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UNIVERSITI TEKNOLOGI PETRONAS

NUMERICAL MODELLING AND SIMULATION OF BONE DRILLING TO MINIMIZE BONE NECROSIS BY CONTROLLING HEAT GENERATIONS

by

MUNAIBAH BINTI MOHD MOKHTAR

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NUMERICAL MODELLING AND SIMULATION OF BONE DRILLING TO MINIMIZE BONE NECROSIS BY CONTROLLING HEAT GENERATIONS

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MUNAIBAH BINTI MOHD MOKHTAR

A Thesis

Submitted to the Postgraduate Studies Programme

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BANDAR SERI ISKANDAR

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JULY 2013

DECLARATION OF THESIS

Title of thesis	Numerical Modelling and Simulation of Bone Drilling to Minimize Bone Necrosis by Controlling Heat Generations

I MUNAIBAH BINTI MOHD MOKHTAR

hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UTP or other institutions.

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DEDICATION

To my mom, dad, husband and brother for their love and supports in this journey.

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First of all, I would like to thank Allah the Almighty, for without His consent it would be impossible to achieve what has been done in this work, for giving me the strength and perseverance to keep going without losing hope. May Allah accept this work count it as a good deed and make it useful to others.

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ABSTRACT

Bone drilling method is one of the medical approaches to handle fracture in trauma injury. It involves the insertion of a screw and/or a plate for temporary support. However, drilling generates heat thus causing thermal necrosis. The temperature which reach above thermal necrosis threshold during drilling causes two problems; the bone tissue losses its regeneration ability and loosening of the surgical fixation over time. This project aims to develop appropriate numerical heat transfer model adaptation of the heat source approach for bone drilling with the purpose of minimizing thermal necrosis. Method of investigations used were numerical modeling and simulation using ANSYS parametric design language (apdl). The relationship of drill speed, feed rate, point angle, helix angle and drill bit diameter were investigated using the heat source model. Prediction of the temperature distribution and a parametric study was conducted. The analysis have been validated by using dry bovine bone. Analytical and experimental results of this study suggested that the feed rate, drill bit diameter and point angle have 11.63%, 73.44% and 25.60% influential on heat generation respectively. Prediction of temperature distribution shows a decrease of 35.47% and 17.43% in temperature with the use of 0.42 mm/s feed rate as compared to 2.2 mm/s and 40° point angle as compared to 118° respectively, while 70.34% increased with the use of 4.5 mm drill bit diameter as compared to 1.5 mm. Thus, the appropriate drilling condition is recommended by using drill bit diameter lower than 3.5 mm, feed rate more than 1.2 mm/s and point angle of 118°.

ABSTRAK

Kaedah penggerudian tulang digunakan dalam bidang perubatan untuk menyambung semula tulang yang patah semasa kecederaan trauma. ia dibuat dengan menggerudi plat atau skru ke dalam tulang tersebut untuk memperolehi sokongan yang sementara. Akan tetapi proses penggerudian ini akan menghasilkan haba nikrosis, jika haba tersebut melebihi had kecederaan tulang, ia akan mengakibatkan masalah kehilangan keupayaan untuk baik sepenuhnya. Fokus penyelidikan ini adalah untuk meminimakan kecederaan tulang dengan memperolehi parameter sesuai untuk pengerudian tulang tersebut. Kaedah yang digunakan adalah pembinaan model numerasi dan simulasi ANSYS menggunakan *parametric design language* (apdl). hubungkait antara kelajuan gerudi, kelajuan putaran, sudut titit, sudut heliks dan bit diameter gerudi telah diberi tumpuan kajian dengan menggunakan model sumber haba (Heat Source Model). Jangkaan tentang taburan suhu dan kajian tentang parameter tersebut telah dijalankan. Kajian telah dijalankan dengan menggunakan tulang bovin yang kering. Hasil kajian secara eksperimen dan analitikal menunjukkan bahawa kadar putaran, bit diameter gerudi dan sudut titik mempengaruhi sebanyak 11.63%, 73.44% dan 25.60% ke atas penghasilan haba masing-masing. Jangkaan tentang pengaruh haba pula menunjukkan penurunan suhu sebanyak 35.47% dan 17.43% apabila menggunakan 0.42 mm/s kadar putaran berbanding dengan kadar putaran 2.2 mm/s dan memilih sudut titik 40^0 berbanding dengan sudut 118^0 masing-masing. Maka keadaan penggerudian yang menasabah adalah dengan menggunakan bit diameter gerudi yang kurang daripada 3.5 mm, kadar putaran yang lebih daripada 1.2 mm/s dan sudut titik 118^0.

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CHAPTER 1
INTRODUCTION

1.1 Overview

This chapter introduces the broad overview of this research topic. The chapter describes the background of this study, case study, general description of the topic which based on actual problem that have been faced. Apart from that, the problem statement is presented to describe what are the patient and doctor problems regarding bone fracture injury and this will strengthen the reason of why this study is important to be undertaken. This chapter includes the established objectives and scope of this research. In the last section of this chapter, the layout of this thesis was described.

1.2 Background of Study

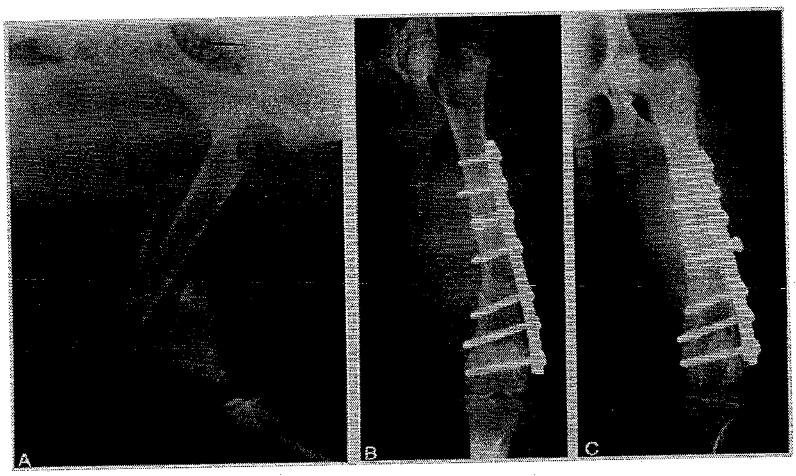


Figure 1.1 (a) Lateral radiograph of femoral fracture in a 7-month-old dog. (b) the fracture following reduction and fixation using a bone plate and screws. (c) radiograph after 5 months [1]

Figure 1.1 above shows a fracture occur in dog aged 7 months. The medical approached used were to insert screw and plate as a temporary support. Inserting the plate and screw into the bone required drilling, which cause thermal necrosis under certain circumstances. This project focuses on minimizing thermal necrosis by obtaining process parameter during the bone drilling procedure. The problem regarding thermal necrosis occurs are; (1) possibility of reoperation, (2) the bone lost its regeneration ability and (3) loosening of implants after surgery. Prediction of the temperature distribution during drilling may help in determining the recommended parameters to be used in order to minimize the thermal necrosis.

1.3 Case Study

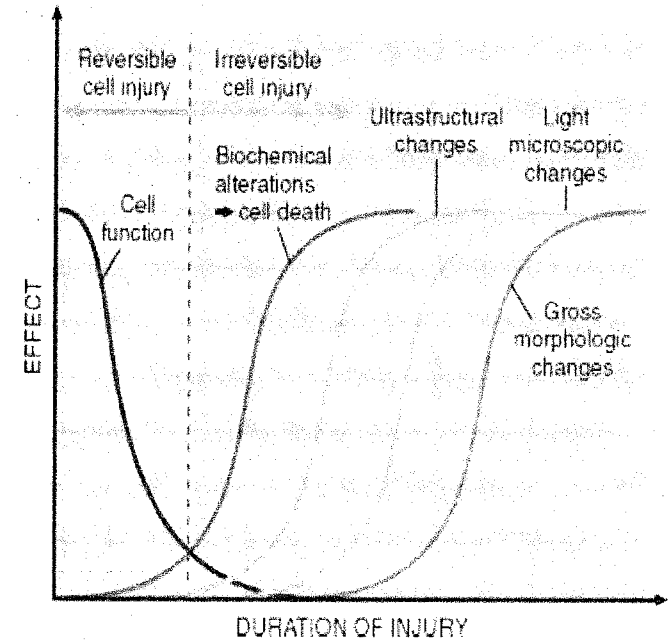


Figure 1.2 Sequential development of biochemical and morphological changes in cell injury [2]

Figure 1.2 shows morphology of cell injury, irreversible cell injury occurs after a certain period of time when the stress or thermal effect had been applied for a longer duration. Cell becomes nonfunctional after biochemical alteration thus resulting death of cell. Thermal injury induced during bone drilling procedure often caused irreversible damage, where the bone cell loss its regeneration ability and properties. A study was conducted by Neander et al, [3] to determine if bone loss is reversible after necrosis, the measurements were repeated 3 and 6 months later, which failed to note any restoration of bone mineral. Ahl et al, [4] and Finsen [5] also failed to note reversibility of bone density after an ankle fracture.

Failures of implant fixation were also due to thermal injury. The heat generated during bone drilling cause transient temperature between the bone and the drill bit. Berning et at [6] investigate a case of proximal tibia due to thermal necrosis of pin tracker placement. Matthews et at [7] measure temperature and time during insertion of different type skeletal immobilization pin in human cortical bone, they found that thermal necrosis can be presented in radiographic as ring around the drilling hole as shown in Figure 1. 3 below;

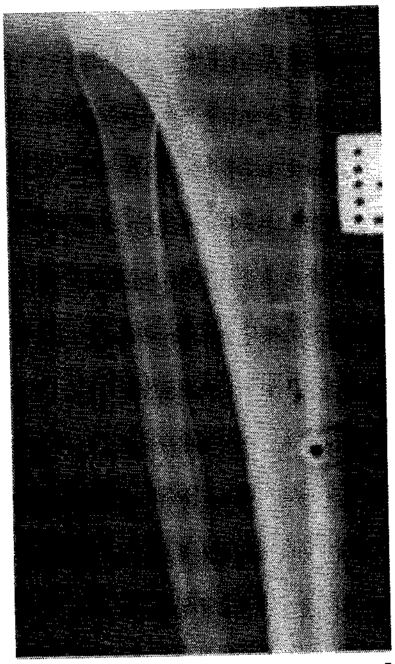


Figure 1.3 Radiographic appearance of thermal necrosis [7]

1.4 Problem Statement

The drilling process generates heat due to the (1) friction of the drill bit to bone and (2) as a result from material removal. Temperature that reach above thermal necrosis threshold during drilling cause two problems. First, the bone tissue lost its regeneration ability. Second, loosening of the surgical fixation over time. In our current project, we (1) identify the heat source model and obtaining the heat flux, (2) predict the temperature distribution during drilling using heat flux data, (3) validating the temperature distribution by comparing experiment and literature review reference and (4) carry out parametric analysis. Our aim in this project is to determine the parametric estimation that could minimize thermal necrosis.

In this study, we develop numerical heat transfer model for bone drilling, and validating the model by comparing it with data from literature review and experimental to determine suitable process parameter that could minimize thermal necrosis.

1.5 Objective of the Research

Develop numerical heat transfer model to predict drilling temperatures as a function of process parameters and the validation of model by building a test rig to perform the drilling experiments. To accomplish this, following objectives have been carried out as follows:

1. To develop numerical heat transfer model for bone drilling using heat source
2. To develop a Finite Element model in ANSYS Parametric Design Language (apdl) and to set up a laboratory scale test rig to measure temperature during drilling for bovine bone as a validation for the modelling.
3. To carry out parametric analysis of minimization thermal necrosis for bone drilling method.

Based on the above objectives, there are a few questions which this research seeks to answer.

1. If there are some differences in the heat source modeling, what are the trends of calculated heat flux and what are their relationships?
2. If there are some differences in the 2-dimensional modeling, what are the trends of temperature distribution prediction and what are their relationships?
3. What are the reasons for producing dissimilarity of predicted temperature distribution data compare to the experimental and literature review data?
4. Is there any adjustments which can be done to produce identical temperature distribution data and what are their correction factors after the adjustment?

These are the initial questions which enabled the study to create objectives for this research work. The questions seek to show the direction to efficiently run this research and facilitate research investigation. In the following section, the scope of the research project related to the above established objectives is discussed.

1.6 Scope of Research Project

Heat modeling is the prediction of heat transfer using mathematical equations. Heat transfer equation such conduction and convection were paired with thermo-mechanics of the drilling operation. This research covers the heat modeling from Davison and James. Davison and James [8] developed thermo-mechanical equation of the machining theory to predict heat transfer during drilling The heat models are further discussed in the next chapter

Heat source modeling are used to calculate the dependency of the heat generation upon the (1) drill speed, (2) drill bit diameter, (3) feed rate, (4) helix angle, and (5) point angle. Heat generation were controlled by varying those parameters. Thus these parameters were further discussed in the chapter 2 and 3.

The FE model are build using ANSYS apdl transient thermal analysis. The model will be built in 2-dimensional and the material properties of the bone will follow all literature review references that will be further discussed in the next chapter. The FE model stability is proven by conducting experimental validation.

1.7 Layout of Thesis

The thesis is comprised of five (5) chapters as follows;

Chapter 1 Introduction; this introductory chapter describes the background of this research work, problem statement, objectives and scope of the research project. This chapter also answers the reasons of conducting this research and the significance thereof.

Chapter 2 Literature Review; this chapter reviews the theories and research done in the past which is related to this research work. The context and basic terms used in this thesis and examples are explained. This chapter demonstrates an idea about the importance of this study by showing the current knowledge and understanding which include the findings from the previous bone drilling studies that have been accomplished.

Chapter 3 Methodology; this chapter explains the process of this research work by showing the overall research work and elaborates on the methods of research analyses. Appropriate methodology flow and approach would be able to make the objective of this research measurable. The first objective of this research is to develop numerical heat transfer model for bone drilling. Heat generated at the bone during drilling via shearing process, which is similar to the machining, thus machining equation is used to develop heat model. The selected equation will be solved using Finite Element method, ANSYS software is selected to solve this numerical implementation. MATLAB would be used to identify which parameters in these equations are important. After identifying the parameters, those parameters will be used in ANSYS for the heat model simulation.

This chapter also includes the bone modeling approach. In this project the model were built manually using tools in ANSYS. Modeling is effective as it simplifies the current problem, but the value inserted need to be as close as possible resembling the nature of the material. The material model values inserted follows literature review reference mentioned in chapter 2.

Chapter 4 Results and Discussion; this chapter answers the hypothesis of this research project. It discusses the analysis of the accomplished results, findings and the implications of these findings. This will provide the estimation of the bone drilling process in medical aspects.

Chapter 5 Conclusion and Recommendations; in this chapter, conclusions are made based on the results of this research work to answer the established objectives. This chapter summarizes the accomplished findings. This is the final chapter of this thesis. The chapter presents some recommendations in order to enhance and develop this study in the future. It may help to guide future research works or other related works in order to achieve more accurate and reliable results. The recommendations provide future direction in bone modeling simulation for the improvement of medical purpose . This will aid in reaching an optimum design leading to the safer surgery. This chapter is extremely valuable to other studies in order to achieve greater levels of the research.

1.8 Summary

This chapter discusses the importance of the project in aiding medical fields with parameter data. The background of the studies provides grandness information needed for this research. The problem statement, objectives, scopes assists for the solid frameworks. Lastly, the layout of the thesis shows an overview of how this research has been carried out.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

Critical literature reviews of the subjects were explained in details, this chapter is divided into three phases;

i. Numerical modeling
ii. Finite element simulation
iii. Experimental approach for bone drilling validation

The first phase discusses about the term of thermal necrosis. Evaluation of the numerical modeling method to predict the heat generations using machining equation were discussed in details.

The second phase explains in depth about finite element modeling, hence the works of finite element modeling regarding bone drilling method were discussed.

The third phase explicated the experimental approach done to predict the temperature distribution of bone drilling. The reasoning of the method was used as importance guidance for conducting the experimental validation part.

2.2 Thermal Necrosis

Thermal necrosis or the death of bone cell caused irreversible damage, which may lead to problems such as infections and the reduction of mechanical strength of the bone [9]. Hence it is important to understand the extent of necrosis, Eriksson and Albrektsson [10] found that it depends on the duration and temperature exposure. Lundskog [11] states that if bone is exposed longer than 30 s at 50°C cellular necrosis will occur. Mortiz and Henrique [12-13] found that when epithelial cells are exposed to a temperature of 70°C they will be immediately damaged. At the exposure of 55°C for 30 s, the result will be the same and at a temperature of 45°C harmful effects will occur after 5 h. Generally, the literature shows that if the temperature rises above 55°C for a period of longer than one-half a minute, serious damage will occur to the bone. Concept of thermal exposure is also define by Sapareto and Deway [14] as ;

$$t_{43} = \int_{t=0}^{t=t_{final}} R(T(t))^{43-T(t)}dt \tag{2.1}$$

$$R(T(t)) = \begin{cases} 0.5 \; if \; T(t) \geq 43^{0}\text{C} \\ 0.25 \text{ otherwise,} \end{cases} \tag{2.2}$$

where t_{43} is exposure time at 43°C , t_{final} is the period of exposure, R is a coefficient of exposure, and T(t) is the temperature at the certain point or location. Assumption of necrosis threshold of 120 equiv. min at 43°C were debated. However, it is commonly accepted that exposure time value is depending at different tissue type under different clinical condition. This project follows Eriksson et al. [15] suggested thermal necrosis threshold, which are initiated when the temperature exceed 47 °C for 60s. Complying with equation (2.1) and (2.2) t_{43} is equal to 16 min.

2.3 Parametric Experiments and its Conflicts

Some researchers found out that by increasing the drilling speed it would significantly increases the temperature generated at the bone [16] and [17] but those result were conflicted with [18], [19] and [20] which stated that drill bit with higher drill speed can reduce the bone temperature rise.The methods of direct experimental approach are expensive and time consuming. There are various parameters influencing temperature distribution during bone drilling. However, those parameters have complex relationship; the relationship between the drill-bit geometry, chip stream, drilling conditions, and bone characteristics possess a great challenge to determine which parameter is favourable. Thus making the optimization of parameters to minimize the thermal effects in experimentation alone is impractical. Due to that, recently the finite element simulation is widely used to investigate the mechanism of cutting process. It is also an effective and efficient way to model the process and gain better understanding of the operations.

2.4 Importance of Finite element modelling

Numbers of researchers have developed analytical models. Loewen and Shaw [21] proposed a prediction of heat partition based on Jaeger's analysis. The model was improved by Agapiou and DeVries [22], who tailoring it to be able to predict thermal phenomena in drilling by developing analytical model for twist drill temperature and used the model for comparison of experimental and analytical. Kalidas et al. [23] investigated influences of drill temperature on hole quality under dry and wet drilling conditions. Later on Agapiou and Stephenson [24] made a subsequent improvement. Other than that, Watanabe et al. [25] also used Loewen and Shaw model to predict the heat flows into the workpiece and the drill. As mentions, Loewen and Shaw model were widely used, however it is too simplified. For example the model assume that the temperature induced in the workpiece on the shear plane is similar or equivalent in some respects to the temperature beneath a frictional slider that dissipates uniform heat flux as it moves with constant speed over the surface of a semi-infinite body. As a result, the classical model can be inaccurate for cutting scenarios that involve large shear angles or slow cutting speeds, which occur commonly in drilling.

The method of direct experimental approach to studies the drilling process and its parameter are expensive and time consuming. Due to that, recently the finite element simulation is widely used to investigate the mechanism of cutting process. It is also an effective and efficient way to model the process and gain better understanding of the operations. Yang and Sun [26] investigated drilling process; a coupled thermo-mechanical finite element model of drilling is developed. Several key technologies, such as material constitutive model, material failure law, contact and friction law, have been implemented to improve the accuracy of finite element simulation. And by comparing the predicted cutting forces with the measured forces shows the finite element model is reasonable. These results confirm the capability of finite element simulation in predicting drilling process and selecting optimal tool and cutting parameters, due to this, long and lengthy experimentation train and error could be minimize.

Many physical phenomena in engineering and science can be described in terms of partial deferential equations (PDE). In general, solving these equations by classical analytical methods for arbitrary shapes is almost impossible. The finite element method (FEM) is a numerical approach by which these PDE can be solved approximately. The FEM is a function/basis-based approach to solve PDE. FE is widely used in diverse fields to solve static and dynamic problems, in this case we are solving complex geometry of drill and how its influence heat generations. In additions, there are lots studies and investigations on drilling, turning, milling and grinding using finite element simulations. Like to those in bone drilling, the thermal effects in metal drilling are caused by heat generation resulting from material shearing which undergo plastic deformations and frictions. For example Davison and James [27]used machining theory developed by Tay et. Al. [28] to predict the heat transfer during drilling and by coupling it with FE.

2.5 Numerical Modelling

Numerical modeling basic concept involves solving a physical problem by simplification of the reality. Approach to theoretical method consist of four steps; constructing the mathematical model closely resemble the physical problem with assumption, development of the approximation of mathematical model, obtaining solution by implementing the numerical model and interpretation of those data.

2.5.1 Heat generation

The heat generated during drilling of bone comes from; firstly, the drilling process. Shear occurs at the surface layer of a material by a drill bit that breaks intermolecular bonds, thus releasing energy. Secondly, the friction from the non-cutting surfaces of a twist drill, such as the flank, flutes and shaft are another source of heat. The heat generated is partially dissipated by the presence of blood and tissue fluid, and part of the heat being carried away by the chips formed. But then again, bone is a poor conductor of heat and the temperature rise can be significant.

Heat generated from the product of shearing. As the drill bit touch the bone, shearing of the surface layer of the bone occur. The shearing process would break the intermolecular bonds of the bone. Intermolecular bond is the forces of attraction which hold an individual molecule together. Breaking the bond would release energy, which is the heat generated during the process. Besides shearing, friction also influences the temperature during drilling. Frictions are the force resisting the relative motion of solid surfaces. Frictions occur from the non-cutting surfaces of a drill, such as the flank, flutes and shaft are another source of heat. Energy used to remove a material is converted into heat [29], thus heat generated by the amount of work is;

$$\frac{\partial Q}{\partial t} = F_s v_s \tag{2.3}$$

where Q is the heat generated, t is time, Fs is the shearing force in the shear plane, vs is the shear velocity, and where the shear force and shear velocity are at the same angle ϕ. Figure 2.1 below shows the concept of material removal by orthogonal cutting

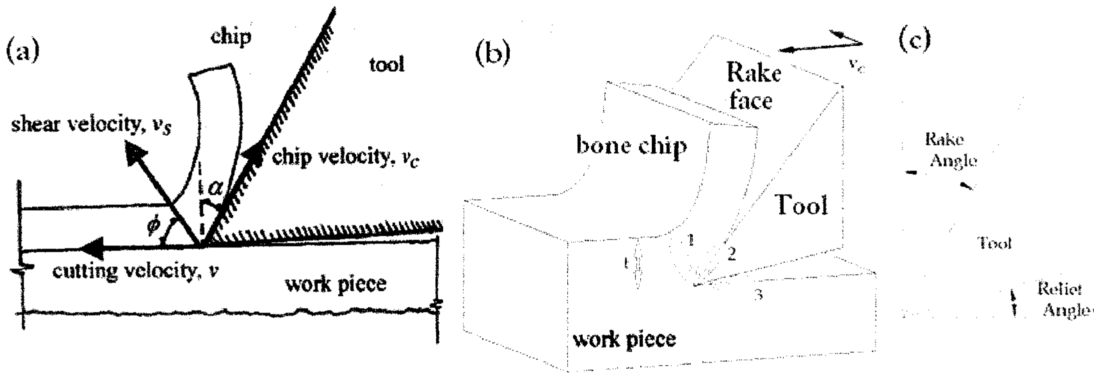


Figure 2.1 Material removal by orthogonal cutting [8] and [30]

Davison and James [8] mathematical model substitution in details; shear velocity is calculated by;

$$v_s = \frac{v}{\cos\phi} \tag{2.4}$$

angle ϕ is calculated using Ernst-Merchant relationship for bone cutting [31] by;

$$2\phi = 90^{\circ} + \beta - \alpha \tag{2.5}$$

where α is define as the rake angle of the cutting tool and the friction angle, β has the value of 0.644 [31]. changes in the rake angle along the cutting lips of a drill is express by Bhattacharyya and Ham [32] and is as follows,

$$\tan(\alpha) = \frac{\left(2r/_{D}\right)\tan(\theta)-\tan\left[\sin^{-1}\left(d_o/_{2r}\sin p\right)\right]\cos p}{\sin p} \quad \textbf{(2.6)}$$

where D is the drill diameter, d_0 is chisel edge diameter, θ is the helix angle, and p is the half-angle at the point (fig 2.1). The average rake angle over the length of the cutting edge was calculated by numerically integrating Eq. (2.6) over the drill radius and dividing the result by the radius. The velocity v also changes along the cutting edges,

$$v = \frac{2\pi r N}{60} \quad \textbf{(2.7)}$$

where N is the rotational speed, in rpm. In this analysis, the average cutting velocity over the radius of the drill was used to calculate, v_s . Tay et al. [28] formula were used to calculate the constant a,

$$a = \frac{t_1^2}{16C^2\sin^4(\phi)[\tan(\alpha)+\cot(\phi)]} \quad \textbf{(2.8)}$$

where t_1 is the undeformed chip thickness, which in this case is the depth of cut per revolution, and C is a material constant value of 6 [28]. Expression for the shear rate in the primary deformation zone, which occurs in the shear plane line AB was calculated from:

$$\gamma_{AB} = \frac{v}{4(\sqrt{a})\sin^2(\emptyset)[\tan(\alpha)+\cot(\emptyset)]^{3/2}}$$

(2.9)

With ϕ known from Eq. (2.5) and a known from Eq. (2.8), values of γ_{AB} were calculated for a known rake angle, α.

Ultimate shear stress on shear rate for bone, Carter and Hayes [33] found that the compressive strength of cortical bone is proportional to the strain rate raised to the 0.060 power, while Carter and Caler [34] found that the tensile strength of cortical bone is proportional to the strain rate raised to the 0.055 power. Thus the ultimate shear strength behaves in a similar fashion with respect to shear rate, i.e. that ;

$$\tau_s \propto 80\gamma_{AB}^{0.06} \quad \textbf{(2.10)}$$

The constant of proportionality from Saha [35] were used. In that study, the ultimate shear stress of bone was measured at 50.46±14.1 MPa. The tests were done at a very low shear rate, at about 0.0004 s^{-1}. Using these values of τ_s and , the constant of proportionality was found to be 80 MPa,

$$\tau_s = 80\gamma_{AB}^{0.06} \quad \textbf{(2.11)}$$

The shear plane area, A_s in Eq. (2.12), was approximated by [8]

$$A_s = \frac{t_1(D-d_o)}{\cos(90°-p)\sin\emptyset} \quad \textbf{(2.12)}$$

and the depth of cut per revolution, t_1, was calculated from eq. (2.13) where f is the feed rate of the drill [36].

$$t_1 = \frac{f/2}{N/60}\sin p \quad \textbf{(2.13)}$$

fraction that enters the work piece, η, is determine from Abouzgia [37] and the value of η for the best agreement was found to be 0.5 [8]. Combining previous equations, the final expression for the rate of heat entering the work piece, $\frac{\partial Q_w}{\partial t}$ is

$$\frac{\partial Q_w}{\partial t} = \eta\frac{\partial Q}{\partial t} = \eta A_s \tau_s v_s \quad \textbf{(2.14)}$$

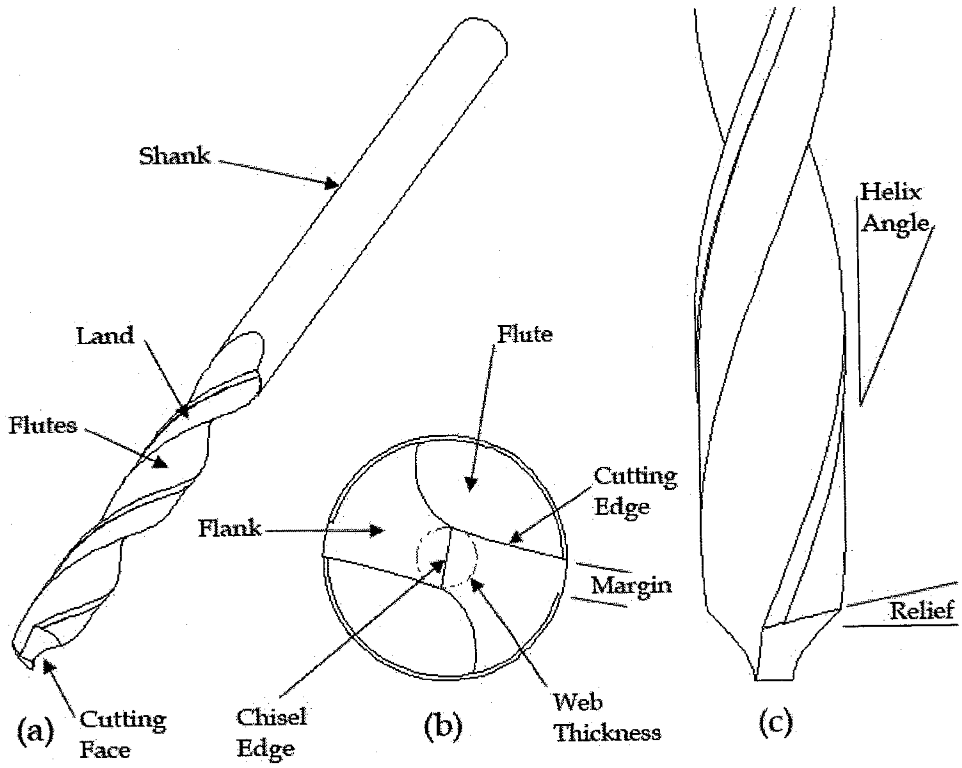


Figure 2.2 Drill bit geometry [30]

Due to slow cutting velocity and large rake angle, the chisel edge leads little cutting and axial thrust force. Influence of chisel edge to axial thrust force relies on length of ratio between chisel and cutting edges. Contribute roughly fifty percentage of thrust force with web thickness of twenty percent of its diameter, the ratio then increase to 30% if contribution doubles [38].

The angle formed by projection of cutting edge onto plane is known as point angle. It is important in orthopaedics as it prevents the walking of the drill [39] and [40]. Several optimal point angles have been advanced in the orthopaedic literature. Jacob and colleagues [31] recommended a point angle of 90°, while both [36] and Natali [41] encouraged a value of 118°. This 118° point angle is very common with the point angle used in machining [38].

The angle between a tangent to the leading edge of the land and the drill-bit long-axis is called helix angle. Machined material which determine this parameter exhibit brittle properties, which producing short chips, while malleable material producing longer chip. Bone drilling produce swarf by the cutting action, which consists of fragments of bone, Surgical twist drill-bits are slow spiral, thus the value helix angle is quite small, is ideal for the drilling of bone [39] as debris is ejected quickly.

2.5.2 Heat Source Model

Few attempts have been made to develop a thermal model for the bone drilling process. Davison and James [8] developed thermo-mechanical equation from the machining theory to predict heat transfer during drilling. The model was coupled with a heat transfer finite element simulations to predict the temperature. The calculation of the heat generated during drilling used the machining theory, which bone is assumed to behave like metal. It was found that the drill speed, feed rate and drill diameter had the most significant thermal impact while changes in drill helix angle, point angle and bone thermal properties had relatively little effect. The conduction equation model was solved by two-dimensional domain using Galerkin's finite-element method. However, they only considered heat generation at the drill-bit tip, while neglecting the significant effects of moving chips, heat transfer between the drill bit body and the bone, and heat convection from the drill bit to the surroundings outside the bone.

Another research performed an analytical study to predict the temperature distribution during dental drilling for implant surgery [16] using A homogenous differential equation of heat conduction was derived in the radial direction only and the one dimensional conduction equation was solved analytically. Tu et. al. [19] presented a model to simulate the temperature rise during bone drilling using commercial finite element software ABAQUS to estimate the bone and drill-bit temperatures.

The most recent investigations, Lee et. al. [17] presented a new thermal model for bone drilling which combines a unique heat-balance equation for the system of the drill bit and the chip stream, by using an ordinary heat diffusion equation for the bone, and heat generation at the drill tip, arising from the cutting process and friction. The model was solved numerically using a tailor-made finite-difference scheme for the drill bit-chip stream system, coupled with a classic finite-difference method for the bone. The main focus of the model is the significance of heat transfer between the drill bit and the bone, heat convection from the drill bit to the surroundings, and the effect of the initial temperature of the drill bit on the developing thermal field.

2.6 Finite Element Theory

In this section, detail explanations of finite element methodology were divided into two parts, (1) the basic concept of modeling, and (2) the main steps to build the final bone model. The basic finite element method was elaborated using the concept of two-dimensional shape functions, along with their elements and properties. Natural coordinates associated with quadrilateral element which were used in the model were presented, and lastly, the derivation of the shape function for rectangular elements to approximate temperature distribution were explained in depth.

Typical analysis in ANSYS has three main steps, which are (1) model generation, (2) solution and (3) reviewing the results. The model is generated in *preprocessor* of ANSYS Parametric Design Language (APDL) mechanical. The *preprocessor* mode involves important tasks, which are specifying the element type, defining the material properties, creating the model geometry and generating the mesh. The finite element model generated in *preprocessor* would be solved in the *processor*. The *processor* steps are, defining the analysis type and options and obtaining the solution. The last step is the *postprocessor,* the results of the model are at a specific time and contour plot are generated.

2.6.1 Modeling Concepts

Bone were modeled to find an optimum temperature distribution of bone during the drilling process by applying heat flus as an input data. The groundworks for the analysis of two-dimension are elaborated below by first studying the two-dimensional shape function and the element.

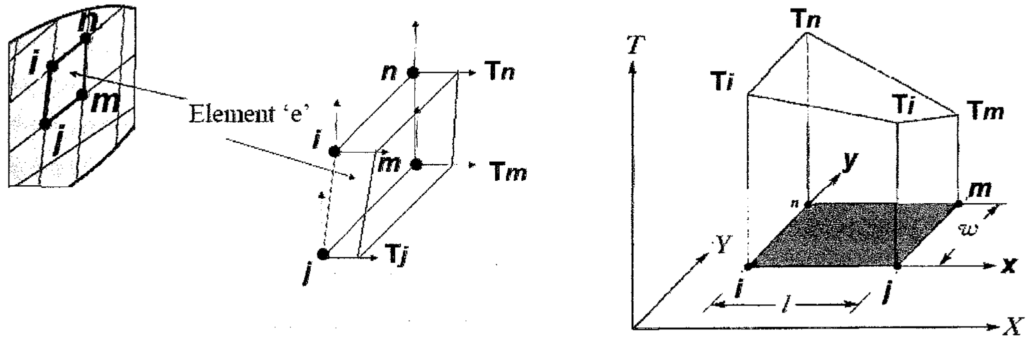


Figure 2.3 using two-dimensional rectangular element to describe temperature distribution, x,y is local coordinate and X,Y is global coordinate system

Figure 2.1 shows that the temperature distribution over the element is a function of both X- and Y- coordinate, thus apporixmation of temperature distribution for an arbitrary rectagular element is :

$$T^{(l)} = b_1 + b_2 x + b_3 y + b_4 y \quad \textbf{(2.15)}$$

the four unknown in Eq. (3.1) can be defined by four nodes :i, k , k ,m , due to the rectangular element system. Obtaining b_1,b_2,b_3 and b_4 using the local coordinate x and y direction by considering nodal temperature, following conditions must be satisfiy:

$$T = T_i \quad at \quad x = 0 \quad and \quad y = 0$$

$$T = T_j \quad at \quad x = l \quad and \quad y = 0$$

$$T = T_m \quad at \quad x = l \quad and \quad y = w$$

$$T = T_n \quad at \quad x = 0 \quad and \quad y = w \quad \textbf{(2.16)}$$

By applying nodal condition given by equation (3.2) in equation (3.1) and solving b_1,b_2,b_3 and b_4:

$$b_1 = T_i$$

$$b_2 = \frac{1}{l}(T_j - T_i)$$

$$b_3 = \frac{1}{w}(T_n - T_i)$$

$$b_4 = \frac{1}{lw}(T_i - T_j + T_m - T_n) \quad \textbf{(2.17)}$$

By substituting equation (3.3) in (3.1) and regrouping parameters, temperature distribution for element in term of shape function are :

$$T^{(e)} = [S_i \ S_j S_m S_n] \begin{Bmatrix} T_i \\ T_j \\ T_m \\ T_n \end{Bmatrix} \qquad \textbf{(2.18)}$$

S representing the shape function, were expressed as :

$$S_i = \left(1 - \frac{x}{l}\right)\left(1 - \frac{y}{w}\right)$$

$$S_j = \frac{x}{l}\left(1 - \frac{y}{w}\right)$$

$$S_m = \frac{xy}{lw}$$

$$S_n = \frac{y}{w}\left(1 - \frac{x}{l}\right) \qquad \textbf{(2.19)}$$

These shape function could representing variation of any unknown variable ψ over a rectangular element in its nodal term ψ_i, ψ_j, ψ_m, and ψ_n. Thus in general :

$$\psi^{(e)} = [S_i S_j S_m S_n] \begin{Bmatrix} \psi_i \\ \psi_j \\ \psi_m \\ \psi_n \end{Bmatrix} \qquad \textbf{(2.20)}$$

Using two-dimensional Cartesian frame as a reference, rate of heat transfer given by Fourier law are :

$$q_X = -kA\frac{\partial T}{\partial X}$$

$$q_Y = -kA\frac{\partial T}{\partial Y}$$

$$q''_X = -kA\frac{\partial T}{\partial X}$$

$$q''_Y = -kA\frac{\partial T}{\partial Y} \qquad (2.21)$$

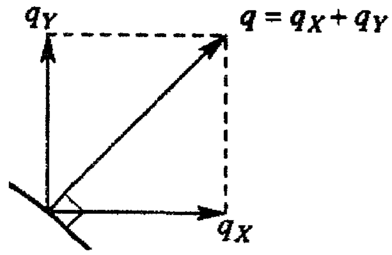


Figure 2.4 Heat flux vector normal to isotherm

Where q_X and q_Y are the rate of heat transfer of X and Y component, and q''_X and q''_Y are the heat flux in X-direction and in Y-direction respectively. k is the thermal conductivity and A is the cross sectional area of medium. $\frac{\partial T}{\partial X}$ and $\frac{\partial T}{\partial Y}$ are the temperature gradient. Figure 3.4 shows that the direction of total heat flux is always perpendicular to the constant temperature on lines or on surface (isotherm). Thus, the heat conduction equation were represented in Cartesian coordinate system are :

$$k_x \frac{\partial^2 T}{\partial X^2} + k_y \frac{\partial^2 T}{\partial Y^2} + q' \qquad \textbf{(2.22)}$$

In this research, constant heat flux were applied to the model surface, thus the boundary condition were represented by :

$$-k \frac{\partial T}{\partial X} | x_0 = q''_o \qquad \textbf{(2.23)}$$

2.6.2 Finite Element Simulation

Yang and Sun [42] investigated the drilling process; a coupled thermo-mechanical finite element model of drilling is developed. Several key technologies, such as material constitutive model, material failure law, contact and friction law, have been implemented to improve the accuracy of finite element simulation. And by comparing the predicted cutting forces with the measured forces shows the finite element model is reasonable. These results confirm the capability of finite element simulation in predicting drilling process and selecting optimal tool and cutting parameters, due to this, long and lengthy experimentation train and error could be minimized.

Kun et. Al [43] measure the temperature rise during bone drilling using dynamic elastic-plastic finite element model. The model simulates the thermal contact behaviour of a drill bit during drilling process. The focus areas are the drill speed and applied force. In the experiment, the thermocouple could not be places closer than 0.5 mm from the edge of drill hole, but by using finite element this problem could be effectively resolved. The result validated by the experimentation method shows that the maximum difference was less than 3.5%.

As the comparative result shows that the finite element method could estimate and predict the value in close proximity to the experimentation, the same researchers also investigated various rotating speeds and applied force in effecting the temperature rise during drilling. The focus area is the region which surroundings the drill hole, thus the shape of a circle or circular disc were chosen for the domain, for the numerical simulation. Cortical bone are larger in mechanical properties compare to cancellous bone, thus temperature rise would be greater during drilling. The effect of the rotating speed and the applied force of the drill bit on the temperature rise have been examined. Based upon the numerical results, the bone temperature varies with the depth of the drill, higher rotating speed would decrease the bone temperature, by increasing the rotating speed could reduce the bone temperature, as well as larger applied force[44].

2.6.3 **Model construction**

- Manually drawn

Manually drawing the bone model considers to be the most simple mode of model construction. Depending on the software used, simple geometrical shape could be done. For example, these researchers carry out the numerical analysis a simplified geo-metrical model of femur. Disc of diameter d1 = 20 mm and height h = 10 mm was established as the model of the femur. The height of the disc corresponded with thickness of cortical tissue of femur. The hole corresponding with diameter of the drill and representing its edge geometry was simulated in the disc (Figure 2 below). The

Inventor Professional 2008 software was applied in order to work out the geometrical models [45].

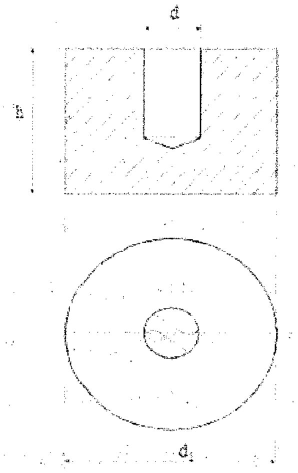


Figure 2.5 Geometrical model of the disc simulated of bone

- Using Medical data to obtain bone modeling

Finite element modeling of human bones is quite useful in biomechanical simulations. Finite element analysis is the most appropriate technique for analyzing mechanical properties of the complex human bone structure. Due to the availability of low cost computing power, three-dimensional analysis and investigation of any complex structure can be done in virtually in no time. Human bone FE models are generated from image data obtained from medical scanning systems like MRI or CT.

Three-dimensional (3D) finite element (FE) stress analysis provides a complete description of the stress field in a bone structure. To some, this information is a key factor for understanding bone functional behaviour in many research and clinical applications. For Example, fracture risk assessment, design and validation of prosthetic implants, are the possible applications of the 3D FE analysis in clinical studies. The bone structures depends on their shape and size, as well as on the mechanical properties of the material of which they are composed [46]

There are several method used from medical data to build the bone modelling in FE; using Computed tomography (CT) scan and Magnetic Resonance Imaging (MRI) scan.

- Using Computed tomography (CT) data obtain from real bone

Finite element analysis (FEA) is widely adopted to investigate the mechanical behaviour of bone structures. Computed tomography (CT) data are frequently used to generate FE models of bone. If properly calibrated, CT images are capable of providing accurate information about the bone morphology and tissue density.

In the early period the methods used to derive bone geometry and mechanical properties were inaccurate and sometimes highly invasive and destructive. More recently, Marom et al. [47] pointed out many of the advantages of using computerised tomography (CT) scans in bone modelling. CT images provide accurate information about bone geometry, the radiographic density (*RD*) reported in the CT images can be related to the mechanical properties of bone, and moreover CT scanning is a mildly invasive routine diagnostic method which permits the modelling of human bones in vivo. CT systems have the capability of measuring the linear attenuation of the tissues under examination.

Generation of subject-specific finite element (FE) models from computed tomography (CT) datasets is of crucial for application of the FE analysis to bone structures. However, a great challenge remains is the automatic assignment of bone material properties from CT Hounsfield Units into finite element models. The researcher [48] proposes a new assignment approach, in which material properties are directly assigned to each integration point. Instead of modifying the dataset of FE models, it divides the assignment procedure into two steps: generating the data file of the image intensity of a bone in a MATLAB program and reading the file into ABAQUS via user subroutines. Its accuracy has been validated by assigning the density of a bone phantom into a FE model. The proposed approach has been applied to the FE model of a sheep tibia and its applicability tested on a variety of element types. The proposed assignment approach is simple and illustrative. It can be easily modified to fit users' situations.

In another works they develop a special program that can read a CT data set as well as the FEA mesh generated from it, and assigning each element of the mesh the material properties derived from the bone tissue density at the element location. The program was tested on phantom data sets and was adopted to evaluate the effects of the discrete description of the bone material properties. A three-dimensional FE model was generated automatically from a 16 bit CT data set of a distal femur acquired in vivo. The strain energy density (SED) was evaluated for each model element for increasing model complexity (number of different material cards assigned to the model). The computed SED were strongly dependent on the material mapping strategy.

Computed tomography (CT) represents, at present, the method of choice for the generation of these subject-specific finite-element models, since from CT data it is possible to define the geometry and the local tissue properties of the bone segment to be modelled. However, the data processing techniques used to extract this information from the CT data may frequently be affected by non-negligible errors that propagate in an unknown way through the various steps of the model generation, affecting in an unpredictable way the accuracy of the model predictions.

In many studies the density information provided by the CT dataset is used to derive an inhomogeneous, although locally isotropic, the distribution of the bone tissues mechanical properties. This procedure involves two steps. At first the CT data are calibrated to correlate the Hounsfield units to the apparent or to the ash density of the bone tissue. This step is sometimes performed using a calibration phantom [49-53], or assuming conventional values derived from literature for selected regions [54]. In both cases the obtained density values cannot be assumed to be error-free. Then the density of the bone tissue is related to its Young's modulus, or to its strength, using empirical equations based on experimental measurements. The coefficients of these equations are affected by an uncertainty due to the significant scattering of these experimental measurements [55-58].

However, using the proposed method to build a finite-element model of a femur from a CT dataset, of a quality usually achievable in the clinical practice, the variation coefficients of the output variables never exceed 9%. This uncertainty on the results seems admissible since these models are commonly used in the orthopaedics research to discriminate between conditions involving much larger differences. Furthermore, the uncertainties related to the boundary conditions definition in the generation of a subject-specific finite- element model of a bone segment are definitely far higher.[59]

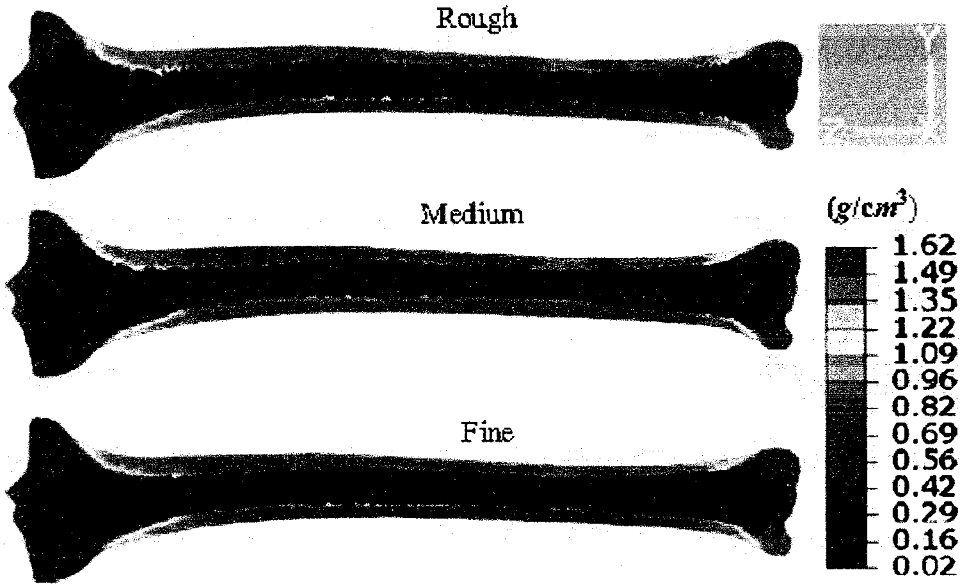


Figure 2.6 Assigning material properties i.e. density from CT scan of bone to FE bone model [60]

- Using MRI data obtain from real bone

The medical scanning system gives an accurate measurement of anatomical geometry. The accurate representation of the anatomically specific geometry in the finite element model enhances its function especially when motion of a joint is of major concern. However, the generation of a suitable finite element model of human body parts with accurate anatomically specific geometry is still a formidable task, especially if hexahedral solid elements are preferred.

Conventional methods adopted in existing FE modeling packages are very time consuming and not suitable for modeling of human bones. So compared to the computational time, the effort needed to generate the finite element model generally dominates the overall process time.

A technique is developed to make FE model of bones from MRI/CT scan data [61]. This technique is a modification over conventionally used techniques. In conventional technique solid modeling processes intermediate solid / surface generation is essential before getting finite element model from the scan data. If this necessity is eliminated, process time and steps are shortened. Conventional process for finite element meshing from MRI scan data requires two intermediate steps first interior and exterior contour point extraction of bones and second solid modeling from contour data extracted. An algorithm is developed and implemented to obtain a meshed model of bones directly from the contours. This technique is developed and implemented to obtain FE meshes from Magnetic Resonance Imaging (MRI) / Computed Tomography (CT) scan data.

Other studies [62] use finite element analysis of the tibia to evaluate stresses developed in the tibia under static loads and to study the effect of varying material properties on these stresses. A 3-D solid model of the human tibia and the fibula was constructed using Magnetic Resonance Imaging and solid modeling software. Loading conditions and material properties used were taken from the literature. Two finite element models were taken into consideration. A model of the tibial post up to a length of 130 mm was studied to compare results to previous literature and a model of the whole tibia under similar loading conditions was analyzed. This model of the tibia proved to be extremely accurate and could be used to study the behavior of the tibia under further varying properties of cancellous bone and under various loading conditions. Moreover, viscoelastic properties of compact bone could be applied to this model. The effect of muscle forces and the fibula on stresses developed would be of extreme interest. This would definitely seem to reduce the deflection of the tibia reported in this study. The geometric characteristics which play a very important part on stresses developed have been captured extremely accurately.

2.7 Experimental Approach

This section discusses the selection of experimental approached done by previous literature studies. It consists of sample preparation, detail on how the sample of the drilled bone was prepared and the selection of material that may exhibit similar properties to bovine bone. The method of temperature measurement during the drilling procedure were also discussed.

2.7.1 Properties of bone

Bone is a porous non-homogeneous material; different location would give variation in the structural density, which would result inherent fluctuation in the drilling temperature. The temperature profile of a material depends on the specific heat capacity and on thermal conductivity. Thermal gradient exists when there is a two different temperature. Thus, heat is transferred and will continue to transfer as long as there is temperature gradient, when these two regions are equal, the specimen is in a state of equilibrium. However, when biological tissues are exposed to heat in drilling, the temperature equilibrium is not achieved, as the exposure times are usually too short. When the temperature reached the non-equilibrium state for the short exposures, it is known as a function of the exposure temperature and time, and the specific heat capacity being constant [63]. Cowin SC. [64] and Kohles SS. [65] states that bone has mechanical properties of anisotropic. Hence isotropy of its thermal conductivity must be counted. Davison [66] also supported that bone is to be treated as isotropic

Heat generation during drilling common problem is due to the sensitivity of bone to heat damage and the difficulty of conducting heat away from the cutting edge, both as a result of the poor conductivity of the bone and the inability to use a coolant because of the danger of causing infection to the area. 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 [67-69]. However, some of the heat generated during drilling may be partly spread out by the presence of blood and tissue fluids and partly carried away by the chips formed.

Table 2.1 Material properties of bone used in FEM

	Thermal Conductivity	Specific heat	Density, kg/m^3	Reference
Human	0.16 to 0.34 W/m °C	1.14 and 2.37 J/gm °C	1900	[70]
Bovine	0.54 W/m K	1260 J/kg K	1800	[66]
PMMA	0.50 W/m K	1297.9 J/kg K	1683	[71]

- Sample preparation

Sample preparation may vary from choice of animal and its specific parts to the condition of the bone i.e. wet or dry. Below are some of the summarize sample preparation methods;

Table 2.2 Bone sample preparations

Type of bone	Storing condition	Preparation	Reference
Fresh dead cortical bone from bovine femur	-10°C	cut into 2 parts, along longitudinal axis ; 1 part (specimen) glue to metal surface block with bone's top surface facing drill	[72]
Freshly extracted cadaverous human femurs	-20°C	experiment carried out in; axial direction – according to Haversian osteon, transverse axis – position perpendicular to anatomically axial direction.	[73]
Pig ribs	−10°C	prepared according to the guidelines established by Sedlin and Hirsch	[74]
Cortical pig femur	-80°C	After defrosting bone were dried at 35°C for 12h The ring-type cortical bone were cut into 2 pieces; thermocouple installed in the pieces- depth 0.5 mm from the surface	[75]

Cattle tibia	-18°C	Special container holding normal saline solution , fitted with heating element for solution maintain at 37°C	[76]
Mid-shaft of bovine femora	Stored in freezer	Wrap in gauze; soaked in mammalian Ringer's solution (mimic physiological fluid) and Wrapped in resealable bag. Stored in freezer	[77]

Researcher conducted various test using cadaveric bone for scientific experimentation practice. Thus Sedlin and Hirsch [78] have clearly established the importance of properly harvesting and storing fresh cadaveric bone, in order to preserve its mechanical properties. Mc Elhaney et. al. [79] demonstrated that preservation of cadaveric bone specimens with formalin altered the mechanical properties of these bones, making them potentially unsuitable for quantitative mechanical tests.

- Using Bovine Bone

Some demonstrated that even the time between death and harvesting of specimens may have some effect on the mechanical properties of harvested bone [80]. Fortunately, changes associated with post mortem enzymatic degradation are probably minimal with regard to hard tissues, such as bone. However, it should be remembered that even the best preparation of cadaveric bone would differ from living, in situ bone in some way.

Properties also vary between the sexes. Investigator found that the drilling temperatures of female bovine tibias are higher compare to the male tibias. This may be due to a higher content of calcium in female bones. 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. Therefore the bone quality around the drill site was found to be worse than the bone samples exposed to low temperatures [81].

- Using Plastic as Bone Substitution

In response to these difficulties, investigators have used plastic foam models for certain types of studies. There are several attractive features associated with these models. Variability from specimen to specimen is greatly reduced, for example, it is highly beneficial for evaluating subtle geometric changes in osteotomy design.

Previous studies have demonstrated that by altering the pore size and distribution (density) within the plastic foam models, the microscopic geometry may resemble that of natural bone [82] Thus for studies in which microstructure plays a significant role, plastic bone models may be an ideal substitute for natural bone. Heat generated during bone drilling cause by the evaluation of heat generated during the cutting of bone. The heat generated is mainly as a result of the surface friction and microstructure changes. Therefore, a substance of uniform character, which approximates the density of bone, would be much more consistent for making this type of evaluation [83].

Landsman [84] attempted to investigate whether the use of plastic bone models would be valid when testing the mechanical integrity of the model was critical for the outcome. He found that there was a great deal of similarity within the elastic ranges of deformation between all of the models tested. Yet, in tests where the specimen was loaded to failure, the first metatarsal anatomic plastic models poorly duplicated the mechanical properties of cadaveric bone. In studies which are purely geometric in nature, anatomic models allow for repeated, side-by-side comparisons, could serve as an excellent pilot study material before actually conducting tests on the more expensive cadaveric bone.

2.7.2 **Temperature measurement**

Former attempts have been made to measure temperature when drilling bone, by inserting thermocouples adjacent to the drill as it progressed into the hole. Krause [85] attempted to measure temperature when drilling bone by cementing a $\phi 1.07$ mm copper constantan thermocouple into a hole previously drilled from the endoesteal surface. The drill under test approached the thermocouple along the same axis from the periosteum surface, stopping just short of it. This gave an indication of the temperature of the cutting edges of the drill as they approached the thermocouple. No irrigation was used during the drilling. As would be expected, unbiased results were obtained using this method.

Methews [86] and Methews and Green [87] cemented thermocouples into four separate ϕ 0.7 mm holes drilled about a centre at radii of 2.5, 3.0, 4.0 and 5.0 mm. They then drilled a ϕ 4 mm hole through the centre and measured the temperature from each thermocouple. Their findings showed that cutting speed had very little effect on temperature change above 55°C but that the force applied to the drill caused a much greater temperature increase.

Attempts to measure temperature during drilling cortical bone have been carried out by placing thermocouples into the bone at given distances from the drilling area. Inconsistent results have been achieved using these methods. It is the opinion of the present authors that because of the poor thermal conductivity of bone, its structural inconstancy and the great difficulty in modelling for heat-transfer purposes, embedding thermocouples in the bone adjacent to the drilling operation is not a satisfactory method of measuring the temperature effects [88].

Infrared thermography use a camera that can converts heat visible to naked eyes, thus relationship between machining process and heat generation can be assisted, while providing non-contact means. T. Udiljak, *et al.* [89] and G. Augustin, *et al.* [90] used a thermographic camera to measure heating process in bone drilling. Thermographic studies were widely used in dentistry [91] and maxillofacial surgery [92].

2.8 Summary

The chapter provides a solid framework for this research. Approach to the problem have been carried out various ways, thus in completing the research patch; this project continues to strengthen by using another approach which would be further discussed in the next chapter.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Overview

This chapter provides detailed information on how this project had been conducted based on the literature review study discussed in chapter 2. This research study was divided into three major parts which consist of :

i. Numerical modeling using non-linear thermal transient
ii. Simulation of FE modeling for bone drilling and experimental validation
iii. Parametric analysis

The first phase of this research is to develop numerical heat transfer model for bone drilling. Heat source models that were discussed in chapter 2 were selected and used to calculate the heat generation, thus parameters that need to be controlled were identified with the calculations.

The second phase, contains the step by step method used to build the FE models using ANSYS apdl. The stability of the FE models then were tested by conducting the experimental validation.

Subsequently the third phase involves the methodology of parametric analysis for feed rate, point angle and drill bit diameter as a function of drilling speed. Figure 3.1 shows the flow chart of the overall research methodology.

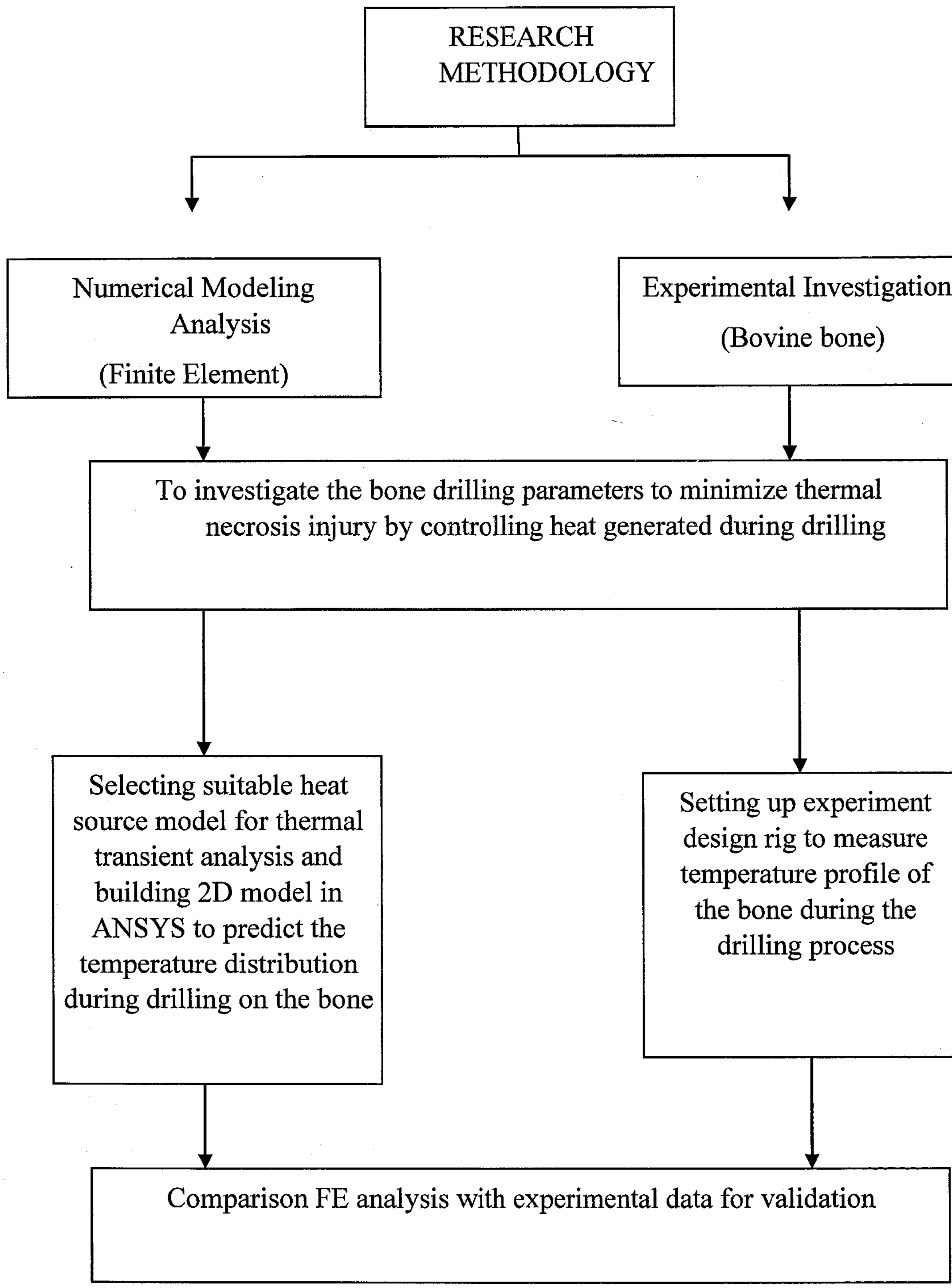


Figure 3.1 Flowchart of overall research methodology

3.2 Numerical Modeling and Analysis

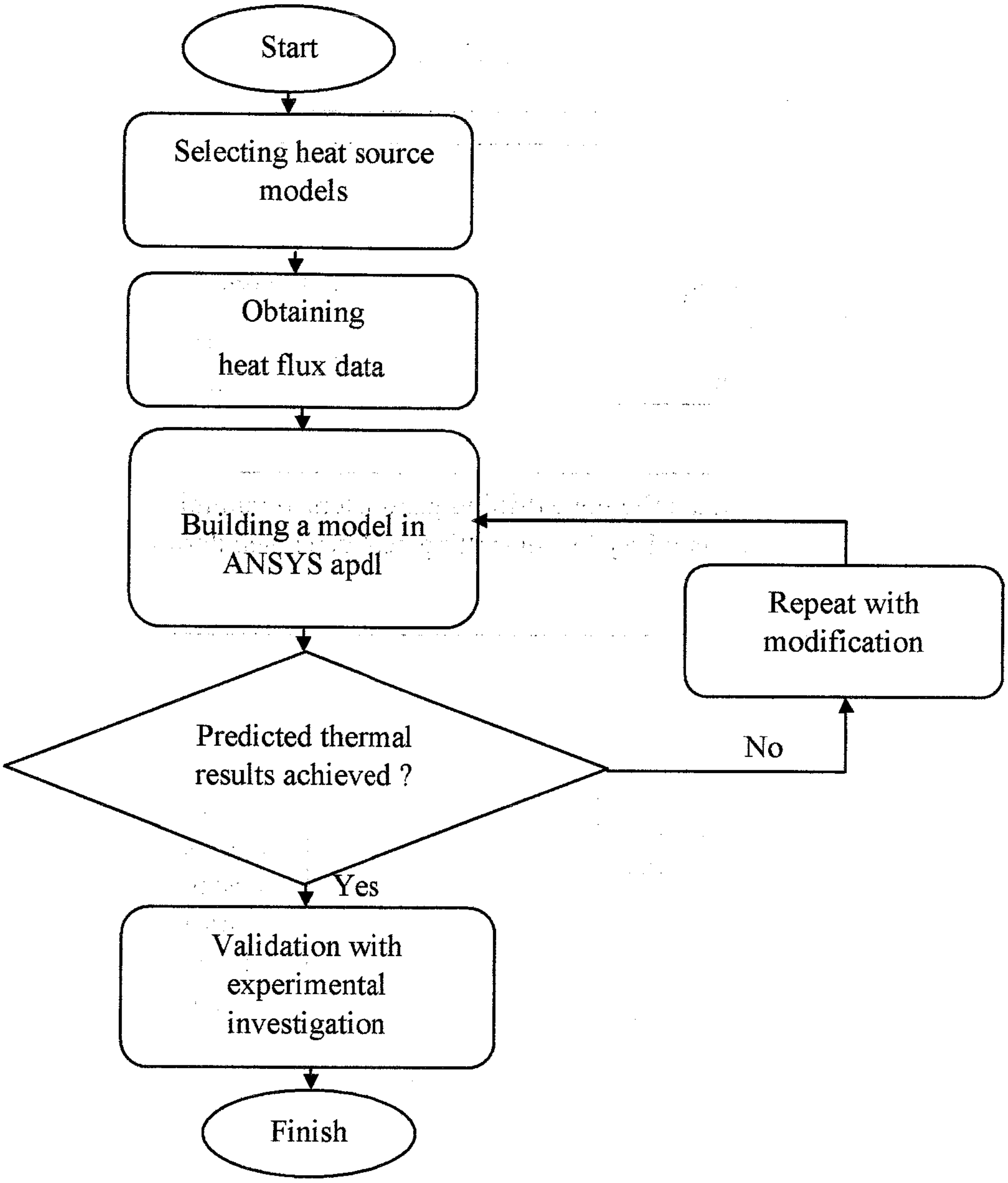


Figure 3.2 Flowchart of numerical analysis

3.2.2 Relationship between Parameters

Since we were looking into the medical practice problem, having the drill geometrically model consistent with the medical practice is important. This parametric investigation would include the spindle speed, feed rate, drill-bit diameter, point angle, and helix angle are summaries in a Table 3.1 below;

Table 3.1 Surgical geometries

Parameter	Values	Literature reference
Spindle speed	400 to 3000 rpm	[93-95]
Feed rate	0.42 to 3.3 mm/s	[12-14]
Drill-bit diameter	1.5 and 4.5 mm	Orthopedic-surgery practice
Point angle	70 to 130° 118°; frequently used in metal cutting	[93, 96]
Helix angle	12 to 38°	[97-98]
Drilling depth	9 mm	Common thickness of the cortical portion of bone, especially for bovine femur or tibia.

These Parameters is mentioned in the Table 3.1 will be calculated using equation mentions in chapter 2 in MATLAB to determine the most influencing parameter of heat generated. The relationship of the parameters discussed in chapter 4.

3.3 Modeling

Good modeling results require various numbers of steps, in this part each step were elaborated in depth, those steps are element type, analysis type and material properties that were used and how to optimize the models were included.

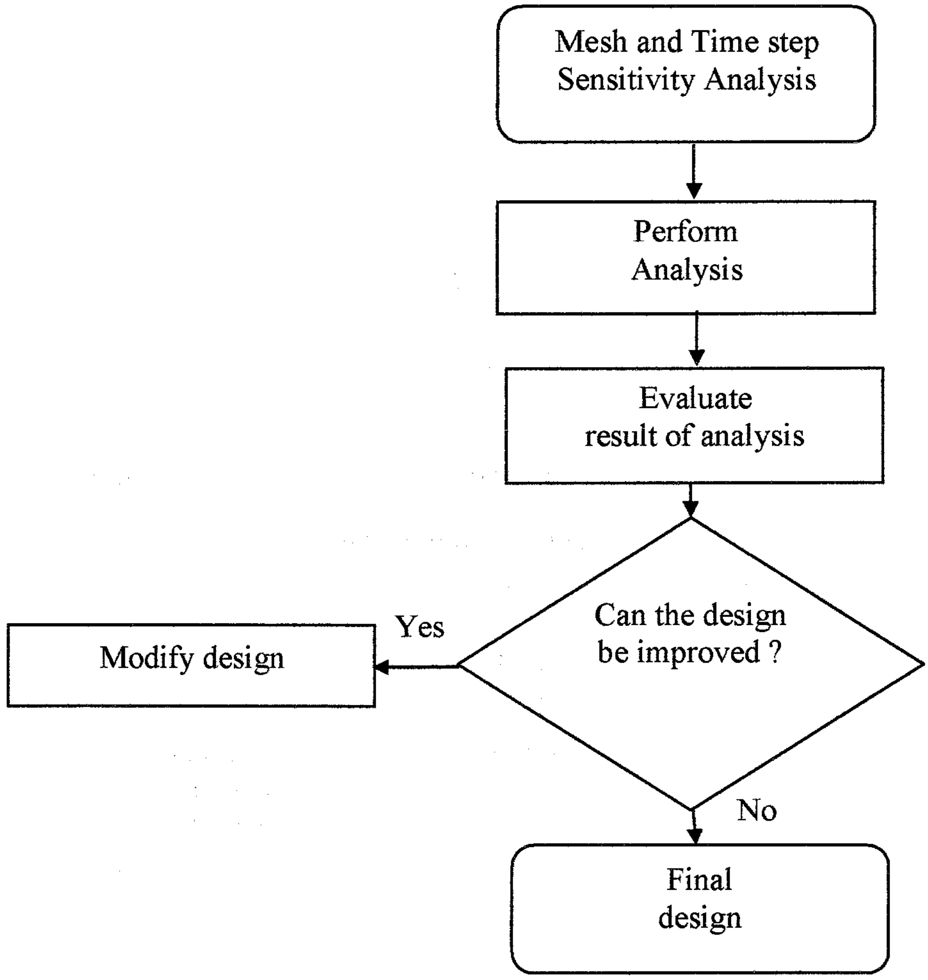


Figure 3.3 Flowchart of optimization procedure

Sensitivity analysis is important to obtain a functional design that would satisfy all the requirements that were applied in the model. Figure 3.3 above shows some basic ideas in design optimization. The procedure begins with initial design, performing analysis and analyzing the results and deciding whether or not the initial design could be improved. A design that were tested are meshing and time step size.

- Element type

  Plane 55 element were selected for modeling two-dimensional heat transfer problem. Subsequently, heat generation data calculated in prior steps would be use as in input data at the element face. The output data of nodal temperature and element data would be collected in latter steps

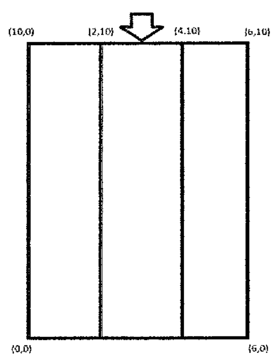
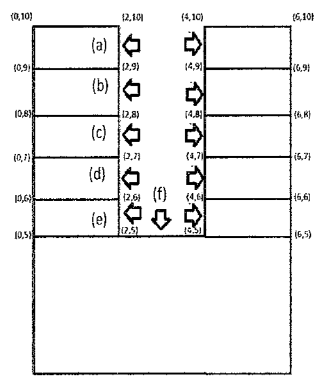
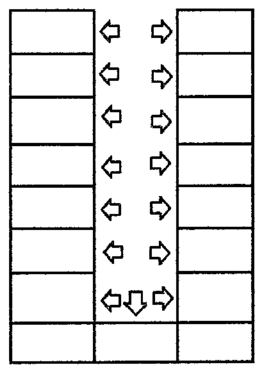
- Analysis type

  Full transient analysis are chosen for this analysis type, this is because it uses full system matrices to calculate transient response without matrix reduction. The transient behaviour of bone drilling prediction. Full transient analysis used to simulate FE model because of the transient behaviour of heat transfer between the bone and the drill bit.

3.3.1 **Model Geometry**

Bone modeling approach could be done in various ways. Drawing the bone geometrically using CAD to work out the geometrical models [99], using CT scan medical data (which material properties are directly assigned to each integration point) [44], and lastly by using MRI scan data [71, 100]. In this project the model were built manually using tools in ANSYS apdl. Model dimension and load applied were shown below;

Table 3.2 Model dimension in FE

Time, s	2s	6s	12s
Dimension and Load Applied			

- Surface load

  The surface loads of heat flux were used and applied base on the Table 3.2 above. The heat generation calculated using heat flux was used as an input for FE model. The areas to be applied on the FE model were calculated to be the same area as the drill bit diameter, representing the area of the drilling hole.

- Loop

  Looping is a command that allows a series of repetition in a number of times. Simulation of the drilling process progressively toward the bone involves applying heat flux repetitively onto a surface area, thus looping syntax were used. Flows of the loop are illustrated below;

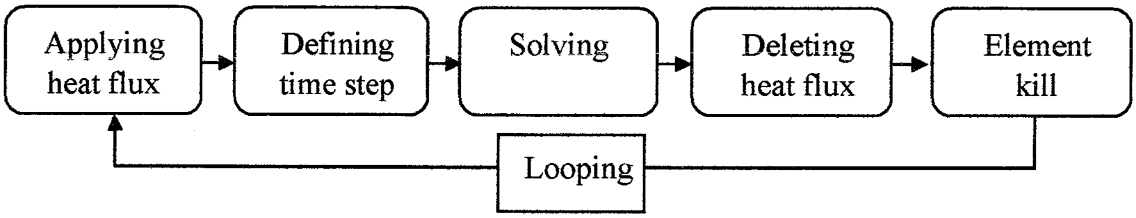


Figure 3.4 flow of loop command used to simulate drilling process using heat flux input data

- Element kill

  The used of element kills plays a role to remove a certain element in the model, as the drilling involves material removal prior to depth of cut. This function is used to deactivate selected element. This step was created in PREP7 at a proper defined load step. Depth of cut 5 mm consist of 10 load steps, as shown in Figure 3.5 below. Importance of element kill is to simulate the drilling motion that penetrate inside of the bone. Element kill role of removing certain element thus, element which are being removed is the bone prior to cutting.

```
OK  Save  Cancel  Help
! First load step
FLST,5,20,2,ORDE,20  !select element
FITEM,5,820
FITEM,5,840
FITEM,5,860
FITEM,5,880
FITEM,5,900
FITEM,5,920
FITEM,5,940
FITEM,5,960
FITEM,5,980
FITEM,5,1000
FITEM,5,1020
FITEM,5,1040
FITEM,5,1060
FITEM,5,1080
FITEM,5,1100
FITEM,5,1120
FITEM,5,1140
FITEM,5,1160
FITEM,5,1180
FITEM,5,1200
CM,_Y,ELEM
ESEL, , , ,P51X
CM,_Y1,ELEM
CMSEL,S,_Y
CMDELE,_Y
!*
/GO
!*
!*
SFE,_Y1,_Z4,HFLUX, , %HFLUX% ! applying heat flux on element - 0.5mm depth
CMDELE,_Y1
!*
FINISH
/SOL
DELTIM,0.1,0,0    !specifiyng time step size
OUTRES,ERASE
OUTRES,ALL,ALL
TIME,1.2      !specifiying time step end
/STATUS,SOLU
SOLVE      !Solve
FINISH
/PREP7
FLST,2,20,2,ORDE,20   !Delete heat flux
FITEM,2,820
FITEM,2,840
FITEM,2,860
FITEM,2,880
FITEM,2,900
FITEM,2,920
FITEM,2,940
FITEM,2,960
FITEM,2,980
FITEM,2,1000
FITEM,2,1020
FITEM,2,1040
FITEM,2,1060
FITEM,2,1080
FITEM,2,1100
FITEM,2,1120
FITEM,2,1140
FITEM,2,1160
FITEM,2,1180
FITEM,2,1200
SFEDELE,P51X,All,HFLUX
FLST,2,20,2
FITEM,2,820
FITEM,2,840
FITEM,2,860
FITEM,2,880
FITEM,2,900
FITEM,2,920
FITEM,2,940
FITEM,2,960
FITEM,2,980
FITEM,2,1000
FITEM,2,1020
FITEM,2,1040
FITEM,2,1060
FITEM,2,1080
FITEM,2,1100
FITEM,2,1120
FITEM,2,1140
FITEM,2,1160
FITEM,2,1180
FITEM,2,1200
EKILL,P51X      !kill element
ESEL,S,LIVE
NSLE,S
NSEL,INVE
D,ALL,ALL,298
NSEL,ALL
ESEL,ALL
! Second load step
```

Figure 3.5 Session editor of ANSYS apdl for one load step

3.3.2 **Material Properties**

Modeling is effective as it simplify current problem, but the value inserted need to be as close as possible resembling the nature of the material. Table 3.3 shows that Davison [101] conducted thermal conductivity of cortical bone experimentally and found out that bovine cortical bone has a thermal conductivity of 0.56±0.039 W/mK . This value had been widely used for finite element modeling, as shown in table 3.3. The other values used by Kun et al was taken from a trusted website, it had been repeatedly used in his works

Table 3.3 Mechanical characteristic of the bone used in FEM analysis

Literature Review Reference	Mechanical Properties of bone	Value	Tested in Finite element simulations by these authors
[101]	Thermal conductivity	0.54 W/m K	• J.lee et al (2011,2012) • K. Alam et al (2010)
	Specific heat	1260 J/ kg K	
	Density	1800 kg/m^3	
Sawbones and Matweb	Thermal conductivity	0.38 W/m °C	• Yuan-Kun et al (2008,2010,2011)
	Specific heat	1260 J/kg °C	
	Density	1700 Kg/m^3	

3.3.3 **Meshing**

Generally, large number of elements would give higher result accuracy, but the excessive element also may increase the round-off error. Therefore, it is important to find the adequate meshing configurations. Initial meshing is also important as to determine a better approximation of the solution and to reduce the CPU time required to solve the problem while retaining its accuracy. Initial meshing was performed first and were analyzed by using twice number of the elements, those solutions were compared to obtain the adequate mesh configuration. The mesh was considered acceptable if the results were close to each other, as presented in the table 8 below, adequate meshing are mesh 9. The model parameters were, 400 rpm, drill diameter 1.5, heat flux 2793 feed rate 0.42, time step end 2.38s.

Table 3.4 Initial meshing procedure

Mesh No	No of element in 1 mm	Total No of elements	Total No of nodes	Maximum nodal temperature, K
Mesh 1	10	300	341	312.82
Mesh 2	15	675	736	313.11
Mesh 3	20	1200	1281	313.22
Mesh 4	25	1875	1976	313.27
Mesh 5	30	2700	2821	313.30
Mesh 6	35	3675	3816	313.32
Mesh 7	40	4800	4961	313.33
Mesh 8	45	6075	6256	313.34
Mesh 9	50	7500	7701	313.35
Mesh 10	55	9075	9296	313.35

3.3.4 Time Step

Since thermal transient analysis involves load in a function of time, it is important to determine the time step size. The smaller time step size value would increase the accuracy of the solution. Similar to the initial meshing selection, too small would waste computing time and too large would introduce errors. Figure 3.9 below shows that selection of time step size should be small enough to resolve the thermal prediction of bone, in this case is 0.01 time step size

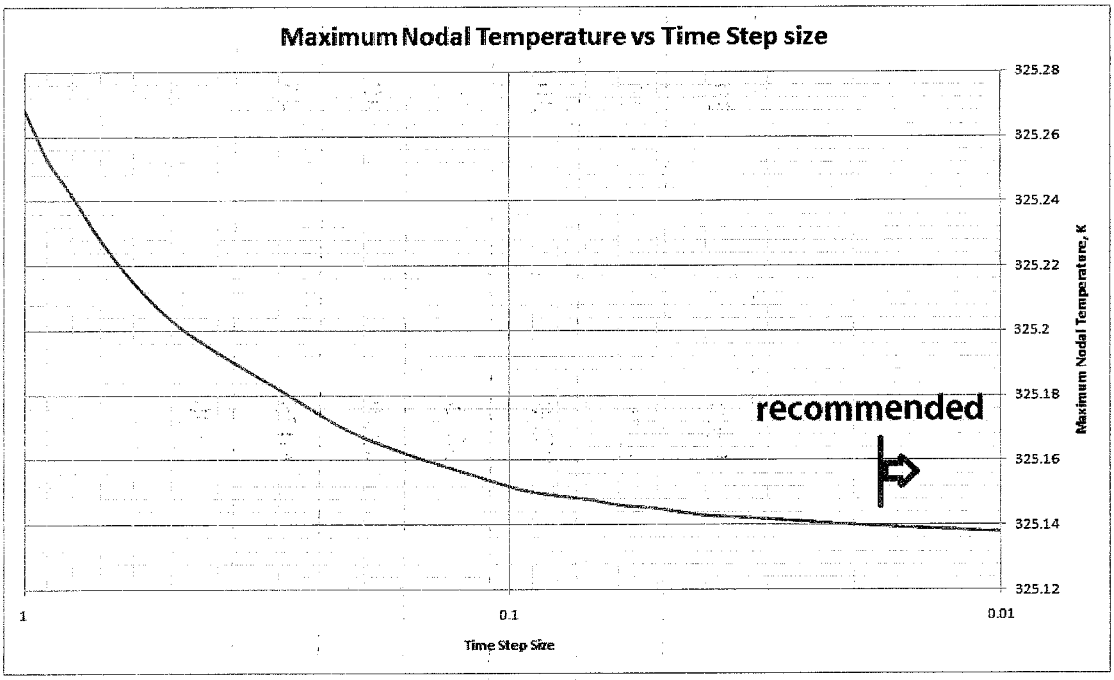


Figure 3.6 Effect of the integration time step in maximum nodal temperature

3.4 Experimental Validations

Numerical modeling and simulation is not useful when it does not validate, hence this phase is for validation. Dry bovine bone was selected for experimental validations, choice of temperature measurements are using thermocouple and thermal imaging camera. Details were discussed in the next sections.

3.4.1 Experimental apparatus

With reference to Figure 3.7 below, the experimental apparatus comprises few key elements:

a) Thermocouple type K
b) thermocouple data logger
c) Mazak high speed drilling machine
d) Thermal imaging camera FLUKE
e) Adhesive white tapes

3.4.2 Sample Preparations

This study uses bovine bone cow leg as the test model. Bone sample were obtain from local slaughter house. The bone dimension is 200 mm x 25 mm. Specimens were kept frozen at -5°C and were dried under the sun to eliminate the bone odor.

3.4.3 Experimental Procedure

Below are the steps used to prepare the experimental setup:

a) The bone sample is fixed onto Mazak clamping system and the smooth surface is used for drilling starting from one end to the other.
b) The thermocouple is placed approximately ±3mm from the drilling site and were connected to the thermocouple data logger as shown in Figure 3.7 (d). A ruler was used for estimation of thermocouple placement Figure 3.7(c).
c) The adhesive white tape was used to fasten the thermocouple onto the bone specimen
d) The Mazak drilling door was kept open during the experiment as to capture thermal images from thermal imaging camera
e) The thermal imaging camera was adjusted manually by free hand with approximately the same level as the drilling head. Figure 3.7(e)
f) The experiment was repeated 3 times and the average temperature reading were taken.

Figure 3.7(a) shows the overview picture where the specimen is clamped using

Mazak current clamper. The background temperature is 23^{0}C and the initial temperature of the drilling site was approximately ±25^{0}C. The Drilling speeds were tested from 12,000 to 20,000 rpm.

Simulation analysis in previous section stated that maximum temperature generated dependency on feed rate is low, thus analysis about the feed rate has not been carried out. This experiment highly focuses on the temperature dependency to drilling speed, where as we increase the drilling speed, the temperature would also increase.

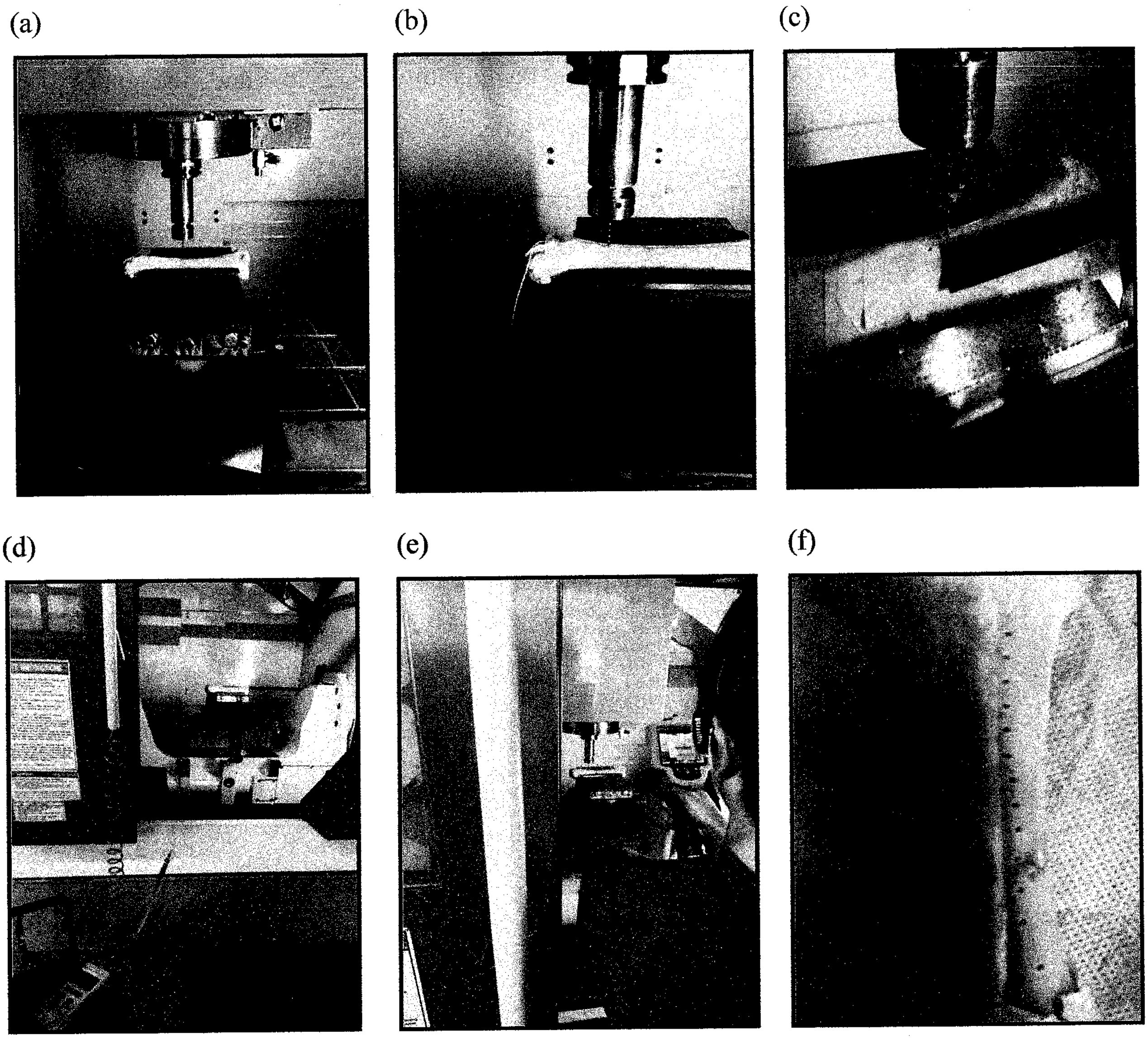


Figure 3.7 (a) overall view , (b) the thermocouple and drill bit position, (c) approximation of 3mm distance from the drill bit and the thermocouple, (d) overview of how thermocouple data logger were connected, (e) the height level of thermal imaging camera were taken, (f) the bone condition after drilling

3.5 Summary

This project had been carried out using the heat source equation, ANSYS apdl for temperature prediction and experimental validation using bovine bone. Results and discussion from these data were presented in chapter 4.

CHAPTER 4

RESULT & DISCUSSION

4.1 Overview

This chapter answers the hypothesis of this research project. It discusses the detail result, analysis, findings and the implications of these findings on recommending for the efficiency bone drilling parameter.

This research study was divided into three major parts which consist of :

i. Numerical modeling using non-linear thermal transient FE analysis of bone drilling
ii. Result and analysis of experimental validation
iii. Parametric analysis

Result base on the previous methodology chapter, were analyzed and explained in depth. The first phase of this research is to analyze numerical heat transfer models for bone drilling. The graphs of heat flux from the selected heat source equation were presented, and their relationships were determined. The relationship between the parameters and heat generation were then used for the second phase.

The second phase contained the results of the FE modeling and experimental validation. The FE model and validation method from previous chapter were represented in elaborated graphs. Validation of the FE models is important in verifying the stability of FE models.

The third phase consists of parametric analysis, the relationship of thermal necrosis by controlling heat generation are presented. The recommended parameters to be used with the purposes of minimizing thermal necrosis were also presented and discuss in details.

4.2 Relationship between parameters and heat generation

Parameters mentioned in Table 3.1 from previous chapter were used in the heat source model equation. Ranges of the value were tested in MATLAB as follows;

Table 4.1 Parameter tested in MATLAB

Parameters	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**
Feed rate, mm/s	0.42 - 2.2	0.42	0.42	0.42	0.42
Drilling speed, rpm	400	400 - 3000	400	400	400
Drill diameter, mm	2	2	1.5 - 4.5	2	2
Point angle, °	118	118	118	70 - 130	118
Helix angle, °	23	23	23	23	12 - 38

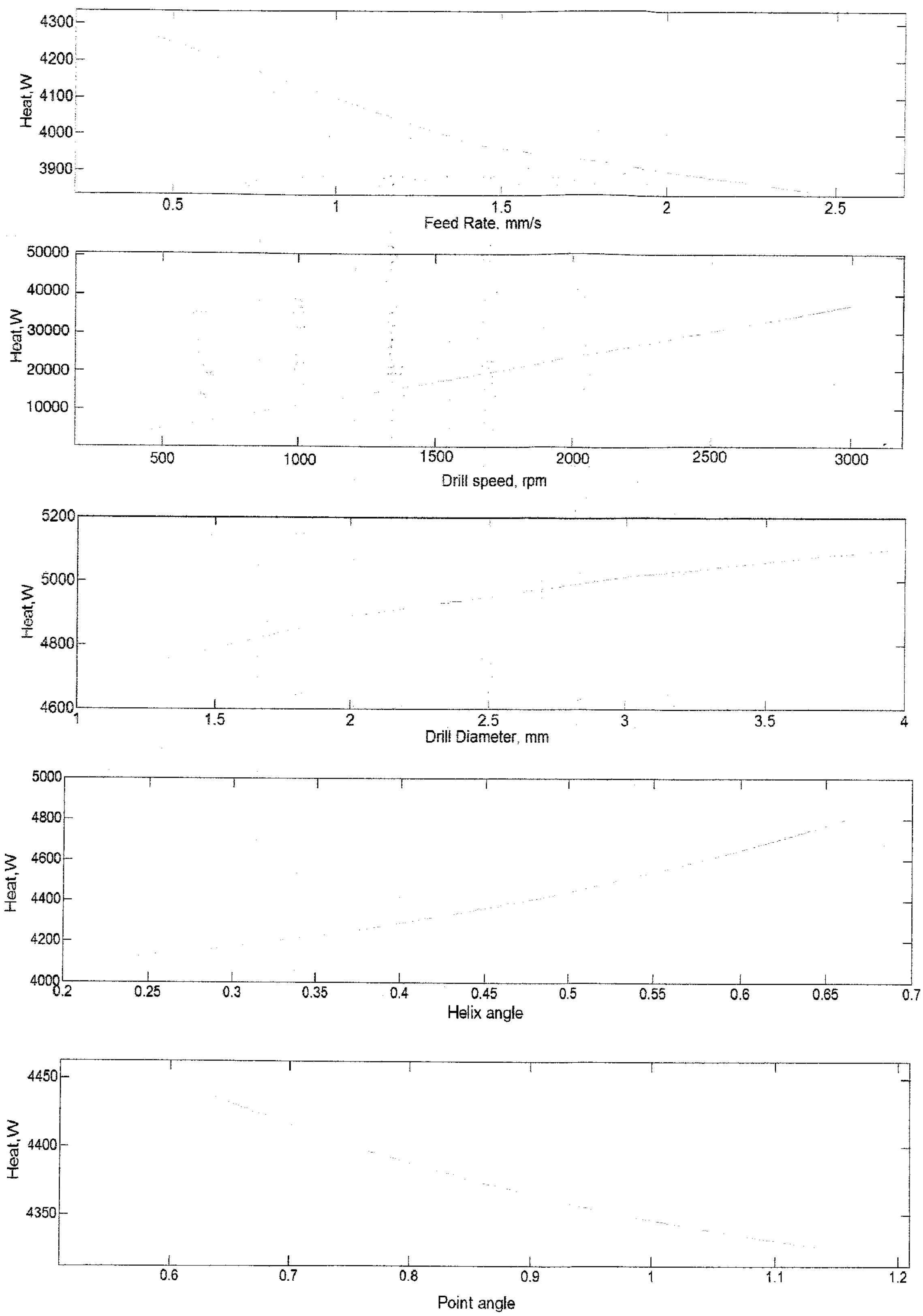
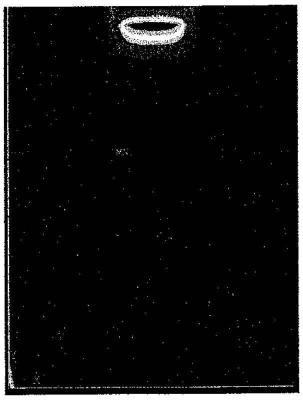
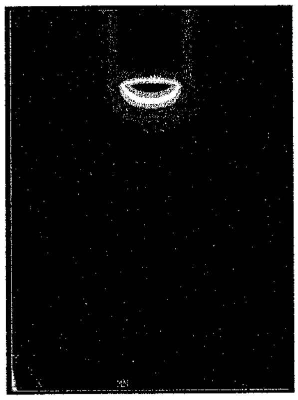
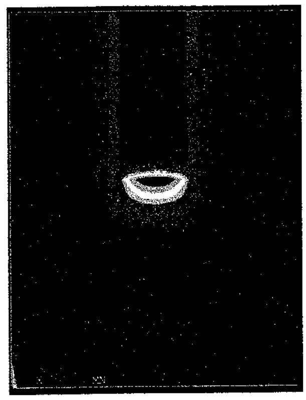


Figure 4.1 Relationship between parameter stated in table 4.1 with heat generation

4.3 Finite Element Modeling

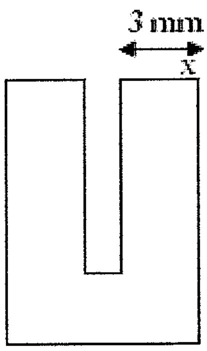
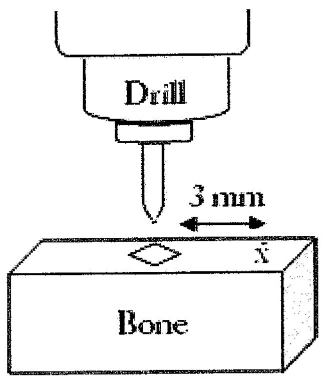
The simulation which had been discussed in Chapter 3 were presented in the table below as a general overview of the model.

Table 4.1 FE simulation

Time, s	2s	6s	12s
Dimension and Load Applied			

4.4 Validation

Table 4.2 FE(1) and experimental approach

FE(I)	Experimental
	

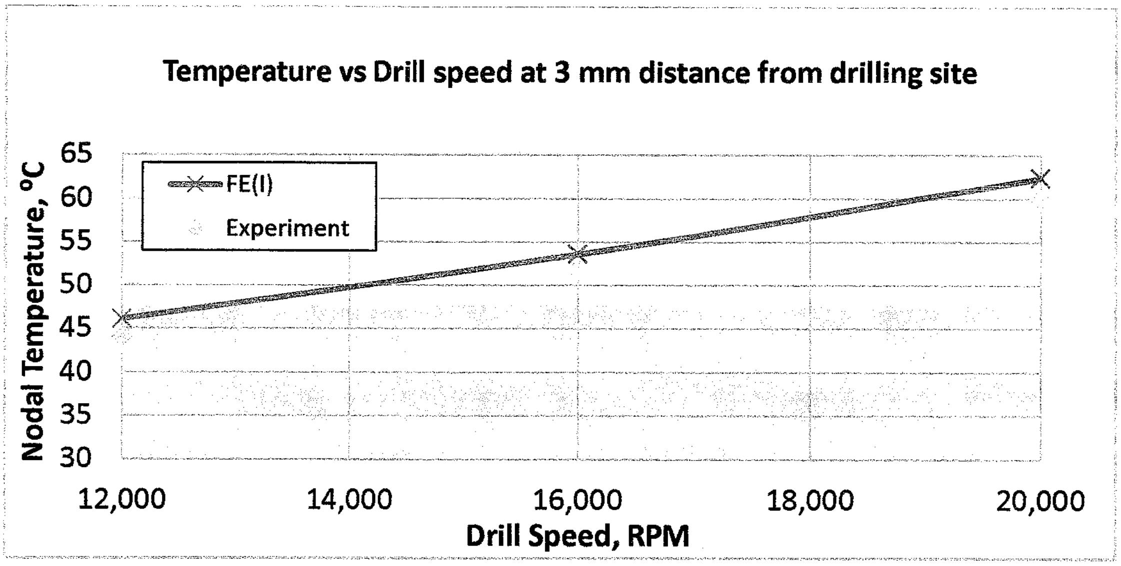


Figure 4.3 Graph of FE(I) and experimental method

The FE(I) model had been built closely resemble experimental bone model condition, as presented in Table 4.2. The experiments were repeated three times for each different drilling speed. Three drill speeds had been tested with 2 mm drill bit diameter and feed rate of 0.42 mm/s. Graph in Figure 4.3 shows the relationship between temperature distribution and drilling speed in model. The temperature increase for both results as the drill speed increase from 12,000 rpm to 20,000 rpm. Most of the heat was carried away by chips by a factor of 0.8.

At high drilling speed, the temperature for experimental is 62.42°C while for FE(I) is 60.00°C with 3.87% difference. The temperature measurement method used was thermocouple at 3 mm distance from drilling site and thermal infrared camera (Figure 4.4). Since the temperature data were taken by two different methods at the same time, thermal infrared camera at 16000 rpm shows 50.30°C while thermocouple probe picks up a reading of 53.63°C with 3.3 differences.

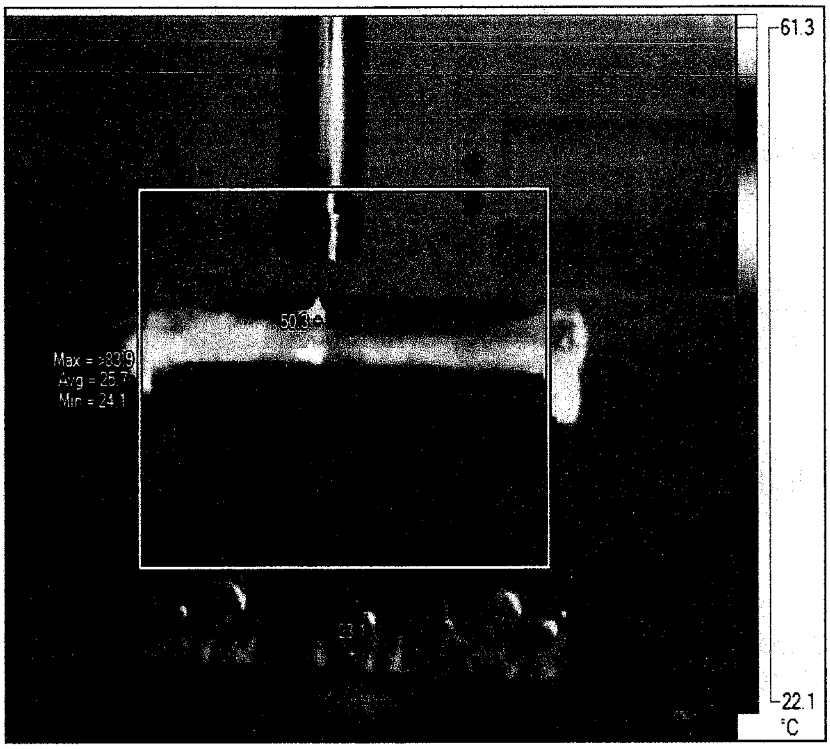
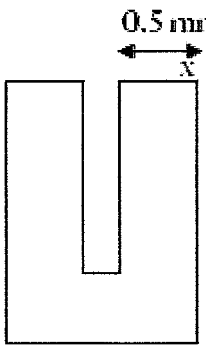
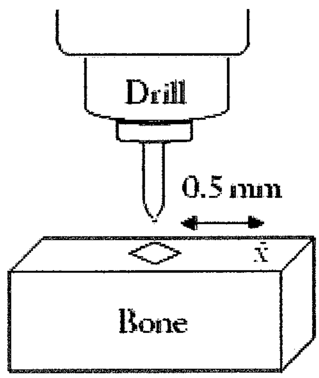


Figure 4.4 Thermal imaging showing maximum temperature of 50.3°C for drilling speed of 16,000 rpm

Table 4.4 FE(II) and literature reference approach

FE(II)	[104]
	

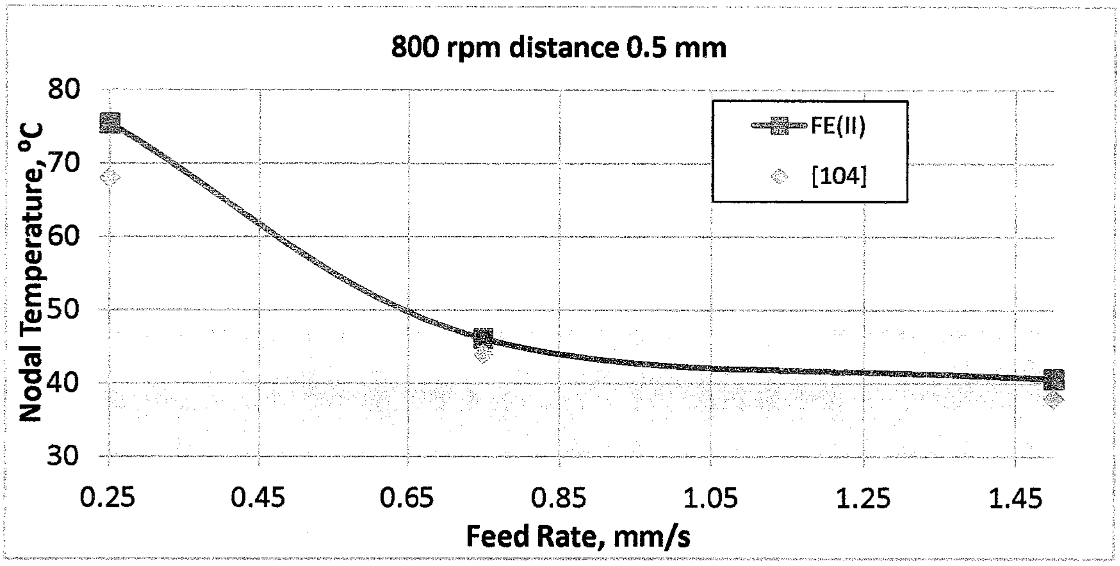


Figure 4.5 Graph of FE(II) and Literature reference

The FE(II) model had been carried out as motioned in the Table 4.4. The temperature measurement method is using thermocouple with 0.5mm distance from the drilling site. Graph in Figure 4.5 shows the relationship between temperature distribution and feed rate in FE(II) model.

At high feed rate, the temperature for experimental is 38°C while for FE(II) is 40.58°C with 2.5% difference. Hence from these two graphs; Figure 4.3 and 4.5, the simulations have been validated accordingly.

4.5 Parametric Analysis

A parametric study has been conducted to investigate the dependency of the temperature upon the feed rate, drill-bit diameter and point angle. The results of the Figure 4.2 indicate that the temperature depends strongly on feed rate, point angle and drill diameter. The parametric analysis are represented in case study chart below;

Table 4.5 Parametric case study

Case	Feed rate, mm/s	Point angle, °	Drill diameter, mm	Drill speed, rpm
1(b)	0.42 - 2.2	118	2.0	400
4(b)	0.42	40 - 118	2.0	400
3(b)	0.42	118	1.5 - 4.5	400
6	0.42	118	2	400-3200
7	1.2	118	2	400-3200
8	2.2	118	2	400-3200

4.5.1 Effect of feed rate

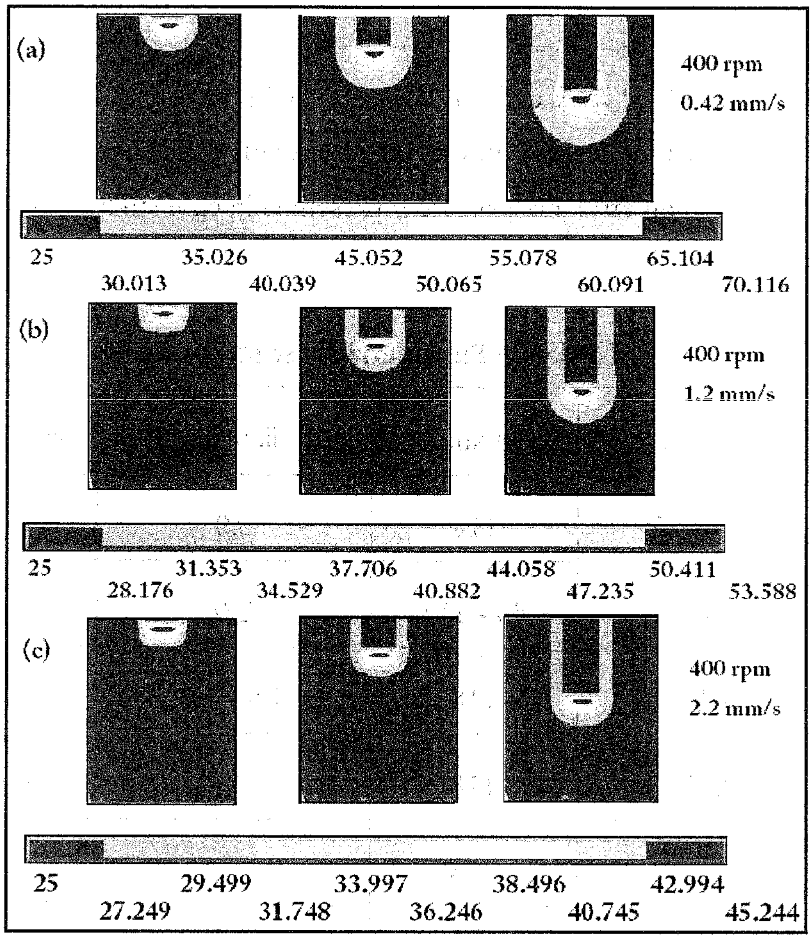


Figure 4.6 Maximum nodal temperature for Case 1

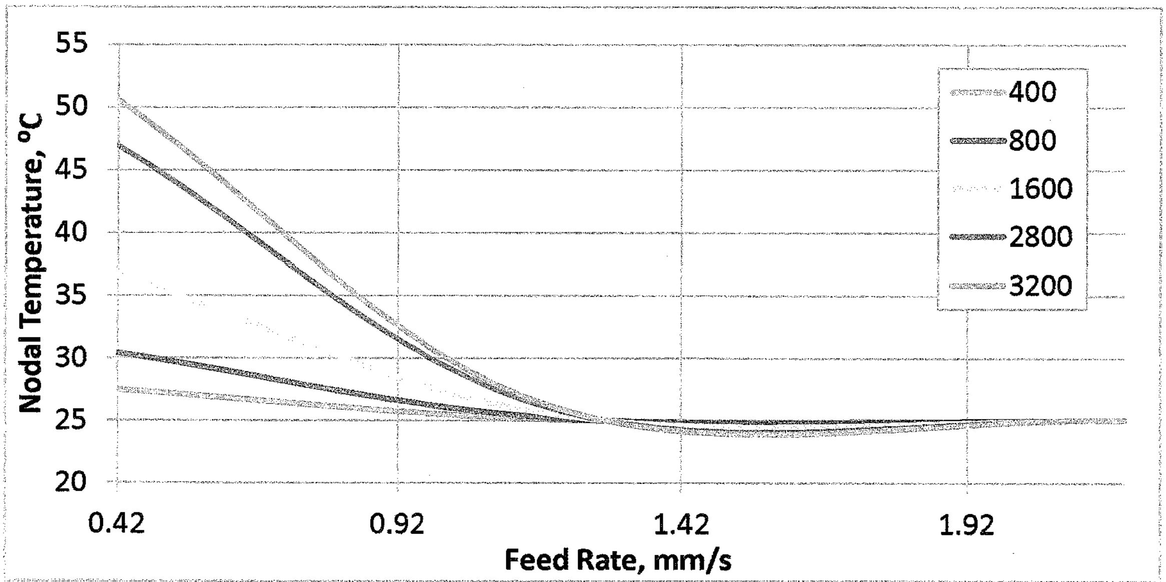


Figure 4.7 Representing case 1 with variation of drilling speed, rpm

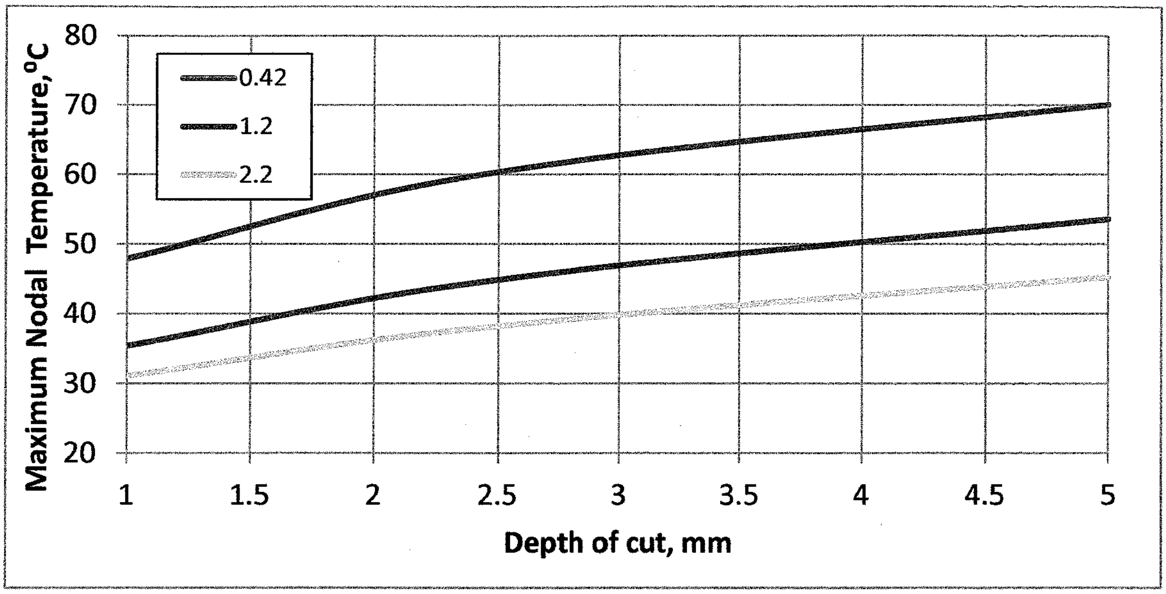


Figure 4.8 Representing case 1 with variation depth of cut, mm

The simulation result of maximum nodal temperature was shown in Figure 4.6 above. It can be observed from Figure 4.7 that the temperature decreases with the increasing feed rate. At 3200 rpm the temperature measured at distance 3 mm from the drill hole shows the highest temperature of 50.61°C while for lower drill speed, 400 rpm the temperature measurement is 27.43°C with increment of 0.43° from the initial temperature. For a given drilling speed, the shearing energy is necessary to cut the bone; and a large portion of this energy is converted into heat. However, the temperature of drill bit may increase at a higher feed rate, but the temperature inside of the bone may decrease due to short time of exposure, as noted in [102],[93]. Likewise, drilling depth that elongate exposure time causes higher maximum nodal temperature generation as shown in Figure 4.8, lower feed rate of 0.42 mm/s has maximum temperature of 60.4°C at 2 mm depth, while at higher feed rates of 2.2 mm/s the maximum temperature is 38.26°C which is also consistent with the literature [15] and [102].

However, if the drilling process is completed in shorter time at higher feed rates, the shorter drilling time also reduces the heat transferred to the bone [103]. The facts that high load during drilling results in increase of feed rate, hence reduce drilling time, this is consistent with literature [15],[94] ,[104] ,[103] ,[105] where increased load was seen to reduce the drilling temperatures during bone drilling.

4.4.2 Effect of point angle

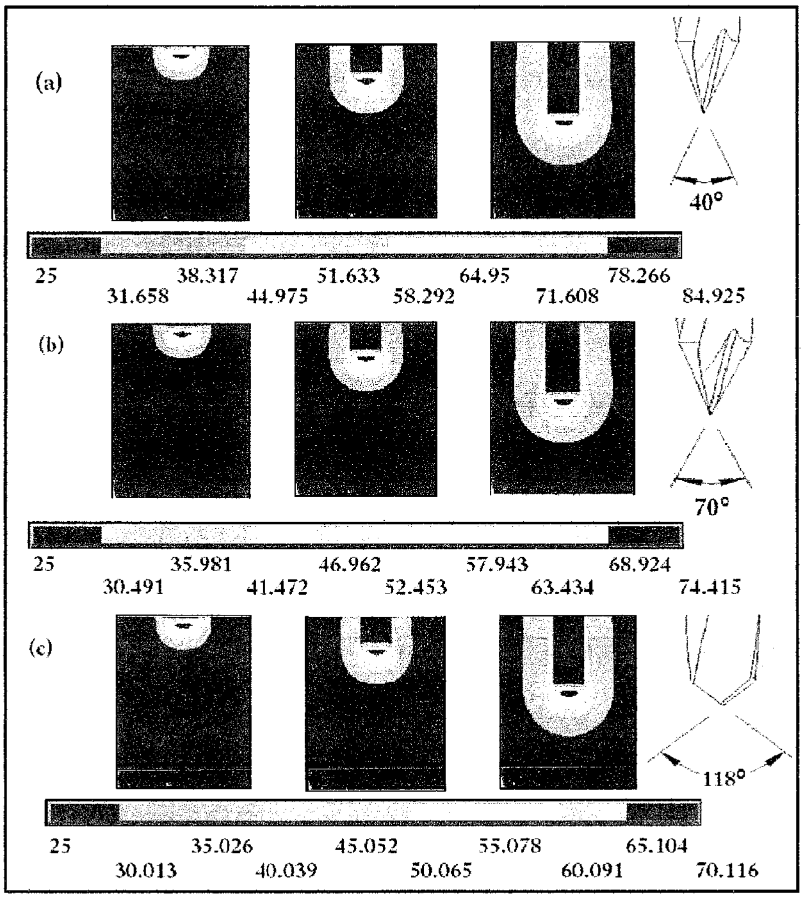


Figure 4.9 Maximum nodal temperature for case 4

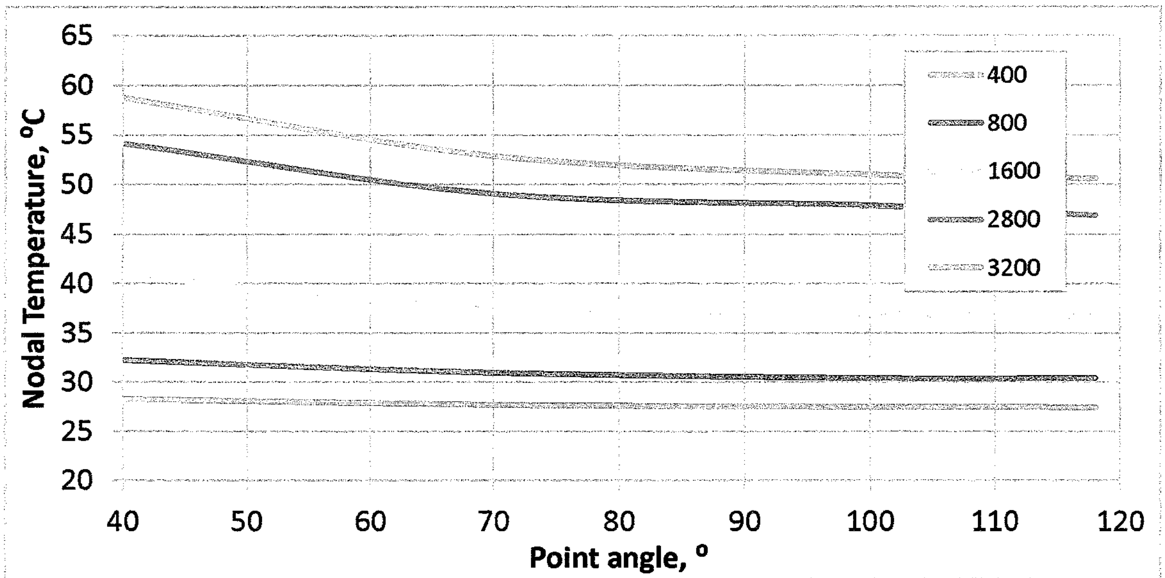


Figure 4.10 Representing case 4 with variation of drilling speed, rpm.

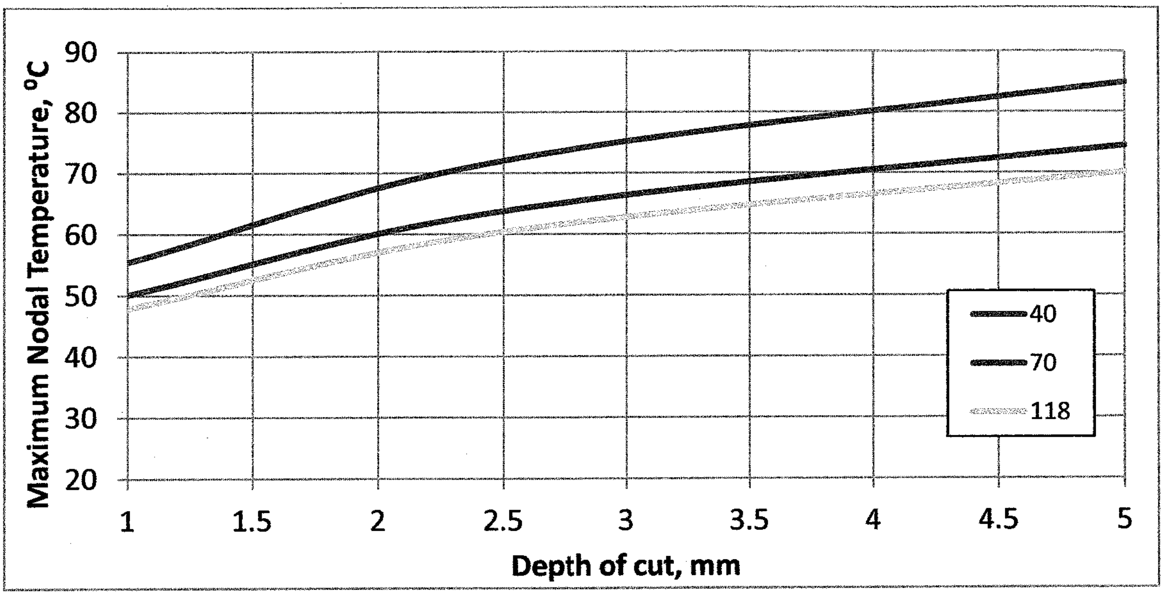


Figure 4.11 Representing case 4 with variation depth of cut, mm

Figure 4.9 shows that point angle is not highly dependent on the different drilling speed, however it does give out large difference when using low point angle with high drilling speed. At 400 rpm the temperature is steadily low, 28.28°C while at 3200 rpm the temperature for low 40° point angle is 58.78°C. The heat generated during drilling is directly determined by the drill-bit geometry [104] and [36]. It has been stated in the literature that the overall effect of point angle is negligibly small [93], [88]. However, depending on the geometric parameters, a higher point angle may affect heat generation in dissimilar ways [106]. The point angle was tested with the range of 40° to 118° consistent with literature that examine the range of 70–130° [10,11]

4.5.2 Effect of drill diameter

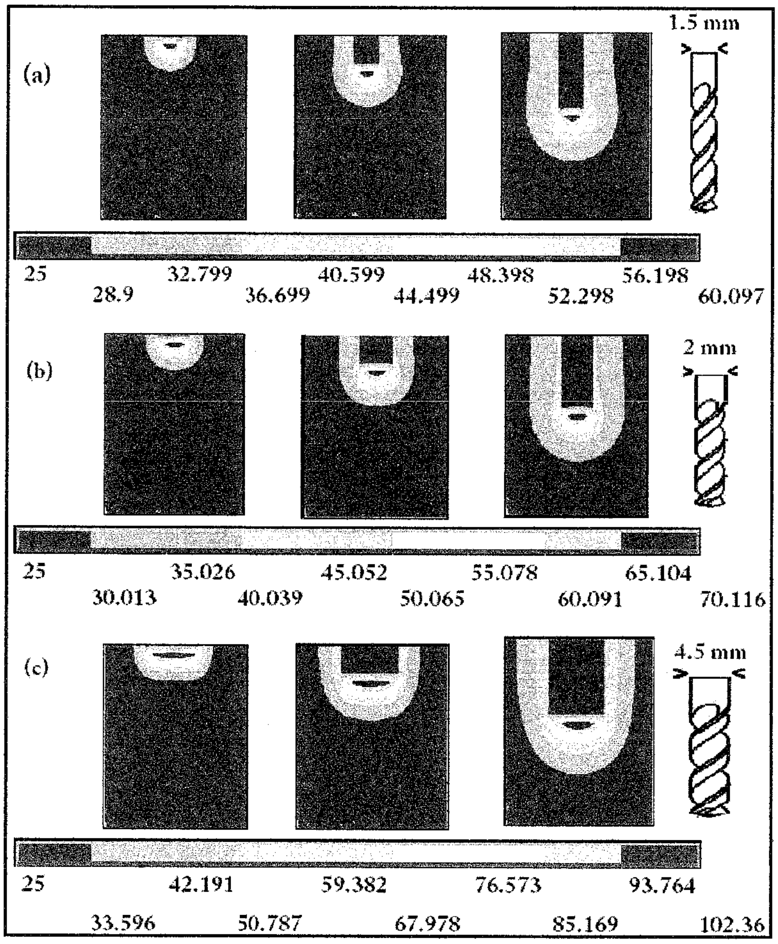


Figure 4.12 Maximum nodal temperature for case 3

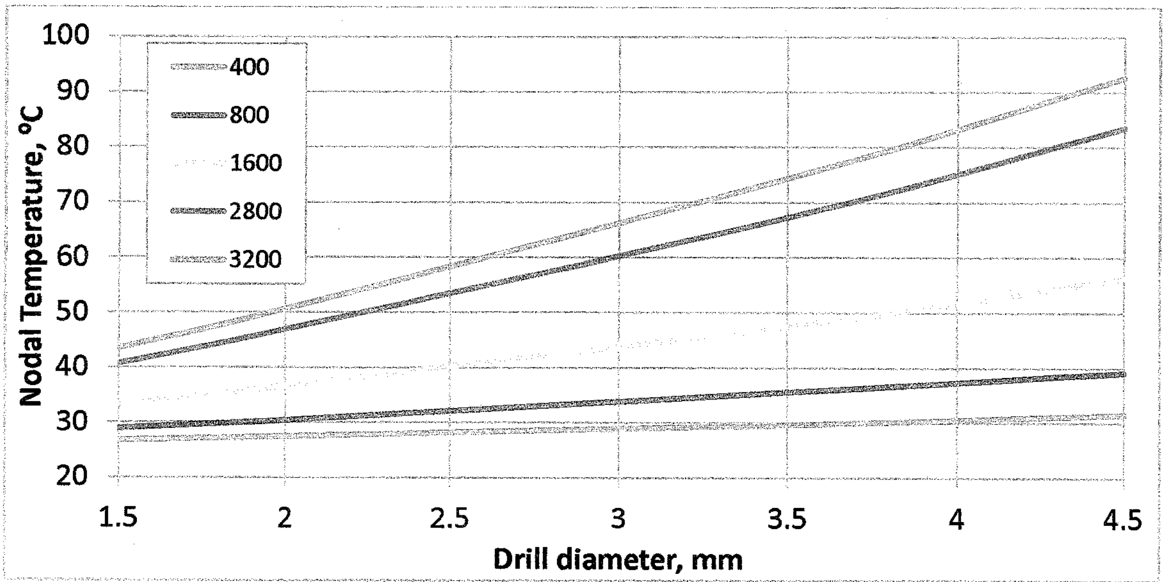


Figure 4.13 Representing case 3 with variation of drilling speed, rpm.

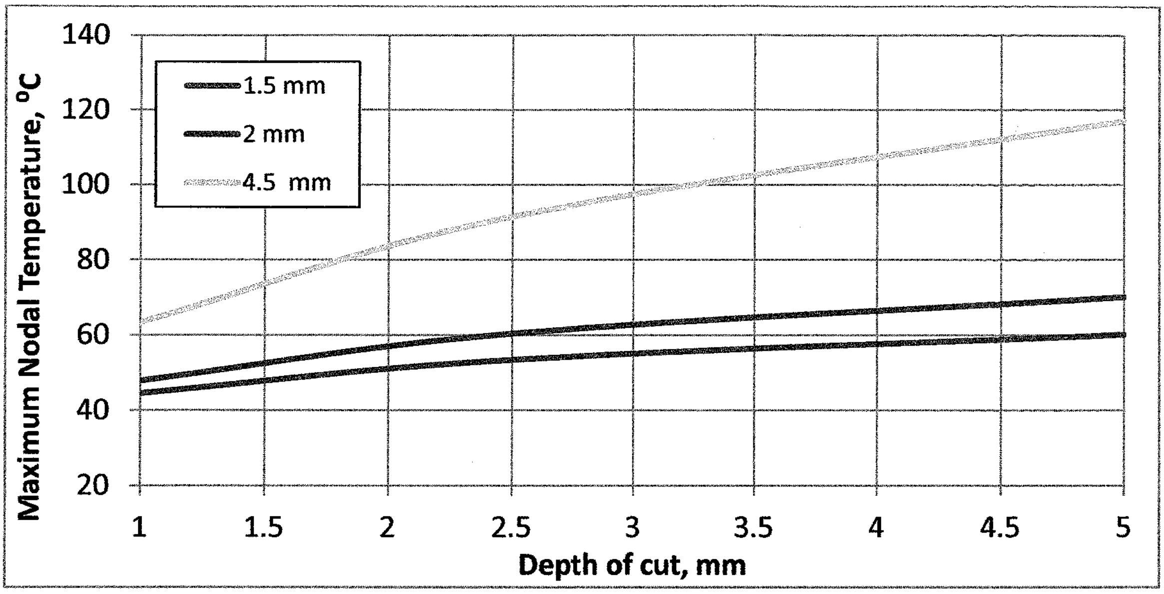


Figure 4.14 Representing case 3 with variation depth of cut, mm

Figure 4.13 shows that as the drill bit diameter increase, the temperature also increases; at drill bit diameter of 4.5 mm the temperature measured at 3 mm distance from drill site is 92.51°C while for drill diameter of 1.5 mm the temperature is 43.43°C.

Figure 4.14 shows that the maximum temperature increase slightly with the increasing drill bit diameter. For 1.5 mm, the maximum temperature ranges from 47.91°C to 60.09°C at 1 to 5 mm depth, while for 4.5 mm of a drill-bit diameter it ranges from 63.43°C to 102.3°C. This effect can be explained by the higher heat conduction capability of larger drill bit, where the drill bit serves as longer cutting edge [44].

The graph in Figure 4.12 is the contour plot of different depth of cut. The result of temperature increase significantly with drill diameter is consistent with literature review [8] . However it is inconsistence with literature review [107] which stated that Maximum temperature decrease slightly with increasing drill bit diameter.

The result of temperature increase significantly with drill diameter is consistent with literature review [8]. However it is inconsistence with literature review [107] which stated that Maximum temperature decrease slightly with increasing drill bit diameter.

4.5.3 Effect of drill motion at point A

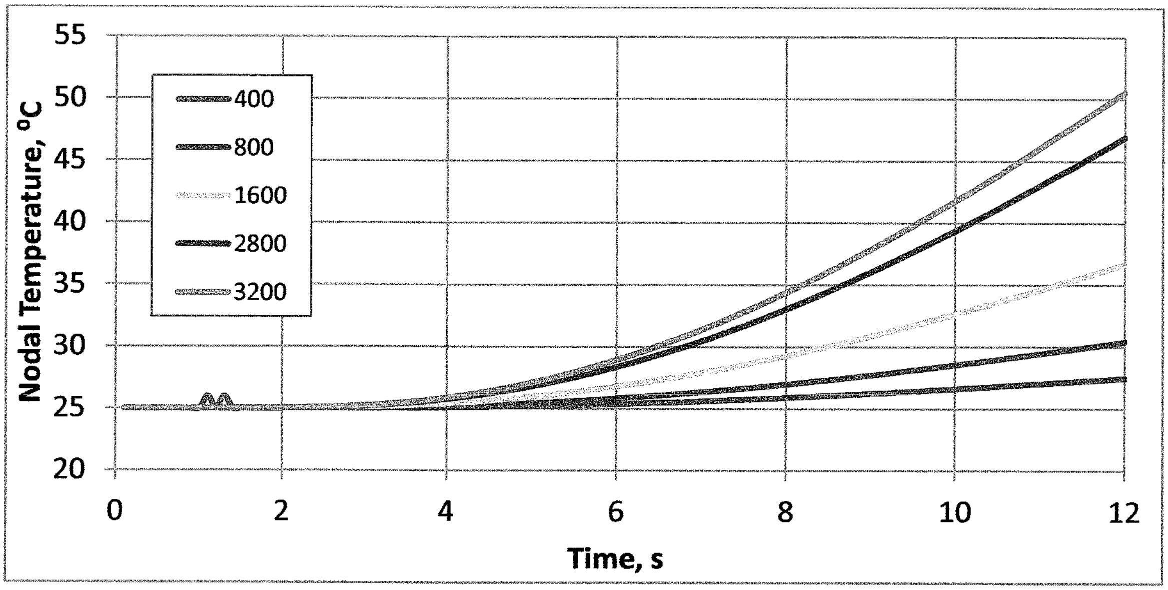


Figure 4.15 Representing case 6

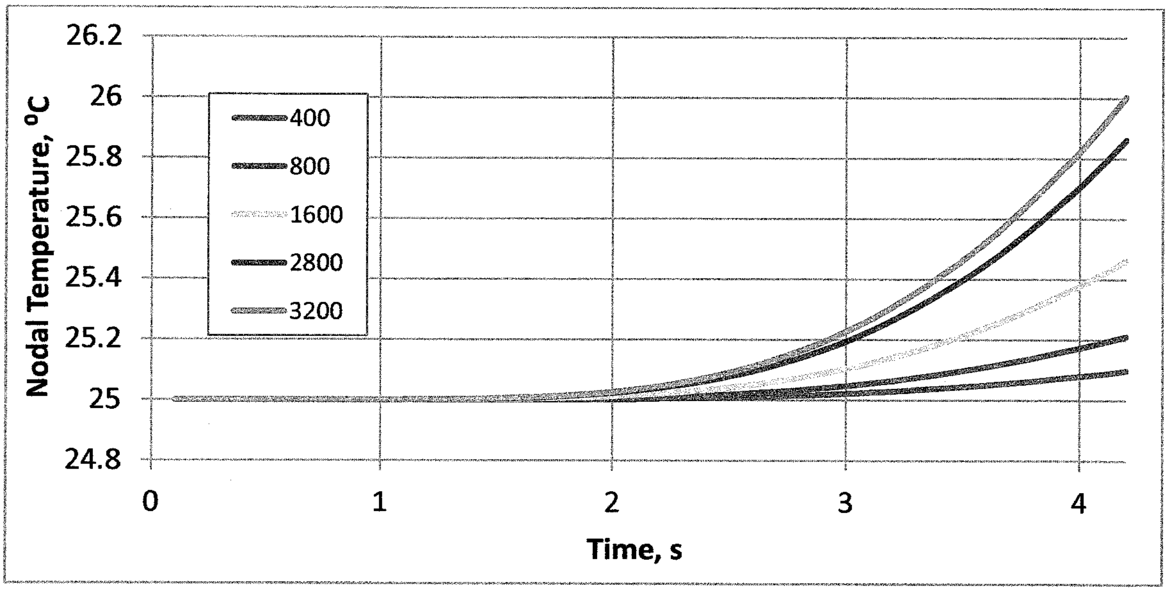


Figure 4.16 Representing case 7

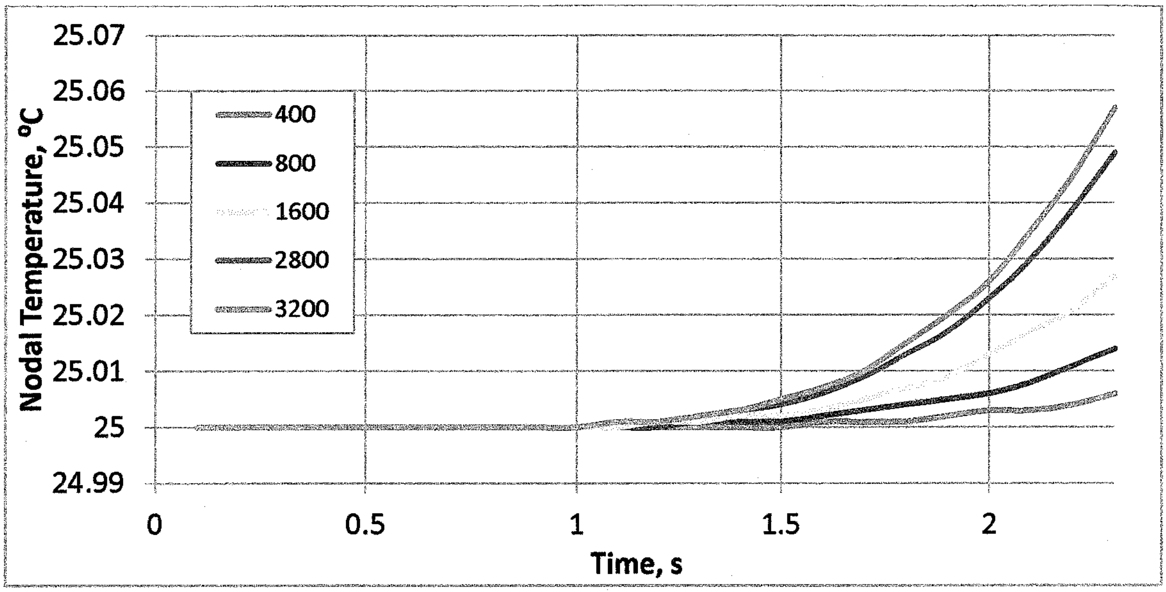


Figure 4.17 Representing case 8

The graph in Figure 4.15, 4.16 and 4.17 displays an exponential increase of heat as the feed rate increase. At feed rate of 0.42 mm/s the temperature becomes independent at 3s while at higher feed rate 2.2 mm/s the temperature become independent much earlier at 1.2s.

Due to the low thermal conductivity of the bone, there is a long period of delay between the start of the drilling process and the instant at which the maximum temperature is measured at the 3 mm distance of thermocouple, Matthews and Hirsch [86] also supports this observation. Increased drilling speed increases the friction energy generation due to the friction forces acting. Since most of this energy is converted into heat, it is reasonable to expect increased temperatures at higher speeds [108]. This is consistent with previous studies [88], [93] and [109].

4.6 Summary

This chapter explained the results obtained from the method used in chapter 3. The relationship of parameters and heat generation are further used for simulation in ANSYS. The conclusion of the result discussed in the next chapter.

CHAPTER 5

CONCLUSION & RECOMMENDATION

5.1 Conclusions

Based on the results and discussions of the FE and experimental validation; the following conclusion was made by accomplishing the objectives stated in the previous chapter:

The numerical methodology of heat flux data shows relationship between influential parameter and heat generation. The helix angle has the lowest dependency to heat generations of 5.7% on the drilling speed while for feed rate, drill bit diameter and point angle have 11.63%, 73.44% and 25.6% respectively. Hence, dependency value more than 10% were classified as influential parameters of heat generation as a function of drilling speed.

The FE simulation shows that modeling of bone drilling using heat flux as in input gave out result of temperature which were 3.3% higher than the experimental results, this is due to the (1) different location at the bone gives out different properties, in the simulation, the bone were assume to have constant properties, (2) the location of the thermocouple were measured approximately using a basic ruler, in some literature experiment, the distance between the drill hole and thermocouple were measured using digital microscope with 200x magnifications, and lastly (3) in the simulation, material removal during drilling were not taken into account, while heat may be removed during experiment by chipping resulting lower temperature.

Maximum nodal temperature in varying drill bit diameter shows that by using 4.5 mm drill bit diameter, the temperature increase as much as 70.34% compared when using smaller drill bit diameter i.e., 1.5 mm. Comparison of varying feed rate and point angle from 0.42 mm/s to 2.2 mm/s and 40^0 to 118^0 point angle, shows a decrease of 35.47% and 17.43% in temperature respectively. Therefore, parametric analysis for the appropriate drilling condition to minimize thermal necrosis is by using drill bit diameter lower than 3.5mm, feed rate more than 1.2 mm/s and point angle of 118^o.

5.2 Recommendation for Future Work

In this research, the prediction of temperature distribution during bone drilling provides parameters that help minimize thermal necrosis. However, this study is limited to the influence of feed rate, drill bit diameter and point angle as a function of drilling speed. The recommendation for future works are;

- Importing bone density properties from CT scan/ MRI data to obtain precise values of bone density regardless of its location i.e. MIMIC
- Model and defining the drill bit condition as to investigate changes in the prediction of temperature
- Bone substitution model for validation to obtain consistence and homogenous material properties. Poly(methyl methacrylate) or PMMA have properties similar to bone and the maximum temperatures may be measure with low uncertainty [110].

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`LIST OF PUBLICATION

M. M. Mokhtar and H. Fawad, "Bone drilling modelling and simulation techniques," in *Business, Engineering and Industrial Applications (ISBEIA), 2012 IEEE Symposium on*, 2012, pp. 357-361.

APPENDIX A

Poly Methyl Methacrylate
a.k.a. PMMA, acrylic, Plexyglas, and many others

Formula	Molecular wt
$[C_6H_{10}O_n]_n$	114.14

Coefficients for the Regression Equation

$rdot = a\, G_{ox}^{n}$

rdot (in/sec)

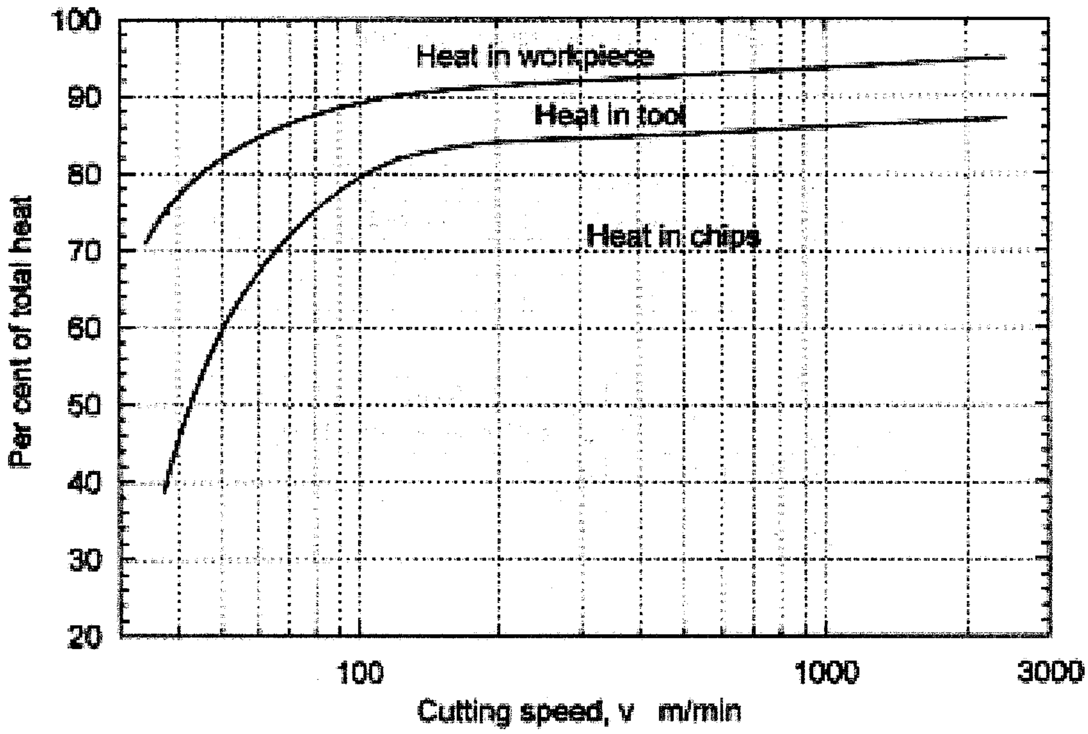
G_{ox} (lbm/sqin-sec)

p.s. sorry i don't currently recall the sources, only the data, if requested, I will find them. -hg

Coefficient	Source 1	Source 2	Source 3
a	0.0440	0.0412	0.0608
n	0.60	0.70	0.61

		Source			
Property	**Symbol**	**Hung**	**Karabeyoglu**	**Wooldridge**	**Units**
Molecular Weight	MW	100.0	-	-	g/gmol
Specific Heat (gas)	C_P	0.35	0.37	-	cal/g-K
		0.35	-	-	Btu/lb_m-R
Specific Heat (solid)	C_P	0.31	-	-	cal/g-K
		0.31	-	-	Btu/g-K
Heat of Formation	h^o	-928	-	-	cal/g
		-1670	-	-	Btu/lb_m
Latent Heat of Gasification	L_V	130	231	350	cal/g
		234	-	-	Btu/lb_m
Latent Heat of Fustion	L_F	85	-	-	cal/g
		155	-	-	Btu/lb_m
Boiling Point	B.P.	374	-	-	K
		673.2	-	-	R
Density	rho_S	1.683	1.1	-	g/cm^3
		150	-	-	lbm/ft^3
Thermal Diffusivity	kappa	-	0.11	-	mm^2/sec
Thermal Conductivity	k_S	0.0012	-	-	cal/sec-cm-K
		0.289	-	-	Btu/hr-ft-R

APPENDIX B



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