Experimental Investigation in Bone Drilling Using Different Types of Tools

A Dissertation Submitted In Partial Fulfilment of the Requirement for the Degree of

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by

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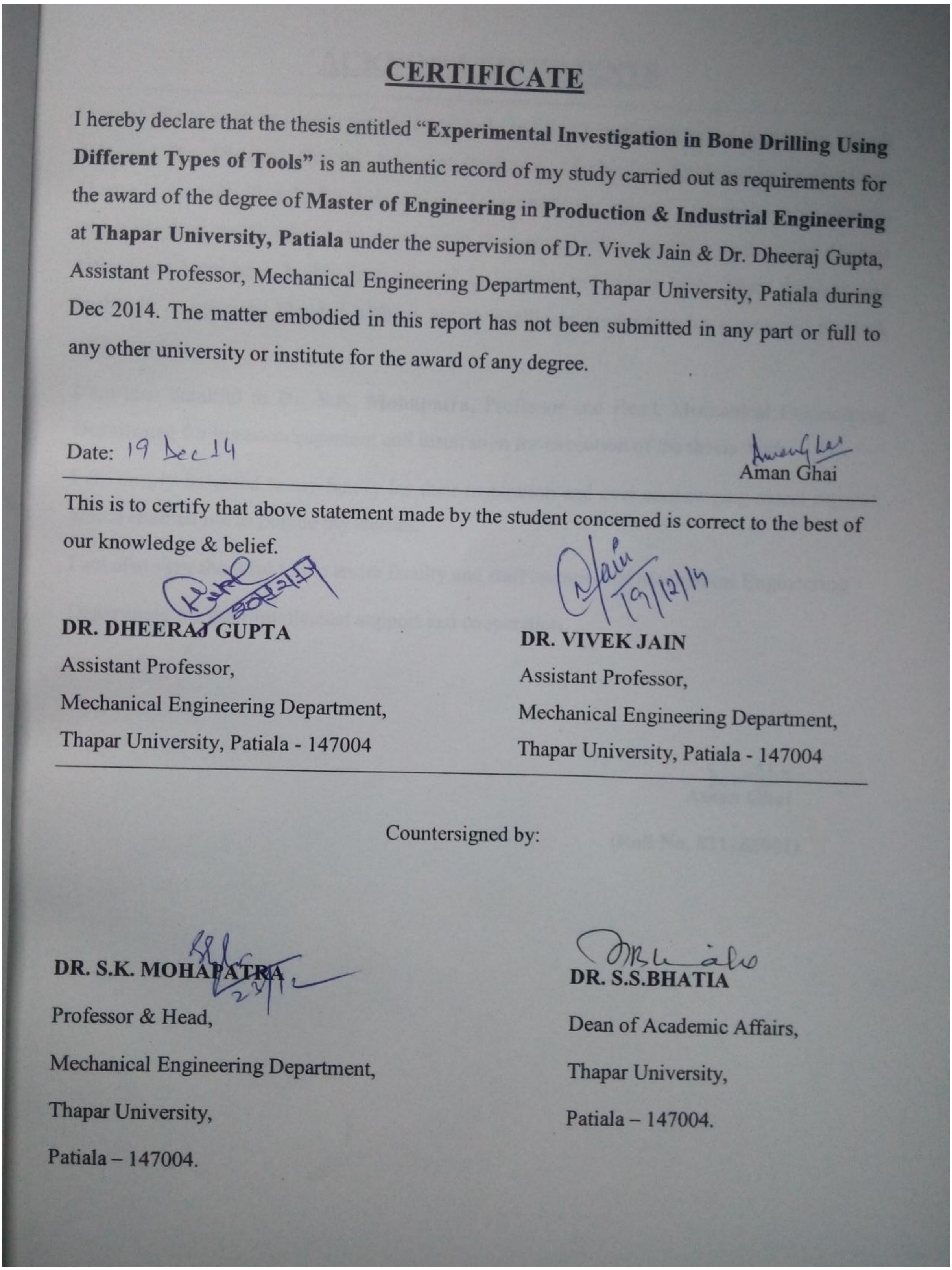

CERTIFICATE

I hereby declare that the thesis entitled "**Experimental Investigation in Bone Drilling Using Different Types of Tools**" is an authentic record of my study carried out as requirements for the award of the degree of **Master of Engineering** in **Production & Industrial Engineering** at **Thapar University, Patiala** under the supervision of Dr. Vivek Jain & Dr. Dheeraj Gupta, Assistant Professor, Mechanical Engineering Department, Thapar University, Patiala during Dec 2014. The matter embodied in this report has not been submitted in any part or full to any other university or institute for the award of any degree.

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This is to certify that above statement made by the student concerned is correct to the best of our knowledge & belief.

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ABSTRACT

Drilling through bone is an old and effective method to get rapid cure from bone injury. During orthopaedic surgery there is a need to fix the bones at their appropriate position so that it can rehabilitee as its natural position. Bone needs to be fixed with implants and screws for this overall curing process. Drilling through bone is thus a necessary action for fulfilling this objective. Drilling mechanism for bone drilling is same as the mechanical drilling. So heat is produced during bone drilling and affects the surroundings.

In the present study a mechanical drilling system is used for successive drilling through bones. A planned DOE is used for experimentation and L9 is used for optimization. It has been observed after the study that a twist drill has induced less force during the drilling and maximum material is removed with the same tool. The surface roughness is a predominant phenomenon for the fixation of screws inside the bone. The use of hollow tool induced the required roughness.

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Nomenclature

ANOVA = Analysis of Variance

DOE = Design of Experiments

CBT = Cortical Bone Thickness

CNC = Computer Numerically Controlled

CD = Conventional Drilling

MRR = Material Removal Rate

Ra = Surface Roughness

RPM = Rotation per Min

SEM = Scanning Electronic Microscopic

SN Ratio = Signal to Noise Ratio

UAD = Ultrasonically-assisted Drilling

Chapter -1

Introduction

Bone fracture is a feature of everyday life due to accident or aging. When a bone is broken the periosteum (outer surface) and endosteum (inner surface touching the marrow) provide bone-forming cells, which endeavour to bridge the fracture. The fracture of the bone is usually covered by drilling the bone at required sites for screw insertion and fixing plates. The cutting of bone is one of the oldest surgical procedures in the history of medicine.

The mechanical properties of bone are dependent on its composition and structure, which includes the arrangement of the components and the bond between fibers and matrix. For example, the arrangement of fibers is different in several types of bones, gives rise to distinct properties.

1.1 Bone: A Natural Composite

Composite materials are solids with two or more distinct constituents at a larger scale than an atomic one. In accordance to this definition, materials or biological tissues such as wood, dentin and bone are regarded as composite natural materials. Bone is regarded as a natural composite material, which appears as it is in nature, rather than the artificial or manmade composites.

Bone is a special type of connective tissue consisting of inter-cellular calcied material. There are two types of bone, the outer hard layer that is called cortical bone and an inner spongy layer called cancellous bone (Fig. 1.1). The outer surface of the bone is covered by a tough layer of osteogenic (boneforming) connective tissue called periosteum. Most of the inside of a bone is hollow and contains bone marrow. The inner surface of the bone is also lined with a similar cell layer with osteogenic properties called endosteum. Both the periosteum and the endosteum contain the bone vascular system which supplies it with nutrients and oxygen for bone growth and repair.

1.2 Chemical composition and Density of Bone

Compact bone and trabecular bone have almost the same elemental composition. Even arthritic bone, in an animal model, has a similar composition compared to control, with calcium=73% and phosphorus=27% (Caetano-Lopes et al., 2009a). Scheme of bone at different scale ranges has been shown in Fig. 1.2.

The density of the compact bone is in the range of 1800-2000 kg/m^3, while the density of each trabeculae is 1820 kg/m^3. The porosity however is much higher in trabecular bone, reaching 80%. As for other cellular materials, density of trabecular bone is usually calculated as the ratio between the density of bone and the density of single trabeculae (Gibson & Ashby, 1999). Bone is a poor conductor of heat, with the thermal conductivity of fresh cortical bone in the region of 0.38± 2.3 J/msK.

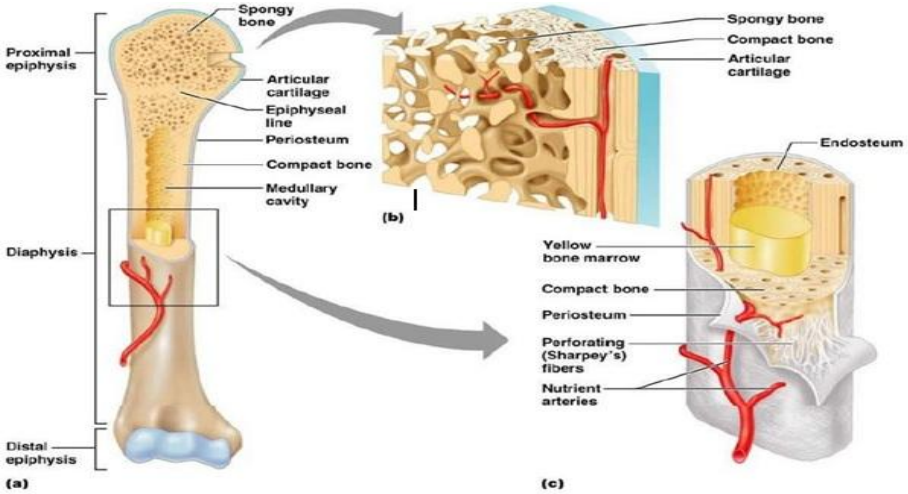


Figure 1.1: (a) Human cortical bone, (b) Cancellous bone (Inner spongy bone structure), (c) Cortical bone (Compact bone): outer layer of bone structure. (Carter, 2011)

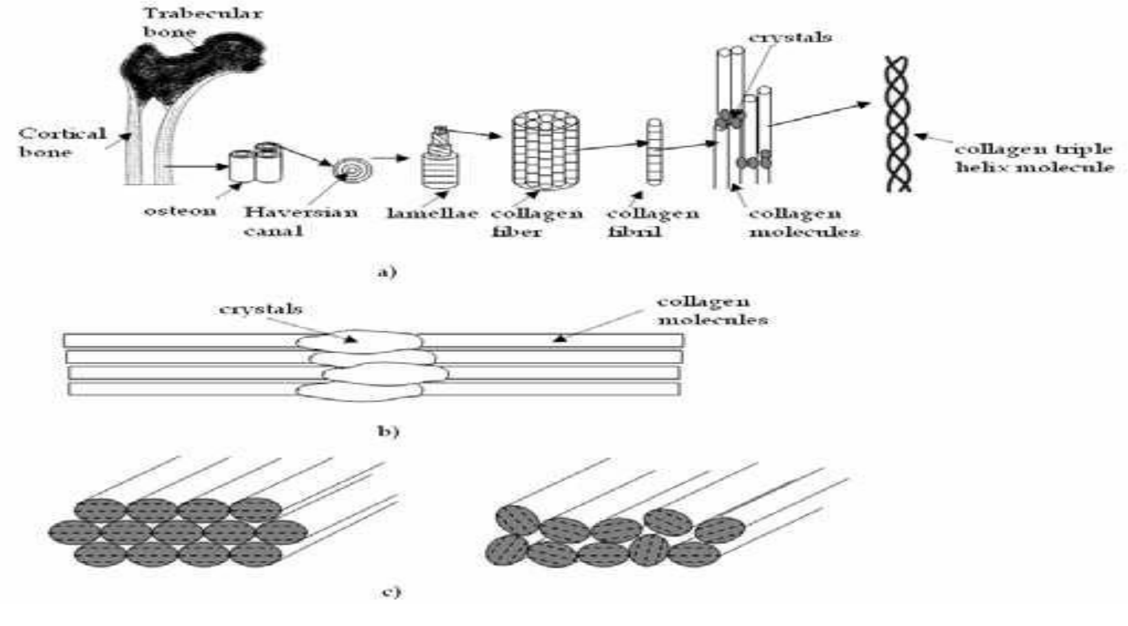


Figure 1.2: a) Scheme of bone at different scale ranges (adapted from (Rho, et al., 1998)), b) Arrangement of the apatite crystals which are aligned with the longitudinal direction of collagen fibers, c) inside one fiber, the fibrils may be aligned with respect to crystal axes and fibril axes, or the fibrils may have only an alignment of the fibril axes (adapted from (Weiner & Wagner 1998))

1.3 Properties of Bones

Knowledge about bone and its properties is necessary so that one can know how the bone is going to behave under various loading conditions and how it will fail or fracture under various conditions. Some of the properties of bones have been explained below:

- **Shear strengths** — A shear strength is applied parallel to the surface of an object, creating internal deformation in an angular direction. The bone fails more quickly when exposed to shear strength rather than a compressive or tensive strength. The shear strengths are responsible for problems in the vertebral discs. **Shear strength may produce spondylolisthesis, in which one vertebra slips over another previously.**
- **Elastic Response** - When the load is firstly applied, a bone is deformed by a change in the extent or angular format. The bone is deformed up to 3%. This is considered the elastic amplitude of the load-deformation curve because, when the load is removed, the bone is recovered and goes back to the original format or extent.
- **Plastic Response** - With the continuous placement of load on the bone tissue, its deformation point is reached, after which the external fibers of the bone tissue will start to cede, experiencing micro-breaks and disconnection of the material within the bone.
- **Anisotropic Characteristics Bone tissue** - The bone is strong to support loads in the longitudinal direction because it is used to receive loads in this direction.
- **Viscoelastic Characteristics** - The bone is also viscoelastic, which means that it responds differently depending on the speed to which the load is applied and the length of the load.
- **Strength** - The strength of the bone or any other material is defined by the point of failure or by the load sustained before the failure. The strength may also be analyzed in terms of storage of energy, the area under the load-deformation or stress-distension curve.
- **Hardness -** The hardness, or elasticity module of a material, is determined by the decrease of the load-deformation curve during the amplitude of the elastic response and is represented by the resistance of the material to the load as the structure is

deformed. This response occurs in many materials, including bones, tendons and ligaments.

- **Tensive Strengths** — A tensive strength is usually applied on the bone surface and it pulls or elongates the bone, tending it to extend and narrow the bone. The maximum stress, as in compression is perpendicular to the applied load. The source of tensive strength is usually the muscle.
- **Bending Strengths** - A bending strength is the strength applied to an area that has no support offered by the framework. When a bone is subjected to a bending strength and deformation occurs, one side of the bone will form a convexity in which will have tensive strengths, and the other side of the bone, will form a concavity in which compressive strengths are present. Typically, the bone will fail and break on the convex side in response to high tensive strengths since the bone may withstand greater compressive strengths than tensive.

1.4 Bone Drilling

Bone fracture due to an accident, aging or diseases is a feature of everyday life. One of the principal methods of repair and reconstruction of such a fracture is based on drilling the bone and fixing its separate parts together using screws, wires and plates. Morphology of the drilled hole surface and fixative components such as screws, pins and hooks influences strength of the bonds between them.

Rehabilitation of the various orthopaedic surgeries involves restoring the affected bone parts to their position and restraining them until the complete healing. For all that, some time we need to drill the bone and fastening them for easy and quick healing of the bones. This orthopaedic drilling is very much similar to mechanical drilling process which results the reactive forces and increase temperature of surrounding bone material, which can cause the osteonecrosis in some of cases and affects the reliability of surgery.

Fractured bone is a severe problem faced by human from the starting of human life on this planet. Self-healing of the bone is a time taking process and sometimes it fixes on wrong position. So allocation of fractured bone at the desired position is a tough task and in this task there are two basic approaches are taken into account: a conventional approach and direct approach. The direct approach is fixing of bones by drilling as shown in Fig. 1.3.

In conventional approach, fractured bone part is restricted to move relatively from outside support. Traumatologist treats the facture by fixing it on desired position and placing the support from outside. With this process minor cracks and injury can be treated easily and successfully. But in case of major dislocation, this process cannot help much better.

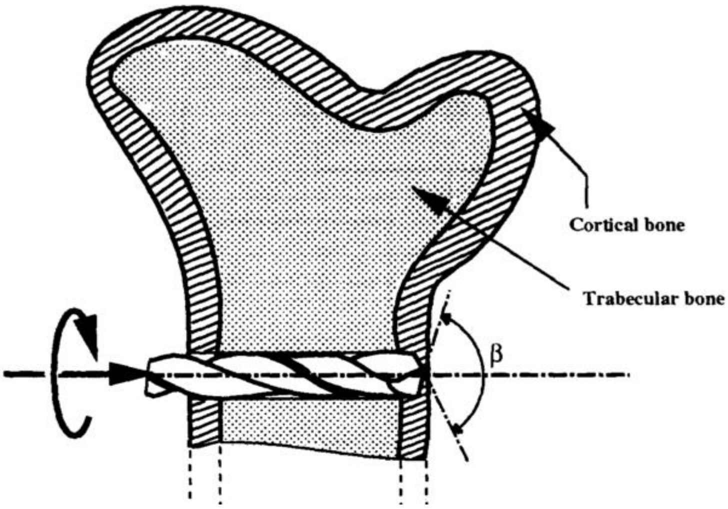


Figure 1.3: Systematic diagram shows drilling through a bone

In direct approach, screws are used to get fix the damaged bones on their desired position. Before tightening the screws, it requires drilling and tapping of bone. Mechanical drill or a similar device is used to make a hole through the bone. These processes are usually carried out using manual, electric or pneumatic drilling tools. The surgeon can control the rotation speed of the drill bit using a pedal or button placed on machine.

During this process, heat is generated due to friction between dill bit and bone surface, which may lead to hyperthermia and carbonization, resulting in cell death and change in natural properties of bone. When temperature increases above the threshold value, bone resorption may occur due to thermal exposure and resulting thermo necrosis. This thermo necrosis is just like the death of bone cells and may lead to the bone death due to insufficient blood supply.

For getting reliability and stability in fixation of screw in damage bone it must be tighten up completely and screw must engage up or grip the bone with in the drilled hole. But necrosis causes failure of bone joint around the implantation site and leading to the loosing of fixation.

1.5 Methods of Bone Drilling

Drilling through bone is very common and simple as simple to drill any mechanical component, but it need proper care and patience. Mostely conventional method of drilling is in practice. Some other unconventional methods of drilling were also tried but not in use, due to some problems associated with them.

Methods of bone drilling can be classified in two major categoies:

1. **1.** Conventional drilling
2. **2.** Unconventional drilling
    - Waterjet drilling
    - Abrasive waterjet drilling
    - Laser drilling
    - Microwave drilling

1.5.1. Conventional Drilling

Conventional drilling is the very common used mechanical drilling process in which rotating drill-bit is used to produce hole in the speciman. Tool is rotating with the help of adjusent power system. With conventional bone drilling some parameters affects the efficiency and quality of drill hole.

These parameters are reported in two major category:-

1. Machining parameters
2. Drill specifications

These two categoreies can be broadly classified as some other direct parametrs related to bone drilling. Machining parameters includes the variables with in the drilling machine used in bone drilling and drill specifications include the permissable changes within the drill bit dimensions used during the done drilling. These two categories can be classifed broadly in Table 1.1.

Table 1.1: Parameters affecting the bone drilling

Machining parameters	**Drill specifications**
Rotational speed	Drill diameter
Feed rate	Flutes and helix angle
Applied drill force	Drill wear
Cooling **1.** Internal cooling **2.** External cooling	Cutting edge angles **1.** Rake angle **2.** Clearance angle and flank
Drill depth Predrilling	Drill point **1.** Point angle **2.** Chisel edge

Machining Parameters

Drilling parameters play a very vibrant role for controlling the temperature generated during drilling. Parameters associated within the setup of hand drill are the machining papametrs and they are closely related with the drilling quality and precission. Thermal necrosis is also depend upon these machining parameters.

Rotational Speed, Feed Rate and Applied Drill Force

These parameters play a very vital role for controlling the temperature generated during drilling. From last few decades many researchers have investigated on this aspect so as to minimize the chances of necrosis during drilling. Measure of drilling speed is in terms of revolution per minute (RPM). When one stationery and one rotating solid strikes, heat is generated due to frictional behaviour of solids, so rotational speed should be so optimum to produce minimum heat. Researchers suggest different set of RPM for different conditions. Using irrelated set of parameters can cause damage of drill-bit with in bone as shown in Fig. 1.4.

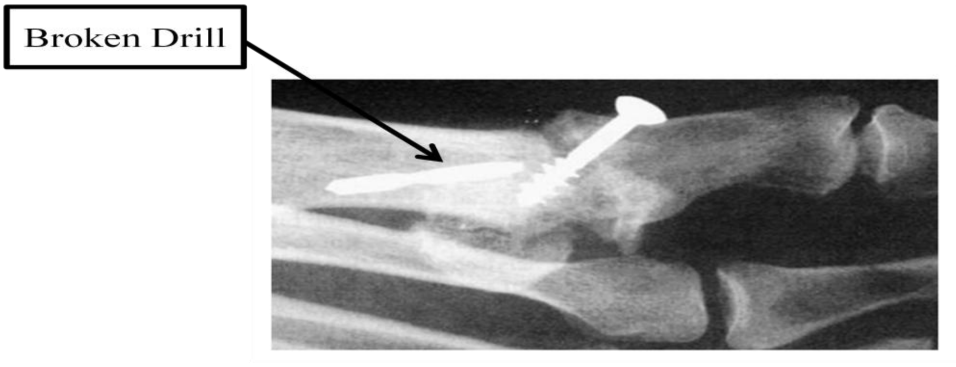


Figure 1.4: Broken drill-bit left in bone (Colin Natali, 1995)

Effect of Coolant

The effect of use of coolant during bone drilling for orthopaedic surgery is investigated by many researchers. They found that cooling is one of the most important factors as it significantly decreases the temperature induced during drilling. Two methods internal and external cooling are often employed for the supply of coolant during drilling (shown in Fig. 1.5 and 1.6 respectively).

The types of cooling systems are:

1) Internal cooling system
2) External cooling system

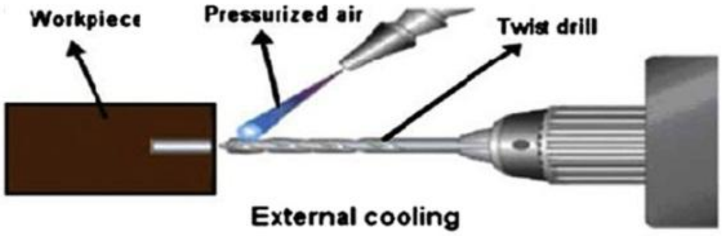


Figure 1.5: View of external cooling.

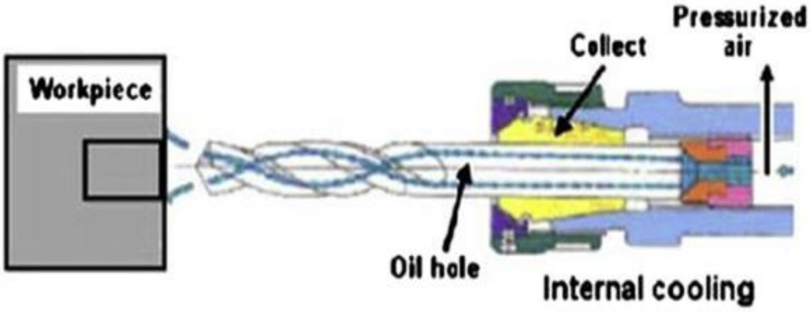


Figure 1.6: Systematic arrangement of internal cooling system.

Internal cooling involves feeding of the coolant to the drill tip through the tubules in the drill shaft whereas external cooling involves feeding the coolant to the surface of the drill at the entry point. In closed type internal cooling system the coolant circulates through the tunnels incorporated inside the drill and back to the central heat exchanger. Cooling is achieved by the mechanism of conduction of heat from the drill to the coolant flowing through tunnels. No contact between coolant and the bone takes place. In open type internal cooling system the coolant flows through the tunnels in the drill and exits from the opening at the drill tip, thereby taking away the heat generated during the drilling process. Besides taking away the heat by conduction, the coolant also provides lubrication and irrigation (excluding closed loop internal cooling system). Lubrication reduces the friction during drilling and hence less heat is generated. Bone produces short chips when it is dry but during orthopaedic treatment it is wet therefore the chips produced get clogged which increases the friction and raises the temperature during drilling. Irrigation causes the effective removal of chips and debris which avoids clogging of flutes during bone drilling and facilitates less heat generation.

Depth of Drill

Depth of drill is also a major factor which is to be taken in account before starting the bone drilling. Heat generation during drilling is a key issue which causes some major problems in recovery of facture. Presently depth is estimated by the skilled operator but if it goes in to more depth as compared to required, it will take more time to recover than the normal. Depth of drill also depends on thickness of bone. The mean cortical thickness of the bovine (7mm-9 mm) and human cadaveric (3mm-5 mm) bone. Depth of drill is also varied with the density of bone. So there is large variation in temperature as we go in depth of the bone. So the depth is the predominant factor influencing the temperature induced during bone drilling.

Predrilling and Step Drilling

Drilling can be done either in single step or in multistep. In single step only one drill of required diameter is used to produce the desired hole whereas in multistep drilling known as predrilling, drill diameter is gradually increased from minimum to the required diameter using a number of drills. This type of drilling is also known as incremental drilling. Drill bit used in step drilling is similar as the drill bit used in general drilling. In pre-drilling, total time of drilling is increased as compared to step drilling so this type tool is preferred over pre-drilling. Drill bit used in conventional drilling and step drilling shown in Fig. 1.7.

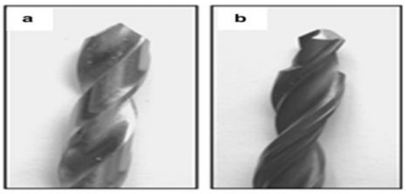


Figure 1.7: (a) Classical surgical drill (b) Step drill (two phase drill).

Drill Bit Specification

Drill specifications are also a major factor influencing the temperature generation during drilling. Several researches showed that many features of drill are responsible for increase in thermal injury to the bone. Any drill is usually characterized by the drill diameter, cutting face, helix angle and the drill point {Fig 1.8 (a)}. The drill cutting face is further specified by rake angle and clearance angle whereas point angle, flank and the chisel edge defines the drill point as shown in Fig 1.8 (b).

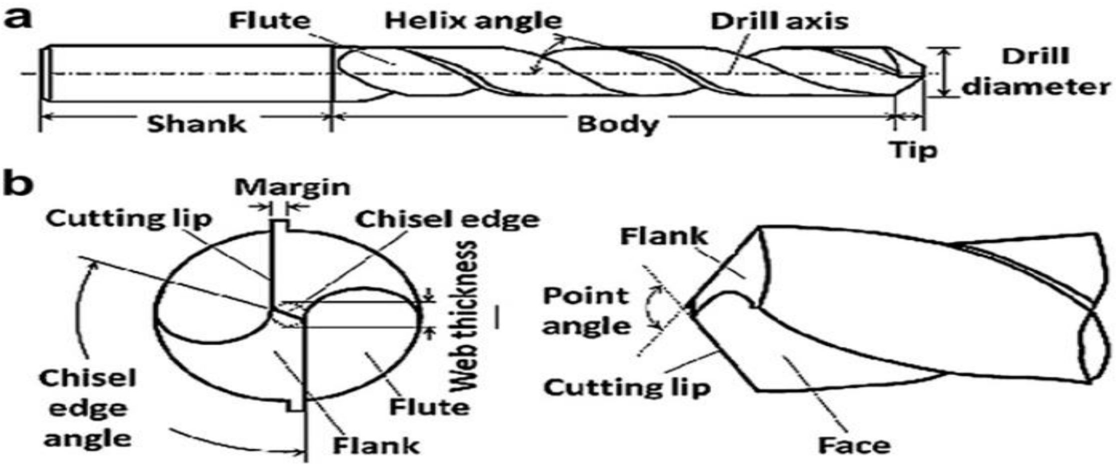


Figure 1.8: (a) Twist Drill Bit (b) Drill Bit Tip.

Drill Diameter

Maximum output diameter required after drilling is the major factor, on which other parameters is to be adjusted. Generally 2.5, 3 and 4 mm drill bits are used to drill the bone. Drill diameter is to be selected according to bone condition (density, position). Diameter of drill also affects the temperature raise during drilling. As the diameter increases, contact surface increases which results in more heat produced. By reducing the diameter greatly may result in the breakage or bending of drill bit.

Flutes and helix angle

The flute is a deep groove that typically twists around the drill, giving the waste material a path out of the hole. In the absence of a flute, the drill would not cut as quickly, as the waste material would need to be removed before drilling could continue. Flutes can vary in size and the drills can be constructed with number of flutes with various helix angles. Two flute and three flute drill bit is shown in Fig 1.9. No of flutes also changes the point angle, as point angle is reduced with increase in no of flutes.

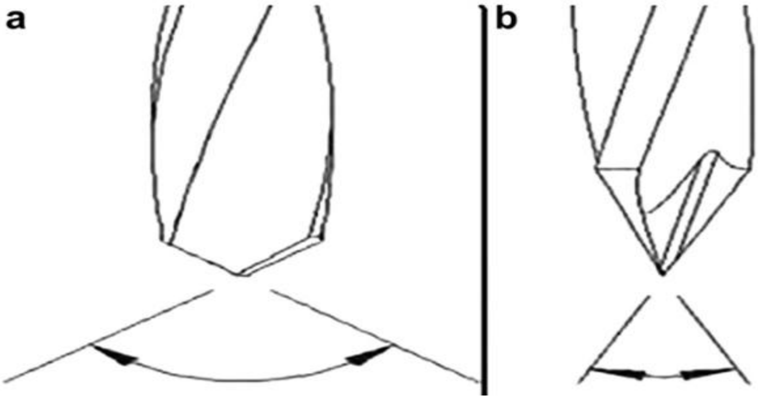


Figure 1.9: (a) Two flute (b) Three flute drill bit

Drill wear

When two hard surfaces slides with each other then some part of material from the surfaces eliminate in the form of small tiny particles. In case of drilling there is wear out of cutting edges due to mechanical and thermal effect. This wear of cutting lips of drill bit may lead to the increase in axial thrust force, temperature and vibrations also.

Cutting Edge angles

Front edge that involves in cutting majorly of a standard drill bit in any type of drilling includes in cutting face of drill bit. It includes:

1) Rake angle
2) Clearance angle and flank

1) Rake angle: It is the angle between the cutting edge and the plane perpendicular to the work piece. Rake angle is critically influencing the cutting forces. Several investigations have been carried out to identify an optimal rake angle for bone drilling. An optimum rake of 20^o-30^o was recommended, as it sufficiently clears the chips and generates very low thrust force.

2) Clearance angle and flank: Flank is the flat part of the drill when viewed from end in (Fig. 1.8(b). The flank of the drill represents a large surface area for friction during drilling. Clearance is the space provided to avoid undesirable contact of the flank with the work piece. This angle helps the flank of the drill to clears the material during drilling. Despite of the

clearance provided the large surface of the flank results in high friction with work piece, causes generation of the frictional heat and hence the temperature during drilling.

Drill point

Drill point includes two major part which helps in efficient drilling and also influence the amount of heat generation. These two parts includes:

1) Point angle
2) Chisel edge

Point angle: It is the angle formed in between the projections of cutting edges on the plane passing through the longitudinal axis of the drill bit. Point angle guides the drill bit to an appropriate point where drilling is to be done. In case of bone drilling accuracy of this kind is needed as much as possible because risk cannot be taken with human on the operation table. The smaller point angle provide more acute tip which can easily stab in the bone, where required. But the problem with more acute tip is that the less portion of cutting lip will be involved during first few revolutions of drill bit and results in higher rate of raise in temperature. On the other side when large point angle is to used then full contact of cutting lip is involved in the cutting action. Investigations, highly recommend the 90^o point angle in most of cases.

Chisel edge: It is defined as the edge at the end of the web that connects the cutting lips. Length of chisel edge is equal to the web thickness and it also determines the difference between the cutting edges about the axis of rotation. Chisel edge having a direct relation with thrust force produced at the time of drill.

1.6 Organization of the Thesis

The dissertation is organized into five chapters. The contents of each chapter are summarized below:

CHAPTER 1: It represents the introduction of bone, different properties of bones and description of conventional method used for drilling of bones.

CHAPTER 2: It contains literature survey on drilling of bones and previous studies on drilling of bones using different methods. Finally the literature gap and analysis has been formulated based on the gaps identified on the past work. This chapter covers the problem formulation, the objectives of present work and plan of the present work.

CHAPTER 3: This chapter contains the Experimental set up, work piece properties, input parameters and out parameters. Methodology has been formulated on the gaps identified from the past work.

CHAPTER 4: This chapter describes the result analysis of the present work on the basis of Taguchi method.

CHAPTER 5: This chapter represents the conclusion and future scope in the field of drilling of bones. Conclusions are explained on the basis of present study.

Chapter-2

Literature Review

Bone cutting is one of the oldest surgical procedures in the history of medicine. Nowadays, knee and hip implant surgeries are performed around the world and considered to be the amongst the most commonly performed operations in clinical practice. In the past years a lot of work has been done to investigate and analyze the effect of various machining methods on bone during surgery.

The literature review has been divided into two parts. First part is conventional techniques for the bone drilling and second part shows some results of non-conventional techniques of drilling.

2.1 Conventional Drilling

***Mustafa et al. (1995*)** carried out a study to investigate the effect of force on drill speed and the energy consumed during the drilling process. Applied force, drill speed, and energy consumed were measured during drilling in bovine cortical bone specimens. A commercial surgical drill was fitted with a custom-designed speedometer for measuring the rotational speed. Tests were conducted for forces between 1.5 and 9.0 N and for free-running speeds from 20,000 to 100,000 rpm (Fig. 2.1). The measurements of electric power showed that the total energy consumed generally decreased with speed and force, primarily because of decreased drilling time. The decrease in energy suggests that drilling at high speed and with a large force may be desirable because bone temperature is reduced.

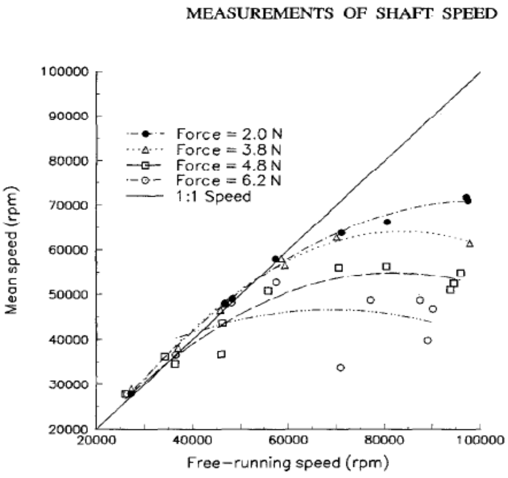


Figure 2.1: Variation in free running speed on application of force (Mustafa et al. 1995)

Colin Natali et al. (1996) studied the various drill bits available for engineering purposes, and compared them with standard orthopaedic drill bits, using continuous temperature recording at 0.5 mm, 1.0 mm and 1.5 mm from the edge of a 2.5 mm hole as it was drilled in fresh cadaver human tibia. Some commercially available drill bits performed better than their orthopaedic equivalents, producing significantly less thermal injury to the surrounding bone and halving the force required for cortical penetration. The optimal bit for orthopaedic purposes should have a split point and a quick helix. Theoretical knowledge of cutting technology predicts that the addition of a parabolic flute will further reduce thermal damage.

K. Alam et al. (2009) investigated the effects of two drilling techniques on surface roughness of holes. The set up used for UAD has been shown in Fig. 2.2. Hole's surface roughness produced with conventional drilling (CD) and ultrasonically assisted drilling (UAD) was measured with, and compared for, various contact and non-contact methods (Fig. 2.3). The difference in surface roughness for both drilling techniques was explained based on high-speed filming of the bone drilling processes.

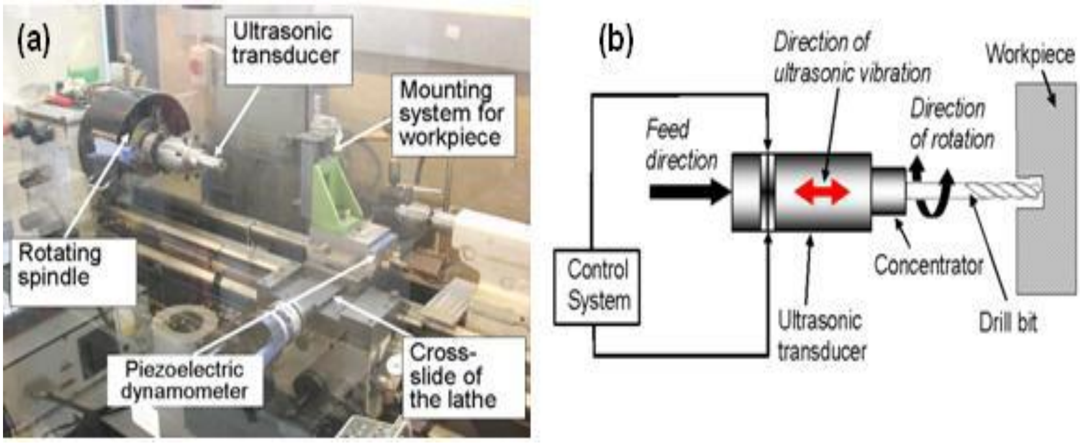


Figure 2.2: Set up used for ultrasonic assisted drilling of bones (K. Alam et al. 2009)

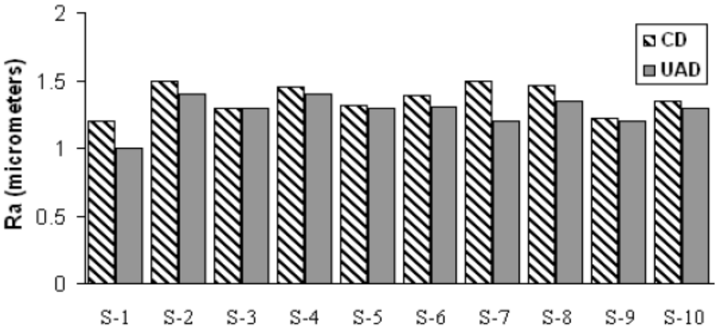
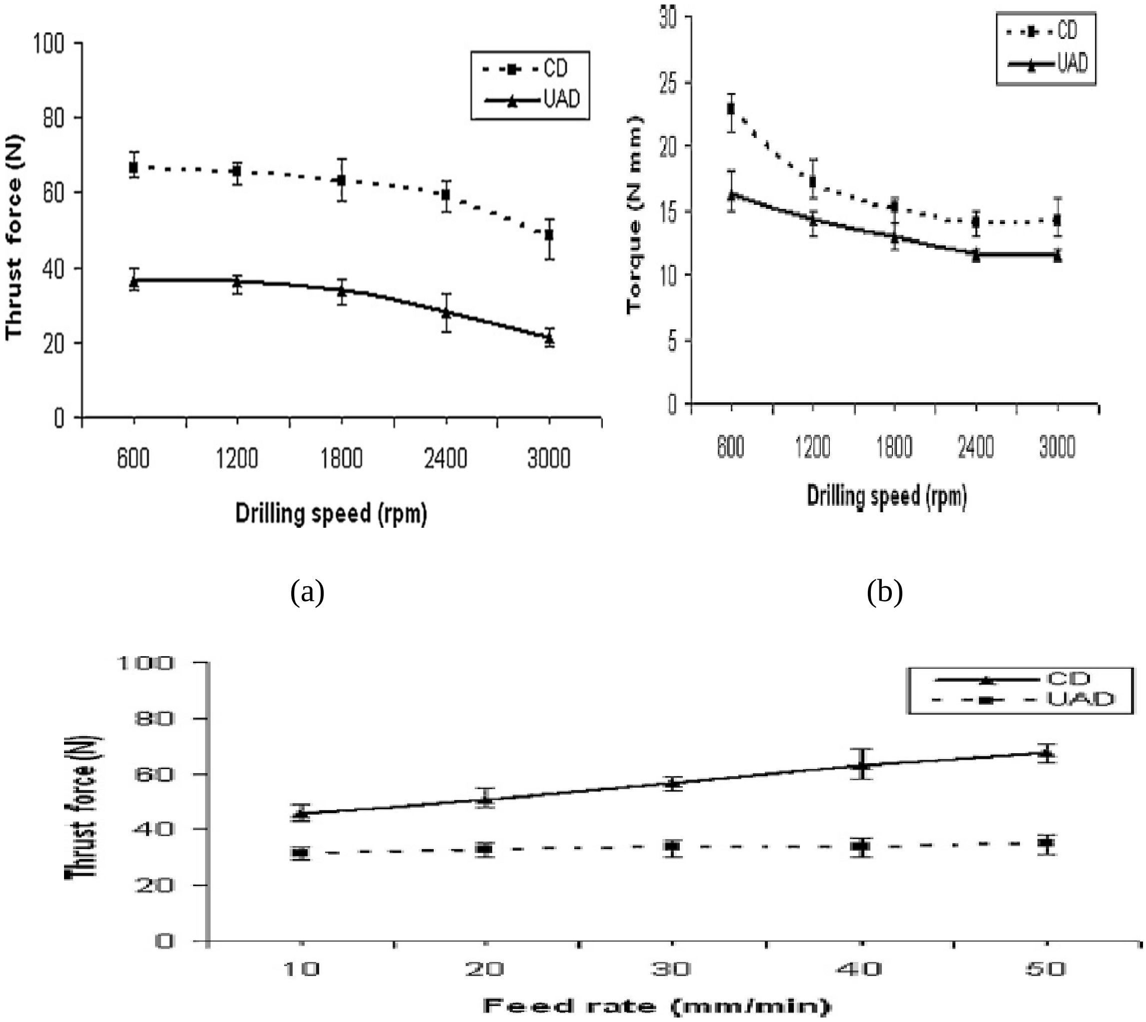


Figure 2.3: The difference in surface roughness obtained by Conventional Drilling and Ultrasonic Assisted Drilling (K. Alam et al. 2009)

K. Alam et al. (2010) carried out this study to investigate the forces and a torque required for conventional and ultrasonically-assisted tool penetration into fresh bovine cortical bone. Drilling tests were performed with two drilling techniques, and the influence of drilling speed, feed rate and parameters of ultrasonic vibration on the forces and torque was studied (Fig. 2.4). Ultrasonically-assisted drilling (UAD) was found to reduce a drilling thrust force and torque compared to conventional drilling (CD). The mechanism behind lower levels of forces and torque was explored, using high-speed filming of a drill‑bone interaction zone, and was linked to the chip shape and character of its formation. It is expected that UAD will produce holes with minimal effort and avoid unnecessary damage and accompanying pain during the incision.



(a) (b)

(c)

Figure 2.4: (a) Variation of Thrust force with drilling speed using CD & UAD (b)Variation of Torque with drilling speed using CD & UAD (c) Variation of Thrust force with Feed rate using CD & UAD (K. Alam et al. 2009)

F. Karaca et al. (2011) carried out a study by considering the bone mineral density, bone sex, drill tip angle, drill speed, drill force and feed-rate. The specimens were taken from the drilled sites of fresh male and female calf tibias. The temperature changes at the drill site were investigated throughout the statistical and histopathological analysis. It was observed that the temperature increased with an increasing drill speed and decreased with high feed-rates and applied drill forces. The drilling temperatures of the female bovine tibias were found to be higher than that of the male tibias and the drill speed was found to be a significant parameter on the maximum temperature. Moreover, the maximum temperature increased with an increasing drill tip angle and bone mineral density. The bone quality around the drill site was found to be worse than the bone samples exposed to low temperatures.

Lee et al. (2011) presented a mechanistic model for the bone drilling process to enable prediction of bone drilling forces as a function of drill-bit geometry and drilling conditions. It was seen that increased speed commonly results in lower drilling forces. However, high speeds were observed to cause increased trauma. The effect of feed rate was also investigated; as expected, higher feed rates were seen to produce higher thrust forces and torques. The effect of drill-bit geometry on bone-drilling forces has also been investigated experimentally. Drill point angle has seen to have a strong effect on the drilling forces (i.e., sharper drill tip) were seen to produce lower forces; they also increased the unwanted drill breakthrough.

M. Matsuoka et al. (2011) measured the heat generated when using a self drilling miniscrew at speeds of 50, 100, 150, and 250 rpm. Specimens were classified into two groups: in the thin group the cortical bone thickness was 1.2 ± 0.02 mm on average and in the thick group it was 2.0 ± 0.03 mm on average. The temperature in the 1.2 mm and 2.0 mm cortical bone specimens was measured according to revolution speed. As the revolution speed increased, the temperature significantly increased in both bone thicknesses. The temperature increased significantly more in the thicker cortical bone. The temperature increase in the 2.0 mm thick bone at 250 rpm exceeded 10°C, regarded as the threshold for bone damage in this study; other temperature increases were below this threshold. Installing self-drilling screws at high speeds with an implanter is not recommended; low speeds of less than 150 rpm should be used.

Lee et al. (2012) presented an experimental investigation of the effects of spindle speed, feed rate, and depth of drilling on the temperature distribution during drilling of the cortical section of the bovine femur (Fig. 2.5). In an effort to reduce measurement uncertainties, a new approach for temperature measurements during bone drilling is presented in this study. The new approach is based on a setup for precise positioning of multiple thermocouples, automated data logging system, and a computer numerically controlled (CNC) machining system. This study suggests that the exposure time during bone drilling far exceeds the commonly accepted threshold for thermal injury, which may prevail at significant distances from the drilled hole.

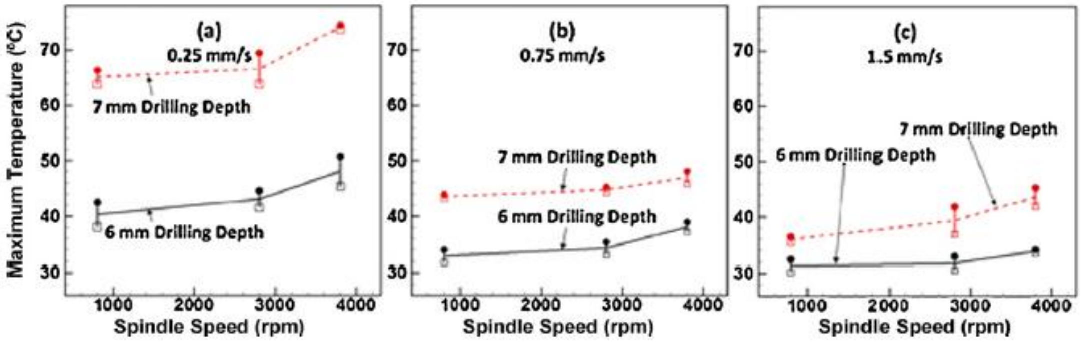


Figure 2.5: Maximum temperature at 3 mm depth as a function of the spindle speed for hole depths of 6 mm and 7 mm, and for an initial temperature of 26°C (Lee et al. 2012)

S. Sezek et al. (2012) in this study analysed the temperature changes during cortical bone drilling for different parameters such as drill rotation speed, feed-rate, drill diameter, drill force, bone mineral density and bone sex via the finite element method, FEM. The analysis has been validated by in vitro experiments using fresh calf cortical bones. Analytical and experimental results showed that the safe drilling parameters and drill temperatures can be estimated. To avoid thermal necrosis, the safe drilling zones (below 45°C) have been determined for various drill parameters during drilling of fresh cortical bones. Temperature increased 10% with 12% increase in bone mineral density and the safe drill parameters obtained to be 370 rpm drill speed, 70 mm/min feed rate and 140 N drill force.

Sui et al. (2013) developed an improved mechanistic model to predict the thrust force and torque for bone-drilling operation. The cutting action at the drill point is divided into three regions: the cutting lips, outer portion of the chisel edge (the secondary cutting edges) and inner portion of the chisel edge (the indentation zone). Models that account for the unique mechanics of the cutting process for each of the three regions are formulated. The models are calibrated to bovine cortical bone material using specific cutting pressure equations with modification to take advantage of the characteristics of the drill point geometry. The models are validated for the cutting lips, the chisel edge, and entire drill point for a wide range of spindle speed and feed rate. The predicted results agree well with experimental results. Only the predictions for the drilling torque on the chisel edge are lower than the experimental results under some drilling conditions. The model can assist in the selection of favourable drilling conditions and drill-bit geometries for bone-drilling operations.

Tuijthof et al. (2013) tried to measure the influence of drill bit geometry on maximum thrust forces required for drilling, and compare this relative to the known influence of feed rate and bone composition. Blind holes were drilled perpendicular to the iliac crest up to 10 mm depth in cadaveric pelvic bones of 20 pigs (adolescent) and 11 goats (full grown) with eight substantially different drill bits of Φ3-3.2 mm. Subsequently, boreholes were drilled perpendicular to the ilium with the same drill bits at three different feed rates (0.58 mm/s, 0.83 mm/s, 1.08 mm/s). The mean maximum thrust force ranges from 10 to 110 N for cortical bone, and from 3 to 65 N for trabecular bone. The results show that both drill bit geometry and feed rate have a significant influence on the maximum thrust forces, with a dominant influence of drill bit geometry in terms of shape of the flutes, sharpness of cutting edges and value of point angle.

Pandey et al. (2014) used a modified algorithm (grey based fuzzy algorithm) to optimize multiple performance characteristics in drilling of bone. Experiments have been performed with different cutting conditions using full factorial design. The quality parameters considered are temperature, force and surface roughness. Grey relational analysis (GRA) coupled with fuzzy logic is employed to obtain a grey fuzzy reasoning grade (GFRG) combining all the quality characteristics. The highest GFRG is obtained for the feed rate of 40 mm/min and the speed of 500 rpm and is the optimal level. Analysis of variance (ANOVA) carried out to find the significance of parameters on multiple performance characteristics revealed that the feed rate has the highest contribution on GFRG followed by the spindle speed.

2.2 Non Conventional Drilling

***Schwieger et al. (2004*)** investigated whether the abrasive jet cutting quality in cancellous bone with a biocompatible abrasive is sufficient for the implantation of endoprostheses or for osteotomies. Sixty porcine femoral condyles were cut with an abrasive water jet and with an oscillating saw. Lactose-monohydrate was used as a biocompatible abrasive. Water pressure (pW = 35 and 70 MPa) and abrasive feed rate (m = 0.5, 1, and 2 g/s) were varied (Fig. 2.6). As a measure of the quality of the cut surface the cutting gap angle (δ) and the surface roughness (*Ra*) were determined. Abrasive water jets are suitable for cutting cancellous bone. The large variation of the cutting gap angle is, however, unfavourable, as the jet direction cannot be adjusted by a predefined value. If it is possible to improve the cutting quality by a further parameter optimization, the abrasive water jet may be the cutting technique of the future for robotic usage.

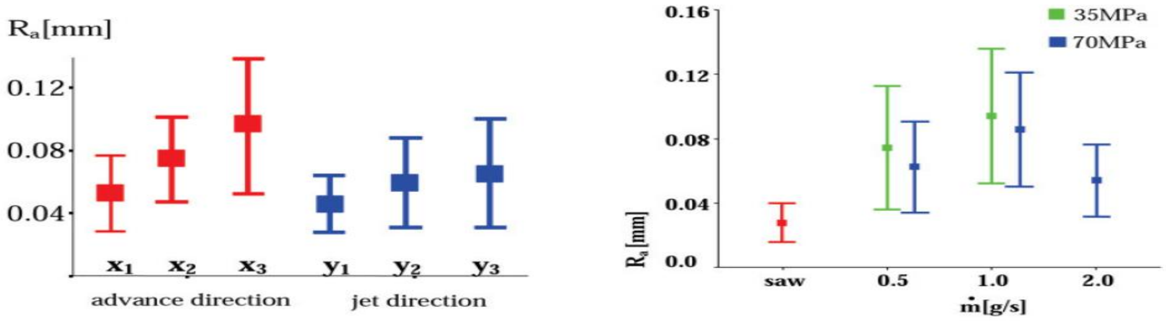


Figure 2.6: Variation in surface roughness depending upon the advance direction, jet direction & water jet pressure (Schwieger et al.2004)

***Biskup et al. (2006*)** investigated to find out the feasibility of water jets for medical applications as water jets are mostly used for applications where no structural changes are allowed. For medical applications the critical temperature is much lower than for industrial use, because bones react very sensitively to heat. The damage to the tissue depends on the temperature and the time of exposure. The tissue is irreversibly destroyed after a period of approximately 10 seconds at 57°C. To avoid this effect, which causes the so-called necrosis formation, and which results in poor bone healing, heat management is required for water-jet osteotomies. The first step has been made in this paper. The heat generation during abrasive water-jet osteotomies was measured by thermocouples that were inserted into the cortical hollow bone segments of cattle. The influence of parameters like pressure, traverse rate, abrasive flow rate and abrasive material have been shown together with the influence of the location of thermocouples Fig. 2.7.

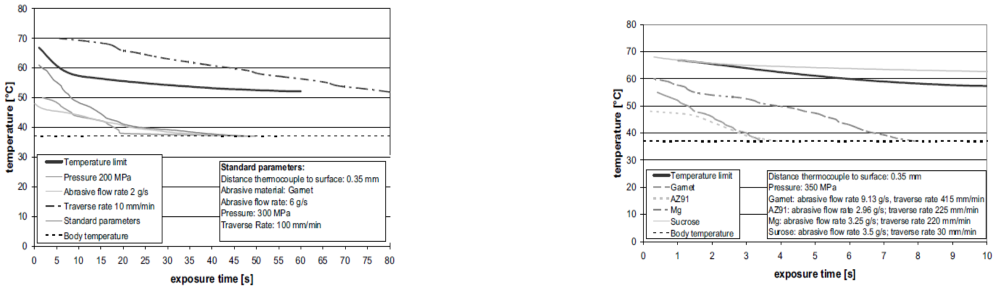


Figure 2.7: Effect of parameters on the temperature and the exposure time (Biskup et al. 2006)

Ozdemir et al. (2013) in this study tried to investigate the required time period of the Er:YAG laser that is used for drilling through cortical bone when pilot hole drilling is needed before mini screw insertion. Even though Er:YAG laser is used in various in vivo and in vitro studies, there is no accepted procedure of laser for depth control during drilling through cortical bone. The study sample consisted of 120 cortical bone segments having 1.5 and 2.0 mm of cortical bone thickness. An Er:YAG laser, with a spot size of 1.3 mm and an air–water spray of 40–50-ml/min, was used. The laser was held 2 mm away from and perpendicular to the bone surface with different laser settings. Twelve specimens were prepared for each subgroup. As the cortical bone thickness increased, the time needed to drill through the bone increased. Frequency increase directly caused a decrease in irradiation duration. When three different frequencies (10 Hz, 12 Hz & 15 Hz), three different energies (200 mJ, 300 mJ & 400 mJ) and four different power values (2.4W, 3W, 3.6W & 4W) were tested for both the 1.5- and 2-mm cortical bone thicknesses, the shortest duration needed to drill through cortical bone was seen in the 3.6W (300 mJ–12 Hz) setting (Fig. 2.8). When pilot holes are drilled prior to mini screw placement in 1.5 to 2 mm of cortical bone using Er:YAG laser, the most appropriate value is found with the 3.6W (300 mJ–12 Hz) setting.

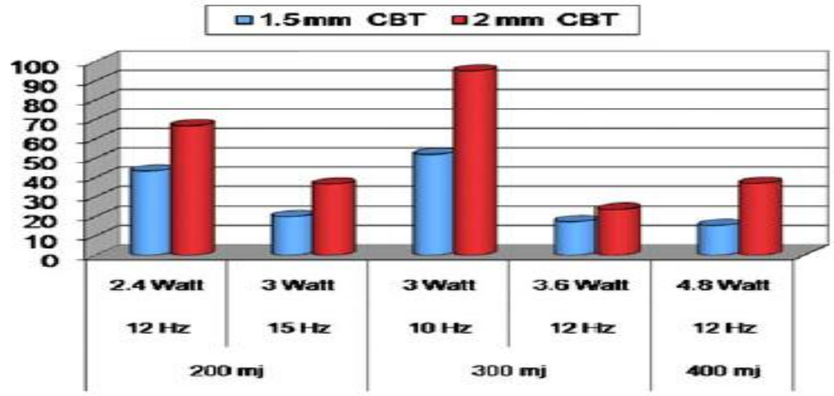


Figure 2.8: Schematic drawing of the mean values of the groups (Ozdemir et al. 2013)

Dunnen et al. (2013) carried out this study with the goal to deduce a descriptive mathematical equation able to predict the hole depth and diameter based on the local structural properties of the bone at given water jet diameters. 210 holes were drilled in porcine femora and tali with water jet diameters (D_{nozzle}) of 0.3, 0.4, 0.5 and 0.6 mm at a pressure of 700bar and a 5s jet time. Hole depths (L_{hole}), diameters (D_{hole}) and bone architectural properties were determined using micro CT scans. The most important bone architectural property is the bone volume fraction (BV/TV). Drilling to a specific depth in bone tissue with a known BV/TV is possible, thereby contributing to the safe application of water jet technology in orthopaedic surgery. Using water jets instead of rigid drill bits for bone drilling can be beneficial due to the absence of thermal damage and a consequent sharp cut. Additionally, water jet technology allows the development of flexible instruments that facilitate manoeuvring through complex joint spaces.

2.3 Research Gaps and Analysis

From the previous literature review it has been seen that authors used different geometries of the drill bit and different parameters were optimized. Some non conventional machining approaches were also used. Based on the previous studies following analysis can be made and further gaps can be postulated:

1. The drilling forces, if, exceeds from a predetermined value can cause the thermal narcosis of bone tissues.
2. Roughness on the bone surface helps in anchoring the screws and also, enhances the growth of tissues.
3. No work has been reported on the comparison of influence of process parameters on forces acting during conventional bone drilling using different types of tools.
4. Few studies focused on surface roughness of hole which is an influential parameter in the fixation of screws during bone surgery.

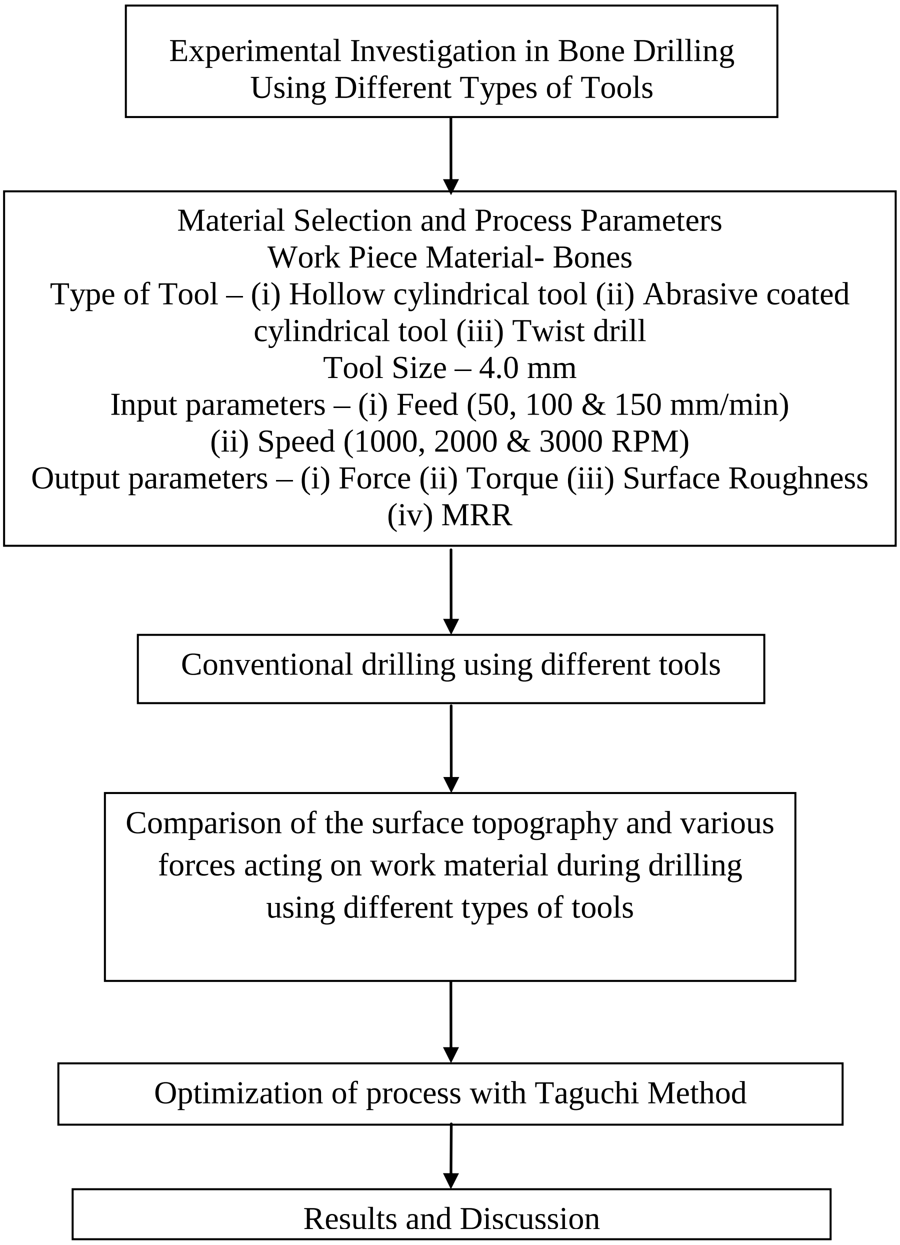
2.4 Problem Formulation

Thus, in the present study all the shortcomings of the previous studies were identified from a comprehensive literature survey and an attempt is made for **"Experimental investigation in bone drilling using different types of tools".**

2.5 Objectives of Present Work

- To investigate the various forces and torque acting during conventional bone drilling using different tools
- To investigate the effect of various process parameters on surface finish of bone during conventional drilling
- Optimization of the process parameters using Taguchi method.

2.6 Work Plan



Experimental Investigation in Bone Drilling Using Different Types of Tools

Material Selection and Process Parameters
Work Piece Material- Bones
Type of Tool – (i) Hollow cylindrical tool (ii) Abrasive coated cylindrical tool (iii) Twist drill
Tool Size – 4.0 mm
Input parameters – (i) Feed (50, 100 & 150 mm/min)
(ii) Speed (1000, 2000 & 3000 RPM)
Output parameters – (i) Force (ii) Torque (iii) Surface Roughness (iv) MRR

Conventional drilling using different tools

Comparison of the surface topography and various forces acting on work material during drilling using different types of tools

Optimization of process with Taguchi Method

Results and Discussion

Chapter-3

Experimentation

This chapter discusses in detail the experimental setup designed to carry out various drilling tests on Bone. The machine & materials required for experiments are:

(i) CNC Vertical Milling Machine
(ii) Dynamometer for measuring forces and torque during drilling operation
(iii) Collets for attachment of drill bit and other tools
(iv) Drill bits and tools (Dia. 4mm)
(v) Work piece material

The detailed description of the machine tool, tool holder, tool type, work piece material and the measurement instruments used for this research work have been discussed in the following sections.

3.1 Description of Machining Setup

3.1.1. CNC Vertical Milling Machine

Whole experiments will be carried out on CNC 3-Axis high-speed Vertical Milling Machine (Fig. 3.1) along with Dynamometer set up to measure the forces and torque acting on work material (bone) during drilling. The maximum power input to the machine is 22.4 kW. The maximum rpm is 8100 rpm, its coolant capacity is 208 L. The maximum length and width of machine is 1219 mm and 457 mm. The maximum tool diameter which can be hold in tool holder is 89 mm. Complete technical specifications for the M/C are given in Table 3.1.

Figure 3.1: CNC Vertical Milling Machine

Table 3.1: Specification of CNC Vertical Milling Machine

TRAVEL	S.A.E	METRIC
X-Axis	40’’	1016 mm
Y-Axis	20’’	508 mm
Z-Axis	25’’	635 mm
Spindle Nose to Table (~ max)	29’’	737 mm
Spindle Nose to Table (~ min)	4’’	102 mm
TABLE	**S.A.E**	**METRIC**
Length	48 "	1219 mm
Width	18 "	457 mm
T-Slot Width	5/8 "	16 mm
T-Slot Center Distance	3.15 "	80.0 mm
Number of Std T-Slots	5	5
Max Weight on Table (evenly distributed)	3500 lb	1588 kg
SPINDLE	**S.A.E.**	**METRIC**
Type	Carousel (SMTC Optional)	Carousel (SMTC Optional)
Capacity	20	20
Max Tool Diameter (full)	3.5 "	89 mm
Max Tool Weight	12 lb	5.4 kg
Tool-to-Tool (avg)	4.2 sec	4.2 sec
Chip-to-Chip (avg)	4.5 sec	4.5 sec

GENERAL	S.A.E.	METRIC
Air Required	4 scfm, 100 psi	113 L/min, 6.9 bar
Coolant Capacity	55 gal	208 L

3.1.2. Dynamometer set up

KISTLER Piezoelectric Dynamometer is used for measuring the forces and torque during the machining operations Fig 3.2. Here it will be used to measure force and torque during drilling through bone. There are four channels in it. Three of them measure force acting in X, Y & Z direction whereas fourth channel measure torque. The whole set up has been shown below:

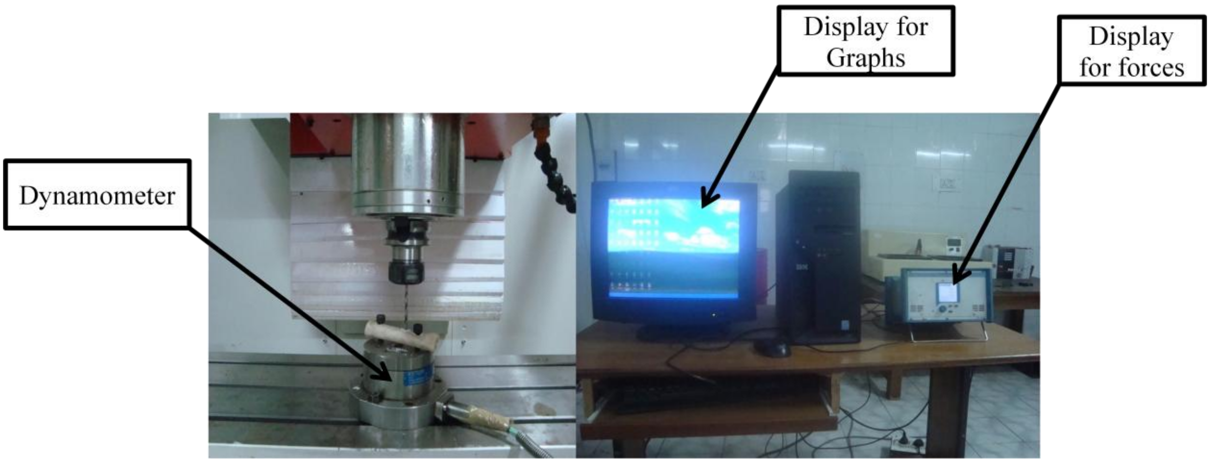


Figure 3.2: Dynamometer set up

3.1.3. Cutting Tool Holder

The tool holder used for drilling on milling machine was a high speed balanceable tool holder. The purpose of tool holder’s balancing was to improve the mass distribution of its body (reduce unbalance) in order to produce centrifugal forces within the prescribed limit, when spinning at high spindle speeds. The tool holder is provided with two counter weights in a single plane at fixed distance from the front end of the tool holder. The two counter weights can be moved circumferentially to reduce the imbalance in this single plane. The tool holder can take spring collets (Fig. 3.3) for locking the rotary tools like mills, drills, reamers, etc. An assembly drawing of the tool holder used is shown as:

Figure 3.3: Collet for griping tool during Experimental Work

3.2 Cutting Tools

3.2.1. Drill Bits

The drill bits used for drilling of bones is HSS drill bits, diameter of 4.0 mm having 2 flutes (Fig. 3.4). Drill bits are incredibly effective in high production applications.

Figure 3.4: High Speed Steel Drill Bit (Φ 4 mm)

3.2.2. Hollow Tools

Hollow tools were made from 4 mm Stainless steel pipe Fig 3.5. The pipe was procured from market. It was having wall thickness of 0.5 mm. It was cut in pieces of 75 mm length with the help of hacksaw. The cut pieces were having burr at their ends. The edges were made smooth with the help of smooth file.

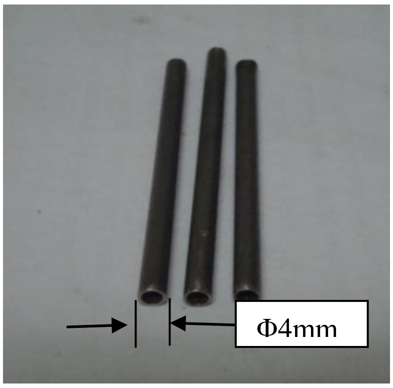


Figure 3.5: Φ 4 mm SS hollow tool

3.2.3. Solid Tools with Abrasive Coating

These types of tools are generally used for finishing of holes already drilled. There are different types of tools of such nature are available in the market. Diamond coated tools were used because diamond dust is bio-compatible. The tools used for experiments have been shown in Fig. 3.6.

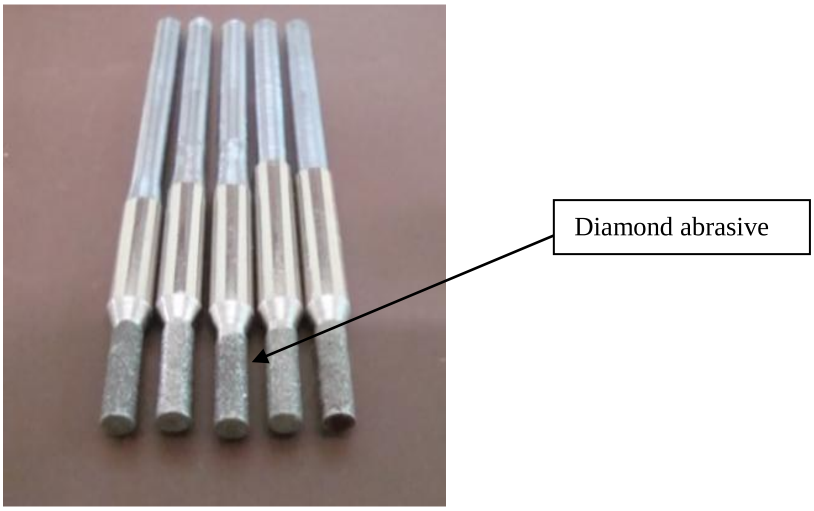


Figure 3.6: Φ 4 mm Tools with Abrasive Coating

3.3 Work Piece Material

The raw material used was natural bone Fig. 3.7. All the bones used in the experiments were taken from slaughter house. Fresh bones were used for the experiments. They were taken directly from the butcher shop and experiments were conducted. The bones used in the experiments were of goat because it has similar properties as human bone has.

Figure 3.7: Bone

The properties of bones are explained below:

3.3.1. Composition

Chemical composition of natural bone is:

Table 3.2: Chemical Composition of bone

Element	Content (%)
Calcium	73%
Phosphors	27%

3.3.2. Mechanical Properties:

Bone has following mechanical properties:

Table 3.3: Mechanical Properties of bone

Tensile strength	65 Mpa
Compressive strength	200 Mpa
Elasticity	1.5%
Hardness	70.36 HRC
Thermal conductivity	0.1-0.3 W/mK
Density	1800 Kg/m^3
Specific heat	1300 J/KgK

3.4 Design of Experiments

Design of Experiment is a strategy to gather empirical knowledge, i.e. knowledge based on the analysis of experimental data and not on theoretical models. It may be applied when investigating a phenomenon in order to gain understanding or improve performance. There are four interrelated steps in building a design e.g. "better understand" or “sort out important variables" or "find the optimum conditions."

3.4.1. Full Factorial Design

The full factorial design is referred as the technique of defining and investigating all possible conditions in an experiment involving multiple factors while the fractional factorial design investigates only a fraction of all the combinations. These approaches are widely used, while they have certain limitations. They are inefficient in time and cost when the number of the variables is large; they require strict mathematical treatment in the design of the experiment and in the analysis of results; the same experiment may have different designs thus produce different results; further, determination of contribution of each factors is not permitted in this kind of design. The Taguchi method has been proposed to overcome these limitations by simplifying and standardizing the fractional factorial design. The methodology involves identification of controllable and uncontrollable parameters and the establishment of a series of experiments to find out the optimum combination of the parameters, which has greatest influence on the performance and the least variation from the target of the design.

3.4.2. Orthogonal Array (OA)

OA plays a critical part in achieving the high efficiency of the Taguchi method. OA is derived from factorial design of experiment by a series of very sophisticated mathematical algorithms including combinatory, finite fields, geometry and error- correcting codes. The algorithms ensure that the OA is to be constructed in a statistically independent manner that each level has an equal number of occurrences within each column; and for each level within one column, each level within any other column will occurs an equal number of times as well. Then, the columns are called orthogonal to each other [Roy, 1990]. OAs is available with a variety of factors and levels in the Taguchi method. Since each column is orthogonal to the others, if the results associated with one level of a specific factor are much different at another level, it is because changing that factor from one level to the next has strong impact on the quality characteristic being measured. Since, the levels of the other factors are occurring at an equal number of times for each level of the strong factor, any effect by these other factors will be ruled out. The Taguchi method apparently has the following strengths:

(i) Consistency in experimental design and analysis

(ii) Reduction of time and cost of experiments

(iii) Robustness of performance without removing the noise factors

3.4.3. Selection of Orthogonal Array

The selection of orthogonal array depends on:

(i) The number of factors and interactions of interest

(ii) The number of levels for the factors of interest

Taguchi‘s orthogonal arrays are experimental designs that usually require only a fraction of the full factorial combinations. The arrays are designed to handle as many factors as possible in a certain number of runs compared to those dictated by full factorial design. The columns of the arrays are balanced and orthogonal. This means that in each pair of columns, all factor combinations occurs at same number of times. Orthogonal designs allow estimating the effect of each factor on the response independently of all other factors. Once the degrees of freedom are known, the next step, selecting the orthogonal array (OA) is easy. The number of treatment conditions is equal to the number of rows in the orthogonal array and it must be equal to or greater than the degrees of freedom. The interactions to be evaluated will require an even larger orthogonal array. Once the appropriate orthogonal array has been selected, the factors and interactions can be assigned to the various columns.

3.4.4. Degree Of Freedom (DOF)

The number of factors and their interactions and level for factors determine the total degree of freedom required for the entire experimentation. The number of levels minus one gives the degree of freedom for each factor. d.o.f. for each factor : k-1
Where K is the no of level for each factor.

3.4.5. Procedure of Experimental Design

The whole procedure of Taguchi method is as under

(i) Establishment of objective function
(ii) Selection of parameters and/or interactions to be evaluated
(iii) Selection of number of levels for the controllable and uncontrollable parameters
(iv) Calculation total degree of freedom needed
(v) Select the appropriate Orthogonal Array (OA)
(vi) Assignment of parameters and/or interactions to columns
(vii) Execution of experiments according to trial conditions in the array
(viii) Analyze results

3.4.6. Establishment of Objective Function

In present study following three objective functions have been considered.

(i) Surface Roughness (Ra)
(ii) Material Removal Rate (MRR)
(iii) Force (F)

The main aim is to maximize the surface roughness without affecting the strength of hole boundaries, Maximize MRR with the use of nominal force.

3.4.7. Selection of Parameters

The objective of this study is to evaluate the main effects of rotational speed, feed and tool shape on the surface roughness, material removal rate and force during drilling. The lists of factors studied with their levels are given in Table 3.4.

Table 3.4: Control variables and their levels

S. No	Factor	Level 1	Level 2	Level 3
01	Type of tool	Abrasive coated	Hollow	Twist Drill
02	Speed (RPM)	1000	2000	3000
03	Feed (mm/min)	50	100	150

3.4.8. Calculation of Total Degree Of Freedom

The degree of freedom (DOF) of a three level parameter is two (number of levels-1). Hence, total degree of freedom is 6.

Table 3.5: Degree of freedom as per level

Interaction	Units	DOF
Rotational speed (A)	RPM	2
Feed (B)	mm/min	2
Tool (C)	--	2
	Total	6

3.4.9. Selection of the Appropriate Orthogonal Array

Out of the standard OA available in Taguchi design, L9 OA has eight degree of freedom and it can accommodate three levels of four parameters, so it has been selected for the experimentation. In addition, the orthogoanlity of an array is not lost if one or more columns are not used. Thus a total of nine experiments are required to be performed. Taguchi also recommends that each Experiment should be repeated three times to minimize the effect of uncontrollable factors. Accordingly, after constructing the control log, each set of nine experiments is to be repeated Three times.

3.4.10. Execution of Experiments

The execution of experiments with various interactions at three levels is given in Table 3.6.

Table 3.6: L9 Array in Taguchi

Experiment No.	Speed (RPM)	Feed Rate (mm/min)	Type of Tool
1.	1000	50	Abrasive coated
2.	1000	100	Hollow
3.	1000	150	Drill
4.	2000	50	Hollow
5.	2000	100	Drill
6.	2000	150	Abrasive coated
7.	3000	50	Drill
8.	3000	100	Abrasive coated
9.	3000	150	Hollow

3.4.11. Analysis of Results

Signal-to-noise ratio

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

Characteristics explained below.

$\sum_{i=1}^{r} y_{j^2}$ = Summation of all response values under each trial

r is the number of tests in a trial (noise of repetitions regardless of noise levels)

MSD = Mean square deviation

Y_j= Observed value of the response characteristic

y_o= nominal or target value of the results

The three different response characteristics are given by the following:

1. ***Higher is Better***: The S/N for higher the better is given by

$$(S/N)_{HB} \;=\; -10\ (MSDHB)$$

Where $\text{MSD}_{\text{HB}} \;=\; \frac{1}{r}\sum_{i=1}^{r}\frac{1}{y_{j2}}$

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

2. ***Nominal is Better***: The S/N for nominal is better is

$$(S/N)_{NB} \;=\; -10\ (MSD_{\text{NB}})$$

Where $\text{MSD}_{\text{NB}} = \frac{1}{r}\sum_{J=1}^{r}(\text{y}_{\text{j}} - \text{y}_{\text{o}})^2$

3. ***Lower is Better***: In this design situation, the mean square deviation (MSD), given by

$$(S/N)_{LB} \;=\; -10\ (MSD_{\text{LB}})$$

Where $MSD_{LB} = \frac{1}{r}\sum_{J=1}^{r}\text{y}_{\text{j}}{}^{2}$

Analysis of variance

The knowledge of the contribution of individual parameters is critically important for the control of the final response. The analysis of variance (ANOVA) is a common statistical technique to determine the percent contribution of each parameter for results of the experiment. It calculates parameters known as sum of squares (*SS*), pure SS, degree of freedom (dof), variance, F-ratio and percentage contribution of each parameter. Since the procedure of ANOVA is a very complicated and employs a considerable of statistical formula, only a brief description of is given as following.

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

Let '*A*' be a parameter under investigation

Where N = Number of response observations, *T* is the mean of all observations *Yj* is the i^{th} response

Parameter Sum of Squares (*SSA)* - Squared deviations of parameter (*A*) averages from overall average

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

Where,

Average of all observations under *Ai* level = *Ai/n Ai*

T = sum of all observations

T = Average of all observations = T / N

N_{Ai} =Number of observations under Ai level

Error Sum of Squares (*SS e)* - Squared deviations of observations from parameter (A) averages

3.5 Experimental Details

The entire experimental research task was divided into following phases:

The first part was carried out to study the drilling characteristics of the material at low, medium and high speed, and different feeds cutting conditions. The responses, for the various desirable outputs, are recorded and used as inputs for the optimization.

The following three independent parameters were selected for this study:

1. Type of Tool
2. Speed
3. Feed rate

The ranges of these parameters were selected on the basis of 'pilot experimentation' conducted to assess the influence of a specific parameter on the machining characteristics of interest (MRR, Ra) by using "one factor at a time approach". The work material for this experimentation was selected as bone.

The complete process had been carried out in following steps:

3.5.1. Preparation of Bone for Drilling

Fresh bones were taken from the butcher shop for the experiments. Two holes Φ 9 mm were drilled in the bones at a centre to centre distance of 60 mm for fixing it onto the dynamometer. Bone fixed on the dynamometer with the help of Φ 8 mm L-key bolt as shown in the Fig. 3.8.

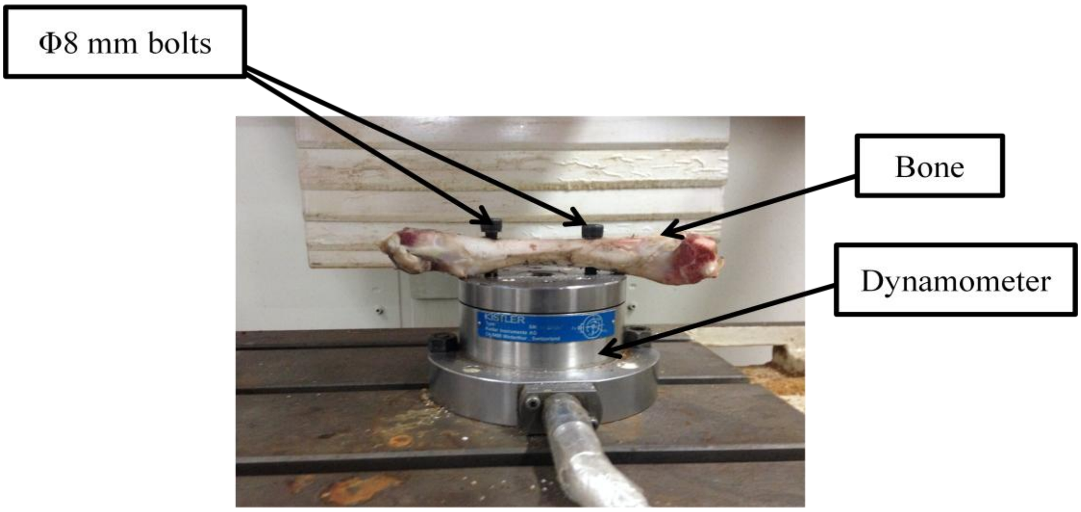
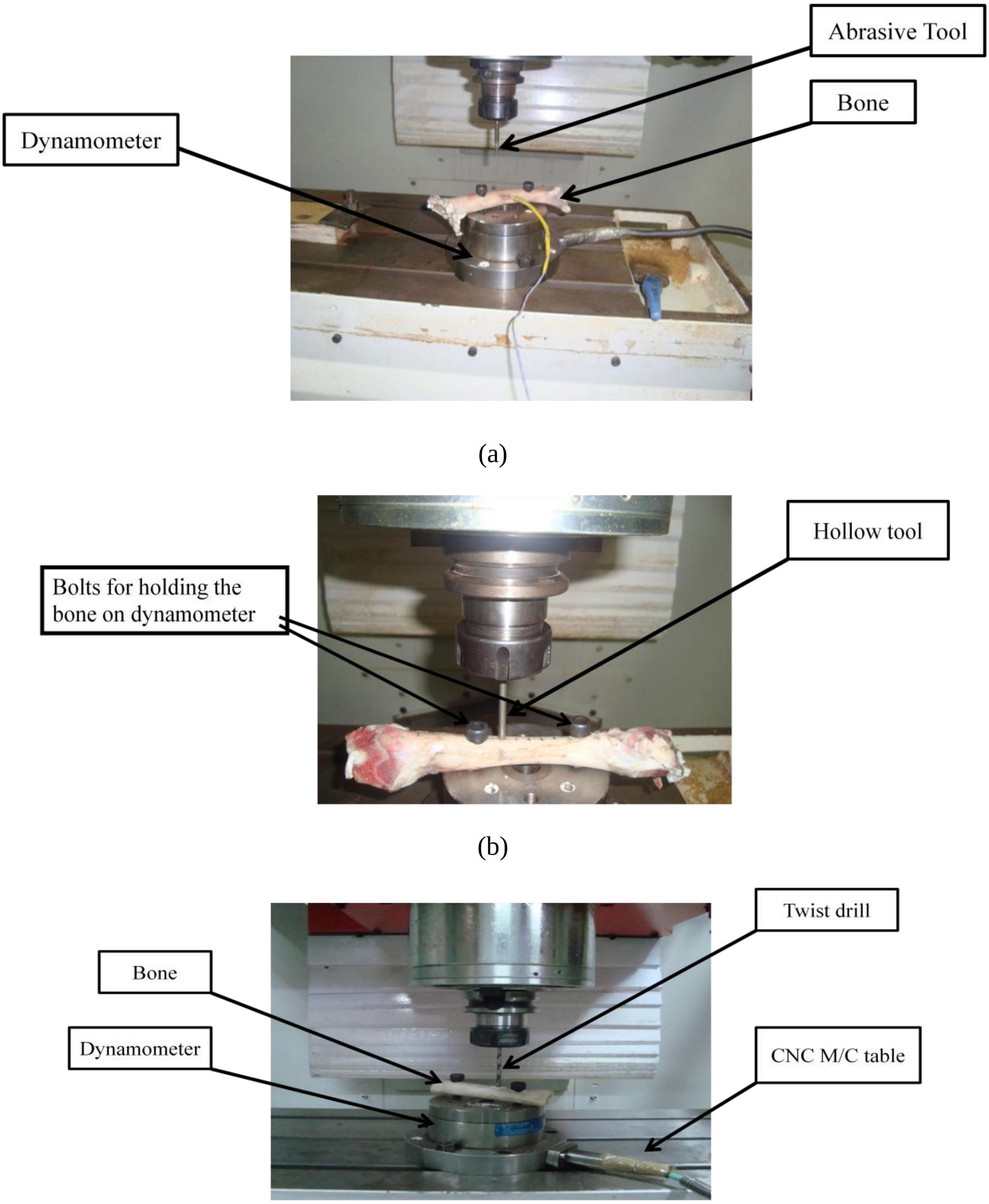


Figure 3.8: Bone fixing with the help of Φ 8 mm bolts on dynamometer

3.5.2. Drilling of Bones

A detailed description of machining setups which were used for drilling of bones using various types of tools had been given in Fig. 3.9.



(a)

(b)

(c)

Figure 3.9: (a) Showing machine set up with abrasive tool (b) machine set up with hollow tool (c) machine set up with twist drill

For performing the experiments the programme is to be fed into the machine.

Programme used

The programme was made using G & M codes. Total nine programmes were written. One of the programmes used was:

```
G01     X0      Y0      Z0      F50;
S1000  M03;
Z-10;
Z0;
M30;
```

Where, F = feed,

S = spindle speed (RPM),

M03 = spindle rotation clockwise,

M30 = programme end and rewind

Left over programmes were written by changing the corresponding values of feed (100&150) and speed (2000&3000) respectively.

Drilling of bones was carried out as per the L9 Table 3.4. Total 27 holes were drilled (Fig. 3.10). The time taken for each drill was measured with the help of stop watch.

(a)

(b)

(c)

Figure 3.10: (a) Holes drilled with the help of abrasive coated tool (b) Holes drilled with the help of hollow tool (c) Holes drilled with the help of twist drill

3.5.3. Measurement of Force and Torque

Force and torque acting on the bone during each drilling was recorded with the help of KISTLER Piezoelectric Dynamometer. Four graphs and an excel sheet was generated for each drill showing the variation of force (all the three axis i.e. X, Y & Z) and torque. Total Graphs for experiment no.1 to 9 had been shown in Fig. 3.11 to Fig.3.19.

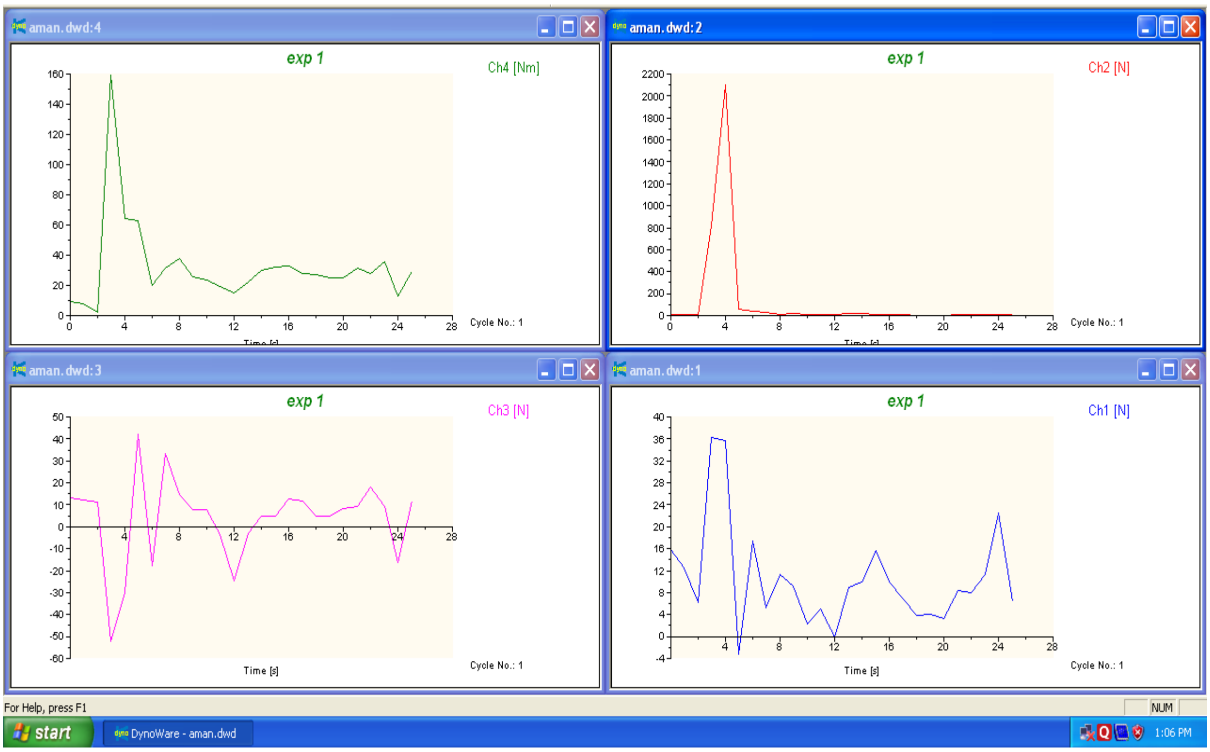


Figure 3.11: Graphs of Force and torque on different channels for experiment No.1

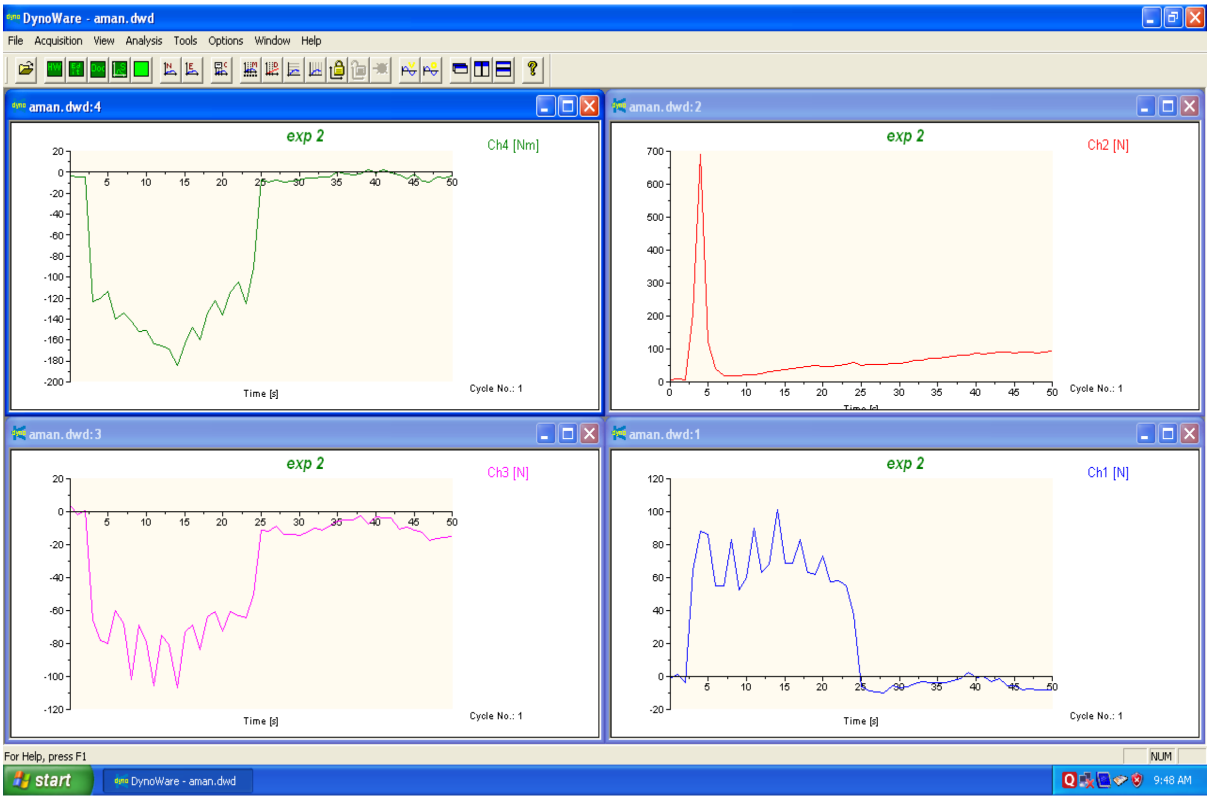


Figure 3.12: Graphs of Force and torque on different channels for experiment No.2

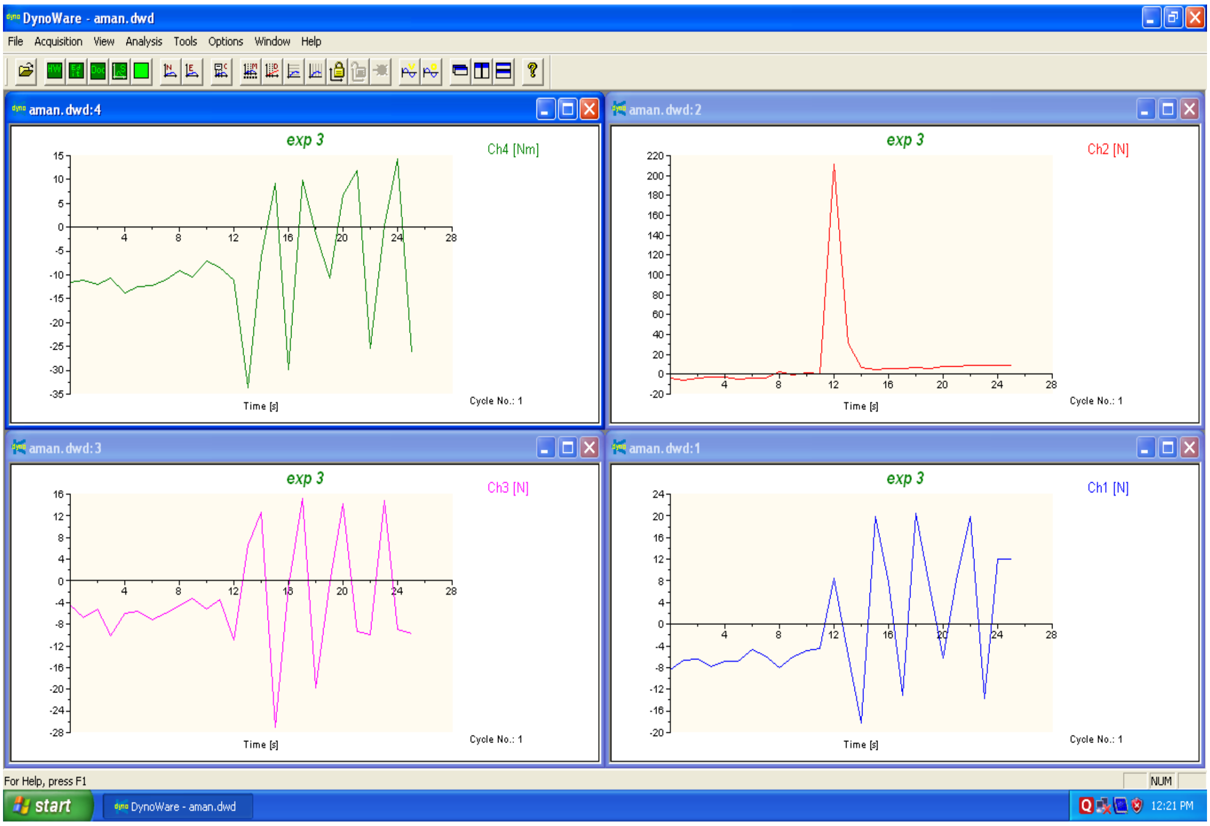


Figure 3.13: Graphs of Force and torque on different channels for experiment No.3

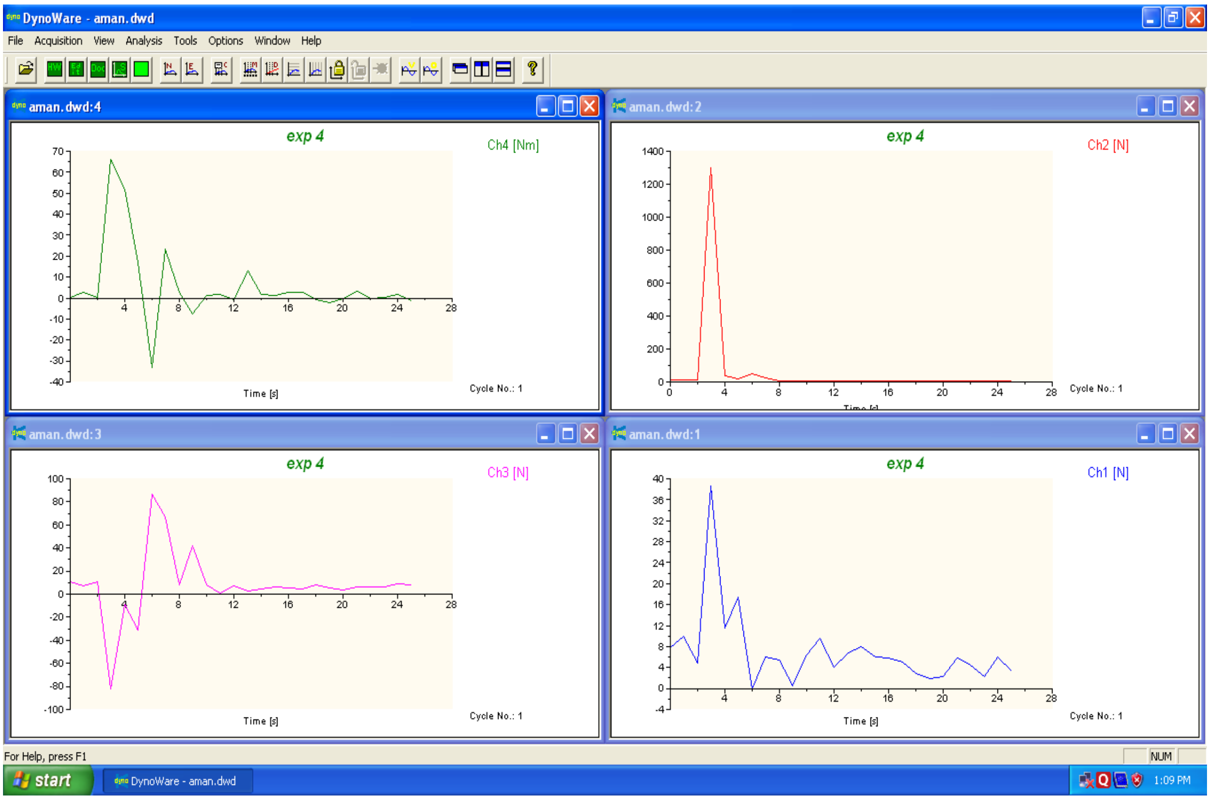


Figure 3.14: Graphs of Force and torque on different channels for experiment No.4

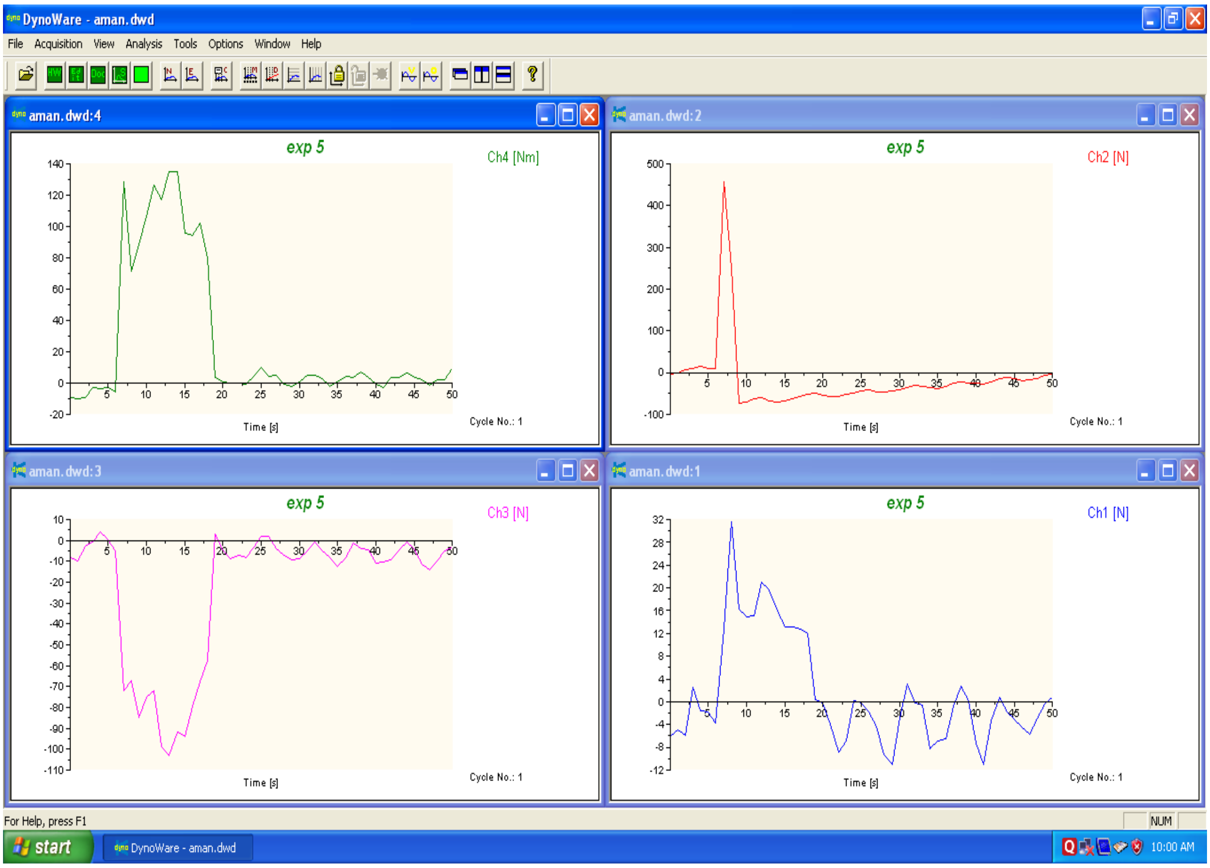
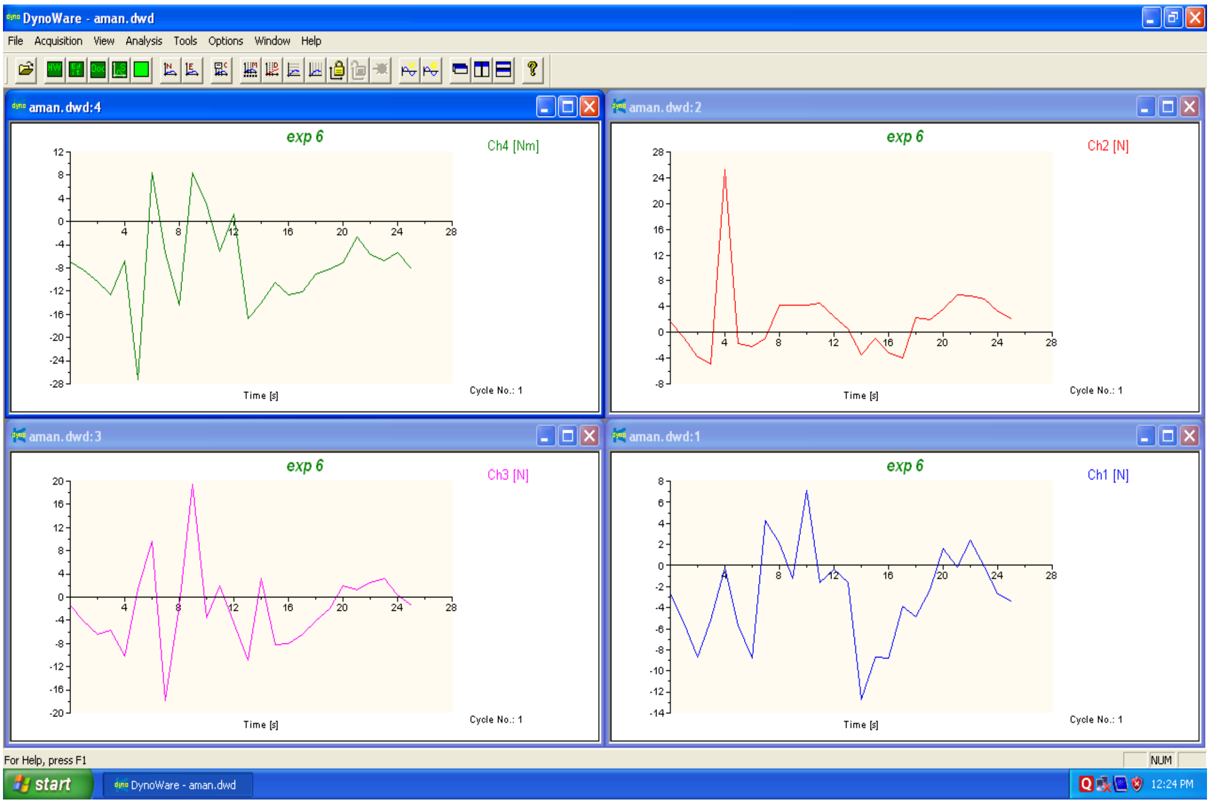


Figure 3.15: Graphs of Force and torque on different channels for experiment No.5



For Help, press F1

Figure 3.16: Graphs of Force and torque on different channels for experiment No.6

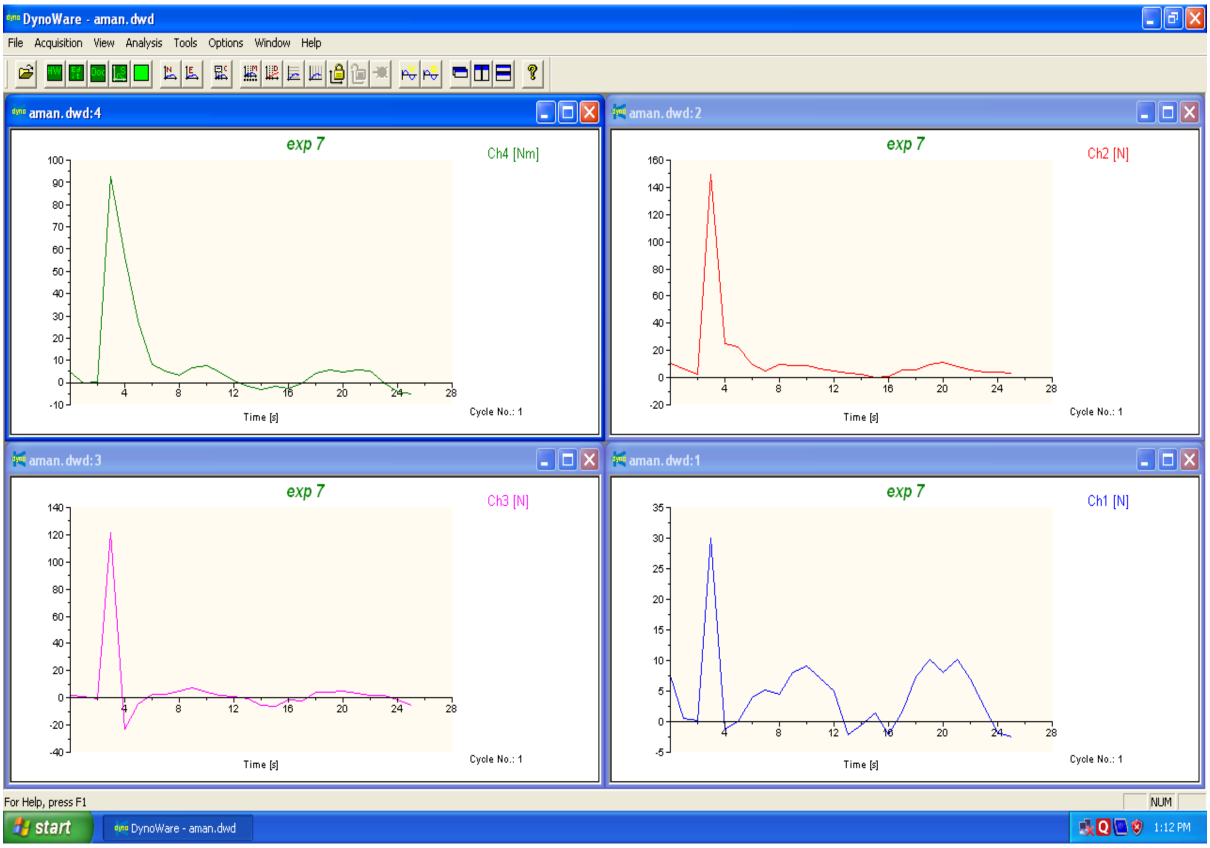


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Figure 3.17: Graphs of Force and torque on different channels for experiment No.7

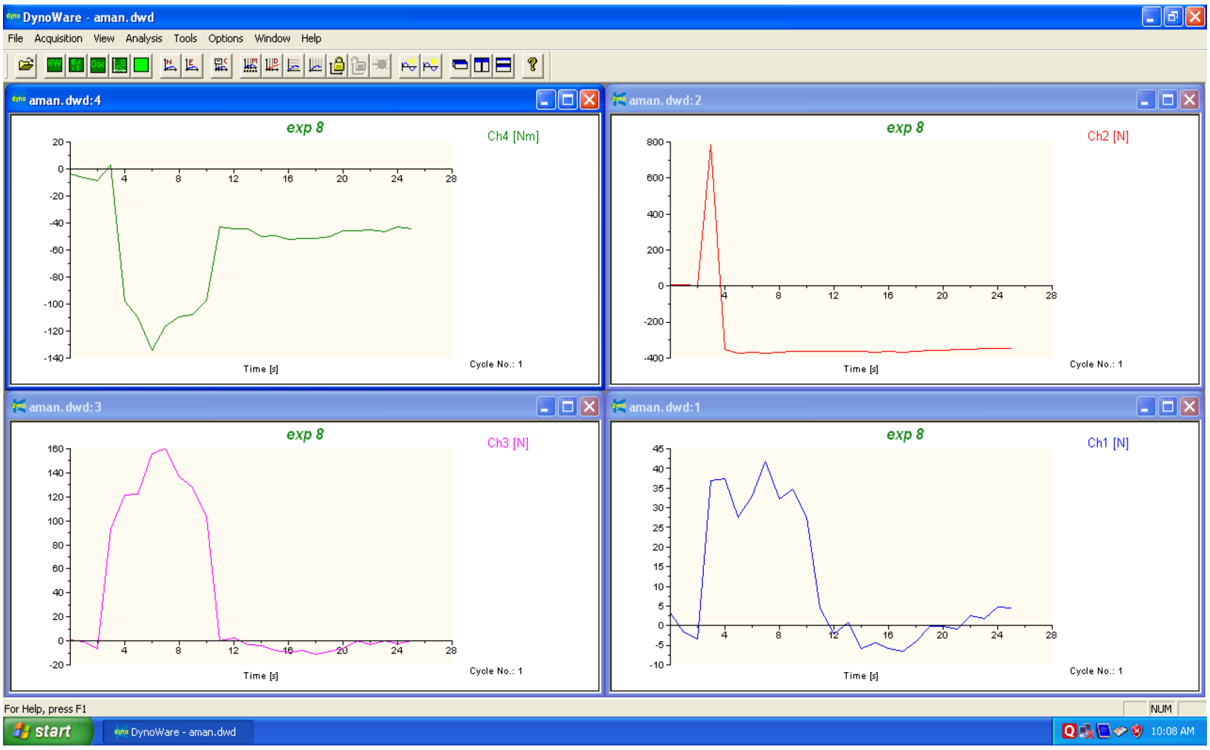


Figure 3.18: Graphs of Force and torque on different channels for experiment No.8

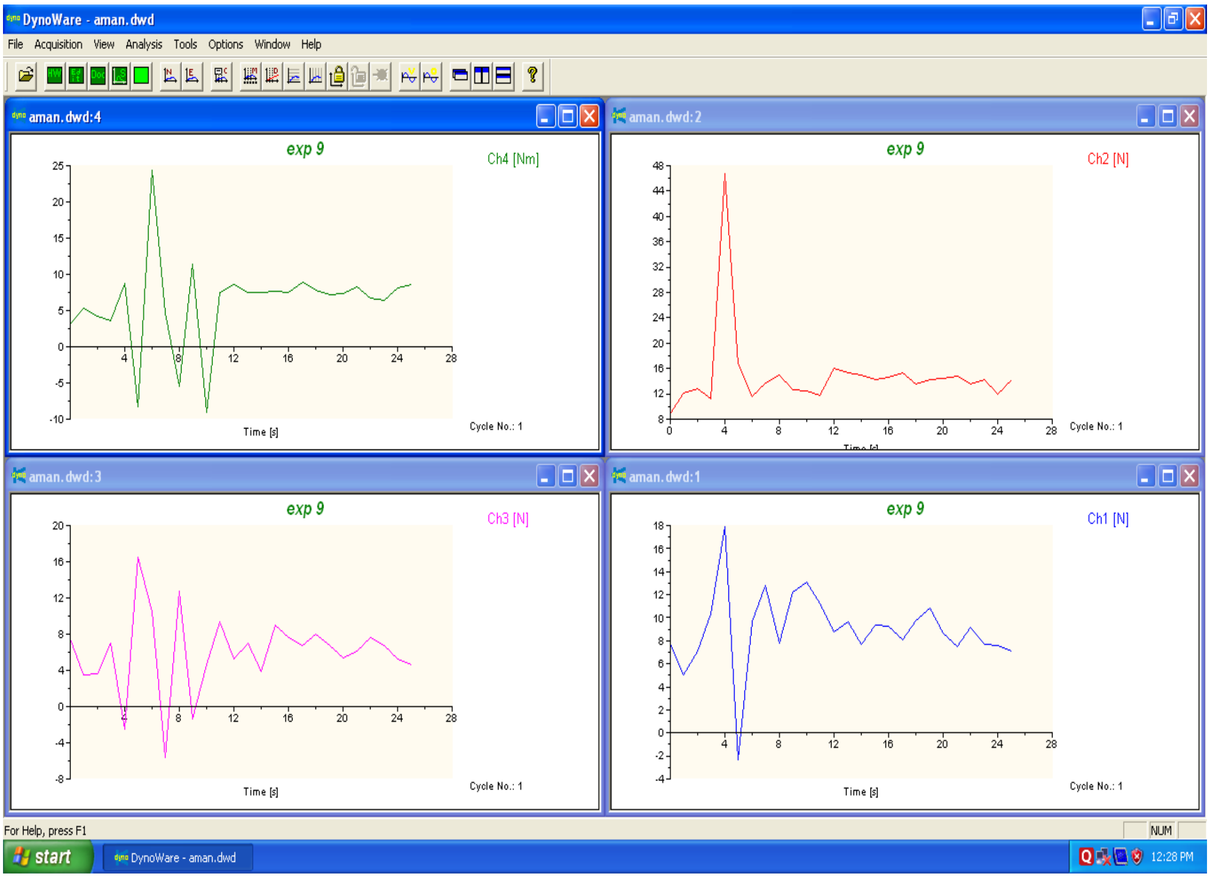


Figure 3.19: Graphs of Force and torque on different channels for experiment No.9

3.6 Surface Roughness Measurement

After drilling the holes in bones, the bones were cut down with the help of hacksaw for analyzing the surface roughness of material. The needle (stylus) which is attached in surface roughness tester slides on the work piece and tells the values. The surface roughness was measured along the depth of the drilled hole with the help of Perthometer of Mitutoyo Company (Surftest SJ-400) Fig. 3.20. The surface roughness was measured at Thapar University Patiala Lab.

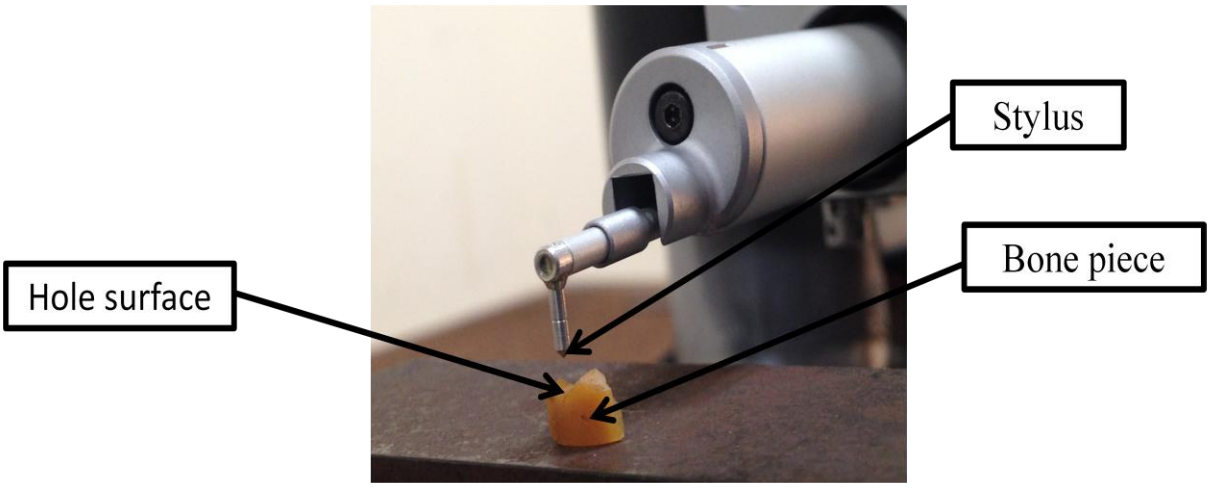


Figure 3.20: Measurement of surface roughness

3.7 SEM

SEM photographs are taken to analyze the surface roughness obtained after using different types of tools and using various feed rates as well as different RPM. In this study, the bone specimens were prepared to investigate the surface roughness and micro structure after drilling. As the bone is a non conducting material so gold plating was carried out on the specimens to make them conductive Fig. 3.21. The SEM equipped with Energy Dispersive X-Ray Spectroscopy (EDAX) was used under various magnifications (X500 & X1000) to capture the appropriate surface images and to determine the micro structure of hole top surface as well as inside the drilled holes.

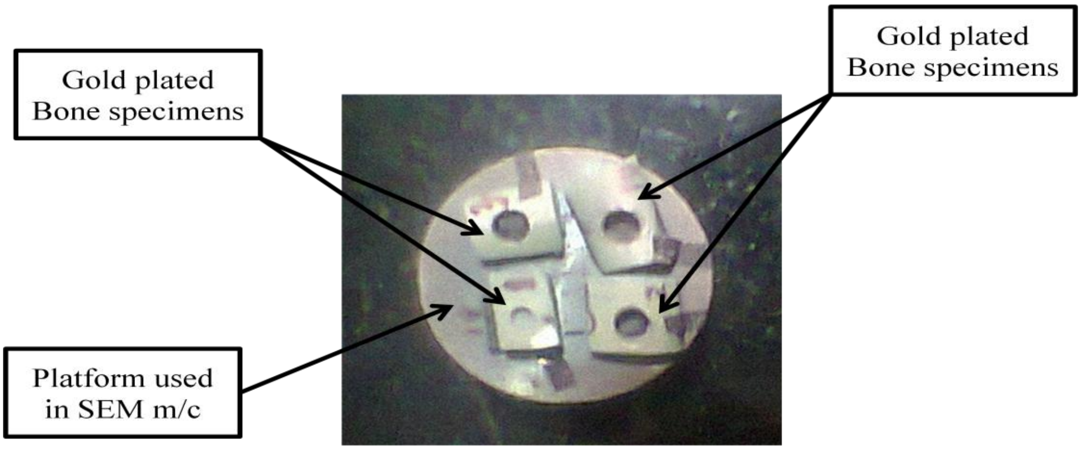


Figure 3.21: Bone specimens used for SEM

Chapter-4

Result, Analysis and Discussion

This chapter focuses on the experimental results, analysis and discussion of main experiments of conventional drilling of bone. In these experiments, the effect of speed, feed and type of cutting tools used on surface roughness (Ra), material removal rate (MRR) and force was studied.

4.1 Results

The values obtained after every experiment for various output parameters have been recorded in various tables i.e. Table 4.1 (Ra), Table 4.2 (MRR) & Table 4.3 (Force).

Table 4.1: 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	1000	50	Abrasive Coated	0.6	0.63	0.66	0.63	-4.0132
2	1000	100	Hollow	1.01	1.05	1.06	1.04	0.3407
3	1000	150	Drill	0.24	0.27	0.3	0.27	-11.3727
4	2000	50	Hollow	1.01	1.07	1.10	1.06	0.5061
5	2000	100	Drill	0.29	0.34	0.39	0.34	-9.3704
6	2000	150	Abrasive Coated	0.65	0.70	0.75	0.7	-3.0980
7	3000	50	Drill	0.10	0.14	0.20	0.15	-16.4782
8	3000	100	Abrasive Coated	0.51	0.57	0.60	0.56	-5.0362
9	3000	150	Hollow	1.23	1.29	1.35	1.29	2.2118

Table 4.2: Result table for MRR

Exp. No.	**Speed (RPM)**	**Feed (mm/min)**	**Type of Tool**	**MRR 1**	**MRR 2**	**MRR 3**	**Average MRR (mm^3/sec)**	**SN Ratio for MRR**
1	1000	50	Abrasive Coated	5.21	5.15	5.09	5.15	14.2361
2	1000	100	Hollow	10.44	10.39	10.31	10.38	20.3239
3	1000	150	Drill	15.10	15.05	15.00	15.05	23.5507
4	2000	50	Hollow	4.73	4.65	4.60	4.66	13.3677
5	2000	100	Drill	10.11	10.04	10.00	10.05	20.0433
6	2000	150	Abrasive Coated	14.80	14.75	14.70	14.75	23.3758
7	3000	50	Drill	5.20	5.10	5.00	5.10	14.1514
8	3000	100	Abrasive Coated	9.80	9.70	9.60	9.60	19.6454
9	3000	150	Hollow	13.96	13.93	13.90	13.93	22.8790

Table 4.3: Result table for Force

Exp. No.	Speed (RPM)	Feed (mm/min)	Type of Tool	Force 1	Force 2	Force 3	Average Force (N)	SN Ratio for Force
1	1000	50	Abrasive Coated	290.35	290.43	290.57	290.45	-49.2614
2	1000	100	Hollow	260.72	260.81	261.11	260.88	-48.3288
3	1000	150	Drill	21.50	21.59	21.62	21.57	-26.6770
4	2000	50	Hollow	333.9	334.01	334.33	334.08	-50.4770
5	2000	100	Drill	27.65	27.72	27.79	27.72	-28.8559
6	2000	150	Abrasive Coated	220.80	220.91	221.11	220.94	-46.8855
7	3000	50	Drill	43.80	43.85	43.90	43.85	-32.8394
8	3000	100	Abrasive Coated	180.35	180.45	180.55	180.45	-45.1271
9	3000	150	Hollow	119.30	119.39	119.48	119.39	-41.5394

4.2. Surface Roughness (Ra)

4.2.1. Analysis of Variance for Ra

The response tables for SN ratio and Mean have been made Table 4.4 and Table 4.5. The results were analyzed using ANOVA for identifying the significant factors affecting the surface roughness. The Analysis of Variance (ANOVA) for the Surface Roughness at 95% confidence interval is given in Table 4.6. 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 shows that speed (F 0.83 value), feed (F 0.99 value), type of tool (F 25.20 value) are the factors that significantly affect the tensile strength. Type of tool has highest contribution to surface roughness. Main effect plots for the SN ratio & Means of surface roughness have been shown in the Fig. 4.1 and Fig. 4.2 which show the variation of surface roughness with the input parameters.

Table 4.4: Response Table for SN Ratio (Ra)

Level	**Speed**	**Feed**	**Tool**
1	-5.015	-6.662	-4.049
2	-3.987	-4.689	1.020
3	-6.434	-4.086	-12.407
Delta	2.447	2.575	13.427
Rank	3	2	1

Table 4.5: Response Table for Means (Ra)

Level	**Speed**	**Feed**	**Tool**
1	0.6447	0.6133	0.6300
2	0.7000	0.6447	1.1300
3	0.6667	0.7533	0.2533
Delta	0.0533	0.1400	0.8767
Rank	3	2	1

Table 4.6: ANOVA for S/N Ratio of Surface Roughness (Ra)

Source	**SS**	**D.O.F**	**Variance**	**F**	**P**	**% contribution**
Speed	9.057	2	4.528	0.83	0.547	2.95
Feed	10.889	2	5.444	0.99	0.500	3.57
Type of Tool	275.821	2	137.911	25.20	0.038	89.92
Residual Error	10.946	2	0.07155			3.56
Total	306.713	8				100

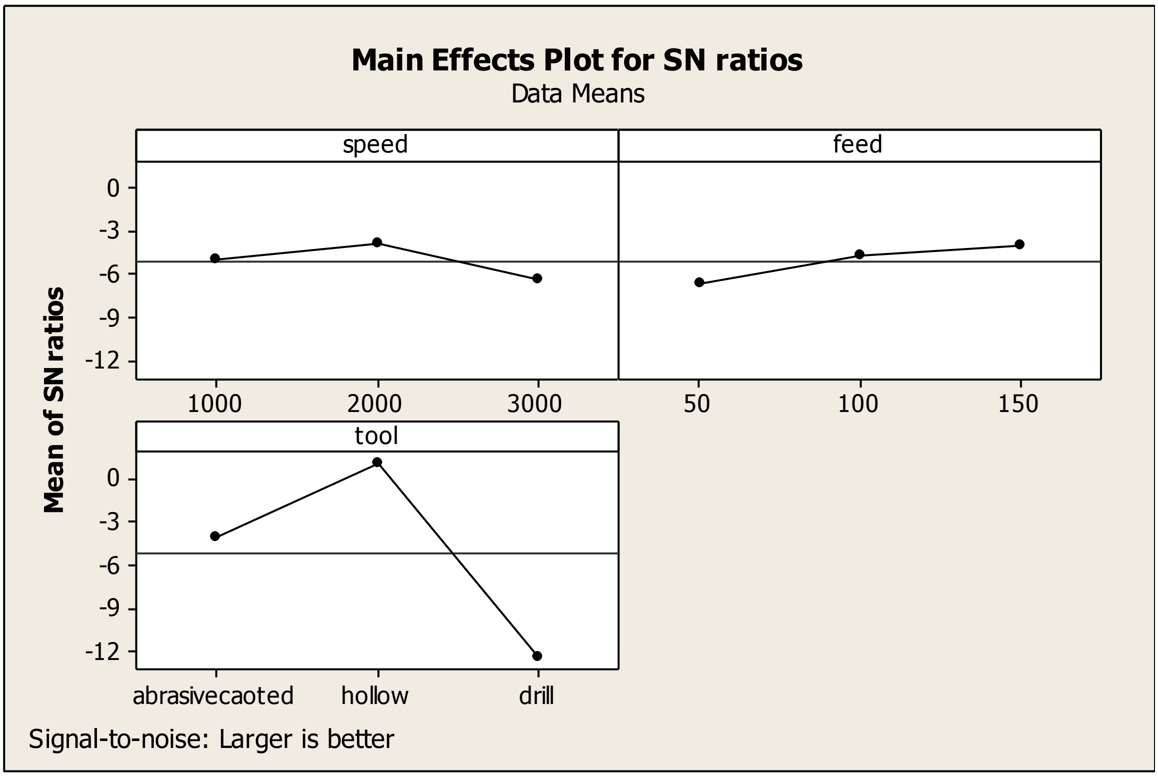


Figure 4.1: SN Ratio Graph for Surface Roughness (Ra)

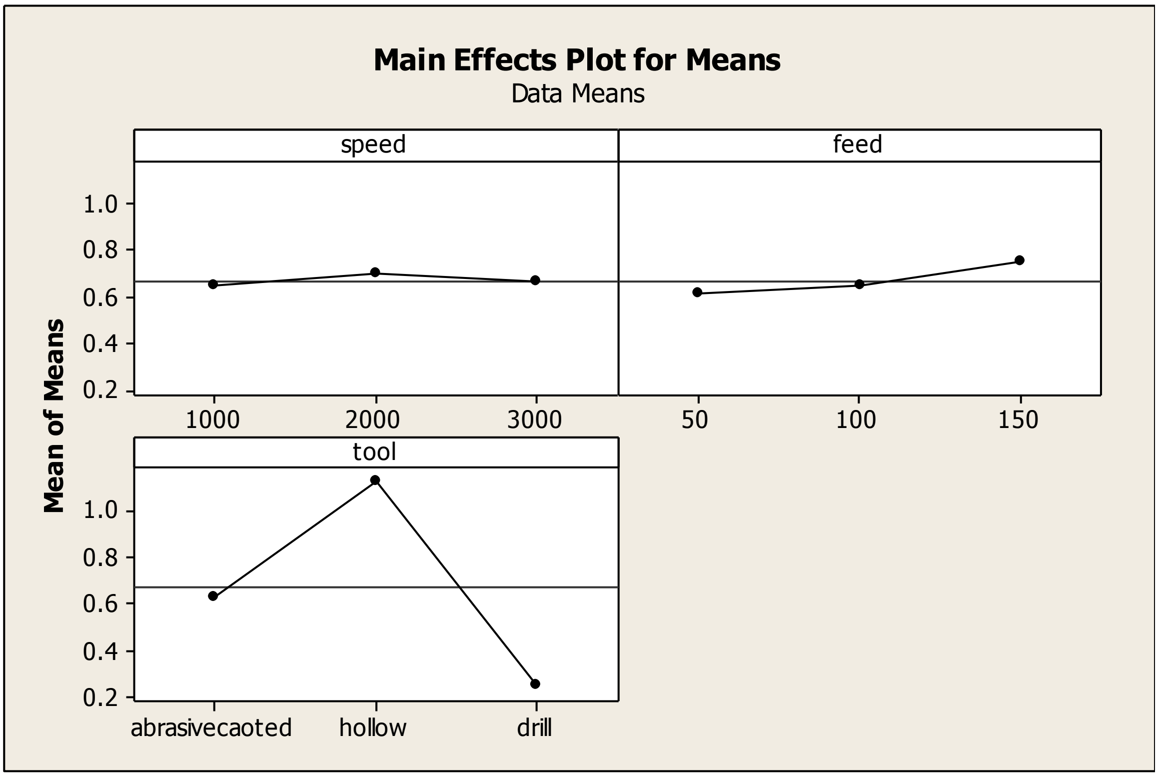


Figure 4.2: Means Graph for Surface Roughness (Ra)

4.3 Material Removal Rate (MRR)

4.3.1. Analysis of Variance for MRR

The results were analyzed using ANOVA for identifying the significant factors affecting MRR. The Analysis of Variance (ANOVA) for MRR at 95% confidence interval is given in Table 4.9. 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 shows that speed (F 1.54 value), feed (F 488.26 value), type of tool (F 0.84 value) are the factors that significantly affect MRR. Feed has highest contribution to MRR. Main effect plots for the SN ratio & Means of MRR have been shown in the Fig. 4.3 and Fig. 4.4 which show the variation of MRR with the input parameters.

Table 4.7: Response Table for SN Ratio (MRR)

Level	**Speed**	**Feed**	**Tool**
1	19.37	13.92	19.09
2	18.93	20.00	18.86
3	18.89	23.27	19.25
Delta	0.48	9.35	0.39
Rank	2	1	3

Table 4.8: Response Table for Means (MRR)

Level	**Speed**	**Feed**	**Tool**
1	10.193	4.970	9.833
2	9.820	10.010	9.657
3	9.543	14.577	10.067
Delta	0.650	9.607	0.410
Rank	2	1	3

Table 4.9: ANOVA for S/N Ratio of MRR

Source	**SS**	**D.O.F**	**Variance**	**F**	**P**	**% contribution**
Speed	0.425	2	0.2125	1.54	0.394	0.4
Feed	135.117	2	67.5586	488.26	0.002	99.3
Type of Tool	0.232	2	0.1161	0.84	0.544	0.2
Residual Error	0.277	2	0.1384			0.1
Total	136.051	8				100

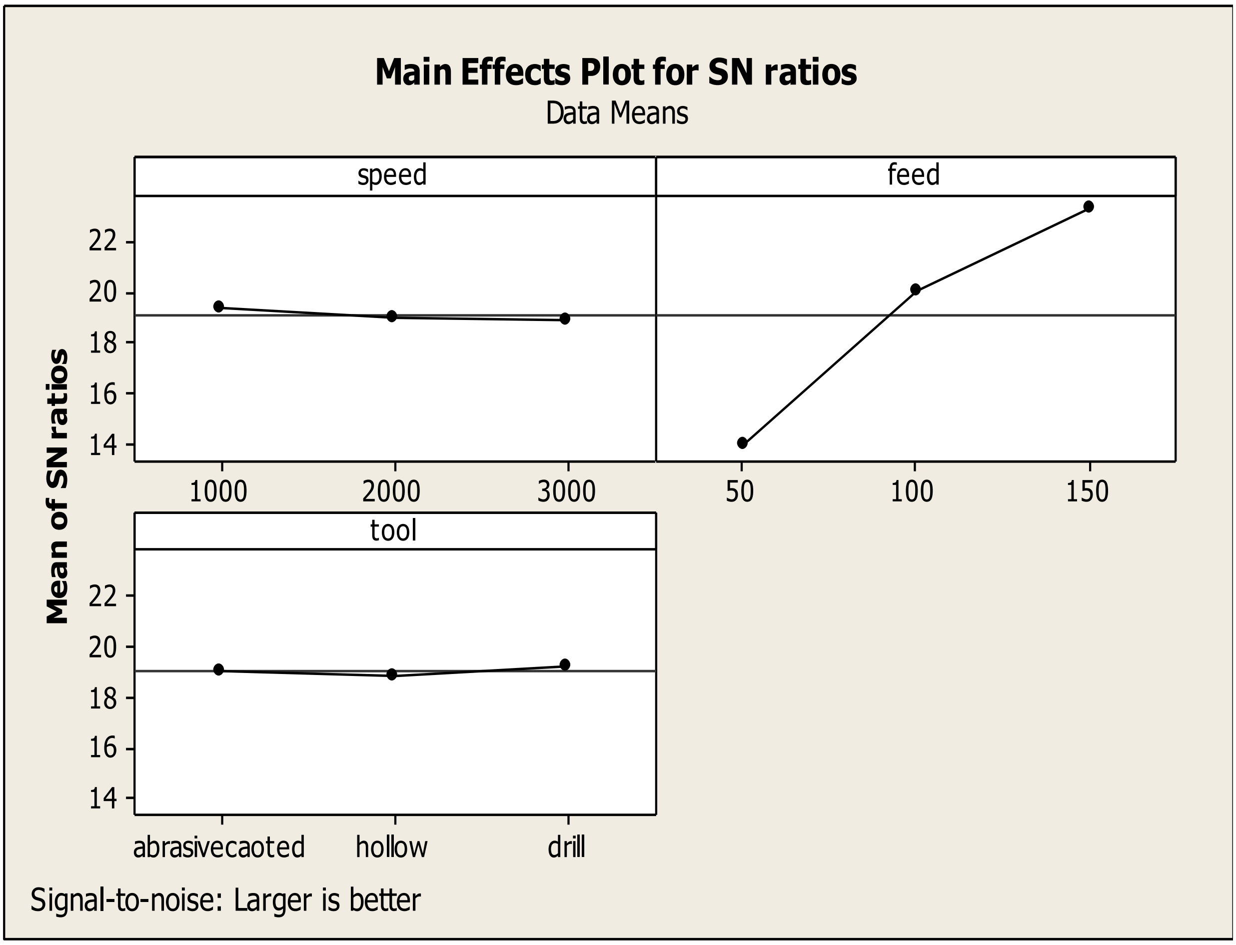


Figure 4.3: SN Ratio Graph for MRR

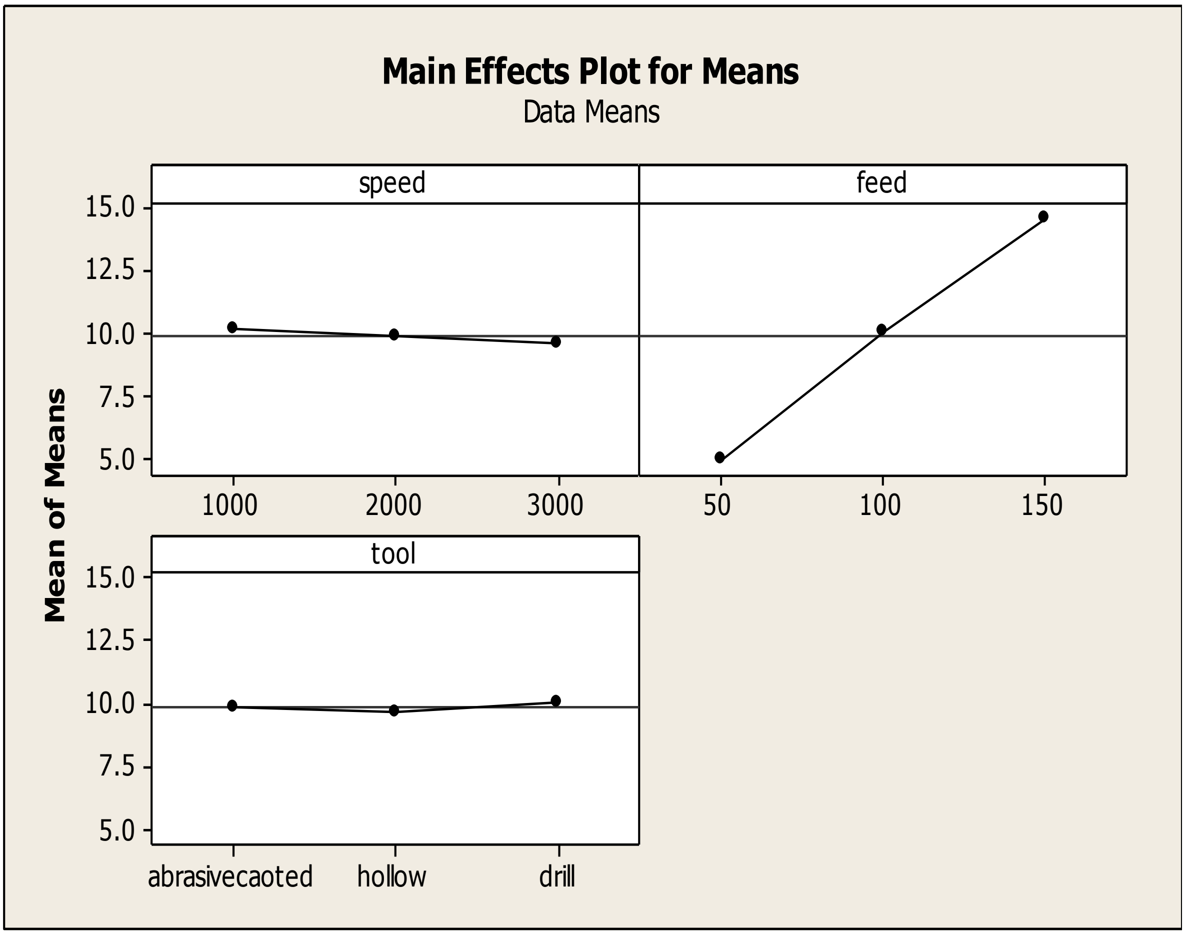


Figure 4.4: Means Graph for MRR

4.4 Force

4.4.1. Analysis of Variance for Force

The results were analyzed using ANOVA for identifying the significant factors affecting force. The Analysis of Variance (ANOVA) for force at 95% confidence interval is given in Table 4.12. 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 shows that speed (F 0.65 value), feed (F 4.18 value), type of tool (F 49.68 value) are the factors that significantly affect force. Type of tool has highest contribution to force. Main effect plots for the SN ratio & Means of force have been shown in the Fig. 4.5 and Fig. 4.6 which show the variation of force with the input parameters.

Table 4.10: Response Table for SN Ratio of Force

Level	Speed	Feed	Tool
1	-41.42	-44.19	-47.09
2	-42.07	-40.77	-46.78
3	-39.84	-38.37	-29.46
Delta	2.24	5.83	17.63
Rank	3	2	1

Table 4.11: Response Table for Means of Force

Level	Speed	Feed	Tool
1	190.97	222.79	230.61
2	194.25	156.35	238.12
3	114.56	120.63	31.05
Delta	79.68	102.16	207.07
Rank	3	2	1

Table 4.12: ANOVA for S/N Ratio of Force

Source	SS	D.O.F	Variance	F	P	% contribution
Speed	7.948	2	3.974	0.65	0.608	1.16
Feed	51.421	2	25.710	4.18	0.193	7.53
Type of Tool	611.183	2	305.592	49.68	0.020	89.5
Residual Error	12.302	2	6.151			1.81
Total	682.854	8				100

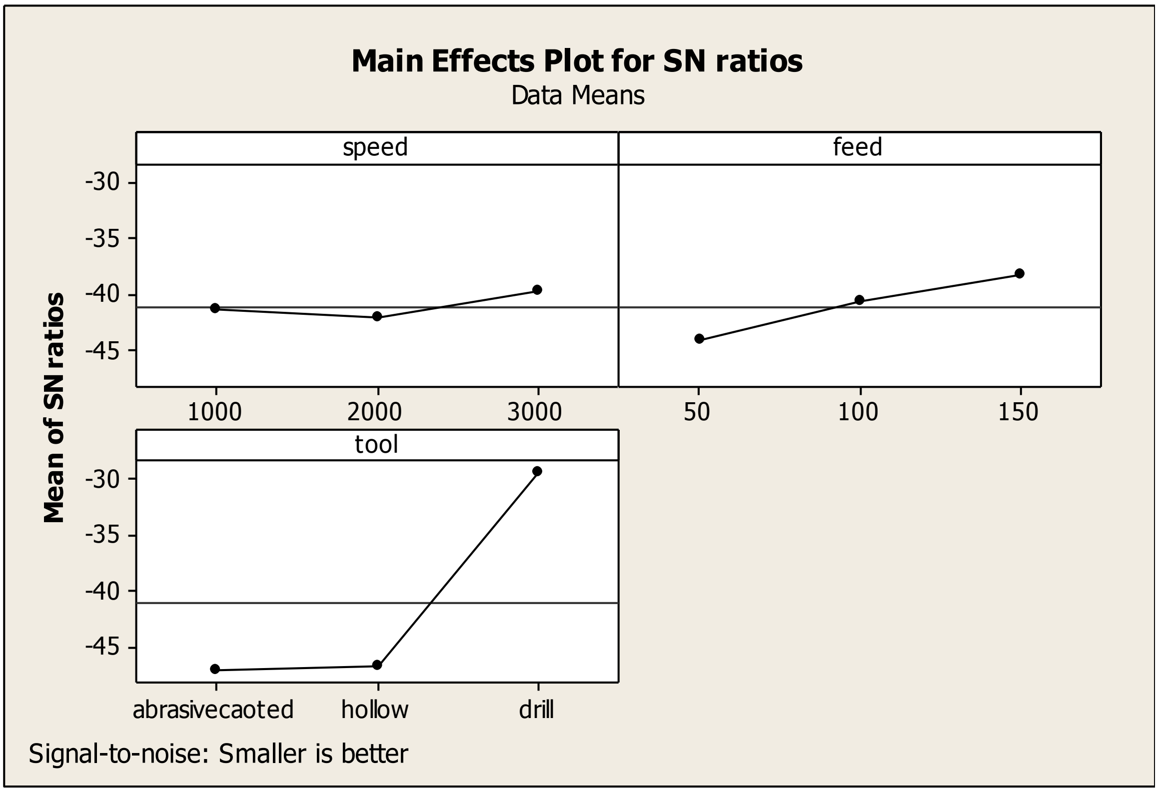


Figure 4.5: SN Ratio Graph for Force

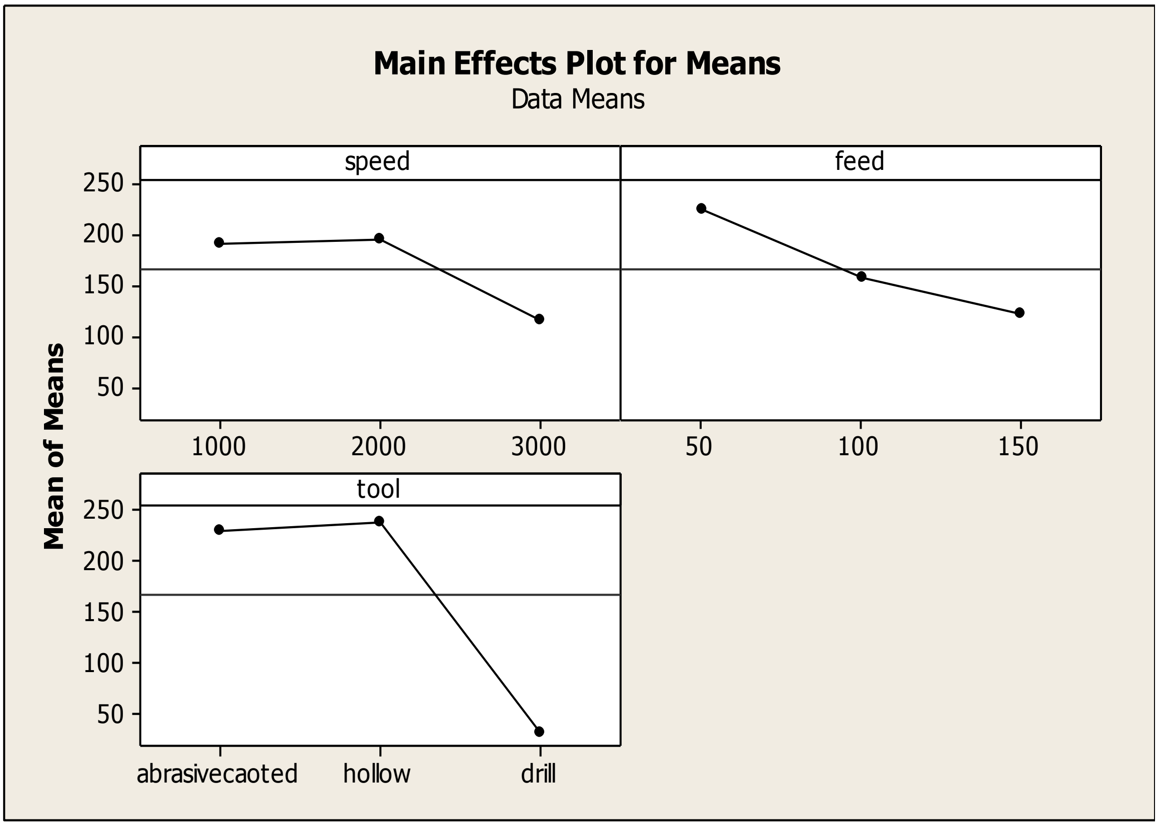


Figure 4.6: Means Graph for Force

4.5 Discussion of Results

4.5.1. Effect on Surface Roughness (Ra)

a) It is observed from Table 4.6 that the surface roughness (Ra) of the hole largely depends on the type of tool used during drilling. The feed used is the second main contributing factor for the surface roughness where as speed has least effect on surface roughness.

b) Type of tool shows largest contribution (Table 4.6) i.e. percentage contribution 89.92% whereas speed has least contribution i.e.2.95%.

c) From graph of SN ratios it is observed that surface roughness obtained is largest in case of hollow tool as compared to abrasive coated as well as twist drill. It is clear that hollow tool gives maximum roughness at 2000 RPM and feed 150 mm/min.

d) From graph of SN ratios it is observed that surface roughness obtained is least in case of twist drill.

4.5.2. Effect on Material Removal Rate (MRR)

a) It is observed from Table 4.9 that the MRR depends on the feed used during drilling. Speed is the second main contributing factor for MRR where as type of tool has least effect on MRR.

b) Feed shows largest contribution (Table 4.9) i.e. percentage contribution 99.3% whereas type of tool has least contribution i.e.0.2%.

c) From graph of SN ratios Fig. 4.3 it is observed that MRR obtained is largest in case of twist drill as compared to abrasive coated as well as hollow tool. It is clear that twist drill gives maximum MRR at a feed of 150 mm/min.

d) From graph of SN ratios it is observed that MRR obtained is least in case of hollow tool.

4.5.3. Effect on Force

a) It is observed from Table 4.12 that the force depends on the type of tool used during drilling. Feed is the second main contributing factor for force where as speed has least effect on force.

b) Type of tool shows largest contribution (Table 4.12) i.e. percentage contribution 89.5% whereas speed has least contribution i.e.1.16%.

c) From graph of SN ratios Fig. 4.5 it is observed that force obtained is least in case of twist drill as compared to abrasive coated as well as hollow tool.

d) From graph of SN ratios it is observed that force is maximum in case of abrasive coated tool.

4.5.4. Analysis with Scanning Electronic Microscopic Images (SEM)

SEM images play an important role to determine the surface roughness of material. SEM images were taken for the holes drilled by twist drill, abrasive coated tool and hollow tool respectively (Fig. 4.7, Fig. 4.8 & Fig. 4.9) at different magnifications i.e. 500 & 1000.

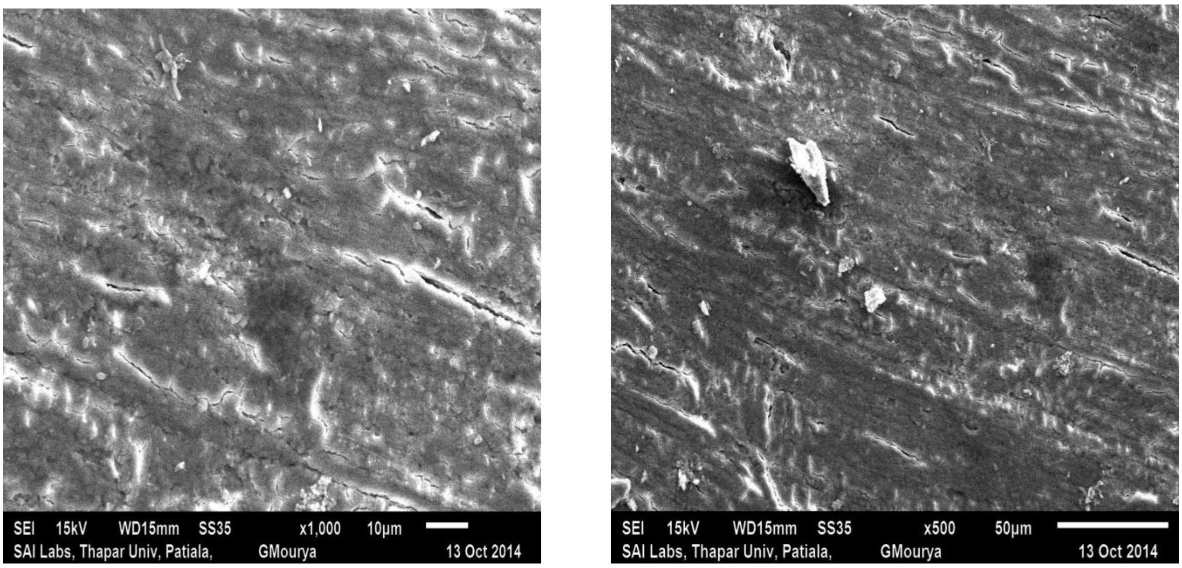


Figure 4.7: Drilling of bone with the help of twist drill

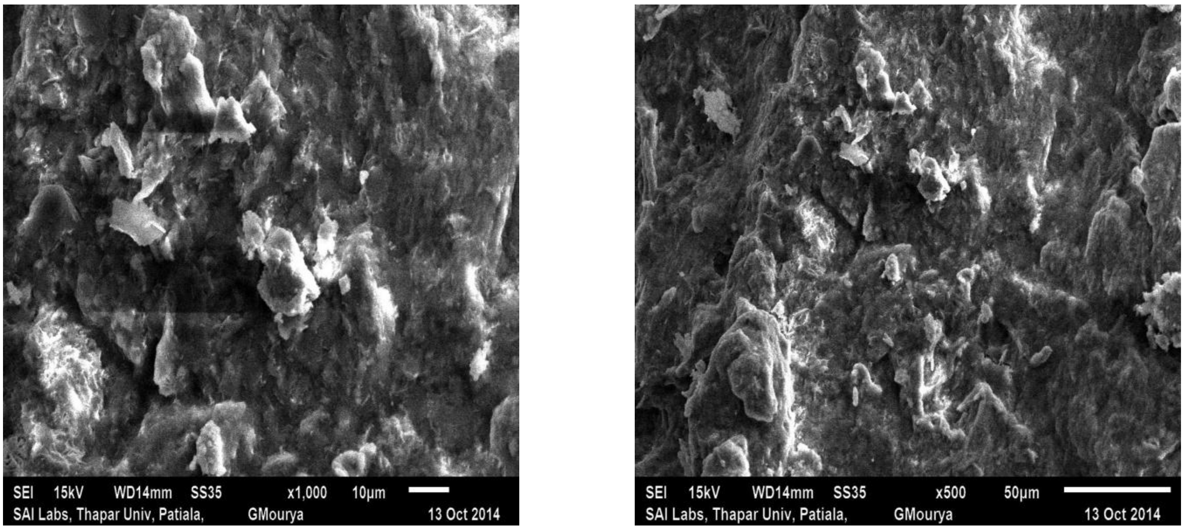


Figure 4.8: Drilling of bone with the help of abrasive tool

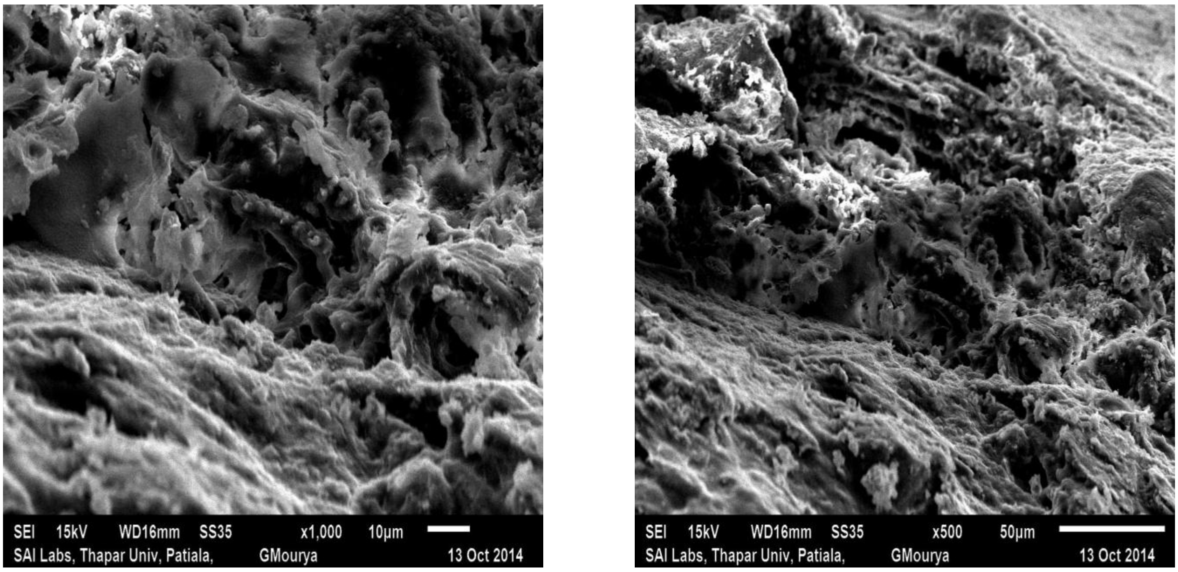


Figure 4.9: Drilling of bone with the help of hollow tool

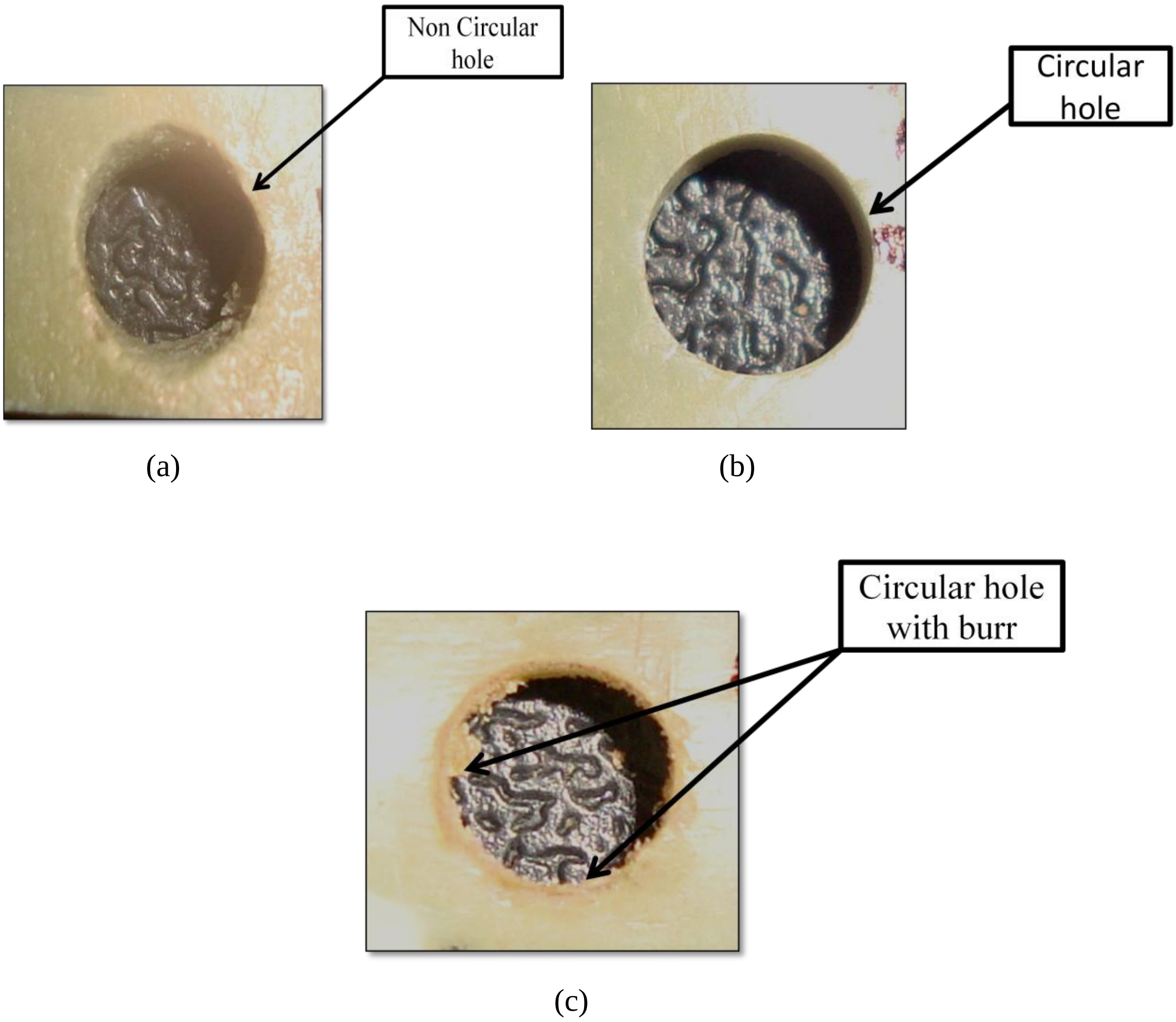
a) The values of surface roughness of the holes drilled in bone were measured and recorded in Table 4.1. After going through the table it is clearly evident that the surface roughness is minimum in case of holes drilled by twist drill. The graphs of SN ratio and Means clearly show the same. Images of SEM (Fig. 4.7) also shows a very smooth surface of the hole drilled by twist drill.

b) Images of SEM (Fig. 4.8) show the surface of the hole drilled by using Abrasive coated tool (abrasive coated). The images represent that the surface of the hole is rough as compared to the hole surface of drilled hole.

c) Images of SEM (Fig. 4.9) show the surface of the hole drilled by using hollow tool. The images represent that the surface of the hole is very rough compared to the hole surface of drilled hole as the grains are not cut, they are sheared.

4.5.5. Analysis of the Quality of Hole

The optical images of the top surface of holes drilled by using different types of tools were taken to know the quality of hole Fig. 4.10. Hole quality in drilling is evaluated in terms of hole diameter and cylindricity, surface roughness, and burr. However, the surface is easily damaged during machining operations.



(a) (b)

(c)

Figure 4.10: (a) Hole drilled by hollow tool (b) Hole drilled by twist drill (c) Hole drilled by Abrasive coated tool

It is clear from the images that the hole produced by the hollow tool is de-shaped i.e. not circular from the top. The hole produced by the drill is complete circular and free from any type of burr. The hole produced by abrasive coated tool shows burr.

Chapter-5

Conclusions and Future Scope

5.1 Conclusion

The following conclusion is drawn based on the performance of response parameters studied in this present work such as surface roughness, material removal rate and force.

1. The preliminary experiments are carried out to find the optimum maximum value of surface roughness in case of abrasive coated tool, hollow tool and twist drill. The maximum value of surface roughness 1.29 micron meter comes out to be with hollow tool. It is evident from the SN ratio graph. In case of material removal rate, feed is the main factor whereas shape of the tool is the least factor responsible for MRR.

2. Material removal rate mainly depends on the feed used. The best material removal rate i.e. 15.05 mm^3/sec obtained is at a feed of 150 mm/min and RPM 1000 using drill as clear from SN ratio graph.

3. Out of all selected parameters shape of the tool is the parameter responsible for surface roughness during drilling of bone. Feed rate is the second contributing parameter. Speed factor is negligible for surface roughness. Minimum value of Surface roughness is obtained using drilling tool.

4. Material removal is mainly affected by feed rate. Speed is the second factor showing effect on MRR. Type of tool has negligible effect as compared to other two parameters.

5. Force is least in case of drill with twist drill i.e. 21.27 N at a RPM 1000 and feed 150 mm/min.

5.2 Scope for Future Work

1. In the present investigation, the effect of three input parameters i.e. type of tool, speed and feed rate has been studied. Study of other parameters like drill having different diameters and depth of cut can also be included.

2. In the present investigation three output parameters are considered. Study of other responses such as tool wear, temperature rise and type of chip formation can also be included.

3. In future drilling of bones using abrasive slurry can also be taken for investigation for surface roughness as well as material removal rate along with the temperature rise.

4. Non conventional drilling (ultrasonic drilling) can also be considered for future investigations as it is a non thermal process.

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