AN INVESTIGATION INTO THE MACHINING CHARACTERISTICS OF COMPOSITES USING CHEMICAL ASSISTED ULTRASONIC MACHINING PROCESS

A thesis submitted in partial fulfillment of the

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DECLARATION

This is to certify that the thesis entitled **"An investigation into the machining characteristics of composites using chemical assisted ultrasonic machining process"** is an authentic record of my study carried out as requirements for the award of the degree of **Master of Engineering in Mechanical (Production and Industrial) Engineering** to **Thapar University, Patiala,** under the guidance of **Dr. Vinod Kumar Singla ,** Associate Professor, Department of Mechanical Engineering, Thapar University, Patiala during **Jan 2012 to Dec 2012.** This matter embodied in this thesis has not been submitted in part or full to other university or institute for the award of any degree.

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ABSTRACT

Ultrasonic Machining (USM) is one of the earliest non-traditional machining process and is a family of relatively modern material finishing and shaping processes described as chip less machining. It is a mechanical material removal process used to erode holes and cavities in hard or brittle work pieces by using shaped tools, high frequency mechanical motion and abrasive slurry.

In the present study, the chemical-assisted ultrasonic machining (CUSM) method is introduced in order to improve the material removal rate and the integrity of the machined surface. For this a low concentration hydrofluoric acid solution is added to the alumina slurry. The effect of different input parameters namely Power Rating, Tool type, Slurry type, Slurry Concentration and Grit Size on the output parameters namely MRR, TWR, SR and Hardness was studied. A number of factors and their different levels are selected. Based on factors and their levels number of experiments are selected using orthogonal array. The effect of various input parameters on output parameters is analysed using statistical technique such as ANOVA. Optimization and verification of the process parameters and the modelling of the results is done by applying Regression Analysis. Main effect plot and Residual plot for significant factors and S/N ratio have been used to determine the optimal design for each output response. In the end, the effect of Chemical Assisted Ultrasonic Machining process is compared with conventional USM process on the basis of output parameters such as MRR and SR.

Through various experiments and comparison with conventional results, the superiority of CUSM is verified. The material removal rate increase to 40% also the surface quality of the material was also determined..

ABBREVATIONS

ANOVA	Analysis of Variance
USM	Ultrasonic Machining
CUSM	Chemical Assisted Ultrasonic Machining
MRR	Material Removal Rate
TWR	Tool Wear Rate
SR	Surface Roughness
SEM	Scanning Electron Microscope
S/N	Signal to Noise Ratio
SS	Stainless Steel
HSS	High Speed Steel

NOTATIONS

OA	Orthogonal Array
A	Tool Material
B	Power Rating(%)
C	Slurry Concentration(%)
D	Abrasive Slurry
E	Abrasive Grit Size
CI	Confidence Interval
SS	Sum of Squares
SS'	Pure Sum of Squares

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1 INTRODUCTION

With the development of technology, the scientists and technologists in the field of manufacturing are facing more and more challenges. Technologically advanced industries such as aeronautics, nuclear reactors and automobiles have been demanding high strength temperature resistant (HSTR) materials having high strength to weight ratio. Researchers in the area of materials science are developing materials having higher strength, hardness, toughness and other diverse properties. This also needs the development of improved cutting tool materials so that productivity is not hampered.

1.1 Introduction to non-traditional machining

It is a well established fact that during conventional machining processes an increase in the hardness of work material results in decrease in the economic cutting speed. It is no longer possible to find tool materials which are sufficiently hard and strong to cut (at economic cutting speeds) materials such as titanium, stainless steel, fiber-reinforced composites, ceramics and stellites. Production of complex shapes in such materials is still more difficult using conventional methods .Other higher level requirements such as better surface quality, low value of tolerances, higher production rates and miniaturization pose greater problems in machining of such materials. Making of holes (shallow entry angles, non-circular, micro holes, large aspect ratio, contoured holes and holes without burr) in is another area where extensive research is needed.

To meet such demands, a different class of machining processes known as non-traditional machining processes has been developed. These new methods are also called unconventional in the sense that conventional tools are not employed for metal cutting. Instead, the energy in its direct form is utilized to remove the material from the workpiece. The range of application of the newly developed machining processes is determined by the work material properties such as electrical and thermal conductivity, melting temperature, electrochemical equivalent etc. The use of these processes is becoming increasingly unavoidable and popular at the shop floor.

Non-traditional machining processes can be classified into four basic categories on the basis of type of energy involved for machining purpose. The material removal mechanism, machining system components, process variables, technological characteristics and industrial applications are different for all these processes [1].

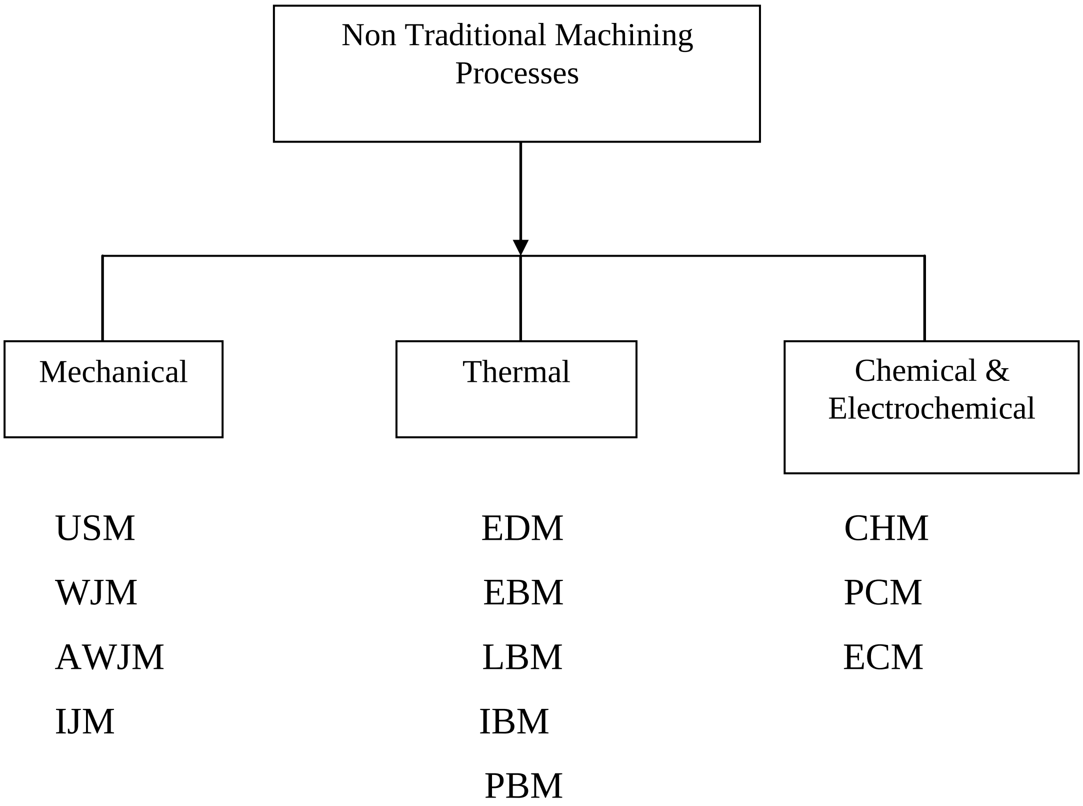


Fig.1.1 Classification of Non-Traditional Machining Processes [1]

1.2 Ultrasonic Machining

Ultrasonic Machining (USM) is a non-conventional mechanical material removal process used for machining both electrically conductive and non-metallic materials; preferably those with low ductility and a hardness above 40 HRC such as inorganic glasses, ceramics, quartz etc. USM has been variously termed ultrasonic drilling; ultrasonic cutting; ultrasonic abrasive machining and slurry drilling.

In USM, process operates at ultrasonic frequencies and typical frequencies used in the ultrasonic machining process range between 20 and 40 KHz. The equipment used is based upon a generator energizing a magnetostrictive or piezoelectric transducer which in turn causes an attached tool to vibrate. The power ratings range from 50 to 3000 W and a controlled static load is applied to the tool to provide feed in the longitudinal direction. Abrasive slurry, which is a mixture of abrasive material such as silicon carbide, boron carbide or alumina suspended in water or some suitable carrier medium is continuously pumped across the gap between the tool and work (25–60 μm). The vibration of the tool causes the abrasive particles held in the slurry to impact the work surface leading to material removal by micro-chipping. The vibrating tool transfers energy to abrasive particles carried, within a slurry, underneath the tool tip. The interaction between these particles and the work piece result in the formation of mirror image of the tool tip in the surface of the work piece.

USM is generally associated with low material removal rates, however its application is not limited by the electrical or thermal characteristics of the work material. Holes as small as 76 μm in diameter can be drilled, however the depth to diameter ratio is limited to 3:1. For efficient machining to take place, the tool and horn must be designed with consideration given to mass and shape so that resonance can be achieved within frequency range capability of the ultrasonic machine.

1.3 Need for Ultrasonic Machining

The process is regarded as competitive only when an operation cannot be practically and economically performed on conventional machining equipment. Materials are not altered either chemically or metallurgically during ultrasonic machining. USM is used to machine very hard and difficult to machine by conventional methods. Glass is a material difficult to machine by any means but good result have been obtained as a result of ultrasonic machining.

1.4 Historical background of Ultrasonic Machining

The history of Ultrasonic Machining (USM) began with a paper by R.W. Wood and A.L Loomis in 1927 and the first patent was granted to L. Balamuth in 1945. The use of ultrasonic in machining was first proposed by J.O. Farrer in 1945. Farrer was the patent agent on the first issued patent, British patent no.602801 (1945), issued to an American engineer, L. Balamuth, who discovered ultrasonic machining accidentally in 1942, while he was investigating the dispersion of solid in liquid by means of a magnetostrictively vibrating nickel tube. The United States patent, for the process, no.2580716 was issued in 1962.In 1960 Rozenberg's crediting to Farrer is an exquisite example of the unfortunate high frequency of "noise" when scientific information crosses language barriers.

The first report on the equipment and technology appeared during 1951-52 by 1954, the machine tools, using the ultrasonic principle, had been designed and constructed. Originally USM was used to be a finishing operation for the component processed by the electro spark machines. However, this use becomes less important because of the development in electric discharge machining. But then with the boom in solid state electronics, the machining of electrically non conducting, semi conductive and brittle material become more and more important For this reason ultrasonic machining is gaining importance and prominence. In recent years, various types of ultrasonic machine tool have been developed. USM technique is still far from perfect.

1.5 Principle of Ultrasonic Machining

It is the removal of material by the abrading action of grit-loaded liquid slurry circulating between the workpiece and a tool vibrating perpendicular to the workface at high frequency and an amplitude in the order of 0.01 mm to 0.06 mm. Ultrasonic machining, also known as Ultrasonic Impact Grinding, is a machining operation in which an abrasive slurry freely flows between the workpiece and a vibrating tool. The tool is pressed against the work surface under a load of few kilograms and fed downwards continuously as the cavity is cut in the work. Fig.1.2 shows USM process principle. The tool never contacts the workpiece and as a result the grinding pressure is rarely more, which makes this operation perfect for machining extremely hard and brittle materials, such as glass, ruby, diamond, and ceramics.

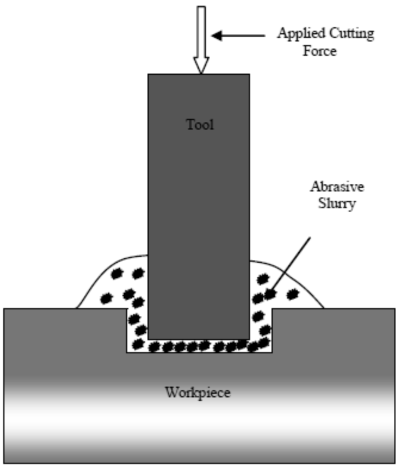


Fig.1.2 USM process principle (tool-abrasives-work piece interactions) [49]

The working process of an ultrasonic machine is performed when its tool interacts with the workpiece or the medium to be treated. The tool is subjected to vibration in a specific direction, frequency and intensity. The vibration is produced by a transducer and is transmitted to the tool using a vibration system, often with a change in direction and amplitude.The workpiece is placed under the face of the tool which is subjected to high frequency vibration perpendicular to the surface being machined. Abrasive slurry is conveyed to the working zone between the face of the tool and the surface being machined. The tool moves towards the workpiece and is subjected to a static driving force. Repetitive impact of the tool on the grains of the abrasive material, falling from the slurry onto the surface to be treated , lead to the fracture of the workpiece material and to the creation of a cavity with the shape mirror formed of the tool. The abrasive particles are propelled or hammered against the workpiece by the transmitted vibrations of the tool. The particles then microscopically erode or "chip away" at the workpiece. The process can cut virtually any material but is most effective on material with hardness greater than HRC= 0.45.

The USM equipment consist of an oscillator (high frequency current generator) that converts the 50Hz (c/s) power supply into high frequency (15 KHz to 30 KHz) power which in turn is converted into mechanical oscillations with the help of a magnetostrictive or piezo-electric transducer of the two type, the piezo-electric transducer are most efficient, i.e. they involve less loss of power and hence do not require cooling. The magnetiostrictive transducers generally found in old machines are less efficient due to high eddy current losses and hence may require cooling.

The power rating of modern machines varies from 0.04 to 4 KW. Some of the designs have rating even up to 10 KW.
Power supply is: potential volts = 220, current = 12A.

1.6 Basic elements of USM

The machine for USM ranges from small, table top sized units to large- capacity machine tools. In addition to part size capacity of a USM machine, suitability for a particular application is also determined by the power rating. The power of USM machine is rated in watts and can range from 40 W to 2400W. The material removal rate is directly related to the power capability of the USM machine. The entire USM machine share common subsystem regardless of the physical size or power. The ultrasonic machining process consists of the following basic element

1.6.1 The ultrasonic power supply and transducer.
1.6.2. The tool holder
1.6.3. The tool

1.6.4. The abrasive slurry

1.6.5. The work-piece

A detailed description of these components is given as following:

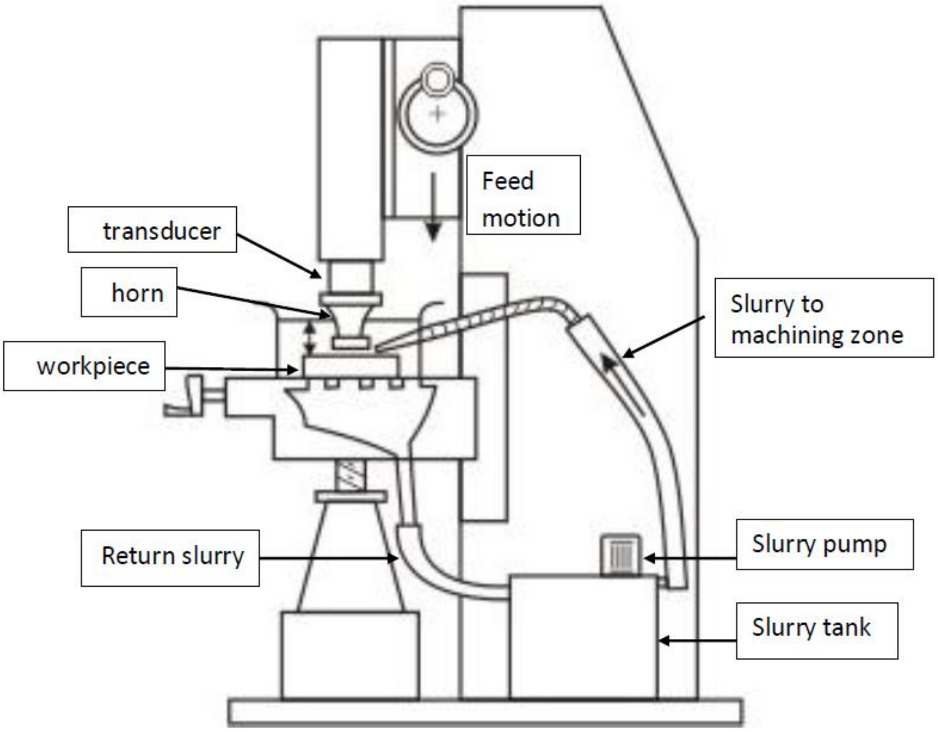


Fig.1.3 Basic Elements of USM [49]

1.6.1 The ultrasonic power supply and transducer

The solid state variable output power supply with internal and external power control converts (50-60) Hz electrical power into 20,000 electrical power. This electrical signal is then supplied to the transducer for conversion into mechanical motion. The power supply for an ultrasonic machine tool is more accurately characterized as a high power sine wave generator that offers the user control over both the frequency and power of the generated signal.

The transducer is a device that converts energy from one form to another. In the case of transducer for USM, electrical energy is converted to mechanical motion.The two types of transducers used for ultrasonic machining are based on two different principles of operations:

a) Piezoelectric Transducer
b) Magnetostrictive Transducer

Because of its lower Q value (Q is a measure of the sharpness of the peak value of energy); the magnetostrictive transducer allows vibration to be transmitted over a wide frequency and [70]. It also allows greater horn design flexibility and can accommodate tool wear. The major drawback of magnetostrictive transducer is high electrical losses and low energy efficiency (about 55-60%). On the other hand, piezoelectric transducers are more energy efficient (90-96%). Also this type of transducers can generate high vibration intensities as compared to magnetostrictive transducers. Magnetostrictive transducers are usually constructed from a laminated stack of nickel sheets.

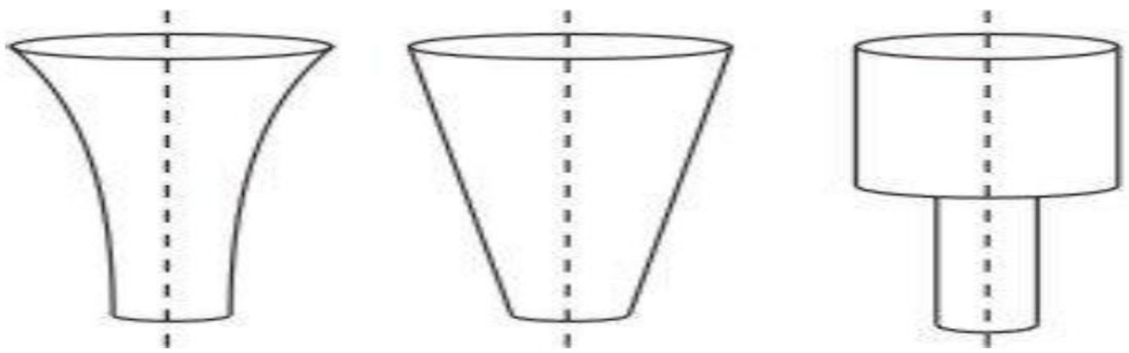
1.6.2. The tool holder

The tool holder transfers the vibrations to the tool end and therefore, it must have adequate fatigue strength. Tool holder is removable part which is fastened to the concentrator and is made of monel metal or stainless steel. Generally, the shape of the tool holder is cylindrical or conical or a modified cone with the centre of mass of the tool on the centre line of the tool holder. It should be free from nicks, scratches and tool marks to reduce fatigue failures caused by the repeated reversal of stresses. In some ultrasonic machines, the trunk (horn) acts itself as a concentrator as well as the tool holder.

The horn or concentrator is a wave-guide, which amplifies and concentrates the vibration to the tool from the transducer. Table 1.4 shows different type of horns. The horn or concentrator can be of different shape like

a) Tapered or conical
b) Exponential
c) Stepped

Machining of tapered or stepped horn is much easier as compared to the exponential one.



(a) (b) (c)

Fig.1.4 Different Horns used in USM [49]

1.6.3. The tool

The tool should be so designed to provide the maximum amplitude of vibration at the free end at a given frequency .The material used should have high wear resistance, good fatigue strength and optimum values of hardness and toughness. For minimum tool wear, tools should be constructed from relatively ductile materials such as stainless steel, brass and mild steel. The harder the tool material the faster its wear rate will be. Depending on the abrasive used, workpiece / tool wear ratio can range from 1:1 to 100:1.

Tools can be joined to the horn either by soldering or brazing, screw fitting. Alternatively, the actual tool configuration can be machined to the end of the horn. Threaded joints have also been used conventionally to achieve the ease of tool changing, however problems such as self-loosening, loss of acoustic power and fatigue failure have been reported for such tools.

1.6.4. The Abrasive Slurry

Several abrasives are available in various sizes for ultrasonic machining (grit). The criteria for selection of an abrasive for a particular application include hardness, usable life, cost and particle size.

In order of hardness, boron carbide, silicon carbide and aluminum oxide are the most commonly used abrasives. The abrasive used for an application should be harder than the material being machined otherwise the usable life time of the abrasive will be substantially shortened. Boron carbide is selected when machining the hardest work piece materials or when the highest material removal rates are desired. Although the cost is five to ten times greater than the next hardest abrasive, silicon carbide, the usable life of boron carbide is 200 machine operating hours before cutting effectiveness is lost and disposal is necessary. This compares with a usable life time of approximately 60 hours for silicon carbide. The combination of high removal rates and extended life time justify the higher cost of boron carbide.

The size of abrasive particles influences the removal rate and surface finish obtained. Abrasive for USM are generally available in grit sizes ranging from 240 to 800 while the coarser grit exhibit the highest removal rates, they also result in the roughest surface finish and are therefore, used only for roughing operation, conversely, 800 grit abrasives will result in fine surface finishes but at a drastic reduction in metal removal rate. The most popular general purpose abrasive used, based on the above considerations, is 320 grit boron carbide. The abrasive material is mixed with water to from the slurry. The abrasive material is mixed with water to form the slurry. The most common abrasive concentration is 50% by weight. However this can vary from 30 to 60 percent. The thinner mixtures are used to promote efficient flow when drilling deep holes or when forming complex cavities. Table 1.1 shows the different types of abrasive used in USM with knoop hardness and relative cutting power.

Table 1.1 Abrasives used in USM

Abrasive	Knoop Hardness	Relative cutting power
Diamond	6500-7000	1
Cubic Boron Nitride	4700	0.95
Boron carbide (B_4C)	2800	0.50-0.60
Silicon carbide (SiC)	2480-2500	0.25-0.45
Alumina (Al_2O_3	1850-1920	0.14-0.18

Once the abrasive has been selected and mixed with water, it is stored in a reservoir at the USM machine and pumped to the tool work piece interface by recirculating pumps at rates up to 26.5 lit/min. Higher power ultrasonic machine require the addition of a light-duty cooling system to remove waste heat from the abrasive slurry.

1.6.5 The Workpiece

There is no limitation to the range of material that can be machined by USM process, expect that they should not dissolve in the slurry media or react with it. While USM can be applied to ductile materials such as soft steel, copper, and brass but it is best suited to machining operation on hard, brittle materials that are not practical to process by other method. In general, USM is not recommended on the work materials which are softer than Rockwell Hardness Number HRC 45. Ultrasonic machining can be used for metals and non-metals, electrical conductors or nonconductor. The ultrasonic drilling technique is especially suited for hard materials like tungsten carbide, titanium carbide, ceramic and diamond. Materials which exhibit high hardness and which have impact brittleness can be successfully machined by this technique. Such materials are germanium, ferrites, glass and quartz.

1.7 Process parameters Ultrasonic Machining

The ultrasonic vibration machining method is an efficient cutting technique for difficult-to-machine materials. It is found that the USM mechanism is influenced by these important parameters.

- Frequency of tool oscillation –greater than 20 kHz
- Type of abrasive -Boron carbide, aluminium oxide and silicon carbide
- Grain size or grit size of the abrasives – 200-800
- depth to diameter ratio of holes – 31
- Power – 50-3000 W
- Workpiece material – electrically conductive and non-metallic workpiece
- Workpiece hardness- above 40 HRC

1.8 Organization of Thesis

Chapter 1 covers brief introduction to non-traditional machining, principle of Ultrasonic Machining, explanation of USM and its various process parameters.

Chapter 2 presents an available literature on USM process. The available literature has been categorized in different categories according to their applications. Summary of literature and gap in literature is also discussed.

Chapter 3 presents the methodology in brief which is being adopted. The detailed explanation of Taguchi and ANOVA is given. Objective and work plan is also discussed. The details of the machine used and workpiece used are also explained.

Chapter 4 presents the analysis and results of MRR. Results after the Analysis of Variance (ANOVA) and Taguchi Signal-to-Noise ratio are outlined in this chapter. Main effect plot and interaction plots for MRR are discussed in this chapter. Optimal design conditions have been discussed.

Chapter 5 presents the analysis and results of TWR. Results after the Analysis of Variance (ANOVA) and Taguchi Signal-to-Noise ratio are outlined in this chapter. Main effect plot and interaction plots for TWR are discussed in this chapter. Optimal design conditions have been discussed.

Chapter 6 presents the analysis and results of SR. Results after the Analysis of Variance (ANOVA) and Taguchi Signal-to-Noise ratio are outlined in this chapter. Main effect plot and interaction plots for SR are discussed in this chapter. Optimal design conditions have been discussed.

Chapter 7 presents the analysis and results of Rockwell Hardness. Results after the Analysis of Variance (ANOVA) and Taguchi Signal-to-Noise ratio are outlined in this chapter. Main effect plot and interaction plots for Hardness are discussed in this chapter. Optimal design conditions have been discussed.

Chapter 8 presents the analysis of surface morphology which is used to understand the microstructure on the surface of the workpiece material.

Chapter 9 presents comparison between USM and CUSM in terms of MRR and Surface roughness

Chapter 10 presents the results, conclusions and recommendations from the experimental work.

This chapter gives an extensive review of literature upon various fields related to USM and its effects on material removal rate and tool wear rate along with hardness, surface roughness of the machined surface. The literature available on USM is given below.

2.1 Material removal mechanism

Kumar et al.[4] explored the use of Ultrasonic Machining, a non traditional machining process of pure titanium and evaluated material removal rate under controlled experimental conditions. A micro-model for prediction of material removal rate in ultrasonic machining of titanium using dimensional analysis was made. The surface finish obtained in USM of titanium was better than many other non-traditional machining processes. Optimum MRR in USM of titanium can be achieved by using a tool material of higher hardness along with a higher power rating , coarse grit size and a hard abrasive material. Also, power rating factor had emerged as most significant factor with a followed by abrasive type and slurry grit size. Tool material factor can be termed as the least significant for MRR.

Singh and Khamba[5] applied Taguchi approach to model the material removal rate during ultrasonic machining of titanium and its alloys. Relationships between material removal rate and other controllable machining parameters such as power rating; tool type; slurry concentration; slurry type; slurry temperature and slurry size had been deduced by using Taguchi technique. The results suggested that Ultrasonic power rating had significantly improves the material removal rate with contribution of 28%, followed by type of tool with contribution of 24.6%. The third significant factor was type of slurry with contribution of 13.3%.

Singh and Khamba[6] investigated Ultrasonic machining of titanium and its alloys.The material removal mechanisms involved and the effect of operating parameters on material removal rate, tool wear rate, and work piece surface finish of titanium and its alloys were reviewed, for application in manufacturing industry.

Brehl and Dow[42] combined Vibration-Assisted Machining(VAM) with small amplitude tool vibration to improve the fabrication process. VAM had been applied to difficult applications such as diamond turning of ferrous and brittle materials, creating microstructures with complex geometries for products like molds and optical elements, and hard alloys such as Inconel or titanium He found VAM offered distinct advantages over conventional precision machining methods over a broad range operating conditions, depths of cut, part sizes, and tool and work materials with reduced tool forces and surface roughness, extended tool life and improved form accuracy.

Chang and Bone[9] had given a novel analytical burr height model to predict the exit burr height in Vibration Assisted Drilling (VAD) of aluminum 6061-T6. He studied the effect of ultrasonic assistance on burr size; chip formation, thrust forces and tool wear and demonstrate that under suitable ultrasonic vibration conditions, the burr height and width can be reduced in comparison to conventional drilling. He concluded that the proposed model improved the accuracy of the existing burr height model for conventional drilling by up to 36%, and also predicted the burr height for VAD within a 10% deviation from the mean values of the experimental results.

Kumar and Khamba[13] used Stellite 6, a cobalt alloy and outlined the effectiveness of the ultrasonic machining in terms of tool wear rate of the tool used and the material removal rate of work piece produced. The optimum combination of various input factors as type of abrasive slurry, their size and concentration, nature of tool material and power rating of the machine for the ductile chip formation had been determined by applying the Taguchi multi-objective optimization technique and F-test. He concluded that the optimum parameter values in the present operating conditions found to be are tool material followed by abrasive slurry and slurry concentration. Also percentage contribution of factors in descending order for MRR was power rating, abrasive grit size tool material, abrasive slurry and slurry concentration.

Liu et al.[7] developed a physics-based cutting force model for Rotary Ultrasonic Machining (RUM) of brittle materials. The model used to predict the influences of input variables on cutting force. These predicted influences are compared with those determined experimentally. The trends of predicted influences of input variables on cutting force agree well with the trends determined experimentally. The result showed that cutting force will increase as abrasive concentration, semi-angle of abrasive particle and feed rate increase. And also it will decrease as abrasive size, vibration amplitude, and spindle speed increase.

Khoo et al.[34] concluded that that the material removal rate increases with increases of applied static load, ultrasonic power and amplitude of tool vibration, rotational speed and grain size. Also, the surface roughness or hole clearance tends to increase with the increase of vibration amplitude and abrasive grit size but decrease with high applied static load. He found Wear occurs on both the end face and lateral face of the tool in RUM of advanced ceramics.

Simon and Gary[43] introduced a high-frequency and low-amplitude vibration model in the direction of drill feed during drilling which had a potential to reduce thrust forces and reduce exit burr height. A novel analytical burr height model predicted the exit burr height in vibration assisted drilling of aluminum 6061-T6 . The presented model incorporated the hypothesis that only positive portion of the thrust force contributed to burr formation, and included elastic spring back of the workpiece material to provide more accurate prediction. Comparisons between experimental results and model predictions had shown the superior accuracy of the developed model and provided an accurate prediction for the favorable vibration frequency.

Lia et al.[44] developed a three-dimensional Finite Element Analysis (FEA) model to study the effects of three parameters (cutting depth, support length, and pretightening load) on the maximum normal stress and Von Mises Stress in the region where the edge chipping initiates. The maximum normal stress criterion and Von Mises Stress criterion were used to predict the relation between the edge chipping thickness and the support length. He proposed a possible solution to reduce the edge-chipping thickness by increasing the support length and the diameter of the blind hole in the fixture underneath the workpiece should be as small as possible.

Liao et al.[22] retrofitted tool holder of a machining center so as to provide axial resonant vibration. Experimental results showed that the chip size was reduced and proportion of segmented chips was increased. The thrust force in drilling was reduced, there was less variation of the torque and the usable life of the drill was prolonged. It was also found that the function of peck drilling can be replaced by the ultrasonic vibration assisted conventional drilling. The application of ultrasonic vibration in drilling can prolong tool life and hence fewer tools were needed.

Ichida et al.[36] proposed a new Non-contact Ultrasonic Abrasive Machining (NUAM) method that was performed using loose abrasives excited by ultrasonic energy in a liquid, and discussed its suitability for application to ultra-precision machining. He found that in order to apply the NUAM to the ultra-precision machining, it was necessary to conduct the removal processing in small-scale removal processing mode conducted by the abrasive grains excited by the ultrasonic energy only by inhibiting the generation of cavitation.

Kumar and Khamba[8] established a relation between the mode of material removal and the energy input rate corresponding to the different process conditions and result showed that the material removal in USM of titanium could be directly related to the energy input rate for the particular process settings used for the machining. A higher level of input energy rate promoted the brittle fracture or cleavage of the work surface For extremely small values of energy input, purely ductile failure mode was observed. Also, minor fluctuations in the process variables such as slurry concentration can cause significant alteration in the results; hence, it was very important to maintain the fixed parameters as constant with the highest possible accuracy.

Wiercigroch et al.[37] postulated the main mechanism of the enhancement of material removal rate in ultrasonic machining with high amplitudes forces generated by impacts, which act on the workpiece and help to develop micro-cracking in the cutting zone. He modeled inherent non-linearity of the discontinuous impact process to generate the pattern of the impact forces. Inherent non-linearity of the discontinuous impact process model to generate the pattern of the impact forces and explains the experimentally observed fall in MRR at higher static forces.

Babitsky[40] designed a prototype of an ultrasonic drilling system and improvements of machining characteristics due to superposition of ultrasonic vibration were demonstrated. He studied vibration excitation and energy transfer during ultrasonically assisted drilling and found the profound effect on their cutting performance when there was superimposition of longitudinal vibration at ultrasonic frequencies onto the normal rotary motion of drilling bits.

Thomas and Babitsky[41] employed a three-dimensional finite element drill bit to understand the drill bit’s vibrational characteristic.The drill bit considered displayed strong vibration mode conversion characteristics during both experimentation and numerical simulation. Its amplitude frequency response curve was also extremely peaky, indicating instability when controlled using traditional frequency control methods.

Zhang et al.[47] proposed an effective micromachining technique for hard–brittle materials.He introduced several innovative strategies such as rotated tool, on machine tool preparation, and vibration-applied workpiece, holes as small as 5 mm in diameter had been machined in quartz glass and silicon. Complex structures like spiral trenches had also been claimed true by use of the path-controlled scanning mode..

Wei et al.[48] proposed Ultrasonic Lapping and compared with conventional lapping in material removal process. He showed that material removal rate of ultrasonic lapping was nearly three times than that of the conventional lapping in the same condition, and the ultrasonic lapping can produce a better tooth surface quality. The results of this set of experiments revealed that the optimum conditions for a high removal rate in the ultrasonic lapping experiments of spiral-bevel gears had a braking torque of 0.12 Nm,pinion rotational speed of 600 rpm and slurry concentration of 20%. The contributions by percentage of torque, speed and concentration to the removal rate are 8.13, 19.26 and 68.11, respectively.

2.2 Process parameters

2.2.1 Abrasive Slurry Properties

Singh and Khamba[11] used stainless steel, titanium and high-speed steel as the tool and silicon carbide, boron carbide and alumina slurry as a slurry . The results suggested that boron carbide slurry and stainless steel tool were giving best material removal rate. Also relative hardness of tool–work piece affects the material removal rate in ultrasonic machining.

Choi et al.[32] explored the use of Chemical-Assisted Ultrasonic Machining for machining of glass. To obtain the chemical effects, a low concentration hydrofluoric acid solution was added to the slurry. The hybrid method was found to be superior in terms of material removal rate and integrity of the machined surface. The surface roughness was also found to improve and the machining load was decreased significantly as compared to the conventional USM method.

Guzzo et al.[33] reported a substantial increase in MRR obtained while using abrasive of larger grain size on account of the increase in the stress caused by the impact of abrasive particle over the workpiece surface.

Ramulu et al.[31] reported that use of boron carbide abrasive resulted in material removal rate which was approximately 75% higher than the silicon carbide abrasive for the 400 grit size and 320% higher for 220 grit size while machining silicon carbide ceramics. The effect of slurry hardness on MRR had been found to be dependent on the other experimental conditions such as work material properties, tool properties, amplitude of vibration and static load; which could be regarded as the reason for a wide reason for a wide inconsistency of the results reported in the literature available on USM.

2.2.2 Work Piece Properties

Jadoun et al.[15] studied the effect of process parameters on production accuracy obtained through ultrasonic drilling of holes in alumina based ceramics using silicon carbide abrasive and production accuracy in ultrasonic drilling involving both dimensional accuracy (hole oversize) and form accuracy (out-of-roundness and conicity). The parameters considered were workpiece material, tool material, grit size of the abrasive, power rating and slurry concentration. He found when hole-oversize was marginally increased, there was increase in alumina content in the work piece. Out-of-roundness decreased with the increase in alumina content in the work piece. Conicity increased with the increase in alumina content in the work piece and increases almost linearly as the grain size increases.

Hsu et al.[12] investigated the machining characteristics of Inconel 718, Nickel-base superalloy, by combining ultrasonic vibration with high-temperature-aided cutting. The influence of various machining parameters such as cutting tool made of different materials, depth of cut, cutting speed, feed rate, working temperature and ultrasonic power on the machining characteristics are clarified. The percentage contributions in descending order was cutting tool ,feed rate, working temperature and depth of cut for surface roughness and cutting force.

Kumar[10] highlighted machining of brittle and fragile material under controlled experimental conditions and focused on parametric optimization of ultrasonic machining of pure titanium metal with TWR as response, and validation of optimized value of TWR by conducting confirmatory experiments .

Liet et al.[17] studied the effects of three parameters (cutting depth, support length, and pre tightening load) on the maximum normal stress and Von Mises Stress in the region where the edge chipping initiates. Two failure criteria (the maximum normal stress criterion and Von Mises Stress Criterion) were used to predict the relation between the edge chipping thickness and the support length. Furthermore, a solution to reduce the edge chipping was proposed based upon the FEA simulations and verified by experiments..

Jianxin and Taichiu[18] investigated the effect of properties and microstructure of work materials on the MRR in USM of alumina-based ceramic composites. MRR was reported to be low while machining composites of higher fracture toughness such as whisker-reinforced composites. The particle reinforced composites yielded higher values of MRR on account of their low fracture toughness. The composites of higher flexural strength demonstrated better surface integrity while machining with USM.

Guzzo et al.[38] investigated potential of ultrasonic machining as a tool to produce seed crystals for hydrothermal growth of synthetic quartz with required surface finish and unconventional geometries and observed that the density of dislocations, nucleated at the early stage of the growth period, increases with increasing roughness of the seed-crystal surface. Cutting rate and the surface roughness were dependent on the abrasive grit size. Material was removed by brittle microcracking which increases with increasing the grit size. USM process can be adopted in the production of seed crystals with unconventional geometries to obtain synthetic quartz of good crystalline perfection.

Li et al.[16] introduced rotary ultrasonic machining (RUM) into drilling Ceramic Matrix Composites (CMC) materials and compared cutting forces and material removal rates (MRR) for machining of CMC with and without ultrasonic vibration. He found that high-quality holes on CMC panels can be achieved by RUM with proper machining parameters and feed rate had the most significant effects on cutting force. Spindle speed, federate and ultrasonic power had significant effects on MRR. Also, Spindle speed and feed rate as well as their interaction had significant effects on hole quality.

Pujana et al.[14] applied ultrasonic vibration for drilling of Ti_6Al_4V workpiece samples. Several parameters of ultrasonic-assisted drilling such as feed force, chip formation by means of high-speed imaging, and temperature measurement on the drill tip by means of infrared radiation thermometry were monitored. He found ultrasonic assistance offered lower feed force and higher process temperatures as compared to conventional drilling. Also concluded higher force reductions and higher temperature increments when vibration amplitude was increased.

Tawakoli and Azarhoushang[45] investigated on dry machining in order to decrease the negative environmental impact of the cutting fluids, diminishing problems concerning waste disposal demand. He found problems frequently occur in terms of high heat generation on grinding wheel surface and workpiece surface, increasing the grinding energy, wear of grinding wheel, low material removal rate and poor surface roughness, so to eliminate these problem application of ultrasonic vibration was done. The obtained result showed that the application of ultrasonic vibration can eliminate the thermal damage on the workpiece and a decrease of up to 60–70% of normal grinding forces and up to 30–50% of tangential grinding forces had been achieved.

Wiercigroch et al.[46] showed that an introduction of high-frequency axial vibration which significantly enhances drilling rates compared to the traditional rotary type method. He found that a light static load causes the tool to be bounced off from the workpiece, with only intermittent and small impact forces. When the static force was too large, the percussive effect disappears and the workpiece was exposed to a static force decreasing drastically the drilling efficiency.

Gao et al.[24] designed ultrasonic grinding vibration device and created the theoretical models of surface roughness for ultrasonic vibration grinding. He studied on ultrasonic grinding of nano-zirconia ceramics and found critical ductile depth of cut was larger than that in common grinding and than that of traditional ZrO_2 engineering ceramics.

Majeed et al.[19] outlined the machining of $Al_2O_3/LaPO_4$ composites using static crease in the hardness of the composite. Results showed that an in $LaPO_4$ improved the machining rate up to a critical limit after which it tends to stabilize. The use of hollow tools was also reported to improve the MRR obtained.

2.2.3 Tool Characteristics

Azarhoushang et al.[21] presented the design of an ultrasonically vibrated tool holder and the experimental investigation of ultrasonically assisted drilling of Inconel 738-LC. The circularity, cylindricity, surface roughness and hole oversize of the ultrasonically and conventionally drilled workpieces were measured and compared. The obtained results showed that the application of ultrasonic vibration can improve the hole quality considerably. Improvements of up to 60% had been achieved.

Adithan[23] had reported that stainless steel tools exhibit low tool wear as compared to tungsten carbide or mild steel tools. This was due to high resistance to cavitation erosion of stainless steel. In USM, hardness of the tool increases by work hardening, therefore the penetration of the abrasive grains into the tool decreases resulting in higher MRR.

Kumar et al.[29] compared the machining performance of high carbon steel and titanium alloys in USM of titanium. High carbon steel tool was found to experience more tool wear as compared to titanium alloy tool because of its higher hardness and poor toughness and impact strength as compared to titanium alloy tool.

Ramu et al.[25] reported an optimum slurry concentration range (1: 5.7) from tool wear aspect in USM of transformation toughened ceramics.

Komaraiah and Reddy [26] investigated the influence of tool material properties i.e. hardness on the material removal rate in USM of glass. Results showed that the MRR increased with an increase in the hardness of the tool material. The different tool materials were arranged in the increasing order of superiority as mild steel < titanium < stainless steel < silver steel < niamonic-80 A < thoriated tungsten. The tool materials used were found to undergo a significantly different amount of work-hardening, which contributed to the variation in their machining performance.

Kumar et al.[28] reported achievement of higher material removal rates using a high carbon steel tool, which had higher hardness in comparison to other tools used for the experimentation. Tools with diamond tips had been shown to have good material removal characteristics.

2.2.4 Surface Properties

Shen et al.[35] investigated the effects of assisted ultrasonic vibration on the surface roughness of machined surfaces in micro-end-milling. He found ultrasonic vibration had a negative effect on the surface roughness of slot bottom surface in the ultrasonic vibration-assisted milling experiment and analyzed that ultrasonic vibration makes a brilliant contribution to the improvement of the surface roughness of vertical side wall surface of slot.

Dvivedi and Kumar[30] investigated ultrasonic drilling of commercially pure titanium and titanium alloy (Ti_6Al_4V).Process parameters such as work piece, grit size, slurry concentration, power rating and tools were changed to explore their effect on the surface roughness. Average surface roughness (R_a) was measured by using the Optical Profiling System. Two-dimensional and three-dimensional contour plots were obtained from the profiling system to quantify and visualize the surface roughness. It was concluded that the effect of slurry concentration and grit size had a significant effect on surface roughness more than other parameters. In addition, the surface roughness was similar in two and three dimensions as visualized from contour plots. Ultrasonic drilling was established as a material removal process with good surface quality.

Wang et al.[39] investigated surface roughness using Rotary Ultrasonic Machining of Potassium Dihydrogen Phosphate (KDP) crystal. He investigated the influence of three process variables (spindle speed, ultrasonic power and feedrate) and tool design on surface roughness in RUM of KDP. He found that the surface roughness obtained when using a tool with a chamfered corner was lower than that obtained using tools with right-angle corners. Smaller diamond grains tended to produce smoother surface and within the tested range (from 20% to 40%).

Dam et al.[20] investigated the material removal rate in ultrasonic drilling of several different ceramic materials. Results showed that for tougher work materials, the MRR observed was quite low as compared to the hard and brittle materials. However, the surface quality obtained (in terms of finish) was found to be superior for tough materials.

Lee and Chan[27] measured the effects on the material removal rate and the surface roughness on the amplitude of the tool tip, the static load applied and the size of the abrasive. He concluded that any increase in power rating, the static load applied and the grit size of the abrasive will result in an increase in the material removal rate and a roughening of the machined surface.

2.3 Summary of literature review

A lot of work has been done different work material, tool material, abrasive slurry, slurry concentration and grit size.

Various investigators [11, 32,31] have reported results indicating that the rate of material removal for a certain abrasive is a function of its concentration, grain size and hardness besides the feed system. On increasing the abrasive girt size or slurry concentration, an optimum value of MRR is reached. Investigations found that reported a substantial increase in MRR obtained while using abrasive of larger grain size on account of the increase in the stress caused by the impact of abrasive particle over the workpiece surface[33]. Use of boron carbide abrasive resulted in material removal rates which were approximately 75% higher than the silicon carbide abrasive for the 400 grit size and 320% higher for 220 grit size while machining silicon carbide ceramics [31]. The effect of slurry hardness on MRR has been found to be dependant on the other experimental conditions such as work material properties, tool properties, amplitude of vibration and static load.

Investigators [21,23,25,28,29] investigated the influence of tool material properties i.e. hardness on the material removal rate in USM of glass. Results showed that the MRR increased with an increase in the hardness of the tool material. The different tool materials were arranged in the increasing order of superiority as mild steel < titanium < stainless steel < silver steel < niamonic-80 A < thoriated tungsten. The tool materials used were found to undergo a significantly different amount of work-hardening, which contributed to the variation in their machining performance [26].

Investigators [35, 30,39] found materials which observed higher MRR were also reported to have higher surface roughness values. Work-piece materials with higher ratio of hardness to elastic modulus involve inferior surface quality. Dam et al [20] concluded that the work materials can be graduated according to their respective machining rates, so that the most productive materials give the greatest surface roughness and vice-versa. Therefore, higher productivity is not obtained without cost as the surface roughness increases.

Results showed power [4, 5, 6,13,8] primarily determines the mass of the tool-horn assembly that can be utilized for an application and the frontal cutting area of the tool. The more is power available in an ultrasonic machine, the larger the frontal cutting area of the tool can be supported. Linear increase in MRR while increasing the amplitude of vibration provided all other factors such as frequency of vibration and abrasive grit size are kept constant. The linear trend of MRR while increasing the amplitude has been found to be more prevalent when high impact strength materials are machined or fine abrasive powders are used for machining. MRR decreases owing to a reduction in the size of abrasive grains reaching the cutting interface [31, 33].

Investigators [15, 12,10,18,17] found work-piece materials machined in this investigation were glass, ferrite, porcelain, alumina and tungsten carbide. MRR was reported to decrease with an increase in work material hardness and fracture toughness in almost linear fashion under controlled experimental conditions. The particle reinforced composites yielded higher values of MRR on account of their low fracture toughness. The composites of higher flexural strength demonstrated better surface integrity while machining with USM.

2.4 Gaps in Literature

It was concluded from the literature review that a limited study has been done on Chemical Assisted Ultrasonic Machining (CUSM). As CUSM enhances the MRR and surface roughness with glass as a workpiece, so there is need to work on CUSM and to find the advantage of CUSM over USM.

2.5 Objective of the Present Work

The objective of the present work has been discussed below:

1) To study the effect of various input parameters like Power rating of the machine, type of abrasive slurry, Concentration of abrasive slurry, Abrasive Grit Size, Tool Material on output parameters like Material Removal Rate (MRR), Tool Wear Ratio (TWR), Surface Roughness and Rockwell Hardness in case of CUSM. Also,to find the comparison between CUSM and USM.

2) The experimentation work will be planned by applying DOE (Design of Experiments) approach.

3) Analysis of results obtained from the experimentation work will be done using the Statistical Techniques such as ANOVA (Analysis of Variance).

4) The optimization and verification of results will be done. Also the modeling of results will be done by applying the Regression Analysis.

5) The machined samples will be studied to find surface morphology.

CHAPTER 3 EXPERIMENTATION AND DESIGN OF STUDY

3.1 Design factors selection

3.1.1 Process parameters selection

Various input process parameters can be varied in the CUSM process, each having its own impact on output parameters such as Material Removal Rate (MRR), Tool Wear Rate (TWR) and Surface Roughness (R_a). The input parameters that are varied:

1. Power rating of the machine
2. Type of abrasive slurry
3. Concentration of abrasive slurry
4. Abrasive Grit Size
5. Tool Material

3.1.2 Response variable selection

The response variables selected in this study were MRR, TWR, Surface Roughness & Rockwell Hardness. These variables are defined as:

Material Removal Rate (MRR) is defined as the weight of material eroded from workpiece surface per unit time. It is measured as:

$$\text{MRR (mm}^3\text{/min.)} = \frac{weight\ difference\ of w/p\ (gm)}{Machining\ time(min.) \times density\ of\ material(\frac{gm}{mm^3})} \quad \text{(Equation 3.1)}$$

Tool Wear Rate (TWR) is defined as the weight of material eroded from tool surface per unit time. It is measured as:

$$\text{TWR (mm}^3\text{/min.)} = \frac{weight\ difference\ of\ tool(gm)}{Machining\ time(min.) \times density\ of\ material(\frac{gm}{mm^3})} \quad \text{(Equation 3.2)}$$

Surface Roughness (R_a) of the machined surface of work piece is expressed in microns. The characteristic of the layer of the work material just below the machined surface is evaluated. It is the arithmetic average roughness of the deviations of the roughness profile from the central line along the measurement.

$$\text{Surface Roughness } (R_a) = \frac{1}{L}\int_0^L |h(x)\ dx| \quad \text{(Equation 3.3)}$$

where h(x) is the value of roughness profile & L is evaluation length

Rockwell Hardness determines the hardness by measuring the depth of penetration of an indenter under a large load compared to the penetration made by a preload. Rockwell scale is a hardness scale based on the indentation hardness of a material. There are different scales, denoted by a single letter, that use different loads or indenters. The result is a dimensionless number noted as HRB where B is the scale letter.

3.1.3 Experimental Design

As the objective of study aimed to carry out result on chemical assisted ultrasonic machining on Soda Glass (as Work Material) different factor levels have been decided depending upon commercial availability, experimental constraints and machine tool capacity. Table 3.1 shows different control variables and their levels.

Table 3.1 Control Variables and their Levels

S.No.	Factors	Levels	Level 1	Level 2	Level 3
1	Tool Material	2	HSS	SS	
2	Power Rating(%)	3	20	40	60
3	Slurry Concentration (%)	3	20	25	30
4	Abrasive Slurry	3	Al_2O_3	50% SiC + 50% Al_2O_3	SiC
5	Abrasive Grit Size	3	280	400	600

For conducting the experiments, it was decided to follow the Taguchi method of experimental design so that the effect of all the parameters could be studied with minimum possible number of experiments and an appropriate orthogonal array had to be selected after taking into consideration the above design variables and experiments were performed as per the set of experiments designed in the orthogonal array. Signal to Noise ratios were also calculated to analyze the Chemical Assisted Ultrasonic Machining more accurately.

The Taguchi method apparently has the following strengths:

1. Consistency in experimental design and analysis.

2. Reduction of time and cost of experiments.

3. Robustness of performance without removing the noise factors.

The whole procedure of Taguchi method is as under.

1. Establishment of objective functions.

2. Selection of factors and/or interactions to be evaluated.

3. Identifications of uncontrollable factors and test conditions.

4. Selection of number of levels for the controllable and uncontrollable factors.

5. Calculation total degree of freedom needed

6. Select the appropriate Orthogonal Array (OA).

7. Assignment of factors and/or interactions to columns.

8. Execution of experiments according to trial conditions in the array.

9. Analyze results.

10. Confirmation experiments

3.1.4 Selection of Orthogonal Array

For the selection of a particular orthogonal array, the number of parameters, the numbers levels and their possible interactions must be taken into consideration. The case under study contains four parameters, one of two levels and three of three levels. Now as per requirements of the study L18 orthogonal array comes out as one of the solution. The L18 orthogonal array is taken in Table 3.2.

Table 3.2 L18 Orthogonal Array

Experiment No.	Columns				
	A	B	C	D	E
1	1	1	1	1	1
2	1	1	2	2	2
3	1	1	3	3	3
4	1	2	1	1	2
5	1	2	2	2	3

6	1	2	3	3	1
7	1	3	1	2	1
8	1	3	2	3	2
9	1	3	3	1	3
10	2	1	1	3	3
11	2	1	2	1	1
12	2	1	3	2	2
13	2	2	1	2	3
14	2	2	2	3	1
15	2	2	3	1	2
16	2	3	1	3	2
17	2	3	2	1	3
18	2	3	3	2	1

3.1.5 Signal-to-noise ratio for Response Characteristics

The parameters that influence the output can be categorized into two classes, namely controllable (or design) factors and uncontrollable (or noise) factors. Controllable factors are those factors whose values can be set and easily adjusted by the designer. Uncontrollable factors are the sources of variation often associated with operational environment. The best settings of control factors as they influence the output parameters are determined through experiments.

Controllable factors are divided into 3 main types:

- Those which affect the average levels of the response of interest, referred to as Target Control Factors (TCF), sometimes called signal factors.
- Those which affect the variability in the response, the Variability Control Factors (VCF).

At the heart of Taguchi philosophy is the quality loss function. The loss function promotes efforts to continually reduce the variation in a product's functional characteristics. The change in quality characteristic of a product under investigation in response to a factor introduced in the experimental design is the 'signal' of the desired effect. The effect of the external factors (uncontrollable factors) on the outcome of quality characteristic is termed as 'noise'. The objective of any experiment is to achieve the best possible S/N ratio.

Finding a correct objective function to maximize in an engineering design problem is very important. Depending upon the type of response, the following three types of S/N ratios are employed in practice:

Higher the Better:

HB: S/N ratio = $-10log_{10}\left[\frac{1}{n}\sum_{i=1}^{n} Y_i^{-2}\right]$ (Equation 3.4)

Lower the Better:

LB: S/N ratio= $-10log_{10}\left[\frac{1}{n}\sum_{i=1}^{n} Y_i^{2}\right]$ (Equation 3.5)

Nominal the Best:

NB: S/N ratio = $10log_{10}\left[\frac{Y^{-2}}{S^2}\right]$ (Equation 3.6)

Where Y_i is the sample mean & S is the sample standard deviation of n observations in each trial. For smaller-the-better type, target value is zero. For larger-the-better, inverse of each large value becomes a small value and again the target value is zero.

For this experimental work, the response characteristics have been studied and is shown in Table 3.3.The representation of factor level is shown in Table3.4 as under:

Table 3.3 Response Variables

Response No.	Response 1	Response 2	Response 3	Response 4
Response Name	MRR	TWR	SR	Hardness
Response Units	mm^3/min	mm^3/min	Microns	HRB
Response Type	Higher the better	Lower the better	Lower the better	Higher the better

Table 3.4 Representation of Factor level

Factors	Level 1		Level 2		Level 3	
Tool Material(A)	A1	HSS	A2	SS		
Power Rating(%) (B)	B1	20	B2	40	B3	60
Slurry Concentration (%) (C)	C1	20	C2	25	C3	30
Abrasive Slurry (D)	D1	Al_2O_3	D2	SiC + Al_2O_3	D3	SiC
Abrasive Grit Size (E)	E1	280	E2	400	E3	600

3.2 Analysis of results using ANOVA

In statistics, analysis of variance (ANOVA) is a collection of statistical models, and their associated procedures, in which the observed variance is partitioned into components due to different explanatory variables. The initial techniques of the analysis of variance were developed by the statistician and geneticist R. A. Fisher in the 1920s and 1930s, and are sometimes known as Fisher's ANOVA or Fisher's analysis of variance, due to the use of Fisher's F-distribution as part of the test of statistical significance.

The purpose of the statistical analysis of variance (ANOVA) is to investigate which design parameter significantly affects the material removal rate, tool wear rate & surface roughness. In my thesis ANOVA table is made with help of **MINITAB 16** Software.

Various formulas for ANOVA are:

Sum of square, SS = $\sum_{i=1}^{N} Y_i^2 - \frac{T^2}{N}$ (Equation 3.7)

DOF = Levels of Parameters-1

Variance = $\frac{SS}{DOF}$ (Equation 3.8)

F-test = $\frac{variation\ due\ to\ parameter}{Variation\ due\ to\ error}$ (Equation 3.9)

e-*pooled = sum of SS due to error and SS of all insignificant factors*

SS' *= SS of significant factor – DOF of that factor* × variation *due to e –pooled*

(Equation 3.10)

C% = $\frac{SS'}{Total\ SS} \times 100$ (Equation 3.11)

If **F-critical > F-test**

Only then the factor is significant for the given conditions.

Where DOF = Degree of Freedom

F test = Fisher's test

C% = Contribution Factor

3.3 Description of the USM Machine

The ultrasonic drilling Machine used for the experimentation consisted of an ultrasonic spindle kit, a constant pressure feed system and slurry flow system. The maximum power input to the machine was 500 W. Figure 3.1 shows the static USM set up used for the experimentation. The ultrasonic spindle kit comprises an ultrasonic spindle mounted with cylindrical horn, a power supply unit that converts 50 Hz electrical supply to high frequency 20 kHz output. Figure 3.1 shows Ultrasonic Machining set up. This high frequency electric signal is applied to a piezoelectric transducer positioned in the spindle. The function of this transducer is to convert the applied electrical signal into mechanical vibrations.

Figure 3.1 Ultrasonic machining Set up [Courtesy by:N.T.M Lab,T.U,Patiala]

The amplitude of vibration was in range of 25.3-25.8 μm with a frequency of 20 kHz +/- 200 Hz. The static load for feed rate was fixed at 1.636 Kg and slurry flow was maintained at 36.4 x 103 mm^3/min.

3.4 Measuring and test equipment used

As the tool materials used for the experimentation possess different values of densities, the tool wear rate in terms of 'change in volume' per unit time could be a better measure of the rate at which the different tool materials are eroded while machining takes place. Hence, the tool wear rate as well as material removal rate was calculated as reduction in volume per unit time (mm^3/min) so as to facilitate more accurate comparison of the TWR for different tool materials under varying process conditions. The details of important test equipment used in experimental study are given below:

3.4.1 Surface Roughness Tester

Surface Roughness was measured using the Perthometer; model M4Pi of Mahr, Germany. The equipment uses the stylus method of measurement, has profile resolution of 12 nm and measures roughness up to 100µm.

3.4.2 Rockwell Hardness Tester

Rockwell hardness was measured by a Rockwell Hardness Tester, Metatech industries, Pune, India. The Rockwell hardness measurement is dependent on the diameter of indentation on the samples. The depth of penetration of an indentor under a large load is determined. The different scales, denoted by a single letter, that use different loads or indentors. The result is a dimensionless number noted as HRB, where B is scale letter.

3.4.3 Scanning Electron Microscope (SEM) Machine

Microstructure was carried out of some selected samples on Scanning Electron Microscope (SEM), model JSM-6610 LV of Jeol, Japan available at IIT, Ropar. Its resolution in high vacuum mode is 3nm. Its maximum magnification range is 3, 00,000x. SEM of samples was carried out on three ranges, namely 200x, 500x and 1000x.

3.4.4 Weighting Machine

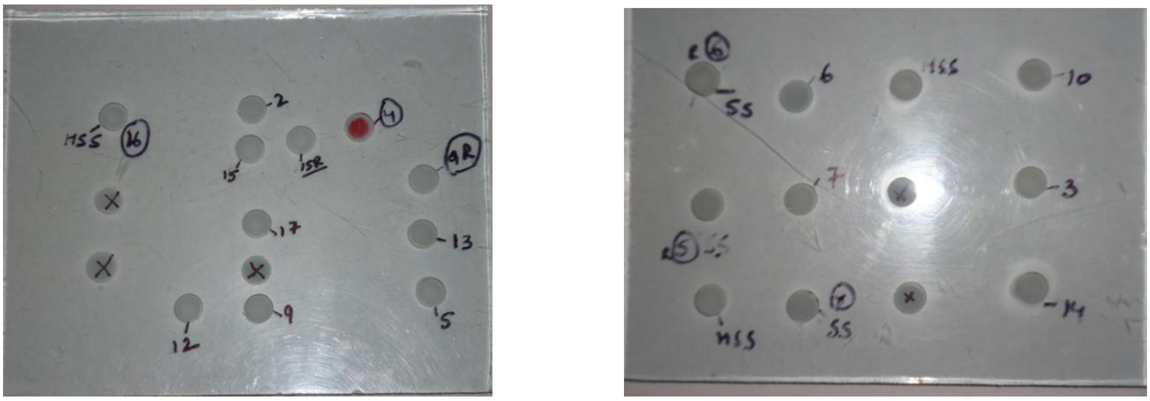
Precision balance was used to measure the weight of the workpiece and tool. This machine capacity is 300gram and accuracy is 0.001 gram and Brand: SHINKO DENSSHI Co. Ltd, Japan. Model: DJ 300S.

3.5 Workpiece description

In general, USM is not recommended on the work materials which are softer than Rockwell Hardness Number HRC 45. Ultrasonic machining can be used for metals and non-metals, electrical conductors or nonconductor. Material which exhibit high hardness and which have impact brittleness can be successfully machined by this technique. Such materials are germanium, ferrites, glass and quartz. The workpiece used in this experiment is Soda Glass.

The dimensions of workpiece were 100 x 100 x 5 mm^3. Table 3.5 shows the chemical composition of workpiece material.

Density of Soda Glass=2.53 gm/cc



(a) (b)

Figure 3.2 Workpiece (Soda Glass)

Table 3.5 Typical Composition of Workpiece Material (%)

SiO_2	Na_2O	CaO	MgO	Al_2O_3	Fe_2O_3	K_2O	TiO_2
71.86	13.13	9.23	5.64	0.08	0.04	0.02	0.01

3.6 Tool description

Two tool material namely High Speed Steel (HSS)**,** Stainless Steel (SS) were used. Table 3.6 shows composition and properties of the tool used.

High Speed Steel M-2 is a general purpose molybdenum-type high speed steel exhibiting well-balanced toughness, wear resistance and red hardness properties. This grade is commonly used in cold work punches and dies and cutting applications involving high speed and light cuts.

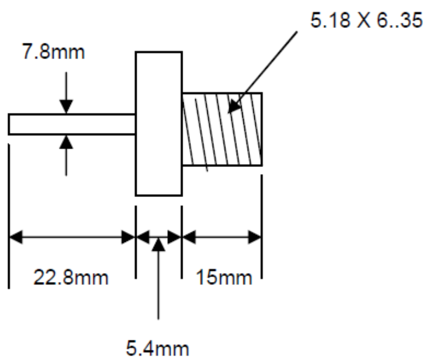
Stainless Steel, Grade has excellent forming and welding characteristics. The balanced austenitic structure of Grade 304 enables it to be severely deep drawn without intermediate annealing, which has made this grade dominant in the manufacture of drawn stainless parts such as sinks, hollow-ware and saucepans. It also has outstanding welding characteristics.

Table 3.6 Typical Composition and properties of Tool Material

Material	Chemical Composition	Density(g/cm^3)	Elastic Modulus (GPa)	Micro-Hardness (GPa)	Fracture Toughness ($MPam^{1/2}$)
High Speed Steel	Fe(77.93%)+ C (0.97%) + Cr (3.5%)+ W (17%) + V (0.6%)	8.2	214	1.68	48
Stainless Steel	Fe(77.44)+C(0.08%) + Cr (9%)+Ni(11%)+Mn(1%)+ Si(1%)+P(0.45%)+S(0.03)	7.9	193	1.38	88

3.6.1 Preparation of Cutting Tool

The cutting tool is made from the cylindrical piece of 35 mm diameter and 50 mm length by turning, facing processes done on the lathe machine. The symmetric and pictorial shape and size of cutting tool is shown in the figure 3.3 and figure 3.4.



Dimensions of tool
Figure 3.3

(a) SS Tool **(b) HSS Tool**
Figure 3.4

The tool tip and tool holder comprises as a single piece. No brazing process is done during the preparation of cutting tool. The threading process has been done to hold the tool in the horn.

3.7 Description of Chemical added

In ultrasonic machining, abrasive slurry which is a mixture of abrasive and fluid such as water is used to achieve the cutting action. In this experimentation, hydrofluoric Acid is added to the slurry and water mixture with glass as the workpiece. A concentration of 3–5% HF solution is added to the slurry.

3.7.1 Mechanism of Chemical assisted ultrasonic machining (CUSM)

A low concentration of hydrofluoric acid solution is added to the alumina slurry. The reaction between Si and the F^- ions and the reaction between oxygen and the H^+ ions occur simultaneously when hydrofluoric acid is added. The total chemical reaction can be described as

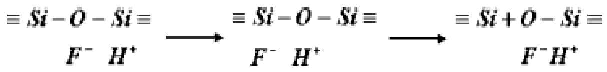


Figure 3.5 Bonding between Si and F ions[32]

When the HF solution reacts with the glass, the bonding force between the Si molecules on the surface area becomes weakened. Figure 3.6 shows the difference in the machining mechanisms between the USM and the CUSM.

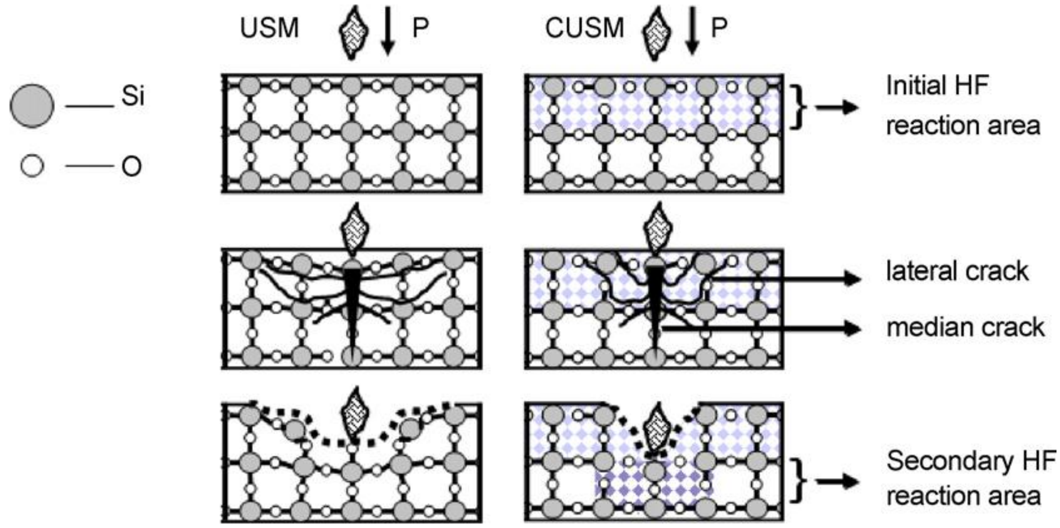


Fig. 3.6 Mechanisms of USM and CUSM[32]

The initiation and propagation of median and lateral cracks contribute to the material removal process. The propagation of impact energy in the lateral direction is limited because the linking forces between the molecules are weakened. Alternatively, in the median direction, the transmitted energy increases and results in deep median cracks. Therefore, the crater size of a single impulse of an abrasive is reduced and the removal rate is increased.

4.1 Introduction

The effects of parameters i.e. tool, power rating, slurry concentration, type of slurry, grit size and interaction between Tool and Type of slurry, Tool and Power Rating were evaluated using ANOVA and factorial design analysis. A confidence interval of 95% had been used for the analysis. One repetition for each of 18 trials was completed to measure the Signal to Noise ratio (S/N Ratio).

4.2. Results for MRR

The results for MRR for each of the 18 treatment conditions with repetition are given in Table 4.1. The MRR is calculated from the loss of weight of the tool during performance trial:

$$MRR = \frac{W_i - W_f}{\rho t} \times 1000 \ \text{mm}^3/\text{min} \qquad \text{(Equation 4.1)}$$

Where W_i= Initial weight of Workpiece (gms)

W_f = Final weight of Workpiece (gms)

t= time period of trial (minutes)

ρ= density of workpiece in gms/cc=2.53 gm/cc

Table 4.1: Results for MRR

Trial No	Tool	Power Rating(%)	Slurry Concentration(%)	Type of Slurry	Grit size	MRR (mm^3/min)	S/N Ratio	Mean
1	HSS	20	20	SiC	280	8.022	18.085	8.022
2	HSS	20	25	Al_2O_3	400	5.154	14.243	5.154
3	HSS	20	30	Mix	600	8.389	18.474	8.389
4	HSS	40	20	SiC	400	9.001	19.086	9.001
5	HSS	40	25	Al_2O_3	600	6.224	15.881	6.224
6	HSS	40	30	Mix	280	9.699	19.735	9.699
7	HSS	60	20	Al_2O_3	280	9.651	19.691	9.651
8	HSS	60	25	Mix	400	11.007	20.833	11.007
9	HSS	60	30	SiC	600	11.890	21.504	11.890
10	SS	20	20	Mix	600	9.139	19.218	9.139
11	SS	20	25	SiC	280	10.240	20.206	10.240

12	SS	20	30	Al_2O_3	400	7.254	17.212	7.254
13	SS	40	20	Al_2O_3	600	7.254	17.211	7.254
14	SS	40	25	Mix	280	11.100	20.906	11.100
15	SS	40	30	SiC	400	12.501	21.939	12.501
16	SS	60	20	Mix	400	13.007	22.283	13.007
17	SS	60	25	SiC	600	13.408	22.547	13.408
18	SS	60	30	Al_2O_3	280	11.570	21.267	11.570

4.3. ANOVA of Means for MRR

The results for MRR were analyzed using ANOVA for identifying the significant factors affecting the performance measures. The Analysis of Variance (ANOVA) for the mean MRR at 95% confidence interval is given in Table 4.2. The variance data for each factor and their interactions were F-tested to find significance of each. . ANOVA table shows that the Power Rating (F value 279.14), Slurry Type (F value 202.62), Tool (F value 194.83), Slurry Concentration (F value 19.950), Grit Size (F value 8.660) and interaction AxD (F value 8.850) are the factors that are significant and affects MRR. The interactions AxB is found to be insignificant. Table 4.3 shows ranks to various input parameters in terms of their relative significance.

Table 4.2: ANOVA of Means for MRR

Sources	SS	v	V	F	F (critical)	SS'	%age contribution	Status
Tool(A)	15.006	1	15.006	194.83	7.71	14.733	15.535	Significant
Power rating(B)	43.001	2	21.500	279.14	6.94	42.453	44.765	Significant
slurry concen(C)	2.548	2	1.274	19.95	6.94	2.001	2.110	Significant
Slurry type(D)	31.212	2	15.606	202.62	6.94	30.665	32.335	Significant
Grit size(E)	1.333	2	0.667	8.66	6.94	0.786	0.829	Significant
AxB	0.063	2	0.031	0.41	6.94			Insignificant
AxD	1.364	2	0.682	8.85	6.94	0.817	0.861	Significant
Error	0.308	4	0.077					
TOTAL	94.836	17	5.579					
e-pooled	1.641	6	0.274				3.564	

Table 4.3: Response table of Means for MRR

Level	Tool	Power Rating (%)	Slurry Concentration (%)	Type of Slurry	Grit size
1	8.782	8.033	9.346	7.851	10.047
2	10.608	9.296	9.522	10.39	9.654
3		11.755	10.217	10.844	9.384
Delta	1.826	3.723	0.872	2.992	0.663
Rank	3	1	4	2	5

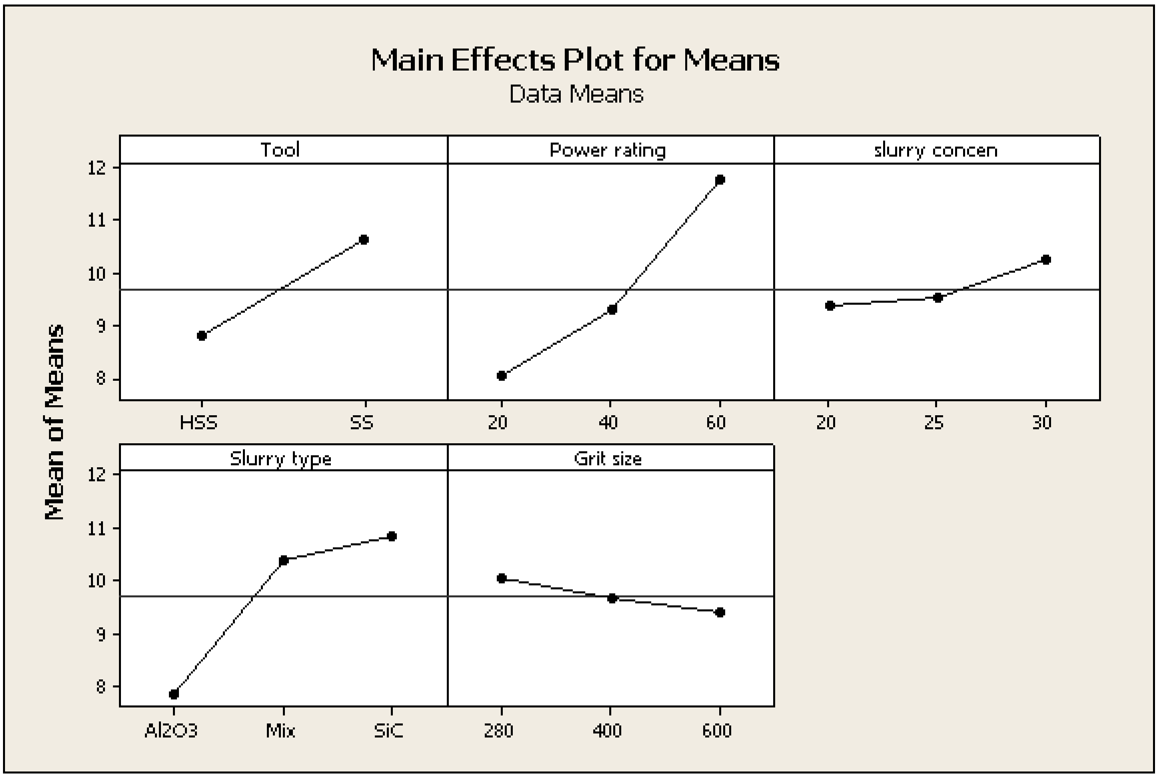


Figure 4.1: Main Effects Plot of Means for MRR

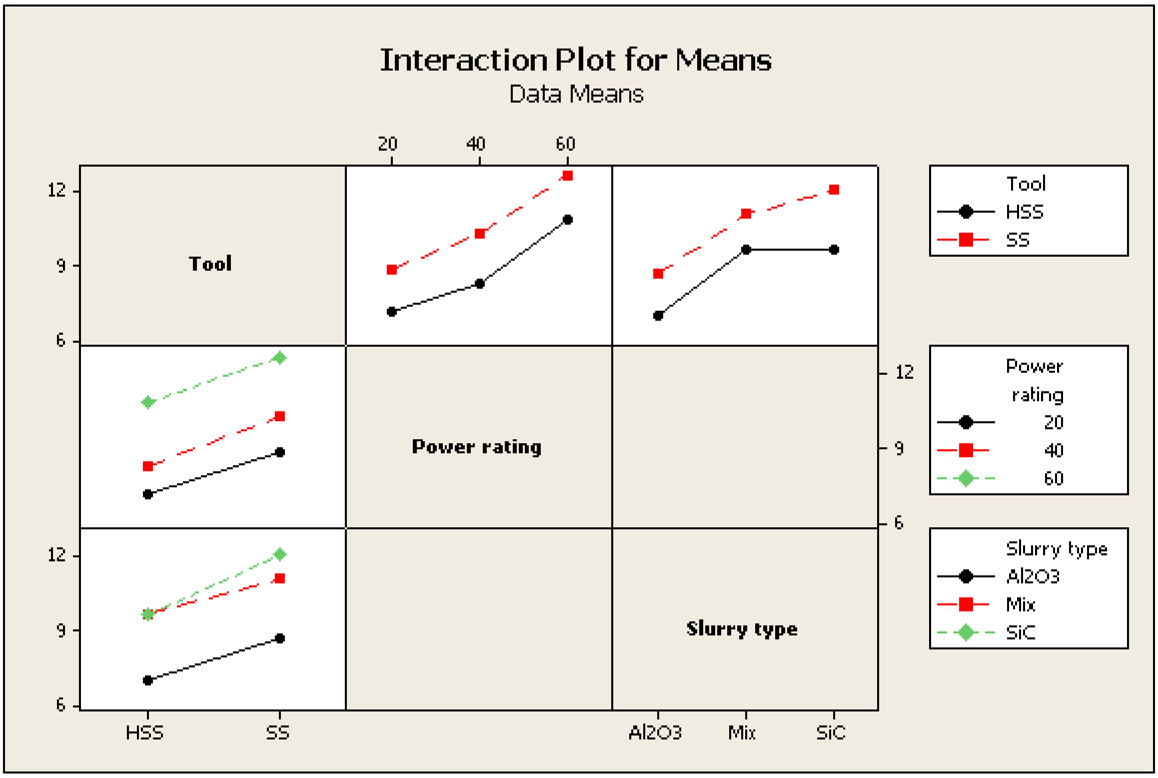


Figure 4.2: Interaction Plots of Means for MRR

4. 4 ANOVA of S/N Ratio for MRR

The S/N ratio consolidates several repetitions into one value and is an indication of the amount of variation present. The S/N ratio has been calculated to identify the major contributing factors and interactions that cause variation in the MRR. MRR is "Higher is better" type response which is given by:

HB:S/N ratio= $-10log_{10}\left[\frac{1}{n}\sum_{i=1}^{n} Y_i^{-2}\right]$ (Equation 4.2)

Table 4.4 shows the ANOVA for S/N ratio for MRR at 95% confidence interval. The Slurry type is the most significant factor in affecting MRR followed by Power Rating and Tool type according to F-test. Main effect plot and Residual plot for S/N ratios for MRR are shown in figure 4.3 and figure 4.4 respectively.

Table 4.4: ANOVA of S/N ratio for MRR

Sources	SS	v	V	F	F (critical)	SS'	%age contribution	Status
Tool(A)	12.931	1	12.93	53.79	7.71	12.021	13.514	Significant
Power rating(B)	36.682	2	18.34	76.29	6.94	34.861	39.193	Significant
slurry concen(C)	2.892	2	1.446	5.88	6.94			Insignificant
Slurry type(D)	32.051	2	16.03	66.66	6.94	30.23	33.987	Significant
Grit size(E)	2.476	2	1.238	5.15	6.94			Insignificant
AxB	0.278	2	0.139	0.58	6.94			Insignificant
AxD	0.677	2	0.338	1.41	6.94			Insignificant
Error	0.962	4	0.24					
TOTAL	88.947	17	5.232					
e-pooled	7.283	8	0.91				13.305	

Table 4.5: Response table of S/N ratio for MRR

LEVEL	Tool	Power Rating(%)	Slurry Concentration(%)	Type of Slurry	Grit size
1	18.61	17.91	19.26	17.58	19.98
2	20.31	19.13	19.1	20.24	19.27
3		21.35	20.02	20.56	19.14
Delta	1.7	3.45	0.92	2.98	0.84
Rank	3	1	4	2	5

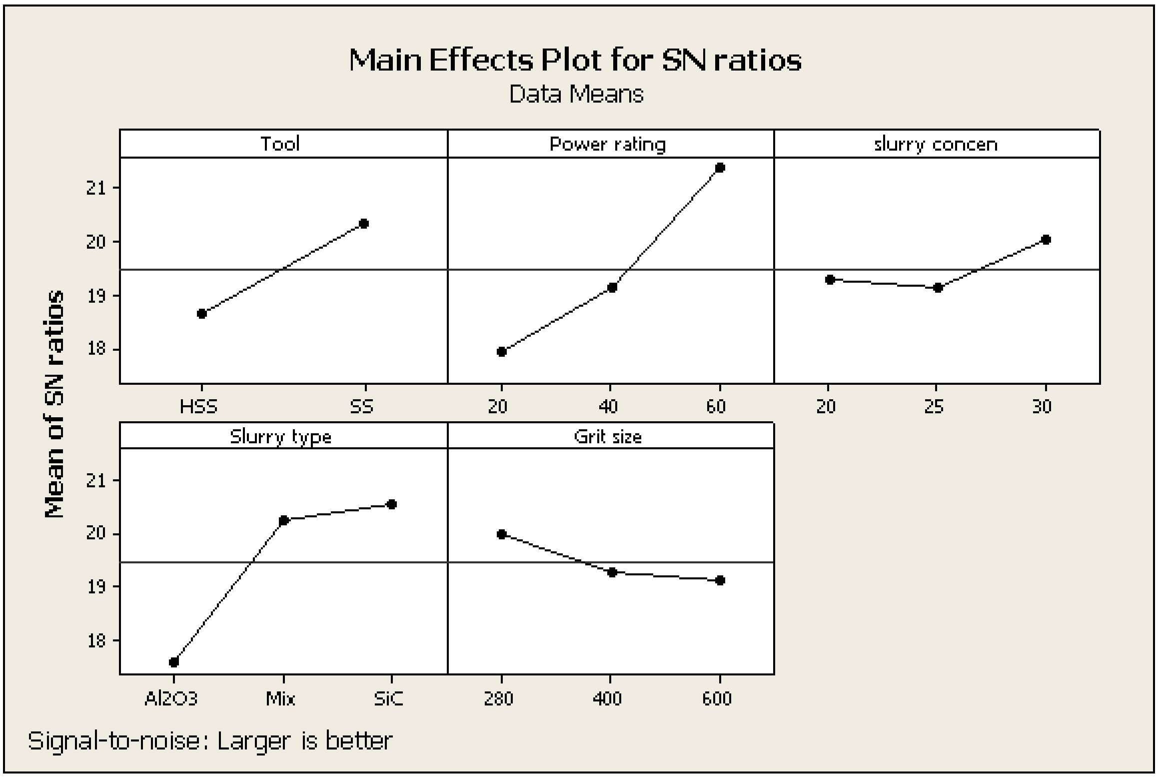


Figure 4.3: Main Effects Plot of S/N ratio for MRR

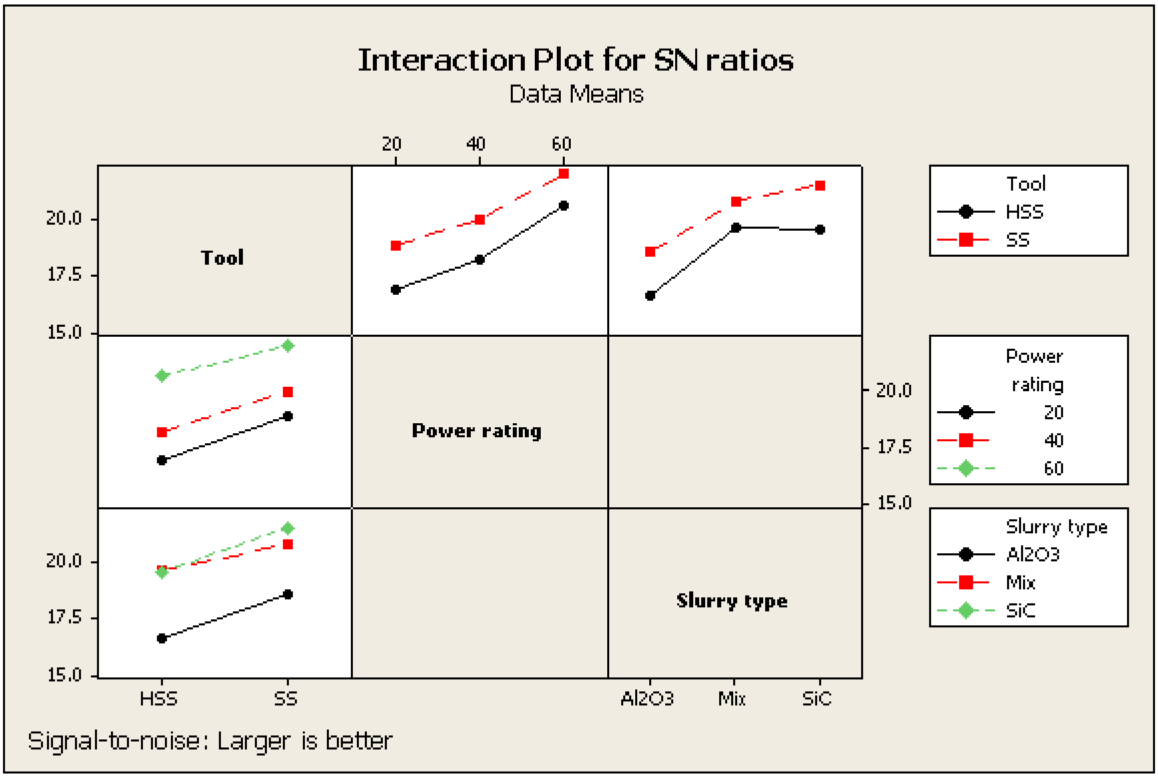


Figure 4.4 : Interaction Plots of S/N ratio for MRR

4.5. Optimal design for MRR

In this experimentation analysis, the main effect plot and interaction plot in Figure 4.1 and Figure 4.2 is used to estimate the mean MRR. From the Table 4.6 it is concluded that Mean and S/N ratio both are affected by Tool, Power Rating and Slurry Type . It is also observed (in case of Mean) that Slurry Concentration ,Grit Size and interaction between Tool and Slurry Type is also affecting MRR but interaction between Tool and Power rating are found insignificant. Also, Slurry Concentration ,Grit Size and both the interactions are found insignificant in case of S/N ratio.MRR assumed to be achieved best when workpiece i.e. Soda Glass is machined by Stainless Steel Tool with Power Rating 60%, abrasive SiC with slurry concentration 30% and Grit Size of 280.

Table 4.6: Significant Factors and Interactions

Factors	Affecting Mean		Affecting Variation	
	Contribution	Best Level	Contribution	Best Level
Tool	Significant	Level2(SS)	Significant	Level2(SS)
Power rating(%)	Significant	Level3(60)	Significant	Level3(60)
slurry concentration(%)	Significant	Level3(30)	Insignificant	
Slurry type	Significant	Level3(SiC)	Significant	Level3(SiC)
Grit size	Significant	Level1(280)	Insignificant	
Tool*Power Rating(%)	Insignificant		Insignificant	
Tool*Type of Slurry	Significant		Insignificant	

Estimating the mean

In experimental analysis, MRR is a higher average response is better (HB) characteristic. Depending on the characteristic, different treatment combinations has been chosen to obtain satisfactory analysis. After conducting the experiments the optimum treatment condition within the experiments determined on the basis of prescribed combination of factor levels is determined to one of those in the experiment. The mean value of MRR($\bar{T}$) is 9.695. The formula for calculating the theoretical optimal value is as under:

$$(MRR)_{opt} = \bar{T} + (A_2 - \bar{T}) + (B_3 - \bar{T}) + (C_3 - \bar{T}) + (D_3 - \bar{T}) + (E_1 - \bar{T}) \quad \text{(Equation 4.3)}$$

$$= 9.695 + (10.608 - 9.695) + (11.755 - 9.694) + (10.217 - 9.694)$$

$+(10.843 - 9.695) + (10.046 - 9.695)$

$= 14.691\ mm^3/min$

Confidence Interval around the Estimated Mean

$$CI = \sqrt{\frac{F_{\alpha,v1,v2} V_e}{\eta eff}} \qquad \text{(Equation 4.4)}$$

Where $F_{\alpha,v1,v2}$ = F ratio

α= risk (0.05) confidence= 1-α

v_1= dof for mean which is always = 1

v_2= dof for error = v_e

ηeff = No. Of tests under that condition using the particular factors

$\eta eff = N/(1 + dof_{A+B+C+D+E}) = 18/(1+2+2+2+2+2) = 1.636$

$CI = \sqrt{(7.71 * 0.274/1.636)}$

$= 1.13$

So, the Confidence Interval around the MRR is given by 14.69 $\pm$ 1.13mm^3/min.

5.1 Introduction

The effects of parameters i.e. tool, power rating, slurry concentration, type of slurry, grit size and interaction between Tool and Type of slurry, Tool and Power Rating were evaluated using ANOVA and factorial design analysis. A confidence interval of 95% has been used for the analysis. One repetition for each of 18 trials was completed to measure the Signal to Noise ratio (S/N Ratio).

5.2Results for TWR

The results for TWR for each of the 18 treatment conditions with repetition are given in Table 5.1.The TWR is calculated from the loss of weight of the tool during performance trial:

$$TWR = \frac{T_i - T_f}{\rho t} \times 1000 \text{ mm}^3/\text{min} \qquad \text{(Equation 5.1)}$$

Where T_i= Initial weight of Tool (gms)

T_f = Final weight of Tool (gms)

t= time period of trial (minutes)

ρ= density of workpiece (gms/cc)

Table 5.1: Results for TWR

Trial No	Tool	Power Rating(%)	Slurry Concen-tration(%)	Type of Slurry	Grit size	TWR (mm3/ min)	S/N Ratio	Mean
1	HSS	20	20	SiC	280	0.224	12.544	0.236
2	HSS	20	25	Al_2O_3	400	0.198	14.088	0.198
3	HSS	20	30	Mix	600	0.214	13.003	0.224
4	HSS	40	20	SiC	400	0.356	8.642	0.370
5	HSS	40	25	Al_2O_3	600	0.261	11.357	0.271
6	HSS	40	30	Mix	280	0.335	9.181	0.347
7	HSS	60	20	Al_2O_3	280	0.414	7.248	0.434
8	HSS	60	25	Mix	400	0.423	7.273	0.433
9	HSS	60	30	SiC	600	0.413	7.341	0.429
10	SS	20	20	Mix	600	0.216	13.301	0.216
11	SS	20	25	SiC	280	0.318	9.965	0.318
12	SS	20	30	Al_2O_3	400	0.290	10.752	0.290
13	SS	40	20	Al_2O_3	600	0.271	11.339	0.271

14	SS	40	25	Mix	280	0.381	8.381	0.381
15	SS	40	30	SiC	400	0.374	8.542	0.374
16	SS	60	20	Mix	400	0.492	6.160	0.492
17	SS	60	25	SiC	600	0.433	7.279	0.433
18	SS	60	30	Al_2O_3	280	0.455	6.840	0.455

5.3. ANOVA of Means for TWR

The results for TWR were analyzed using ANOVA for identifying the significant factors affecting the performance measures. The Analysis of Variance (ANOVA) for the mean MRR at 95% confidence interval is given in Table 5.2. The variance data for each factor and their interactions were F-tested to find significance of each. ANOVA table shows the Power Rating (F value 147.3) , Type of Tool (F value 22.01) and Grit Size (F value 14.81) are the factors that are significant and affects TWR. The Slurry Concentration, Slurry Type and the interactions AxB and AxE are found to be insignificant. Table 5.3 shows ranks to various input parameters in terms of their relative significance.

Table 5.2: ANOVA of Means for TWR

Sources	SS	v	V	F	F (critical)	SS'	%age contribution	Status
Tool(A)	0.009	1	0.009	22.01	7.71	0.008	5.358	Significant
Power rating(B)	0.115	2	0.057	147.3	6.94	0.113	78.169	Significant
slurry concen(C)	0.001	2	0.000	0.06	6.94			Insignificant
Slurry type(D)	0.005	2	0.002	6.07	6.94			Insignificant
Grit size(E)	0.012	2	0.006	14.81	6.94	0.010	6.843	Significant
AxB	0.001	2	0.001	1.39	6.94			Insignificant
AxE	0.001	2	0.001	1.9	6.94			Insignificant
Error	0.002	4	0.000					
TOTAL	0.145	17	0.009					
e-pooled	0.010	12	0.001				9.630	

Table 5.3: Response table of Means for TWR

Level	Tool	Power Rating(%)	Slurry Concentration (%)	Type of Slurry	Grit size
1	0.3588	0.2431	0.3288	0.3147	0.3543
2	0.3152	0.3296	0.3354	0.3435	0.3555
3		0.4383	0.3468	0.3528	0.3012
Delta	0.0437	0.1952	0.0179	0.0381	0.0543
Rank	3	1	5	4	2

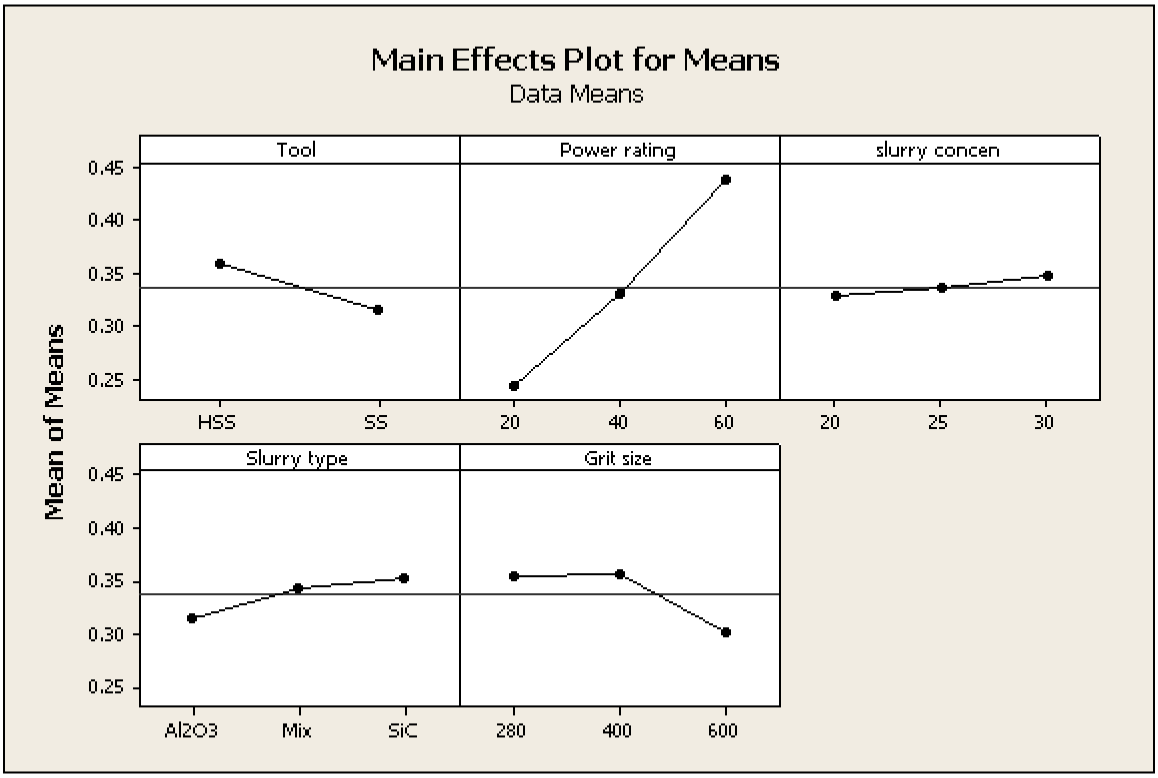


Figure 5.1: Main Effects Plot of Means for TWR

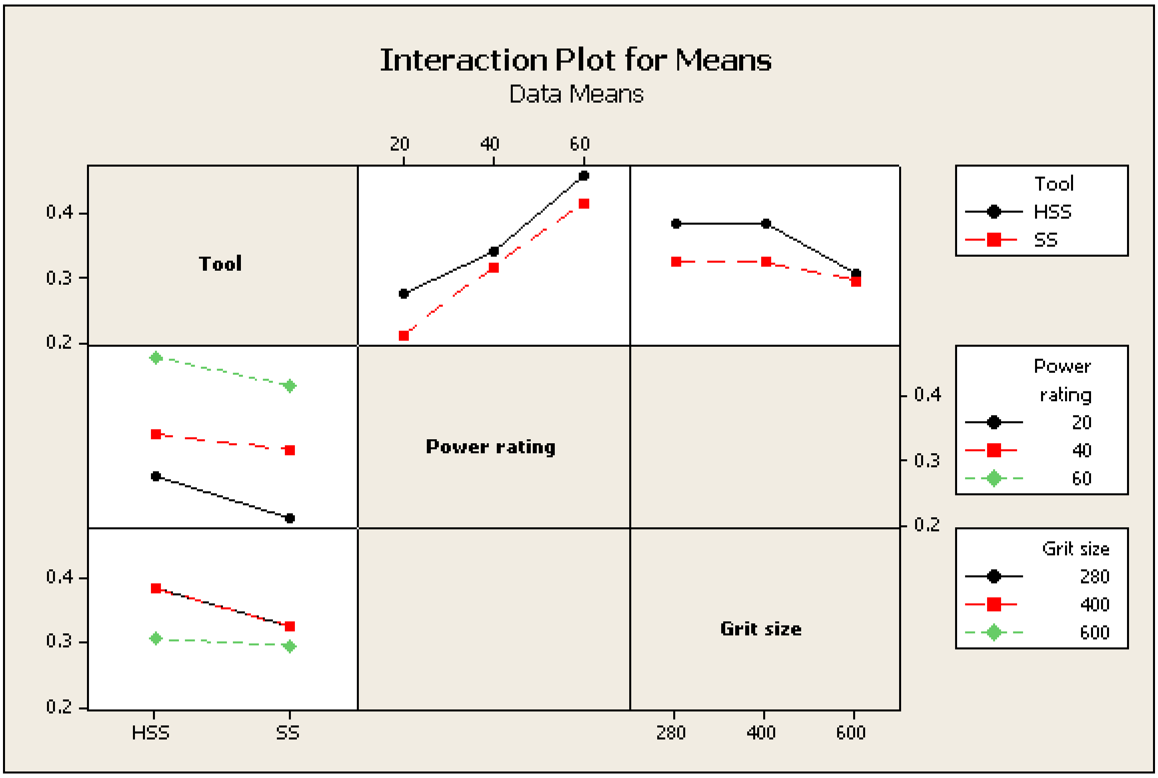


Figure 5.2 : Interaction Plots of Means for TWR

5.4. ANOVA of S/N Ratio for TWR

The S/N ratio consolidates several repetitions into one value and is an indication of the amount of variation present. The S/N ratio has been calculated to identify the major contributing factors and interactions that cause variation in the TWR. TWR is "Lower is better" type response which is given by:

LB: S/N ratio= $-10log_{10}\left[\frac{1}{n}\sum_{i=1}^{n} Y_i^2\right]$ (Equation 5.2)

Table 5.4 shows the ANOVA for S/N ratio for TWR at 95% confidence interval. The power rating is the most significant factor in affecting TWR followed by grit size and type of tool according to F-test. Main effect plot and interaction plot for S/N ratios for TWR are shown in figure 5.3 and figure 5.4 respectively.

Table 5.4: ANOVA of S/N ratio for TWR

Sources	SS	v	V	F	F (critical)	SS'	%age contribution	Status
Tool(A)	6.61	1	6.610	14.33	7.71	5.531	5.121	Significant
Power rating(B)	82.338	2	41.169	89.24	6.94	80.179	74.236	Significant
slurry concen(C)	1.161	2	0.581	0.13	6.94			Insignificant
Slurry type(D)	4.03	2	2.015	4.37	6.94			Insignificant
Grit size(E)	9.063	2	4.532	9.82	6.94	6.904	6.392	Significant
AxB	2.056	2	1.028	2.23	6.94			Insignificant
AxE	0.902	2	0.451	0.98	6.94			Insignificant
Error	4.804	4	1.201					
TOTAL	108.006	17	6.353					
e-pooled	12.953	12	1.079				14.251	

Table 5.5: Response table of S/N ratio for TWR

Level	Tool	Power Rating (%)	Slurry Concentration (%)	Type of Slurry	Grit size
1	9.173	12.42	10.073	10.393	9.227
2	10.385	9.737	9.811	9.703	9.33
3		7.181	9.454	9.242	10.781
Delta	1.212	5.238	0.62	1.151	1.554
Rank	3	1	5	4	2

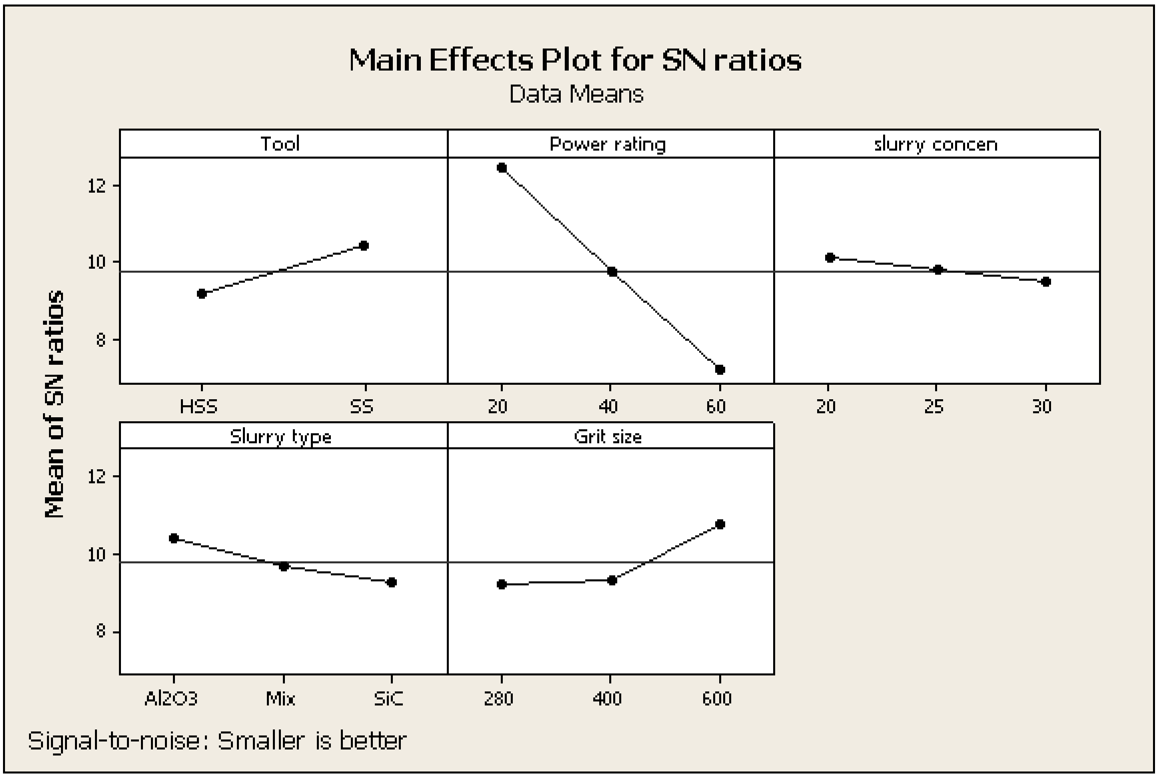


Figure 5.3: Main Effects Plot of S/N ratio for TWR

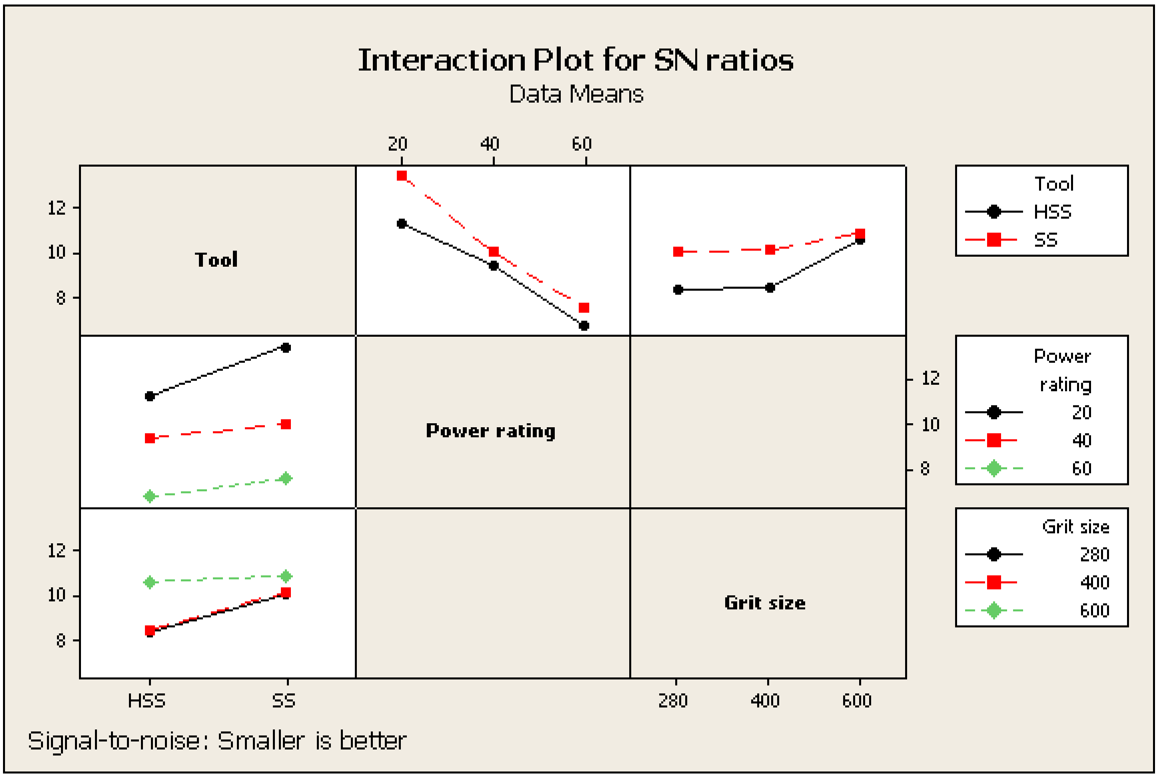


Figure 5.4: Interaction Plots of S/N ratio for TWR

5.5. Optimal design for TWR

In this experimentation analysis, the main effect plot and interaction plot in Figure 5.1 and Figure 5.2 are used to estimate the mean TWR. From the Table 5.6 it is concluded that in case of Mean and S/n ratio, lowest TWR is observed when workpiece is machined by Stainless Steel, Power Rate 20% with Grit size of 600. It is observed that Slurry Concentration, type of Slurry and interaction A×B, A×D were not affecting TWR. So, TWR is assumed to achieve best results if workpiece i.e. Soda glass is machined by Stainless Steel, Power Rate 20%, abrasive slurry Al_2O_3 with Grit size of 600.

Table 5.6: Significant Factors and Interactions

Factors	Affecting Mean		Affecting Variation	
	Contribution	Best Level	Contribution	Best Level
Tool(A)	Significant	Level2(SS)	Significant	Level2(SS)
Power rating (%)(B)	Significant	Level1(20)	Significant	Level1(20)
Slurry concentration(%)(C)	Insignificant		Insignificant	
Slurry type(D)	Insignificant		Insignificant	
Grit size(E)	Significant	Level3(600)	Significant	Level3(600)
Tool*Power Rating(%)	Insignificant		Insignificant	
Tool*Type of Slurry	Insignificant		Insignificant	

Estimating The mean

In experimental analysis, TWR is a lower average response is better (LB) characteristic. Depending on the characteristic, different treatment combinations had been chosen to obtain satisfactory analysis. After conducting the experiments the optimum treatment condition within the experiments determined on the basis of prescribed combination of factor levels was determined to one of those in the experiment. The mean value of TWR ($\bar{T}$) is 0.337. The formula for calculating the theoretical optimal value is as under:

$$(TWR)_{opt} = \bar{T} + (A_2 - \bar{T}) + (B_1 - \bar{T}) + (E_3 - \bar{T}) \quad \text{(Equation 5.2)}$$

$$= 0.337 + (0.359 - 0.337) + (0.243 - 0.337) + (0.301 - 0.337)$$

$$= 0.184 \text{ mm}^3/\text{min}$$

Confidence Interval around the Estimated Mean

$$CI=\sqrt{\frac{F_{\alpha,v1,v2}V_e}{\eta eff}} \quad \text{(Equation 5.2)}$$

Where $F_{\alpha,v1,v2}$ = F ratio

α= risk (0.05) confidence= 1-α

v_1= dof for mean which is always = 1

v_2= dof for error = v_e

ηeff = No. Of tests under that condition using the particular factors

ηeff =N/ (1+ dof $_{A+B+D+E}$) = 18/ (1+2+2+2+2) =2

CI=√ (7.71*0.001/2)

=0.062

So, the Confidence Interval around the TWR is given by 0.184 $\pm$ 0.062 mm^3/min.

6.1 Introduction

Surface Roughness (R_a) is the arithmetic average roughness of the deviations of the roughness profile from the central line along the measurement. It is a 'Lower is Better' phenomena. Surface Roughness was measured using the Perthometer; model M4Pi of Mahr, Germany available at Thapar University, Patiala. The equipment uses the stylus method of measurement, has profile resolution of 12 nm and measures roughness up to 100µm.

Surface Roughness (R_a) = $\frac{1}{L}\int_0^L |h(x)\,dx|$ (Equation 6.1)

where h(x) is the value of roughness profile & L is evaluation length.

6.2. Results for SR

The results for surface roughness for each of the 18 treatment conditions with repetition are given in Table 6.1.

Table 6.1: Results for SR

Trial No	Tool	Power Rating(%)	Slurry Concentration(%)	Type of Slurry	Grit size	SR (µm)	S/N Ratio	Mean
1	HSS	20	20	SiC	280	1.131	-1.068	1.131
2	HSS	20	25	Al_2O_3	400	1.226	-1.770	1.226
3	HSS	20	30	Mix	600	1.211	-1.659	1.211
4	HSS	40	20	SiC	400	1.320	-2.411	1.320
5	HSS	40	25	Al_2O_3	600	1.350	-2.607	1.350
6	HSS	40	30	Mix	280	1.300	-2.280	1.300
7	HSS	60	20	Al_2O_3	280	1.615	-4.163	1.615
8	HSS	60	25	Mix	400	1.595	-4.055	1.595
9	HSS	60	30	SiC	600	1.311	-2.352	1.311
10	SS	20	20	Mix	600	1.246	-1.908	1.246
11	SS	20	25	SiC	280	1.200	-1.584	1.200
12	SS	20	30	Al_2O_3	400	1.143	-1.164	1.143
13	SS	40	20	Al_2O_3	600	1.389	-2.854	1.389
14	SS	40	25	Mix	280	1.321	-2.419	1.321
15	SS	40	30	SiC	400	1.050	-0.424	1.050

16	SS	60	20	Mix	400	1.578	-3.964	1.578
17	SS	60	25	SiC	600	1.411	-2.991	1.411
18	SS	60	30	Al_2O_3	280	1.534	-3.717	1.534

6.3. ANOVA of Means for SR

The results for SR were analyzed using ANOVA for identifying the significant factors affecting the performance measures. The Analysis of Variance (ANOVA) for the mean SR at 95% confidence interval is given in Table 6.2. The variance data for each factor and their interactions were F-tested to find significance of each. ANOVA table shows that the Power Rating (F value 63.6), Slurry Type (F value 13.06) and Slurry concentration (F value 9.85) are the significant factors that are affecting SR. The type of tool, grit size and the interactions BxC are found to be insignificant. Table 6.3 shows ranks to various input parameters in terms of their relative significance.

Table 6.2: ANOVA of Means for SR

Sources	SS	v	V	F	F (critical)	SS'	%age contribution	Status
Tool(A)	0.002	1	0.002	0.78	7.71			Insignificant
Power rating(B)	0.312	2	0.156	63.6	6.94	0.307	65.427	Significant
slurry concen(C)	0.048	2	0.024	9.85	6.94	0.043	9.105	Significant
Slurry type(D)	0.077	2	0.038	13.06	6.94	0.071	15.164	Significant
Grit size(E)	0.004	2	0.002	2.01	6.94			Insignificant
BxC	0.016	4	0.004	1.59	6.39			Insignificant
Error	0.010	4	0.002					
TOTAL	0.469	17	0.028					
e-pooled	0.031	11	0.003				10.305	

Table 6.3: Response table of Means for SR

Level	Tool	Power Rating(%)	Slurry Concentration(%)	Type of Slurry	Grit size
1	1.319	1.193	1.38	1.376	1.35
2	1.34	1.288	1.351	1.375	1.319
3		1.507	1.258	1.237	1.32
Delta	0.021	0.315	0.122	0.139	0.031
Rank	5	1	3	2	4

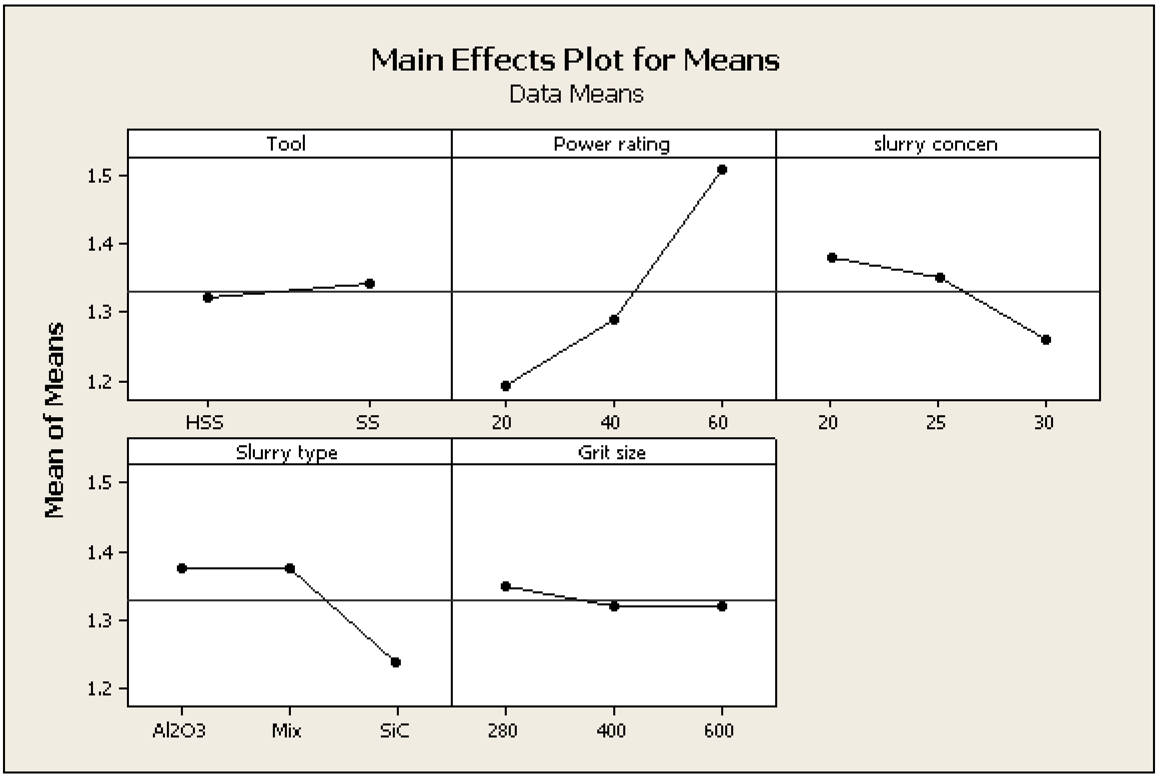


Figure 6.1: Main Effects Plot of Means for SR

Figure 6.2 : Interaction Plots of Means for SR

6.4. ANOVA of S/N Ratio for SR

The S/N ratio consolidates several repetitions into one value and is an indication of the amount of variation present. The S/N ratio has been calculated to identify the major contributing factors and interactions that cause variation in the SR. SR is "Lower is better" type response which is given by:

LB: S/N ratio= $-10log_{10}\left[\frac{1}{n}\sum_{i=1}^{n}Y_i^2\right]$ (Equation 6.2)

Table 6.4 shows the ANOVA for S/N ratio for SR at 95% confidence interval. The power rating is the most significant factor in affecting SR followed by grit size and type of tool according to F-test. Main effect plot and interaction plot for S/N ratios for SR are shown in figure 6.3 and figure 6.4 respectively.

Table 6.4: ANOVA of S/N ratio for SR

Sources	SS	v	V	F	F (critical)	SS'	%age contribution	Status
Tool(A)	0.100	1	0.100	0.93	7.71			Insignificant
Power rating(B)	12.718	2	6.359	59.23	6.94	12.435	63.115	Significant
slurry concen(C)	2.130	2	1.065	9.92	6.94	1.847	9.373	Significant
Slurry type(D)	3.299	2	1.649	13.35	6.94	3.016	15.308	Significant
Grit size(E)	0.176	2	0.088	2.1	6.94			Insignificant
BxC	0.851	4	0.213	1.98	6.39			Insignificant
Error	0.429	4	0.107					
TOTAL	19.703	17	1.159					
e-pooled	1.556	11	0.141				12.204	

Table 6.5: Response table of S/N ratio for SR

Level	Tool	Power Rating(%)	Slurry Concentration(%)	Type of Slurry	Grit Size
1	-2.336	-1.526	-2.728	-2.713	-2.539
2	-2.485	-2.166	-2.571	-2.714	-2.298
3		-3.54	-1.933	-1.805	-2.395
Delta	0.149	2.015	0.795	0.909	0.241
Rank	5	1	3	2	4

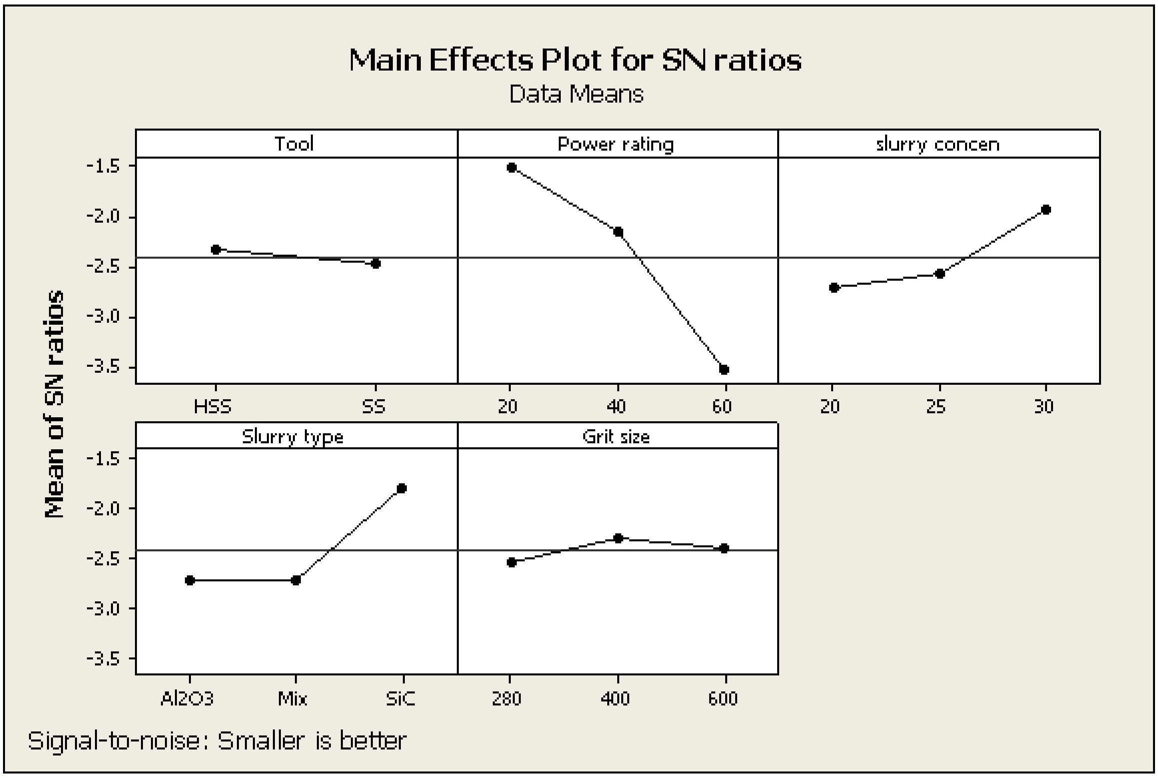


Figure 6.3: Main Effects Plot of SR for S/N ratio

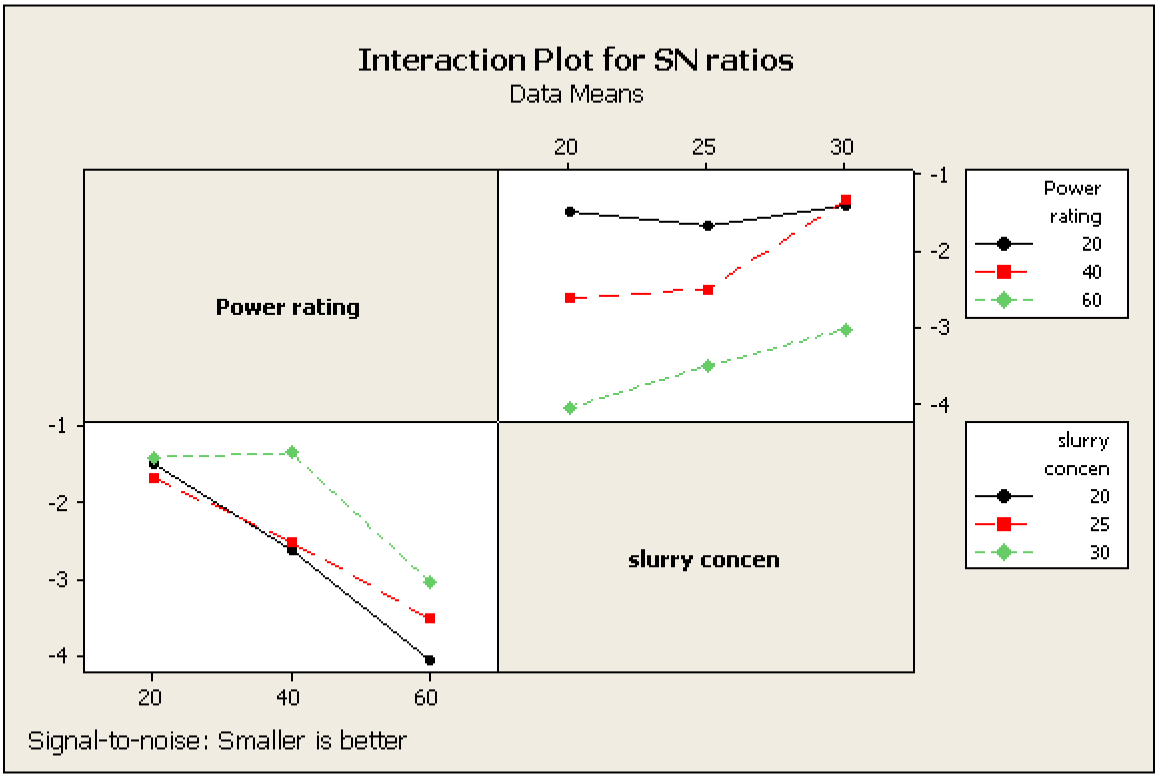


Figure 6.4: Interaction Plots of S/N for SR

6.5. Optimal design for SR

In this experimentation analysis, the main effect plot and interaction plot in Figure 6.1 and Figure 6.2 were used to estimate the mean SR. From the Table 6.6 it is concluded that lowest SR is observed when workpiece was machined at Power Rate 20%, abrasive slurry as Silicon Carbide and Slurry Concentration of 30 %. It is also observed that Type of Tool, Grit Size and interaction BxC are not affecting SR. The Best SR value was comprised to get best results.SR assumed to be achieved best result if workpiece i.e. Soda glass is machined at Power Rating of 20%, slurry concentration of 30 % and abrasive slurry as Silicon Carbide.

Table 6.6: Significant Factors and Interactions

Factors	Affecting Mean		Affecting Variation	
	Contribution	Best Level	Contribution	Best Level
Tool(A)	Insignificant		Insignificant	
Power rating(%)(B)	Significant	Level1(20)	Significant	Level1(20)
slurry concentration(%)(C)	Significant	Level3(30)	Significant	Level3(30)
Slurry type(D)	Significant	Level3(SiC)	Significant	Level3(SiC)
Grit size(E)	Insignificant		Insignificant	
Power Rating*slurry concentration(%)	Insignificant		Insignificant	

Estimating the mean

In experimental analysis, SR is a lower average response is better (LB) characteristic. Depending on the characteristic, different treatment combinations had been chosen to obtain satisfactory analysis. After conducting the experiments the optimum treatment condition within the experiments determined on the basis of prescribed combination of factor levels was determined to one of those in the experiment. The mean value of SR ($\bar{T}$) is 1.029. The formula for calculating the theoretical optimal value is as under:

$$(SR)_{opt} = \bar{T} + (B_1 - \bar{T}) + (C_3 - \bar{T}) + (D_3 - \bar{T}) \quad \text{(Equation 6.3)}$$

$$= 1.0295 + (1.027 - 1.029) + (1.025 - 1.029) + (1.023 - 1.029)$$

$$= 0.891\ \mu m$$

Confidence Interval around the Estimated Mean

$$CI = \sqrt{\frac{F_{\alpha,v1,v2} V_e}{\eta eff}}$$

Where $F_{\alpha,v1,v2}$ = F ratio

α= risk (0.05) confidence= 1-α

v_1= dof for mean which is always = 1

v_2= dof for error = v_e

ηeff = No. Of tests under that condition using the particular factors

ηeff =*N*/ (1+ dof $_{B+C+D}$) = 18/ (1+2+2+2) =2.57

CI= √ (7.71*0.003/2.57)

= 0.094

So, the Confidence Interval around the SR is given by 0.891 ± 0.094 µm .

CHAPTER 7 RESULTS AND ANALYSIS OF HARDNESS

7.1 Introduction

The Rockwell scale is a hardness scale based on the indentation hardness of a material. The Rockwell test determines the hardness by measuring the depth of penetration of an indenter under a large load compare to the penetration made by a preload.

7.2 Results for Hardness

The results for Hardness for each of the 18 treatment conditions with repetition are given in Table 7.1.

Table 7.1: Results for Hardness

Trial No	Tool	Power Rating(%)	Slurry Concentration(%)	Type of Slurry	Grit size	Hardness (HRB)	S/N Ratio	Mean
1	HSS	20	20	SiC	280	74	37.385	74
2	HSS	20	25	Al_2O_3	400	74	37.385	74
3	HSS	20	30	Mix	600	74.5	37.443	74.5
4	HSS	40	20	SiC	400	75	37.501	75
5	HSS	40	25	Al_2O_3	600	74.5	37.443	74.5
6	HSS	40	30	Mix	280	75	37.501	75
7	HSS	60	20	Al_2O_3	280	74	37.385	74
8	HSS	60	25	Mix	400	75.5	37.559	75.5
9	HSS	60	30	SiC	600	75	37.501	75
10	SS	20	20	Mix	600	75	37.501	75
11	SS	20	25	SiC	280	74.5	37.443	74.5
12	SS	20	30	Al_2O_3	400	74.5	37.443	74.5
13	SS	40	20	Al_2O_3	600	75	37.501	75
14	SS	40	25	Mix	280	75.5	37.559	75.5
15	SS	40	30	SiC	400	75.5	37.559	75.5
16	SS	60	20	Mix	400	76	37.616	76
17	SS	60	25	SiC	600	76	37.616	76
18	SS	60	30	Al_2O_3	280	75.5	37.559	75.5

4.3. ANOVA of Means for Hardness

The results for Hardness were analyzed using ANOVA for identifying the significant factors affecting the performance measures. The Analysis of Variance (ANOVA) for the mean Hardness at 95% confidence interval is given in Table 7.2. The variance data for each factor and their interactions were F-tested to find significance of each. ANOVA table shows the Tool (F value 115.20), Power Rating (F value 77.60), Slurry Type (F value 39.20),Grit Size(F value 10.40)and interaction AxB (F value 7.20) are the significant factors that are affecting hardness. Slurry Concentration and the interactions AxD were found insignificant. Table 7.3 shows ranks to various input parameters in terms of their relative significance.

Table 7.2: ANOVA of Means for Hardness

Sources	SS	v	V	F	F (critical)	SS'	%age contribution	Status
Tool(A)	2.00	1	2.000	115.200	7.71	1.920	27.650	Significant
Power rating(B)	2.69	2	1.347	77.600	6.94	2.535	36.500	Significant
slurry concen(C)	0.11	2	0.056	3.600	6.94			Insignificant
Slurry type(D)	1.36	2	0.681	39.200	6.94	1.201	17.300	Significant
Grit size(E)	0.36	2	0.181	10.400	6.94	0.201	2.900	Significant
AxB	0.25	2	0.125	7.200	6.94	0.090	1.300	Significant
AxD	0.10	2	0.049	2.800	6.94			Insignificant
Error	0.07	4	0.017					
TOTAL	6.94	17	0.408					
e-pooled	0.64	8	0.080				14.350	

Table 7.3: Response table of Means for Hardness

Level	Tool	Power Rating(%)	Slurry Concentration(%)	Type of Slurry	Grit size
1	75.28	74.42	74.83	74.58	74.75
2	74.61	75.08	75	75.25	75.08
3		75.33	75	75	75
Delta	0.67	0.92	0.17	0.67	0.33
Rank	3	1	5	2	4

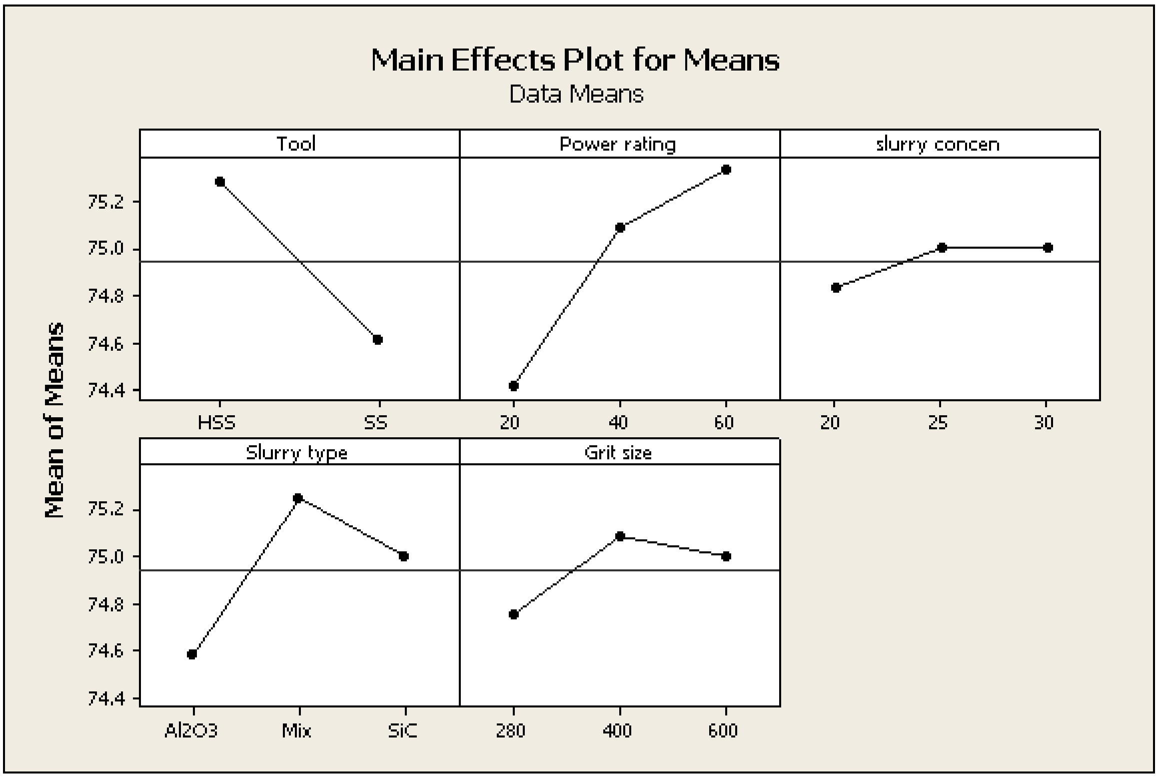


Figure 7.1: Main Effects Plot of Means for Hardness

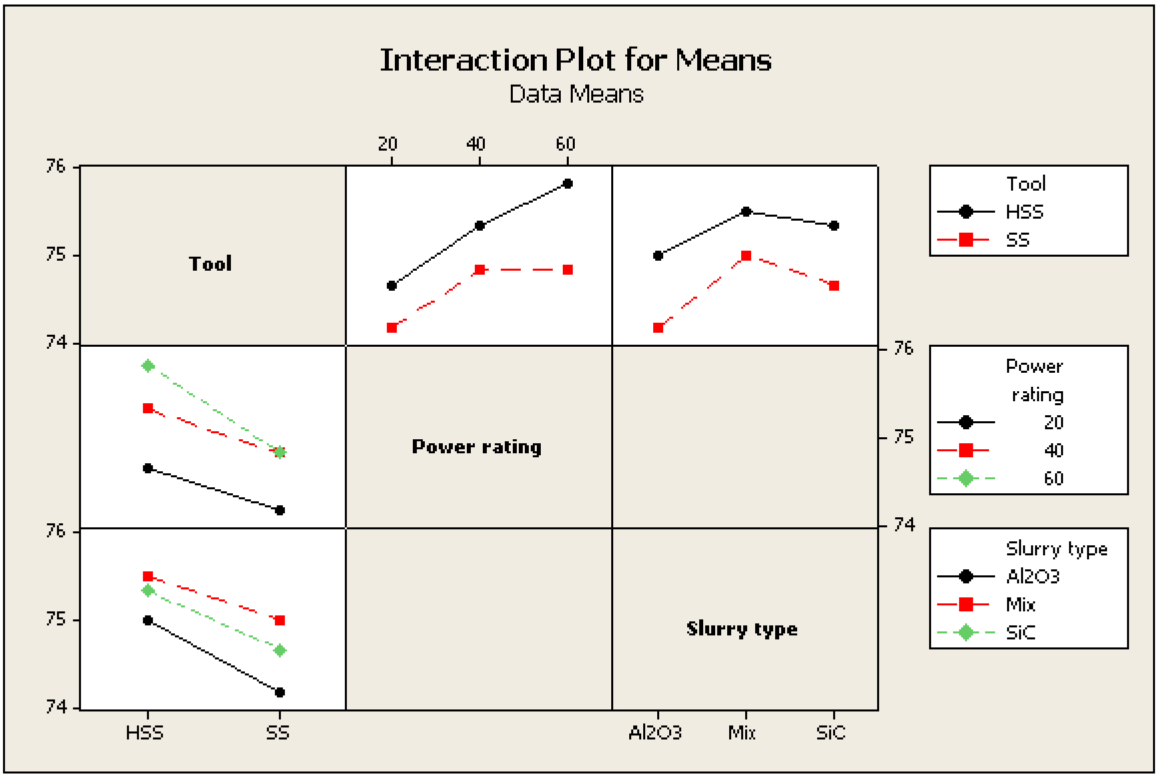


Figure 7.2: Interaction Plots of Means for Hardness

7. 4 ANOVA of S/N Ratio for Hardness

The S/N ratio consolidates several repetitions into one value and is an indication of the amount of variation present. The S/N ratio has been calculated to identify the major contributing factors and interactions that cause variation in the hardness. Hardness is "Higher is better" type response which is given by:

HB: S/N ratio= $-10 log_{10} \left[\frac{1}{n}\sum_{i=1}^{n} Y_i^{-2}\right]$ (Equation 7.1)

Table 4.4 shows the ANOVA for S/N ratio for Hardness at 95% confidence interval. The Power Rating is the most significant factor in affecting Hardness followed by Tool type and Slurry type according to F-test. Main effect plot and Residual plot for S/N ratios for Hardness are shown in figure 7.4 and figure 7.5 respectively.

Table 7.4: ANOVA of S/N Ratio for Hardness

Sources	SS	v	V	F	F (critical)	SS'	%age contribution	Status
Tool(A)	0.027	1	0.027	113.81	7.71	0.026	28.289	Significant
Power rating(B)	0.036	2	0.018	76.57	6.94	0.035	37.735	Significant
slurry concen(C)	0.002	2	0.001	3.58	6.94			Insignificant
Slurry type(D)	0.018	2	0.009	38.81	6.94	0.017	18.622	Significant
Grit size(E)	0.005	2	0.002	10.29	6.94	0.004	4.191	Significant
AxB	0.003	2	0.002	7	6.94	0.002	2.524	Significant
AxD	0.001	2	0.001	2.83	6.94			Insignificant
Error	0.001	4	0.000					
TOTAL	0.093	17	0.005					
e-pooled	0.004	8	0.0005				12.830	

Table 7.5: Response table of S/N Ratio for Hardness

Level	Tool	Power Rating(%)	Slurry Concentration(%)	Type of Slurry	Grit size
1	37.53	37.43	37.48	37.45	37.47
2	37.46	37.51	37.5	37.53	37.51
3		37.54	37.5	37.5	37.5
Delta	0.08	0.11	0.02	0.08	0.04
Rank	3	1	5	2	4

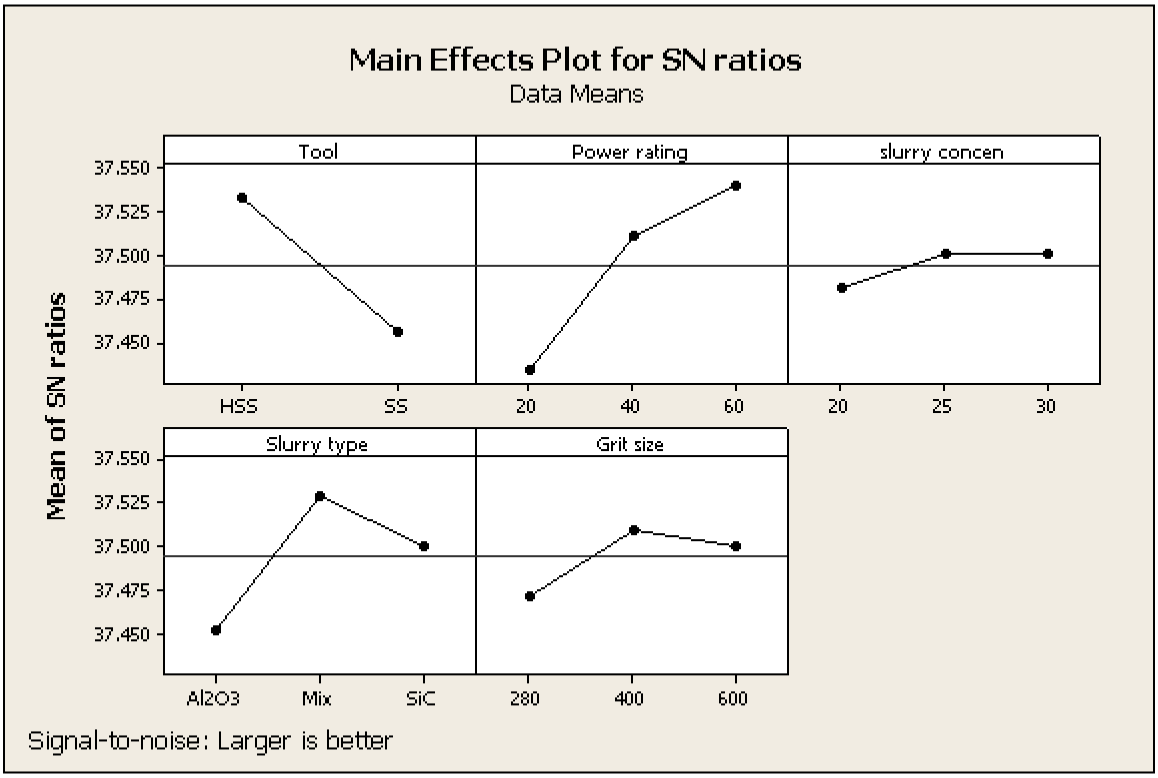


Figure 7.3: Main Effects Plot of S/N Ratio for Hardness

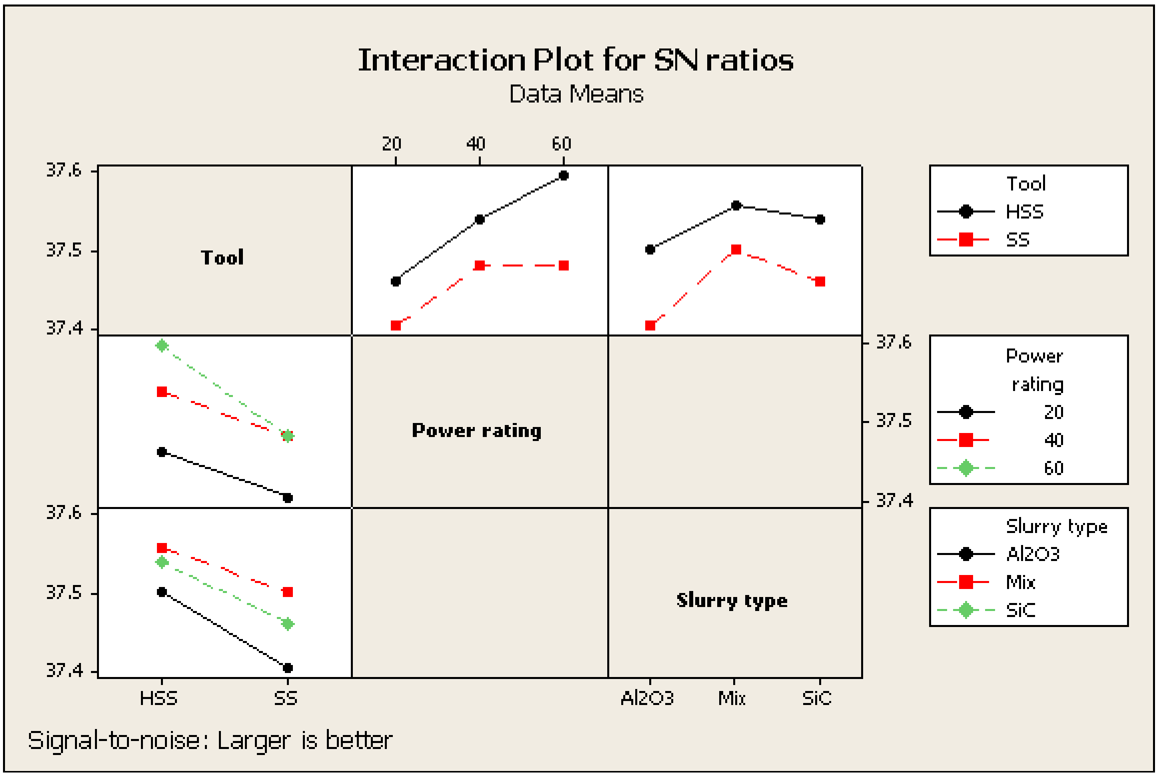


Figure 7.4 : Interaction Plots of S/N Ratio for Hardness

7.5 Optimal design for Hardness

In this experimentation analysis, the main effect plot and interaction plot in Figure 7.1 and Figure 7.2 were used to estimate the mean Hardness. From the Table 7.5 it is concluded that Mean and S/N ratio both are affected by Tool, Power Rating, Slurry Type and Grit Size. It is also observed (in case of Mean) that interaction between Tool and Power Rating is also affecting hardness but interaction between Tool and Slurry Type is found insignificant. Hardness assumed to be achieved best when workpiece i.e. Soda Glass is machined by High Speed Steel Tool with Power Rating 60% with abrasive slurry as mix and Grit Size of 400.

Table 7.6: Significant Factors and Interactions

Factors	Affecting Mean		Affecting Variation	
	Contribution	Best Level	Contribution	Best Level
Tool(A)	Significant	Level1(HSS)	Significant	Level1(HSS)
Power rating(%)(B)	Significant	Level3(60)	Significant	Level3(60)
Slurry concentration(%)(C)	Insignificant		Insignificant	
Slurry type(D)	Significant	Level2(Mix)	Significant	Level2(Mix)
Grit size(E)	Significant	Level2(400)	Significant	Level2(400)
Tool*Power Rating(%)	Significant		Significant	
Tool*Type of Slurry	Insignificant		Insignificant	

Estimating the mean

In experimental analysis, Hardness is a higher average response is better (HB) characteristic. Depending on the characteristic, different treatment combinations had been chosen to obtain satisfactory analysis. After conducting the experiments the optimum treatment condition within the experiments determined on the basis of prescribed combination of factor levels was determined to one of those in the experiment. The mean value of Hardness ($\bar{T}$) is 74.94. The formula for calculating the theoretical optimal value is as under:

$$(\text{Hardness})_{opt} = \bar{T} + (A_1 - \bar{T}) + (B_3 - \bar{T}) + (D_2 - \bar{T}) + (E_2 - \bar{T}) \quad \text{(Equation 7.2)}$$

$$= 74.94 + (74.611 - 74.94) + (75.33 - 74.94) + (75.25 - 74.94) + (75.083 - 74.94)$$

$$= 75.944 \text{ HRB}$$

Confidence Interval around the Estimated Mean

$$CI=\sqrt{\frac{F_{\alpha,v1,v2}V_e}{\eta eff}} \qquad \text{(Equation 7.3)}$$

Where $F_{\alpha,v1,v2}$ = F ratio

α= risk (0.05)   confidence= 1-α

v_1= dof for mean which is always = 1

v_2= dof for error = v_e

ηeff = No. Of tests under that condition using the particular factors

ηeff =*N*/ (1+ dof $_{A+B+D+E}$) = 18/ (1+2+2+2+2) =2

CI=√ (7.71*0.080/2)

=0.555

So, the Confidence Interval around the Hardness is given by 75.944 ± 0.555 HRB.

8.1 Introduction

Further analysis of the machined surfaces after confirmation experiments was performed to find out surface morphology and microstructure and it has been presented in this part. Micro structural analysis of machined surface was evaluated by using Scanning Electron Microscope (SEM). In this work, the effect of various input parameters i.e. tool, power rating, slurry concentration, type of slurry, and grit size on the surface microstructure of the workpiece material were evaluated.

8.2 Microstructure Analysis

Microstructure analysis was carried out on three selected samples using Scanning Electron Microscope to study the change in microstructure after machining. The samples were prepared as per standard before SEM analysis on three different magnifications namely 200 X, 500 X and 1000X.

8.2.1 Preparing Samples for SEM

The steps for the preparation of sample for SEM are given below:

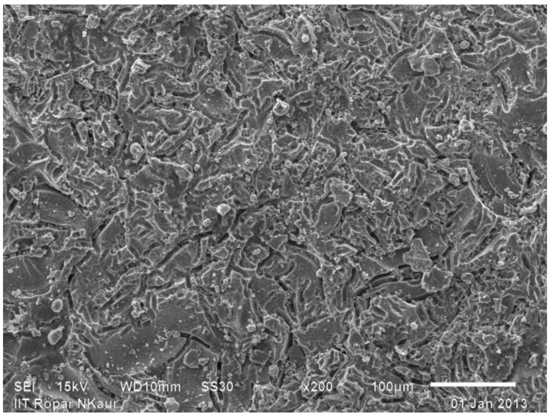
All the samples are cut into size of φ 10 mm.

Clean the surface of sample with wire brush

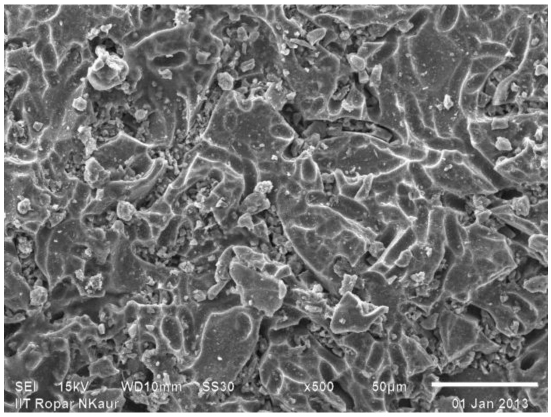
Clean the samples with acetone using cotton so as to remove debris from the machined surface.

8.3 SEM Analysis

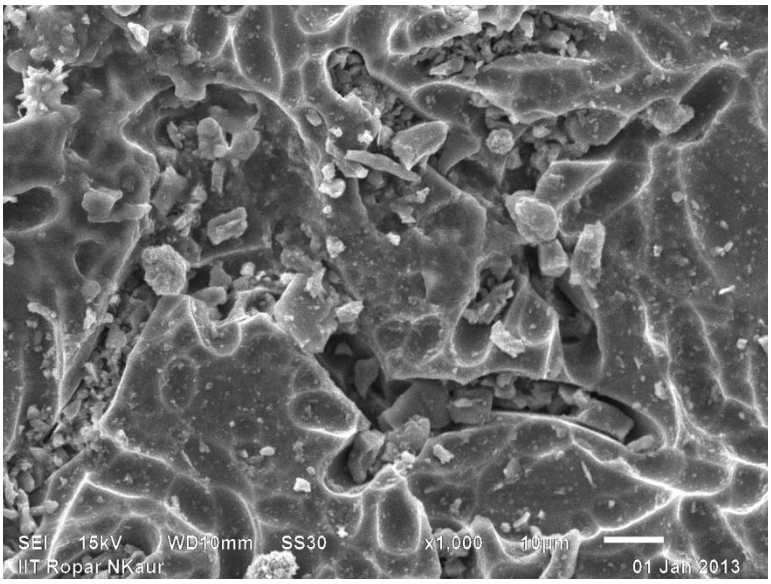
The mode of material removal in USM is also decided by the work material properties such as fracture toughness and hardness. Fracture toughness has been found to be the most important parameter affecting the mode of material removal. While machining a material with high fracture toughness value, the brittle fracture of the surface is preceded by plastic deformation and strain hardening of the work surface as the abrasive grains have a tendency to embed in the work surface during machining. As the tool vibrates, it pushes down the abrasive slurry until the grain impact the brittle workpiece. The workpiece is broken down while the tool bends very slightly.



(a) 200X



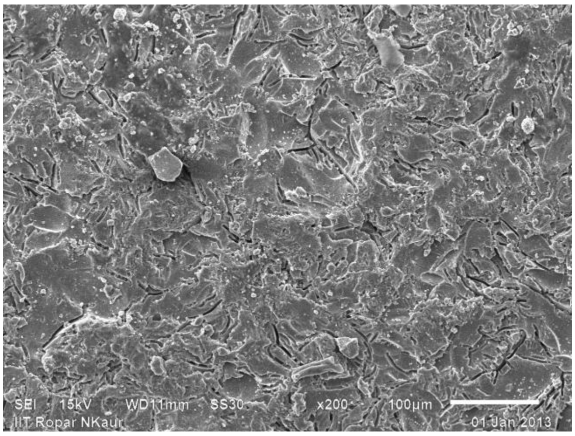
(b) 500X



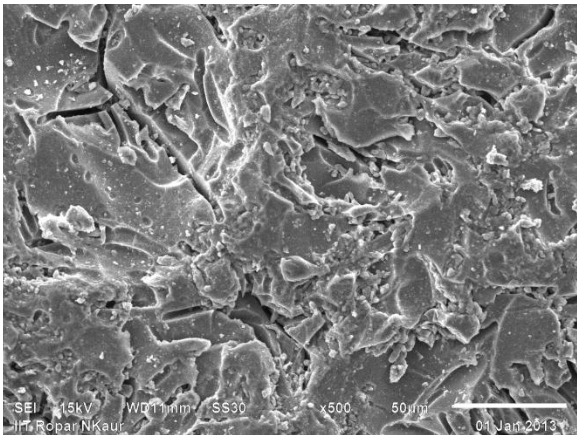
(c) 1000X

Figure 8.1: SEM micrograph of Soda Glass machined [Experiment No.12]

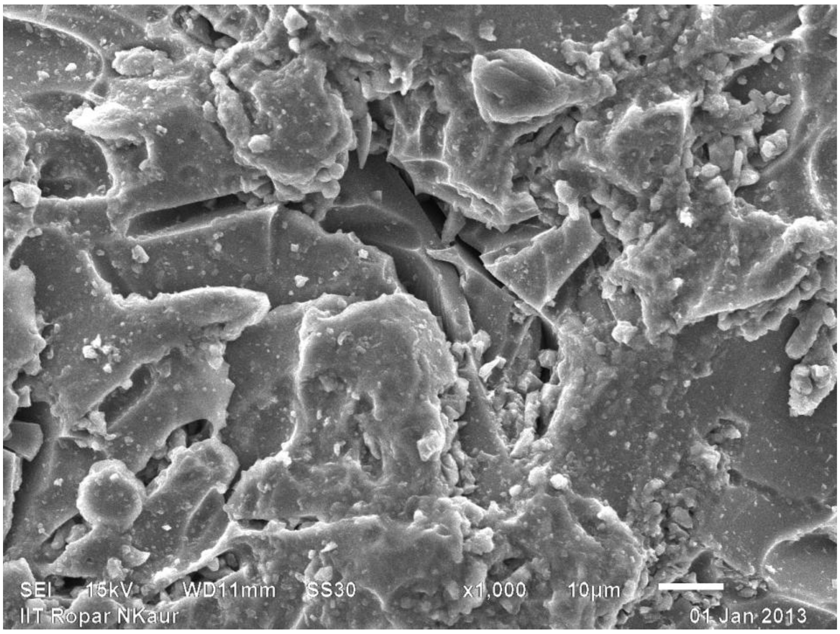
Figure 8.1depicts the microstructure of Soda Glass after machining with USM at 1000 X and 500 X and 200 X under the experimental conditions corresponding to experiment no. 12. It could be observed that the material faced significant amount of deformation before failure. The material was machined by brittle failure of the work material. This could be attributed to the extremely low energy input into the abrasive as the experimental conditions involved use of a softer abrasive (alumina) with very low power rating (20%). An uneven cracks has been obtained on the workpiece due to impact and hammering action of abrasive particle, speed of vibration tool and chemical action of abrasive slurry. Due to low power rating and moderate grain size of 400 rate of machining was very low, also it took a comparatively larger time period to machine the work surface to the desired depth



(a) 200X



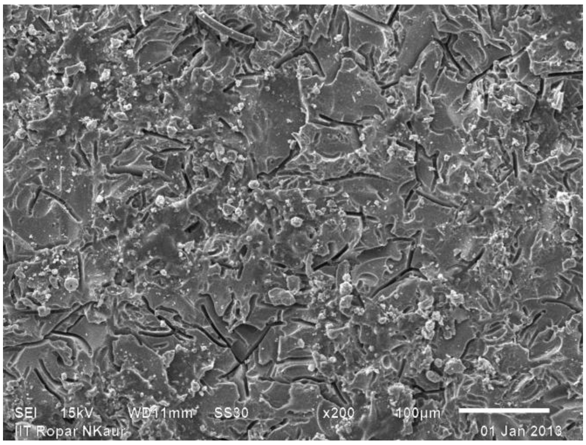
(b) 500X



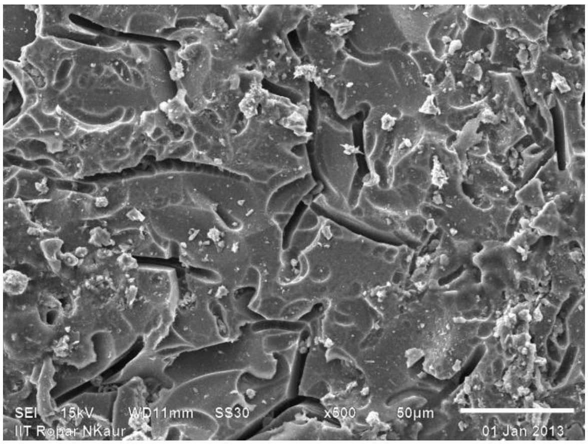
(c) 1000X

Figure 8.2: SEM micrograph of Soda Glass machined [Experiment No.17]

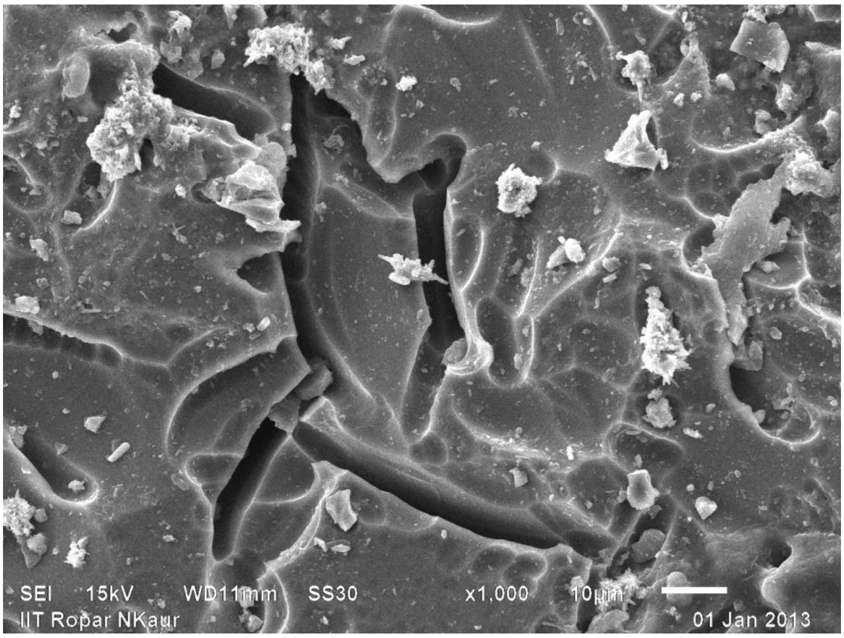
Figure 8.2 shows the microstructure of Soda Glass after machining with USM under the experimental conditions corresponding to experiment no. 17 at magnification levels of 1000 X and 500 X and 200 X. The parameter settings corresponding to this experimental condition include silicon carbide as slurry which is comparatively harder and high level of power rating (60%)and Stainless Steel as the Tool Material. The rate of machining is high which leads to a gain in the surface hardness for the work material. The fractured surface is comparatively larger than that observed in case of high energy input conditions .



(a) 200X



(b) 500X



(c) 1000X

Figure 8.3: SEM micrograph of Soda Glass machined [Experiment No.5]

Figure 8.3 shows the microstructure of Soda Glass after machining with USM under the experimental conditions corresponding to experiment no. 6 at magnification levels of 1500 X and 1000 X. The parameter settings for this trial include mix slurry with a fine grit size of 600,and moderate level of power input (40%) with High speed Steel as the Tool Material. In this the fractured surface is higher due to the presence of relatively harder tool material as compared to previous experiments. Hence a significant amount of plastic deformation is observed with a number of cracks.

CHAPTER 9

COMPARISION OF MRR AND SR BETWEEN CUSM AND USM

9.1 Introduction

The experiments were conducted for the same input parameters for CUSM and USM to observe the difference between these two processes. The tool, power ratings, slurry concentration, type of slurry and grit size were taken as input parameters. One repetition for each of 6 selected experiments was completed to compare the output parameters like MRR and SR.

9.2. Analysis of MRR for CUSM and USM

The results for MRR for each of the 6 treatment conditions with repetition are given in Table 9.1.

Table 9.1: Comparison of MRR for CUSM and USM

Trial No	Tool	Power Rating(%)	Slurry Concentration(%)	Type of Slurry	Grit Size	MRR in CUSM (mm^3/min)	MRR in USM (mm^3/min)
1	HSS	20	20	SiC	280	8.022	5.06
2	HSS	40	25	Al_2O_3	600	6.224	4.545
3	HSS	60	25	Mix	400	12.007	8.44
4	SS	20	25	SiC	280	8.24	6.06
5	SS	40	20	Al_2O_3	600	7.254	4.54
6	SS	60	20	Mix	400	13.007	10.47

As in MRR a higher average response characteristic is better has been seen that the MRR in USM is much less that of CUSM. So in order to compare the MRR results, the mean value of MRR is found for both the cases. Figure 9.1 represents the comparison in values of MRR for both the processes graphically.

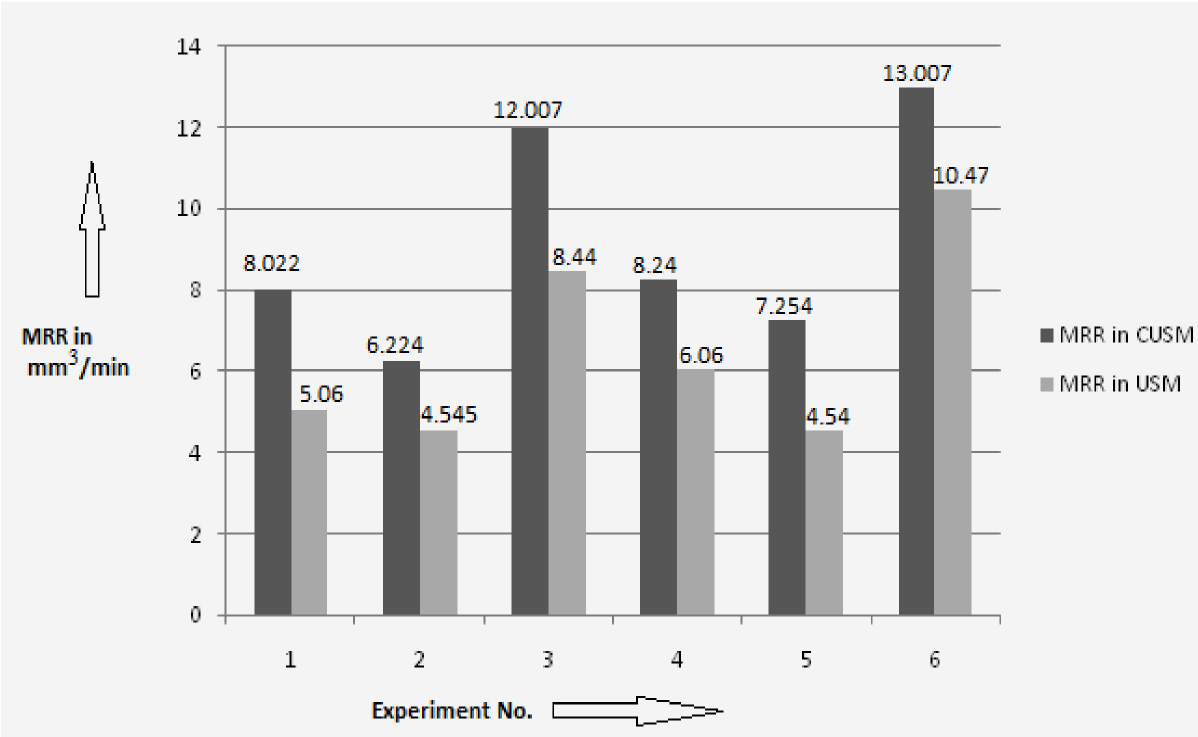


Figure 9.1 Graphical representation of MRR in CUSM and USM

From Table 9.1 it was concluded that the mean value of MRR in CUSM ($\bar{T}$) is 9.125 and in USM ($\bar{T}$) is 6.519.An increase in MRR is obtained leads to higher machining rate as compared to conventional USM process.

9.3 Analysis of SR for CUSM and USM

The results for SR for each of the 6 treatment conditions with repetition are given in Table 9.2.

Table 9.2: Comparison of SR for CUSM and USM

Trial No	Tool	Power Rating(%)	Slurry Concentration(%)	Type of Slurry	Grit Size	SR in CUSM (mm^3/min)	SR in USM (mm^3/min)
1	HSS	20	20	SiC	280	1.231	1.415
2	HSS	40	25	Al_2O_3	600	1.350	1.659
3	HSS	60	25	Mix	400	1.595	2.027
4	SS	20	25	SiC	280	1.200	1.315
5	SS	40	20	Al_2O_3	600	1.389	1.614
6	SS	60	20	Mix	400	1.578	1.878

As in SR a lower average response characteristic is better, it has been seen that the SR in USM has a higher value than that CUSM. Figure 9.2 represents shows the comparison in values of SR for both the processes graphically.

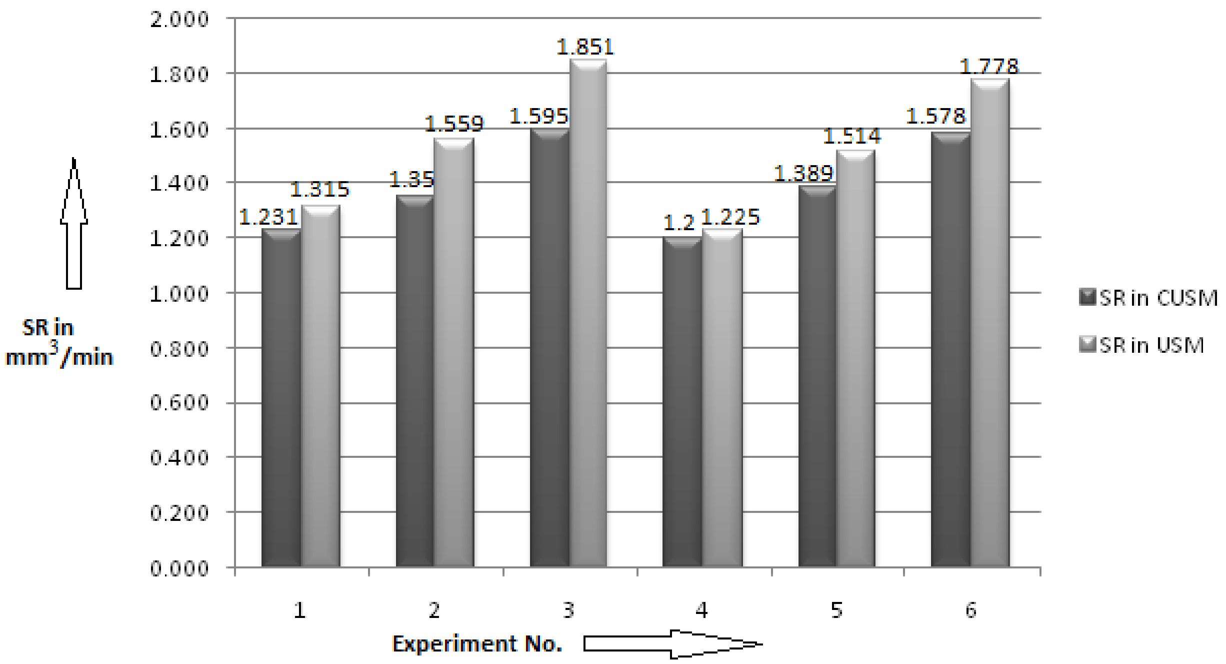


Figure 9.2 Graphical representation of SR in CUSM and USM

The mean value of SR is found for both the cases in order to compare SR results. From Table 8.2 it was concluded that the mean value of SR in CUSM ($\bar{T}$) is 1.391 and in USM ($\bar{T}$) is 1.540. Hence a lower surface roughness is obtained which leads to better surface quality of the machined part.

CHAPTER 10 RESULTS,CONCLUSIONS & RECOMMENDATIONS

10.1 Results of MRR,TWR, SR and Hardness

The effects of parameters i.e. tool, power rating, slurry concentration, type of slurry, grit size and their interactions were evaluated using ANOVA and factorial design analysis. The purpose of the ANOVA was to identify the parameters in prediction of MRR, TWR, Surface Roughness and Rockwell Hardness. Some results consolidated from ANOVA and plots are given below:

10.1.1 Material Removal Rate

From the Table 4.2, it was observed that Power Rating was found to be the most significant factor with contribution of 44.76 % followed by Slurry type, type of Tool, Slurry Concentration, Interaction between Tool and Type of slurry and Grit Size with a contribution of 32.33 %, 15.53% ,2.1% ,0.86% and 0.82 % respectively. The interaction between Tool and Power Rating was found insignificant

For S/N ratio Power Rating, Slurry type and type of Tool were found to be significant to MRR for reducing the variation.

Table 4.3 and 4.5 shows the ranks of different factor.1st rank is given to Power Rating that has highest contribution to MRR.2nd rank is given to type of Slurry,3rd Rank is given to type of Tool that have minimum contribution to MRR.
Highest MRR was observed when the Workpiece is machined on Power Rating of 60%, Abrasive Slurry as Silicon Carbide, Tool Material be Stainless Steel, Slurry Concentration of 30% and 280 as its Grit Size. With 95% confidence interval mean value of MRR was found to be 14.691 $\pm$ 1.13mm^3/min

10.1.2 Tool Wear Rate

From the Table 5.2, it was observed that Power Rating was found to be the most significant factor with contribution of 78.16 % followed by Grit Size and type of Tool with a contribution of 6.84 % and 5.35% respectively.Type of Slurry,Slurry Concentration, Interaction between Tool and Grit Size and interaction between Tool and Power Rating and Slurry Concentration was found insignificant.

For S/N ratio Power Rating, Grit Size and type of Tool were found to be significant to TWR for reducing the variation.

Table 5.3 and 5.5 shows the ranks of different factor.1st rank is given to Power Rating that has highest contribution to TWR.2nd rank is given to type of Grit Size, 3rd Rank is given to type of Tool, 4th rank is given to type of Slurry and the 5th Rank is given to Slurry Concentration that have minimum contribution to TWR.

Lowest TWR was observed when the workpiece is machined on Power Rating of 20%, Tool Material be Stainless Steel and 600 as its Grit Size. With 95% confidence interval mean value of TWR was found to be 0.184 $\pm$ 0.062 mm^3/min

10.1.3 Surface Roughness

From the Table 6.2, it was observed that Power Rating was found to be the most significant factor with contribution of 65.43% followed by Slurry type and Slurry Concentration with a contribution of 15.16% and 9.1% respectively. Type of tool, Grit Size and Interaction between Power Rating and slurry Concentration was found insignificant.

For S/N ratio Power Rating, type of Slurry and Slurry Concentration were found to be significant to SR for reducing the variation.

Table 6.3 and 6.5 shows the ranks of different factor.1st rank is given to Power Rating that has highest contribution to SR.2nd rank is given to type of Slurry and 3rd Rank is given to Slurry Concentration that have minimum contribution to SR.

Lowest SR was observed when the Workpiece is machined on Power Rating of 20%, Abrasive Slurry as Silicon Carbide and slurry Concentration be 30.With 95% confidence interval mean value of SR was found to be 0.891 $\pm$ 0.094 µm.

10.1.4 Hardness

From the Table 7.2, it was observed that Power Rating was found to be the most significant factor with contribution of 36.5 % followed by type of Tool, Slurry type,Grit Size and and Interaction between Tool and Power Rating with a contribution of 27.65%,17.3%,2.9% and 1.3% respectively. Slurry Concentration and Interaction between Tool and Slurry type was found insignificant.

For S/N ratio Power Rating,,type of tool, type of Slurry, Grit Size and and Interaction between Tool and power Rating were found to be significant to Hardness for reducing the variation.

Table 7.3 and 7.5 shows the ranks of different factor.1st rank is given to Power Rating that has highest contribution to Hardness.2nd rank is given to type of Slurry and 3rd Rank is given to type of Tool, 4th rank is given to Grit Size and the 5th Rank is given to Slurry Concentration that have minimum contribution to TWR.

Highest Hardness was observed when the Workpiece is machined on Power Rating of 60%, Abrasive Slurry as Silicon Carbide + Aluminium Oxide, High Speed Steel as Tool Material and 400 as its Grit Size. With 95% confidence interval mean value of SR was found to be 75.944 $\pm$ 0.555 HRB.

10.2 Results of comparing USM and CUSM

From the Table 8.1 and 8.2,it was found that a poorer performance was obtained in USM as compared to CUSM in terms of MRR and a better surface finish is obtained in CUSM. It was found that in CUSM the MRR was increased by 40%.

10.3 Conclusions

The following conclusions were drawn from present study:-

1. The MRR is mainly affected by Power rating and abrasive slurry
2. The TWR is mainly affected by Power Rating and grit size
3. Maximum effect on machined surface finish is due to type of Abrasive slurry and Power Rating.
4. Rockwell Hardness depends on Power Rating, Tool Material and Grit Size
5. The chemical-assisted ultrasonic machining process, which uses a low concentration HF solution for chemical effect, is developed to overcome the disadvantages of the conventional USM process like less material removal rate and poor surface quality for machining glass
6. From experiments and analysis, it is verified that the material removal rate and surface roughness were improved up to 40% and 10% respectively with soda glass as workpiece.

10.4 Recommendations for Future Work

1. A low concentration of 3 % is added to Abrasive Slurry.The effect on different parameters can be found if the concentration of the acid be increased.
2. Comparison of SEM Analysis can be done of USM and CUSM and the variation can be found.
3. Different type of glass and tool material can be used and the variations in results can be found.
4. Different type of slurry and grit size can be used to know the variations in results.

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