

Thesis

On

**INVESTIGATING THE EFFECT OF TOOL AND WORK
MATERIAL IN ULTRASONIC MACHINING OF TITANIUM
ALLOYS**

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IN

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Submitted By

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DECLARATION

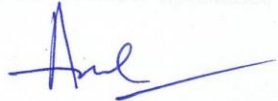
I hereby declare that the report entitled **"INVESTIGATING THE EFFECT OF TOOL AND WORK MATERIAL IN ULTRASONIC MACHINING OF TITANIUM ALLOYS"** submitted by Mr. Parveen Kumar Saini in the fulfillment of the requirement for the award of **Master of Engineering in Mechanical (CAD/CAD and Robotics) Engineering at Thapar Institute of Engineering and Technology, Patiala**, under the guidance of **Dr. Ajay Batish**, Professor and Head, Department of the Mechanical Engineering, Thapar University, Patiala during **July 2010 to July 2011**.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University/Institute for the award of any degree.


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ABSTRACT

By way of the development of technology, the scientists and technologists in the field of manufacturing are facing more and more challenges. Technologically advanced industries such as aeronautics, nuclear reactors and automobiles have been demanding high strength temperature resistant (HSTR) materials having high strength to weight ratio. Ultrasonic Machining (USM) is one of the non-traditional machining processes that are widely used in commercial machining of hard and brittle materials such as ceramics, refractory materials and precision stones. USM is a process known for its capabilities in providing excellent surface finish without any significant alterations in surface integrity or structure of the work material. Moreover, the compressive stress induced in the sub-surface as a result of repeated impacts of abrasive grains contributes in improving the fatigue strength of the machined components; which is a very important aspect especially for a material like titanium and its alloys. Hence, the study was aimed to investigate the machining characteristics of commercially pure titanium (ASTM Grade-2) and its alloys (ASTM Grade-5) as work material, in combination with three different tool materials (High carbon steel; High speed steel and Stainless steel) with cryogenic treatment and non-cryogenic treatment of tool in ultrasonic machining and to model these characteristics for their application in the concerned manufacturing industry. The machining characteristics investigated are material removal rate (MRR); tool wears rate (TWR); micro hardness and surface roughness. The effect of various input parameters on output responses have been analyzed using Analysis of Variance (ANOVA). Microstructure analysis has been completed to understand the form and amount of deposition on the surface of the workpiece material. Main effect plot and interaction plot for significant factors and S/N ratio have been used to determine the optimal design for each output response. Grey relational analysis and Genetic Algorithms were used to determine the optimum combination of input parameters to get the best results.

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ABBREVIATIONS



ANOVA	Analysis of Variance
USM	Ultrasonic machine
HCS	High-Carbon Steel
HSS	High Speed Steel
SS	Stainless Steel
MRR	Material Removal Rate
TWR	Tool Wear Rate
SR	Surface Roughness
SEM	Scanning Electron Microscope
S/N	Signal to Noise Ratio
MSD	Mean Square Deviation
CT	Cryogenic Treatment

NOTATIONS



OA	Orthogonal Array
A	Workpiece Material
B	Tool Material
C	Abrasives
D	Grit Size
E	Concentration
F	Power Rating
G	Powder
Ra	Surface Roughness

1.1 INTRODUCTION TO NON-TRADITIONAL PROCESSES

"The entire history of mechanical engineering is of learning from failure" The human race has distinguished itself from all other form of life by using tool and intelligence to create items that serves to make life easier and more enjoyable. By way of the development of technology, the scientists and technologists in the field of manufacturing are facing more and more challenges. Technologically advanced industries such as aeronautics, nuclear reactors and automobiles have been demanding high strength temperature resistant (HSTR) materials having high strength to weight ratio. Researchers in the area of materials science are developing materials having higher strength, hardness, toughness and other diverse properties.

It is a well established fact that during conventional machining processes an increase in the hardness of work material results in a decrease in the economic cutting speed. It is no longer possible to find tool materials which are sufficiently hard and strong to cut (at economic cutting speeds) materials such as titanium, stainless steel, nimonics, fiber-reinforced composites, ceramics and satellites. With the advancement in new engineering material having improved thermal, chemical and mechanical properties, low rigidity structure and production difficult parts having complex shapes with high tolerances and fine surface quality.

There are number of treatment processes used for different metals which cause them to behave differently under different conditions [3]. However, the mechanism of microstructure changes in alloys under various treatments, are not yet fully understood [1]. Change in microstructure effects on tool life under certain treatments [4]. Empirical studies have demonstrated that the life of cutting tools steel can be increased by cryogenic treatment. Reducing tool wear is important in various manufacturing processes in order to increase tool life which in turns reduces cost of production [5]. The efficiency of the tool depends upon the time for which it is used for cutting or in other words, longer is the

cutting time, better is its performance. However, while the wear of the cutting edge gradually increases, the precision and the quality of the surface finish of the work piece decreases [6].

The life time of a cutting tool is consequently an important economic factor, creating huge competition among cutting tool producers [2]. The tools have to withstand high temperature and stress during cutting, and have to absorb cutting forces produced during machining [1]. Also tool material must be corrosion resistant and chemically inert towards the work piece material [6]. Moreover, the metal working industry demands not only a long tool life, but also trying to increase the limits of the tools still further, as higher and higher cutting speeds are required for high speed machining which causes decrease in cycle time and increase in production [7]. To meet such demands, a different class of machining processes known as non-traditional machining processes has been developed. These newer methods are also called unconventional in the sense that conventional tools are not employed for metal cutting. The processes are non-conventional in the sense that these don't employ a conventional tool for the material removal. Instead these utilize energy in direct form to remove the materials from workpiece. The range of applications of newly developed machining process is determined by workpiece properties like electrical and thermal conductivity, melting temperature, electrochemical equivalent etc. These techniques can be classified into three categories, i.e. mechanical, electro-thermal, and electrochemical machining processes. The mechanical non-conventional techniques (abrasive jet machining, ultrasonic machining, and water jet machining) utilizes kinetic energy of either abrasive particles or a water jet to remove the material. In electro-thermal method (plasma arc machining, laser beam machining, and electron beam machining) the energy is supplied in form of heat, light, and electron bombardment which results melting, or vaporization and melting both of work material. In the chemical machining, etching process is being done.

During the last 55 years, over 20 different non-traditional manufacturing processes have been invented and successfully implemented into production.

1.1.1 Classification of Unconventional Manufacturing Processes

The non-conventional manufacturing processes are not affected by hardness, toughness or brittleness of material and can produce any intricate shape on any workpiece material by suitable control over the various physical parameters of the processes.

The non-conventional machining processes can be classified into four basic categories on the basis of type of energy involved for machining purpose.

- i. Type of energy required, namely, mechanical, electrical, chemical etc.
- ii. Basic mechanism involved in the processes, like erosion, ionic dissolution, vaporization etc.
- iii. Source of immediate energy required for material removal, namely, hydrostatic pressure, high current density, high voltage, ionised material, etc.
- iv. Medium for transfer of those energies, like high velocity particles, electrolyte, electron, hot gases, etc

1.1.2 Comparative Analysis of Unconventional Manufacturing Processes

A comparative analysis of the various unconventional manufacturing processes should be made so that a guide-line may be drawn to find the suitability of application of different processes.

A particular manufacturing process found suitable under the given conditions may not be equally efficient under other conditions. Therefore, a careful selection of the process for a given manufacturing problem is essential. The analysis has been made from the point of view of:

- i. Physical parameters involved in the processes;
- ii. Capability of machining different shapes of work material;
- iii. Applicability of different processes to various types of material, *e.g.* metals, alloys and non-metals;
- iv. Operational characteristics of manufacturing and
- v. Economics involved in the various processes.

1.2 ULTRASONIC MACHINING (USM)

The use of Ultrasonic machining processes of hard and brittle material is known since early 1950's. Ultrasonic Machining (USM) is a non-conventional mechanical material removal process used for machining both electrically conductive and non-metallic materials; preferably those with low ductility and a hardness above 40 HRC [60, 62, 67, 76] such as inorganic glasses, ceramics, quartz etc.

USM has been variously termed ultrasonic drilling; ultrasonic cutting; ultrasonic abrasive machining and slurry drilling. In USM, high frequency electrical energy is converted into mechanical vibrations via a transducer/booster combination, which are then transmitted to an energy focusing as well as amplifying device known as horn. This causes the tool to vibrate along its longitudinal axis at high frequency; usually greater than 20 kHz with an amplitude of 10–50 μm [14, 20-22, 36, 40, 50-53]. The power ratings range from 50 to 3000 W and a controlled static load is applied to the tool to provide feed in the longitudinal direction. Abrasive slurry, which is a mixture of abrasive material such as silicon carbide, boron carbide or alumina suspended in water or some suitable carrier medium is continuously pumped across the gap between the tool and work (20–60 μm).

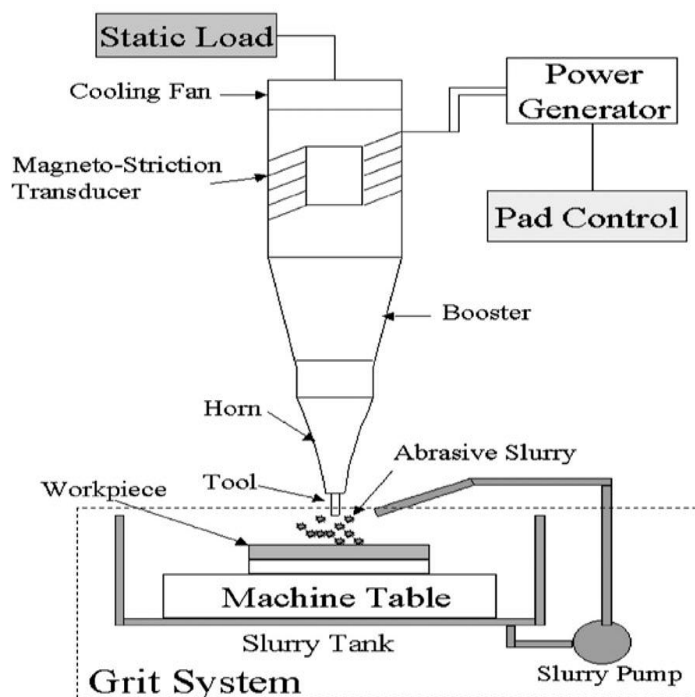


Fig: 1.1 Basic Elements of USM Setup

The vibration of the tool causes the abrasive particles held in the slurry to impact the work surface leading to material removal by micro-chipping [43, 64]. Figure 1.2 shows the basic elements of an USM set up using a magnetostrictive or piezoelectric transducer with brazed or screwed tooling.

USM is generally associated with low material removal rates; however its application is not limited by the electrical or thermal characteristics of the work material. Because the process is non-thermal and non-chemical, the materials processed are not altered either chemically or metallurgically [76]. Holes as small as 76 μm in diameter can be drilled, however the depth to diameter ratio is limited to 3:1 [36, 71]. For efficient machining to take place, the tool and horn must be designed with consideration given to mass and shape so that resonance can be achieved within frequency range capability of the ultrasonic machine.

Variations of this basic configuration include:

1. Variations of this basic configuration of USM include Rotary Ultrasonic Machining (RUM). In this process, tool vibrates and rotates simultaneously thereby improving the material removal rate (MRR), tool wear rate (TWR) and reducing the geometric inaccuracies; for example, oversize and out of roundness, etc. [30, 41, 54-56, 59, 72, 79, 81]. The construction of RUM machines is similar to USM except for the addition of a 0.37-0.56 kW rotary spindle motor capable of rotating up to 5000 rpm [58].
2. USM combined with electric discharge machining (EDM) [70, 75, 80, 82-83].
3. Ultrasonic assisted cutting or grinding. Ultrasonic aided turning is the most common process in this category and is claimed to reduce machining time, work residual stresses and improve surface quality and tool life compared to conventional turning [11, 13, 16, 32-33, 35, 42, 45].
4. Other non-machining applications such as cleaning, welding and coating.

1.3 BASIC SUBSYSTEMS OF USM

All ultrasonic machines share common subsystems regardless of the physical size or power [14]. The most important of these subsystems are the power supply, transducer element, tool holder or horn and abrasive supply system. A detailed description of these

components is given as following:

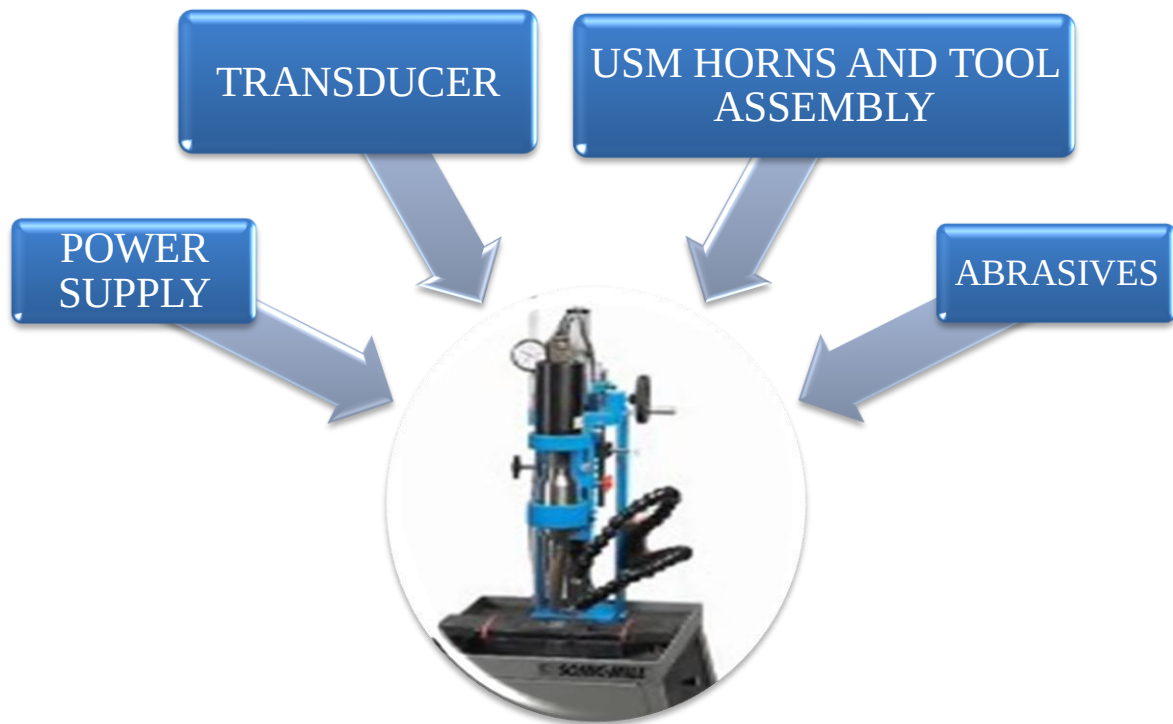


Fig: 1.2 Subsystems of USM

1.3.1 The Ultrasonic Power Supply and Transducer

The power supply for an ultrasonic machine is a high power sine wave generator that offers the user control over both the frequency and power of the generated signal [14]. It converts low frequency (50 Hz) electrical power to high frequency (approx. 20 kHz). This electrical signal is applied to the transducer for further conversion into the mechanical motion in form of vibrations. The power supplied depends upon the size of transducer [12].

In case of USM transducer, the ultrasonic vibrations are produced by the transducer. Transducers convert electrical energy into mechanical motion. With a conventional generator system, the tool and horn are set up and mechanically tuned by adjusting their dimensions to achieve resonance [23]. They can accommodate very small errors in set up or tool wear, giving minimum acoustic energy loss and very small heat generation [38].

Two types of transducers used for USM are based on two different principles of operation:

- Piezoelectric transducer
- Magnetostrictive transducer [14, 40].

Because of its lower Q value (Q is a measure of the sharpness of the peak value of energy); the Magnetostrictive transducer allows vibration to be transmitted over a wide frequency band [34]. It also allows greater horn design flexibility and can accommodate tool wear. The major drawback of magnetostrictive transducer is high electrical losses and low energy efficiency (about 55-60%). On the other hand, piezoelectric transducers are more energy efficient (90-96%). Also this type of transducers can generate high vibration intensities as compared to magnetostrictive transducers [14, 20, 22, 60, 65, 78].

Magnetostrictive transducers are usually constructed from a laminated stack of nickel sheets that when influenced by strong magnetic field, have a change in their length.

1.3.2 The USM Horn and Tool Assembly

The main function of the horn i.e. tool holder is to hold the tool to the transducer. The tool holder transfers the vibrations i.e. sonic energy to the horn and therefore, it must have adequate fatigue strength. With a good tool design, an amplitude gain of 6 over the stack can be obtained. Tool holder is attached to the transducer by mean of large, loose-fitting screw [84]. Half hard copper washers are used between the transducer and tool holder to dampen and cushion the interface, which reduces the chances of any unwanted ultrasonic welding [60].

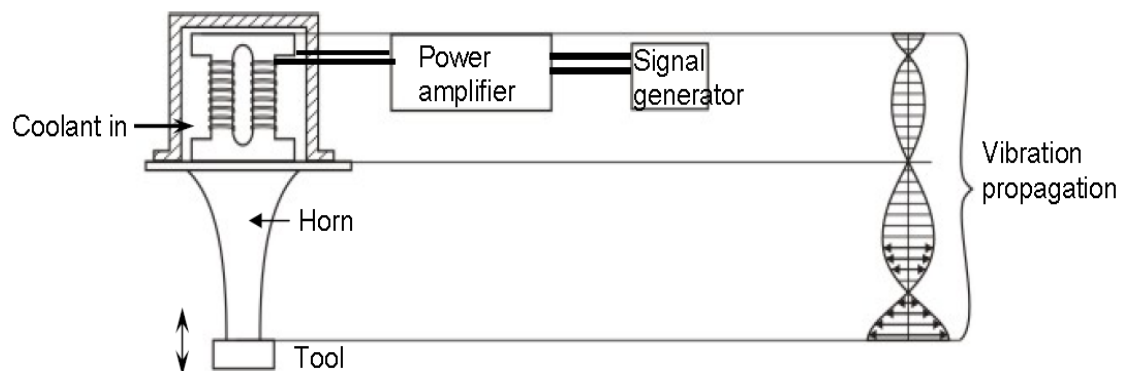


Fig. 1.3 Magnetostrictive Transducer along with Horn

Figure: 1.3 shows a typical magnetostrictive transducer along with horn. The horn or concentrator is a wave-guide, which amplifies and concentrates the vibration to the tool from the transducer.

Tool holders are available in two configurations: amplifying and non-amplifying. Non-amplifying tool holder is cylindrical and results in the same stroke amplitude at the output end as at the input ends.

Figure 1.4 shows the amplifying tool holders and mechanically attached tools for USM [85].

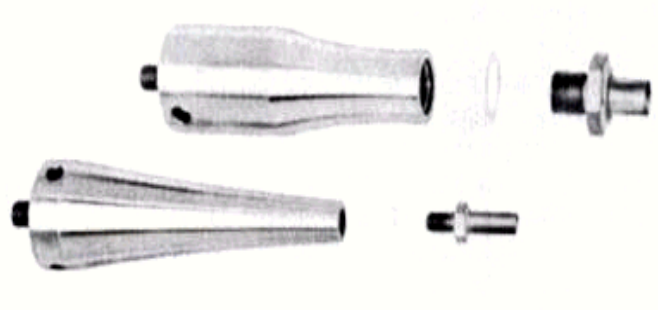


Fig. 1.4 Tool Holders and Tool Assembly

The material used for fabrication of horn must possess high wear resistance, well elastic and fatigue strength properties; and corrosion resistance. Monel, titanium, stainless steel and aluminium bronze materials are used for making tool holder for ultrasonic machines.

The tool material employed in USM should be tough and ductile. The tool should be so designed to provide the maximum amplitude of vibration at the free end at a given frequency [86-87]. The material used should have high wear resistance, good fatigue strength and optimum values of hardness and toughness [84]. Tungsten carbide, Silver steel, Monel is the commonly used tool materials. Polycrystalline diamond (PCD) has recently been detailed for the machining of very hard work materials such as hot isostatically pressed silicon nitride [88].

The mass length of the tool is very important. Too great a mass absorbs much of the ultrasonic energy, reducing the efficiency of machining. Long tool causes overstressing of the tool. Most of the USM tools are less than 25 mm long. In practice the slenderness ratio of the tool should not exceed 20. The under sizing of the tool depends coupon the

grain size of the abrasive. It is sufficient if the tool size is equal to the hole size minus twice the size of the abrasives.

1.3.3 Abrasives

In ultrasonic machining, abrasive slurry is used to achieve the cutting action. Different types of abrasive materials can be used for making the slurry. Aluminium oxide, silicon carbide and boron carbide are the most commonly used abrasive materials. For precision machining and very hard workpiece materials diamond powder is also used as abrasive.

Boron carbide is by far the fastest cutting abrasive and it is quite commonly used abrasive in USM operation. The abrasive is carried in slurry of water with 30-60% [34] by volume of the abrasives. When using large-area tools, the concentration is held low to avoid circulation difficulties.

The most important characteristic of the abrasive that highly influences the material removal rate and surface finish of the machining is the grit size or grain size of the abrasive. It has been experimentally determined that a maximum rate of machining is achieved when the grain size becomes comparable to the tool amplitude. Grit sizes of 200-400 are used for roughing operations and a grit size of 500-1000 for finishing.

1.4 WORKING PRINCIPLE OF USM:-

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 16KHz to 30 KHz and 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 HRC= 0.45

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.

A simple schematic diagram of this process is shown in Figure 1.5.

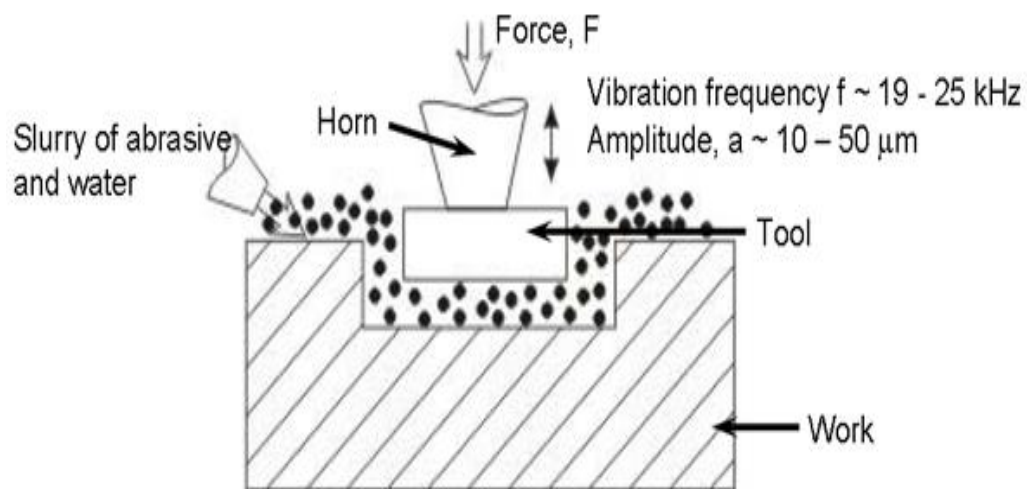


Fig: 1.5 Ultrasonic Process

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 (c/s) power supply into high frequency (15 KHz to 30 KHz) power which in turn is converted into mechanical oscillations with the help of a magnetostrictive or piezo-electric transducer of the two type, the piezo-electric transducer are most efficient, i.e. they involve less loss of power and hence do not require cooling. The magnetostrictive transducers generally found in old machines are less efficient due to high eddy current losses and hence may require cooling. The power rating of modern machines varies from 0.04 to 4 KW. Some of the designs have rating even up to 10 KW.

1.5 APPLICATIONS OF USM

Currently, the principle fields of application of ultrasonic machining are:

- Manufacture of hard alloy wire drawing, punching and blanking dies, also making small complicated dies of steel.
- Machining semi-conducting material such as germanium and silicon.
- Machining ferrite and other special-ceramic materials used in electrical installations.
- Making instruments and optical parts of glass, quartz, fluoride and barium titanate.
- Making components of porcelain and special ceramics.
- Cutting accurate shallow holes of rectangular or other section in cemented or nitride steel.
- Cutting of industrial diamonds.
- Grinding of glass, quartz and ceramics.
- Cutting holes with curved or spiral center line and cutting threads in glass and mineral ceramics.
- Machining the graphite electrodes used in EDM process.
- Countersinking of silicon nitride or ceramics turbine blades.
- Drilling multiple holes simultaneously in ceramics metal composite matrix (CMC) panels.

1.6 PROCESS CAPABILITIES OF CONVENTIONAL WORK AND TOOL MATERIAL

USM is valuable process for precision machining of hard, brittle materials. Although USM is not limited by high-hardness materials, best machining rates are obtained for materials having hardness more than HRC 60 [60, 63, 67, 73, 76]. Materials such as carbides, ferrites, germanium, ceramics, glass and tungsten are representative of those that are difficult to process conventionally and can benefit the most from the USM process [12-13, 25-26, 28-29, 37, 39, 42, 68]. Penetration rates ranging from 0.025-25 mm/min can be obtained depending upon the shape being machined input parameter settings and work material properties [46-47, 57, 89]. Performance of USM for different work materials while using a cold rolled steel tool and a boron carbide abrasive (particle size 32 μm).

From the literature available on USM, best surface finish is reported while using 800 grit abrasives and is of the order of 0.25 μ m[15]. Because USM is a non-thermal and non-electrical process, the work material properties remain unaltered [46-47, 49-53]. Table 1.1 shows the machining performance of USM for different work material while using a cold rolled steel tool and boron carbide abrasive (32 μ m)[44].

Table 1.1 Typical machining performance characteristics of USM

Material	Ratio or MRR to TWR	Max. machining area(sq. mm)	Avg. machining rate(mm/min)
Glass	100:1	25.8	3.81
Ceramics	75:1	19.4	1.51
Tool steel	1:1	5.6	0.13
Ferrite	100:1	22.6	3.18
Quartz	50:1	19.4	1.65
Boron carbide	2:1	5.6	0.20
Tungsten carbide	15:1	7.7	0.25
Germanium	100:1	22.6	2.16
Synthetic ruby	2:1	5.6	0.51
Carbon graphite	100:1	19.4	2.00
Glass bonded mica	100:1	22.6	3.18

Table 1.2 Shows various materials have been reported to be successfully machined by using USM.

Satellite	Stainless steel	Brass	Carbide
Diamond	Ceramics	Ferrite	Tool steel
Glass	Glass bonded mica	Graphite	Hardened steel
Limestone	Molybdenum	Plaster of Paris	Silicon carbide
Carbon	Germanium	Plastic	Ti- alloy
Tungsten	Aluminium	Granite	Marble

Table 1.3 Presents detailed operational summary of the processes.

Power	200-4000W
Frequency	15-30 KHz(mostly 20 KHz is used)
Abrasives	
Types	Diamond (very few cases) Boron Carbide (specific applications) Silicon Carbide (most commonly used) Alumina (frequently)
Size	Mesh 120-1200 Size: 06-142µm
Concentration	20-60% by volume with water as medium Oil is used for finishing operation
Flow rate	Max. 36.5 L/min
Amplitude	5-70 µm
Static load	0.45 to 5 kg, generally 4.5 kg is used
Tool Material	High Carbon Steel, Stainless Steel, High Speed Steel, etc.
Tool Conditions	With and without Cryogenic Treatment
Cutting gape	10 -150 µm
Over-cut	Twice the grit size
Depth of cut	Upto 90mm , normally 60 mm
Accuracy	± 25µm
Taper	0.5 µm/mm
Surface roughness	0.25 to 1.5 µm
Min. size of dole drilled	75 µm

1.6.1 Titanium and Its Machining

Background:

With its low mass, high strength, and excellent resistance to corrosion, titanium solves many engineering challenges. Titanium is 30% stronger than steel but is nearly

50% lighter. Titanium is 60% heavier than aluminum but twice as strong. The aerospace industry is the single largest market for titanium products. Titanium applications are most significant in jet engine and airframe components that are subject to temperatures up to 1100 °F and for other critical structural parts. Titanium is alloyed with aluminum, manganese, iron, molybdenum and other metals to increase strength, to withstand high temperatures and to lighten the resultant alloy. Titanium's high corrosion resistance is also a valuable characteristic. When exposed to the atmosphere, titanium forms a tight, tenacious oxide film that resists many corrosive materials. In the 1950's the titanium metal industry was established primarily in response to the emerging aerospace industry that used it in the manufacture of airframe structural components and skin, aircraft hydraulic systems, air engine components, rockets, missiles, and spacecraft, where these properties are invaluable. The military also uses titanium in its guided missiles and in artillery. As the 1970's approached, the cost of titanium dropped making it more available for other practical applications such as shipbuilding: primarily in submarines, in ship's propellers, shafts, rigging, and other highly corrosive parts [10, 19, 31, 62, 77].

Titanium is being increasingly used for medical applications due to its lightweight, its strength, and its hypoallergenic properties, as titanium is nickel-free. Titanium products are being utilized in other industries as well, from petrochemical applications to sporting goods.

For automotive applications, titanium is used for engine valves, connecting rods, wheel-rim screws, exhaust systems, and suspension springs. Titanium engine components increase horsepower and torque while improving fuel economy and solving problems with noise and vibration. When used in exhaust systems, titanium reduces material weight approximately 50% compared to traditional systems and substantially increases product life. Titanium suspension springs give OEMs greater mass reduction, up to 70%, over conventional springs performing the same function in less space, allowing increased payload and engine or passenger compartment space. While the material once had a reputation for being expensive, advances in production technology and increased consumption in industrial markets have allowed steep cost reductions.

Titanium is notorious as difficult-to-machine material owing to its distinct properties as discussed above. The machining characteristics of titanium and its alloys have been summarized as following [30]:

- ✓ Titanium and its alloys are poor thermal conductors. As a result, the heat generated when machining titanium cannot dissipate quickly; rather, most of the heat is concentrated on the cutting edge and tool face. About 50% of the heat generated is absorbed by into the tool while machining titanium alloy (Ti-6Al-4V) [8, 19, 69].
- ✓ During machining, titanium alloys exhibit thermal plastic instability that leads to unique characteristics of chip formation. The shear strains in the chip are not uniform; rather, they are localized in a narrow band that forms serrated chips [9, 24, 31].
- ✓ The contact length between the chip and the tool is extremely short (less than one-third the contact length of steel with the same feed rate and depth of cut). This implies that the high cutting temperature and the high stress are simultaneously concentrated near the cutting edge [74].
- ✓ Serrated chips create fluctuations in the cutting force; this situation is further promoted when alpha-beta alloys are machined. The vibration force, together with the high temperature, exerts a micro-fatigue loading on the cutting tool, which is believed to be partially responsible for severe flank wear [27, 77].
- ✓ The surface finish achieved by a single machining process is poor. Hence, use of some finishing process is a must for obtaining acceptable surface quality while machining titanium or its alloys [66, 69]

Therefore, there is a crucial need for reliable and cost-effective machining processes for titanium and its alloys.

Nontraditional machining processes such as electric discharge machining and laser beam machining have been applied to the machining of titanium and its alloys in recent time but even these processes have their own limitations; the most prominent are the surface finish and dimensional inaccuracies besides their undesirable effects on the machined s zone, recast layer and thermal stresses [40]. These adverse effects can lower the working life of the components critically. Loss of fatigue strength and hence surface integrity is another problematic area in machining of titanium.

The basic fatigue properties of many titanium alloys rely on a favorable compressive surface stress induced by tool action during machining [9, 17]. Ultrasonic Machining (USM) could be another alternative machining process for commercial machining of titanium due to the following characteristics:

1. Titanium and its alloys have low thermal conductivity and in USM there is a thinner zone affected by machining, generous quantity of cutting fluid is used resulting in better heat dissipation, efficient slurry flow can be maintained, depth of cut can be maintained due to rigidity of the tool fixed in the horn and chemically active medium can be used to transfer the heat efficiently and there are no cutting forces between the tool and workpiece [20, 22, 47-48, 61].
2. Titanium has a tendency to react with the cutting tools which contributes to seizing, galling, and abrasion and picks up on the cutting edges and faces and in USM there is no tool work contact preventing all the above-mentioned side effects.
3. USM is known to be free from all the possible adverse effects on the machined component. Moreover, the repeated impacts of abrasive grains on the work surface lead to induction of a favorable compressive surface stress in the micro layers thereby improving the fatigue life of titanium components and hence the surface integrity [17-18, 48].
4. USM is better than other non-traditional processes in terms of simplicity, cost of tooling and provides better stability and control [43-44, 49-53].

In the present investigation, an attempt has been made to explore the use of ultrasonic machining for machining Ti (ASTM Grade-2) and Ti (ASTM Grade-5) and to establish cost effective methods while machining titanium with USM.

1.6.2 Cryogenic Treated Tool Material

Background:

Cold treatments or subzero temperature treatments have documented research from as far back as the 1930s, when German companies used it on components of aircraft engines. Cryogenic processing had its U.S. origins in the 1940s, but that was a very primitive process compared to today's procedures. During the 1950s, research related to Cryogenic Treatment was reported in the form of articles in magazines like *Tooling and Production*, etc. The most notable and persistent pioneer of cryogenics was Dr. Randall Barron of Louisiana Technical university. Papers written by him are widely cited in the cryogenics research and industry [91-93]. Till around the 1960s, attempts have been done by direct immersion into liquid nitrogen results cracking of many components. Subsequently, the research about CT has been validated during the 1980s by the first result in machine tools

[90, 94]. Later, with research and development, computerized temperature control systems have been developed to get crackles cryogenic treated components to achieve maximum benefits [95-98].

A cryogenic treatment is the process of treating material to cryogenic temperature (i.e. below $-190\text{ }^{\circ}\text{C}$ ($-310\text{ }^{\circ}\text{F}$), usually using liquid nitrogen to remove residual stresses and improve wear resistance on steel. It can have a profound effect on the mechanical properties of certain steels, provided their composition and prior heat treatment are such that they retain some austenite at room temperature. It is designed to increase the amount of martensite in the steel's crystal structure, increasing its strength and hardness, sometimes at the cost of toughness. Presently this treatment is being practiced over tool steels, high-carbon, and high-chromium steels to obtain excellent wear resistance. Recent research shows that there is precipitation of fine carbides (eta carbides) in the matrix during this treatment which imparts very high wear resistance to the steels [91, 94].

1.6.2.1 Treatment Parameters

A fundamental distinction among different CT is given by the parameters of the cooling-warming cycle. In two families depending on the minimum temperature reached during the cycle are categorized [99]:

- Shallow Cryogenic Treatment (SCT) or Subzero Treatment: the samples are placed in a freezer at 193 K and then they are exposed to room temperature;
- Deep Cryogenic Treatment (DCT): the samples are slowly cooled to 77 K, held-down for many hours and gradually warmed to room temperature.

Figure 1.6 shows an example of a common DCT temperature profile. The typical process parameters are: minimum temperature ($T_{\min}$), hold time, cooling and warming rate.

- In some cases, the actual $T_{\min}$ could be higher than the nominal one because of thermal insulation limits, especially after a significant exploitation of the system and the consequent ageing of the chamber seals.
- Each new material needs to be treated and tested at different temperature levels, in order to identify optimum conditions. In most cases, two or three temperature levels (i.e. 88 K, 143 K and 193 K) are enough to obtain a quick indication in the

selection of a specific temperature by means of microstructure changes investigation (i.e. calorimetric or acoustic emission);

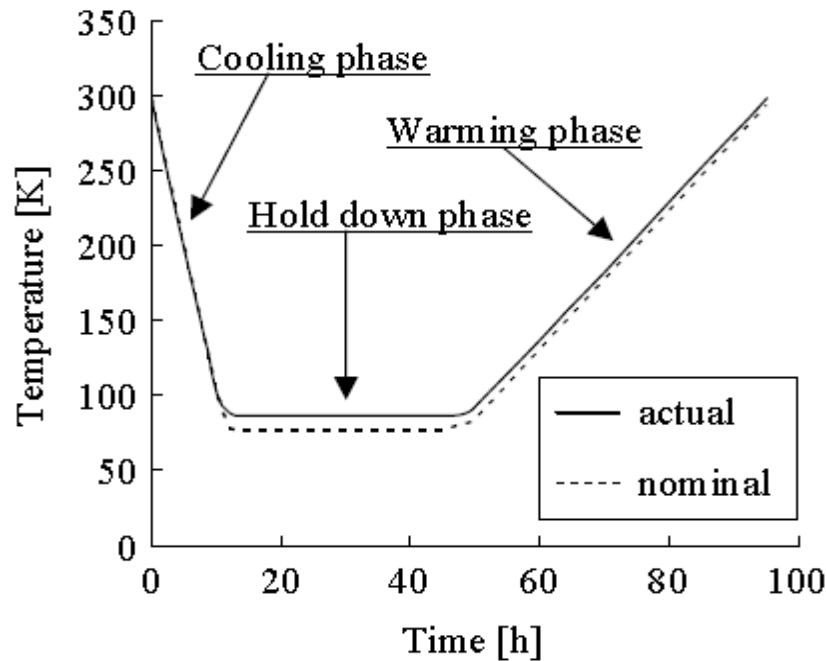


Fig. 1.6 Example of DCT temperature profile.

- Hold time over 36 hours does not bring significant improvements and in most cases 24 hours are enough to obtain results;
- Cooling rate values range is restricted in order to prevent thermal-shock cracking. Commonly, the applied values vary from 0.3 K/min to 1.2 K/min;
- In many cryogenic systems warming rate is not closely controllable and little importance to this parameter is given in literature despite of some suggested hypothesis about carbides precipitation during the warming phase.

In the Taguchi Design of Experiment (DOE) method is applied to identify and to optimize the critical parameters of DCT on an 18% Cr martensitic stainless steel used for piston rings. The Analysis of Variance (ANOVA) of wear test results has pointed out that the most significant factor has been the soaking temperature (72% in contribution), followed by the soaking time (24%) and the cooling rate (10%). Little importance (2%) for the temperature of the tempering process performed after DCT has been observed, while the tempering time is emerged as an irrelevant parameter. Little or no significance for parameters interactions has been calculated and in the end the authors have obtained an

optimal combination of 89 K soaking temperature, 36 hours soaking time, 1 K/min cooling rate and 1 hour tempering at 523 K, predicting a wear loss of 2.26 mg (95% in confidence). A test performed on samples treated with these parameters has confirmed the result.[153]

1.6.2.2 Cryogenic System

A cryogenic system is to control temperature in the cryogenic range into a chamber, using liquid nitrogen or helium. Until the end of the Sixties, any attempt to perform CT had been done by direct immersion into liquid nitrogen, with the catastrophic result of cracking the components. The cryogenic treatment system developed by Ed Busch (Cryo-Tech, Detroit, MI) in the late 1960s and later improved by Peter Paulin (300 Below Inc., Decatur, IL) with a temperature feedback control on cooling and heating rate, allows to perform effective and crackles CT. As a result, many companies have developed systems to perform CT, mainly in the USA and in Canada, but also in China, India and Japan.

The three most important cooling systems are described in [101]:

- Heat Exchanger: the liquid nitrogen flows through a heat exchanger and the output cooled gas is diffused inside the chamber by a fan. There is no contact between nitrogen and samples;
- Direct Nebulization: the liquid nitrogen is nebulizer directly in the chamber or in a cavity around the chamber. A fan allows obtaining a homogeneous temperature distribution; the liquid nitrogen is dispersed around the samples;
- Gradual Immersion: the samples are immersed into the liquid nitrogen for a specific time, and then they are extracted and gradually led back to the room temperature by means of a flow of temperature controlled air.

Another type of cooling system is the so-called “Hybrid System”, which combines direct nebulization and gradual immersion during different phases of the cooling process, in order to reduce liquid nitrogen consumption.

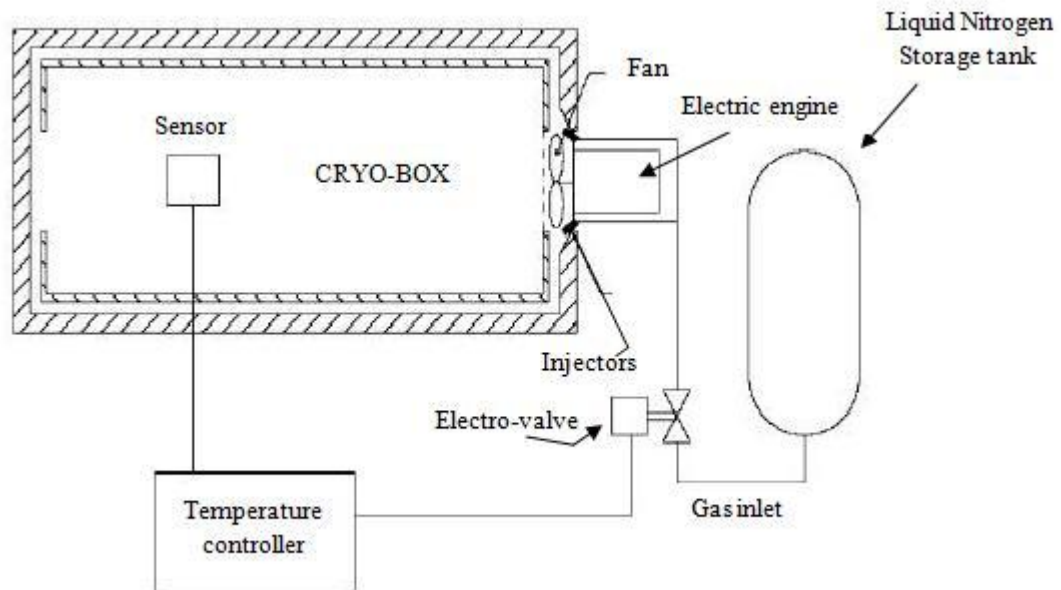


Fig. 1.7 Shows the layout of a direct nebulization cryogenic system.

The temperature control unit receives the temperature information from the sensor placed in the Cryo-chamber. The temperature control unit operates on the electro-valve by the regulation of the liquid nitrogen flow through the injectors. The fan, which is controlled by an electric engine, helps to diffuse the nitrogen homogeneously. The temperature control unit allows controlling the cycle parameters and it provides a print of time temperature diagram. In a direct nebulization system with a chamber of about 0.25 m^3 , an ordinary cycle requires from 1000 l to 2000 l of liquid nitrogen usually stored in a tank, depending on cycle parameters and on the treating material quantity.

1.6.2.3 Benefits of Cryogenic Treatment

- Wear resistance (due to higher hardness and the presence of hard ETA-carbides);
- Improve mechanical strength;
- Increase Toughness;
- Fatigue strength (due to low residual stresses and homogeneous structure);
- Low coefficient of friction (due to higher hardness and the presence of hard ETA-carbides);
- Machining, grinding and polishing finish (due to no/little soft austenite);

1.6.2.4 Applications of Cryogenic Treatment of Steels

- Cutting tools for different machining operations: sawing, milling, drilling, broaching, turning, slitting, shearing;
- Metal forming tools: dies, molds, punches.
- High precision parts: gauges, guides, shafts;
- Parts of high performance (sport) car engines and transmissions: crankshafts, connecting rods, piston rings, engine blocks, gear parts, camshafts.

1.7 ORGANIZATION OF THE THESIS

The thesis has been divided into six chapters. Brief description of the contents of each chapter has been given as following:

Chapter 1 contains introduction to non-traditional machining methods, their comparative features, applications and relative merits and demerits. Various aspects of Ultrasonic machining (USM) have been detailed; including the basic principle, USM equipment, tooling considerations and applications. Process capability of ultrasonic machining has been explored for conventional tool and work materials. A brief introduction to titanium and its alloys has also been included in this chapter. Introduction to cryogenic treatment process, their treatment parameters and system with various applications and relative benefits.

Chapter 2 contains a detailed literature review on machining characteristics of USM such as material removal rate (MRR), tool wear rate (TWR) and surface roughness and the factors affecting these machining characteristics in ultrasonic machining. The literature reported on the effect of cryo-treated (deep) and untreated tool and work piece to investigate the effect on machining characteristics of work materials properties, tool material properties has been reviewed. Summary of the literature and gap in literature also discussed.

Chapter 3 details the selection of input factors and factor levels for the experimentation (pilot experimentation), presents the area of research work to be undertaken has been identified. Objective and work plan also discussed. Methodology to be adopted also

described in brief. Extensive review has also been done on application of Taguchi's robust design methodology for designing and analyzing the experiments.

Chapter 4 presents the analysis and results of the material removal rate (MRR), tool wear rate (TWR), Surface roughness (Ra), micro-hardness and Dimensional error with the use of **non-cryogenic treated tool material**. Results after the Analysis of Variance (ANOVA), Taguchi Signal-to-Noise ratio and Main effect plot for MRR, TWR, Ra and Micro-hardness are outlined in this chapter. Optimal design conditions using grey relational analysis have been discussed.

Chapter 5 presents the analysis and results of the material removal rate (MRR), tool wear rate (TWR), Surface roughness (Ra), micro-hardness and Dimensional error with the use of cryogenic treated tool material. Results after the Analysis of Variance (ANOVA), Taguchi Signal-to-Noise ratio and Main effect plot for MRR, TWR, Ra and Micro-hardness are outlined in this chapter. Optimal design conditions using grey relational analysis have been discussed.

Chapter 6 presents the analysis of surface properties. Microstructure analysis has been completed to understand the microstructure of the titanium surface machined with different set of experiments.

Chapter 7 presents the results, conclusions and recommendations from the experimental work.

CHAPTER 2

LITERATURE REVIEW



2.1 HISTORICAL BACKGROUND OF USM

The history of ultrasonic machining (USM) began with a paper by **R. W. Wood and A. L. Loomis in 1927**[52, 71] and the first patent was granted to **L. Balamuth in 1945**[60, 71, 76]. USM has been variously termed ultrasonic drilling; ultrasonic cutting, ultrasonic dimensional machining; ultrasonic abrasive machining and slurry drilling, however, from the early 1950s it was commonly known either as ultrasonic impact grinding or USM [35].

In this chapter the existing or available published literature pertaining to ultrasonic machining and the machining characteristics of titanium and its alloys by using ultrasonic machine and cryogenic treated tool material is presented with an aim to be apprised of the status of the subject, the focus of the latest work being carried out by researchers.

2.2 MECHANISMS OF MATERIAL REMOVAL IN USM

As has been mentioned earlier, USM is generally used for machining brittle work material. Material removal primarily occurs due to the indentation of the hard abrasive grits on the brittle work material. As the tool vibrates, it leads to indentation of the abrasive grits. During indentation, due to Hertzian contact stresses, cracks would develop just below the contact site, then as indentation progresses the cracks would propagate due to increase in stress and ultimately lead to brittle fracture of the work material under each individual interaction site between the abrasive grits and the workpiece. The tool material should be such that indentation by the abrasive grits does not lead to brittle failure. Thus the tools are made of tough, strong and ductile materials like steel, stainless steel and other ductile metallic alloys.

Wang et.al [102] discussed on fundamental principles of ultrasonic machining, the material removal mechanism and the calculation of critical factors. Ductile machining of brittle materials, even at a high critical depth-of-cut, was realized by applying ultrasonic

vibration to a diamond tool tip. A surface roughness R_a of $100\text{ }\mu\text{m}$ at a $2\text{ }\mu\text{m}$ depth of cut was achieved.

Shaw [64] and miller [43], Cook [103], Rozenberg [60] have done extensive work on the mechanism for the material removal. Most of the work is on machining mechanism for hard and brittle material. These mechanisms are detailed in Figure 2.1 and comprise of:-

- ✓ Material abrasions by direct hammering of the abrasives particle against the work piece surface [43, 61, 64, 103-107]
- ✓ Micro chipping by impact of the free moving abrasive particles [23, 43, 61, 106, 108].
- ✓ Cavitation effect from the abrasive slurry [23, 64, 109-110].
- ✓ Chemical action associated with the fluid employed [64, 76].

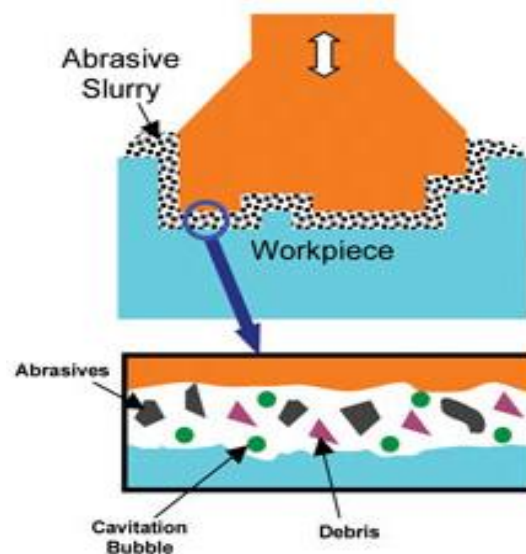


Fig: 2.1 USM material removal mechanisms [64]

The experiment verification has shown that the MRR decreased with the ratio of work piece hardness and tool hardness. Thus, if work piece hardness increases it is expected that the tool hardness is also increased. The choice of tool material is one of the most important decisions, for making maximizing MRR and minimizing tool cost.

During indentation by the abrasive grit onto the workpiece and the tool, the local spherical bulges contact the surfaces and the indentation process is characterised by d_b

rather than by d_g . Figure: 2.2 show the interaction between the abrasive grit and the workpiece and tool.

As the indentation proceeds, the contact zone between the abrasive grit and workpiece is established and the same grows. The contact zone is circular in nature and is characterised by its diameter ' $2x$ '. At full indentation, the indentation depth in the work material is characterised by δ_w . Due to the indentation, as the work material is brittle, brittle fracture takes place leading to hemi-spherical fracture of diameter ' $2x$ ' under the contact zone.

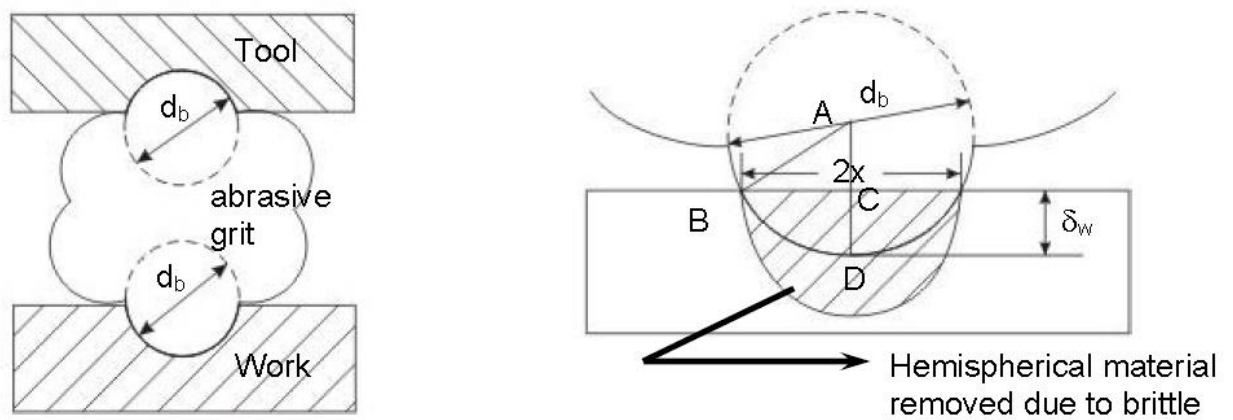


Fig. 2.2 shows the interaction between the abrasive grit and the workpiece and tool [36].

Rosenberg [60] concluded that the MRR is primarily due to hammer blows by the tool on the abrasives in contact with the work surface. **Saha and Bhattacharya [63]** conducted an exhaustive study for the development a comprehensive analytical model for the estimation of MRR and also investigating the mechanism of MRR by considering the major influencing parameters. The experimental results highlighted that fall in MRR at high static load occur.

Riddie [109] and Bulat[111] reported that the cavitation bubbles formed during the ultrasonic oscillation produce a pressure more than $1000\text{kgf}/\text{cm}^2$ on the workpiece surface when they collapse. This pressure rise causes some material removal.

Goetze[112] reported that for tool with equal contact area, there is an increase in penetration rate for tools with larger perimeter leading to more MRR; the effect is mainly due to difficulty of adequately distributing the abrasive slurry over the machining zone.

Kainth et.al [104] presented an analysis of material removal in ultrasonic machining considering direct impact of abrasive grains on the workpiece. Non-uniformity of abrasive grains was considered by using a probability distribution for the diameter of the abrasive particles.

Majeed et.al [113] studied $\text{Al}_2\text{O}_3/\text{LaPO}_4$ composites of varying compositions in order to evaluate the response to machining. They illustrated the significance of LaPO_4 addition on machinability of $\text{Al}_2\text{O}_3/\text{LaPO}_4$ composites in terms of MRR, AE response and whole geometry and associated defects.

Pei and Ferreira [54] worked on the modeling of ductile-mode material removal in rotary ultrasonic machining and concluded that as the vibration amplitude, static force increased and the tool rotational speed increased, MRR increased.

Table 2.1 MRR Models for USM

Mechanism of material removal	Assumptions	Limitations
1. Wiercigroch et al.[107]		
Micro-cracking due to impacts of grains	MRR is a function of the magnitude of impact force and its frequency. Diamond is uniformly distributed over the working part of tool with a uniform grit size. Ultrasonic vibration amplitude, frequency and tool geometry remain unchanged.	Applicable to hard and brittle materials only. Tool geometry changes with progress in machining as the wear on the surface of tool is not uniform.

2. Wang and Rajurkar [114]		
Combined effects of impact indentation and fracture phenomenon	Work-piece is assumed to be semi-infinite solid. Axis of moving grit is perpendicular to the free surface during machining.	Can be used for perfectly brittle material only like amorphous glass. Results are not true for material which exhibits some plastic behavior like carbides
3. Rozenberg Kazantsev[61]		
Brittle fracture	Abrasive particles are incompressible and are of irregular shape but can be considered as spheres proportional to the mean dimensions of particle. Based on the experimental evidence, the statistical distribution of abrasive particle size d is given by: $\phi(d) = 1.095 \frac{N}{d_m} \left[1 - \left(\frac{d}{d_m} - 1 \right)^2 \right]^3$ Where N is number of active abrasive grains, d_m is the mean diameter of grains.	Involves tedious computation and its solution requires numerous integration.
4. M.C. Shaw [64]		
Direct hammering of abrasive particle (Primary) Impacting by free moving particles	All abrasive particles are identical, rigid, and spherical in shape. All impacts are identical. Material removal is proportional to volume of material removed per impact, number of particles impacting per cycle and frequency of impacting.	Analysis does not agree with experimental results qualitatively. Does not predict the effect of variation in amplitude, feed force or frequency correctly.

5. G.E. Miller [43]		
By chipping plastically deformed and work hardened material. In ductile material, MRR depends upon work hardening	Abrasive particles are of cubical size. Plastic deformation is directly proportional to the stress. Plastic flow stress equals Burger vector times shear modulus. Cross –sectional area of the cut does not change during machining. Viscosity effects in water slurry are almost negligible.	Applicable to ductile materials only as MRR is assumed to depend on plastic deformation. Some non realistic assumptions such as cubical shape of grains and participation of all grains in cutting action have been made.

2.3 PROCESS PARAMETERS AFFECTING MATERIAL REMOVAL RATE (MRR) AND TOOL WEAR RATE (TWR).

The major process parameters that affect material removal rate, tool wear rate and surface finish in USM are ultrasonic power, abrasive grain size, amplitude of vibrations, tool material and frequency. The literature corresponding to these factors has been reviewed and presented here:

2.3.1 Work-piece properties

Khairy [115] presented an assessment of the influence of work material properties on mechanism of material removal in USM. Results showed that hard and brittle materials such as glass were machined by brittle fracture at selective cleavage planes, whereas the tough materials face considerable plastic deformation before failure. The contribution of free impact mechanism in material removal was also found to be more in case of brittle materials.

Guzzo et.al [116] investigated the ultrasonic abrasion of different work piece materials like alumina, Zirconia, quartz, glass, ferrite by using a stationary ultrasonic machine. They concluded that in the case of alumina, Zirconia and quartz, the rates of material removal decreased with the depth of machining.

Singh and Khamba [66] investigated the ultrasonic machining of tough materials like titanium and its alloys. The results of study highlighted that higher hardness of work piece was not the criteria for higher material removal rate in machining of titanium and its alloys.

M. Abdul Majeed et al. [113] presents an experimental investigation of the machining characteristics of Al₂O₃/LaPO₄ composites with ultrasonic machining (USM). Al₂O₃/LaPO₄ composites of varying compositions were drilled on an ultrasonic machine with low carbon steel tools (solid and hollow), in order to evaluate the response to machining. Vickers hardness for different compositions indicates critical load dependency on LaPO₄ content. Significance of LaPO₄ content on material hardness highlights the critical content for good sinterability. X-ray diffraction was done to study the phase content. An acoustic emission (AE) signal emitted by the work piece during machining was also analyzed. Ultrascan inspection was carried out to check for any internal defects.

The significance of LaPO₄ addition on machinability of Al₂O₃/LaPO₄ composites in terms of MRR, AE response and hole geometry and associated defects.

1. As the LaPO₄ content was increased, machinability also increases. But with higher-order LaPO₄ content, MRR sets in, explaining the significance of reinforcement content.
2. In all cases, with hollow tool, appreciable enhancement in MRR is observed.
3. Power spectra of monitored AE clearly indicate good machinability with 70:30 composite.
4. XRD intensity profile of machined powder indicates possible relaxation.

Thus, it can be concluded that the addition of LaPO₄ up to 30% is advisable since will improve machinability and sinterability of the composites.

Thoe et.al[71] reviewed the fundamental principles of ultrasonic machining, the material removal mechanisms involved and the effect of operating parameters on material removal rate, tool wear rate and work piece accuracy with particular emphasis on the machining of engineering ceramics.

George et.al [117] determined that electrode wear rate reduced substantially, within the region of experimentation, if the parameters were set at their lowest values, while the parameters set at their highest values increased the MRR drastically for the electric discharge machining of carbon composites.

Singh and Khamba [118] reviewed machining of titanium and its alloys with three different slurries (namely silicon carbide, boron carbide and alumina) and detailed background work on machinability of the same in ultrasonic drilling.

Zhou et.al [119] investigated the ultrasonic vibration diamond cutting of glasses to determine the effect of tool vibration on the brittle–ductile transition mechanism. The effect of cutting speed on the critical depth of cut was studied by groove cutting experiments.

2.3.2 Tool Characteristics

Adithan and Venkatesh [120] reported that the tool wear is maximum at a particular static load, which may be considered optimum for the point of view of MRR. The tool wear increases linearly with the total depth of holes drilled. As the depth of hole drilled increases, there is a reduction in the MRR and an increase in the associated tool wear. The tool wear is proportional to the cutting time and the rate of tool wear has been found to increase with time. They found that for all tool and work combinations, the tool wear rate is proportional to the wear that has already taken place.

Adithan [121] has reported that stainless steel tools exhibit low tool wear as compared to tungsten carbide or mild steel tools. This is due to high resistance to cavitation erosion of stainless steel. In USM, hardness of the tool increases by work hardening, therefore the penetration of the abrasive grains into the tool decreases resulting in higher MRR.

In addition, material removal from the periphery of the work zone becomes greater so that a convex surface is formed in the work piece. This causes plastic deformation of the centre of the tool face, forming a dish. It has also been found that the degree of hardening is higher at the periphery and lowest at the centre for all tool materials.

As a result, soft materials such as copper and brass are unsuitable as tools as they develop burrs at large oscillatory amplitudes. They are also acoustically poor and attenuate the stress wave in large tools. The use of hard metals such as tungsten carbide reduces plastic deformation of the tool surfaces.

Lia et.al [122] investigated the feasibility to machine CMC using RUM. A three-variable two-level full factorial design was employed to reveal main effects as well as interaction effects of three RUM process parameters (spindle speed, feed rate, and ultrasonic power).

Xiao et. al [123] investigated the effect of tool nose radius in ultrasonic vibration cutting of hard material and developed a vibration cutting method. They outlined that in the case of nickel base alloy inconel 600, the allowable tool nose radius in vibration cutting was 0.2 mm, while one in conventional cutting was 0.02 mm. The nearest value ($R_n = 4.7 \mu\text{m}$) of the predicted surface as a suitable nose radius. The vibration cutting's experiment using the suitable nose radius of 0.2 mm showed that the tool fracture was prevented and the machining accuracy was improved in comparison with an initial nose radius of 0.02 mm.

Ezugwu and Wang(1997) in this review on machinability titanium alloys recommended some special machining techniques such as use of ledge and rotary tool and other non-conventional machining methods for titanium as alternative to traditional method for better metal removal rate.

Traditionally, these alloys have been termed as difficult to cut material due to high cutting temperature resulting because of poor thermal conductivity of metal among the other factor like short chip-tool contact length and thin secondary zone. also the cutting tool material undergoes severe thermal and mechanical loads during machining of titanium due to high temperature near the cutting edge thus greatly influencing wear rate and tool life.

2.3.3 Abrasive Slurry Properties

A number of 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, and cost and particle size [124-125]. In order of hardness, boron carbide, silicon carbide and aluminum oxide are the most commonly used abrasives. The abrasive used

for an application should be harder than the material being machined; otherwise the usable life time of the abrasive will be substantially shortened.

Boron carbide is selected when machining the hardest work piece materials or when the highest material removal rates are desired [126,127]. 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 boron carbide (320 grit).

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[128-130].

Guzzo et al. [131] reported a substantial increase in MRR obtained while using abrasive of larger grain size on account of the increase in the stress caused by the impact of abrasive particle over the workpiece surface.

Ramulu [127] reported that use of boron carbide abrasive resulted in material removal rates which were approximately 75% higher than the silicon carbide abrasive for the 400 grit size and 320% higher for 220 grit sizes while machining silicon carbide ceramics. The effect of slurry hardness on MRR has been found to be dependent on the other experimental conditions such as work material properties, tool properties, amplitude of vibration and static load; which could be regarded as the reason for a wide inconsistency of the results reported in the literature available on USM.

Goetze [112] has reported the optimum value of slurry concentration to be close to 12% for all the abrasive grit sizes used in the investigation. The optimum concentration is thought to be one providing a single layer of abrasive over the entire work surface [84]. The values given for the optimum concentration are inconsistent, with a range of 30% to 60% [89], 25% to 40% [49] and 15% to 40 % [52].

The disagreement in the quoted values for the optimum range of concentration can be attributed to the variation of concentration within the working zone under the tool. Obviously such effective local concentration under the tool cannot be the same as that of the feed suspension especially when the static load is too high for the particular acoustic setting [40].

Kennedy et al. [37] pointed out the difficulty of machining a flat at the bottom of a hole because of uneven slurry distribution across the machining face, resulting in fewer active grits at the tool centre.

2.3.4 Surface Roughness

Guzzo et.al [51] investigated the wear mechanisms associated with the ultrasonic abrasion of quartz. Ultrasonic abrasion was carried out in X-, Y-, Z- and AT-cut plates of natural quartz and Z-cut plates of synthetic quartz. They concluded that the wear rate was affected by the crystallographic orientation of quartz specimens.

Spur et.al [131] investigated on ultrasonic assisted creep feed grinding of sintered silicon nitride and alumina. It was concluded that in order to improve the machining process of

advanced ceramics, grinding could be combined with ultrasonic vibrations at high frequencies of about 22 kHz and low amplitudes between 4 and 15 μm .

Scott and Yung [132] presented in process monitoring and control of surface roughness during machining processes via ultrasonic sensing. It was outlined that it was possible to maintain surface roughness within 10% of the target value for tool wear up to 0.3mm.

Simon et.al [16] presented the design of an ultrasonically vibrated work piece holder, and a two stage experimental investigation of ultrasonically assisted drilling of aluminum work pieces.

Pei and Ferreira [133] investigated an experiment of the newly developed rotary ultrasonic face milling machine (RUFM) process and studied the main effects as well as the interaction effects of the process parameters on the process outputs such as material Removal Rate (MRR), cutting force, material removal mode and surface roughness.

Babitsky et.al[11] presented the results of the research in ultrasonically assisted machining and outlined that the application of ultrasonic vibration could improve the surface quality considerably and improvements of up to 25–50% was achieved.

Jain et.al [134] intended to fulfill this need in the area of advanced machining. Various analytical and some semi-empirical/empirical material removal models (approximately 40) for different mechanical type advanced machining processes were comprehensively and exhaustively reviewed, and were presented in a format suitable for quick reference. The performance of any machining process was evaluated in terms of machining rate and surface finish produced.

Jones and Hull [135] developed a better polishing method called as ultrasonic flow polishing and the surface finish was improved by factor of up to 10.1, it was investigated that the process had the capacity to produce a high quality finish on the surface of the cavity and caused minimal deterioration to its profile or dimensional accuracy.

Dhar et.al [136] evaluated the effect of current (c), pulse-on time (p) and air gap voltage (v) on metal removal rate (MRR), tool wear rate (TWR), radial over cut (ROC) on electric discharge machining of Al–4Cu–6Si alloy–10 wt.% SiC_p composites.

Guzzo et.al [137] investigated the potential of ultrasonic machining as a tool to produce seed crystals for hydrothermal growth of synthetic quartz with required surface finish and unconventional geometries. They observed that the density of dislocations, nucleated at the early stage of the growth period, increased with increasing roughness of the seed-crystal surface based on X-ray topographic images.

Adithan and Venkatesh [138] investigated the influences of certain important parameters such as static load, machining time, type of abrasives, grit size and work material on dimensional and form accuracy

2.4 OPERATING PARAMETERS AFFECTING MRR

Power primarily determines the mass of the tool-horn assembly that can be utilized for an application and the frontal cutting area of the tool. The more is power available in an ultrasonic machine, the larger the frontal cutting area of the tool can be supported [14].

The amplitude of vibration (ξ) has been found to affect the machining performance of USM by a number of investigators [43, 60, 104, 112, 139-143]. Higher amplitude is obtained by using a tool with a larger transformation ratio i.e. the ratio of transducer/tool diameter [36, 38, 40, 71].

Shaw [64] showed that MRR is proportional to $\xi^{3/4}$ while other researchers [43, 104, 112, 139, 143] have advocated that MRR is linearly proportional to ξ and yet others [49-51, 57, 61, 76, 142] have suggested that MRR depends upon ξ^2 for constant frequency and static load conditions.

Goetze [112] reported a linear increase in MRR while increasing the amplitude of vibration, provided all other factors such as frequency of vibration and abrasive grit size are kept constant. The linear trend of MRR while increasing the amplitude has been found to be more prevalent when high impact strength materials are machined or fine abrasive powders are used for machining.

Lee and chan [105] reported an optimum value of amplitude beyond which the MRR obtained tends to stabilize. When a larger grit size of the abrasive is coupled with a low value of amplitude, the MRR obtained is reported to be substantially poor due to ineffective circulation of slurry under the tool.

Kainth et al. [104] carried out an analysis considering the non uniformity of abrasive grains to assess the relation between the removal rate and static load/amplitude. Their calculations yielded approximately a linear relation between material removal rate and static load.

Koops [144] indicated that use of a smaller than optimum value for static load is better for reducing the abrasive wear and increasing the tool life. Above the optimum value, the MRR decreases owing to a reduction in the size of abrasive grains reaching the cutting interface (due to crushing effect) and inefficient slurry circulation [25, 36, 50, 52, 143]. The optimum static load for the maximum machining rate has been found to be dependent on the tool configuration, amplitude of vibration and mean grit size [40, 49]. A previous analysis carried out by **Markov [89]** on the experimental results of ENIMS yielded a wide range for the power exponent relating MRR with amplitude for different static loads. The values ranged from 0.5 to 1.7 depending upon the value of static load used.

Experiments conducted by **Neppiras [51]** have shown that in the range of 20 to 50 kHz, the removal rate is proportional to square root of the vibration frequency.

However, **Kazantsev [34]** stated that the abrasion rate is proportional to the frequency while the non linear frequency dependence of machining rate is due to the variation in abrasive concentration in the working zone. Some other researchers have also reported the linear dependence of machining rate on frequency of vibration [112]. Above an upper threshold value, the MRR falls off rapidly where MRR is proportional to square root of frequency [52, 139].

2.5 COMBINATION OF USM WITH OTHER PROCESSES

Sharma et al. [65] outlined a new longitudinal mode ultrasonic transducer with an eccentric horn for micro machining. This device can produce an angular vibration of the order of 40 kHz at the cutting tip attached at the end of the horn. The vibrating tip can be used for precision machining of straight micro grooves, which are difficult to cut using existing precision machine tools. The appearance of machined surface has been found to be excellent when compared with that obtained in conventional groove machining.

Ishikawa et al. [32] contrived a new drilling method that combines ultrasonic vibrations of a diamond core drill and low-frequency vibrations of the work-piece and produced a combined vibration drilling apparatus for experimentation. The drilling force was observed to decrease by 70% as compared to conventional drilling using this newly developed method. Roughness of the drilled hole was found to be higher than non-vibration drilling, but chipping at the edge of the hole was reduced significantly.

Kai and Takahira [33] highlighted micro machining by the application of work-piece vibration. Using this set up, successful machining of micro holes in quartz, glass and silicon substrates has been achieved.

Chang and Bone [16] outlined the application of ultrasonic vibration for burr size reduction in drilling process. High-frequency and low-amplitude vibration were added in the feed direction during drilling of the work-piece which was composed of aluminium. The results demonstrated that under suitable ultrasonic vibration conditions, the burr height and width could be reduced in comparison to conventional drilling.

Choi et al. [145] explored the use of chemical-assisted ultrasonic machining for machining of glass. To obtain the chemical effects, a low concentration hydrofluoric acid solution was added to the slurry. The hybrid method was found to be superior in terms of material removal rate and integrity of the machined surface. The surface roughness was also found to improve and the machining load was decreased significantly as compared to the conventional USM method.

Lau et al. [147] investigated the ultrasonic-aided laser drilling of alumina-based metal matrix composites. The conventional pulsed Nd: YAG laser drilling involved problems of

limited depth of drill, non-cylindrical hole profile and the presence of excessive recast layer. The hybrid ultrasonic-laser drilling technique was found to improve the capabilities in deep hole drilling with more precision. The thickness of heat affected zone (HAZ) was reduced by 30% under the action of ultrasonic vibration which aided in effective utilization of the laser energy in vaporizing the material. A mathematical model was also proposed to describe the shape of the machined hole.

Tsutsumi et al. [73] investigated the machining performance of ultrasonic-aided core drilling method for machining of ceramics. The thrust force was reported to decrease by 70% without affecting the surface quality of the machined hole. This was contributed to the more effective penetration of diamond grits into the surface of work material, reducing the required drilling thrust force. The width of the chip produced was increased and the chipping of the edges was found to be lowered.

2.6 CRYOGENIC TREATMENT ON DIFFERENT TOOL MATERIALS

Cold treatments or subzero temperature treatments have documented research from as far back as the 1930s, when German companies used it on components of aircraft engines. Cryogenic processing had its U.S. origins in the 1940s, but that was a very primitive process compared to today's procedures. During the 1950s, research related to CT was reported in the form of articles in magazines like *Tooling and Production*, etc. The most notable and persistent pioneer of cryogenics was Dr. Randall Barron of Louisiana Technical university. Papers written by him are widely cited in the cryogenics research and industry [91–93]. Till around the 1960s, attempts have been done by direct immersion into liquid nitrogen results cracking of many components. Subsequently, the research about CT has been validated during the 1980s by the first result in machine tools [90, 94]. Later, with research and development, computerized temperature control systems have been developed to get crackles cryogenic treated components to achieve maximum benefits [95-98].

Sekhar et al.[148] studied the effect of cryogenic treatment on wear resistance of M1(molybdenum high speed steel),EN 19(chromium molybdenum constructional steel) and H 13(hot die steel) tool steel. The samples were first heat treated and re-tempered after

cryogenic treatment which was carried out at 0C, -20C, -40C, -80C and 190C. the results were highly significant as improvement in wear resistance under deep cryogenic treatment range from 315% in EN19 to 382% in M1 samples.

Akhbarizadeh et al. [149] study the effect of deep (-185C) and shallow (-63C) cryogenic treatment on wear behavior of die steel by performing wear test using a pin-on-disc wear test. They finding revealed that cryogenic treatment decrease the retained austenite and hence improve the wear resistance and hardness. The improvement was significant in DCT due to more homogenized carbide distribution, the retained austenite elimination and higher chromium carbide percentage in comparison with shallow cryogenic treatment.

Barron[150] proposed that beside the transformation of the retained austenite into martensite, the improvement in wear resistance of tool was also carried out by presence of hard and small carbide particles well distributed among the larger carbide particles within the martensite that resulted due to cryogenic treatment. Before the cryogenic treatment the microstructure showed relatively large carbide of the order of 20 μm dispersed in the matrix. However after the cryogenic treatment carbide particle as small as 5 μm were found.

Silva et al.[151] carried out experiments after deep cryogenic treatment of M2 high speed steel, lathe tool, twist drill and milling cutter tool to verify the effect of cryogenic treatment. It was found that the retained austenite after treatment was near 0%. The laboratory test on lathe tool didn't indicate any effect on hardness of treated tool while on rapid facing test it was discovered that cryogenically treated tool presented longer tool lives at different spindle speed and feed rates.

Gill et al.[152] discussed the wear behavior of cryogenic treated tungsten carbide inserts under dry and wet conditions and concluded that performance of cryogenically treated carbide insert depend a lot on cutting conditions. The fact that tungsten carbide insert retained superior properties included by cryogenic temperature for a relative longer time during wet machining was attribute to the application of coolant which reduce tool workpiece interface temperature.

J. D. Darwin et al.[153] Taguchi Design of Experiment (DOE) method is applied to identify and to optimize the critical parameters of DCT on an 18% Cr martensitic

stainless steel used for piston rings. The Analysis of Variance (ANOVA) of wear test results has pointed out that the most significant factor has been the soaking temperature (72% in contribution), followed by the soaking time (24%) and the cooling rate (10%). Little importance (2%) for the temperature of the tempering process performed after DCT has been observed,

Hong and Ding [154] applied the cryogenic treatment to conventionally machined Ti-6Al-4V alloys. The study was carried out to evaluate the cutting temperature in these difficult to machine alloys under different set of cooling conditions. Jet liquid nitrogen was used to provide the cooling at cutting interface and results of various cooling approaches were found. The study concluded that applying liquid nitrogen in close proximity to the tool cutting edge can significantly reduce the tool temperature. It was also found out that with cryogenic cooling, titanium diffusivity to tool material, a characteristics responsible for most tool wear in Ti-6Al-4V machining become negligible.

Reddy et al. (155-156) observed that the surface roughness of the workpiece was lower by approximately 20% when the workpiece was machined with deep cryogenic treated tungsten carbide tool inserts in comparison with untreated inserts for cutting speeds in the range between 200 and 350 m/min.

2.7 SUMMARY AND GAP IN LITERATURE REVIEW

The engineers and technologists know the process of USM for over five decades now, but accelerated developments in this area have occurred only during the last few years. Extensive research in this field has led to better understanding of the phenomenon of metal erosion, development of processes leading to higher rates of metal removal, excellent surface finish and low tool wear. Some machines with numerical and adaptive controls have also appeared in the market. Qualitative information about tool wear or the work piece erosion has been investigated. A comprehensive review of literature on diverse aspects of ultrasonic machining and machining characteristics of tungsten carbide, satellite and diamond has been investigated, which has helped to identify the areas explored in this study. A few researchers have presented their work on ultrasonic machining of titanium in past and results have been modeled for the different tool materials, slurry types, grit size and power ratings for the different grades of titanium. However no work up till now has been reported about impact of cryogenic treatment on

different tool materials (HSS, HCS, SS) in ultrasonic machining. Cryogenic treatment, as suggested by several researchers, has been found to improve the wear heavier and machining characteristics of certain material under conventional machining. The effect of same at different temperature ranging from plane to deep cryo-treatment can be studied to know the impact on parameters like MMR, TWR and Surface roughness in ultrasonic machining of titanium. Mixing of various additives and chemicals of different slurries may have different effect on material removal and other relative parameters but no such literature has found in ultrasonic machining of titanium. Machining characteristics of titanium has been explored using USM for their application in concerned manufacturing industry.

DESIGN OF EXPERIMENTATION**3.1 INTRODUCTION**

Ultrasonic drilling machine AP-500 (Sonic Mill, USA) was used for this experimentation shown in Figure 3.1. An experimental set-up having a provision for variation in process parameters was designed and fabricated. The dimensions of the tool were decided keeping in view the limitations of the horn shape to economize the machining operation. An electronic balance (Metler, Least count: 0.1 mg); and stop watch (Least count: 0.01 min) were used to determine MRR and TWR. Two repetitions were made for the entire experimentation and corresponding MRR, TWR, SR and Micro-hardness were recorded.



Fig: 3.1 Sonic-Mill AP500 watts (USA)

In order to minimize the effect of slurry temperature variation on the machining characteristics of titanium and its alloys, the entire experimentation was carried out in

controlled temperature conditions with maximum permissible variation of 2°C. Each experimental run was replicated twice during the entire experimentation to minimize the effect of noise in the machining parameters. The corresponding material removal rate (MRR) and toolwear rate (TWR) for each experimental run were recorded.

The microstructure testing of the machined samples was performed on a scanning electron microscope (SEM) at a magnification of 250X and 500X, after preparing and treating the samples with Kroll's reagent (2% HF, 10% HNO₃ 88% distilled water). For measuring surface roughness (Contact Profilometer PGI 120 (Taylor Hobson Make)) was used. The hardness testing of the machined samples was performed on micro hardness tester under a static load of 100 gm. The samples for micro-hardness testing were prepared by polishing the machined cavities with boron carbide abrasive powder with a very fine slurry grit size (420 and 600, mean particle size 10 µm) to obtain the required surface finish for the testing.

3.2 DESCRIPTION OF ULTRASONIC MACHINE

The USM machine tool used for the study is of 500 W capacities, which consists of an ultrasonic spindle kit; a constant pressure feed system and slurry flow system. The ultrasonic spindle kit comprises an ultrasonic spindle, mounted with cylindrical horn of 25.4mm diameter, a power supply unit

The ultrasonic spindle kit comprises an ultrasonic spindle mounted with cylindrical horn; a power supply converts 50 Hz electric supply to high frequency 20 kHz AC output. This is fed to piezoelectric transducer located in the spindle. The transducer converts the electrical input into mechanical vibrations. The amplitude of vibrations is made fixed in range of 0.0253-0.0258 mm with a frequency of 20 kHz +/- 200 Hz. The static load for feed rate was fixed at 1.724 kg and slurry flow rate at 26.4 L/min. The replaceable tools used for machining were made as solid, single piece unit by machining on center lathe. All tools having same area of cross-section i.e. Ø 10 mm. The Figure 3.2 represents the ultrasonic machine tool geometry which is used in the experimentation work.

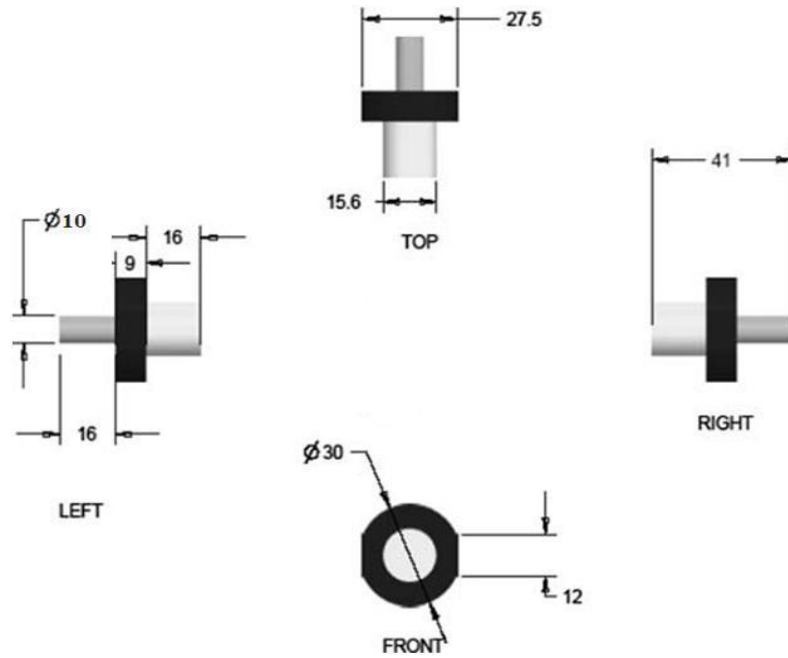


Figure 3.2 Represents the detailed drawing of the tool.

The other parts of the experimental set up shown in figure 3.7, amplitude coupling (figure 3.3), ultrasonic transducer (figure 3.4), Pump for re-circulation of abrasive slurry (figure 3.5) and Power rating set-up (figure 3.6)



Figure 3.3
Amplitude coupling for
compact 500W ultrasonic
machine



Figure 3.4
Ultrasonic transducer for
compact 500W ultrasonic
machine



Figure 3.7
Ultrasonic machining setup
(Type: Sonic Mill, USA)



Figure 3.5
Pump for re-circulation of
abrasive slurry



Figure 3.6
Power rating set-up for
ultrasonic machine

3.3 OBJECTIVE AND ISSUES

The study was aimed to carry out research on ultrasonic machining to investigate the machining characteristics of titanium (ASTM Grade-2 and Grade-5) using different tool materials with and without cryogenic treated and different abrasives slurries and proposed to develop an empirical model using the significant parameters from the study for use in manufacturing industry.

The following issues have been taken up during this research work:

1. Material removal rate (MRR) and Surface roughness (RS) of titanium (ASTM Grade-2 and Grade-5) as work material has been explored in ultrasonic machining with the following tool materials; High carbon steel, High speed steel, Stainless steel.
2. Tool wear rate (TWR) and Dimensional accuracy of aforesaid tool materials (without cryogenic and with cryogenic treated) has also been explored with Titanium and its alloys as a work material.
3. To investigate the effect of various abrasives slurries like Alumina, Boron carbide and combination of different slurries using titanium and its alloys as a work material.
4. Material characteristics like microstructure and hardness have also been determined for the given work samples.
5. The optimal combination has obtained for their application in the concerned manufacturing industry.

3.4 OVERALL METHODOLOGY OF THE STUDY

The overall research work has been divided into following phases:

- 1) Detailed Literature Survey
- 2) Preliminary Experimentation followed by detailed Experimental Design
- 3) Experimental trials as per design
- 4) Experimentation with different tool material and slurries.
 - Without Cryogenic treatment
 - With Cryogenic treatment

- 5) Multi-response optimization using Grey relational analysis technique.
- 6) Empirical model for multiple responses.

Literature on ultrasonic machining and its constituent aspects has been reviewed extensively to design a methodology for carrying out analysis on machining characteristics of titanium and its alloys. The literature survey has been paying attention on various aspects of USM covering economic and technical viability. In the beginning of D.O.E. phase, pilot experiments have been performed for preliminary study of the capability of USM for machining of titanium and its alloys. The various machining conditions, their ranges and levels have been selected based upon the results of Preliminary study.

Using D.O.E. methodology, statistical planning and designing of experiments has been performed to determine MRR of titanium (ASTM Grade-2) and titanium alloy (ASTM Grade-5) with different tool materials (H.C.S., H.S.S. and SS) under controlled experimental conditions. Accordingly tool wear rate (TWR) of the aforesaid tool materials in combination with titanium as work material has been established. Taguchi technique for robust design, using L18 orthogonal array has been used to design the experiments.

The experimentation work will be carried out with cryo-treated (deep) and untreated tool and work piece to investigate the effect on machining characteristics of work materials and the comparison between the two will be made to access the effect of cryo-treatment. The impact of input parameters on MRR, TWR, Surface Roughness (SR) and Micro Hardness has been established for machining of titanium with aforesaid tool materials. The input parameters considered are given as following:

- Type of Abrasives used
- Grain size of the Abrasives
- Power rating of the ultrasonic drilling machine
- Slurry concentration

The results showed that the response variables were strongly influenced by the control factors (input parameters). So, the results obtained after experimentation have been modeled using Grey relational analysis technique.

3.5 TAGUCHI APPROACH FOR DESIGN

There are certain steps that Taguchi has suggested to be taken in conducting the experimental study using robust design approach, which are discussed as following

Steps in conducting experimental study:

1. **Define the problem:** This is concerned with establishment of the aim of the experimental research. A clear and accurate statement of the problem to be solved is a must before going ahead with the investigation.
2. **Determine the objective:** Identification of the output characteristics or response of interest that is to be optimized is done. The response must be measurable and preferably, with good additivity. To establish measurement reliability, additional experiment may be required.
3. **Conduct a brainstorming session:** This is undertaken by the people who are closely related to the product or process under investigation to collectively decide the controllable and uncontrollable factors, to define the experimental range and appropriate factor levels. Taguchi believes that it is generally preferable to include as many factors as possible for the initial screening. The information required can also be obtained from the already available literature or research data.
4. **Design the experiment:** In this phase, the selection of appropriate experimental design is done by assigning the levels of the design factors and their interactions to the columns of the inner array. Taguchi has also recommended some rules for appropriate allocation of columns to the interactions and these must be followed while designing the experiment. The noise factors levels are allocated to outer array columns.
5. **Conduct the experiment:** Perform the experimental trials, preferably replicating each trial (with randomization) to minimize the effect of experimental error. The experimental results are collected and recorded.
6. **Analyze the data:** The performance measures are evaluated for each trial of the inner array and analysis is made using appropriate statistical techniques such as analysis of variance, regression etc.
7. **Interpret the results:** The optimal levels for variability control factors (VCF) and

target control factors (TCF) are identified from the information obtained by conducting analysis phase.

8. ***Run a confirmatory experiment:*** It is necessary to verify, by some follow up trails that the new parameter settings; which are claimed to be optimal, improve the response or performance measures over their value at initial settings. Hence, experiments are conducted at the optimal process settings to conform the optimality of the solution. A successful confirmation experiment alleviates the concerns regarding the possibilities of wrong selection of factor levels or assumptions of no interactions or any other improper assumptions underlying the response model.

If the predicted results are not conformed, additional experiment may be required or reiteration of steps 3-8 may be necessary.

3.6 PRELIMINARY STUDY TO ASSESS THE EXISTING STATUS

In order to identify the process parameters that affects the machining performance in term of MRR, TWR and quality of components processed by USM. The parameter can be classified as follows:

1. ***Machine based parameters:*** Ultrasonic power, amplitude and frequency of vibrations, medium flow rate, temperature of medium, type of tool material, shape of tool horn
2. ***Media based parameters:*** Viscosity, type of abrasive material, grain size (type and shape), slurry concentration of abrasives in medium (by volume or mass).
3. ***Work-piece based parameters:*** Geometry of work-piece (circular, rectangular, or irregular shape etc.), workpiece thickness, and chemical composition of the work material.

The following six independent parameters have been chosen for this study:

1. Work materials
2. Tool materials
3. Different types of abrasives
4. Abrasive grit sizes

5. Abrasive slurry concentrations
6. Power ratings of ultrasonic machine

The range of these parameters will be selected on the basis of preliminary experiments conducted by using one variable at a time approach. The work pieces selected are Pure Titanium (ASTM Grade-2) and Titanium (ASTM Grade-5) alloy. Three different tool materials: High Carbon Steel, High Speed Steel and Stainless Steel with two different conditions: Cryogenic treated and non cryogenic treated. Two abrasive materials and one is the mixtures of both materials were chosen for the slurry preparation: Alumina oxide (Al_2O_3), Boron Carbide (B_4C) and Mixture of Alumina and Boron carbide ($Al_2O_3 + B_4C$). The slurry was prepared with different volumetric concentrations of different abrasive material with water as a slurry medium.

3.7PARAMETER DESIGN

This is the part of technique that identifies those settings of the controllable factors that reduce performance variation caused by the noise factors while keeping the response of interest on target. At this stage once attempt to reduce or remove the effect of noise factors rather than the noise factors themselves. This variation is simulated during the experiment, by systematically varying the noise factors at each of the various settings of the controllable factors under study.

The controllable factor settings studied are those suggested by the rows of an experiment design (inner array), usually a fractional orthogonal array; in such a design, every level of a factor occurs with every level of all other factors the same number of times.

At every level-combination of the controllable factors, some observations should be obtained while changing the settings of the noise factors, assuming of course that the noise factors can be controlled and changed, at least for the purposes of the experiment. A fractional orthogonal array can then be utilized to determine the level combinations of the noise factors. In such a case, the experimenter can simulate the variability of the noise factors on each controllable factor setting and determine the setting which minimizes the variability.

3.8 SELECTION OF FACTORS LEVELS

As the objective of study is aimed to carry out research on ultrasonic machining to investigate the machining characteristics of titanium (ASTM Grade-2 and Grade-5) as a work material using different tool materials with different conditions i.e. cryogenic and non cryogenic treatment and different abrasives slurries and proposed to develop an empirical model using the significant parameters from the study for use in manufacturing industry. In light of above objective, the factors levels have been decided depending upon commercial availability, experimental constraints and machine tool capacity. This information is available from preliminary examinations. For example, six levels of tool were selected because these three commercially available tools resulted in different behaviors of MRR and TWR. So, each tool material has been designated as a level. Similarly three levels of slurry concentration, slurry type, power rating and slurry grit size were designated. These levels represent threshold points from where change in trend has been observed. Table 3.1 shows different control variables and their levels.

Table 3.1 CONTROL VARIABLES AND THEIR LEVELS

Sr. No:	Factors	Levels	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6
A	Tool	6	Without Cryogenic Treatment			With Cryogenic Treatment		
			HSS	HCS	SS	HSS	HCS	SS
B	Slurry type	3	Alumina	Boron carbide	Alumina + Boron carbide			
C	Slurry grit size	3	220	320	500			
D	Slurry concentration	3	20	25	30			
E	Power rating	3	20	50	80			

3.9 SELECTION OF ORTHOGONAL ARRAY

Orthogonal arrays are special experimental designs that require only a small number of experimental trials to discover main factor effects. Orthogonal arrays could be considered as “fractional factorial designs” and symmetrical subsets of all combinations of treatments in the corresponding full factorial designs. Before one attempts to select an orthogonal array to guide the design optimization experiments, one must answer the following critical questions [66].

1. How many factors are to be studied?
2. How many treatment levels are possible for each factor?
3. What specific 2-factor interactions are to be investigated?
4. Would one encounter any particular difficulty during the runs i.e. some factors may not permit frequent treatment changes?

For the selection of a particular orthogonal array, the number of parameters, the number of levels, and their possible interactions must be taken into consideration. The case under study involves six parameters, having one is of six levels (i.e. tool material) and left is of three levels. Now as per requirements of the study L18 OA comes out as one of the solution. The modified L18 OA is shown in table 3.2. Interaction between column 1 and 2 can be estimated without sacrificing any column. Column 1 and 2 can be combined to form a 6-level column. Interactions between any other pair of columns are confounded partially with the remaining columns. Based upon the standard L18 OA, response variables and control log for experimentation has been shown in tables 3.3 & 3.4 respectively.

Table 3.2: L18 Orthogonal Arrays

Experiment Number	Column							
	1	2	3	4	5	6	7	8
1	1	1	1	1	1	1	1	1
2	1	1	2	2	2	2	2	2
3	1	1	3	3	3	3	3	3
4	1	2	1	1	2	2	3	3
5	1	2	2	2	3	3	1	1
6	1	2	3	3	1	1	2	2
7	1	3	1	2	1	3	2	3
8	1	3	2	3	2	1	3	1
9	1	3	3	1	3	2	1	2
10	2	1	1	3	3	2	2	1
11	2	1	2	1	1	3	3	2
12	2	1	3	2	2	1	1	3
13	2	2	1	2	3	1	3	2
14	2	2	2	3	1	2	1	3
15	2	2	3	1	2	3	2	1
16	2	3	1	3	2	3	1	2
17	2	3	2	1	3	1	2	3
18	2	3	3	2	1	2	3	1

The levels for each factor during each trial are more conveniently expressed by means of experimenter's log sheet (refer table 3.4). In the present investigation, five response variables have been selected-Material Removal Rate (MRR), Tool Wear Rate (TWR), Surface Roughness (SR) and Micro-hardness. The details of these response variables are given in table 3.3.

Table 3.3: Response Variables

Response No:	Response Name	Response Units	Response Type
Response 1	Material Removal Rate(MRR)	mm^2/min	Higher the better
Response 2	Tool Wear Rate(TWR)	mm^2/min	Lower the better
Response 3	Surface	Microns(μm)	Lower the better

	Roughness(S.R.)		
Response 4	Micro-hardness	HV	Higher the better
Response 5	Dimensional error	Microns(μm)	Lower the better

Table 3.4: Control Log for Experimentation

Trial No:	Work Material	Tool Material	Abrasives	Grit Size	Concentration	Power Rating
1	Ti(Grade-2)	HCS	Al ₂ O ₃	220	20	20
2	Ti(Grade-2)	HCS	B ₄ C	320	25	50
3	Ti(Grade-2)	HCS	Al ₂ O ₃ +B ₄ C	500	30	80
4	Ti(Grade-2)	HSS	Al ₂ O ₃	220	25	50
5	Ti(Grade-2)	HSS	B ₄ C	320	30	80
6	Ti(Grade-2)	HSS	Al ₂ O ₃ +B ₄ C	500	20	20
7	Ti(Grade-2)	SS	Al ₂ O ₃	320	20	80
8	Ti(Grade-2)	SS	B ₄ C	500	25	20
9	Ti(Grade-2)	SS	Al ₂ O ₃ +B ₄ C	220	30	50
10	Ti(Grade-5)	HCS	Al ₂ O ₃	500	30	50
11	Ti(Grade-5)	HCS	B ₄ C	220	20	80
12	Ti(Grade-5)	HCS	Al ₂ O ₃ +B ₄ C	320	25	20
13	Ti(Grade-5)	HSS	Al ₂ O ₃	320	30	20
14	Ti(Grade-5)	HSS	B ₄ C	500	20	50
15	Ti(Grade-5)	HSS	Al ₂ O ₃ +B ₄ C	220	25	80
16	Ti(Grade-5)	SS	Al ₂ O ₃	500	25	80
17	Ti(Grade-5)	SS	B ₄ C	220	30	20
18	Ti(Grade-5)	SS	Al ₂ O ₃ +B ₄ C	320	20	50

The 18 sets of experiments were performed in order to accommodate all the factors shown in table 3.4. These 18 sets of experiments have been repeated two times and final conclusions have been made by taking averages of results of two sets of observations.

3.10 EXPERIMENTATION WORK

The experimentation for the study undertaken consisted of eighteen set-ups. In the first set-up, experiment was performed to determine the effect of HCS tool on Titanium (ASTM Grade-2) work using alumina slurry of 220 grit size with 20% concentration by weight in distilled water as suspension media. The experiment was started by setting power rating of the machine at 20 % (of 500W) i.e. 125W of ultrasonic drilling machine. Figure 3.8 shows the schematic of the ultrasonic machine tool used for experimentation for eighteen set-ups.

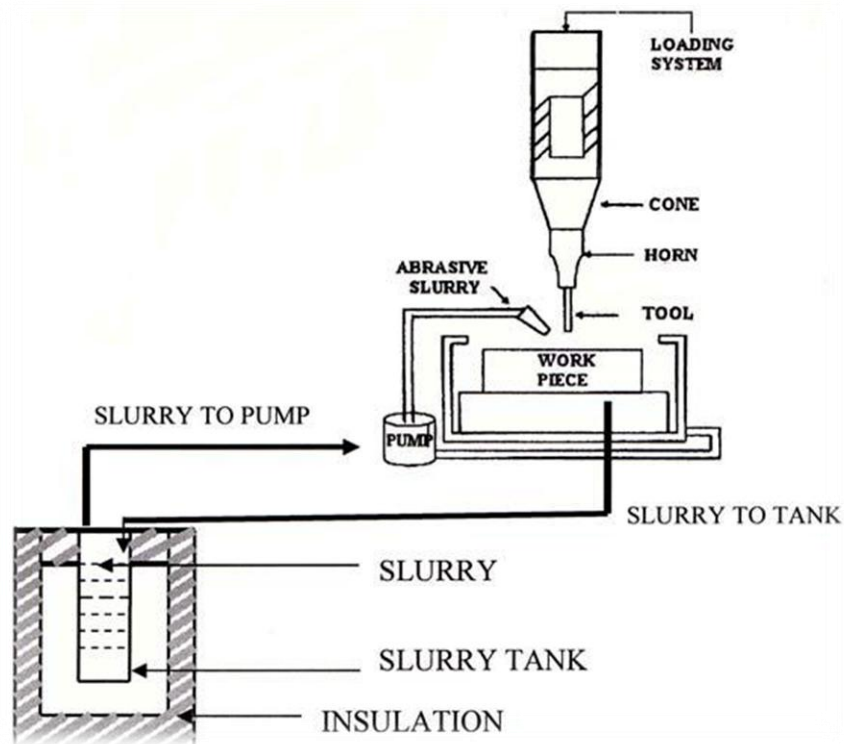


Figure 3.8 Schematic representation of USM process[51].

The initial weight of titanium work-piece and H.C.S. tool was measured with the help of electronic balance (Least count: 0.1 mg). Then the machine was allowed to drill the hole until a time limit of 10 min was reached. Meanwhile, the slurry flow rate was maintained at the predefined values (table 3.5). The time taken for machining 10 min of cut was recorded using a stop watch. The tool used was of solid cylindrical cross section. The weight of the tool as well as work-piece was measured again after the machining. The material removal rate

(MRR) was calculated by taking the ratio of weight loss of work to the product of machining time and density of work material. The tool wear rate (TWR) was calculated by taking the ratio of weight loss of tool to the product of machining time and density of tool.

Table 3.5 Constant Parameters

Process Parameters	Descriptions
Frequency of vibration	21 kHz
Static load	1.63 k g
Amplitude of vibration	25.3-25 .8 μm
Time taken for each cut	10 min
Thickness of workpiece	5.2 mm
Tool Geometry	Straight cylindrical 10 mm $\varnothing$
Mass of the Tool	56 gm
Slurry Temperature (ambient temp.)	28° C
Slurry Flow rate	36.4x10 mm /min
Slurry Media	Water

3.11 MEASURING AND TEST EQUIPMENT IS USED

Micro hardness, surface roughness and dimensional error tests were conducted on all the samples, produced after each of the 18 trials. Also, MRR was measured using a weighing machine, while TWR was measured using a Vernier Calliper. The details of important test equipment used in experimental study are given below:

3.11.1 Surface Roughness Tester

Surface roughness was measured using the *Contact Mechanical Profiler PGI 120 (Taylor Hobson Make)* available in the Optics lab of CSIO, Chandigarh. It uses conical stylus

diamond tip which record height variation of surface along a straight line at a time being in contact with surface. The equipment uses the stylus method of measurement, has profile resolution of 12.8 nm at 10mm range and measure roughness upto 100 μ m. A tracing length of 10 mm was used for analysis. Surface roughness of each sample was measured at two different positions of each machined sample.



Fig 3.9: Contact Profilometer PGI 120 (Taylor Hobson Make)

Table 3.6: Technical Specifications Of PGI-120 Mechanical Profiler	
Traverse Length	120mm
Measuring Speed:	1mm and 0.5mm/sec
Traverse Speed	Up to 5mm/sec
Gauge Type	Phase Grating Interferometer
Measuring range	10mm
Resolution	12.8 nm at 10 mm range
Range to resolution ratio	780,000:1
Straightness accuracy	0.5 μ m over 120mm traverse

Measurement Capabilities Of PGI-120	
Compatible	With aspheric surface generator and polisher
Analysis	Form, figure and finish
Job diameter	120mm
Roughness accuracy	~10-15 nm at 10mm
Figure accuracy	~0.1 μm / 20mm and ~0.5 μm /120mm

3.11.2 Scanning Electron Microscope (SEM) Machine

Microstructure was carried out of some selected samples on Scanning Electron Microscope, (model EVO® MA 15) of ZEISS, Germany, available in Central Forensic Science Laboratory (CFSL), Chandigarh. The range of magnification from $< 5\times$ to 1,000,000x. SEM of samples was carried out on 250x.



Fig: 3.10: Scanning Electron Microscope[CFSL LAB]

3.11.3 Micro Hardness Machine

Micro hardness was measured on a computer interfaced Micro Hardness Tester, (LEICA VMHT AUTO) available at Terminal Ballistics Research Laboratory (TBRL) in Ramgarh, Haryana. The micro hardness measurement is dependent on the diameter of indentation on the samples. The indents formed in the pyramid shaped indenter were measured with Quantimet software using a static load of 100gm for 20 seconds. The micro hardness was measured at machined as well as non machined region.



Figure: 3.11:Micro Hardness Machine, (LEICA VMHT AUTO)

3.12 ANALYSIS OF RESULTS

3.12.1 Signal-to-Noise Ratio

The signal to noise ratio is obtained from Taguchi's methodology. The term "signal" represents the desirable value (mean) and the "noise" represents the undesirable value (standard deviation). In the taguchi method, a loss function has been defined to gauge the deviation between the experimental and desired value of a performance characteristics. The loss function is further transformed into a signal-to-noise ratio. Finding a correct objective function to maximize in an engineering design problem is very important. Failure to do, can lead to great inefficiencies in experimentation and even wrong conclusions about the optimum levels. The task of finding what adjustments are meaningful in a particular problem

and determine the correct S/N ratio is not always easy. Three categories of performance characteristics are usually used in the analysis of the S/N ratio, i.e. lower-the-better, Higher-the-better and nominal-the-best. These are explained as follows:

❖ ***Lower-the-Better type problem***

For lower the better type problem, the quality characteristics is continuous and non negative i.e. it can take any value from 0 to ∞ . Its most desired value is zero. Such problems are characterized by the absence of a scaling factor or any other adjustment factor. Because there is no adjustment factor in these problems, one should simply minimize the quality loss without adjustment i.e. we should minimize:

$Q = k$ (mean square quality characteristics)

$$Q = k \left(1/n \sum_{i=1}^n y_i^2 \right)$$

Minimizing Q is equivalent to maximizing, defined by the following equation\

$$\eta = -10 \log_{10} \left(1/n \sum_{i=1}^n y_i^2 \right)$$

where η is the inspection index, defined as the signal-to-noise ratio (unit: dB), n is the number of repetitions for each trial independently of the values assigned to noise factors, and y_i is the value of the response obtained in the i^{th} repetition of the trial. In this case the signal is constant, to make quality characteristics equal to zero. Therefore, the S/N ratio measures merely the effect of noise.

❖ ***Higher-the-Better type problem***

Here, the quality characteristic is continuous and non-negative and one would like to be as large as possible. Also, there was no adjustment factor. The objective function to be maximized in this case is given by:

$\eta = -10\log_{10}$ (mean square reciprocal quality characteristics)

$$\eta = -10\log_{10}\left(1/n \sum_{i=1}^n 1/y_i^2\right)$$

❖ ***Nominal-the-Best type problem***

Here, as in lower-the-better type problem, the quality characteristic is continuous and non-negative i.e. it can take any value from 0 to ∞ . Its target value is non zero and finite. For these problems when the mean becomes zero, the variance also becomes zero. Also, for these problems we can find a scaling factor that can serve as adjustment factor to move the mean on target. This type of problem occurs frequently in engineering design. The objective function to be maximized for such problem is:

$$\eta = 10\log_{10}(\mu^2 / \sigma^2)$$

$$\sigma^2 = 1/(n-1) \sum_{i=1}^n (y_i - \mu)^2$$

Where μ is mean and σ^2 is variance.

The optimization of the nominal-type-best problems can be accomplished in two steps:

1. Maximize or minimize sensitivity to noise. During this step we select the levels of control factors to maximize while we ignore the mean.
2. Adjust the mean on target. During this step we use the adjustment factor to bring the mean on target without changing.

For the case under study larger is the best for MRR and Micro-hardness, smallest is the best for TWR and SR type situation is selected as objective function, as because there were four response parameters namely MRR, TWR SR and Micro-hardness and all three output responses are interrelated and have interdependence among each other.

3.12.2 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 characteristic due to the change in that process parameter. F value is defined as:

$$F = \frac{MS_{for\ term}}{MS_{for\ the\ error\ term}} \text{ (Equation....3.7)}$$

Computation 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.

Analysis of variance

The knowledge of the contribution of individual factors is critically important for the control of the final response. The analysis of variance (ANOVA) is a common statistical technique to determine the percent contribution of each factor for results 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 a brief description of is given as following.

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

Let 'A' be a factor under investigation

$$SS_T = \sum_{i=1}^N (y_i - \bar{T})^2 \text{ (Equation....3.8)}$$

Where N = Number of response observations, $\bar{T}$ is the mean of all observations y_i is the i^{th} response

Factor Sum of Squares (SS_A) - Squared deviations of factor (A) averages from overall average

$$SS_A = \left[\sum_{i=1}^{k_A} \left(\frac{A_i^2}{n_{Ai}} \right) \right] - \frac{T^2}{N} \quad (\text{Equation....3.9})$$

Where

A_i = Average of all observations under A_i level = A_i / n_{Ai}

T = sum of all observations

$\bar{T}$ = Average of all observations = T / N

n_{Ai} = Number of observations under A_i level

Error Sum of Squares (SS_e) - Squared deviations of observations from factor (A) averages

$$SS_e = \sum_{j=1}^{k_A} \sum_{i=1}^{n_{Ai}} (y_i - \bar{A}_j)^2 \quad (\text{Equation....3.10})$$

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

$$SS_{A \times B} = \left[\sum_{i=1}^c \left(\frac{(A \times B)_i^2}{n_{(A \times B)_i}} \right) \right] - \frac{T^2}{N} - SS_A - SS_B \quad (\text{Equation....3.11})$$

Sum of Squares of factors for dummy treatment level

The level symbols for A_1 & $A_{1^{**}}$, both indicate the same test condition w.r.t. factor A. Therefore

$$SS_A = \frac{(A_1 + A_{1^{**}})^2}{n_{A1} + n_{A1^{**}}} + \frac{A_2^2}{n_{A2}} - \frac{T^2}{N} \quad (\text{Equation....3.12})$$

$$SS_e = \frac{(A_1 - A_1^{**})^2}{n_{A1} + n_{A1^{**}}} \quad (\text{Equation....3.13})$$

$$SS_{A \times B} = \left[\sum_{i=1}^c \left(\frac{(A \times B)_i^2}{n_{(A \times B)_i}} \right) \right] - \frac{T^2}{N} - SS_A - SS_B - SS_e \quad (\text{Equation....3.14})$$

3.13 TEST RESULTS FOR WORKPIECE & TOOL MATERIALS

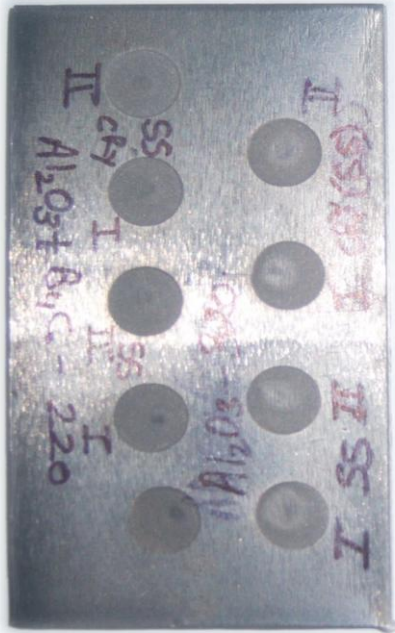
Titanium as a workpiece material in two different grades (ASTM Grade-2 and Grade-5) and three tool materials High carbon steel, High speed steel, Stainless steel having with or without cryogenic treatment were used. Before the start of experimentation, the chemical composition of workpiece and electrode material was measured on an Optical Emission Spectrometer DV-6. The typical percentage composition and important mechanical properties of titanium and its alloy is used in this work have been detailed in Table 3.7 and Table 3.8.

Table 3.7: Chemical Compositions of Titanium (ASTM Grade-2)

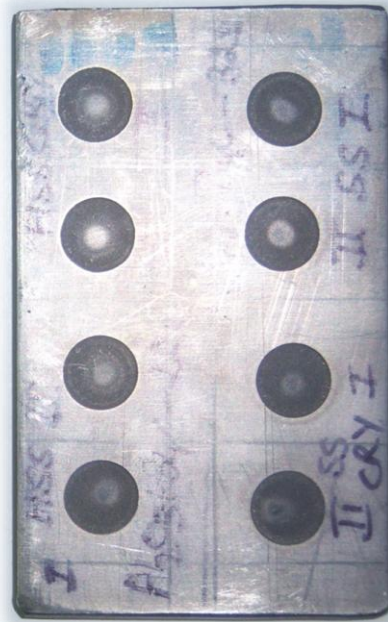
Chemical Compositions (by weight %) of Titanium (ASTM Grade-2)					
N	C	H	Fe	O	Ti
0.03	0.01	0.015	0.05	0.20	Balance
Mechanical Properties					
Yield strength		: 275 MPa	Density		: 4.5 g/cm ³
Ultimate strength		: 345 MPa	Mod. of elasticity		: 103 GPa
Hardness		: 160 HV			

Table 3.8: Chemical Compositions of Titanium alloy(ASTM Grade-5)

Chemical Compositions (by weight %) of							
Titanium(ASTM Grade-5)							
N	C	H	Fe	O	Al	V	Ti
0.03	0.1	0.015	0.3	0.25	5.5-6.75	3.5-4.5	Balance
Mechanical Properties							
Yield strength				: 828 GPa		Density : 4.42 g/cm ³	
Ultimate strength				: 895 GPa		Mod.of elasticity : 114 GPa	
Hardness				: 396 HV			



a) Ti (ASTM Grade-2)



b) Ti-6Al-4V (ASTM Grade-5)

Figure 3.12: Workpiece material

The typical percentage composition and important mechanical properties of tool material is used in this work have been detailed in Table 3.9.

Table 3.9: Chemical Composition and Properties of Tool Materials

Material	Chemical Compositions	Density(g/cm^3)	Elastic Modulus (GPa)	Micro- Hardness (GPa)	Fracture Toughness($\text{MPam}^{1/2}$)
High Carbon Steel	Fe + C(1.01%) + Cr(0.5)	7.5	195	1.90	37.5
High Speed Steel	Fe+C (0.97%) + Cr (3.5%) + W (17%) + V (0.6%)	8.0	214	1.68	48.0
Stainless Steel	Fe + C (0.08%) + Cr (3.5%) + Mn (0.67%) + P (0.035%) + Si (0.16%)	8.060	193	210 HV	88.0



a) HSS Tool



b) SS Tool



c) HCS Tool

Figure 3.13: Different types of Tool material used

CHAPTER 4

RESULTS AND ANALYSIS

USING NON CRYOGENIC TREATED TOOL

4.1 INTRODUCTION

The effects of parameters i.e. work material, tool material, abrasives, abrasive concentration, abrasive grit size and power rating were evaluated using ANOVA and factorial design analysis. A confidence interval of 95% has been used for the analysis. One repetition for each of 18 trails was completed to measure the Signal to Noise ratio(S/N Ratio).

4.2 RESULTS FOR MRR

In the first set-up, experiment was performed to determine the effect of HCS toolon Titanium (ASTM Grade-2) work using alumina slurry of 220 grit size with 20% concentration by weight in distilled water as suspension media. The experiment was started by setting power rating of the machine at 20 %(of 500W) i.e.125W of ultrasonic drilling machine. The results for MRR for each of the 18 experiments using without cryogenic treated tool material with one repetition are given in Table 4.1. MRR of each sample is calculated from weight difference of workpiece before and after the performance trial, which is given by:

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

Where W_i = Initial weight of workpiece material (gms)

W_f = Final weight of workpiece material (gms)

t = Time period of trails in minutes

ρ = Density of workpiece in gms/mm^3

Table 4.1: Results for MRR

Trial No:	Work material	Tool Material	Abrasives	Grit Size	Concentration	Power rating	MRR mm ³ /min		S/N Ratio	Mean MRR
							I	II		
1	Ti (Grade-2)	HCS	Al ₂ O ₃	220	20	20	0.222	0.444	-11.0317	0.3330
2	Ti (Grade-2)	HCS	B ₄ C	320	25	50	0.444	0.222	-11.0317	0.3330
3	Ti (Grade-2)	HCS	Al ₂ O ₃ + B ₄ C	500	30	80	0.222	0.222	-13.0729	0.2220
4	Ti (Grade-2)	HSS	Al ₂ O ₃	220	25	50	0.444	0.444	-7.0523	0.4440
5	Ti (Grade-2)	HSS	B ₄ C	320	30	80	0.666	0.444	-5.6390	0.5550
6	Ti (Grade-2)	HSS	Al ₂ O ₃ + B ₄ C	500	20	20	0.222	0.222	-13.0729	0.2220
7	Ti (Grade-2)	SS	Al ₂ O ₃	320	20	80	0.222	0.222	-13.0729	0.2220
8	Ti (Grade-2)	SS	B ₄ C	500	25	20	0.444	0.444	-7.0523	0.4440
9	Ti (Grade-2)	SS	Al ₂ O ₃ + B ₄ C	220	30	50	0.666	0.444	-5.6390	0.5550
10	Ti (Grade-5)	HCS	Al ₂ O ₃	500	30	50	0.226	0.226	-12.9178	0.2260
11	Ti (Grade-5)	HCS	B ₄ C	220	20	80	0.453	0.453	-6.8780	0.4530
12	Ti (Grade-5)	HCS	Al ₂ O ₃ + B ₄ C	320	25	20	0.226	0.226	-12.9178	0.2260
13	Ti (Grade-5)	HSS	Al ₂ O ₃	320	30	20	0.226	0.226	-12.9178	0.2260
14	Ti (Grade-5)	HSS	B ₄ C	500	20	50	0.226	0.226	-12.9178	0.2260
15	Ti (Grade-5)	HSS	Al ₂ O ₃ + B ₄ C	220	25	80	0.453	0.453	-6.8780	0.4530
16	Ti (Grade-5)	SS	Al ₂ O ₃	500	25	80	0.226	0.226	-12.9178	0.2260
17	Ti (Grade-5)	SS	B ₄ C	220	30	20	0.226	0.226	-6.8780	0.4530
18	Ti (Grade-5)	SS	Al ₂ O ₃ + B ₄ C	320	20	50	0.226	0.226	-10.8728	0.3395

4.3 ANOVA FOR MRR

The results for MRR were analyzed using ANOVA for identifying the significant factors affecting the performance measures. The Analysis of Variance (ANOVA) for the mean MRR at 95% confidence interval is given in Table 4.2. The variance data for each factor and their interactions were F-tested to find significance of each. The principle of the F test is that the larger the F value for a particular parameter, the greater the effect on the performance characteristic due to the change in that process parameter. ANOVA table shows that Grit size of the abrasives factors that significantly affect the MRR. All other factors are insignificant to affect the MRR. Table 4.3 shows the ranks of various factors in terms their relative significance. Grit sizes has the highest ranksignifying highest contribution to MRR and Power rating has the lowest and was observed to be insignificant in affecting MRR. As can be seen MRR increases with decreases the grit size from 500 to 220. MRR is decreased with addition of power rating.

Table: 4.2 Analysis of variance for mean ratio of MRR

Source	Degree of freedom	Sum of square	Variance	F value	Significance
Work material	1	0.013972	0.013972	2.05	Not Significant
Tool material	2	0.017952	0.008976	1.31	Not Significant
Abrasives	2	0.081926	0.035963	5.80	Significant
Grit size	2	0.111194	0.055597	8.14	Significant
Concentration	2	0.017582	0.008791	1.29	Not Significant
Power rating	2	0.005543	0.002771	0.41	Not Significant
Residual error	6	0.040988	0.006831		
Total	17	0.259157			

Table 4.3: Response table for means of MRR

Level	Work material	Tool material	Abrasives	Grit size	Concentration	Power rating
1	0.3700	0.2988	0.2795	0.4485	0.2993	0.3173
2	0.3143	0.3543	0.3363	0.3169	0.3543	0.3539
3		0.3733	0.4106	0.2610	0.3728	0.3552
Delta	0.0557	0.0744	0.1312	0.1875	0.0736	0.0378
Rank	5	3	2	1	4	6

Main Effect Plot for MRR:-

Main effect plots for material removal rate are shown in the figure 4.1. Main effect plot shows the variation in material removal rate with respect to work material, tool material, abrasives, grit size, concentration and power rating. It observed that the maximum MRR is given while using SS tool and boron carbide slurry with a coarse grit size of 220 and slurry concentration of 30 % when titanium and its alloys was machined. X axis represents change in level of the variable and y axis represents the change in the resultant response. The mean line is shown by the straight horizontal line.

Mean MRR = 0.56130

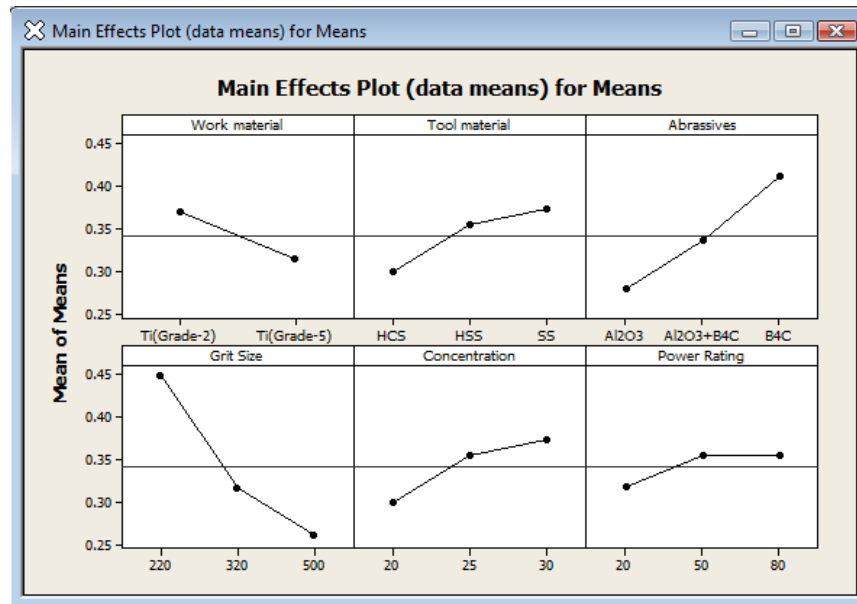


Figure 4.1:
effects plot
for Means

**Main
of MRR**

4.4 ANALYSIS OF S/N RATIO FOR MRR

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

$$(S/N)_{HB} = -10 \log (MSD_{HB}) \quad (\text{Equation 4.2})$$

$$\text{Where } MSD_{HB} = \frac{1}{r} \sum_{j=1}^r \left(\frac{1}{y_j^2} \right) \quad (\text{Equation 4.3})$$

MSD_{HB} = Mean Square Deviation for higher-the-better response.

Table 4.4 shows the ANOVA results for S/N ratio of MRR without cryogenic treated tool material at 95% confidence interval. Grit size of abrasives was observed to be the most significant factor affecting the MRR, followed by abrasive, tool material according to F test. All the interactions are insignificant. Main effects plot of S/N ratio for MRR are shown in the figure 4.2.

Table: 4.4 Analysis of variance for S/N ratio of MRR

Source	Degree of freedom	Sum of square	Variance	F value	Significance
Work material	1	4.941	4.941	1.30	Not Significant
Tool material	2	22.354	16.177	3.63	Not Significant
Abrasives	2	42.319	26.160	6.26	Significant
Grit size	2	71.105	35.552	9.37	Significant
Concentration	2	12.043	6.022	1.59	Not Significant
Power rating	2	2.500	1.250	0.33	Not Significant
Residual error	6	22.755	3.793		
Total	17	158.018			

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

Level	Work material	Tool material	Abrasives	Grit size	Concentration	Power rating
1	-9.629	-11.308	-11.652	-7.393	-11.308	-10.645
2	-10.677	-9.746	-10.409	-11.075	-9.642	-10.072
3		-9.409	-8.400	-11.992	-9.5111	-9.743
Delta	1.048	1.903	3.252	4.599	1.797	0.902
Rank	5	3	2	1	4	6

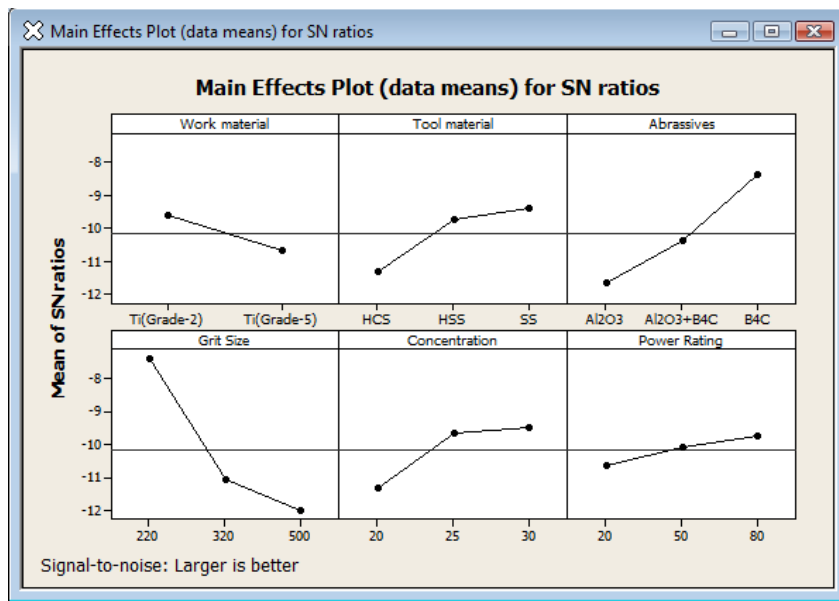


Figure 4.2: Main effects plot of MRR for S/N ratio

4.5 RESULTS FOR TWR

In the first set-up, experiment was performed to determine the effect on HCS tool of Titanium (ASTM Grade-2) workpieces using alumina slurry of 220 grit size with 20% concentration by weight in distilled water as suspension media. The experiment was started by setting power rating of the machine at 20 % (of 500W) i.e.125W of ultrasonic drilling machine. The results for TWR for each of the 18 experiments using without cryogenic treated tool material with one repetition are given in Table 4.6. TWR of each sample is

calculated from weight difference of tool material before and after the performance trial, which is given by:

$$\text{TWR} = \frac{(T_i - T_f)}{\rho \times t} \text{ mm}^3/\text{min} \quad (\text{Equation 4.4})$$

Where T_i = Initial weight of tool material (gms)

T_f = Final weight of tool material (gms)

t = Time period of trails in minutes

ρ = Density of tool material in gms/mm^3

Table 4.6: Results for TWR

Trial No:	Work material	Tool Material	Abrasives	Grit Size	Concentration	Power rating	TWR mm ³ /min		S/N Ratio	Mean TWR
							I	II		
1	Ti (Grade-2)	HCS	Al ₂ O ₃	220	20	20	0.255	0.382	9.7685	0.3185
2	Ti (Grade-2)	HCS	B ₄ C	320	25	50	0.255	0.255	11.8692	0.2550
3	Ti (Grade-2)	HCS	Al ₂ O ₃ + B ₄ C	500	30	80	0.127	0.255	13.9172	0.1910
4	Ti (Grade-2)	HSS	Al ₂ O ₃	220	25	50	0.368	0.245	10.1000	0.3065
5	Ti (Grade-2)	HSS	B ₄ C	320	30	80	0.490	0.368	7.2639	0.4290
6	Ti (Grade-2)	HSS	Al ₂ O ₃ + B ₄ C	500	20	20	0.245	0.245	12.2167	0.2450
7	Ti (Grade-2)	SS	Al ₂ O ₃	320	20	80	0.249	0.374	9.9594	0.3115
8	Ti (Grade-2)	SS	B ₄ C	500	25	20	0.125	0.249	14.1102	0.1870
9	Ti (Grade-2)	SS	Al ₂ O ₃ + B ₄ C	220	30	50	0.374	0.249	9.9594	0.3115
10	Ti (Grade-5)	HCS	Al ₂ O ₃	500	30	50	0.382	0.382	8.3587	0.3820
11	Ti (Grade-5)	HCS	B ₄ C	220	20	80	0.255	0.127	13.9172	0.1910
12	Ti (Grade-5)	HCS	Al ₂ O ₃ + B ₄ C	320	25	20	0.255	0.382	9.7685	0.3185

13	Ti (Grade-5)	HSS	Al ₂ O ₃	320	30	20	0.123	0.368	11.2334	0.2455
14	Ti (Grade-5)	HSS	B ₄ C	500	20	50	0.245	0.245	12.2167	0.2450
15	Ti (Grade-5)	HSS	Al ₂ O ₃ + B ₄ C	220	25	80	0.245	0.368	10.1000	0.3065
16	Ti (Grade-5)	SS	Al ₂ O ₃	500	25	80	0.125	0.125	18.0618	0.1250
17	Ti (Grade-5)	SS	B ₄ C	220	30	20	0.374	0.249	9.9594	0.3115
18	Ti (Grade-5)	SS	Al ₂ O ₃ + B ₄ C	320	20	50	0.249	0.374	9.9594	0.3115

4.6 ANOVA FOR TWR

The results for TWR were analyzed using ANOVA for identifying the significant factors affecting the performance measures. The Analysis of Variance (ANOVA) for the mean TWR at 95% confidence interval is given in Table 4.7. Main effects plot for TWR are shown in the Figure 4.3. Table 4.8 shows ranks to various factors; Grit size and concentration has highest rank, most significant that affecting TWR. The tool material, power ratings are least significant in TWR.

Table: 4.7 Analysis of variance for mean ratio of TWR

Source	Degree of freedom	Sum of square	Variance	F value	Significance
Work material	1	0.000780	0.000780	0.20	Not Significant
Tool material	2	0.004030	0.002015	0.35	Not Significant
Abrasives	2	0.000516	0.000258	0.03	Not Significant
Grit size	2	0.042169	0.021084	2.38	Significant
Concentration	2	0.021959	0.015980	0.98	Significant
Power rating	2	0.005883	0.002942	0.67	Not Significant
Residual error	6	0.048256	0.008043		
Total	17	0.093594			

Table 4.8: Response table for means of TWR

Level	Work material	Tool material	Abrasives	Grit size	Concentration	Power rating
1	0.2839	0.2760	0.2815	0.2909	0.2704	0.2710
2	0.2707	0.2963	0.2807	0.3118	0.2498	0.3019
3		0.2597	0.2698	0.2292	0.3118	0.2590
Delta	0.0132	0.0366	0.0117	0.0827	0.0620	0.0429
Rank	5	4	6	1	2	3

Main Effect Plot for TWR:-

Main effect plots for tool wear rate are shown in the figure 4.3. Main effect plot shows the variation into tool wear rate with respect to work material, tool material, abrasives, grit size, concentration and power rating. It observed that the minimum tool wear is given while using SS tool and boron carbide slurry with a coarse grit size of 500 and slurry concentration of 25 % when titanium and its alloys was machined. X axis represents change in level of the variable and y axis represents the change in the resultant response. The mean line is shown by the straight horizontal line.

Mean TWR = 0.16390

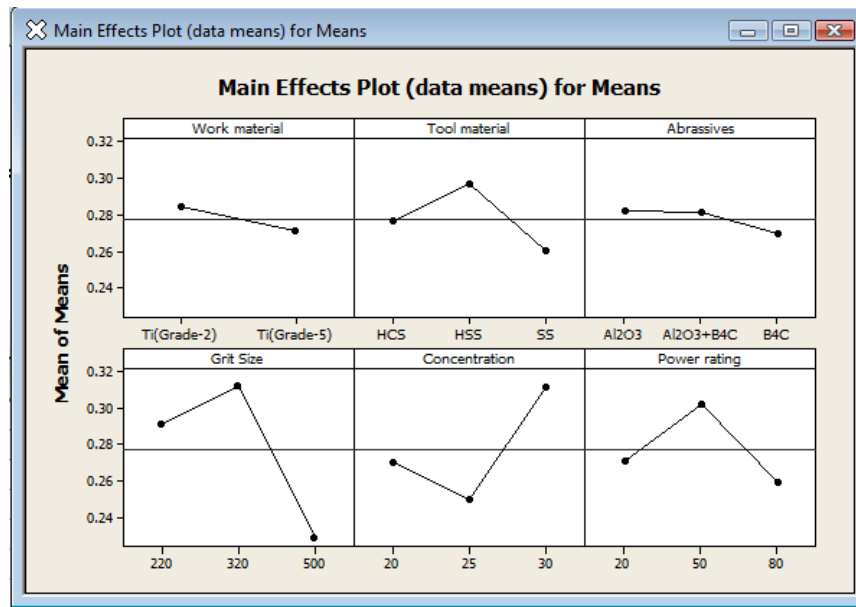


Figure 4.3: Main effects plot for mean of tool wear rate

4.7 ANALYSIS OF S/N RATIO FOR TWR

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

$$S / N_{LB} = -10 \log(MSD) = -10 \log\left(\frac{1}{r} \sum_{i=1}^r y_i^2\right) \text{ (Equation 4.5) Where } MSD_{LB} =$$

$$\frac{1}{r} \sum_{j=1}^r (y_j^2) \text{ (Equation 4.6)}$$

Table 4.9 shows the ANOVA for S/N ratio for TWR at 95% confidence interval. The grit size is the most significant in affecting TWR followed by concentration and power rating according to F test. Main effect plot of S/N ratios for TWR are shown in the Figure 4.4.

Table: 4.9 Analysis of variance for S/N ratio of TWR

Source	Degree of freedom	Sum of square	Variance	F value	Significance
Work material	1	1.081	1.0807	0.15	Not Significant
Tool material	2	6.570	3.2850	0.46	Not Significant
Abrasives	2	0.974	0.4872	0.07	Not Significant
Grit size	2	43.103	26.5513	4.32	Significant
Concentration	2	24.832	17.4161	3.04	Significant
Power rating	2	11.710	6.8548	0.68	Not Significant
Residual error	6	42.734	7.1224		
Total	17	109.004			

Table: 4.10 Response table for S/N ratio of TWR

Level	Work material	Tool material	Abrasives	Grit size	Concentration	Power rating
1	11.02	11.27	11.25	10.63	11.34	11.18
2	11.51	10.52	10.99	10.01	12.33	10.41
3		12.00	11.56	13.15	10.12	12.20
Delta	0.49	1.48	0.57	3.14	2.22	1.79
Rank	6	4	5	1	2	3

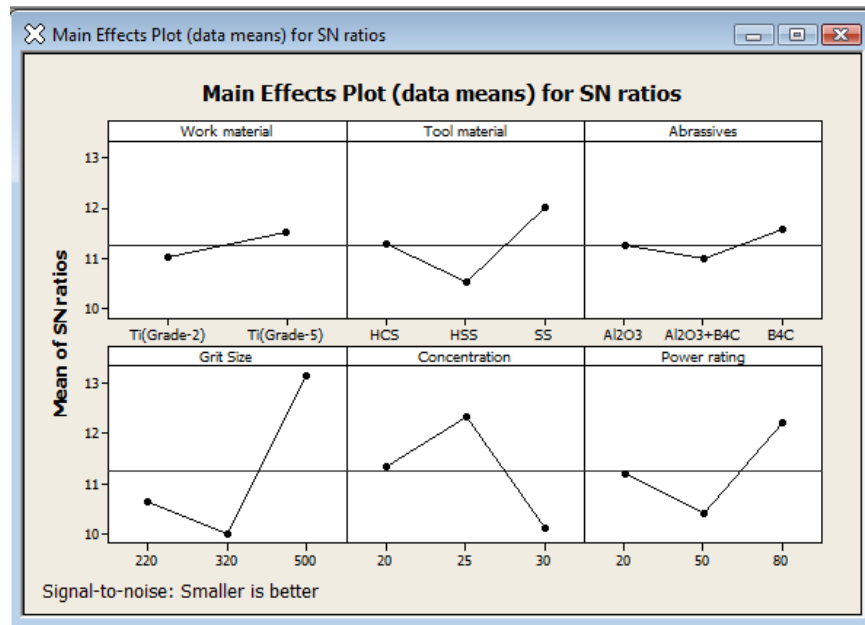


Figure 4.4: Main effects plot for S/N ratio of tool wear rate

4.8 ANOVA FOR SURFACE ROUGHNESS

The results for surface roughness were analyzed using ANOVA for identifying the significant factors affecting the performance measures given in Table 4.12. The work material, tool material, abrasives, grit size, concentration and power rating are input parameters which affect the surface roughness. Main effect plots had shown in the Figure 4.5. The workpiece material also affects the surface roughness. Table 4.13 shows ranks to various input parameters in terms their relative significance.

Table 4.11: Results for Surface Roughness

Trial No:	Work material	Tool Material	Abrasives	Grit Size	Concentration	Power rating	Surface Roughness			S/N Ratio	Mean
							I	II	III		
1	Ti (Grade-2)	HCS	Al ₂ O ₃	220	20	20	1.2709	1.1084	1.0126	-1.1049	1.1306
2	Ti (Grade-2)	HCS	B ₄ C	320	25	50	0.8612	0.8112	0.9909	1.0025	0.8877
3	Ti (Grade-2)	HCS	Al ₂ O ₃ + B ₄ C	500	30	80	1.0245	1.0012	0.9976	-0.0678	1.0077
4	Ti (Grade-2)	HSS	Al ₂ O ₃	220	25	50	1.2952	1.1112	1.0092	-1.1736	1.1385
5	Ti (Grade-2)	HSS	B ₄ C	320	30	80	1.3674	1.2761	1.2212	-2.2094	1.2882
6	Ti (Grade-2)	HSS	Al ₂ O ₃ + B ₄ C	500	20	20	1.4123	1.2212	1.3321	-2.4390	1.3218
7	Ti (Grade-2)	SS	Al ₂ O ₃	320	20	80	0.9606	0.8192	0.9911	0.6615	0.9236
8	Ti (Grade-2)	SS	B ₄ C	500	25	20	0.8418	0.7122	0.9984	1.3221	0.8508
9	Ti (Grade-2)	SS	Al ₂ O ₃ + B ₄ C	220	30	50	1.6283	1.5021	1.4412	-3.6703	1.5238
10	Ti (Grade-5)	HCS	Al ₂ O ₃	500	30	50	0.4712	0.6002	0.4007	6.0623	0.4907
11	Ti (Grade-5)	HCS	B ₄ C	220	20	80	1.0527	1.001	1.2318	-0.8249	1.0951
12	Ti (Grade-5)	HCS	Al ₂ O ₃ + B ₄ C	320	25	20	0.7894	0.8529	0.7124	2.0805	0.7849
13	Ti (Grade-5)	HSS	Al ₂ O ₃	320	30	20	0.6852	0.7032	0.5001	3.9287	0.6295
14	Ti (Grade-5)	HSS	B ₄ C	500	20	50	0.6521	0.7853	1.0889	1.2928	0.8421
15	Ti (Grade-5)	HSS	Al ₂ O ₃ + B ₄ C	220	25	80	1.3072	1.0773	1.1016	-1.3384	1.1620
16	Ti (Grade-5)	SS	Al ₂ O ₃	500	25	80	0.5996	0.9076	0.6211	2.8149	0.7094
17	Ti (Grade-5)	SS	B ₄ C	220	30	20	0.8788	0.7314	0.9163	1.4532	0.8421
18	Ti (Grade-5)	SS	Al ₂ O ₃ + B ₄ C	320	20	50	0.993	0.8216	0.888	0.8802	0.9008

Table: 4.12 Analysis of variance for mean ratio of Surface Roughness

Source	Degree of freedom	Sum of square	Variance	F value	Significance
Work material	1	0.38026	0.38026	23.21	Significant
Tool material	2	0.08305	0.04152	2.53	Not Significant
Abrasives	2	0.23523	0.11761	7.18	Significant
Grit size	2	0.27822	0.13911	8.49	Significant
Concentration	2	0.03956	0.01978	1.21	Not Significant
Power rating	2	0.03358	0.01679	1.03	Not Significant
Residual error	6	0.09829	0.01638		
Total	17	1.14818			

Table 4.13: Response table for means of Surface Roughness

Level	Work material	Tool material	Abrasives	Grit size	Concentration	Power rating
1	1.1192	0.8995	0.8371	1.1487	1.0357	0.9266
2	0.8285	1.0637	1.1169	0.9025	0.9222	0.9640
3		0.9585	0.9677	0.8704	0.9637	1.0310
Delta	0.2907	0.1642	0.2798	0.2783	0.1135	0.1044
Rank	1	4	2	3	5	6

Main Effect Plot for Surface Roughness:-

Main effect plots for surface roughness are shown in the figure 4.5. Main effect plot shows the variation in surface roughness with respect to work material, tool material, abrasives, grit size, concentration and power rating. It observed that the maximum SR is given while using Ti (ASTM Grade-5), while Ultrasonic power rating of 80% with SS tool and Alumina slurry with a coarse grit size of 500 and slurry concentration of 30 %, when titanium and its alloys were machined. X axis represents change in level of the variable and Y axis represents the change in the resultant response. The mean line is shown by the straight horizontal line.

Mean SR = 0.54528

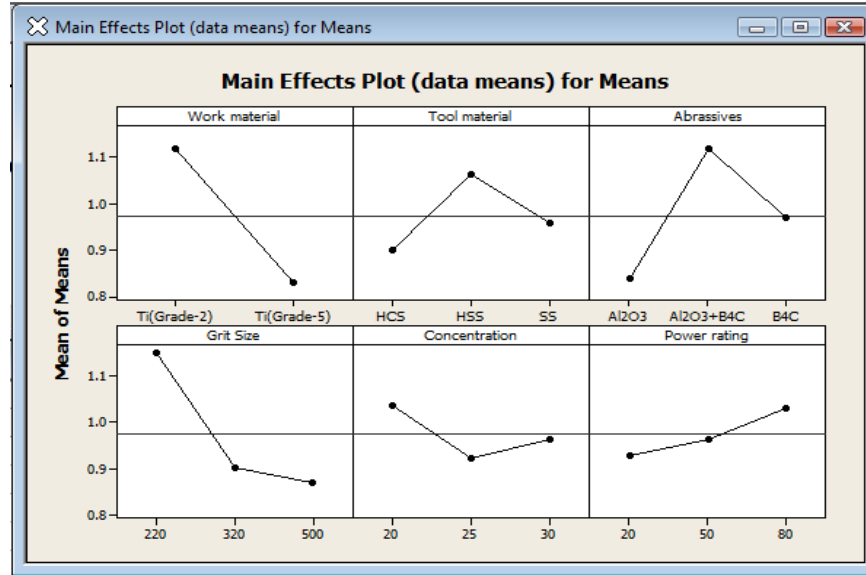


Figure 4.5: Main effects plot for mean of surface roughness

4.9 ANALYSIS OF S/N RATIO FOR SURFACE ROUGHNESS (R_a)

The S/N ratio several repetitions into one value which reflects the amount of variation present. The values of all the results according to Taguchi array parameter design layout are presented in this section. The S/N ratios have been calculated to identify the major contributing factors in the roughness values. In this design situation, roughness is the type of 'lower is better', which is a logarithmic function based on the mean square deviation (MSD), given by

$$S / N_{LB} = -10 \log(MSD) = -10 \log\left(\frac{1}{r} \sum_{i=1}^r y_i^2\right)$$

$$\text{Where } MSD_{LB} = \frac{1}{r} \sum_{j=1}^r (y_j^2)$$

Table 4.14 shows the ANOVA for S/N ratio for roughness at 95% confidence interval. Among all the factors are work material, tool material, abrasives, grit size, concentration and power rating are input parameters which affect the surface roughness. Work material has most significant which has highest contribution in roughness.

Table: 4.14 Analysis of variance for S/N ratio of Surface Roughness

Source	Degree of freedom	Sum of square	Variance	F value	Significance
Work material	1	32.075	32.0751	35.54	Significant
Tool material	2	6.962	3.4812	3.86	Not Significant
Abrasives	2	20.838	10.4189	11.55	Significant
Grit size	2	23.377	11.6887	12.95	Significant
Concentration	2	4.946	2.4728	2.74	Not Significant
Power rating	2	3.774	1.8868	2.09	Not Significant
Residual error	6	5.414	0.9024		
Total	17	97.386			

Table 4.15: Response table for S/N ratio of Surface Roughness

Level	Work material	Tool material	Abrasives	Grit size	Concentration	Power rating
1	-0.8532	1.1913	1.8648	-1.1098	-0.2557	0.8734
2	1.8166	-0.3232	-0.7591	1.0574	0.7847	0.7323
3		0.5769	0.3394	1.4975	0.9161	-0.1607
Delta	2.6698	1.5145	2.6240	2.6074	1.1718	1.0341
Rank	1	4	2	3	5	6

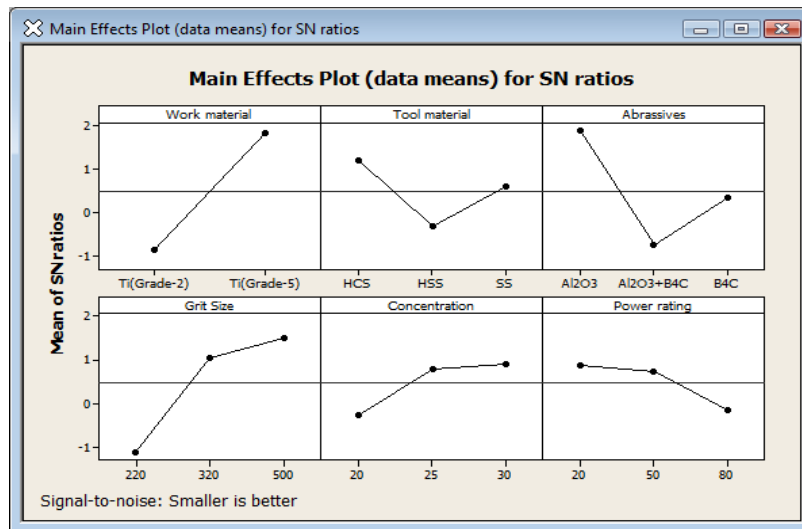


Figure 4.6: Main effects plot for S/N ratio of surface roughness

4.10 ANOVA FORMICRO HARDNESS

The micro hardness measurement is dependent on the diameter of indentation on the samples. The indents formed in the pyramid shaped indenter were measured with Quantimet software using a static load of 100gm for 20 seconds.

Table 4.16: Results for Micro hardness

Trial No:	Work material	Tool Material	Abrasives	Grit Size	Concentration	Power rating	Micro Hardness		S/N Ratio	Mean
							I	II		
1	Ti (Grade-2)	HCS	Al ₂ O ₃	220	20	20	193	202	45.9046	197.5
2	Ti (Grade-2)	HCS	B ₄ C	320	25	50	221	210	46.6605	215.5
3	Ti (Grade-2)	HCS	Al ₂ O ₃ + B ₄ C	500	30	80	235	240	47.5118	237.5
4	Ti (Grade-2)	HSS	Al ₂ O ₃	220	25	50	193	200	45.8631	196.5
5	Ti (Grade-2)	HSS	B ₄ C	320	30	80	205	209	46.3182	207.0
6	Ti (Grade-2)	HSS	Al ₂ O ₃ + B ₄ C	500	20	20	178	176	44.9590	177.0
7	Ti (Grade-2)	SS	Al ₂ O ₃	320	20	80	213	209	46.4845	211.0
8	Ti (Grade-2)	SS	B ₄ C	500	25	20	222	245	47.3341	233.5
9	Ti (Grade-2)	SS	Al ₂ O ₃ + B ₄ C	220	30	50	210	225	46.7337	217.5
10	Ti (Grade-5)	HCS	Al ₂ O ₃	500	30	50	433	440	52.7988	436.5
11	Ti (Grade-5)	HCS	B ₄ C	220	20	80	455	448	53.0924	451.5
12	Ti (Grade-5)	HCS	Al ₂ O ₃ + B ₄ C	320	25	20	430	425	52.6183	427.5
13	Ti (Grade-5)	HSS	Al ₂ O ₃	320	30	20	420	429	52.5561	424.5
14	Ti (Grade-5)	HSS	B ₄ C	500	20	50	410	424	52.3990	417.0
15	Ti (Grade-5)	HSS	Al ₂ O ₃ + B ₄ C	220	25	80	433	441	52.8085	437.0
16	Ti (Grade-5)	SS	Al ₂ O ₃	500	25	80	420	427	52.5362	423.5

17	Ti (Grade-5)	SS	B4C	220	30	20	427	431	52.6489	429.0
18	Ti (Grade-5)	SS	Al ₂ O ₃ + B4C	320	20	50	438	420	52.6434	429.0

Table: 4.17 Analysis of variance for mean ratio of micro hardness

Source	Degree of freedom	Sum of square	Variance	F value	Significance
Work material	1	218350	218350	1055.97	Significant
Tool material	2	1061	530	2.57	Significant
Abrasives	2	343	172	0.83	Not Significant
Grit size	2	19	9	0.05	Not Significant
Concentration	2	425	213	1.03	Not Significant
Power rating	2	543	271	1.31	Not Significant
Residual error	6	1241	207		
Total	17	221982			

Table 4.18: Response table for means of micro hardness

Level	Work material	Tool material	Abrasives	Grit size	Concentration	Power rating
1	210.3	327.7	314.9	321.5	313.8	314.8
2	430.6	309.8	320.9	319.1	322.3	318.7
3		323.9	325.6	320.8	325.3	327.9
Delta	220.3	17.8	10.7	2.4	11.5	13.1
Rank	1	2	5	6	4	3

Main Effect Plot for Micro Hardness:-

Main effect plots for micro hardness are shown in the figure 4.7. Main effect plot shows the variation in micro hardness with respect to work material, tool material, abrasives, grit size, concentration and power rating. It observed that the micro hardness is dependent on the hardness of the material and hardness of the tool material but remaining all the factors

was insignificant. X axis represents change in level of the variable and Y axis represents the change in the resultant response. The mean line is shown by the straight horizontal line.

Mean SR = 442.944

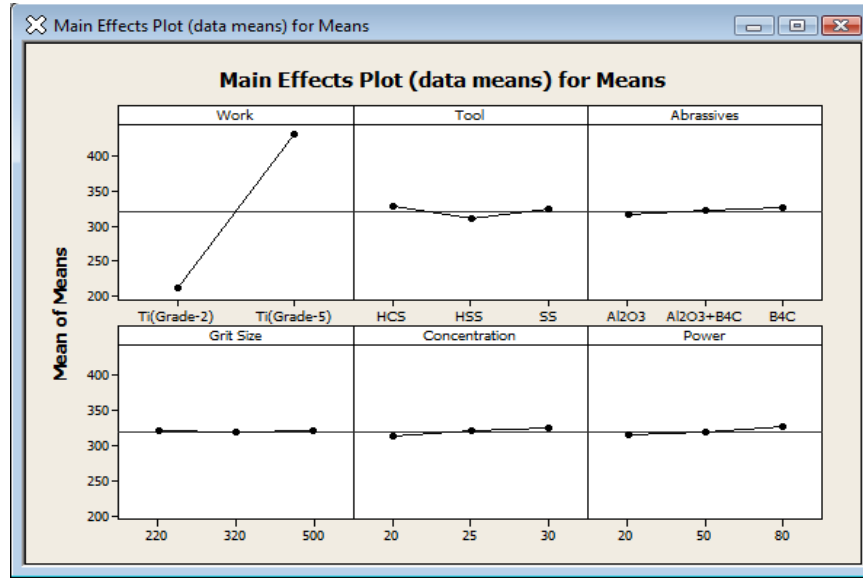


Figure 4.7: Main effects plot for mean of micro hardness

4.11 ANALYSIS OF S/N RATIO OF MICROHARDNESS

Micro hardness is “Higher is better” type response, for which S/N ratio was calculated by using equation 4.2. Table 4.19 shows the ANOVA for S/N ratio for micro hardness at 95% confidence interval. Tool material is the significant factor which affects the micro hardness. Work material has most significant which has highest contribution in micro hardness according to F value and percentage contribution. Main effect plot of S/N ratio for micro hardness shown in the Figure 4.8

Table: 4.19 Analysis of variance for S/N ratio of micro hardness

Source	Degree of freedom	Sum of square	Variance	F value	Significance
Work material	1	176.295	176.295	573.34	Significant
Tool material	2	1.427	0.714	2.32	Significant

Abrasives	2	0.445	0.222	0.72	Not Significant
Grit size	2	0.020	0.010	0.03	Not Significant
Concentration	2	0.863	0.432	1.40	Not Significant
Power rating	2	0.631	0.315	1.03	Not Significant
Residual error	6	1.845	0.307		
Total	17	181.525			

Table 4.20: Response table for S/N ratio of micro hardness

Level	Work material	Tool material	Abrasives	Grit size	Concentration	Power rating
1	210.3	327.7	314.9	321.5	313.8	314.8
2	430.6	309.8	320.9	319.1	322.3	318.7
3		323.9	325.6	320.8	325.3	327.9
Delta	220.3	17.8	10.7	2.4	11.5	13.1
Rank	1	2	5	6	4	3

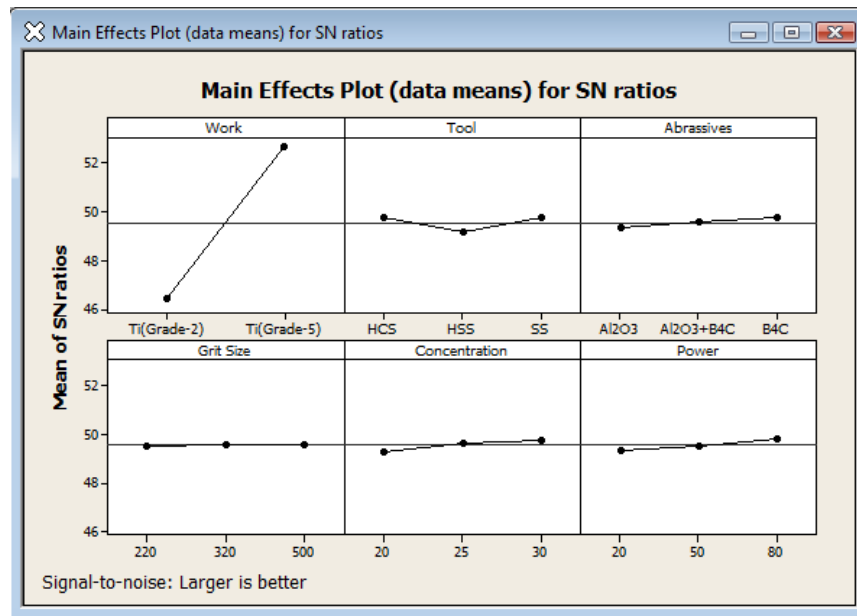


Figure 4.8: Main effects plot for S/N ratio of micro hardness

4.12 DIMENSIONAL ERROR

Tool wear is the most important variable in USM. Tool diameter is affected by work material and abrasives used in experimentation. The biggest disadvantage of dimensional accuracy of the machining ultrasonic drill is to increase the diameter of the tool while machining. In the ultrasonic machining exact tool dimensions setting is to be done to achieve accurate results. So the following steps were done to achieve the required dimensions and to calculate the dimensional error.

1. Before the trial run was made, measure the exact diameters of the tool using with digital vernier calliper
2. After the trial run was made, measure the diameters of the hole made by machining using with optical microscope
3. The diameter reading obtained had some deviation from the desired diameter reading.
4. Offset dimensions were given in the parametric consideration and then machining was done so that result obtained should be exactly near to the desired value.
5. The measured deviation is shown in the table 4.21.

Table 4.21 : Deviation of machining diameter done with using non-cryogenic treated tool material observed from optical microscope

Expt no.	Required Diameter (mm)	Resultant diameter (mm)	Deviation in microns
1	10	10.083	83
2	10	10.098	98
3	10	10.073	73
4	10	10.066	66
5	10	10.033	33
6	10	10.019	19
7	10	10.057	57
8	10	10.026	26
9	10	10.074	74
10	10	10.043	43
11	10	10.098	98
12	10	10.057	57
13	10	10.079	79
14	10	10.036	36

15	10	10.098	98
16	10	10.010	10
17	10	10.020	20
18	10	10.045	45

4.13 OPTIMAL SOLUTION USING GREY RELATIONAL ANALYSIS[157-158]

The grey relational analysis is used to convert multi response process optimization problem in to single response optimization problem and then grey relational grade is determined. The objective is to maximise the grey relational grade and determine the optimal combination.

Following steps are used to calculate the grey relational grade

1. **Calculation of pre processed data result:-** For higher the better characteristic following equation is to be used to calculate the data

$$x_i(k) = \frac{y_i(k) - \min y_i(k)}{\max y_i(k) - \min y_i(k)}$$

For lower the better characteristic following equation is to be used to calculate data

$$x_i(k) = \frac{\max y_i(k) - y_i(k)}{\max y_i(k) - \min y_i(k)}$$

Where $x_i(k)$ is the value after grey relational generation, $\min y_i(k)$ is smallest value of $y_i(k)$ for the k^{th} response, and $\max y_i(k)$ is largest value of $y_i(k)$ for the k^{th} response. The data is calculated in table 4.22

2. **Calculation of Grey relational coefficient :-** The grey relational coefficient is calculated in table 4.23 by the following relation

$$\xi(x_{0j}, x_{ij}) = \frac{\Delta_{\min} + \zeta \Delta_{\max}}{\Delta_{ij} + \zeta \Delta_{\max}}$$

$$\Delta_{ij} = |x_{0j} - x_{ij}|$$

$$\Delta_{\min} = \min \{\Delta_{ij}, i = 1, 2, \dots, m; j = 1, 2, \dots, n\},$$

$$\Delta_{\max} = \max \{\Delta_{ij}, i = 1, 2, \dots, m; j = 1, 2, \dots, n\},$$

ζ is the distinguishing coefficient and its value is usually taken as 0.5.

3. **Calculation of grey relational grade:** - Find the average of all individual response coefficients by following relation as calculated in table 4.24

$$\gamma (x_{0j}, x_{ij}) = \frac{1}{n} \sum_{k=1}^n \xi(x_{0j}, x_{ij})$$

4. **Response table for grey relational grade:** - The response table is made for every factor. This is done by adding the grey relational grades value for the factors as done in table 4.25. For example to determine the mean of grey relational grades for hardness at level 1, level 2 and level 3. Find the mean of grey relational grades for values 1-9 and 10 -18 correspondingly.

Table 4.22 : Preprocessed data obtained from experimental values.

Experimental data						Preprocessed data				
S.No	Material removal rate	Tool wear rate	Surface roughness Ra	Micro Hardness HV	Deviation in microns	MRR	TWR	Ra	Hv	Dv
1	0.333	0.3185	1.1306	197.5	83	0.3333	0.3634	0.3806	0.0747	0.1704
2	0.333	0.255	0.8877	215.5	98	0.3333	0.5723	0.6157	0.1402	0
3	0.222	0.191	1.0077	237.5	73	0	0.7828	0.4996	0.2204	0.2841
4	0.444	0.3065	1.1385	196.5	66	0.6667	0.4029	0.3729	0.0710	0.3636
5	0.555	0.429	1.2882	207	33	1	0	0.2280	0.1092	0.7386
6	0.222	0.245	1.3218	177	19	0	0.6052	0.1955	0	0.8977
7	0.222	0.3115	0.9236	211	57	0	0.3865	0.5810	0.1239	0.4659
8	0.444	0.187	0.8508	233.5	26	0.6667	0.7960	0.6514	0.2058	0.8182
9	0.555	0.3115	1.5238	217.5	74	1	0.3865	0	0.1475	0.2727
10	0.226	0.382	0.4907	436.5	43	0.0120	0.1546	1	0.9453	0.625
11	0.453	0.191	1.0951	451.5	98	0.6937	0.7828	0.4150	1	0
12	0.226	0.3185	0.7849	427.5	57	0.0120	0.3634	0.7152	0.9126	0.4659

13	0.226	0.2455	0.6295	424.5	79	0.0120	0.6036	0.8656	0.9016	0.2159
14	0.226	0.245	0.8421	417	36	0.0120	0.6052	0.6598	0.8743	0.7045
15	0.453	0.3065	1.162	437	98	0.6937	0.4029	0.3502	0.9472	0
16	0.226	0.125	0.7094	423.5	10	0.0120	1	0.7883	0.8980	1
17	0.453	0.3115	0.8421	429	20	0.6937	0.3865	0.6598	0.9180	0.8864
18	0.3395	0.3115	0.9008	429	45	0.3528	0.3865	0.6030	0.9180	0.6023

Table 4.23 : Determination of Grey relational coefficient

Preprocessed data					Grey relational coefficient				
MRR	TWR	Ra	Hv	Dv	ξ MRR	ξ TWR	ξ Ra	ξ Hv	ξ Dv
0.3333	0	0.3806	0.0747	0.1704	0.6	0.5790	0.5678	0.8700	0.7458
0.3333	0.3282	0.6157	0.1402	0	0.6	0.4662	0.4481	0.7809	1
0	0.6589	0.4996	0.2204	0.2841	1	0.3897	0.5002	0.6940	0.6377
0.6667	0.0620	0.3729	0.0710	0.3636	0.4286	0.5537	0.5728	0.8756	0.5789
1	-0.5711	0.2280	0.1092	0.7386	0.3333	1	0.6868	0.8206	0.4037
0	0.3798	0.1955	0	0.8977	1	0.4523	0.7189	1	0.3577
0	0.0362	0.5810	0.1239	0.4659	1	0.5640	0.4625	0.8014	0.5176
0.6667	0.6796	0.6514	0.2058	0.8182	0.4286	0.3857	0.4342	0.7084	0.3793
1	0.0362	0	0.1475	0.2727	0.3333	0.5640	1	0.7721	0.6470
0.0120	-0.3282	1	0.9453	0.625	0.9765	0.7638	0.3333	0.3459	0.4444
0.6937	0.6589	0.4150	1	0	0.4189	0.3897	0.5465	0.3333	1
0.0120	0	0.7152	0.9126	0.4659	0.9765	0.5790	0.4114	0.3540	0.5176
0.0120	0.3773	0.8656	0.9016	0.2159	0.9765	0.4530	0.3661	0.3567	0.6984
0.0120	0.3798	0.6598	0.8743	0.7045	0.9765	0.4523	0.4311	0.3638	0.4151

0.6937	0.0620	0.3502	0.9472	0	0.4189	0.5537	0.5881	0.3455	1
0.0120	1	0.7883	0.8980	1	0.9765	0.3333	0.3881	0.3576	0.3333
0.6937	0.0362	0.6598	0.9180	0.8864	0.4189	0.5640	0.4311	0.3526	0.3606
0.3528	0.0362	0.6030	0.9180	0.6023	0.5863	0.5640	0.4533	0.3526	0.4536

Table 4.24 : Calculation of Grey relational grade

ξ Mrr	ξ Twr	ξ Ra	ξ Hv	ξ Dv	grey relational grade γ
0.6	1	0.5678	0.8700	0.7458	0.672530245
0.6	0.6037	0.4481	0.7809	1	0.659067548
1	0.4314	0.5002	0.6940	0.6377	0.644340158
0.4286	0.8896	0.5728	0.8756	0.5789	0.601923607
0.3333	-7.0364	0.6868	0.8206	0.4037	0.648879094
1	0.5683	0.7189	1	0.3577	0.705796565
1	0.9325	0.4625	0.8014	0.5176	0.669132381
0.4286	0.4239	0.4342	0.7084	0.3793	0.467259102
0.3333	0.9325	1	0.7721	0.6470	0.663310295
0.9765	2.9098	0.3333	0.3459	0.4444	0.572814438
0.4189	0.4314	0.5465	0.3333	1	0.537682807
0.9765	1	0.4114	0.3540	0.5176	0.567729109
0.9765	0.5699	0.3661	0.3567	0.6984	0.570171876
0.9765	0.5683	0.4311	0.3638	0.4151	0.527783796
0.4189	0.8896	0.5881	0.3455	1	0.581238722
0.9765	0.3333	0.3881	0.3576	0.3333	0.477793444
0.4189	0.9325	0.4311	0.3526	0.3606	0.425443848
0.5863	0.9325	0.4533	0.3526	0.4536	0.481955479

Table 4.25: Optimum conditions table

Parameters	level 1	level 2	level 3
Work Material	0.636915444	0.52695706	0
Tool Material	0.501637358	0.60596561	0.530815758
Abrasives	0.594060998	0.5443527	0.607395055
Grit size	0.468266547	0.59948925	0.565964584
Concentration	0.599146879	0.55916859	0.587493285
Power rating	0.568155124	0.58447586	0.593177768

From the following table the optimal conditions determined are

- A. Work material - Ti(ASTM Grade-2)
- B. Tool material –HSS
- C. Abrasives – $\text{Al}_2\text{O}_3 + \text{B}_4\text{C}$
- D. Grit size - 320
- E. Concentration - 20%
- F. Power rating - 80%

Therefore the **A₁B₂C₃D₂E₁F₃** is the most optimum combination with using non cryogenic treated tool material for machining.

CHAPTER 5

RESULTS AND ANALYSIS

USING CRYOGENIC TREATED TOOL

5.1 INTRODUCTION

The effects of parameters i.e. workpiece, tool material, abrasive material, abrasive concentration, abrasive grit size and power rating were evaluated using ANOVA and factorial design analysis. A confidence interval of 95% has been used for the analysis. One repetition for each of 18 trails was completed to measure the Signal to Noise ratio(S/N Ratio).

5.2 RESULTS FOR MRR

In the first set-up, experiment was performed to determine the effect of HCS toolon Titanium (ASTM Grade-2) work using alumina slurry of 220 grit size with 20% concentration by weight in distilled water as suspension media. The experiment was started by setting power rating of the machine at 20 %(of 500W) i.e.125W of ultrasonic drilling machine. The results for MRR for each of the 18 experiments using without cryogenic treated tool material with one repetition are given in Table 5.1. MRR of each sample is calculated from weight difference of workpiece before and after the performance trial, which is given by:

$$MRR = \frac{(W_i - W_f)}{\rho \times t} \text{mm}^3/\text{min} \text{(Equation 5.1)}$$

Where W_i = Initial weight of workpiece material (gms)

W_f = Final weight of workpiece material (gms)

t = Time period of trails in minutes

ρ = Density of workpiece in gms/mm^3

Table 5.1: Results for MRR

Trial No:	Work material	Tool Material	Abrasives	Grit Size	Concentration	Power rating	MRR mm ³ /min		S/N Ratio	Mean MRR
							I	II		
1	Ti (Grade-2)	HCS	Al ₂ O ₃	220	20	20	0.444	0.444	-7.0523	0.4440
2	Ti (Grade-2)	HCS	B ₄ C	320	25	50	0.444	0.666	-5.6390	0.5550
3	Ti (Grade-2)	HCS	Al ₂ O ₃ + B ₄ C	500	30	80	0.222	0.222	-13.0729	0.2220
4	Ti (Grade-2)	HSS	Al ₂ O ₃	220	25	50	0.222	0.444	-11.0317	0.3330
5	Ti (Grade-2)	HSS	B ₄ C	320	30	80	0.444	0.666	-5.6390	0.5550
6	Ti (Grade-2)	HSS	Al ₂ O ₃ + B ₄ C	500	20	20	0.444	0.222	-11.0317	0.3330
7	Ti (Grade-2)	SS	Al ₂ O ₃	320	20	80	0.444	0.444	-7.0523	0.4440
8	Ti (Grade-2)	SS	B ₄ C	500	25	20	0.222	0.444	-11.0317	0.3330
9	Ti (Grade-2)	SS	Al ₂ O ₃ + B ₄ C	220	30	50	0.666	0.444	-5.6390	0.5550
10	Ti (Grade-5)	HCS	Al ₂ O ₃	500	30	50	0.444	0.226	-10.9081	0.3350
11	Ti (Grade-5)	HCS	B ₄ C	220	20	80	0.679	0.453	-5.4667	0.5660
12	Ti (Grade-5)	HCS	Al ₂ O ₃ + B ₄ C	320	25	20	0.226	0.453	-10.8728	0.3395
13	Ti (Grade-5)	HSS	Al ₂ O ₃	320	30	20	0.453	0.226	-10.8728	0.3395
14	Ti (Grade-5)	HSS	B ₄ C	500	20	50	0.226	0.453	-10.8728	0.3395
15	Ti (Grade-5)	HSS	Al ₂ O ₃ + B ₄ C	220	25	80	0.453	0.679	-5.4667	0.5660
16	Ti (Grade-5)	SS	Al ₂ O ₃	500	25	80	0.453	0.226	-10.8728	0.3395
17	Ti (Grade-5)	SS	B ₄ C	220	30	20	0.679	0.453	-5.4667	0.5660
18	Ti (Grade-5)	SS	Al ₂ O ₃ + B ₄ C	320	20	50	0.679	0.226	-5.4667	0.5660

5.3 ANOVA FOR MRR

The results for MRR were analyzed using ANOVA for identifying the significant factors affecting the performance measures. The Analysis of Variance (ANOVA) for the mean MRR at 95% confidence interval is given in Table 5.2. The variance data for each factor and their interactions were F-tested to find significance of each. The principle of the F test is that the larger the F value for a particular parameter, the greater the effect on the performance characteristic due to the change in that process parameter. ANOVA table shows that Grit size and abrasives that significantly affect the MRR. All other factors are insignificant to affect the MRR. Table 5.3 shows the ranks of various factors in terms their relative significance. Grit sizes has the highest ranksignifying highest contribution to MRR and all other factors was observed to be insignificant in affecting MRR.

Table: 5.2 Analysis of variance for mean ratio of MRR

Source	Degree of freedom	Sum of square	Variance	F value	Significance
Work material	1	0.001861	0.001861	0.24	Not Significant
Tool material	2	0.012827	0.006414	0.83	Not Significant
Abrasives	2	0.088482	0.039241	4.49	Significant
Grit size	2	0.118353	0.059177	7.65	Significant
Concentration	2	0.004280	0.002140	0.28	Not Significant
Power rating	2	0.012328	0.006164	0.80	Not Significant
Residual error	6	0.046393	0.007732		
Total	17	0.234524			

Table: 5.3 Response table for means of MRR

Level	Work material	Tool material	Abrasives	Grit size	Concentration	Power rating
1	0.4193	0.4103	0.3725	0.5050	0.4488	0.3925
2	0.4397	0.4110	0.4303	0.4665	0.4110	0.4473
3		0.4673	0.4858	0.3170	0.4288	0.4488
Delta	0.0203	0.0570	0.1133	0.1880	0.0378	0.0563
Rank	6	3	2	1	5	4

Main Effect Plot for MRR:-

Main effect plots for material removal rate are shown in the figure 5.1. Main effect plot shows the variation in material removal rate with respect to work material, tool material, abrasives, grit size, concentration and power rating. It observed that the maximum MRR is given while using SS tool and boron carbide slurry with a coarse grit size of 220 and slurry concentration of 30 % when titanium and its alloys was machined. X axis represents change in level of the variable and y axis represents the change in the resultant response. The mean line is shown by the straight horizontal line.

Mean MRR = 0.648681

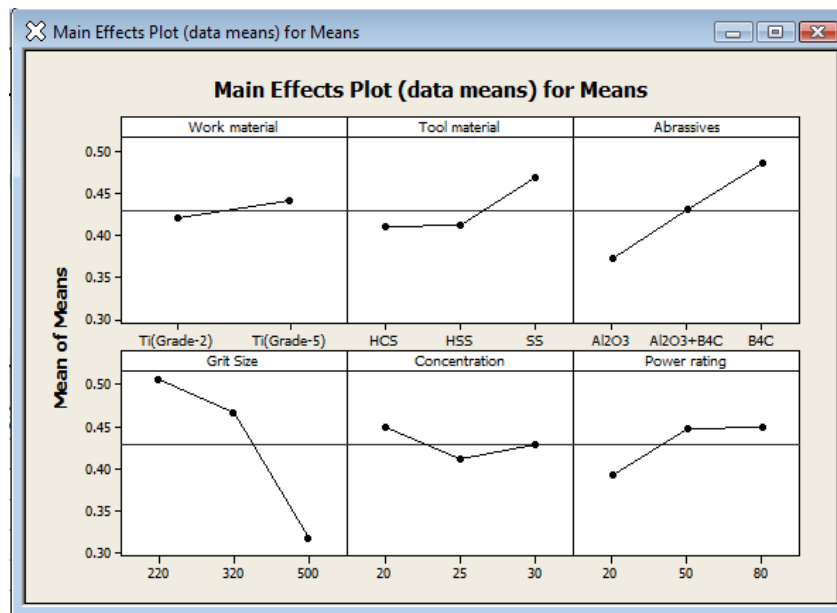


Figure 5.1: Main effects plot of MRR for Means

5.4 ANALYSIS OF S/N RATIO OF MRR

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

$$(S/N)_{HB} = -10 \log (MSD_{HB})$$

(Equation 5.2)

$$\text{Where } MSD_{HB} = \frac{1}{r} \sum_{j=1}^r \left(\frac{1}{y_j^2} \right) \text{ (Equation 5.3)}$$

MSD_{HB} = Mean Square Deviation for higher-the-better response.

Table 5.4 shows the ANOVA results for S/N ratio of MRR without cryogenic treated tool material at 95% confidence interval. Grit size of abrasives was observed to be the most significant factor affecting the MRR, followed by abrasive, tool material according to F test. All the interactions are insignificant. Main effects plot of S/N ratio for MRR are shown in the figure 5.2.

Table: 5.4 Analysis of variance for S/N ratio of MRR

Source	Degree of freedom	Sum of square	Variance	F value	Significance
Work material	1	0.047	0.0474	0.01	Not Significant
Tool material	2	8.205	4.1027	0.94	Not Significant
Abrasives	2	35.621	21.8106	7.80	Significant
Grit size	2	71.654	35.8270	8.24	Significant
Concentration	2	5.346	2.6731	0.61	Not Significant
Power rating	2	7.027	3.5135	0.81	Not Significant
Residual error	6	26.098	4.3496		
Total	17	133.999			

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

Level	Work material	Tool material	Abrasives	Grit size	Concentration	Power rating
1	-8.577	-8.835	-9.632	-6.687	-7.824	-9.388
2	-8.474	-9.152	-8.592	-7.590	-9.152	-8.260
3		-7.588	-7.353	-11.298	-8.600	-7.928
Delta	0.103	1.564	2.279	4.611	1.329	1.460
Rank	6	3	2	1	5	4

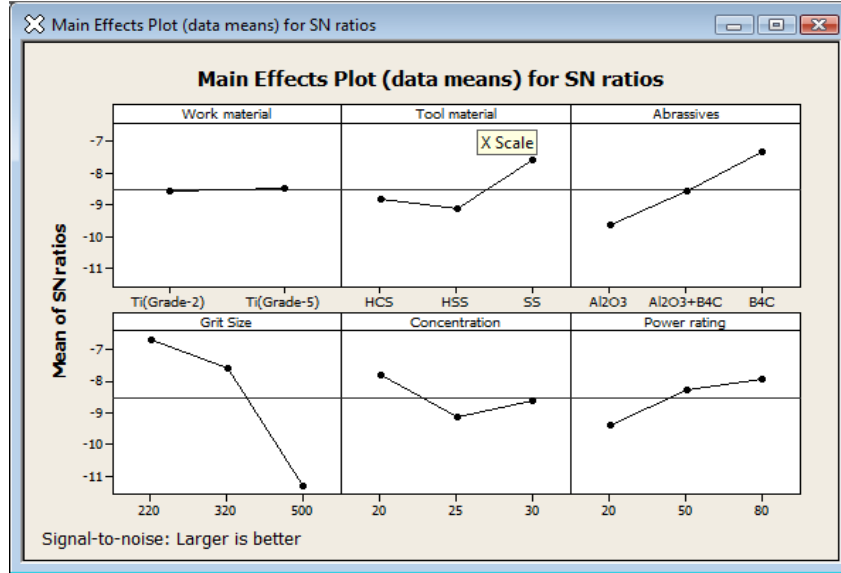


Figure: 5.2: Main effects plot of MRR for S/N ratio

5.5 RESULTS FOR TWR

In the first set-up, experiment was performed to determine the effect on HCS tool of Titanium (ASTM Grade-2) workpieces using alumina slurry of 220 grit size with 20% concentration by weight in distilled water as suspension media. The experiment was started by setting power rating of the machine at 20 %(of 500W) i.e.125W of ultrasonic drilling machine. The results for TWR for each of the 18 experiments using without cryogenic treated tool material with one repetition are given in Table 5.6.TWR of each sample is calculated from weight difference of tool material before and after the performance trial, which is given by:

$$\text{TWR} = \frac{(W_i - W_f)}{\rho \times t} \text{ mm}^3/\text{min} \quad (\text{Equation 5.4})$$

Where W_i = Initial weight of tool material (gms)

W_f = Final weight of tool material (gms)

t = Time period of trails in minutes

ρ = Density of tool material in gms/mm^3

Table 5.6: Results for TWR

Trial No:	Work material	Tool Material	Abrasives	Grit Size	Concentration	Power rating	TWR mm ³ /min		S/N Ratio	Mean TWR
							I	II		
1	Ti (Grade-2)	HCS	Al ₂ O ₃	220	20	20	0.255	0.127	13.9172	0.1910
2	Ti (Grade-2)	HCS	B ₄ C	320	25	50	0.255	0.255	11.8692	0.2550
3	Ti (Grade-2)	HCS	Al ₂ O ₃ + B ₄ C	500	30	80	0.255	0.127	13.9172	0.1910
4	Ti (Grade-2)	HSS	Al ₂ O ₃	220	25	50	0.245	0.245	12.2167	0.2450
5	Ti (Grade-2)	HSS	B ₄ C	320	30	80	0.245	0.123	14.2508	0.1840
6	Ti (Grade-2)	HSS	Al ₂ O ₃ + B ₄ C	500	20	20	0.123	0.245	14.2508	0.1840
7	Ti (Grade-2)	SS	Al ₂ O ₃	320	20	80	0.249	0.374	9.9594	0.3115
8	Ti (Grade-2)	SS	B ₄ C	500	25	20	0.125	0.249	14.1102	0.1870
9	Ti (Grade-2)	SS	Al ₂ O ₃ + B ₄ C	220	30	50	0.249	0.125	14.1102	0.1870
10	Ti (Grade-5)	HCS	Al ₂ O ₃	500	30	50	0.255	0.255	11.8692	0.2550
11	Ti (Grade-5)	HCS	B ₄ C	220	20	80	0.127	0.255	13.9172	0.1910
12	Ti (Grade-5)	HCS	Al ₂ O ₃ + B ₄ C	320	25	20	0.255	0.127	13.9172	0.1910
13	Ti (Grade-5)	HSS	Al ₂ O ₃	320	30	20	0.245	0.245	12.2167	0.2450
14	Ti (Grade-5)	HSS	B ₄ C	500	20	50	0.123	0.245	14.2508	0.1840
15	Ti (Grade-5)	HSS	Al ₂ O ₃ + B ₄ C	220	25	80	0.245	0.368	10.1000	0.3065
16	Ti (Grade-5)	SS	Al ₂ O ₃	500	25	80	0.125	0.125	18.0618	0.1250
17	Ti (Grade-5)	SS	B ₄ C	220	30	20	0.125	0.125	18.0618	0.1250
18	Ti (Grade-5)	SS	Al ₂ O ₃ + B ₄ C	320	20	50	0.249	0.249	12.0760	0.2490

5.6 ANOVA FOR TWR

The results for TWR were analyzed using ANOVA for identifying the significant factors affecting the performance measures. The Analysis of Variance (ANOVA) for the mean TWR at 95% confidence interval is given in Table 4.7. Main effects plot for TWR are shown in the Figure 5.3 that shows TWR increases with increase in power rating and TWR decreases with increase of concentration. Table 5.8 shows ranks to various factors; power rating and abrasives has highest rank, most significant that affecting TWR.

Table: 5.7 Analysis of variance for mean ratio of TWR

Source	Degree of freedom	Sum of square	Variance	F value	Significance
Work material	1	0.000228	0.000228	0.16	Not Significant
Tool material	2	0.002248	0.001124	0.39	Not Significant
Abrasives	2	0.005454	0.002727	0.81	Significant
Grit size	2	0.008121	0.004060	1.05	Significant
Concentration	2	0.001681	0.000841	0.22	Not Significant
Power rating	2	0.005692	0.002846	0.84	Significant
Residual error	6	0.023153	0.003859		
Total	17	0.046575			

Table:5.8 Response table for means of TWR

Level	Work material	Tool material	Abrasives	Grit size	Concentration	Power rating
1	0.2151	0.2123	0.2288	0.2076	0.2184	0.1872
2	0.2079	0.2248	0.2181	0.2393	0.2183	0.2292
3		0.1974	0.1877	0.1877	0.1978	0.2182
Delta	0.0071	0.0273	0.0411	0.0516	0.0206	0.0420
Rank	6	4	3	1	5	2

Main Effect Plot for TWR:-

Main effect plots for tool wear rate are shown in the figure 5.3. Main effect plot shows the variation into tool wear rate with respect to work material, tool material, abrasives, grit size, concentration and power rating. It observed that the minimum tool wear is given while using

SS tool and boron carbide slurry with a course grit size of 500 and slurry concentration of 25 % when titanium and its alloys was machined. X axis represents change in level of the variable and y axis represents the change in the resultant response. The mean line is shown by the straight horizontal line.

Mean TWR = 0.098909

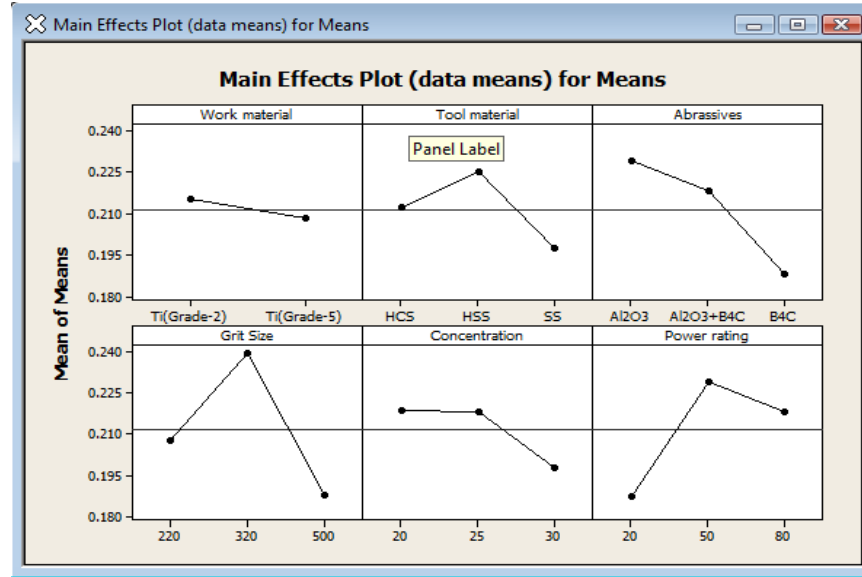


Figure 5.3: Main effects plot for mean of tool wear rate

5.7 ANALYSIS OF S/N RATIO FOR TWR

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

$$S / N_{LB} = -10 \log(MSD) = -10 \log\left(\frac{1}{r} \sum_{i=1}^r y_i^2\right) \text{ (Equation 5.2)}$$

Where $MSD_{LB} = \frac{1}{r} \sum_{j=1}^r (y_j^2)$ (Equation 5.3)

Table 5.9 shows the ANOVA for S/N ratio for TWR at 95% confidence interval. The grit size and power rating is the most significant in affecting TWR followed by abrasives used according to F test. Main effect plot of S/N ratios for TWR are shown in the Figure 5.4.

Table: 5.9 Analysis of variance for S/N ratio of TWR

Source	Degree of freedom	Sum of square	Variance	F value	Significance
Work material	1	1.914	1.914	0.30	Not Significant
Tool material	2	7.545	3.773	0.79	Not Significant
Abrasives	2	7.389	3.694	0.58	Not Significant
Grit size	2	12.766	6.383	1.01	Significant
Concentration	2	3.195	1.597	0.25	Not Significant
Power rating	2	8.637	4.319	0.98	Significant
Residual error	6	38.043	6.340		
Total	17	79.488			

Table: 5.10 Response table for S/N ratio of TWR

Level	Work material	Tool material	Abrasives	Grit size	Concentration	Power rating
1	13.18	13.23	13.04	13.72	13.06	14.41
2	13.83	12.88	13.06	12.38	13.38	12.73
3		14.40	14.41	14.41	14.07	13.37
Delta	0.65	1.52	1.37	2.03	1.01	1.68
Rank	6	3	4	1	5	2

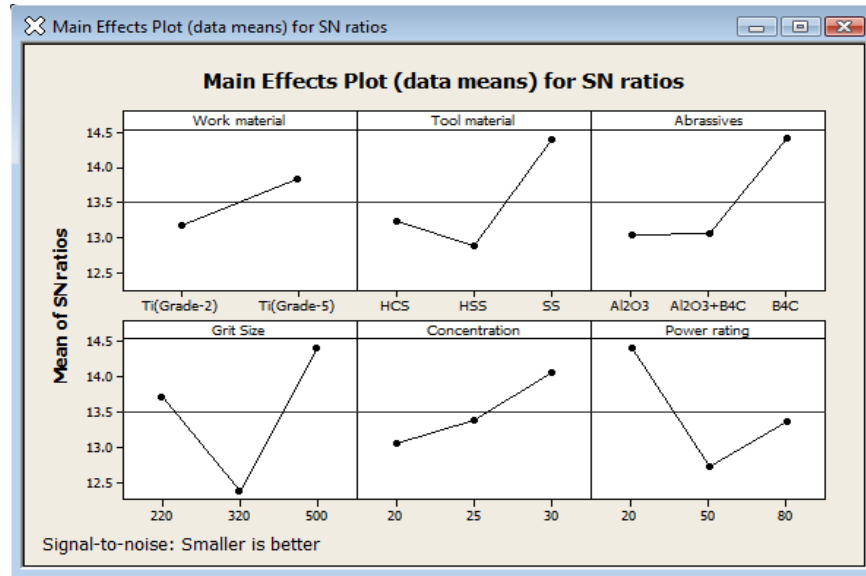


Figure 5.4: Main effects plot for S/N ratio of tool wear rate

5.8 ANOVA FOR SURFACE ROUGHNESS

The results for surface roughness were analyzed using ANOVA for identifying the significant factors affecting the performance measures. ANOVA for the mean surface roughness at 95% confidence interval is given in Table 5.12. The work material, tool material, abrasives, grit size, concentration and power rating are input parameters which affect the surface roughness. Main effect plots had shown in the Figure 5.5. The workpiece material and abrasives is the most significant factor affects the surface roughness. Table 5.13 shows ranks to various input parameters in terms their relative significance.

Table 5.11 : Results for Surface Roughness

Trial No:	Work material	Tool Material	Abrasives	Grit Size	Concentration	Power rating	Surface Roughness			S/N Ratio	Mean
							I	II	III		
1	Ti (Grade-2)	HCS	Al2O3	220	20	20	1.7326	1.4918	1.3162	-3.65473	1.5135
2	Ti (Grade-2)	HCS	B4C	320	25	50	0.8214	0.9701	0.9926	0.61973	0.9280
3	Ti (Grade-2)	HCS	Al2O3 + B4C	500	30	80	1.0072	0.9168	0.9934	0.23525	0.9724

4	Ti (Grade-2)	HSS	Al ₂ O ₃	220	25	50	1.1491	0.9802	1.0027	-0.39630	1.0440
5	Ti (Grade-2)	HSS	B ₄ C	320	30	80	1.2476	1.5064	1.1121	-2.27245	1.2887
6	Ti (Grade-2)	HSS	Al ₂ O ₃ + B ₄ C	500	20	20	0.8474	0.806	0.8121	1.70218	0.8218
7	Ti (Grade-2)	SS	Al ₂ O ₃	320	20	80	1.3272	1.0001	0.977	-0.92977	1.1014
8	Ti (Grade-2)	SS	B ₄ C	500	25	20	0.8584	0.947	0.6914	1.52490	0.8322
9	Ti (Grade-2)	SS	Al ₂ O ₃ + B ₄ C	220	30	50	1.6823	1.5001	1.5103	-3.89841	1.5642
10	Ti (Grade-5)	HCS	Al ₂ O ₃	500	30	50	0.2991	0.3512	0.4499	8.58851	0.3667
11	Ti (Grade-5)	HCS	B ₄ C	220	20	80	1.0044	1.0068	0.9912	-0.00715	1.0008
12	Ti (Grade-5)	HCS	Al ₂ O ₃ + B ₄ C	320	25	20	0.622	0.7126	0.7712	3.04101	0.7019
13	Ti (Grade-5)	HSS	Al ₂ O ₃	320	30	20	0.5501	0.45	0.5823	5.50684	0.5274
14	Ti (Grade-5)	HSS	B ₄ C	500	20	50	0.5915	0.6271	0.5412	4.61751	0.5866
15	Ti (Grade-5)	HSS	Al ₂ O ₃ + B ₄ C	220	25	80	1.0012	1.018	1.0112	-0.08778	1.0101
16	Ti (Grade-5)	SS	Al ₂ O ₃	500	25	80	0.8956	0.6901	0.711	2.25761	0.7655
17	Ti (Grade-5)	SS	B ₄ C	220	30	20	0.8412	0.6279	0.7714	2.47456	0.7468
18	Ti (Grade-5)	SS	Al ₂ O ₃ + B ₄ C	320	20	50	1.1513	1.2685	1.0021	-1.18211	1.1406

Table: 5.12 Analysis of variance for mean ratio of Surface Roughness

Source	Degree of freedom	Sum of square	Variance	F value	Significance
Work material	1	0.57595	0.57595	12.24	Significant
Tool material	2	0.06935	0.03467	0.74	Not Significant
Abrasives	2	0.08257	0.04129	0.88	Not Significant
Grit size	2	0.53576	0.26788	5.69	Significant
Concentration	2	0.07230	0.03615	0.77	Not Significant
Power rating	2	0.08255	0.04128	0.88	Not Significant
Residual error	6	0.28236	0.04706		
Total	17	1.70084			

Table 5.13: Response table for means of Surface Roughness

Level	Work material	Tool material	Abrasives	Grit size	Concentration	Power rating
1	1.1185	0.9139	0.8865	1.1466	1.0275	0.8573
2	0.7607	0.8798	1.0352	0.9480	0.8803	0.9384
3		1.0252	0.8972	0.7242	0.9111	1.0232
Delta	0.3578	0.1454	0.1487	0.4223	0.1471	0.1659
Rank	2	6	4	1	5	3

Main Effect Plot for Surface Roughness:-

Main effect plots for surface roughness are shown in the figure 5.5. Main effect plot shows the variation in surface roughness with respect to work material, tool material, abrasives, grit size, concentration and power rating. It observed that the maximum SR is given while using Ti (ASTM Grade-5), while Ultrasonic power rating of 80% with SS tool and Alumina slurry with a coarse grit size of 500 and slurry concentration of 30 %, when titanium and its alloys were machined. X axis represents change in level of the variable and Y axis represents the change in the resultant response. The mean line is shown by the straight horizontal line.

Mean SR = 0.51106

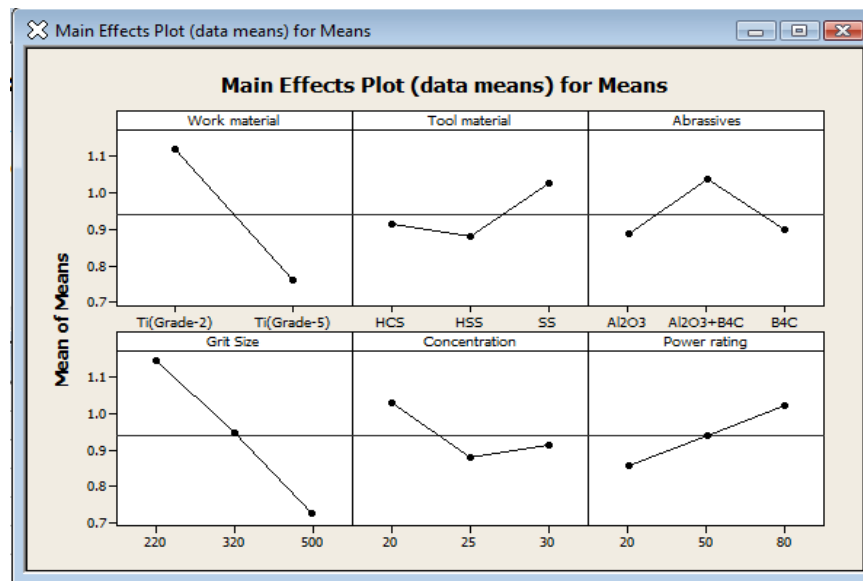


Figure 5.5 : Main effects plot for mean of surface roughness

5.9 ANALYSIS OF S/N RATIO FOR SURFACE ROUGHNESS (R_a)

The S/N ratio several repetitions into one value which reflects the amount of variation present. The values of all the results according to Taguchi array parameter design layout are presented in this section. The S/N ratios have been calculated to identify the major contributing factors in the roughness values. In this design situation, roughness is the type of 'lower is better', which is a logarithmic function based on the mean square deviation (MSD), given by

$$S / N_{LB} = -10 \log(MSD) = -10 \log\left(\frac{1}{r} \sum_{i=1}^r y_i^2\right)$$

$$\text{Where } MSD_{LB} = \frac{1}{r} \sum_{j=1}^r (y_j^2)$$

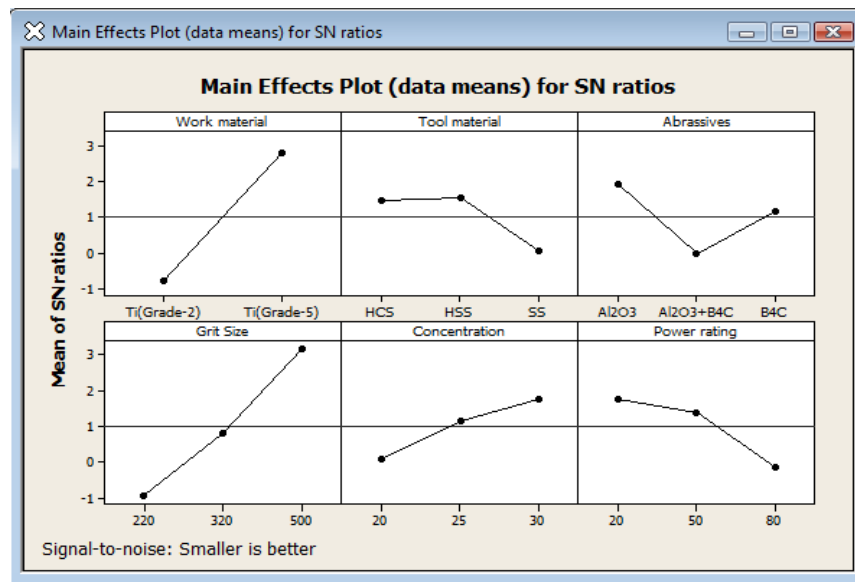
Table 5.14 shows the ANOVA for S/N ratio for roughness at 95% confidence interval. Among all the factors are work material, tool material, abrasives, grit size, concentration and power rating are input parameters which affect the surface roughness. Work material and grit size of the abrasives has most significant factors which has highest contribution in roughness.

Table: 5.14 Analysis of variance for S/N ratio of Surface Roughness

Source	Degree of freedom	Sum of square	Variance	F value	Significance
Work material	1	57.883	57.883	16.93	Significant
Tool material	2	8.415	4.207	1.23	Not Significant
Abrasives	2	11.348	5.674	1.66	Not Significant
Grit size	2	50.403	25.201	7.37	Significant
Concentration	2	8.690	4.345	1.27	Not Significant
Power rating	2	12.153	6.077	1.78	Not Significant
Residual error	6	20.515	3.419		
Total	17	169.406			

Table 5.15 : Response table for S/N ratio of Surface Roughness

Level	Work material	Tool material	Abrasives	Grit size	Concentration	Power rating
1	-0.78551	1.47044	1.89536	-0.09094	0.09094	1.76580
2	2.80097	1.51167	-0.03169	0.79716	1.15986	1.39144
3		0.04108	1.15952	3.15433	1.77238	-0.13405
Delta	3.58648	1.47059	1.92706	4.08263	1.68144	1.89984
Rank	2	6	3	1	5	4

**Figure 5.6 : Main effects plot for S/N ratio of surface roughness**

5.10 ANOVA FORMICRO HARDNESS

Themicro hardness measurement is dependent on the diameter of indentation on the samples.The indents formed in the pyramid shaped indenter were measured with Quantimet software using a static load of 100gm for 20 seconds. The results for micro hardness for each of the 18 experiments using without cryogenic treated tool material with one repetition are given in Table 5.16. ANOVA Table 5.17 shows that tool material and power rating is the significant factor which is affecting the micro hardness. Work material is the most significant factor affecting micro hardness. Table 5.18 shows relative ranks of various input parameters

according to significance. Among all the factors are insignificant but work and tool material are significant according to their ranks. Main effect plots had shown in the Figure 5.7.

Table 5.16 : Results for Micro hardness

Trial No:	Work material	Tool Material	Abrasives	Grit Size	Concentration	Power rating	Micro Hardness		S/N Ratio	Mean
							I	II		
1	Ti (Grade-2)	HCS	Al ₂ O ₃	220	20	20	227	219	46.9619	223.0
2	Ti (Grade-2)	HCS	B ₄ C	320	25	50	241	243	47.6761	242.0
3	Ti (Grade-2)	HCS	Al ₂ O ₃ + B ₄ C	500	30	80	201	205	46.1487	203.0
4	Ti (Grade-2)	HSS	Al ₂ O ₃	220	25	50	210	216	46.5650	213.0
5	Ti (Grade-2)	HSS	B ₄ C	320	30	80	181	190	45.3592	185.5
6	Ti (Grade-2)	HSS	Al ₂ O ₃ + B ₄ C	500	20	20	216	213	46.6279	214.5
7	Ti (Grade-2)	SS	Al ₂ O ₃	320	20	80	226	236	47.2661	231.0
8	Ti (Grade-2)	SS	B ₄ C	500	25	20	226	231	47.1762	228.5
9	Ti (Grade-2)	SS	Al ₂ O ₃ + B ₄ C	220	30	50	440	444	52.9082	442.0
10	Ti (Grade-5)	HCS	Al ₂ O ₃	500	30	50	456	450	53.1214	453.0
11	Ti (Grade-5)	HCS	B ₄ C	220	20	80	436	430	52.7291	433.0
12	Ti (Grade-5)	HCS	Al ₂ O ₃ + B ₄ C	320	25	20	421	434	52.6157	427.5
13	Ti (Grade-5)	HSS	Al ₂ O ₃	320	30	20	428	424	52.5879	426.0
14	Ti (Grade-5)	HSS	B ₄ C	500	20	50	438	441	52.8590	439.5
15	Ti (Grade-5)	HSS	Al ₂ O ₃ + B ₄ C	220	25	80	430	432	52.6895	431.0
16	Ti (Grade-5)	SS	Al ₂ O ₃	500	25	80	437	431	52.7492	434.0
17	Ti (Grade-5)	SS	B ₄ C	220	30	20	438	436	52.8096	437.0
18	Ti (Grade-5)	SS	Al ₂ O ₃ + B ₄ C	320	20	50	227	219	46.9619	223.0

Table: 5.17 Analysis of variance for mean ratio of micro hardness

Source	Degree of freedom	Sum of square	Variance	F value	Significance
Work material	1	217141	217141	1815.88	Significant
Tool material	2	998	499	4.17	Significant
Abrasives	2	287	144	1.20	Not Significant
Grit size	2	20	10	0.09	Not Significant
Concentration	2	362	181	1.51	Not Significant
Power rating	2	490	245	2.05	Not Significant
Residual error	6	717	120		
Total	17	220015			

Table 5.18: Response table for means of micro hardness

Level	Work material	Tool material	Abrasives	Grit size	Concentration	Power rating
1	216.2	333.1	320.6	327.3	320.3	319.4
2	435.9	315.8	327.6	324.7	326.8	326.6
3		329.3	330.0	326.3	331.2	332.2
Delta	219.7	17.3	9.4	2.6	10.9	12.7
Rank	1	2	5	6	4	3

Main Effect Plot for Micro Hardness:-

Main effect plots for micro hardness are shown in the figure 5.7. Main effect plot shows the variation in micro hardness with respect to work material, tool material, abrasives, grit size, concentration and power rating. It observed that the micro hardness is dependent on the hardness of the material and hardness of the tool material but remaining all the factors was insignificant. X axis represents change in level of the variable and Y axis represents the change in the resultant response. The mean line is shown by the straight horizontal line.

Mean SR = 448.528

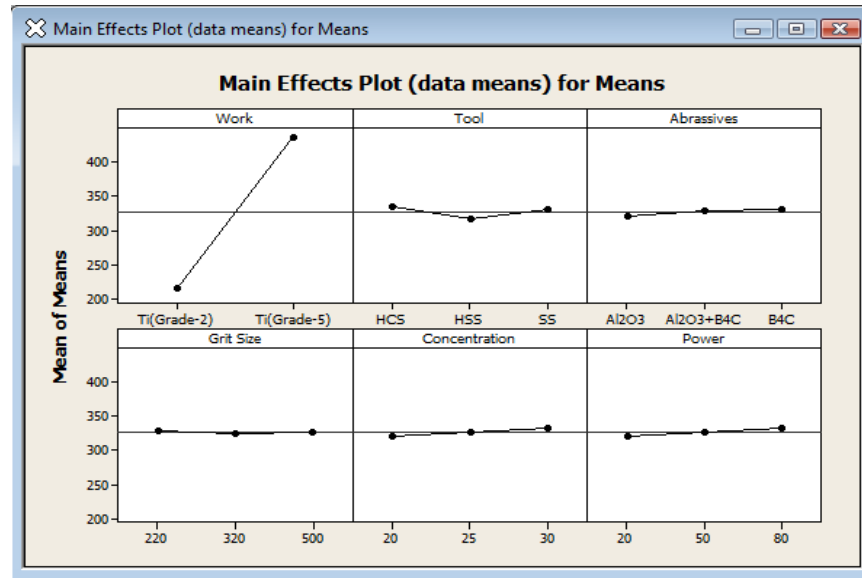


Figure 5.7: Main effects plot for mean of micro hardness

5.11 ANALYSIS OF S/N RATIO FOR MICROHARDNESS

Micro hardness is “Higher is better” type response, for which S/N ratio was calculated by using equation 5.2. Table 5.19 shows the ANOVA for S/N ratio for micro hardness at 95% confidence interval. Tool material is the significant factor which affects the micro hardness. Work material has most significant which has highest contribution in micro hardness according to F value and percentage contribution. Main effect plot of S/N ratio for micro hardness shown in the Figure 5.8

Table: 5.19 Analysis of variance for S/N ratio of micro hardness

Source	Degree of freedom	Sum of square	Variance	F value	Significance
Work material	1	168.310	0.626	846.57	Significant
Tool material	2	1.252	0.177	3.15	Significant
Abrasives	2	0.353	0.002	0.89	Not Significant
Grit size	2	0.004	0.370	0.01	Not Significant
Concentration	2	0.740	0.282	1.86	Not Significant
Power rating	2	0.564	0.199	1.42	Not Significant
Residual error	6	1.193			
Total	17	172.416			

Table 5.20: Response table for S/N ratio of micro hardness

Level	Work material	Tool material	Abrasives	Grit size	Concentration	Power rating
1	45.67	49.94	49.54	49.72	49.46	49.49
2	52.79	49.36	49.77	49.72	49.78	49.77
3		49.89	49.88	49.75	49.95	49.92
Delta	6.12	0.58	0.34	0.03	0.49	0.43
Rank	1	2	5	6	3	4

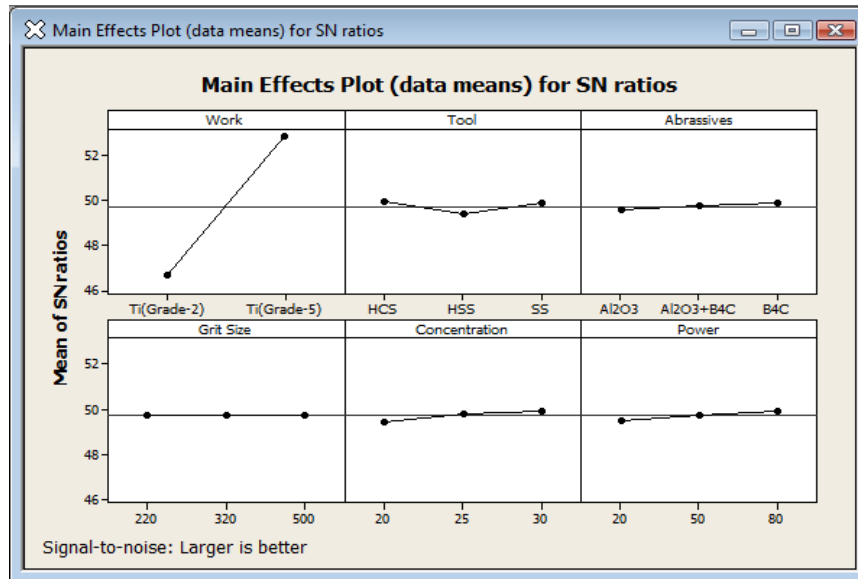


Figure 5.8 : Main effects plot for S/N ratio of micro hardness

5.12 DIMENSIONAL ERROR

Tool wear is the most important variable in USM. Tool diameter is affected by work material and abrasives used in experimentation. The biggest disadvantage of dimensional accuracy of the machining ultrasonic drill is to increase the diameter of the tool while machining. In the ultrasonic machining exact tool dimensions setting is to be done to achieve accurate results. So the following steps were done to achieve the required dimensions and to calculate the dimensional error.

6. Before the trial run was made, measure the exact diameters of the tool using with Digital Vernier Calliper
7. After the trial run was made, measure the diameters of the hole made by machining using with optical microscope
8. The diameter reading obtained had some deviation from the desired diameter reading.
9. Offset dimensions were given in the parametric consideration and then machining was done so that result obtained should be exactly near to the desired value.
10. The measured deviation is shown in the table 5.21.

Table 5.21: Deviation of machining diameter done with using cryogenic treated tool material observed from the digital vernier micrometer

Expt no.	Required Diameter (mm)	Resultant diameter (mm)	Deviation in microns
1	10	10.051	51
2	10	10.073	73
3	10	10.045	45
4	10	10.032	32
5	10	10.015	15
6	10	10.009	09
7	10	10.024	24
8	10	10.008	08
9	10	10.031	31
10	10	10.017	17
11	10	10.063	63
12	10	10.021	21
13	10	10.034	34
14	10	10.019	19
15	10	10.033	33
16	10	10.002	02
17	10	10.011	11
18	10	10.022	22

5.13 OPTIMAL SOLUTION USING GREY RELATIONAL ANALYSIS[157-158]

The grey relational analysis is used to convert multi response process optimization problem in to single response optimization problem and then grey relational grade is determined. The objective is to maximize the grey relational grade and determine the optimal combination.

Following steps are used to calculate the grey relational grade

3. **Calculation of pre processed data result:-** For higher the better characteristic following equation is to be used to calculate the data

$$x_i(k) = \frac{y_i(k) - \min y_i(k)}{\max y_i(k) - \min y_i(k)}$$

For lower the better characteristic following equation is to be used to calculate data

$$x_i(k) = \frac{\max y_i(k) - y_i(k)}{\max y_i(k) - \min y_i(k)}$$

Where $x_i(k)$ is the value after grey relational generation, $\min y_i(k)$ is smallest value of $y_i(k)$ for the k^{th} response, and $\max y_i(k)$ is largest value of $y_i(k)$ for the k^{th} response. The data is calculated in table 5.22

4. **Calculation of Grey relational coefficient :-** The grey relational coefficient is calculated in table 5.23 by the following relation

$$\xi(x_{0j}, x_{ij}) = \frac{\Delta_{\min} + \zeta \Delta_{\max}}{\Delta_{ij} + \zeta \Delta_{\max}}$$

$$\Delta_{ij} = |x_{0j} - x_{ij}|$$

$$\Delta_{\min} = \min \{\Delta_{ij}, i = 1, 2, \dots, m; j = 1, 2, \dots, n\},$$

$$\Delta_{\max} = \max \{\Delta_{ij}, i = 1, 2, \dots, m; j = 1, 2, \dots, n\},$$

ζ is the distinguishing coefficient and its value is usually taken as 0.5.

5. **Calculation of grey relational grade:-** Find the average of all individual response coefficients by following relation as calculated in table 5.24

$$\gamma(x_{0j}, x_{ij}) = \frac{1}{n} \sum_{k=1}^n \xi(x_{0j}, x_{ij})$$

- 4. Response table for grey relational grade:** - The response table is made for every factor. This is done by adding the grey relational grades value for the factors as done in table 5.25. For example to determine the mean of grey relational grades for MRR at level 1, level 2 and level 3. Find the mean of grey relational grades for values 1-9 and 10 -18 correspondingly.

Table 5.22: Preprocessed data obtained from experimental values.

Experimental data						Preprocessed data				
S.No	Material removal rate	Tool wear rate	Surface roughness Ra	Micro Hardness HV	Deviation in microns	MRR	TWR	Ra	Hv	Dv
1	0.444	0.191	1.5135	205.5	51	0.6453	0.6461	0.0423	0.0748	0.3098
2	0.555	0.255	0.9280	223	73	0.9680	0.3029	0.5313	0.1402	0
3	0.222	0.191	0.9725	242	45	0	0.6461	0.4942	0.2112	0.3944
4	0.333	0.245	1.044	203	32	0.3227	0.3566	0.4344	0.0654	0.5775
5	0.555	0.184	1.2887	213	15	0.9680	0.6836	0.2301	0.1028	0.8169
6	0.333	0.184	0.8218	185.5	9	0.3227	0.6836	0.6199	0	0.9014
7	0.444	0.3115	1.1014	214.5	24	0.6453	0	0.3865	0.1084	0.6901
8	0.333	0.187	0.8323	231	8	0.3227	0.6676	0.6112	0.1701	0.9155
9	0.555	0.187	1.5642	228.5	31	0.9680	0.6676	0	0.1607	0.5915
10	0.335	0.255	0.3667	442	17	0.3285	0.3029	1	0.9589	0.7887
11	0.566	0.191	1.0008	453	63	1	0.6461	0.4705	1	0.1408
12	0.3395	0.191	0.7019	433	21	0.3416	0.6461	0.7201	0.9252	0.7324
13	0.3395	0.245	0.5275	427.5	34	0.3416	0.3566	0.8658	0.9047	0.5493
14	0.3395	0.184	0.5866	426	19	0.3416	0.6836	0.8164	0.8991	0.7606
15	0.566	0.3065	1.0101	439.5	33	1	0.0268	0.4627	0.9495	0.5634
16	0.3395	0.125	0.7656	431	2	0.3416	1	0.6669	0.9177	1
17	0.566	0.125	0.7468	434	11	1	1	0.6826	0.9290	0.8732
18	0.566	0.249	1.1406	437	22	1	0.3351	0.3537	0.9402	0.7183

Table 5.23: Determination of Grey Relational Coefficient

Preprocessed data					Grey relational coefficient				
MRR	TWR	Ra	Hv	Dv	ξ MRR	ξ TWR	ξ Ra	ξ Hv	ξ Dv
0.6453	0.6461	0.0423	0.0748	0.3098	0.4365	0.4362	0.9219	0.8699	0.6174
0.9680	0.3029	0.5313	0.1402	0	0.3406	0.6227	0.4848	0.7810	1
0	0.6461	0.4942	0.2112	0.3944	1	0.4362	0.5029	0.7030	0.5590
0.3227	0.3566	0.4344	0.0654	0.5775	0.6078	0.5837	0.5351	0.8843	0.4640
0.9680	0.6836	0.2301	0.1028	0.8169	0.3406	0.4224	0.6848	0.8294	0.3797
0.3227	0.6836	0.6199	0	0.9014	0.6078	0.4224	0.4464	1	0.3568
0.6453	0	0.3865	0.1084	0.6901	0.4365	1	0.5640	0.8218	0.4201
0.3227	0.6676	0.6112	0.1701	0.9155	0.6078	0.4282	0.4499	0.7462	0.3532
0.9680	0.6676	0	0.1607	0.5915	0.3406	0.4282	1	0.7567	0.4581
0.3285	0.3029	1	0.9589	0.7887	0.6035	0.6227	0.3333	0.3427	0.3880
1	0.6461	0.4705	1	0.1408	0.3333	0.4362	0.5152	0.3333	0.7802
0.3416	0.6461	0.7201	0.9252	0.7324	0.5941	0.4362	0.4098	0.3508	0.4057
0.3416	0.3566	0.8658	0.9047	0.5493	0.5941	0.5837	0.3661	0.3559	0.4765
0.3416	0.6836	0.8164	0.8991	0.7606	0.5941	0.4224	0.3798	0.3574	0.3966
1	0.0268	0.4627	0.9495	0.5634	0.3333	0.9491	0.5194	0.3449	0.4702
0.3416	1	0.6669	0.9177	1	0.5941	0.3333	0.4285	0.3527	0.3333
1	1	0.6826	0.9290	0.8732	0.3333	0.3333	0.4228	0.3499	0.3641
1	0.3351	0.3537	0.9402	0.7183	0.3333	0.5987	0.5857	0.3472	0.4104

Table 5.24: Calculation of Grey Relational Grade

ξ MRR	ξ TWR	ξ Ra	ξ Hv	ξ Dv	Grey Relational Grade γ
0.4365	0.4362	0.9219	0.8699	0.6174	0.656409896
0.3406	0.6227	0.4848	0.7810	1	0.645831582
1	0.4362	0.5029	0.7030	0.5590	0.640254097
0.6078	0.5837	0.5351	0.8843	0.4640	0.614986751
0.3406	0.4224	0.6848	0.8294	0.3797	0.531400674
0.6078	0.4224	0.4464	1	0.3568	0.566685308
0.4365	1	0.5640	0.8218	0.4201	0.648502577
0.6078	0.4282	0.4499	0.7462	0.3532	0.517072686
0.3406	0.4282	1	0.7567	0.4581	0.596724101
0.6035	0.6227	0.3333	0.3427	0.3880	0.458050755
0.3333	0.4362	0.5152	0.3333	0.7802	0.479667868
0.5941	0.4362	0.4098	0.3508	0.4057	0.439345418
0.5941	0.5837	0.3661	0.3559	0.4765	0.475282191
0.5941	0.4224	0.3798	0.3574	0.3966	0.430081353
0.3333	0.9491	0.5194	0.3449	0.4702	0.523389045
0.5941	0.3333	0.4285	0.3527	0.3333	0.408387092
0.3333	0.3333	0.4228	0.3499	0.3641	0.360694477
0.3333	0.5987	0.5857	0.3472	0.4104	0.455058299

Table 5.25 : Optimum conditions table

Parameters	level 1	level 2	level 3
Work Material	0.601985297	0.44777294	0
Tool Material	0.535861104	0.62836506	0.597287846
Abrasives	0.54360321	0.49412477	0.536909378
Grit size	0.429243707	0.53257012	0.503421882
Concentration	0.539400884	0.52483543	0.510401049
Power rating	0.502581663	0.53345547	0.538600225

From the following table the optimal conditions determined are

- G. Work material - Ti(ASTM Grade-2)
- H. Tool material - HSS
- I. Abrasives – Al_2O_3
- J. Grit size - 320
- K. Concentration - 20%
- L. Power rating - 80%

Therefore the **A₁B₂C₁D₂E₁F₃** is the most optimum combination with using cryogenic treated tool material for machining.

Compare the effect of input parameters on response variables with two different tool conditions shown in table 5.26

Response Name	Non Cryogenic treatment	Cryogenic treatment
Material Removal Rate(MRR)	0.51696	0.56130
Tool Wear Rate(TWR)	0.20169	0.16390
Surface Roughness (SR)	1.56215	0.54528
Micro Hardness	437.828	442.944

MICROSTRUCTURE ANALYSIS

6.1 INTRODUCTION

Microstructure was carried out on some selected samples on Scanning Electron Microscope, (model EVO® MA 15) of ZEISS, Germany, available in Central Forensic Science Laboratory (CFSL), Chandigarh. The range of magnification from $< 5x$ to $1,000,000x$. SEM of samples was carried out on $250x$.

To study the microstructure of titanium and its alloy after machining with USM, scanning electron microscopy (SEM) was performed on the machined samples.



Fig: 6.1 Scanning Electron Microscope

6.2 METHOD OF SAMPLE PREPERATION FOR SEM

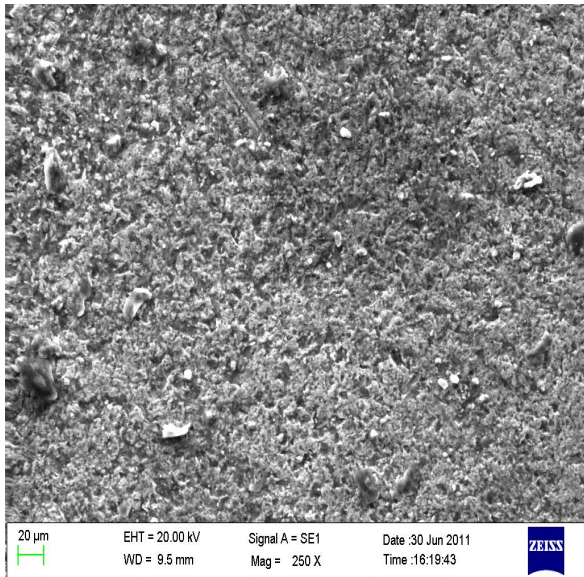
The steps for the sample preparation for SEM are given below:

- 1) Cut out the samples in 20×16mm on diamond wheel cutter.
- 2) Clean the samples with acetone.
- 3) Clean the samples with ultrasonic gel to remove any dust particles.

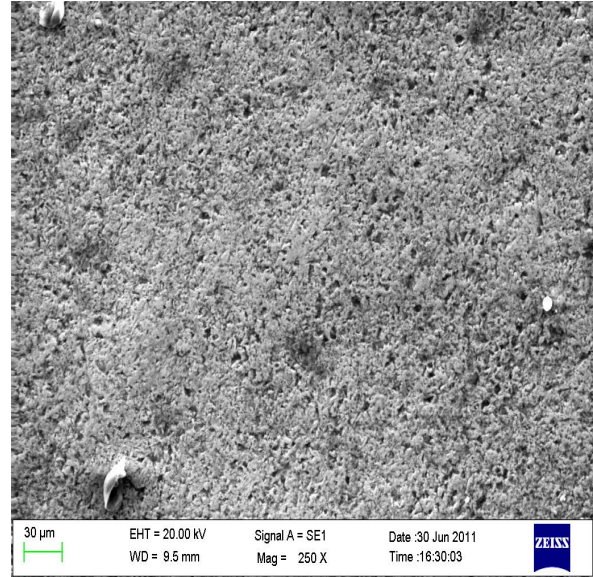
6.3 RESULTS FOR MICROSTUCTURE ANALYSIS

Test Data Experiment No: 1

1. Workpiece material = Ti (grade-2)
2. Tool material = HCS
3. Slurry type = Alumina
4. Slurry grit size = 220
5. Slurry concentration = 20%
6. Power rating = 20%(100W)



a) Non Cryogenic treatment



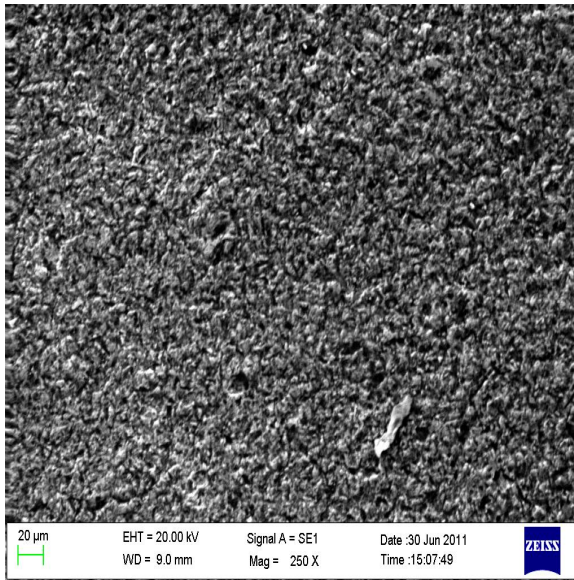
b) Cryogenic treatment

Figure 6.2 Depicts the Microstructure of Titanium (Grade-2)

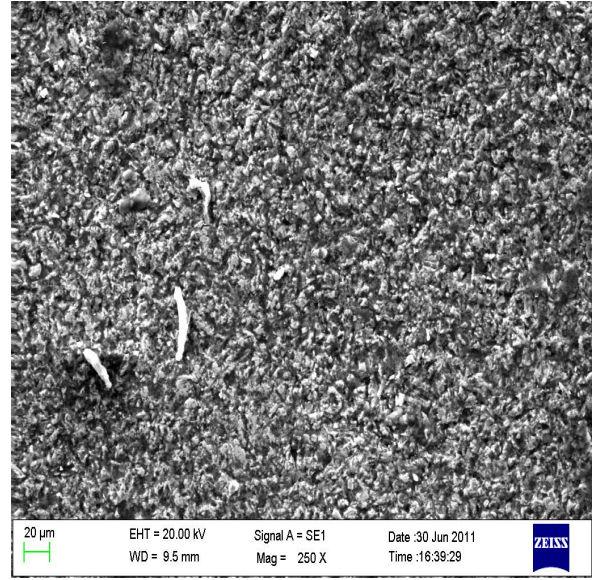
Figure 6.2(a) depicts the microstructure of titanium using non cryogenic treated tool material and Figure 6.2(b) depicts the microstructure of titanium using cryogenic treated tool material after machining with USM under the experimental conditions corresponding to experiment no. 1 at magnification levels of 250x. Because of cryogenic treatment the force of the tool become harder, thereby created more impact on abrasives grit (rather than embedding into the tool force) to create larger penetration depth. This is to increase MRR. Figure 6.2(b) as compare to 6.2(a) shows more amount of impression or dents created by abrasives.

Test Data Experiment No: 8

1. Workpiece material = Ti (grade-2)
2. Tool material = SS
3. Slurry type = Boron Carbide
4. Slurry grit size = 500
5. Slurry concentration = 25%
6. Power rating = 20%(100W)



a) Non Cryogenic treatment



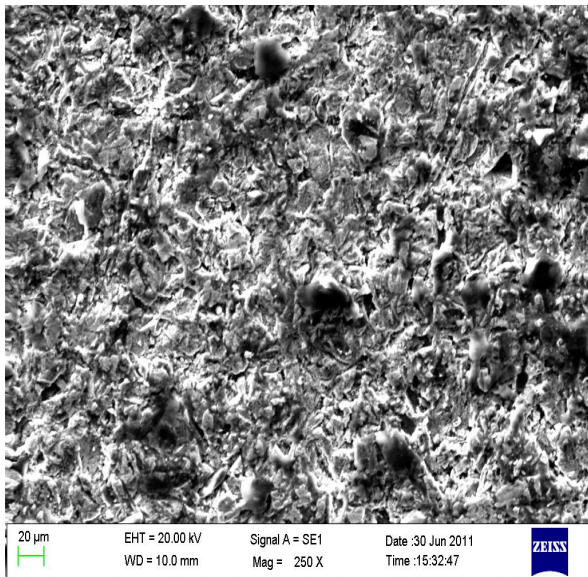
b) Cryogenic treatment

Figure 6.3 Depicts the Microstructure of Titanium (Grade-2)

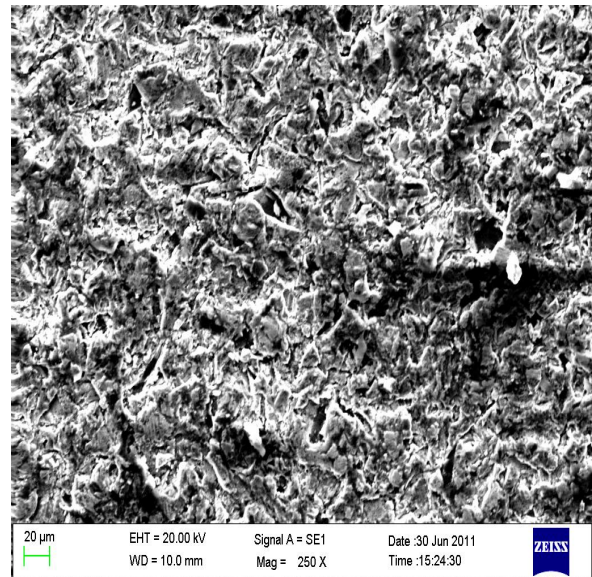
Figure 6.3(a) depicts the microstructure of titanium using non cryogenic treated tool material and Figure 6.3(b) depicts the microstructure of titanium using cryogenic treated tool material after machining with USM under the experimental conditions corresponding to experiment no. 8 at magnification levels of 250x. The abrasive used for experiment no: 8, was 500 grit sizes, therefore the grains are much finer. Thus the harder of tool by cryogenic treatment does not affect tool surface, since major mode of MRR may be due to grain in KE by the nitration of the tool. Thus penetration by abrasives all over the machined surface shows uniformity.

Test Data Experiment No: 9

1. Workpiece material = Ti (grade-2)
2. Tool material = SS
3. Slurry type = Alumina + Boron Carbide
4. Slurry grit size = 220
5. Slurry concentration = 30%
6. Power rating = 50%(250W)



a) Non Cryogenic treatment



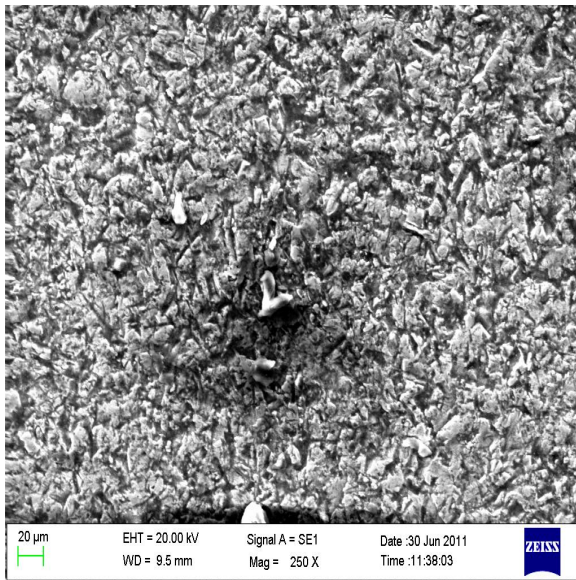
b) Cryogenic treatment

Figure 6.4 Depicts the Microstructure of Titanium (Grade-2)

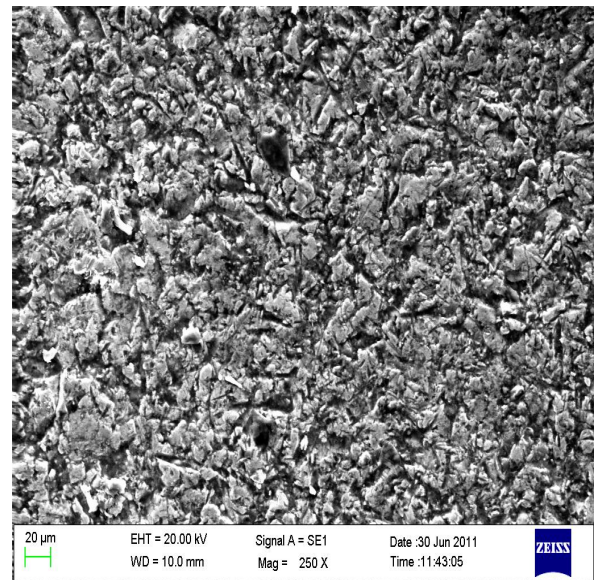
Figure 6.4(a) depicts the microstructure of titanium using non cryogenic treated tool material and Figure 6.4(b) depicts the microstructure of titanium using cryogenic treated tool material after machining with USM under the experimental conditions corresponding to experiment no. 9 at magnification levels of 250x. Cryogenic treatment does not shows the mesh improvement in MRR but undulations is machined surface earned to be minimizing after cryogenic treatment.

Test Data Experiment No: 10

1. Workpiece material = Ti (grade-5)
2. Tool material = HCS
3. Slurry type = Alumina
4. Slurry grit size = 500
5. Slurry concentration = 30%
6. Power rating = 50%(250W)



a) Non Cryogenic treatment



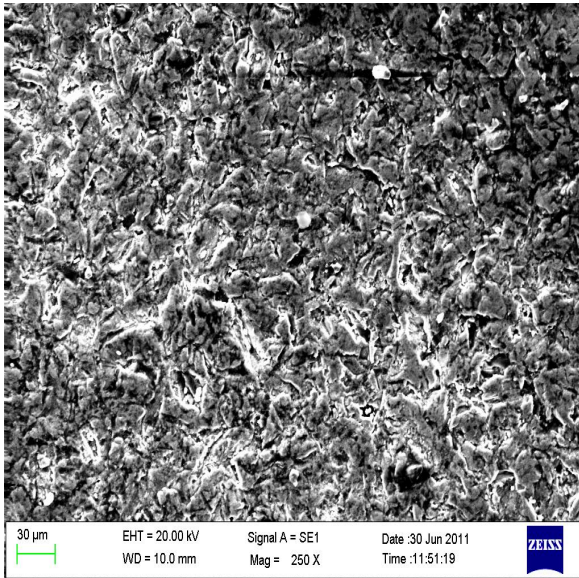
b) Cryogenic treatment

Figure 6.5 Depicts the Microstructure of Titanium (Grade-5)

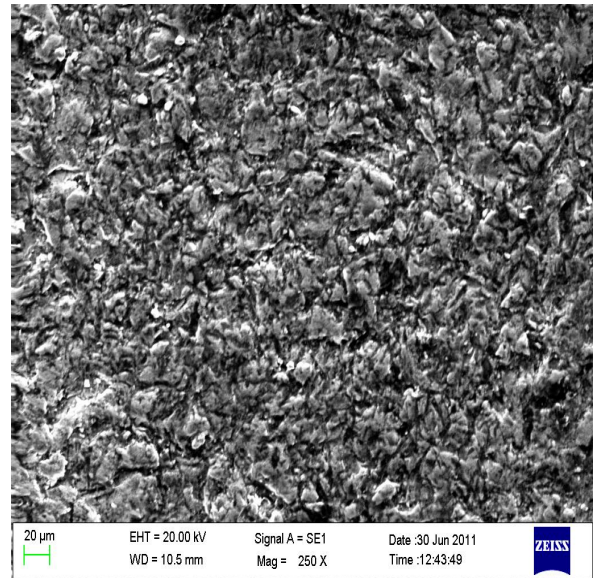
Figure 6.5(a) depicts the microstructure of titanium using non cryogenic treated tool material and Figure 6.5(b) depicts the microstructure of titanium using cryogenic treated tool material after machining with USM under the experimental conditions corresponding to experiment no. 10 at magnification levels of 250x. Due to increase in power rating, the amount of material removal has been increased as shown in figure 6.5(b). Cryogenic treatments of tool shows further improvement and due to use of finer grain size the indentation depth are also smaller.

Test Data Experiment No: 15

1. Workpiece material = Ti (grade-5)
2. Tool material = HSS
3. Slurry type = Alumina + Boron Carbide
4. Slurry grit size = 220
5. Slurry concentration = 25%
6. Power rating = 80%(400W)



a) Non Cryogenic treatment



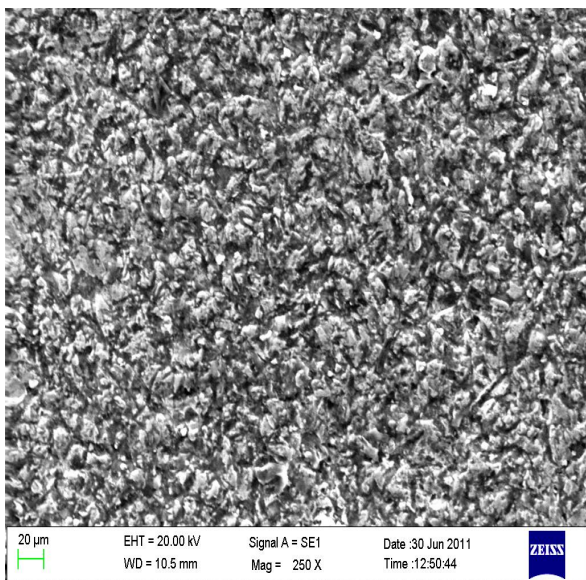
b) Cryogenic treatment

Figure 6.6 Depicts the Microstructure of Titanium (Grade-5)

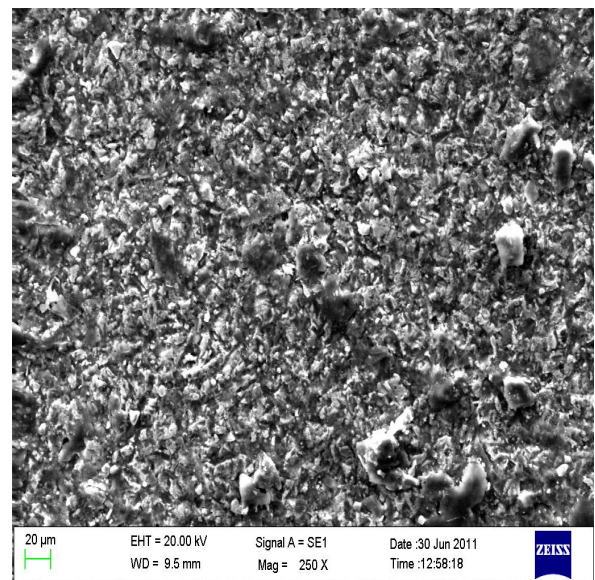
Figure 6.6(a) depicts the microstructure of titanium using non cryogenic treated tool material and Figure 6.6(b) depicts the microstructure of titanium using cryogenic treated tool material after machining with USM under the experimental conditions corresponding to experiment no. 15 at magnification levels of 250x. Due to increase in power rating, and use of course grains more uneven surface is made after machining of titanium using non cryogenic treated tool. After the Cryogenic treatments of tool shows much deeper penetration and less irregularity in indentations.

Test Data Experiment No: 18

1. Workpiece material = Ti (grade-5)
2. Tool material = SS
3. Slurry type = Alumina + Boron Carbide
4. Slurry grit size = 320
5. Slurry concentration = 20%
6. Power rating = 50%(250W)



a) Non Cryogenic treatment



b) Cryogenic treatment

Figure 6.7 Depicts the Microstructure of Titanium (Grade-5)

Figure 6.7(a) depicts the microstructure of titanium using non cryogenic treated tool material and Figure 6.7(b) depicts the microstructure of titanium using cryogenic treated tool material after machining with USM under the experimental conditions corresponding to experiment no. 18 at magnification levels of 250x. Due to cryogenic treatment much more uniformity in indentation thereby improvement in MRR. Some of the chipped out material also observed to be attached on the machined surface this shows high impact by abrasives grains due to cryogenic treatment of tool.

CONCLUSIONS AND SCOPE OF FUTURE WORK

7.1 CONCLUSIONS

Based on the experiments conducted in the present study, the following conclusions have been drawn.

1. The grey relational analysis is used to convert multi response process optimization problem into single response optimization problem and then grey relational grade is determined. The objective is to maximize the grey relational grade and determine the optimal combination. The most predicted and experimental optimum result when MRR, TWR, Surface roughness and Micro hardness with using non cryogenic treated tool material considered simultaneously for machining was found to be $A_1B_2C_3D_2E_1F_3$ i.e. work material: Titanium (ASTM Grade-2), tool material: High Speed Steel, abrasive slurry: Alumina oxide + Boron Carbide, abrasive grit size: 320, slurry concentration: 20%, and power rating: 80%.
2. The most predicted and experimental optimum result when MRR, TWR, Surface roughness and Micro hardness with using non cryogenic treated tool material considered simultaneously with using cryogenic treated tool material for machining was found to be $A_1B_2C_1D_2E_1F_3$ i.e. work material: Titanium (ASTM Grade-2), tool material: High Speed Steel, abrasive slurry: Alumina oxide, abrasive grit size: 320, slurry concentration: 20% and power rating: 80%.
3. The hardness of the machined surface has been found to be correlated with the MRR and surface quality obtained in USM of titanium. It has been found that the process settings that result in more MRR or better machining performance in terms of MRR also result in more work hardening of the machined surface, thereby promoting a large increment in the hardness of the work material after machining with USM.
4. Cryogenic treatment of tool shows a better surface finish due to much more uniformity in indentation. Due to cryogenic treatment, tool becomes harder, thereby

created more impact on abrasives grit (rather than embedding into the tool force) to create larger penetration depth as compare to non cryogenic treated tool.

5. With the use of cryogenic treated tool, dimensional error while machining have been reduced and improve machining accuracy as compared to non cryogenic treated tool. It is necessary to restore the shape of the tool before performing another experiment.
6. The selection of tool materials and design of the tools are very critical from point of view of MRR and TWR in ultrasonic machining of titanium. Initial weight of the tool is another important factor. Tool weight should not exceed the maximum limit of 50 g for optimum performance in USM for the present set-up. Improper design of the tools and excessive length leads to high temperature generation at the tool face and may also lead to fatigue failure.

7.2 SCOPE OF FUTURE WORK

1. In the present investigation, only six process parameters viz. work material, tool material, abrasive type, slurry grit size, slurry concentration and power rating was included as input factors. Study of other process parameters such as amplitude of vibration, tool geometry, flow rate of abrasive slurry, temperature of the abrasive slurry, static load and type of tool horn can be included.
2. Further study can be focused on rotary USM or hybrid USM-EDM processes that may involve five or six times superior efficiency in terms of MRR as compared to static USM used for the present investigation. Also, the flow of slurry can be magnetized while machining with static USM on tungsten carbide, stellite and Polycrystalline diamond.
3. The study can be extended to other tougher and harder materials such as copper alloys, titanium and their different alloys etc for their application in manufacturing industry.

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