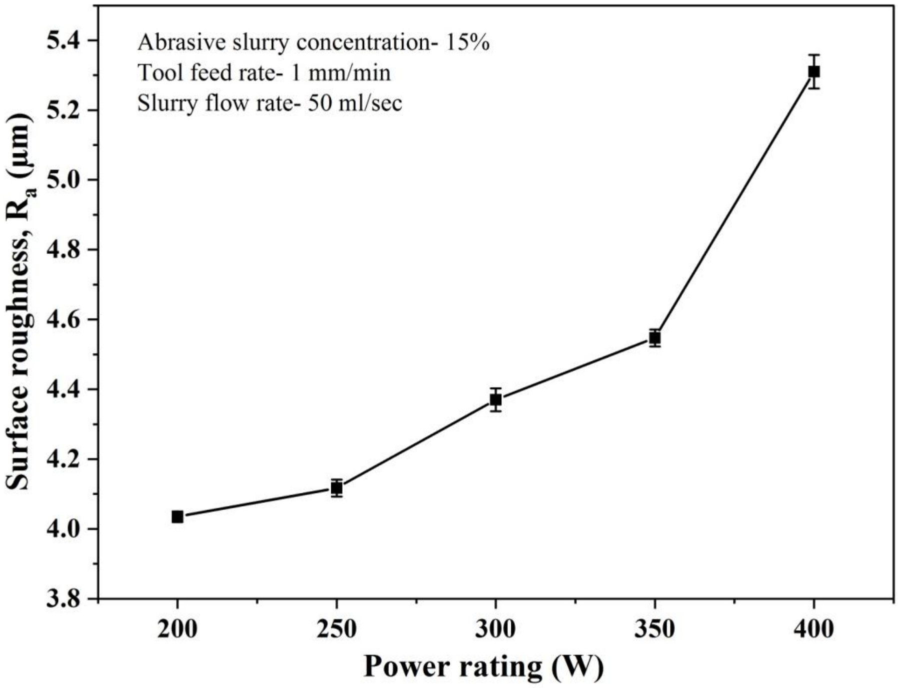


Figure 6.7 Influences of power rating on surface roughness

6.4 Influences of abrasive slurry concentration on MRR, width overcut, taper angle and surface roughness

Figure 6.8 shows the effect of abrasive slurry concentration on MRR. Abrasive slurry concentration is varying from 5 % to 25 % by weight. Other process parameters like power rating, tool feed rate and slurry flow rate are kept constant at 300 W, 1 mm/min and 50 ml/sec respectively. Abrasive slurry concentration is an important process parameter for ultrasonic micromachining. At 5% slurry concentration, MRR of 1.306 mm^3/min is obtained. As slurry concentration increases, more abrasive particles are present at the bottom of the micro tool. Because of this, numbers of impact are more and hence more material is removed. At 25% slurry concentration MRR of 3.97 mm^3/min is achieved during micro channel generation on zirconia by micro ultrasonic machining.

The width overcut of micro channel on quartz is affected by abrasive slurry concentration as shown in fig. 6.9. Abrasive slurry concentration is an influential process parameter. At 5% slurry concentration the width overcut of 42 μm is obtained. As the abrasive slurry concentration increases, more abrasive particles are involved in machining and these are also present near the channel sidewalls. Hence, more material is removed from the channel sidewalls. Thus, the width overcut of micro channel becomes large. At 25% slurry concentration the larger width overcut of 83 μm is obtained.

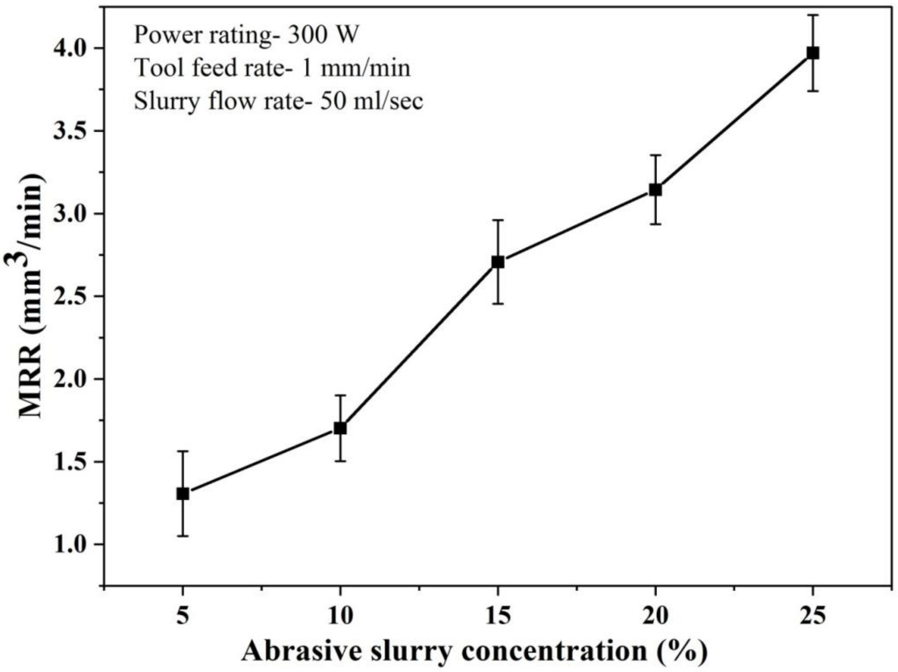


Figure 6.8 Influence of abrasive slurry concentration on MRR

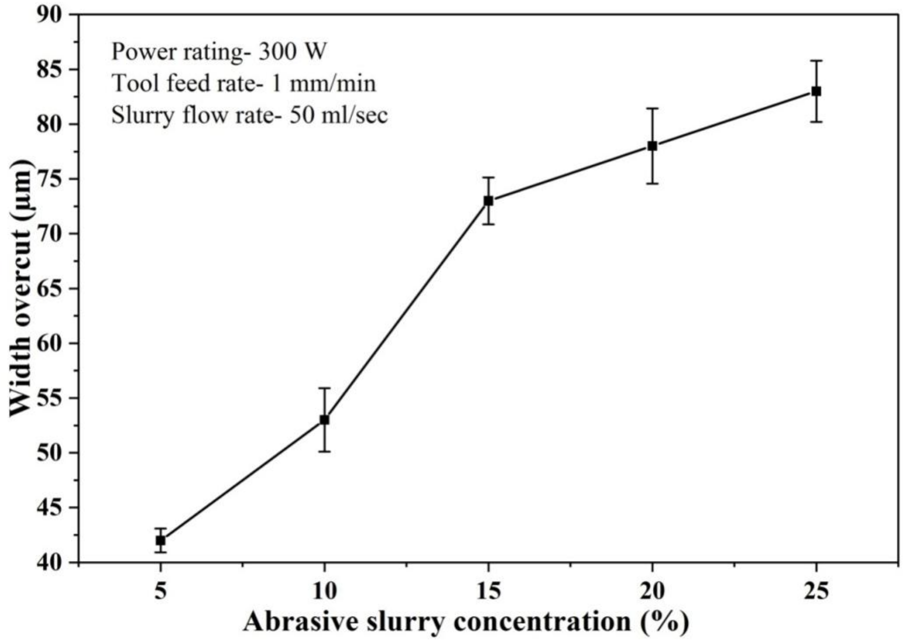


Figure 6.9 Influence of abrasive slurry concentration on width overcut

Figure 6.10 shows the effect of abrasive slurry concentration on taper angle of micro channel on zirconia. At 5 % abrasive slurry concentration by weight, taper angle of 1.331^{o} is obtained. With the increase in abrasive slurry concentration, taper angle increases gradually but after 20% abrasive slurry concentration taper angle increases slowly. As abrasive slurry concentration increases, more abrasive particles are available at bottom surface of micro tool as well as side wall of micro channel. So, more materials remove from the upper part of the micro channel. Hence taper angle increases as abrasive slurry concentration increases. Taper angle at 25 % abrasive slurry concentration is obtained as 1.802^0.

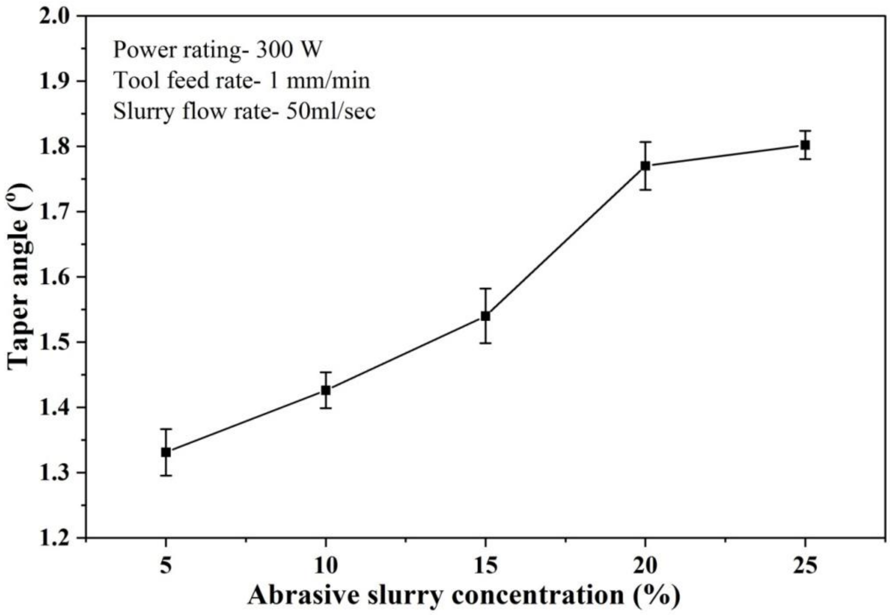


Figure 6.10 Influence of abrasive slurry concentration on taper angle

Figure 6.11 shows the effect of abrasive slurry concentration on surface roughness. The better surface finish is achieved at 5% (by weight) abrasive slurry concentration. With the increase in slurry concentration surface roughness also increases. This higher abrasive slurry concentration results in large number of indentations on the workpiece bottom surface which in turn deteriorates surface roughness. At 5% abrasive slurry concentration, surface roughness, R_a value is obtained as 3.813 μm and at 25 % abrasive slurry concentration, surface roughness, R_a value is obtained as 5.352 μm.

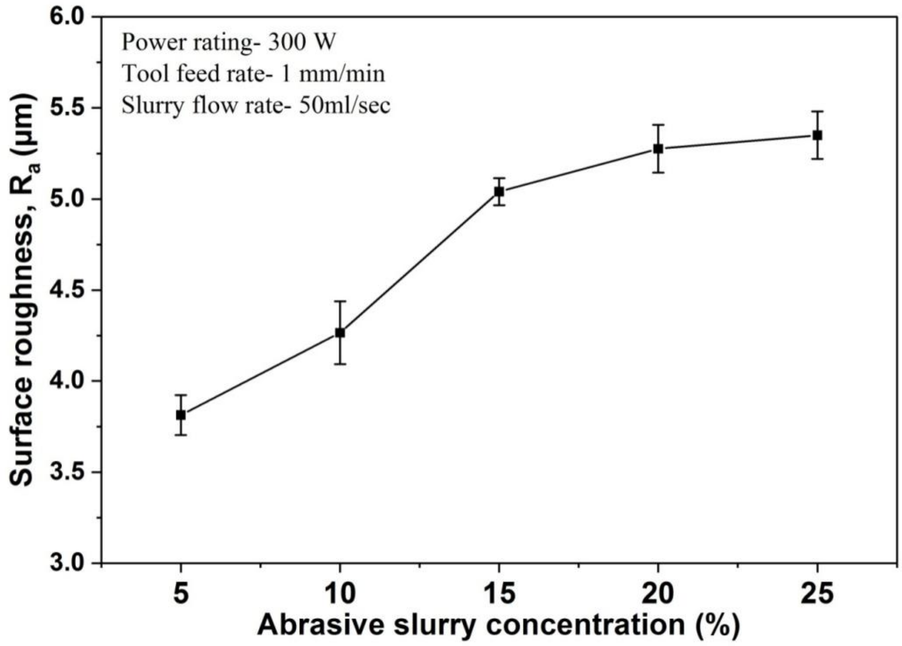


Figure 6.11 Influence of abrasive slurry concentration on surface roughness

6.5 Influences of tool feed rate on MRR, width overcut, taper angle and surface roughness

Figure 6.12 show the effect of tool feed rate on MRR. Tool feed rate means the rate of tool movements towards the workpiece. Tool feed rate is important process parameter for ultrasonic micromachining. The tool feed rate is varied from 0.8 mm/min to 1.2 mm/min. At the same time other process parameters such as power rating, abrasive slurry concentration and slurry flow rate are kept at 300 W, 15 % and 50 ml/sec respectively. At tool feed rate of 0.8 mm/min, MRR is obtained as 1.834 mm^3/min. With the increase in tool feed rate, MRR increases slowly up to 1.2 mm/min. When the tool feed rate increases, the impact force of micro tool on the abrasive particles is more, so crater depth of indentation is more and as a result MRR increases. At 1.2 mm/min tool feed rate MRR is observed as 3.065 mm^3/min.

Figure 6.13 shows the results of tool feed rate on width overcut. Width overcut of 26 μm is obtained at 0.8 mm/min tool feed rate. With the increase in the tool feed rate, width overcut increases gradually. Impact force on the work surface is more by increasing the tool feed rate hence crater size of indentation is large. Hence, more material is also removed from side wall of micro channel at large tool feed rate, which in turn increases the width overcut. Width overcut of 64 μm is obtained at 1.2 mm/min tool feed rate

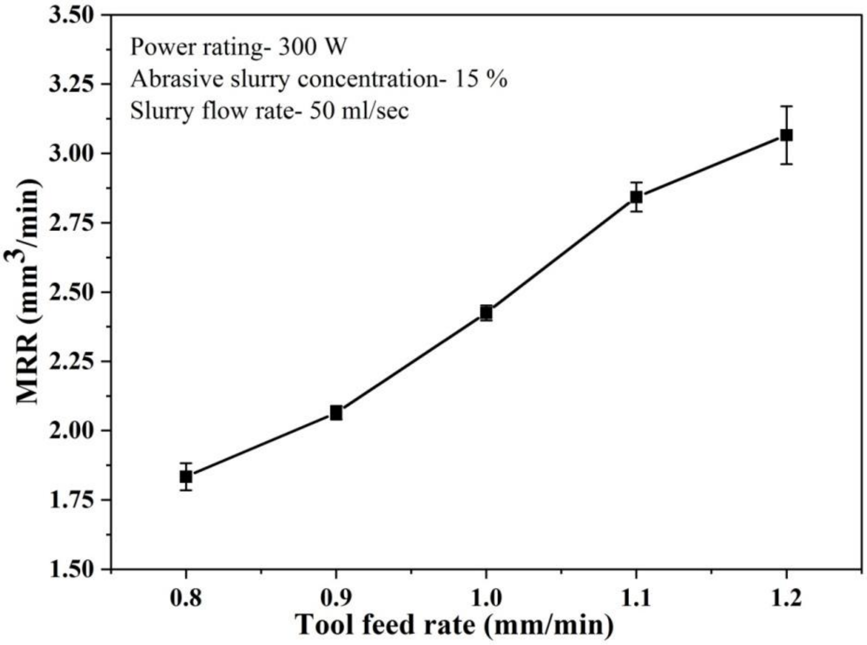


Figure 6.12 Influences of tool feed rate on MRR

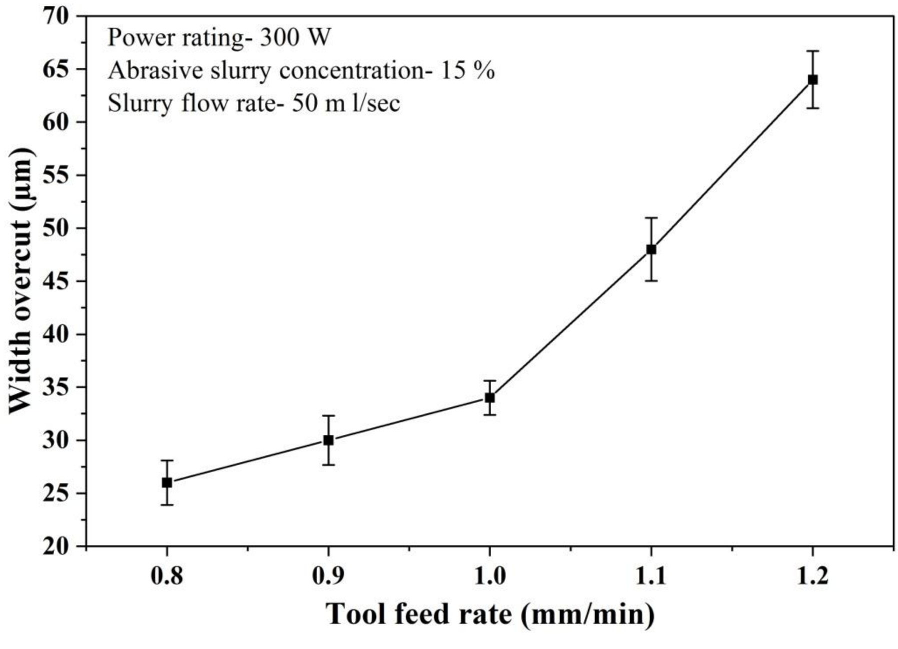


Figure 6.13 Influences of tool feed rate on width overcut

Tool feed rate also affects the taper angle which is shown in fig. 6.14. At tool feed rate of 0.8 mm/min, micro channel has less taper i.e. 0.931^0. After increasing tool feed rate, taper angle is observed as large because at higher tool feed rate, impact force on work surface increases. Material removed from the top portion of micro channel is more since more abrasive particles are available for machining from in both side wall of micro channel. Due to this, top width of cut is more than that of bottom surface of the micro channel, so taper angle increases. Less taper angle can be achieved at lower tool feed rate setting. At tool feed rate of 1.2 mm/min, micro channel has 2.27^0 taper angles.

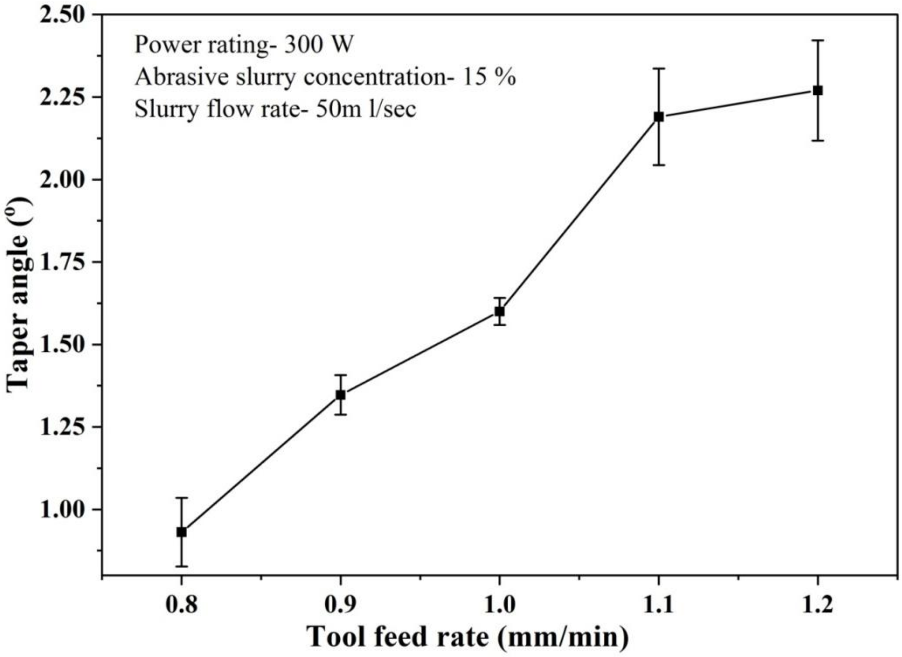


Figure 6.14 Influences of tool feed rate on taper angle

Figure 6.15 shows the effect of tool feed rate on surface roughness. From figure, it is clear that surface roughness increases as tool feed rate increases. The lower surface roughness is obtained at lower tool feed rate. With the increase in tool feed rate, impact force increases and larger size craters are formed at bottom surface of micro channel which results in large surface roughness, R_a value. The surface roughness, R_a of machined surface of micro channel on zirconia is obtained as 2.1172 µm and 5.986 µm at 0.8 mm/min and 1.2 mm/min tool feed rate respectively.

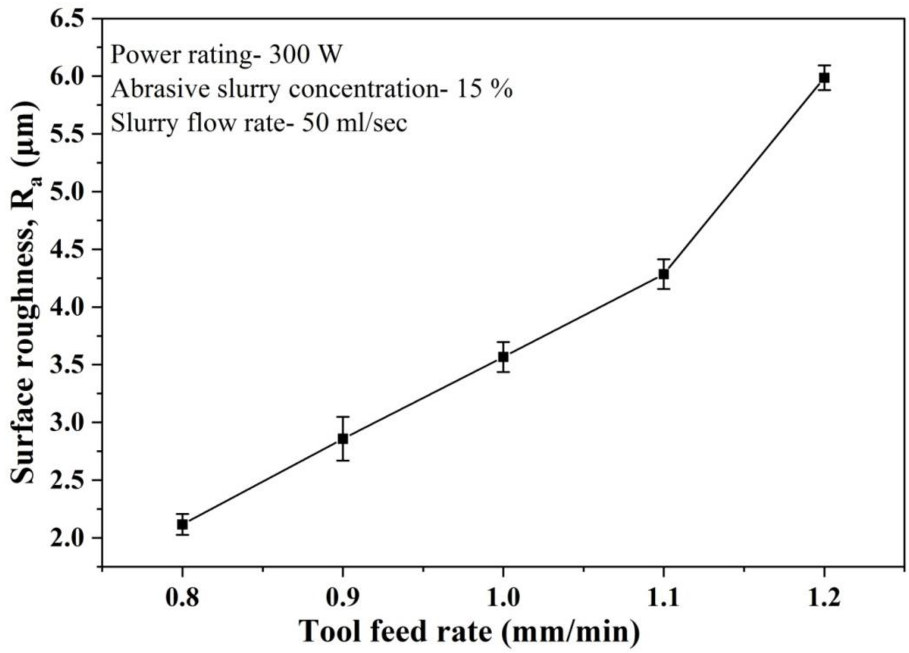


Figure 6.15 Influences of tool feed rate on surface roughness

6.6 Influences of slurry flow rate on MRR, width overcut, taper angle and surface roughness

Figure 6.16 shows the influence of slurry flow rate on MRR during micro channel fabrication on zirconia ultilizing multi tips micro tool. At the same time other process parameters such as power rating, abrasive slurry concentration and tool feed rate are kept fixed at 300 W, 15 % and 1 mm/min respectively. At low slurry flow rate (40 ml/sec) the MRR is obtained 1.464 mm^3/min. MRR increases as the slurry flow rate increases. The availability of fresh abrasive particles at the tool work contact improves as the slurry flow rate increases. Because of the presence of new abrasive particles at the tool-work contact, penetration into the work is increased. As a result, MRR increases as the abrasive slurry flow rate increases. At high slurry flow rate i.e. 60 ml/sec, MRR is obtained as 3.282 mm^3/min.

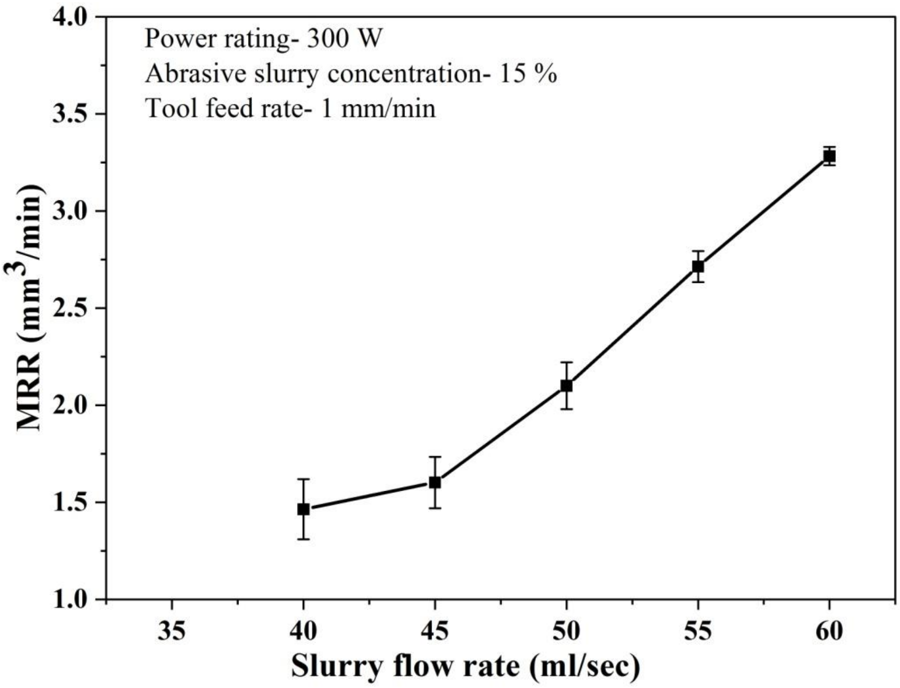


Figure 6.16 Influences of slurry flow rate on MRR

Slurry flow rate also affects the width of micro channel as shown in fig. 6.17. At low abrasive slurry flow rate, width overcut is large. With higher slurry flow rate, width overcut becomes less. Due to increase in slurry flow rate, availability time of abrasive particles between workpiece and micro tool decreases. So width overcut of micro channel decreases. The width overcut of micro channel on zirconia is obtained as 81 µm and 38 µm at 40 ml/sec and 60 ml/sec slurry flow rate respectively.

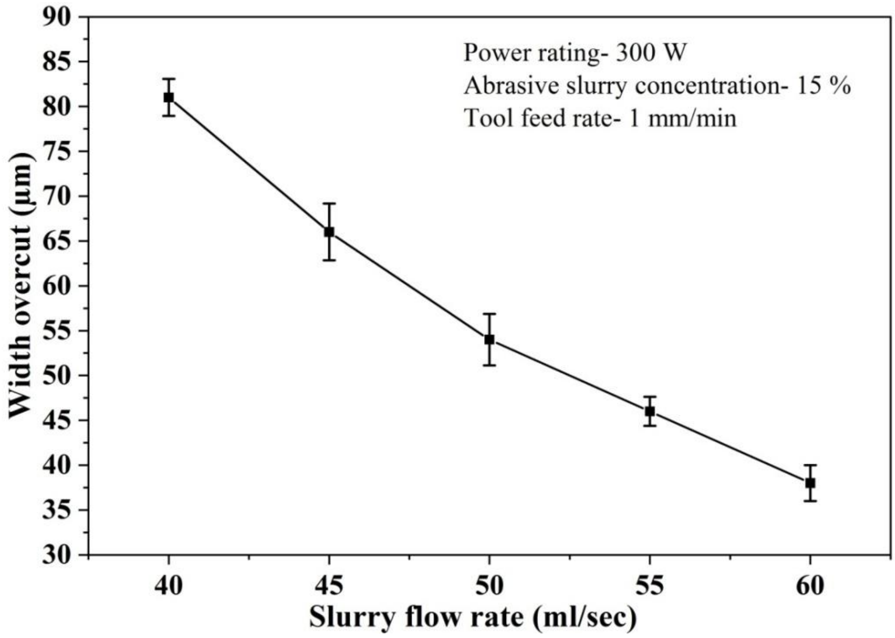


Figure 6.17 Influences of slurry flow rate on width overcut

The taper angle of micro channel is also influenced by slurry flow rate. The variation is shown in fig. 6.18. At 40 ml/sec slurry flow rate, taper angle is observed as 1.36^0. Taper angle increases as slurry flow rate increases. At 60 ml/sec slurry flow rate, taper angle is observed as 2.31^0.

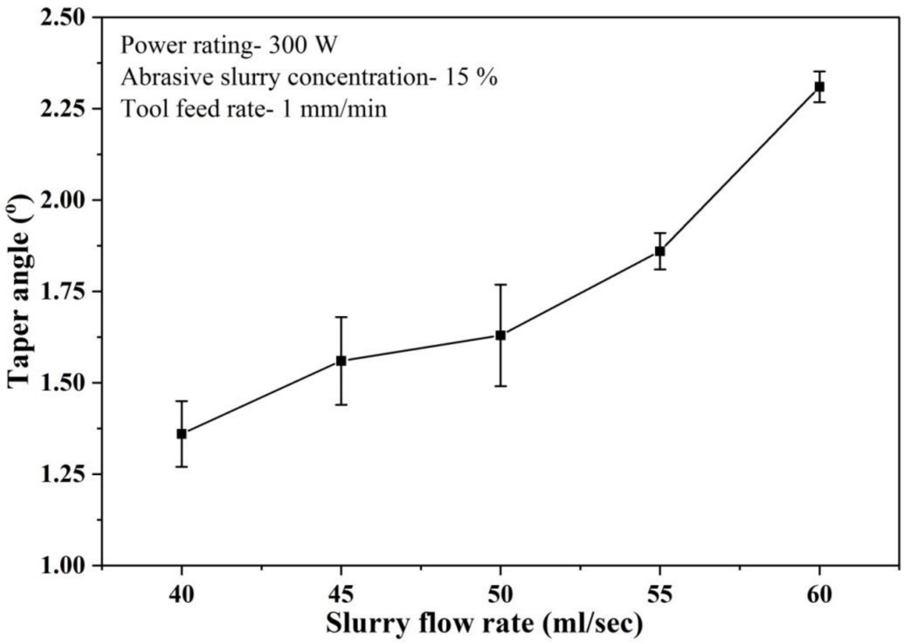


Figure 6.18 Influences of slurry flow rate on taper angle

Figure 6.19 shows the effect of slurry flow rate on surface roughness of micro channel fabricated on zirconia by USMM. At 40 ml/sec slurry flow rate, surface roughness, R_a value is observed as 3.117 µm. Surface roughness increases as slurry flow rate increases. At 60 ml/sec slurry flow rate, roughness value, R_a is obtained as 5.471 µm.

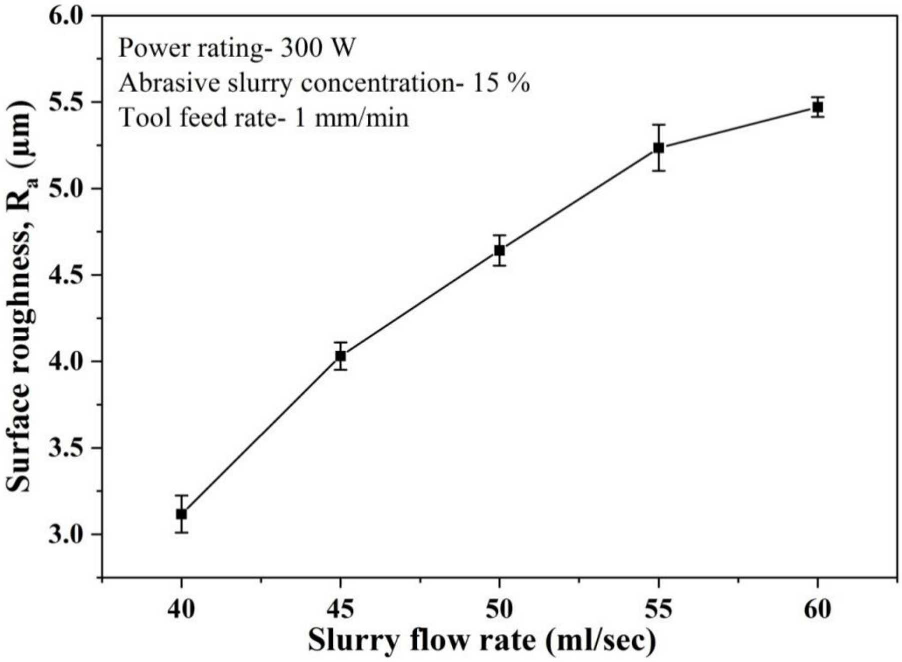


Figure 6.19 Influences of slurry flow rate on surface roughness

The surface of machined micro channel on zirconia has been examined using scanning electron microscopy to characterize the nature of damages resulting from the machining process. The machined surface topography reveals the presence of certain defects, including micro-cavities and micro-cracks and plastically deformed layers on the surface at high power rating. Figure 6.20 shows the SEM micrograph of the multiple micro channels fabricated on zirconia using multiple tips micro tool utilizing USMM process. Figure 6.21 shows the enlarged view of a single micro channel showing the side wall and edge chipping at entrance surface. Zirconia is a ceramic material that exhibits brittleness and when it subjected to high stress concentration or high impact force, the brittles zirconia material can fail and chip at the edges of micro channel. When hard abrasive particles strike by the micro tool onto the work surface, the zirconia materials exhibits combination of plastic deformation and micro cracking due to indentation. If the indentation is formed close to the channel edges, micro crack may propagates easily towards the channel edge surface which result in edge chipping at the micro channel's entrance surface.

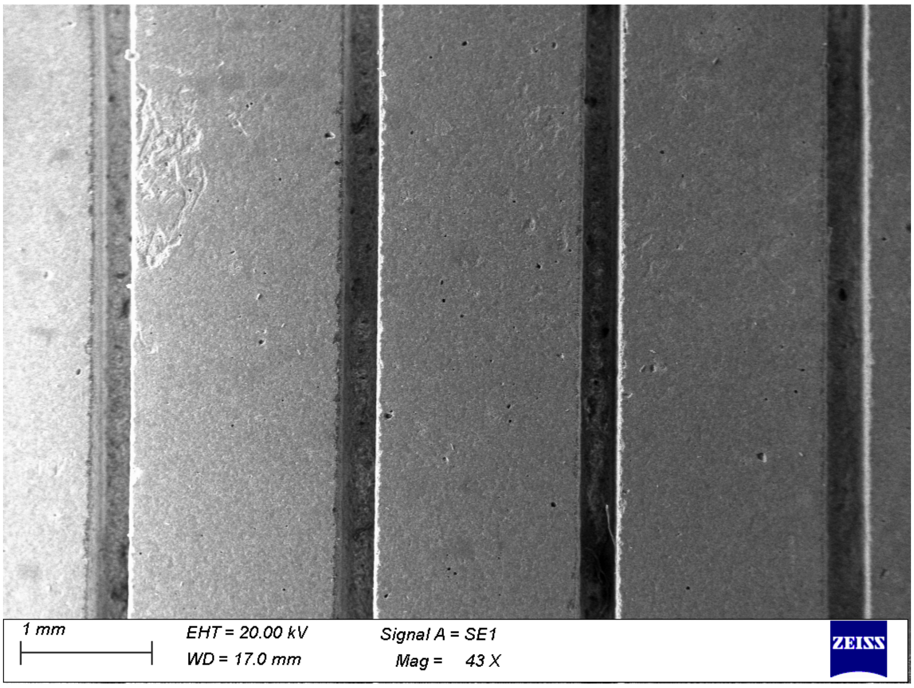


Figure 6.20 SEM micrograph of micro channels on zirconia

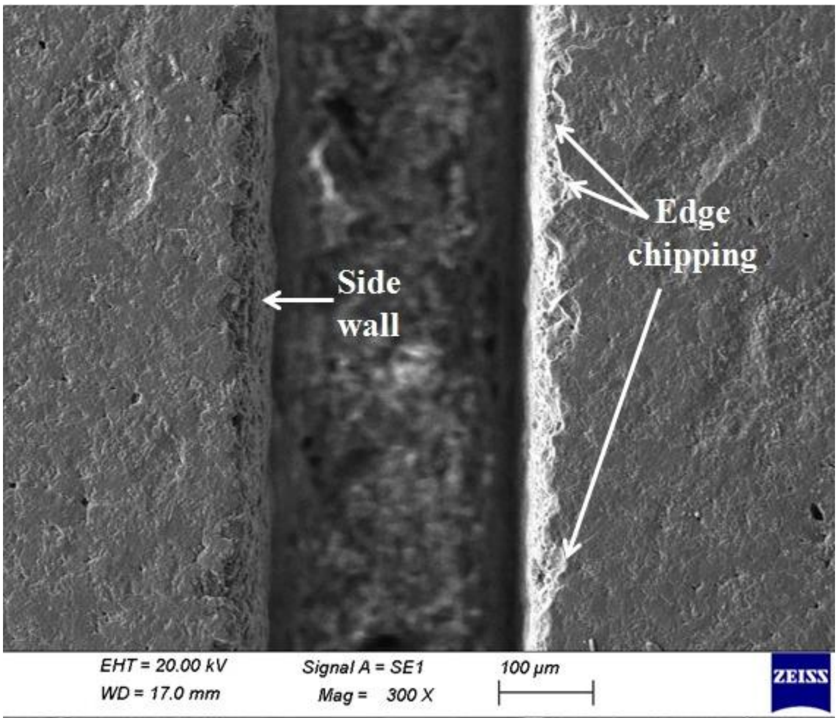


Figure 6.21 SEM micrograph of micro channels on zirconia

Figure 6.22 shows the scanning electron micrograph showing micro cavities and micro crack at bottom surface of micro channel due to high impact on work material by the hard abrasive particle and plastic deformation of material. 3D optical image and depth profile of micro channel is shown in fig. 6.23. The depth of micro channel is 549 µm.

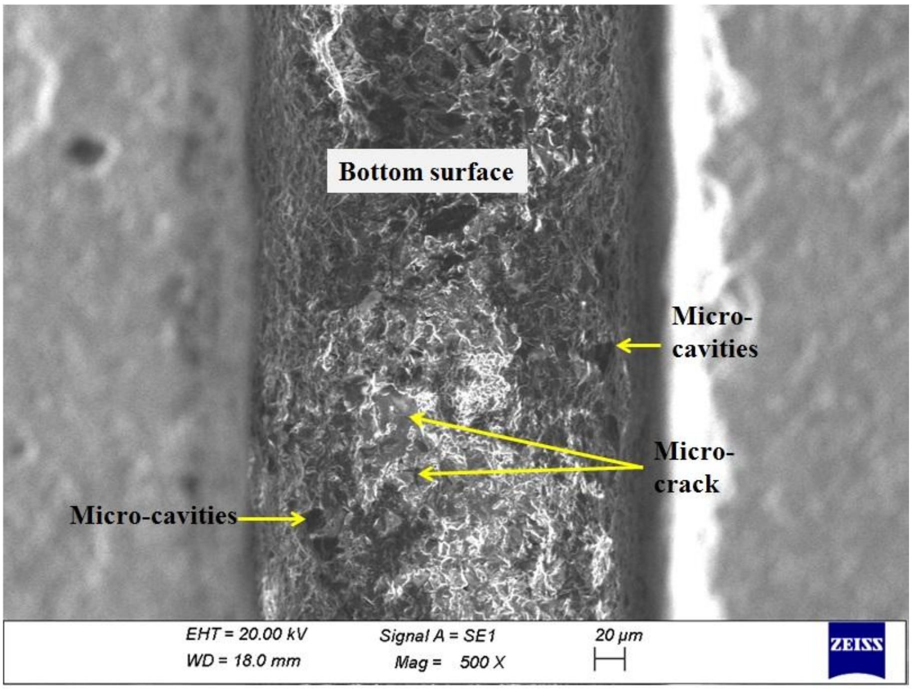


Figure 6.22 SEM micrograph of micro channels on zirconia with micro cavities and micro crack at bottom surface

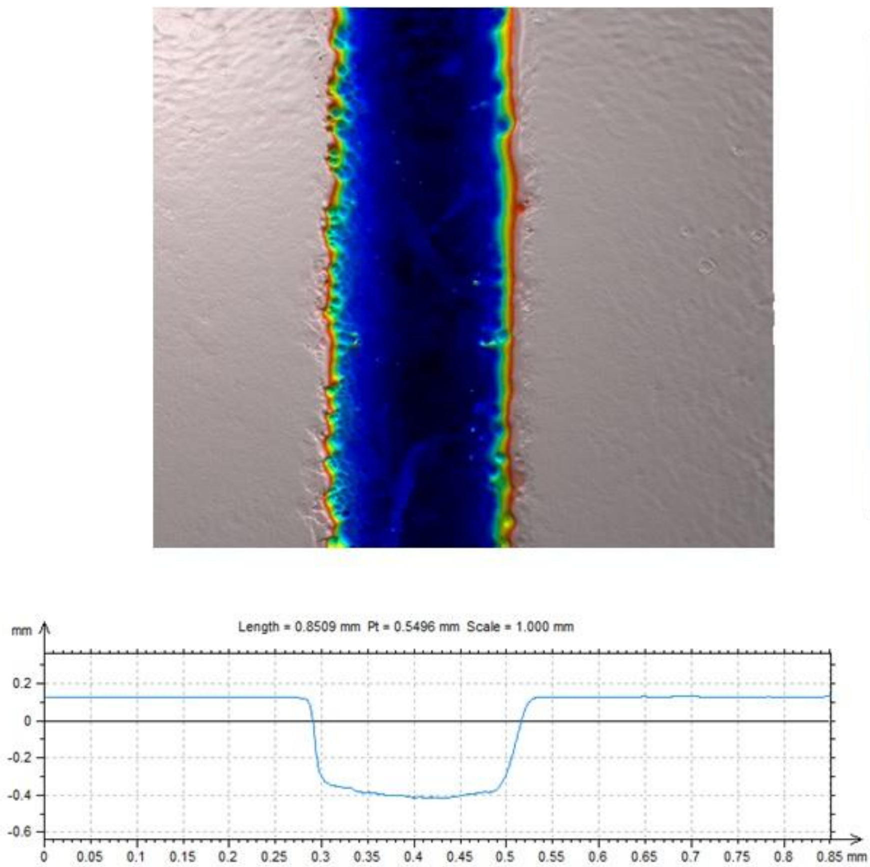


Figure 6.23 3D optical image and depth profile of micro channel

6.7 Outcomes of the present research

Present research work mainly consists of experimental investigations into ultrasonic micro machining of micro channels on zirconia by utilizing multi tips micro tools. Multi tips micro tool is first designed and then developed by wire EDM. Micro-channels were successfully fabricated on zirconia by micro ultrasonic machining process. The influence of process parameters, including power rating, abrasive slurry concentration, tool feed rate and slurry flow rate on machining accuracy in terms of overcut, taper, and material removal rate, surface finish of the micro channels have been investigated. USMM process parameters have a significant effect on MRR, width overcut, taper angle and surface roughness. The aspect ratio of micro channel has been obtained as 3. From the experimental results, it can be observed that lowest width overcut of micro channel is obtained as 26 μm at tool feed rate of 0.8 mm/min. The lesser value of taper angle obtained as 0.931^0 at lower tool feed rate. The lower value of surface roughness, R_a is obtained as 3.117 μm at lower slurry flow rate. The machined surface micro channel on zirconia has also been observed scrutinize through scanning electron microscopy to discern the nature of the damages resulting from the machining process. The machined surface topography exhibits alterations like edge chipping, micro-cavities, micro-crack on the surface at high power rating. The micro channels on zirconia have wide range of application in biomedical science, micro fuel cell and cooling of components of micro electronics etc. So, fabrication of multiple micro channels on zirconia at a time is very much essential using multiple tips micro tool by ultrasonic micro machining process to save time and obtain high productivity and accuracy. However, other types of micro features such as square micro hole array is also necessary to be machined on quartz for micro engineering applications. Hence, to investigate the influence of USMM process parameters on responses during generation of square micro hole array on quartz, further experimentation is needed utilizing array of square micro tool.

EXPERIMENTAL INVESTIGATION INTO ULTRASONIC MICRO-MACHINING PROCESS FOR ARRAY OF SQUARE MICRO HOLE GENERATION ON QUARTZ EMPLOYING DEVELOPED MULTI TIPS MICRO TOOL

7.1 Introduction

The aim of this chapter is to produce square micro hole array on quartz utilizing the developed tool by USMM. The design and development of multi tips square micro tool has already been discussed in chapter 2. The arrays of micro holes are widely used in the various micro engineering applications in the fields of biomedical science, micro fuel cell, and cooling of components of microelectronics, micro-electro-mechanical system (MEMS), optical interconnection, inkjet printer, aerostatic air bearing system etc. The concept of micro hole array fabrication using a single tool is shown in fig. 7.1. The influence of various major process parameters of USMM, i.e. power rating, abrasive slurry concentration, tool feed rate and slurry flow rate on MRR, width deviation, angular deviation and taper angle of array of square micro hole on quartz have also been investigated.

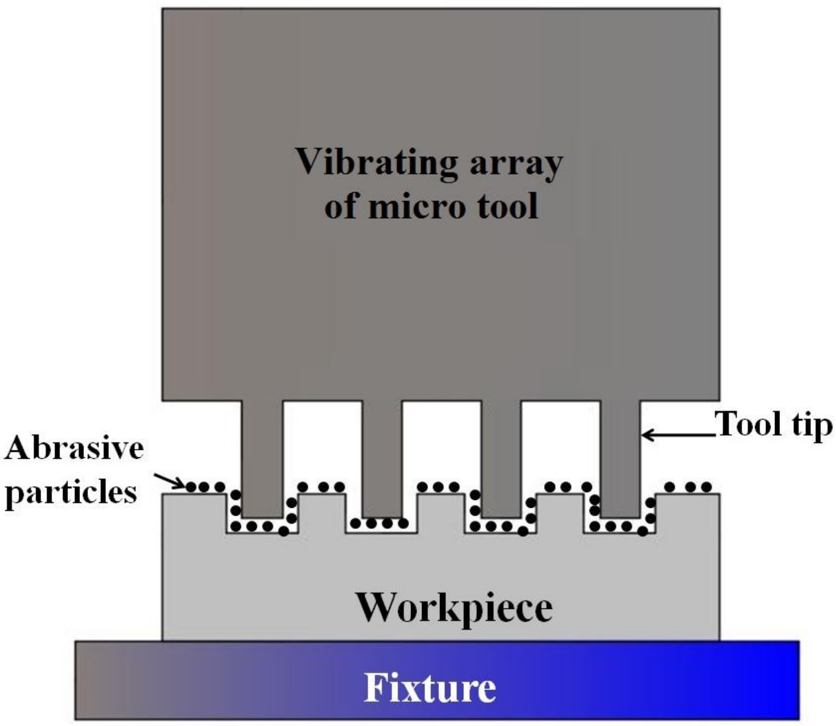


Figure 7.1 Concept of USMM using array of micro tool

7.2 Experimental planning

Each experiment was carried out using an AP sonic Mill 1000. The square quartz workpiece plate of size 25 mm X 25 mm X 2 mm was fixed on fixture using wax. The wire-EDM technique was used to make the micro array tool as discussed in chapter 2. The tool comprises of a 4×4 array of micro-tool. Figure 7.2 shows a schematic view of array of square micro tool. Each tool tip consists of square shape of 280×280 μm^2 cross section and 4000 μm height. The utilization of a 4x4 array micro-tool results in reduced machining time, serving the purpose of swiftly validating batch fabrication concepts. The square micro-tool array can be scaled up to larger sizes for generation more number of square micro holes within less period of machining time.

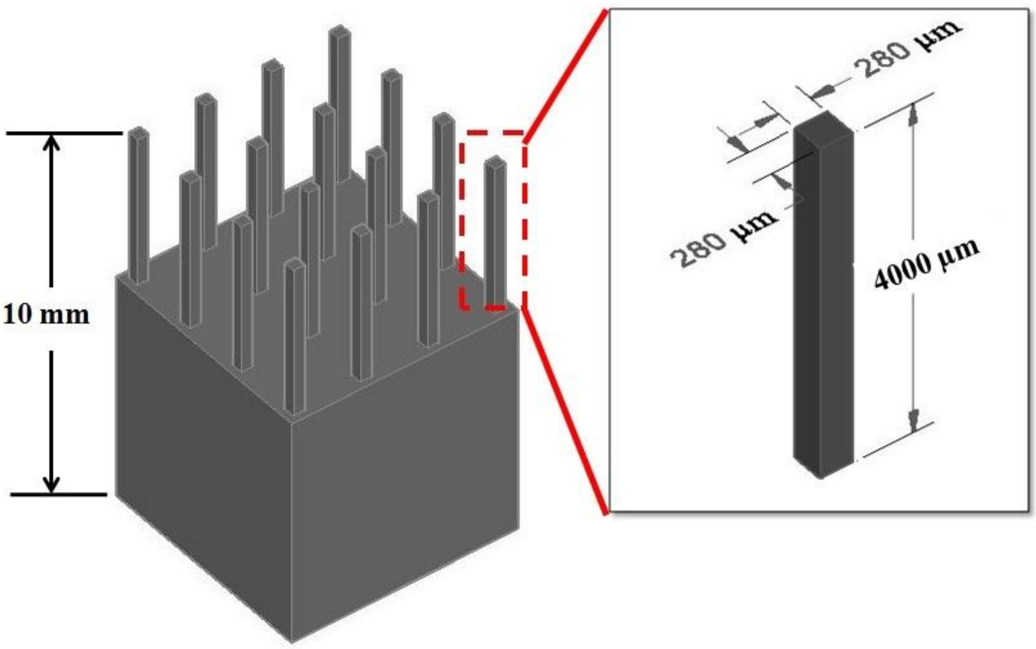


Figure 7.2 Schematic view of micro array tool

Al_2O_3 was taken as abrasive slurry particle because it is less hard than B_4C and SiC. In this experimentation, array of square micro tool is used so Al_2O_3 is preferred for less chipping and cracking. The average size of Al_2O_3 abrasive particle is 4 μm. Water is used as liquid media and mixed with abrasive to form slurry. It is continuously supplied in the gap between workpiece and tool. Abrasive slurry concentration varies from 5 % to 25 % by weight. Power rating varies from 200 W to 400 W during experimentation. Tool feed rate varies from 0.8 mm/min to 1.2 mm/min during experimentation. Slurry flow rate varies from 40 to 60 ml/sec Table 6.1 represents the experimental conditions of ultrasonic micromachining for fabricating array of micro hole on quartz. The SEM image of array (4x4) of micro hole fabricated on quartz utilizing developed multiple tip square micro tool by ultrasonic micromachining is shown in fig. 7.3.

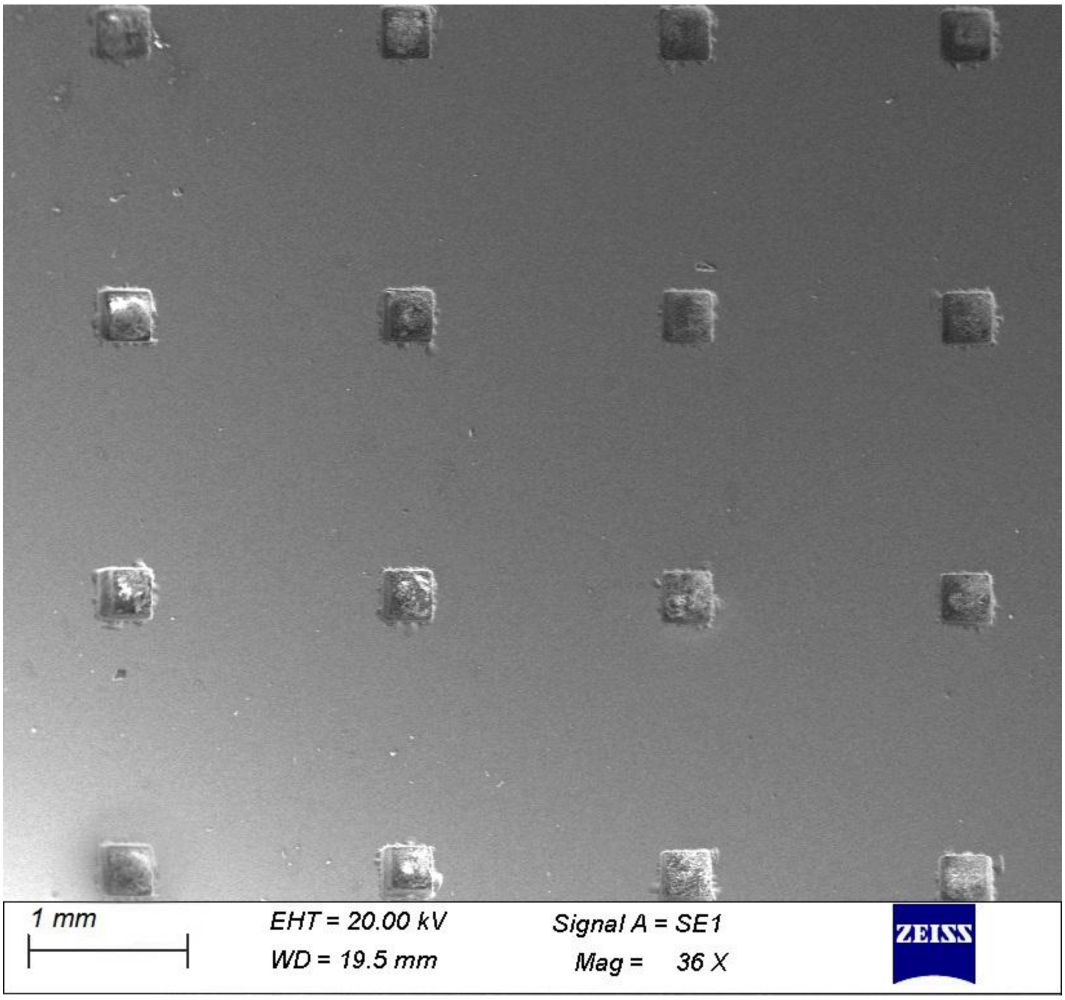


Figure 7.3 SEM image of the array of square micro hole on quartz

7.3 Measurement of responses

The measurement procedure and calculations of responses such as MRR, width deviation, angular deviation and taper angle are described in the subsequent subsections.

7.3.1 Measurement of material removal rate

The width of entrance surface of square micro hole is measured by optical measuring microscope (made: Leica *DM 2500 M*). The width is taken at both side of all micro holes and average width is calculated. The material removal rate is calculated by equation 7.1.

The material removal rate (MRR) is calculated by:

$$MRR = \frac{16\ (W_e * W_e * d)}{t} \tag{7.1}$$

Where, W_e and d are the average width at entrance and depth of square micro hole respectively which are illustrated through the diagram as shown in fig. 7.4 and t is the machining time for generating array of square micro hole on quartz.

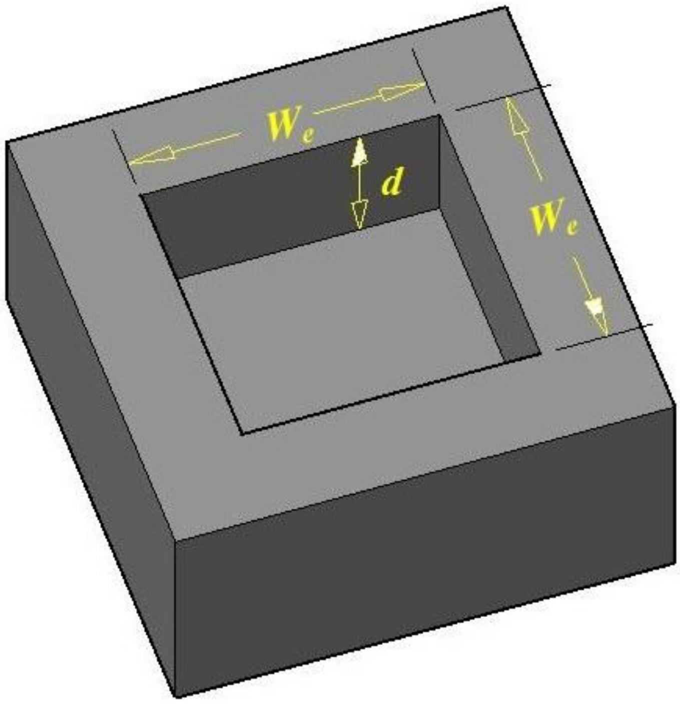


Figure 7.4 Schematic view of micro hole

7.3.2 Measurement of width deviation

The width deviation across flat surfaces of the square micro hole can be calculated by measuring the distance of a flat surfaces on both sides of square micro hole. The difference of measured average width between the flat surfaces of micro hole on the machined quartz workpiece and average width of the utilized array of square micro tool tip will give width deviation. The width is taken at entrance of square micro hole on both side and so for a single machining operation, width is the average of 32 measurements of 16 numbers of square micro holes. After the measurement of width deviation of square micro holes and width of square micro tool tip, width deviation (WD) is calculated by using equation 7.2.

The Width deviation (WD) of square micro hole is given by:

$$Width\ deviation\ (WD) = W_e - W_t \quad (7.2)$$

Where, W_e average width at entrance of square micro hole on quartz workpiece and W_t is the average width of square micro-tool tip.

7.3.3 Measurement of angular deviation

The angular deviation at the corners of square micro holes is calculated as the disparity between the experimentally observed angles (in degrees) at each corner of the machined hole and the angles of the corner of the micro tool. This deviation for a specific machined corner is derived from the difference between the experimentally determined angles of the workpiece and the angle at the tool's corner. The values of angular deviations (D_A) for square micro holes were assessed by averaging the angles of all four corners of the machined micro holes."

7.3.4 Measurement of taper angle

After the measurement of average width at top and bottom surfaces of micro holes the taper angle is calculated by equation 7.3.

The taper angle is calculated by:

$$\text{Taper angle } (\alpha) = \tan^{-1}\frac{W_e - W_b}{2d} \quad (7.3)$$

Where, W_e is the average width of square micro hole at entrance surface, W_b is the average width of square micro hole at bottom surface and d is the depth of square micro hole on quartz..

7.4 Influence of power rating on MRR, width deviation, angular deviation and taper angle

The influence of power rating on MRR is shown in fig. 7.5. At the same time other parameters such as abrasive slurry concentration, tool feed rate and slurry flow rate are fixed at 15 %, 1 mm/min and 50 ml/sec respectively   The MRR is 0.513 mm^3/min at 200 W power rating. It has been observed that MRR gradually increasing with increase in power rating. When power rating increases, the impact energy of the abrasive particles also increases and resulting in greater erosion of material from the workpiece. The higher value of MRR 0.920 mm^3/min is obtained at 400 W.

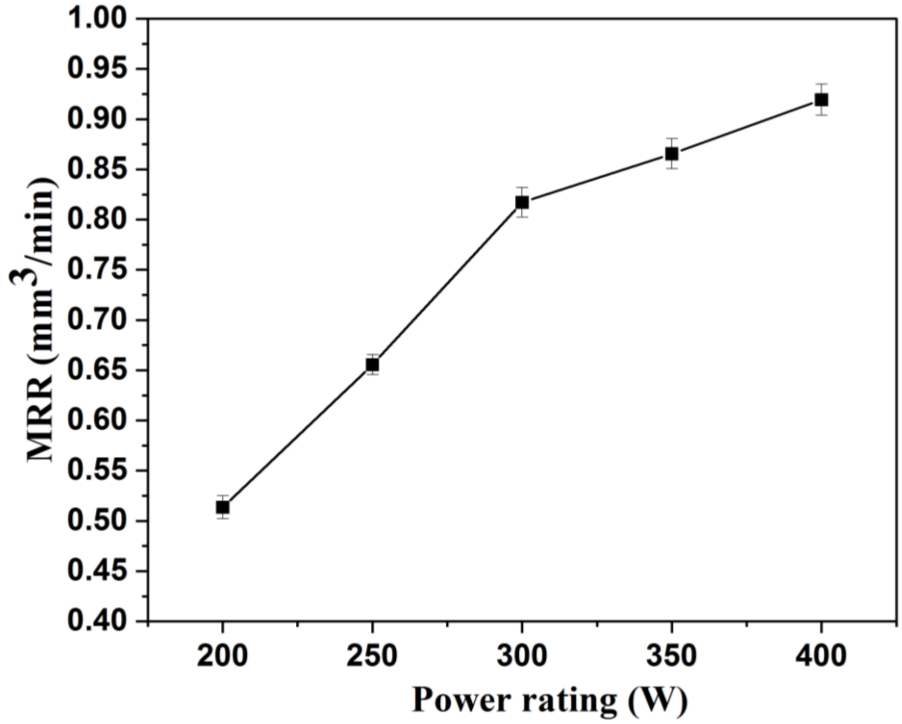


Figure 7.5 Influence of power rating on MRR

Figure 7.6 shows the influence of power rating on width deviation of square micro holes produced on quartz. The lower width deviation has been observed as 59 µm at 200 W power rating. As the power rating increase, the abrasive particles strikes with higher striking energy, is forming larger indentation. Consequently, a greater amount of material is removed from the work surface, leading to an increase which in width deviation of square micro hole. From the experiments, it has been observed that the higher width deviation is 75 µm at 400W. It has been also observed that standard deviation is more due to generation of more holes in a single operation. In 4 x 4 array of square micro holes, outer holes (i.e. 12 holes) at the periphery of the array has more width deviation compare to inner holes (i.e. 4 holes).

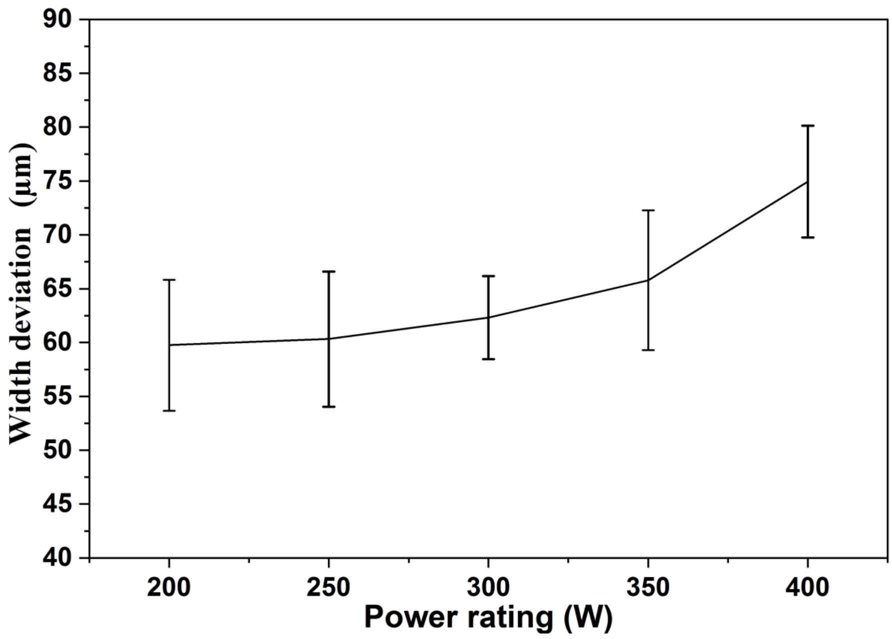


Figure 7.6 Influence of power rating on width deviation

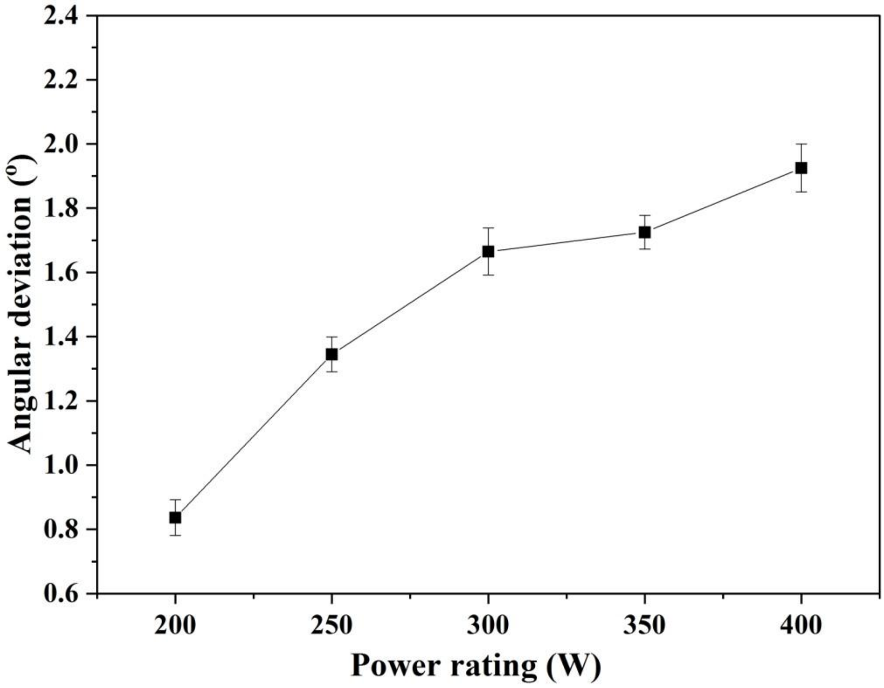


Figure 7.7 Influence of power rating on angular deviation

The influence of power rating on angular deviation is shown in fig. 7.7. The smaller angular deviation has been observed at lower power rating. Angular deviation has been gradually increases with the increased in power rating. It has been observed that angular deviation changes from 0.8366 to 1.925^{o} while power rating changes from 200 W to 400 W. Figure 7.8 shows the influence of power rating on taper of square micro hole on quartz. Higher taper is observed at lower power rating and it decreases with the increase in power rating. This is attributed to the higher kinetic energy of abrasive particles resulting in a higher cutting rate. As a consequence materials are uniformly removed from the bottom part of the square micro holes, leading to reduces taper at higher taper ratings. Specifically, at power ratings of 200 W and 400 W, taper angle of as 2.252^0 and 1.11^0 are obtained, respectively.

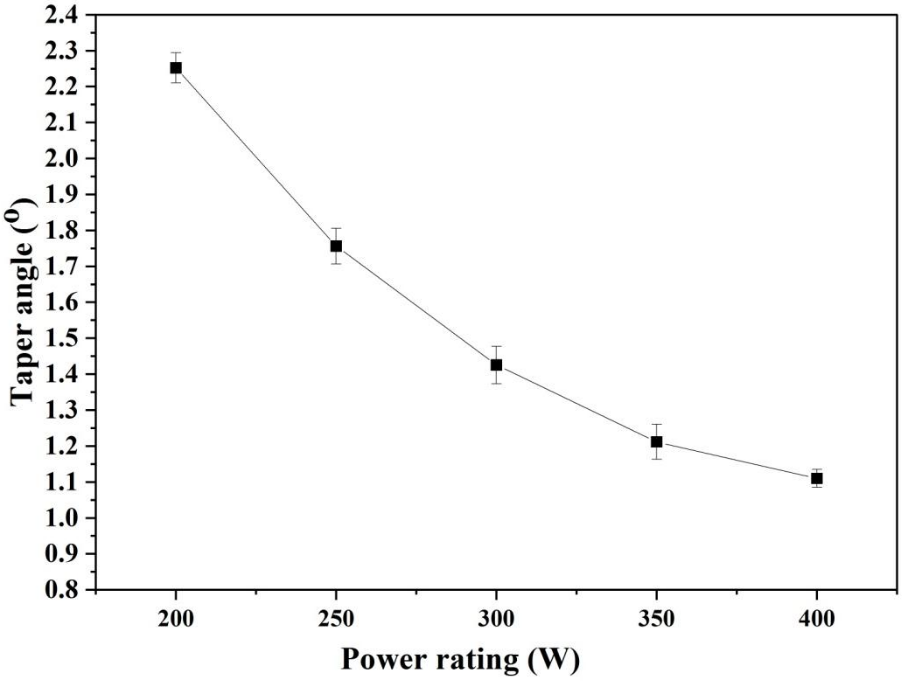


Figure 7.8 Influence of power rating on taper angle

7.5 Influence of abrasive slurry concentration on MRR, width deviation, angular deviation and taper angle

The influences of abrasive slurry concentration during generation of square micro holes on quartz utilizing array of micro tool have been discussed in this section. At the same time keeping other parameters constant i.e. power rating of 200 W, feed rate of 0.8 mm/min and slurry flow rate of 40 ml/sec. Abrasive particles are primarily responsible for removing the material from the workpiece, the MRR depends on both the quantity of abrasive particles used in the machining process and also the unit removal volume per particle, both of which are influenced by slurry concentration. The influence of abrasive slurry concentration on MRR during array of micro hole generation on quartz is shown in fig. 7.9. Based on the experimental results, it has been observed that MRR significantly changes from 0.806 to 1.427 mm^3/min with the change in slurry concentration from 5 to 25 %. The Influence of abrasive slurry concentration on width deviation of micro square holes on quartz is shown in fig. 7.10. It has been observed that abrasive slurry concentration has less effect on width deviation when it changes from 5 to 15%. It is also observed that width deviation gradually increases while abrasive slurry concentration varies from 15 to 25 %. The width deviation is obtained as 37 µm and 47 µm at 5 % and 25 % abrasive slurry concentration respectively.

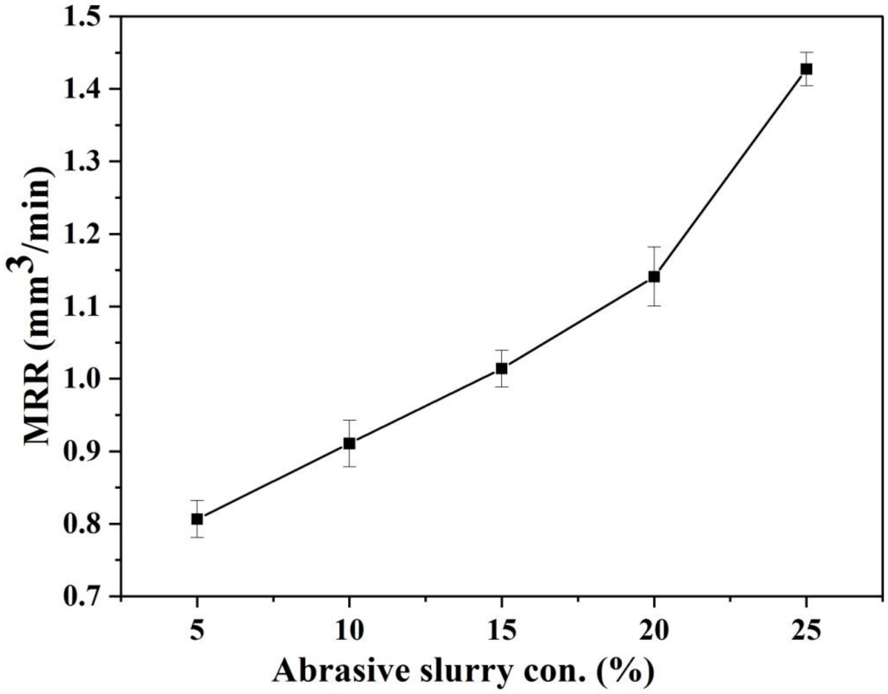


Figure 7.9 Influence of abrasive slurry concentration on MRR

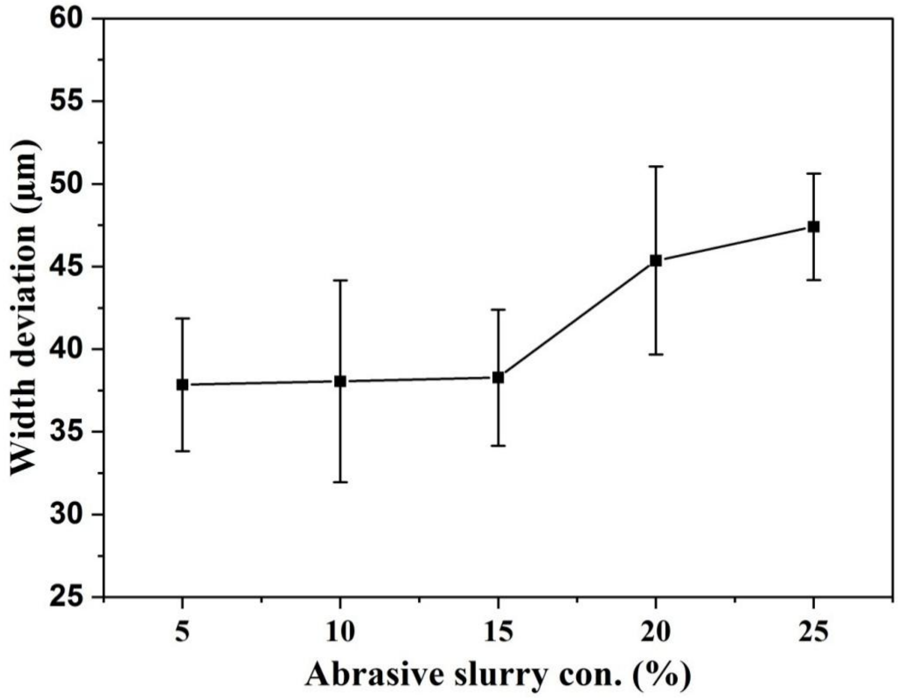


Figure 7.10 Influence of abrasive slurry concentration on width deviation

The influences of abrasive slurry concentration on angular deviation during array of square micro holes generation on quartz is shown in fig. 7.11. It has been observed that angular deviation changes from 1.39 to 1.67^{o} while concentration changing from 5 to 25%. Higher slurry concentration typically leads to increased tool wear, thereby contributing to higher width deviation and angular deviation in the square micro holes. Figure 7.12 shows the influences of slurry concentration on taper of square micro holes. The lower taper is obtained at 5% abrasive slurry concentration. Taper of square micro holes increases with increase in abrasive slurry concentration. The taper angle is obtained as 1.109^{0} and 1.512^{0} at 5 % and 25 % abrasive slurry concentration respectively. In higher slurry concentrations, the mixture contains a greater amount of abrasive particles combined with water, resulting in more MRR but diminished accuracy.

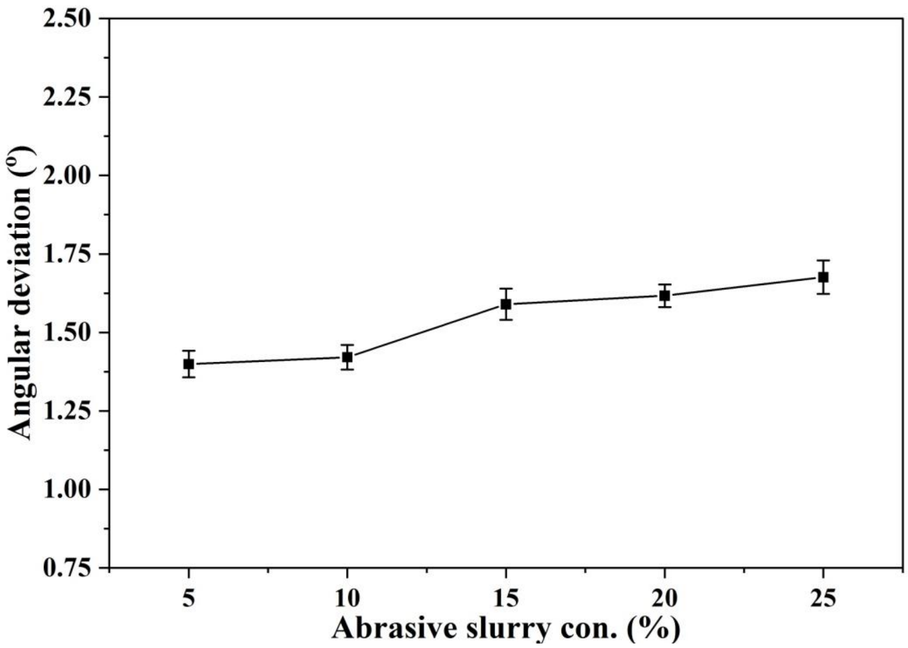


Figure 7.11 Influence of abrasive slurry concentration on angular deviation

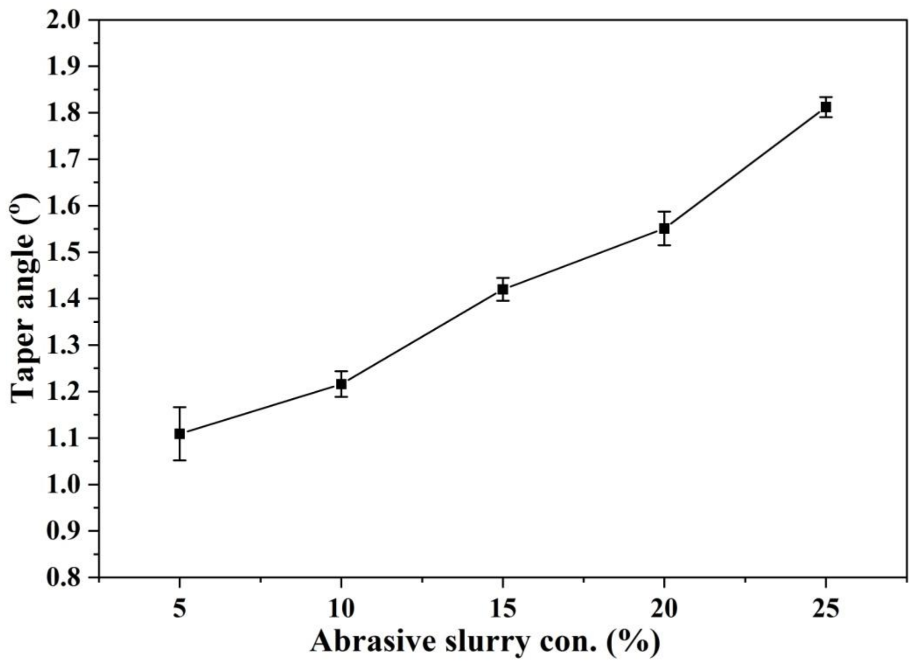


Figure 7.12 Influence of abrasive slurry concentration on taper angle

7.6 Influence of tool feed rate on MRR, width deviation, angular deviation and taper angle

Tool feed rate is an important parameter for ultrasonic micro machining and it can be defined as tool movement towards stationary workpiece per unit time. The tool feed rate was varied from 0.8 to 1.2 mm/min. The effects of tool feed rate have been analysed while other parameters like power rating, abrasive slurry concentration and slurry flow rate are kept fixed at 300 W, 15 % and 50 ml/sec respectively. The influence of tool feed rate on MRR is shown in fig. 7.13. MRR increases slowly from 0.8 to 1 mm/min tool feed rate and then increases sharply. With the increase in tool feed rate, impact force increases and hence MRR increases. The higher MRR is obtained as 1.413 mm^3/min, at 1.2 mm/min tool feed rate. Figure 7.14 shows the influence of tool feed rate on width deviation. At low tool feed rate abrasive particle striking at smaller force hence width deviation is low. When tool feed rate increases, striking force of abrasive particle also increases and hence width deviation also increases. Width deviation is larger at higher value of tool feed rate. It has been observed that the angular deviation of square micro holes decreases up to tool feed rate 1 mm/min and then increases as shown in fig. 7.15. Higher feed rate with same static force may cause higher tool wear so angular deviation is more. Figure 7.16 shows the influence of tool feed rate on taper of square micro hole on quartz.

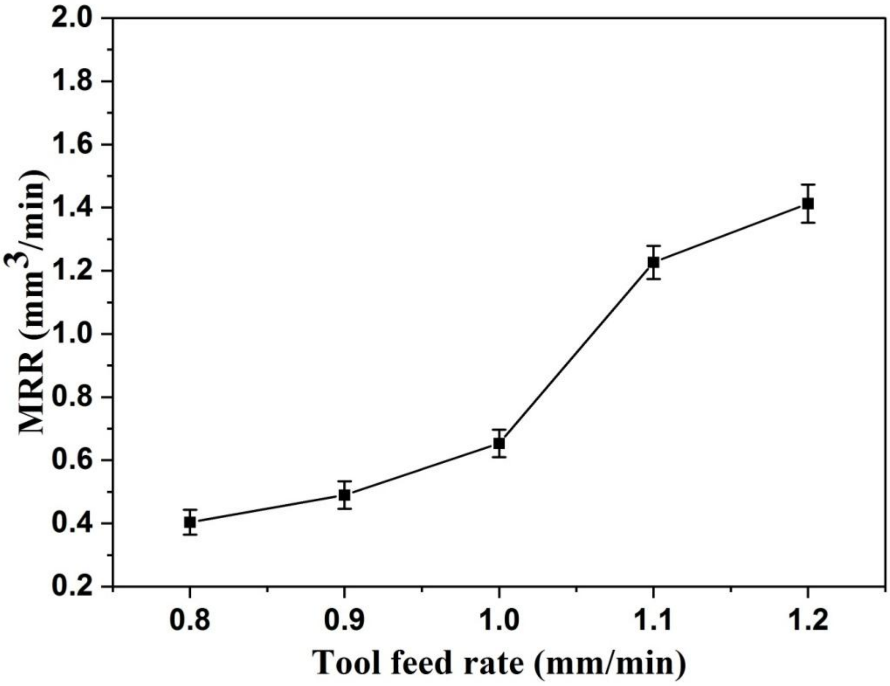


Figure 7.13 Influence of tool feed rate on MRR

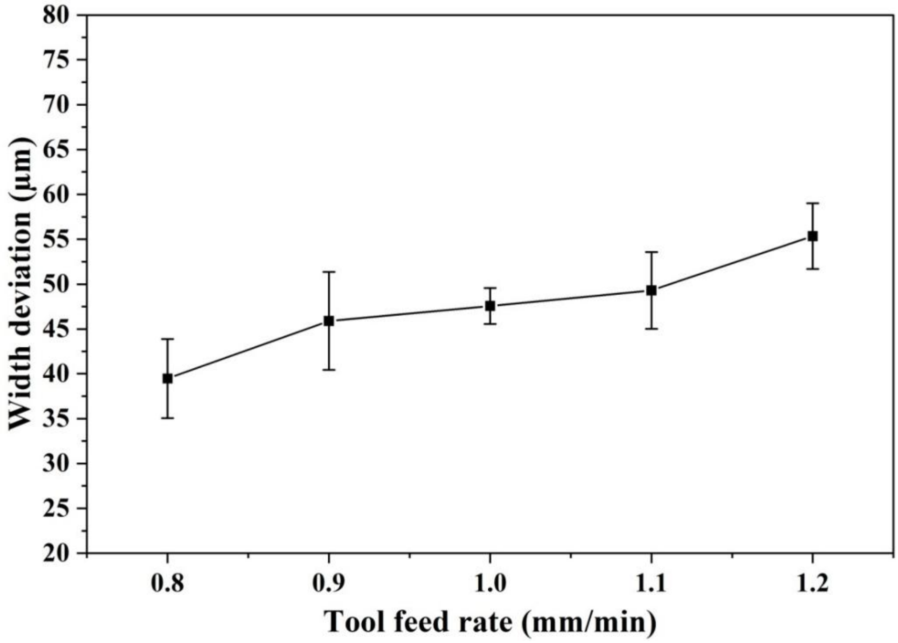


Figure 7.14 Influence of tool feed rate on width deviation

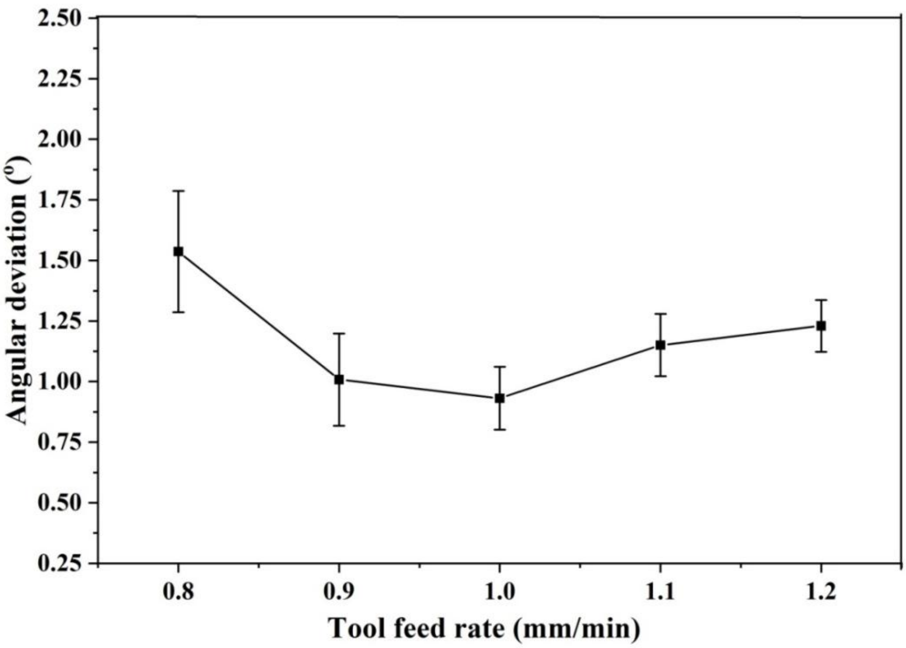


Figure 7.15 Influence of tool feed rate on angular deviation

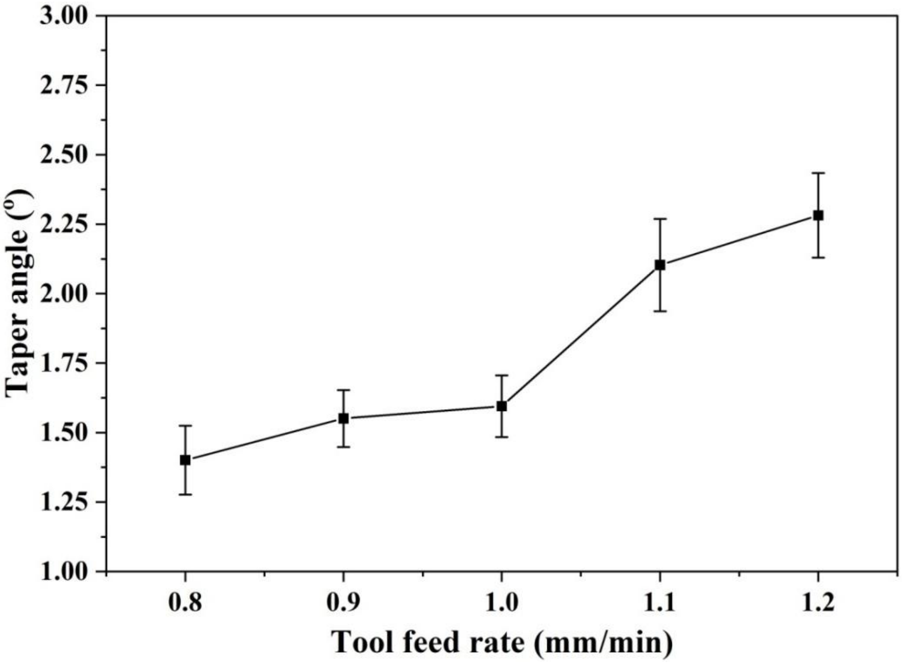


Figure 7.16 Influence of tool feed rate on taper angle

7.7 Influence of slurry flow rate on MRR, width deviation, angular deviation and taper angle

The slurry flow rate means the abrasive particles per unit time taking part in machining. Slurry flow rate was varied from 40 to 60 ml/sec. Figure 7.17 shows the influence of slurry flow rate on MRR. At the same time other process parameters such as power rating, abrasive slurry concentration and tool feed rate are kept fixed at 300 W, 15 % and 1 mm/min respectively. At lower abrasive slurry flow rate, MRR is low i.e. 0.518 mm^3/min. With higher slurry flow rate, MRR becomes more. Due to increase in slurry flow rate fresh abrasive involved in machining and also debris particles comes out between tool and work surface, so MRR increases. At 60 ml/sec slurry flow rate MRR is obtained as 1.2672 mm^3/min. Figure 7.18 shows the influence of slurry flow rate on width deviation of square micro holes. Width deviation is taken both sides of micro holes. At lower slurry flow rate, width deviation is low i.e. 43 µm and it increases with increase in slurry flow rate. At 60 ml/sec slurry flow rate, width deviation is obtained as 66 µm. Figure 7.19 shows the influence of slurry flow rate on angular deviation of square micro holes. Angular deviation is not so much effected by slurry flow rate. Angular deviation is 0.91^o at lower slurry flow rate and it slowly increases up to 1.28^o. Figure 7.20 shows the influence of slurry flow rate on taper of square micro holes. Taper of micro hole slowly increases with slurry flow rate ranging from 40 ml/sec to 50 ml/sec after that it suddenly increases at higher slurry flow rate.

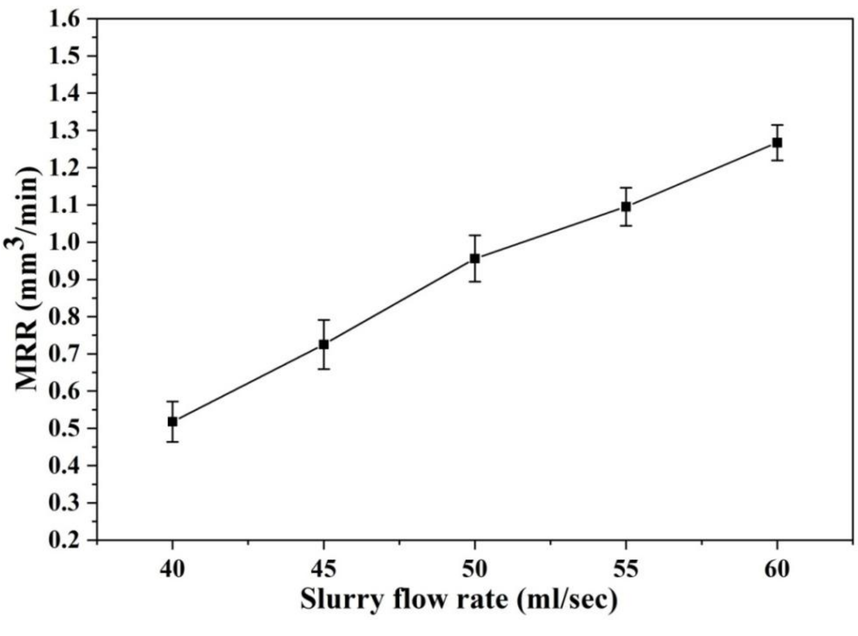


Figure 7.17 Influence of slurry flow rate on MRR

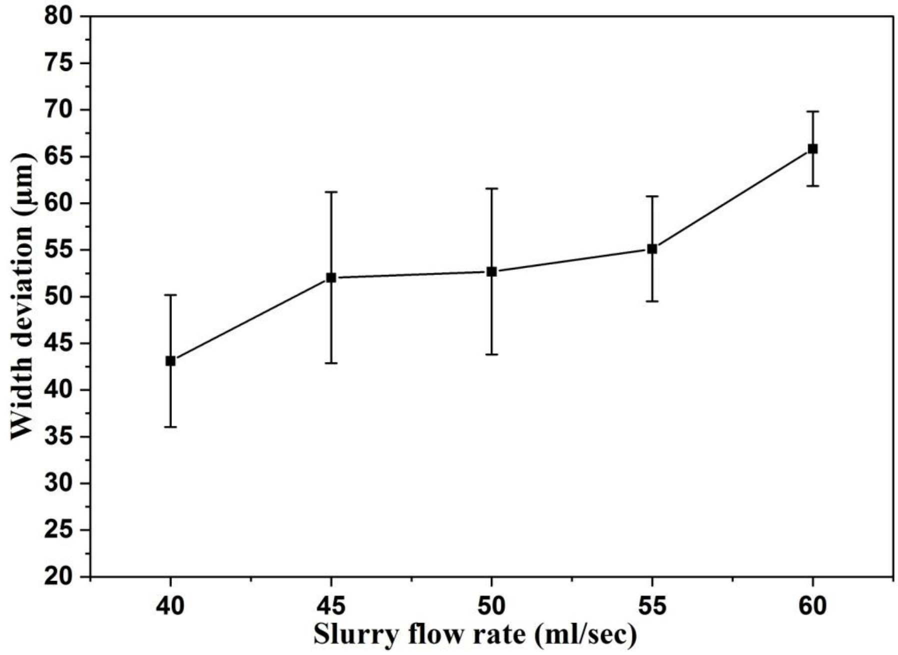


Figure 7.18 Influence of slurry flow rate on width deviation

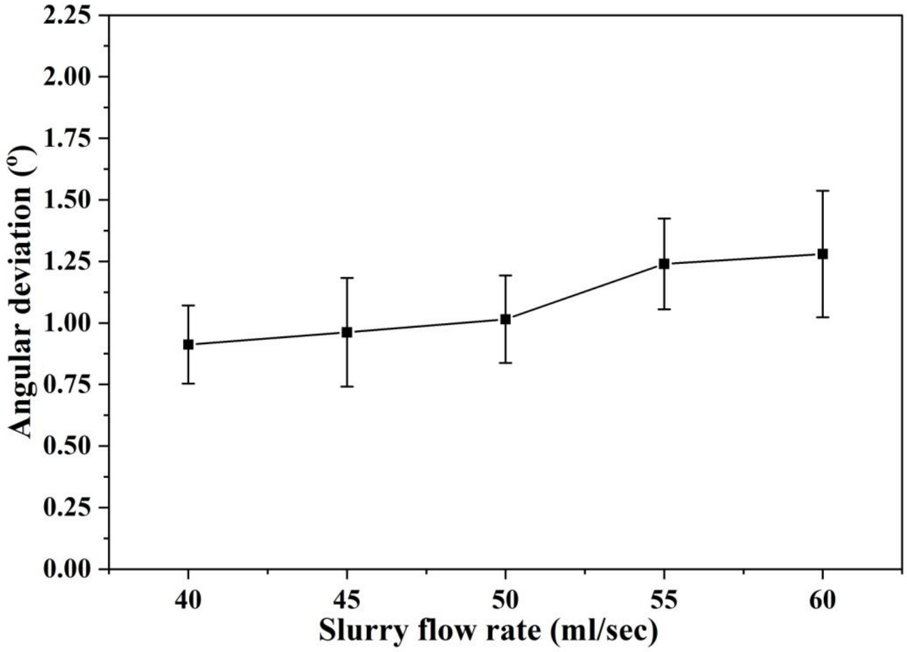


Figure 7.19 Influence of slurry flow rate on angular deviation

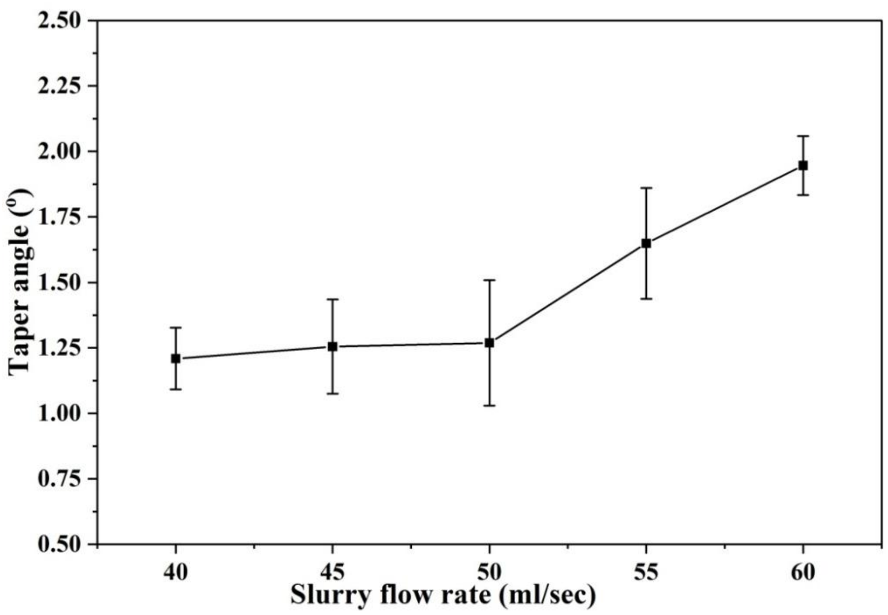


Figure 7.20 Influence of slurry flow rate on taper angle

Morphology of the machined square hole's surface was also studied using scanning electron microscope (SEM). Figure 7.21 (a) shows the scanning electron micrographs of array of square micro holes (4x4) produced on quartz by utilizing developed array of square micro tool. Some edge chipping are observed at entrance surface of square micro hole which is shown in fig. 7.21 (b) in 500 magnification. Figure 7.21 (c) shows the corner accuracy of square micro hole at 1000X magnification.

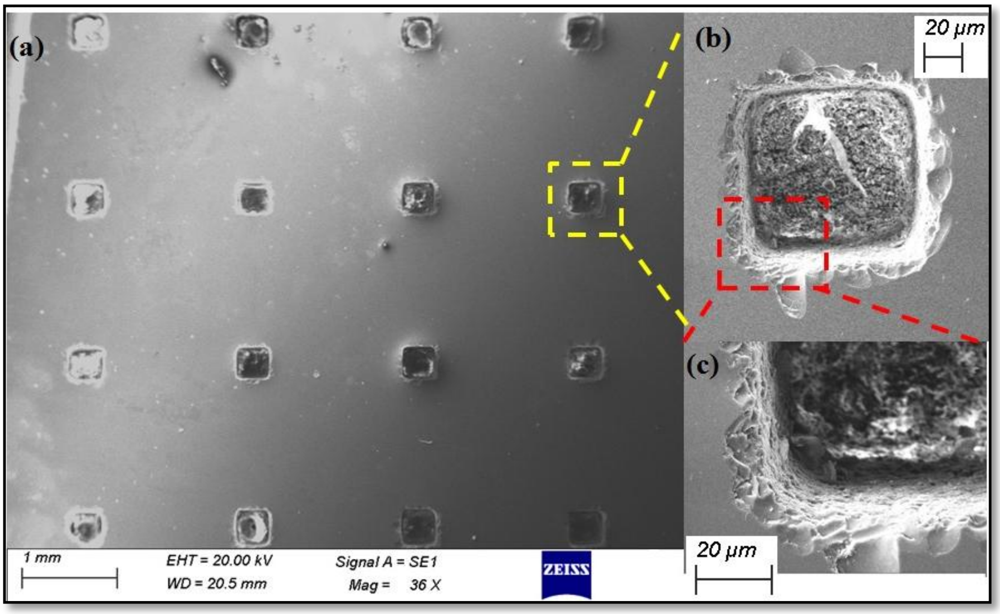


Figure 7.21 SEM image of (a) array of micro holes (4x4) on quartz; (b) enlarged view of a single hole at mag. 500X, (c) zoom view at mag. 1000X

Figure 7.22 (a) shows the micro hole at 400X magnification which revealed that side wall of square micro hole has good surface finish. Figure 7.22 (b) shows the 2D profile of square micro hole which exhibited the corner accuracy at bottom surface and also machined surface profile at bottom.

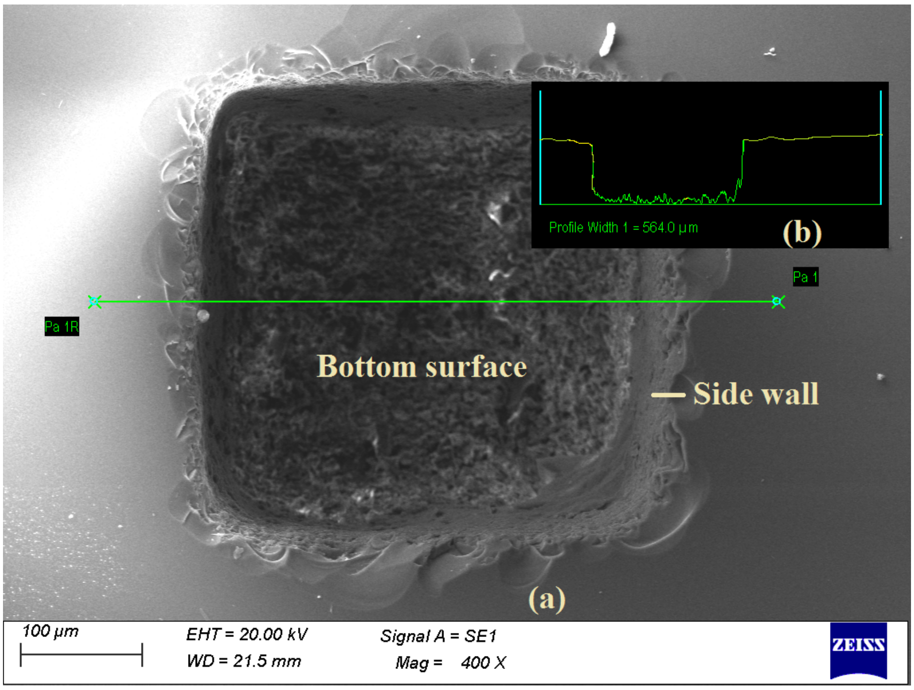


Figure 7.22 SEM image of (a) micro hole on quartz (b) 2D profile of micro hole at a section

Figure 7.23 shows SEM image of the bottom surface of the machined square micro hole generated using ultrasonic micro machining. Some shallow dents grooves are observed on the bottom surface due to the repetitive indentation of abrasives on the work surface. However, workpiece is cleaned by ultrasonic cleaning system and it has been observed that few abrasive particles are embedded on the machined surface due to repetitive indentation of abrasive as well as improper slurry flow in the bottom region of square micro hole of the quartz workpiece surface during machining.

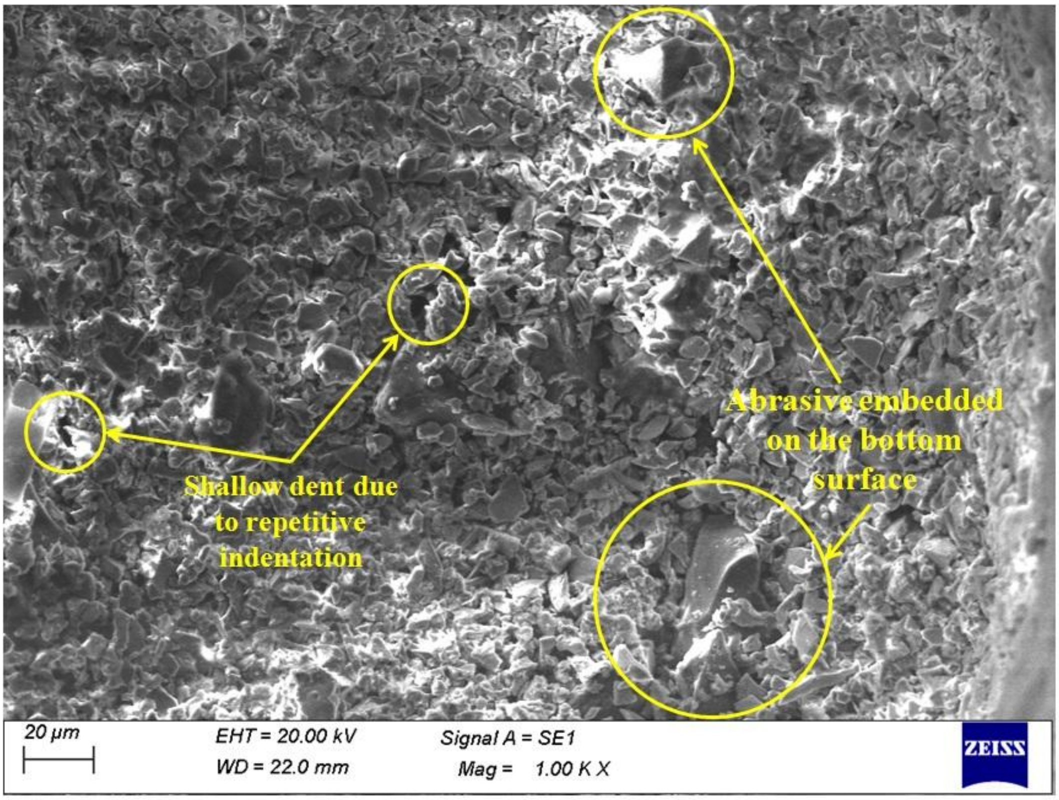


Figure 7.23 SEM image of bottom surface of micro hole

7.8 Outcomes of the present research

Present research work mainly consists of experimental investigations into ultrasonic micro machining for fabrication of array of square micro holes on quartz by utilizing developed array micro tools. Array of micro tool (4 x4) is first designed and fabricated by wire EDM. Array of micro holes are successfully fabricated on quartz by ultrasonic micromachining process. The influence of process parameters including power rating, slurry concentration, tool feed rate and slurry flow rate on MRR and machining accuracy in terms of width deviation, angular deviation and taper angle of the array of micro holes have been investigated. USMM process parameters have a significant effect on width overcut, taper angle and surface roughness. From the experimental result, it has been observed that lower width deviation of micro holes is obtained as 37 μm and lower taper angle is 1.109^{o} at 5 % abrasive slurry concentration. The lower value of angular deviation is obtained as 0.836^{o} at lower power rating. The higher MRR is obtained as 1.427 mm^3/min at higher abrasive slurry concentration i.e. 25%. The machined surface of array of micro holes on quartz has been observed through scanning electron microscopy to recognize the nature of damages resulting from the machining process. The topography of the machined surface reveals alterations, including edge chipping and shallow micro-dents, particularly prominent at high power ratings. The array of micro holes has wide range of applications in biomedical science, micro fuel cell and cooling of components of micro electronics micro-electro-mechanical system (MEMS), optical interconnection, inkjet printer, aerostatic air bearing system etc. So, fabrication of array of square micro holes on quartz at single machining operation using array of square micro tip tool by ultrasonic micro machining process is widely acceptable to enhance the productivity and quality of quartz machining.

GENERAL CONCLUSIONS

8.1. General conclusions

The ultrasonic micro machining (USMM) process has enormous prospective for machining various micro features on quartz and zirconia for micro engineering applications. It has been observed that the performance criteria of USMM such as material removal rate and accuracy in terms of taper angle, overcut as well as surface quality during generation of different micro machined features depends on selection of process parametric combination of ultrasonic micro machining operations. Ultrasonic micro machining has been effectively utilized for generating micro hole, multiple micro channels, array of square micro hole on quartz and multiple micro channels on zirconia. The following broad conclusions could be drawn from the results and observation of experimental investigation, developed mathematical models and analysis, as well as optimisation findings during ultrasonic micromachining of quartz and zirconia:

(i) Cylindrical micro tools, multiple tips micro tool and array of square micro tool have been successfully developed for in-depth experimental investigations into ultrasonic machining process and it is concluded that developed micro tools are capable to produce micro features on different hard and brittle materials such as quartz and zirconia.

(ii) Ultrasonic micromachining process has been successfully applied for generation of micro holes on quartz using the cylindrical shaped micro tool. From the experimental results, it can be summarized that performance of ultrasonic micro machining is very much influenced by abrasive slurry concentration compared to power rating and tool feed rate. For achieving higher MRR, higher power rating, higher abrasive slurry concentration and higher tool feed rate are preferred during USM for micro drilling on quartz. Higher MRR i.e. 0.376 mm^3/min is obtained at 400 W power rating. For achieving lower overcut and taper angle of micro hole, low value of abrasive slurry concentration, low value of power rating and low tool feed rate are to be selected during USM for micro drilling on quartz. Lesser overcut i.e. 55 µm and lesser taper angle i.e. 0.588^0 of micro hole are obtained at low value of abrasive slurry concentration during USM for micro drilling on quartz.

(iii) The created mathematical models for material removal rate (MRR), overcut, and taper angle have been determined to be suitable for evaluating the impact of various process parameters on the outcomes of micro hole production on quartz using the method of ultrasonic micromachining. Form the response graphs based on RSM models; it is observed that MRR increases with increases in abrasive slurry concentration with little variation on values of power rating. Lower overcut has been achieved with a combination of medium power rating and higher value of slurry concentration. At the intersection of a moderate tool feed rate and an intermediate concentration of abrasive slurry, a reduced taper angle has been noticed.

(iv) Based on single objective optimization, for achieving maximum MRR, the optimal combination of process parameters obtained as abrasive slurry concentrations of 31.71 %, power rating of 400 W and tool feed rate of 1.03 mm/min for micro hole generation on quartz with SS304 tool using B_4C abrasive particle by USMM. The maximum MRR is obtained as 0.4631 mm^3/min. For achieving minimum overcut the optimal combination of process parameters obtained as abrasive slurry concentrations of 20 %, power rating of 200 W and tool feed rate of 0.8 mm/min. The minimum overcut is obtained as 30.16 µm. For achieving minimum taper angle the optimal combination of process parameters obtained as abrasive slurry concentrations of 30 %, power rating of 220.20 W and tool feed rate of 0.90 mm/min. The minimum half taper angle is obtained as 0.3371^0.

(v) The multi objective optimization has also been performed based on developed mathematical models to obtain the optimal setting of process parameters for maximum MRR, minimum overcut and minimum taper angle for micro hole generation on quartz with SS304 tool using B_4C abrasive particle by USMM. The most favourable configuration is identified as follows: an abrasive slurry concentration of 23.43%, a power rating of 290 W, and a tool feed rate of 0.80 mm/min. This arrangement yields the highest Material Removal Rate (MRR) at 0.2008 mm3/min. Furthermore, it results in the lowest overcut measurement of 50.29 µm and the most minimal taper angle of 0.7880^0.

(vi) The experiments are conducted at optimal process parametric settings to generate micro hole on quartz with SS304 tool using B_4C abrasive particle by USMM and the percentage of errors based on the results of actual and predicted values of responses for single objective as well as multi objective optimization lie within 5%. Therefore, the results are quite adequate and acceptable.

(vii) One of the significant contributions of the present research is generation of multiple micro channels on quartz. Multiple micro channels on quartz has been successfully produced by ultrasonic micromachining process utilizing developed multi tips micro tool. Micro USM process parameters have a significant effect on MRR, width overcut, taper angle and surface roughness. The aspect ratio of micro channel has been obtained as 3. The lesser width overcut of micro channel is obtained as 16 μm at slurry flow rate of 60 ml/sec. The lesser value of taper angle obtained is obtained as 1.31^0 at lower tool feed rate. The lower value of surface roughness, R_a is obtained as 3.657 μm at lower abrasive slurry concentration. Based on SEM micrographs, some phenomenon such as micro chipping and edge chipping is also observed at bottom surface and both sides of entrance surface of the machined micro channels.

(viii) Multiple micro-channels are also successfully fabricated on zirconia by micro ultrasonic machining process utilizing developed multi tips micro tool and can be considered as a major contribution of the present research. The aspect ratio of micro channel has been obtained as 3. From the experimental result it can be observed that best width overcut of micro channel is obtained as 26 μm at tool feed rate of 0.8 mm/min. The lesser value of taper angle is obtained as 0.931^0 at lower tool feed rate. The lower value of surface roughness, R_a is obtained as 3.117 μm at lower slurry flow rate. The machined surface topography consists of the alteration such as edge chipping, micro-cavities, micro-crack on the surface at high power rating as observed through SEM micrographs.

(ix) Array of square micro holes are successfully fabricated on quartz by ultrasonic micromachining process utilizing developed multi tips square micro tool and can also be considered one of the significant contributions of this investigation. From the experimental result, it has been observed that lower width deviation of micro holes is obtained as 37 μm and lower taper angle is 1.109^o at 5 % abrasive slurry concentration. The lower value of angular deviation is obtained as 0.836^o at lower power rating. The higher MRR is obtained as 1.427 mm^3/min at 25% abrasive slurry concentration. Based on SEM micrographs, it can be observed that the machined surface topography consists of the alteration such as edge chipping, shallow micro dent at bottom surface, at high power rating.

Table 8.1 Comparison of performance USMM of quartz and zirconia

Responses	**Quartz**	**Zirconia**
Higher MRR	5.48 mm^3/min	3.97 mm^3/min
Lower width overcut	16 μm	26 μm
Lower taper angle	1.31^0	0.93^0
Lower Surface roughness	3.657 μm	3.117 μm

The author has made sincere efforts to present the research work by exploring the machining of quartz and zirconia for generation of micro holes, micro channels, and array of square micro holes on quartz as well as zirconia utilizing cylindrical shaped and multiple tips micro tools. Table 8.1 shows the comparison of performance of USMM for generation of micro channel on quartz and zirconia. This experimental investigation and discussion will be useful to researchers, scientists as well as engineers who are working on ultrasonic machining in micro domain with different hard and brittle materials. It can also provide direction for development of micro tools for ultrasonic machining for industrial applications in micro domain and also for fabrication of different complex micro features on various hard and brittle materials, which have prospective applications in biomedical science, micro fuel cell and cooling of components of micro electronics, micro-electro-mechanical system (MEMS), optical interconnection, inkjet printer, aerostatic air bearing system etc..

8.2 Future scope of research work

The outcomes of this current research endeavour are anticipated to introduce novel perspectives and avenues for both foundational and practical investigations within the realm of ultrasonic micromachining and also improve accuracy and productivity of the ultrasonic micromachining system. However, from the experimental investigations, author feels that there are few aspects which need to be taken up as future scope of research which are follows:

(i) To developed complex micro tool for fabricating complex micro features on quartz, zirconia and other ceramic as well as ceramic composites.

(ii) Mathematical model on economic analysis for productivity can also be developed during micro-USM using multi tips tools for generation of array of micro-hole.

(iii) Models on tool wear during ultrasonic micro machining with single as well as multiple tips micro tool can be developed for further improvement of machining accuracy.

(iv) By design modification of micro tools as well as developing specialized micro tool with wear resistance coating for further improvement of accuracy, surface finish and reduction of surface damages may be achieved to extend the scope of USMM in various industries for micro engineering applications.

However, the author believes that the present set of experimental investigation and subsequent analyses will furnish valuable and technical insights for researchers, scientists, and engineers actively engaged in the domain of ultrasonic micromachining (USMM) processes. These findings hold the potential to guide the progression of USMM techniques and the development of micro tools for intricate micro feature generation on different ceramics as well as metal matrix composites which are highly demanded in micro engineering applications for modern manufacturing industries.

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Micro hole fabrication on quartz using ultrasonic micromachining process

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Abstract: Ultrasonic micromachining (USMM) has immense potential for micro-machining on quartz which is used in different field of applications such as optics, metrology and micro electro mechanical system (MEMS) etc. In this paper the influences of process parameters such as power rating, abrasive slurry concentration and tool feed rate on material removal rate (MRR), overcut and taper angle of the micro hole on quartz by USMM have been investigated. Stainless steel of grade 304 has been selected as the micro-tool material for ultrasonic micro drilling on quartz. The higher value of MRR of 0.4235 mm/min has been obtained at power rating of 400 W, abrasive slurry concentration of 40% and tool feed rate of 1.2 mm/min. The lower value of overcut of 55 μm and taper angle of 0.600 of micro hole have been obtained at abrasive slurry concentration of 20%, power rating of 300 W and tool feed rate of 1 mm/min.

Keywords: USMM; ultrasonic micromachining; quartz; MRR; material removal rate; overcut and taper angle.

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Experimental investigation into Micro Ultrasonic Machining of Quartz

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Abstract. Quartz has been broadly applied in industries including electronics, optics, micro electromechanical system (MEMS), biomedical. Micro ultrasonic machining (Micro USM), is a non traditional micro machining technique, extensively used to produce micro features and parts on quartz, silicon, ceramics and glass. A micro tool of stainless steel having diameter 330µm has been develop for generating micro hole on quartz. Experiments have been done by using different types of abrasives like boron carbide, silicon carbide and aluminum oxide of average grain size 14 µm. Experiments have been performed under different parametric setting of tool feed rate and power rating. The range of tool feed rate is 0.8 to 1.1 mm/min. The range of power rating is 200 to 500 W. Micro hole has been generated on quartz. Overcut and taper angle has been considered as response of micro ultrasonic drilling. In the present research effect of tool feed rate and power rating on taper angle and overcut has been investigated while using different type of abrasives.

1. Introduction

Quartz is widely applied in industries including electronic, optics, micro electro mechanical system (MEMS) and biomedical etc. Due to hard and brittle nature, quartz is difficult to machine. This material is machined by non-traditional technique of machining. Due to non-conducting in nature, it is not machined by ECM, EDM etc. Micro ultrasonic machining (Micro USM) is a nontraditional micro machining process; employ to produce micro features on hard and brittle materials like quartz, silicon and glass and its parts [1]. The advantages of micro USM are no thermal injury to the workpiece and no limitation by the electrical or chemical aspects of workpiece materials [2]. A tool vibrates at ultrasonic frequency with low amplitude. In micro USM, the material is removed by the shock of abrasive grains with high kinetic energy generated by the vibration of an acoustic system. The objectives of this paper are to investigate micro hole characteristics such as overcut and taper angle produced by micro-USM using simple cylindrical shape micro-tool.

Some research work have been performed on ultrasonic machining on different materials but still more in depth studies are very much needed to explore the micro ultrasonic drilling on quartz materials. The machined surface roughness varies on depth of cut. Low surface roughness was obtained when low depth and the small size abrasive particles are used [3]. Micro drill produces on borosilicate glass by USM. The MRR mainly depends on static load while tool wear rate depends on abrasive size [4]. In micro-USM, material removal is decided by the workpiece crack propagation and abrasive particle wear. By using harder and spherical abrasive bigger chip removal occur [5]. During quartz machining by USMM process, slurry concentration is a great influenced compare to power

Chapter 46
Parametric Optimization of Micro Ultrasonic Drilling of Quartz Based on RSM

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Abstract Micro ultrasonic machining is the process for micro hole drilling on hard and brittle materials like ceramic, glass, quartz, silicon, etc. Quartz has wide applications in microelectromechanical systems (MEMS), lenses, pressure and flow sensors, and micro-optical systems. In the present research work, optimization of the process parameters for responses such as material removal rate, overcut, and taper angle during micro ultrasonic drilling has been performed utilizing the developed empirical relationship between the responses and process parameters. Three different process parameters— power rating, abrasive slurry concentration, and tool feed rate were considered for this experimental investigation. The parametric studies have also been made based on response surface plot. Based on multi-objective optimization, optimal parametric setting for maximum material removal rate, minimum overcut and minimum taper angle have been obtained.

Keywords Micro ultrasonic machining · Quartz · Material removal rate · Overcut · Taper angle · Optimization

46.1 Introduction

The employment of hard and brittle materials has been increased largely in industrialized fields such as the optical component, aeronautic, automotive, and semiconductor sector, for uniqueness. The uniqueness of hard and brittle materials, including their high hardness, high strength at superior temperatures, high heat resistance, low wear rate, and lightweight in comparison to metals [1], are precious in the making of meticulousness mechanical equipment. Yet, the machining of these materials leftovers pose a big for this superior uniqueness. For these materials, it is not easier to make tools that can machine with no compromise in profile accuracy.

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Strategies for Improving Performance of Ultrasonic Micromachining Process

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Abstract Advanced materials are not easy to machine due to technological and industrial development and which discover extensive applications in nuclear engineering, aviation industries, etc. The manufacture of complex shape with high-quality surface finish and superior accurateness can be easily obtained by nonconventional machining processes. This manuscript covers the significant issues about the performance improvement of ultrasonic micromachining process. This book chapter also focuses on accuracy of ultrasonic micromachining process with process development. The two types of ultrasonic micromachining processes, i.e., stationary USM and rotary USM, are also discussed. Novel development for accuracy on ultrasonic micromachining (USMM) process has been emphasized and discussed. Strategies for development of ultrasonic micromachining system for performance enhancement are discussed for both stationary and rotary ultrasonic micromachining in this chapter. Micro-type tools developments for ultrasonic micromachining process with various strategies have been presented. In this section, influences of process parameters of USMM on different responses have been studied.

Keywords Ultrasonic micromachining · Transducer · Horn · Micro-tool · Taper angle · Micro-channel

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Effect of Process Parameters on Accuracy of Holes Drilled on Quartz by Micro-USM

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1 Introduction

Ultrasonic micro machining (USMM) is an abrasive-based method, which is applied to conductive and non-conductive hard and brittle materials like glass, quartz and advanced ceramics to create through holes and different micro features. Abrasive slurry is disbursed into the work surface, where micro tool tip is ultrasonically vibrated. When the free abrasive particles come at the tool–workpiece interface, they get energized through the aid of ultrasonic vibration in the down stroke of tool tip and ultimately remove materials through fatigue failure. Various micro machining technologies are available for producing micro features. But, other process like micro-EDM and micro-ECM is not appropriate for electrically non-conductive materials. Using micro laser beam machining method, hard and brittle materials can be machined but due to thermal process, it can source thermal spoil to machined features of the job material [1, 2]. Unlike laser beam machining, USMM neither thermally spoils the work material nor produces significant levels of stresses. USMM is therefore suitable in machining fragile components of hard and brittle materials, where it is essential to reduce stresses or thermal distortions. It is also not a chemical and electrical process; so there is no change in chemical or physical properties of the workpiece.

For watch making industry, microfluidic, optical applications, there is need of generation of micro 3D features on materials like glass, quartz, etc. Ultrasonic micro machining is a promise technique for these applications [3]. Technique for measurement and also theoretical model to estimate the micro tool wear had been proposed [4, 5]. The mechanism of material removal in micro-USM was in both ductile and brittle manner [6]. Tool wear is a major issue in USMM, because it has an impact on

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Experimental Investigation into Ultrasonic Micromachining on Quartz

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ABSTRACT

Ultrasonic micromachining is one of the most efficient method for machining hard, brittle and nonconductive materials, such as ceramics, glass, quartz and silica etc. In this methd, most of the material removed through the impact of abrasive particles under ultrasonic vibration. Quartz is an extremely versatile material used in different applications including lenses, mirror substrates, crucibles, UV transmitting optics, IR transmitting optics, Metrology components and MEMS etc. Stainless steel of grade 304 was selected as micro-tool material. This paper includes the development of micro tool used for ultrasonic micro drilling on quartz. In this present research, machining criteria like material removal rate (MRR), overcut and taper angle are considered as machining performance criteria during ultrasonic micromachining (USMM) of quartz. Three process parameters such as power rating, abrasive slurry concentration and tool feed rate were considered for this experimental investigation. The significant parameters were identified and their effects on material removal rate, overcut and taper angle of micro hole on quartz by micro-USM were investigated.

1. Introduction

Miniaturized components and products are highly demanded in the present days because of their unique advantages such as less space requirement, less energy and material consumption, easiness in carrying, and/or handling and can be cheaper. The growth of Micro Electro Mechanical Systems (MEMS) and the related research in different industries such as electronics, optics, medical, biotechnology, automotive, communications, and avionics are largely attributed to these micro components. But product miniaturization with multiple features demands innovative research in micro-machining technologies to ensure the processing of a wide range of materials [1]. Micro-structures, micro-parts, and micro-products are in ever increasing demand in a number of areas, including the electronics, optical, medical equipment, automotive, and communications industries. Hard and brittle materials such as ceramics, glass, and quartz etc. are used in the manufacture of these products because of their high strength-to-weight ratio, heat and corrosion resistance, shock resistance, and erosion resistance [2]. Micro-electric discharge machining and micro-electrochemical machining are unsuitable because these materials are non-conductive. Up to now, ultrasonic micro machining and micro-laser beam machining have been the two major methods for processing hard and brittle materials, but micro-laser beam machining is a thermal process and can cause thermal damage to processed surface of the workpiece.

Ultrasonic micromachining (USMM) is the process which is popular for micro-machining of hard and brittle materials such as silicon, glass, ceramics and quartz. It is a purely mechanical process based on abrasive material removal and applicable to both conductive and non-conductive materials. The USMM requires micro sized tool, smaller amplitude of impact and micro-sized abrasive particles [3].

The USMM employs the mechanical vibration of ultrasonic frequency within the range of 20 to 40 kHz. The tool is mechanically vibrated at an ultrasonic frequency and amplitude of few micrometers. The abrasive slurry, a mixture of sharp edge fine abrasive particles of size 24 µm, and a liquid medium is fed into the gap between the tool and workpiece. As the vibrating tool head hits the free abrasives in the slurry, they attain momentum and impact upon the target workpiece location. A localized fatigue stress is developed in the impact zone owing to repetitive impact, and micro chipping occurs resulting in material removal. Moreover, a small amount of material removal might also be contributed by the mechanical abrasion of the hard micro-abrasives. Further, implosion of the gas bubbles, also called cavitations, can play a key role in material removal at micro level. Although water is usually preferred as the slurry medium, there exists a possibility that the chemical impurities present in the slurry medium can selectively cause instantaneous degradation of the work material resulting in loss of material. A continuous supplies of slurry flushes away the debris from the machining zone and refills the gap with fresh slurry.

Guodong Lia et all discuss the mode of material removal according to the surface roughness of the machined surface of quartz crystal by using Polycrystalline diamond (PCD) Powder with Tungsten tool material which is costly [4]. U-shaped and ⊔-shaped microfluidic channels and also deep holes and microfluidic channels with a high slenderness ratio (width/depth) can be obtained by using micro ultrasonic machining technology. [5]. Drilling operation by micro USM has been successfully applied on borosilicate glass. Some

Parametric Analysis on Ultrasonic Micro Machining of Quartz

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Abstract

Ultrasonic micromachining (USMM) is a non-conventional mechanical material removal process which is extensively applied for generating micro features on parts of hard and brittle materials such as silicon, glass and quartz. The advantage of ultrasonic micromachining is that there is no thermal damage to the work-piece and there is also no limitation due to electrical or chemical properties of substrate materials. Quartz has been widely useful in industries such as optical, communication, high quality imaging system, beam wave front measurements, multiple beams shaping etc and the market for quartz components is vast. Being hard and brittle material, quartz is difficult to machine. USM process is able to make micro hole on quartz of thickness 1mm. A micro tool of stainless steel having diameter 330µm has been utilized for USM process for micro drilling operation. Experiments have been done by using different types of abrasives like boron carbide, silicon carbide and aluminum oxide of average grain size 15µm. Experiments have been performed under different parametric setting of abrasive slurry concentration, power rating and tool feed rate. The abrasive slurry concentration varies from 10 to 40 % by weight, power rating from 200 to 500 W and tool feed rate from 0.8 to 1.1 mm/min. Micro hole has been generated on quartz and volumetric material removal rate have been considered as response of ultrasonic micromachining. The effects of various types of abrasives, slurry concentration, power rating and tool feed rate on volumetric material removal rate (MRR) have been analyzed in this present research.

Keywords: Ultrasonic micromachining, quartz, MRR, micro hole, Boron carbide, silicon carbide and aluminum oxide.

1. INTRODUCTION

Hard and brittle materials like quartz, glass, silicon, and ceramics are progressively used in MEMS because of their material properties such as resistance to high temperature, chemical erosion and wear. Most of the nontraditional machining processes have difficulty in machining these materials. Micro Electrical discharge machining (µEDM) and electrochemical micromachining (EMM) are not used for machining these materials because of most of these hard and brittle materials are not electrically conductive. Cracks are easily formed when machined by laser beam due to thermal effects of laser beam machining. Ultrasonic micromachining (USMM) is one of nontraditional micro machining process, which is mainly used to machine hard and brittle materials. Ultrasonic micromachining (USMM) is the downscaling of conventional USM for generation of micro features by utilizing micro sized tool and fine abrasive particles of micrometer even nanometer order for achieving very good surface finished and high accuracy [1].

The trend towards miniaturization of industrial products is inevitable. This trend is presently realized in light weight, miniaturized products of high functionality. Quartz is extensively used in resonators, filters and sensors, optical instruments, semiconductors and precision equipments because of its exceptional properties like transmission ability in both ultraviolet and infrared spectra, good corrosion resistance, high compressive strength, and excellent wear resistant properties. [2-4].

In ultrasonic machining, the material is removed due to erosion by impacting abrasive particles at an ultrasonic frequency. In Ultrasonic micromachining, micro features can be generated using easy shaped micro tools [5]. The ultrasonic machining result from the conversion of high frequency electrical energy into mechanical longitudinal vibrations, which is transmitted via a horn to the cutting tool and the abrasive slurry is fed between the tool and the workpiece. The frequency of tool Vibration is generally set at 20 kHz. The tool is fed into the workpiece under a constant static load and accelerates the abrasive particles against the workpiece surface at high velocity, causing them to erode the material from the workpiece material by micro chipping, leaving a precise reverse form of the tool shape. The fundamental mechanisms of the micro chipping action in ultrasonic micromachining have been well-known to be mainly localized hammering and free impact by abrasive grains in the slurry. Cavitation can also occur during material removal. Sometimes, it is possible to assist the mechanical erosion due to the presence of an aggressive slurry medium inducing chemical effects accompanying the hammering process.

Z. Yu et al. studied the influence of machining parameters on the performance and reported that the machining speed was decreased after the application of a certain value of static load, similar to the phenomena in macro USM. The debris accumulation was identified as the dominant reason, which caused a part of static load to be consumed in impacting the debris instead of the abrasive particles [6]. A. Schorderet et al. reported that the net machining speed was evaluated for a wire tool and a twist drill with two different diameters (100 and 200 µm). The results showed that the use of twist drill as micro tool to drill deep holes with a constant speed. With cylindrical WC tools, the speed obtained at the start of the drilling is almost 6 times higher than the average drilling speed [7]. S. Cherku et al. presented the results of micro ultrasonic machining using oil based abrasive slurry and reported that machining with water based slurry is suitable only for finer particles sizes with higher concentration or medium particles sizes with medium concentration or coarser particle sizes with lower particles where as machining with oil based slurry is always suitable for all the particle sizes with low concentration and also concluded that machining with oil based slurry gives good surface finish compared to the water based slurry [8]. Sandeep Kuriakose et al. investigated for the machining of micro features on metallic glass by micro hole drilling operation using micro-USM and reported that micro-USM can be used to machine micro holes in metallic glass in room temperature without any heat generation

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Parametric Optimization of Micro Ultrasonic Drilling of Quartz Based on RSM

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Abstract

Micro ultrasonic machining is the process for micro hole drilling on hard and brittle materials like ceramic, glass, quartz, silicon etc. Quartz is a material that has a wide application such as micro-electromechanical systems (MEMS), lenses, mirror substrates, metrology components, pressure and flow sensors and micro optical systems. In the present research work, optimization of the process parameters for responses such as material removal rate, overcut and taper angle during micro ultrasonic drilling has been performed utilized the developed empirical relationship between the responses and process parameters. Three different process parameters- power rating, abrasive slurry concentration and tool feed rate were considered for this experimental investigation. The parametric studies have also been made based on response surface plot. Based on multi objective optimization, optimal parametric setting for maximum material removal rate, minimum overcut and minimum taper angle has been obtained as abrasive slurry concentration of 23.43 g/lit, power rating of 290 W and tool feed rate of 0.80 mm/min.

Keywords: Micro ultrasonic machining, Quartz, material removal rate, overcut, taper angle, optimization.

1. INTRODUCTION

The use of hard and brittle materials has been increased largely in industrial fields such as the optical component, aerospace, automotive and semiconductor industries, because of their unique properties. The uniqueness of hard and brittle materials, including their high hardness, high strength at elevated temperatures, high heat resistance, low wear rate, and light weight in comparison to metals [1], are valuable in the production of precision mechanical equipment. However, the machining of these hard and brittle materials still remains a great challenge because of this superior uniqueness. For these materials, it is difficult to make tools that can machine without any damage from the cutting edge and to produce high accuracy on the machined surface. Due to electrically nonconductivity combined with high hardness, brittleness and chemical inertness of quartz materials there is difficulties for micro-machining of quartz for achieving accurate micro hole with less overcut and large MRR.

Micro ultrasonic machining (micro-USM) is the emerging and effective machining technology among all the mechanical energy based micromachining technique to generate micro features with high aspect ratio in these hard and brittle materials such as quartz, silicon, glass and ceramics [2-5]. In micro USM, the material is removed by the impact of solid abrasive particles into the workpiece with ultrasonic vibration. Micro USM has been used to drill micro holes in micro products and components of quartz. There is a strong demand for miniaturized components from diverse industries such as electronics, optics, medical, biotechnology, automotive, communications, and avionics industries where micro-USM can be applied for micro machining.

Generally, material removal rate in micro-USM increases with the increase in the size of abrasive particle for both aqueous abrasive slurry and oil based abrasive slurry, but material removal rate is higher using aqueous abrasive slurry medium [6]. Micro USM has been successfully applied to drill borosilicate glass. The MRR is most influenced by static load while abrasive size mainly affects the tool wear rate (TWR) [7]. The machining speed has been decreased after a certain value of static load, similar to the phenomena in macro USM. The debris accumulation was identified as the dominant reason, which caused a part of static load to be consumed in impacting the debris instead of the abrasive particles [8]. The net machining speed was evaluated for a wire tool and a twist drill with two different diameters (100 and 200 μm). The twist drill as micro tool is useful to drill deep holes with a constant speed. With cylindrical WC tools, the speed obtained at the start of the drilling is almost 6 times higher than the average drilling speed [9]. Performance of ultrasonic micro machining is very much influenced by abrasive slurry concentration compared to power rating and tool feed rate during the generation of micro hole on quartz [10].

It has been analyzed from the previous published works that the performance of micro-USM has to be optimized to enhance the ability of micro machining of quartz. The present research work is to establish the empirical model between machining performance and convenient machining parameters such as power rating; abrasive slurry concentration and tool feed rate using response surface

Experimental investigation into Micro Ultrasonic Machining of Quartz

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Abstract. Quartz has been broadly applied in industries including electronics, optics, micro electromechanical system (MEMS), biomedical. Micro ultrasonic machining (μUSM), is a mechanical material removal process, extensively used to produce micro features and parts on quartz, silicon, ceramics and glass. A micro tool of stainless steel having diameter 330μm has been develop for generating micro hole on quartz. Experiments have been done by using different types of abrasives like boron carbide, silicon carbide and aluminum oxide of average grain size 14 μm. Experiments have been performed under different parametric setting of power rating and tool feed rate. The power rating varies from 200 to 500 W and tool feed rate from 0.8 to 1.1 mm/min. Micro hole has been generated on quartz. Overcut and taper angle has been considered as response of micro ultrasonic drilling. In the present research effect of power rating and tool feed rate on overcut and taper angle has been invstigated while using different type of abrasives.

Keywords: Micro ultrasonic drilling, Quartz, overcut, taper angle.

1. Introduction

Quartz is widely applied in industries including electronic, optics, micro electromechanical system (MEMS) and biomedical etc. Due to hard and brittle nature, quartz is difficult to machine. This material is machined by non-traditional approaches. Due to non-conducting in nature, it is not machined by ECM, EDM etc. Micro ultrasonic machining (μUSM) is a mechanical material removal process, utilized to produce micro features on parts of hard and brittle materials such as quartz, silicon and glass [1]. The advantages of micro USM are no thermal damage to the work-piece and no limitation by the electrical or chemical characteristics of substrate materials [2]. A tool vibrates at a frequency of 20 kHz with amplitude of 25 μm. In μUSM, the material is removed by the impact of abrasive grains to with high kinetic energy generated by the ultrasonic vibration of an acoustic system. The objectives of this paper are to investigate micro hole characteristics such as overcut and taper angle produced by μ-USM using simple cylindrical shape micro-tool.

Generation of micro channel on Quartz by micro-USM process

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Abstract: Hard and brittle materials such as quartz, glass and ceramics have exceptional thermal, chemical and wear resistant properties. Fabrication of micro features to these materials is not easy by conventional machining process. Micro ultrasonic machining process is suitable for machining these hard and brittle materials. Multi tool has been developed for fabrication of micro channel on quartz by micro ultrasonic machining process. Micro channel has been broadly used in micro fluidic, micro reactors, micro mixers and micro sensor etc. Experiments have been done on micro-USM by using multi tool and SiC abrasive of average grain size 4 μm. The different input parameters such as power rating, abrasive slurry concentration; tool feed rate and slurry flow rate are varied to investigate the effects of process parameters on width overcut of micro channel on quartz.

Keywords: *Micro USM, multi tool, Quartz, micro channel, Width overcut, SiC.*

1. Introduction

Hard and brittle materials such as quartz, glass and ceramics have exceptional thermal, chemical and wear resistant properties. They also have broad applications in MEMS and micro product such as micro-fluidic, micro-reactors, micro-mixers and micro sensor. Machining of these materials is difficult by conventional machining process. Chemical processes such as lithography and etching are costly. Micro-ECM and micro-EDM have limitations to machine these materials because these are electrically non-conductive in nature. Micro-USM process is convenient for machining these materials [1]. The variations of machining various shape through micro ultrasonic machining has been investigated by various researchers [2-4]. Micro-channel can be simply fabricated by using cylindrical μ-tool in micro ultrasonic machine [5]. Micro channels are used in micro-fluidic devise like micro-fluidic chip for mixing and transportation for liquids [6].

Micro ultrasonic machining becomes an essential for micro-channel fabrication. However, the development of micro tool for fabrication of micro-channel in ultrasonic machining is a challenging task. The generation of multiple micro-channels in micro USM with a single tool is very much needed to reduce the time and to increase the productivity. So, using of multi tools to produce multiple micro-channels in a single machining is a best choice.

In the present study integrated multi tools are used for fabrication of micro channel. The variation of width overcut of micro channels with process parameters such as power rating, abrasive slurry concentration; tool feed rate and slurry flow rate have been investigated and discussed.

2. Experimental Setup and planning

The micro ultrasonic machining setup consists of various basic components which are tool vibration unit, power supply, controller, micro-tool assembly and abrasive slurry supply unit. Experiments were conducted on “AP 1000 sonic mill” ultrasonic machine. Figure 1 shows the schematic diagram of micro ultrasonic machining system. In micro USM, transducer is used to convert electrical energy into mechanical ultrasonic vibration. This ultrasonic vibration of micro-tool is then move to the abrasive particle. The abrasive slurry is supplied between micro-tool and workpiece. Micro-tool is vibrating at ultrasonic frequency (20 kHz) with low amplitude value (25 μm).

For micro-tool fabrication, SS304 (stainless steel) is used because it is extremely efficient for micro USM which is not hard but tough. It is also easily available and less expensive. Figure 2 shows the CAD model of micro tool. This micro-tool has been developed with the help of wire-EDM process. This micro-tool has been silver brazed on hexagonal bolt and mounted to horn. Quartz material has been used as workpiece on which micro channel are generated. Quartz has been paste on the fixture made of mild steel and fixed on the magnetic base. Silicon carbide has been used as abrasive which is mixed with water and continuously supplied during machining. For this investigation multi-tool is used for generation of micro channel. Each experiment has been conducted for three

Effect of process parameters on accuracy of holes drilled on quartz by micro-USM

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Abstract. Ultrasonic micro machining (USMM) is well known abrasive based method, which is applied to numerous conductive and non-conductive hard and brittle materials like glass, quartz, advanced ceramics for producing through holes and different 3D intricate parts. In USMM, micro hole can be generated using cylindrical shaped micro tools. For watch making industry, micro fluidic, optical applications, there is requirement of generation of micro 3D feature on hard and brittle materials like glass, quartz. Ultrasonic micro machining is a promising technique for these applications. SS304 (Stainless steel) was chosen for micro-tool material. Three different types of abrasives (B_4C, SiC and Al_2O_3) were taken for experimental analysis. Machining criteria like overcut and taper angle are analyzed during ultrasonic micro hole drilling on quartz. For this experimental analysis, variable process parameters such as abrasive slurry concentration and slurry flow rate were taken into account. The effects of process parameters on overcut and taper angle of µ-hole drilled on quartz by micro-USM were investigated.

Keywords: Ultrasonic machining, Micro-hole drilling, Quartz, Micro tool, Overcut, Taper angle

1. INTRODUCTION

Ultrasonic micro machining (USMM) is an abrasive based method, which is applied to conductive and non-conductive hard & brittle materials like glass, quartz, advanced ceramics to create through holes and different micro features. Abrasive slurry is disbursed into the work surface where micro tool tip is ultrasonically vibrated. When the free abrasive particles come at the tool–workpiece interface, they get energized through the aid of ultrasonic vibration in the down-stroke of tool tip and ultimately remove materials through fatigue failure. Various micro machining technologies are available for producing micro features. But, other process likes micro-EDM, micro-ECM are not appropriate for electrically non-conductive materials. Using micro laser beam machining method, hard and brittle materials can be machined but due to thermal process and it can source thermal spoil to machined features of the job material [1, 2]. Unlike laser beam machining, USMM neither thermally spoil the work material nor produce significant levels of stresses. USMM is therefore suitable in machining fragile components of hard and brittle materials, where it is essential to

Experimental Investigation into micro-ultrasonic machining of zirconia using multiple tips micro-tool

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Abstract

The usage of micro products has grown significantly over the past ten years in a variety of industries, including engineering, automotive, health care, and electronics. Materials that are hard and brittle is frequently used to make microproducts like microreactors, microfluidic devices etc. Micro ultrasonic machining (μ-USM) is most excellent micro machining process to produce micro features on ceramic materials. The multiple tips micro-tool has been fabricated to generate multiple micro-channel on zirconia by μ-USM process. The effect of process parameters such as power rating, abrasive slurry concentration, tool feed rate and slurry flow rate on width overcut and material removal rate (MRR) of micro channels generated on zirconia were investigated. By using multiple tips micro-tool, micro-channels were produced using μ-USM which increases productivity of μ-USM. The higher value of MRR and lower width overcut achieved as 3.970mm^3/min and 26μm respectively during multiple micro channel fabrication.

Keywords: μ-USM, Zirconia, MRR, Width overcut, Micro-channels, Multiple tips micro-tool

1. Introduction

Over the past ten years, the use of micro products in industries such as engineering, automotive, health care, optical components, and electronics has rapidly increased [1]. The micro products like micro reactors, micro fluidic devices etc are commonly made of hard and brittle materials like ceramics, glass, silicon etc. Due to their exceptional qualities, including strong corrosion resistance, high hardness, high strength, wear resistance, and high thermal resistance, these materials are ideal for the aforementioned product [2]. Because of these characteristics, these materials are particularly challenging to process. μ-USM is the most excellent micro machining technique for producing miniature features on fragile and hard materials. The ability to process both conductive and nonconductive materials is μ-USM's main benefit. μ-USM is quite same to the USM except the tool tip dimension, abrasive size which are used into micron range [3]. A vibrating micro tool is used in this procedure to repeatedly pierce the work surface as abrasives constantly flow through the machining zone. The mechanical, chemical, and physical properties of the workpiece material are not altered, just like in other micro machining methods including electric discharge machining (EDM), electro chemical machining (ECM), and laser beam machining (LBM). Due to the fact that this procedure does not need a clean room environment, it is also a cost-effective method for micro-machining extremely hard and brittle materials.

The micro-diamond tools have been developed using electroless composite plating and further micro-machining operation performed on silicon to observe the tool life [4]. Ultrasonic machining has been utilised to generate hexagonal hole on alumina ceramic and also find the optimum parametric combination [5]. Ultrasonic machining has been utilised to generate stepped hole on zirconia ceramic and develop the mathematical model [6]. Longitudinal-torsional coupled rotary ultrasonic machining to generate the hole on ZrO_2 ceramics to investigate the cutting force and machined surface roughness [7]. Micro hole and 3D micro cavity generated on silicon generated by micro USM also applying the tool wear compensate method to reduce the tool wear and accuracy of hole [8]. Three advanced ceramic materials (silicon carbide, zirconia, and alumina) are used for drilling operation by using ultrasonic machining. The tool of stainless steel (diameter 0.7 mm to 3 mm) was used to observed the hole integrity at entrance of hole [9]. The MRR achieved during micro channel generation on glass by rotary ultrasonic machining at optimal condition was 1.30 mm^3/min. The tool used for this experiment was tungsten carbide of 600 μm [10].

The current work, multiple tips micro-tool has been developed by using wire-cut electro discharge machining (W-EDM) for generation of multiple micro-channels on zirconia materials. The fabrication of micro channels using single tip micro-tool of circular cross section is taking more time for generation of multiple micro-channels. It also hampers the accuracy of micro-channels by repetition of same tool during successive machining and also due to tool wear. To solve this problem multiple tips micro tool has been designed and developed by wire-EDM process. By using multiple tips micro tool productivity can be increased in μ-USM for micro channel fabrication. The effect of process parameters such as power rating, abrasive slurry concentration, tool feed rate and slurry flow rate on width overcut and material removal rate (MRR) of multiple micro-channels generated on zirconia were investigated.

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