

Thesis
on
**EXPERIMENTAL INVESTIGATION OF PERFORMANCE
CHARACTERISTICS OF AN ULTRASONIC MACHINING
PROCESS**

Submitted in partial fulfillment of requirement for award of degree of
MASTER OF ENGINEERING
IN
PRODUCTION AND INDUSTRIAL ENGINEERING

Submitted By:
Gagandeep Singh
Roll No: 820982008

Under the guidance of:
Dr. V.P Agarawal
Visiting Professor
Thapar University, Patiala



DEPARTMENT OF MECHANICAL ENGINEERING
THAPAR UNIVERSITY
PATIALA-147004, INDIA
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I am highly grateful to the authorities of Thapar University, Patiala for providing this opportunity to carry out the present thesis work.

I would like to express a deep sense of gratitude and thanks profusely to my thesis guide Dr. VP Agarwal, Visiting Professor, Department of Mechanical Engineering, Thapar University, for their sincere and invaluable guidance, suggestion and sympathetic attitude which inspired me to submit this thesis report in the present form.

I would also like to thank all the staff members and my co-students who were always there at the need of the hour and provided with all the help and facilities, which I required for the completion of my thesis.

I am also thankful to the authors whose works I have consulted and quoted in this work. Last but not the least I would like to thank God for not letting me down at the time of crisis and showing me the silver lining in the dark clouds.



GAGANDEEP SINGH MAVI

CERTIFICATE

This is to certify that the thesis entitled "EXPERIMENTAL INVESTIGATION OF PERFORMANCE CHARACTERISTICS OF AN ULTRASONIC MACHINING PROCESS" an authentic record of my study carried out as requirement 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. V.P Agrawal, Visiting Professor, Department of Mechanical Engineering, Thapar University, Patiala. This matter embodied in this thesis has not been submitted in part or full to any other university or institute the award of degree.


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This is to certify that the above declaration made by the student concerned is correct to best of my knowledge and belief.


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
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GAGANDEEP SINGH MAVI

ABSTRACT

Ultrasonic machining is one of the most widely used non-traditional machining processes for the machining of non-conductive, brittle materials. Unlike other processes, ultrasonic machining does not damage the work surface thermally which contributes to the successful performance of these materials in service. Its material removal mechanism includes impacting, hammering and cavitations. The USM is effective and practical for all brittle materials, including glass, ceramics, carbides, and graphite. The experiments have been performed on ultrasonic machine, Sonic Mill, 500 Watts (USA). The abrasive slurries alumina and silicon carbide of three different grit sizes has been taken. The concentration of abrasive slurry has been taken differently. Grit size used were 320, 400, 600 mesh. In this experiment three work piece were used i.e. Metal matrix composites with Aluminium as baseline material with ZrO_2 , SiC and Al_3Zr as particulate reinforcement in respective three work pieces. Power output, slurry concentration, slurry type and grit size were variable input parameters

Finally, the effect of ultrasonic machining process on tool and work materials has been investigated experimentally by examining the surface roughness, micro-structure, surface hardness, material removal rate as output parameters. The machined surfaces have been analyzed by using the scanning electron microscope (SEM) and surface roughness values of machined surface were measured using the surface roughness measuring instrument "Perthometer M4pi". In addition to discussing the characteristics, also an attempt has been made to optimize the process parameters proposed by various researchers, as well as to review and sample the wide variety of current applications of the same, in the field of Non-traditional machining.

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ABBREVIATIONS

ANOVA	Analysis of Variation
MRR	Metal removal rate
TWR	Tool wear rate
DOF	Degree of freedom
SEM	Scanning Electron Microscope
S/N	Signal to Noise ratio
SR	Surface Roughness
D2	High Carbon High Chromium steel

NOTATIONS

OA	Orthogonal Array
A	Power rating
B	Work piece
C	Slurry type
D	Slurry concentration
E	Grit size
SS	Sum of Squares
SS'	Pure sum of square
CI	Confidence Interval
C%	contribution percent

CHAPTER 1

INTRODUCTION

1.1 ULTRASONIC MACHINING

The Ultrasonic machining is a ‘non-traditional’ machining technique and is part of a family of relatively modern finishing and shaping process described as ‘chip less machining’. These processes don’t use cutting tool and do not create residual stresses in the work piece. Ultrasonic machining is often used in combination with other chip less machining techniques, such as electro discharge machining, in the manufacturing of precision component.

In contrast, ultrasonic machining (UM or USM) is a non-thermal, non-chemical and non-electrical machining process that leaves the chemical composition, material microstructure and physical properties of the work piece unchanged. Sometimes referred to as ultrasonic impact grinding (UIG) or vibration cutting, the USM process can be used to generate wide range of intricate features in advance materials.

Ultrasonic machining (USM) is a mechanical material removal process used to erode holes and cavities in hard and brittle work piece by using shaped tools, high frequency mechanical motion, and an abrasive slurry. A relatively soft tool is shaped as desired and vibrates against the work piece while a mixture of fine slurry and water flows between them. The friction of abrasive particles gradually cuts the work piece.

Materials such as hardened steel, carbides, rubies, quartz, diamonds, glass, ceramics can be easily be machined by USM. Ultrasonic machining is able to effectively machine all the materials harder than HRC 40 (Rockwell hardness measured in the C scale), irrespective of material is conductive or insulator.

The need for methods of working these “unworkable” materials has led to the introduction of special methods e.g. electrochemical, electro erosion, electron beam and ultrasonic machining is one of them. USM process is can be used to machine precision micro-features, round and odd-shape holes, blind cavities.



Figure 1.1 Ultrasonic Machine [N.T.M Lab, T.U, Patiala]

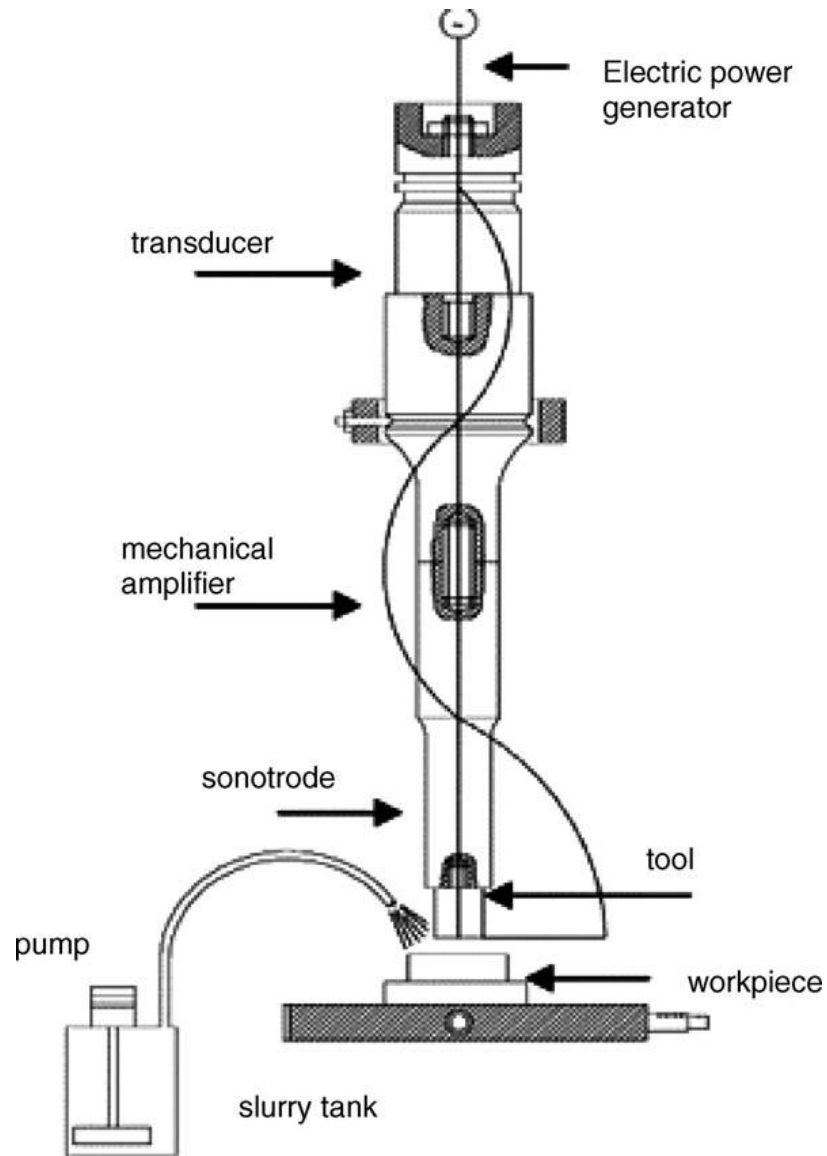


Figure 1.2 shows the schematic diagram of USM apparatus [27]

A constant stream of abrasive slurry passes between the tool and the work piece. Commonly used abrasive include diamond, boron carbide, alumina and silicon carbide. The abrasive grains are suspended in water or a suitable chemical solution. In addition to providing abrasive grain to the cutting zone, the slurry is used to flush away debris. The vibrating tool, combined with abrasive slurry, abrades the material uniformly, leaving precise reverse image of tool shape.

Ultrasonic machine is a loose abrasive machine process that require a very low force applied to abrasive grain, which leads to reduced material requirements and minimal to no damage to the surface.

Material removal during USM process can be classified in two mechanisms:

- a) Mechanical abrasion by the direct hammering of abrasive particles into work piece [9, 23, 49, 50]
- b) Micro chipping through impact of free moving abrasive particles [9, 26, 49, 27]
- c) Cavitation effect from the abrasive slurry [26, 34, 27]
- d) Chemical action associated with fluid employed [9, 34]

Material removal rate and surface roughness generated on machined surface depend on the material properties and process parameters including type and size of abrasive grain employed and the amplitude of vibration as well as material porosity, hardness and toughness.

1.2 ULTRA-SONICS

The term ultrasonic is used to describe vibration waves having a frequency above the hearing range of normal human ear i.e. beyond 15 KHz. This would include a wide range of ultrasonic's is largely dependent on the generator, practical limitation imposing a maximum frequency in the region of 500 Mc/s.

The range of wavelengths in varying media is very wide. For example, when propagated in a solid medium, a wave with the frequency of 25 Kc/s will have a wave length of about 200 mm, while one with a frequency of 500 Mc/s will have a wavelength of the order of 0.008 mm. The acoustic range of vibration is the one which the human ear perceives i.e. in the frequency range of 30 to 15000 Hz, the ultrasonic range of vibrations lies above this i.e. frequencies beyond 15000 Hz. There is no physical difference between the upper acoustic range 5000 to 15000 Hz and the ultrasonic range 15000 to 30000 Hz. Both the range of frequencies of certain intensities of sound will be heard as loud noise by the human ear and can permanently damage the auditory system.

Ultrasonic frequencies of the same intensities of sound cannot be heard by the human ear and they are less harmful. Ultrasonic frequencies provide satisfactory working condition and hence they are alone used for material removal purposes. There are two types of waves, namely shear waves and longitudinal waves. Longitudinal waves are mostly used in ultrasonic application since they are easily generated. They can be propagated in solids, liquids and gases and can travel at a high velocity so that their wavelength is short in most media.

1.3 APPLICATIONS OF ULTRASONICS

1. Ultra-sonic machining
2. Ultra-sonic casting, welding, brazing and soldering of metals.
3. Ultra-sonic forming of plastics.
4. Measurement of velocity of moving fluids.
5. Measurement of density, viscosity and elastic constant.
6. Measurement of hardness and grain size determination of metals.
7. Nondestructive residual stress determination.
8. Flaw detection, leak detection etc.

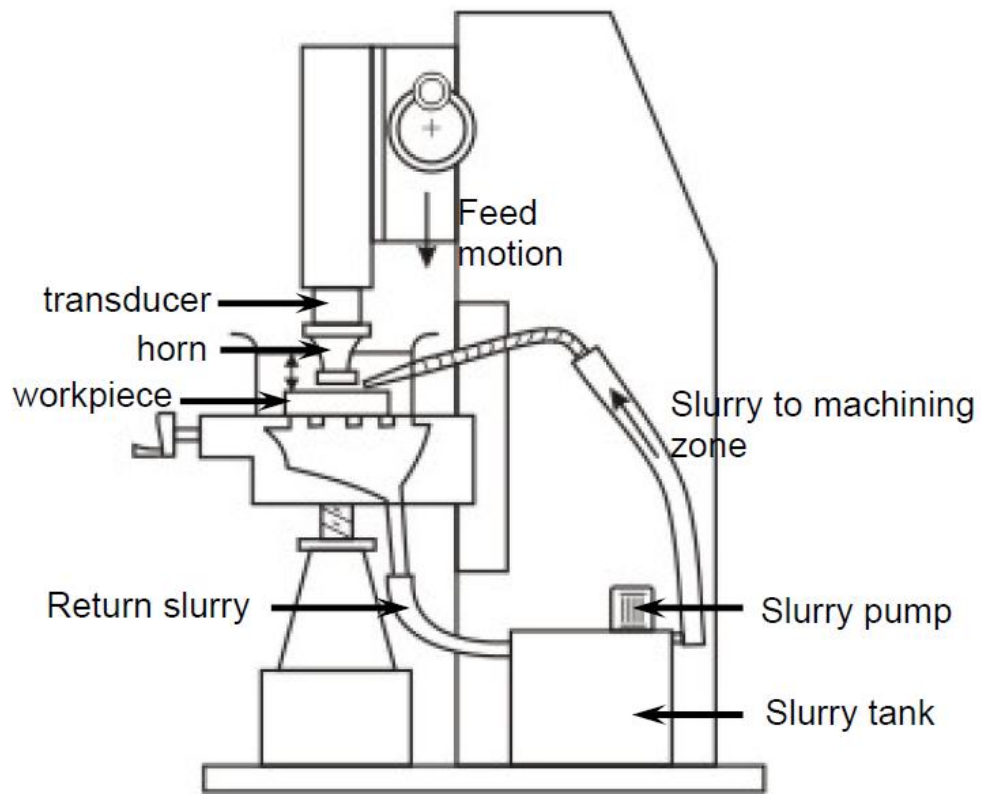


Figure 1.3 shows ultrasonic machine set up [28]

1.4 SPECIFIC FEATURES OF USM

USM have several specific features:

1. Acoustic head
2. Feed mechanism
3. Abrasive feed system
4. Power source
5. Table
6. Position indicator

The acoustic head as shown in Figure (1.3) contain the electro mechanical converter which drives the tool via a special holder (waveguide). The feed mechanism applies the necessary force (5-8kgs) between tool and work piece. The abrasive feed system continuously brings in fresh abrasive to the cutting area, removes products and cools the components. The power supplies the ultrasonic current to the acoustic head, various vacuum tube system are in common use and some high power magnetostriction heads have recently been used with high frequency alternators, which appear very promising.

Ultrasonic cutting is a technique as yet they are not very reliable and are costly, and are of very low efficiency. Ultrasonic cutting techniques are only beginning to be exploited. No really reliable methods are available for calculating the dimensions of component, especially cutting tools.

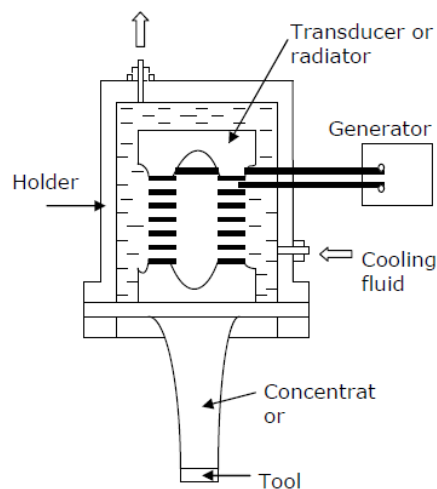


Figure 1.4 Schematic diagram of acoustic head [29]

1.5 NEED FOR ULTRASONIC MACHINING

The process is regarded as competitive only when an operation cannot be practically and economically performed on conventional machining equipment. The ultimate value of USM lies in the ability to do work that cannot be practically accomplished in any other way because USM is non-chemical and non-thermal.

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.

1.6 HISTORICAL BACKGROUND OF ULTRASONIC MACHINING (USM)

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's 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 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 and, for this reason, ultrasonic machining again gained importance and prominence. In recent years, various types of ultrasonic machine tool have been developed. The USM technique is still far from perfect.

1.7 PRINCIPLE OF ULTRASONIC MACHINING

In ultrasonic machining, material is removed due to action of abrasive grain which are hammered into the work surface by a tool oscillating at high frequency of 16 KHz to 30KHz and an amplitude in the order of 0.01 mm to 0.06 mm, have been found to be appropriate. 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. The tool is shaped as the approximate mirror image of the configuration of the cavity desired in the work. The tool cross-section is of a shape as the approximate mirror image of the configuration of the cavity desired in the work. The tool cross-section is of a shape similar to that of the desired hole-only it is a little smaller in size in order to compensate for the over cut during the process. The process can cut virtually any material but is most effective on material with hardness greater than 40 HRC

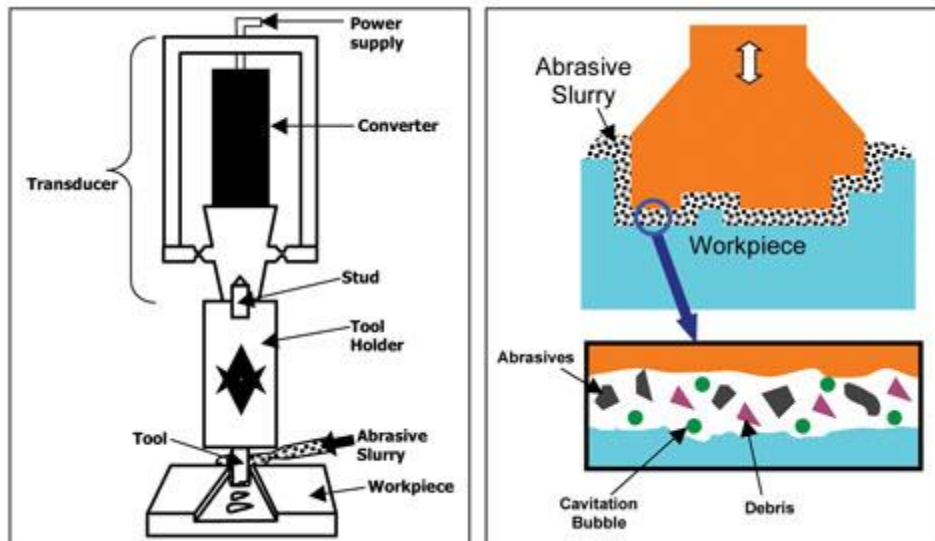


Figure 1.5 Principle of USM process [27]

A simple schematic diagram of this process is shown in Fig. 1.5. The tool is made of soft and tough materials (usually brass, carbide, mild or tool steel). The abrasive grains are carried to the gap (generally in order of 0.02 to 0.10 mm) between the tool and the work piece with the help of a carrier fluid, generally water. The circulation of slurry (mixture of abrasive grains and the carrier fluid) also takes away the worn-out grains and the machining debris, and replaces them by new grains, thus maintaining a good cutting rate. During machining, along with the work piece, the tool also gets reduced in size due to the cutting action of the abrasive grits. Thus the drilled hole by ultrasonic machining is tapered, i.e. larger at the top. By compensating the tool wear properly, close tolerances can be obtained.

The USM equipment consist of an oscillator (high frequency current generator) that converts the 50Hz 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 magnetostrictive transducers generally found in old machines are less efficient due to high eddy current losses and hence may require cooling.

1.8 ELEMENTS OF ULTRASONIC MACHINING

The machine for USM ranges from small, table top sized units to large- capacity machine tools as illustrated in Fig.2.1 respectively. 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. The high frequency oscillating current generator or oscillator.
2. The transducer
3. The velocity transformer
4. The tool holder
5. The tool
6. The abrasive slurry
7. The work-piece

1.8.1 THE HIGH FREQUENCY OSCILLATING CURRENT GENERATOR OR OSCILLATOR

The power supply for USM 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. It converts low frequency 60 Hz electrical power to high frequency approx. 20 KHz electrical power. This electrical signal is then supplied to the transducer for conversion into mechanical motion. The main requirements of a generator are:-

- a. Reliability and durability
- b. Efficiency
- c. Simplicity in design and low cost
- d. Compactness and easy to operate
- e. Stable frequency with possibility of being regulated over a specific range
- f. Controlled power output over a wide range

1.8.2 THE TRANSDUCER

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:

1. Piezoelectric Transducer
2. Magnetostrictive Transducer

1.8.2.1 PIEZOELECTRIC TRANSDUCER

These are used for USM to generate mechanical motion through the piezoelectric effect by which certain materials, such as quartz or lead Zirconate titanate will generate a small electric current when compressed. Conversely, when an electric current is applied to one of these material, the material increases minutely in size. When the current is removed, the material intently returns to its original shape. Piezoelectric transducer, by nature, exhibit an extremely high electro-mechanical conversion efficiency (up to 96%), which eliminates the need for water cooling of transducer. These transducers are available with power capabilities up to 900W.

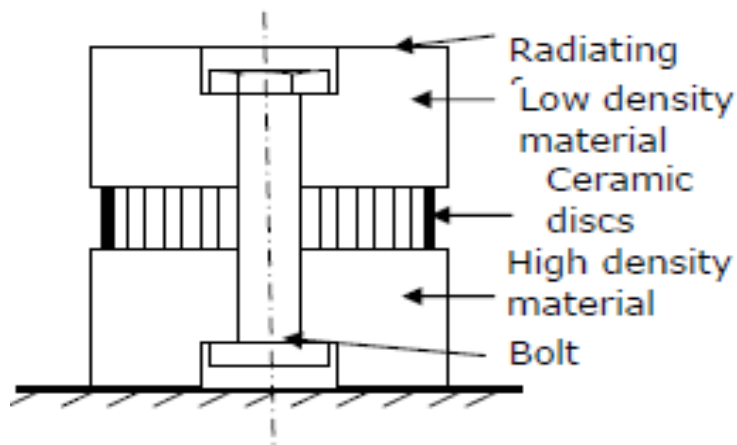


Figure 1.6 Piezoelectric ultrasonic transducer [29]

1.8.2.2 MAGNETOSTRICTIVE TRANSDUCER

These are usually constructed from a laminated stock of nickel or nickel alloy sheets which, when influenced by a strong magnetic field, will change length. Magnetostrictive transducers are rugged but have electro-mechanical conversion efficiencies ranging from 20 to 30%. The lower efficiency results in the need to water cool magnetostrictive devices to remove the waste heat. Magnetostrictive transducers are available with power capabilities up to 2400W. The magnitude of the length change that can be achieved by both piezoelectric and magnetostrictive transducer is limited by the strength of transducer material. In both types of transducer the limit is approximately 0.025mm (0.01 in).

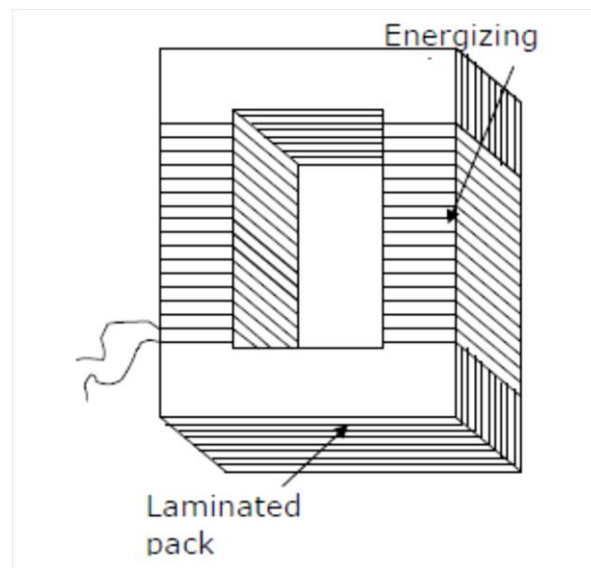


Figure 1.7 Magnetostrictive transducer [29]

1.8.3 THE VELOCITY TRANSFORMER

The velocity transformer has got several names like concentrator, trunks. Mechanical focusing device, shank, horn, amplifier, tool cone, transformer stub or convergent wave-guide, etc. it amplifies and focuses the mechanical energy produced by the transducer and imparts this to work-piece in such a way that energy utilization is optimum. It is simply a velocity transformer with the exception that it is made slightly shorter than the half wavelength. The amplitude of the vibratory motion of the transducer is small and is usually inadequate for material removal purpose, and hence the tool is connected to the transducer by means of a concentrator which is simply a convergent waveguide to produce the desired amplitude at the tool end. Thus the trunk amplifies and focuses the vibrations of the transducer to intensity

necessary to drive the tool to do its work. The increase in amplitude of the vibrations at the tool end is obtained by reducing the cross-section of the trunk at the tool end. The trunks are specially shaped to provide a reduction in cross-section at the tool end because the trunk should be of such sizes and shape that it is mechanically resonant or tuned to the frequency of the transducer vibrations and under working conditions giving maximum amplitude at the tool end with minimum energy losses. The trunk provides increased amplitude in the order of 30 to 120 microns at the tool face.

Trunks may be of different shapes or configurations. Some typical shapes are as follows

1. Exponential
2. Stepped (symmetrical)
3. Tapered

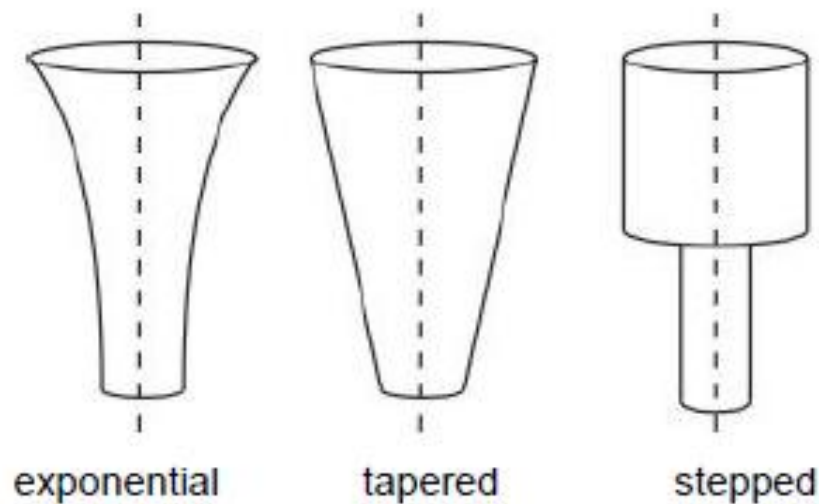


Figure 1.8 Different horns used in USM [28]

1.8.4 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.

1.8.5 THE TOOL

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, work piece / tool wear ratios can range from 1:1 to 100:1.

Whenever possible, USM tools to be used for hole drilling are constructed from easily obtained materials such as music wire, stainless steel tubing or hypodermic needles. Solid tools used to produce cavities can be fabricated by machining, casting or coining; however finishing or polishing operations are sometimes necessary because the tool holders should be free from scratches, nicks and heavy machining marks, because these produce risers and lead to early fatigue failure.

Because of the overcut that occurs with this process, allowances must be made to use tool are slightly smaller than the desired hole or cavity e.g. to allow for the diameter of tubing to drill holes should be equal to the desired hole diameter minus twice the abrasive particle size. The most desirable method of attaching the tool to the holder is silver brazing. This eliminates the fatigue problems associated with mechanical screw attachment method.

1.8.6 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 aluminium 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 form 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. 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.

1.8.7 THE WORK-PIECE

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. These materials often cannot withstand the forces needed for ordinary mechanical working. Materials that can be machined by ultrasonic drilling efficiently are shown in table (1.1)

Table 1.1 Materials that can be machined by USM [29]

Agate	Alabaster	Barium carbide (sintered)
Ceramics	Corundum	Diamond
Earthenware	Felspar	Ferrites
Fluorites	Germanium	Glass
Glass-Micanite	Granite	Graphite
Gypsum	Hard alloy (tungsten and titanium carbide)	Marble
Jadeite	Jasper	Mother-of-pearl
Nephrite	Onyx	Porcelain
Quartz (crystalline and fused)	Rock crystal	Ruby
Sapphire	Silicon	Stealite
Thermo corundum	Tourmaline	Zirconium boride

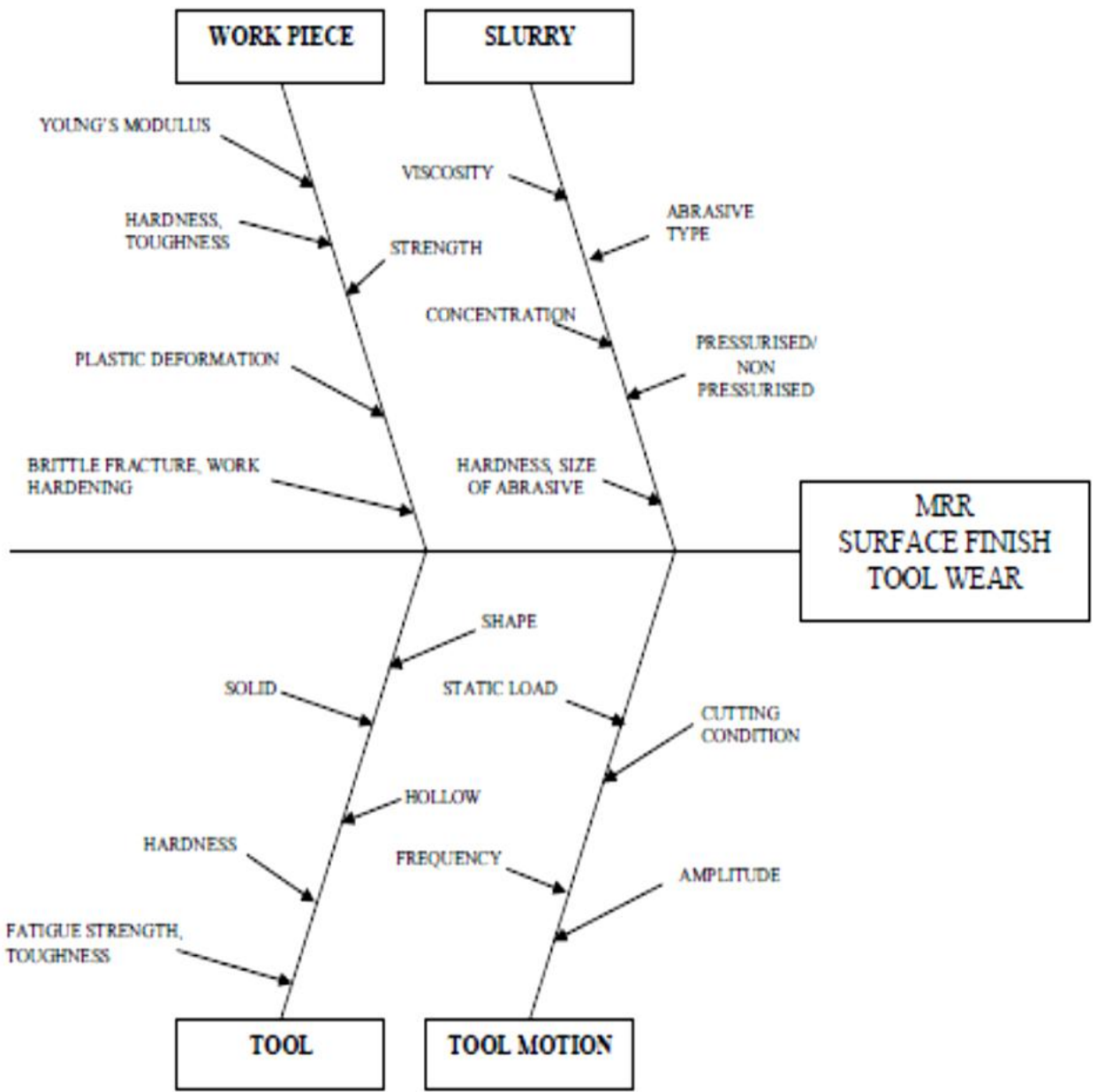


Figure 1.9 Fishbone diagram for Ultrasonic machining

1.9 ORGANIZATION OF THESIS

Chapter 1 covers brief introduction to non conventional machining process, principle of Ultrasonic machining, mechanism of metal removal, elements of ultrasonic machining and process parameters

Chapter 2 presents an available literature for Ultrasonic machining. The available literature has been presented according to the year of the research work carried. Summary of the literature and gap in literature also discussed

Chapter 3 presents area of research work to be undertaken has been identified. Objective and work plan has been discussed.

Chapter 4 present methodology used. Brief introduction to Taguchi's Design of Experiments have been provided also introduction to Analysis of Variance (ANOVA) has been provided.

Chapter 5 presents analysis and results of MRR. Results after Analysis of variance (ANOVA) and Taguchi Signal to noise ratio are outlined in the chapter. Main effect plots, optimal design condition have been discussed

Chapter 6 presents analysis and results of TWR. Results after Analysis of variance (ANOVA) and Taguchi Signal to noise ratio are outlined in the chapter. Main effect plots, optimal design condition have been discussed

Chapter 7 presents analysis and results of surface roughness (R_a). Results after Analysis of variance (ANOVA) and Taguchi Signal to noise ratio are outlined in the chapter. Main effect plots for surface roughness (R_a) are discussed in this chapter. Optimal design conditions have been discussed.

Chapter 8 presents analysis and results of Hardness. Results after Analysis of variance (ANOVA) and Taguchi Signal to noise ratio are outlined in the chapter. Main effect plots for Hardness are discussed in this chapter. Optimal design conditions have been discussed.

Chapter 9 presents the result, conclusion and recommendations from the experimental work. Scanning Electron Microscope has been used for analysis of microstructure of machined surface. The same has been discussed in this chapter.

Chapter 10 presents the references.

CHAPTER 2

LITERATURE SURVEY

2.1 INTRODUCTION

The method of ultrasonic working was proposed by Farrer in 1945. Many scientists and engineers have been working for the last 60-70 years and the results are before us on ultrasonic machining/working. Rozenberg's crediting to Farrer is an exquisite example of the unfortunate high frequency of "noise" when scientific information crosses language barriers. Farrer was the patent agent on the first issued patent, British Patent No. 602,801 (1945) issued to Lewis Balamuth, who discovered ultrasonic machining accidentally in 1942, while he was investigating the dispersion of solids in liquids by means of Magnetostrictive vibrating nickel tube. The United States Patent for the process No. 2580,716 was issued in 1962.

The first communication on equipment and techniques for ultrasonic cutting appeared in 1953-54. The first ultrasonic tools had been made, mostly on the basis of drilling and milling machines. This was the period of early development of ultrasonic cutting; recent years have seen the introduction of ultrasonic machine tools of various types and sizes for variety of purpose. Some models have begun to come into regular production, and detailed studies have begun on physics of ultrasonic cutting; much experience on the design of ultrasonic machine has accumulated.

The rapid progress in this field is clear from the number of published papers.

T.C. Lee *et al.* (1997) [23], the study investigated the mechanism of ultrasonic machining of ceramic composites. Principles of ultrasonic machining were also stated. The effect on metal removal rate and the surface roughness were studied when varying amplitude of tooltip, static load applied and size of abrasive used were changed. Mechanism of fracture was studied and explained i.e. crack formation and crack propagation. Model representing shocking force and material removal rate was deduced and verified. Also it was concluded that any increase in work/energy imparted to machined ceramic in terms of amplitude of tool tip, the static load

applied and the grit size of abrasive will result in increase in material removal rate and roughening of the machined surface.

Deng Jianxin *et al.* (2002) [10], The study revealed the effect of parameters on ultrasonic machining of Alumina based ceramic composite. The study investigated the effect of microstructure and properties of material on the Material removal rate and surface finish. Material used was hot-pressed alumina based ceramic composite, $\text{Al}_2\text{O}_3/\text{TiC}$, $\text{Al}_2\text{O}_3/\text{SiC}$ (Whiskered reinforced), $\text{Al}_2\text{O}_3/\text{TiB}_2$, $\text{Al}_2\text{O}_3/(\text{Ti}, \text{W})\text{C}$. Effect of properties and microstructure on MRR & Surface roughness, integrity of machined surface, tool material used Mild steel, abrasive used Boron Carbide (80 grit)

G. Ya *et al.* (2002) [18], The study was conducted to observe the movement of abrasive particle in the tool tip of rotary ultrasonic machining. The impact and grinding of abrasive in the tool tip on the machined surface were considered as the main factor for material removal rate. The crack propagation in rotary USM was investigated using theory of fracture mechanics. Based on the above description of abrasive, three mechanism involved in rotary USM were involved

1. Impacting: with rotation motion of tool the abrasive particle in tool end face impact the machined surface in different place.
2. Abrasion: with the rotational motion of tool and the feed mechanism of work piece, the abrasive particles scratch out micro-grooves on the machined surface.
3. Ultrasonic cavitation

In this study formation and propagation of crack was analyzed under the assumption that the entire abrasive particle has spherical shape.

Wang A. Cheng *et al.* (2002) investigate of the use of ultrasonic vibration lapping to enhance the precision of micro holes drilled by micro electro-discharge machining. In the investigation first a circular or stepped circular micro tool was made by the micro electro discharge machining process, and the tool was used to create a micro hole on a small piece of titanium plate in the same machining process. Finally, the abrasive particles driven by the same tool were utilized to grind this hole in the micro ultrasonic vibration lapping (MUVL) procedure, and hole with diameter about $100\ \mu\text{m}$ can be obtained. Owing to the micro tool and work piece not taking apart from the clamping apparatus during different machining steps, the micro hole was processed in

the co-axial situation, so the precise shape and perfect surface can be obtained easily. On the basis of experimental results they concluded the followings:-

1. The machining method that compounded the MEDM and MUVL process had a good ability to produce precision micro holes with high aspect ratio.
2. Because of the horizontal manufacturing mode of the MUVL methods, the concentrations of slurry should be carefully set to obtain the high precision and fine shape of micro holes. For example, a slurry concentration of 20% was more suitable for the circular tool processes, while a concentration of 10% was effective in the stepped circular tool processes.
3. If circular tools were used in the MUVL processes, the variations between entrances and exits would decrease with increasing ultrasonic vibration amplitudes. Furthermore, if stepped circular tools were used, the differences between the diameters of the entrances and exits were smallest at the vibration amplitudes of 5.4 μm .
4. Tool rotating speed significantly affected the grinding effect of abrasive particles for the MUVL method. Grinding influence was worst when the tools were not rotated, and a better grinding result caused a reduction of the differences in the diameters of the entrances and exits. Furthermore, appropriate rotating speeds were necessary to improve the diameter differences of the entrances and exits.
5. The micro holes had poor roundness in the pure MEDM processes, and roundness obviously improved after the MUVL processes. However, a little debris could surround the micro holes if the circular tools were utilized a situation that was improved by using the stepped circular tools.
6. In the surface roughness modification, the improvement was unclear when the circular tools were used in the MUVL processes. However, improvements were apparent if the stepped circular tools were used.

Z.C. Li *et al.* (2005) [2], This study examined the feasibility of Rotary Ultrasonic machining on Ceramic matrix composite (CMC). Ceramic Matrix Composite combine reinforcing ceramic phase with ceramic matrix to create material with superior properties (like light weight, high-temperature stability, high thermal –shock resistance) providing unique engineering solution. The combination of these properties makes CMC attractive alternative to traditional materials such as high alloy steel and refractory metals. In this study Rotary Ultrasonic Machining (RUM)

with rotating core drill was used. Core drill having metal-bonded diamond abrasive is ultrasonically vibrated in axial direction and fed toward the work piece at constant feed rate or constant force. The results were compared with conventional Ultrasonic machining, RUM was found to be 10 times faster, the surface quality obtain was also much superior. The experiment was conducted on two types of CMC materials for the first time. Cutting force and Material Removal Rate (MRR) were compared for machining CMC with and without vibration and for two types of CMC (one type with 92% alumina) Chipping at hole exit induced by RUM was studied. The interaction of various parameters (feed rate, spindle speed, ultrasonic power) with cutting force and MRR was studied. For measuring cutting force along federate direction KISTLER 9257 dynamometer (Kistler Instrument Corp, Amherst, NY, US) was used, to inspect chipping Digital Video Microscope of Olympus DVM-I (Olympus America Inc., Melville, NY, USA) was utilized. The hole quality is quantified by thickness and size of edge chipping formed on machined CMC rod.

W.M. Zeng *et al.* (2005) [5], The study investigates tool wear in the Rotary Ultrasonic Machining of Silicon Carbide (SiC) with metal-bonded diamond abrasive tool ultrasonically vibrated and fed towards work piece at constant force. As for tool wear in RUM, specific tool wear (ratio of volume of material removed to volume of tool wear) was used to evaluate the tool wear. The effect of process parameters (static load, ultrasonic vibration and amplitude, diamond concentration, diamond type, grit size and bond strength) on specific tool wear was investigated. Tool surface at different wear stages were observed under a digital microscope. Cutting force during the process was measured and was correlated to the stages of tool wear.

Y. Ichida *et al.* (2005) [9], The study investigated the suitability of non contact ultrasonic abrasive machining for ultra-precision machining. This process used loose abrasives excited by ultrasonic energy in a liquid. The experiment was conducted on Aluminium alloy (JS-2014), using machining fluids mixed with Al_2O_3 abrasive grains of mean diameter $1\mu m$ to investigate the material removal mechanism of Non-contact ultrasonic abrasive machining. The three kinds of processing modes were explained:

- i) Material removal by cavitation erosion
- ii) Material removal by colliding and sliding of abrasive grains.
- iii) Small scale material removal arising from abrasive grain excited by ultrasonic energy.

Machining fluid used : water, water mixed with 6 wt.% abrasive grains, methyl alcohol, methyl alcohol mixed with 6 wt.% abrasive grain, methyl alcohol mixed with 12 wt.% abrasive grain. Abrasive used was Al_2O_3 . MRR, surface finish, using different fluids (water, methyl alcohol) with Al_2O_3 during three modes of material removal mechanism was analyzed.

Z.C. Li *et al.* (2006) [22], The study reveals the effect of rotary ultrasonic machining of ceramics. Edge chipping occurs in rotary ultrasonic machining which increase the cost.. Finite Element Analysis model was developer to study the effect of three parameters i.e. cutting depth, pre-tightening load and support length on 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 relation between edge chipping thickness and support length. Furthermore solution for reducing the edge chipping were proposed based on FEA simulation and was verified by experiment.

ZHENG Jian-xin *et al.* (2006) [3], The study was performed to determine the surface quality of ceramic blade surface using Numerical control contour evolution ultrasonic grinding method using simple shape grinding wheel on Al_2O_3 ceramics. Creep feed grinding of Al_2O_3 ceramics was performed with and without vibration so as to implore the effect of different process parameters on machined surface quality. Surface roughness obtained is measured using roughometer and by observing surface topography using a Scanning Electron Microscope (SEM). Machining parameters used were: diameter of electroplated diamond wheel is 3 mm with the grain size #240 and concentration 75%: rotation of grinding wheel 6000 r/min: given feed rate f_z 0.1 mm/min (f_x 0.086 mm/min, f_y 0.006 mm/min: rotational speed 0.3($^\circ$)/min, vibration frequency 'f' is 19.96kHz, amplitude (A) is 5 μm , direction of vibration is parallel to feed motion f_z .

J.P. Choi *et al.* (2007) [1], The present study was carried aiming the improvement of material removal rate for Ultrasonic machining on glass by using low concentration Hydrofluoric acid in slurry used for machining of glass. When glass is dipped in Hydrofluoric acid (HF) solution, the reaction between Si and F^- ions takes place and also reaction between oxygen and H^+ ion takes place. This makes the bonding force between Si molecules on the surface week, hence increasing the MRR by 200% as compared to Conventional Ultrasonic machining. It was found that surface finish was also improved and machining load decreased dramatically.

A. Dvivedi *et al.* (2007) [14], The first time study of ultrasonic machining on pure titanium and titanium alloy (Ti-6Al-4V) was investigated in this study. During the process parameters such as work piece, grit size, slurry concentration, power rating and tool were changed to explore the effect on surface roughness. Taguchi method was applied to obtain an optimal setting of ultrasonic machining. Experiment was conducted and from the observation and their analysis it was concluded that slurry concentration and grit size has significant effect on surface roughness more than other parameters.

M. Abdul Majeed *et al.* (2008) [4], In this study two phase composite consisting of Alumina and Lanthanum Phosphate was prepared and subjected to Ultrasonic drilling using low carbon steel tools (solid and hollow) of 3 mm diameter. The effect of LaPO₄ on machining was studied by analyzing Acoustic Emission signals emitted by work piece during machining. Acoustic emission is relatively weak elastic stress waves emitted by a material under stress and it is reliable indicator of a status of the material. The higher frequency and low amplitude signal are picked up by a broad band sensor and amplified further for signal analysis. Various specimen LaPO₄/Al₂O₃ composite powders with LaPO₄ content (pure alumina, 30 wt. % LaPO₄, 50 wt. % LaPO₄ and pure LaPO₄) were ball milled for 24 h, dried using rotary vaporizer and cold pressed at 150 MPa and then sintered at 1600° C for 2 h and cooled down slowly at to room temperature. The performance in terms of MRR and profile of hole was studied using profile projector with magnification of 20.

Jatinder kumar *et al.* (2008) [8], The study investigates the effect of several process parameters on the machining of pure titanium (*ASTM Grade-I*). The machining characteristics being investigated were tool wear, and quality of machined surface. The mechanism of material removal rate was also correlated with machining conditions. Four different input parameters were considered: Tool material, abrasive material, grit size of slurry used, power rating of machine. The optimal setting of parameters were determined through the experiment planned, conducted and analyzed using Taguchi method. Ultrasonic drilling of pure titanium was performed. Tool material: HCS, HSS, Cemented Carbide and Titanium, abrasive slurry: Alumina, Sic, Boron Carbide, and grit size: 100, 250, 400: slurry concentration: 25%, Slurry temperature: 28° C, slurry media used was water. Taguchi's design of experiments was used to establish relation between various input and output parameters.

C. Khoo *et al.* (2008) [11], The study investigates rotary ultrasonic machining of advanced ceramics. The emphasis was given on effect of Rotary ultrasonic machining parameters such as applied load, rotational speed, ultrasonic power, vibration amplitude, abrasive grit size and coolant on machinability parameter such as material removal rate, surface finish and tool wear. The characteristics of edge chipping were also reported. A core drill tool with metal bonded diamond abrasives in rotational motion, ultrasonically vibrating simultaneously, is fed toward the work piece at constant feed rate and constant force (pressure). Effect of controlled variables on the performance of Rotary ultrasonic machine was depicted. The study concluded that MRR increase with increase in Static load, rotational speed, amplitude of vibration, abrasive grit size and ultrasonic power. The surface roughness tends to increase with increase in vibration amplitude and abrasive grit size but decrease with high static load.

A. Curodeau *et al.* (2008) [21], The study investigated ultrasonic abrasive μ -machining with an alternative proposed tooling. A visco-elastic thermoplastic composite material was used as tolling to conduct ultrasonic micro-machining operation. Such tooling is used within the ultrasonic abrasive μ -machining process in which polymer composite tool was formed by compression moulding, against the very same work piece to be finished, before being used as ultrasonic μ -machining. To demonstrate the feasibility, the experiment was conducted, using acetal and higher-molecule weight polyethylene composite polymer tooling. Two tests were conducted:

1. A uniform micron scale layer was removed in hammering mode from P20 tool steel sample.
2. Similar P20 tool steel with initial Electric discharge machining (EDM) surface finished was μ - polished in contact less machining mode.

The samples after machining and polishing are viewed for surface finish and metal removal rate.

Jatinder Kumar *et. al* (2008) [31], The study presented review on the problems encountered in machining titanium and application of USM in machining titanium and its alloys. Experiments was conducted to assess the effect of three factors-tool material, grit size of the abrasive slurry and power rating of ultrasonic machine on machining characteristics of titanium (ASTM Grade I) using full factorial approach for design and analysis of experiments. It was concluded that all

factors have significant effect on Material Removal Rate (MRR), Tool Wear Rate (TWR) and surface roughness of the machined surface. Two-way interactions having significant effect on MRR, TWR and surface roughness were identified using Minitab14 software. The levels for each factor that contribute the most to the variation in machining performance of USM of titanium had also been established. It was concluded that titanium is fairly machinable with USM process. Moreover, the surface finish obtained was better than many of the other non-traditional processes.

R.S. Jadoun *et al.* (2009) [12], The study used Taguchi's method to optimize the process parameters for production accuracy in ultrasonic drilling of engineering materials. Ultrasonic drilling of Alumina based ceramics was performed using Silicon Carbide abrasive. The parameters considered were work piece material, tool material, grit size of abrasive, power rating and slurry concentration. The result parameters were hole oversize, roundness of hole and conicity. Taguchi's optimization approach was applied to obtain optimal parameter. Hot pressed alumina based ceramic composite was used for investigation. Silicon Carbide particles were added to Al₂O₃ matrix. Tool was made of high carbon steel, high speed steel and tungsten carbide. Tool was silver brazed (at temperature 648° C) to the replaceable threaded tip. Silicon Carbide was used as abrasive in drilling, grit size used were 220, 320, 500. Conclusion was made regarding the effect of controlled variable on output variables. This study considered the optimization of single parameter but in practical situation simultaneously several parameters has to be looked into.

Vinod Kumar *et al.* (2009) [13], The study reveals the effectness of ultrasonic machining of satellite 6 in terms of tool wear of the tool used and the material removal rate of work piece produced. The optimized combination of combination of various factors as type of abrasive slurry, their size and concentration, nature of tool material, power rating of machine for ductile chip formation in machining of satellite 6 has been determined by applying Taguchi method.

Simon *et al.* (2009) [19], The study used vibration assisted drilling of Aluminum 6061-T6. The study was done to predict the thrust force during the vibration assisted drilling of aluminum 6061-T6 in thrust force model. The model incorporated plowing force and strain rate- dependent shear strength to provide more accurate prediction then what was existng.72 drilling

experiments were carried on with TiN-coated standard twisted drill. The predictions from thrust model were compared with experimental results. The comparison concluded that maximum deviation between the prediction and the experimental measurements were 20% using existed model and only 7% with model that was proposed.

Yuan-Feng Chan *et al.* (2009) [16], In this study novel approach was studied to combine approach that integrate Electric discharge machining (EDM) and Ultrasonic machining (USM) to investigate machining performance and surface modification on Al-Zn-Mg alloy. TiC was added to dielectric to explore the combined process on material removal rate, related electrode wear ratio, surface roughness and expansion of the hole. Micro hardness and wear resistance test was carried on to evaluate the modification cause in the machine surface by combined process. The results after analysis relieved that the combined process was associated with improved machining performance.

J. Pujana *et al.* (2009) [20], In this study ultrasonic assisted drilling was applied to Ti6Al4V work piece. Several parameters of ultrasonic assisted drilling were monitored, including feed force, chip formation by high-speed imaging and temperature measurement on the tip of drill by infrared radiation thermometry. The sample used was 3 mm thick and 50 mm in diameter. It was concluded that when ultrasonic assisted drilling was applied the feed force decreased by 10-20% on an average and decrease in force was more notorious when amplitude was increased. Tool tip temperature was higher when Ultrasonic assisted drilling was applied. The temperature variations were increased with increase in vibration amplitude. There existed a correlation between temperature variation and feed force variation, but it was not explained due to thermal softening effect of Ti6Al4v.

Hu Gong *et al.* (2010) [24], The study was reveals the study of mechanism of side milling in rotary ultrasonic machining. The study showed that rotary ultrasonic machining has less tool wear than grinding at lateral direction of the cutter under same condition. The kinematics of diamond grits were employed to for the theoretical analysis. Also when slim diamond cutters were used, two different strategies were used to side mill the microstructure and grooves on semi-sphere. An improvement strategy for material removal rate was also discussed using experimental results. Work piece used: K9 optical glass, rotation speed: 4000 rpm. Vibration

frequency: 25 KHz, Power: 25-28W, Amplitude: 4 μm , Feed rate: 300mm/min, depth of cut: 1mm.

DeFu Liu *et al.* (2012) [17], Ultrasonic machining of brittle materials was performed to modeling of cutting force in rotary ultrasonic machining. The relation between cutting force and input variables were established on the basis of the indentation fracture mechanics under pyramidal indenters. In this model a proportionality parameter was used to describe ratio between actual material removed by one abrasive particle in one vibration cycle and the theoretical value of fracture zone induced by the abrasive particle. Input parameters used were spindle speed, feed rate, vibration amplitude, abrasive size and abrasive concentration lower than conventional drilling.

Chandra Nath *et al.* (2012) [7], The study investigated effect of material removal mechanism on the hole integrity, wall roughness and subsurface damage during the drilling of Structural ceramics. Drilling was performed on three materials Silicon Carbide, Zirconia, Alumina. During the machining operation three crack modes and their growth characteristics were used to explain the experimental finding. Tool used was stainless steel; abrasive used was SiC, B₄C. Grit size #150, frequency and amplitude 25 kHz, 40-80 μm . The three modes studied were

- i) Direct indentation or hammering
- ii) Cavitations –erosion sliding or colliding action
- iii) Angle penetration and the rolling action.

The profile of hole was observed and concluded the entrance chipping and the wall integrity of holes are due to radial and lateral cracks, which propagate away from tool periphery in radial direction. Also the length or size of crack was about 2-4 times larger than the radius of abrasive used.

Jing Liu *et al.* (2012) [6], This study investigates the feasibility study of Rotary Ultrasonic Elliptical Machining on Carbon Fiber Reinforce Plastic (CFRP). CFRP being advanced material is characterized by high specific strength, high specific stiffness and good corrosion resistance. Conventional machining of this material result in rapid tool wears due to their high rigidity and low thermal expansion of High Speed Steel (HSS) and Tungsten carbide (WC). Although Polycrystalline diamond (PCD) drills have higher tool life, high cost of tool material restricts

their wide application. Investigation of seven output variables i.e. Metal Removal Rate (MRR), chip removal, Surface roughness of hole, tool wear, precision of holes, exit de-lamination, cutting force was done. Cutting force along federate direction was measure by KISTLER 9254 dynamometer. A COIC is utilized to observe surface de-lamination at entrance and exit of hole and to view surface roughness. To calculate MRR a relation was used:

$$MRR = \frac{\pi \left[\left(\frac{D_{out}}{2} \right)^2 - \left(\frac{D_{in}}{2} \right)^2 \right] d}{T}$$

where D_{out} , D_{in} , d , T are Diameter of drilled hole, Diameter of machined-out rod, work piece thickness and time taken to drill the hole, respectively. Other parameters were also observed and comparison was made with conventional drilling. It was observed that RUEM has better chip removal than conventional drilling, also it was seen that tool wear was less compared to Conventional drilling. MRR in RUEM was reduced by 9% than conventional drilling. This was due to the properties of CFRP. It was observed that cutting forces reduced significantly i.e. about 45% lower than conventional drilling.

2.2 SUMMARY OF LITERATURE SURVEY

A lot of work gas been done in machining a number of materials using Ultrasonic machining.

Table 2.1 Summary of literature

S. No.	Title of Paper	VOLUME NO.	Year	Pg No.	Author	Remarks	Result
1	Chemical assisted ultrasonic machining of glass	Journal of Material Processing Technology 191	2007	153-156	J.P Choi, B.H. Jeon, B.B. Kim	Low concentration Hydrofluoric acid is added to slurry, Material removal mechanism was studied. Material used was glass.	Metal removal rate and surface finish was improved using Hydrofluoric acid.

2	Rotary Ultrasonic machining of ceramic composites: Feasibility study and Designed experiment	International Journal of Machine tool and manufacture 45	2005	1402-1411	Z.C. Li, Y. Jiao, T.W. Deines, Z.J.Pei, C. Treadwell	Ceramic Matrix Composite(CMC) subjected to rotary Ultrasonic machining,3-variable,2-level full factorial design was employed to reveal main effect as well as interaction of feed rate spindle speed and power	Diamond abrasive tool was used for machining CMC to study Cutting forces, MRR and Hole Quality(in terms of chipping dimension)
3	Experimental Research on the Ground Surface Quality of Creep Feed Ultrasonic Grinding ceramics	Chinese Journal of Aeronautics 19	2006	359-365	Zheng Jian-Xin, XU Jia-wen	Creep feed grinding mechanism was with or without vibration were analyzed. Work piece used Al ₂ O ₃ ceramic	Surface quality was observed. It was seen that when vibration were parallel to creep feed surface roughness decreases, otherwise it get worse.
4	A.E monitoring of Ultrasonic machining of Al ₂ O ₃ /LaPO ₄ composite	Journal of Material Processing Technology 207	2008	321-329	M.Abdul Majeed, L. Vijayaraghavan, S.K Malhotra, R. Krishanmoorthy	Ultrasonic drilling was performed on LaPO ₄ content of Al ₂ O ₃ /LaPO ₄ composite. Effect of machining on Composite was studied by analyzing Acoustic Emission signals emitted by work piece during machining	Material Removal Rate was calculated by noting down machining time, Microstructure of hole was studied using Profile projector using magnification of 20
5	Experimental observation of tool wear in rotary ultrasonic machining of ceramics	International journal of machine tool and manufacture 45	2005	1468-1473	W.M. Zeng, Z.C. Li, Z.J. Pei, C. Treadwell	tool wear of metal bonded diamond abrasive in RUM of Silicon Carbide(SiC) is investigated.	Material Removal Rate, tool wear cutting force, surface finish was investigated by controlling input variable spindle speed, vibration amplitude and frequency, diamond type ,size and concentration.
6	Feasibility study of rotary ultrasonic elliptical machining on Carbon fibre reinforced plastics (CFRP)	effect of drilling	2012	141-150	Jing Liu, Deyuan Zhang, Longgang Qin, Linson Yan	Ultrasonic elliptical drilling is performed on CFRP	MRR, Cutting Force, Delamination at entrance and exit of hole, surface roughness, cutting force were investigated and compared with conventional drilling

7	Influence of material removal mechanism on hole integrity in ultrasonic machining of structural ceramics	Ultrasonics	2012		chandra Nath, G.C. Lim, Hongyu Zheng	Hole was drilled on three materials Silicon carbide, Zirconia, Alumina. Initiation of three different crack modes and their growth characteristics were used to explain experimental finding	Effect of Material removal mechanism on hole integrity, wall surface, subsurface damage,
8	An experimental studies on Ultrasonic Machining of Pure titanium Using Designed Experiment	Journal of Brazilian society of Mech. & Sci. Engg.	2008	231-238	Jatinder Kumar, J.S. Khamba	Ultrasonic drilling carried on Pure Titanium. Taguchi method was used. effect of tool material, grit size (200,320,500), power rating (100,250,400W) of machine was studied	Surface finish, tool wear, MRR optimization by Taguchi, ANOVA and S/N ratio
9	Material Removal Mechanism in non contact abrasive machining	Wear 258	2005	107-114	Y. Ichida, R. Sato, Y. Morimoto, K. Kobayashi	Machining experiment of Al alloy(JIS 2014) using fluid mixed with Al ₂ O ₃ with 1 μm was conducted to study modes of material removal mechanism	MRR, surface finish, using different fluids (water, methyl alcohol) with Al ₂ O ₃ during three modes of material removal mechanism
10	Ultrasonic machining of Alumina based ceramic composites	Journal of European ceramic society 22	2002	1235-1241	Deng Jianxin, Lee Taichiu	material used was hot-pressed alumina based ceramic composite, Al ₂ O ₃ /TiC, Al ₂ O ₃ /SiC(Whiskered reinforced), Al ₂ O ₃ /TiB ₂ , Al ₂ O ₃ /(Ti, W)C	Effect of properties and microstructure on MRR & Surface roughness, integrity of machined surface,
11	A review of Rotary Ultrasonic machining of Advanced Ceramics	Jurnal Mekanikal 25	2008	9 to 23	C. Khoo, Esah Hamzah, Izman Sudin	Rotary Ultrasonic machining, Input parameters applied static load, rotational speed, vibrational amplitude, ultrasonic power, grit size and coolant	Material removal rate, surface finish and tool wear

12	Taguchi's optimization of process parameters for production accuracy in ultrasonic drilling of engineering ceramics	Prod. Eng. Res. Devel.3	2009	243-253	R.S. Jadoun, Pardeep Kumar, B.K. Mishra	Taguchi optimization approach is used to obtain optimal parameters. Parameters considered were work piece material, tool material, grit size og abrasive, power rating and slurry concentration. Al ₂ O ₃ matrix containing SiC(1µm sized)	Hole oversize, out of roundness, conocity were studied.
13	Parametric optimization of ultrasonic machining of co- based super alloy using the taguchi multi-objective approach	Prod. Eng. Res. Devel.3	2009	417-425	Vinod Kumar, J.S. Khamba	Satellite 6 Co alloys subjected to Ultrasonic machining, Taguchi method used , Input parameters: types of abrasive slurry, their size and concentration , nature of tool material and power ration, Statica 7.0 used	Optimization of MRR and tool wear rate.
14	Surface Quality evaluation in Ultrasonic drilling through the Taguchi technique	Int J Adv Manuf Technol 34	2007	131-140	A. Dvivedi, P. Kumar	Ultrasonic Drilling of Titanium Alloy (Ti-6Al-4V), input parameters: work piece, grit size, slurry concentration, and tool. Application of Taguchi method	Surface roughness, MRR
15	Optimization of correlated multiple response of ultrasonic machining process	Int J Adv Manuf Technol 53	2011	1115-1127	Susanta Kumar Gauri, Rina Chakravorty, Shankar Chakravorty	Past data on USM analyzed using three methods with multiple correlated responses Weighted Principle component (WPC), PCA based TOPSIS method, PCA-based grey rational analysis method.	PCA based TOPSIS method give better optimization performance than PCA-basedgrey rational analysis method.WPC is preferable because of simpler computational procedure

16	Surface modifications of Al-Zn-Mg alloy using combined EDM with Ultrasonic Machining And Addition of TiC Particles into the Dielectri	Journal of Material Processing Technology 209	2009	4343-4350	Yuan-Feng Chen, Yang-Cherng Lin	Integration of EDM and USM on Al-Zn-Mg alloy. Tic particles added to dielectric	MRR, Relative Electrode wear ratio (REWR), surface roughness and machining accuracy, expansion of hole.
17	A cutting force model for rotary Ultrasonic machining of brittle materials	International Journal of Machine tool and manufacture 52	2012	77-84	DeFu Liu, W.L. Cong, Z.J. Pei, YongJun Tang	Cutting force for machining of brittle materials. Relation of input variables on Cutting force is discussed.	Cutting force
18	Analysis of rotary ultrasonic machining mechanism	Journal of Material Processing Technology 129	2002	182-185	G. Ya, H.W. Qin, S.C. Yang, Y.W. Xu	MRR in rotary USM combined with CNC technology.	MRR, Crack propagation and surface finish
19	Thrust force modelling for vibration-assisted drilling of Aluminum 6061-T6	International Journal of Machine tool and manufacture 49	2009	1070-1076	Simon S.F. Chang, Gary M. Bone	Vibration assisted work piece holder was used. TiN-coated twisted drill was used. Spindle speed 4000rpm, 0.06mm/rev feed was used.	Thrust force was calculated using kistler type 9255B table dynamometer
20	Analysis of ultrasonic assisted drilling of Ti ₆ Al ₄ V	International Journal of Machine tool and manufacture 49	2009	500-508	J. Pujana, A. Rivero, A. Celaya, L.N Lopez de Lacelle	Several input parameters studied feed force, chip formation by high speed imaging.	chip formation, analysis of the process on Ti6Al4V

21	ultrasonic abrasive μ machining with thermoplastic tooling	International Journal of Machine tool and manufacture 48	2008	1553-1561	A. Curodeau, J. Guay, D. Rodrigue, L. Brault, D. Gagne, L.-P. Beaudoin	tool used acetal and high - molecular-weight polyethylene composite polymer tooling, μ machining was performed observing three metal removal mechanism	two modes of machining was studies i.e. hammering mode for μ machining and non contact mode for μ polishing
22	Edge chipping reduction in rotary ultrasonic machining of ceramics: finite element analysis and experimental verification	International Journal of Machine tool and manufacture 46	2006	1469-1477	Z.C. Li, Liang-Wu Cai, Z.J. Pei, C. Treadwell	Machine variables: Spindle speed, feed rate, coolant pressure, vibration frequency and power. FEA model was developed to study effect of cutting depth, support length, pretightening load on max. normal stress and Van mises region	Effect of cutting depth, support length, pretightening load on edge chipping region.
23	Mechanism of ultrasonic machining of ceramics composites	Journal of Material Processing Technology 71	1997	195-201	T.C Lee, C.W. Chan	Model representing the shock force and MRR was deducted and verified. Mechanism of USM was also observed.	Effect on MRR and surface roughness.
24	Kinematic view of tool life in rotary ultrasonic side milling of hard and brittle material	International Journal of Machine tool and manufacture	2010	303-307	Hu Gong, F.Z. Fang, X.T. Hu	Kinematics of diamond grit is employed for theoretical analysis. Frequency: 20KHz, ultrasonic power: 25-28 W, amplitude: 4 μ m. Work piece K9 optical glass, speed 4000rpm	MRR, Tool Wear

2.3 GAP IN LITERATURE

1. Ultrasonic Drilling of Alumina, Zirconia, Silicon Carbide has been done by taking the three materials separately as work piece, effect of material removal mechanism on hole integrity, surface of wall of hole and subsurface damage was reported[7]. Also initiation of crack by three methods and crack propagation characteristics were used to explain the experiment.
2. No study has been reported on Ultrasonic machining of **Alumina-Zirconia composite (a metal matrix composite with Zirconia particulate) and Aluminium matrix reinforced with Alumina (Al_2O_3) and Trialumane Zirconium (Al_3Zr) materials and Al-SiC composite**. For the first time in this thesis work metal removal rate, surface finish and tool wear will be studied using by varying various input parameters and optimum combination of input parameters for metal removal rate, tool wear rate and surface roughness related to input parameters will be done.
3. In this thesis it is proposed to use two work pieces on which ultrasonic machining will be performed i.e. Alumina - Zirconia composite and Aluminium matrix reinforced with Alumina (Al_2O_3) and Trialumane Zirconium (Al_3Zr) materials and Al- SiC composite. Effect on Metal Removal Rate, Tool Wear Rate and Surface Roughness will be studied by varying different parameters (Type of abrasive, slurry concentration, power rating and grit size of abrasive).
4. Also the experimental observations would be used to find optimal condition of input parameters in Metal Removal Rate, Tool Wear Rate and Surface Roughness. The optimization in this is not done before using above mentioned work materials.

CHAPTER 3

EXPERIMENTAL DETAILS

3.1 EXPERIMENT OBJECTIVE

Experiment has been conducted on three work piece i.e. metal matrix composite with Aluminium as base metal [(Al-SiC), (Al-ZrO₂), Al/(Al₂O₃+Al₃Zr)], and Zr and Si as reinforcement with High Carbon High Chromium steel as tool, to investigate effect of various input parameters on MRR and TWR in ultrasonic machining process by using different types of abrasive slurry (Al₂O₃, SiC, 50%Al₂O₃-50%SiC) of different concentration.

3.2 EXPERIMENTAL DETAILS

The Ultrasonic machine used during experiments is Sonic-Mill 500 Watts (USA) in the Non-traditional machining lab at Mechanical Engineering department at Thapar University, Patiala.



Figure 3.1 Sonic Mill 500 watts (USA)

3.2.1 PRINCIPLE OF SONIC-MILL PROCESS

A power supply generates a KHz signal that is applied to a piezoelectric converter. This converts high frequency electrical energy into mechanical motion. The motion from the converter is amplified and transmitted to the horn and the cutting tool. This causes the horn and attached cutting tool to expand and contract perpendicular to the tool face 20,000 times per second with little measurable side motion. Recirculating pump forces a slurry of abrasive material, the abrasive particles propelled by the tool, strike the work piece at 150,000 times their own weight. These tiny abrasive particles chip off microscopic flakes and grind a counterpart of the tool face. With the stationary Sonic-Mill process the work material is not overly stressed, distorted or heated because the grinding force is seldom over 2 lbs there is never any direct tool to work contact and the presence of the cool slurry make this cold cutting process.

Requirement

Electrical: (a) 100-120 volt system

(b) 208-240 volt 1phase system

Air (If required): (a) Minimum 80 PSIG at 2.5 CFM

(b) Maximum 120 PSIG at 2.5 CFM

3.2.2 GENERAL COMPONENT DESCRIPTION OF SONIC-MILL

The main components of Sonic-Mill are described as follows:

3.2.2.1 POWER SUPPLY

This solid state variable output power supply with internal or external power control, converts 50/60 Hz electrical power into 20,000 Hz electrical power. The power supply is designed for continuous duty industrial operation. For optimum efficiency it is equipped with automatic frequency control and automatic load compensation providing constant output amplitude at desired setting to meet the different energy requirement encountered during the operation cycle. The power supply incorporates an overload monitor to protect the system from conditions that could normally result in failure if an overload condition occurs. The monitor shut off the ultrasonic for the balance of the cycle and activates the front panel overload indicator lamp.

Although the monitor will automatically reset itself for subsequent operation until the fault condition is eliminated. The monitor will reactivate on each operating cycle preventing damage to the transistors.

3.2.2.2 CONVERTER

The 20,000Hz electrical energy from the power supply is applied to the transducer element, herein after referred to as the converter, which transforms the high frequency electrical oscillation into high frequency mechanical vibration. The heart of the converter is a Lead Zirconate Titanate electrostrictive element which when subjected to an alternating voltage, expand and contract at the frequency of the voltage. This electrostrictive converter is highly efficient and the degree of energy conversion is 96%.

3.2.2.3 HORN

The purpose of the horn is to transfer the ultrasonic vibration from the converter to the tool. Material for horn should have good acoustical properties. Titanium horns are considered the best all around material for the fabrication of horns. Horns are also made of Brass, Steel and Monel. These horns are generally used for tools that are over 1” (25.4mm) in diameter.

3.2.2.4 REPLACEABLE TIPS

Tips attach to 1/2”(12.7mm) and 1”(24.5mm) titanium horns and are available in a range of head thickness in order to maintain weight relationships with the horn for varying weights and lengths of tools. This allows the horn/tip/tool to operate at optimum frequency.

3.2.2.5 COUPLERS

Coupler attaches between the converter and horns. Allows for clamping of the converter, coupler, horn assembly provides amplitude choice for various application as listed below.

Amplitude	Code Color
0.5 to 1 Amplitude Reduction	Blue
1 to 1 No Amplitude Gain	Green
1 to 1.5 Amplitude Increase	Gold

3.2.2.6 MILL MODULE ASSEMBLY

Provide “Z” motion control and mounting of coupler, converter and horn assembly allows for mounting of option: feed/force control, adjustable converter clamp. Positive stop fine tool height adjust and digital depth indicator.

3.2.2.7 AUTOPAC IIB

AutoPac IIB is an electro-pneumatic control unit that performs a number of functions for the Sonic-Mill system

1. Provide accurate depth control for the Sonic-Mill process
2. Monitor and control air pressure for raising and lowering “Z” axis
3. Provide a tool lift system to allow slurry under the tool
4. Control ON/OFF electrical timing of major function: slurry, sonic and tool down
5. Provide manual control for the option magnetic work table

3.2.2.8 HIGH VOLUME ABRASIVE SYSTEM

There are two systems

- (i). 7.6 Liters
- (ii). 3.8 Liters

Recirculating system with container and pump assembly with agitation jets helps to keep the E/Z pump grit in suspension. Both units accept the optional chiller for some applications.

3.3 CUTTING TOOL USED FOR THE ULTRASONIC MACHINING

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, work piece / tool wear ratios can range from 1:1 to 100:1.

The cutting tool have been used in this experiment is made of **High Carbon High Chromium Steel (D2)**.

Table 3.1 Composition of tool (D2)

C	Cr	Mo	V	Si	Mn
2.00	12.00	0.75	0.90	0.30	0.30

D-2 tool steel (DENSITY: 7.8 gm/cc) is a versatile high-carbon, high-chromium, and air-hardened tool steel, that is characterized by high attainable hardness and numerous large chromium rich alloy carbide in the microstructure. These carbides provide good resistance to wear from sliding contact with other metal and abrasive materials. Although other steels with improved toughness and improved wear resistance are available. Tool steel (D2) provide an effective combination of wear resistance and toughness, tool performance, price and wide variety of product forms.

3.3.2 PREPARATION OF CUTTING TOOL

The cutting tool is made from the cylindrical piece of 35 mm diameter and 41 mm length by turning, facing processes done on the lathe machine. The shape and size of cutting tool is shown in the figure (3.1)



Figure 3.2 Tool Used for Ultrasonic Machining

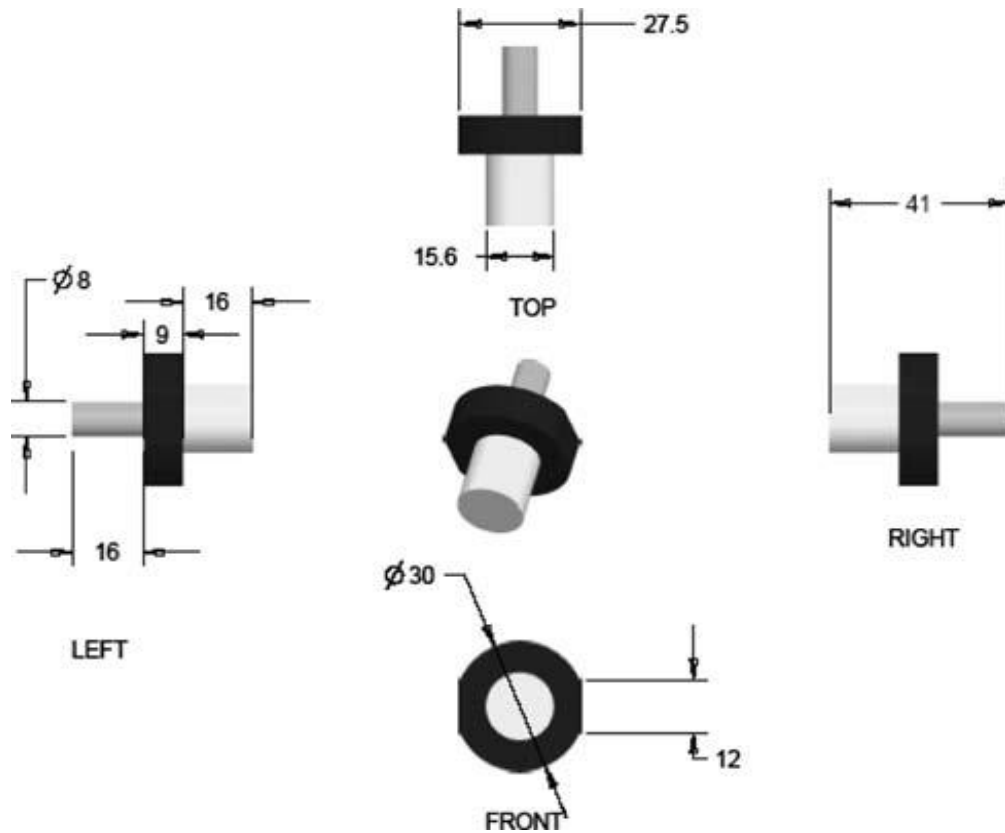


Figure 3.3 Dimension of tool

3.4 WORK MATERIAL

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 non-conductor. The USM process is used on three material i.e. metal matrix composite

1. Al-SiC composite (16.85 % Silicon particulate)

Table 3.2 Composition

Si	Mg	Cu	Ni	Fe	Mn	Zn	Pb	Al
16.85	0.9	0.25	0.82	0.25	0.05	0.2	0.2	remaining

PROPERTIES

- 1. Density 2.95 gm/cc
- 2. Thermal Conductivity 200 W/m•K
- 3. Bending Strength 350 – 500 MPa
- 4. Micro Hardness 266 HVN

2. Al-ZrO₂ (with 10% wt particulate reinforcement of ZrO₂)

Table 3.3 Composition

Si	Mg	Cu	Ni	Fe	Mn	Zn	Pb	Al
2.2	0.51	2	0.2	0.61	0.02	0.2	0.2	remaining

PROPERTIES

- 1. Density 2.630 gm/cc
- 2. Thermal Conductivity 13 W/m•K
- 3. Thermal Shock Resistance 500° C
- 4. Micro Hardness 249 HVN

3. Al/(Al₂O₃+ Al₃Zr) (with 15 % wt particulate reinforcement of Al₃Zr)

Table 3.4 Composition

Si	Mg	Cu	Ni	Fe	Mn	Zn	Pb	Al
2	0.2	4.95	----	0.7	0.2	0.2	0.2	remaining

PROPERTIES

- 1. Density 2.86 gm/cc
- 2. Bending Strength 400 – 550 MPa
- 3. Elastic Modulus 260 – 320 GPa
- 4. Micro Hardness 256 HVN

Aluminium based metal matrix composite are prepared for the study with Al 356 as baseline metal ZrO₂ as reinforcement in one work piece to a percentage of 10% by weight was used and Al₃Zr in other work piece up to 15% by weight was used, third composite Al-SiC with 16.85%wt

SiC particulate reinforcement. Composition of the same are mentioned above. The work pieces were prepared in form of plate with dimension 95mm × 95 mm × 10mm.

Figure 3.4 shows the three type of work material used for Ultrasonic machining.

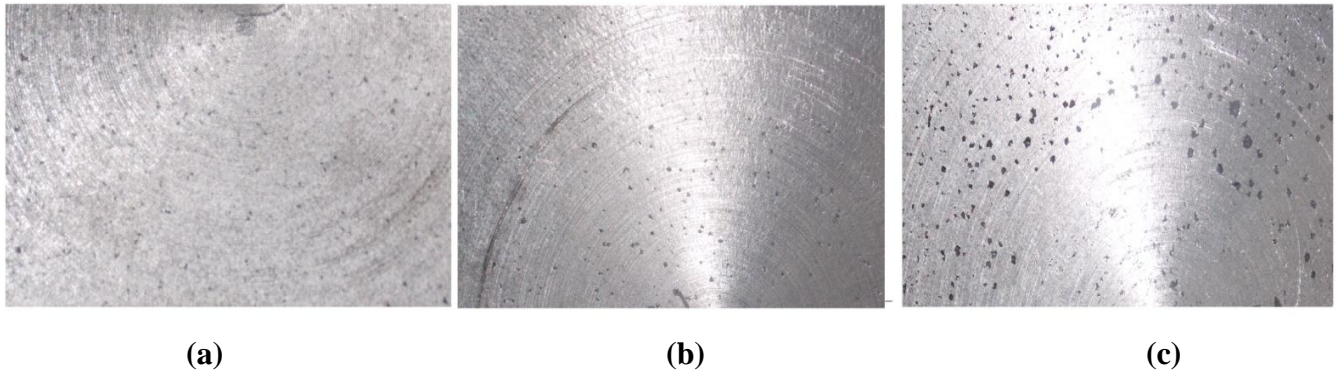


Figure 3.4 Work piece (a) Al-SiC, (b) Al- ($\text{Al}_2\text{O}_3+\text{Al}_3\text{Zr}$), (c) Al- ZrO_2

3.5 ABRASIVE SLURRY

The slurry used in ultrasonic machining process is a mixture of abrasive grains and a liquid carrier mainly water, kerosene, benzene, glycerol or thin oil. The ratio of abrasives to liquid can vary from 1:4 to 1:1 (by weight). Slurry can be fed externally or internally. In the case of external feeding, the slurry is pump fed by several jets covering the circumference of the tool or by a single jet. In the case of internal feeding hollow tools carry the abrasive slurry centrally to the work piece. The slurry is to be fed continuously to avoid any drying up at the tool face. Several abrasives are available in various particle (Grit) sizes for ultrasonic machining. The criteria for selection of an abrasive for a particular application include hardness, usable life, cost, shape and size of particles. 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.

The performance characteristics of an ultrasonic machining process have investigated by using the different abrasive slurry of different grit numbers. The slurry has been used during the experiments are of three different types which are give as follows:-

1. Aluminium Oxide (Al_2O_3)
2. Silicon carbide (SiC)
3. 50% Aluminium Oxide (Al_2O_3) + 50% Silicon carbide (SiC)

Grit size: 320 (44 micron), 400 (23.6 micron), 600 (16 micron)

Slurry medium: Water

3.6 RESPONSE PARAMETERS

The performance of ultrasonic machining process has been evaluated on the basis of the following parameters:

3.6.1 MATERIAL REMOVAL RATE

It is expressed as penetration rate in mm/min for a given cross-section of the tool, or expressed as volume material removal rate in **mm³/min**.

3.6.2 TOOL WEAR RATE

Gradual erosion of the tool material takes place. The tool wears as a result of contact with the abrasive, which tend to erode the tool; cavitations and other such effect also affect the tool. Most of wear occur at the end and the wear sides is about ten times less. It is usual to specify the wear as a percentage of the depth of cut. The wear is proportional to the working time and is expressed in **mm³/min**

3.6.3 SURFACE ROUGHNESS OR SURFACE FINISH

Surface roughness of the machined surface of work piece is expressed in **microns**. The characteristics of the layer of the work material just below the machined surface can also be evaluated.

$$\text{Surface Roughness } (R_a) = \frac{1}{L} \int_0^L |h(x) dx| \quad (\text{Equation ...3.1})$$

Where, h(x) is average roughness profile and L is evaluation of length

3.6.4 INFLUENCE OF THE TYPE AND GRAIN SIZE OF THE ABRASIVE ON MRR.

The abrasive particle of different types will have different properties like hardness, fracture behavior, etc. The hardness of the abrasive in relation to the hardness of the work piece seems to play an important role on material removal rate. The relative hardness of the abrasive

with respect to the work piece (H_a/H_w) is observed to have direct effect on material removal rate. The grain size or grit size of the abrasive has great influence on the material removal rate.

3.7 ANALYSIS OF MACHINED SURFACE

After the machining of the work specimens by using different experimental condition as mentioned above, the machined surface has been analyzed by using the following equipment

1. Scanning electron microscope (SEM)
2. Surface roughness tester “Perthometer M4Pi”
3. Micro hardness tester

3.7.1 SCANNING ELECTRON MICROSCOPE (SEM)

The microstructure had been analyzed by using Scanning electron microscope in laboratory at Indian Institute of Technology, Delhi. The basic specifications of Scanning electron microscope (SEM) are as follows:

1. Model No – Zeiss EVO 50
2. Magnification – 5x to 1,000,000x
3. Company – Carl Zeiss, United States



Figure 3.5 Scanning Electron Microscope (SEM)

3.7.2 SURFACE ROUGHNESS TESTER

The surface roughness had been analyzed by using Surface roughness tester “Perthometer M4Pi” in the Metrology lab at Mechanical Engineering department at Thapar Institute of Engineering and Technology, Patiala. The basic specifications of Surface roughness tester “Perthometer M4Pi” are given as follows:



Figure 3.6 Perthometer M4Pi

1. Principle of measurement – Stylus method
2. Measurement ranges – 100 - 150 μm
3. Cut-off wavelengths – 0.08 – 0.25 – 0.8 – 2.5 mm
4. Tracing lengths – 1.5 – 4.8 – 15 mm
5. Number of sampling lengths – 15 selectable
6. Parameters – R_a , R_q , R_z , R_{max} , R_p , R_t , M_r (material ratio)
7. Tolerance monitoring – Maximum/minimum for all parameters selected.
8. Measuring unit - μm , μin selectable
9. Dimensions (W x D x H) – 175 x 85 x 70 mm
10. Weight – Approx. 600g

3.7.3 MICRO HARDNESS TESTER

Micro hardness was measured on the computer interfaced Micro Hardness Tester, (Model MVH-2) Metatech industries, Pune, India available at Thapar University, Patiala. The micro hardness measurement depends on the diameter of indentation on the sample. The indent formed by pyramid shaped indenter was measured with Quantimet software using load of 1 kg with dwell time 20 seconds. The micro hardness was measured for un-machined as well as machine surface.



Figure 3.7 Micro Hardness Tester

1. Maximum load – 1 kg
2. Model No – MVH-2
3. Company – Metatech Industries, Pune (INDIA)

4.1 INTRODUCTION TO TAGUCHI METHOD

Every experimenter has to plan and conduct experiments to obtain enough and relevant data so that he can infer the science behind the observed phenomenon. He can do so by,

(1) TRIAL-AND-ERROR APPROACH:

Performing a series of experiments each of which gives some understanding. This requires making measurements after every experiment so that analysis of observed data will allow him to decide what to do next - "Which parameters should be varied and by how much". Many a times such series does not progress much as negative results may discourage or will not allow a selection of parameters which ought to be changed in the next experiment. Therefore, such experimentation usually ends well before the number of experiments reaches a double digit! The data is insufficient to draw any significant conclusions and the main problem (of understanding the science) still remains unsolved.

(2) DESIGN OF EXPERIMENTS:

A well planned set of experiments, in which all parameters of interest are varied over a specified range, is a much better approach to obtain systematic data. Mathematically speaking, such a complete set of experiments ought to give desired results. Usually the number of experiments and resources (materials and time) required are prohibitively large. Often the experimenter decides to perform a subset of the complete set of experiments to save on time and money! However, it does not easily lend itself to understanding of science behind the phenomenon. The analysis is not very easy (though it may be easy for the mathematician/statistician) and thus effects of various parameters on the observed data are not readily apparent. In many cases, particularly those in which some optimization is required, the method does not point to the BEST settings of parameters. A classic example illustrating the drawback of design of experiments is found in the planning of a world cup event, say football. While all matches are well arranged with respect to the different teams and different venues on

different dates and yet the planning does not care about the result of any match (win or lose)!!!! Obviously, such a strategy is not desirable for conducting scientific experiments (except for coordinating various institutions, committees, people, equipment, materials, etc.).

(3) TAGUCHI METHOD:-

Dr. Taguchi of Nippon Telephones and Telegraph Company, Japan has developed a method based on “ORTHOGONAL ARRAY” experiments which gives much reduced “variance” for the experiment with “optimum settings “of control parameters. Thus the marriage of Design of Experiments with optimization of control parameters to obtain BEST results is achieved in the Taguchi Method. "Orthogonal Arrays" (OA) provide a set of well balanced (minimum) experiments and Dr. Taguchi's Signal-to-Noise ratios (S/N), which are log functions of desired output, serve as objective functions for optimization, help in data analysis and prediction of optimum results.

4.2 PREPARATION OF ORTHOGONAL ARRAY

Taguchi’s Design of Experiment approach is used to determine the number of experimental run to be carried. Variable factors were identified and their levels were determined. Five variable factors were selected whose effect is to be studied during machining with their determined levels as shown below:

Table 4.1 Input variables

S.No	Factor	Level I	Level II	Level III
A	Power Rating (V)	40	60	-----
B	Work piece	Al(Al ₂ O ₃ + Al ₃ Zr)	Al-ZrO ₂	Al-SiC
C	Slurry type	Al ₂ O ₃	Sic	50% Al ₂ O ₃ +50% SiC
D	Slurry concn. (wt %)	30	40	50
E	Grit size (mesh)	320	400	600

For conducting the experiments, it has been 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 is to be selected after taking into consideration the above design variables and experiments have been performed as per the set of experiments designed in the orthogonal array. Signal to Noise ratios are also calculated to analyze the effect of input parameters on MRR, TWR and Surface roughness more accurately.

Out of a number of design variables, the orthogonal array was to be selected for five design variables (namely Power rating, work piece, slurry type, slurry concentration, grit size) which would constitute the orthogonal array. Tool and depth of cut are fixed (2 mm) for all the experiments because it is desirable setting for material removal to occur. 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.

4.2.1 CONSTANT PARAMETERS

Table 4.2 Constant Parameters

Frequency of vibration	21 KHz
Static load	1.63 Kg
Amplitude of vibration	25.3–25.6 μm
Depth of cut	2 mm
Thickness of work piece	10 mm
Tool geometry	Straight cylindrical with diameter 8 mm
Slurry temperature	28°C (ambient room temperature)
Slurry flow rate	$26.4 \times 10^3 \text{ mm}^3/\text{min}$
Slurry media	Water

4.2.2 SELECTION OF ORTHOGONAL ARRAY

In this experiment, there are five parameters, one parameter with level 2 and four parameters with level three respectively. The degree of freedom (DOF) of a two level parameter is 1 and degree of freedom of three level parameter is 2 (number of levels-1); hence total DOF for the experiment is 9. There are three interactions (between power rating, slurry concentration and grit size) which are to be studied in the experiment. Total DOF of the interactions is 8. The DOF of the orthogonal array selected should be higher than that of total DOF of the experiment. Total DOF for this experiment is 17. So the Orthogonal Array (OA) which is to be used is L_{18} .

Table 4.3 Levels of factor

S No.	Factors	Levels	Level 1	Level 2	Level 3
A	Power rating	2	A1	A2	-----
B	Work piece	3	B1	B2	B3
C	Slurry type	3	C1	C2	C3
D	Slurry concen.	3	D1	D2	D3
E	Grit size	3	E1	E2	E3

Table 4.4 shows degree of freedom for various input parameters.

Table 4.4 DOF allocation to various factor combinations

Interaction	Units	DOF
Power rating (A)	Watt	1
Work piece (B)	-	2
Slurry type (C)	-	2
Slurry concentration (D)	gm/lit	2
Grit size (E)	Mesh	2
A×D	-	2
A×E	-	2
Total	-	13

4.2.3 ORTHOGONAL ARRAY

Table 4.5 L₁₈ Orthogonal Array (Taguchi Design)

No. of Exp	power rating	work piece	slurry type	Slurry Concen.	grit size
1	(40)	Al(Al ₂ O ₃ + Al ₃ Zr)	(Al ₂ O ₃)	(30)	(320)
2	(40)	Al(Al ₂ O ₃ + Al ₃ Zr)	(SiC)	(40)	(400)
3	(40)	Al(Al ₂ O ₃ + Al ₃ Zr)	(Al ₂ O ₃ +SiC)	(50)	(600)
4	(40)	Al-ZrO ₂	(Al ₂ O ₃)	(30)	(400)
5	(40)	Al-ZrO ₂	(SiC)	(40)	(600)
6	(40)	Al-ZrO ₂	(Al ₂ O ₃ +SiC)	(50)	(320)
7	(40)	Al-SiC	(Al ₂ O ₃)	(40)	(320)
8	(40)	Al-SiC	(SiC)	(50)	(400)
9	(40)	Al-SiC	(Al ₂ O ₃ +SiC)	(30)	(600)

10	(60)	Al(Al ₂ O ₃ + Al ₃ Zr)	(Al ₂ O ₃)	(50)	(600)
11	(60)	Al(Al ₂ O ₃ + Al ₃ Zr)	(SiC)	(30)	(320)
12	(60)	Al(Al ₂ O ₃ + Al ₃ Zr)	(Al ₂ O ₃ +SiC)	(40)	(400)
13	(60)	Al-ZrO ₂	(Al ₂ O ₃)	(40)	(600)
14	(60)	Al-ZrO ₂	(SiC)	(50)	(320)
15	(60)	Al-ZrO ₂	(Al ₂ O ₃ +SiC)	(30)	(400)
16	(60)	Al-SiC	(Al ₂ O ₃)	(50)	(400)
17	(60)	Al-SiC	(SiC)	(30)	(600)
18	(60)	Al-SiC	(Al ₂ O ₃ +SiC)	(40)	(320)

A- POWER RATING

A1- 40

A2- 60

B- WORK PIECE

B1- Al (Al₂O₃+ Al₃Zr)

B2- Al-ZrO₂

B3- Al-SiC

C- SLURRY TYPE

C1- Al₂O₃

C2- SiC

C3- 50% Al₂O₃+50% SiC

D- SLURRY CONCENTRATION

D1- 30

D2- 40

D3- 50

E- GRIT SIZE

E1- 320

E2- 400

E3- 600



Figure 4.1 Machine surface of Work piece Material

4.3 ANALYSIS AND RESULT

4.3.1 SIGNAL-TO-NOISE RATIO

The parameters that influence the output can be categorized in two types, namely controllable (or design) and non-controllable (or noise) factors. Controllable factors are those which can be set and easily adjusted by designer. Uncontrollable factors are the sources of variation often associated with operational environment. The best setting of control factors as they influence the output parameters are determined through experiments. From the analysis point of view, there are three possible types of response characteristics explained below.

4.3.1.1 Higher the better. In this design situation, MRR is type of “lower the better “, which is logarithmic function based on the mean square deviation (MSD), given by: The S/N ratio for higher better is given by:

$$(S/N)_{HB} = -10 \log_{10} (MSD_{HB}) \quad (\text{Equation 4.1})$$

$$\text{where } MSD_{HB} = \frac{1}{r} \sum_{i=1}^r \left(\frac{1}{y_i^2} \right) \quad (\text{Equation 4.2})$$

4.3.1.2 Nominal the better. S/N ratio for nominal the better is:

$$(S/N)_{NB} = -10 \log_{10} (MSD_{NB}) \quad (\text{Equation 4.3})$$

$$\text{where } MSD_{NB} = \frac{1}{r} \sum_{i=1}^r (y_i - y_0)^2 \quad (\text{Equation 4.4})$$

4.3.1.3 Lower the better. In this design situation, TWR and surface roughness is type of “lower the better “, which is logarithmic function based on the mean square deviation (MSD), given by:

$$(S/N)_{LB} = -10 \log (MSD_{LB}) \quad (\text{Equation 4.5})$$

$$\text{where } MSD_{LB} = \frac{1}{r} \sum_{i=1}^r (y_i^2) \quad (\text{Equation 4.6})$$

r is number of test in a trial (noise of repetition regardless of noise level)

MSD = Mean square deviation

y_i = observed value of response characteristics

y_o = target value of the results

$\sum_{i=1}^r y_i^2$ = summation of all response values under each trial

4.3.2 SIGNAL TO NOISE RATIO FOR RESPONSE CHARACTERISTICS

The factors that influence the output can be categorized in two categories, controllable and uncontrollable factors. The control factors that may contribute to reduced variation can be quickly identified by looking at the amount of variation present in response. The uncontrollable factors are the sources of variations often associated with operational environment. For this experimental work, response characteristics have given in table.

Table 4.6 Response Variables

Response number	Response 1	Response 2	Response 3	Response 4
Name	MRR	TOOL WEAR	SR	Micro Hardness
Unit	mm ³ /min	mm ³ /min	Micron	HVN
Type	Higher the better	Lower the better	Lower the better	Higher the better

4.3.3 MEASUREMENT OF F-VALUE OF FISHER'S F RATIO

The principle of the F test is that the larger the F value for a particular parameter, the greater the effect on the performance characteristics due to the change in that process parameter. F value is defined as:

$$F = \frac{MS \text{ for a term}}{MS \text{ for the error term}} \quad (\text{Equation 4.7})$$

4.3.4 COMPUTING OF AVERAGE PERFORMANCE:

Average performance of a factor at certain level is the influence of the factor at this level on the mean response of the experiments.

4.4 ANALYSIS OF VARIANCE (ANOVA)

The knowledge of contribution of individual factors is critically important for the control of the final response. The analysis of variation (ANOVA) is common statistical technique to determine the percent contribution of each factor for result of the experiment. It calculates parameters known as sum of squares (SS), pure SS, degree of freedom (DOF), variance, F-ratio and percentage of each factor. Since the procedure of ANOVA is a very complicated and employs a considerable of statistical formulae, only brief description is given below:

The sum of squares (SS) is a measure of the deviation of experimental data from the mean value of the data.

Let 'A' is factor under investigation

$$SS_T = \sum_{i=1}^N (y_i - \bar{T})^2 \quad (\text{Equation 4.8})$$

where

N = number of response observations, \bar{T} is mean of all observations and y_i is the i^{th} response.

Factor sum of squares (SS_A) – Squared deviation of factor (A) averages from overall average

$$SS_A = \left[\sum_{i=1}^{k_A} \left(\frac{A_i^2}{n_{A_i}} \right) \right] - \frac{T^2}{N} \quad (\text{Equation 4.9})$$

where

A_i = Average of all observation under A_i level = A_i / n_{A_i}

T = sum of all observations

\bar{T} = average of all observations = T/N

n_{A_i} = number of observation under A_i level

Error Sum of Squares (SS_e) – Squared deviation of observations from factor (A) averages

$$SS_e = \sum_{j=1}^{k_A} \sum_{i=1}^{n_{A_i}} (y_i - \bar{A}_j)^2 \quad (\text{Equation 4.10})$$

Sum of Square ($SS_{A \times B}$) for interactions

$$SS_{A \times B} = \left[\sum_{i=1}^C \left(\frac{(A \times B)_i^2}{n_{(A \times B)_i}} \right) \right] - \frac{T^2}{N} - SS_A - SS_B \quad (\text{Equation 4.11})$$

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

SS' = SS of significant factor – DOF of that factor \times variation due to e-pooled

$$C\% = \frac{SS'}{\text{Total } SS} \times 100 \quad (\text{Equation 4.12})$$

If F- test > F- critical

Only then the factor is significant for the given conditions.

where DOF = Degree of freedom

F-test = Fisher's test

C% = Contribution factor

CHAPTER 5

RESULT AND ANALYSIS OF MRR

5.1 INTRODUCTION

The effect of parameters i.e. work piece, slurry type, slurry concentration, power ration and abrasive grit size and interaction between power rating of machine in percentage of max. (500 watts) and abrasive slurry concentration, power rating and grit size were evaluated using ANOVA. The confidence interval of 95% has been used for analysis. The trial was followed by a repetition to reduce noise level.

5.2 RESULTS FOR MRR

The results for MRR for each 18 treatment condition with repetition are given in table 5.1. MRR for each sample is calculated from the weight difference of work piece before and after the performance trial, which is given by

$$\text{MRR} = \frac{(w_i - w_f)}{\rho \times t} \times 1000 \text{ mm}^3/\text{min} \quad (\text{Equation 5.1})$$

Where, w_i = initial weight of work piece material (gms)

w_f = final weight of work piece material (gms)

t = time period of trials in minutes

ρ = density of work piece material

Table 5.1 Results for MRR

Exp No.	power rating	work piece	slurry type	Slurry concen.	grit size	MRR (mg/min)	S/N ratio	Mean
1	(40)	Al(Al ₂ O ₃ + Al ₃ Zr)	(Al ₂ O ₃)	(30)	(320)	10.4850	20.4114	10.4850
2	(40)	Al(Al ₂ O ₃ +)	(SiC)	(40)	(400)	10.6362	20.5357	10.6362

		Al ₃ Zr)						
3	(40)	Al(Al ₂ O ₃ + Al ₃ Zr)	(Al ₂ O ₃ +SiC)	(50)	(600)	10.6654	20.5596	10.6654
4	(40)	Al-ZrO ₂	(Al ₂ O ₃)	(30)	(400)	10.6127	20.5165	10.6127
5	(40)	Al-ZrO ₂	(SiC)	(40)	(600)	10.6749	20.5672	10.6749
6	(40)	Al-ZrO ₂	(Al ₂ O ₃ +SiC)	(50)	(320)	11.2964	21.0588	11.2964
7	(40)	Al-SiC	(Al ₂ O ₃)	(40)	(320)	10.3183	20.2722	10.3183
8	(40)	Al-SiC	(SiC)	(50)	(400)	10.9993	20.8273	10.9993
9	(40)	Al-SiC	(Al ₂ O ₃ +SiC)	(30)	(600)	10.4233	20.3601	10.4233
10	(60)	Al(Al ₂ O ₃ + Al ₃ Zr)	(Al ₂ O ₃)	(50)	(600)	10.2611	20.2239	10.2611
11	(60)	Al(Al ₂ O ₃ + Al ₃ Zr)	(SiC)	(30)	(320)	11.2612	21.0317	11.2612
12	(60)	Al(Al ₂ O ₃ + Al ₃ Zr)	(Al ₂ O ₃ +SiC)	(40)	(400)	11.4554	21.1802	11.4554
13	(60)	Al-ZrO ₂	(Al ₂ O ₃)	(40)	(600)	10.5564	20.4703	10.5564
14	(60)	Al-ZrO ₂	(SiC)	(50)	(320)	11.6192	21.3035	11.6192
15	(60)	Al-ZrO ₂	(Al ₂ O ₃ +SiC)	(30)	(400)	11.2565	21.0281	11.2565
16	(60)	Al-SiC	(Al ₂ O ₃)	(50)	(400)	10.2914	20.2495	10.2914
17	(60)	Al-SiC	(SiC)	(30)	(600)	10.9265	20.7696	10.9265
18	(60)	Al-SiC	(Al ₂ O ₃ +SiC)	(40)	(320)	11.5842	21.2773	11.5842

5.2 ANALYSIS OF VARIANCE – MRR

The results for MRR were analyzed using ANOVA for identifying the significant factors affecting the performance measure. Analysis of Variance (ANOVA) for mean MRR at 95% confidence interval is given in table 5.2. The variance data for each factor and their interaction were calculated. The Contribution percent for significant factors were calculated using the expression explain in previous chapter. It was observed that P value for significant factors was less than 0.05.

Table 5.2 Analysis of variance of Mean

Source	Seq SS	DOF	Adj MS (variance)	F test	P	F critical	SS'	C%	Status
Power (%)	0.53403	1	0.53403	17.39	0.014	7.71	0.488	13.678	Significant
W/Piece	0.21030	2	0.10515	3.425	0.136	6.94			Insignificant
Ab. Slurry	1.69437	2	0.8472	27.59	0.030	6.94	1.602	44.888	Significant
Sl. Concen.	0.00579	2	0.002895	0.009	0.912	6.94			Insignificant
Grit Size	0.78386	2	0.39193	12.77	0.018	6.94	0.691	19.362	Significant
Power* Sl. Concen.	0.21035	2	0.1051	3.423	0.023	6.94			Insignificant
Power*grit size	0.00736	2	0.00368	0.119	0.890	6.94			Insignificant
Error	0.12280	4	0.0307						
Total	3.56886	17	0.20993						
e- pooled	0.5566	12	0.04638					22.072	

Table 5.3 shows the rank of various input parameters in terms to their relative significance

Table 5.3 Response Table for Mean of MRR

Level	Power rating	W/Piece	Slurry type	Sl. Concen.	Grit size
1	10.68	10.79	10.42	10.83	11.09
2	11.02	10.76	11.11	10.87	10.88
3		11.00	11.02	10.86	10.58
Delta	0.34	0.25	0.69	0.04	0.51
Rank	3	4	1	5	2

Figure 5.1 shows the main effect plot for mean for MRR and figure 5.2 shows interaction plot for mean for MRR.

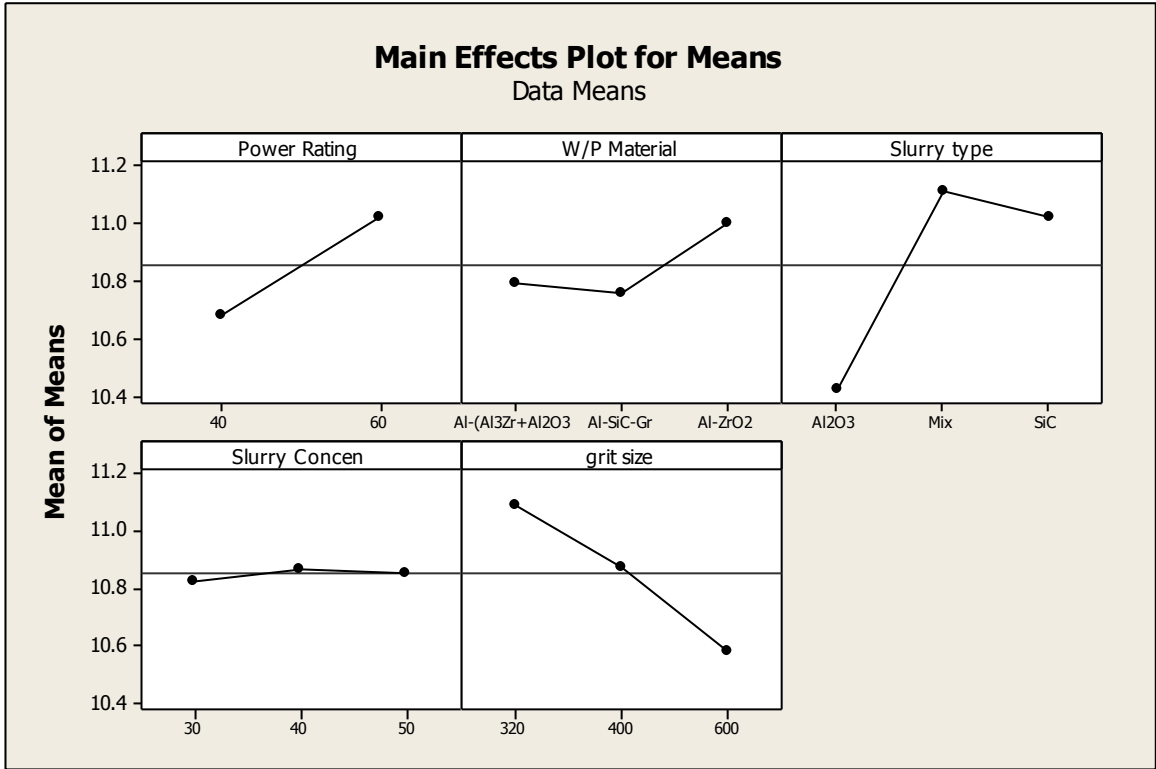


Figure 5.1 Main effect plot of MRR for means



Figure 5.2 Interaction Plot for MRR

5.4 RESULT FOR S/N RATIO FOR MRR

The S/N Ratio consolidates several repetitions into one value and indicates the amount of variation present. The S/N ratios have been calculated to identify the major contributing factor and interaction that cause variation in the MRR. MRR is “Higher the better” type response which is represented by:

$$(S/N)_{HB} = -10 \log_{10} (MSD_{HB}) \quad (\text{Equation 5.2})$$

where ,MSD is Mean Square Deviation for Higher the better response

$$MSD_{HB} = \frac{1}{r} \sum_{i=1}^r \left(\frac{1}{y_i^2} \right) \quad (\text{Equation 5.3})$$

Table 5.4 shows the results of S/N ratio of MRR at 95% confidence interval

Table 5.4 S/N ratio for MRR

Source	Seq SS	DOF	Adj MS (variance)	F test	P	F critical	SS'	C%	Status
Power (%)	0.32679	1	0.32679	17.03	0.015	7.71	0.2969	13.15	Significant
W/Piece	0.13617	2	0.06809	3.54	0.130	6.94			Insignificant
Ab. Slurry	1.08716	2	0.54358	9.70	0.029	6.94	1.0274	45.50	Significant
Sl. Concen.	0.00289	2	0.00144	0.08	0.929	6.94			Insignificant
Grit Size	0.48549	2	0.21274	12.65	0.019	6.94	0.4257	18.86	Significant
Power* Sl. Concen.	0.13802	2	0.06901	2.25	0.221	6.94			Insignificant
Power*grit size	0.00456	2	0.00228	0.12	0.891	6.94			Insignificant
Error	0.07677	4	0.01919						
Total	2.25784	17	0.13281						
e- pooled	0.35841	12	0.02987					28.20	

Table 5.5 shows the rank of various input parameters in terms to their relative significance

Table 5.5 Response table for S/N for MRR

Level	Power rating	W/Piece	Slurry type	Sl. Concen.	Grit size
1	20.57	20.66	20.36	20.69	20.89
2	20.84	20.63	20.91	20.72	20.72
3		20.82	20.84	20.70	20.49
Delta	0.27	0.20	0.55	0.03	0.40
Rank	3	4	1	5	2

Figure 5.3 shows the main effect S/N Ratio plot for MRR and figure 5.4 shows interaction plot S/N Ratio for MRR

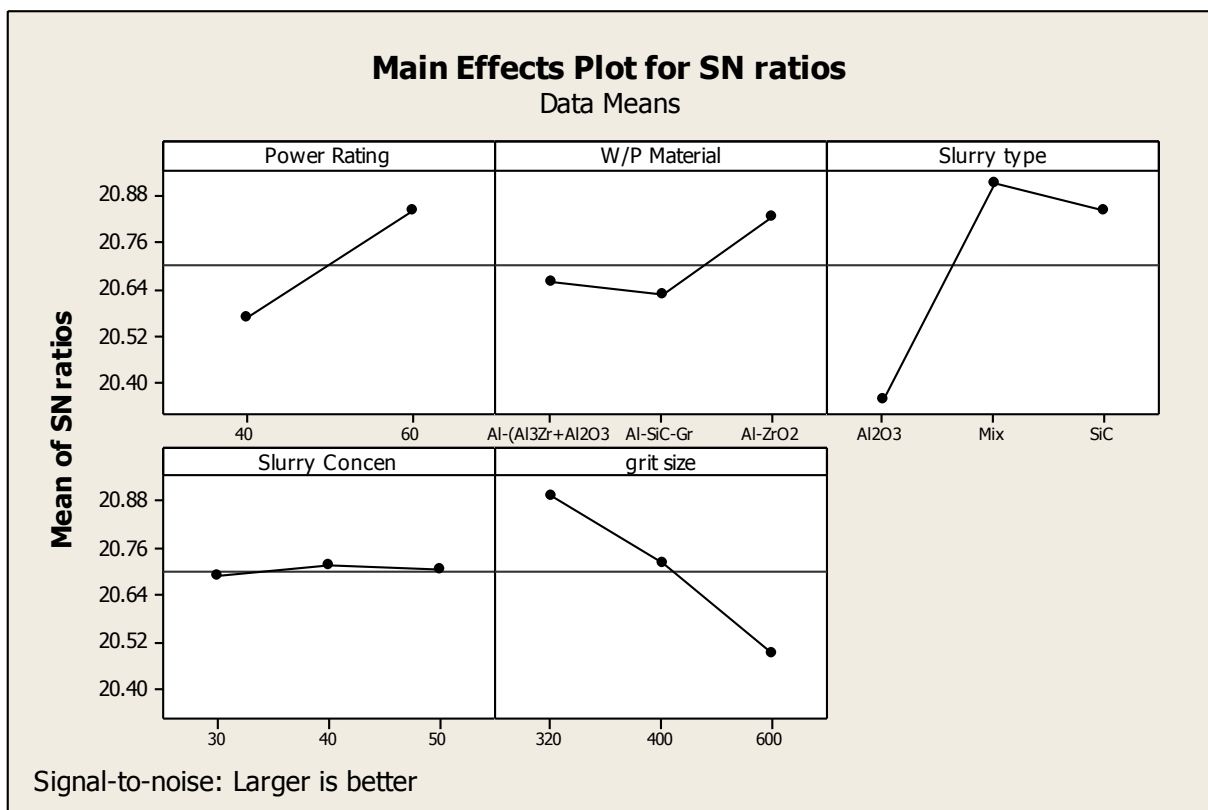


Figure 5.3 Main effect S/N Ratio for MRR

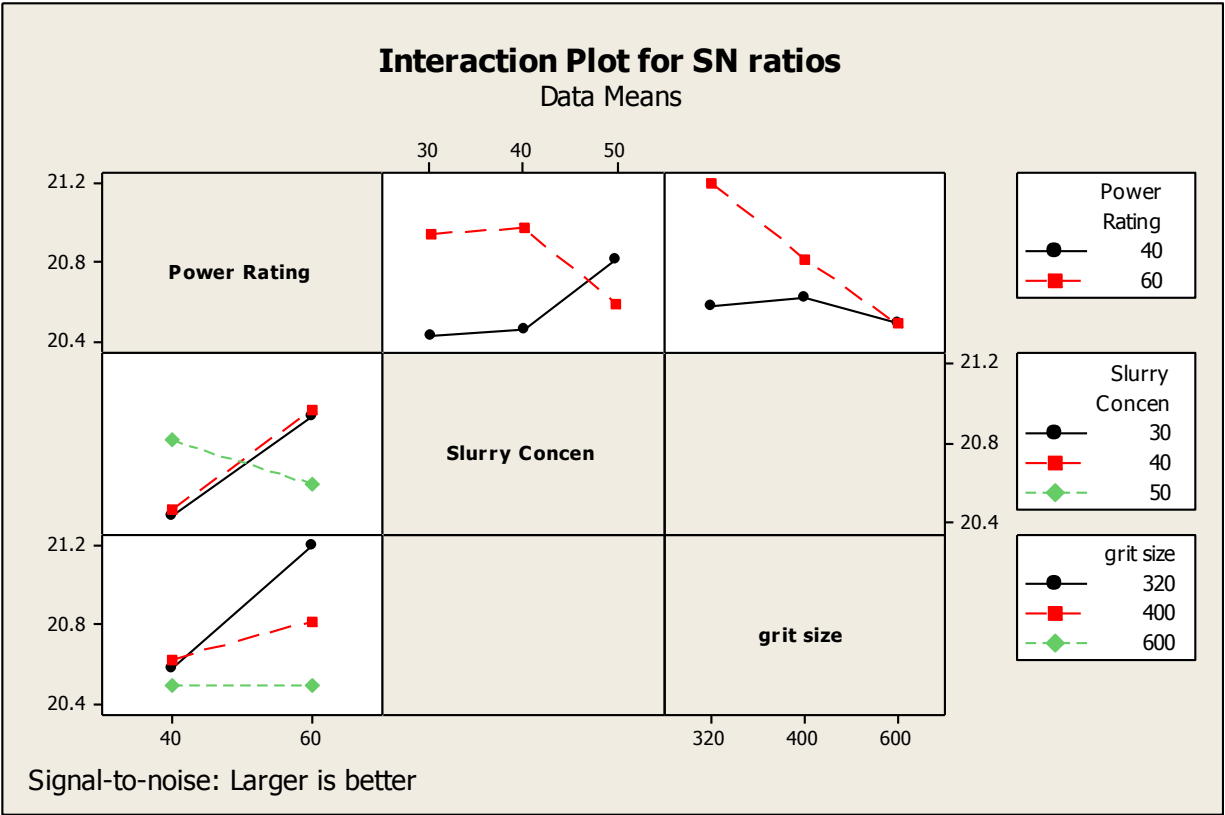


Figure 5.4 Interaction of S/N Ratio for MRR

5.5 OPTIMAL DESIGN FOR MRR

In this experimental analysis, the main effect and interaction plot in Figure 5.1 and 5.2 used to estimate mean MRR. From the, Table 5.6 it is concluded that highest MRR is observed when machining is done on power rate 60%, abrasive slurry using 50% SiC+ 50% Al₂O₃, and grit size 320. It is observed that slurry concentration and interactions have not significant effect on MRR. It is also observed that type of work piece used has not much significant effect on MRR. MRR is assumed to be achieved best result if machining carried on Al-ZrO₂ composite with power rating 60%, abrasive slurry mixture of 50% Silicon Carbide + 50% Aluminium Oxide and grit size 320.

Table 5.6 Significant factor and interactions

Factors	Affecting Mean		Affecting Variance	
	Contribution	Best level	Contribution	Best level
Power (%)	Significant	Level-2 (60)	Significant	Level-2 (60)
W/Piece	Insignificant		Insignificant	
Ab. Slurry	Significant	Level-3 (Mix)	Significant	Level-3 (Mix)
Sl. Concen.	Insignificant		Insignificant	
Grit Size	Significant	Level-1 (320)	Significant	Level-1 (320)
Power* Sl. Concen.	Insignificant		Insignificant	
Power*grit size	Insignificant		Insignificant	

Estimating the mean

In the experiment analysis, the MRR is a higher average response is better (HB) characteristic. Depending on the characteristics, the different treatment combinations has been chosen to obtain satisfactory results. After conducting the experiments the optimum treatment conditions within the experiments determined on the basis of prescribed combination of the factor levels is determined to one of those in the experiments [45].

Mean value of MRR

$$\begin{aligned}
 \mu_{A_2C_3E_1} &= A_2 + C_3 + E_1 - 2T \text{ (Mean of all experiments)} && \text{(Equation 5.4)} \\
 &= 11.023 + 11.113 + 11.094 - (2 \times 10.851) \\
 &= 11.528 \text{ mm}^3/\text{min}
 \end{aligned}$$

Confidence Interval around the estimated mean

The confidence interval is a maximum and minimum value between which the true average should fall at some stated percentage of confidence. The estimate of mean μ is only a point based on the average of result obtained from the experiment. Statistically this provides a 50% chance of the true averages being greater than μ and a 50% chance of true average being less than μ . It is, therefore, customary to represent the value of statistical parameter as a range within which it is likely to fall, for a given level of confidence [45].

$$CI_1 = \sqrt{\frac{F_{\alpha, v_1, v_2} V_e}{n_{eff}}} \quad (\text{Equation 5.5})$$

where, F_{α, v_1, v_2} = F – ratio at confidence level of $(1 - \alpha)$ against D.O.F 1 and error degree of freedom v_2 (for MRR $v_2= 4$, so $F_{\alpha}= 7.71$)

α = risk (0.05)

Confidence = $1 - \alpha$

v_1 = D.O.F for mean which is always =1

v_2 = D.O.F for error = v_e

V_e = variance of e-pooled

η_{eff} = number of test under that condition using the participating factor

$$\eta_{eff} = N / (1 + \text{dof}_{A,C,E})$$

$$= 18 / (1+1+2+2) = 3.0$$

$$CI_1 = \sqrt{\frac{F_{\alpha, v_1, v_2} V_e}{n_{eff}}}$$

$$CI_1 = \sqrt{7,71 \times 0.0464 / 3}$$

$$= \pm 0.345 \text{ mm}^3/\text{min}$$

So the confidence interval around the MRR is given by $11.528 \pm 0.345 \text{ mm}^3/\text{min}$

CHAPTER 6

RESULT AND ANALYSIS OF TWR

6.1 INTRODUCTION

The effect of parameters i.e. work piece, slurry type, slurry concentration, power rating and abrasive grit size and interaction between power rating of machine in percentage of max. (500 watts) and abrasive slurry concentration, power rating and grit size were evaluated using ANOVA. The confidence interval of 95% has been used for analysis. The trial was followed by a repetition to reduce noise level.

6.2 RESULTS FOR TWR

The result for tool wear rate (TWR) for each of 18 treatment condition with repetition are given in table 6.1

Tool wear rate can be calculated by using relation:

$$\text{TWR} = \frac{(w_i - w_f)}{\rho \times t} \times 1000 \text{ mm}^3/\text{min} \quad (\text{Equation 6.1})$$

Where, w_i = initial weight of tool (gms)

w_f = final weight of tool (gms)

t = time period of trials in minutes

ρ = density of tool material

Table 6.1 Result for TWR

Exp No.	power rating	work piece	slurry type	Slurry concen.	grit size	TWR (mm ³ /min)	S/N ratio	Mean
1	(40)	Al(Al ₂ O ₃ + Al ₃ Zr)	(Al ₂ O ₃)	(30)	(320)	0.1614	15.8410	0.1614
2	(40)	Al(Al ₂ O ₃ + Al ₃ Zr)	(SiC)	(40)	(400)	0.1621	15.8018	0.1621

3	(40)	Al(Al ₂ O ₃ + Al ₃ Zr)	(Al ₂ O ₃ +SiC)	(50)	(600)	0.1564	16.1129	0.1564
4	(40)	Al-ZrO ₂	(Al ₂ O ₃)	(30)	(400)	0.1623	15.7928	0.1623
5	(40)	Al-ZrO ₂	(SiC)	(40)	(600)	0.1636	15.7246	0.1636
6	(40)	Al-ZrO ₂	(Al ₂ O ₃ +SiC)	(50)	(320)	0.1584	16.0054	0.1584
7	(40)	Al-SiC	(Al ₂ O ₃)	(40)	(320)	0.1611	15.8560	0.1611
8	(40)	Al-SiC	(SiC)	(50)	(400)	0.1575	16.0558	0.1575
9	(40)	Al-SiC	(Al ₂ O ₃ +SiC)	(30)	(600)	0.1598	15.9258	0.1598
10	(60)	Al(Al ₂ O ₃ + Al ₃ Zr)	(Al ₂ O ₃)	(50)	(600)	0.1654	15.6276	0.1654
11	(60)	Al(Al ₂ O ₃ + Al ₃ Zr)	(SiC)	(30)	(320)	0.1699	15.3910	0.1699
12	(60)	Al(Al ₂ O ₃ + Al ₃ Zr)	(Al ₂ O ₃ +SiC)	(40)	(400)	0.1683	15.4783	0.1683
13	(60)	Al-ZrO ₂	(Al ₂ O ₃)	(40)	(600)	0.1695	15.4187	0.1695
14	(60)	Al-ZrO ₂	(SiC)	(50)	(320)	0.1702	15.3813	0.1702
15	(60)	Al-ZrO ₂	(Al ₂ O ₃ +SiC)	(30)	(400)	0.1713	15.3258	0.1713
16	(60)	Al-SiC	(Al ₂ O ₃)	(50)	(400)	0.1682	15.4831	0.1682
17	(60)	Al-SiC	(SiC)	(30)	(600)	0.1686	15.4647	0.1686
18	(60)	Al-SiC	(Al ₂ O ₃ +SiC)	(40)	(320)	0.1674	15.5227	0.1674

5.3 ANALYSIS OF VARIANCE – TWR

The results for TWR were analyzed using ANOVA for identifying the significant factors affecting the performance measure. Analysis of Variance (ANOVA) for mean TWR at 95% confidence interval is given in table 6.2. The variance data for each factor and their interaction were calculated. The Contribution percent for significant factors were calculated using the expression explain in previous chapter. It was observed that P value for significant factors was less than 0.05.

Table 6.2 Analysis of variance of Mean

Source	Seq SS	DOF	Adj MS (variance)	F test	P	F critical	SS'	C%	Status
Power (%)	0.000322	1	0.000322	1391.59	0.000	7.71	0.0000321	81.79	Significant
W/Piece	0.000016	2	0.000008	34.99	0.003	6.94	0.0000145	3.380	Significant
Ab. Slurry	0.000009	2	0.000045	7.39	0.045	6.94	0.000007	1.594	Significant
Sl. Concen.	0.000031	2	0.000016	66.62	0.001	6.94	0.000029	7.207	Significant
Grit Size	0.000004	2	0.000002	8.34	0.037	6.94	0.000002	0.319	Significant
Power* Sl. Concen.	0.000007	2	0.000003	5.43	0.072	6.94			Insignificant
Power*grit size	0.000003	2	0.000001	5.66	0.068	6.94			Insignificant
Error	0.000001	4	0.000000						
Total	0.000392	17	0.000023						
e- pooled	0.000011	8	0.0000014					5.71	

Table 6.3 shows the rank of various input parameters in terms to their relative significance

Table 6.3 Response table for Mean of TWR

Level	Power rating	W/Piece	Slurry type	Sl. Concen.	Grit size
1	0.1603	0.1640	0.1647	0.1656	0.1648
2	0.1688	0.1638	0.1636	0.1653	0.1650
3		0.1659	0.1653	0.1627	0.1639
Delta	0.0085	0.0021	0.0017	0.0029	0.0011
Rank	1	3	4	2	5

Figure 6.1 shows the main effect plot for mean for TWR and figure 6.2 shows interaction plot for mean for TWR

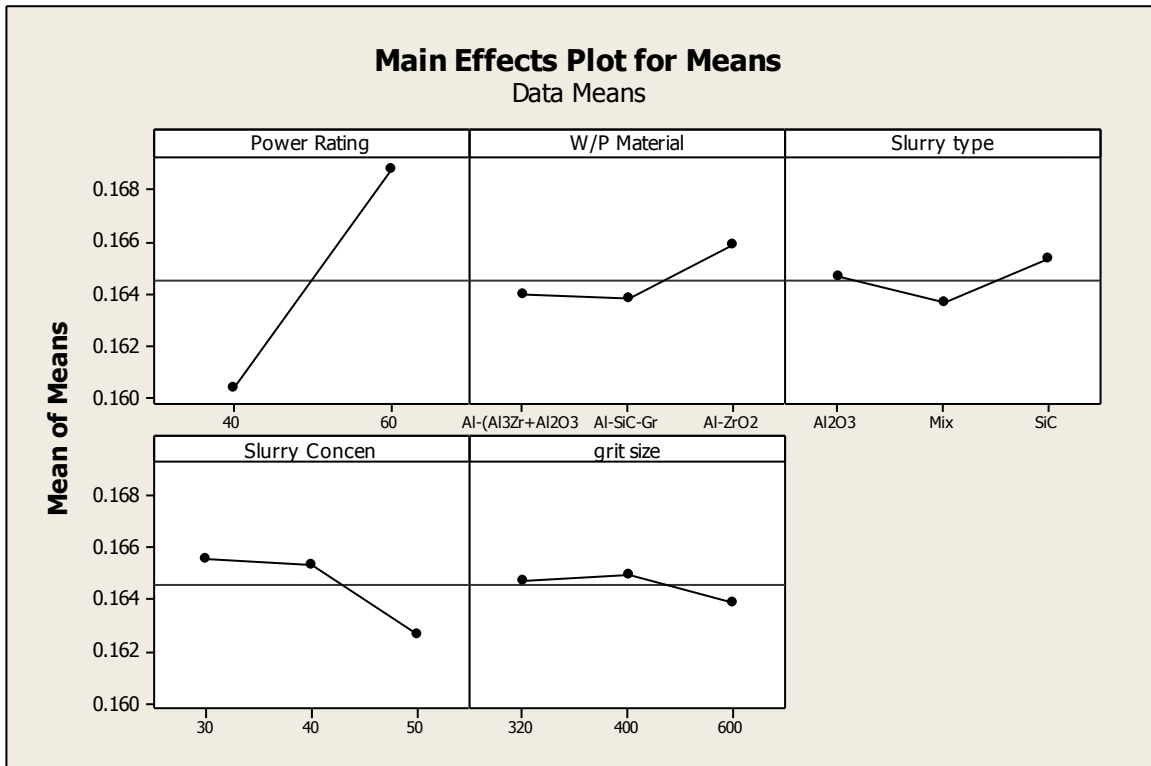


Figure 6.1 Main effect plot of TWR for means

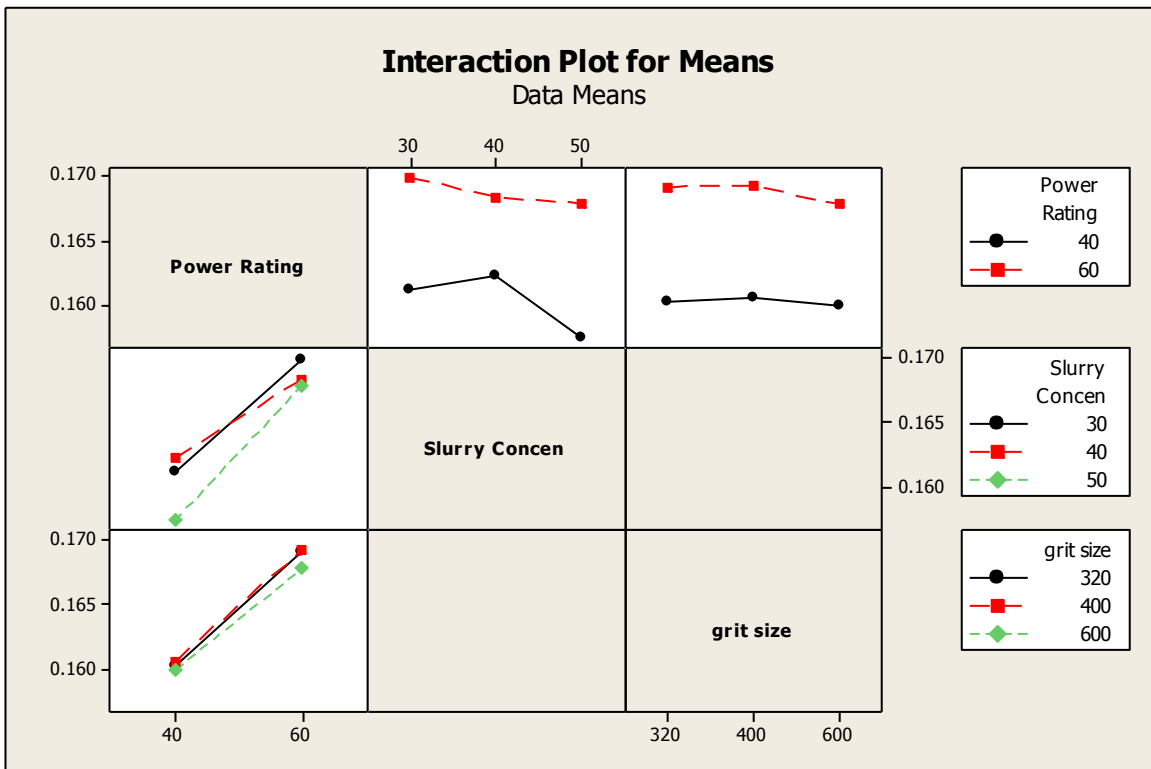


Figure 6.2 Interaction plot of TWR for means

6.4 RESULT FOR S/N RATIO FOR TWR

The S/N Ratio consolidates several repetitions into one value and indicates the amount of variation present. The S/N ratios have been calculated to identify the major contributing factor and interaction that cause variation in the TWR. TWR is “Lower the better” type response which is represented by:

$$(S/N)_{LB} = -10 \log (MSD_{LB}) \quad (\text{Equation 6.2})$$

$$\text{where } MSD_{LB} = \frac{1}{r} \sum_{i=1}^r (y_i^2) \quad (\text{Equation 6.3})$$

MSD = Mean square deviation for lower the better

Table 6.4 shows the results of S/N ratio of TWR at 95% confidence interval. Power rating (%) was observed to be most significant factor affecting the TWR, followed by slurry concentration and type of work piece used, Ab. Slurry and grit size are significant according to p value. Also Interaction between Power (%) and slurry concentration are also significant.

Table 6.4 S/N Ratio for TWR

Source	Seq SS	DOF	Adj MS (variance)	F test	P	F critical	SS'	C%	Status
Power (%)	0.89877	1	0.89877	1590.1	0.000	7.71	0.8979	81.58	Significant
W/Piece	0.04465	2	0.022325	39.50	0.002	6.94	0.0430	3.904	Significant
Ab. Slurry	0.02594	2	0.01297	8.45	0.037	6.94	0.0242	2.204	Significant
Sl. Concen.	0.08912	2	0.04456	78.84	0.001	6.94	0.0874	7.944	Significant
Grit Size	0.01075	2	0.005375	9.51	0.030	6.94	0.0091	0.824	Significant
Power* Sl. Concen.	0.02222	2	0.01111	7.06	0.049	6.94	0.0205	1.866	Significant
Power*grit size	0.00696	2	0.00348	6.16	0.060	6.94			Insignificant
Error	0.00226	4	0.000565						
Total	1.10067	17	0.06475						
e- pooled	0.009220	11	0.000838					1.678	

Table 6.5 shows the rank of various input parameters in terms to their relative significance

Table 6.5 Response table for S/N Ratio for TWR

Level	Power rating	W/Piece	Slurry type	Sl. Concen.	Grit size
1	15.90	15.71	15.67	15.62	15.67
2	15.45	15.72	15.73	15.63	15.66
3		15.61	15.64	15.78	15.71
Delta	0.45	0.11	0.09	0.15	0.06
Rank	1	3	4	2	5

Figure 6.3 shows the main effect S/N Ratio plot for TWR and figure 6.4 shows interaction plot S/N Ratio for TWR

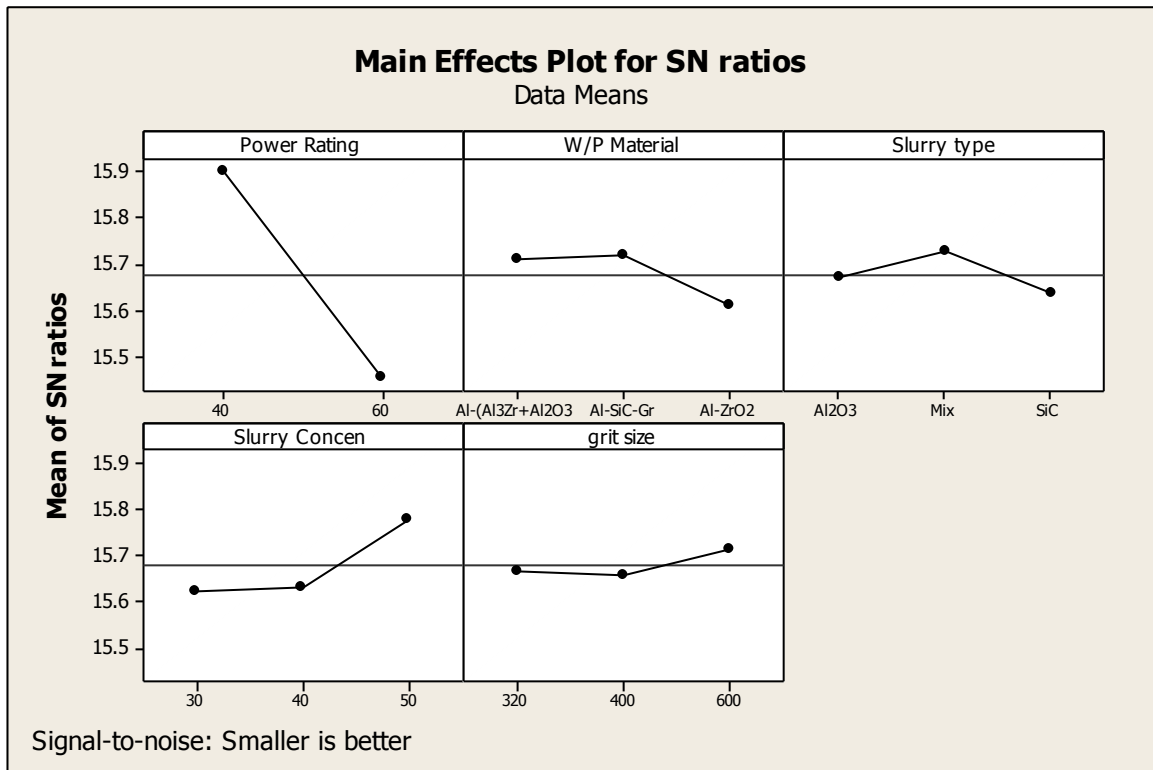


Figure 6.3 Main effect S/N ratio for TWR

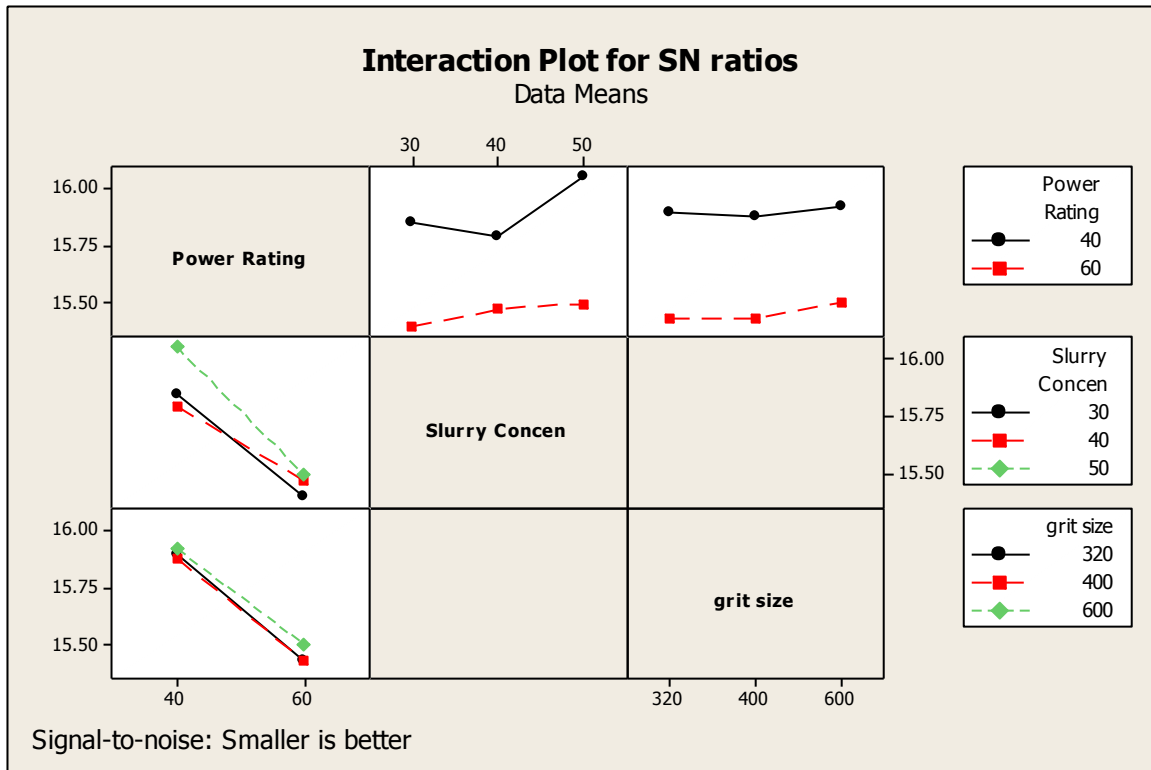


Figure 6.4 Interaction Plot for S/N ratio for TWR

6.5 OPTIMAL DESIGN FOR TWR

In this experimental analysis, the main effect and interaction plot in Figure 5.1 and 5.2 used to estimate mean TWR. From the, Table 5.6 it is concluded that lowest Tool Wear Rate is observed when machining is done on power rate 40%, on work piece Al-SiC-Gr, using slurry mixture of Al₂O₃ and SiC, with slurry concentration 50% and grit size 600 . It is also observed that power rating, slurry concentration and type of work piece to be machined affect the TWR. Interactions have no effect on TWR. TWR is assumed to be achieved best result if machining carried on Al-SiC-Gr composite with power rating 40%, abrasive slurry mixture of 50% Silicon Carbide + 50% Aluminium Oxide and grit size 600.

Table 6.6 Significant factors and interactions

Factors	Affecting Mean		Affecting Variance	
	Contribution	Best level	Contribution	Best level
Power (%)	Significant	Level-1 (40)	Significant	Level-2 (60)
W/Piece	Significant	Level-2 (Al-SiC)	Significant	Level-3 (Al-ZrO ₂)
Ab. Slurry	Significant	Level-3 (Mix)	Significant	Level-2 (SiC)
Sl. Concen.	Significant	Level -3 (50)	Significant	Level-1(30)
Grit Size	Significant	Level-3 (600)	Significant	Level-2 (400)
Power* Sl. Concen.	Insignificant		Significant	A ₂ D ₁
Power*grit size	Insignificant		Insignificant	

Estimating the mean

In experimental analysis, TWR is a Smaller average response is better (SB) characteristic. Depending upon the characteristic, different treatment combinations has chosen to obtain satisfactory results. After conducting the experiments the optimum treatment conditions within the experiments determined on the basis of prescribed combination of the factor levels is determined to one of those in the experiments [45].

Mean value of TWR

$$\begin{aligned} \mu A_1 B_2 C_3 D_3 E_3 &= A_1 + B_2 + C_3 + D_3 + E_3 - 4T \text{ (Mean of all experiments)} && \text{(Equation 6.4)} \\ &= 0.1603 + 0.1638 + 0.1636 + 0.1627 + 0.1639 - (4 \times 0.1645) \\ &= 0.1563 \text{ mm}^3/\text{min} \end{aligned}$$

Confidence Interval around the estimated mean

The confidence interval is a maximum and minimum value between which the true average should fall at some stated percentage of confidence. The estimate of mean μ is only a point based on the average of result obtained from the experiment. Statistically this provides a 50% chance of the true averages being greater than μ and a 50% chance of true average being less than μ . It is, therefore, customary to represent the value of statistical parameter as a range within which it is likely to fall, for a given level of confidence [45].

$$CI_1 = \sqrt{\frac{F_{\alpha, v_1, v_2} V_e}{n_{eff}}} \quad \text{(Equation 6.5)}$$

where, $F_{\alpha v_1 v_2} = F$ – ratio at confidence level of $(1 - \alpha)$ against D.O.F 1 and error degree of freedom v_2 (for TWR $v_2 = 4$, so $F_{\alpha} = 7.71$)

$\alpha = \text{risk (0.05)}$

Confidence = $1 - \alpha$

$v_1 = \text{D.O.F for mean which is always } = 1$

$v_2 = \text{D.O.F for error}$

$V_e = \text{variance of e-pooled}$

$\eta_{eff} = \text{number of test under that condition using the participating factor}$

$$\begin{aligned} \eta_{eff} &= N / (1 + \text{dof}_{A,B,C,D,E}) \\ &= 18 / (1 + 1 + 2 + 2 + 2 + 2) = 1.8 \end{aligned}$$

$$CI_1 = \sqrt{\frac{F_{\alpha, v_1, v_2} V_e}{n_{eff}}}$$

$$CI_1 = \sqrt{7.71 \times 0.0000014 / 1.8}$$

$$= \pm 0.00245 \text{ mm}^3/\text{min}$$

So the confidence interval around the TWR is given by $0.1563 \pm 0.00245 \text{ mm}^3/\text{min}$

CHAPTER 7

RESULT AND ANALYSIS OF SR

7.1 INTRODUCTION

Surface roughness of the machined surface of work piece is expressed in microns. The characteristic of layer of work material just below the machined surface can also be evaluated

7.2 RESULTS FOR SR

The result for surface roughness are given in table 7.1

Table 7.1 Result for SR

Exp No.	power rating	work piece	slurry type	Slurry concen.	grit size	SR (microns)	S/N ratio	Mean
1	(40)	Al(Al_2O_3 + Al_3Zr)	(Al_2O_3)	(30)	(320)	0.89	1.10220	0.89
2	(40)	Al(Al_2O_3 + Al_3Zr)	(SiC)	(40)	(400)	0.68	3.34982	0.68
3	(40)	Al(Al_2O_3 + Al_3Zr)	(Al_2O_3 +SiC)	(50)	(600)	0.75	2.49877	0.75
4	(40)	Al-ZrO ₂	(Al_2O_3)	(30)	(400)	0.81	1.83030	0.81
5	(40)	Al-ZrO ₂	(SiC)	(40)	(600)	0.56	5.03624	0.56
6	(40)	Al-ZrO ₂	(Al_2O_3 +SiC)	(50)	(320)	0.86	1.31003	0.86
7	(40)	Al-SiC	(Al_2O_3)	(40)	(320)	0.75	2.49877	0.75
8	(40)	Al-SiC	(SiC)	(50)	(400)	0.52	5.67993	0.52
9	(40)	Al-SiC	(Al_2O_3 +SiC)	(30)	(600)	0.71	2.97483	0.71
10	(60)	Al(Al_2O_3 + Al_3Zr)	(Al_2O_3)	(50)	(600)	1.16	-1.28916	1.16
11	(60)	Al(Al_2O_3 + Al_3Zr)	(SiC)	(30)	(320)	1.06	-0.50612	1.06
12	(60)	Al(Al_2O_3 + Al_3Zr)	(Al_2O_3 +SiC)	(40)	(400)	1.25	-1.9382	1.25

		Al ₃ Zr)						
13	(60)	Al-ZrO ₂	(Al ₂ O ₃)	(40)	(600)	1.13	-1.06157	1.13
14	(60)	Al-ZrO ₂	(SiC)	(50)	(320)	0.91	0.81917	0.91
15	(60)	Al-ZrO ₂	(Al ₂ O ₃ +SiC)	(30)	(400)	1.91	-1.51094	1.91
16	(60)	Al-SiC	(Al ₂ O ₃)	(50)	(400)	0.91	0.35458	0.91
17	(60)	Al-SiC	(SiC)	(30)	(600)	0.88	1.11035	0.88
18	(60)	Al-SiC	(Al ₂ O ₃ +SiC)	(40)	(320)	1.18	-1.43764	1.18

7.3 ANALYSIS OF VARIANCE- SURFACE ROUGHNESS (R_a)

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 Surface Roughness at 95% confidence interval given in table 7.2. The variance data for each factor and interactions was obtained to determine the P value to find significance for each. From table 7.2 power rating (%), work piece material, Ab. Slurry, slurry concentration, grit size have P value less than 0.05 this means these are significant factor. Table 7.3 shows rank to various input parameters in terms their relative significance.

Table 7.2 Analysis of Variance for Roughness of Mean

Source	Seq SS	DOF	Adj MS (variance)	F test	P	F critical	SS'	C%	Status
Power (%)	0.56534	1	0.56534	571.1	0.000	7.71	0.5634	67.53	Significant
W/Piece	0.05248	2	0.02624	26.51	0.005	6.94	0.0487	5.842	Significant
Ab. Slurry	0.16748	2	0.08374	84.59	0.003	6.94	0.1637	19.62	Significant
Sl. Concen.	0.01648	2	0.00824	8.32	0.037	6.94	0.0127	1.527	Significant
Grit Size	0.01764	2	0.00882	8.91	0.034	6.94	0.0139	1.666	Significant
Power* Sl. Concen.	0.00284	2	0.001415	0.01	0.992	6.94			Insignificant
Power*grit size	0.00815	2	0.004075	4.21	0.107	6.94			Insignificant
Error	0.00396	4	0.00099						
Total	0.83436	17	0.04908						
e- pooled	0.01495	8	0.00187					3.815	

Table 7.3 shows the rank of various input parameters in terms of their relative significance

Table 7.3 Response table for Mean Surface Roughness

Level	Power rating	W/Piece	Slurry type	Sl. Concen.	Grit size
1	0.7256	0.9650	0.9500	0.9233	0.9417
2	1.0800	0.8333	0.9900	0.9250	0.9017
3		0.9100	0.7683	0.8600	0.8650
Delta	0.3544	0.1317	0.2217	0.0650	0.0767
Rank	1	3	2	5	4

Figure 7.1 shows the main effect plot for mean for SR and figure 7.2 shows interaction plot for mean for SR

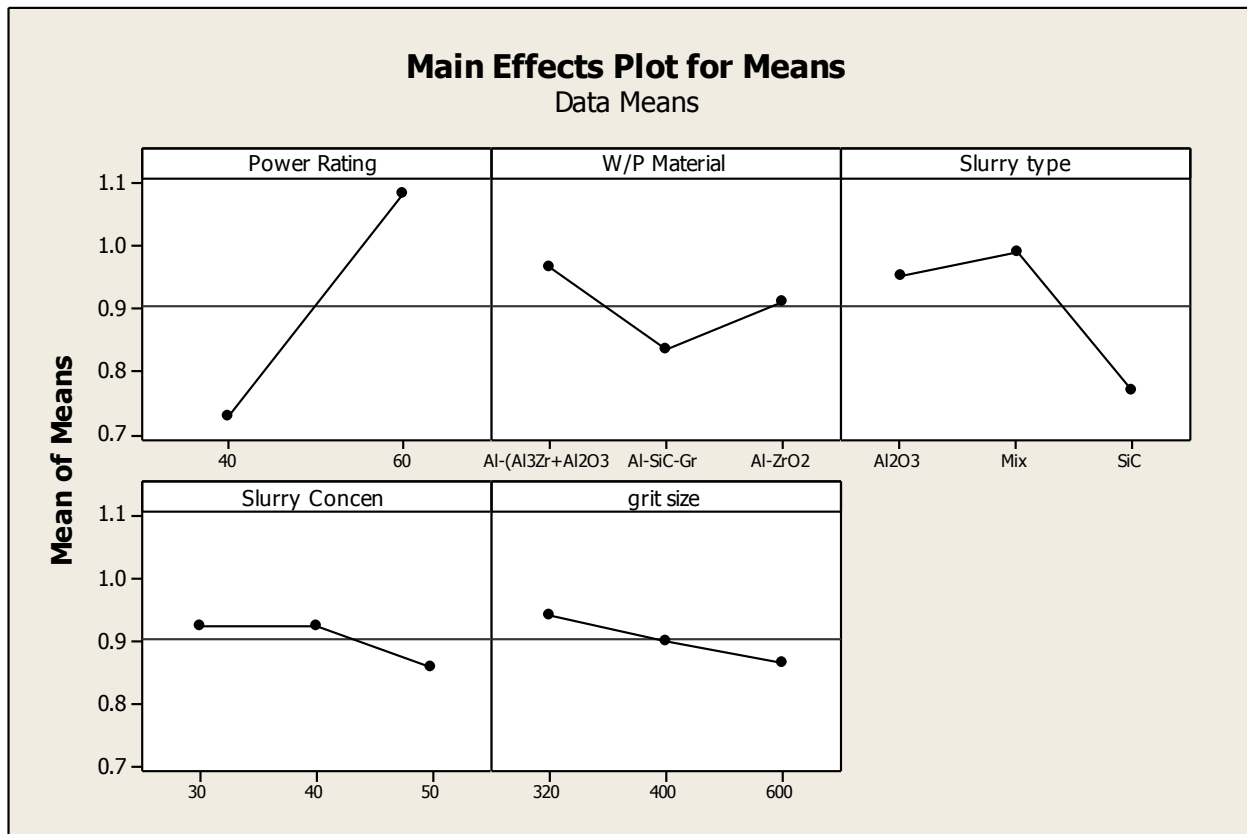


Figure 7.1 Main effect plot of Mean for Surface roughness

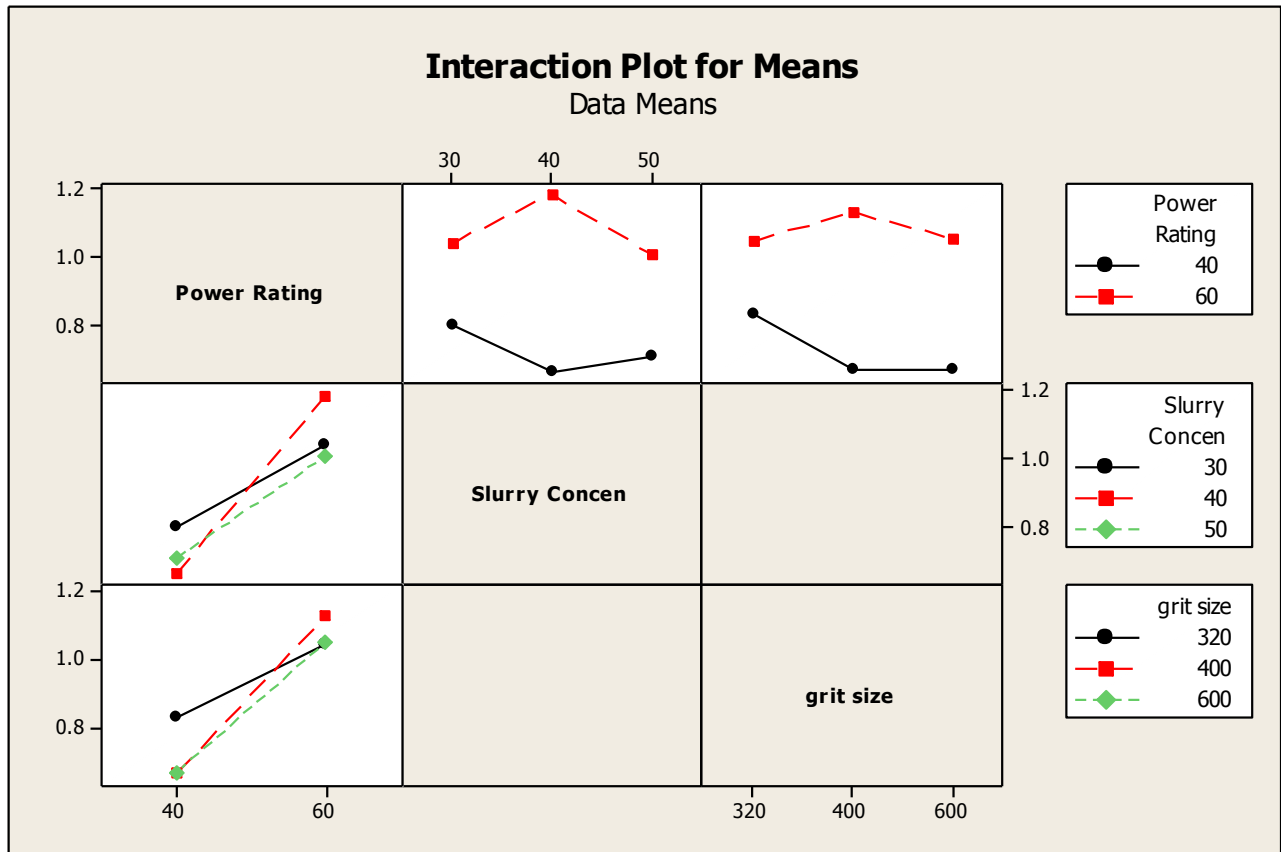


Figure 7.2 Interaction plot for Surface Roughness

7.4 RESULT FOR S/N RATIO FOR SR

The S/N Ratio consolidates several repetitions into one value and indicates the amount of variation present. The S/N ratios have been calculated to identify the major contributing factor and interactions that cause variation in the SR. Surface Roughness is “Lower the better” type response which is represented by:

$$(S/N)_{LB} = -10 \log (MSD_{LB}) \quad (\text{Equation 7.2})$$

$$\text{where } MSD_{LB} = \frac{1}{r} \sum_{i=1}^r (y_i)^2 \quad (\text{Equation 7.3})$$

MSD = Mean square deviation for lower the better

Table 7.4 shows the results of S/N ratio of Surface Roughness at 95% confidence interval. Power rating (%) was observed to be most significant factor affecting the SR, followed by slurry type used, and then the effect of work piece on Surface roughness was observed. Grit size and slurry

concentration had a very little effect on surface roughness . Interaction between Power (%) and Grit size also found to be significant to some extent.

Table 7.4 S/N Ratio for SR

Source	Seq SS	DOF	Adj MS (variance)	F test	P	F critical	SS'	C%	Status
Power (%)	55.6528	1	55.6528	1025.4	0.0	7.71	55.603	64.97	Significant
W/Piece	5.4643	2	2.73215	50.339	0.001	6.94	5.365	6.27	Significant
Ab. Slurry	18.5743	2	9.28715	171.113	0.001	6.94	18.475	21.59	Significant
Sl. Concen.	1.7132	2	0.8566	15.783	0.013	6.94	1.614	1.89	Significant
Grit Size	2.7710	2	1.3855	25.527	0.005	6.94	2.672	3.12	Significant
Power* Sl. Concen.	0.0805	2	0.04025	0.7415	0.522	6.94			Insignificant
Power*grit size	1.1053	2	0.55265	10.182	0.027	6.94	1.006	1.18	Significant
Error	0.2171	4	0.054275						
Total	85.5786	17	5.034035						
e- pooled	0.2976	6	0.0496					0.98	

Table 7.5 shows rank of various input parameters in terms to their relative significance

Table 7.5 Response table for S/N Ratio for SR

Level	Power rating	W/Piece	Slurry type	Sl. Concen.	Grit size
1	2.9101	0.5212	0.5575	0.8184	0.6161
2	- 0.6066	1.8635	0.3161	1.0746	1.2942
3		1.0705	2.5816	1.5622	1.5449
Delta	3.5167	1.3423	2.2654	0.7438	0.9288
Rank	1	3	2	5	4

Figure 7.3 shows the main effect S/N Ratio plot for SR and figure 7.4 shows interaction plot S/N Ratio for SR

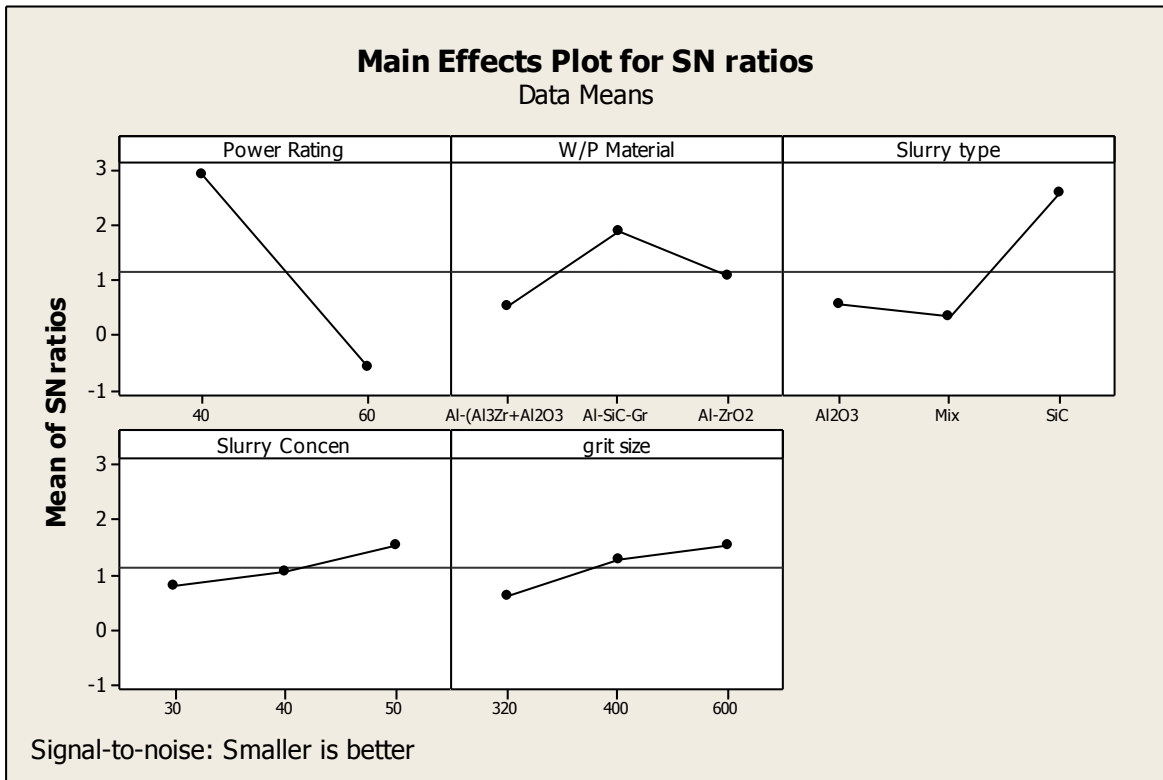


Figure 7.3 Main effect S/N Ratio for SR

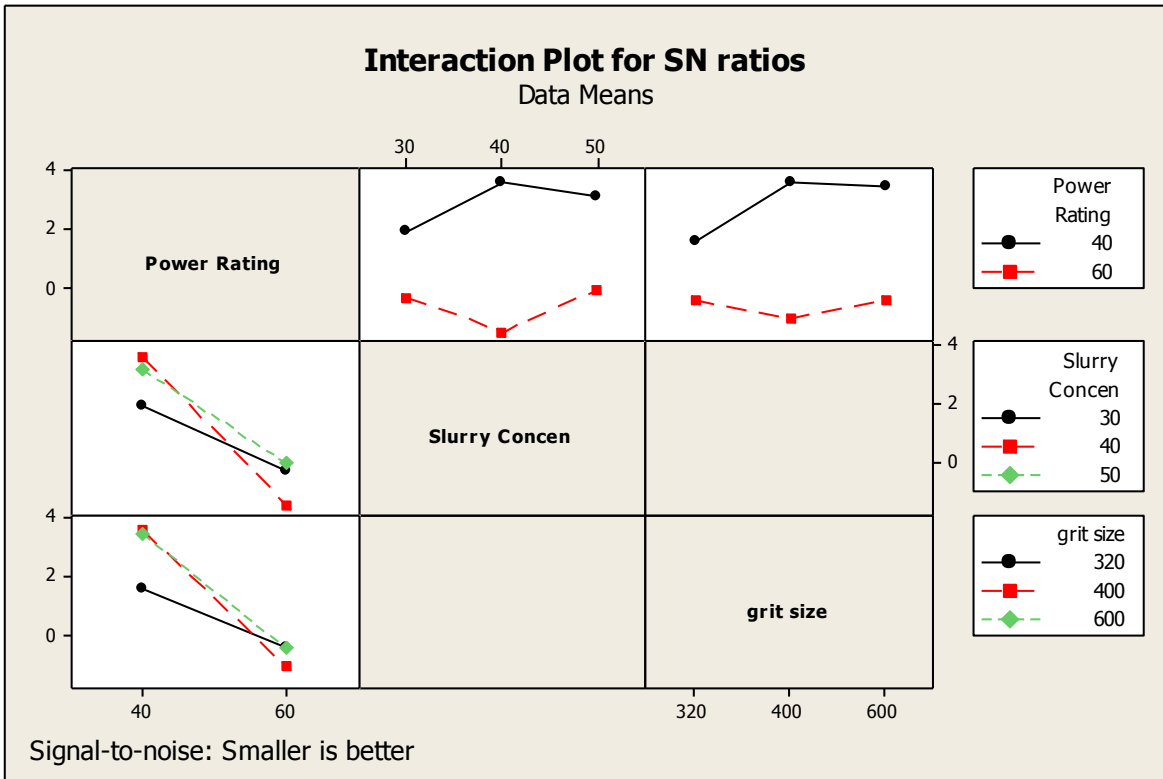


Figure 7.4 Interaction plot S/N Ratio for SR

7.5 OPTIMAL DESIGN FOR SURFACE ROUGHNESS

In this experimental analysis, the main effect and interaction plot in Figure 7.1 and 7.2 used to estimate mean SR. From the, Table 7.6 it is concluded that lowest Surface Roughness is obtained when Al-SiC-Gr is machined at power rating 40% ,using abrasive slurry Silicon Carbide with 50% and grit size 600. It is also observed that power rating, abrasive slurry and type of work piece used have significant effect on surface roughness. Interactions have no effect on Surface roughness. SR is assumed to achieve best result if machining is carried on Al-SiC- Gr composite with power rating 40%, abrasive slurry Silicon carbide, and grit size 600 with concentration 50%.

Table 6.6 Significant factors and interactions

Factors	Affecting Mean		Affecting Variance	
	Contribution	Best level	Contribution	Best level
Power (%)	Significant	Level -1(40)	Significant	Level-2
W/Piece	Significant	Level -3	Significant	
Ab. Slurry	Significant	Level -2(SiC)	Significant	Level- 3
Sl. Concen.	Significant	Level -3	Significant	Level -1
Grit Size	Significant	Level- 3	Significant	Level -1
Power* Sl. Concen.	Insignificant		Insignificant	
Power*grit size	Insignificant		Significant	$A_2 \times E_2$

Estimating the mean

In experimental analysis, SR is a smaller average response is better (SB) characteristic. Depending upon the characteristic, different treatment combinations has chosen to obtain satisfactory results. After conducting the experiments the optimum treatment conditions within the experiments determined on the basis of prescribed combination of the factor levels is determined to one of those in the experiments [45].

Mean value of SR

$$\mu_{A_1 B_3 C_2 D_3 E_3} = A_1 + B_3 + C_2 + D_3 + E_3 - 4T \text{ (Mean of all experiments)} \quad \text{(Equation 7.4)}$$

$$= 0.72556 + 0.825 + 0.76833 + 0.85167 + 0.865 - (4 \times 0.94)$$

$$= 0.28556 \mu\text{m}$$

Confidence Interval around the estimated mean

The confidence interval is a maximum and minimum value between which the true average should fall at some stated percentage of confidence. The estimate of mean μ is only a point based on the average of result obtained from the experiment. Statistically this provides a 50% chance of the true averages being greater than μ and a 50% chance of true average being less than μ . It is, therefore, customary to represent the value of statistical parameter as a range within which it is likely to fall, for a given level of confidence [45].

$$CI_1 = \sqrt{\frac{F_{\alpha, v_1, v_2} V_e}{n_{eff}}} \quad \text{(Equation 7.5)}$$

where, $F_{\alpha v_1 v_2} = F$ – ratio at confidence level of $(1 - \alpha)$ against D.O.F 1 and error degree of freedom v_2 (for SR $v_2 = 4$, so $F_{\alpha} = 7.71$)

$\alpha = \text{risk (0.05)}$

Confidence = $1 - \alpha$

$v_1 = \text{D.O.F for mean which is always } = 1$

$v_2 = \text{D.O.F for error}$

$V_e = \text{variance of e-pooled}$

$\eta_{eff} = \text{number of test under that condition using the participating factor}$

$$\eta_{eff} = N / (1 + \text{dof}_{A,B,C,D,E})$$

$$= 18 / (1 + 1 + 2 + 2 + 2 + 2) = 1.8$$

$$CI_1 = \sqrt{\frac{F_{\alpha, v_1, v_2} V_e}{n_{eff}}}$$

$$CI_1 = \sqrt{7.71 \times 0.00187 / 1.8}$$

$$= \pm 0.0895 \mu\text{m}$$

So the confidence interval around the MRR is given by $0.28556 \pm 0.0895 \mu\text{m}$

CHAPTER 8

RESULT AND ANALYSIS OF MICRO HARDNESS

8.1 INTRODUCTION

The effect of parameters i.e. work piece, slurry type, slurry concentration, power ration and abrasive grit size and interaction between power rating of machine in percentage of max. (500 watts) and abrasive slurry concentration, power rating and grit size were evaluated using ANOVA. The confidence interval of 95% has been used for analysis. The trial was followed by a repetition to reduce noise level and to find S/N Ratio.

8.2 RESULTS FOR MICROHARDNESS

The micro hardness measurement is dependent on the diameter of indentation on the sample. The indents formed in the pyramid shaped indenter were measured with Quantimet software using a load of 1 kg for 20 seconds.

The results for micro hardness for each 18 treatment condition with repetition are given in table 8.1.

Table 8.1 Result for Micro Hardness

Exp No.	power rating	work piece	slurry type	Slurry concen.	grit size	MICRO HARDNESS	S/N ratio	Mean
1	(40)	Al(Al_2O_3 + Al_3Zr)	(Al_2O_3)	(30)	(320)	475	53.5339	475
2	(40)	Al(Al_2O_3 + Al_3Zr)	(SiC)	(40)	(400)	479	53.6067	479
3	(40)	Al(Al_2O_3 + Al_3Zr)	(Al_2O_3 +SiC)	(50)	(600)	478	53.5886	478
4	(40)	Al-ZrO ₂	(Al_2O_3)	(30)	(400)	478	53.5886	478
5	(40)	Al-ZrO ₂	(SiC)	(40)	(600)	478	53.5886	478

6	(40)	Al-ZrO ₂	(Al ₂ O ₃ +SiC)	(50)	(320)	478	53.5886	478
7	(40)	Al-SiC	(Al ₂ O ₃)	(40)	(320)	476	53.5521	476
8	(40)	Al-SiC	(SiC)	(50)	(400)	480	53.6248	480
9	(40)	Al-SiC	(Al ₂ O ₃ +SiC)	(30)	(600)	478	53.5886	478
10	(60)	Al(Al ₂ O ₃ + Al ₃ Zr)	(Al ₂ O ₃)	(50)	(600)	484	53.6969	484
11	(60)	Al(Al ₂ O ₃ + Al ₃ Zr)	(SiC)	(30)	(320)	485	53.7148	485
12	(60)	Al(Al ₂ O ₃ + Al ₃ Zr)	(Al ₂ O ₃ +SiC)	(40)	(400)	485	53.7148	485
13	(60)	Al-ZrO ₂	(Al ₂ O ₃)	(40)	(600)	484	53.6969	484
14	(60)	Al-ZrO ₂	(SiC)	(50)	(320)	486	53.7327	486
15	(60)	Al-ZrO ₂	(Al ₂ O ₃ +SiC)	(30)	(400)	485	53.7148	485
16	(60)	Al-SiC	(Al ₂ O ₃)	(50)	(400)	485	53.7148	485
17	(60)	Al-SiC	(SiC)	(30)	(600)	486	53.7327	486
18	(60)	Al-SiC	(Al ₂ O ₃ +SiC)	(40)	(320)	486	53.7327	486

8.2 ANALYSIS OF VARIANCE – MICRO HARDNESS

The results for Micro Hardness were analyzed using ANOVA for identifying the significant factors affecting the performance measure. Analysis of Variance (ANOVA) for mean Micro Hardness at 95% confidence interval is given in table 8.2. The variance data for each factor and their interaction were calculated. The Contribution percent for significant factors were calculated using the expression explain in previous chapter. It was observed that P value for significant factors was less than 0.05.

Table 8.2 Analysis of Variance for Micro Hardness of Mean

Source	Seq SS	DOF	Adj MS (variance)	F test	P	F critical	SS'	C%	Status
Power (%)	242	1	242	2180.1	0.000	7.71	241.67	91.389	Significant
W/Piece	2.111	2	1.0555	9.5090	0.030	6.94	1.4585	0.5515	Significant
Ab. Slurry	12.444	2	6.222	56.054	0.017	6.94	11.791	4.4589	Significant
Sl. Concen.	1.444	2	0.722	6.5045	0.055	6.94	0.7915	0.2993	Insignificant
Grit Size	3.111	2	1.5555	14.013	0.016	6.94	2.4585	0.9296	Significant
Power* Sl. Concen.	0.722	2	0.361	3.2522	1.000	6.94	0.0695	0.0262	Insignificant
Power*grit size	2.167	2	1.0835	9.7612	0.029	6.94	1.5145	0.5727	Significant
Error	0.444	4	0.111						
Total	264.444	17	15.55553						
e- pooled	2.61	8	0.32625					2.0977	

Table 8.3 shows the rank of various input parameters in terms of their relative significance.

Table 8.3 Response table for Mean Micro Hardness

Level	Power rating	W/Piece	Slurry type	Sl. Concen.	Grit size
1	477.8	481.0	480.3	481.2	481.0
2	485.1	481.8	481.7	481.3	482.0
3		481.5	482.3	481.8	481.3
Delta	7,3	0.8	2.0	0.7	1.0
Rank	1	4	2	5	3

Figure 8.1 shows the main effect plot for mean for Micro Hardness and figure 8.2 shows interaction plot for mean for Micro Hardness.

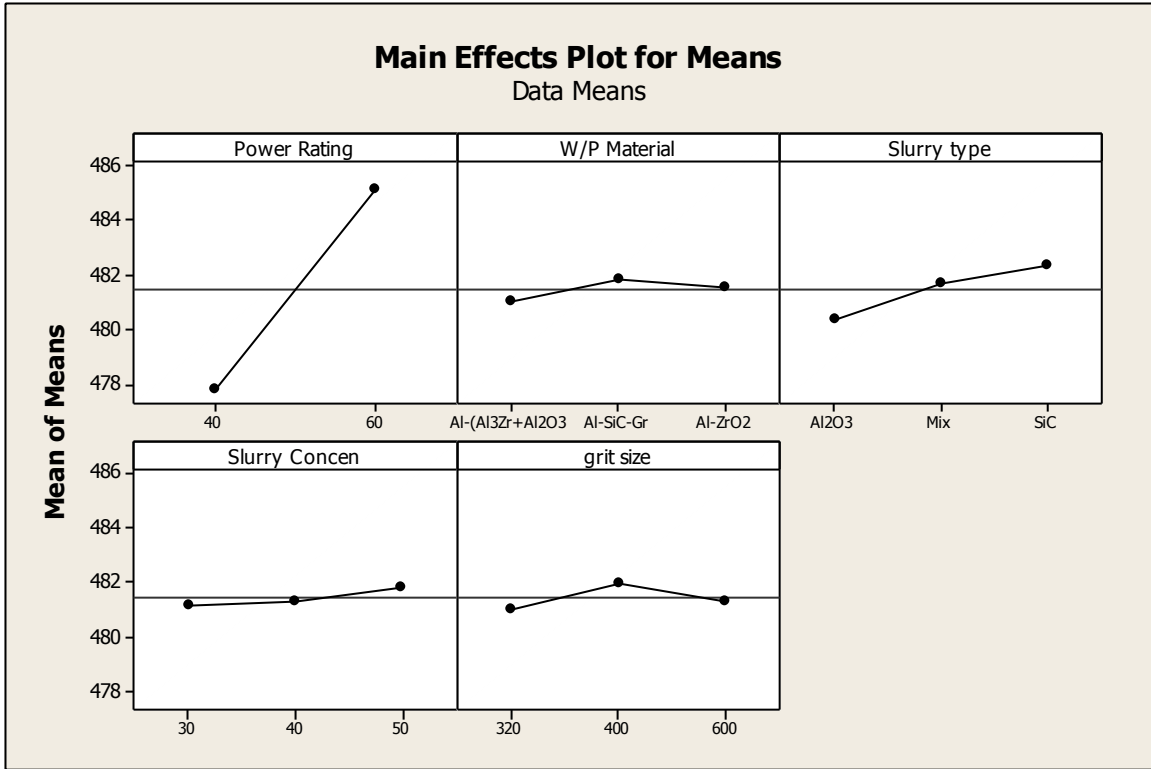


Figure 8.1 Main effect plot of Mean for Micro Hardness

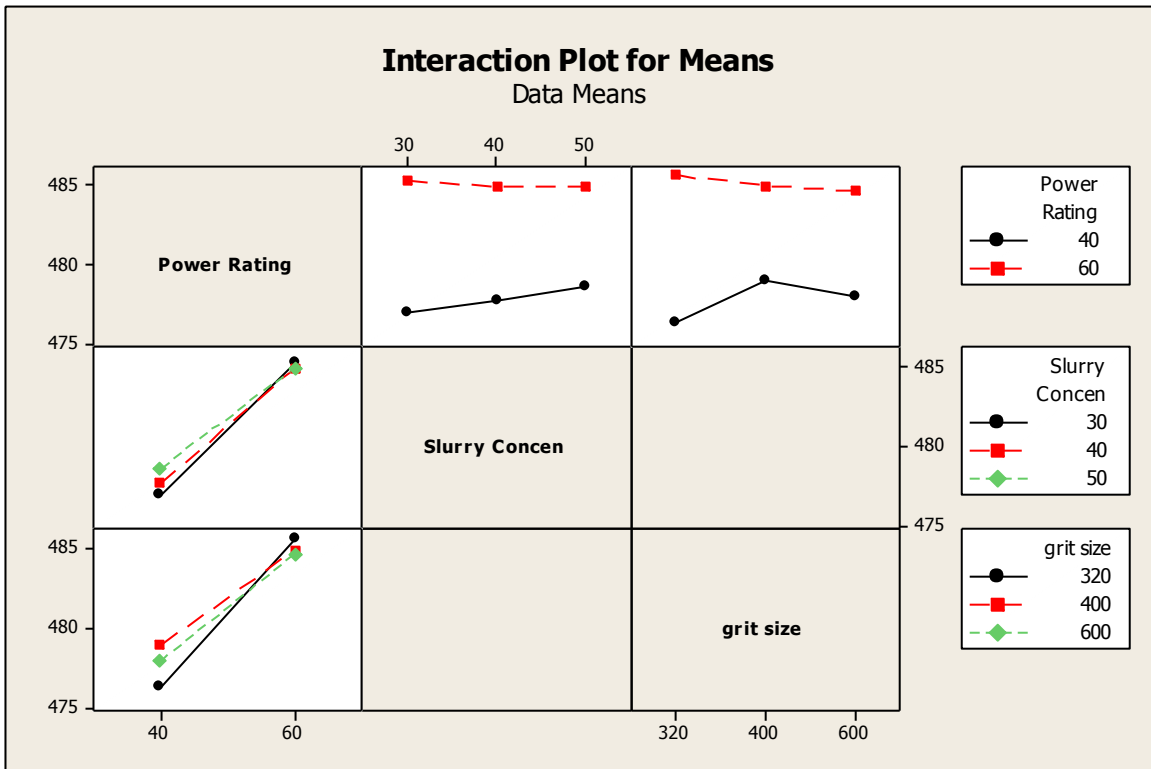


Figure 8.2 Interaction plot for Micro Hardness

8.4 RESULT FOR S/N RATIO FOR MICROHARDNESS

The S/N Ratio consolidates several repetitions into one value and indicates the amount of variation present. The S/N ratios have been calculated to identify the major contributing factor and interaction that cause variation in the Micro Hardness. Micro hardness is “Higher the better” type response which is represented by:

$$(S/N)_{HB} = -10 \log_{10} (MSD_{HB}) \quad (\text{Equation 8.2})$$

where ,MSD is Mean Square Deviation for Higher the better response

$$MSD_{HB} = \frac{1}{r} \sum_{i=1}^r \left(\frac{1}{y_i^2} \right) \quad (\text{Equation 8.3})$$

Table 8.4 shows the results of S/N ratio of MRR at 95% confidence interval

Table 8.4 S/N ratio for Micro Hardness

Source	Seq SS	DOF	Adj MS (variance)	F test	P	F critical	SS'	C%	Status
Power (%)	0.078804	1	0.078804	2173.9	0.000	7.71	0.0787	91.312	Significant
W/Piece	0.000686	2	0.000343	9.4620	0.030	6.94	0.0005	0.5462	Significant
Ab. Slurry	0.004076	2	0.002038	56.220	0.017	6.94	0.0038	4.4796	Significant
Sl. Concen.	0.00048	2	0.00024	6.6206	0.054	6.94			Insignificant
Grit Size	0.001038	2	0.000519	14.317	0.015	6.94	0.0008	0.9546	Significant
Power* Sl. Concen.	0.000236	2	0.000118	3.2551	1.000	6.94			Insignificant
Power*grit size	0.000718	2	0.000359	9.9034	0.028	6.94	0.0005	0.5833	Significant
Error	0.000145	4	0.0000362						
Total	0.086184	17	0.0050696						
e- pooled	0.000861	8	0.0001076						

Table 8.3 shows the rank of various input parameters in terms of their relative significance.

Table 8.5 Response table for S/N for Micro Hardness

Level	Power rating	W/Piece	Slurry type	Sl. Concen.	Grit size
1	53.58	53.64	53.63	53.65	53.64
2	53.72	53.66	53.65	53.65	53.66
3		53.65	53.67	53.66	53.65
Delta	0.13	0.02	0.04	0.01	0.02
Rank	1	4	2	5	3

Figure 8.3 shows the main effect plot for S/N Ratio for Micro Hardness and figure 8.4 shows interaction plot for S/N Ratio for Micro Hardness.

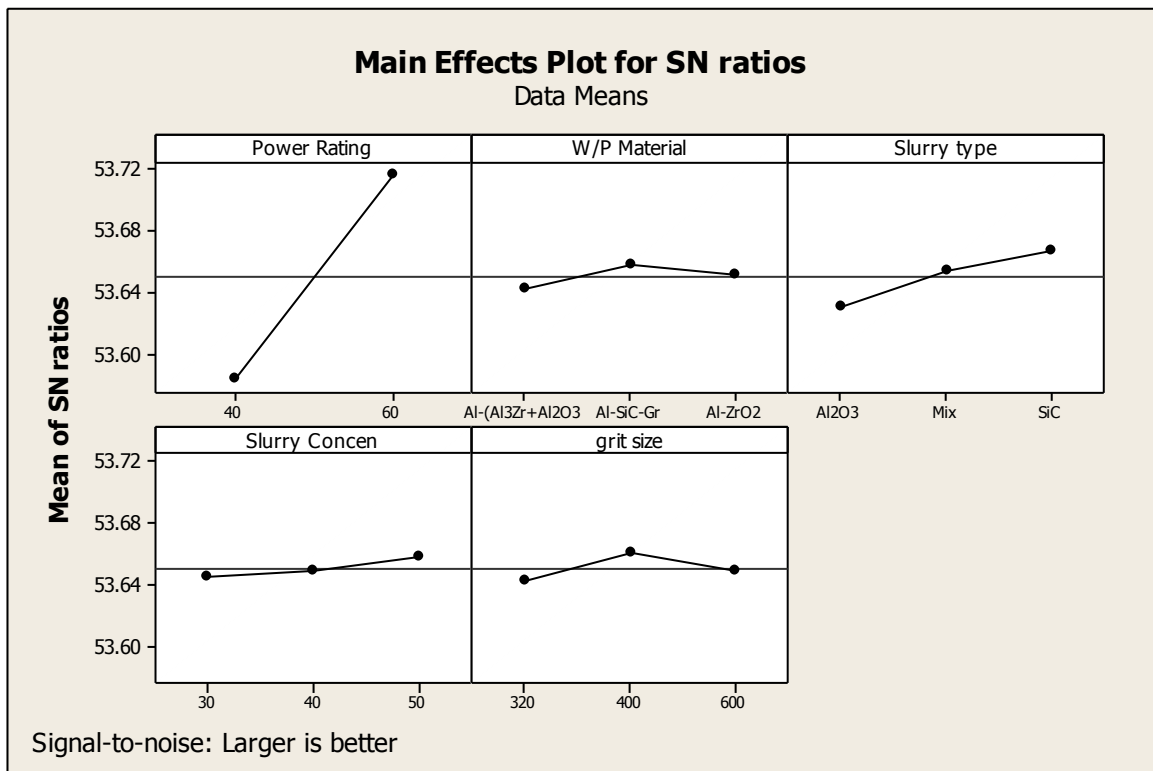


Figure 8.3 Main effect S/N Ratio for Micro Hardness

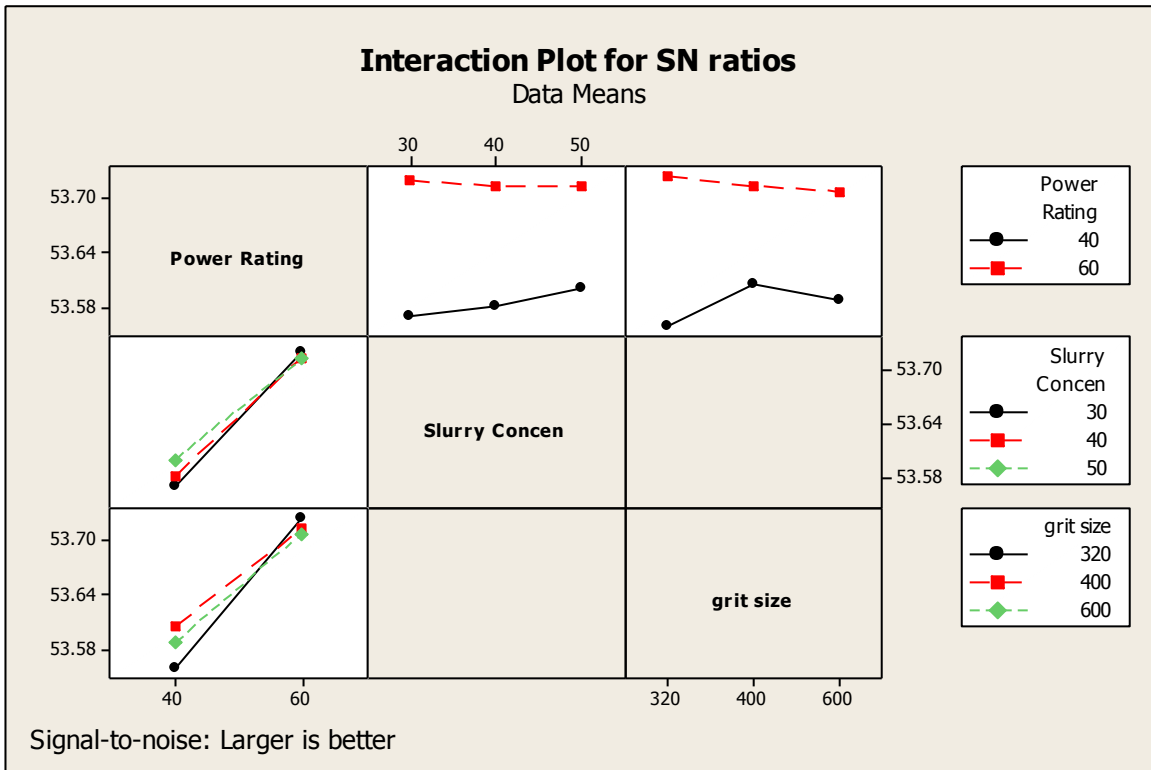


Figure 8.4 Interaction of S/N Ratio for Micro Hardness

8.5 OPTIMAL DESIGN FOR MICRO HARDNESS

In this experimental analysis, the main effect and interaction plot in Figure 8.1 and 8.2 used to estimate mean Micro Hardness. From the, Table 8.6 it is concluded that highest Micro Hardness is observed when machining is done on Al-SiC as work piece material with power rate 60%, abrasive slurry using Silicon Carbide, and grit size 400. It is observed that slurry concentration and interaction between power rating and Slurry concentration have not significant effect on Micro Hardness. It is also observed that type of work piece used has not much significant effect on Micro Hardness. Micro Hardness is assumed to be achieved optimum result if machining carried on Al-SiC composite with power rating 60%, abrasive slurry mixture of Silicon Carbide and grit size 400.

Table 8.6 Significant factor and interactions

Factors	Affecting Mean		Affecting Variance	
	Contribution	Best level	Contribution	Best level
Power (%)	Significant	Level-2 (60)	Significant	Level-2 (60)
W/Piece	Significant	Level 3(Al-SiC)	Insignificant	Level 3(Al-SiC)
Ab. Slurry	Significant	Level-2 (SiC)	Significant	Level-2 (SiC)
Sl. Concen.	Insignificant		Insignificant	
Grit Size	Significant	Level-2 (400)	Significant	Level-2 (400)
Power* Sl. Concen.	Insignificant		Insignificant	
Power*grit size	Significant	$A_2 \times E_1$	Significant	$A_2 \times E_1$

Estimating the mean

In the experiment analysis, the Micro Hardness is a higher average response is better (HB) characteristic. Depending on the characteristics, the different treatment combinations has been chosen to obtain satisfactory results. After conducting the experiments the optimum treatment conditions within the experiments determined on the basis of prescribed combination of the factor levels is determined to one of those in the experiments [45].

Mean value of MRR

$$\begin{aligned} \mu_{A_2C_2E_2(A_2E_1)} &= A_2 + B_3 + C_2 + E_2 + A_2E_1 - 4T \text{ (Mean of all experiments)} && \text{(Equation 8.4)} \\ &= 485.1111 + 481.8333 + 482.3333 + 482 + 485.6667 - (4 \times 481.444) \\ &= 491.1667 \text{ HVN} \end{aligned}$$

Confidence Interval around the estimated mean

The confidence interval is a maximum and minimum value between which the true average should fall at some stated percentage of confidence. The estimate of mean μ is only a point based on the average of result obtained from the experiment. Statistically this provides a 50% chance of the true averages being greater than μ and a 50% chance of true average being less than μ . It is, therefore, customary to represent the value of statistical parameter as a range within which it is likely to fall, for a given level of confidence [45].

9.1 RESULTS

The effect of parameters i.e. Power rating, work piece material used, type of Abrasive slurry, slurry concentration and grit size and interaction between power rating and slurry concentration, also interaction between power rating and grit size evaluated using Taguchi's design of experiment approach and Analysis of Variance (ANOVA) technique. The purpose of ANOVA technique was to identify the important parameters in prediction of MRR, TWR and Surface Roughness. The design of experiments approach was used to identify the number of trials to be performed. Some results consolidated from ANOVA and plots are given below:

9.1.1 MATERIAL REMOVAL RATE

The effect of parameters i.e. power rate, work piece, abrasive slurry, slurry concentration, and grit size and some interaction were evaluated using ANOVA. The confidence interval of 95% has been used for the analysis. L_{18} orthogonal array have been used. Each trial was followed by one repetition to reduce noise level and to measure the Signal to Noise Ratio (S/N Ratio).

Abrasive slurry was found most significant (44.89%) with F value highest i.e. 27.59 followed by grit size (F value 12.77), then power rating (F value 17.39) were the factors that significantly affected the MRR which had contribution to MRR as 19.36% and 13.68% respectively. The interactions between Power rating and slurry concentration (F value 3.423) and interaction between power concentration and grit size (F value 0.119) were found to be insignificant. In table 5.3, shows the rank for various factors. 1st rank is given to Slurry type with highest contribution, 2nd to grit size, 3rd to power rating, 4th to type of work piece used, and 5th rank is assigned to Slurry concentration.

For S/N Ratio Power rating, slurry type and grit size were found to be significant in MRR for reducing the variation.

The best result for MRR was observed when machining is done on power rate 60%, abrasive slurry using 50% SiC+ 50% Al₂O₃, and grit size 320. It was observed that both the interaction had insignificant effect on MRR. The MRR assumed to be highest when Al-ZrO₂ work piece material is machined using power rate 60%, abrasive slurry using 50% SiC+ 50% Al₂O₃, and grit size 320. With 95% confidence interval mean value of MRR was found to be $11.528 \pm 0.345 \text{ mm}^3/\text{min}$

9.1.2 TOOL WEAR RATE

The effect of parameters i.e. power rate, work piece, abrasive slurry, slurry concentration, and grit size and some interaction were evaluated using ANOVA. The confidence interval of 95% has been used for the analysis. Each trial was followed by one repetition to reduce noise level and to measure the Signal to Noise Ratio (S/N Ratio).

Power rating (F value 1391.59) was found to be most significant factor and has contribution of 81.79% on Tool Wear Rate, followed by slurry concentration(F value 66.62), type of work piece (F value 34.99), Abrasive slurry (F value 7.39) and grit size found to be least significant (F value 8.34) with contribution 7.21%, 3.38%, 1.59%, 0.319% respectively. The interactions were found to be insignificant on TWR. Table 6.3 shows rank of various factors according to their contribution. 1st rank to power rating, 2nd to slurry concentration, 3rd to work piece material, 4th rank to slurry type, 5th to grit size in contribution to minimum TWR.

For S/N Ratio Power rating, slurry concentration, type of work piece material, slurry type and grit size were found to be significant in TWR for reducing the variation. The interaction between power rating and slurry concentration (F value 7.06) was found to be significant with contribution 1.866%.

The best result for TWR would be suggested if machining is done on power rate 40%, on work piece Al-SiC-Gr, using slurry mixture of Al₂O₃ and SiC, with slurry concentration 50% and grit size 600. It was observed that both the interaction had insignificant effect on TWR. The TWR assumed to be highest when Al-ZrO₂ work piece material is machined using power rate 60%, abrasive slurry using 50% SiC+ 50% Al₂O₃, and grit size 320. With 95% confidence interval mean value of MRR was found to be $0.1563 \pm 0.00245 \text{ mm}^3/\text{min}$

9.1.3 SURFACE ROUGHNESS

The effect of parameters i.e. power rate, work piece, abrasive slurry, slurry concentration, and grit size and some interaction were evaluated using ANOVA. The confidence interval of 95% has been used for the analysis. Each trial was followed by one repetition to reduce noise level and to measure the Signal to Noise Ratio (S/N Ratio).

Power rating (F value 571.1) was found to be most significant factor and has contribution of 67.53% on Surface Roughness, followed by Abrasive Slurry (F value 84.59), type of work piece (F value 26.51), grit size (F value 8.91) and Slurry concentration found to be least significant (F value 8.32) with contribution 19.62%, 5.84%, 1.66%, 1.53% respectively. The interactions were found to be insignificant on SR. Table 7.3 shows rank of various factors according to their contribution. 1st rank to power rating, 2nd to Abrasive slurry, 3rd to work piece material, 4th rank to grit size, 5th to slurry concentration in contribution to minimum SR.

For S/N Ratio Power rating, slurry concentration, type of work piece material, slurry type and grit size were found to be significant in SR for reducing the variation. The interaction between power rating and grit size (F value 10.182) was found to be significant with contribution 1.18%.

The optimal result for SR would be suggested if machining is done on power rate 40%, on work piece Al-SiC-Gr, using slurry Silicon Carbide, with slurry concentration 50% and grit size 600. It was observed that both the interaction had insignificant effect on SR. The SR assumed to be highest when Al-ZrO₂ work piece material is machined using power rate 40%, abrasive slurry using Silicon Carbide, and grit size 600 and slurry concentration 50%. With 95% confidence interval mean value of MRR was found to be $0.28556 \pm 0.0895 \mu\text{m}$

9.1.3 MICRO HARDNESS

The effect of parameters i.e. power rate, work piece, abrasive slurry, slurry concentration, and grit size and some interaction were evaluated using ANOVA. The confidence interval of 95% has been used for the analysis. Each trial was followed by one repetition to reduce noise level and to measure the Signal to Noise Ratio (S/N Ratio).

Power rating (F value 3128.7) was found to be most significant factor and has contribution of 91.19% on Micro Hardness, followed by Abrasive Slurry (F value 16.13), grit size (F value 8.91) with contribution 4.807%, 1.413% respectively. The interaction between power rating (%) and grit size was also found to be significant with F value 22.91 and contribution 1.171%. Table 8.3 shows rank of various factors according to their contribution. 1st rank to power rating, 2nd to Abrasive slurry, 3rd to grit size, 4th rank to work piece material, 5th to slurry concentration in contribution to maximum Micro Hardness.

For S/N Ratio Power rating, slurry concentration, type of work piece material, slurry type and grit size were found to be significant in Micro Hardness for reducing the variation. The power rating, Abrasive type, grit size and interaction between the power rating and grit size were found to be significant.

The optimal result for Micro Hardness would be suggested if machining is done on power rate 60%, on work piece Al-ZrO₂, using slurry Silicon Carbide, with slurry concentration 50% and grit size 400. It was observed that interaction between power rating and grit size had significant effect on Micro Hardness. The Micro Hardness assumed to be highest when Al-ZrO₂ work piece material is machined using power rate 60%, abrasive slurry using Silicon Carbide, and grit size 400 and slurry concentration 50%. With 95% confidence interval mean value of MRR was found to be 152.1199 ± 0.898 HVN

9.2 MICROSTRUCTURE ANALYSIS

The microstructure of the machined surface was obtained for randomly selected 6 trial machined sample by using scanning electron microscope at a magnification level 1000x. The microstructure of each machined sample at other magnifications was also obtained in order to perform a detailed study of the machined surface. The samples were prepared for SEM analysis:

Firstly, Samples were cut to round shape with 9 mm diameter and 4 mm thickness with flat base. After that machine surface was cleaned with wire brush, clean them with acetone and ultrasonic gel in order to remove dust particle.

Figure 9.1 shows the un-machined surfaces of Al-ZrO₂, Al / (Al₂O₃ + Al₃Zr), Al-SiC respectively at 400x.

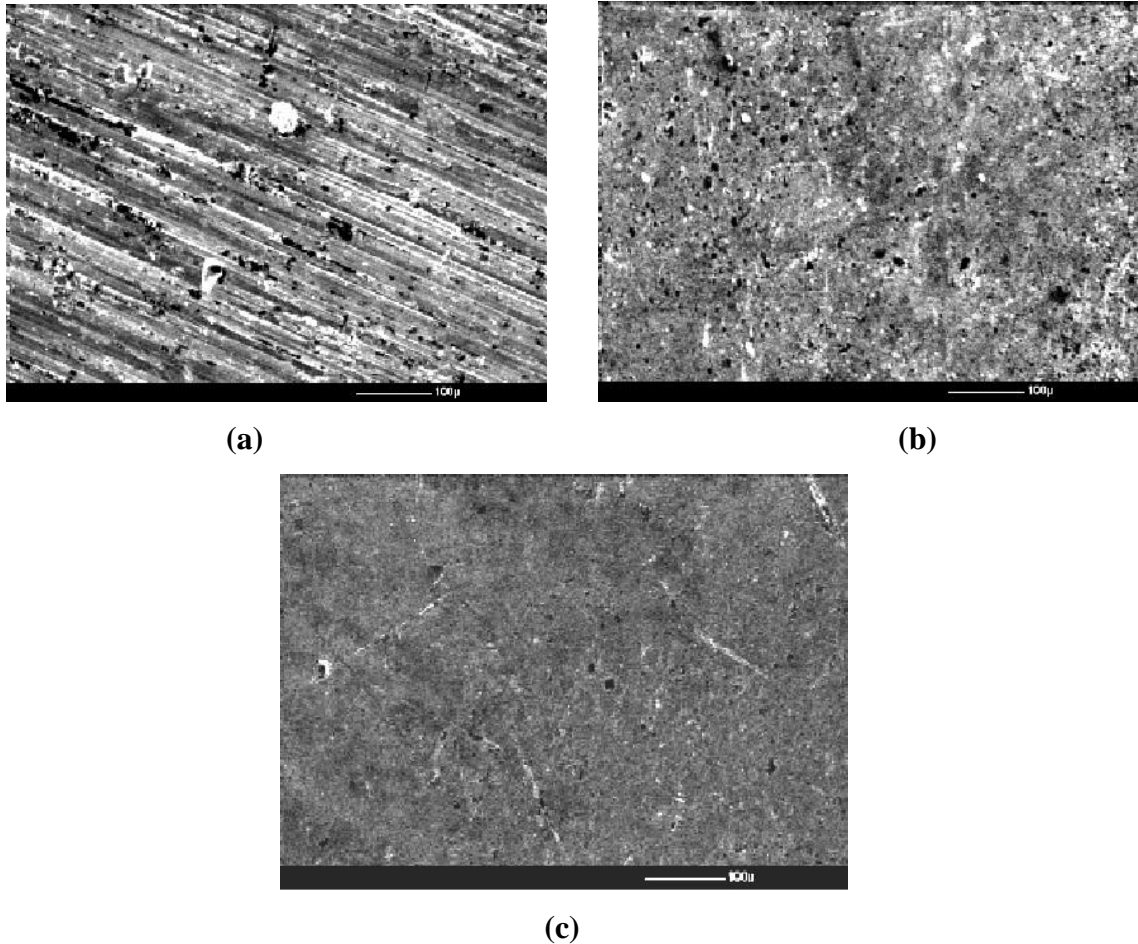


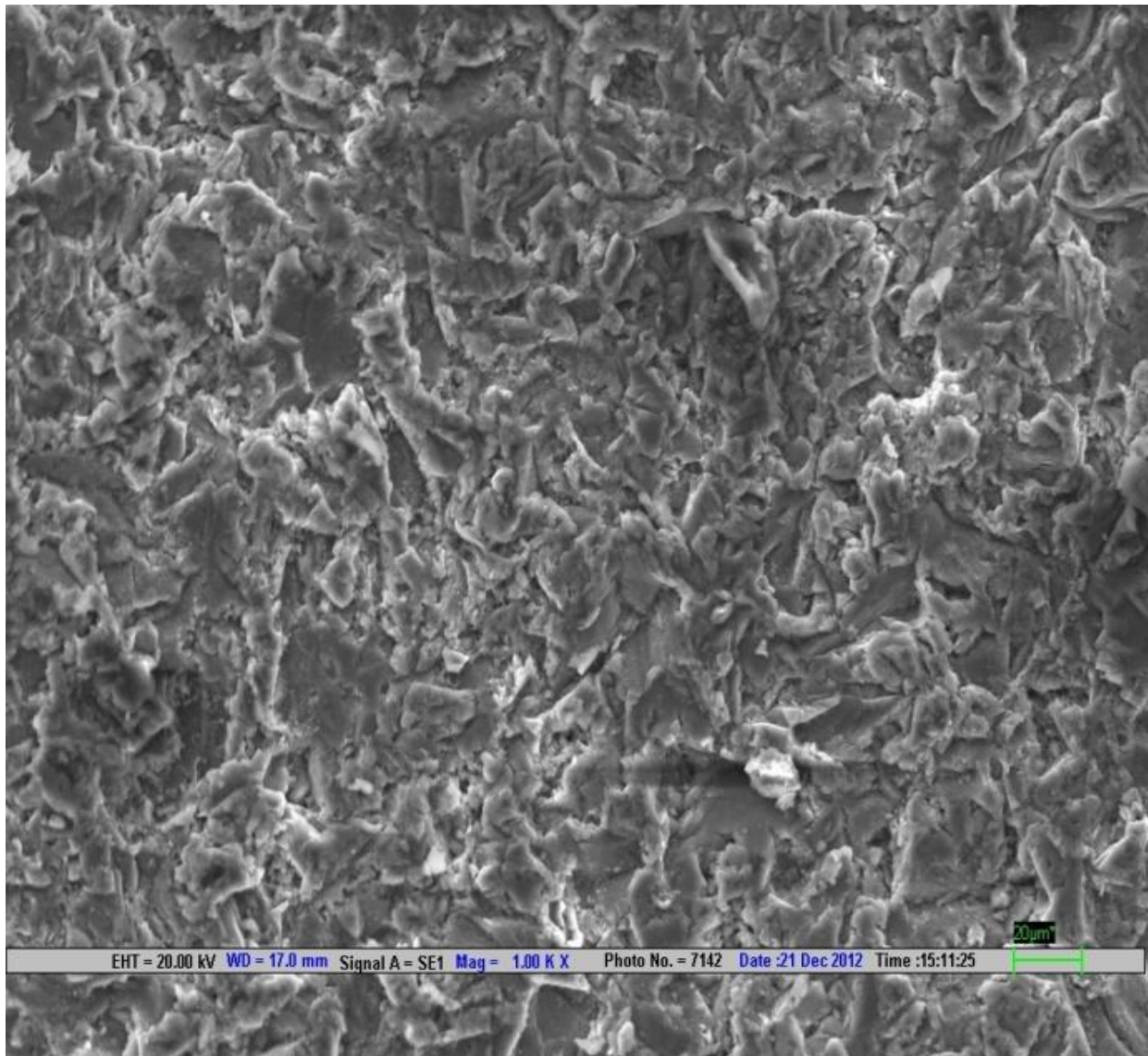
Figure 9.1 Un-machined surfaces of (a) Al/ (Al₂O₃+Al₃Zr), (b) Al-ZrO₂, (c) Al-SiC

Material removal in USM process is believed to occur by brittle fracture mode. In mechanical shaping processes for brittle materials such as USM, material has been found to be removed by the propagation and intersection of cracks [10, 51]. While the cutting of brittle materials is performed, in general, by brittle fracture, the chip can be removed plastically at an extremely small depth of cut [2, 51]. In other words, the mechanism of material removal may change from brittle to plastic deformation at extremely

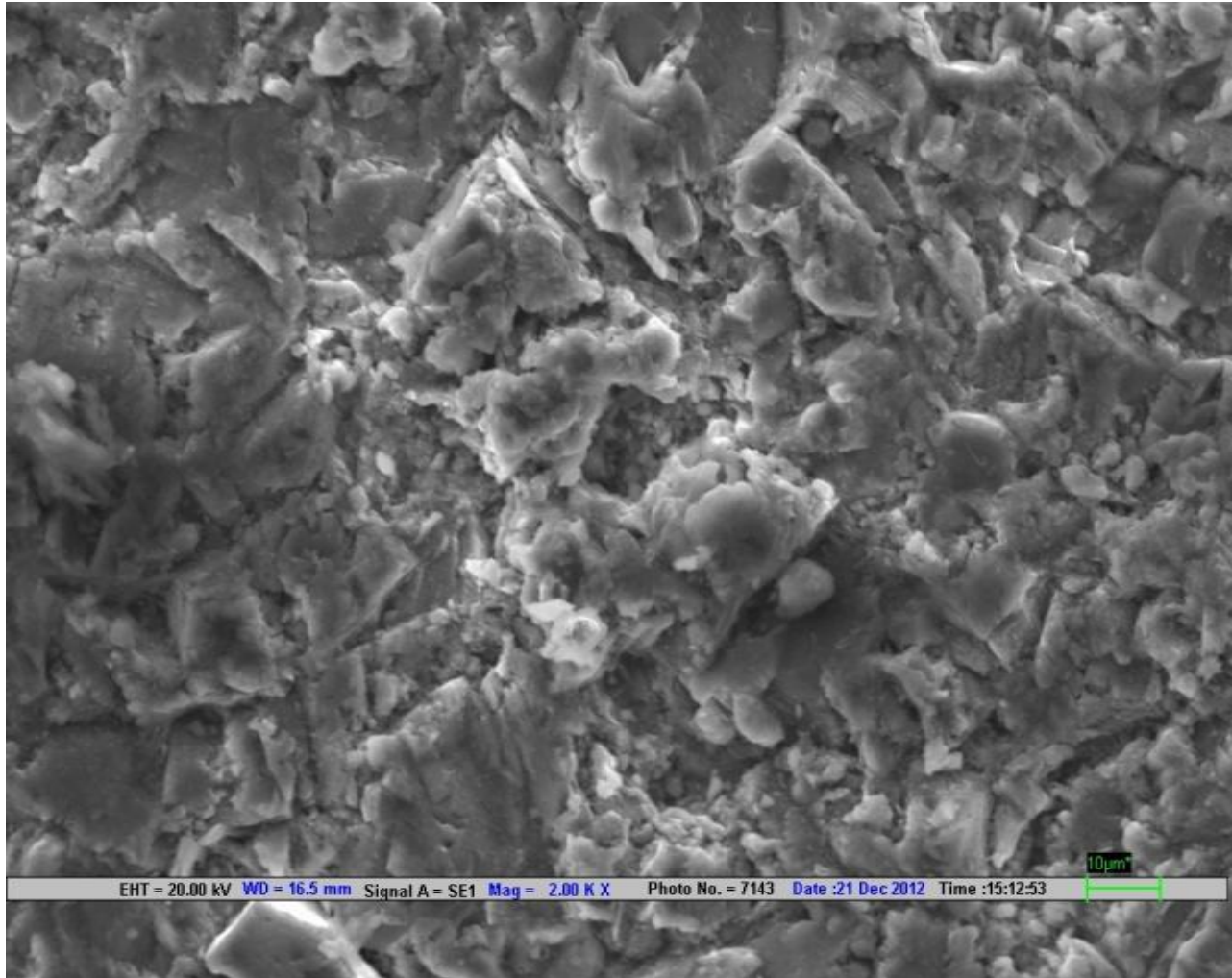
Pei et al. [36, 38] has established “under all machining conditions, the material removal modes involve the combination of brittle fracture and plastic flow”. It has also been suggested that any increase in the variables affecting input energy to the abrasive/tool such as amplitude, grain size of the abrasive, vibration frequency promotes the brittle fracture of the work surface. By manipulating the values of the key parameters affecting energy input to the process, different ratios of the two modes of material removal can be obtained [38, 52]. The mode of material

removal in USM is also decided by the work material properties such as fracture toughness and hardness.

Figure 9.2 depicts the microstructure of work piece Al-(Al₂O₃+Al₃Zr) after machining with USM under the experimental conditions corresponding to experiment no. 1.



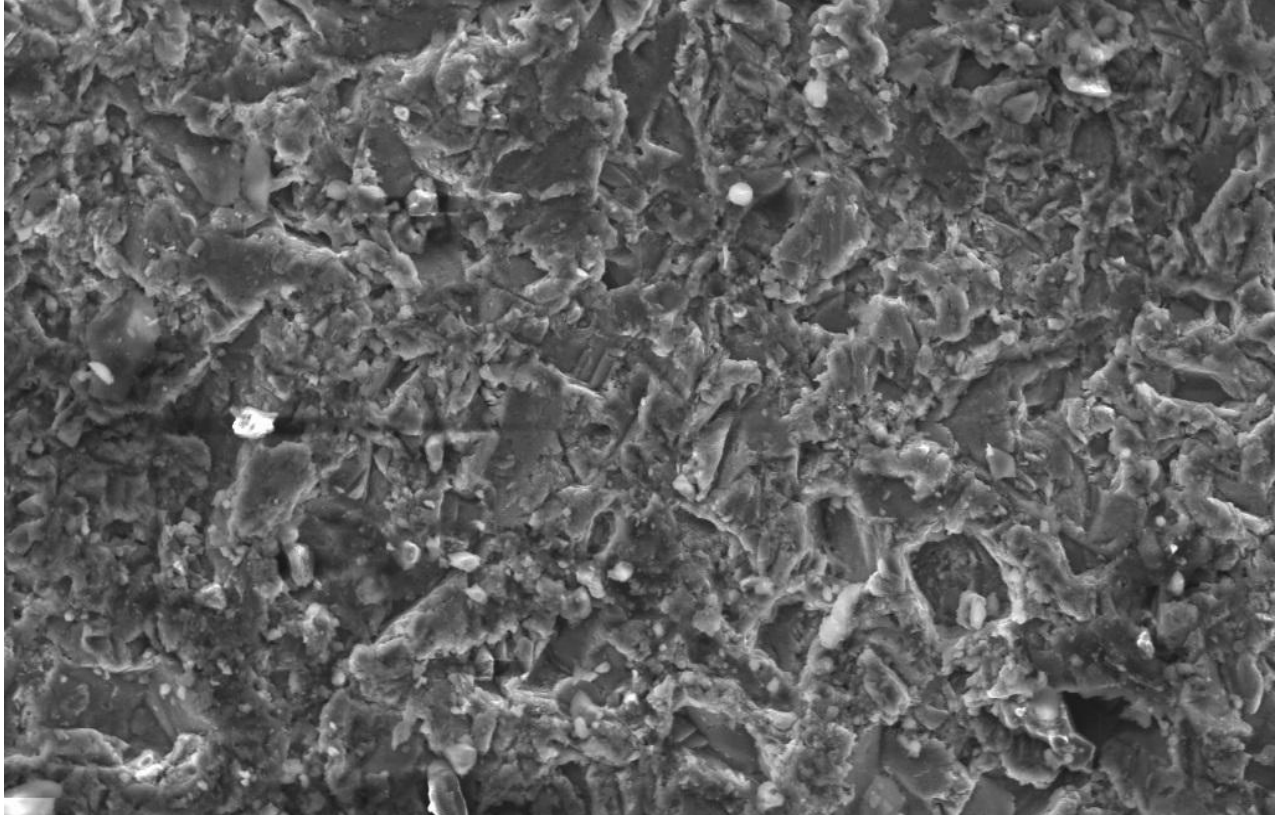
(a)



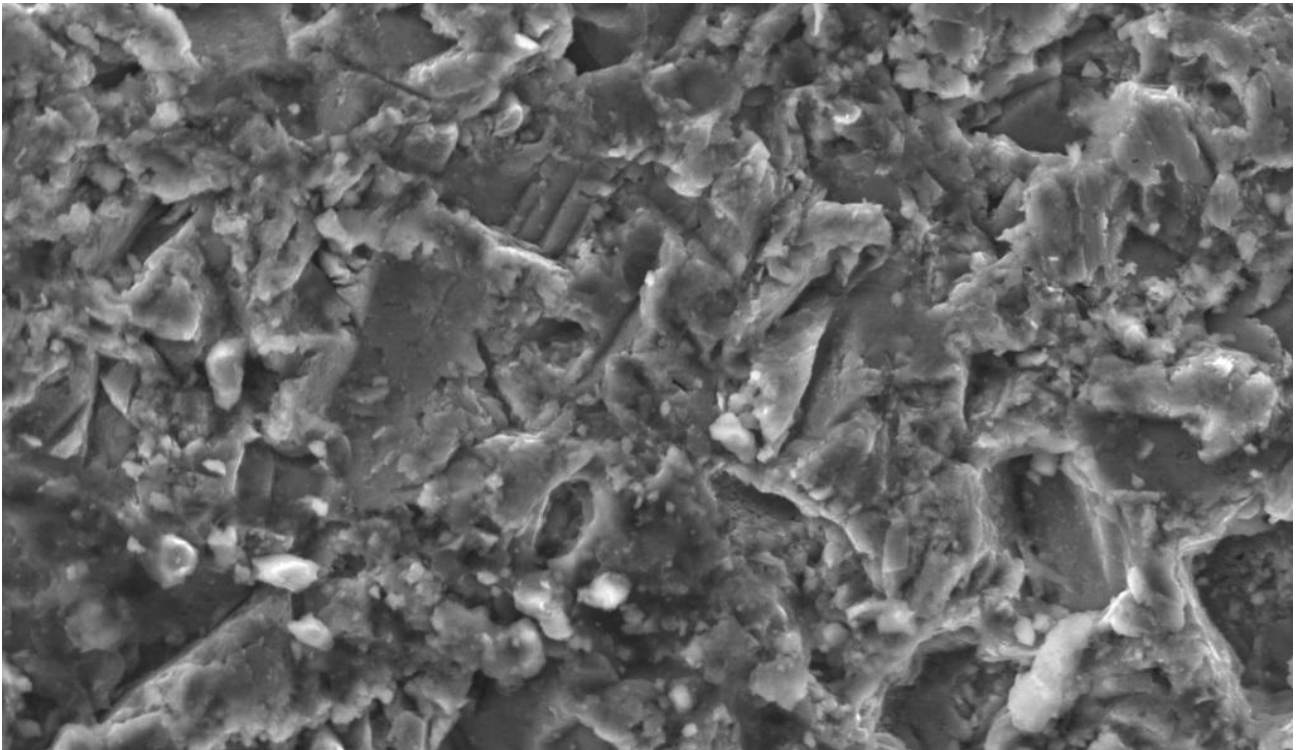
(b)

Figure 9.2 SEM Photograph for Experiment No. 1 (a) at 1000x, (b) at 2000x

It could be observed that the material faced significant amount of plastic deformation before failure and there is no evidence of brittle fracture. Hence, the material was machined by ductile 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 (Al_2O_3) with low power rating (40%) with concentration 30% and grit size 320. The work piece material used Al-($\text{Al}_2\text{O}_3+\text{Al}_3\text{Zr}$). Also, the high fracture toughness associated with the work material has contributed towards the increment in the hardness of the work surface due to work hardening.



(a) 1000x



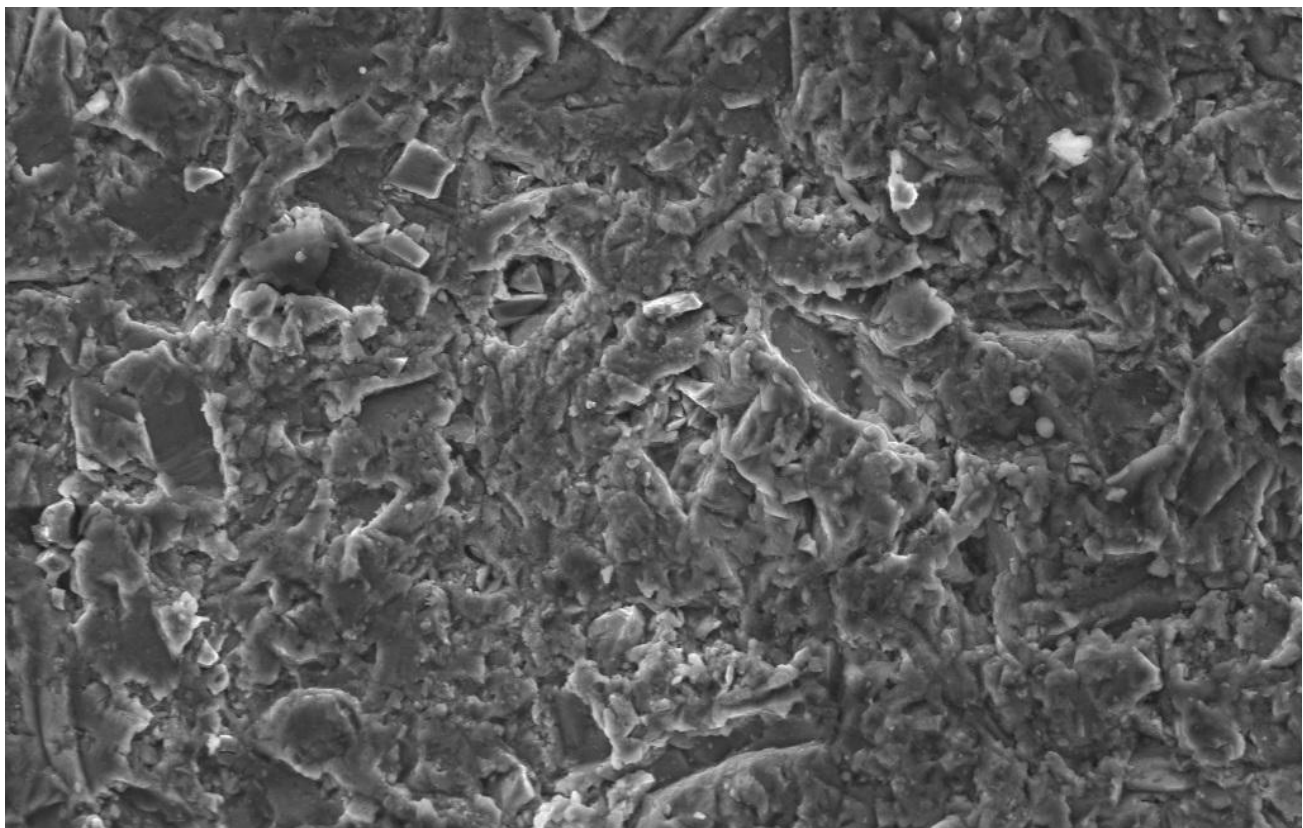
(b) 2000x

Figure 9.3 SEM Photograph for Experiment No. 3

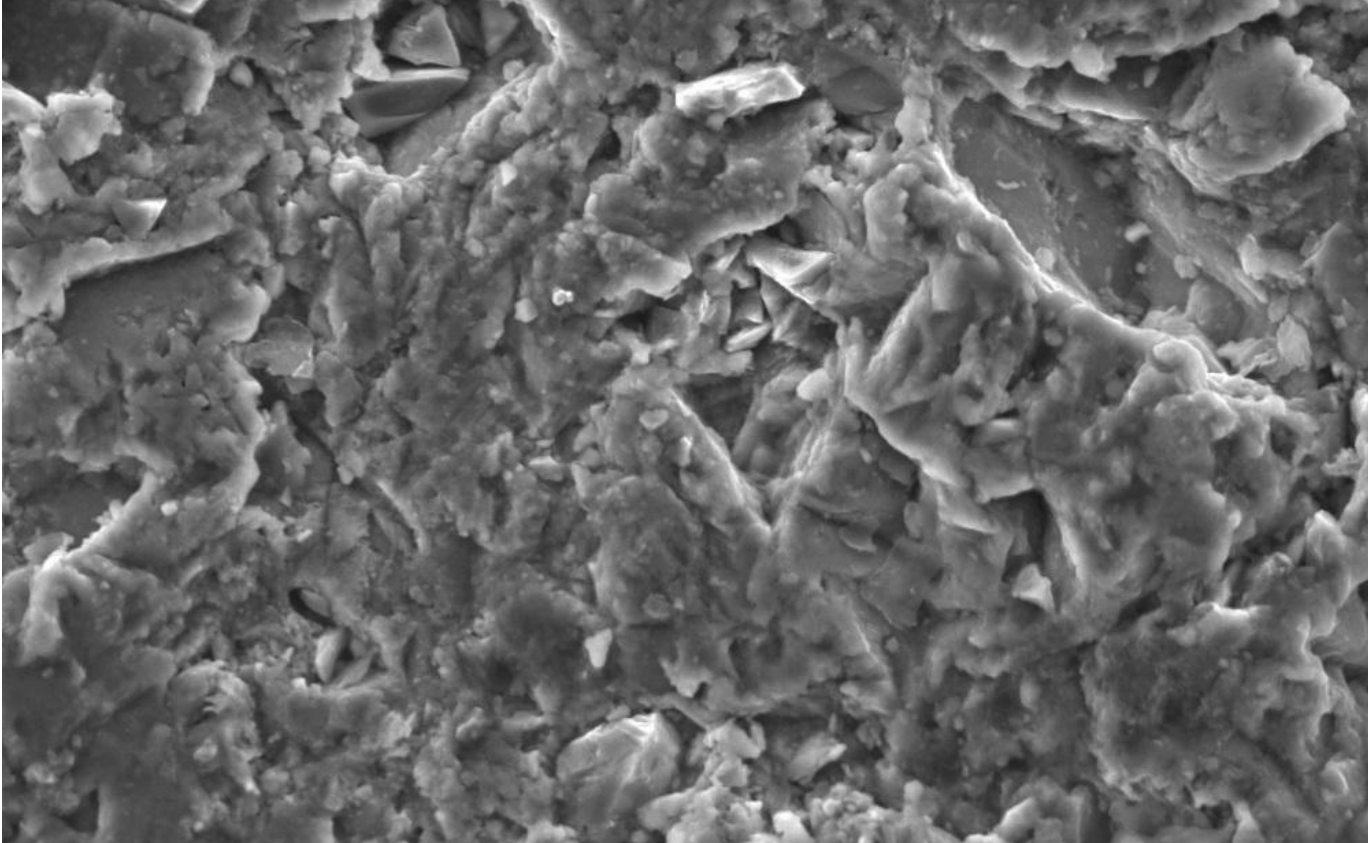
Figure 9.3 depicts the microstructure of Al- ($\text{Al}_2\text{O}_3+\text{Al}_3\text{Zr}$) after machining with USM under the experimental conditions corresponding to experiment no. 3 at magnification levels of 1000x and 2000x. It could be observed that ductile failure dominated the fracture of work surface, but some signs of brittle fracture were also observed in the form of sharp edges. Use of a fine grit size (600) has possibly resulted in considerable plastic deformation of the work surface in this case.

Figure 9.3 (b) also suggests a mixed mode of material removal with greater contribution from ductile failure.

Figure 9.4 shows the microstructure of Al-SiC after machining with USM under the experimental conditions corresponding to experiment no. 8 at magnification levels of 1000 X and 2000 X. The process settings include silicon carbide slurry with grit size 400 with 50% concentration and power rating 40%. It can be observed from figure 9.4 that the cleavage type of fracture took place. The increase in the surface hardness is moderately high because of a longer machining time required as the machining rate observed was quite low.

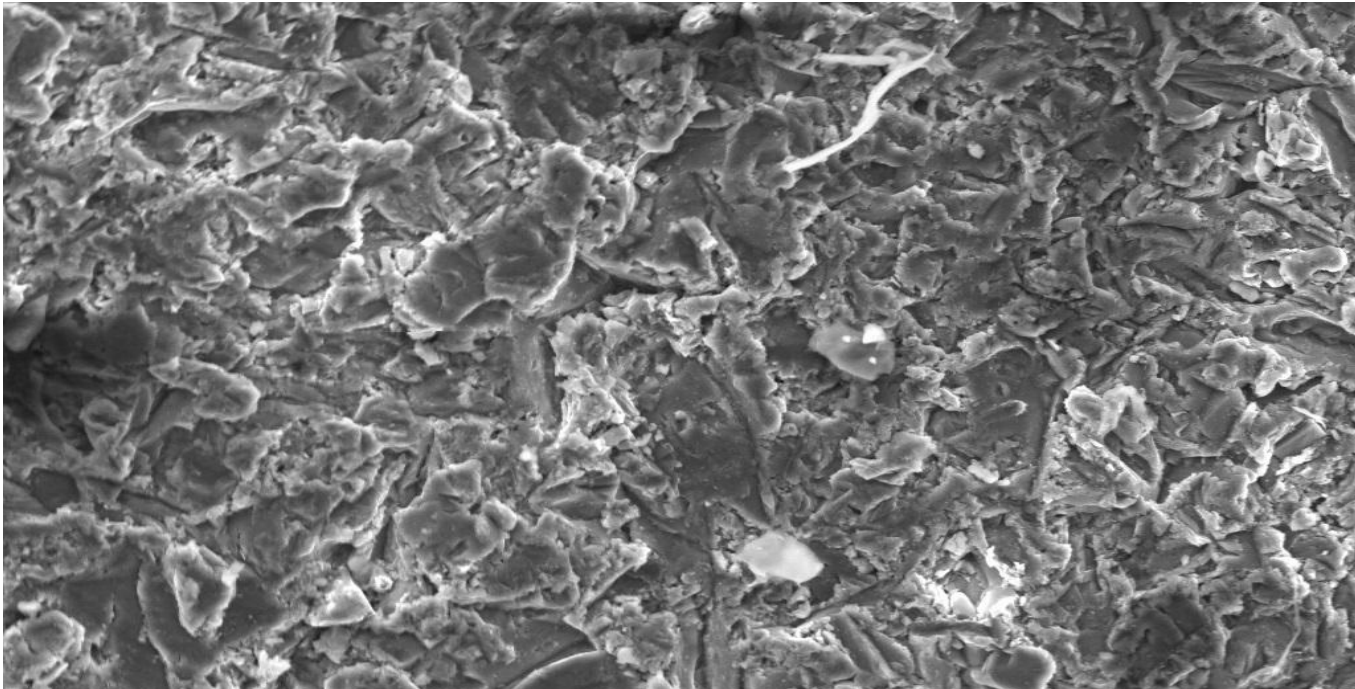


(a) 1000x

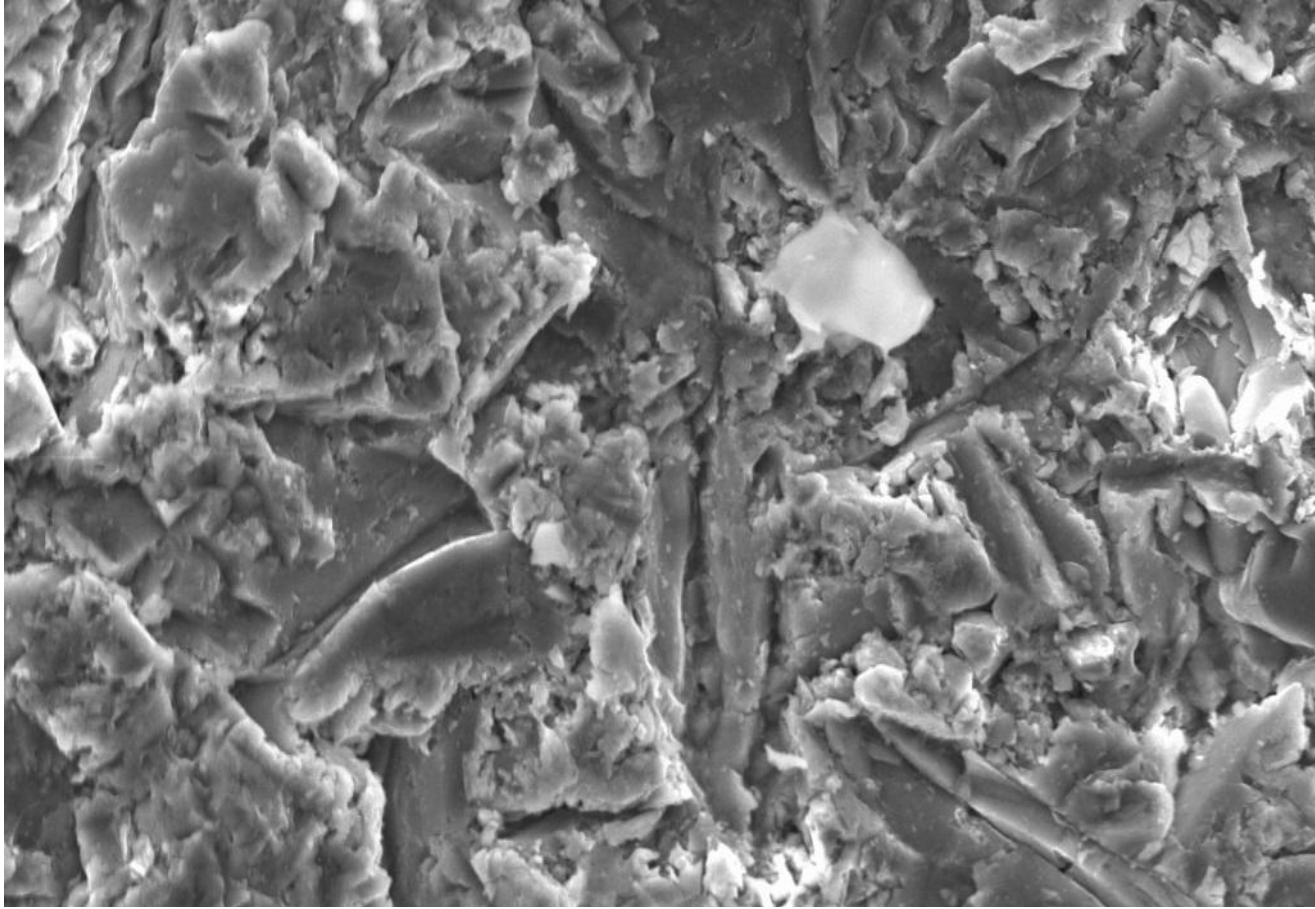


(b) 2000x

Figure 9.4 SEM Photograph for Experiment No. 8



(a) 1000x

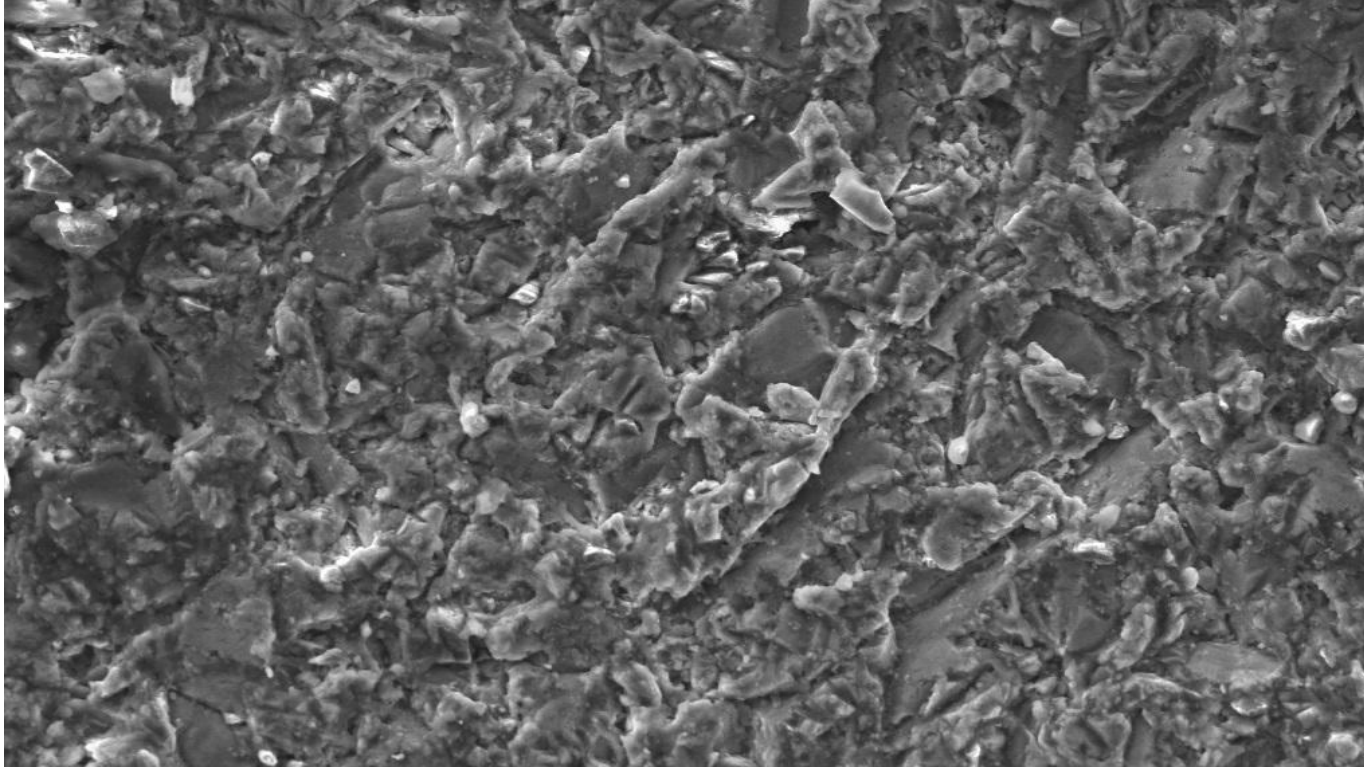


(b) 2000x

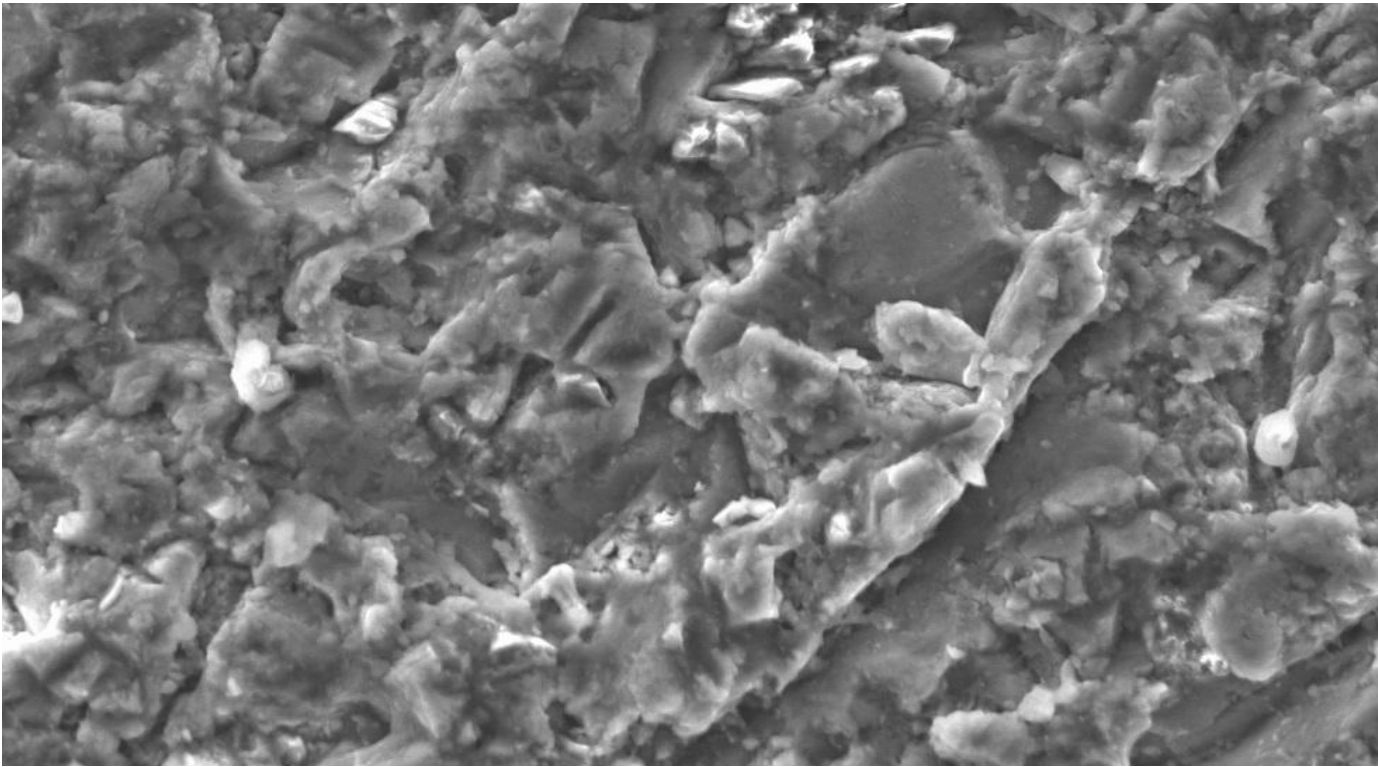
Figure 9.5 SEM Photograph for Experiment No. 12

Figure 9.5 shows the microstructure of $\text{Al}(\text{Al}_2\text{O}_3 + \text{Al}_3\text{Zr})$ after machining with USM under the conditions corresponding to experiment no. 12 at magnification levels of 1000 X and 2000 X. The input parameters settings for this trail include mixture of 50% Al_2O_3 +50% SiC with a medium grit size (400) and concentration 40%. Power rating used was (60%). The figure suggest predominant brittle fracture (90-95%) with a very few localized ductile failure regions and indicates uniform abrasion of the work surface. The rate of machining observed is quite moderate.

Figure 9.6 shows the microstructure of Al-ZrO_2 after machining with USM under the conditions corresponding to experiment no. 13 at magnification levels of 1000 X and 2000 X. Purely brittle fracture is observed as the parameter settings indicate a moderate to high level of energy input into the work. The input parameters settings for this trail include Al_2O_3 as abrasive slurry with a medium grit size (600) and concentration 40%. Power rating used was (60%).



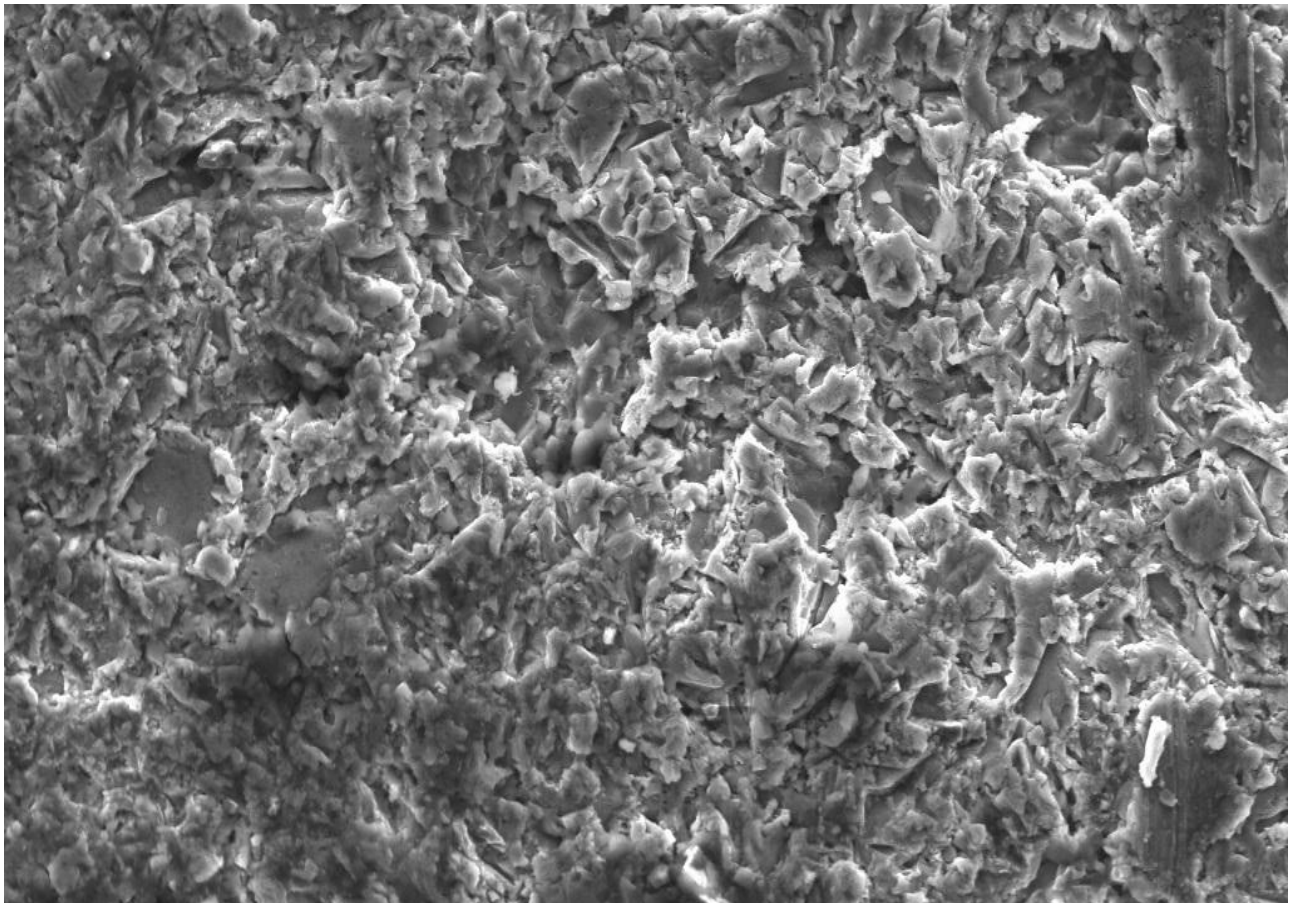
(a) 1000x



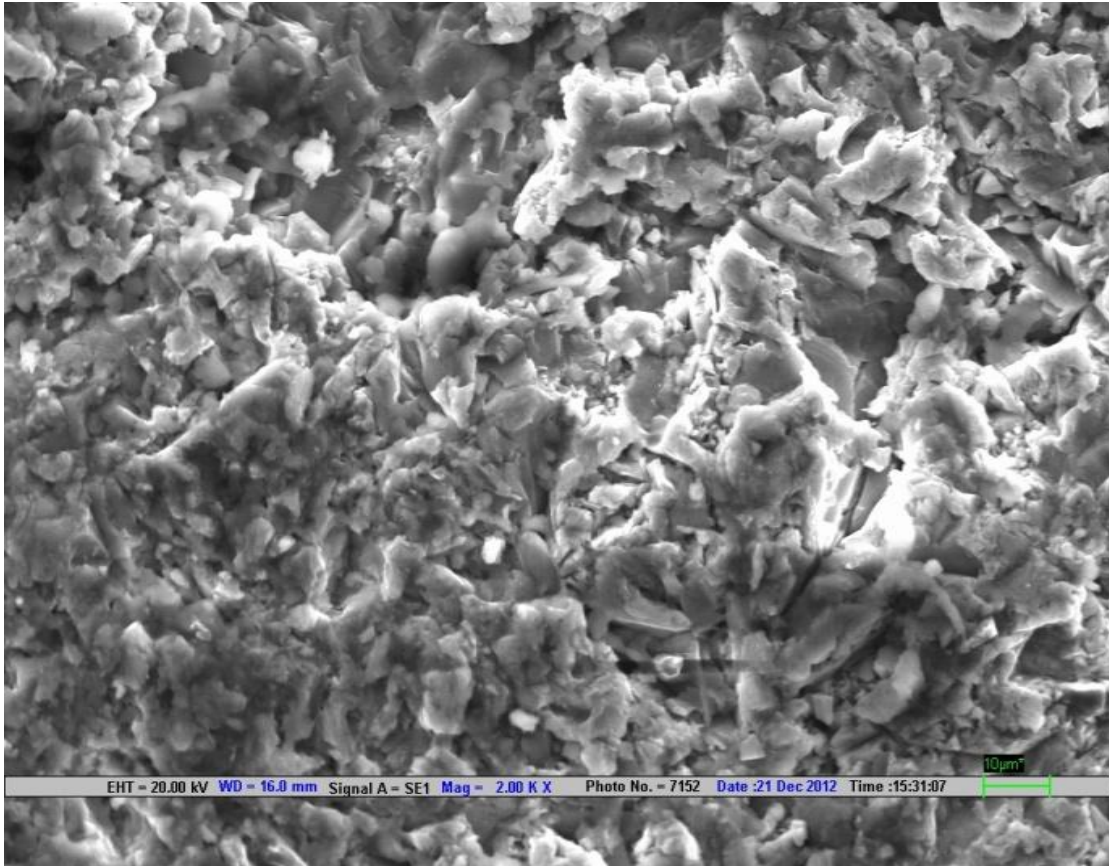
(b) 2000x

Figure 9.6 SEM Photograph for Experiment No. 13

Figure 9.7 shows the microstructure of Al-SiC after machining with USM under the conditions corresponding to experiment no. 17 at magnification levels of 1000 X and 2000 X. The input parameters settings for this trail include SiC as abrasive slurry with a medium grit size (600) and concentration 30%. Power rating used was (60%). The process settings in this case render a low rate of energy input to the with USM tool/abrasive, so purely ductile type of failure has been observed which is in consistent with the low machining rates achieved in this case. There is no evidence of any brittle fracture of the work surface as sharp edges have not been observed. The increment in work surface hardness is extremely high which can be attributed to shear plastic deformation occurring in this case that lead to more strain hardening of the work surface.



(a) 1000x



(b) 2000x

Figure 9.7 SEM Photograph for Experiment No. 17

9.3 CONCLUSION

The present study was carried out to study the effect of input parameters on the MRR, TWR, Surface roughness, Micro Hardness and on the surface properties. The following conclusions were drawn from the study:

- MRR was mainly affected by Power rating, type of abrasive slurry used and the grit size of abrasive particle.
- TWR is affected by power Rating, slurry concentration, work piece material, slurry type and grit size. No interactions are affecting the TWR
- All the three work piece show increase in Micro hardness. The Micro hardness is affected by power rating, type of work material used, type of abrasive and grit size.
- The interaction between power rating and grit size has affect the Micro hardness significantly.

- The power rating was found to be main factor in all the response variable and slurry concentration to be least responsible
- Surface roughness was mainly affected by power rating and type of abrasive used. Type of work piece material, slurry concentration and grit size also had significant effect but the percentage contribution is less.
- The slurry concentration has less effect on the output variables.
- Higher surface finish can be obtained using low power rating and Al-SiC as work material and grit size 600.
- To increase the hardness the higher power rating is used with Silicon carbide as abrasive and 400 grit size.
- The SEM analysis showed the three types of fracture that took place during machining. It is also observed that the power rating and the type of abrasive particle and the size of abrasive particle affect the removal of material during machining.
- It is also observed that the concentration of slurry used also affect the mechanism of material removal during the machining

9.4 RECOMMENDATION FOR FUTURE WORK

Only three work materials were used namely Al-ZrO₂, Al-(Al₂O₃+Al₃Zr) and Al-SiC. Other materials such as Al with other reinforcement that may be particulate, whisker or fiber can be used. Reinforcements other than ZrO₂ such as MgO, carbon fibre etc can be used. In this study single tool was used i.e. HCHCr, the experimentation can be performed using more than one tool material. Abrasive slurry used here was Silicon carbide, Aluminium oxide and their mixture. The machine can be carried out using the abrasive slurry other than these two such as Boron Carbide. Also machining can be done by changing the slurry concentration and the power rating. Also one can perform the experimentation by varying the size of abrasive particle, other than used in this study.

CHAPTER 10

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