EXPERIMENTAL INVESTIGATIONS INTO ULTRASONIC MICRO MACHINING OF QUARTZ MATERIALS

By

BHAGABATI HANSDA

B.Tech. (Mechanical Engineering), 2013

KALYANI GOVERNMENT ENGINEERING COLLEGE

EXAMINATION ROLL NO – M4PRD1604

THESIS

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF MASTER OF PRODUCTION ENGINEERING IN THE FACULTY OF ENGINEERING & TECHNOLOGY, JADAVPUR UNIVERSITY

2016

DEPARTMENT OF PRODUCTION ENGINEERING

JADAVPUR UNIVERSITY

KOLKATA-700032

INDIA

JADAVPUR UNIVERSITY
FACULTY OF ENGINEERING AND TECHNOLOGY

Certificate of Recommendation

I HEREBY RECOMMEND THAT THE THESIS ENTITLED **"EXPERIMENTAL INVESTIGATIONS INTO ULTRASONIC MICRO MACHINING OF QUARTZ MATERIALS"** SUBMITTED BY **BHAGABATI HANSDA** MAY BE ACCEPTED IN THE PARTIAL FULLFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF **"MASTER OF PRODUCTION ENGINEERING"**.

(Dr. Biswanath Doloi)
Thesis Supervisor
Professor
Dept. of Production Engineering
JADAVPUR UNIVERSITY
Kolkata-700032

(Dr. Debamalya Banerjee)
HEAD, Dept. of Production Engineering
JADAPUR UNIVERSITY
Kolkata-700032

(Prof. Sivaji Bandyopadhyay)
DEAN, F.E.T.
JADAVPUR UNIVERSITY
Kolkata-700032

JADAVPUR UNIVERSITY
FACULTY OF ENGINEERING AND TECHNOLOGY

CERTIFICATE OF APPROVAL*

The foregoing thesis is hereby approved as a creditable study of an engineering subject carried out and presented in a manner of satisfactory to warrant its acceptance as a pre-requisite to the degree for which it has been submitted. It is understood that by this approval, the undersigned do not necessarily endorse or approve any statement made, opinion expressed and conclusion drawn therein but approve the thesis only for the purpose for which it has been submitted.

COMMITTEE ON FINAL EXAMINATION FOREVALUATION OF THE THESIS

____

____

***** Only in case the recommendation is concurred in

ACKNOWLEDGEMENT

I owe a deep debt of gratitude to my thesis advisor **Dr. Biswanath Doloi**, *Professor, Department of Production Engineering, Jadavpur University for his invaluable and untiring guidance, encouragement and supervision, throughout this research work. His effective skill knowledge and experience have made it possible for me to successfully complete the thesis work within the stipulated time. I am very much indebted to him and express my sincere gratitude to him.*

I take the opportunity to express my sincere gratitude to **Dr. D. Banerjee**, H.O.D *of Production Engineering Department, Jadavpur University for his encouragement inspiration and help in every strata of my thesis work.*

Special thanks to Dr. B. Bhattacharyya and Dr S. Chakraborty, Professors, Department of Production Engineering, Jadavpur University, for encouraging and supporting me during my research work.

Special thanks to Santosh Kumar, Research Scholar, Department of Production Engineering, Jadavpur University, for helping, encouraging and supporting me during my research work.

I also take this opportunity to express my gratitude to all the faculty members of Production Engineering Department for their mental support, immense help and co-operation during the course of my research work.

I express my heartiest thanks to Sandip Kunar,Research Scholar, Department of Production Engineering, Jadavpur University, for this useful assistance, co-operation and support.

I also wish to extend my thanks to Mr. Subhrajit Debnath and Mr. Kousik Mishra Research Scholars, and my classmates for providing continuous encouragement throughout the course of present work.

I am also thankful to the librarian and research scholars of Production Engineering Department, Jadavpur University for their cordial assistance.

Special thanks to Mr. Somnath Das for his support and encouragement during my research work.

I thankfully acknowledge the support of all those people, who some time or the other directly or indirectly rendered their help at different stages of this work.

Finally, special thanks to my beloved parents, sisters and brothers as they always stood by me, caring least for the prevalent situation.

(Bhagabati Hansda)

TABLE OF CONTENTS

Chapter-1

Introduction

1. INTRODUCTION

The growth of micro electro mechanical systems (MEMS), Nano electro mechanical systems (NEMS) and the related research in different industries such as electronics, optics, medical, biotechnology, automotive, and communications has largely enhanced the use of newer harder materials & their micromachining technology. Increasing industrial demand for the fabrication of three-dimensional micro-shapes using various materials, many methods have been developed to meet this requirement. These methods include micro-milling micro-cutting, micro-punching, micro EDM, micro WEDG (wire electro discharge grinding), and laser machining and micro-ultrasonic machining etc. However, several materials are still considered as difficult-to-machine materials in the field of micro machining.

Micro-Ultrasonic machining (MUSM) is a unique method as non-conventional machining process for the mechanical machining & generation of micro-features on parts of hard and brittle materials such as glass, ceramics, silicon & quartz. Micro-USM can machine all conductive and nonconductive materials. Furthermore, micro-USM does not cause any thermal or chemical deviation to the workpiece. Micro USM that is nothing but ultrasonic machining at micro level.

USM produces a better precision surface finish compared to other material removal processes however, USM has not been used in the micromachining field because of the difficulties faced in fabricating micro-tools and mounting them on the USM setup & also USM is not capable of drilling micro-holes less than 100μm in diameter due to lack of corresponding co-axial micro tools. In order to overcome these difficulties, intensive research on micro USM is really needed.
In micro USM, it is possible to generate micro features with high aspect ratio in hard and brittle materials like glass, ceramics, composites, quartz and graphite where the other known methods are not successful.

Micro USM can be used to drill micro holes of diameter 5μm in silicon & quartz. These micro holes will meet the requirement of the Integrated circuit packages which are required to hold devices having micro dimensions. The micro holes are also required for various parts including fluidic filters, grids, biomedical filters, ink-jet printer nozzles, fuel injection nozzles, optical apertures, high-pressure orifices, micropipettes, etc.

Now day's quartz material is widely used in electromechanical devices such as resonators, filters and sensors due to its piezoelectric, elastic and mechanical properties. A well known application of quartz is that it is used as an oscillator in electric circuits in watches and computers and also it is used as a membrane in ultrasonic devices. In case of machining of quartz the accuracy is very important because higher accuracy in machining of quartz indicates the good quality of devices, the present research work explores the micro drilling on quartz material by micro USM.

1.1.Types, Properties & Application of Quartz Material

Quartz is a very common mineral, a chemical compound of silicon and oxygen. Silicon dioxide (SiO_2) is commonly called silica. Quartz is an important rock-forming mineral, being a constituent of many common rocks, like granite. Quartz is a term that includes both well crystallized and compact forms of silica. Their common chemical nature was discovered by the Swedish chemist Bergmann at the end of the 18th century, and for some time silica was considered a chemical element. In 1823 his fellow countryman J.J. Berzelius decomposed quartz and discovered it is the chemical compound of oxygen and a new element, silicon.

1.1.1. Quartz classifications of quartz

The crystalline forms are commonly called macro crystalline quartz, while the dense and compact forms are either called cryptocrystalline or microcrystalline quartz. The classification was mostly based on the visual appearance and the possibility to resolve structural elements in an optical microscope.

(i) Macrocrystalline Quartz - varieties that develop visible crystals or are made of large inter grown crystals.
(ii) Quartz - compact varieties made of tiny crystal grains that are visible in an optical microscope.
(iii) Cryptocrystalline Quartz - dense varieties whose structure cannot be resolved in an optical microscope

1.1.2. Properties of quartz

Quartz has several interesting properties those are mentioned follows.

i. Piezoelectricity

Quartz was considered as the first piezoelectric crystal to be used widely. Piezoelectric property of quartz is mainly used to control the frequency of oscillators and to produce very selective filters. This property can be used to both excite and detect mechanical vibrations. This property is conveniently used in microstructures for which the basic component is a resonator. For example, external data (humidity, strength, acceleration etc) can be measured through variation in the frequency of the system. This natural property of quartz makes it superior to silicon for transducer applications.

ii. Mechanical property

It is observed that quartz has high modulus of elasticity and some other mechanical strength. It is also considered as an almost perfectly elastic material.

iii. Chemical inertness

Usually quartz is chemically inert due to its own oxide. Quartz has a low aging rate property. In generally, quartz can only be etched by HF-based etchant and due to this property quartz can be used to the application of chemical sensor or work in harsh environment.

iv. Insulator

Another interesting property of quartz is that it behaves as an insulator. This insulating property of quartz is required in high voltage applications where the breakdown voltage of a standard insulating oxide is exceeded. For examples of such requirement are Electrophoresis and electro-osmotic pumping. Because of this property, quartz has an advantage over silicon for devices in which there is no leakage of current.

v. **UV-Transparence**:

Quartz has UV-transparent properties so that's why quartz is often demanded by biotechnical applications. The transparency property is also important for fluid or particle handling systems.

vi. **Etching anisotropic property**:

The anisotropy of the properties is noticeable in the quartz material. This property is dependent on the crystal orientation. This property would provide the possibility to the fabrication of high aspect ratio microstructure**.**

1.1.3. Application of quartz

Colored quartz varieties have been used for jewelry for ages, but most quartz is used as a component of concrete: quartz sand and quartz gravel.

Pure quartz is needed for producing glass, ceramics, and chemical apparatus. Quartz glass, also known as "fused quartz" or "fused silica" (produced by quickly cooling molten quartz) has a number of interesting properties: its thermal expansion coefficient is very low, it is transparent for ultraviolet light, it is chemically almost inert, and it can form very thin but strong threads used in physical instruments.

A well known application of quartz is its use as an oscillator in electric circuits in watches and computers. Less well known is, for example, its use as a membrane in ultrasonic devices.

Quartz is of course the major "ore" of silicon, used in the integrated circuits or chips of computer. Quartz crystal is widely used in electromechanical devices such as resonators, filters and sensors due to its piezoelectric, elastic and mechanical properties.

1.2. Fundamentals of Micro-USM

The USM process begins with the conversion of low frequency electrical energy to a high-frequency electrical signal, which is then fed to a transducer. The transducer converts high-frequency electrical energy into mechanical vibrations, which are then transmitted through an energy-focusing device, i.e. horn or tool assembly. This causes the tool to vibrate along its longitudinal axis at high frequency. In ultrasonic machining, tool of desired shape vibrates at ultrasonic frequency about 18kHz amplitude 25 to 50 μm and. over work piece. Generally, tool is pressed down with a feed force between the tool and work, machining zone is flooded with hard abrasive particles generally in the form of water based slurry. As the tool vibrates over the work piece, abrasive particles acts as indenter, indent both work, and tool material. As the abrasive particles are indent, the work material would remove the material from both tool and work piece. In general micro USM is carried out with water as the medium due to its properties of excellent coolant, easy removal of debris from machining zone due to low viscosity, low cost and easy availability. The unit removal which is defined as the part of a work piece removed during one cycle of removal action can be realized in μUSM when the submicron particles are available for use as abrasive. In Ultrasonic machining material removal is due to crack initiation, propagation and brittle fracture of material. USM is used for machining hard and brittle materials, which are poor conductors of electricity and thus cannot be processed by electrochemical machining or Electro discharge machining (EDM).

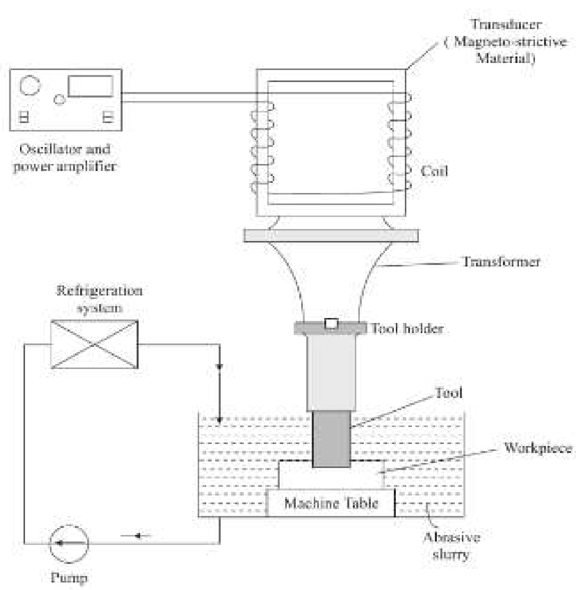

Fig.1.1. Schematic diagram of USM

Fig.1.2. Complete setup of 1000 W of USM

A technological basis to achieve more efficient utilization of the USM process requires an understanding of the mechanism of material removal. The mechanism of material removal in ultrasonic machining process is carried out by four mechanisms:

1) Mechanical abrasion by direct hammering of the abrasive particles against the work piece Surface.
2) Micro chipping by impact of the free moving abrasive particles.
3) Cavitations effects from the abrasive slurry
4) Chemical action associated with the fluid employed

It has been showed that only a small fraction of the material removed is due to the impact to moving grit sand the bulk of the material is removed by the direct impact of the tool vibration following Fig.1.3 represents the mechanism of material removal of USM

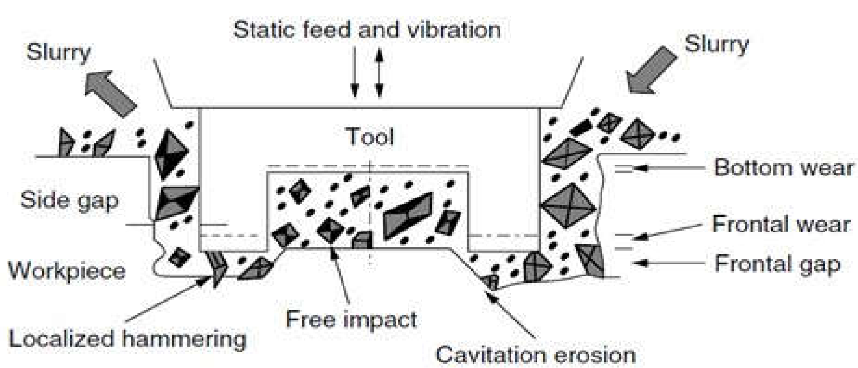

Fig.1.3 Mechanism of material removal of USM

1.3. Need for Micro-Ultrasonic Machining

The process is regarded as competitive only when an operation cannot be practically and economically performed by conventional machining equipment. The ultimate value of USM lies in the ability to do work that cannot be practically accomplished in any other way as the USM is non chemical and non thermal process. USM is used to machine very hard and not easy to machine material by conventional methods. Glass is a material not easy to machine by any means but excellent result has been obtained with the help of ultrasonic machining processing.

1.4. Applications & Advantages of micro-USM

The application of micro-USM is mentioned as follows:

1.4.1. Applications

I. Potential applications of micro-USM with rotated tool include the production of high-aspect-ratio microhole (less than 100μm in diameter) in silicon and glass wafers, which are in great demand for pressure and flow sensors.

II. Various specific applications include drilling small holes in helicopter power transmission shafts and gears, machining of watch bearings and jewels, slicing semiconductor components, for example, cutting circular wafers and drilling small holes in borosilicate glass.

III. Self-aligned multilayer machining and assembly (SAMMA) is a combined machining and assembly method, which specifies that the machining and the assembly of micro parts are fulfilled on the same machine without separate processes. Two 3D micro air turbines made up of three layers have been developed using SAMMA and micro-USM.

IV. Ultrasonic micromachining can also be efficiently used to micro machine as well as micro-polish a tool steel surface with a thermoplastic tool as shown in following Fig.1.4.

Fig.1.4. Micro polished tool steel surface

V. The micro-USM process can be of extremely useful for the semiconductor industry as the industry needs processing of characteristically brittle materials. The applications of the process can also be explored for processing metal-based materials relatively ductile with suitable adaptations which can be of high demand in micro fluidics and heat transfer applications.

VI. With the increased awareness of micro fluidic physics and the surface science of silicon, polymers, glass, and ceramics, these newer and harder work materials are strongly recommended for the micro-electromechanical system (MEMS). All of these micro fluidic systems require the use of micron-sized channels and cavities for liquid or gas delivery and storage. Especially, micro channels and their fabrication technologies are playing an important role in the current development of bio-MEMS. Recently, micro-USM is used to fabricate such micro channels on glass and silicon using a conventional MUSM at 20 kHz with silicon carbide abrasives of 20µm size.

1.4.2 Advantages of micro-USM

The advantages of using the micro USM process over the other micromachining processes are:

a) Complex shape features can be machined using any hard material regardless of the electrical, chemical, or thermal properties of the work piece materials.
b) Since the USM process is a non-electrical and non-thermal machining process, high surface quality micro features can be achieved without surface cracks or thermal damages (e.g. heat affected zone). Moreover, the surface roughness of the machined features is low (down to ~ 0.2 µm) compared to the other micromachining processes.
c) The applied mechanical stress on the work piece surface during machining is low compared to the other mechanical machining processes. Therefore, the produced parts experience fewer residual stresses that lead to more reliable parts.
d) The micro USM is an environmentally friendly process. The micro USM process is also known in different forms of micro machining such as micro ultrasonic assisted lapping, micro ultrasonic impact grinding, and micro ultrasonic drilling.

1.5. Review of the Past Research Work

A lot of research work has already been done in the area of micro USM in different field. Some of the past research related to the present research have been reviewed and discussed herein after

Anjali Gupta et. al. [1] discussed on the potentialities and limitations as well various developments in micro ultrasonic machining method. In this paper the author, gave a brief outlook on the micro USM process, described that with increasing demands for miniaturized products there were a lot of developments in the micro manufacturing methods for the fabrication of the three dimensional micro shapes made up of different materials. Micro ultrasonic machining was a promising technique for the fabrication of micro shapes on the hard, brittle and nonconductive materials like glass, ceramics and silicon with high aspect ratio. Due to its non-thermal, non-electrical and non-chemical nature this process did not change much the physical, chemical or the metallurgical properties of the materials .But the main concern in this process was the difficulty in handling the micro tool due to dynamic nature of the system and hence the accuracy of the set up.

Kai Egashira and Takahisa Masuzawa [2] described that a new method for micro ultrasonic machining (MUSM) has developed. This methods does not allow the vibration of tools, the work piece was vibrated during machining. They said that the greatest advantage of oscillating the work piece instead of tool was that it allows a free tool system design because it does not include the set of transducer, horn and cone. Using this setup, it was possible in machining micro-holes as small as 5μm in diameter in quartz glass and silicon. In this machining range, high tool wear created a problem. To overcome from this problem, they developed sintered diamond tool and it was proven to be effective.

For their experiment they have used tungsten carbide (WC) alloy tool. WC alloy was one of the suitable materials because it can be machined into a small tool of around 5μm diameter and is tough enough to withstand machining load

They also stated that USM has not been used in the micromachining field because of the difficulties faced in fabricating micro-tools and mounting them on the USM setup. Due to this reason, USM has not been used for the formation of micro holes less than Øl00 μm in diameter.

Xi-Qing Sun et. al [3] described that micro ultrasonic machining was a combined machining method for the fabrication of three-dimension (3D) microstructures with high aspect ratio . it is a combination of WEDG, EDM and USM on a micro-USM machine. The combination of WEDG and EDM was capable of machining co-axial micro tools and hence the micro-USM of brittle materials had become feasible & micro holes as small as 15 μm in diameter and some complex shapes such as inclined holes, square holes and 3D chambers have achieved for the first time. They have taken tungsten carbide as a suitable tool material for micro-USM. They found that the tool wears increased with a decreased in tool diameter. A 3D micro air turbine made up of three layers was developed successfully on the micro-USM machine with the combination of WEDG, EDM and USM.

W. Pei et. al [4] investigated the influence of abrasive particles on the profile of machined surface by micro USM. It was found that machined surface profiles show convex or concave shapes and amplitude of vibration, diameter of tool and the depth of hole affected the profile. They also described process ability of USM in hard and brittle materials such as silicon, glass and ceramics. Micro USM was used to generate micro features in these materials. In micro USM, material was removed using a tool that impacted abrasive particles into the work piece, chipping material away from the work piece. Abrasive particles were distributed randomly in the machining area. In micro USM, the profile of machined surface had a closer relationship with the distribution of abrasive particles, which was suspends in slurry during machining. In this paper, it was described that the abrasive particles move towards to the centre of machining area during vibration and the debris accumulated in the centre of machining blocks the movement of abrasive particles, resulting in convex or concave bottom shape of a micro hole.

The authors stated that at the initial stage of machining, the debris accumulated in the centre blocks the abrasive particles move to the centre. The surface profiles were convex. Under the same conditions, the bottom surface was generated to concave shape easily with the increase of particle size. When the vibration amplitude increased, the moving speed of particle increased, resulting in concave bottom shape. Using a tool with a small diameter, the time of a particle moving to the centre was shorter than that using a large size tool, leading to the concave bottom shape.

AnupamViswanathet.et.al. [5] described the design and characterization of a high resolution micro ultrasonic machining (HR-μUSM) process suitable for post-fabrication trimming of 3-Dmicrostructures made from fused silica and other materials. Low machining rates, high resolution, and high surface quality were taken into consideration as target in this process. The author investigated that the typical machining rates of this process averaged up to ≈100 nm/sec, for a fix distance of 35 μm. The minimum machining rate was 10 nm/sec, for a fixed distance i.e. distance between tool and work of 40 μm. This allowed trimming with high resolution in the vertical direction. The HR-μUSM provided good surface finishes i.e. an average surface roughness of 30 nm was obtained using 10 nm diamond abrasive particles in the slurry. This was nearly about 7x smaller than that achieved using conventional USM.

A. Schorderet et.al. [6] discussed the influence of the hole diameter (100 or 200 μm), and the type of tool (wire or drill), on the basis of the experimental results for glass deep hole micro-machining. It was concluded that the use of drills help to keep a higher mean drilling speed while the cylindrical wire tools provide a higher speed (twice) in the first 20% of the drilling depth and the drilling speed in glass deep m drilling is depending on depth and type of tool used.

Manjot S. Cheema et.al [7] discussed on Tool wear in fabrication of micro-channels in ultrasonic micromachining. It was concluded that tungsten carbide tool provided a better form accuracy in comparison to the micro-channel machined by stainless steel tool. The tool wear mechanism in both materials is proposed by considering scanning electron micrographs of the tool as evidence. A one factor at a time approach was used to study the effect of various process parameters.

K.P. Rajurkar and Murali M Sundaram [8] described some process improvements achieved in micro USM and micro EDM. It was found that in micro USM, in addition to size ratio and hardness ratio, the slurry medium also plays a role in determining the two bodies and three-body mechanism of material removal. High-performance ceramics, glass, graphite and a part of the fiber-reinforced plastics etc. materials could be machined in micro USM. Geometrical capabilities of micro USM were testified by drilling, slot machining and 3D machining. Micro holes with a diameter less than 10 µm were successfully drilled on silicon, quartz glass and alumina. The tool wear compensation strategy “Uniform Wear Method” originally developed for micro EDM could be applied in micro USM to generate 3D micro cavities. Micro USM could be used to provide solutions to easily and quickly achieve the larger MEMS structures as well as packaging for both prototype and production in silicon, glass and ceramic.

Vivek Jain et.al. [9] has given an overview of the main issues concerning different aspects of micro-USM, its performance, and limitations in the application. The paper focused on the principle of micro-USM, the types of USM processes, tooling, USM process parameters, and the process performance measures, namely, material removal rate and the tool wear ratio. Categorizations of micro-USM processes according to the operating principles used and tool head used were described in this paper. A comparison with respect to major features of the widely used micromachining processes was presented. Geometrical capabilities of the micro-USM process were also explored in this paper.

Reimund Neugebauer et.al [10] discussed the use of hybrid processes for cutting operations in order to intentionally alter the material characteristics in the chip formation area or the working mechanisms of processes by overlapping additional energies. Again it was described the application of this technology demands development and utilisation of process-specificultrasound converters inducing oscillation in the kilohertz range. It was concluded that decreased cutting forces and an enhanced chip breaking can be observed as positive effects in drilling overlapped with ultrasound.

Tsunemoto Kuriyagawa et.al. [11] developed an ultrasonic vibration spindle, which is capable of supporting an ultrasonic vibrator unit with an aerostatic bearing and rotating a small-diameter tool with high precision while providing axial ultrasonic vibration. The machining of holes is performed under 1-axis control, slits are machined under 2-axis control, and 3D structures are machined under 3-axis control. In this paper, they discussed that they machined a micro-hole in glass, and basic machining characteristics including the influence of tool diameter and tool rotation were examined.

Huan Qi.et.al [12] performed ultrasonic-vibration assisted micro-channeling process on glasses by an abrasive slurry jet (ASJ) and it is presented and discussed both numerically and experimentally. A model was developed a model that explore the effect of ultrasonic vibration on the stagnation zone, particle impact velocity and impact angle, and viscous flow induced erosion process. It has been found that the static pressure in the stagnation zone, particle impact velocity and impact angle are varied periodically with an assistance of the ultrasonic vibration on the work piece. Ultrasonic vibration could affect the material removal process in ASJ micro-channeling of glasses. They also concluded that ultrasonic vibration assisted ASJ micro channeling increases the material removal rate, channel depth and top channel width, while decreases the channel wall inclination angle, as compared to the traditional ASJ micro-channeling process at the same experimental condition.

E.Kai et al. [13] performed micro ultrasonic machining on soda-lime glass using tungsten carbide abrasive 0.6 µm in grain size with oscillate amplitudes of 0.4-1.6µm, a machining load of 0.025-0.2N and oscillation frequency of 40kHz. It was found that drilling speed increases with increase in machining load in case of single tools using cemented carbide tool . It also concluded that machining load or oscillation amplitude has no influence on tool wear ratio. They also stated that with respect to zero tool wear ratio, PCD tools has more excellent resistance capabilities than cemented carbide tools.

Yu et al. [14] stated that debris accumulation as the main cause leading to low machining efficiency. It was observed that the machining speed decreases with increase in the average static load beyond a certain value and considered particle size as the main factor that influence surface roughness. It was concluded that the debris accumulation in the working area leads to a part of static load consumed in impacting the debris instead of removing the material from the work piece resulting in lower machining efficiency.

Yu et al. [15] identified the main factor that causing tool wear in micro USM. A theoretical model was proposed to estimate tool wear. Experimental results of tungsten and stainless steel with 316L were compared. It was concluded that tool rotation has no influence on tool wear. It was also found that large errors are generated in case of small diameter tools and large sized abrasive particle.

Zarepour and Yeo [16] developed a model that predicts material removal modes in ductile and brittle material when the brittle material is impacted by single sharp abrasive particle in micro ultrasonic machining process. The material removal modes for silicon <100> and fused quartz were discussed. It was observed that there were three modes of material removal namely pure ductile, partially ductile (transition mode) and pure brittle.

Chen Zhang et.al [17] discussed and analyzed on the effectiveness of both the linear and ultrasonic elliptical vibration-assisted machining technique in micro-groove turning. It was investigated that mechanisms of micro-groove generation induced by the linear and elliptical vibration modes. Micro-groove turning experiments are also conducted to compare the influences of the two vibration modes on the cutting forces and the surface roughness. It was concluded that linear vibration-assisted micro-groove turning leads to better surface roughness as compared to the elliptical vibration-assisted case, while elliptical vibration-assisted micro-groove turning shows advantages in terms of decreasing the cutting forces.

J. Wang et.al. [18] Proposed a novel edge chipping mechanism for the machining of holes considering machining-induced cracks. It was stated that the initiation of edge chipping is determined by both the magnitude of the driving force and the size of the machining-induced crack. It was concluded that the reduction of the size of machining-induced cracks in rotary ultrasonic drilling is another important factor contributing to the reduction of the size of edge chipping in rotary ultrasonic drilling, comparing with conventional diamond drilling.

Based on the review of past research, the major research issues in micro USM have been highlighted in the subsequent section.

Zeng et al. [19] determined the result of tool wear and cutting forces in RUM of SiC. They stated that tool wear on end face is much more than on lateral face and maximum cutting force increases with number of holes drilled during first tool wear stage and starts decreasing during a second tool wear stage. It was concluded that the tool wear in RUM of SiC has two stages. In the first stage, attritious wear dominates whereas in the next stage, bond fracture dominates.

Liu et al. [20] developed a cutting force model for rotary ultrasonic machining (RUM) of brittle materials. It was discussed on influences of input variables on cutting force and determined trends experimentally. (1) Cutting force increase with increase in abrasive concentration and feed rate and (2) cutting force decreases with decrease in abrasive size, vibration amplitude, and spindle speed

Zarepour and Yeo [21] developed an approach of single abrasive particle impingement in micro ultrasonic machining with the purpose of providing insights into material removal modes. As a result an improvement in surface integrity of the machined micro features as well as material removal rate in micro USM process was found.

Kang et al. [22] investigated the material removal rate and surface quality of the alumina (Al_2O_3) which was ultrasonically machined using SiC abrasive under various machining conditions. Material removal rate increases as the static pressure and slurry concentration increases. It was concluded higher material removal rate in case of rectangular sectional profile of the tool as compared to square sectional profile of the tool when tool of same cross-section area are used. An improved surface roughness of about 0.76 μm was observed when machining was done by using abrasive of mesh number 600.

Vinod Yadava and Aniruddha Deoghare [23] developed finite element method (FEM) for the design of a horn for rotary ultrasonic machining (RUM). They developed a mathematical model for the determination of displacement within the horn used in rotary ultrasonic machining (RUM). They concluded that the amplification factor is more for rotary USM over conventional USM in case of no horn rotation. They also concluded that the stresses at the bottom surface of the horn are approximately equal to zero and the stresses obtained for the resonance frequency is much less than that obtained for the other frequencies.

Curodeau et al. [24] proposed a new μ-machining process, namely the ultrasonic abrasive micro machining process (UAMM) by using thermoplastic tooling material. It was investigated that two different m-machining modes sthat is application of the hammering mode for μmachining and application non-contact ultrasonic machining mode for μ polishing.

Churi et al. [25] studied the effects of machining variables in Rotary ultrasonic machining of titanium alloy. They concluded that cutting force and surface Roughness decreases as spindle speed increases. It was also concluded that cutting forces, MRR and surface roughness increases as the feed rate increases. It was concluded that cutting force decreases initially and then increases as ultrasonic power increases and surface roughness decreases as the ultrasonic power increases.

Wang et al. [26] discussed fundamental principles of ultrasonic machining, the material removal mechanism and important factors are calculated. It was concluded that the average cutting forces in ultrasonic vibration cutting are smaller than those in conventional cutting. The decrease in the cutting speed of the work-piece and/or increase in the vibration frequency will result in better surface quality.

Haw et al. [27] studied the surface integrity of the USMed surface and developed a way to minimize the scattered cracks so that good surface finish could be achieved. They developed a multistage micro-USM process and achieved the value of surface roughness better than 0.2 μm. They observed a rough surface with scattered chippings and deep penetrated cracks when large grit size abrasives and/or fast feed rate were used. They concluded that slower the feed rate the better will be surface roughness and the sub-surface cracks under the same oscillation amplitude/frequency and the same abrasives.

Guzzo et al. [28] presented the ultrasonic abrasion of different hard and brittle materials using stationary USM. Results show that machining rate decreased with increase in hardness of the work material.

G.Dong et. al. [29] Carried out an experiment on ultrasonic vibration-assisted turning on aluminium alloy Al2024 reinforced with SiC particles by using polycrystalline diamond (PCD) tools to investigate the effect of the tool geometries on the cutting force and the machined surface roughness. Experimental results showed that tool rake angle and tool nose radius exerted a considerable influence on the cutting force and machined surface integrity. A comparison of tool flank wear pattern between the conventional turning and the ultrasonic-assisted turning revealed that the tool wear was reduced significantly during the ultrasonic vibration assisted turning.

Shrikrushna B. Bhosale.at al [30] performed experimental investigation and analysis of material removal rate,tool wear rate, and surface roughness in ultrasonic machining of alumina–zirconia ceramic composite. The experiments were conducted using the full factorial DoE method with an L8 (23) orthogonal array. They investigated The effects of amplitude, slurry concentration and slurry type on the above responses. Based on analysis of results it was concluded that the amplitude has a significant effect on the MRR and surface roughness. An increase in amplitude causes higher MRR and surface roughness. Pure SiC abrasives give better surface finish, whereas the mixed abrasives produce higher tool wear and MRR

Deng Jianxin et al. [31] proposed that in ultrasonic machining (USM), the material was removed primarily by repeated impact of the abrasive particles, and the material removal rate (MRR) and surface integrity were influenced by various factors including the material parameters of the workpiece materials. The distributions of strength of the ultrasonic machined specimens were used to evaluate the surface integrity. Results showed that fracture toughness of the ceramic composite played an important role with respect to MRR. As the fracture toughness increases, there was a reduction in MRR and in surface roughness. In USM of whisker reinforced ceramic composites, the MRR and the surface roughness depend on the whisker orientation, and vary on surfaces with different direction angle normal to the hot pressing direction. Studies of strength distributions of alumina-based composites machined by USM demonstrated that the flexural strength of the ultrasonic machined specimens varied narrowly from the mean value, and the composites with high fracture toughness showed higher Weibull modulus.

R. Singh and J. S. Khamba [32] studied the effect of six input parameters that is tool material power rating, slurry type, slurry heat, slurry concentration, and slurry grit size on the tool wear rate in the ultrasonic machining of titanium and its alloys. Mathematical model for tool wear rate was developed using Buckingham's π-theorem for stationary ultrasonic machining of titanium and its alloys. They developed the model by considering the interactions among input parameters.

Guodong Li et.al. [33] Investigated on material removal modes of quartz crystal by micro USM. For experiment in this paper Z-cut sample of quartz crystals are taken as the experimental material. It was found that the surface roughness, *Rpk*, could identify the material removal modes of quartz crystal by micro USM. The value of Rpk was observed as less than 350*nm*, the machined surface by micro USM is relatively smooth, indicating ductile machining. Otherwise, the machined surface is covered with sharp tips and cracks.

Xingzhi Xiao et.al [34] investigated both experimentally and theoretically on the cutting force is the key factor that affects the machined surface/subsurface quality. A cutting force model was developed. This theoretical model can be applied to evaluate the cutting force, and it can provide better understanding of the effects of ductile removal and brittle fracture removal on the cutting force during UVASG of ceramics.

Kuruc M et.al. [35] investigated the machining of poly-crystalline cubic boron nitride (PCBN) by using rotary ultrasonic machining (RUM) . In the experiment A tool for friction stir welding (FSW) was manufactured. It was concluded that If roughness of the tool is too high, the welded material will stick on the tool and the weld cannot be fabricated and rotary ultrasonic machining (RUM) seems to be a proper method to manufacture a FSW tool.

1.6. Major Researched Issues in Micro-USM

In experimental investigations, micro-USM has been recognized as a promising micromachining process for generating micro-scale features on non-conducting, hard and brittle materials. However, research works on micro-USM so far are mainly focused on exploring the feasibility and geometrical ability of machining. One of the possible reasons is that to a certain extent some aspects of micro-USM are similar to macro-USM and can be directly implemented. However, issues with micro-USM need not be similar to that of macro-USM.

Various research issues in the micro-USM process can be categorized as illustrated in following Fig. 1.5 Most of these issues are concerning the major task of process improvement for micro-USM.

Fig. 1.5 Major research issues in micro-USM

Interactions between abrasive particles and workpiece are very intricate in micro-USM. A well-structured study for understanding of the material removal mechanism for micro-USM is yet to be carried out. Further analysis of the material removal mechanism associated with the machining process is required. The contribution of each probable phenomenon that might be active during the removal of material including micro chipping, abrasion, cavitations, and chemical reaction needs to be investigated. In a micro-cutting situation, localised temperature might play a significant role too, which can be considered for further research.

The process output parameters such as material removal rate and surface roughness etc. of micro-USM depend mainly on the physical or mechanical phenomena at the machining gap. In such processes, many research issues can be originated from the practical requirements such as surface finish and existing limitations such as serious tool wear, particle size, and surface finish of the process. Studies on process capabilities and process modelling are few aspects that can contribute immensely towards making the process cost effective.

Micro tooling is another aspect, which could contribute significantly towards process capability, and such issues need to be addressed early.

There are some other research issues which can be classified in following way.

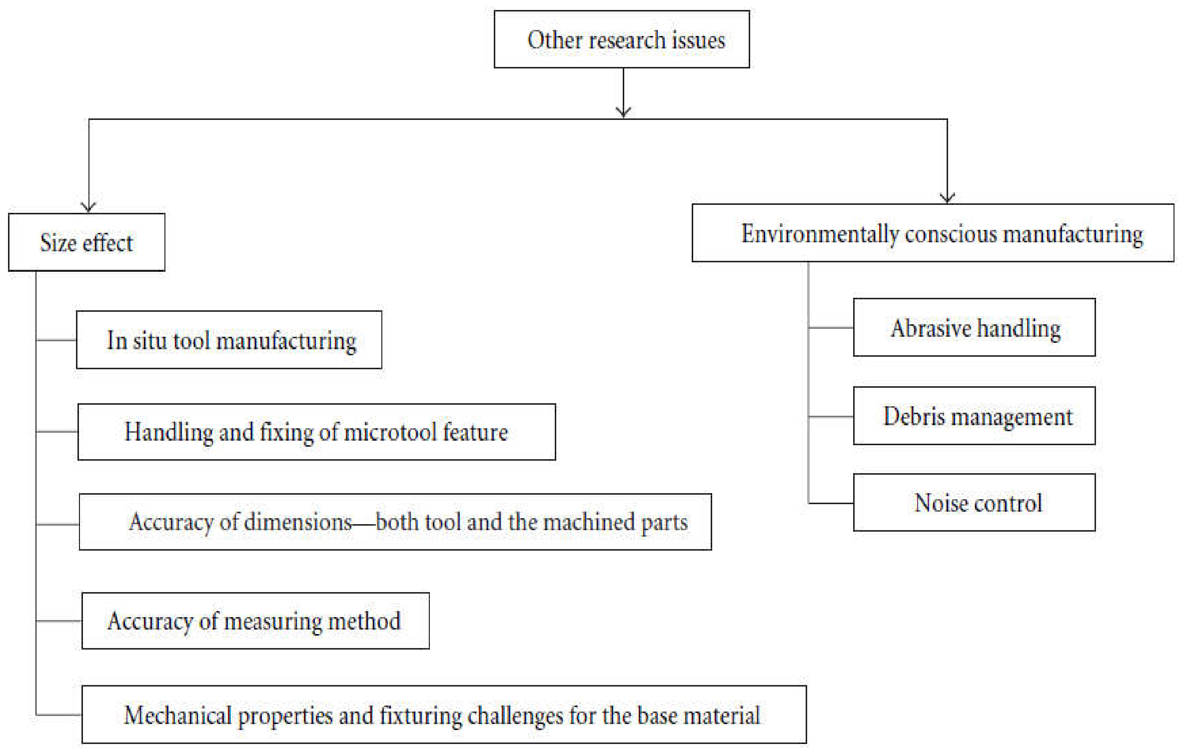

Fig.1.6. Some research issues

So the research issues of micro USM process can be summarized as the following:

a) Integrate the micro USM process performance such as the tool wear rate with a CAD/CAM method to create complex 3D features.
b) Improve the design, precision, capabilities, and performance of micro USM Machine tools in order to commercialize the process.
c) Improve the repeatability and stability of the micro USM machining performance by using the machining gap on-line sensing, monitoring, and control techniques.
d) Model and predict the material removal mechanism of micro USM process.
e) Improve the quality of the micro machined features (dimensional accuracy mainly by reducing the machining gap).

1.7. Objective of the Present Research

Ultrasonic Machining process has been extensively utilized at the macro level and as well as micro level machining operation with regard to the effect of machining parameters. However, downscaling of USM to micro level is essential to produce miniature features or parts of hard and brittle materials. The goal of this thesis is to conduct a feasibility study and develop a knowledge base for micro ultrasonic machining (MUSM). Keeping all the consideration in view the following research objectives have been moduled.

I. To develop micro tool and holding arrangement for micro USM operation and perform experiments on micro drilling on quartz materials.

II. To study the basic influences of process parameters such as abrasive slurry concentration, power rating and tool feed rate on material removal rate, and over cut & taper angle during micro ultrasonic drilling on quartz materials.

III. To carry out single objective optimization for each response characteristics for determining the optimal combinations of process parameters for achieving optimum quality micro holes during ultrasonic machining of quartz material.

IV. To carry out multi objective optimization for all the responses for determining the optimal process parametric combination and also compare with the actual value of responses for determining the percentage of error for achieving optimum quality micro holes during ultrasonic drilling of quartz material.

Chapter-2

Experimental Set-Up of Micro-Ultrasonic Machining and Machining Procedure

2.1 Experimental Setup Details

Micro ultrasonic abrasive machining is characterized by the use of smaller tools (micro tools) than those used in conventional ultrasonic abrasive machining. This results in a series of new problems and issues such as the manufacture of smaller tools, tool breakage, the mechanism of applying machining pressure, and maintaining adequate supply of abrasive particles between the tool and the work piece.

The micro ultrasonic machining process consists of the following basic elements such as power supply unit, micro tool vibration unit, abrasive slurry supply unit, & work piece holding unit etc.

Fig: 2.1 USM set up

2.1.1 Power Supply & Controlling Unit

It is a source of power, is required to supply power to the machine. For maintaining constant voltage stabilizer is used. Generally 220 voltages is required to be set machining.. Additionally there is an auto adjust mode which protected the machine from any type of disturbance.

Controlling Unit in Ultrasonic Machine there is a precision for changing the power rating for generally 200 to 1000 watt power can be supplied in the USM experimental set-up. In this system one adjusting switch is there. To control this switch the power is adjusted. One very important indicator is there that is tuning. If the machine is in over load condition then the red light is blinking. Then by controlling the tuning switch the over load condition can be removed. Following Fig 2.2 & Fig 2.3 shows the photographic view of power supply & controlling unit of USM system.

Fig. 2.2. Automatic Control unit for USM

Fig. 2.3. Power supply & control unit

2.1.2 Micro tool Vibration Unit:

In USM system vibration unit is one of the major parts & in this unit the subsystems are

A. Ultrasonic Transducer.

B. Coupler

C. Horn

D. Micro tool & tool holding unit

Fig 2.4. Shows the photographic view of tool vibration unit for micro USM.

Fig 2.4. Tool vibration unit

A) Ultrasonic Transducer:

Transducer is such a device that converts one form of energy to another form of energy**.** There are two types of transducers used in micro USM based on two different principles of operations to convert the supplied electrical energy to mechanical energy or vibration. Piezo-electric transducer and Magneto-stricitve transducer.

- **Piezo-electric transducer:**

This transducer generates a small electric current when they are compressed. In addition, when the electric current is passed though crystal it expands. When the current is removed, crystal attains its original size and shape. Such transducers are available up to 900 Watts. Piezo electric crystals have high conversion efficiency of 95%.For micro USM piezo electric transformer is preferred

- **Magneto-strictive transducer:**

This transducer is made of nickel, nickel alloy sheets that changes its length when subjected to strong magnetic field. Their conversion efficiency is about 20-30%. Such transducers are available up to 2000 Watts. The maximum change in length can be achieved is about 25 microns.

B) Coupler

The coupler attaches between the converter or transducer and horn. This allows for clamping of the converter and horn assembly and provides amplitude choices for various applications.

C) The Horn

The horn or concentrator mechanically amplifies the vibration to the required amplitude of 15 to 50 μm. and transfer the vibration to the tool tip. The horn is made of titanium material or stainless steel. The function of horn is that it concentrates the vibration at the single point. It is nothing but a simply velocity transformer & it is made slightly shorter than the half wavelength. As the amplitude of the vibratory motion of the transducer is small and is usually insufficient for material removal purpose, so that's why the tool is connected to the transducer by means of a concentrator, which is simply amplifies the vibration to produce the desired amplitude at the tool end. This amplitude is increased by reducing the cross section of horn at the tool end. The horns are specially designed to provide a reduction in cross-section at the tool end so that it can produce maximum amplitude with minimum energy loss under working condition. There are mainly three shapes of horn used. (1) Exponential, (2) Tapered or conical & (3) Stepped. Which are shown in Fig 2.5. For most of the cases specially micro machining operation exponential horn can be used for better performance. The different sizes of horns are used for required amplitude of vibration.

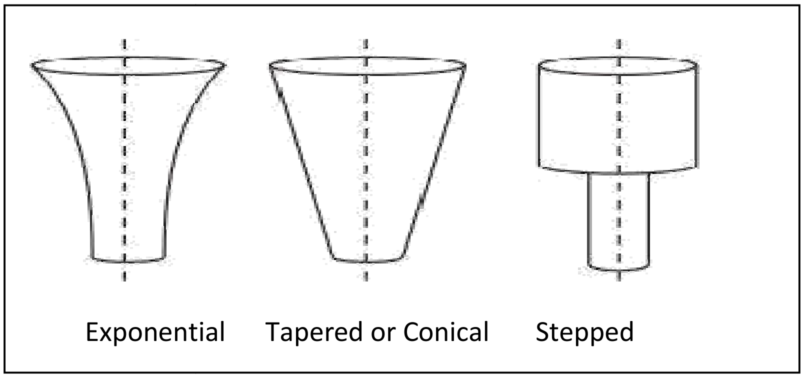

Fig: 2.5 Different shapes of horn.

D) Micro tool & tool holding Unit:

The tools are made of tough, ductile material with high wear resistance & good fatigue strength. Usually mild Steel is usually used as tool material. Tools are normally soldered or brazed to tool holder & finally fitted with horn by Screw fitting. Otherwise, the actual tool configuration can be machined to the end of the horn. The tool is designed such that it can provide the maximum amplitude of vibration at the free end at a given frequency. As tool is held against the work piece by a static load exerted via pneumatic/hydraulic or solenoid feed system. To get optimum results, a uniform working force must be maintained during machining and be sufficiently sensitive to overcome the resistance due to cutting action. Static load values of about 0.1 to 30 N are generally used.

2.1.3. Micro-Tool development for USM

At first, stainless steel of grade 304 was selected for fabricating the cylindrical micro tool. Next stainless steel was machined with the help of CNC lathe as per design in 2D Cad model, and 3D cad model. Following steps was performed for micro tool fabricating

1. Tooling layout preparation for the given work piece.
2. Set the cutting tool in their respective position of the tool post.
3. Next the work piece is chucked and checked for the rotation.
4. Switch on the motor after selecting the proper speed.
5. Next by moving the cross slide facing operation is done

6. After shortening the height of the work piece turning operation is completed.
7. Make the step turning operation as per requirement the dimension.
8. Next chamfer the corners and check the dimensions.

Next developed micro tool was properly cleaned and joined it by silver brazing with bolt.
Silver brazing uses filler metals and alloys such as silver, copper, zinc, cadmium, etc. Silver brazing is such a joining process, carried out by heating a non-ferrous filler metal, alloy ,to melting temperature. At this temperature, the molten filler metal interacts with a thin layer of the base metal and after cooling it provides an exceptionally strong, sealed joint due to grain structure interaction

Silver brazing is such a joining process that produces joints that meet specifications that meet mechanical performance, electrical conductivity, pressure tightness, corrosion resistance, and service temperature. The photographic view of the developed tool is shown in fig 2.6. Fig.2.7 shows that the develop tool joined with hexagonal bolt which acts as a tool holder often carried out by silver brazing.

Fig.2.6. Fabricated micro tool.

Fig. 2.7 Fabricated micro tool brazed with hexagonal bolt.

2.1.4 Abrasive Slurry Supply System

A mixing tank of abrasive slurry & water is used. This mixture of abrasive and water in a certain ratio as per the requirement is supplied through nozzle via pipe with desired flow rate. The abrasive slurry also provides a good acoustic bond between the tool, the abrasive, and the work-piece, allowing efficient energy transfer. The different types of abrasives used in micro USM are diamond, cubic boron nitride CBN, boron carbide, silicon carbide and aluminum oxide. Boron carbide is most widely used abrasive in USM process. The size of abrasive affects the surface finish. Smaller grit size produces finer finish but reduces machining rate. The rule used in selecting a grit size is that the grit size should be equal to the amplitude of vibration.

The transport medium for the abrasive should possess low viscosity with a density, good wetting properties and, preferably, high thermal conductivity and specific heat for efficient cooling. Water meets most of these requirements. The machining rate and surface roughness is directly proportional to the abrasive grain size. For micro USM operation very fine abrasive are required for achieving better micro machining accuracy. Fig 2.4 shows the photographic view of the abrasive slurry supply unit system.

Fig. 2.8 Abrasive Slurry Supply System.

2.2. Machining Procedure of micro-USM:

Following steps are carried out during micro machining of quartz material by micro USM

I. Slurry preparation by mixing water and abrasive slurry according to desired concentration.
II. Tool fitted with horn by screw fitting.
III. Power supply on for micro USM machining
IV. Testing of tool of micro USM.
V. Next parameter setting for machining operation
VI. After machining removed the work piece from the work holding device and clean the work piece
VII. Next measure the all responses for analysis.

Chapter-3

Analysis of Process Parametric & Its Influence on Performance Criteria of Ultrasonic Micro-Drilling of Quartz.

3. ANALYSIS OF PROCESS PARAMETRIC & ITS INFLUENCE ON PERFORMANCE CRITERIA OF ULTRASONIC MICRO- DRILLING OF QUARTZ

3.1. Experimentation

Experiments were conducted on an ‘AP-500’ Sonic-Mill ultrasonic machine with the frequency of vibration of ultrasonic machine is about 20 kHz and the power supply can be varied from 200 to 1000W. The square flat quartz plate workpiece of 1 mm thick was pasted on the work holding plate made of mild steel. Tool feed rate was varied along the Z axis of mill module. Boron carbide powder of average grain sizes 24 µm mixed with water at room temperature was used as abrasive slurry solution. Stainless steel (S304) cylindrical tools of 20 mm long and of 400 µm and less diameter were fabricated as per desired shape and silver-brazed to the tool tip. Slurry concentrations varies from 20 to 40%, power supply rating varies from 200 to 400W and tool feed rate varies from 0.80 to 1.2 mm/min during experimentation.

3.2. Procedural steps for measurement of responses

Machining was done on quartz plate material as per design. Fig. 3.1 and Fig.3.2 show that the tool face and workpiece face after machining respectively. After machining the workpiece responses were measured. The responses criteria were taken as the material removal rate, overcut and taper angle.

Fig. 3.1 Developed tool for USM.

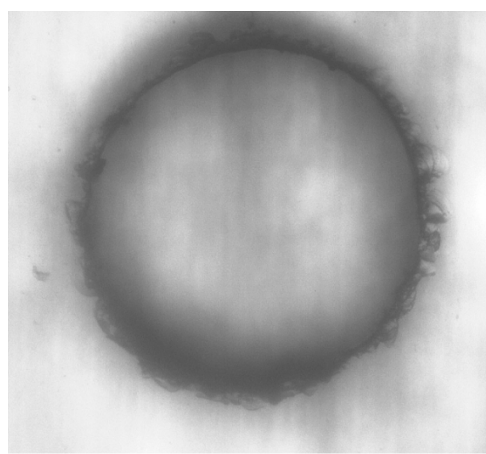

Fig. 3.2 Top surface of the machined hole one workpiece.

3.2.1. Measurement of Material Removal Rate

At first the diameter of hole was measured after machining and then calculates the volume of the material removed. Then the value was divided by total machining time. The material removal rate was calculated for each experiment.

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

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

T= Total machining time (min)

3.2.2. 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 overcut was calculated for each experiment.

3.2.3. Measurement of Taper angle

The workpiece was cleaned by acetone carefully. Entrance diameter and exit diameter of hole on workpiece was measured by measuring microscope ((Leica DM 2500, Germany) for calculating taper angle. The following formula used to calculate the half taper angle. ˉ

$$Half\,Taper\ angle = \tan^{-1}\frac{D_{entry}-D_{exit}}{2t}$$

D_{entry} = Entry diameter of hole

D_{exit} = Exit diameter of hole

t = Thickness of workpiece

3.3. Influence of process parameter on performance criteria of micro USM.

3.3.1. Influence of abrasive slurry concentration on MRR

In micro ultrasonic machining process the abrasive slurry concentration is one of the important parameters. The effect of abrasive slurry concentration on MRR, Overcut and taper angle has been observed, presented through various figures and analyzed in the subsequent discussions.

Fig. 3.3 shows 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. If abrasive slurry concentration is less, then the number of abrasive grains available at the machining zone will become less. Hence, the penetration rate will also be less. Thus due to less number of abrasive grains taking part in the material removal, the MRR is less. When the abrasive slurry concentration is 20 g/l then the MRR is very less and when concentration is 40 g/l MRR is more.

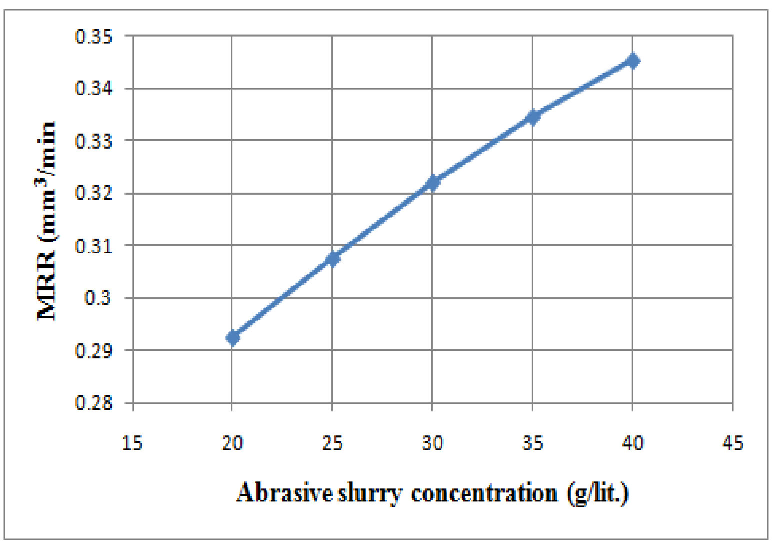

Fig. 3.3 Influence of abrasive slurry concentration on MRR

3.3.2. Influence of power rating on MRR

Power rating is also one of the key parameter in micro USM process. The effect of power rating on MRR has been observed and analyzed through graphs.

Fig. 3.4 shows power rating Vs MRR graph. When the power rating is 400 W then the MRR is high. Generally low power rating gives the low MRR. Actually if the power increases then

MRR also increases because with more ultrasonic power, abrasive particle in slurry were striking with more momentum and kinetic energy hence eroding more material. And at low power rating abrasive particle in slurry striking with low momentum and kinetic energy and it increases with increase in power rating and hence, material removal rate also increases.

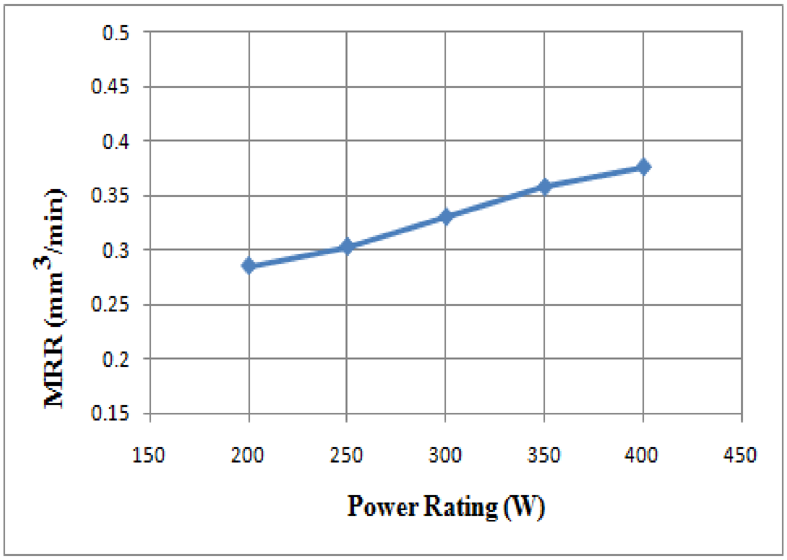

Fig. 3.4 Influence of power rating on MRR

3.3.3. 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.

Fig.3.5 shows that the effect on MRR with changing the tool feed rate. From fig. 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 particle striking at small force on work piece. When tool feed rate increases abrasive particle striking force at workface also increases, hence MRR also increases.

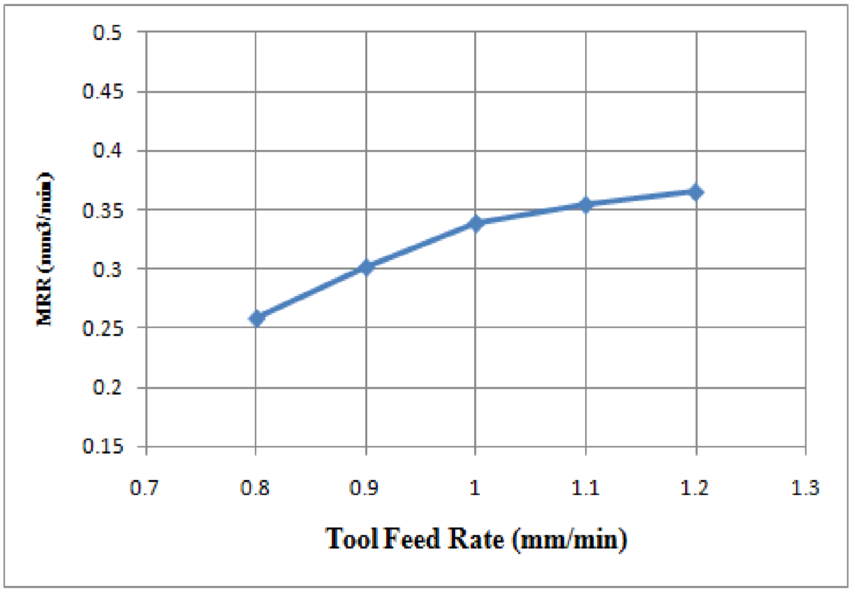

Fig. 3.5 Influence of tool feed rate on MRR

3.3.4. Influence of abrasive slurry concentration on overcut

Fig. 3.6 shows that overcut is less when abrasive slurry concentration is 20 g/l and it is slowly increasing up to 25 g/l and the fast increase and at 40 g/l it is more. When abrasive slurry concentration is less overcut is also less because less number of abrasive particles is available. And when abrasive slurry concentration increases circulation of abrasive particle is less so overcut is also more.

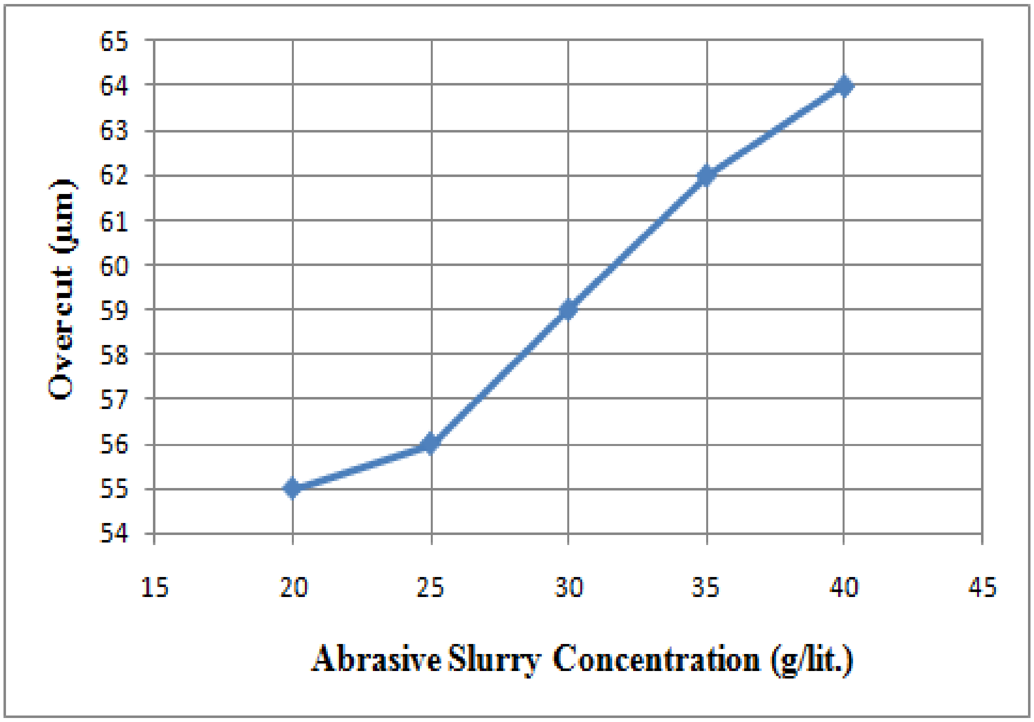

Fig. 3.6 Influence of abrasive slurry concentration on overcut

3.3.5. Influence of power rating on overcut

Fig.3.7 shows that as power rating is increasing the overcut is also increasing slowly but after sometimes it increased at faster rate. When power rating is low the overcut is minimum because at low power rating abrasive particle is striking workpiece at low momentum and kinetic energy. When power rating increases, the striking of abrasive particle present in slurry with more momentum and kinetic energy so removal of material is more. With constant feed rate of tool as more materials are removed, the diameter of the hole increases. As a result overcut increases.

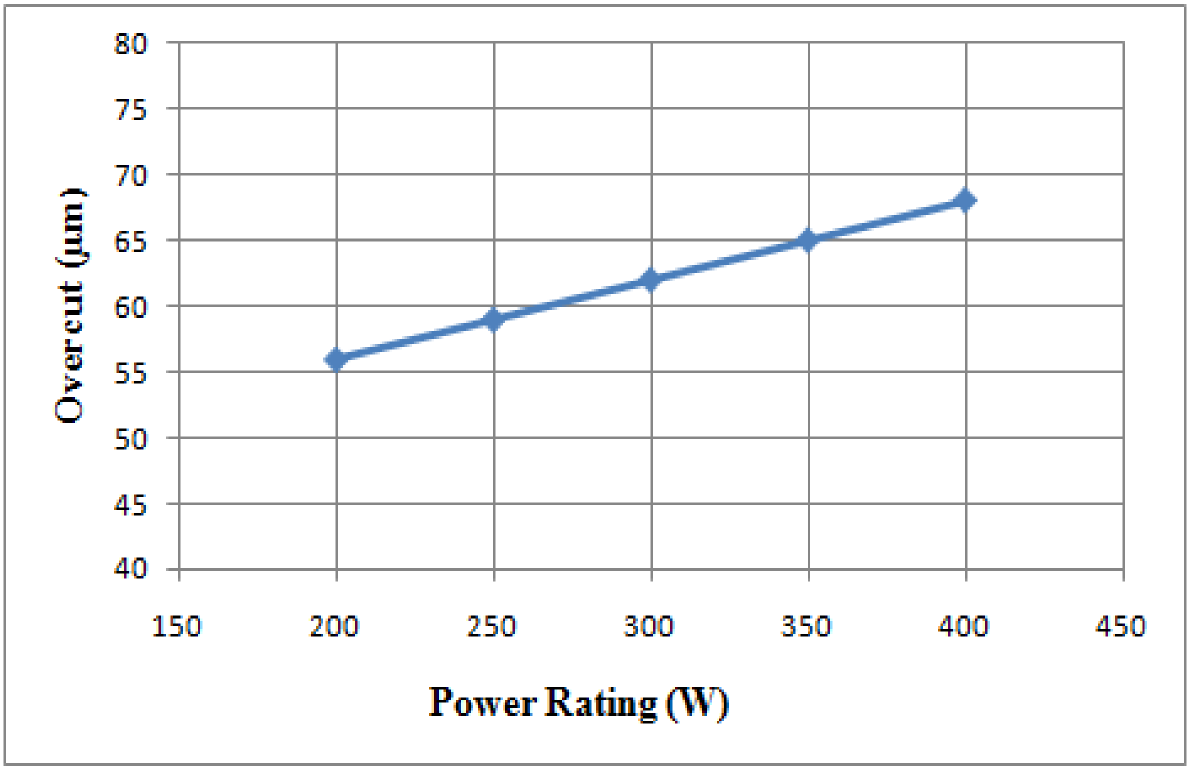

Fig. 3.7 Influence of power rating on overcut

3.3.6. Influence of tool feed rate on overcut

Fig. 3.8 shows that when tool feed rate is increasing overcut are 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 also increases. Overcut is larger at higher value of tool feed rate.

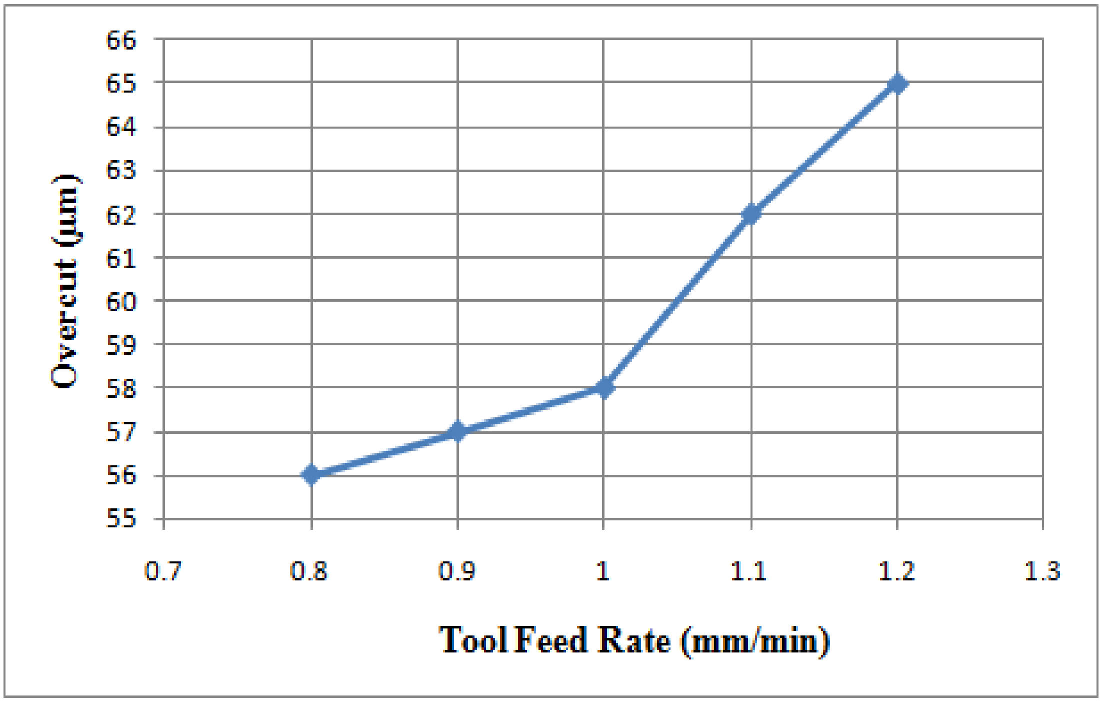

Fig. 3.8 Influence of tool feed rate on overcut

3.3.7. Influence of abrasive slurry concentration on taper angle

Fig. 3.9 shows that taper angle is less when abrasive slurry concentration is low (20 g/l) and then it is being slowly increased when concentration is 35 g/l. When abrasive slurry concentration is less machining rate is less but uniform therefore taper angle is less. Variation in taper angle is more with abrasive slurry concentration. The main reason of the taper angle is non-uniform machining surrounding the tool.

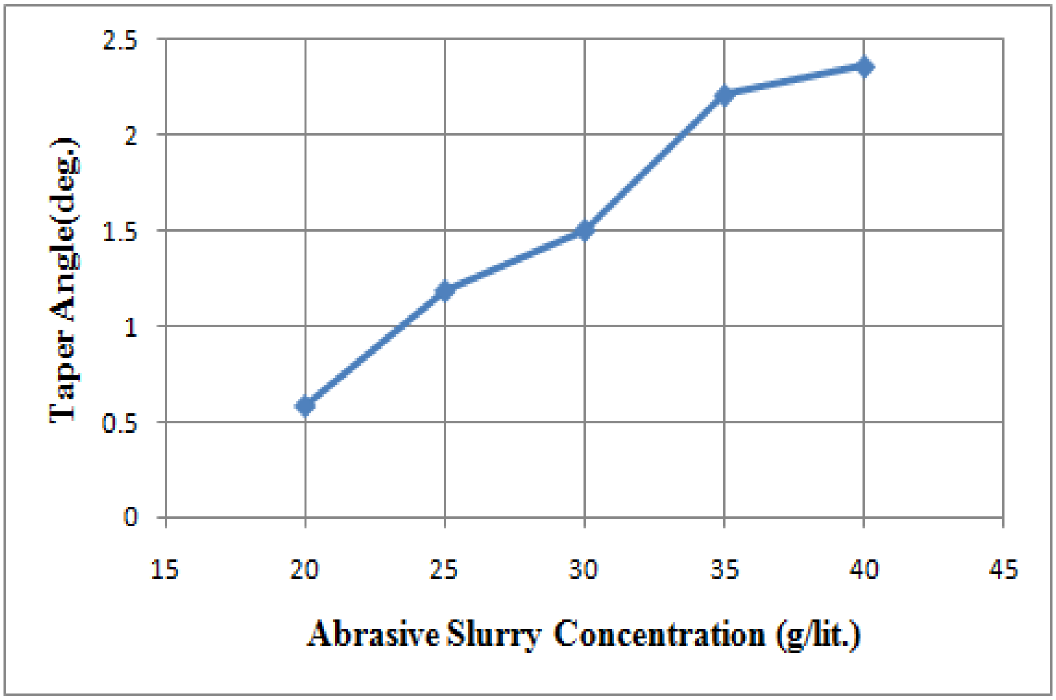

Fig. 3.9 Influence of abrasive slurry concentration on taper angle

3.3.8. Influence of power rating on taper angle

Fig. 3.10 shows that the variation of taper angle with power rating. When power rating is low the abrasive particle present in slurry with less momentum and kinetic energy. When power rating increases, taper angle is also increases with slow rate because abrasive particles present in slurry with more momentum and kinetic energy but with all over the surface of generated cavity so taper angle increases.

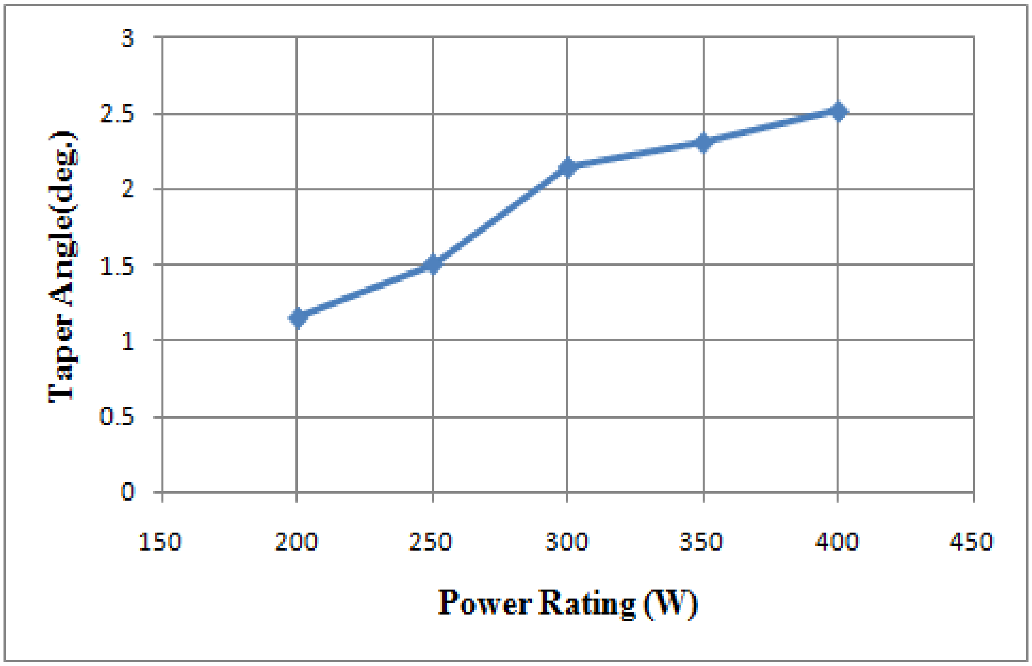

Fig. 3.10 Influence of power rating on taper angle

3.3.9. Influence of tool feed rate on taper angle

Fig. 3.11 shows the effect of tool feed rate on taper angle. 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 so taper angle increases.

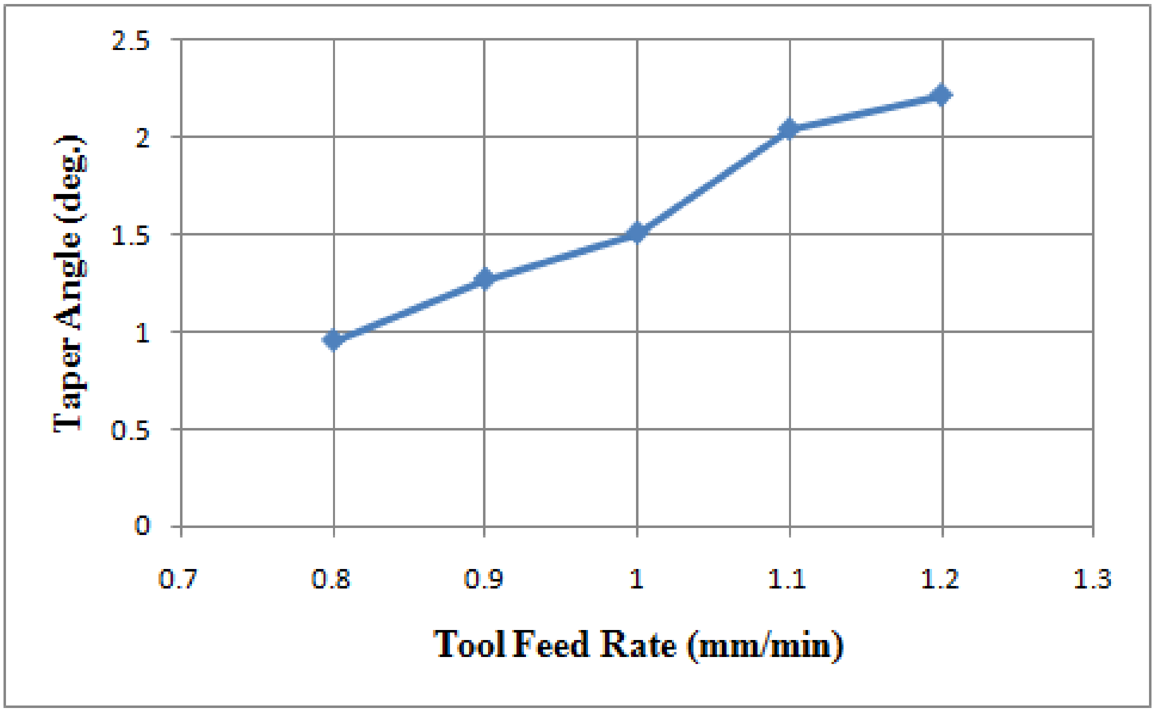

Fig. 3.11 Influence of tool feed rate on taper angle

From the basic experimental investigations and parametric studies the range of process parameters are selected and optimization analysis has to be performed for determining the optimal parametric condition for achieving minimum overcut and taper angle and maximum material removal rate during ultrasonic micro drilling of quartz materials.

CHAPTER-4

Optimization Analysis of Ultrasonic Micro Drilling of Quartz Material Based on RSM

4. OPTIMIZATION ANALYSIS OF ULTRASONIC MICRO DRILLING OF QUARTZ MATERIAL BASED ON RSM

The experiments on ultrasonic micro drilling of Quartz have been performed based on design plan of response surface methodology. Using the experimental results the empirical models have been developed to establish the relationship between the responses such as the MRR, overcut and taper angle and the micro USM process parameters. The developed models are tested by analysis of variance. The parametric influencies on the responses are analyzed through response plots. The single objective as well as multi objective optimization of responses has been performed to find the optimal micro USM process parameters for achieving maximum MRR, minimum overcut and minimum taper angle of through hole on quartz.

4.1. Experimentation

Experimental plan has been made based on design of experiments (DOE) to observe the effect of process parameters on responses of micro USM. The (statistical) design of experiments (DOE) is an efficient method for planning experiments so that the data obtained can be analyzed to yield valued and objective conclusions. The choice of an experimental design depends on the objectives of the experiment and the number of factors to be investigated. In order to find the machining characteristics of the micro Ultrasonic Machining on a flat quartz work piece 1 mm thick and square. The experimental scheme was designed by using response surface methodology to develop the mathematical co-relation between the process parameters and responses.

From the review of the literatures, it was concluded that certain parameters have a great influence in the machining. The process parameters such as abrasive slurry concentration, power rating and tool feed rate are varied. Central composite half design (CCD) with 20 runs was selected with an alpha value of 1.68. CCD is a very efficient method for fitting a second-order model. Experiments were carried out based on the design with 7 canter points. Three factors with five levels were considered for experimental purpose. The ranges of each factor were decided after conducting some pilot experiments. The actual and coded values are given in the Table 4.1.

Table 4.1. Actual and Coded values of Ultrasonic Machining

Factor	Unit	Symbol	Level				
			-1.68	-1	0	1	1.68
Abrasive Slurry Concentration	g/l	X_1	20	25	30	35	40
Power Rating	W	X_2	200	250	300	350	400
Tool feed Rate	mm/min	X_3	0.8	0.9	1	1.1	1.2

The table 4.2 given below shows the design of experiments as designed with the help of MINITAB software.

Table 4.2. Coded values as per design of experiment with the help of MINITAB software

Experiment No.	Abrasive Slurry Concentration	Power Rating	Tool Feed Rate
1	-1	-1	1
2	1	-1	1
3	-1.68	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	-1.68
8	0	0	0
9	0	-1.68	0
10	-1	-1	-1
11	1	1	1
12	0	1.68	0
13	1	1	-1
14	1	-1	-1
15	0	0	1.68
16	-1	1	1
17	0	0	0
18	-1	1	-1
19	0	0	0
20	1.68	0	0

The actual values of the USM parameters as per experiment design are listed below in Table 4.3

Table 4.3. Actual values of process parameters as per design of experiments

Experiment No.	Abrasive Slurry Concentration (g/l)	Power Rating (W)	Tool Feed Rate (mm/min)
1	25	250	1.1
2	35	250	1.1
3	20	300	1.0
4	30	300	1.0
5	30	300	1.0
6	30	300	1.0
7	30	300	0.8
8	30	300	1.0
9	30	200	1.0
10	25	250	0.9
11	35	350	1.1
12	30	400	1.0
13	35	350	0.9
14	35	250	0.9
15	30	300	1.2
16	25	350	1.1
17	30	300	1.0
18	25	350	0.9
19	30	300	1
20	40	300	1

The experimental observation and values of responses of micro USM are given in Table 4.4

Table 4.4. values of responses of micro Ultrasonic Machining

Experiment No.	MRR (mm^3/min)	Overcut (μm)	Half taper angle (deg.)
1	0.3661	62.30	1.2864
2	0.3673	63.01	1.3000
3	0.4931	66.91	2.5200
4	0.1912	54.00	0.7540
5	0.2111	58.00	1.0100
6	0.3156	54.00	1.2070
7	0.4543	64.09	2.0400
8	0.3661	62.00	1.3020
9	0.6436	66.19	2.8190
10	0.1977	55.00	0.7540
11	0.2127	52.00	1.0000
12	0.3881	62.00	1.2200
13	0.3690	62.00	0.9000
14	0.1511	51.00	0.6640
15	0.4739	66.00	2.6909
16	0.3673	62.78	0.9200
17	0.3661	62.98	1.2520
18	0.3432	66.03	1.3200
19	0.3002	64.16	1.1890
20	0.3517	67.99	1.8862

4.2. Development of empirical model based on response surface methodology

Response surface modelling has been made to establish the mathematical relationship between the responses and the various machining parameters. General second-order polynomial response surface equation, which is considered to analyze the parametric influences on the various response criteria, is given 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 above equation, Y_u is the corresponding response. X_{iu} are coded values of the i_{th} machining process parameters. The terms β_0, β_i, β_{ii} and β_{ij} are the regression coefficients and the residual, ϵ_u measures the experimental error of the u_{th} observations. The process parameters have been selected based on literature review. The range of each process parameter has been selected based on the results of pilot experiments. With those pilot experimentations the process parameters was identified as concentration of abrasive slurry (A), power rating (B) and tool feed rate (C). In this experimentation four factors with five levels were considered. Table 1 illustrates the actual and corresponding coded values of ultrasonic machining process parameters. Empirical models of the responses have been established based on Eq. 4.1.

Hence the corresponding empirical equation for the responses represented as material removal rate (Y_{MRR}), overcut (Y_{OC}) and taper angle (Y_{TA}). Based on RSM have been established and given as follows;

The equation corresponding to Material removal Rate (Y_{MRR}) is:

$$\mathbf{Y_{MRR}} = 0.359999 + 0.040065\ X_1 + 0.092684\ X_2 + 0.058961\ X_3 - 0.011284\ X_1^2 + 0.004091\ X_2^2 - 0.009714\ X_3^2 + 0.007618\ X_1 X_2 + 0.009332\ X_1 X_3 - 0.005557\ X_2 X_3 \quad \text{..........(4.2)}$$

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

$$\mathbf{Y_{OC}} = 62.6051 + 1.3681\ X_1 + 3.8956\ X_2 + 1.6281\ X_3 - 0.4556\ X_1^2 - 0.9319\ X_2^2 - 0.4669\ X_3^2 + 1.0260\ X_1 X_2 - 2.0035\ X_1 X_3 - 2.0110\ X_2 X_3 \quad \text{......... (4.3)}$$

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

$$\mathbf{Y_{TA}} = 1.12257 + 0.33050\ X_1 + 0.39814\ X_2 + 0.24824\ X_3 + 0.12185\ X_1^2 + 0.12661\ X_2^2 + 0.10048\ X_3^2 + 0.16977\ X_1 X_2 + 0.03273\ X_1 X_3 - 0.04152\ X_2 X_3 \quad \text{...........(4.4)}$$

4.3 Analysis of variance for testing the models

In order to ascertain the fitness of the developed empirical models for the responses of material removal rate, overcut and taper angle of the micro ultrasonic machining process for generating micro hole on quartz plate, analysis of variance (ANOVA) test has been concluded.

Table 4.5 represents the results of analysis-of-variance for material removal rate. The p-value of all the process parameters are less than 0.05. The F-value of the lack-of-fit is 1.59 which is less than the tabulated value i.e. 4.77. The lack-of-fit is insignificant that means the fit is significant. The associated p values for linear effect as well as three process parameters are less than 0.05 for MRR at 95% confidence level. This indicates that the developed empirical model on MRR represented by equation 4.2 can be considered as statistically significant and adequate at 95% confidence level.

Table 4.5. 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%			

From ANOVA table 4.6, it is observed that for overcut hole, the F-value of the lack-of-fit is 1.47 which is less than the tabulated value i.e.4.77. The lack-of-fit is insignificant that means the fit is significant. The associated p value for linear effect and four process parameters are less than 0.05 for overcut. This indicates that the developed empirical model on overcut represented by equation 4.3 can be considered as statistically significant and adequate at 95% confidence level.

Table 4.6. 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 4.7, it is found that taper angle of the F-value of the lack-of-fit is 2.84 but the tabulated value is 4.77. The lack-of-fit is insignificant as the calculated value of F is less than the tabulate value. The associated p value for linear effect and four process parameters are less than 0.05 for taper angle. This shows the developed empirical model on taper angle represented by equation 4.4 is highly significant and adequate at confidence level of 95% to represent the relationship between overcut of smaller diameter of stepped hole and the USM process parameters.

Table 4.7. 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%			

4.4. Parametric Analysis for Achieving Better Ultrasonic Machining Characteristics Based on Response Surface Plots

The effects of different process parameters of micro USM like abrasive slurry concentration, power rating and tool feed rate on responses like the material removal rate, overcut and taper angle during machining of quartz plate have been analyzed based on the response surface plots.

4.4.1. Parametric effects on material removal rate (MRR)

Abrasive slurry concentration is one of the important parameter which influences the machining characteristics. The response surface graph shown in Fig. 4.1 illustrate the influence of abrasive slurry concentration and power rating on material removal rate at the same preset values of tool feed rate. Higher MRR can be obtained with higher value of abrasive slurry concentration and power rating, because more material is removed with higher abrasive slurry concentration in micro ultrasonic machining. As power rating is high the abrasive particles strike on the workpiece with high applied force as a result material removal rate becomes high at higher abrasive slurry concentration and high power rating.

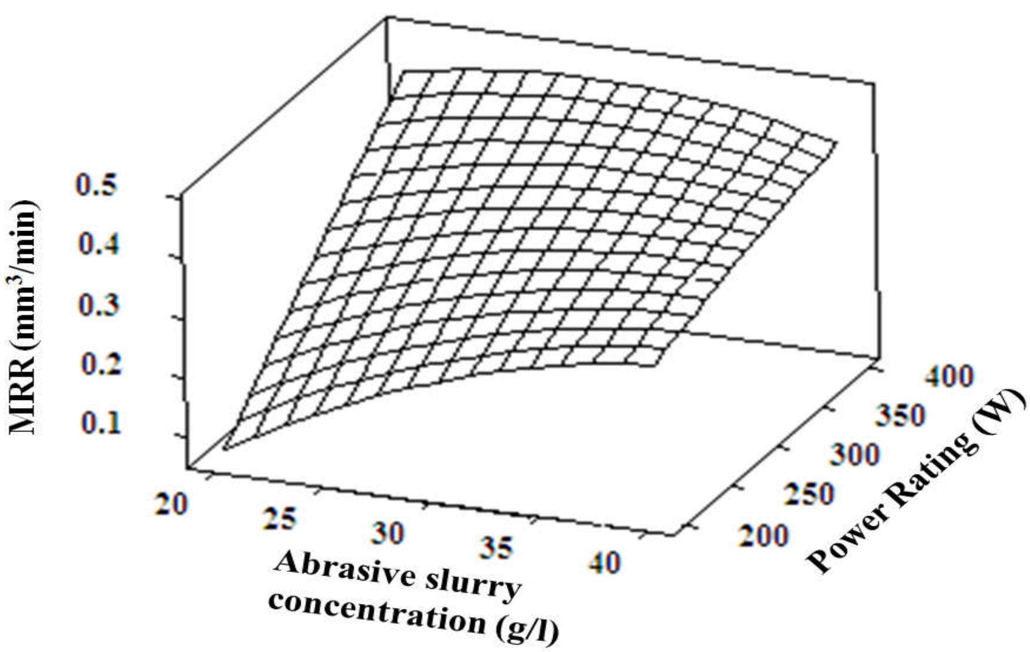

Fig. 4.1 Influences of Abrasive slurry concentration and Power rating on MRR

Fig. 4.2 shows the influences of power rating and tool feed rate on MRR at the same preset value of abrasive slurry concentration. From figure it is clear that MRR increases with increase in power rating and also with increase in tool feed rate. As Tool feed rate increases the momentum of the abrasive particles increases as a result MRR increases.

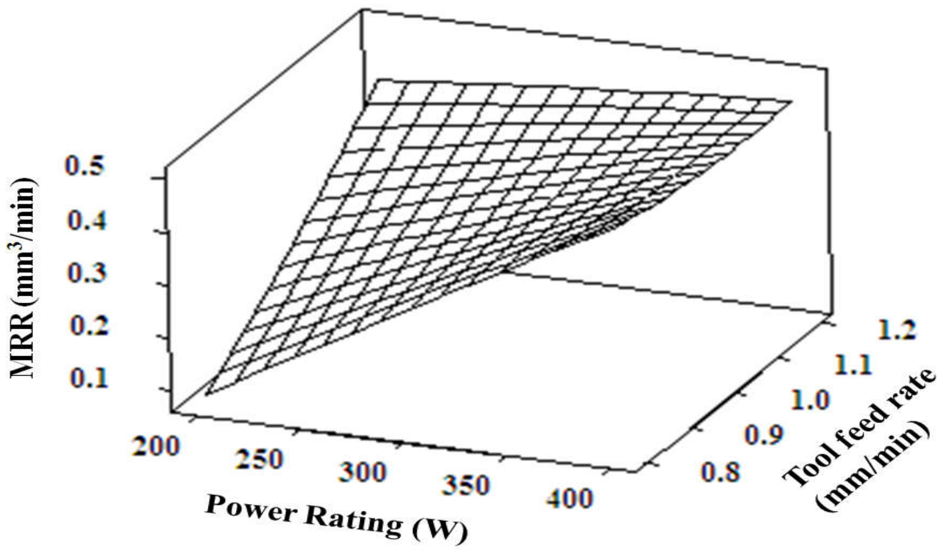

Fig. 4.2 Influences of Power rating and Tool feed rate on MRR

4.4.2. Parametric Effects on Overcut

Fig 4.3 illustrates the influence of abrasive slurry concentration and power rating on overcut of hole at the same preset values of tool feed rate. From the graph it is clear that lowest value of overcut of hole have been observed at the lowest value of abrasive slurry concentration and power rating. Overcut increases from lower value to higher value of abrasive slurry concentration while it changes gradually with abrasive slurry concentration and power rating both.

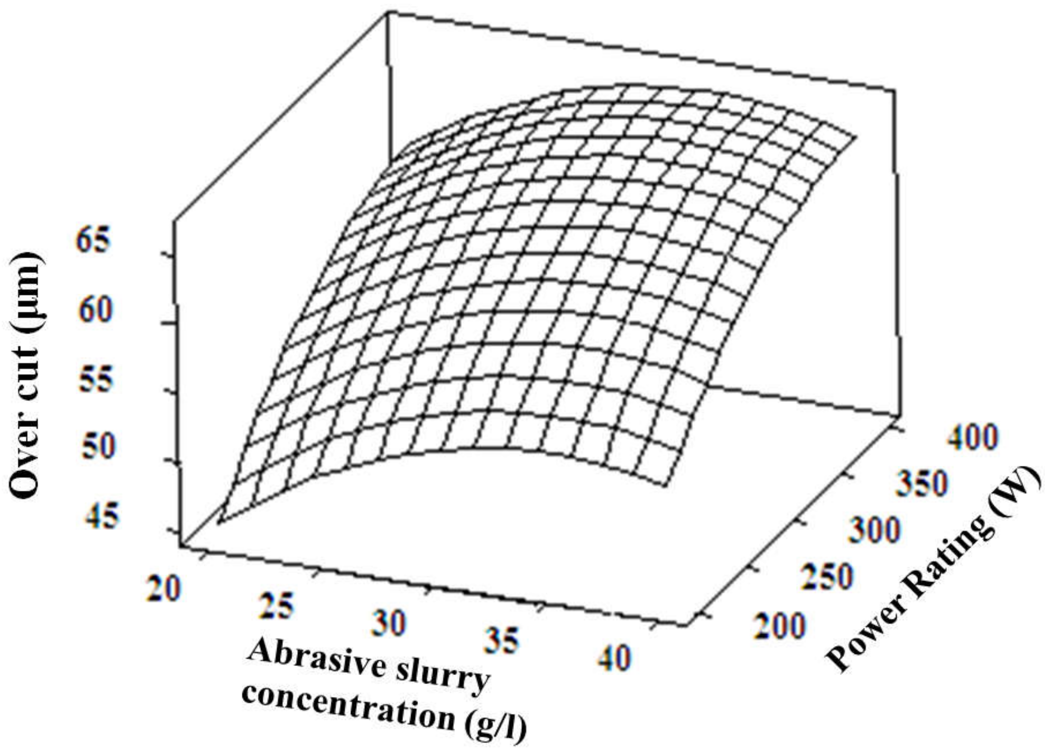

Fig. 4.3 Influences of Abrasive slurry concentration and power rating on overcut

Fig. 4.4 shows the influences of power rating and tool feed rate on overcut of hole at the same preset value of abrasive slurry concentration. From response graph it is observed that lower value of overcut of hole has been observed at the lower value tool feed rate and lower value of power rating. Diametrical deviation is increases slowly with increase in power rating at low feed tool rate and also increased with increase in power rating with high tool feed rate.

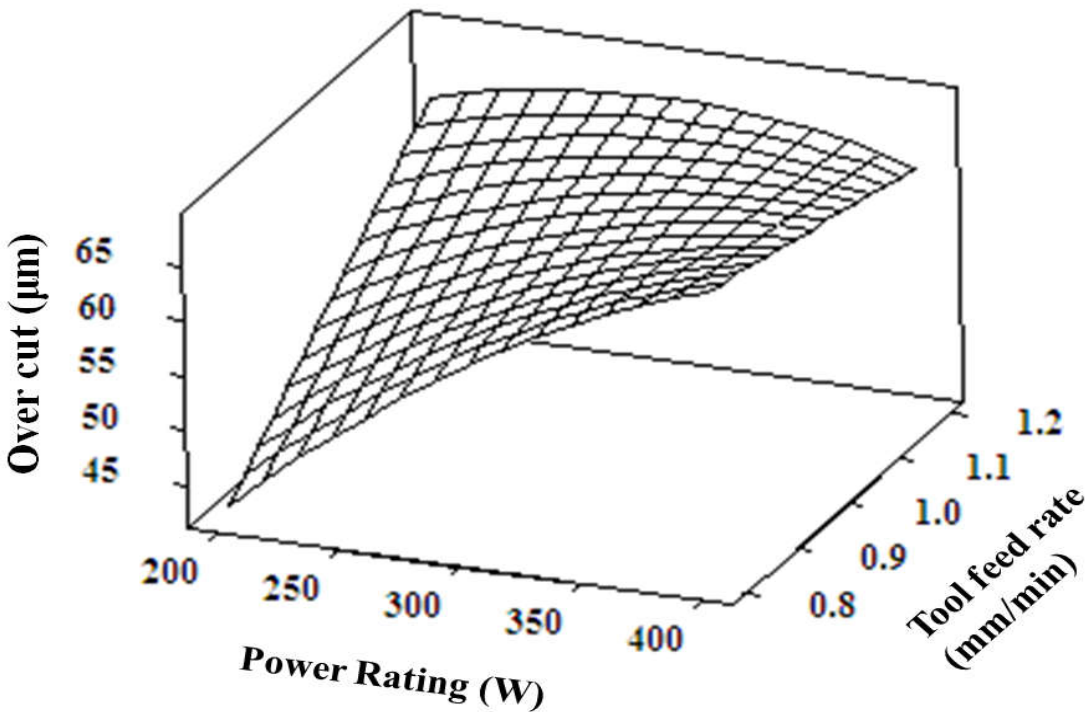

Fig. 4.4 Influences of Power rating and Tool feed rate on overcut

4.4.3. Parametric Effects on Taper Angle

Fig. 4.1 illustrates the influence of abrasive slurry concentration and power rating on taper angle at the same preset values of tool feed rate. Low value of taper angle can be obtained with lower value of abrasive slurry concentration and power rating.

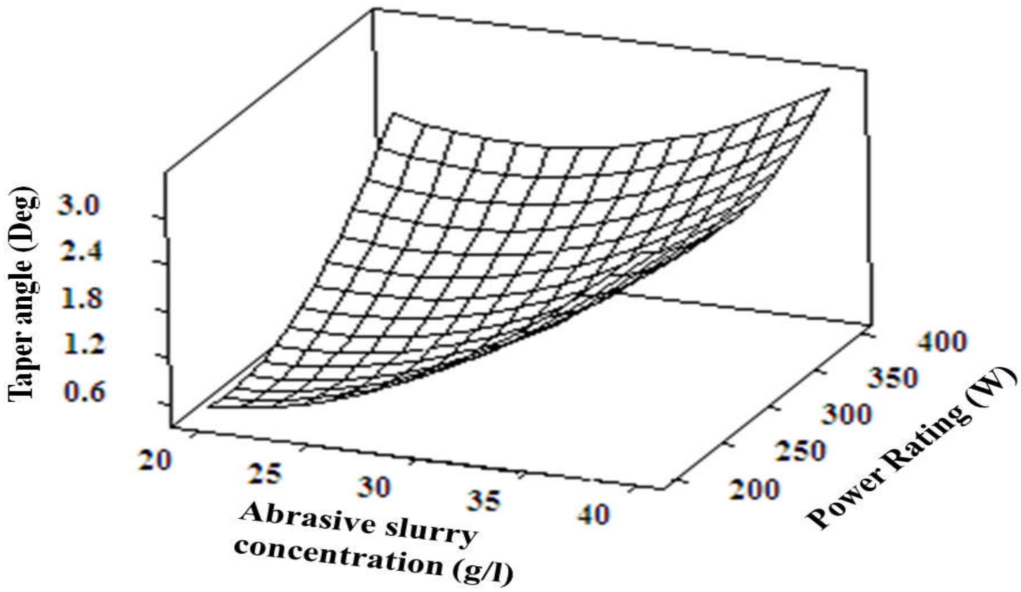

Fig. 4.3 Influences of Abrasive slurry concentration and power rating on taper angle

Fig. 4.6 illustrates the influence of power rating and tool feed rate on taper angle of generated hole at the same preset values of abrasive slurry concentration. From response graph it is clear that lower value of taper angle of generated hole have been observed at the lower value of tool feed rate and lower value power rating. Taper angle of generated hole sharply increase with increases in tool feed rate while power rating is high.

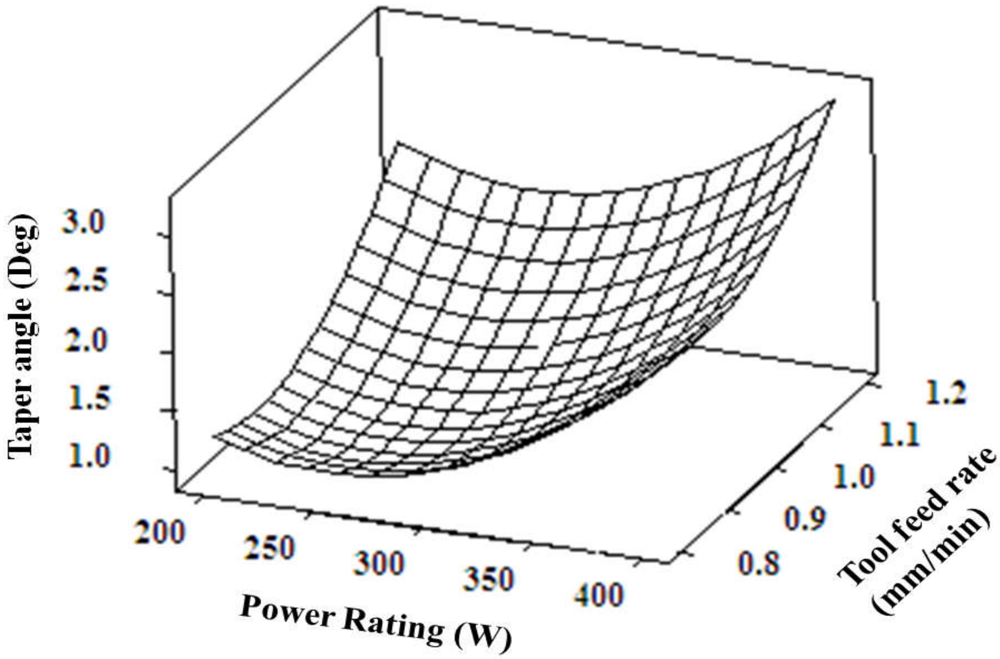

Fig. 4.6 Influences of Power rating and Tool feed rate on taper angle

4.5. Optimization of ultrasonic micro machining of quartz

Single objective optimization as well as multi objective optimization of ultrasonic machining process parameters for generating hole on quartz plate has been performed using MINITAB software. The responses of ultrasonic machining process such as the material removal rate, overcut and taper angle are considered.

4.5.1 Single Objective optimization of ultrasonic micro machining Characteristics

Fig. 4.7 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, high value of power rating and middle value of tool feed rate. For achieving maximum MRR the optimal combination of process parameter are obtained as abrasive slurry concentration of 31.71g/lit, 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 taken as 1.

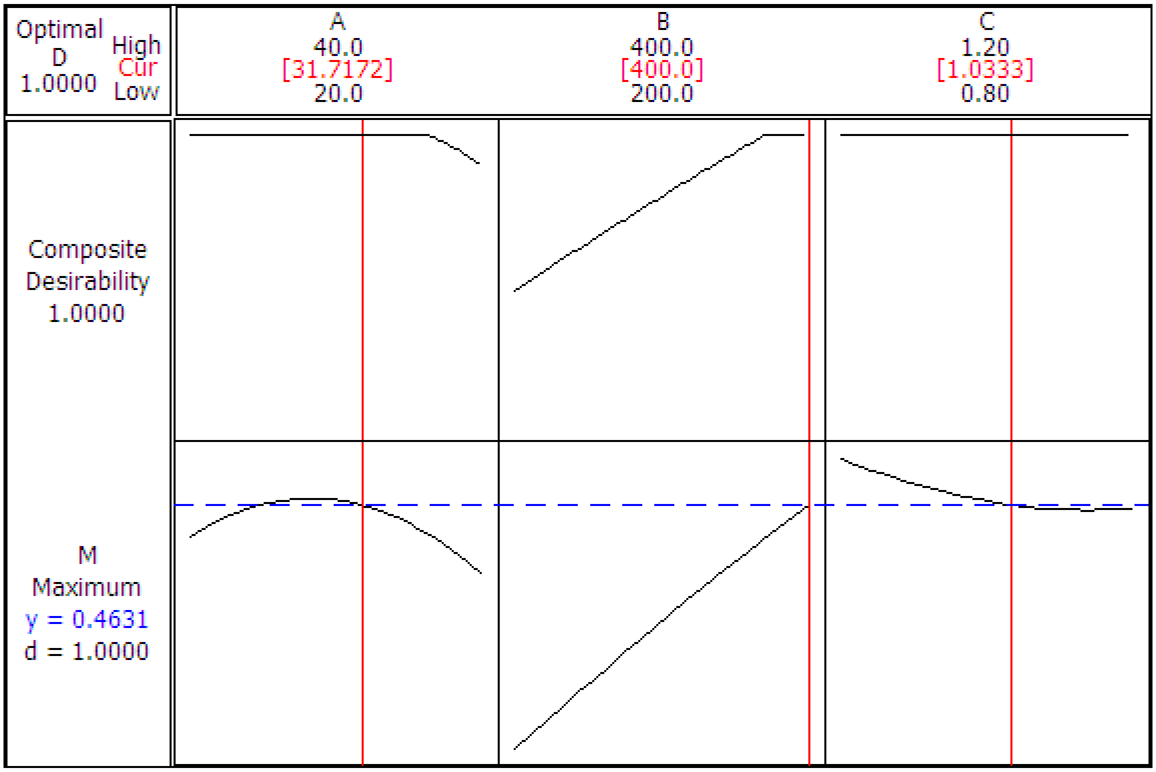

Fig. 4.7 Single objective optimization of material removal rate

Fig. 4.8 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 g/lit, 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 taken as 1.

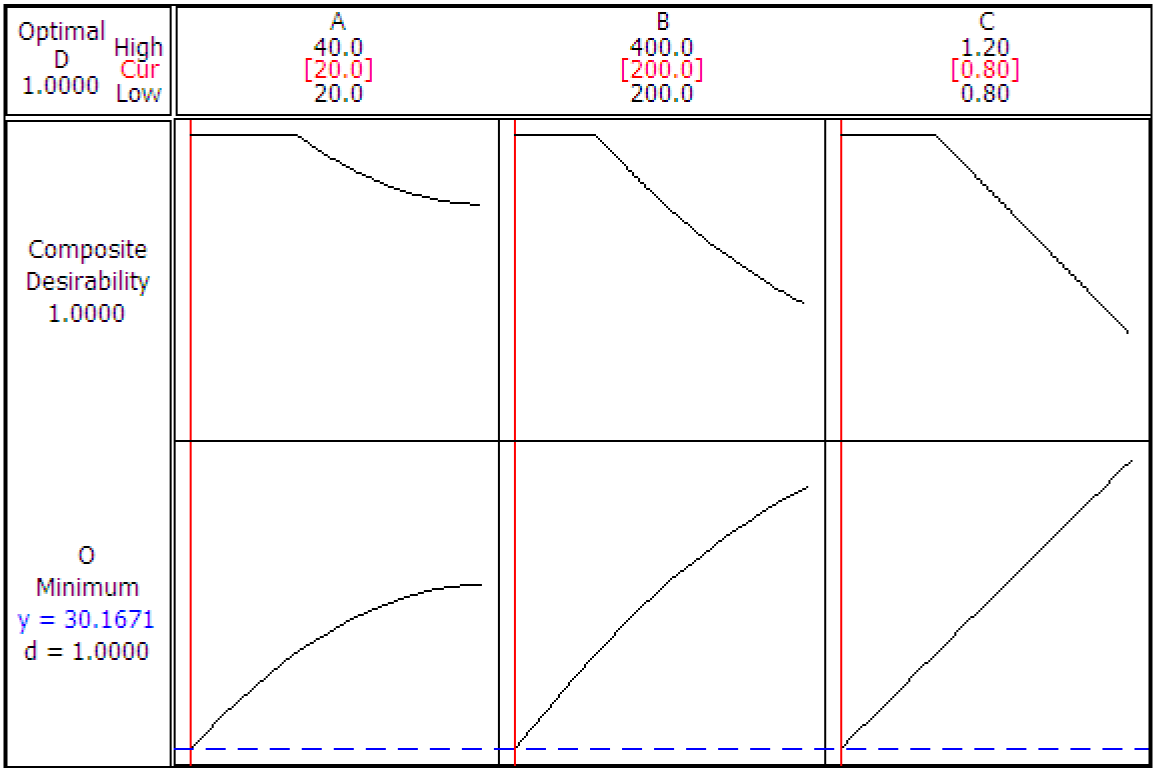

Fig. 4.8 Single objective optimization of overcut of drilled hole

Fig. 4.9 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 g/lit, power rating of 220.2020 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 taken as 1.

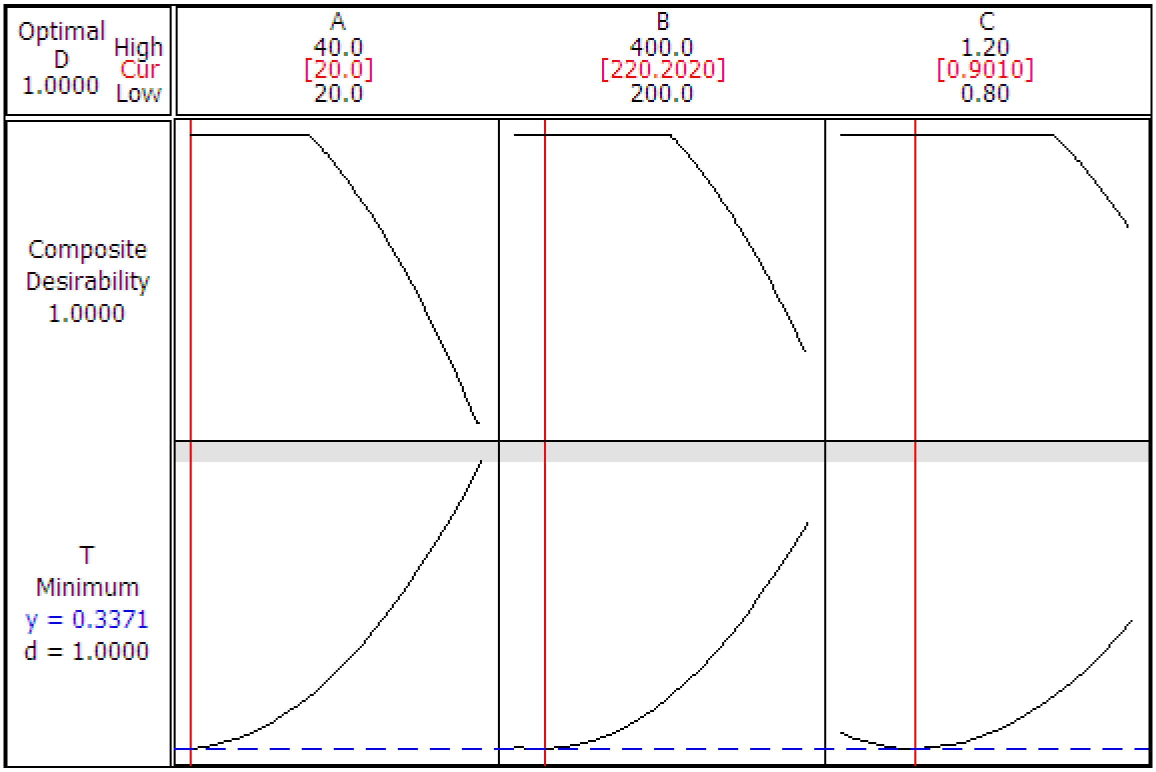

Fig. 4.9 Single objective optimization of taper angle

Table 4.8 shows the results of single objective optimization and compare with actual value and also percent of error.

Table 4.8. 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 g/lit, Power rating 400 W and Tool feed rate 1.0 mm/min	0.4631	0.4502	2.78%
Overcut (µm)	Abrasive slurry concentration 20 g/lit, Power rating 200 W and Tool feed rate 0.8 mm/min	30.1671	31.01	2.79%
Taper angle (degree)	Abrasive slurry concentration 20 g/lit, Power rating 220 W and Tool feed rate 0.90 mm/min	0.3371	0.3425	1.6%

4.5.2. Multi Objective optimization of ultrasonic micro machining Characteristics

The multi objective optimization has been done to obtain the optimal combination of process parameters for maximum material removal rate, minimum overcut and minimum taper angle. Fig. 4.10 shows the result of multi objective optimization of material removal rate, overcut and taper angle. The optimal values of process parameters are obtained as abrasive slurry concentration of 23.43 g/lit, power rating of 290.84 W and tool feed rate of 0.80 mm/min. The maximum value of MRR is of 0.2008 mm^3/min, minimum value of overcut achieved is 50.29 µm and minimum value of half taper angle achieved is 0.7880^0 through optimization. The value of overall composite desirability (d) is taken as 1.

In the optimal solution 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 slurry concentration is more significant than quantity of slurry flow under normal working conditions whereas lower 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 have been performed at optimal parametric combination and the actual responses were observed. Table 4.10 shows the result of multi objective optimization and compare with actual value and also percent of errors are listed. It is found that the percentage of errors for all the responses is within 5%.

Table 4.8 percentage of error for multi objective optimization

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

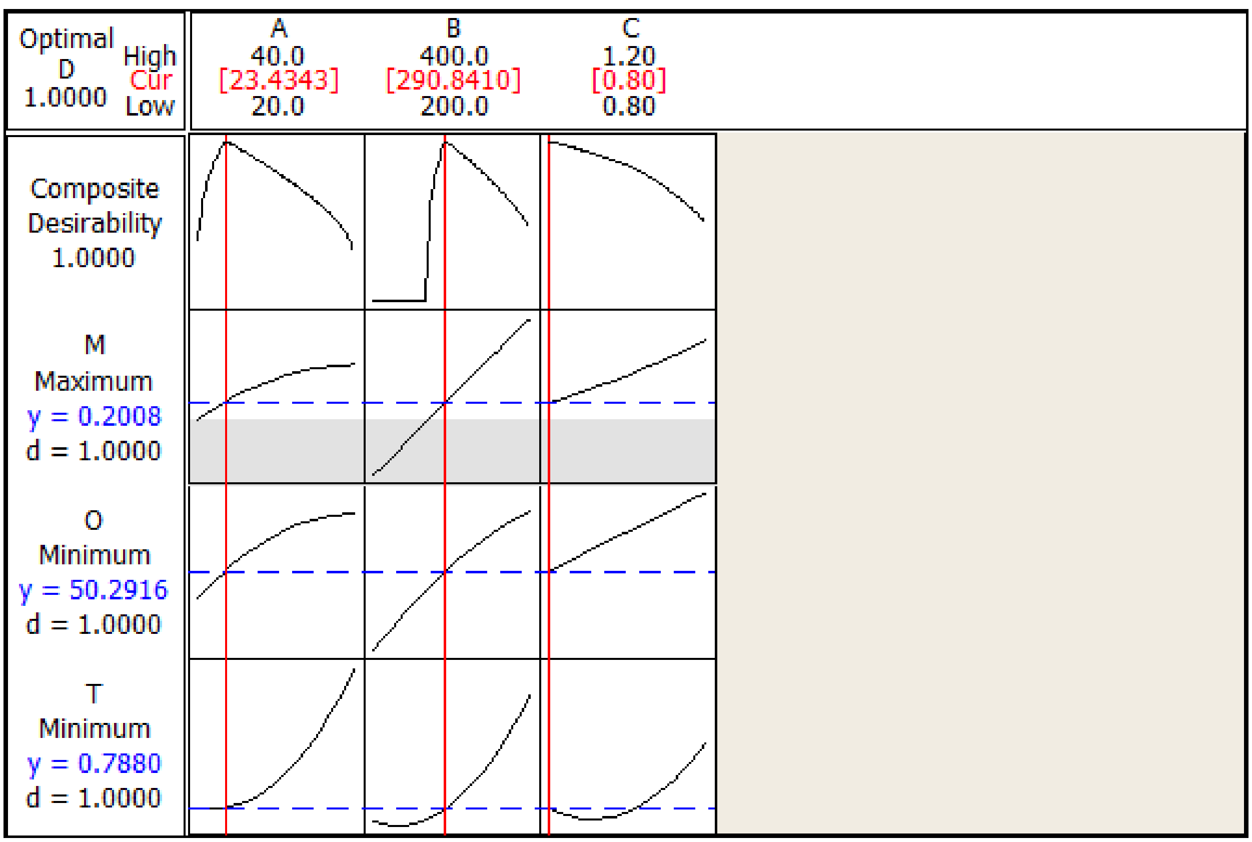

Fig. 4.10 Multi objective optimization of material removal rate, overcut, and taper angle during micro ultrasonic machining of quartz

4.6. Analysis Based on Photographic Exhibits of Micro-Drilled Hole on Quartz Materials

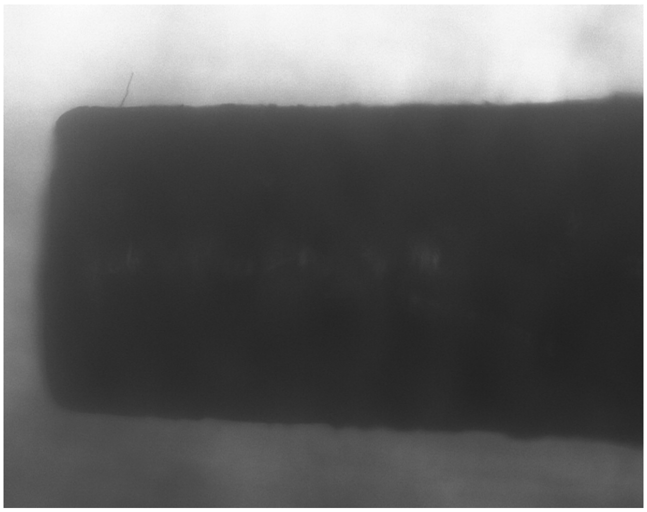

Fig.4.12 Tool tip before machining

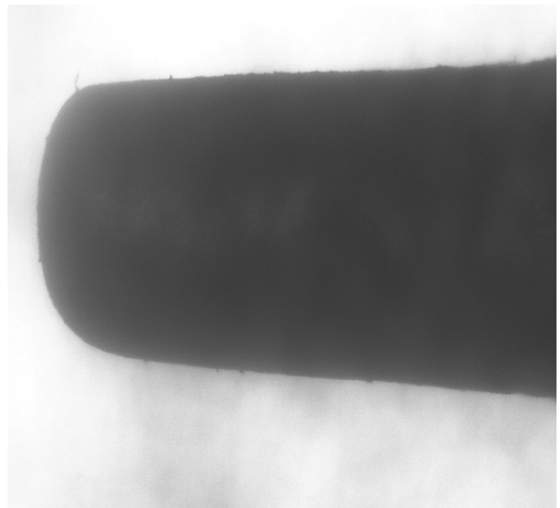

Fig.4.13 Tool tip after machining

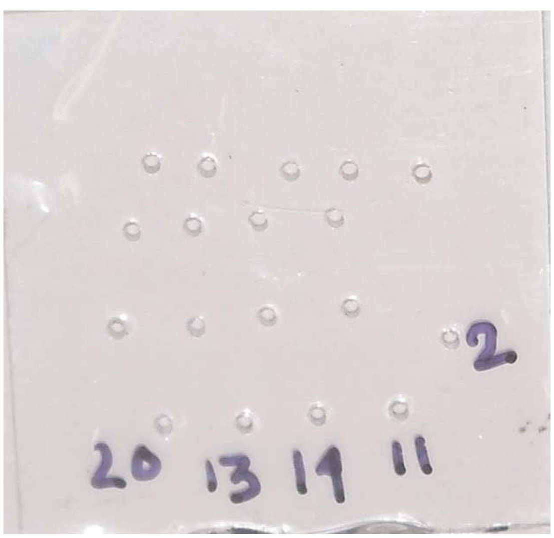

Fig. 4.11 Photographic view of the machined workpiece after machining

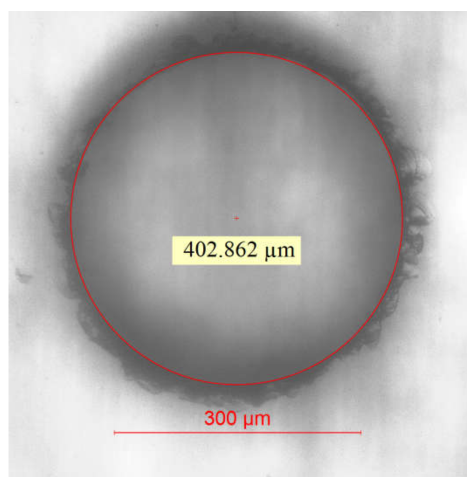

Fig. 4.12 Photographic view of the machined workpiece at multi objective parametric setting

CHAPTER-5

General Conclusion

5. GENERAL CONCLUSIONS

The experimental investigations highlights that the ultrasonic machining characteristics like material removal rate, overcut and taper angle for generating micro hole on quartz are influenced by the various major machining parameters as abrasive slurry concentration, power rating and tool feed rate. Response surface methodology used in the present research work has proved its adequacy to be an effective tool for analysis of the micro USM process. The influence of different process parameters on machining performance criteria are exhibited through response surface plots. Based on the basic parametric studies and optimization analysis in the present investigation, the following conclusions have been drawn:

I. Micro ultrasonic machining process can be effectively used to generate micro hole.

II. From the basic parametric studies it is observed that the abrasive slurry concentration and tool feed rate are the most important parameters which had more influence of the MRR, overcut and taper angle.

III. The developed mathematical models on MRR, overcut and taper angle are found as adequate to analyse the effects of process parameters on response characteristics of hole on quartz by micro ultrasonic machining process.

IV. Form the response graphs based on RSM models it is observed that MRR increases with increases in abrasive grit size with little variation on values of power rating. Less overcut has been achieved with a combination of medium power rating and higher value of slurry concentration. Lower value of taper angle has been observed at the medium level of tool feed rate and medium level of slurry concentration.

V. For achieving maximum MRR the optimal combination of process parameters obtained as abrasive slurry concentrations of 31.71 g/lit, power rating of 400 W and tool feed rate of 1.03 mm/min. The maximum MRR is obtained as 0.4631mm^3/min.

VI. For achieving minimum overcut the optimal combination of process parameters obtained as abrasive slurry concentrations of 20 g/l, power rating of 200 W and tool feed rate of 0.8 mm/min. The minimum overcut is obtained as 30.16 μm.

VII. For achieving minimum half taper angle the optimal combination of process parameters obtained as abrasive slurry concentrations of 30 g/l, 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$^{0.}$

VIII. The multi objective optimization was performed to obtain the optimal parameters to gate maximum material removal rate, minimum overcut and minimum taper angle. The optimal values are abrasive slurry concentration of 23.43 g/lit, power rating of 290 W and tool feed rate of 0.80 mm/min. The maximum value of MRR is 0.2008 mm^3/min, minimum value of overcut achieved is 50.29 µm and minimum value of taper angle achieved is 0.7880^0.

IX. The experiments are conducted at optimal process parametric settings and the percentage of error 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 result and analysis is quit adequate and acceptable.

It is evident from the present research work on ultrasonic machining process on quartz material will be useful in the area of optical and micro sensor etc. The observed results can be used as information in the technical guidelines for carrying out further research activities in the areas of ultrasonic machining. Research activities on optimization of USM based on RSM will open up many challenging possibilities such as selection of controlling parameters for production of non-circular holes and cavities, micro channel on quartz with geometrical and dimensional accuracy with high aspect ratio.

The further scope of research includes the following:

a. To generate non circular micro holes of various complicated shapes on quartz material, further experimental investigation into Ultrasonic micro machining can be carried out.
b. Further experimental investigation into Ultrasonic machining of quartz can be carried out for generating the array of micro holes.

c. Further experimental investigation into Ultrasonic micro-machining of various quartz can be carried out by developing different tool shape and size for micro machining operation such as micro channeling and micro milling etc for generating various features needed for industrial micro engineering applications.

BIBLIOGRAPHY

[1] Anjali Gupta, Jaswinder Singh Mehta, Rajesh Madan, Micro Ultrasonic Machining: A Brief Outlook; Conference paper on Emerging Trends in Engineering and Technology. 03. AETS. (2013).3.250.

[2] Kai Egashira, Takahisa Masuzawa, Micro ultrasonic Machining by the Application of Work piece Vibration, Annals of ClRP, (1999), 48, 7,799.

[3] Xi-Qing Suni, T. Masuzawa, M. Fujino, Micro ultrasonic machining and its applications in MEMS; Sensors and Actuators A: Physical, November (1996), Vol 57; no. 2, pp. 159-164.

[4] W. Peia, Z. Yua,b, J. Lia, C. Maa, W. Xua, X. Wanga, W. Natsuc, Influence of abrasive particle movement in micro USM. Procedia CIRP, (2013), pp.551 – 555.

[5] Anupam Viswanath, Tao Li, Yogesh B. Gianchandani, High Resolution micro Ultrasonic Machining (HR-μUSM) For post fabrication Trimming Of Fused SIlica 3-D microstructures, IEEE International Conference on Micro Electro Mechanical Systems (MEMS), (2014), pp. 494-497.

[6] A. Schorderet, E. Deghilage, K. Agbeviade, Tool type and hole diameter influence in deep ultrasonic drilling of micro-holes in glass, Procedia CIRP, (2013), vol. 6, pp. 565 – 570.

[7] Manjot S. Cheema , Akshay Dvivedi, Apurbba K. Sharma, Tool Wear Studies in Fabrication of Microchannels in Ultrasonic Micromachining, Ultrasonics, (2015),vol. 57, pp. 57–64.

[8] K.P. Rajurkar, Murali M Sundaram, An article on Process improvements in micro USM and micro EDM, (2008), Vol 2,pp. 221-226.

[9] Vivek Jain, Apurba Sharma, Pradeep Kumar, Recent Developments and Research Issues in Microultrasonic Machining, International Journal, (2011), Article ID 413231,

[10] Reimund Neugebauer, Andrea Stoll, Ultrasonic application in drilling, Journal of Materials Processing Technology, (2004), vol.149, pp. 633–639

[11] Kuriyagawa, Tsunemoto, Micro Ultrasonic Abrasive Machining for Three-Dimensional Milli-Structures of Hard–Brittle Materials, Proceedings of the 16th ASPE Annual Meeting, (2001).

[12] Huan Qi, Donghui Wen , Congda Lu, Gang Li, Numerical and experimental study on ultrasonic vibration-assisted micro-channeling of glasses using an abrasive slurry jet, International Journal of Mechanical Sciences, (2016) ,vol. 110, pp. 94–107.

[13] E. Kai, T. Tomoya, T. Hachiro and M. Makoto, Micro-ultrasonic Machining Using Multitools, in Proceedings of The 7th International Conference on Progress of Machining

Technology, Japan,(2004).

[14] Z. Yu, X. Hu, K. P. Rajurkar, Influence of Debris Accumulation on Material Removal and Surface Roughness in Micro Ultrasonic Machining of Silicon, CIRP Annals- Manufacturing Technology, (2007), vol. 55, no. 1, pp. 201-204.

[15] Z. Yu, C. Ma, J. Li, D. Guo, Prediction of Tool Wear in Micro USM, CIRP Annals - Manufacturing Technology, (2012), vol. 61, no. 1, pp. 227–230.

[16] H. Zarepour, S. H. Yeo, Single Abrasive Particle Impingements as a Benchmark to Determine Material Removal Modes in Micro Ultrasonic Machining, Wear, (2012) vol. 288, pp. 1-8.

[17] Chen Zhang, Ping Guo, Kornel F. Ehmann, Yingguang Li, Effects of Ultrasonic Vibrations In Micro-Groove Turning, Ultrasonics, (2016), vol.67, pp. 30–40.

[18] Jianjian Wang, Huiting Zha, Pingfa Feng, Jianfu Zhang, On The Mechanism of Edge Chipping Reduction in Rotary Ultrasonic Drilling: A Novel Experimental Method, Precision Engineering, (2016), vol. 44, pp 231–235.

[19] W. M. Zeng, Z. C. Li, Z. J. Pei, C. Treadwell, Experimental Observation of Tool Wear in Rotary Ultrasonic Machining of Advanced Ceramics, International Journal of Machine Tools & Manufacture, (2005),vol. 45, no. 12-13, pp. 1468–1473.

[20] D. Liu, W. L. Cong, Z. J. Pei, Y. Tang, A Cutting Force Model for Rotary Ultrasonic Machining of Brittle Materials, International Journal of Machine Tools & Manufacture,(2012) vol. 52, no. 1, pp. 77-84.

[21] H. Zarepour, S. H. Yeo, Single Abrasive Particle Impingements as a Benchmark To Determine Material Removal Modes in Micro Ultrasonic Machining, Wear, (2012), vol. 288, pp. 18.

[22] I. S. Kang, J. S. Kim, Y. W. Seo, J. H. Kim, An Experimental Study on the Ultrasonic Machining Characterstics of Engineering Ceramics, Journal of Mechanical Science and Technology,(2006), vol. 20, no. 2, pp. 227-233.

[23] V. Yadava, A. Deoghare, Design of Horn for Rotary Ultrasonic Machining Using the Finite Element Method, International Journal Advanced Manufacturing Technology, (2008), vol. 39, no. 1-2, pp. 9–20.

[24] A. Curodeau, J. Guay, D. Rodrigue, L. Brault, D. Gagne, L. P. Beaudoin, Ultrasonic abrasive micro-machining with thermoplastic tooling, International Journal of Machine Tools and Manufacture,(2008), vol. 48, no. 14, pp. 1553– 1561.

[25] N. J. Churi, Z. J. Pei, C. Treadwell, Rotary Ultrasonic Machining of titanium alloy: Effects of machining variables, Machining Science and Technology, (2006) vol. 10, no. 3, pp. 301-321.

[26] X. Wang, M. Zhou, J. K. Gan, B. Ngoi, Theoretical and Experimental Studies of Ultra-precision Machining of Brittle Materials with Ultrasonic Vibration, International Journal Advanced Manufacturing Technology,(2012), vol. 20, no. 2, pp. 99–102.

[27] F. W. Haw, C. C. Lii, C. W. Chen, C. T. Tung, C. C. Woei, Study on the Surface Integrity of Micro-Ultrasonic Machined Glass-ceramic Material, Key Engineering Materials, (2009),Vol. 407-408, pp. 731-734.

[28] P. L. Guzzo, A.H. Shinohara, A Comparative Study on Ultrasonic Machining of Hard and Brittle Materials, Journal of Brazilian Society of Mechanical Sciences and Engineering, (2004), vol. 26, pp. 56-64

[29] Guojun Dong, Haijun Zhang, Ming Zhou, Yuanjing Zhang, Experimental Investigation on Ultrasonic Vibration-Assisted Turning of SiCp/Al Composites Materials and Manufacturing Processes, (2013), Vol.28, pp. 999–1002,

[30] Shrikrushna B. Bhosalea, Raju S. Pawade, P.K. Brahmankar, Effect of Process Parameters on MRR, TWR And Surface Topography In Ultrasonic Machining of Alumina–Zirconia Ceramic Composite. Ceramics International, (2014), vol.40, pp. 12831–12836,

[31] Deng Jianxina, Lee Taichiub, Ultrasonic Machining of Alumina-Based Ceramic Composites, Journal of the European Ceramic Society, (2002), vol. 22, pp. 1235–1241.

[32] R. Singh, J. S. Khamba, Mathematical Modeling of Tool Wear Rate in Ultrasonic Machining of Titanium, International Journal of Advanced Manufacturing Technology, (2009),vol. 43, no. 5-6, pp. 573–580.

[33] Guodong Lia, Zuyuan Yua, Jiawen Songa, Can Lia, Jianzhong Lia, Wataru Natsu; Material Removal Modes of Quartz Crystals by Micro USM, Procedia CIRP, (2016),vol.42, pp. 842 – 84.

[34] Xingzhi Xiao, Kan Zheng, Wenhe Liao, Heng Meng, Study On Cutting Force Model In Ultrasonic Vibration Assisted Side grinding of Zirconia Ceramics, International Journal of Machine Tools & Manufacture, (2016), vol.104, pp. 58–67.

[35] M. Kuruc, T. Vopát, J., Peterka Surface Roughness of Poly-Crystalline Cubic Boron Nitride after Rotary Ultrasonic Machining, Procedia Engineering, (2015), vol.100, pp. 877 – 884.