EXPERIMENTAL INVESTIGATIONS TO STUDY CUTTING TEMPERATURE AND FORCES DURING CORTICAL BONE DRILLING

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CERTIFICATE

This is to certify that the thesis titled, **"EXPERIMENTAL INVESTIGATIONS TO STUDY CUTTING TEMPERATURE AND FORCES DURING CORTICAL BONE DRILLING"**, being submitted by **Mr. Rohit Jindal** , Registration No. **801482026**, in partial fulfilment of the requirements for the award of degree of Master of Engineering in Production Engineering at **Thapar University, Patiala** under the supervision of Dr. Vivek Jain and Dr. Dheeraj Gupta, Assistant Professor, Mechanical Engineering Department, Thapar University, Patiala submitted in Mechanical Engineering Department of Thapar University, Patiala during July, 2014 to July,2016. No part of the matter embodied in this report has been submitted to any other University or institute for award of any degree to the best of my knowledge.

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ABSTRACT

Drilling through bone is necessary action during the orthopaedic surgery. The drilling through the bones is majorly same as the mechanical drilling but it need more expertise and skills because it involved human as part of work. The mechanical drilling during orthopaedic surgery may harm the subject bone and bring to the surgeon for cure. For better treatment the surgeon must do the drilling in a manner that it should not damage the surroundings. To keep these points in consideration this research work has been carried out. The main drilling parameters i.e. rotational speed, feed rate and type of drill are under observation at different levels. This research work focuses to optimize the involving parameters for the less thermal necrosis, less surface damage and less thrust force exerted between tool and work material. Using L 16 taguchi mixed orthogonal array the optimized set of parameters has been suggest for all the response. Scanning electrode microscopy (SEM) images of the bone drilled samples helps to get the level of surface damage and the supports the results of surface roughness. An analytical model has been purposed for raise in temperature for all the experiments performed. The experimental and analytical results are in better agreement.

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Chapter-1

Introduction

Fracture in a bone is a serious concern one may come across due to accidents and aging to human or animals. When a bone is wrecked then the external surface (periosteum) and internal surface (endosteum) affects the bone marrow, which acts as a bridge for the cracked bone. But, usually the fracture of the bone is roofed by drilling of the bone at places with the help of fixing plates through insertion of screws.

Treatment of bone is one of the long standing surgical methods in the Indian history of medication. Susruta-Samhita which was written in the 800 – 600 BCE also have a lot of description about the surgery of skull, bones and joints and many other texts by different author also refers about fracture and its surgery. Now a day, hip and knee implant is one of the most common surgeries performed around the whole world. Fixation and joint replacement of the parts in human joint are very famous treatment for bone surgical treatment. Also, bone machining for development of bone screws to exchange metal screws is becoming famous. The different procedures of cutting of bone like shearing, grooving, boring, grafting, sawing, drilling and scraping are reported in literature. Among all these procedures, drilling is the most discussed surgical operations in literature.

Cutting of bones has always been an issue for doctors because of its high sensitivity to osteotomies. An extreme amount of manual labor is desired by doctors to cut the bone with the help of a chisel or for creating hole in the bone with the help of drilling machine. Conventional tools for cutting bone are painful as oscillating saws and chisel needs large exposure associated with trauma to muscles and nerves [1]. The bigger concern in such operations are the heat produced during high speed cutting method, which may affect thermal loss and flagging of fixative devices. These high speed cutting method such as drilling will produce heat and ends up in trauma. The cut will also become inefficient as the cutting flutes become blocked. Force and temperature measurement are very vital in forecasting the thermal 1nalysing1c1s threshold level and also for controlling the cutting tool to escape any loss to the spineless tissues.

1.1 Bone Structure

There are many terms used for describing the structure and identification of bone properties. Few of them are discussed below.

- **Cortical bone**: It is also known as compact bone and it is outer hard layer of bone.
- **Cancellous bone**: It is also termed as trabecular bone and it is spongy layer of bone. It has less strength as compared to cortical bone.

There also few types of bone identified microscopically according to arrangement of collagen's. Those are termed as:

- **Woven bone**: It is described as random organisation of collagen and it is mechanically weak.
- **Lamellar bone**: In which there is systematic parallel arrangement of collagens into sheets and these are mechanically strong.
- **Osteons**: Every osteons have concentric layers that surrounded a central canal that termed as haversian canal and it's also fundamental functional unit of cortical or compact bone.
- **Haversian canal**: It has blood supply for bone.
- **Volkmann's canal**: It joins two harversian canal with each other.

All the terms that describe above are shown in fig. 1.1.

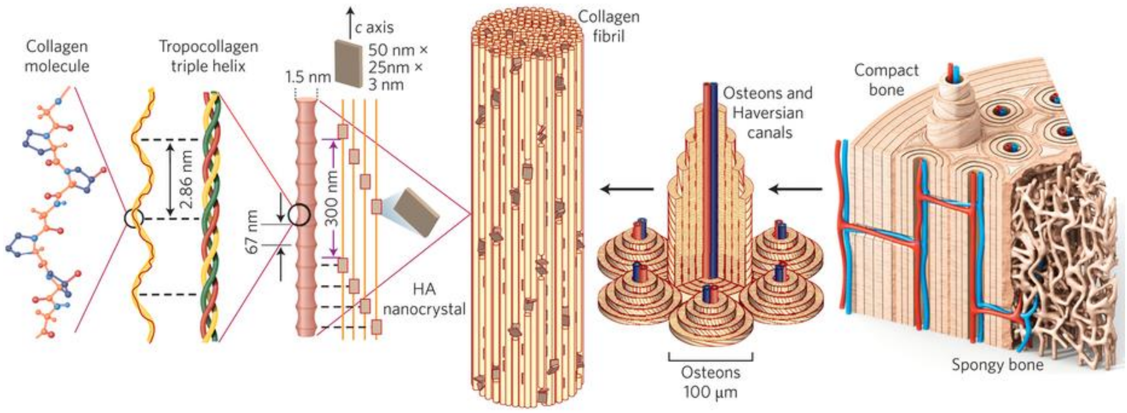


Figure 1.1 Hierarchical model of bone

1.2 What is Bone

To comprehend osteoporosis, it is vital to know about bone. Bone is living, developing tissue most part of which is made of collagen. Collagen is a protein that gives a delicate system, and calcium phosphate is a mineral that includes quality and solidifies the structure. This mix of collagen and calcium makes bone solid and sufficiently adaptable to withstand stress. Bone is considered as a composite fabric containing an elastic mineral 'fibers' embedded into an organic matrix having openings filled with liquids. Cortical and trabecular bone are commonly reported to have either transverdely isotropic or orthotropic material properties. Lamellar bone tissue can also be understood as a mineral crystals and fiber-reinforced composite of collagen fibrils. At the microstructural level, a Haversian bone tissue can also be understood as a set of secondary osteons embedded in the grid of interstitial lamellae.

1.2.1 Mechanical / Structural Properties of Cortical Bone

Knowledge about any element is necessary before working on it, likewise knowledge about bone and its features is very important to understand the behaviour of bone in different loading conditions and how the climatic conditions will affect the fracture or any serious bone injury.

Theories focussing on the fracture procedure mainly depend upon the mechanical properties of bone. One of the most vibrant features of cortical bone is its density lies between 1.7 and 2.0 g cm^{-3} and its porosity differentiat with 30% to 90%. Similar to other engineering materials, bone responds differently to quasistatic and dynamic loadings. Damage and failure of bovine compact bone have already been studied in quasi-static tensile experiments and have shown large variations of stress failure, from 100 to 200 MPa, and failure strain, from 0.4% to 4% [2] [3] [4]. According to study, when loading rate increase then elatic modulus of compact bone also increase [5] [6].

1.3 Requirement of Drilling in Bone

Fracture is an everyday event due to the aging effect, accidents and diseases. Repair and reconstruction of such fracture is usually based on the drilling of the bone and fitting the separate pieces together with the help of wire, plates and screws. Improved morphology of drilled hole surface on bones and fixative components like screw, hooks and pegs will increase the strength of the bonds between them.

Recovery of various orthopaedic surgeries include, restoring the bone parts to their position and restraining them until completely recovered. Sometime drilling and fastening of the bone is necessary for easy and speedy healing process. The orthopaedic drilling process is like a mechanical drilling due to the reactionary surfaces and thermodynamics of the bone.

One can correlate fracture from the stone age homo sapiens. While self-healing of the bone is a very time consuming method with a high probability of modified positioning of the bone.

Therefore, the allocation of bone parts at the allocated position is a difficult task. This task has two approaches for completion: conventional approach and direct approach.

In the conventional approach, fractured part of the bone is constrained from movement with the help of outside support. Traumatologist treats the fracture by identifying the location and fixing at that location with the help of outside support. This process is helpful in minor cracks and injury but not as efficient in the serious injuries.

In direct approach, the fractured bone is located at its original position with the help of screws, plate and wire. Before fastening of the screws, bone is drilled and tapped. Mechanical drill or a similar device is used to make a hole through the bone. Such operations are usually done with the help of manual drilling tools. Direct approach for the fixing of the bone by drilling is shown in the fig. 1.2

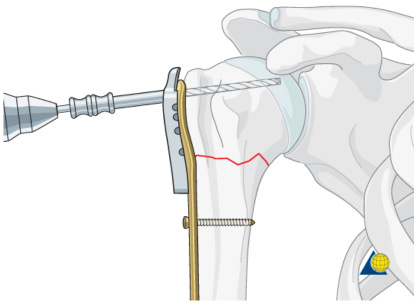


Figure 1.2: Systematic diagram shows drilling through a bone

For getting credibility and constancy in the damaged area, the screw is tightened up completely and it also grips the inside of the bone. But necrosis can cause failure and joint around the implantation site and heading looses down the fixation.

1.4 Methods of Bone Drilling

Bone drilling is as simple as drilling any other material but it needs proper attention and patience. There are two methods of drilling: conventional drilling and unconventional drilling.

1.4.1 Conventional Drilling

Conventional drilling is normally used mechanical methods in which drill-bit is used to make hole in the material. The tool is rotating with the help of the adjacent power system. There are many parameters which affect the quality and efficiency of the drill hole.

The parameters described in the major categories are machining parameteres and drill parameters. These two categories can be classified as direct parameters related to bone drilling. The parameters used for machining rotational speed, feed rate, drill depth, cooling etc. These parameters play a very important role in influencing the temperature and these are also important for the quality and accuracy. The problem like thermal necrosis depends upon these parameters.

Coolant

Heat due to friction in drilling may cause necrosis which will be dangerous for the patient. For reducing the generated heat, coolants are used during 5nalysing5c surgery. The coolant significantly reduces the temperature induced during drilling which will result in better surgeries. For this purpose different type of cooling system were generated such as external cooling system and internal cooling system (shown in Fig. 1.3).

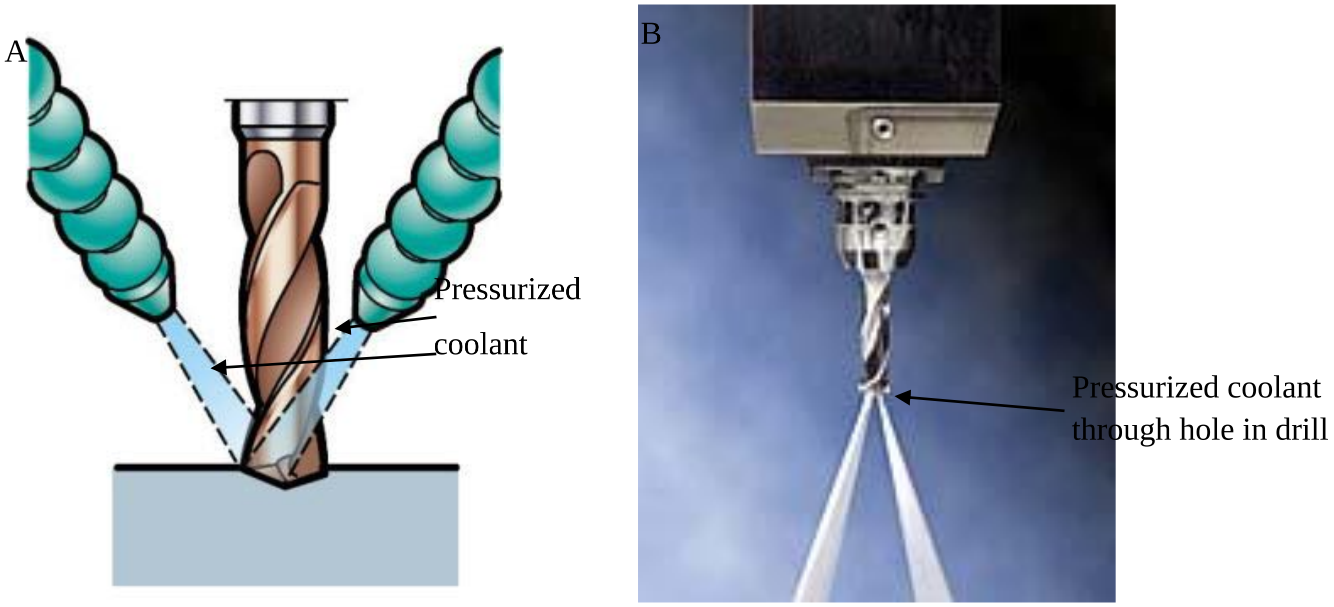


Figure 1.3: (A) View of external cooling and (B) arrangement of internal cooling system

Internal cooling means providing the coolant at the drill tip through the internal hole of drill bit, whereas in the external cooling, the coolant is is provided at the entry level. Internal cooling system consist of two types: closed type and open type.

1.4.2 Non-conventional machining

It is defined as group of techniques in which material is removed by various methods for example chemical, themal and mechanical energies methods. In this machining there is no use of any use sharp tool and here material may be removed in the form of chip. The following methods used for bone drilling are:

- Abrasive water jet drilling
- Water jet drilling
- Ultrasonic assisted drilling
- Microwave drilling
- Laser drilling

1.5 Medical challenges in Bone Drilling

The following majors problems occur during bone drilling are:

- Thermal necrosis
- Pull out strength

Thermal Necrosis

During drilling process, heat is generated due to friction between both the surfaces, which may lead to hyperthermia and carbonization, ending up in the death of cell and change in its basic characteristics. Due to increase in temperature above the threshold value, bone resorption may happen due to thermal exposure and ends up in thermo necrosis. Thermo necrosis is like the damaging of bone cells and may leads to the death of bone death due to lack of blood supply.

Pull out strength

As name signifies when screw is placed in drilled hole and when screw does not grips well with drilled hole then pull out strength problem occurs. It mainly occurs due to necrosis because it cause breakdown near the holes site. So it leads the loosening of fixation.

Based on the above two medical challenges the aim of the present work is to measure the cutting temperature during bone drilling. Hence, optimize the machining parameters for minimum thermal necrosis.

1.6 Organization of the Thesis

The thesis is divided into six chapters. The subjects of each chapter are précised below:

CHAPTER 1: It represents the first appearance of bone, different attributes of bones and description of conventional method used for drilling of bones.

CHAPTER 2: It contains a literature study on the drilling of bones using different methods**.** Finally the literature gap and analysis has been devised based on the gaps identified on the past work. This chapter extends the problem formulation, the aims of the present study and design of the present methodology.

CHAPTER 3: This chapter contains the Experimental set up, work piece properties, input and output parameters. The experiments planned according to 'design of experiment' are discussed in this chapter.

CHAPTER 4: This chapter includes the analytical model of heat generation and forces encountered during he bone drilling

CHAPTER 5: This chapter contain the overall brainstorming over the results and thus the results have been postulated.

CHAPTER 6: Conclusions are explained along the groundwork of the present work in this chapter. Further, future scope in the field of drilling of bones is also suggested in the same chapter.

Chapter – 2

Literature Survey

The present survey is based on the critical problem of themal nacrosis during bone surgery. Thermal nacrosis depends upon the certain environment factors, bone properties and mainly on drill type and its geometry.

The present literature review divided into following section:

- Traditional machining

  Traditional machining is further divided into two section:

  - Machining parameter affecting thermal necrosis
  - Drill geometry affecting thermal necrosis
- Non-traditional drilling

2.1 Traditional Machining

In traditional machining material is removed in the form of chip using wedge shape sharp tool and tool is harder than the work-piece material under machining condition.

2.1 a Machining Parameter affecting Thermal Nacrosis

Drill Speed and feed rate

Some article shows the drift in decreasing temperature by rising in axial speed, because here time taken for drill is less due to more speed of penetration. As per results here less heat produced for lesser amount of time. When the time period of temperature above critical value is less than 1 minute then thermal necrosis wouldn't happen in bone. Threshold value for human bone is 47°C for 1 minute [7]. Some survey indicates that when drilling speed used above the 200,000 rpm then tissue damage is avoided [7,8,9]. As per the observation, temperature raise was increased with in the distance of 2.5 mm to 5 mm from the drilling site when spindle speed was increased from 125 to 2000 rpm [10]. Most of the drilling experiments with bovine bone without coolant for forces in the range of 1.5N to 9N and speed of the spindle should be in the range of 27000 rpm to 97000 rpm as per observations. The results from these experiments states that the temperature decreases with increase in the speed and there is increases in temperature with force range up to 3.5 N, then temperature decreases as force increases above 3.5 N. Hence, with increase in force the heat generation rate also increases but the drilling period reduces, which reduces the amount of heat conducted to the the bone [11]. The temperature raise is increased around the hole as we go in the depth and suggested RPM is 800-1400 and there is no significant difference in the temperature when drilling with different point angles (70^o, 80^o ,90^o**)** and positive rake angle 23^o [12]. The temperature increase during the preparation of cavity with increase in drill speed [13]. Study with the human beings cadaveric femora, stated that with rise in rotational speed from the 345 rpm to 2900 rpm there is no significant change in the temperature during drilling. But rise in the thrust force was cooperated with reduction in both maximum temperature and time duration. They measured the effect of applied force from 19.6 N to 117.6 N, drill speed varying from 345 rpm to 2900 rpm and experimented that both the time and temperature above 50^0C reduces the applied load increases [14]. Experiments on the cadaveric femur have shown that at 820 rpm, period and magnitude of highest temperature decrease with the rise of axial thrust force [15]. Experiment on bovine ribs at 600 rpm and 1200 rpm specified that temperature rise when increase either the force or speed [16]. Experiments performed using 4 thermocouples technology to calculate the heat produced with using three different rpm (1225,1667,2500) and confirmed that time for drilling, average rise in temperature decrease with drilling speed increase [17]. Experiments on the effect of feed rate and drilling speed on the bovine femur and specified that the maximum temperature rises with gradual rise in the spindle speed and decreases with rise in feed rate as shown in fig. 2.1 [18].

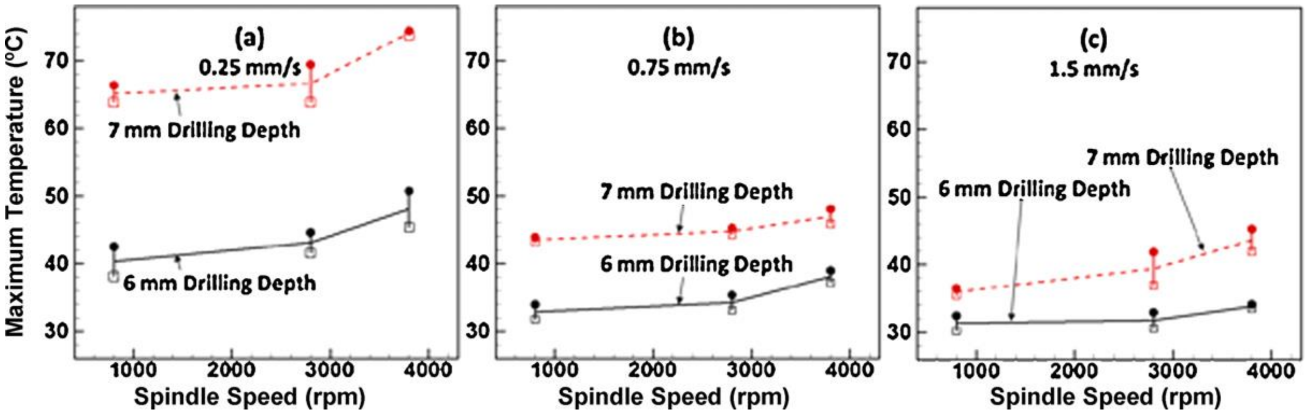


Figure 2.1: variation of bone temperature with feed rate and speed[18]

Experiments had compared the torque and forces in ultrasonic assisted and conventional drilling, detailed that with variation in drilling speed from 600 rpm to 3000rpm the force reduces by 27% in conventional drilling as shown in fig. 2.2 [19]. As per the literature survey, we found out that there is no clear signal about the optimum drilling speed and axial drilling force on bone but most of the experiments suggested that the high speed with larger force for minimum temperature production is better for bone drilling.

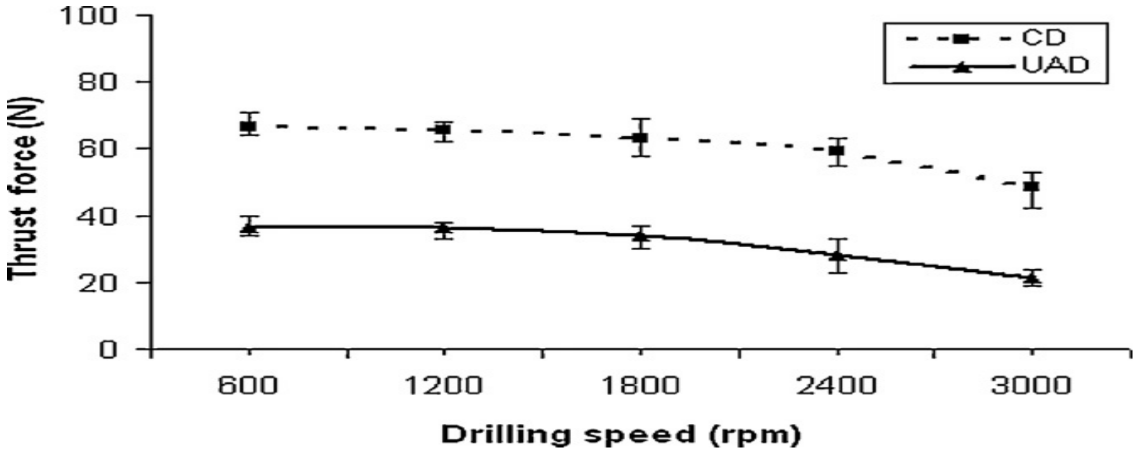


Figure 2.2: Influence of drilling speed on thrust force in CD and UAD[19]

Irrigation

The thermal loss is affected by irrigation. Temperature is diminished during drilling with the use of coolant [20,21]. It is observed that internal irrigation reduced the frictional heat [22]. By using the coolant temperature decrease but it does not completely avoid temperature variation in the bone [23]. Experiments observed the effects of cooling during drilling of human cortical bone and disussed that for limiting the maximum temperature cooling is highly desirable [24]. Irrigation and drilling has to be done simultaneously for lowering down the temperature with the help of water at flow rates of 300, 500 and 1000ml per minute. The results show that the significance of temperature never raised above 50^0 C for the irrigation rate of 500 ml/min [24] (shown in fig.2.3).

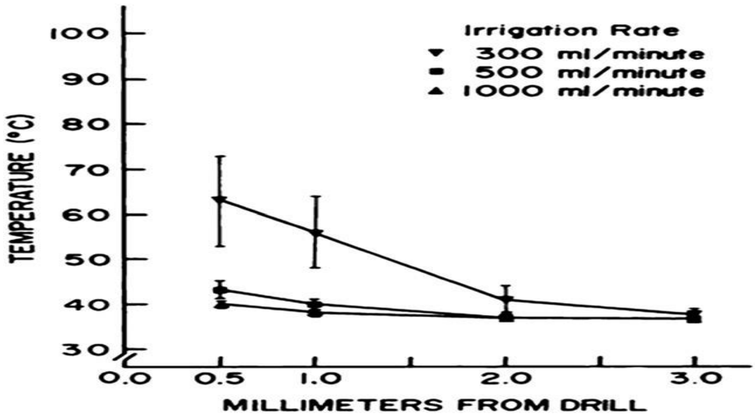


Figure 2.3 : Effect of cooling rates at specific distances from the drill [24]

2.1 b Drill geometry affecting Thermal Nacrosis

Helix angle

The helix angle of the drill affects the temperature rise while drilling. For larger diameter drills larger helix angle used. The helix angle of drill bit changes with drill diameter. The ideal range for helix angle observed as 24-36 degrees [25]. Most of the 11nalysing11c drill bit has slow helix angle and this geometry is optimum in case when drilled in to dry bone where debris and short chipping removed easily. But in vitro case it is found that quick helix angle is more capable when debris is mixed and wet with medullar fat [26]. Experiments recommended parabolic flutes because they found that temperature decrease steadily with increasing helix angle and variation of helix angle shoen in figure 2.4.

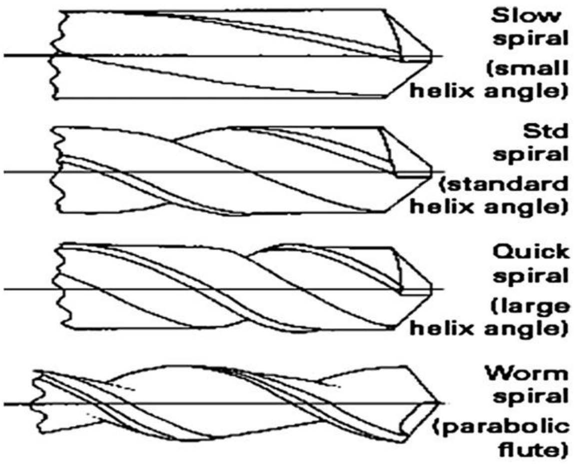


Figure 2.4 – Variations in helix angle

Point angle

Drilling in a flat surface is not possible, and cannot be guided always. Therefore, surgical drill must be self centering and should not travel when initiating the hole in the cortex. To prevent the drill for traveling an ideal point angle required [27]. Study with three different drill bit with point angle 80^0 ,100^0 ,120^0 and found out that any efficient changes on the rising of bone temperature during drilling of three different diameter drills (2.7,3.2 and 4.5 mm) [28]. To increase the capability of bone drill, larger point, helix angles and positive rake angle is recommended [29]. The optimum angle for 11nalysing11c drills is 90^0 for lowering the temperature. The periosteum prohibit the chip flow over drill flutes. For avoid this type of problem a split point design required and with the use of split point there is less friction occur then less heat generated [26].

Drill sharpness

It has been observed that blunt drill bits produce more thermal damage [26,20,21]. Time duration for temperature peak and maximum temperature observed when worn tool is used for drilling and it is found that with the use of worn reamers there is change of 10^0C temperature compare with sharper reamers [30]. Figure 2.5 shows the drill bit tip, however it was wear before and after the using for drill.

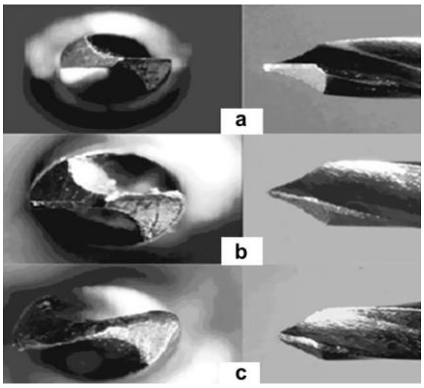


Figure 2.5 : Three drills end and side view. (a) fresh drill. (b) Worn drill, (c) Worn drill (used for several months)

Flute

It is the path that is necessary to required for removing of chips from cutting zone when the drill remains to penetrate. Researched showed that cutting capability of 3-fluted design is better than 2-fluted design but this does not mean that the maximum temperature during drilling will decrease during drilling. With the help of 3-fluted design, tendency of cutting lips to meet at a point causes reduction of chisel edge due to which reduction in axial thrust force occurred [31].

Type of tool

Optimize the bone drilling parameters for better surface finish and material removal rate. Experiments conducted on bovine bone with varying tools and drilling parameters woth L9 orthogonal array taguchi combination. For better surface roughness, the optimum set of parameters are R2 (2000 rpm), F1 (50 mm/min)and T3(twist drill) and for better Material removal rate the optimum set of parameters are R3 (3000 rpm), F3 (150 mm/min) and T3 (twist drill) [32].

2.2 Non-Traditional Machining

A study was conducted with abrasive water jet machining during bone drilling. The Lactose-monohydrate was used as an abrasive which is a bio-compatible material. Different water pressure and abrasive feed rate used and it is observed that surface roughness was increased when feed rate of abrasive increased. Also, author concluded that with abrasive water-jet, necrosis may be avoided to an extend and is proved to be good alternate for cutting of bone [33]. In an another study temperature was measured by thermocouples that were inserted into the cortical hollow bone during abrasive water injection jet (AWIJ). The influence of parameters like pressure, traverse rate, abrasive flow rate and abrasive material are observed. From results it was revealed that with lower pressure and lower abrasive feed rate less temperature raise in bone surrounding [34]. The feasibility of bone drilling with microwave energy was exploited by Eshet et al. From optical and scanning electron microscopy it is evident that microwave drilled hole are substantially smoother then the holes drilled by mechanical drilling machine. Researchers found that microwave drilling helps to control the formation of debris and rupture of bone vasculature during drilling but thermal necrosis is high in this case of microwave drilling. However, carburizing of bone near by the drilled point shows some damage to the bone tissue [35]. Singh et al. compared the conventional drilling of bovine bone with the non-conventional technique. Surface roughness and MRR of bone specimen were observed. Roughness of the conventionally drilled specimen was found to be around 20% higher than the non-conventional drilled sample. MRR was more in case of conventional drill bit [36].

2.3 Research Gap

- There has been no symmetric response recorded for the consequence of drill speed on heat generation. Some express an increment in temperature with increment in speed while some contradict the published results.
- The conventional way of bone drilling is applicable in real time bone surgery.
- Different types of drill bit can be used to analyse the effect on thermal nacrosis and forces.
- A mathematical modelling is required for the approximation of heat generating during bone drilling.

2.4 Problem Formulation

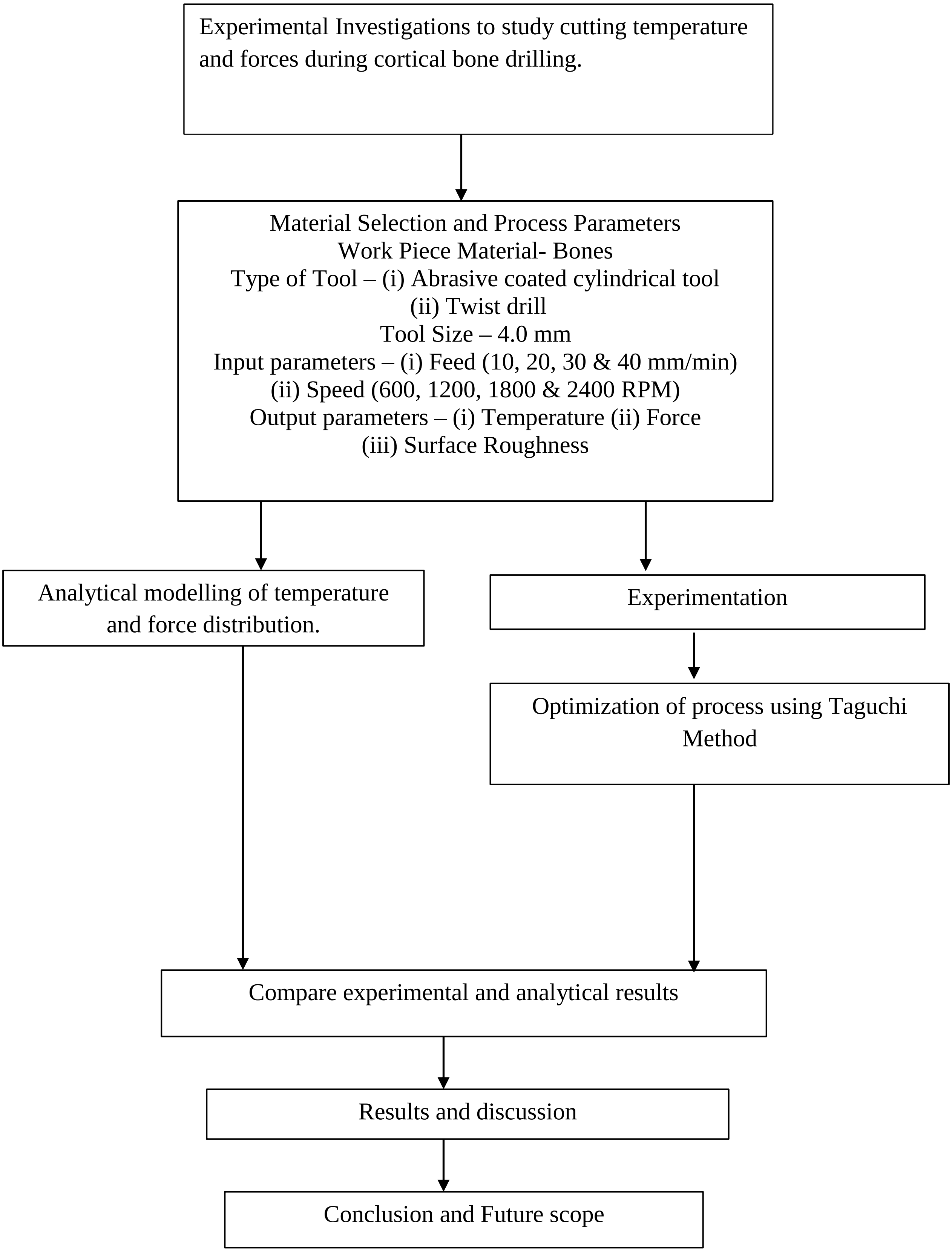
Thus, in the current study all the shortcomings of the previous studies were identified from a literature survey and attempt is made for "**Experimental Investigations to study cutting temperature and forces during cortical bone drilling**".

2.5 Objectives

The main objectives of this study:

- To investigate and analyse the influence of various process parameters on performance characteristics of bone drilling and process optimization.
- To mathematically model the heat generation during bone drilling.
- To characterize the bone samples using different characterization techniques such as SEM, Surface roughness tester etc.
- To compare the analytical and experimentation results of heat generation during bone drilling.

2.6 Work Plan



Experimental Investigations to study cutting temperature and forces during cortical bone drilling.
Material Selection and Process Parameters
Work Piece Material- Bones
Type of Tool – (i) Abrasive coated cylindrical tool
(ii) Twist drill
Tool Size – 4.0 mm
Input parameters – (i) Feed (10, 20, 30 & 40 mm/min)
(ii) Speed (600, 1200, 1800 & 2400 RPM)
Output parameters – (i) Temperature (ii) Force
(iii) Surface Roughness
Analytical modelling of temperature and force distribution.
Experimentation
Optimization of process using Taguchi Method
Compare experimental and analytical results
Results and discussion
Conclusion and Future scope

Chapter-3

Experimentation

Experiments are carried out for the output data that certify the temperature and mechanical forces. The complete explanation of the machine tool, tool holder, tool type, the workpiece and the material of the measuring instruments used for this research are discussed in the following sections.

3.1 Description of Machining Setup

3.1.1 CNC Vertical Milling Machine

Whole experiments were carried out in 3-axis CNC high speed vertical milling machine (Fig. 3.1), together with the dynamometer configured to measure the forces and torque induced on the working material (bone) during drilling. The maximum consumption of the machine is 22.4 KW with maximum rpm of 8100 rpm and its cooling volume is 208 L. The length and width of the machine is 1219 mm high and 457 mm. The maximum diameter of the tool can be held in the tool holder is 89 mm. Full technical specification for the m/c are given in Table 3.1

Fig.3.1: CNC Vertical Milling Machine

Table 3.1: Specification of CNC Vertical Milling Machine

Specification	Units	Parameters
Table(width*length)	mm	315/1060
Stroke(X/Y/Z)	mm	1016/508/635
Power	kW	22.4
Spindle speed	rpm	60-6000
Feed Rate	mm/min	1-5000
Current	Ampere	26
Voltage	Volt(DC)	24
Coolant capacity	L	208

3.1.2 Tool holder :

In this setup, high speed balanced tool is used. The aim of balancing the tool holder is to refine the distribution of the mass of the body (reduce the imbalance) in order to generate the centrifugal forces with in the essential boundary until spindle is rotating at high speed. The tool holder have installed with counter weights in a single plane at a specified distance from the front end of the instrument holder. The tool holder can adopt collets attachment for securing the rotary tools like mills, drills, reamers, etc. An assembly drawing the support of the tool used is shown later in figure 3.4.

3.2 Cutting Tool

During this study two types of cutting tools were used for drilling. They are described in below section.

Drill Bits

For the experiments a drill bit of 4 mm diameter is used for drilling purpose. The material of drill bit is High Speed Steel (HSS) and its specification is similar to surgical drill bit. These drill bits are used high production manufacturing and shown in figure 3.2 A.

Abrasive Coating Solid Tools

Abrasive coated tools initially used for glass cutting but now a days it is widely used in others areas also. They are very easily available in market as per quality of tools. In this study diamond coated tool is used for drilling. The diamond coated tool is prefered because it is bio-compatible. Diameter of abrasive coated tool is also 4 mm as shown in figure 3.2.b.

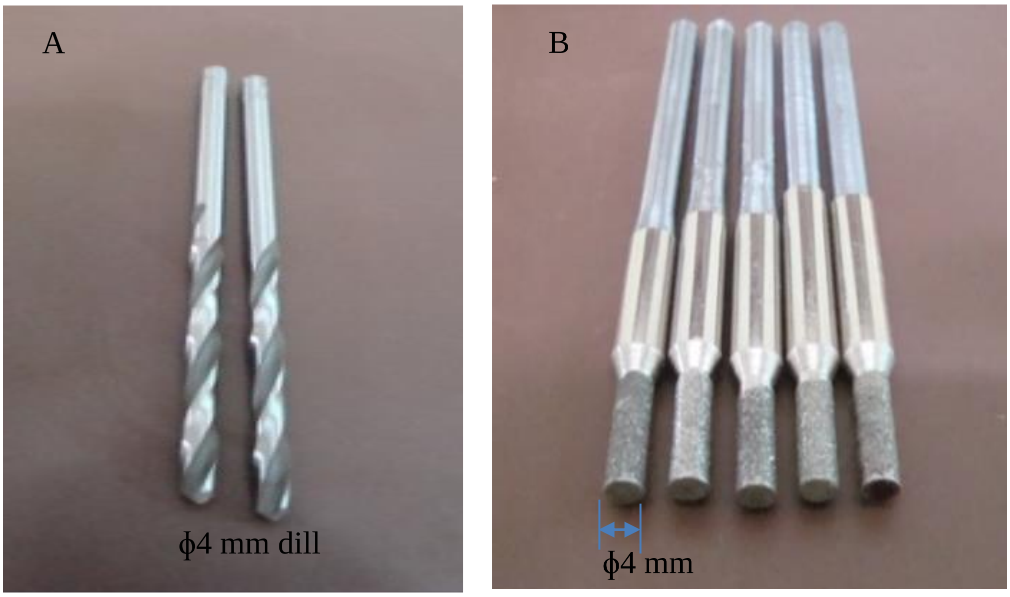


Figure 3.2: Represent (A) drill bit and (B) abrasive coated tool

3.3 Work Piece Material

In this study cortical bone of goat is used as a work material (shown in figure 3.3). All the bones used for the experiment were bought from the same slaughter house. Experiments are performed on fresh bone that directly taken from butcher shop. Goat bone is used because it has approximately same mechanical properties of Human bone. Bone is made of calcium and phosphors with density of 1800 Kg/m^3. Total 25 sample were used for the study.

Figure 3.3: Work-Piece Image during Experiment

3.4 Design of Experiment

It is a method to gather the experimental knowledge and that knowledge based on the experimental details and not on theortical model. It is really helpful in determining the significant parameters inducing the quality features of intrest. It is scientifically varying the administrable input aspects in the process and finding the effect of these attributes on the output product parameters.

The advantages of design of experiments are summarized as follows:

- Number of trials is significantly reduced.
- Identification of important decision variables, which control and improve the performance of the product or the process.
- Optimal setting of the parameters can be found out.
- Determination of 'experimental error' can be made.
- Inference regarding the effect of parameters on the characteristics of the process can be made.

In the following sections, the analysis procedures for the technique 'Taguchi method' used in the present research work is presented.

3.4.1 Taguchi Experimental Design Strategy

The traditional full-factorial designs require experimental data for all the possible combinations of the factors involved in the study; consequently a very large number of trials need to be performed. Therefore, in case of the experiments involving relatively more number of factors, only a small fraction of combinations of factors are selected that produces most of the information to reduce experimental effort. This approach is called fractional-factorial design of experiment. . The analysis of results in this approach is complex due to non-availability of generally accepted guidelines [Ryan (1988)]. The Taguchi method gives a solution to this problem. Taguchi method simplifies and standardizes the fractional factorial design by introducing orthogonal array (OA) for constructing or laying out the design of experiments. It also suggests a standard method for the analysis of results.

Taguchi suggests two different routes to carry out the analysis of the experiments. In the first approach, the results of a single run or the average of repetitive runs are processed through main effect and ANOVA analysis (Raw data analysis). The second approach is for multiple runs where signal to noise ratio (S/N ratio) is used.

Assumptions of the Taguchi method

Since the effect of each factor may be linear, quadratic or of higher order, but the taguchi method assumes that interactions of individual factor i.e. their cross product is not available. This implies that the effect of one independent variable does not depend on any other independent parameter with their different levels and vice versa. If in any case, this assumption is despoiled then it alters the additivity of main effects and interaction occur between the variables.

3.4.2 Selection of OA

In selecting an appropriate OA, the following prerequisites are required:

1. Selection of process parameters and/or their interactions to be evaluated.
2. Selection of number of levels for the selected parameters.

Brainstorming, flow-charting, cause-effect diagrams are some of the methods for the selection of parameters to be included in the experiment. Two levels for each parameter are recommended to minimize the size of experiment. However, if curved or higher order polynomial relation between parameters is expected, at least three levels are required [Barker (1990)]. Increasing number of levels for parameters increases the degree of freedom (DOF) in the experiment and hence the number of trials. The basic kind of OA developed by Taguchi [Taguchi and Wu (1980)] is either two-level arrays (L_4, L_8, L_{12}, L_{16}, L_{32}) or three level arrays (L_9, L_{18}, L_{27}). The subscript in the array designation indicates the number of trials in that array.

When a particular OA is selected for an experiment the following inequality should be satisfied.

3.4.3 Degree of Freedom

DOF required for parameters and interactions. It is determine by number of trials minus one: N-1

Where N is the number of trials.

3.4.4 Procedure of Experiment Design

There are following steps for taguchi method :

i. Founding of obectives function.
ii. Seletion of input variables and relations to be measured.
iii. Selections of number of levels for the dependent and independent variables.
iv. Calculate total degree of freedom.
v. Choosed suitable Orthogonal Array.
vi. Provision of parameters to columns.

vii. Implementation of experiments allowing to experimental situations in the array.

viii. Analyze results.

Data Analysis

A number of methods have been suggested by Taguchi for 21nalysing the data: observation method, ranking method, column effect method, ANOVA, S/N ANOVA, plot of average responses, interaction graphs, etc. [Ross (1995)]. In the present work, following methods are used.

1. Plot of average response curves
2. ANOVA for raw data
3. ANOVA for S/N data

Signal to Noise Ratio

S/N ratio is used as an objective function for parameter optimization. Control factors can be adjusted easily and their values are define by us. Quality characteristic is mainly depend on these control factors. Noise factors like temperature, humidity, weather etc. are difficult or impossible to control. The ratio of the mean (signal) with the standard deviation (noise) is termed as the S/N ratio. For analysis purpose, taguchi gave three type of S/N ratio which described below-

(1) SMALLER-THE-BETTER:

n= -10 $\log_{10}$ (mean sum of square of experimental data)

This is mainly selected for all unwanted characteristics whom we want minimum like defects etc. Also, it is used to find the difference between the standard or ideal value of any data to it's measured value (like in case of measuring surface roughness of any material, if required value is 0.02 µm and experimental value are in some finite rate) then the difference between the standard data and experimental data is require to minimum. Then formula for calculating S/N ratio is,

N= -10 $\log_{10}$ [mean sum of square of (experimental data – ideal data)]

(2) THE-LARGER-THE-BETTER:

N = -10 $\mathbf{log_{10}}$ [mean sum of squares of reciprocal of experimental data].

This is require for maximizing some data. This is generally used for desired results, as they require to be maximum as possible like material removal rate.

(3) THE-NOMINAL-THE-BEST:

This case is used for achieving a required value. It was used when a certain value is desirable and neither higher nor small value from that value is require.

3.5 Experimental Details

The objective of the experimental study is to find out the forces and how the temperature distributed in the bone during drilling. There are many parameters that are affecting the output characterstics during drilling like cutting speeds, feed, tool type etc.

Selection of Parameters

Aim of this study is to determine the effect of rotational speed, feed rate and type of tool on cutting temperature, forces and surface roughness during bone drilling. Input parameters for this study are decided on the basis of pilot experiment, literature review and machine constraint. The list given in the table 3.2.

Degree of freedom is determined from total no. of level minus one. Hence total degree of freedom is 7. As shown in tha table 3.2.

Table 3.2: Controlled parameters and levels

Serial No.	**Factor**	**Level 1**	**Level 2**	**Level 3**	**Level 4**
1	Tool type	Drill bit	Abrasive coated	-	-
2	Speed (RPM)	600	1200	1800	2400
3	Feed (mm/min)	10	20	30	40

Table 3.3 Represent Degree of Freedom

Interaction	Units	DOF
Feed rate	mm/min	3
Speed	rpm	3
Tool	---	1
	Total	7

Output Parameters

In the current study the following output parameter have been chosen.

i. Cutting Temperature (^{0}C)
ii. Force (N)
iii. Surface roughness (µm)

The goal of the study is to minimize the temperature distribution, forces and surface roughness during bone drilling without affecting the properties of bone.

There is following step/procedure to perform this study. They are following as:

1. Preparation of specimen
2. Drilling of bones
3. Temperature measurement
4. Measurement of force and torque
5. Surface roughness measurement
6. Metallurgical characterization

Constant Parameters:

The following parameters are assumed constant in this study :

- **Bone Dimensions :** In this study bone volumetric dimensions is assumed constant for the analytical model. Total 25 samples were used.
- **Ambient condtion:** 37 ^{0}C room temperature is assumed constant for the study.

3.5.1 Preparation of Specimen

All the bones are fresh during experiment and are directly bought from the butcher shop. The specimen are prepared according to experiment needs. For clamping on the dynamometer, two holes of Φ 9 mm were drilled with a centre to centre distance of 60 mm with manual drilling. For online monitoring of temperature, RTD sensors were used. Three thermocouples at distance of 2 mm from each other were inserted in the bone. For insertion of thermocouples holes were drilled at a depth of approximately 3 mm in the bone.

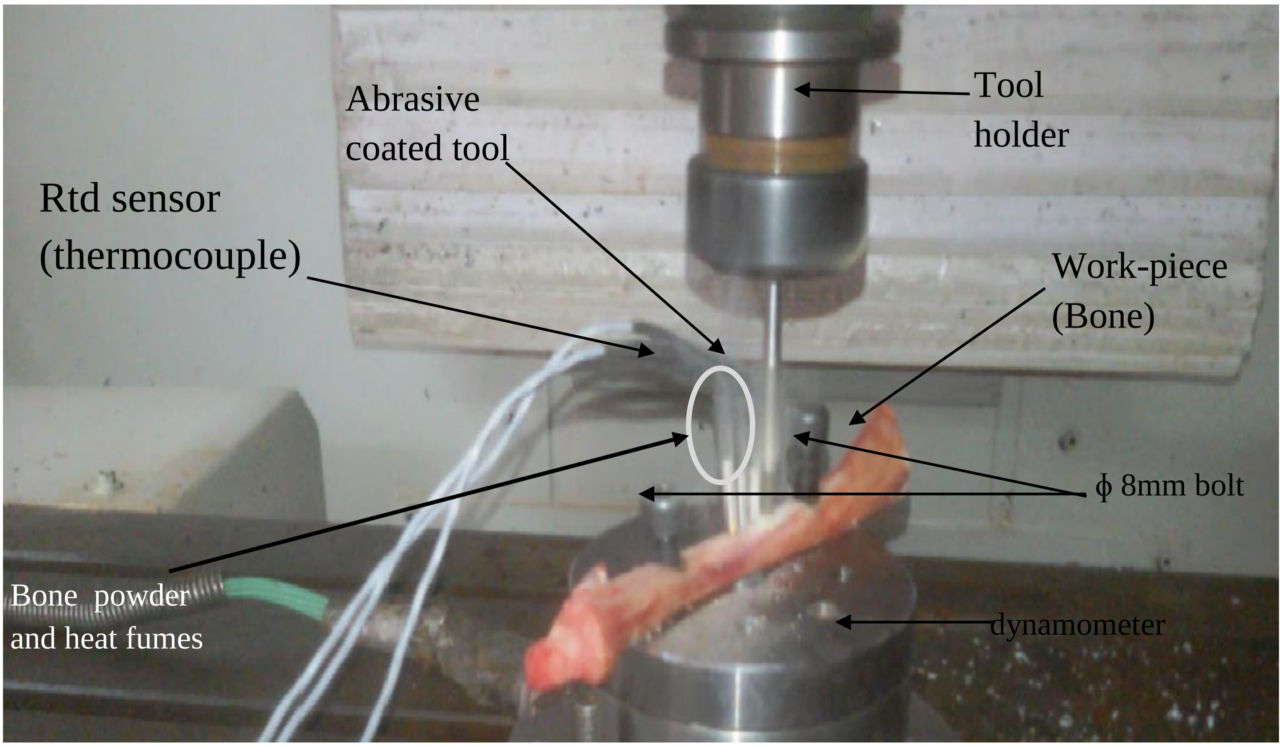


Figure 3.4: Clamping of bone on Dynamometer

3.5.2 Drilling of Bones

Drilling of bone is performed , according to ‘taguchi’ methodology. For drilling L16 and mixed array is used. During drilling, some factors assumed constant like surrounding temperature and dimensions of bones. In this study 48 number of holes are drilled according to L 16 theory. Execution of experiment represent in the table 3.4.

Table: 3.4 L16 array in Taguchi

Experiment no.	Speed (rpm)	Feed (mm\mn.)	Tool type
1	600	10	Twist drill

2	600	20	Twist drill
3	600	30	Abrasive coated
4	600	40	Abrasive coated
5	1200	10	Twist drill
6	1200	20	Twist drill
7	1200	30	Abrasive coated
8	1200	40	Abrasive coated
9	1800	10	Abrasive coated
10	1800	20	Abrasive coated
11	1800	30	Twist drill
12	1800	40	Twist drill
13	2400	10	Abrasive coated
14	2400	20	Abrasive coated
15	2400	30	Twist drill
16	2400	40	Twist drill

3.5.3 Temperature Measurement

During drilling heat is created due to plastic deformation and friction between work piece and tool. So during drilling temperature is measured by the help of thermocouple or thermographic camera but in this research temperature is measured with the help of PT100 rtd sensor (thermocouple) and reading is measured on the digital meter or indicator. Here three sensor criteria is used for measuring temperature variation in radial direction with centre to centre distance of 2 mm, 4 mm and 6 mm from the experimental hole as shown in fig. 3.5. Sensor is placed radially due to anisotropic behaviour of bone.

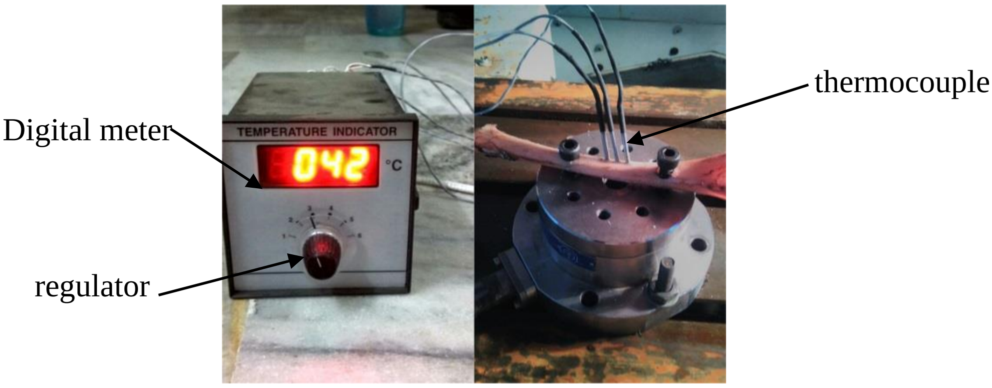


Figure 3.5 Sensor setup

3.5.4 Forces Measurement

For measuring the forces and torque during drilling KISTLER Piezoelectric dynamometer is used in this study as shown in the fig. 3.6. It has four channels and in which three measure the forces and one channel measure the torque. Here channel 2 measures the force in Z direction and channel 4 measure the torque. It shows the variation of forces in the form of graphs and Excel sheets.

Figure 3.6: Dynamometer Setup

3.5.5 Surface Roughness Measurement

Surface roughness of holes was measured from the help of Perthometer of Mitutoyo Company (Surftest SJ-400) as shown in fig. 3.7 at Thapar University Lab. The roughness is measured along the depth of drill hole. Here stylus of perthometer which travel along the depth of drill and then give the roughness result. For the roughness measurement here bone was cut with the help of hacksaw.

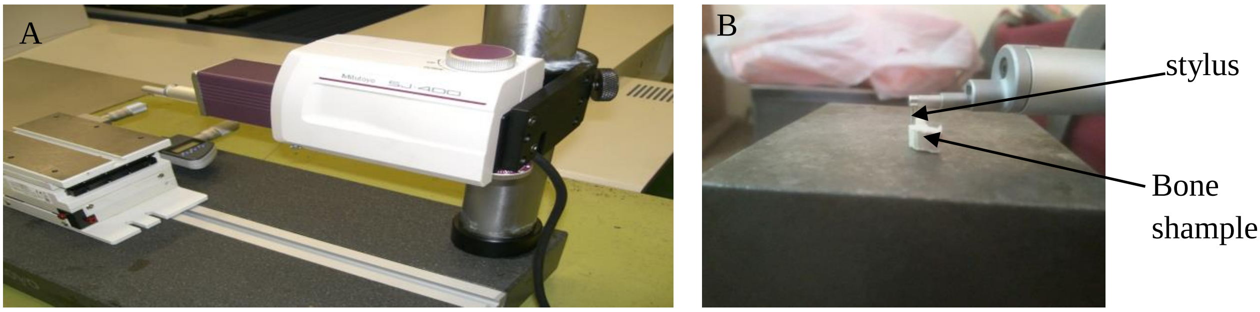


Figure 3.7: (A) Represent surface roughness measurement setup. (B) Image during surface roughness test

3.5.6 Metallurgical Characterization

After the used of different tools and variation of parameters surface roughness analysed with the help of Scanning electronic microscope photographs. So first prepare the bone for the SEM and bone is non-conductive material so makes them conductive with the help of gold plating as shown in Fig. 3.8 Energy Dispersive X-Ray Spectroscopy used for SEM and images were taken to found out the proper microstructure of holes.

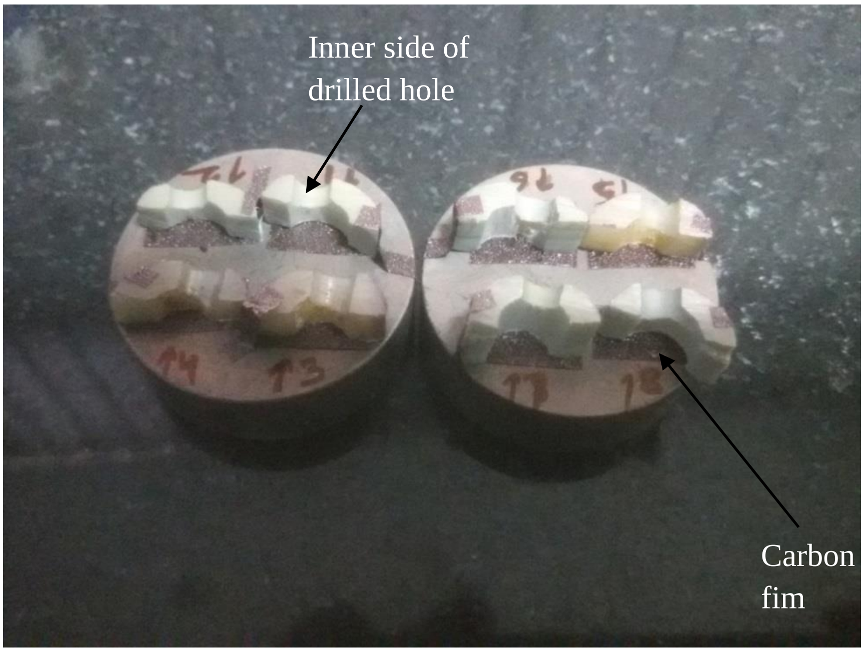


Figure 3.8 : Sample used for SEM

Chapter-4

Analytical Modelling of Heat Generation

An analytical model is required to predict the heat generation during drilling in the cortical bone. Therefore, a model is established in this present work to execute a parametric analysis of surgical drilling processes.

There are basically two reasons due to which heat is generated during bone drilling. One of them is plastic deformation and other one is friction. Plastic deformation and friction take place during drilling between bone and cutting tool. The energy used for drilling is converted in to heat that raise the temperature.

As drill bit geometry plays a vital role in generation the heat, it is advisable to discuss the basic geometry of a surgical drill bit before actual implementation of model.

4.1 Drill Bit Geometry

There are many features which a drill bit has to qualify for, like cutting face, drill diameter, drill point and helix angle {Fig 4.1 (a)}. The drill cutting face is further explained in many characteristics such as rake angle and clearance angle, whereas point angle, chisel edge and flank defines the drill points as shown in Fig 4.1 (b).

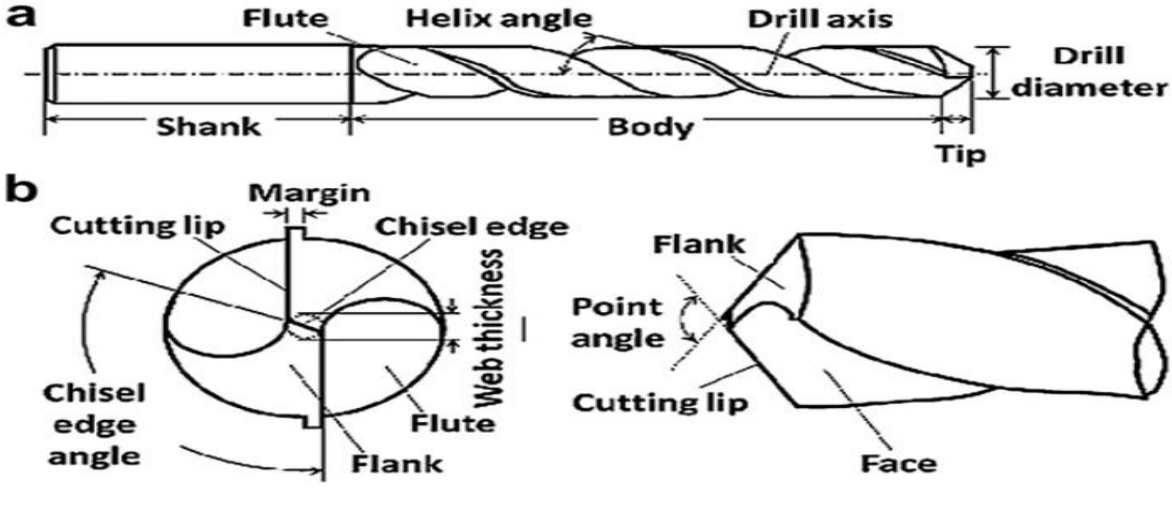


Figure 4.1: (a) Twist Drill Bit (b) Drill Bit Tip

Drill Diameter

Normal diameters in the surgical drill bits used are 2.5, 3 and 4 mm. Drill diameter directly affects the heat induced and temperature in the bone for which increase in every bit in diameter is very important. Diameter of drill should also not be reduced exponentially otherwise drill bit may get break or bend.

Flutes and Helix Angle

Flute is also an important part of the drill. Flute is needed to remove waste material from the the drilling area, if it would not be their than the cutting process would be slow. Flutes can vary in size and drills can also be constructed by no. of flutes and helix angles. Two flutes and three flute drill bit are shown in Fig 4.2

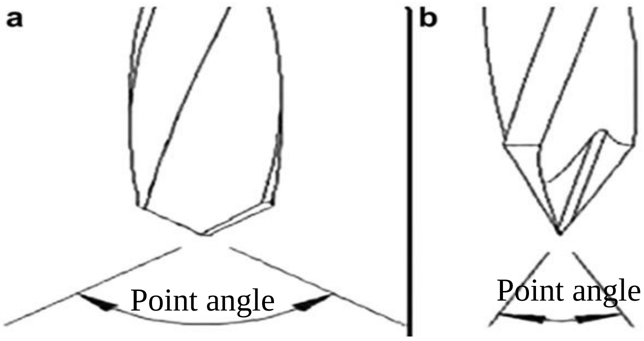


Figure 4.2: (a) Two flute (b) Three flute drill bit

Cutting Edge angles

Cutting edge angles includes:

1) Rake angle
2) Clearance angle and flank

1) **Rake angle**: The angle between plane perpendicular to the work piece and cutting edge is called rake angle. Cutting forces are influenced by the rake angle which defines the importance of it. Different studies had been conducted to identify an optimal rake angle for bone drilling. Recommended optimum angle of the rake is 20 to 30 degree, as it reduces the chips and generates low thrust force.

2) **Clearance angle and flank**: The flat section viewed from the end is flank (Fig. 4.1 (b). It represents a big surface area for friction. Clerance is the area provided for avoiding undesirable contact of the flank with the work piece. The angle helps the flank of drill to clear

the waste material during drill. The clearance provided by the heavy surface of flank ends up in high friction with work part. It increases the the frictional heat and temperature during drill.

Drill point

For efficient drilling and also for determining the amount of heat generated, two major components are included in the drill. These parts are as follows:

1) Point angle
2) Chisel edge

Point Angle: The angle formed between the projections of cutting edges the plane surface going through longitudinal axis of drill bit. It helps the drill bit to an exact point where drilling has to be performed. It provides accuracy for reducing risks to mankind during operations. Smaller point angle gives more precise point, which can easily penetrate the bone, where needed. The only issue regarding acute tip is that the low percentage of cutting lip will be included in the initial few rotations and ends in higher rates of temperature. Studies recommends 90 degrees point angle of the objects.

Chisel edge:

It is delineated as the edge at the end of the web that links the cutting edge. Length of chisel edge is identical to the web thickness and it also defines the variance between the cutting lip about the axis of revolution. Chisel edge having a direct connection with thrust force generates at the time of the exercise.

4.2 Heat Generation due to Bone Drilling

In the bone drilling process, cutting happens when stress utilized by the tool to affect the strength of the bone. Due to which some amount of heat is generated in the bone. During elastic deformation, there is no heat generation in the material because the energy is utilized in returning the material in its original shape. But in the case of plastic deformation, most of the energy is transformed in to heat.

Although, the cutting procedure in drilling is expected to be oblique which is more complex. Hence for the sake of simplicity and calculation purpose in the present model, the simple orthogonal cutting is assumed. The basic chip removal mechanism is considered as in single point cutting tool which is in agreement with other researchers.

In cutting process heat is produced in three zones as shown in fig. 4.3 that represents the cutting method at the principal cutting edges. Most of the heat caused in the primary zone occurs because of plastic deformation at the shear plane. In secondary deformation zone, heat is produced because of friction between the chips and cutting tool. In the tertiary deformation area, heat is produced by the friction amongst the flank and work-piece.

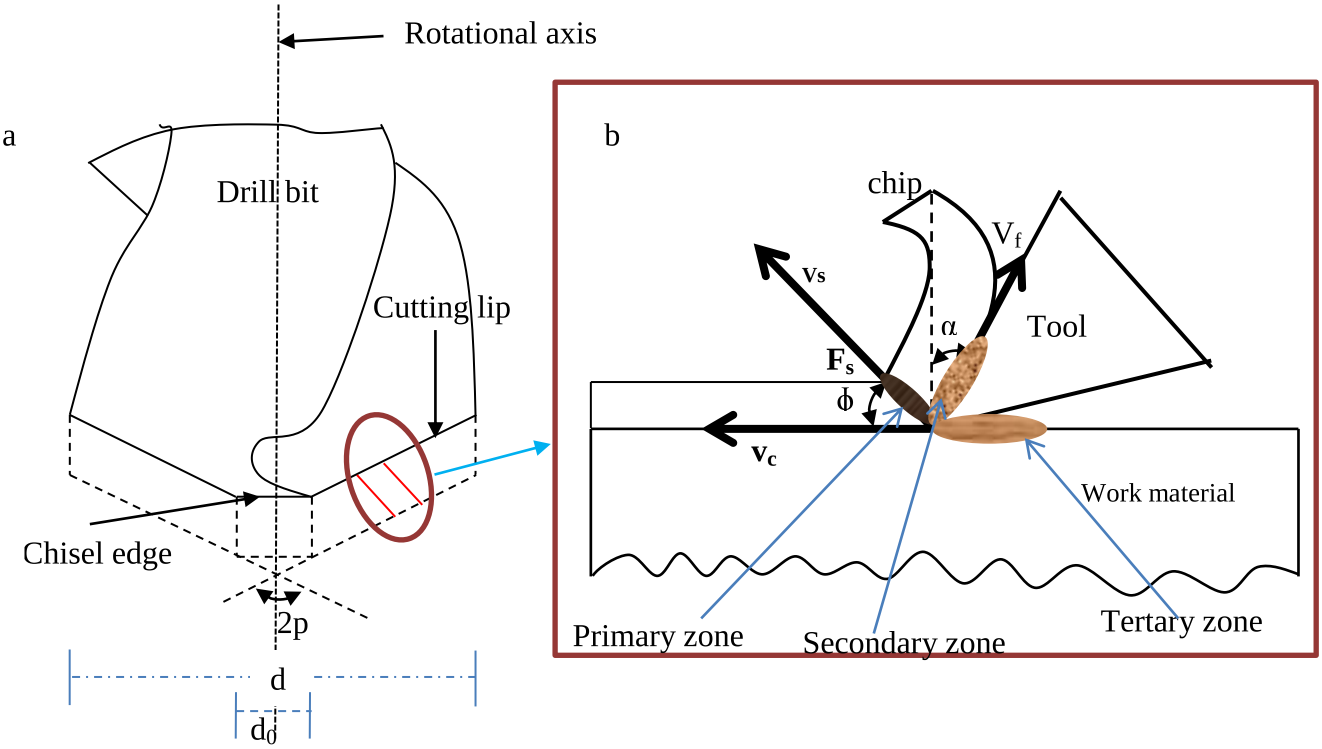


Figure 4.3: Schematic design of drilling: (a) work-piece element with cutting wedge, (b) Heat caused zones

4.2.1 Assumption and Terminology used in this Model

Assumptions

1. Perfectly sharp tool used for drilling.
2. Material is homogeneous.
3. Uncut chip thickness is constant.
4. The surface where shear is happening is a plane.
5. width of shear plane which is equal to width of cutting lip.
6. The stresses on the shear plane are uniformly distributed.

Terminology:

$\dot{Q}_1 =$ Heat produced during primary zone

$\dot{Q}_2$ = Heat produced during secondary zone

F_S = Shear force in Newton

V_S = Shear velocity in shear plane in m/s

V_c = Cutting velocity in m/s

V_f = flow velocity

ϕ = Shear angle

β = friction angle

α = rake angle

α_i = orthogonal rake angle with distance 'i' from rotational axis

d = drill diameter

d_i = drill diameter at a distance 'i' from rotational axis

θ = helix angle of drill bit

p = half point angle of drill bit

r_i = radial distance from the rotational axis of drill

N = rotational speed of spindle in rpm

τ_s = ultimate shear stress

Υ = shear strain rate

A_S = Area of shear plane

L_S = length of shear plane

W = width of shear plane which is equal to width of cutting lip

t_1 = uncut chip thickness

t_2 = chip thickness

t= time taken to complete one cycle

r_c = cutting ratio

f = feed rate (mm/min)

r and r_o = radius of drill bit and chisel edge

F_f = friction force between chip and tool in Newton

F_c = cutting force

F_t = normal thrust force

R = Resultant cutting force

4.3 Heat Generation during Primary Deformation Zone

In primary zone heat is generated due to plastic deformation and from figure 4.4 it is shown that heat caused in the primary deformation zone it is depend upon the force and velocity on the shear plane. It can be calculated using equation,

$$\dot{Q}_1 = F_S V_S \quad (1)$$

The reason for the heat generation because of plastic deformation in the bone due to tool, it means that it overcomes the ultimate shear stress.

4.3.1 Calculating Shear Velocity

From figure 4.4 shear velocity can be calculated from the help of cutting velocity and shear angle.

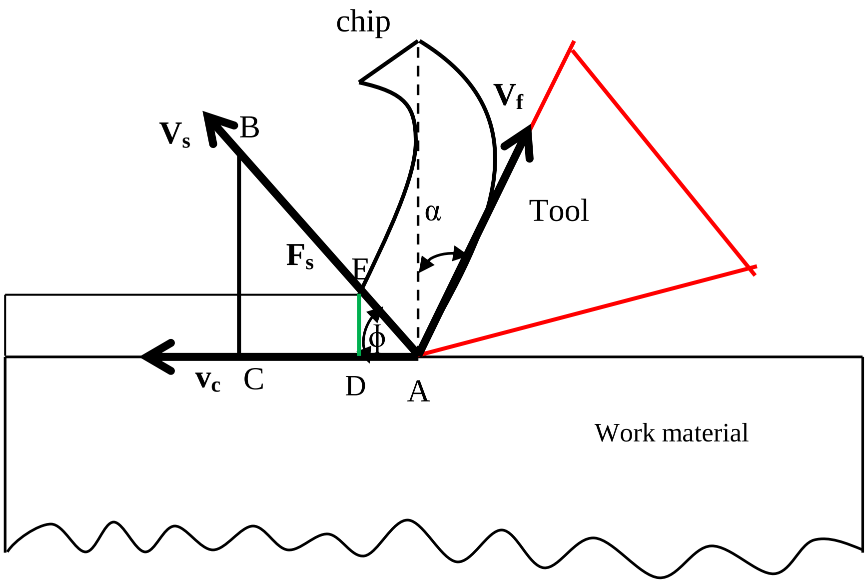


Figure 4.4: Directions of cutting and shear forces and velocities

From the help of triangle ABC shear velocity is calculated as :

$$V_S = \frac{V_C}{\cos \phi} \quad (2)$$

The shear angle calculated by the help of Ernest and Merchant Theory,

$$2\phi + \beta - \alpha = 90^0 \tag{3}$$

Friction angle β is mainly depend upon the friction coefficient. It is different for different material, from the literature study friction angle used in the model is 37^0 [37].

The rake angle 'α' varies with the cutting edges of drill bit and expression for the α_i at distance 'i' from the rotational axis given by Bhattacharyya and Ham [37] with equation 4.

$$\tan \alpha_i = \frac{\frac{d_i}{d} \tan\theta - \tan(\sin^{-1}(\frac{d_i}{d_o}) \sin p) \cos p}{\sin p} \tag{4}$$

The cutting velocity V_c also varies with respect to cutting edges and it is calculated by,

$$V_C = \frac{2\pi r_i N}{60} \tag{5}$$

Here 'r_i' is not constant it varies with cutting lip during drilling . So here average cutting velocity was calculated.

$$V_{avg} = \int_{d_o/2}^{d/2} \frac{2\pi r_i \frac{N}{60} dr_i}{\frac{1}{2}(d - d_0)} = \frac{(d + d_o)\pi N}{120} \tag{6}$$

Effect of chisel edge diameter is very small so it is neglected in this model.

4.3.2 Shear Force

It can be calculated as:

$$F_S = \tau_s A_S \tag{7}$$

4.3.2.1 Ultimate Shear Stress of Bone

The shear stress can be calculated by expression derived by Davidson and James [26].

$$\tau_s = 80\, \dot{\Upsilon}^{.06} \tag{8}$$

4.2.2.2 Area of Shear Plane

Area of shear plane is calculated as:

$$A_S = L_S \times W \tag{9}$$

Length of shear plane is calculated by the help of triangle ADE represent in figure 4.4 and also shown below in figure 4.5.

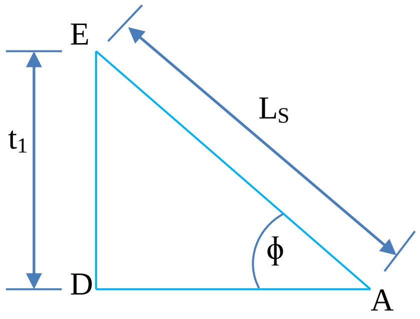


Figure 4.5: Represent the triangle for length of shear plane

$$L_S = \frac{t_1}{\sin \phi} \tag{10}$$

Uncut chip thickness was calculated with the help of rotational speed and feed rate of cutting tool. The distance travelled by tool per unit time is known as feed rate. So for half cycle assume distance covered by tool in the bone is ‘x’ as represent in the fig. 4.6.

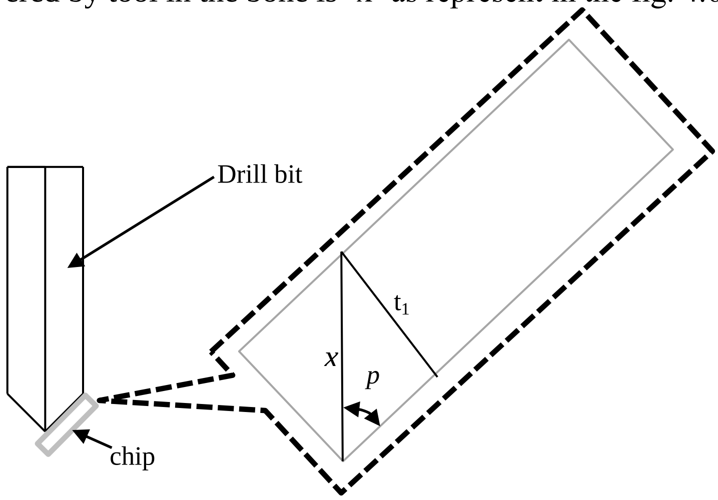


Figure 4.6: Represent the distance covered in half cycle

$$x = \frac{t_1}{\sin p} \tag{11}$$

Time taken by the tool to complete one period of cycle is given as

$$t = \frac{60}{N} \tag{12}$$

And feed rate also calculated by the help of equations 11 and 12. So formula is:

$$f = \frac{x}{t} = \frac{Nt_1}{60 \sin p} \tag{13}$$

Uncut chip thickness is calculated as:

$$t_1 = \frac{60f \sin p}{N} \tag{14}$$

Put equation no. 14 in equation no. 10 to find out the value of 'L_S' length of shear plane.

$$L_S = \frac{60f \sin p}{N \sin \phi} \tag{15}$$

For calculating the shear plane area width of cutting edge also needed so it is calculated as:

$$W = \frac{r - r_o}{\sin p} \tag{16}$$

So area of shear plane is calculated by putting the equation 15 and 16 in equation 9.

$$A_S = \frac{60f(r - r_o)}{N \sin \phi} \tag{17}$$

After calculating the values of shear force, shear area and shear velocity from the formulae then heat in primary zone can be find out.

4.4 Heat Generated in Secondary Zone

In secondary zone heat is produced due to the friction between chips and cutting tool during drilling. It is calculating from the equation (18).

$$\dot{Q}_2 = F_f V_f r_c \tag{18}$$

From the help of figure 4.7 F_f can be calculated from the help of Merchant circle :

$$F_f = F_c \sin \alpha + F_t \cos \alpha \tag{19}$$

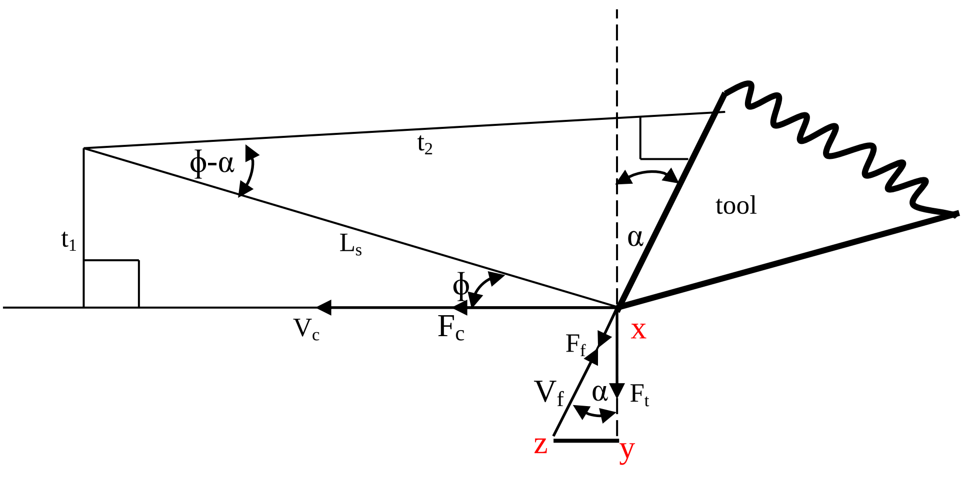


Figure 4.7: Directions of velocities and forces

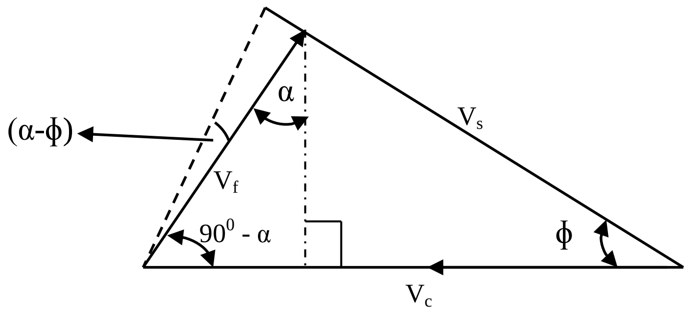


Figure 4.8 Velocity diagram

From the help of triangle XYZ as shown in figure 4.7, V_f is calculated as:

$$V_f = \frac{V_{avg}}{\sin\alpha} \qquad (20)$$

Where V_{avg} is the average cutting velocity as given in equation (6) so V_f is:

$$V_f = \frac{(d + d_o)\pi N}{120\sin\alpha} \qquad (21)$$

Cutting chip thickness 'r_c' is the ratio of uncut chip thickness and chip thickness of the work –piece. It is calculated as:

$$r_c = \frac{t_1}{t_2} = \frac{L_s\sin\phi}{L_s\cos(\phi-\alpha)} = \frac{\sin\phi}{\cos(\phi-\alpha)} \qquad (22)$$

4.4.1 Calculating Cutting Force and Thrust Force

From the help of Earest and Merchant model cutting and thrust force is calculated.

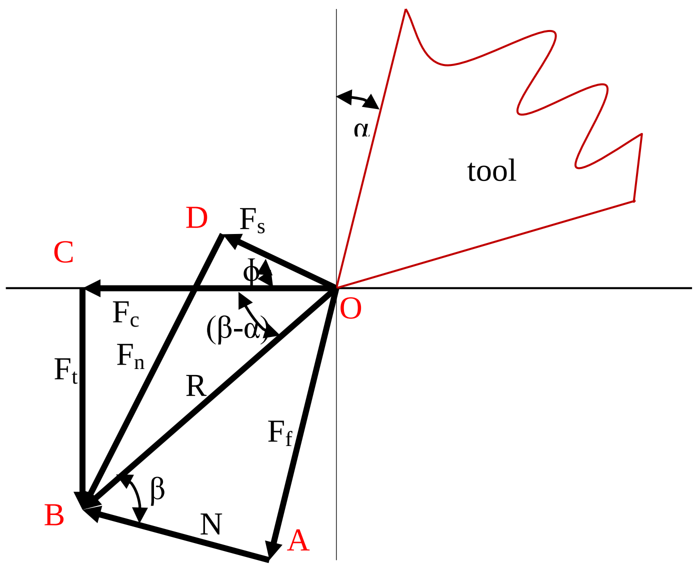


Figure 4.9: Merchant's force diagram

In this theory it is assumed that cutting edge is straight, sharp and shear stress is constant.

Shear force is calculated according to theory of machining as:

$$F_s = \frac{\tau_s A_s}{\sin \phi} \tag{23}$$

Cutting force (F_c) is calculated from triangle OBC as:

$$F_c = R \cos(\beta - \alpha) \tag{24}$$

Shear force (F_s) also calculated from triangle OBD as:

$$F_s = R \cos(\phi + \beta - \alpha) \tag{25}$$

By dividing the equation (24) and (25), then equation obtained as:

$$\frac{F_c}{F_s} = \frac{\cos(\beta - \alpha)}{\cos(\phi + \beta - \alpha)} \tag{26}$$

Use equation (23) in equation (26), new equation obtained as:

$$F_c = \frac{\tau_s A_s \cos(\beta - \alpha)}{\sin \phi \cos(\phi + \beta - \alpha)} \tag{27}$$

thrust force F_t is calculated from triangle OBC as:

$$F_t = R \sin(\beta - \alpha) \tag{28}$$

Heat produced in the secondary zone is calculated by the equation (22, 21, 19) in equation (18).

$$\dot{Q}_2 = \frac{\pi N (F_c \sin \alpha + \dot{F}_t \cos \alpha)(d + d_o) sın\phi}{120 \sin \alpha \cos(\phi - \alpha)} \tag{29}$$

4.5 Heat Generated in Tertiary Zone

In the current model, the heat is generated in third zone was neglected because perfectly sharp tool is used for drilling process. The assumption that the use of sharp tools is recommended by literature study and found that less thermal damage occurs due to the use of new tools in tertiary zone.

4.6 Total Heat Generated during Bone Drilling

Hence total heat generated in the process is the summation of heat produced in the primary zone and secondary zone. It is shown as:

$$Q = \dot{Q}_1 + \dot{Q}_2 \tag{30}$$

Chapter-5

Result, Analysis and Discussion

This chapter contributes the experimental results analysis and discussion of the experimentations. In this chapter, the outcomes of the analytical model, experimental tests of the cutting temperature, forces and surface roughness with the use of different tools are discussed and then submitted in order to receive the conclusions. In this study 'Minitab statistical software' is used for analysis purpose.

5.1 Results

The values gained after every experiment for several output parameters have been registered in several tables, i.e. Table 5.1 (temperature), Table 5.2 (forces) & Table 5.3 (R_a).

Table 5.1: Result table for Temperature

Exp. No.	**Speed (RPM)**	**Feed (mm/min)**	**Type of Tool**	**Temp. 1**	**Temp. 2**	**Temp. 3**	**Average Temp. (^{0}C)**	**SN Ratio for Temp.**
1	600	10	Drill	37	39	38	38	-31.5957
2	600	20	Drill	38	40	42	40	-32.0412
3	600	30	Abrasive Coated	55	50	51	52	-34.3201
4	600	40	Abrasive Coated	59	61	66	62	-35.8478
5	1200	10	Drill	38	40	39	39	-31.8213
6	1200	20	Drill	40	41	45	42	-32.4650
7	1200	30	Abrasive Coated	54	55	59	56	-34.9638
8	1200	40	Abrasive Coated	60	62	61	61	-35.7066
9	1800	10	Abrasive Coated	53	45	52	50	-33.9794

10	1800	20	Abrasive Coated	56	51	55	54	-34.6479
11	1800	30	Drill	49	50	57	52	-34.3201
12	1800	40	Drill	58	62	57	59	-35.4170
13	2400	10	Abrasive Coated	47	48	52	49	-33.8039
14	2400	20	Abrasive Coated	50	51	58	53	-34.4855
15	2400	30	Drill	55	53	55.5	54.5	-34.7279
16	2400	40	Drill	61	64	61	62	-35.8478

Table 5.2: Result table for Forces

Exp. No.	**Speed (RPM)**	**Feed (mm/min)**	**Type of Tool**	**Force 1**	**Force 2**	**Force 3**	**Average Force (N)**	**SN Ratio for Force**
1	600	10	Drill	1.932	1.489	1.5959	1.6723	-4.4663
2	600	20	Drill	2.4	2.384	2.41	2.3980	-7.5970
3	600	30	Abrasive Coated	28.485	28.582	28.4432	28.5034	-29.0979
4	600	40	Abrasive Coated	26.273	26.251	26.2845	26.2695	-28.3890
5	1200	10	Drill	1.05	1.003	0.95	1.0010	-0.0085
6	1200	20	Drill	1.6564	1.6098	1.6226	1.6296	-4.2416
7	1200	30	Abrasive Coated	12.258	12.834	12.1425	12.4115	-21.8765
8	1200	40	Abrasive	16.104	15.958	16.0214	16.0278	-24.0975

			Coated					
9	1800	10	Abrasive Coated	4.435	4.2304	3.9346	4.2000	-12.4650
10	1800	20	Abrasive Coated	8.8825	8.89	8.5224	8.8983	-18.9861
11	1800	30	Drill	1.597	1.6	1.6096	1.6022	-4.0943
12	1800	40	Drill	1.95	2.15	1.8784	1.9928	-5.9893
13	2400	10	Abrasive Coated	4.501	4.3256	4.3935	4.4067	-12.8823
14	2400	20	Abrasive Coated	4.102	3.962	4.1217	4.0619	-12.1746
15	2400	30	Drill	1.286	1.294	1.29	1.2900	-2.2118
16	2400	40	Drill	1.498	1.519	1.531	1.5160	-3.6140

Table 5.3: Result table for Surface Roughness (Ra)

Exp. No.	**Speed (RPM)**	**Feed (mm/min)**	**Type of Tool**	**Ra 1**	**Ra 2**	**Ra 3**	**Average Ra (μm)**	**SN Ratio for Ra**
1	600	10	Drill	0.16	0.14	0.15	0.15	16.4782
2	600	20	Drill	0.26	0.29	0.29	0.28	11.0568
3	600	30	Abrasive Coated	0.81	0.77	0.76	0.78	2.1581
4	600	40	Abrasive Coated	0.91	0.95	0.90	0.92	0.7242
5	1200	10	Drill	0.29	0.30	0.31	0.3	10.4576
6	1200	20	Drill	0.56	0.61	0.60	0.59	4.5830
7	1200	30	Abrasive Coated	1.21	1.16	1.17	1.18	-1.4376
8	1200	40	Abrasive	1.36	1.33	1.27	1.32	-2.4115

			Coated					
9	1800	10	Abrasive Coated	0.48	0.38	0.40	0.42	7.5350
10	1800	20	Abrasive Coated	0.95	0.86	0.83	0.88	1.1103
11	1800	30	Drill	0.87	0.91	0.92	0.90	0.9151
12	1800	40	Drill	1.01	1.04	1.10	1.05	-0.4238
13	2400	10	Abrasive Coated	0.82	0.76	0.82	0.8	1.9382
14	2400	20	Abrasive Coated	1.14	1.15	1.19	1.16	-1.289
15	2400	30	Drill	1.36	1.31	1.29	1.32	-2.4115
16	2400	40	Drill	1.70	1.69	1.71	1.70	-4.6090

5.2 Effect of Process Parameter on Temperature

It is found that temperature distribution during drilling is depend upon the input variables. Experimental results are represent in the table 5.1. The average values of S/N ratio at different levels are plotted in Figure 5.1. The quality characteristic is ‘smaller is better’ type.

It is observed from the graph that temperature increase when spindle speed increase. Temperature value is more when feed rate is 20 mm/min instead of 10 mm/min. But it rapidly increase when feed rate is more than 20 mm/min beceause high feed rate imparts high pressure on the tool. Abrasive coated tool has more influenced temperature rather than drill bit. Using abrasive coated tool temperature value also increase beceause there is no chip flow occurred. Optimum range for minimum temperature is using low spindle speed and feed rate respectively.

Table 5.4 shows the response table of S\N ratio for temperature. From this table, it is observed that how the input parameter affect the temperature distribution. Here according to rank, the effect of variables on temperature are feed rate, speed and tool type. It means feed

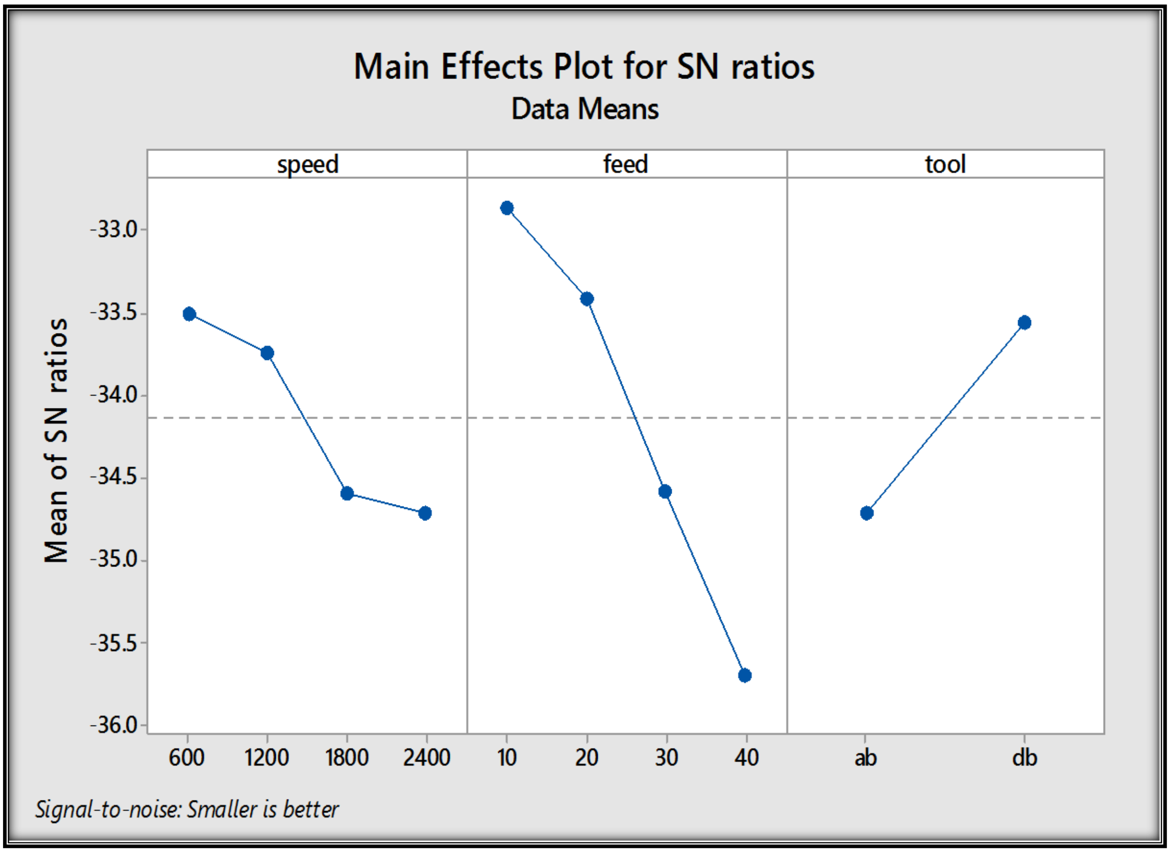


Figure 5.1: SN Ratio Graph for Temperature

rate is the major factor and tool type is the minor factor that affect the temperature distribution.

Table 5.4: Response Table for SN Ratio of Temperature

Level	**Speed (rpm)**	**Feed**	**Tool**
1	-33.51	-32.86	-34.72
2	-33.75	-33.41	-33.56
3	-34.59	-34.58	-
4	-34.72	-35.70	-
Delta	1.21	2.85	1.16
Rank	2	1	3

Table 5.5, represent the all the significant variables and their percent contribution on temperature in ANOVA for 95% confidence level. It is observed that feed 65.45%, speed

14.87% and type of tool 18.306% of contribution on temperature distribution. The analysis is correct beceause p value is very small. It also represent in pie diagram (fig. 5.2).

Table 5.5: ANOVA for S/N Ratio of Temperature

Source	**Seq SS**	**D.O.F**	**Adj SS**	**Adj MS**	**F**	**P**	**% contribution**
Speed	4.3848	3	4.3848	1.46161	29.03	0.000	14.87
Feed	19.3015	3	19.3015	6.43383	127.77	0.000	65.4545
Type of Tool	5.3979	1	5.3979	5.39788	107.20	0.000	18.306
Residual Error	0.4028	8	0.4028	0.05035	_		1.1366
Total	29.4870	15	29.4870				

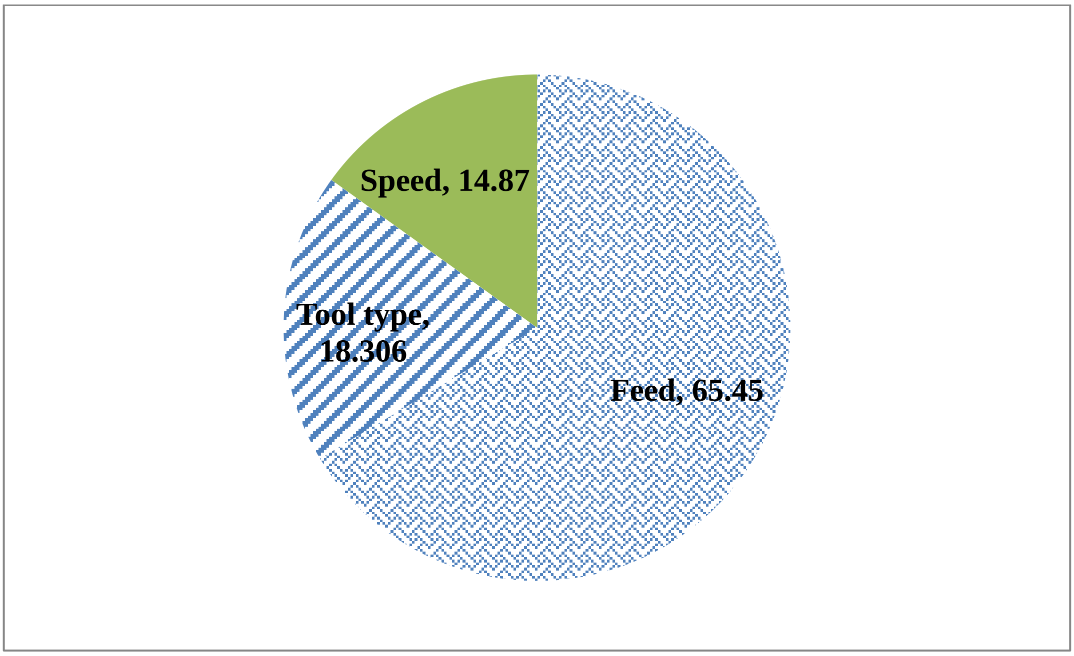


Figure 5.2: Represent input variable percent contribution

5.3 Effect of Process Parameter on Force

For better results of temperature and forces depth of cut was assumed 9 mm in this study. Due to which channel 2 of some graph represent two peaks. First peak when material is removed of upper part of bone and second peak represent the force that removed the material of bone after the hollow part of bone.

Force variation during drillingshown in figure 5.3. In which graph is divided in to following section like when tool touch workpiece then tool at center and when tool drill hole.

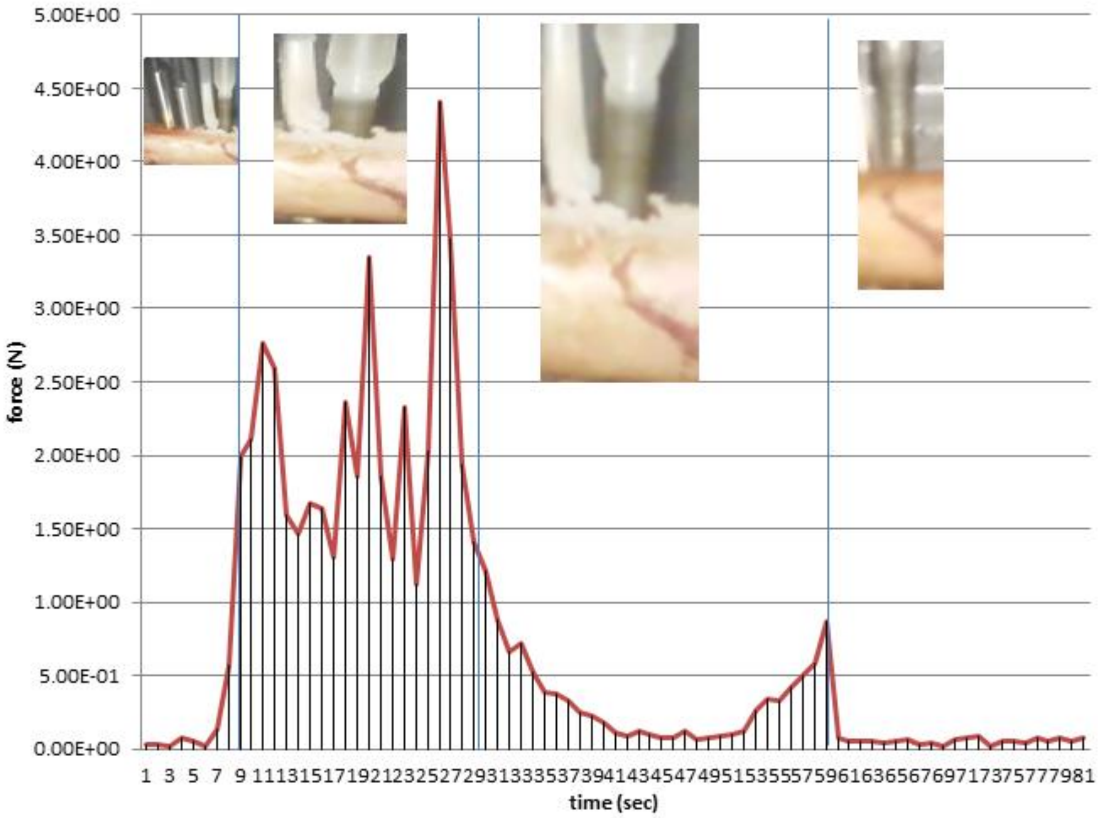


Figure 5.3 Force variation during experiment

It is observed that thrust force distribution during drilling is depend upon the input variables. Experimental results are represent in the table 5.2. The average values of and S/N ratio at different levels are plotted in Figure 5.4. The quality characteristic is 'smaller is better' type. It is observed from the graph that force decrease when spindle speed increase. Force value is more when feed rate is 20 mm/min instead of 10 mm/min. But it rapidly increase when feed rate is more than 20 mm/min beceause high feed rate imparts high pressure on the tool and that induced stress on the work-piece. Abrasive coated tool has more influenced forces rather than drill bit. Using abrasive coated tool force value also increase beceause there is no chip flow occurred and tool tip is flat. Optimum range for minimum force is using high spindle speed and low feed rate respectively.

Table 5.6 shows the response table of S\N ratio for force. From this table, it is observed that how the input parameter affect the forces. Here according to rank, the effect of variables on force are tool type, speed and feed rate. It means tool type is the major factor and feed rate is the minor factor that affect the forces.

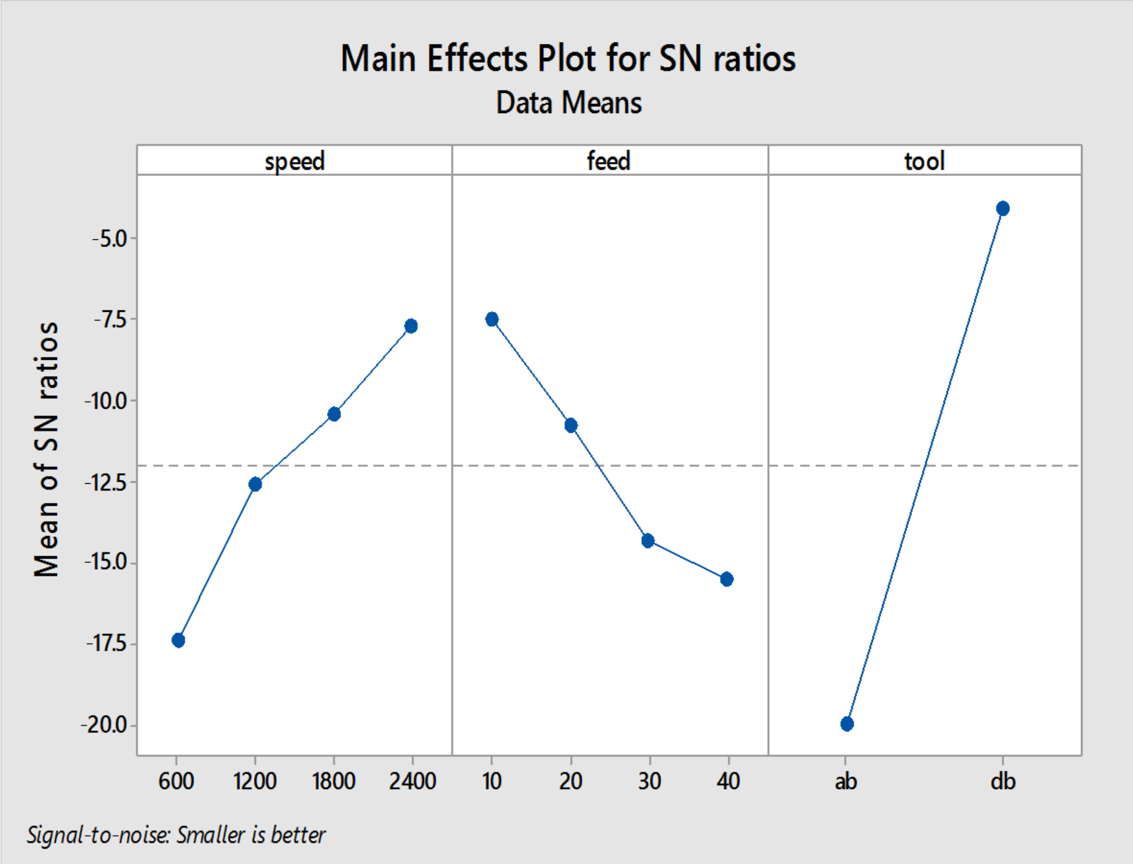


Figure 5.4: SN Ratio Graph for Force

Table 5.7, represent the all the significant variables and their percent contribution on temperature in ANOVA for 95% confidence level. It is observed that feed 11.43%, speed 14.364% and type of tool 72.875% of contribution on force distribution.

Table 5.6: Response Table for SN Ratio of Force

Level	Speed (rpm)	Feed	Tool
1	-17.388	-7.456	-19.996
2	-12.556	-10.750	-4.028
3	-10.384	-14.320	-
4	-7.721	-15.522	-
Delta	9.667	8.067	15.968
Rank	2	3	1

The analysis is correct beceause p value is very small. It also represent in pie diagram (fig. 5.5). The variation 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 for S\N ratio shows that speed (F 28.89 value), feed (F 23 value), type of tool (F 72.845 value) are the factors that significantly affect force.

Table 5.7: ANOVA for S/N Ratio of Force

Source	**Seq SS**	**D.O.F**	**Adj SS**	**Adj MS**	**F**	**P**	**% contribution**
Speed	201.04	3	201.04	67.01	28.89	0.000	14.364
Feed	160.02	3	160.02	53.34	23	0.000	11.433
Type of Tool	1019.94	1	1019.94	1019.94	439.74	0.000	72.875
Residual Error	18.56	8	18.56	2.32			1.326
Total	1399.56	15					

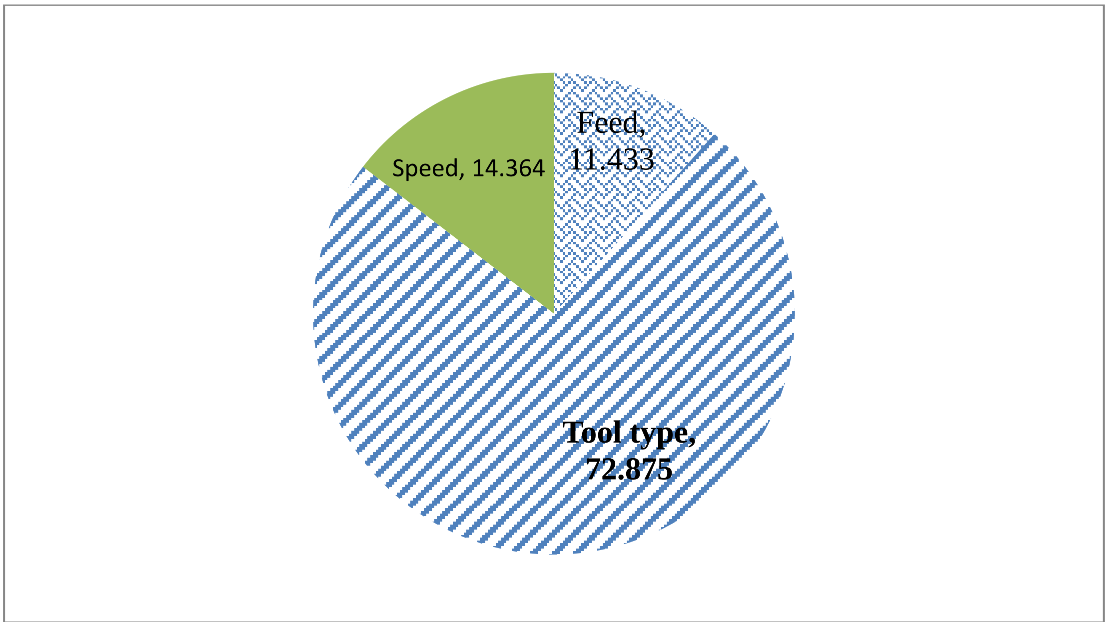


Figure 5.5: Represent input variable percent contribution for force

5.4 Effect of Process Parameter on Surface roughness

It is observed that surface roughness during drilling is depend upon the input variables. Experimental results are represent in the table 5.3. The average values of and S/N ratio at different levels are plotted in Figure 5.6. The quality characteristic is ‘smaller is better’ type. It is observed from the graph that surface roughness increase when spindle speed increase. Surface roughness value is rapidly increase when feed rate increase from 10 mm\min beceause high feed rate imparts high pressure on the tool and that induced stress on the work-piece. Abrasive coated tool has more influenced the surface roughness rather than drill bit. Using abrasive coated tool surface roughness value also increase beceause there is no chip flow occurred and it mainly affect the edges of drilled hole beceause of flat tip. Optimum range for minimum surface is using low spindle speed and low feed rate respectively.

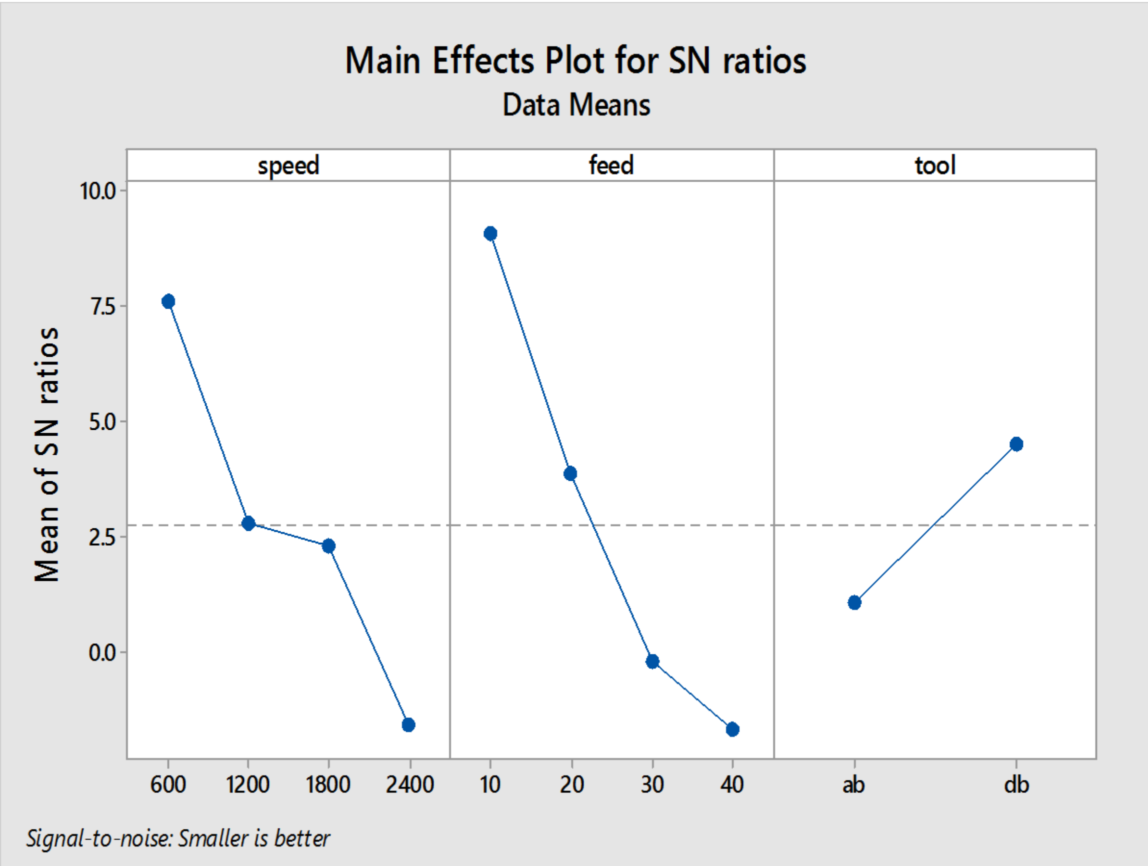


Figure 5.6: SN Ratio Graph for Surface Roughness (Ra)

Table 5.8 give the response table result of S\N ratio for surface roughness. From this table, it is observed that how the input parameter affect the surface roughness. Hence according to rank, the effect of variables on force are feed rate, speed and tool type. It means feed rate is the major factor and type of tool is the minor factor that affect the surface roughness.

Table 5.9, represent the all the significant variables and their percent contribution on temperature in ANOVA for 95% confidence level. It is observed that feed 55.283%, speed 33.72% and type of tool 9.429% of contribution on surface roughness. It also represent in pie diagram (fig. 5.7). The variation data for each factor and their interactions were F-tested to find significance of each.

Table 5.8: Response Table for SN Ratio (Ra)

Level	Speed (rpm)	Feed	Tool
1	7.6043	9.1022	1.0410
2	2.7979	3.8652	4.5058
3	2.2842	-0.1940	-
4	-1.5929	-1.6800	-
Delta	9.1972	10.7822	3.4649
Rank	2	1	3

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 for S\N ratio shows that speed (F 33.732 value), feed (F 55.283 value), type of tool (F 9.49 value) are the factors that significantly affect surface roughness.

Table 5.9: ANOVA for S/N Ratio of Surface Roughness (Ra)

Source	Seq SS	D.O.F	Adj SS	Adj MS	F	P	% contribution
Speed	170.568	3	170.568	56.8561	60.47	0.000	33.732
Feed	279.538	3	279.538	93.1792	99.10	0.000	55.283
Type of Tool	48.021	1	48.021	48.0208	51.07	0.000	9.49
Residual Error	7.522	8	7.522	0.9403			1.487
Total	505.649	15					

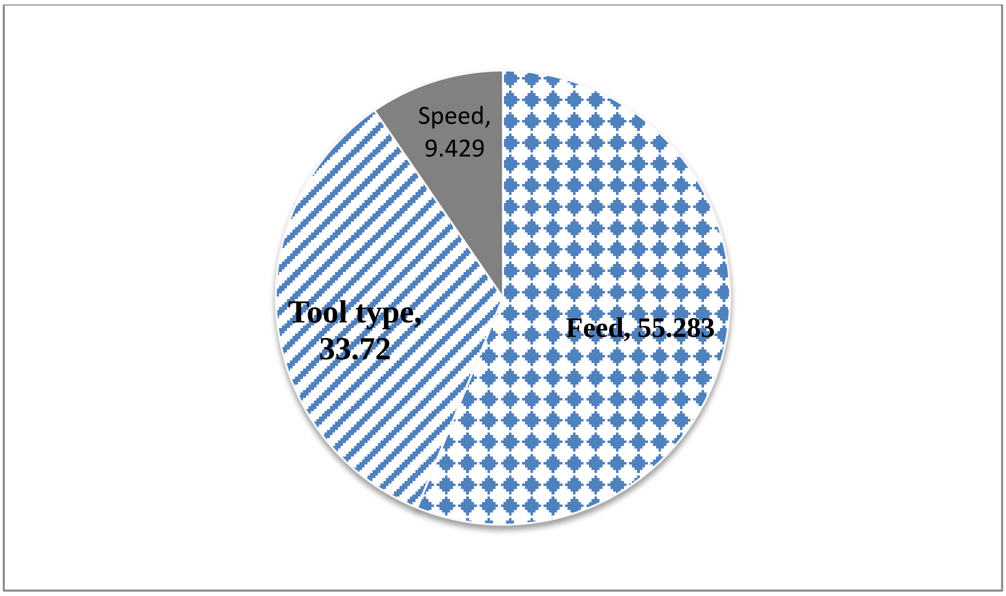


Figure 5.7: Represent input variable percent contribution for force

5.5 Result of Analytical Model

Table 5.10 shows the result of heat generation and thrust force that found with the help of analytical model and figure 5.8 shows the relation of heat generation.

Sample Calculation

Here values are calculated for experiment 1 as a sample.

Constant values:

Diameter of drill bit (d) = 0.004 m

Feed rate for exp 1 = 10 mm\min = 0.1666 mm\min

Spindle speed = 600 RPM

Shear strain rate from literature = 0.0004 s^{-1}

Friction angle from literature = 37^0

So first calculate shear angle using equation (3). Here rake angle taken 25^0 for a point.

$2\phi = 90^0 + 25^0 - 37^0$

$\phi = 39^0$

Now, calculate the average cutting velocity using equation (6). Here chisel edge diameter neglected due to very small as compared to drill bit diameter.

V_{avg} = (3.14*0.004*600)/120

V_{avg} = 0.0628 m/min

Put this value in equation (2) to calculate shear velocity.

$V_s = 0.0628/\cos(39^0)$

V_s = 0.0808 m\min

Ultimate shear stress for cortical bone is calculated using equation (8). That is considered constant for this study 50.02 Mpa.

Area of shear plane is calculated using equation (17).

$A_s = (60*0.1666*2)/(600*\sin(39^0))$

$A_s = 0.053763\ mm^2$

Put the value of shear area and ultimate shear stress in equation (7) to calculate shear force.

F_s = 0.053763*50.02

F_s= 2.6892N

Put value of shear force and shear velocity in equation (1) to calculate primary zone heat.

$\dot{Q_1}$ = 2.6892*0.0808

$\dot{Q_1}$ = 0.2172894 W

Now calculation for thrust force and heat for secondary zone.

Shear force in secondary zone is calculated using equation (23).

F_s = (50.02*0.053763)/sin(39)

F_s = 4.33 N

Now, calculate the resultant force using equation (25).

$R = 4.33/\cos(39^0+37^0-25)$

R= 4.33/0.6293

R= 6.895 N

Now, calculate the value cutting force using equation (24).

$F_c = 6.895*\cos(37^0-25^0)$

$F_c = 6.744$ N

Calculate the thrust force using equation (28).

$F_t = 6.895*\sin(37^0-25^0)$

$F_t = 1.42744$ N

Put the values of thrust force, cutting force and drill bit diameter in equation (29).

$\dot{Q}_2 =$ $(3.14*600(6.744*\sin(25^0) + 1.42744*\cos(25^0))*0.004*\sin(39))/(120*\sin(25^0)*\cos(39^0-25^0)$

$\dot{Q}_2 = 0.391619$ W

All the experiments value are calculated by above process similarly.

Table 5.10 Heat generation and thrust force result of cortical bone with the help of analytical model

Experiment	Primary Heat (W)	Secondary heat (W)	Thrust force (N)
1	0.217314	0.39162	1.427443
2	0.43471	0.783256	2.798384
3	0.581714	10.52058	13.49428
4	0.775614	14.02744	17.97352
5	0.16885	0.394422	0.713721
6	0.337769	0.788844	1.399192
7	0.581714	3.339414	6.747139

8	0.775619	4.452551	8.986759
9	0.1949888	1.113138	1.514011
10	0.387809	2.226276	2.998728
11	0.506654	1.675402	1.45446
12	0.675539	2.23387	1.903257
13	0.194988	1.111752	1.35508
14	0.387809	2.223504	2.49046
15	0.506654	1.629173	1.090845
16	0.675539	2.172231	1.427443

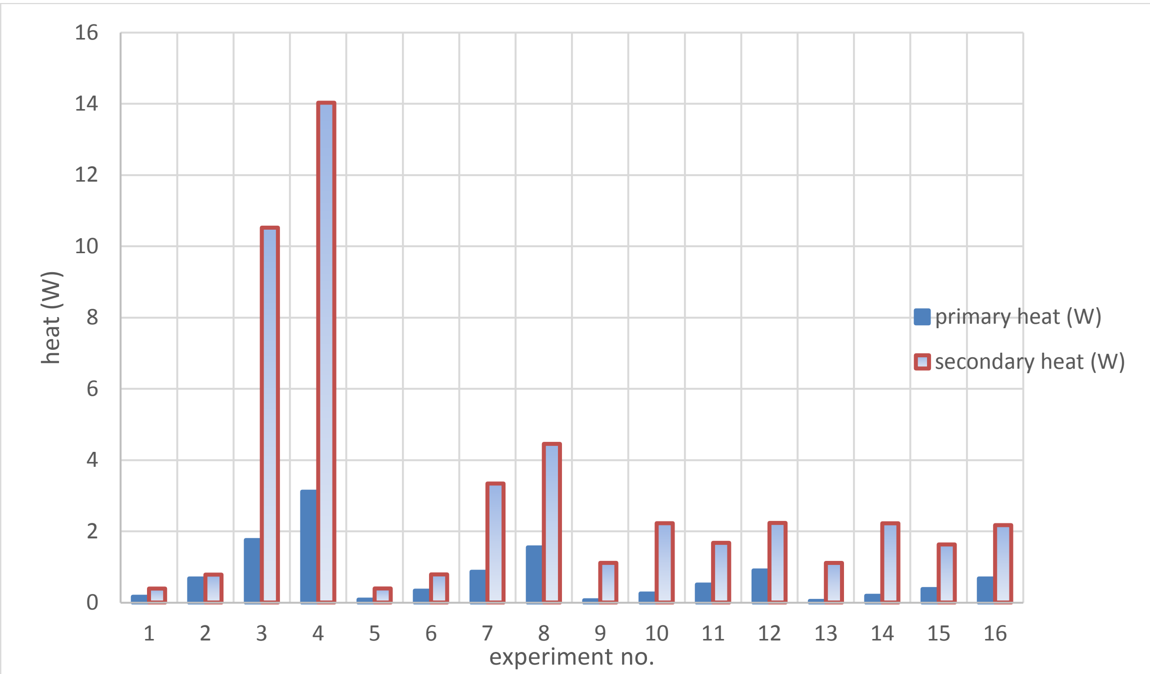


Figure 5.8 Represent primary and secondary zone heat

5.6 Heat Calculation during Experimentation

During bone drilling heat is distributed\transfer by heat transfer modes like conduction , convection and many more. But in this model only heat occur due to only conduction is considerd. So here Fourier's law of heat conduction is used and it is shown below.

$$\dot{Q_{exp}} = -KA\frac{dt}{dx} \quad \text{(a)}$$

Where,

$\dot{Q_{exp}}$ = experimental heat flow (W)

A = surface area perpendicular to heat flow direction (m^2)

dt = temperature difference (^oC or K)

dx= thickness of body in the direction of heat flow (m)

K= thermal conductivity

Sample Calculation

Here values are calculated for experiment 1 as a sample. For calculation a systematic diagram of conduction mode as shown in figure 5.9.

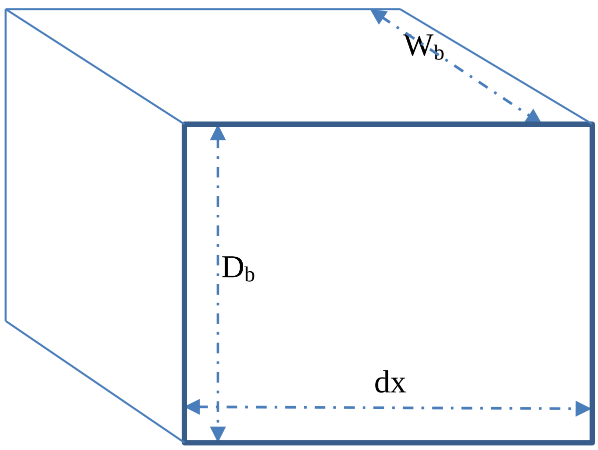


Figure 5.9 : Model for Conduction Mode

Where,

D_b and W_b = depth and width of bone

Depth and width of bone is assumed constant for this study. Average value is taken that is 14.4 mm and 10 mm respectively. Thermocouple is placed at distance of 2 mm, so dx is also 2 mm. Thermal conductivity is also assumed constant, its value is taken from the literature review i.e 0.32 W/m^2 [7].

dt = 1 K

so put all the values in equation ‘a’.

$$\dot{Q_{exp}} = \frac{0.32 * .0144 * 0.010 * 1}{.002}$$

$$\dot{Q_{exp}} = 0.2304\ W$$

All the experimental value is calculated similarly as above process.

In this model surface area and thickness of bone is considered constant and represented result for heat generation is shown in Table 5.11.

Table 5.11: Heat values during experimentation

Experiment no.	Change in temperature (K)	Heat (W)
1	1	0.02304
2	3	0.06912
3	15	0.3456
4	25	0.576
5	2	0.04608
6	5	0.1152
7	19	0.43776
8	24	0.55296
9	13	0.29952
10	17	0.39168
11	15	0.3456
12	22	0.50688
13	12	0.27648

14	16	0.36864
15	17.5	0.4032
16	25	0.5760

Comparison of graph for the analytical and experimental results as shownin figure 5.10, 5.11 and 5.12. From the figure 5.10, 5.11 and 5.12 it is observed that trend of analytical result with experimental results approximately same. There is some deviation in the results because of the assumptions in the model as described earlier. In the figure 5.10 and 5.11 heat observed by the experiment is less as compared to analytical model because thermocouple is placed at some distance from the hole locations.

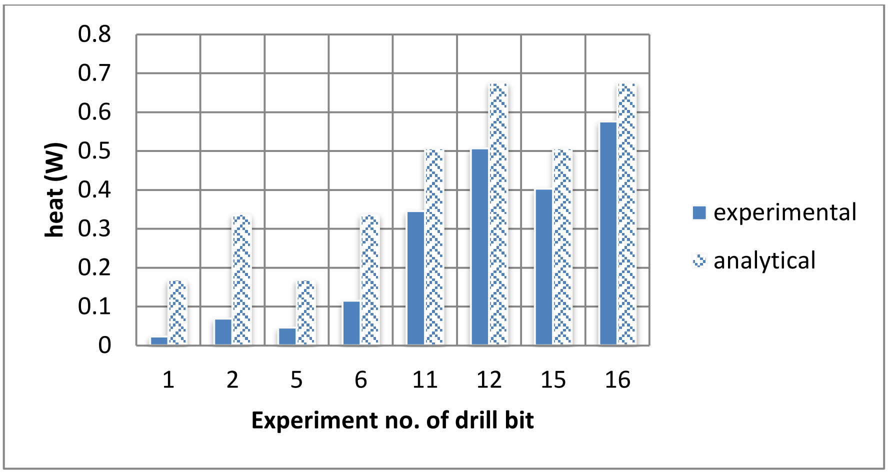


Figure 5.10 Compare the analytical and experimental result using Drill bit

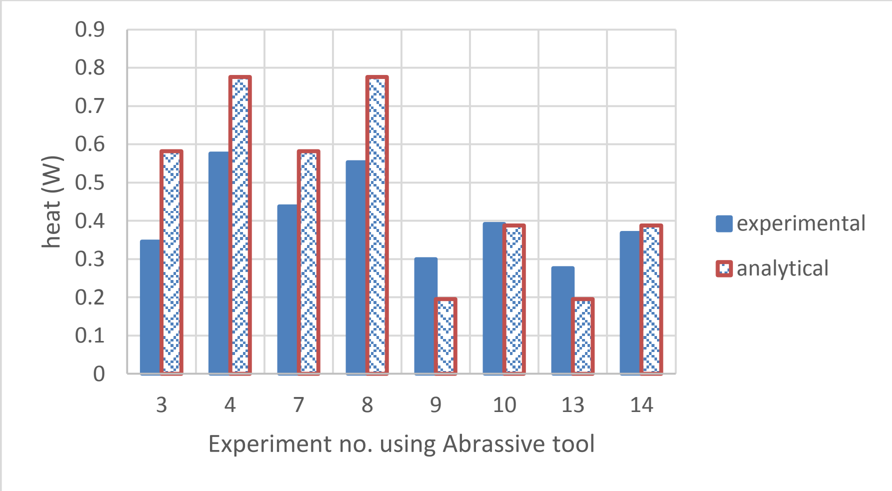
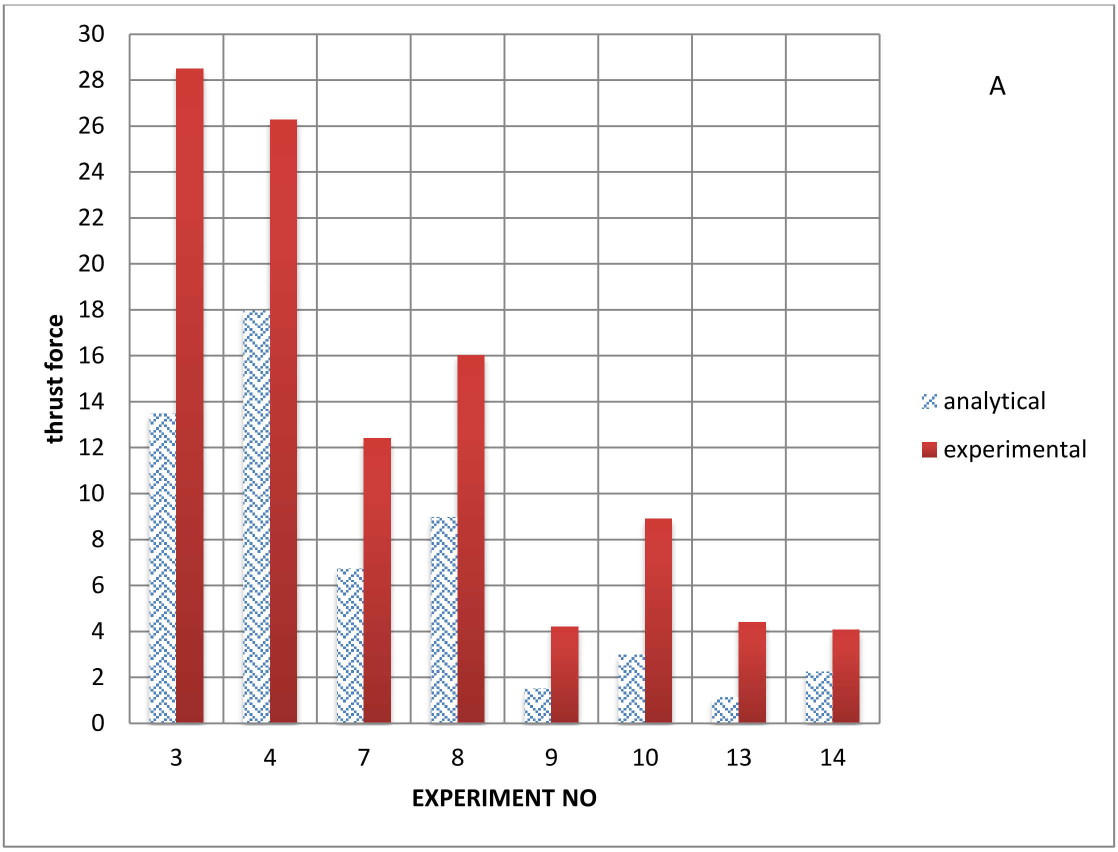


Figure 5.11 Compare the analytical and experimental result of Heat using Abrasive Bit



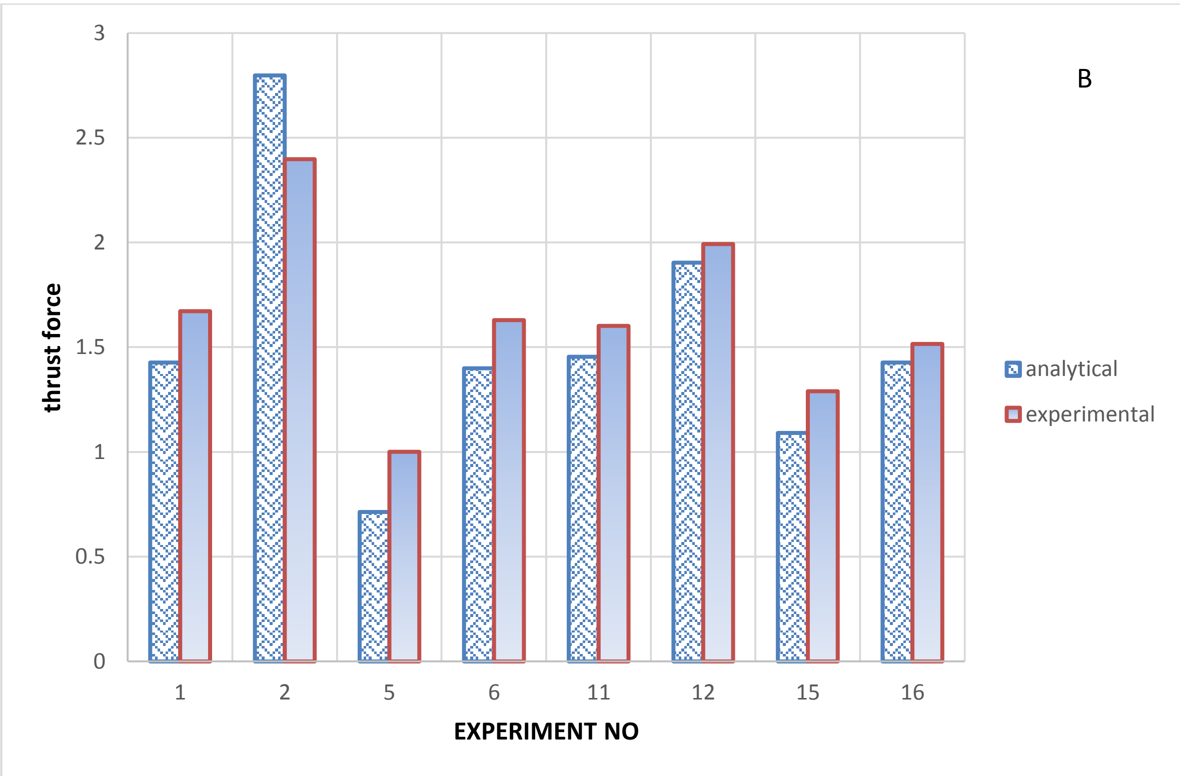


Figure 5.12: Comparison result for (A) thrust force using Abrasive coated tool, (B) thrust for using drill bit

5.7 Surface Characterization

SEM images describe the surface topology with the help Energy Dispersive X-Ray Spectroscopy. The samples are used for the SEM is chossen according to their surface roughness value. Here SEM images shows the surface roughness\ quality of drilled hole using twist drill and abrasive coated tool at various magnification as shown in figures below.

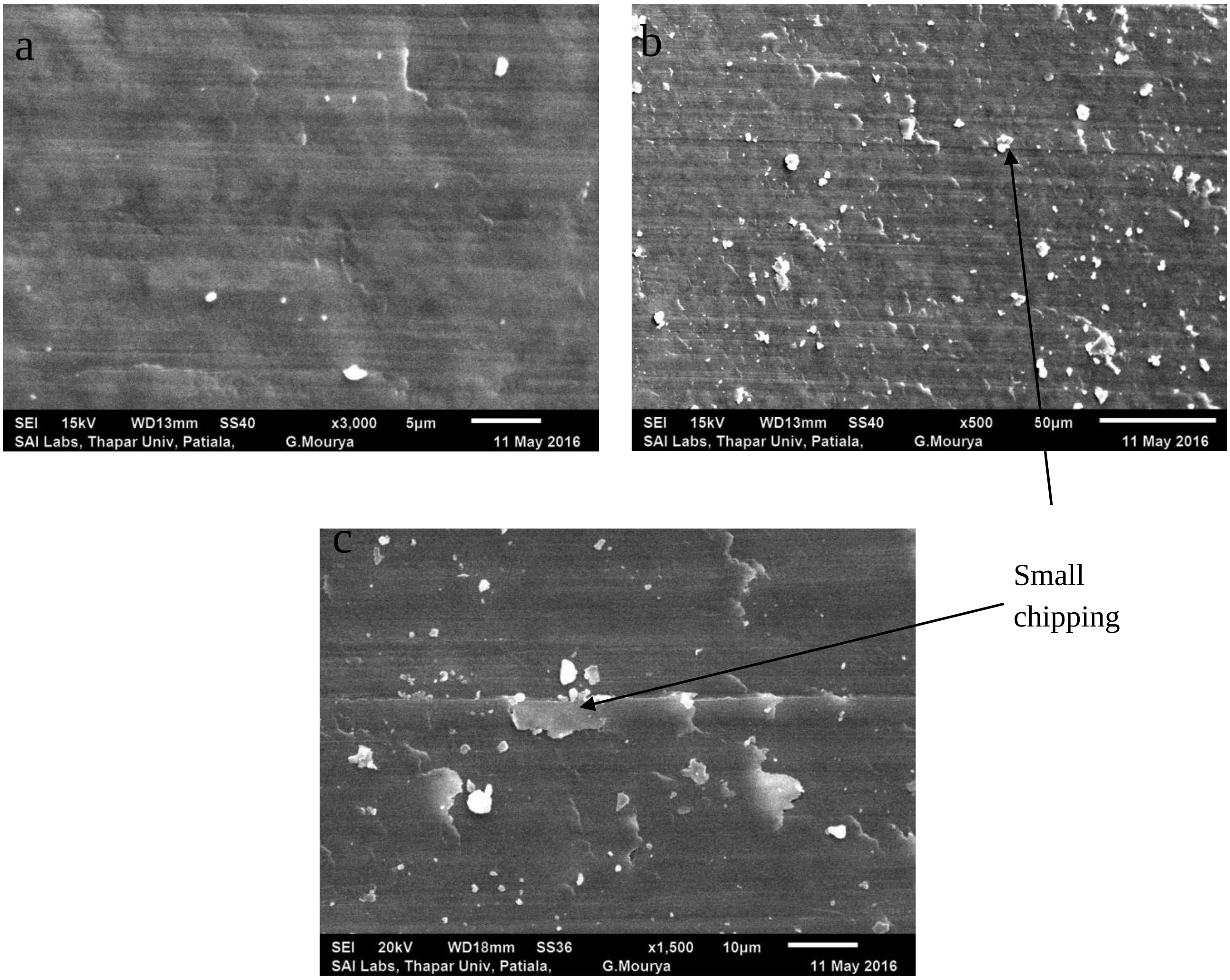


Figure 5.13: a, b and c shows the hole quality at different magnification for exp. 1

Experiment 1 is performed using drill bit on parameter 600 rpm and feed of 10 mm/min. from the SEM image it is observed that the material is removed very smoothly and in the form of small chipping. Parallel streamlines in SEM images supports the results of surface roughness.

Experiment 5:

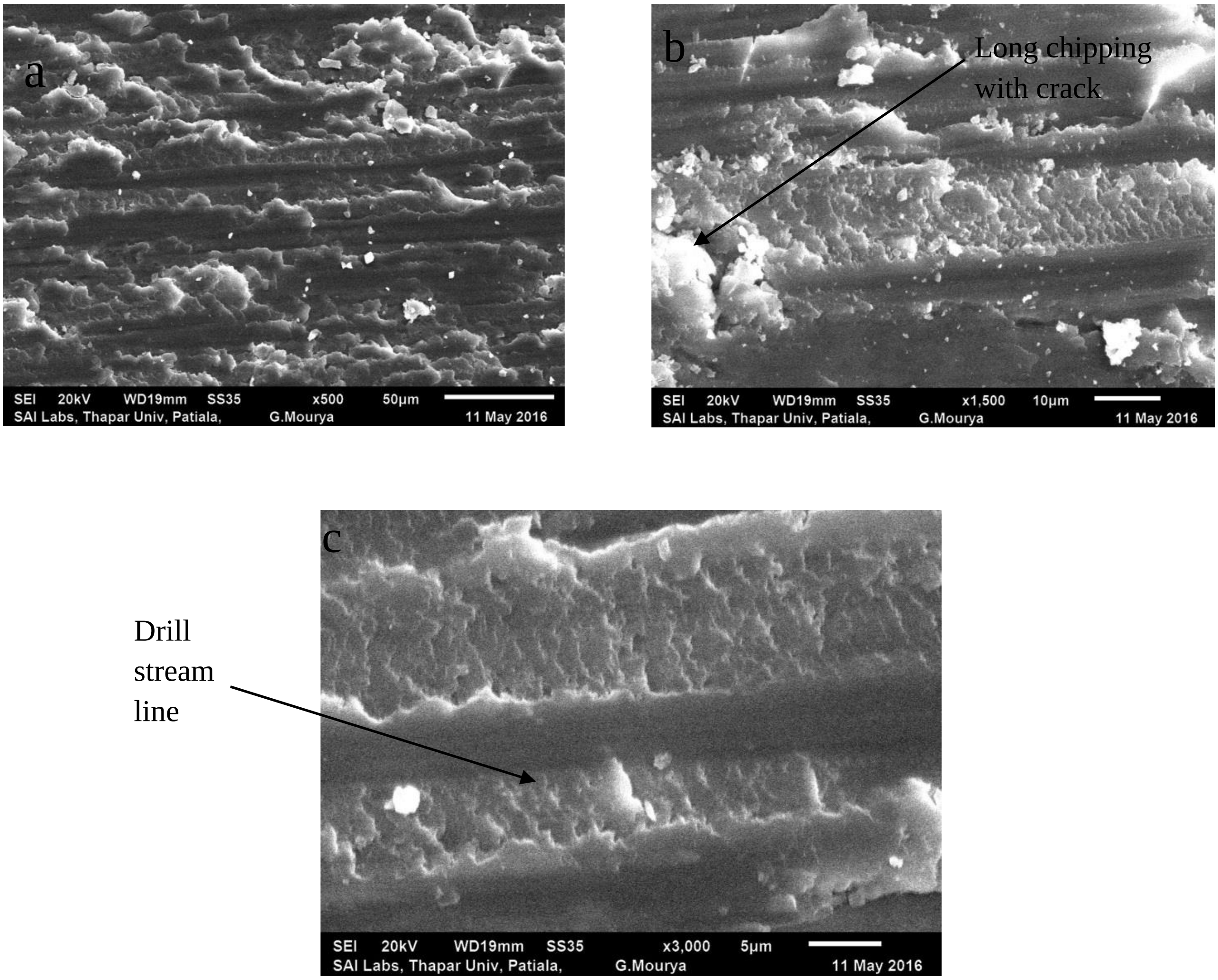


Figure 5.14: a, b and c shows the hole quality at different magnification for exp. 5

In experiment 5, feed rate is same as experiment 1 but here speed is 1200 rpm and here it is observed from figure 5.14 that material is removed faster so drill stream lines occur on the bone and material is removed as long chipping. Surface is not smoother as compared to experiment 1.

Experiment 9:

Experiment 9 is performed using abrasive coated tool at parameter 1800 rpm and feed at 10 mm/min. From figure 5.14 it is observed that here edge is roughed here material is removed in the form of powder. Images represent the same scenario as surface roughness test. The use of abrasive coated tool cause the damage on the inner edge of the hole as shown in figure 5.15 (c). Abrasive tool gives the parallel stream lines. But the material removal was not as smooth as compared with drill bit. With lower feed rate the contact time in tool and bone was also more so the effect of abrasive can be easily observed in the form of rough surface in figure 5.15 (a).

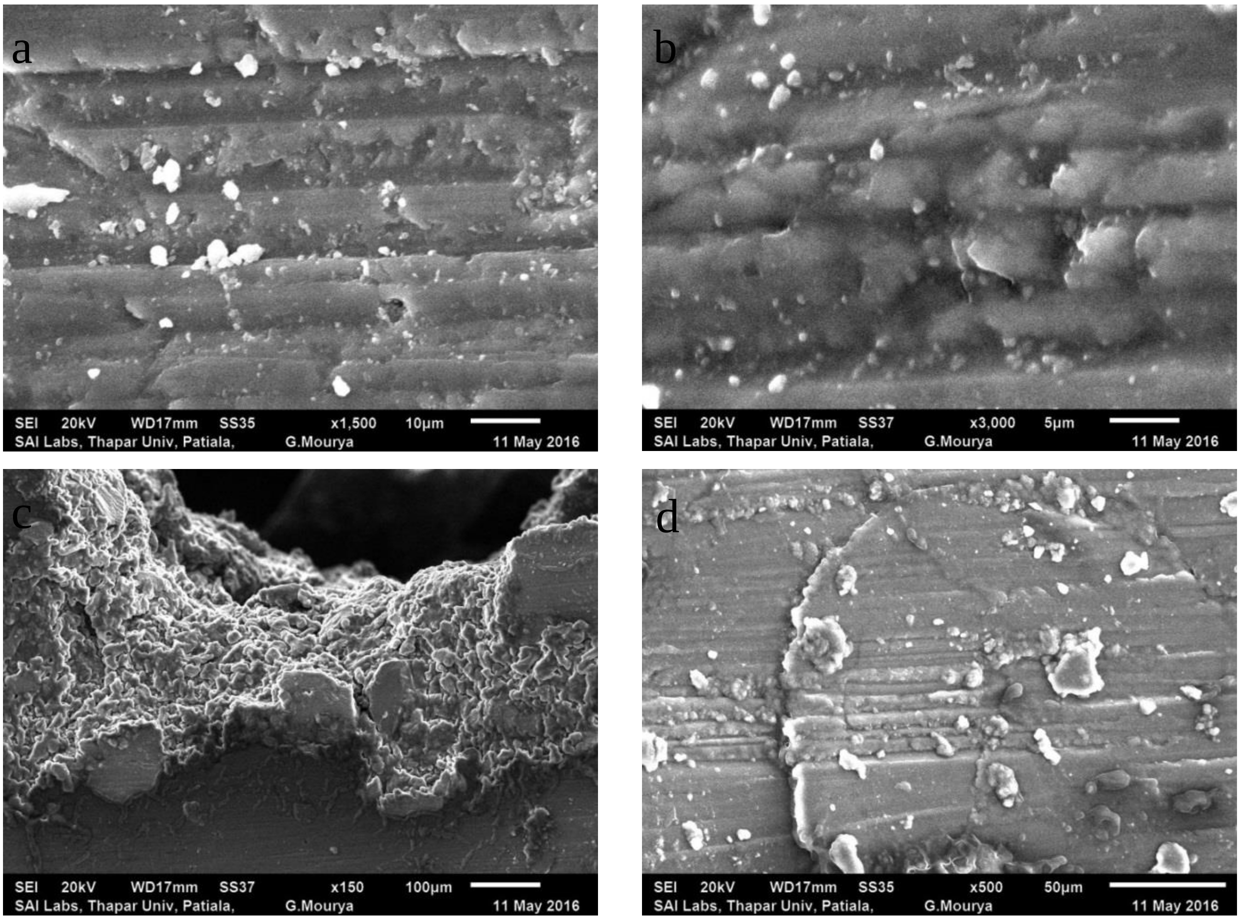


Figure 5.15: a, b ,c and d shows the hole quality at different magnification for exp. 9

Experiment 14:

In experiment 14 abrasive coated tool is used and here the material removed forcefully at 2400 rpm with less feed rate so here void or cracks is occurred in this experiment and it is one of the reason of the high temperature. Rough surface and cavities in the drilled walls. Material removal was not smooth and discontinuous. So long cavities form in the drilled walls. Which increase the surface roughness and damage the surface topography of the drilled walls. Larged void formed during drill shown in figure 5.16 (C).

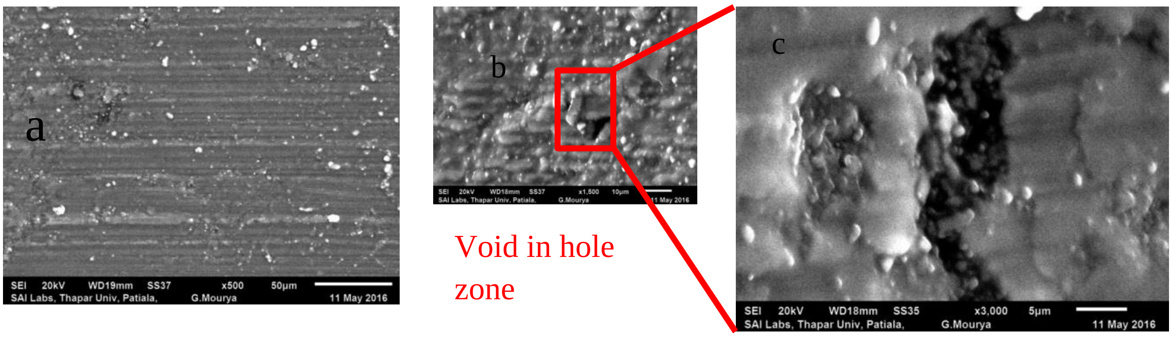


Figure 5.16: a, b and c shows the holes quality at different magnification for exp. 14

Experiment 10:

Here from the figure 5.17, it is observed that surface is very rough and here edge is break due to forcefully material removal by abrasive coated tool at 1800 rpm. Images represent the same result as by surface roughness test.

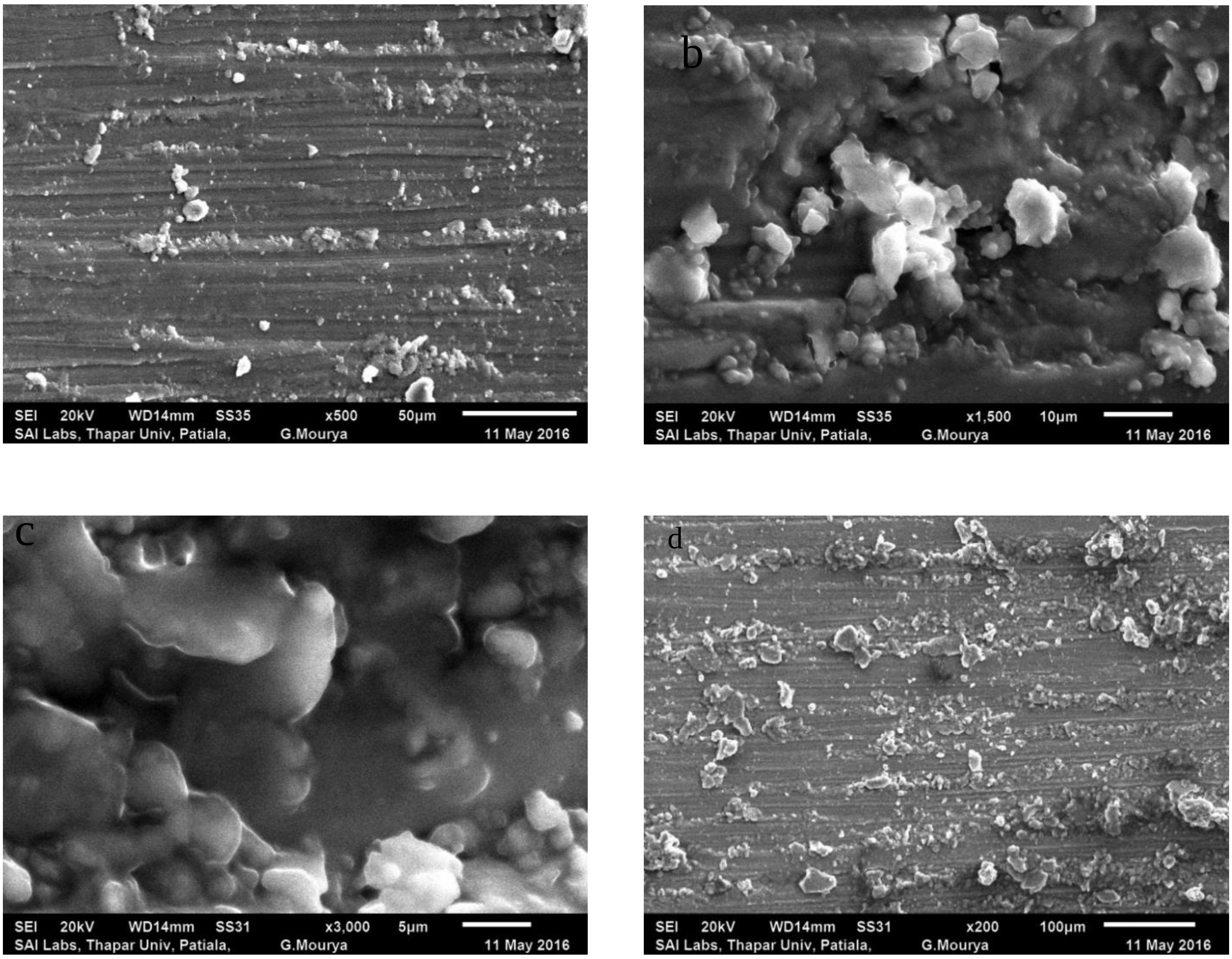


Figure 5.17: a, b, c and d shows the hole quality at different magnification for exp. 10

Experiment 8:

In this experiment SEM images represent that surface is very rough and it is damaged. Here hole shape is not symmetric and some cracks also here. The images at 3000x, 1500x, 22x and 500x clearly show the large in the cracks in the drilled hole walls and images shows the large rapture at entering edge of drilled hole.

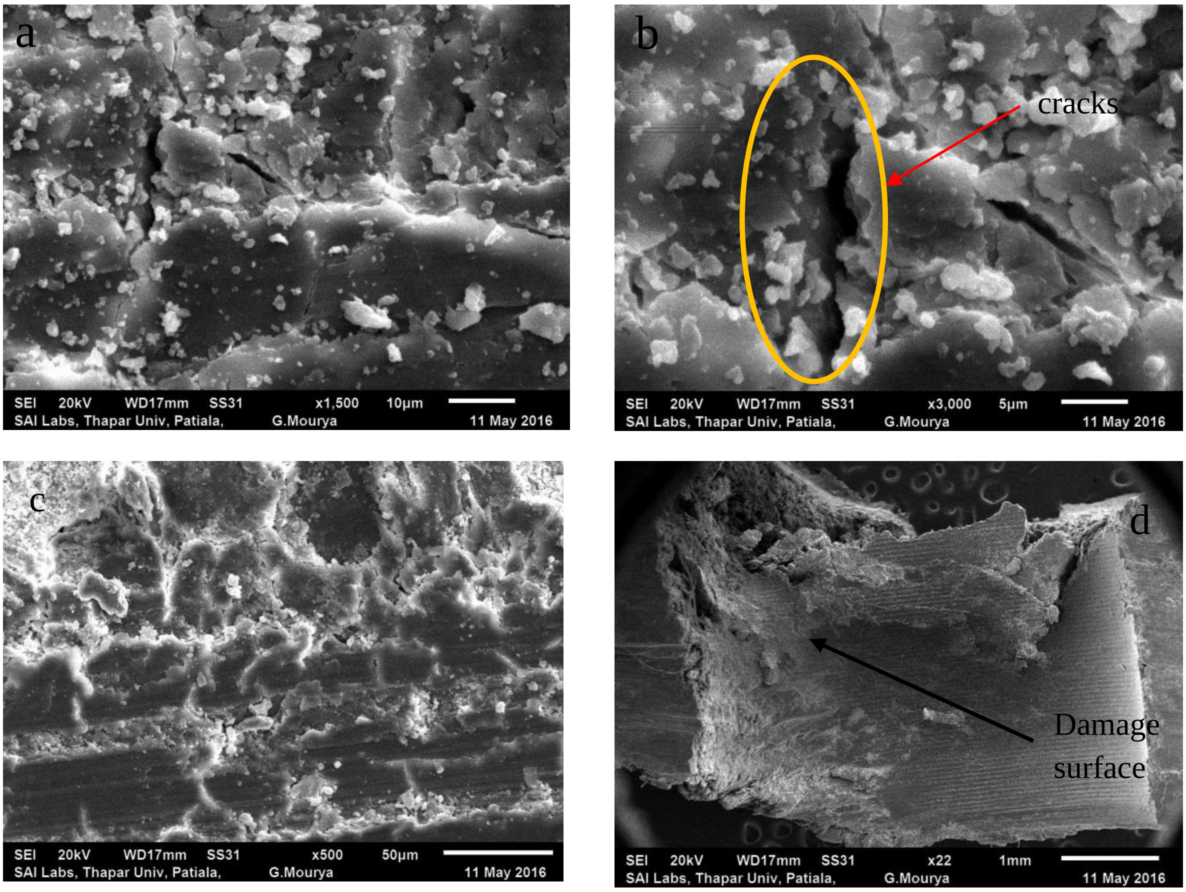
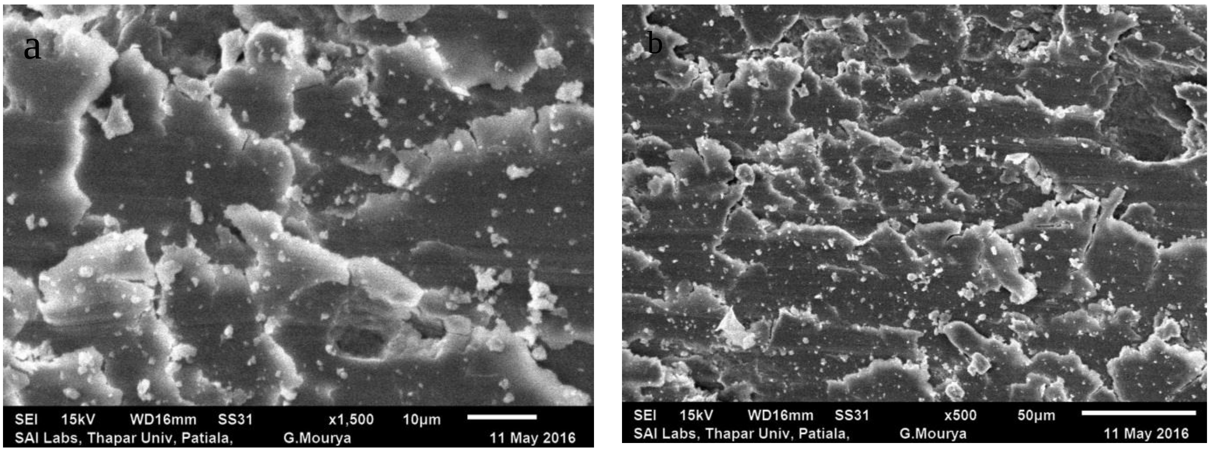


Figure 5.18: a, b ,c, d, e and f shows the hole quality at different magnification for exp. 8

Experiment 15:



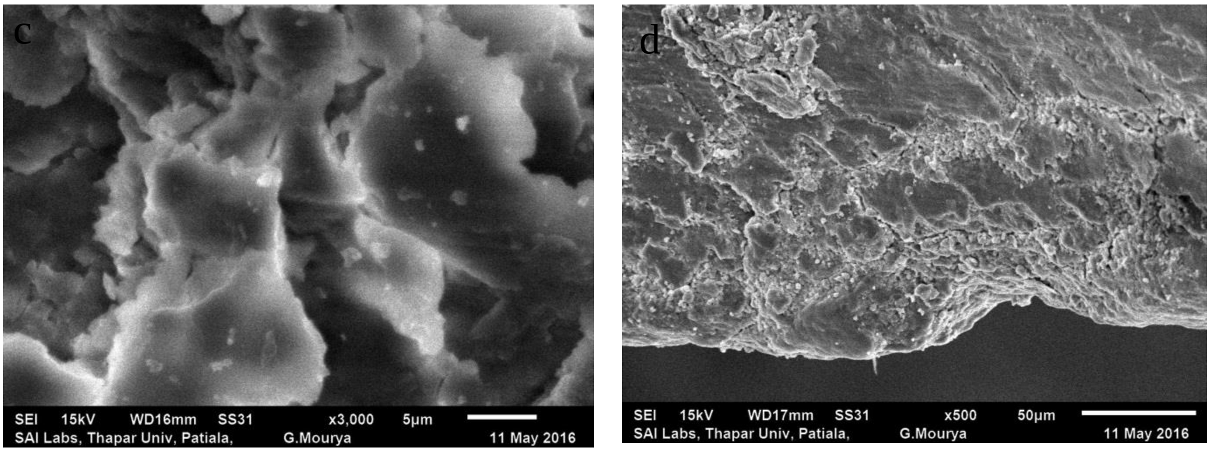
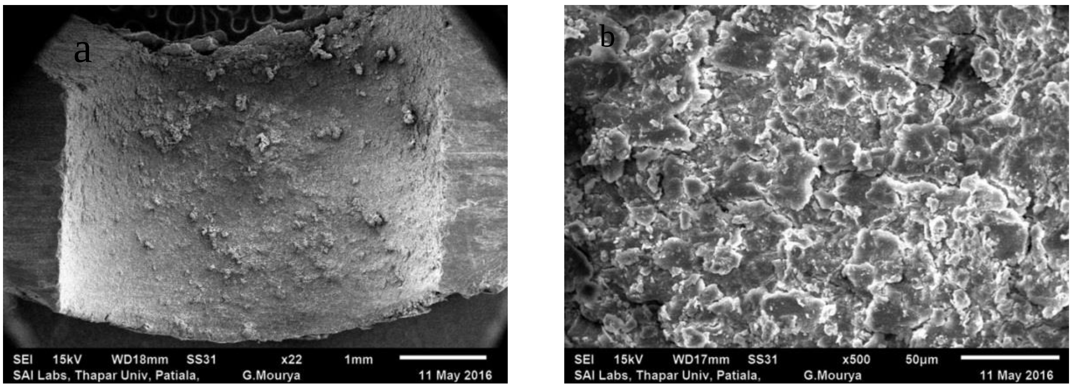


Figure 5.19: a, b ,c and d shows the hole quality at different magnification for exp. 15

This experiment is performed with 2400 rpm, 300 mm/min feed rate and standard drill bit. The material removed was smooth and in the form of thin layers. The cutting edge of the bone in figure d is also less damaged as compared to exp 8.

Experiment 16:

In experiment 16, surface roughness is maximum here and cracks occur continuously. Here inner edge of the hole also damaged. It is one of the reason that here temperature also maximum. Parameter used here speed is 2400 rpm and feed is 40 mm\min. The surface topography in this SEM images contains large cracks as compared to exp 15. The large surface damage cracks see from figure c and d. Entery edge is more damaged beceause of increasing feed rate.



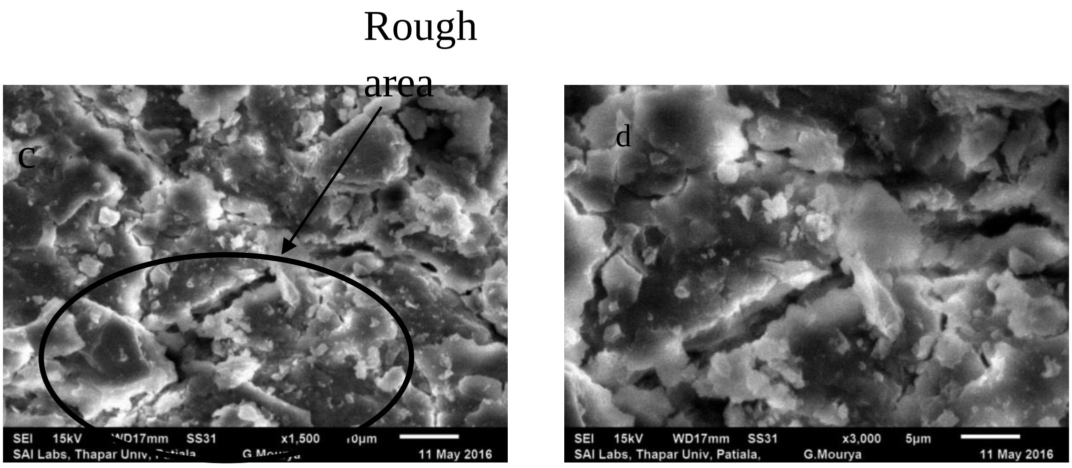


Figure 5.20: a, b ,c and d shows the hole quality at different magnification for exp. 16

Chapter 6

Conclusions and Future Scope

6.1 Conclusions

After results analysis and discussion there following conclusions are made :-

1. Experiments are performed to find out optimize results of temperature, heat, force and surface roughness using twist drill and abrasive coated tool. It is found that temperature is mainly depend upon the feed rate. It is maximum in the case of abrasive coated tool and peak value of temperature 62 ^{o}C using feed rate 40 mm\min.
2. Analytical and experimental results for heat distribution and thrust force follows the same trend.
3. Thrust force is maximum in the case abrasive coated tool with the use speed 600 rpm and feed 40 mm\min.
4. Feed is the predominate factor for surface roughness. Abrasive coated tool has more effect on surface roughness and peak value is 1.70 micron meter using drill bit with 2400 rpm and feed 40 mm\min.
5. Temperature, heat generation, surface roughness and thrust force is minimum in the case of drill bit using speed 600 rpm and feed rate 10 mm\min.

6.2 Scope of Future Work

- Some more associated surgical challenges such as pull out strength and post drilled hole quality of bone drilling can be addressed in the future study.
- Study of tool wear for a specific type of bone must be included for the future prospect. No of successive drilling holes with a single tool, can be find out with experimentation.
- Some non-conventional methods has been tried for bone drilling but they need to improve for better engagement in case of bone drilling.
- Hybrid machining can also be one other option which can overcome the demerits of conventional drilling with the using of benefits from the non-conventional drilling technique.

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