Summer 7-26-2012

EXPERIMENTAL INVESTIGATION OF HARD AND BRITTLE MATERIALS MACHINING USING MICRO ROTARY ULTRASONIC MACHINING

Amey V. Patwardhan
University of Nebraska-Lincoln, ameyvpatwardhan@gmail.com

EXPERIMENTAL INVESTIGATION OF HARD AND BRITTLE MATERIALS MACHINING USING MICRO ROTARY ULTRASONIC MACHINING

by

Amey Patwardhan

A THESIS

Presented to the Faculty of

The Graduate College at the University of Nebraska

In Partial Fulfillment of Requirements

For the degree of Master of Science

Major: Industrial and Management Systems Engineering

Under the Supervision of Professor Kamlakar P.Rajurkar

Lincoln Nebraska

August, 2012

EXPERIMENTAL INVESTIGATION OF HARD AND BRITTLE MATERIALS MACHINING USING MICRO ROTARY ULTRASONIC MACHINING

Amey Patwardhan, M.S.

University of Nebraska, 2012

Advisor: Kamlakar P.Rajurkar

The demand for miniaturized device and components is rapidly increasing in fields of aerospace, energy, optics, electronics and communication, automation and medical. Rotary Ultrasonic Machining (RUM) is capable of machining hard and brittle materials such as advanced ceramics, glass and silicon used in many industries. Rotary Ultrasonic Machining (RUM) is a hybrid machining process in which material is removed by conventional grinding and ultrasonic machining. Micro RUM is a downscaled version of a macro RUM and is similar to micro Ultrasonic Machining (micro USM), where the vibration takes place in work piece instead of tool.

The goal of this thesis is to conduct a feasibility study and investigate material removal mechanism for micro rotary ultrasonic machining (micro RUM). The effect of the spindle speed, tool tip geometry, static load, coolant, coolant concentration, work piece property on the material removal rate (MRR) and tool wear of micro RUM was studied. In RUM water is normally used as a coolant. In this study, milk was first introduced as new slurry in micro RUM and comparison experiments were conducted by adopting water with conventional polycrystalline diamond (PCD) powder mixture and water only as slurry. It was discovered that as MRR increase with an increase in the spindle speed, vibration amplitude and static load irrespective of

type of working fluid. Milk as a working fluid resulted in the higher MRR, a better surface finish and less tool wear as compared to water, honey, coffee and PCD slurry as working fluids. Capability of micro RUM process for machining bovine bone was investigated. It was also found that viscosity of coolant plays a vital role in the material removal process. Temperature rise during machining was recorded using micro thermocouples. Scanning Electron Microscope (SEM) examination at higher magnifications revealed that using milk as the coolant showed a higher occurrence of ductile mode than water as a coolant. Milk was used as a working fluid during machining of bovine bone because viscosity of milk and blood is 20, 10 centipoises respectively. Surface quality of bone machined part using micro RUM is much better than other traditional and non-traditional machining methods. Finally, material removal rate predictive model was proposed and verified.

ACKNOWLEDGEMENTS

I am extremely grateful to my advisor, Prof. K.P.Rajurkar, for his guidance and support during my Master's study. I would like to thank Prof. K.P.Rajurkar for giving me opportunities to handle different projects as well as to work at Center for Nontraditional Manufacturing Research (CNMR). His dedication to research, perfectness and discipline has been a constant source of motivation.

I wish to thank Dr.Lin Gu for his guidance during the process of this thesis.

I thank Dr.Fred Choobineh and Dr. Linxia Gu for taking time to be on my thesis defense committee. Their valuable comments and insights are appreciated.

I wish to thank Dr. Velarde from biomedical lab for his help with the Scanning Electron Microscope.

I want to thank my friends and colleagues at CNMR for their wonderful support. I like to thank my parents, sister and brother in law for their love and encouragement. I want to thank Avinash, Jessica, Kriste, Annalisa and Lyndsey for their wonderful support.

Finally, I dedicate this thesis to my parents, who have great influence on my personal, academic choice and career path. This thesis would not be possible without them.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 Micromanufacturing

The demand of miniaturized devices and components is increasing rapidly in fields of aerospace, energy, optics, electronics, communication, automation and medical. As per each work pieces' physical and chemical properties, different micro manufacturing processes are required. Typical micro products include medical implants, analysis equipment's, sensors, micro-scale pumps, ink jet printers, reading caps for hard drives, optical lenses, and pacemakers, etc.

Manufacturing processes are connected to the micro and nano level products because every industry needs these products using advanced ceramics, metals and polymers. Product miniaturization is necessary in micro-electro-mechanical system (MEMS) devices as well as a strong need for an efficient use of space, energy and materials. Key parameters in the manufacturing of micro parts and devices are: high tolerance, accuracy, high precision, machining productivity, surface quality, process capability and work piece property.

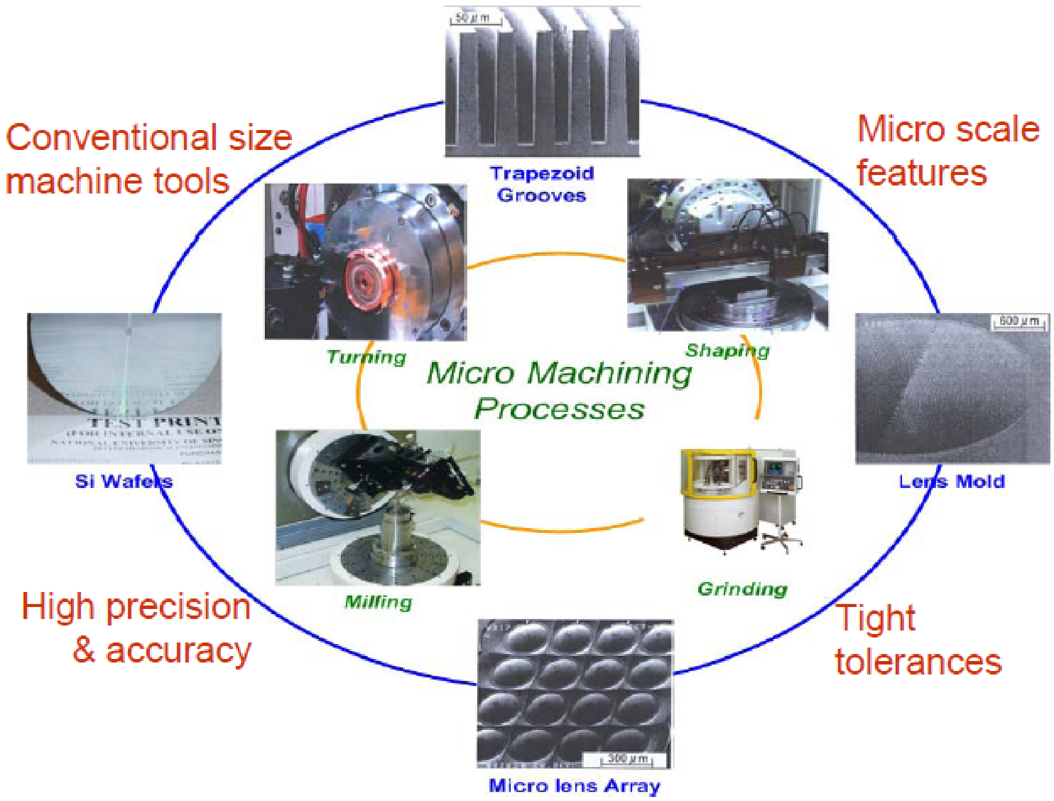


Figure 1.1. Micromachining using conventional machine tool [1]

Micro machining is defined as the ability to produce features with the dimensions between 1 μm to 999 μm [2]. When using a conventional machining process such as drilling, turning is difficult to machine advance ceramics, silicon and titanium alloys. Using the traditional method in manufacturing, a cutting tool is used to machine the work piece; but in non traditional methods, a cutting tool is used to machine the work piece but it is a non-contact process between the tool and work piece. Micro manufacturing research mainly focuses on developing techniques for machining materials which includes: electro discharge machining (EDM), electro chemical machining (ECM), laser, ultrasonic machining, and micro wave machining.

Table 1.1 Different materials for micro products and related process [3]

Material	Processes
Silicon based material	lithography, wet etching, CVD, RUM, EDM and MEMS
Metals and alloys	Micro forming, EDM, drilling, milling, ECM and LIGA
Plastic/polymers	Injection modeling, ion etching
Advanced ceramics	Laser, RUM, grinding
Advance metal ceramics	Laser, EDM, ECM

*CVD = Chemical Vapor Deposition

RUM= Rotary Ultrasonic Machining

EDM= Electrical Discharge Machining

MEMS=Microelectromechanical systems

ECM= Electrochemical Machining

LIGA= Lithography, electroforming, and molding

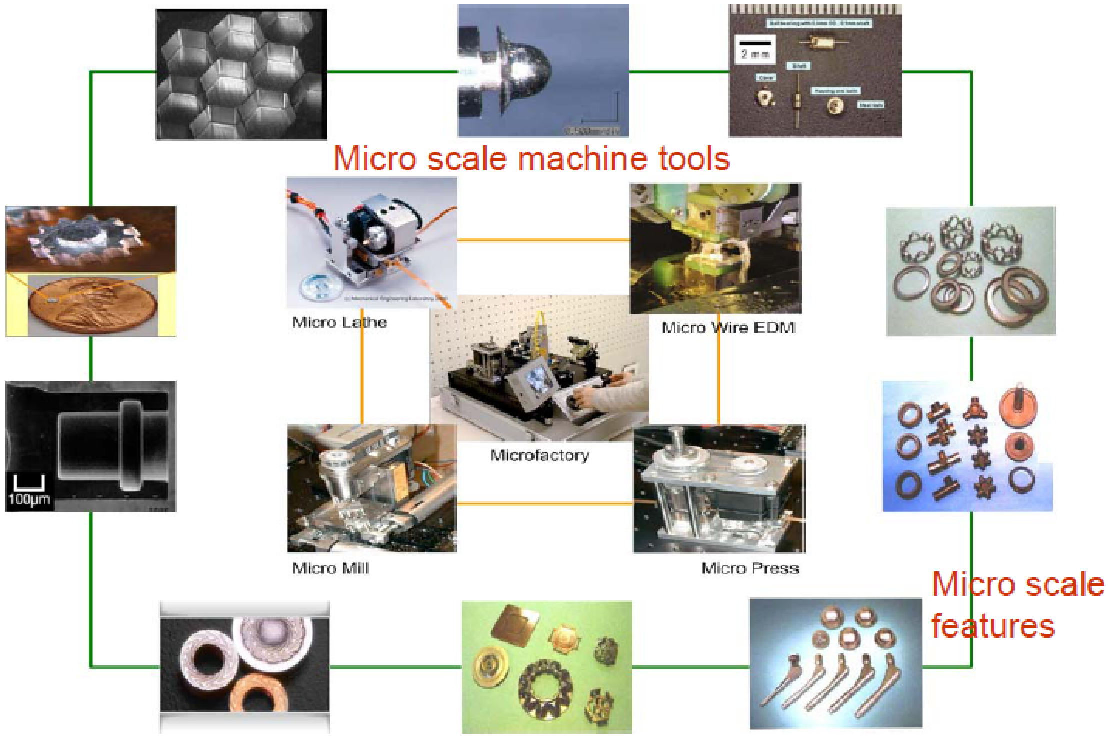


Figure 1.2. Micromachining with miniaturized machine tools and micro factories [1]

1.2 Rotary Ultrasonic Machining

Using RUM for machining hard and brittle material is a conventional and cost saving approach. In Rotary Ultrasonic Machining process material is removed by ultrasonic machining and conventional grinding.

The components of the RUM process are: Ultrasonic spindle kit, feeding device and a coolant system [4]. A coolant was injected between the tool and work piece which flushed away the debris. A good surface finish, improved hole accuracy and capability to drill a hole with low pressure was achieved by using RUM [5].The use of diamond integrated tool in RUM helped to improve hole accuracy and it was easy to drill a deeper hole.

1.3 Micro Rotary Ultrasonic Machining

Micro rotary ultrasonic machining (RUM) is derived from macro RUM, which is able to machine hard and brittle materials. This process is not commercialized at the micro level. Micro RUM is a similar process to Macro RUM but instead of tool vibration, the work piece is vibrated ultrasonically at a frequency of 39.5 KHz. The rough performance assessment of the micro RUM in comparison to other micro machining processes is presented in table.1.2 [3]. Micro RUM is a non- electrical, non-thermal and environmentally safe process. Complex shape features can be machined regardless of electrical and chemical properties of work piece materials.

Table 1.2 Micro machining process comparison

Process	Machining Speed	Material	Accuracy	Spindle
Micro RUM	High	Brittle and Hard	Medium	High
Micro EDM	Low	Electrically Conductive	High	Low or zero
Micro ECM	Low	Electrically Conductive	Medium	Low or zero
Micromechanical Machining	High	Softer than tool	High but burr	Low

1.4 Research Objectives and Thesis Organization

The overall goal of this thesis is to develop a relationship between micro RUM parameters and understand the material removal mechanism of micro RUM process.

Objectives of this thesis are:

1. Perform a parametric study to find out process parameter relation to the performance of micro RUM by experiments.
2. Use different coolants and concentration to perform several experiments to find out effect of coolant on the micro RUM process.
3. Understand mechanisms of material removal and tool wear.
4. Effect of different process parameters of micro RUM on surface quality of different work piece.
5. Develop and verify a predictive model for material removal rate (MRR) of micro RUM.

Chapter 2 presents a literature review on RUM in general and micro-RUM in detail.

Chapter 3 includes the details of the in-house designed and built experiments, machining parameters selected and experiments performed.

Chapter 4 entails the use of new coolant i.e. milk used in micro-RUM process and the effect of process parameters on machining performance. Scanning electron microscope (SEM) images were used to understand the material removal mechanism, surface quality and tool wear.

Chapter 5 encompasses the use of milk as a coolant in bovine bone machining. A comparative study between bone and silicon work piece after machining is also discussed.

Chapter 6 presents the development of a predictive model for material removal rate in micro-RUM.

Chapter 7 includes the results of this thesis, conclusions and recommendation for future work.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

This chapter discusses the process mechanism of RUM and micro RUM. It describes the current research on the mechanism of the material removal rate and machining parameters of micro and macro RUM.

2.2 Rotary Ultrasonic Machining (RUM)

Rotary ultrasonic machining (RUM) is a hybrid machining process which includes the material removal mechanism of diamond grinding and ultrasonic machining [6, 7]. The set up of RUM consists of diamond impregnated and an ultrasonically vibrated rotating tool which fed towards the work piece at a constant feed rate. A coolant is injected between the tool and the work piece through a hollow tube which washes away debris and prevents jamming of the drill as well as maintains a cool state [8].

2.3 Evolution of RUM

Rotary Ultrasonic Machining was invented in 1964 by Percy Legge [9]. Figure 2.1 shows the Principle of Ultrasonic Machining. The power supply produces an alternating electric current at frequency 18 to 24 KHz [10]. The tool is vibrated at 20 KHz frequency and fed towards the work piece. Abrasive slurry (mixture of diamonds powders and a working fluid) is fed between ultrasonically vibrating tool and the work piece.

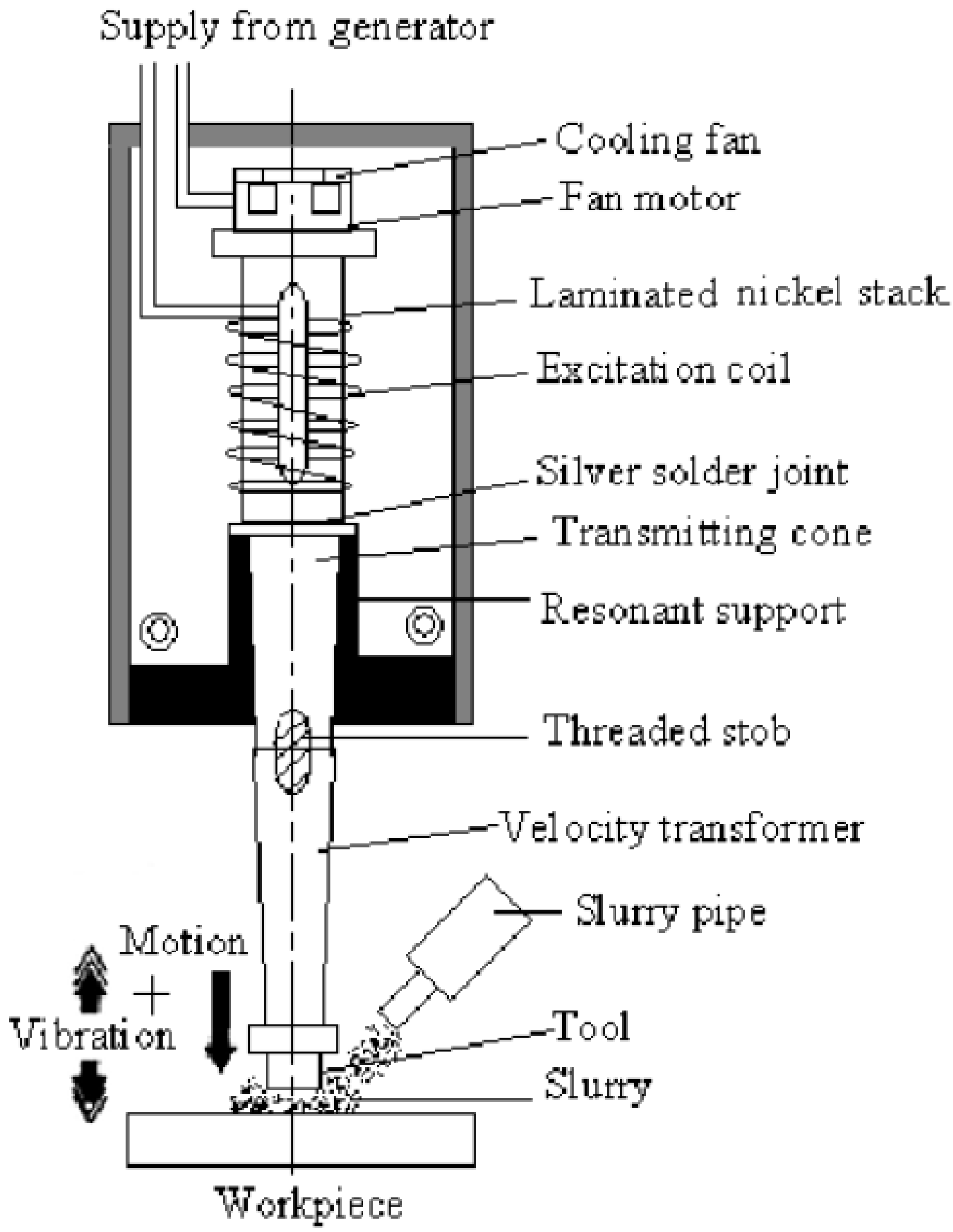


Figure 2.1. Principle of Ultrasonic Machining [10]

In Rotary Ultrasonic Machining (RUM), the abrasive slurry is replaced by a diamond impregnated tool. Figure 2.2 Illustrate the process of RUM. It was reported that MRR obtained from RUM is 6-10 times higher than the conventional grinding process [11, 12]. Comparing RUM with USM, RUM is 10 times faster. It is easier to drill deep holes with RUM, and hole accuracy is improved [13, 14]. When using RUM, it is easy to achieve high material removal rates while maintaining a low cutting pressure, which results in good surface finish and strength degradation [11].

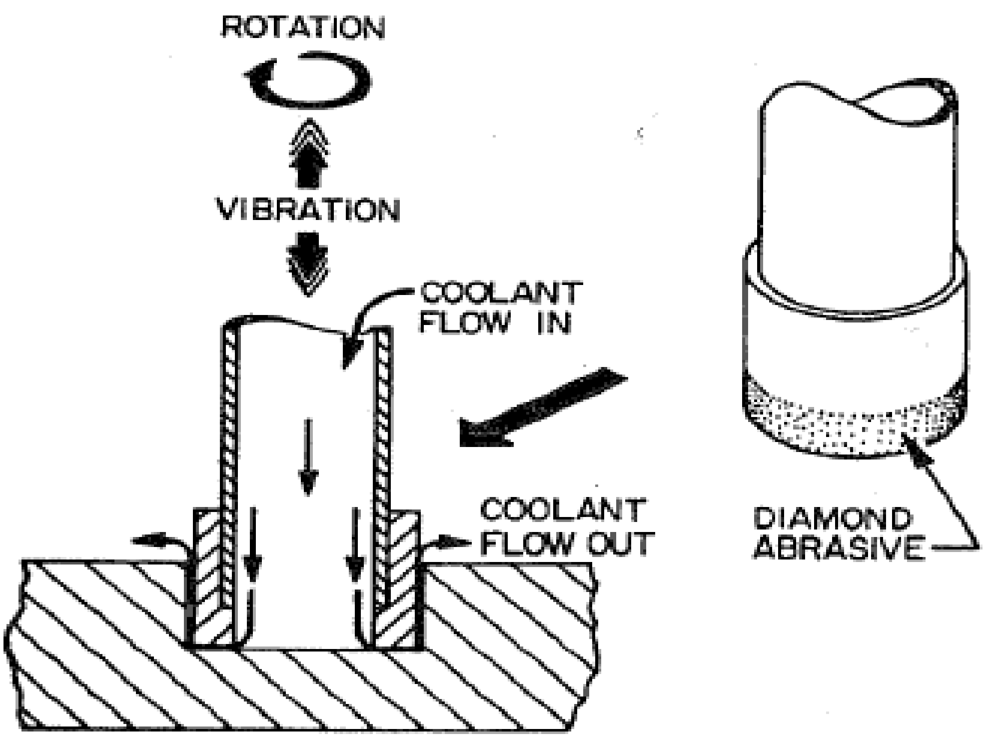


Figure 2.2: Illustration of RUM process [15]

2.3.1 Review on RUM history

Percy Legge presented rotary ultrasonic machining in 1964, but the idea of combining drilling with vibration assistance was proposed by G.C. Brown et al patent (U.S. Patent 2,943,383).

In first RUM device, the slurry was abandoned and a diamond impregnated tool and rotating work piece was used. The work piece was held in rotating chuck, only circular holes could be machined; and a small work piece could be drilled.

Improvement in RUM carried out at United Kingdom Atomic Energy Authority (UKAEA) led to development of a machine with a rotating ultrasonic transducer. It was possible to precisely machine stationary work pieces to close tolerance [15].

RUM is also known as Ultrasonic Vibration Grinding [16, 17], Ultrasonic twist drilling [18], and Ultrasonic Drilling [9].

2.4 RUM Experimental Work

Table 2.1 shows the different work piece materials machined by RUM and USM

Work piece	Experimental study	Theoretical study
Glass	[19, 20, 21]	[22]
Polycrystalline Diamond compacts	[23]	
Canasite	[15]	
Silicon Carbide	[24, 25 26]	
Silicon Nitride	[24]	
Stainless Steel	[24]	
Alumina	[27, 28, 29]	[30]
Titanium	[31, 32, 33]	
Zirconia	[11, 12]	[34]
Potassium dihyrogen phosphate (KDP)	[35]	
Macor (Dental Ceramic)	[36]	
Inconel	[37]	

2.4.1 Material Removal Mechanism

Impact mode, grinding dominant mode and erosion mode are three major modes involved in rotary ultrasonic machining [38]. Figure 2.3 shows the movement of abrasives on the tool during the machining process.

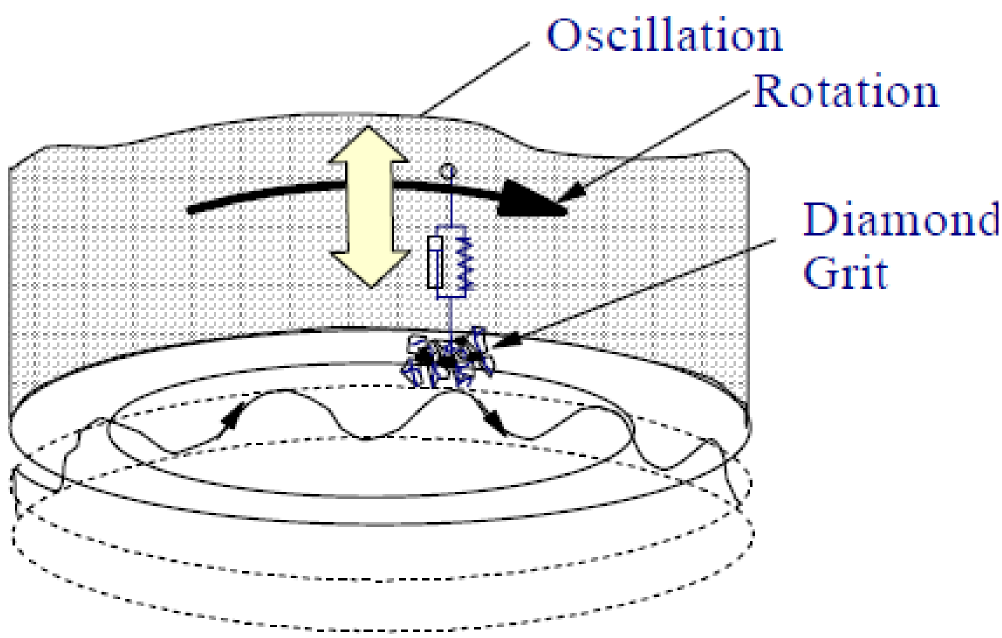


Figure 2.3. Tool abrasive trajectory [38]

It is not easy to observe machining surface or chips generated in RUM process due to the intrinsic features of RUM process [39]. It was noticed that if the specimen size decreases, the probability of stress concentration decreases, and fracture strength increases [12].

In RUM, hammering of the vibrating tool on a work piece causes brittle failure in the work surface which leads to chip formation and materials removed from the work piece [40].

In comparison to other ultra precision machining processes such as polishing, lapping etc., ductile regime machining is cost effective and less time consuming [41]. Researcher Bifano postulated a hypothesis about ductile regime grinding that all materials, regardless of their hardness or brittleness will undergo a transition from brittle machining regime to a ductile machining regime if the grinding rate is made small [42].

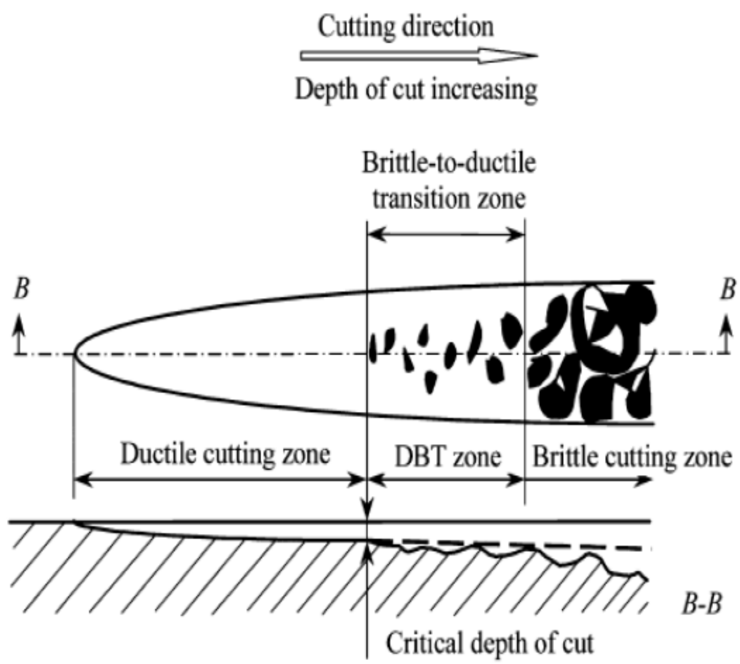


Figure 2.4: Ductile regime machining [43]

Figure 2.4 shows the three different zones formed after the tool indentation in work piece. Continuous formation of chips and absence of micro cracks and craters are characteristics of the first ductile cutting zone. Holes, cracks and surface damage are the features of a brittle cutting zone [43].

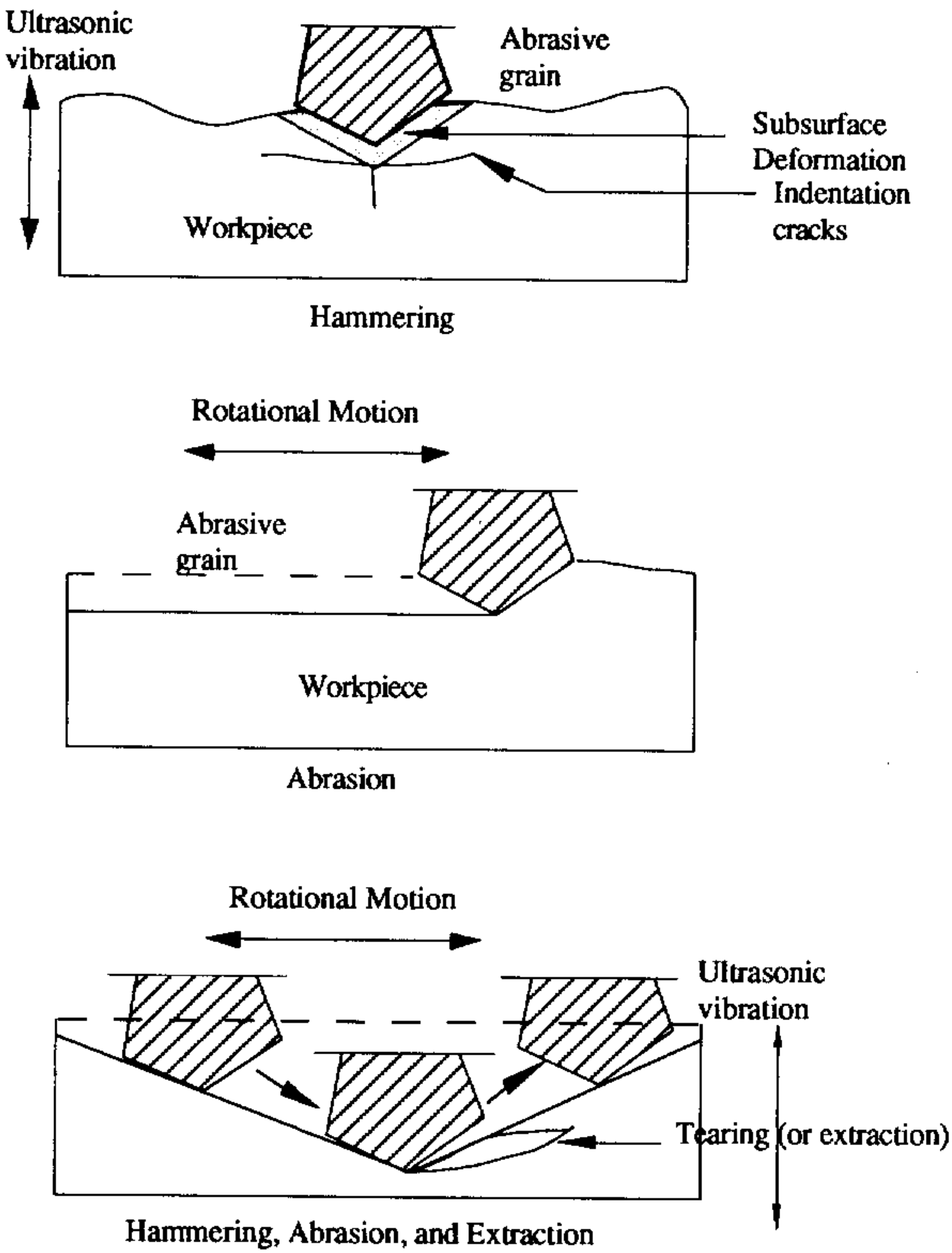


Figure 2.5. Material removal mechanism in RUM [40]

2.5 Machining Parameters

In this section, past research and experimental investigation about the effect of RUM parameter such as static load, material removal rate, spindle speed, feed rate etc, on performance of RUM with different work piece as stated in table 2.1 are reviewed.

2.5.1 Static pressure (Force)

Static pressure has a significant effect on RUM drilling performance. Advance ceramic machining such as zirconia, alumina etc. It was noticed that as static pressure increases, MRR increases and at a higher load MRR decreases [30, 44]. As static pressure increases, the tool cannot vibrate properly and debris accumulated in the gap and hence MRR decreases. For composite material C/SiC, it was observed as load increases, MRR increases; but hole clearance (surface roughness) decreases [45-48]. As static pressure increases, surface roughness increases [12].

2.5.2 Ultrasonic vibration

Increase in vibration amplitude leads to increase in MRR. For C/SiC composites, with optimal vibration, MRR increases along with an increase in hole clearance [45]. High amplitude of tool vibration results in a large force, and it flushes debris out from the gap, hence MRR increases. It was discovered that, while machining of dental ceramic macor, cutting force is reduced when ultrasonic vibration power increases from 20 % to 30%. Surface roughness increases and then decreases after a certain value and also chipping size increases when ultrasonic vibration power increases [36]. Similarly, a researcher noticed that as ultrasonic vibration power increased, cutting force was decreased while machining of alumina [49], increased for CMC [50] and also didn’t vary much for silicon carbide [33].

2.5.3 Rotation speed

Research noticed that the MRR increases when rotation speed increased but not proportionally [12, 30, 51]. It was observed that as the spindle speed increases surface roughness decreases also chip size decreases [36].

2.5.4 Abrasive size

For advanced ceramics, MRR increases as diamond concentration increase up to an optimum value [12, 45]. It was reported that optimal value depends upon the tool oscillation amplitude [52]. Hole clearance was found to increase as the abrasive grit size increases [12].

2.5.5 Coolant

It was noticed that coolant pressure doesn't have significant effect on MRR. The synthetic coolant and tap water show effective performance in RUM drilling than water based solution [27]. Tap water and synthetic coolant provide a higher cutting force than water based coolant, and these coolant types have an insignificant effect on MRR and surface roughness [53]. An air operated double diaphragm pump was introduced into RUM coolant system to decrease the machined surface roughness [23].

2.5.6 Tool wear

Separation of diamond grains from grinding debris is difficult while machining of advanced ceramics [26]. In grinding, total weight loss of a wheel and wear of a wheel is determined by grain fracture and bond fracture [54]. There are four types of wheel wear mechanism: attritious wear, grain fracture, bond fracture and grain pullout [55].

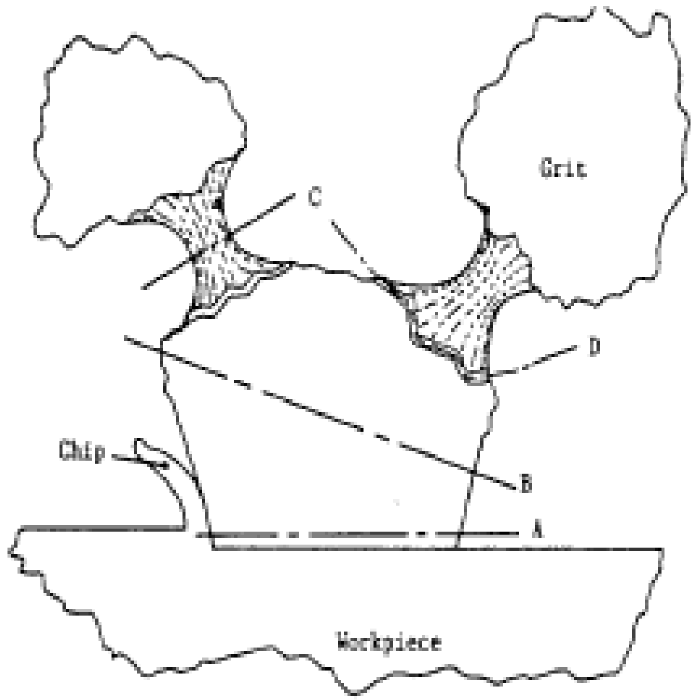


Figure 2.6: Wheel wear mechanism [56]

It was found that while machining, a grain pulled out from tool which resulted in a hole in tool. The reason found behind this was the weakening of the interface between diamond grains, and the metal bond is due to mechanical impact and high temperature [26].

2.5.7 Edge chipping

The main obstacle in drilling high quality holes is nothing but chipping. Low feed rate and high spindle speed result in a lower chipping [57]. Total cost of machining is higher because of larger edge chipping thickness [58] reported that the most influential factor on edge chipping is the cutting force.

2.6 Micro RUM

In the RUM process, the rotating and ultrasonically vibrating tool with metal bonded diamond abrasives feeds towards the work piece at a constant static load. The tool is vibrated at a frequency of about 20 KHz. The use of a diamond integrated tool in micro-RUM helps to improve hole accuracy and can easily drill a deeper hole. The basic difference in the RUM and USM process is that in the RUM process, the tool is impregnated with abrasive particles while the abrasive particles are added to the working fluids in the USM process. An investigation shows that a larger tool in micro-RUM provides higher material removal rate. The bigger tool covers a larger machining area and has more abrasives; therefore, more cutting action takes place. Surface roughness values were in range of 0.3-0.8 μm for sampling length of 0.08mm [59]. For bone machining, the material removal rate was found to increase with increasing spindle speed and abrasive grit size [59]. However, higher spindle speed and larger static load resulted in lager hole enlargement compared to lower spindle speed and static force. Drilling depth achieved by a cylindrical tool was always higher than a conical tool. Working fluid plays an important role in micro RUM by improving the machining conditions as well as removing debris out of the gap. Figure 2.7 shows the bone machined by micro rotary ultrasonic machining.

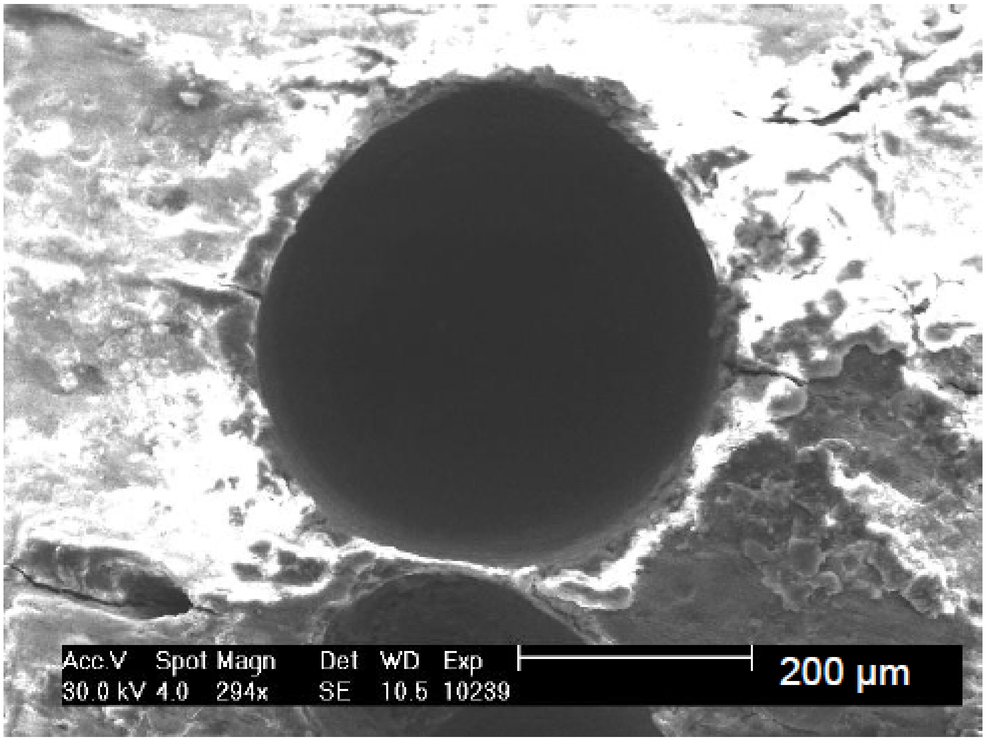


Figure 2.7: Bone machined using micro rotary ultrasonic machining [59]

2.6.1Micro RUM experimental work

Table 2.2 shows micro RUM experimental work

Work piece	Experimental study	Theoretical study
Silicon	[59, 60]	
Bovine bone	[61]	

CHAPTER 3

EXPERIMENTS

3.1 Introduction

In house designed and built experimental set up was used for machining. The experimental set up is explained in section 3.2 .1. Different types of tools used are explained in section 3.2.2. Section 3.2.3 describes the experimental conditions.

3.2 Experimental Setup

3.2.1 Micro ultrasonic machine

Micro rotary ultrasonic machining experiments were performed by using an in-house designed and built set up of micro ultrasonic machine. Ultrasonic vibration system (transducer and generator), positioning system (XYZ-stages), cutting force feedback sensor, system controller, machine spindle, tool holder and work piece holder are the basic component necessary to build the micro ultrasonic machine system. The system is an assembly of a piezoelectric ultrasonic transducer, a spindle for rotating tool and position of tool was controlled in X, Y and Z axes by a precision motion controller with 25 nm resolution. The work piece was vibrated ultrasonically at 39.5 KHz by mounting it on the free end of the transducer. A working fluid was injected into the gap between the tool and work piece. Figure 3.1 describes the system design. Figure 3.2 explains principle of operation of micro RUM. Figure 3.3 shows modified experimental set up of micro RUM.

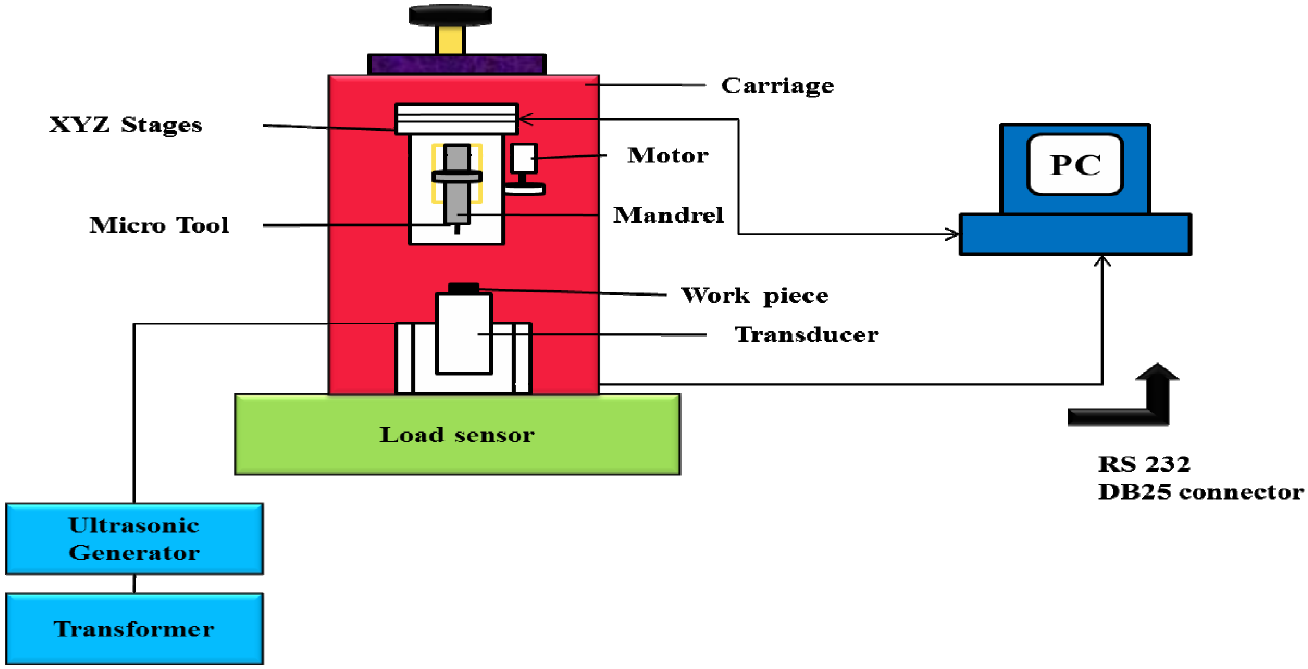


Figure 3.1. System design diagram

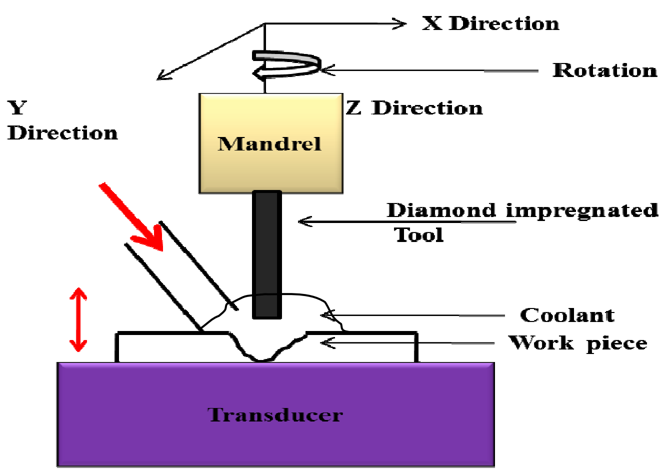


Figure 3.2. Principle of Micro rotary ultrasonic machining

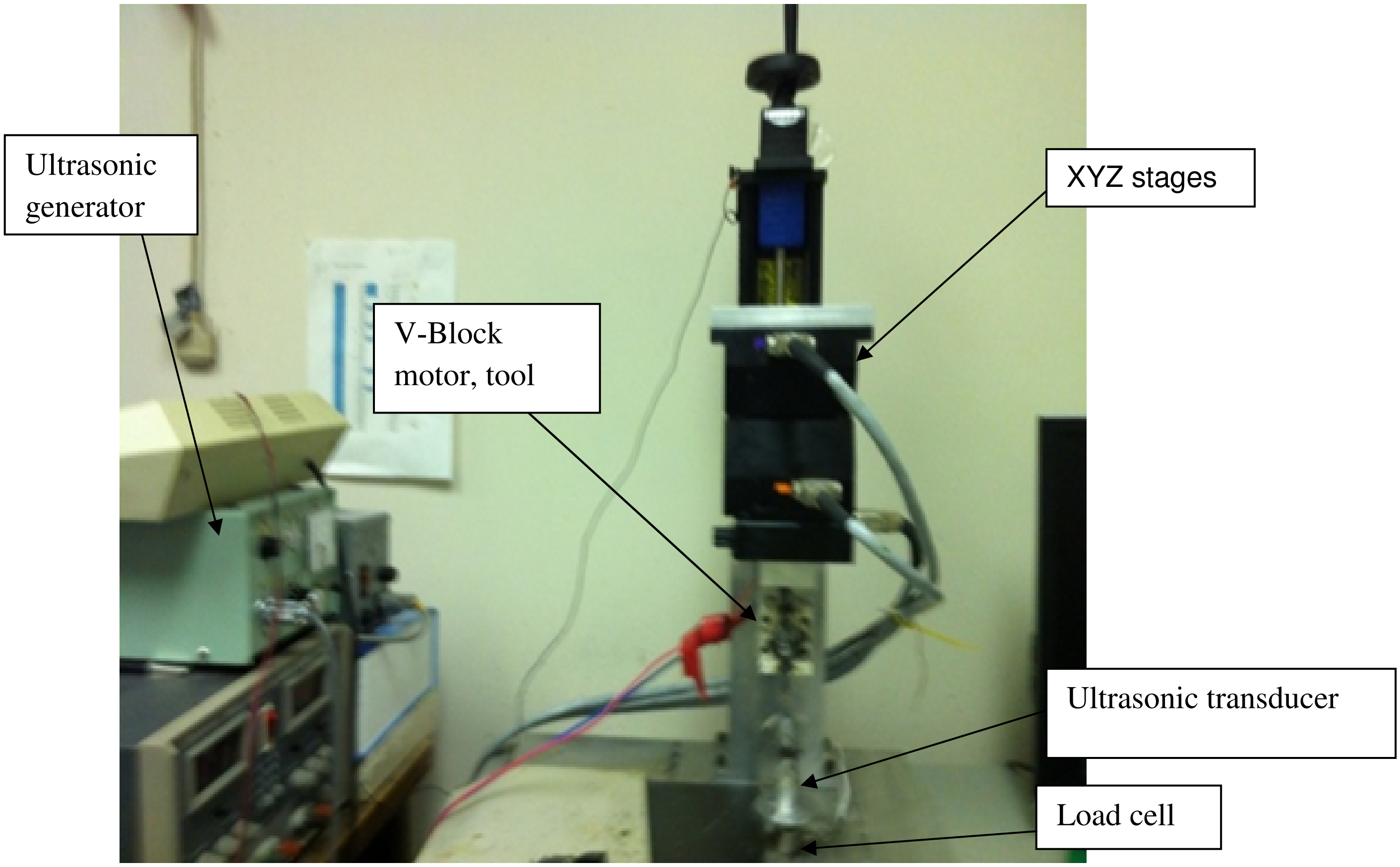
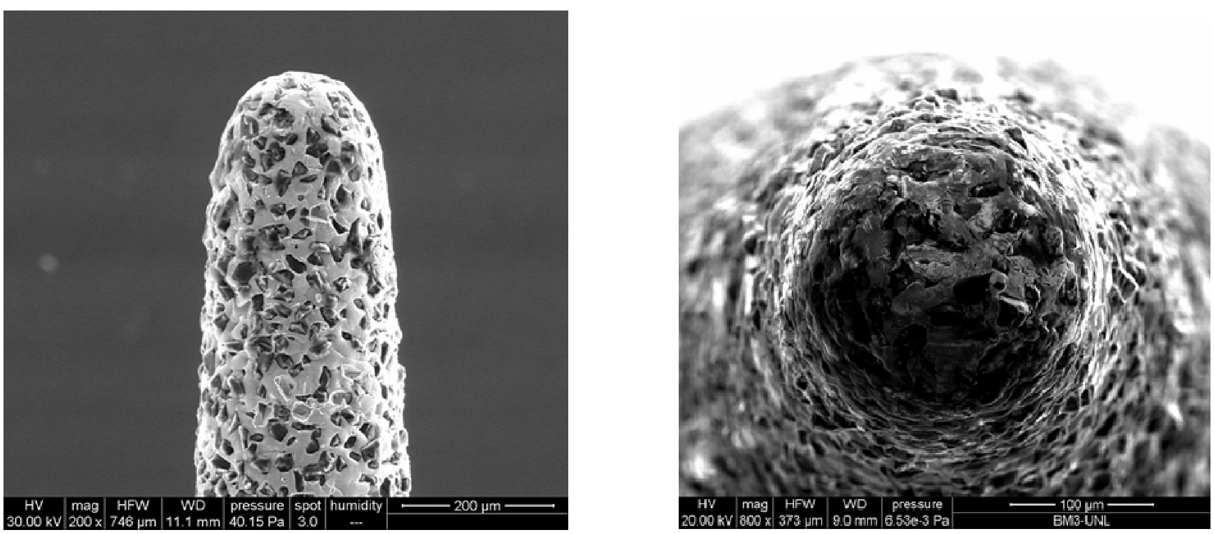


Figure 3.3. Modified experimental set up of micro RUM



(a) **(b)**

Figure 3.4. SEM images of conical tool (a) and tool tip (b)

3.3 Experimental Conditions

Experiments were conducted using the dental tool under the experimental conditions presented in Table 3.1. Experiments were focused on understanding influence of different working fluid, spindle speed and static load on material removal rate, surface of work piece and tool shape after machining. The vibration frequency was 39.5 KHz and the amplitude was 1 µm. The machining time of each experiment was 60 sec. For RUM process water is normally used as coolant. Till now, no work has ever been reported on using soft particles as slurry medium in micro-RUM. In present work, milk was first introduced as new slurry in micro-RUM and a set of comparison experiments were conducted by adopting water with conventional PCD powder mixture and water only as slurry. Bovine milk, water and 1%wt Polycrystalline diamond powder (PCD-5) slurry were used as working fluids for experiments. Milk contains large and particles which are not brittle but they are the fat molecules, an enzyme varies in size 0.1 micron to 90 micron [62]. The average diameter of the PCD abrasive particles is 5µm.

Table 3.1 Machining parameters

Parameters	**Values**
Static Load (g)	3, 5, 6, 7, 8, 9, 10
Working fluid	Milk, Water, Water + PCD(1%wt) slurry
Spindle Speed (rpm)	500, 1000, 3000
Work piece	Silicon, PZT

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

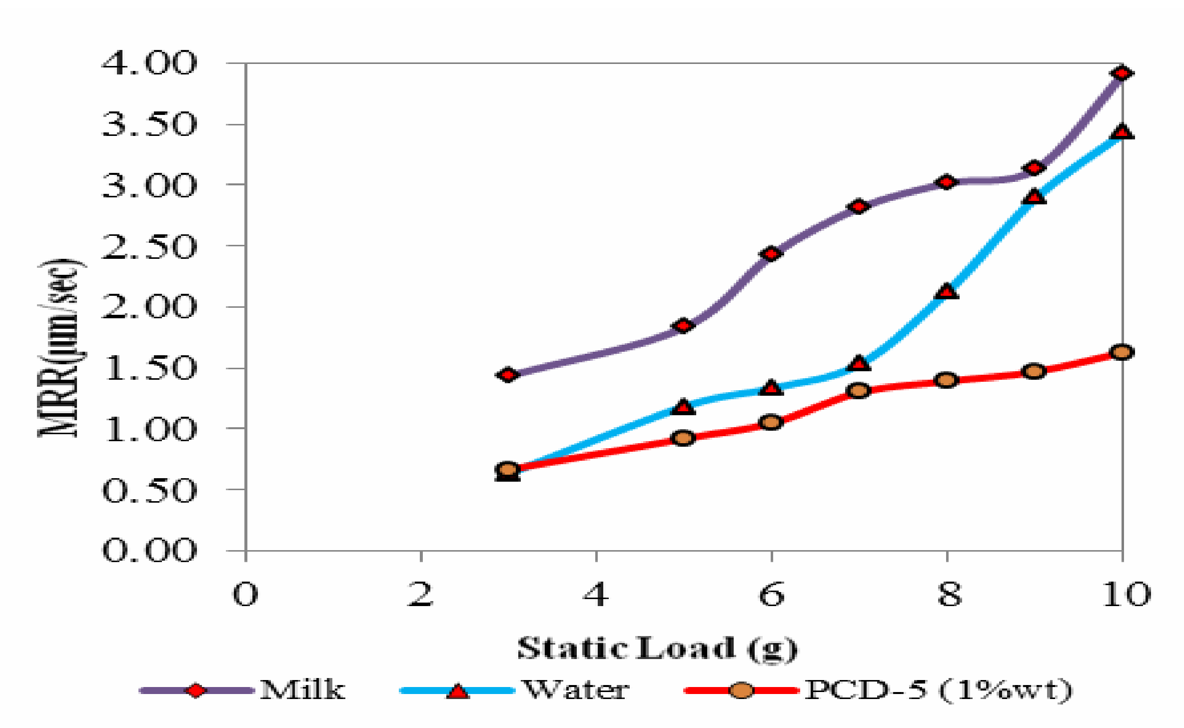
This chapter discusses the results of the experiments conducted on silicon and PZT material using conical dental tool in section 4.2. Section explains tool wear (SEM images) as result of machining and section 4.3 describes the surface quality (SEM images of machined surface) comparison between different working fluids.

4.2 Experimental results with conical dental tool

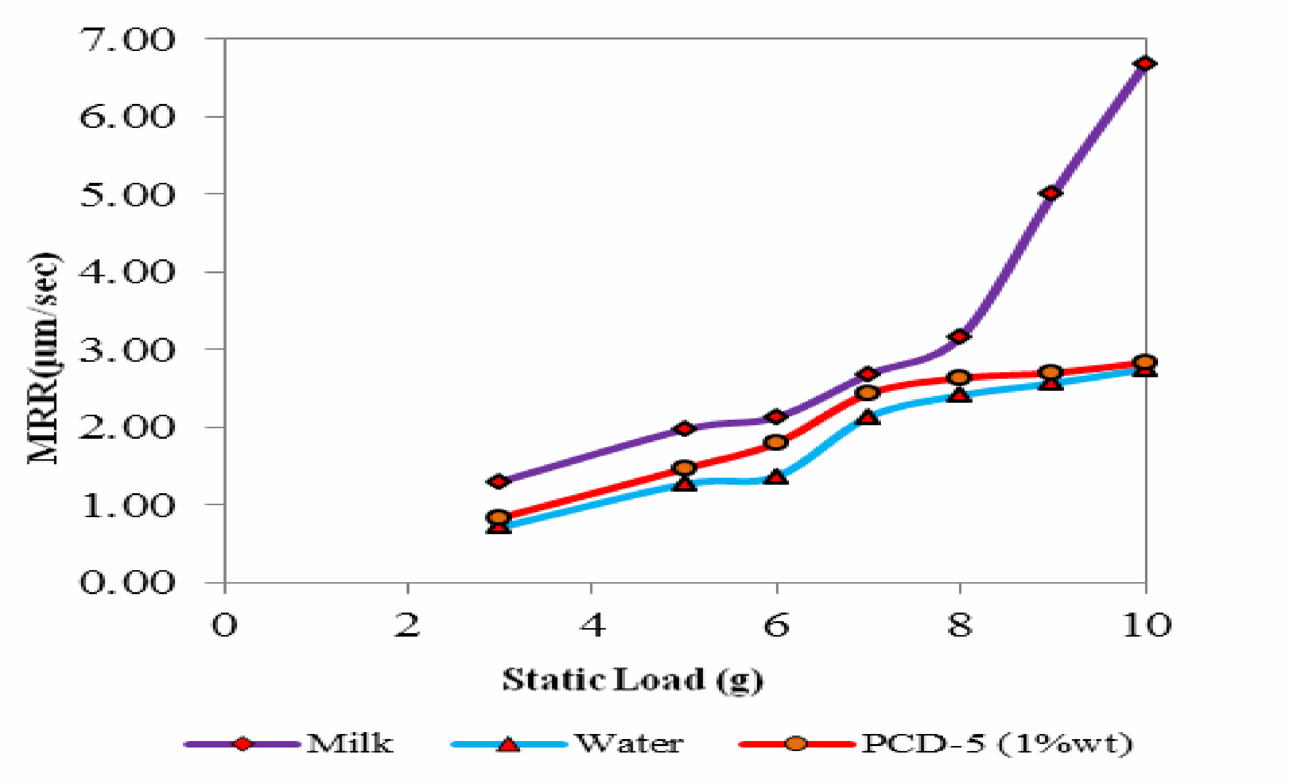
The effect of static load, spindle speed on material removal is discussed in the following sections.

4.2.1 Effect of static load

Fig. 4.1 (a) and 4.1 (b) show the effect of static load on MRR for silicon and PZT materials respectively, for a tool rotation speed of 3000 RPM. For the same working fluid and the rotation speed, a higher static load would induce a larger pressure on working fluid particles resulting in a higher MRR. When machining silicon with micro-RUM, the MRR achieved by using PCD slurry was the lowest. The reason may be that while machining by larger size abrasives, some particles interact with tool particles and tool particles accumulate in the gap resulting in lower MRR. When machining PZT material, the MRR achieved by using water as working fluid was the lowest despite it was close to that of PCD slurry. For both work piece materials, it was found that using milk as the working fluids leads to the highest MRR. It seems that the non-brittle molecule particles of the milk have a significant effect on material removal rate. This result can be attributed to the influence of molecule weight on MRR. Unlike abrasives, milk molecules are like polymers. These molecules are much heavier than other molecules of abrasive particles. Therefore, so during machining process as load increases, impact energy of the molecules increases and due to the heaver weight of milk molecules, is exerted on work piece leading to higher MRR.



(a) Silicon

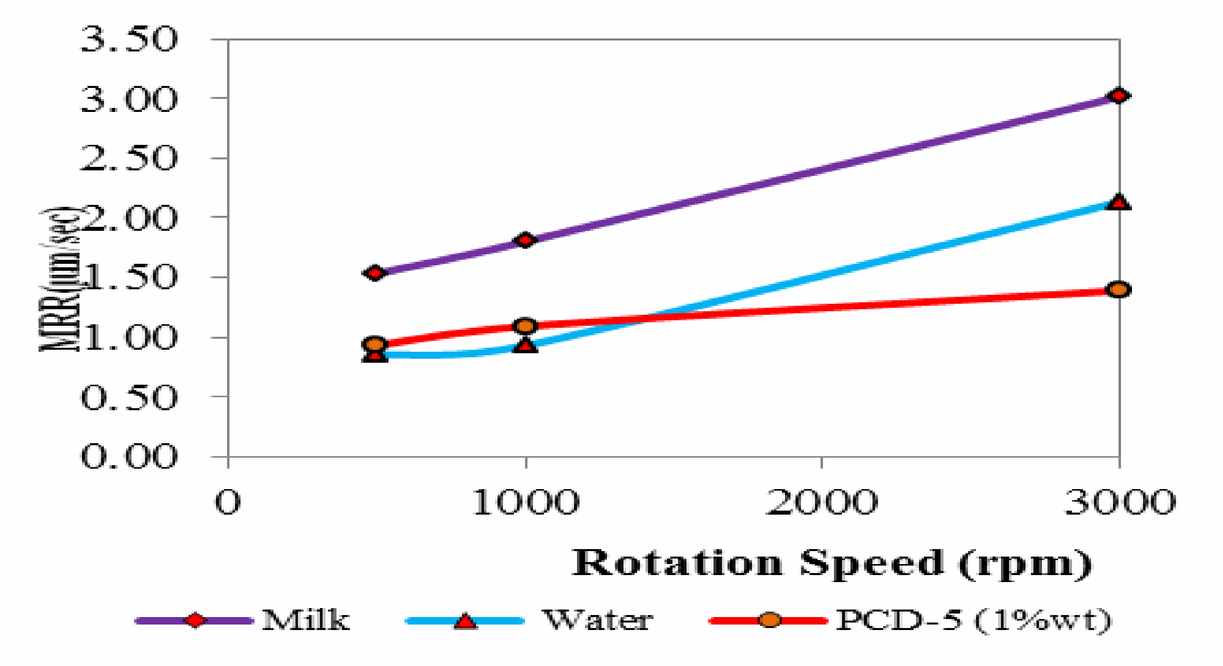


(b) PZT

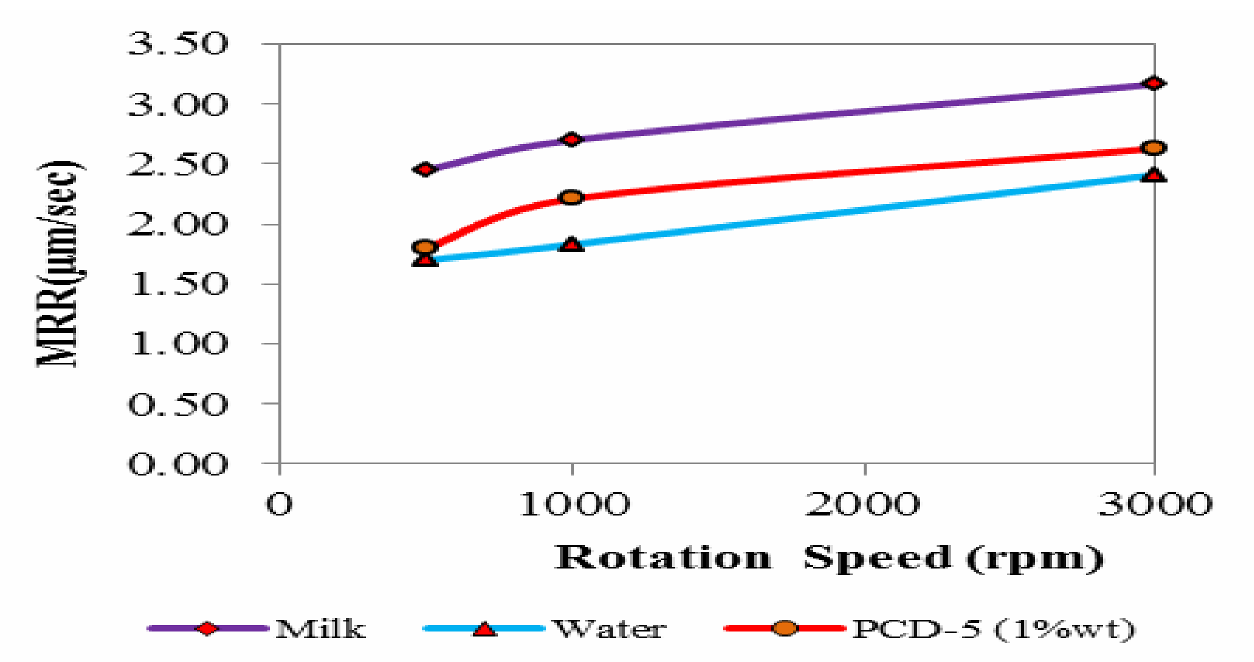
Figure 4.1. Effect of static load on MRR (working fluid=Milk, Water, PCD-5(1% wt), r=3000 rpm)

4.2.2. Effect of spindle speed

Fig. 4.2 (a) and 4.2 (b) show the relationship of MRR of silicon and PZT with spindle speed by using different working fluid at constant load of 8g. MRR increases with the increasing of spindle speed irrespective of work material and working fluid. When the spindle speed increases, the effective number of cutting edges of the abrasive on the tool surface that contact with work piece also increases and the material removal process is accelerated [63]. A tachometer was used in the experiments to check the speed spindle while machining. It was noticed that spindle speed was not constant during machining process. Another reason for the increase in MRR is the faster debris removal effect due to the rotation of tool. The chipped materials come in contact with abrasives and get crushed and act as slurry medium. From the figures, it can be seen that irrespective of work piece material, the highest MRR is achieved by using milk as the working fluid.



(a) Silicon

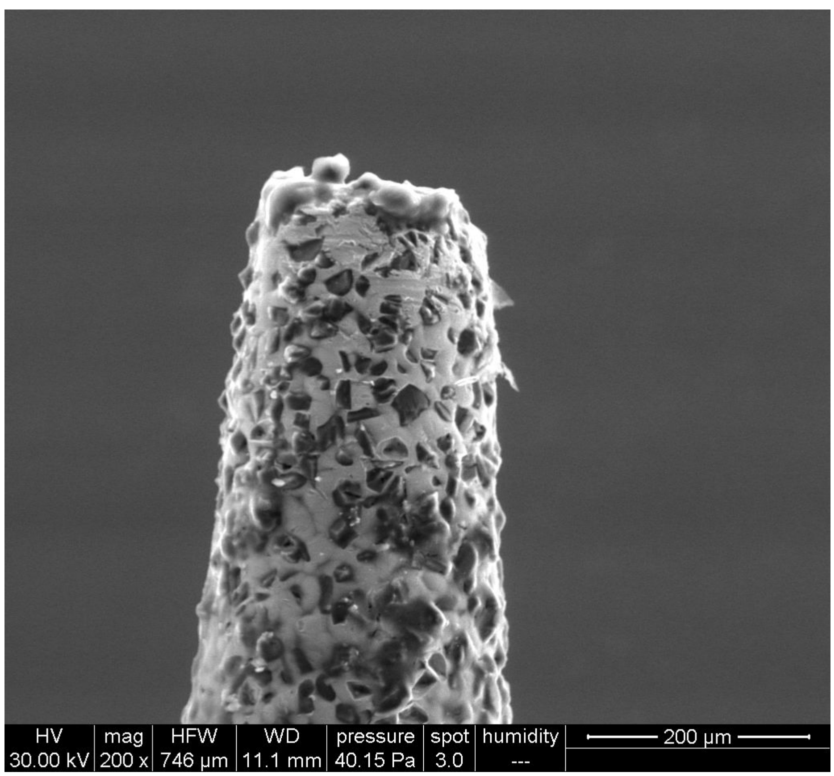


(b) PZT

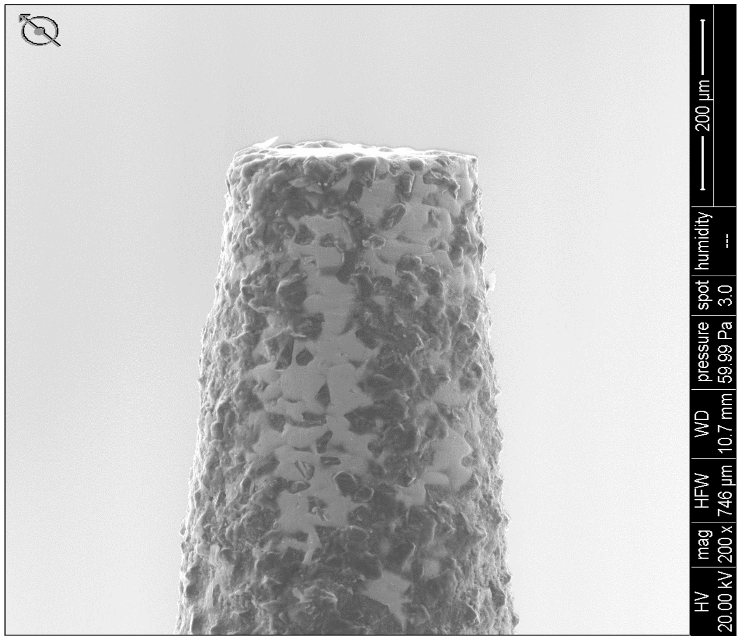
Figure 4.2. Effect of rotation speed on MRR (working fluid=Milk, Water, PCD-5 (1%wt))

4.2.3. Tool Wear

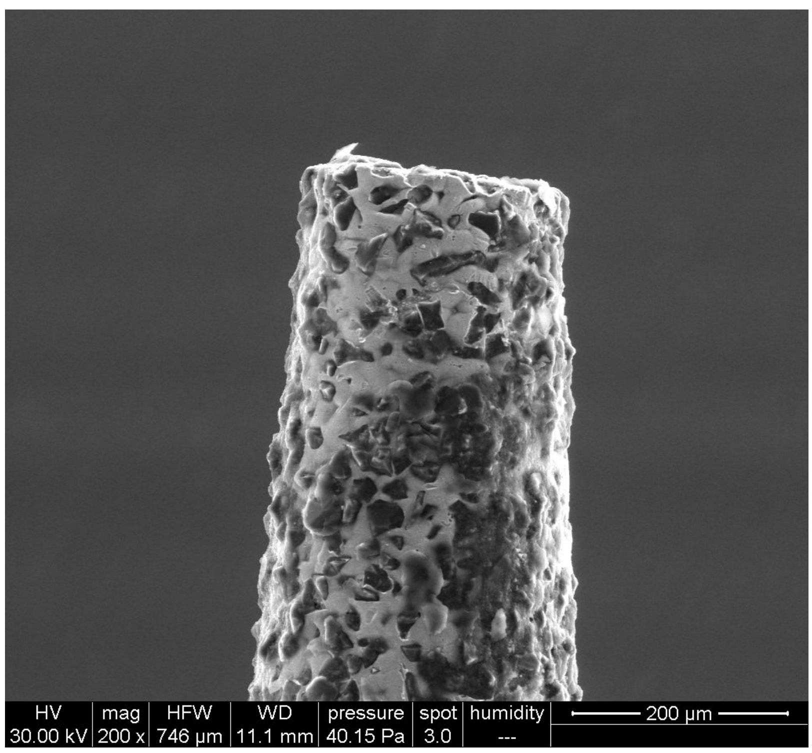
Tools used in micro-RUM are metallic and usually have a short life due to the fast tool wear [64]. Tools after machining were tested under microscope. Fig.4.3 and Fig. 4.4 show the tool shape after a series of micro-RUM machining of silicon and PZT material with milk, water and PCD slurry. It was found that tool used for machining with milk shows the least tool wear compared to those machined with abrasive slurry and water. It was noticed that abrasive slurry has significant effect on tool surface and tool wear.



(a) Milk

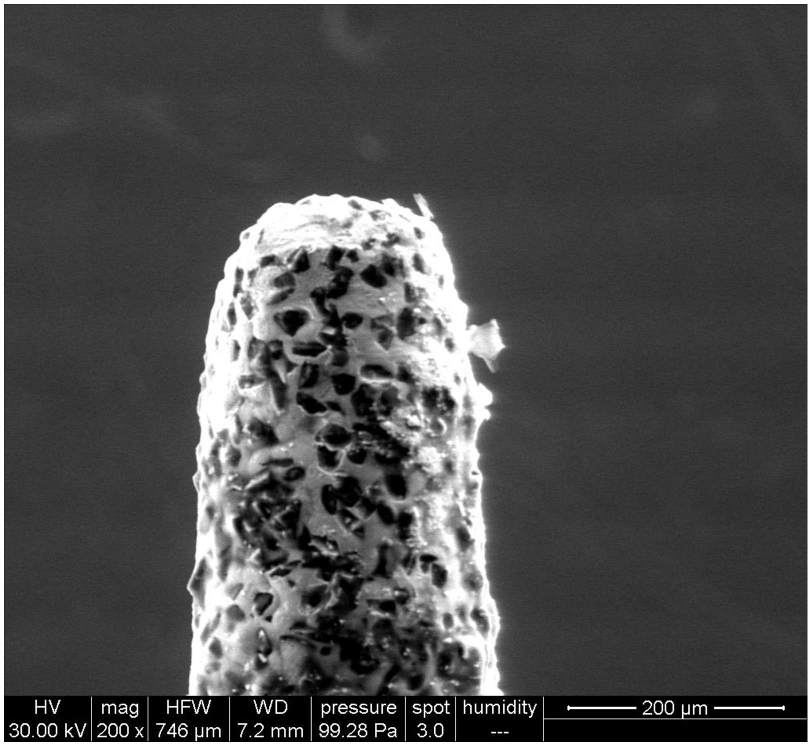


(b) Water

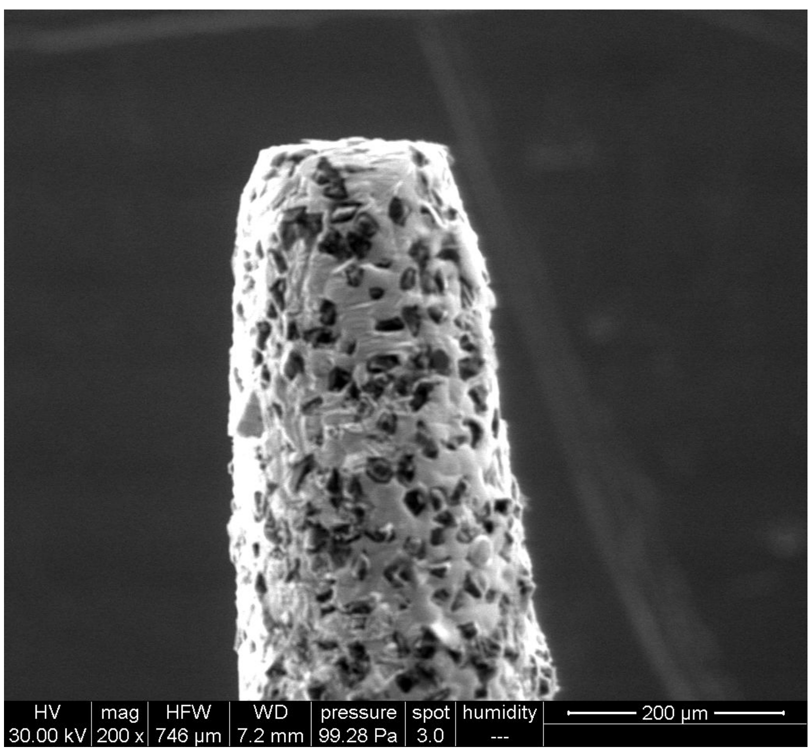


(c) PCD slurry

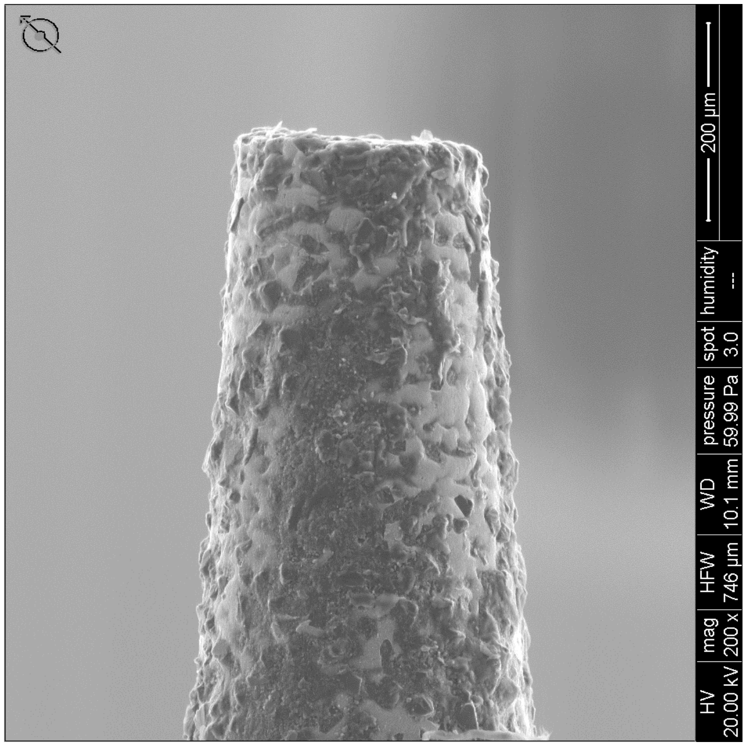
Figure 4.3. Tool surface after machining with different fluids on silicon(r=3000rpm, A=1µm, t=60sec)



(a) Milk



(b) Water

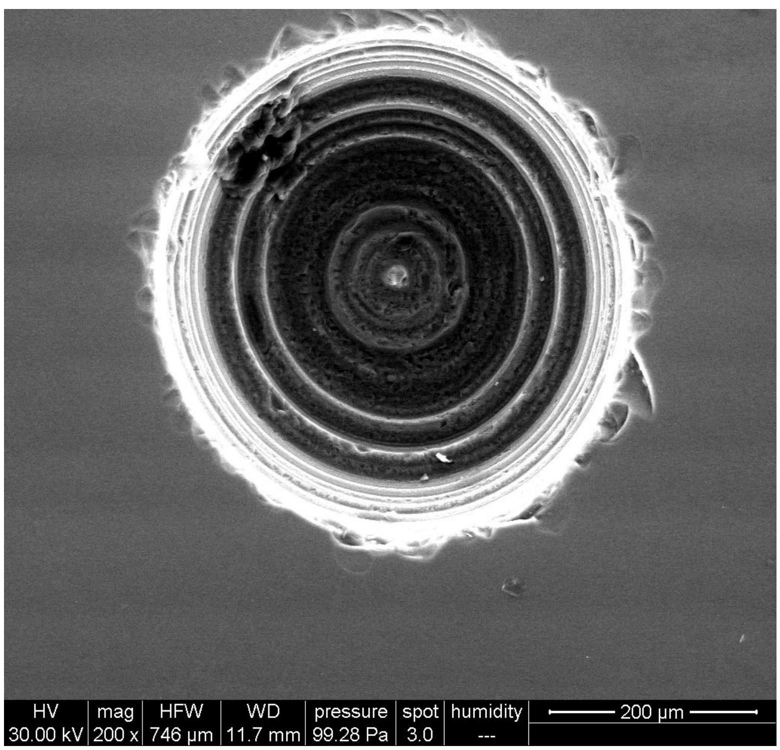


(c) PCD slurry

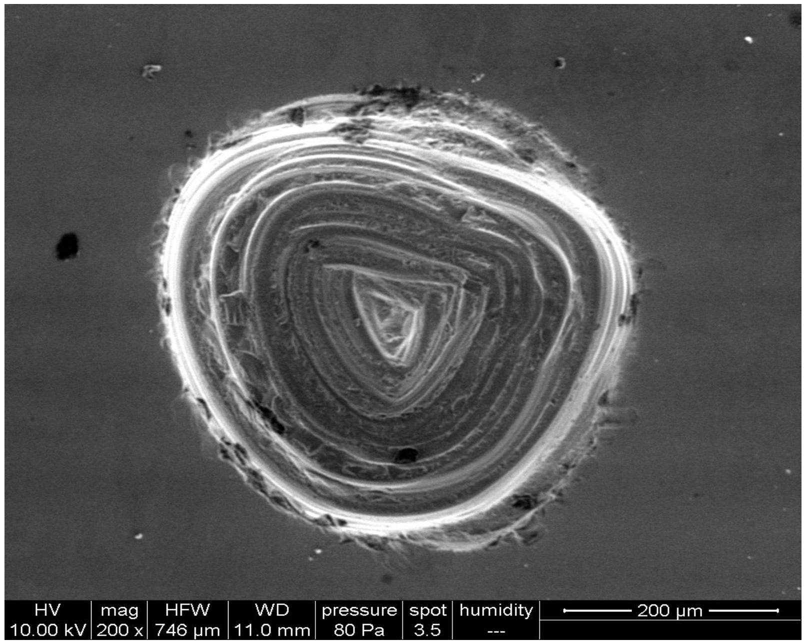
Figure 4.4. Tool surface after machining with different fluids on PZT(r=3000rpm, A=1µm, t=60sec)

4.2.4. Surface Quality

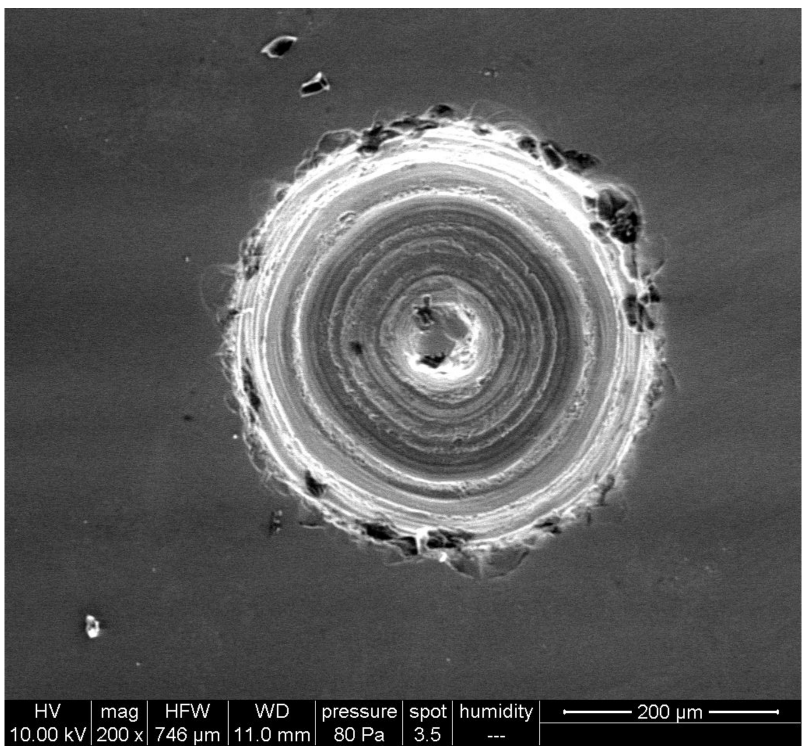
Edge Quality of the work piece material after machining is an important performance measure in micro-machining. It was found that abrasive particle size plays an important role in edge quality, as small abrasive particles size produce better edge quality [64]. Fig. 4.5 and Fig. 4.6 show the surface quality of work piece after machined with different working fluids. It was noticed that soft but heavier and larger particle size molecules of working fluid such as milk as slurry fluid give much better surface finish in both materials than water and PCD slurries. While machining with water and PCD the material from work piece gets chipped off and that prevents further machining resulting in a burr like structure. The soft milk molecules get mixed with chipped material and form very fine slurry resulting in a better surface finish.



(a) Milk

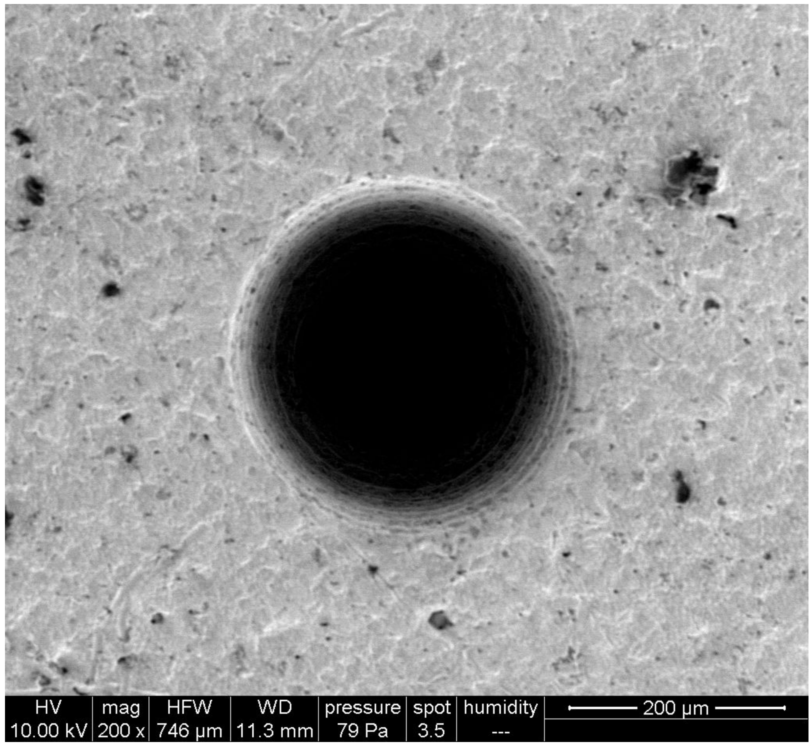


(b) Water

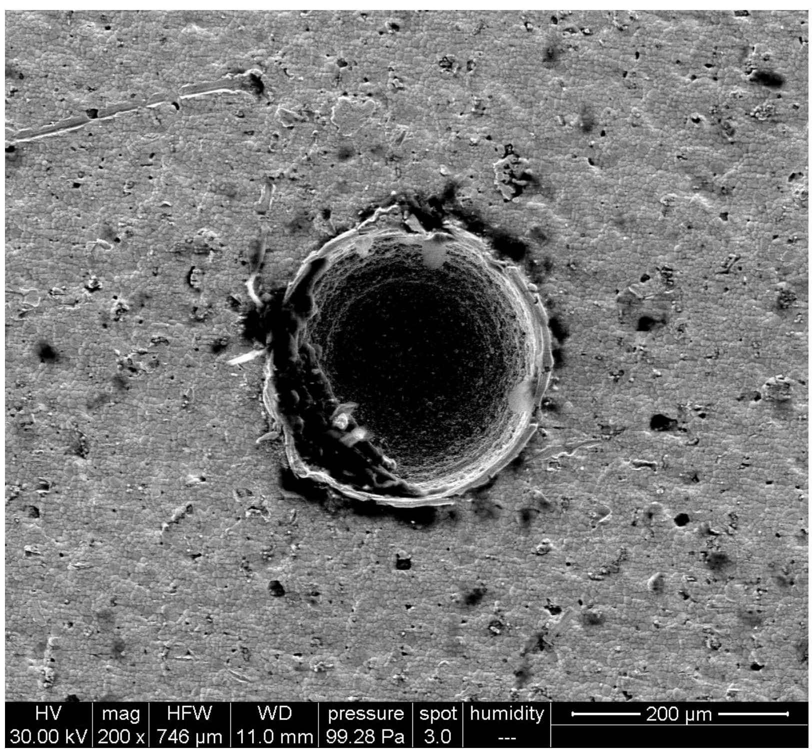


(c) PCD slurry

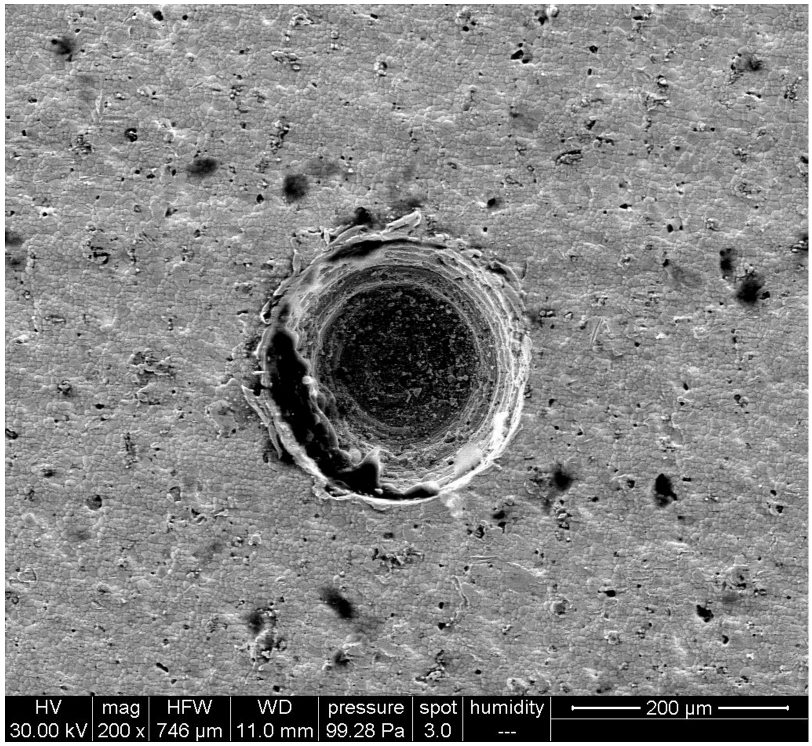
Figure 4.5. Surface of silicon work piece after machined with different working fluids (r=3000rpm, A=1μm, t=60sec)



(a) Milk



(b) Water



(c) PCD slurry

Figure 4.6. Surface of PZT work piece after machined with different working fluids. (r=3000rpm, A=1μm, t=60sec)

CHAPTER 5

BONE DRILLING

5.1 Introduction

In orthopedic and trauma surgery; many problems are encountered when drilling bone such as: hole accuracy, drill wander and heat generation. This study reports an experimental investigation of the effect of micro- RUM parameters on productivity, surface quality and temperature rise in machining of bovine bone. In present work, milk is used as working fluid during micro-RUM of bovine bone because viscosity of milk is 20 centipoises and is expected to maintain a lower temperature. The influence of spindle speed and static load on material removal rate, surface of material, heat generation and tool wear has been studied. Literature review, the in- house built experimental system used in this study, design of experiments, results and discussions as well as conclusions are described in the following sections .

5.2 Literature Review

5.2.1 Bone structure

Being classified as the body's main structural supportive material, outer hard layer of bone is known as cortical bone whereas inner spongy layer called cancellous bone (Figure 5.1). Periosteum and the endosteum contain the bone vascular system which provides it with nutrients and oxygen for bone growth and repair.

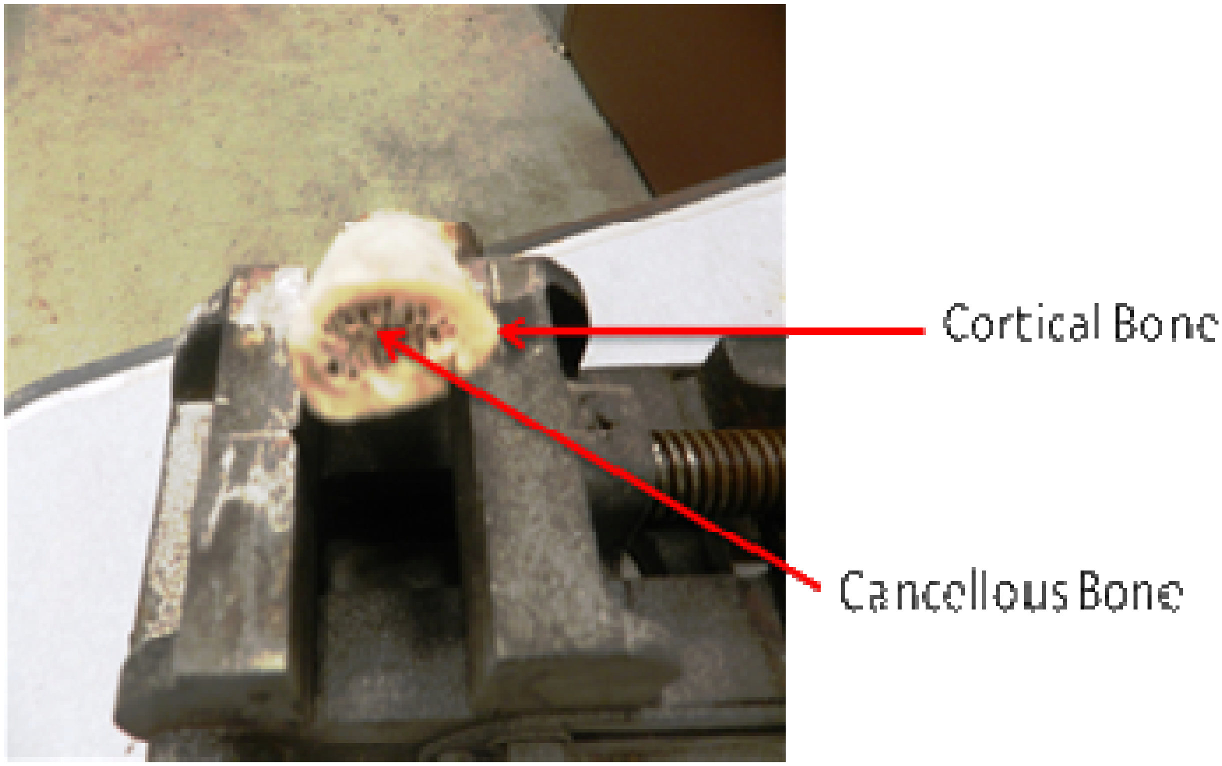


Figure 5.1. Stucture of bone used as work piece

5.1.2 Bone machining

It is reported that while machining, if bone is exposed for longer than 30 s at 50^0 C, cellular necrosis will be induced [65]. Because bone is a poor conductor of heat and its thermal conductivity is in range of 0.38-2.3 J/msK, the highest average temperature measured was $93.1\ ^0$ C at drill speed of 2900 rpm and a force of two kilogram [66]. It was found that as load increased, the drilling temperature also increased [66]. Effect of heat on bone depends upon the temperature and duration of exposure [67].Literature indicates that common range of applied force during drilling was 6 and 24 N. Fracture, loss of trabeculae from cancellous bone and soft tissue defects are common results of grinding bone [68]. It was found that in a 1.2 mm thick pig bone, the changes in temperature at 50, 100, 150, and 250 rpm were 2.6^0, 4.4^0, 4.5^0, and 4.7^0 C, respectively [69]. It was observed that as revolution speed increased, the temperature increased significantly irrespective of thickness [69]. The maximum recorded temperature during drilling of female bovine tibia at 800 rpm was 49.6^0 C. Temperature decreased as feed rate increased. It was found that bone sex has a significant effect on drilling temperature because drilling temperature for female bone is always higher than for male bone. The high calcium content in female bone leads to higher temperature during drilling [70]. The drilled bone quality was found to be better with an uncoated drill compared to a TiBN coated drill for bone drilling [70]. Series of discrete fractures lead to bone chip formation and that resulted from action of the chisel edge at the drill bit's tip [71]. During bovine bone drilling, temperature generation was higher than human bone drilling [65]. Low temperature embrittllement reduced the specific energy of orthogonal machining and drilling of bone [72]. It was found that temperature increased with force during drilling of a bovine femur [73]. Use of coolant, as expected can minimize the temperature elevation during bone drilling [67]. Cutting heat is generated because of plastic deformation in the tissue as well as between the cutting tool and machined surface [74]. Drill speed at 345, 885and 2900 rpm leads to the maximum temperature of bone at75^0 C, 65^0 C and 93.1^0 C respectively in absence of the coolant [75].Table 5.1 shows the thermal conductivity of cortical bone [76] ,table 5.2 shows different technique for bone machining and table 5.3 indicate different bone drilling temperature [67].

Table 5.1 Thermal conductivity of cortical bone [76]

Researcher	**Thermal Conductivity (W/mK)**	**Note**
Biyikli et al	0.2	Human bone dry
Zelenov	12.8, 9.7,9.9	Human bone longitudinal, radial, circumferential
Lundskog	3.56	Human bone
Vachon et al	0.601, 2.27	Ox bone dry, fresh
Kirkland	0.888-3.08	Bovine and caprine bone
Chato	0.38	Human bone fresh

Table 5.2 Bone machining techniques

Bone Machining techniques	**Purpose**
Wet grinding	Provides a more precise implant bed for implants and faster healing [68]
Milling	Find out maximum temperature increment during milling of bone under various cutting conditions [77]
Self drilling and self tapping	Screwing the implant in the body [69]
Bone condensing	Preparation of the implant site in the bone because it generates less heat than drilling [78]
Microwave drilling	Penetrate bone tissue [79, 80]
Ultrasonically assisted drilling	Compared performance with conventional drilling [81]
Drilling	Investigate compatibility with implant [82] investigate drilling process in bone [72], find out thermal changes caused by varying drilling

	speeds into bone [83]
Machining with coated cutting tool	Prepare bone for biomedical implant [84]
Laser machining	To produce an implant with define surface macrostructure[85], Rotational Acetabular Osteotomy (RAO) [86], Bone-implant contact was found using laser machining implant [87]
Cutting method based on crack propagation	Machining process for biomaterials, analysis of crack propagation in bone [74]
Piezo-electric bone cutting	Find out effect of piezo-electric bone cutting on formation of vascular thrombi in the bone [88]
Abrasive water jet cutting	Investigate whether the abrasive jet cutting quality in cancellous bone with a biocompatible abrasive is sufficient for the implantation of endoprostheses or for osteotomies [89]
Ultrasonic osteotomy	new method for correct condition of jaw and face as well as bone cutting [90]
Micro –rotary ultrasonic machining	Machinability of bovine bone was investigated [59]

Table 5.3 Temperature recorded in different bone drilling [67]

Table 2 Temperatures recorded in bone during drilling.

Study	Max temp (°C)	Distance from drill periphery	Bone type	Type of study	Cooling	Free running drill speed rpm	Force or feed rate
Thompson[23]	65.5	2.5	Dog mandible	In vivo	No	125–2000	Not indicated
Pallan[24]	65	2	Dog mandible	In vivo	No	125–2000	Not indicated
Rafel[25]	23.5	3	Human mandible	In vitro	No	35,000	Not indicated
Mathews and Hirsch[18]	140	0.5	Human femur	In vitro	No	345,885	
Mathews and Hirsch[18]	<50	0.5	Human femur	In vitro	Yes	2900	20, 59 N
Eichler and Berg[26]	95	0.5	Human femur	In vitro	No	700	10, 20 and 30 N
Jacobs and Ray[27]	38	2	Rat radius	in vivo	Yes	2500	Not indicated
Tetsch[28]	300	1	Cat mandible	In vivo	No	20,000	Not indicated
Tetsch[28]	76	1	Cat mandible	In vivo	Yes	20,000	Not indicated
Lavelle and Wedgewood[29]	89	0.5	Human femur	In vitro	No	350	59 N
Lavelle and Wedgewood[29]	74	0.5	Human femur	In vitro	Ext irrigation	350	59 N
Lavelle and Wedgewood[29]	50	0.5	Human femur	In vitro	Int irrigation	350	59 N
Pal and Saha[30]	>60	1	Bovine long bones	In vitro	No	65–2800	0.128 mm/rev
Krause et al.[19]	55	Near	Bovine femur	In vitro	No	20,000	1.8–6.36 mm/s
Krause et al.[19]	130	Near	Bovine femur	In vitro	No	100,000	1.8–6.36 mm/s
Eriksson et al.[31]	41	0.5	Rabbit femur	In vivo	Yes	20,000	Not indicated
Eriksson et al.[31]	57	0.5	Dog femur	In vivo	Yes	20,000	Not indicated
Eriksson et al.[31]	96	0.5	Human femur	In vivo	Yes	20,000	Not indicated
Mathews et al.[32]	185	0.5	Human femur	In vitro	No	60–700	60–120 N
Eriksson and Adel[33]	33.8	0.5	Human mandible	In vivo	Yes	1500–2000	Low and intermittent

The literature review clearly indicates that problems related to maintaining or reducing temperature rise while increasing the productivity and surface quality during bone machining need to be addressed. This experimental study attempts to address some aspects of the problem.

5.2 Experiments

Experimental setup is shown in Figure 5.2 .Experiments were conducted under conditions listed in Table 5.4. Experiments were focused on understanding influence of different working fluid, spindle speed and static load on material removal rate, temperature and surface of bone and tool shape after machining. The vibration frequency was 39.5 KHz and the amplitude was 1 μm. The machining time of each experiment was 60 sec. Different concentration of bovine milk and water was used as working fluids for experiments.

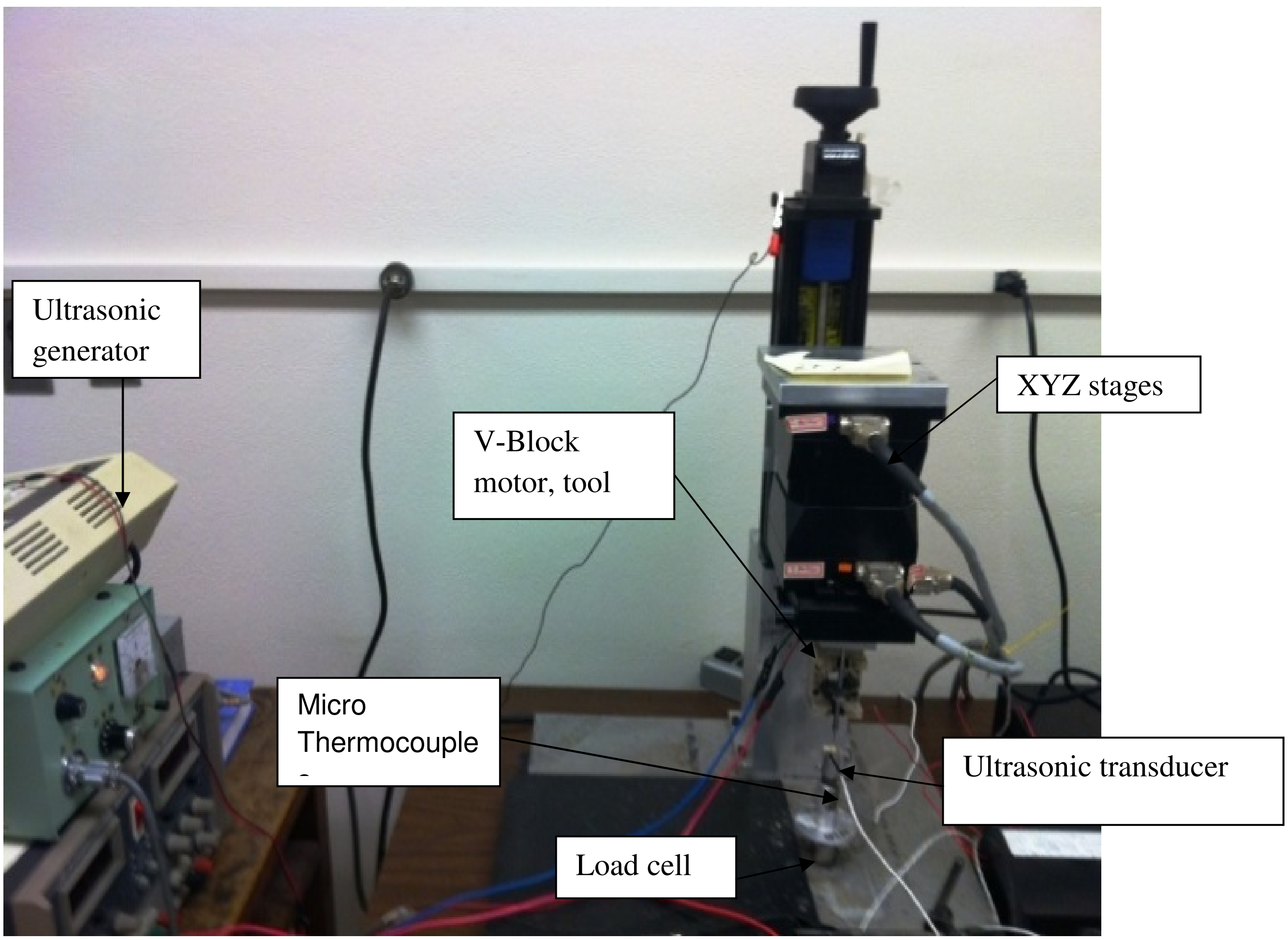


Figure 5.2. Experimental set up for bone machining

Table 5.4 Experimental conditions

Parameters	Values
Static load (g)	3, 5, 10
Working fluid	Fat free bovine Milk, Water and Milk (10% wt, 50% wt) and 100% wt) in water
Spindle speed (rpm)	500,1500, 3000
Work piece	Bovine bone, Silicon

A preserved bovine rib (1976) was cut into small flat pieces. The flat pieces of cortical bone were obtained by grinding away cancellous bone and the curved portion of the cortical bone. Figure 5.1 shows a section of bone exhibiting the spongy cancellous inside and the hard cortical outside.

A 2^3 (two level three factor) full factorial design was used. The experiments were focused on the study of the following machining parameters:

- Rotation speed: rotation speed of tool
- Static load: load applied on work piece
- Coolant: coolant used in the process of machining

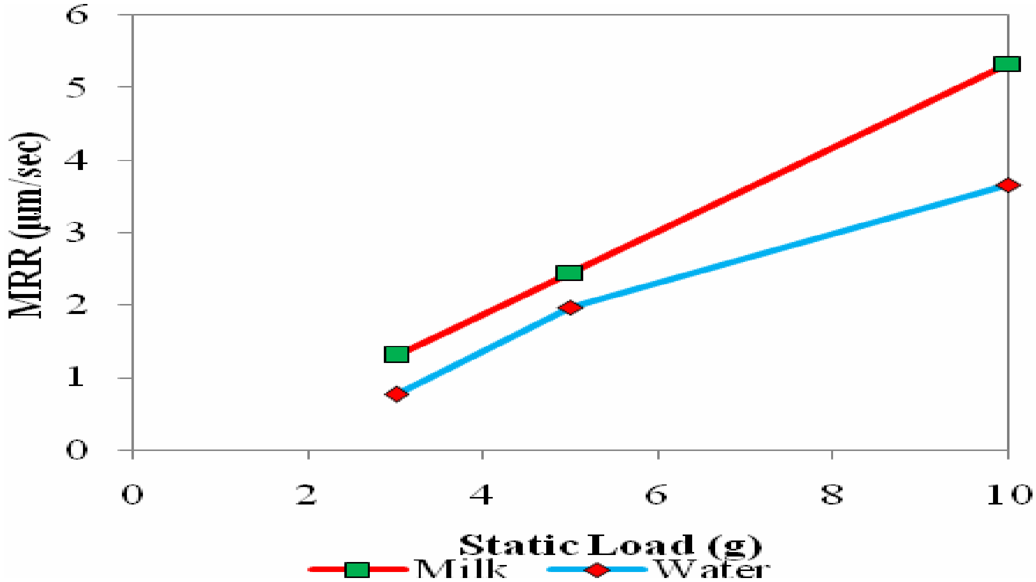
Table 5.5 Low and High level of process variables

Process Variable	Unit	Low level (-)	High level (+)
Rotation speed	rpm	500	3000
Static load	g	3	10
Coolant viscosity	centipoises	Water (1.004)	Milk (20)

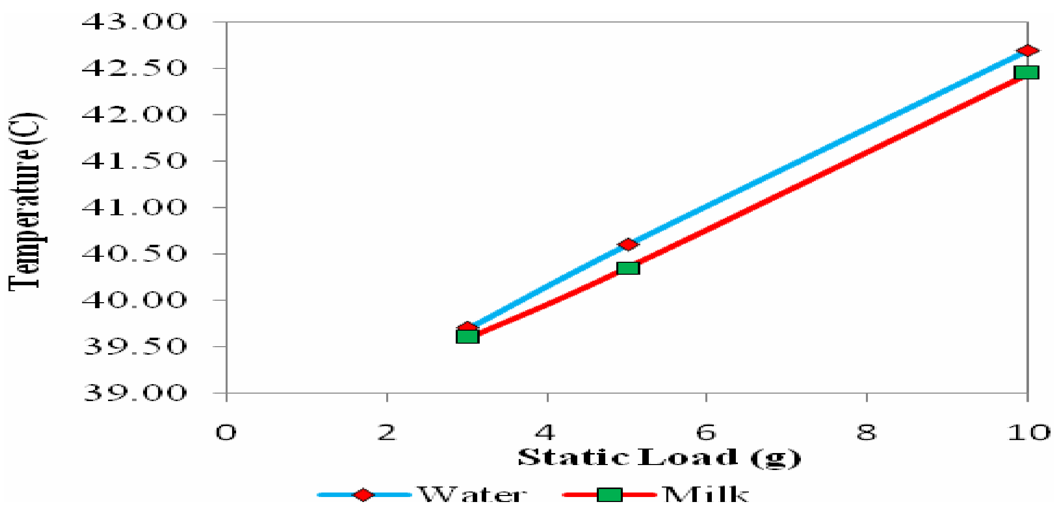
5.4 Results and Discussion

5.4.1 Effect of static load on MRR and temperature with different working fluids

Fig. 5.3 (a) and Fig. 5.3 (b) show the effect of static load on MRR and temperature for bovine bone for tool rotation speed of 3000 RPM respectively. The material removal rate (MRR) was found to increase with an increase in static load. Between two different working fluids, it was found that milk resulted in higher MRR than water. It seems that non brittle particles of milk and milk viscosity have a significant effect on material removal rate. Milk molecules are heavier in weight than water molecules, therefore, during the machining process, impact energy due to molecules increases, leading to a higher MRR. It was found that temperature of bone increased with increase in static load. The main reason was the heat generated due to cutting action of the tool and friction between the tool and work piece. As the load increases: impact energy from the tool to the work piece increases and friction occurs between the tool and the work piece leading to a higher temperature. However this increase is smaller than reported for other processes mentioned in literature review. Temperature range during machining of bone using different processes varies from 49.6^0 C to 93.1^0 C. In this study, highest temperature observed was 42.1^0 C and 42.7 ^{0}C using milk and water as coolant respectively which are less than other machining techniques



(a) Static load vs MRR

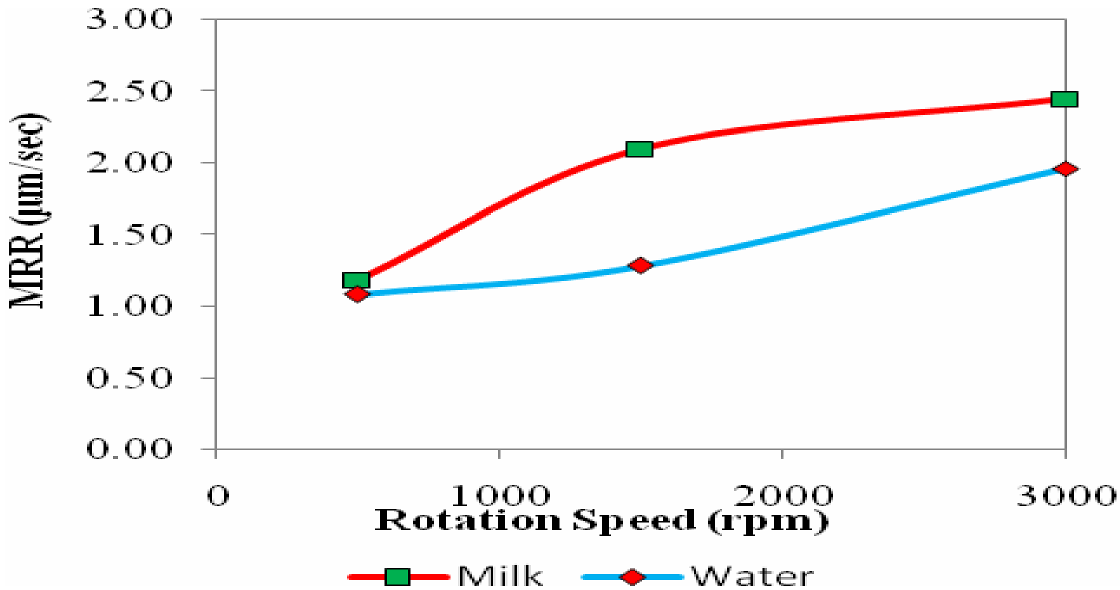


(b) Static load vs Temperature

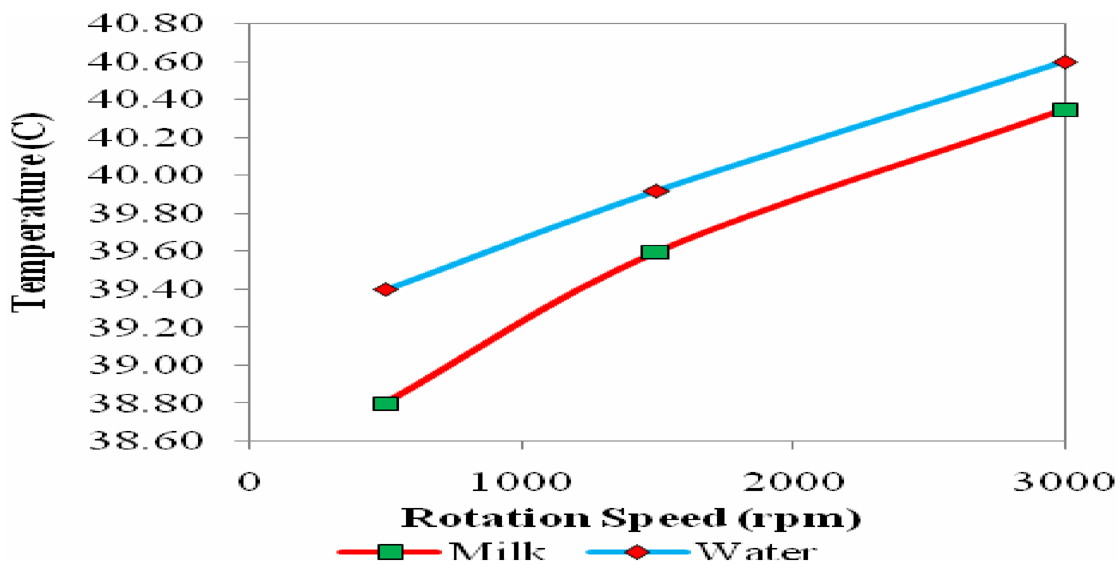
Figure 5.3. Effect of static load on MRR and temperature rise (working fluid= Milk and Water, r=3000 rpm)

5.4.2 Effect of spindle speed on MRR and temperature with different working fluids

Figure 5.4 (a) and 5.4 (b) show the relationship of MRR and temperature of the bovine bone with spindle speed by using different working fluids with a constant load of 5 g respectively. MRR increases with increase in spindle speed irrespective of working fluid. When the spindle speed increases, the effective number of cutting edges of the abrasive on the tool surface that contact with work piece also increases and the material removal process is accelerated, similar to an observation reported in [63] for rotary ultrasonic grinding. It can be seen that, the higher MRR is achieved by using milk as a working fluid. Temperature was found to increase with an increase of rotation speed. Similar to the effect of spindle speed on temperature rise, this increase is smaller than reported for other processes. Temperature range during machining of bone using different processes was varies from 49.6^0 C to 93.1^0 C (as mentioned earlier) where as highest temperature observed during this study was 40.3^0 C, $40.6\ ^0$C using milk and water as coolant respectively.



(a) Rotation speed vs MRR

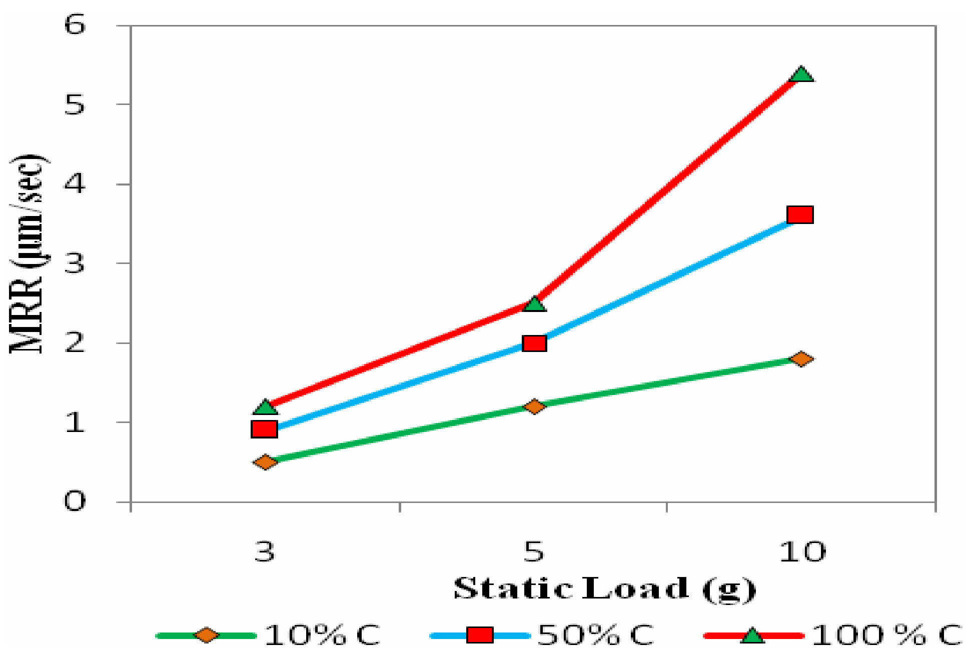


(b) Rotation speed vs Temperature

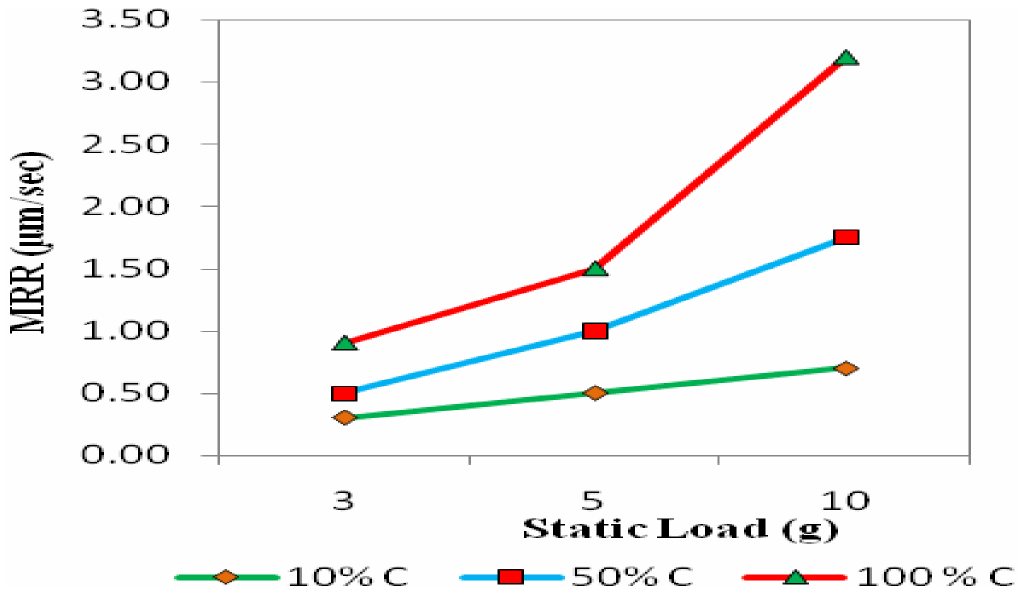
Figure 5.4. Effect of spindle speed on MRR and temperature rise of workpiece (working fluid= Milk and Water)

5.4.3 Effect of coolant concentration on MRR

Figure 5.5 (a) and 5.5 (b) show the relation of MRR of bovine bone and silicon with different concentration of milk in water. MRR increased with the increasing of concentration of milk. Higher concentration provides more particles in the coolant to be involved in the machining process and increase in material removal rate.



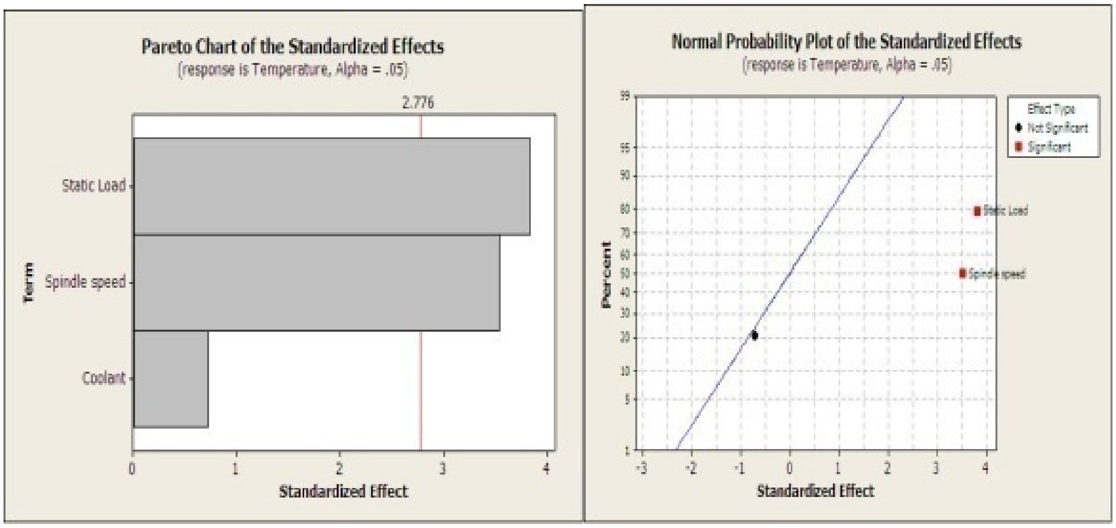
(a) Bone



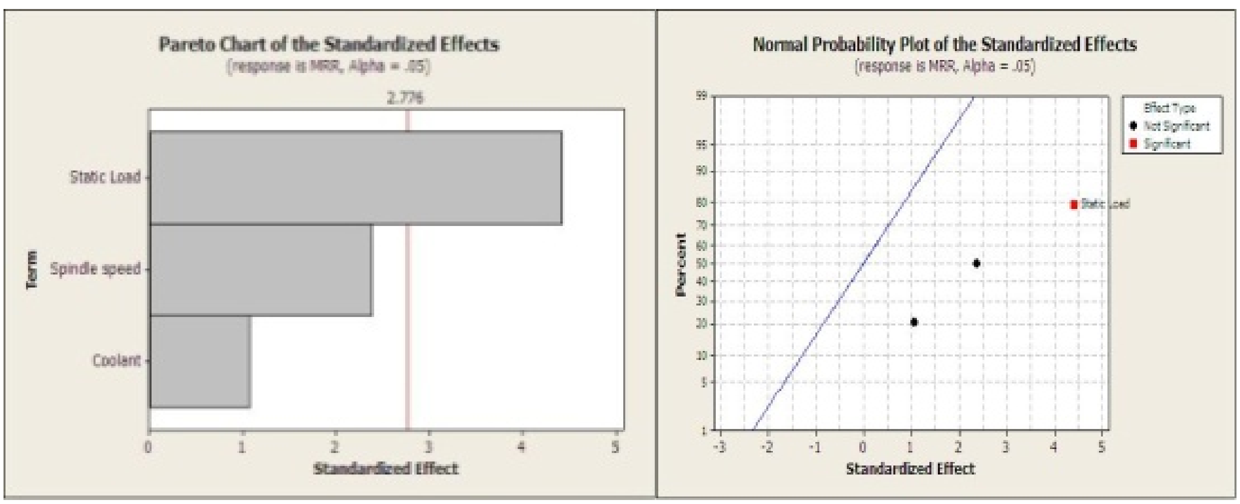
(b) Silicon

Figure 5.5. Effect of coolant concentration on MRR (working fluid= Milk (10% C, 50% C and 100% C) in Water, Work piece= Bone, Silicon)

Minitab 14 software was used to analyze data. Spindle speed, coolant concentration and Static load used to find of more influence factor on MRR and rise in temperature of bone during machining. Figure 5.6 (a) shows the Pareto chart and normal probability plot of the standardized effects for temperature. It was found that 80% of static load and around 50% of spindle speed has influence on the rise in temperature of bone during machining. Figure 5.6 (b) shows the Pareto chart and normal probability plot of the standardized effects for MRR. It was found that 80% of static load has influence on MRR.



(a) Temperature

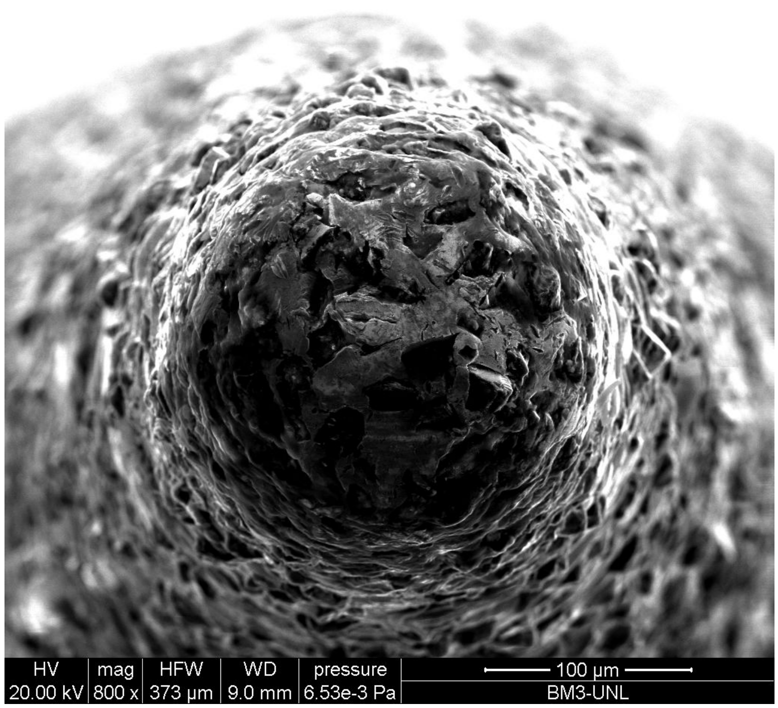


(b) MRR

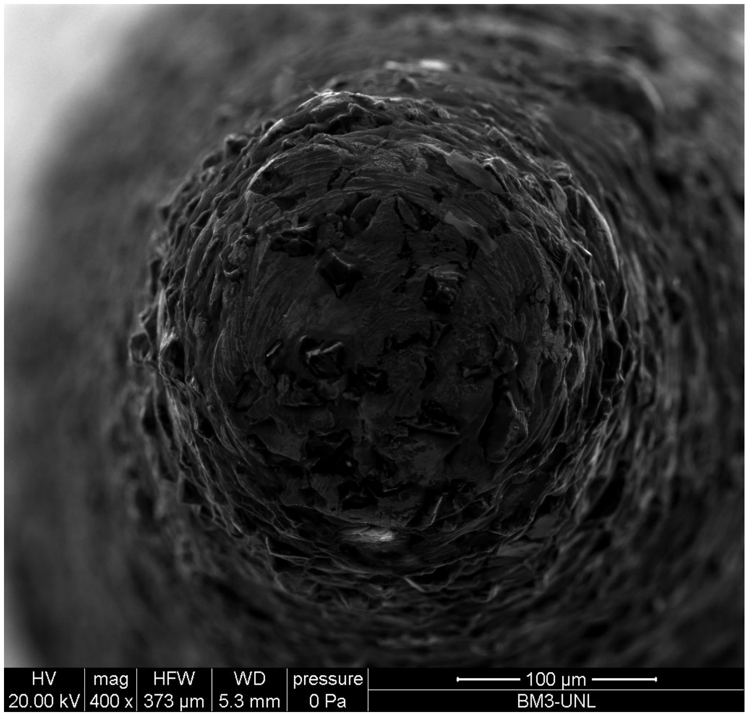
Figure 5.6. Pareto chart and normal probability plot for Temperature and MRR

5.4.4. Tool wear

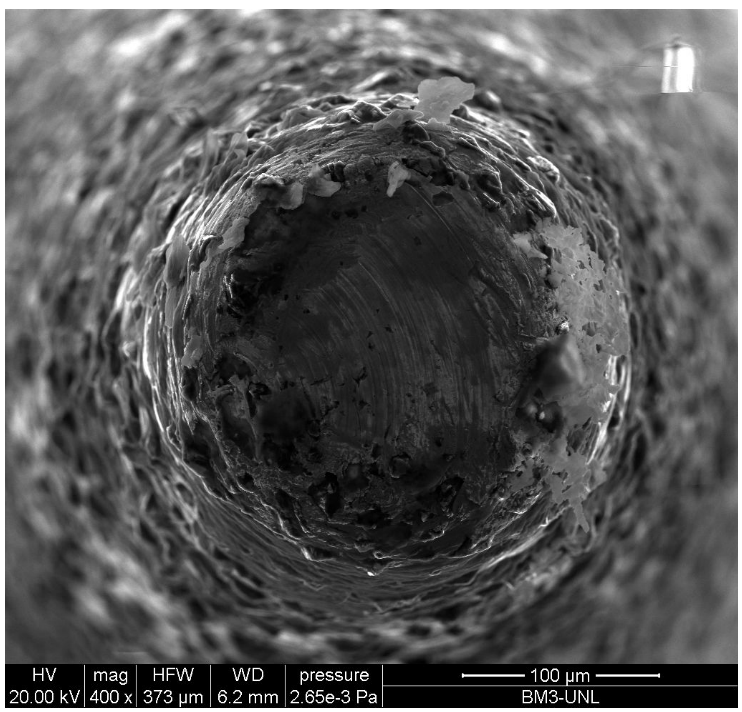
Tools after machining were tested under a scanning electron microscope (SEM). Figure 5.7 shows the tool tip shape after a series of micro-RUM machining of bovine bone with milk and water. It was found that the tool used for machining with milk shows the least tool wear compared to those machined with water. From SEM it was found that there were 18 diamonds on the original conical tool tip. It was noticed that after machining with water as the coolant, there were 3 diamonds left on the conical tool tip .When milk was used as the coolant, there were 10 diamonds left on the conical tool tip. Water as the coolant shows more tool wear because the increased amount of loosened diamonds impacted on the tool surface and tool wear occurred.



(a) Original conical tool tip



(b) Milk



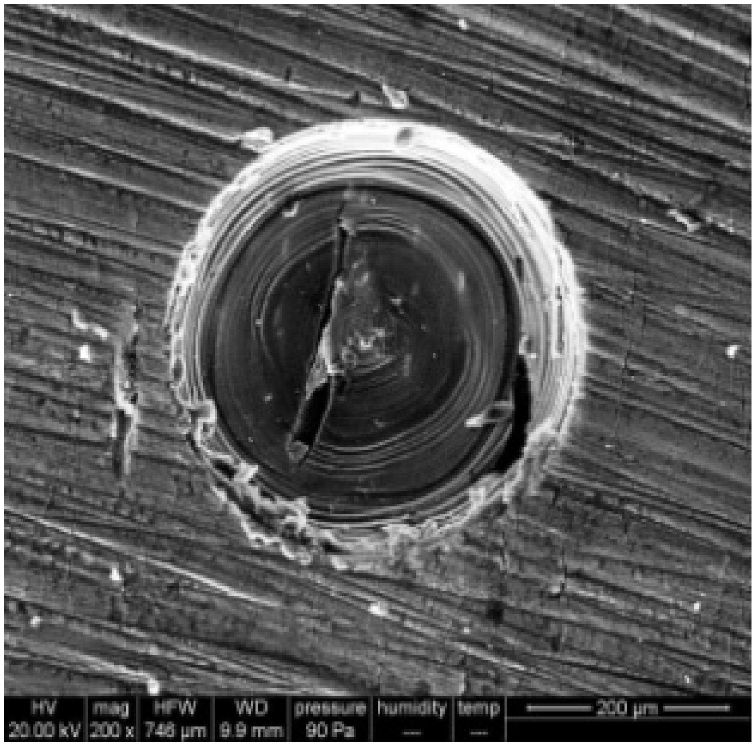
(C) Water

Figure 5.7. Conical tool (250 micron) tip surface after machining with different working Fluids (r=3000 rpm, A=1µm, t=60 sec)

5.4.5. Surface quality

The surface quality of the work piece after machining in different working fluids is observed. It was noticed that using milk as a slurry fluid gives much better surface finish in bovine bone. It was noticed that using milk as the coolant shows higher occurrence of ductile machining mode than water as coolant. While machining with water the material from work piece gets chipped off and that prevents further machining resulting in a burr like structure. The soft milk molecules get mixed with chipped material and form very fine slurry resulting in a better surface quality.

(a) Milk

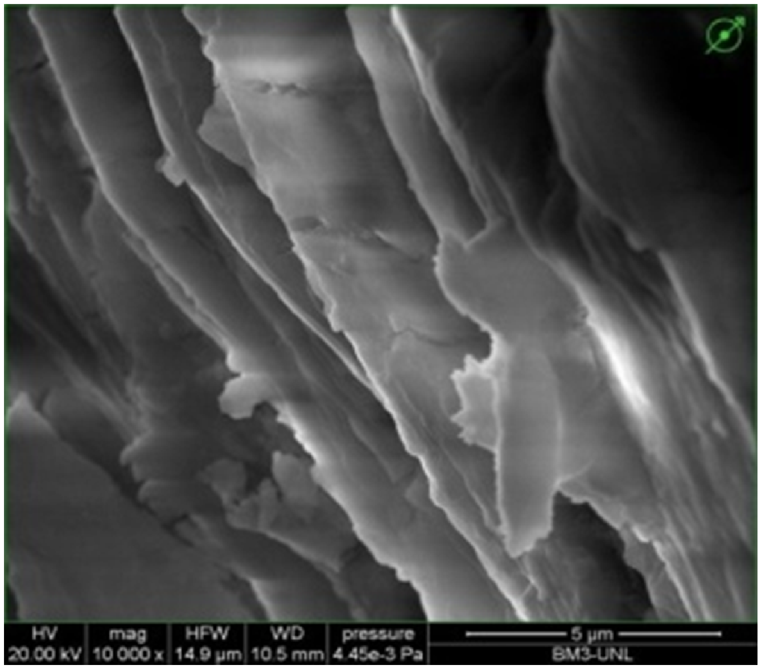


(b) Water

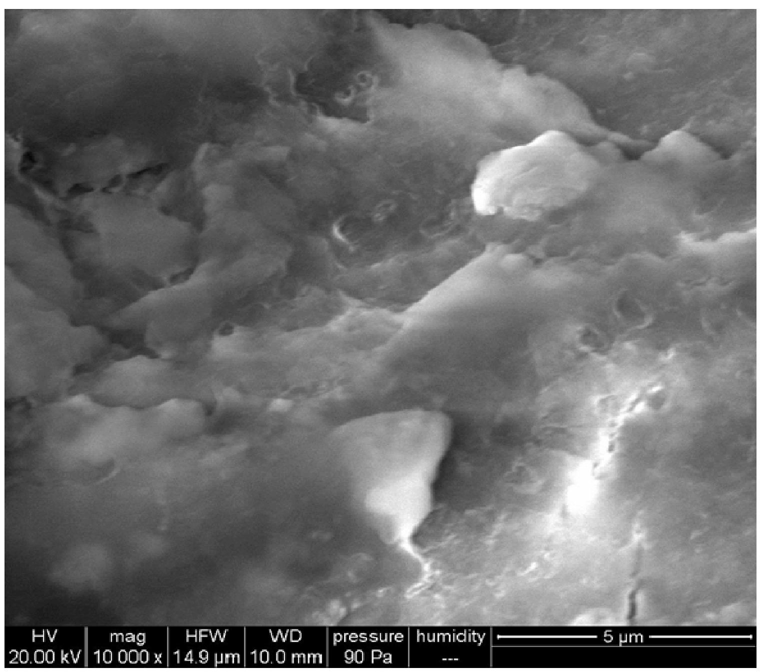
Figure 5.8. Surface of bovine bone after machining with different coolant (tool=conical (250 micron), r=3000 rpm, A=1µm, t=60 sec)

5.4.5.1 Material removal mechanism

As per the hypothesis about ductile-regime grinding, regardless of hardness or brittleness all materials will undergo from brittle to ductile machining regime if the feed rate is small [42].Ductile machining mode evidence was found in both materials. The scratching and cutting action due to abrasive grain on the machined surface could be seen in image.

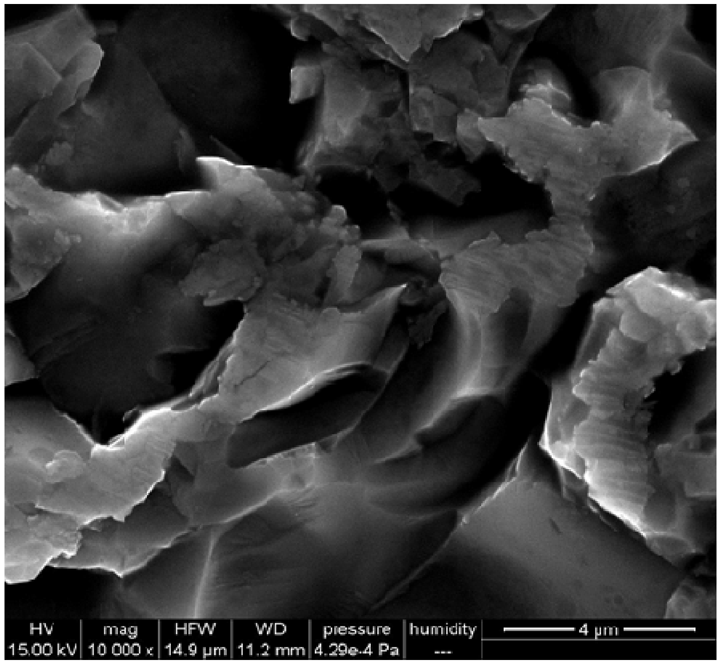


(a) Milk

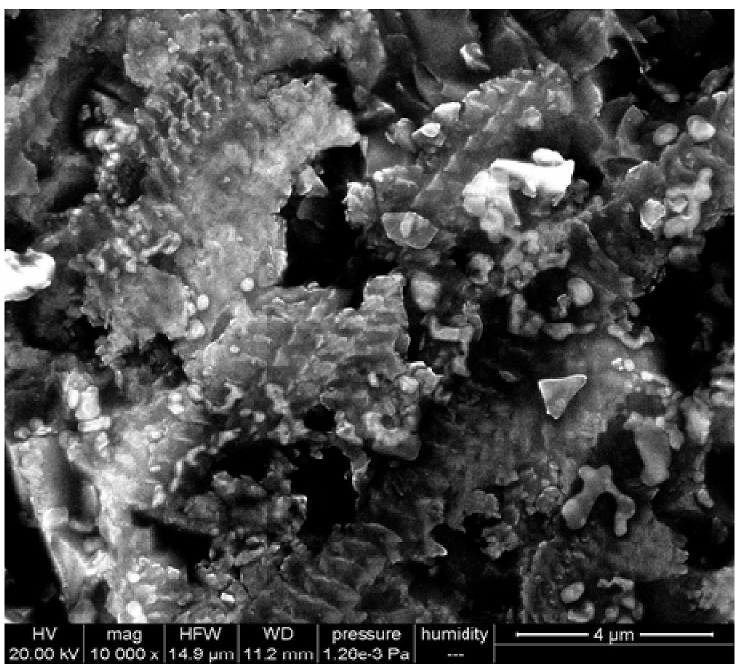


(b) Water

Figure 5.9. Ductile mode machining of bovine bone using milk and water as coolant (r=3000rpm, A=1µm, t=60sec, magnification=10000X)



(a) Milk



(b) Water

Figure 5.10. Ductile mode machining in silicon using milk and water as coolant (r=3000rpm, A=1µm, t=60sec, magnification=10000X).

5.5 Summary

The effect of different working fluids, different concentrations, static load and spindle speed on MRR, work piece surface quality and tool wear in micro rotary ultrasonic machining has been studied. A novel working fluid, milk and its different concentrations were used as a coolant for bone machining. It is found that milk molecules can effectively improve performance of micro RUM using different work piece materials.

CHAPTER 6

DUCTILE MODE MODEL FOR MATERIAL REMOVAL RATE

6.1 Introduction

Modeling the MRR during micro rotary ultrasonic machining of silicon is proposed and applied to prediction of MRR. In brittle fracture mode, hammering effect of tool oscillation leads to crack formation and material is removed [40]. Number of grit size and shape, tool size, number of abrasive participation in material removal process all these parameters are uncertain, so it is difficult to incorporate the effect of all the parameters in the modeling of material removal rate.

6.2 Model Assumptions

1. Material is removed in ductile mode only

2. All abrasive grits are the same size of sphere with equal space distribution

3. All abrasive grits take part in machining process

4. Tool tip is cylindrical

5. Tool wear has not much effect on material removal process

6. Abrasive particles don't deform during machining process

6.3 Terminology

F = Max force on tool, N;

N = The number of abrasive on end face of tool;

D= Diameter of tool, m;

d= Diameter of abrasive particle, m;

E= Young's modulus of work piece, Pa;

v= Poisson's ratio of work piece;

A= Vibration amplitude, m;

s = Spindle speed, rad/s;

Δt = Contacting time between the grit and work piece during each vibration period;

r= Radius of abrasive grit, m;

W= Volume of material removed by single grit in each vibration period

δ = Cutting depth, m;

f= Ultrasonic vibration frequency, Hz;

L= Distance move by diamond particle during work piece penetration, m;

6.4 Development of Model

6.4.1. Indentation depth by diamond particle [12]

$$L = \frac{\pi D S \Delta t}{60} \tag{6.1}$$

$$\delta = \left[\frac{9(F/N)^2}{16(d/2)} \left(\frac{1-\upsilon^2}{E} \right) \right]^{1/3} \tag{6.2}$$

The contact time Δt can be estimated using grit trajectory equation and cutting depth δ

Trajectory of a single grit is a sinusoidal curve shown in figure 6.1 [12].

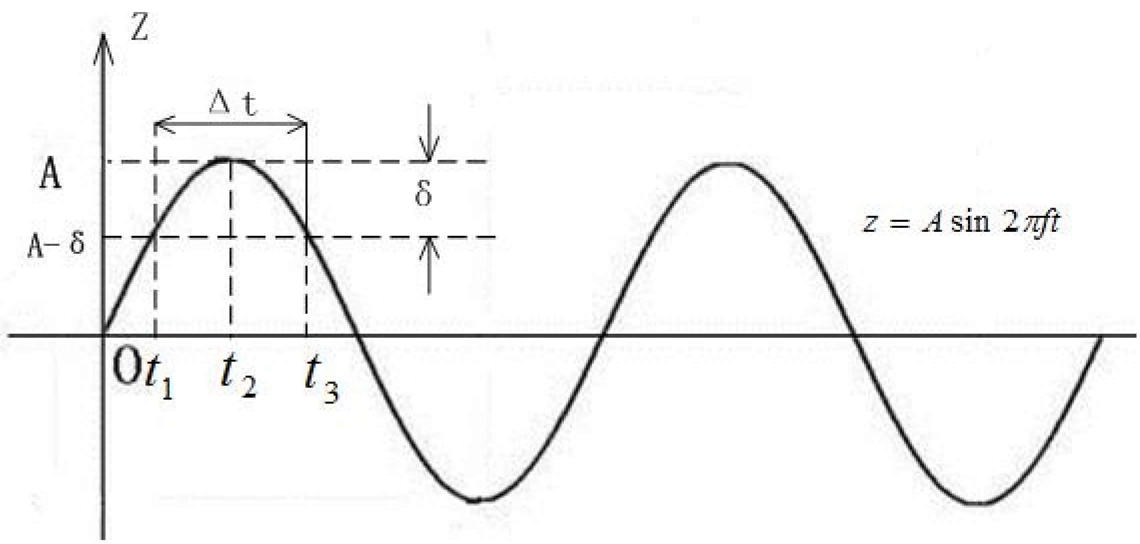


Figure. 6.1. Vibration trajectory of a single grit

$$Z = A\sin(2\pi ft) \tag{6.2}$$

Each vibration period, an abrasive grit contacts with work piece at t_1 firstly, and at t_2 it reaches to maximum depth and finally separate from work piece at t_3 . So contact time Δt can be represented as

$$\Delta t = 2(t_2 - t_1) = \frac{1}{\pi f}(\frac{\pi}{2} - \sin^{-1}(1 - \frac{\delta}{A}) \tag{6.3}$$

The maximum cutting depth to which diamond particle penetrates to work piece can be calculated using following equation

$$MRR = KNf\pi\left(1 + \frac{L}{d}\right)\left(\frac{d}{2} - \frac{\delta}{3}\right)\delta^2 \tag{6.4}$$

6.5 Model Verification

In this section the model is compared with the experimental data. Table 6.1 presents the machining conditions and material properties. Model was verified for different static load

Table 6.1. Machining conditions and material properties

Vibration frequency	39.5 (KHz)
Vibration Amplitude	1 (µm)
Abrasive particle diameter	150 (µm)
Young's modulus of Silicon	130 (GPa)
Poisson's ratio	0.22
Spindle speed	3000 (rpm)
Tool diameter	835 (µm)
Static load	3, 5, 10 (g)
Number of diamond particles on tool tip	28

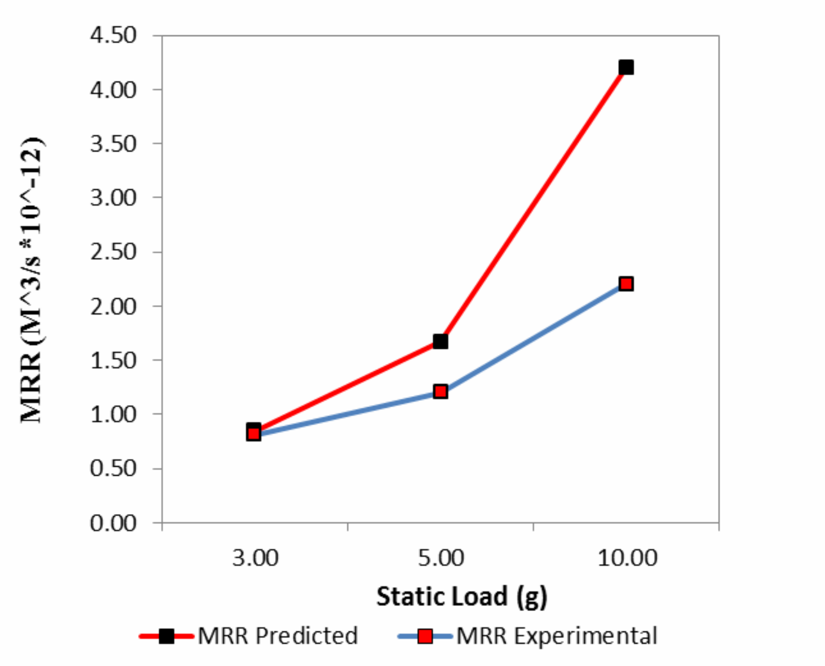


Figure 6.2. Experimental and predicted MRR for different load values

The model overestimates the MRR for experimental conditions. Predicition of MRR is closer at lower load i.e. 3 g. However the difference increased as load increases. The MRR value is dependent on K value. As value of K is decreases difference in MRR decreases at higher load value.

6.6 Limitation of the Model

This model does not consider tool wear effect, also number of diamonds particles left on tool tip after machining needs to be considered for model development. The value of K should be calculated using material properties of work piece. Plastic flow in material removal is not considered. Coolant density should consider while developing model, also number of particle accumulation in machining gap need to be address.

CHAPTER 7

CONCLUSIONS AND RECOMMENTATIONS

7.1 Conclusion

The following conclusions are drawn from this thesis work

1. MRR was found to significantly increase due to the increase of the static load and the spindle speed irrespective of working fluid.

2. Milk as a working fluid, resulted in a higher MRR.

3. Milk, as working fluid, provides a better surface finish and less tool wear as compared to water and PCD slurry as the working fluid.

4. It was found that while using micro RUM, the surface finish that was achieved was much better than other machining techniques.

5. Material removal rate increased as the coolant concentration and coolant viscosity increased.

6. Temperature of bone was found to increase as the static load and spindle speed increased. The highest temperatures that were noticed were **42.1 C, 42.7 C.** These temperatures were collected after using milk and water as coolants respectively which is less than the temperature rise during other machining processes.

7. Ductile mode machining evidence was found after bone and silicon machining.

7.2 Recommendations for future work

System design

- Instead of stainless steel tool, cemented carbide, PCD tool can be used to obtain optimal performance in terms of material removal rate, tool wear and surface finish.

- It was found that rotation speed was not constant during the machining process. The use of E2530 variable speed electric motor might improve the accuracy and efficiency of micro rotary ultrasonic machining.

- Micro thermocouples were used to measure the temperature during machining. The use of Nano temperature sensor might be helpful to find out the inner temperature of the work piece during machining process.

Coolant

- Fat free milk was used as a coolant. Instead of fat free, try several types of milk and see their effect on machining conditions such as tool wear and surface finish material removal rate.

- Use of “green coolant” might be useful to reduce tool wear and increase MRR, and it is environmental friendly.

References

1. Ehmann, K.F., Bourell, D., Culpepper, M.L., Hodgson, T.J., Kurfess, T.R., Rajurkar, K.P., Devor, R.E. (2007). “Micromanufacturing-International Research and Development,” SpringerLink Publication.

2. McGeough, J. (2002). “Micro Machining of Engineering Materials,” Marcel Dekker Inc.

3. Hu, Xiao. (2007). “Mechanism, Characteristic and Modeling of micro ultrasonic machining,” PhD thesis, UNL.

4. Sarwde, A. (2010). “Study of micro rotary ultrasonic machining,” Master’s thesis, UNL.

5. Treadwell, C., Pei, Z.J. (2003). “Machining of ceramic with rotary ultrasonic machining,” *Ceramic industry*, pp.39-44.

6. Dam, H., Jensen, J., Quist, P. (1993). “Surface Characterization of Ultrasonic Machined Ceramics with Diamond Impregnated Sonotrode,” *Machining of Advanced Materials*, Vol.847, pp.125-133.

7. Prabhakar, D., Pei, Z.J., Ferreira, P.M., Haselkorn, M. (1993). “A Theoretical Model for Predicting Material Removal Rates in Rotary Ultrasonic Machining of Ceramics,” *Transactions of the North American Manufacturing Research Institution of SME*, Vol.21, pp.167-172.

8. Churi, N.J., Pei, Z.J., Shorter, D.C. (2009). “Rotary Ultrasonic Machining of Dental Ceramics,” *International Journal of Machining and Machinability of Materials*, Vol. 6, pp.270-284.

9. Legge, P. (1964). “Ultrasonic Drilling of Ceramics,” *Industrial Diamond Review*, Vol. 24, pp.20-24.

10. Goldman, R. (1962). “Ultrasonic Technology,” *Reinhold Publishing Corporation*, London.

11. Prabhakar, D. (1992). “Machining Advanced Ceramic Materials Using Rotary Ultrasonic Machining Process,” MS Thesis, University of Illinois at Urbana, Champaign.

12. Pei, Z.J. (1995). “Rotary Ultrasonic Machining Of Ceramics,” PhD. Thesis, University of Illinois at Urbana, Champaign.

13. Cleave, D.V. (1976). “Ultrasonic Gets Bigger Jobs in Machining and Welding,” *Iron age*, Vol. 218, pp.69-72.

14. Graff, K. F. (1975). “Ultrasonic Machining,” *Ultrasonics*, Vol. 13, pp.103-109.

15. Pei, Z.J., Khanna, N., Ferreira, P. (1995). “Rotary Ultrasonic Machining of Structural Ceramics-A Review,” *Ceramic Engineering Science Proceeding*, Vol.16, pp.259-278.

16. Moore, D. (1986). “Ultrasonic Impact Grinding,” *Carbide and Tool Journal*, Vol.11-12, pp.21-23.

17. Kohls, J. (1984). “Ultrasonic Manufacturing Process: Ultrasonic Machining and Ultrasonic Impact Grinding,” *Carbide and Tool Journal*, Vol.9-10, pp.12-15.

18. McGeough, J. (1988). “Advance Methods of Machining,” Chapman and Hall ltd, London.

19. Ya, G., Qin, H.W., Xu, Y.W. (2001). “An Experimental Investigation on Rotary Ultrasonic Machining,” *Key Engineering Materials*, Vol. 202-203, pp. 277-280.

20. Pei, Z.J., Treadwell, C. (2003). “Machining Ceramics with Rotary Ultrasonic Machining,” *Ceramic Industry*, Vol.7, pp.39-42.

21. Gong, H., Fang, F.Z., Hu, X.T. (2010). “Kinematic View of Tool Life in Rotary Ultrasonic Side Milling of Hard and Brittle Materials,” *International Journal of Machine Tools and Manufacturing*, Vol.50, pp. 303-307.

22. Luzner, L. (1973). “Diamond Drilling in Glass,” *Machine Design*, Proceeding of 18th symposium on an art of glassblowing pp.21.25.

23. Li, Z., Jiao, Y., Deines, T., Pei, Z.J., Treadwell, C. (2004). “Experimental Study on Rotary Ultrasonic Machining of Polycrystalline Diamond Compacts,” CD-ROM Proceeding of the 13th Annual Industrial Research Conference.

24. Dam, H. (1993). “Surface Characterization of Ultrasonic Machined Surface with Diamond Impregnated Sonotrode,” *Machining of advanced ceramics*, Vol.847, pp.125-133.

25. Hocheng, H., Tai, N.H., Liu, C.S. (2000). “Assessment of Ultrasonic Drilling of C/Sic Composite Material,” *Composites: Part A Applied Science and Manufacturing*, Vol. 31, pp. 133-142.

26. Zeng, W.M., Li, Z.C., Pei, Z.J., Treadwell, C. (2005). “Experimental Observation if Tool Wear in Rum of Advanced Ceramics,” *International Journal of Machine Tools and Manufacture*, Vol.45, pp.1468-1473.

27. Hu, P., Zhang, J., Jiao, Y., Pei, Z.J., Treadwell, C. (2003). “Experimental Investigation on Coolant Effect on Rotary Ultrasonic Machining,” Proceeding of the NSF Workshop on Research Needs in Thermal Aspects of Material Removal Process, pp.340-345.

28. Li, Z.C., Jiao, Y., Deines, T., Pei, Z.J., Treadwell, C. (2005). "Development of an Innovative Coolant System for Rotary Ultrasonic Machining," *International Journal of Manufacturing Technology and Management*, Vol.7, pp. 318-328.
29. Tyrrell, W. R. (1970). "New Method for Machining Hard and Brittle Materials," *SAMPE Quarterly*, Vol. 1, pp. 55-59.

30. Zhang, Q., Wu, C., Jia, Z., Sun, J. (2000). "Mechanism of Material Removal in Ultrasonic Drilling of Ceramics," *Proceedings of the Institutional Mechanical Engineers, Part B-Journal of Engineering Manufacturer*, Vol.214, pp. 805-810.

31. Churi, N. J., Li, Z.C., Pei, Z.J., Treadwell, C. (2005). "Rotary Ultrasonic Machining of Titanium Alloy: A Feasibility Study," *Proceeding of IMECE*, Vol.16, pp. 885-892.

32. Churi, N.J., Pei, Z.J., Treadwell, C. (2006). "Rotary Ultrasonic Machining of Titanium Alloy: Effect of Machining Variables," *Machining Science and Technology*, Vol. 10, pp. 301-321.

33. Churi, N.J., Pei, Z.J., Treadwell, C. (2007). "Wheel Wear Mechanism in Rotary Ultrasonic Machining of Titanium," *Proceeding of IMECE*, Vol. 3, pp. 399-407.

34. Zhang, Q., Zhang, J., Jia, A., Ai, X. (1998). "Fracture at Exit of the Hole During the Ultrasonic Drilling of Engineering Ceramics," *Journal of Material Processing Technology*, Vol.84, pp. 20-24.

35. Wang, Q., Cong, W., Pei, Z.J., Gao, H., Kang, R. (2009). "Rotary Ultrasonic Machining of Potassium Dihyrogen Phosphate (Kdp) Crystal: An Experimental Investigation on Surface Roughness," *Journal of Manufacturing Process*, Vol.11, pp.66-73.

36. Churi, N.J., Pei, Z.J., Treadwell, C., Shorter, D.C. (2009). "Rotary Ultrasonic Machining of Dental Ceramics," *International Journal of Machining and Machinability of Materials*, Vol.6, pp. 270-284.

37. Liao, Y.S., Chen, Y.C., Lin, M.H. (2007). “Feasibility Study of the Ultrasonic Vibration Assisted Drilling of Inconel Superalloy,” *International Journal of Machine Tools and Manufacture*, Vol. 47, pp. 1988-1996.

38. Chao, C.L., Chou, W.C., Chao, C.W., Chen, C.C. (2007). “Material Removal Mechanism Involved in Rotary Ultrasonic Machining of Brittle Materials,” *Key Engineering Materials*, Vol.329, pp.391-396.

39. Pei, Z.J., Ferreira, P.M., Haselkorn, M. (1995). “Plastic Flow in Rotary Ultrasonic Machining of Ceramics,” *Journal of Material Processing Technology*, Vol.48, pp.771-777.

40. Prabhakar, D., Ferreira, P.M., Haselkorn, M. (1992). “An Experimental Investigation of Material Removal Rates in Rotary Ultrasonic Machining,” *Transaction of North American Manufacturing Research Institute of SME*, Vol. XX, pp.211-218.

41. Fang, F.Z., Liu, X.D., Lee, L.C. (2003). “Micro Machining of Optical Glass-A Review of Diamond Cutting Glasses,” *Indian Academy of Science*, Vol. 28, pp. 945-955.

42. Bifano, T.G., Blake, P., Dow, T.A., Scattergood, R.O. (1987). “Precision Machining of Ceramic Materials,” *American Ceramic Society Bulletin*, Vol. 67, pp.1038-1044.

43. Liu, K., Li X.P., Rahman M., Liu, X.D. (2004). “A Study of Cutting Modes in the Grooving of Tungsten Carbide,” *International Journal of Advanced Manufacturing Technology*, Vol.24, pp.321-326.

44. Hocheng, H., Kuo, K., Lin, J. (1999). “Machinability of Zirconia Ceramics in Ultrasonic Drilling,” *Materials and Manufacturing Processes*, Vol. 14, pp.713-724.

45. Hocheng, H., Tai, N., Liu, C. (2000). “Assessment of Ultrasonic Drilling of C/Sic Composite Material,” *Composite: Part A*, Vol. 31, pp.133-142.

46. Liu, Y., Chen, Y. (1996). “Ultrasonic Circular Vibration Drilling for Deep Holes,” *Journal of China Coal Society*, Vol.21, pp.8-9.

47. Jiao, Y., Hu, P., Pei, Z.J., Treadwell, C. (1998). “Rotary Ultrasonic Machining of Ceramics: Design of Experiments,” *Machining and Science Technology*, Vol.2, pp.137-154.

48. Petrukha, P. (1970). “Ultrasonic Diamond Drilling of Deep Holes in Brittle Materials,” Russian Engineering Journal, Vol.50, pp.70-74.

49. Jiao, Y., Hu, P., Pei, Z.J., Treadwell, C. (2005). “Rotary Ultrasonic Machining of Ceramics: Design of Experiments,” *International Journal of Manufacturing Technology and Management*, Vol. 7, pp.1192-306.

50. Li, Z.C., Jiao, Y., Deines, T., Pei, Z.J., Treadwell, C. (2005). “Rotary Ultrasonic Machining of Ceramic Matrix Composites: Feasibility Study and Designed Experiments,” *International Journal of Machine Tool and Manufacturing*, Vol. 45, pp. 1402-1411.

51. Pei, Z.J., Ferreira, P.M. (1998). “Modeling of Ductile Mode Material Removal in Rotary Ultrasonic Machining,” *International Journal of Machine Tool and Manufacturer*, Vol.38, pp.1399-1418.

52. Kainth, G.S., Nandy, A., Singh, K. (1979). “The Mechanics of Material Removal in Ultrasonic Machining,” *International Journal of Machine Tool Design and Research*, Vol. 19, pp. 33-41.

53. Khoo, C.Y., Hamzah, E., Sudin, I. (2008). “A Review on The Rotary Ultrasonic Machining of Advanced Ceramics,” *Journal Mekanikal*, Vol. 25, pp. 9-23.

54. Yoshikawa, H., Sata, T. (1963). "Study on Wear of Grinding Wheels," *Journal of Engineering for Industry*, Vol. 85, pp. 39-43.

55. Shaw, M. (1996). "Principle of Abrasive Processing," Oxford University Press, New York.

56. Sathyanarayanan, G., Pandit, S. (1985). "Fracture and Attritious Wear in Grinding by Data Dependent Systems," *North American Manufacturing Research Conference Proceeding*, Vol. 13, pp.314-320.

57. Jiao, Y., Liu, W. J., Pei, Z.J., Xin, J., Treadwell, C. (2005). "Study on Edge Chipping in Rotary Ultrasonic Machining of Ceramics: An Investigation of Designed Experiments and Finite Element Method Analysis," *Journal of Manufacturing Science and Engineering*, Vol.127, pp.752-758.

58. Li, Z. C., Liang, W.C., Pei, Z.J., Treadwell, C. (2006). "Edge-Chipping Reduction in RUM of Ceramics: FEA and Experimental Verification," *International Journal of Machine Tools and Manufacture*, Vol.46, pp.1469-1477.

59. Sarwade, A., Sundaram, M.M., Rajurkar, K.P. (2010). "Investigation of Micro Hole Drilling in Bovine Rib using Rotary Ultrasonic Machining," *ISEM*, Vol.16, pp.411-416.

60. Sarwade, A., Sundaram, M.M., Rajurkar, K.P. (2009). "Micro Rotary Ultrasonic Machining," *North American Manufacturing Research Conference,* Vol. 37, pp. 621-628.

61. Sarwade, A., Sundaram, M.M., Rajurkar, K.P. (2010). "Micro Rotary Ultrasonic Machining: Effect of Machining Parameters on Material Removal Rate," *North American Manufacturing Research Conference*, Vol.38, pp.113-120.

62. Duranda, G.V., Franksb, R.W., Hosken. (2003). “Particle Size and Stability of UHT bovine, Cereal and Grain milks,” *Food Hydrocolloids*, Vol.17, pp.671-678.

63. Ferreira, P.M., Khanna, N., Pei.Z.J. (1997). “Rotary Ultrasonic Grinding Apparatus and Process,” United States Patent 5655956.

64. Xiao, H. (2007). “Mechanism, Characteristics and Modeling of Micro Ultrasonic Machining,” PhD thesis, UNL.

65. Hillery, M.T., Shuaib, I. (1999). “Temperature Effects in the Drilling of Human and Bovine Bone,” *Journal of Material Processing Technology*, Vol. 92-93, pp.302-308.

66. Yang, Y., Wang, C., Qin, Z., Xu, L., Song, Y and Chen, H. (2010). “Drilling Force and Temperature of Bone by Surgical Drill,” *Advanced Materials Research*, Vol.126-128, pp. 779-784.

67. Karmani, S. (2006). “The Thermal Properties of Bone and the Effects of Surgical Intervention,” *Current Orthopedic*, Vol. 20. pp.52-58.

68. Draenert, F, G., Mathys, R., Ehrenfeld, M., Draenert, Y and Draenert, K. (2007) “Histological Examination of Drill Sites in Bovine Rib Bone after Grinding in Vitro with Eight Different Devices,” *British Journal of Oral and Maxillofacial Surgery*, Vol. 45, pp.548-552.

69. Matsuoka, M., Motoyoshi, M., Sakaguchi, M., Shinohara, A., Shigeede, T., Saito, Y., Matsuda, M., Shimizu, N. (2011). “Friction Heat during Self-Drilling of an Orthodontic Miniscrew,” *International Journal of Oral and Maxillofacial Surgery*, Vol.40, pp.191-194.

70. Karaca, F., Aksakal, B., Kom, M. (2011). "Influence of Orthopedic Drilling Parameters on Temperature and Histopathology of Bovine Tibia: An in Vitro Study," *Medical Engineering and Physics,* Vol.33, pp.1221-1227.

71. Park, S. Y., Shin, S, Y., Yang, S, M., Kye, S, B. (2010). "Effect of Implant Drill Design on the Particle Size of Bone Collected During Osteotomy," *International Journal of Oral and Maxillofacial Surgery*, Vol.39, pp. 1007-1011.

72. Wiggins, K, L., Malkin, S. (1976) "Cryogenic Enhancement of Machinability of Bone," *Advances in Bioengineering*, Vol. 9, pp. 553-554.

73. Eichler, J., Berg, R. (1972). "Temperatureinwirkung Auf Die Kompakta Beim Bohren," *Journal of orthopedic*, Vol.110, pp. 909-913.

74. Sugita, N., Mitsuishi, M. (2009). "Specification for Machining the Bovine Cortical Bone in Relation to its Microstructure," *Journal of Biomechanics*, Vol. 42, pp.2826-2829.

75. Matthews, L, S., Hirsc, C. (1972). "Temperature Measured in Human Cortical Bone when Drilling," *Journal of Bone and joint Surgery*, Vol.54, pp. 297-308.

76. Davidson, S, R, H., James, D, F. (2000) "Measurement of Thermal Conductivity of Bovine Cortical Bone," *Medical Engineering and Physics*, Vol. 22, pp. 741-747.

77. Shin, H, C., Yoon, Y, S. (2006). "Bone Temperature Estimation during Orthopedic Round Bur Milling Operations," *Journal of Biomechanics*, Vol. 39, pp. 33-39.

78. Misic, T., Markovic, A., Todorovic, A., Colic, S., Miodrag, S., Milicic, B. (2011). "An in Vitro Study of Temperature Changes in type 4 Bone during Implant Placement: Bone Condensing Versus Bone Drilling," *Oral Surgery Oral Medicine Oral Pathology Oral Radiology,* Vol. 112, pp. 28-33.

79. Eshet, Y., Mann,R.R., Anaton, A., Yacoby, T. (2004). "Microwave Drilling of Bones," *IEEE Transaction on Biomedical Engineering*, Vol. 53, pp. 1174-1182.

80. Mann, R.R., Aktushev, O., Gefen, A., Jerby, E. (2006). "Modeling the Thermal Conditions around Sites of Microwave Drilling in Bone," *Journal of Biomechanics*, Vol. 39, pp. 382-383.

81. Alam, K., Mitrofanov, A, V., Silberschmidt, A. (2011). "Experimental Investigation of Forces and Torque in Conventional and Ultrasonically –Assisted Drilling of Cortical Bone," *Medical Engineering and Physics*, Vol. 33, pp. 234-239.

82. Ohashi, H., Therin, M., Meunier, A., Christel, P. (1994). "The Effect of Drilling Parameters on Bone," *Journal of Material Science: Materials in Medicine*, Vol.5/4, pp.225-231.

83. Thompson, H. (1958). "Effect of Drilling into Bone," *Journal of Oral Surgery*, Vol. 16, pp. 22-30.

84. Jackson, M.J., Robinson, G, M., Sein, H., Ali, N., Ahmed, W. (2004). "Machining Cancellous Bone using Coated Cutting Tools," *Proceedings of the 3rd international Engineering congress*, Vol. 3, pp. 45-52.

85. Li, J., Fartash, B., Hammarstrom, L. (1994). "Effect of Macro Texture Produced by Laser Beam Machining on the Retention of Ceramics Implant in Bone in Vivo," *Journal of Material Science: Materials in Medicine*, Vol.5, pp. 760-763.

86. Kim, D., Owada, H., Hata, N., Dohi, T. (2004). "An Er: YAG Laser Bone Cutting Manipulator for Precise Rotational Acetabular Osteotomy," *Conference Proceeding IEEE Engineering Bio Soc*, Vol. 4, pp. 2750-2753.

87. Hallgren, C., Reimers, H., Chakarov, D., Gold, J., Wennerberg, A. (2003) “An in Vivo Study of Bone Response to Implants Topographically Modified by Laser Micromachining,” *Biomaterials*, Vol. 24, pp. 701-710.

88. See, C, V., Gellrich, N, C., Rucker, M., Kokemuller, H., Kober, H., Stover, E. (2011). “Investigation of Perfusion in Osseous Vessels in Close Vicinity to Piezo-electric Bone Cutting,” *British Journal of Oral and Maxillofacial Surgery*, 2011. (http://www.sciencedirect.com/science)

89. Schwieger, K., Carrero, V., Rentzsch, R., Becker, A., Bishop, N., Hille, E., Louis, H., Morlock, M., Honl, M. (2004). “Abrasive Water Jet Cutting as A New Procedure For Cutting Cancellous Bone—In Vitro Testing in Comparison with the Oscillating Saw,” *Inc. Journal of Biomed Mater Res Part B: Appl Biomater*, Vol. 71B, pp. 223-228.

90. Beziat, J, L., Bera, J, C., Lavandier,B., Gleizal, A. (2007). “Ultrasonic Osteotomy as a New Technique in Craniomaxillofacial Surgery,” *International Journal of Oral and Maxillofacial Surgery*, Vol. 36, pp. 493-500.