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OPTIMIZATION OF DRILL DESIGN AND COOLANT SYSTEMS DURING DENTAL IMPLANT SURGERY

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ABSTRACT OF THESIS

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Dental implants are an effective alternative for the replacement of missing teeth. The success of the implant depends on how well a bone heals around the implant, a process known as osseointegration. However, excessive heat generated during the bone drilling will cause cell death and may prevent osseointegration of the implant, resulting in early failure. There are many factors which contribute to the heat generation during drilling.

Experiments were carried out to investigate the affect of variable drilling factors on heat generation during drilling operation. Natural bone is not an ideal material for such research, as it varies widely in density and other parameters of interest.. It would be desirable to have a more uniform and consistent material to use in such studies. However, such a material must be similar to bone to allow the results to be extrapolated to the clinical situation. The current study describes and validates a model for use in such studies. Polymethylmethacrylate (PMMA) is the material chosen for our studies.

A theoretical model was developed to study the effect of different drilling parameters on temperature rise during drilling operations. Comparison of observed results obtained from experiments was made with the results from theoretical study. Comparison of results for PMMA and human bone are also shown explaining how PMMA material can be substituted for human bone. The results suggest that the PMMA model is an acceptable surrogate for bone in such studies.

Keywords: Dental implants, PMMA, Human bone, Heat generation, Drilling parameters, Coolant system.

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RULES FOR THE USE OF THESIS

THESIS

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THESIS

A thesis submitted in partial fulfillment of the requirements
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TO MY FAMILY AND FRIENDS.

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In addition to the technical and instrumental assistance above, I received equally important assistance from my family and friends. Finally, I would like to thank my friends from the University of Kentucky College of Dentistry (Division of Periodontology), Drs. Aaron Carner, Neil Lemmerman, and the IAES group, with whom I've shared and discussed this project in several versions. I would also like to thank Richard and other people from Center for manufacturing in University of Kentucky for helping me to carry out experiments. Their help, advice, and support have been vital throughout.

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CHAPTER 1
INTRODUCTION

1.1 BACKGROUND

Despite significant progress in treatment and prevention of dental disease, many teeth are lost due to disease and trauma. Life's simple pleasures can cause problems and pain for millions of people who suffer from permanent tooth loss. Men and women of all ages are self conscious about their dentures, bridges or missing tooth. Some have difficulty speaking because their dentures slip or click. For others, the irritation and pain caused by dentures are constant reminders of the limitations they feel. Many are concerned about their appearance and may feel that their tooth loss has "aged them" before their time. Some regularly decline invitations to social events because they are unwilling to face the uncertainties of eating, speaking and laughing in public.

A number of options exist for the replacement of missing teeth. The most recent of these is dental implant. Modern dental implants are the treatment of choice for the replacement of missing teeth. Dental implants offer an excellent alternative to the limitations of conventional dentures, bridges and missing teeth. Dental implants are changing the way people live, they are rediscovering the comfort and confidence to eat, speak, laugh and enjoy life.

National surveys have documented the increased interest in dental implants on the part of patients and the dental profession. One recent survey reported that [3]:

- Dental implant use has nearly tripled since 1986 and is expected to continue to rise rapidly.
- People of all ages are turning to dental implants to replace a single tooth, several teeth or a full set of dentures.
- Leading reasons cited for choosing dental implants are:
    - To restore normal eating and speaking abilities.
    - To enhance facial appearance and confidence.
    - To increase denture retention.

According to the survey, the reasons for the increased demand are:

- Growing public awareness of the significant functional and esthetic advantages of dental implants over conventional dentures and bridges.
- The availability of data on the long-term success of dental implants.

Dental implants are a great option for patients missing natural teeth, because they act as a secure anchor for artificial replacement teeth and eliminate the instability associated with surface adhesives and removable bridges. Natural teeth absorb biting pressure of up to 540 Psi [3]. Long-time denture-wearers can often absorb no more than 50 Psi. Dental implants, when properly placed, can withstand 450 Psi of biting pressure. Dental implants are made of materials that are compatible with human bone and tissue.

1.2 DENTAL IMPLANT SURGERY

Dental implant surgery, where the dentist implants a metallic tooth-root in the bone of human jaw and allows the bone to heal on it for a reasonable period of time until the bone and the metallic root union is strong enough to support a prosthetic tooth crown. The implant root is made out of titanium, a metal that is very well tolerated by the human body.

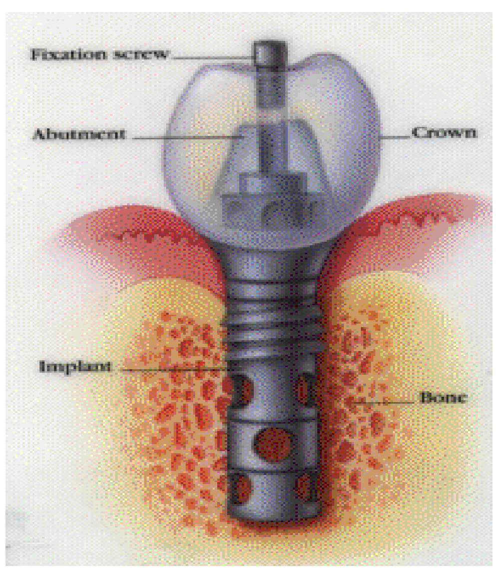

Figure 1.1: Schematic of Dental Implant

Dental implant surgery takes place in two stages:

1) Surgical placement and

2) Uncovering the implant.

1.2.1 Surgical Placement

A hole is being drilled into the bone where the implant is supposed to be placed. An implant is screwed or tapped into the surgically prepared site. The gum tissue is closed over the implant. After this stage has been completed, an average time between 3 to 6 months is given to allow the bone to heal around implant. The suitable time depends upon the bone of the patient. For the first three to six months following surgery, the implants are beneath the surface of the gums, gradually bonding with the jawbone. During this time, the patient should be wearing temporary dentures and eat a soft diet. While the implants are bonding with the jawbone, new replacement teeth are fashioned by dentist. The replacement teeth must clip onto the implants, fit securely in the mouth and withstand the day-to-day movement and pressure created by chewing and speaking.

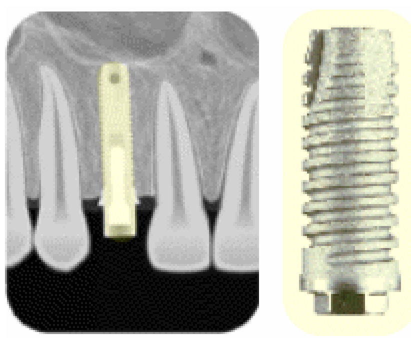

Figure 1.2: Implants placed inside Bone

Most currently used dental implants consist of a root-shaped portion that is anchored to the bone. Various types of dental restorations (e.g., single crowns, bridges, and even complete over dentures) can be attached to the root-form implant. The surgical placement of the implant involves preparing a hole in the jaw that corresponds in size and shape to the implant. This is known as the osteotomy site. The implant is then threaded into the hole (in a manner somewhat similar to wood screw) or is a tight press-fit. Over a period of time, bone becomes deposited on the implant surface, a phenomenon known as Osseo integration. While the nature of this interface has not been fully elucidated, it is robust. Many studies have shown implants to be a predictable method of tooth replacement, often achieving successful 5-year survival rates exceeding 95%.

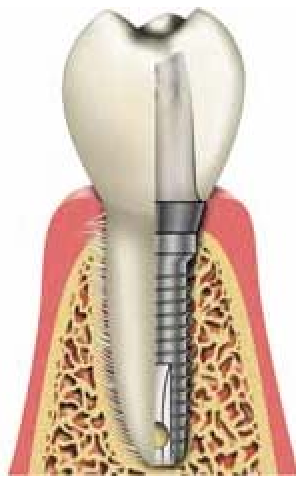

Figure 1.3: Root Form Implant

1.2.2 Uncovering the implant

Once the implants have bonded to the jawbone, the second phase of the procedure begins. At this time, the oral and maxillofacial surgeon uncovers the implants and attaches small posts, which will act as anchors for the artificial teeth. The posts protrude through the gum line but are not visible when artificial teeth are attached.

1.3 DENTAL IMPLANT FAILURES

Implants do sometimes fail in service. This may occur due to a failure to be Osseo integrated (early failure) or during later service (delayed failure). Early failure is often a result of problems during osteotomy site preparation. One such problem is overheating the bone during the drilling process. When the mechanized cutting tools such as saws and drills are used, heat is produced which raises the temperature of both the tool and the material being cut. In orthopedic and dental practices, high-speed tools are applied to bone, and heat from these operations may result in thermal necrosis [1,2]. Since thermal necrosis has a negative impact on the outcome of a drilling procedure, bone temperature must be kept below the threshold temperature that results in necrosis. As for the thermal properties of the bone, it is important to note that the relative water content (about 35%), as well as fluid movement within the living bone tissue (i.e. blood and lymph) is significant variables in the ability of bone to withstand thermal damage. Accordingly, in thermal conductivity studies using living oxen bone tissue, Vacheon et al 1967 [4]. For dry versus living oxen bone, the values reported for thermal conductivity were $1.45 * 10^{-3}$ and $5.45 * 10^{-3}$ cal/cm-sec respectively. Bone is a poor conductor of heat, with thermal conductivity of fresh cortical bone in the region of 0.38-2.3 J/msK. It has been documented that bone cell death may occur when bone is heated over 47 ^{0}C [1,5]. In the absence of irrigation, bone temperatures may exceed 100 ^{0}C. This may result in a failure of bone to bond to the implant, leading to early failure.

Implant therapy involves some expense and inconvenience to the patient. It is important to improve outcomes and minimizing treatment failures. Given the deleterious effect of heat on bone viability, one strategy for optimizing implant outcomes may be reduction of heat during osteotomy site instrumentation. This strategy is likely to find application in other disciplines such as orthopedic and plastic surgery.

Various strategies have been employed to reduce heat generation during implant site preparation, including variations in drill design and coolant delivery. There are many factors that contribute to heat generation during the drilling operation. However, there is lack of unanimity regarding the optimal combination of drill design features and coolant delivery and there is relatively little in the implant literature on these topics. The factors can be listed as :

1) Drilling speed
2) Drill feed
3) Drilling status (continuous or graduated drilling)
4) Drilling depth
5) Drill design
6) Irrigation (coolant delivery) systems
7) Drill Sharpness
8) Miscellaneous Factors.

To check how these factors affect heat generation we carry out a series of experiments under different conditions. This needs large number of human bone samples, which is a big problem in obtaining. So we looked for an alternative material that can be easily available which is similar to that of a bone in properties and functioning. The material we are considering here is polymethylMethacrylate (PMMA).

1.4 OBJECTIVES

The Primary objective of this research study is to reduce the amount of heat generated during the Osseo integration process and create a thermal model that can explain how the temperature increases during drilling process.

The main objectives of this thesis can be listed as follows:

1) Study the effect of different drilling operation parameters on temperature rise during drilling process on PMMA (as replacement to human bone) by conducting series of experiments.
2) Create a thermal model that can describe the temperature increase as function of variable drilling parameters.
3) Validate the thermal model by comparing its results with the experimental results and explain how it can be interpolated for human bone.
4) To come out with optimal drilling conditions that can help dental surgeons in reducing dental implant failures.

1.5 METHODOLOGY

To obtain the objectives listed this study is being carried out in three stages:

1. Formulating a theoretical model that can help in explaining the temperature rise during drilling process.
2. Carry out series of experiments varying different drilling parameters and check how these factors are going to affect temperature rise. These experiments are performed on PMMA
3. Compare the experimental results with theoretical results to validate the thermal model developed for this case.

1.6 THESIS OVERVIEW

Chapter 2 gives the detailed back ground on reasons for dental implant failures. It also explains how previous researchers differed in their findings about the affect of variable drilling conditions on temperature increase during the drilling process for placing implants. Chapter 3 explains about the materials and method used for carrying out experiments. It explains in detail why polymethylmethacrylate(PMMA) being considered instead of human bone for experiments. It also includes detailed description of the experimental setup used for experiments and explains t why this setup is being used. Chapter 4 explains modeling approach used for deriving the thermal model to predict temperature rise as a function of drilling parameters. It also includes in detail the derivation for that equation and nomenclature used. Results obtained during experimental study are discussed in chapter 5. Comparisons of results obtained from thermal model and experiments are compared in this chapter. Chapter 6 summarizes the whole study and results obtained and also explain about how the future work can be done in this field.

CHAPTER 2
LITERATURE SURVEY

2.1 BACKGROUND

Dental implant surgery process involves drilling a hole inside the bone. This drilling operation causes heat generation due to the friction between the drill and bone. Majority of heat generated during this process is absorbed by drill but bone also absorbs significant amount of heat inside it. Heat absorbed by human bone causes the temperature to rise inside it.

The negative affect of heat on bone results in the denaturation of the enzymatic and membrane proteins, hyperemia, necrosis, fibrosis, decreased osteoclastic and osteoblastic activity, dehydration, and desiccation, which may all contribute to cell death [5, 6, 7, 8, 9]. Historically, temperatures anywhere from 56^{o}C to 70^{o}C have been deemed responsible for the denaturation [10,11]. However, in a landmark study by Eriksson and Albrektsson [12,13,14], it was determined that the critical temperature of bone is in the range of 44^{o}C to 47^{o}C. They found that the threshold temperature for heat induced bone injury is 47^{o}C for 1 minute. A temperature of more than 47^{o}C was shown to result in bone restoration and fat-cell degeneration. Heating the bone to temperatures lower than 47^{o}C did not seem to affect the bone tissue on the microscopic level, but vascular injury, as seen with increased capillary injury, was seen by others to occur at lower temperatures [15]. As a result of Eriksson and Albrektsson's study, the critical temperature is widely believed to be 47 ^{o}C. However, it must be observed that this experiment did not involve drilling of the bone but merely heating the saline solution to a desired temperature, which was in direct contact to the bone.

2.2 FACTORS AFFECTING HEAT GENERATION

There are many factors that affect the heat generation during the drilling process. After a detailed literature survey, the factors that can affect temperature raise during drilling process can be listed as follows:

1) Drilling Speed
2) Drilling Status (single step or incremental drilling)
3) Drilling Depth
4) Drill Diameter

5) Irrigation (coolant delivery) systems
6) Drill Sharpness
7) Miscellaneous factors.

In this section we describe how different factors affect the heat generation during bone drilling. The details given below are collected from the results obtained by different researchers, which are been collected as part of the literature survey that has been done regarding the project.

2.2.1 Drilling Speed

There are many varying results from different researchers about the optimal speed for dental implant surgery. Thompson and Pallan,[17,18] measured in vivo the temperature rise in bone increased with drill speed, from 125 rpm to 2000 rpm. Eriksson has shown that using high torque and low rpm (1500-2000) are ideal to avoid temperature rise and to increase drilling accuracy. Matthews and Hirsch, [16] however did not find any significant change in temperature rise with speed (350 to 2900 rpm) while drilling in human cadaveric femora. Vaughn and Peyton found that the temperature rise increased with drill speed (from 1155 rpm to 11,300 rpm). In the more recent studies, Abouzgia and James [19] found that the maximum temperature rise decreased with speed, for free running speeds from 27,000 rpm to 97,000 rpm. Except for the study by Matthews and Hirsch [16], there seems to be general agreement that the temperature rise increases with drill speed up to approximately 10,000 rpm. Results from the majority of histological studies and from the temperature measurements from Abouzgia and James [19] appear to indicate that lower temperatures are generated at very high drill speeds.

2.2.2 Drilling Status

Drilling to widen the site to exact diameter of the future implant can be performed either one step or gradually. In continuous or one step drilling the hole is being drilled in a single step using a single drilling tool. In incremental or multi-step drilling the diameter is increased gradually starting from the minimum to the final diameter using a series of drilling tools.

Eriksson [20] has described a single step technique while Branemark [21] has recommended an incremental enlargement of the osteotomy site. Branemark's[21] hypothesis on the incremental drilling sequence was that each drill bit gradually enlarges the osteotomy site, which would help dissipate heat better than a one-stage drill sequence. In a later study, Eriksson did an in vivo study in which animals and humans are subjected to either incremental or one-stage osteotomy preparation. In this study, Eriksson found that the incremental drilling is better on reducing heat production compared to single drilling.

2.2.3 Drilling Depth

Depth of the recipient site is usually determined by several factors. Cordioli and Majzoub [22] reported a significant increase in temperature at depths of 8 mm versus 4 mm, regardless of the diameter of the drill used. However, Tehemar [23] believes that the implant depth may not be as important as having irrigation at the apical extent of the drill that would thus decrease heat production.

2.2.4 Drill Design and Flute Geometry

Root-form implants vary considerably in design for biologic and mechanical reasons. Because the end result of the drilling cascade has to be a recipient bony bed of the same diameter and shape of the proposed implant, the drills usually follow the morphologic and topographic skeleton of the implant. With the great variety of dental systems commercially available, comparison between the different designs and shapes of drills seems to be impossible.

In general, twist drills and taps are used to prepare sites for screw-shaped implants, and triflute drills are used to prepare sites for cylindrical implants. Investigations performed on animals and human bone have demonstrated that flute geometry and drill design contribute to the temperature rise during drilling. Cordioli and Majzoub [22] compared the different types of drills on heat generated in bovine bone blocks. They reported that a triflute drill 4 mm in diameter generated less heat than 2 and 3 mm twist drills and a 3.3 mm triflute drill regardless of the cavity depth. They also found out that temperature took longer to return to baseline using a smaller diameter drill versus a large diameter drill. However Tehemar [23] believes the opposite. He believes that the wider diameter burs take less bone than the smaller diameter drills which results in wider diameter drills producing less heat.

2.2.5 Irrigation Systems

In an effort to increase heat dissipation during dental implant drilling and thus, decrease bone temperature, implant systems have began to use irrigation systems with coolants. There are two types of cooling: internal and external. If one does not use any coolant, then the critical bone temperature is always exceeded. Kirschner and Meyer [24] introduced internally cooled drills to dentistry. They hypothesized that since the coolant entered closer to the tip of the drill, it would create a combined rinsing and cooling effect on the bone, which would surpass the externally cooled drill or a drill with no coolant at all. Huhule [25] was the first to propose the internal irrigation system which he believed would help prevent bone "clogging" of the implant drill and that its efficacy would be continuous because all depths of the osteotomy preparation could be reached with the coolant.

Despite the promising results reported using internal irrigation systems, this issue requires further study. The only report present in the literature is that of Haider [26] et al. In their histological and histochemical study, this group demonstrated that additional external cooling seemed to be beneficial for any internal system, particularly in compact bone. Thus, it appears that irrigation is a key implant in implant osteotomy preparation and is worthy of more investigation.

2.2.6 Drill Sharpness

The condition of drill plays a role in regulating the temperature of bone during drilling. There are many factors that reduce the sharpness of a drill, density of bone, use of the drill, the debris released during the process, material construction & surface treatment of drill. A worn drill will thus have more heat production than a sharper drill. Previous analysis using scanning electron microscopy revealed tangible wear on the cutting edges of trephine drills after 12 to 18 milling procedures. Although the number of sites to be prepared before drill change is usually suggested by some manufacturers, visual examination or the observation of when the drill fails to progress rapidly, frequently indicate the need for a new drill.

2.2.7 Miscellaneous Factors

The temperature produced also depends on many factors like drilling time, age of the patient, density of the bone, texture of the bone etc. it has been well documented that older patients, certain physiological changes occur. Bony structures tend to become denser and more fragile, the medullary cavity space enlarges faster resulting in a net decrease of cortical thickness and mass, and healing capability is usually impaired. Although some features of bone have been evaluated in terms of heat, the effect of heat in relation to age has not been studied.

Bone usually varies in density from person to person, bone to bone in the skeleton, and from site to site in the same bone. Regarding the effect of density on the temperature generated, Yacker and Klein[29] reported that bone density is a far greater indicator of bur temperature than depth of the osteotomy. However, further studies are necessary to resolve this issue.

Time can be considered as the time of drilling, or the time required for the heated part to return to its normal temperature. The time taken for drilling is directly proportional to the amount of heat generated during drilling. Results show that heating bone at 47°C for 5 minutes results in 20% resumption of original over 30 days. The ideal fastest time for drilling from the previous results was obtained as 2400 rpm with 2.4 kg of pressure to drill 7 mm hole with least temperature rise.

During the literature survey we find that there has been divergence in the opinion between the different researchers regarding how different factors affect the heat generation. More over majority of the observations which are listed above are being observed from an in vitro study. But the in vivo situation is different compared to that from in vitro due to the effects of ambient body temperature, heat transfer via bodily fluids, etc in order to obtain accurate results we need to include all the factors and the observations must be done in real time.

CHAPTER 3
MATERIALS & METHODS

To check how different factors as listed in previous chapter affect heat generation, series of experiments are planned under variable drilling conditions. This needs large number of consistent human bone samples. Since human bone differ in its density and shape depending upon gender, age and other factors, it is extremely difficult to obtain consistent quality human bone samples. This resulted in looking for an alternative material that can be easily available with consistent quality and similar to that of a human bone in properties and functioning. The material that is being considered here is poly methyl Methacrylate (PMMA).

3.1 PMMA

Polymethylmethacrylate or acrylic bone cement is the most commonly used non-metallic implant material in orthopedics. PMMA is one of the earliest polymers and is well known around the world by a variety of trade names Lucite, Oroglas, Perspex and Plexiglas, which vary with the country you are in. PMMA (Polymethyl methacrylate) was first discovered in Germany in 1902 by the chemist O. Röhm and was patented in 1928. The first medical use of PMMA was in 1936 as dental prostheses.

The original PMMA was seen as a replacement for glass in a variety of applications and is currently used extensively in glazing applications. The material is one of the hardest polymers, rigid, glass-clear with glossy finish and good weather resistance. PMMA is a member of a family of polymers which chemists call acrylates, but the rest of the world calls acrylics. PMMA is a vinyl polymer, made by free radical vinyl polymerization from the monomer methyl methacrylate.

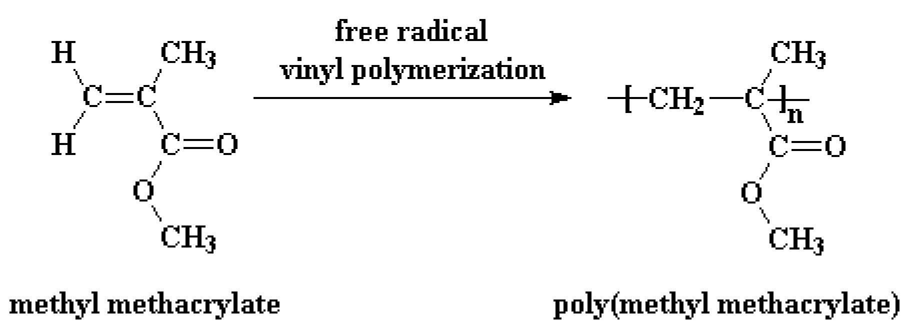

Figure2.1:Structure of PMMA

PMMA has become essential ingredient in making dentures. In mid 1950s charnley [31] first introduced a self-curing PMMA to orthopedic surgery. He successfully fixed both the femoral and actebular components in a total hip replacement using PMMA, and with more pioneering efforts, Charnley and his group, revolutionized reconstructive surgery of the hip and other joints as well. Today most total joint replacement surgery, including hip, knee, and ankle, use acrylic bone cement as fixation of the prosthesis to the bone. Bone cement is also often used in the fixation of pathological features, and it has also been utilized in the repair of bone defects. Acrylic bone cement is still utilized as dental cement due to its low water absorption, non-toxicity, dimensional stability, and ease of forming.

3.1.1 General Properties

PMMA is a glassy polymer with an amorphous structure. It has a density of 1.19 g/cm3 and has very low water absorption. The refractive index ranges from 1.49 to 1.51 depending on the type. Parts made of PMMA have high mechanical strength and good dimensional stability. Other properties include a high Young's modulus and good hardness with low elongation at break. PMMA does not shatter on rupture. PMMA is one of the hardest thermoplastics and is also highly scratch resistant.

3.1.2 Comparison of thermal properties for Human bone and PMMA

PMMA has similar thermal properties compared to the human bone. Properties of both the bone and PMMA can be seen in the following table [32]:

Table 3.1: Comparison of properties for Bone and PMMA

Properties	Bone	PMMA
Thermal conductivity (W/m K)	0.15-0.35	0.15-0.4
Specific heat (J/Kg K)	1300	1400
Thermal diffusivity (m^2/sec)	$0.3*10^{-6}$	$0.11*10^{-6}$
Density (Kg/m^3)	1800	1400

3.2 METHOD

To check the effect of variable drilling factors on the temperature rise during drilling operations series of experiments are planned. Experiments are being carried out on Drilling machine (HAAS VFOE 20HP) in CMS (Center for Manufacturing Systems) machine shop at the University of Kentucky. PMMA specimens of 5cm diameter and 2cm thickness are prepared to perform the experiments.

3.2.1 Positioning of thermocouples

The thermocouples locations are chosen based on the images obtained from infrared thermograph camera during drilling operation. Images from the infrared thermograph helped in determining the isothermal lines distribution around the drilled hole, as shown in the figure 3.1.

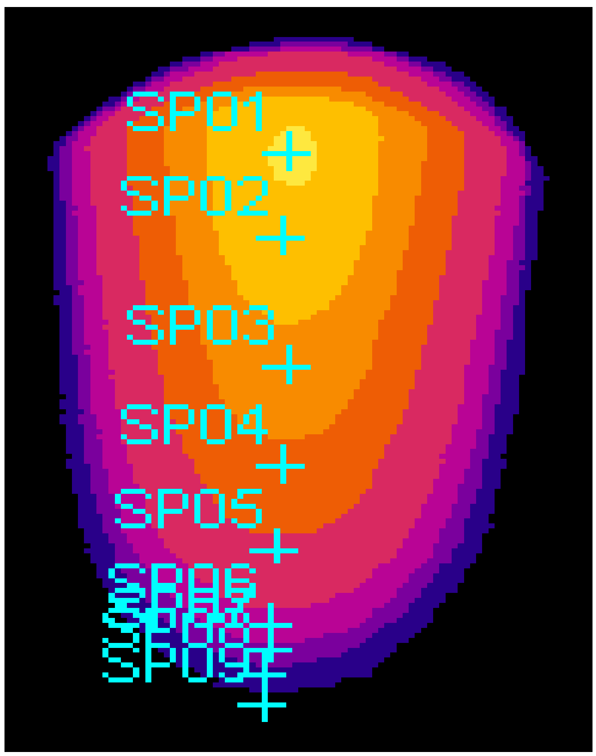

Figure 3.1: Heat generation recorded using infrared camera

The isothermal lines showed that heat is radially conducted from the drilled hole. The images are taken by FLIR IR camera, which has a wavelength dector of 7.5-13 μm . From the table temperatures recorded at different positions during drilling process can be observed. Maximum temperature obtained during the drilling process is of main concern. Tip of the thermocouples should be placed where it can record accurately the maximum temperature absorbed by the specimen during the drilling process and should be careful that thermocouples does not touch the drill during the drilling operation. Higher temperatures recorded at SPO1 and SP02 positions corresponds to the temperature absorbed by the drill. SPO3 is the position where the thermocouples can be placed to record maximum temperatures obtained to the drilling process without any damage to it.

Locations for placing thermocouples are calculated using Adobe Photoshop software. To record the maximum temperatures that are produced during drilling, Thermocouple 1 should be placed at a distance of 6 mm from the top and 6 mm away from the center and Thermocouple 2 is to be placed 6 mm below the first one but at the same distance from the center.

3.2.2 Experimental Setup

Experimental setup for carrying out these experiments include two type K thermocouples for recording temperatures, Data acquisition equipment for retrieving data from thermocouples, drilling machine and a PMMA specimen. Two holes are drilled into the PMMA specimen for placing thermocouples. These holes are drilled in such a way that thermocouples can be inserted easily into the specimen and can reach the exact positions they are supposed to be. These holes are being drilled using 0.9 mm diameter drills. Type K thermocouples (Omega) are used for recording the temperature rise during the drilling operation. These thermocouples are connected to data acquisition equipment (Data Acquisition System: IO Tech DaqBook/260, 14 channels). This data acquisition system acquires temperature data during the drilling process by the rate of 10 temperatures–samples/second.

Data acquisition system is directly connected to a laptop, which transfers the data directly to Microsoft Excel sheet. Data recording from thermocouples will be started and stopped by manual trigger. For a specific drilling condition, experiments are carried out on three specimens. Average value of the maximum temperatures obtained for three identical specimens under the same identical conditions will be taken and that value will be recorded as the temperature obtained for that specific drilling condition. Experiments will be repeated for variable drilling conditions.

The schematic of experimental setup can be seen from the following figure:

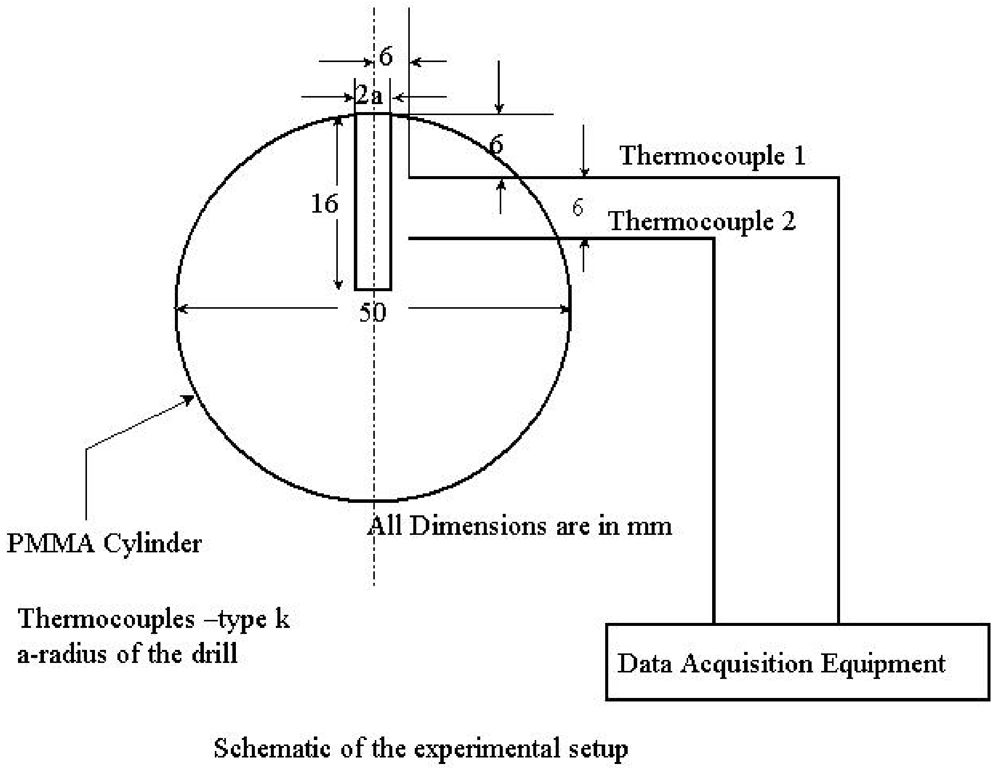

Figure 3.2: Schematic of the experimental setup

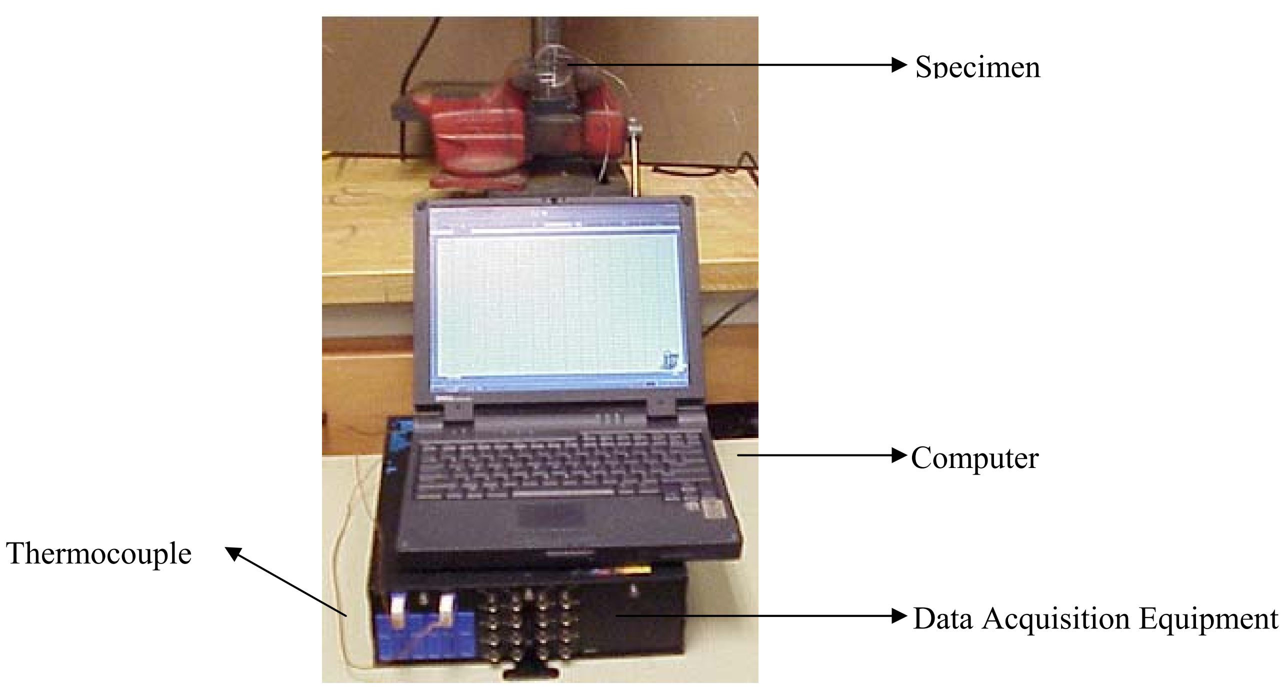

Figure 3.3: Experimental Setup

Figure 3.3 shows thermocouples inserted in the specimen being connected to the data acquisition equipment, which in turn is connected to the computer that collects the data. Each PMMA specimen is used for performing two experiments. The following figure shows a PMMA specimen that is being used for two series of experiments. We can also observe the holes drilled for placing thermocouples.

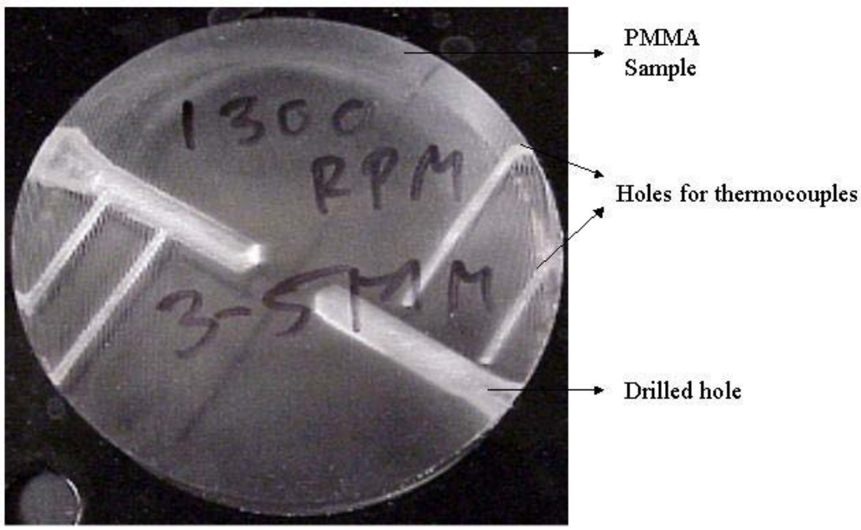

Figure 3.4: PMMA Specimen drilled at 1300 RPM with 3.5 mm diameter drill

3.2.3 Experimental Conditions

Series of experiments are going to be performed using the above experimental setup to check how different drilling parameters affect temperature. To check each parameter for a drilling condition other drilling conditions and parameters are maintained constant. Experiments are performed at a standard condition of 1200 RPM, 16 mm depth, using a 2 mm diameter drill and at a feed rate of 0.00508 m/sec. To check a certain condition, i.e. drilling speed, speed is varied from 1200 RPM to 1800 RPM and then to 2200 RPM, other conditions are maintained same (i.e. depth, diameter and feed rate). Again for every parameter of a certain condition experiments are carried out on three PMMA specimens. Table 3.2 shows the list of parameters and conditions under which drilling operations are going to be performed. Along with these parameters, experiments are also carried out to check how external coolant and incremental drilling procedures affect the temperature change during drilling operations.

Table 3.2: Table of drilling parameters

CONDITIONS	PARAMETERS
Drilling Speed (R.P.M)	1200, 1800, 2200
Drilling Depth (mm)	8, 12, 16
Drill Bit Diameter (mm)	2.00, 3.50, 4.30
Drill Feed Rate (m/sec)	0.00508, 0.01016,0.01524

3.2.4 Data Analysis

Data Acquisition equipment (IO Tech DaqBook/260) is used to record temperatures generated during drilling process. It records ten temperature samples for every second and it is connected directly to laptop, which allows the data to be stores in Microsoft Excel software. Following two graphs show the temperatures recorded by thermocouples:

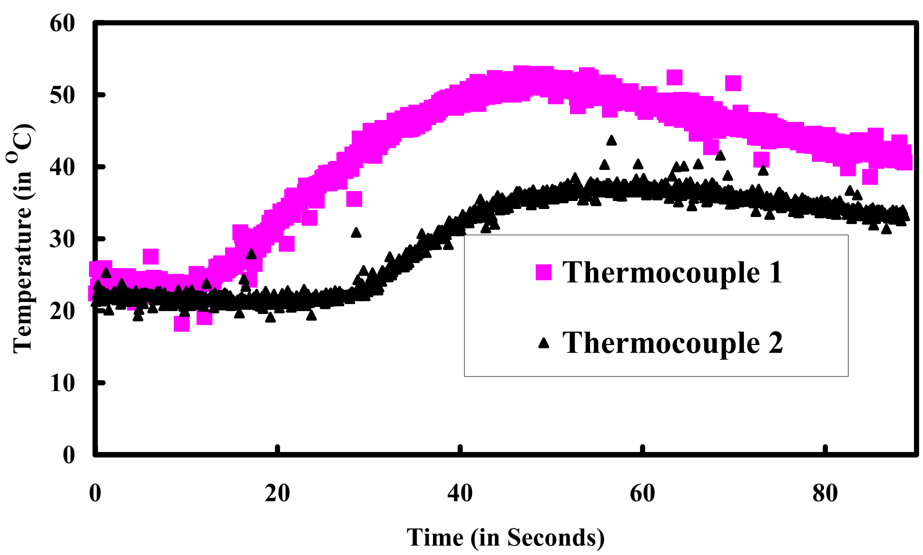

Figure 3.5 Thermocouple readings using 2 mm drill at 1200 rpm and 16 mm depth

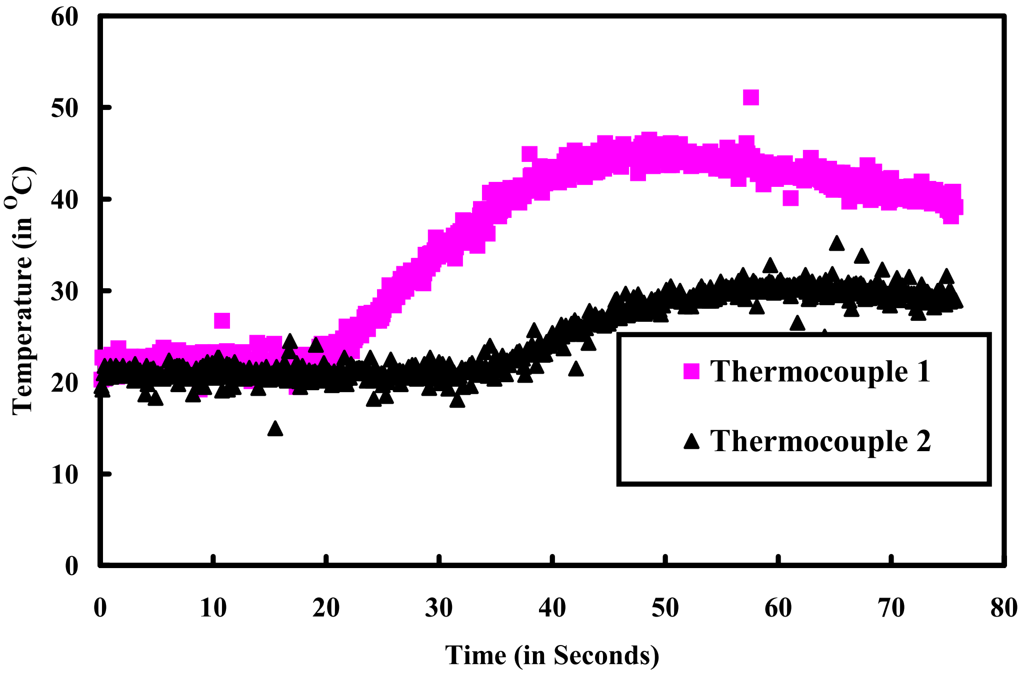

Figure 3.6: Thermocouple readings using 2mm drill at 1200 rpm and 12 mm depth

During the data analysis, maximum temperatures obtained during a drilling operation is of much importance as the main goal of this study is to see how these maximum temperatures can be reduced. For every drilling parameter, experiments are performed on three specimens. Average of the maximum temperatures obtained by drilling three specimens is taken as the maximum temperature obtained for that drilling parameter. These results are been tabulated and were discussed in chapter 5.

CHAPTER 4
THEORETICAL EQUATION

4.1 MODELING APPROACH

In order to build a predictive model for the temperature and heat flux in the current problem, a global pattern for the heat distribution must be determined. The predictive model will help dentists to scale the temperature profiles and the amount of heat flux entering into the human bone during drilling operation. Therefore, proper drilling parameters can be chosen.

Finite element analysis is carried out on PMMA model and also thermograph images are taken using infrared camera process to check how heat spreads out during drilling process for formulating a theoretical model.

4.1.1 Thermal Analysis

Thermal analysis is carried out using finite element analysis software ANSYS. To carry out thermal analysis, a symmetric model of PMMA cylinder similar to that of specimen used for experiments is designed. Thermal and physical properties are substituted for this model and steady state thermal analysis is carried out on PMMA.

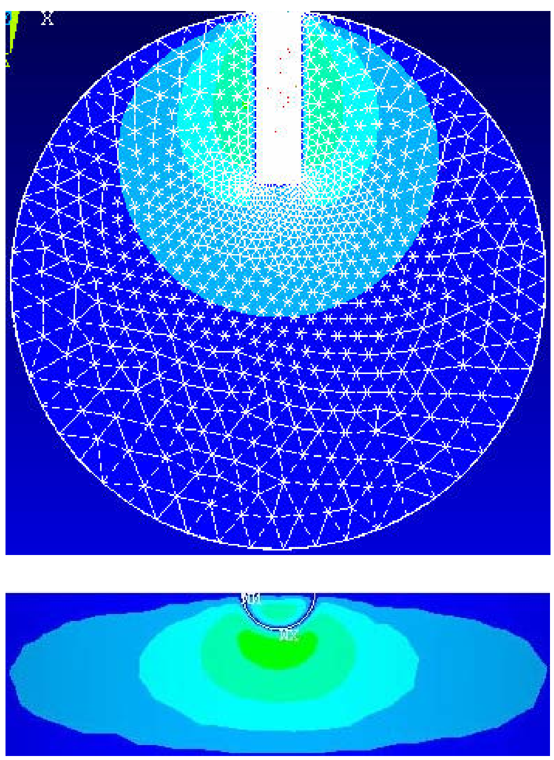

Figure 4.1: Thermal analysis on PMMA using ANSYS software

Results from thermal analysis shows that the heat generated during the drilling process spreads out in radial direction across the model.

4.1.2 Thermograph Image

Thermograph images of the drilling process are being taken using infrared camera as explained in chapter 3. Figure 4.2 is one of the pictures that have been taken using infrared camera. Observations made from this picture also confirm that heat generated during drilling process spreads in radial direction.

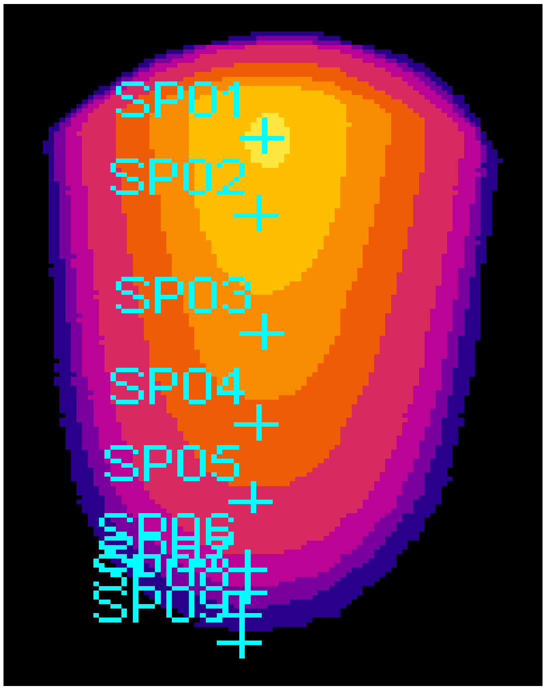

Figure 4.2: Heat generation recorded using infrared camera

4.1.3 Assumptions

Observations from thermograph images and thermal analysis help us in developing one of the main assumptions for our model, i.e. heat spreads inside the body in radial direction. Thermal conductivity of the material is small, which helps us in assuming the body to be a semi-infinite solid.

Following assumptions are used for building the predictive model:

- Heat distribution in the body is in a radial direction.

- Body is considered to be semi-infinite solid.

4.2 DERIVATION

Drilling procedure inside PMMA cylinder increase temperature. There are many drilling factors like drill speed, depth of the drilling, drill diameter and others, which affect the temperature increase. In this section an equation is derived to predict the temperature rise as the function of these drilling parameters. Equation is being derived based upon the above assumptions.

Consider the homogenous differential equation of heat conduction in the cylindrical coordination system,

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} = \frac{1}{\alpha_1}\frac{\partial T}{\partial t} \qquad \text{For} \quad a \le r < \infty \tag{4.1}$$

Where temperature T is a function of radius r and time t. α_1 is the thermal diffusivity of the material.

Boundary conditions are as follows:

At $r = a$, $\frac{\partial T}{\partial r} = -\frac{q}{k}$ q is the constant heat flux being generated. (4.1.1)

At $r = \infty$, $\frac{\partial T}{\partial r} = 0$ we assume heat flux is zero at infinite boundary. (4.1.2)

Initial condition:

For $t = 0$, $T = T_R$ T_R is the room temperature. (4.1.3)

We define dimensionless parameters to convert non-homogenous boundary conditions into homogenous boundary conditions as follows:

$$\theta = \frac{T - T_R}{\Delta T_c} \Rightarrow T = \theta \Delta T_c + T_R \tag{4.2.1}$$

$$\eta = \frac{r}{r_c} \Rightarrow r = \eta r_c \tag{4.2.2}$$

$$\tau = F_O = \frac{t}{t_c} \Rightarrow t = \tau t_c . \tag{4.2.3}$$

Where θ is the dimensionless temperature, η is the dimensionless radius, τ is the dimensionless time and F_O is Fourier number, r_c is radius of the drill, t_c is the time at which we start drilling and we define $\Delta T_c = -\frac{k}{qr_c} = -\frac{k}{qa}$.

After substituting the dimensionless parameters in Equation (4.1) we get the following differential equation:

$$\frac{\partial^2 \theta}{\partial \eta^2} + \frac{1}{\eta}\frac{\partial \theta}{\partial \eta} = \frac{\partial \theta}{\partial \tau} \quad \text{For } 1 \le \eta < \infty \tag{4.3}$$

The boundary conditions are as follows:

$$\text{At } \eta = 1, \frac{\partial \theta}{\partial \eta} = 1. \tag{4.3.1}$$

$$\text{At } \eta \to \infty, \frac{\partial \theta}{\partial \eta} = 0. \tag{4.3.2}$$

$$\text{At } \tau = 0, \theta = 0. \tag{4.3.3}$$

The equation (4.3) is dependant on both η and τ. To solve the problem let us define $\upsilon = \frac{\eta^2}{4\tau}$.

(4.4)

Differentiating (4.4) both with respect to η and τ we get:

$$\partial \upsilon = \frac{\eta}{2\tau}\partial \eta \Rightarrow \frac{\partial \upsilon}{\partial \eta} = \frac{\eta}{2\tau}. \tag{4.4.1}$$

$$\partial \upsilon = -\frac{\eta^2}{4\tau^2}\partial \tau \Rightarrow \frac{\partial \upsilon}{\partial \tau} = -\frac{\eta^2}{4\tau^2}. \tag{4.4.2}$$

Substituting the above in Equation (3.0) we get

$$\frac{\partial^2 \theta}{\partial \eta^2} + \frac{1}{\eta}\frac{\partial \theta}{\partial \eta} = \frac{\partial \theta}{\partial \tau}$$

$$\frac{d}{d\upsilon}\left(\frac{\partial \theta}{\partial \upsilon}\frac{\partial \upsilon}{\partial \eta}\right)\frac{\partial \upsilon}{\partial \eta} + \frac{1}{\eta}\frac{\partial \theta}{\partial \upsilon}\frac{\partial \upsilon}{\partial \eta} = \frac{\partial \theta}{\partial \upsilon}\frac{\partial \upsilon}{\partial \tau}$$

$$\frac{\partial}{\partial \upsilon}\left(\frac{\partial \theta}{\partial \upsilon}\frac{\eta}{2\tau}\right)\frac{\eta}{2\tau}+\frac{1}{\eta}\frac{\partial \theta}{\partial \upsilon}\frac{\eta}{2\tau}=-\frac{\eta^2}{4\tau^2}\frac{\partial \theta}{\partial \upsilon}$$

$$\frac{\eta^2}{4\tau^2}\frac{d^2\theta}{d\upsilon^2}+\frac{1}{2\tau}\frac{d\theta}{d\upsilon}=-\frac{\eta^2}{4\tau^2}\frac{d\theta}{d\upsilon}$$

$$\frac{\upsilon}{\tau}\frac{d^2\theta}{d\upsilon^2}+\frac{1}{2\tau}\frac{d\theta}{d\upsilon}=-\frac{\upsilon}{\tau}\frac{d\theta}{d\upsilon}$$

Dividing the above equation by $\frac{\upsilon}{\tau}$ we get,

$$\frac{d^2\theta}{d\upsilon^2}+\frac{1}{2\vartheta}\frac{d\theta}{d\upsilon}=-\frac{d\theta}{d\upsilon}$$

$$\frac{d^2\theta}{d\upsilon^2}+\left(\frac{1}{2\upsilon}+1\right)\frac{d\theta}{d\upsilon}=0\,. \tag{4.5}$$

The boundary conditions will be changed as follows:

As $\eta=1\Rightarrow\upsilon=\frac{1}{4\tau}.\frac{\partial\theta}{\partial\eta}=1\Rightarrow\frac{d\theta}{d\upsilon}\frac{\partial\upsilon}{\partial\eta}=1\Rightarrow\frac{d\theta}{d\upsilon}=\frac{2\tau}{\eta}=2\tau$ (4.5.1)

As $\eta\to\infty\Rightarrow\upsilon\to\infty,\frac{\partial\theta}{\partial\eta}=0\Rightarrow\frac{d\theta}{d\upsilon}=0$. (4.5.2)

At $\tau=0,\upsilon\to\infty,\frac{d\theta}{d\upsilon}=0$. (4.5.3)

Let us define $\frac{d\theta}{d\upsilon}=y$ then the equation (4.5) would be as follows:

$$\frac{dy}{d\upsilon}+\left(\frac{1}{2\upsilon}+1\right)y=0\,. \tag{4.6}$$

This equation is of the form:

$$\frac{dy}{dx}+Py=Q \tag{4.7}$$

The solution of the above equation is:

$$y=e^{-\int Pdx}\int Qe^{\int Pdx}dx+C_1e^{-\int Pdx}\,. \qquad [33]$$

Comparing the Equation(6) and Equation(7) we have $P=\frac{1}{2\upsilon}+1, Q=0$. The solution would be:

$$y = C_1 e^{-\int\left(\frac{1}{2\upsilon}+1\right)d\upsilon}$$

$$= C_1 \frac{e^{-\upsilon}}{\sqrt{\upsilon}}.$$

Also,

$$\frac{d\theta}{d\upsilon} = C_1 \frac{e^{-\upsilon}}{\sqrt{\upsilon}}.$$

At boundary condition $\upsilon = \dfrac{1}{4\tau}$ we have $\dfrac{d\theta}{d\upsilon} = 2\tau \Rightarrow C_1 \dfrac{e^{-\frac{1}{4\tau}}}{\sqrt{\frac{1}{4\tau}}} = 2\tau \Rightarrow C_1 = \sqrt{\tau} e^{\frac{1}{4\tau}}$.

$$d\theta = C_1 \frac{e^{-\upsilon}}{\sqrt{\upsilon}} d\upsilon.$$

Integrating on both sides we get,

$$\int_0^\theta d\theta = C_1 \int_{\frac{1}{4\tau}}^{\infty} \frac{e^{-\nu}}{\sqrt{\upsilon}} d\upsilon + C_2.$$

Let us consider the following integral:

$$\int_x^\infty \frac{e^{-t}}{t^\nu} dt = \Gamma(1-\nu) - \frac{1}{1-\nu} x^{1-\nu} + \int_0^x \frac{1-e^{-t}}{t^\nu} dt. \qquad [34]$$

We need $\displaystyle\int_{\frac{1}{4\tau}}^{\infty} \frac{e^{-\upsilon}}{\sqrt{\upsilon}} d\upsilon$, comparing the above two equations we have $\nu = 0.5, x = \dfrac{1}{4\tau}$ hence we get

$$\int_{\frac{1}{4\tau}}^{\infty} \frac{e^{-\upsilon}}{\sqrt{\upsilon}} d\upsilon = \Gamma(1-0.5) - \frac{1}{1-0.5}\left(\frac{1}{4\tau}\right)^{1-0.5} + \int_0^{\frac{1}{4\tau}} \frac{1-e^{-\upsilon}}{\sqrt{\upsilon}} d\upsilon$$

$$= \Gamma(0.5) - \frac{1}{\sqrt{\tau}} + \int_0^{\frac{1}{4\tau}} \frac{1-e^{-\upsilon}}{\sqrt{\upsilon}} d\upsilon.$$

also here $\displaystyle\int_0^{\frac{1}{4\tau}} \frac{1-e^{-\upsilon}}{\sqrt{\upsilon}} d\upsilon = \left[2 * \sqrt{\upsilon} - \sqrt{\pi} * erf(\sqrt{\upsilon})\right]_0^{\frac{1}{4\tau}}$

$$= \frac{1}{\sqrt{\tau}} - \sqrt{\pi} erf(\frac{1}{2\sqrt{\tau}})$$

Hence we get

$$\int_{\frac{1}{4\tau}}^{\infty} \frac{e^{-\upsilon}}{\sqrt{\upsilon}} d\upsilon = \Gamma(0.5) - \frac{1}{\sqrt{\tau}} + \frac{1}{\sqrt{\tau}} - \sqrt{\pi} * erf(\frac{1}{2\sqrt{\tau}}).$$

$$\int_{\frac{1}{4\tau}}^{\infty} \frac{e^{-\upsilon}}{\sqrt{\upsilon}} d\upsilon = \Gamma(0.5) - \sqrt{\pi} * erf(\frac{1}{2\sqrt{\tau}}).$$

Hence we have the final equation as

$$\theta = \sqrt{\tau} e^{\frac{1}{4\tau}} \left(\Gamma(0.5) - \sqrt{\pi} erf(\frac{1}{2\sqrt{\tau}}) \right)$$

$$= \sqrt{\tau} e^{\frac{1}{4\tau}} \left(1.775 - \sqrt{\pi} * erf\left(\frac{1}{2\sqrt{\tau}} \right) \right)$$

Substituting back the value of τ from our previous assumptions, we get

$$\theta = \frac{\sqrt{t\alpha_1}}{a} e^{\frac{a^2}{4t\alpha_1}} \left(1.775 - \sqrt{\pi} * erf(\frac{a}{2\sqrt{t\alpha_1}}) \right)$$

But we know that $\theta = -\frac{(T - T_R)qa}{k} \Rightarrow -\frac{k\theta}{qa} + T_R = T$. Substituting this expression we get the final equation as follows:

$$T = T_R - \frac{k\sqrt{t\alpha_1}}{qa^2} e^{\frac{a^2}{4t\alpha_1}} \left(1.775 - \sqrt{\pi} * erf(\frac{a}{2\sqrt{t\alpha_1}}) \right) \tag{4.8}$$

The above expression gives expression for temperature rise during drilling process as a function of heat flux (q), thermal conductivity (k), time taken for drilling (t), and thermal diffusivity (α_1). Here we know the values of thermal conductivity and thermal diffusivity of PMMA, and also the time taken for drilling process. We need to determine the value of heat flux (q) generated during drilling process.

Amount of heat flux generated during drilling process depends on many drilling parameters. In the next few steps I am going to explain in detail how the expression is derived for heat flux during drilling process.

4.3 EXPRESSION FOR HEAT FLUX

Energy involved in material removal is converted into heat. The heat generated is therefore well approximated by the amount of work done.

$$\frac{\partial Q}{\partial t} = F_S v_S \qquad [35] \qquad (4.9)$$

where Q is the heat generated by the cutting action, t is time, F_s is the shearing force in the shear plane, v_S is the shear velocity.

4.3.1 Calculation of shear velocity

The shear velocity v_S is related to cutting velocity v and shear angle ϕ as

$$v_S = \frac{v}{\cos\phi} \qquad (4.10)$$

Shear angle ϕ is calculated using the Ernst-Merchant relationship, $2\phi + \beta - \alpha = 90^0$.
Where α is rake angle of the cutting tool and the friction angle, β, is equal to 0.644 [37]

An expression for α at a distance r from the rotational axis was developed by Battacharya and Ham [38], as follows:

$$\tan\alpha = \frac{(2r/D)\tan\theta - \tan\left[\sin^{-1}(d_0/2r)\sin(p)\right]\cos(p)}{\sin(p)} \qquad (4.11)$$

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.

The velocity v can be calculated as follows:

$$v = \frac{2\pi rN}{60} \quad \text{where N is the rotational speed, in rpm.} \qquad (4.12)$$

4.3.2 Calculation of Shear Force

The shear force, F_S , in the material being removed by the drill was calculated from

$$F_S = \tau_S A_{S,} \quad [36] \qquad (4.13)$$

Where τ_S is the ultimate shear stress and A_S is the area of the shear plane. Bone is viscoelastic material and one consequence is that the ultimate stress τ_S varies with the shear rate.

The expression for maximum shear rate γ in primary deformation zone is calculated by Tay et al. as :

$$\gamma = \frac{v}{4\sqrt{a}\, sin^2(\phi)[tan(\alpha) + cot(\phi)]^{\frac{3}{2}}} \qquad (4.14)$$

Here a can be calculated from following equation:

$$a = \frac{t_1^2}{16C^2\, sin^4(\phi)[tan(\alpha) + cot(\phi)]}. \qquad (4.15)$$

where $C = 6$ from Tay et al [39].

t_1 - undeformed chip thickness:

$$t_1 = \frac{f/2}{N/60} sin(p) \text{ , } f \text{ is the feed rate of the drill.[40]} \qquad (4.16)$$

The dependence of ultimate shear stress on shear rate was determined for bone by combining the results of several studies.

$$\tau_S \infty \gamma^{0.06} \text{. [41]}$$

To find the constant of proportionality, the results of saha were used.

$$\tau_S = 80\gamma^{0.06} \quad [42] \qquad (4.17)$$

Substituting equation (4.14) and equation (4.15) in equation (4.17.0) shear stress can be written as follows:

$$\tau_S = 80\left(\frac{v}{4\sqrt{\dfrac{t_1^2}{16C^2\, sin^4(\phi)[tan(\alpha)+cot(\phi)]}}\left(sin^2(\phi)[tan(\alpha)+cot(\phi)]^{\frac{3}{2}}\right)}\right)^{0.06}$$

$$= 80\left[\frac{vC}{t_1[tan(\alpha)+cot(\phi)]}\right]^{0.06} \tag{4.18}$$

The shear plane area,

$$A_S = \frac{t_1(D-d_0)}{cos(90^0 - p)sin(p)} \tag{4.19}$$

We know from Equation(13)

$$F_S = \tau_S A_S$$

Substituting Equation (4.18) and Equation (4.19) in Equation (4.13) we get the expression for shear force:

$$F_S = 80\left[\frac{vC}{t_1[tan(\alpha)+cot(\phi)]}\right]^{0.06} \frac{t_1(D-d_0)}{cos(90^0 - p)sin(p)}. \tag{4.20}$$

The heat generated is given by the Equation(4.9) as follows:

$$\frac{\partial Q}{\partial t} = F_S v_S$$

Substituting Equation (4.9) and Equation (4.19) in Equation (4.8) we get :

$$\frac{\partial Q}{\partial t} = 80\left[\frac{vC}{t_1[tan(\alpha)+cot(\phi)]}\right]^{0.06} * \frac{t_1(D-d_0)}{cos(90^0 - p)sin(p)} * \frac{v}{cos\,\phi} \tag{4.21}$$

The heat generated by cutting conducts to the tool, the chip, and the work piece. Determining the fraction of heat that enters the work piece η is exceedingly difficult to determine from the fundamentals of mechanics and heat conduction.

$$\frac{\partial Q_w}{\partial t} = \eta \frac{\partial Q}{\partial t} \qquad [45] \tag{4.22}$$

Substituting Equation(4.21) in Equation(4.22.0) we have:

$$\frac{\partial Q_w}{\partial t} = \eta * 80\left[\frac{vC}{t_1[tan(\alpha)+cot(\phi)]}\right]^{0.06} * \frac{t_1(D-d_0)}{cos(90^0-p)sin(p)} * \frac{v}{cos\phi} \quad (4.23)$$

4.3.3 Heat Flux

Heat flux is calculated as follows:

$$q = -\frac{\partial Q_W}{\partial t}\frac{\Delta t}{2\pi\Delta zR} \quad [44] \qquad (4.24)$$

Where $\frac{\partial Q_w}{\partial t}$ - rate of heat generated by the drill that enters the work piece.

Δz Height of the element where the heat flux us applied.

R radius of the drill/hole.

Δt time.

Substituting the Equation (4.23) in Equation(4.24) we get the final expression for heat flux:

$$q = -\eta * 80\left[\frac{vC}{t_1[tan(\alpha)+cot(\phi)]}\right]^{0.06} * \frac{t_1(D-d_0)}{cos(90^0-p)sin(p)} * \frac{v}{cos\phi}\frac{\Delta t}{2\pi\Delta zR}$$

$$= -\eta * 40\left[\frac{\pi N^2}{150 f\, sin(p)(tan\,\alpha + cot\,\phi)}\right]^{0.06}\left(\frac{ft(D-d_0)}{\Delta z * R * cos(90-p)cos\,\phi}\right) \quad (4.25)$$

Equation 25 includes drilling speed, drilling depth, drill diameter, feed rate and drill design that can help us in explaining how different drill factors affect temperature rise during drilling operation.

4.4 FINAL EQUATION

Substituting the expression for heat flux (4.25) in the equation (4.8) we get the final expression for temperature rise during drilling process. The final expression is as follows:

$$T = T_R - \frac{k\sqrt{t\alpha_1}e^{\frac{a^2}{4t\alpha_1}}\left(1.775 - \sqrt{\pi} * erf(\frac{a}{2\sqrt{t\alpha_1}})\right)}{-\eta * 40\left[\frac{\pi N^2}{150 f\, sin(p)(tan\,\alpha + cot\,\phi)}\right]^{0.06}\left(\frac{ft(D-d_0)}{\Delta z * R * cos(90-p)cos\,\phi}\right)a^2} \quad \text{…………(4.26)}$$

4.5 NOMENCLATURE

T_R	Room temperature
α_1	Thermal diffusivity of the material.
k	Thermal conductivity of the material.
t	Time taken for drilling.(sec)
N	Drill speed in R.P.M.
F	Drill feed rate in m/sec.
Δz	Height of the element where the heat flux is applied or Drilling Depth (m)
a	Radius of the hole (m).
η	Fraction of heat that enters the work piece.
D	Drill diameter (m),
d_0	Chisel edge diameter of the tool (m),
θ	Helix angle of the cutting tool,
p	Half-angle at the point.
α	Rake angle of the cutting tool.

CHAPTER 5
RESULTS & DISCUSSION

This chapter is divided into two main sections. In the first section, experimental results obtained by drilling PMMA with different drilling parameters are being presented. Experiments were carried out to check how different drilling parameters: speed, depth, bit diameter, feed rate, external coolant and also comparison between temperatures obtained using single step drilling procedure and incremental drilling procedures were made on PMMA. Comparisons of temperatures obtained from theoretical model and experiments were made in the second section of this chapter to validate thermal model developed. Comparison of temperature profiles obtained from theoretical model is also made between PMMA and human bone.

5.1 EXPERIMENTAL RESULTS

This section includes results obtained from experiments and a brief discussion about the results. Series of experiments were carried out to check how variable drilling conditions would affect the temperature increase. Number of PMMA samples has been prepared for testing. Experiments are carried out on three similar PMMA samples for a particular drilling parameter, which is to be tested by having other drilling parameters constant.

5.1.1 Drill speed

To study the optimum drilling speed experiments are performed for three different speeds of 1200, 1800 and 2200 RPM, while the feed rate is kept constant at 0.0508 m/sec, hole is being drilled for 16 mm in depth and drill diameter is 2 mm. Figure 5.1 shows the maximum temperatures obtained at different speeds. As shown in the figure, increasing the drilling speed as expected significantly increases temperature. This increase in temperature is due to the fact that increase in cutting speed causes shear rate to increase which leads to increase in friction between the drill and the work piece. Increase in friction causes more heat generation during the drilling process, which eventually leads to higher temperature inside the specimen. Plotted data gives good information for the dentist to avoid the drilling speed that is leading to temperature that causing gum inflammation.

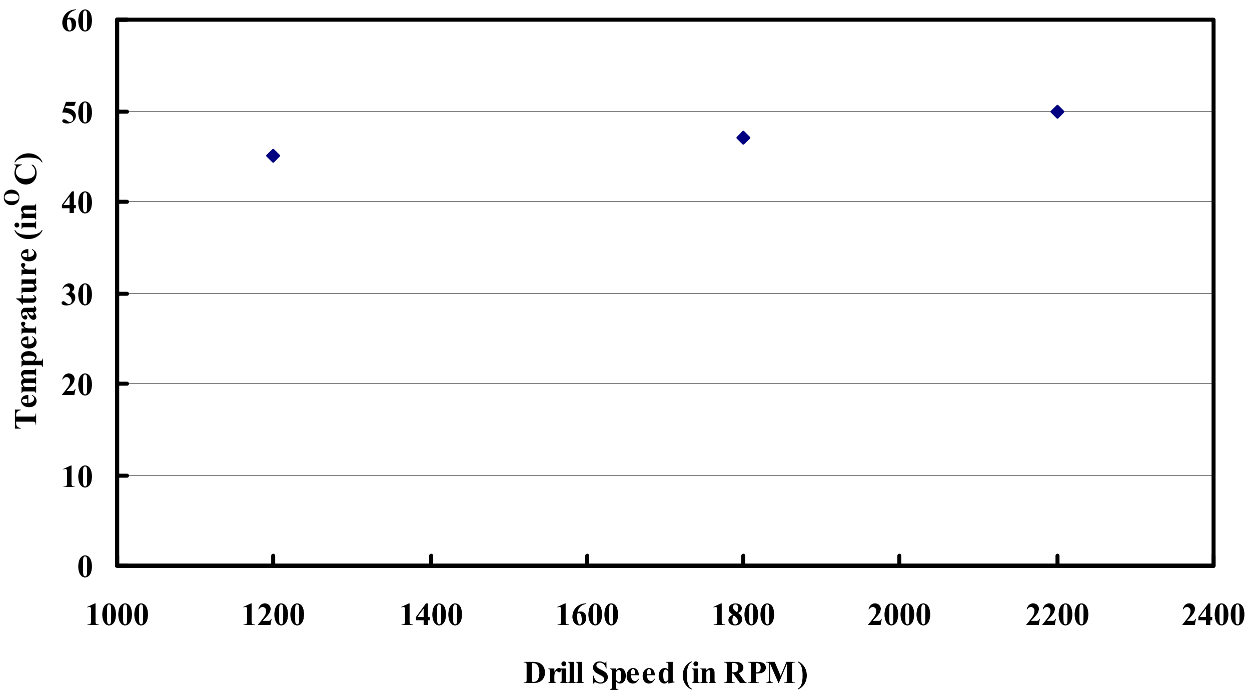

Figure 5.1:Temperatures at drilling speed of 1200,1800 and 2200 RPM

5.1.2 Drilling depth

To study the affect of drilling depth on temperature during drilling process experiments have been carried out for three different depths of 8,12 and 16 mm. These experiments are carried out at a constant feed rate of 0.00508 m/sec, constant speed of 1200 RPM and with drilling tool of 2 mm diameter. Figure 5.2 shows the maximum temperatures obtained at different depths. As shown in the figure, increasing the drilling depth significantly increases temperature. Increase the drilling depth increases the time of contact between the work piece and drilling tool, which causes in overall increase in friction resulting in higher heat generation. This higher heat generated during drilling process leads to overall increase in temperature. but as it reaches higher depths it increases the heat transfer surface area and hence PMMA absorption volume. That explains the flatness of the curve after 12mm depth. The drilling depth is mainly dependent on plantation parameters.

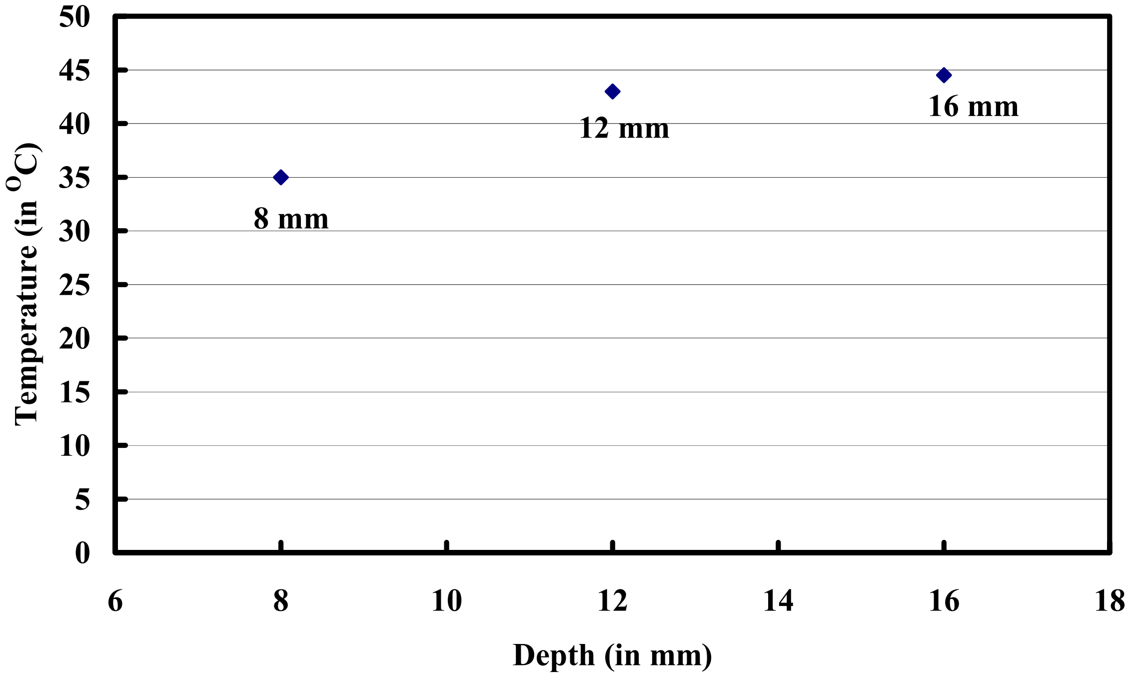

Figure 5.2: Temperatures measured at drilling depths of 8,12,16 mm

5.1.3 Drill diameter

To study the drill diameter we have considered three different diameters of 2,3.5 and 4.3mm. These diameters are studied at a feed rate of 0.42 mm/sec and 1200-RPM drill speed. Figure 5.3 shows the maximum temperatures obtained at different drill diameters. As shown in the figure, increasing the drilling diameter exponentially increases temperature. This shows clearly that the thick drill bit generates more heat and high probability of gum inflammation. Friction generated during the drilling process is directly proportional to the amount of area of contact between drill and work piece. As the drill diameter increases, area of contact also increases thus increasing the amount of heat generated. This increase in heat generation leads to increase in temperature of both the drill and work piece. Figures 5.1 and Figure 5.2 shows that the thicker drill bit has more influence on the heat generation more than the deeper drilling. According to these results, it has been found that thinner, slower and lesser depth drilling reduces the risk of gum inflammation and dead tissue.

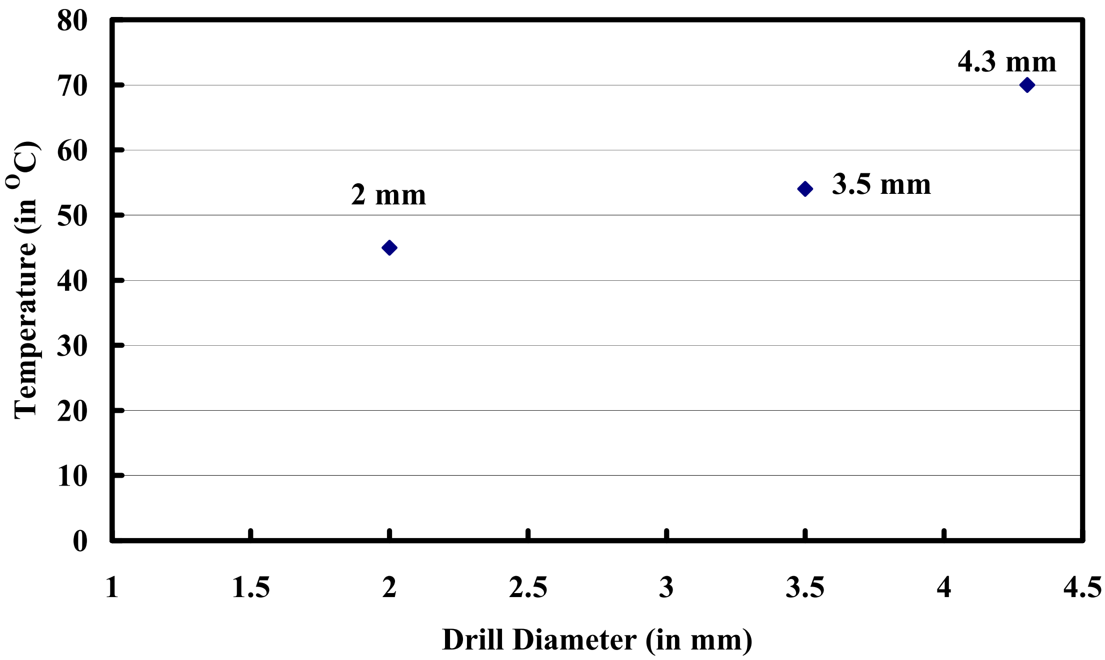

Figure 5.3: Temperatures measured with drills of 2,3.5and 4.3 mm diameter

5.1.4 External Coolant

Previous experiments were performed without any coolant. We can observe there is significant temperature rise without coolant. To check how external coolant impacts the temperature rise we performed series of experiments using external coolant. External coolant used in the experiment is the regular industrial coolant, which is used along with the CNC machines. The experiments are performed at a drill speed of 1200 RPM, 2 mm Drill diameter, and at a feed rate of .00508 m/sec drilled to 16 mm in depth. The maximum temperature obtained when drilling with external coolant is 41^{0}C compared to a maximum temperature of 45^{0}C obtained during drilling without any coolant. This reduction in temperature is due to the fact that coolant allows faster dissipation of heat generated during drilling process. The following figure shows the maximum temperatures obtained when drilling with and without external coolant.

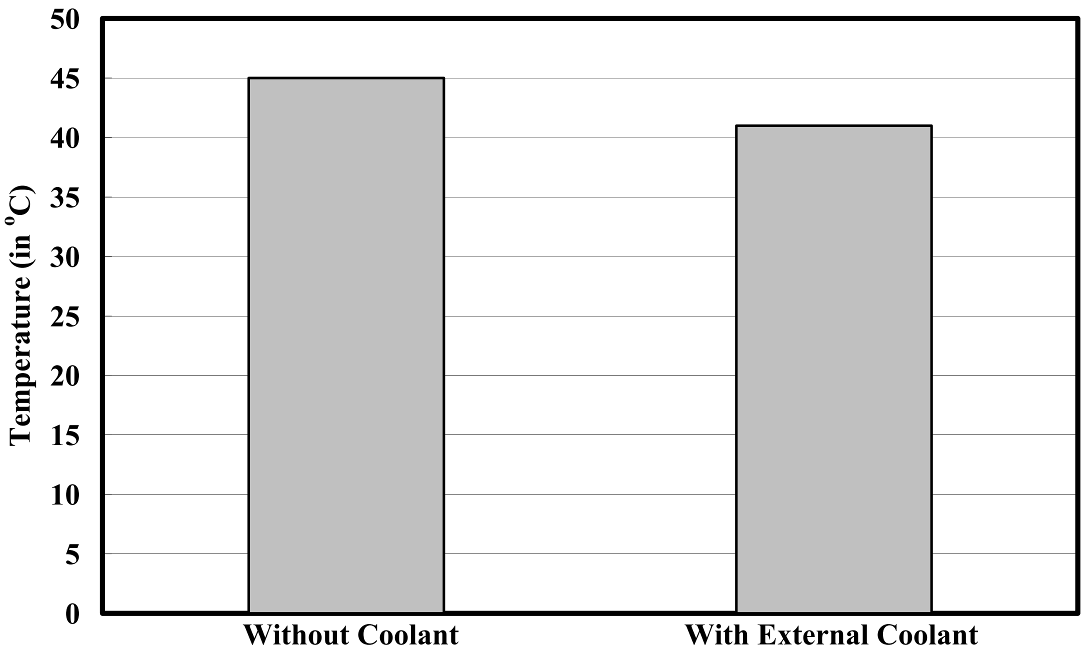

Figure 5.4:Temperatures measured when drilling with/without external coolant

5.1.5 Drill feed rate

Experiments performed until now are performed at a drill feed rate of 0.0508 m/sec. To check how different drill feed rates will affect the heat generation during the drilling operation we have performed experiments at feed rates of 0.0508 m/sec, 0.1016 m/sec and 0.1524 m/sec. maximum temperatures that are obtained using three feed rates are plotted in the following figure. We can observe that as the drill feed rate is being increased the maximum temperature decreases during the drilling operation. We can see that the temperature obtained at drilling feed rate of 0.1524 m/sec is 32^0C compared to 37 C at 0.1016 m/sec and 45^0C at 0.1524m/sec. Experiments are performed at drilling speed of 1200 RPM, with drill diameter of 2 mm and for a depth of 16mm. For the same depth as feed rate increases the amount of time taken to drill is less. Lesser time means lesser time of contact between the drill and work piece reducing the total friction generated. As the friction is decreased heat generation also decreases reducing the final temperatures of the work piece.

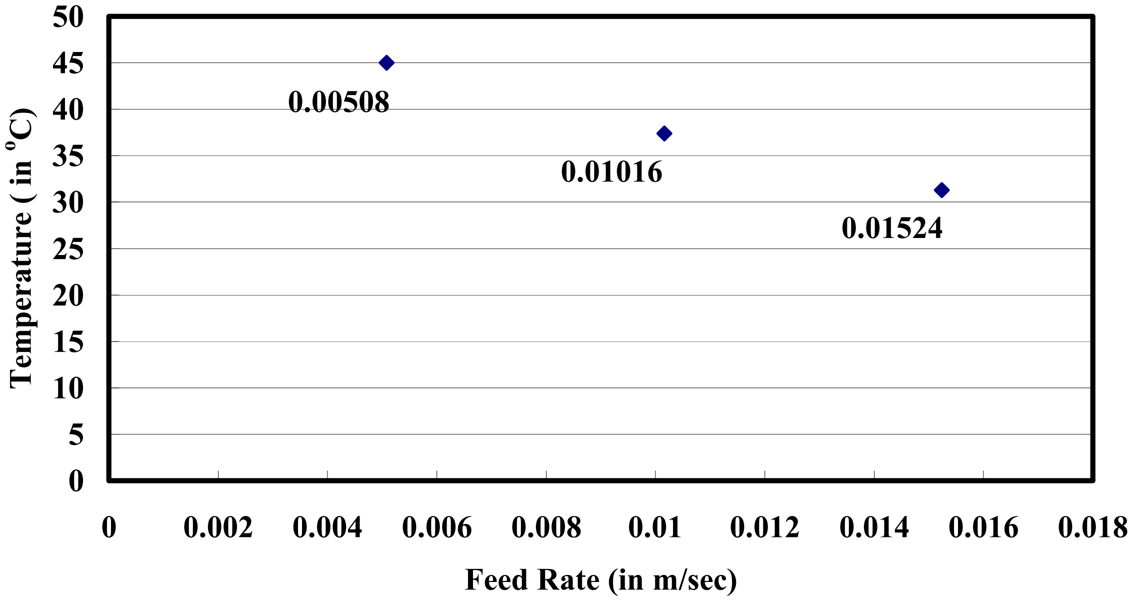

Figure 5.5: Temperatures measured at different feed rates

5.1.6 Single step or Incremental drilling

To check how single step or incremental drilling affects the temperature increase during drilling operation, experiments are performed drilling 3.5 mm hole directly and gradually increasing the diameter from 2mm to 3.5 mm. Experiments are also carried out for drilling 4.3 mm diameter hole directly and by gradually incrementing the diameter from 2 mm to 3.5 mm and from 3.5 mm to 4.3 mm. Time gap of 30 seconds is been given for changing drill bits. These experiments again are performed at a drill speed of 1200 RPM, for 16 mm depth and at a feed rate of 0.0508 m/sec. We can see the comparisons of temperature obtained during continuous and graduated drilling in the following figure. The maximum temperature obtained by drilling a 3.5 mm diameter drill is 55 C where as the maximum temperature obtained by gradually increasing the diameter from 2 mm to 3.5 mm is about 45 C. The maximum temperature obtained by drilling a 4.3 mm hole is 70 C where as the maximum temperature obtained by increasing the diameter of the hole from 2 mm to 3.5 mm and then to 4.3 mm hole is 59 C. We can see from these experiments that the maximum temperature obtained during incremental drilling is far less than drilling a large diameter hole at a single stretch. This may be due to the time gap that is being allowed while changing the drills that allows the material to cool down and the new drill, which is being used, for drilling will be cooler to start drilling again.

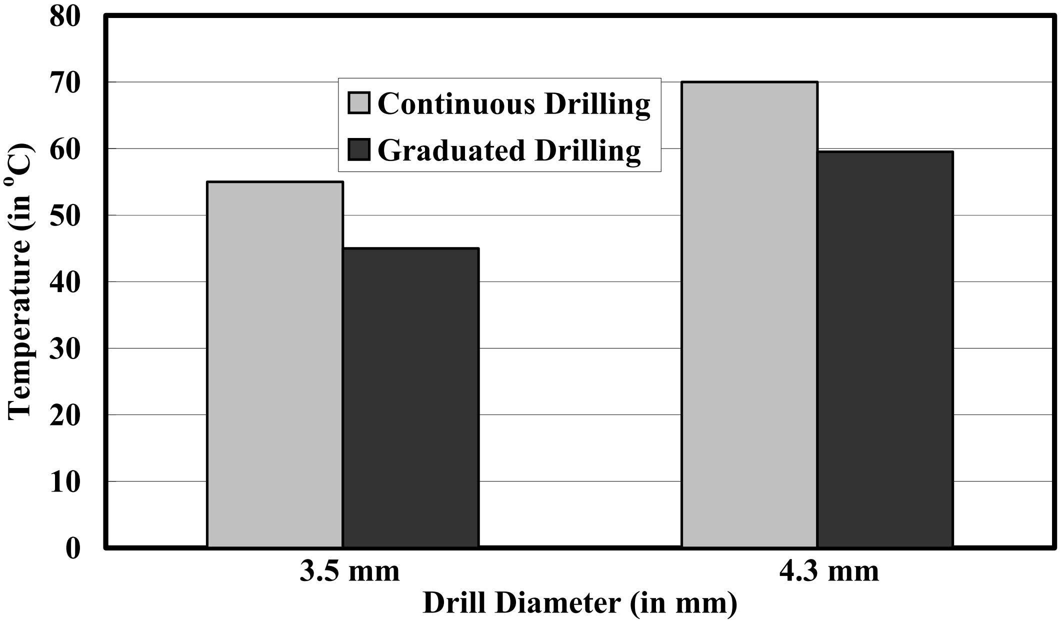

Figure 5.6: Temperatures when drilled continuously & gradually for 3.5 and 4.3 mm holes

Results obtained during the different experiments on PMMA samples help us understand how different drilling parameters can affect temperature rise during drilling operations. From the experimental results we can see that maximum temperatures obtained increases for increase in drilling speed, drilling diameter and drilling depth. Whereas the maximum temperature obtained during drilling process decreases with increase in drilling feed rate, by use of external coolant during drilling and by gradually increasing the diameter of the hole instead of drilling hole continuously. In the next section comparisons is being made between experimental and results obtained from theoretical model. It also show how the temperature rise is similar for PMMA and for human bone which can help us in interpreting the above results for predicting temperature rise in dental implant surgeries. These results would provide good information for dentists how to reduce the temperatures so that they can reduce the implant failures and also gum inflammation.

5.2 MODEL VALIDATION

Theoretical model developed in the as shown in equation (4.26) from previous chapter for predicting temperature rise during drilling process is given as follows:

$$T = T_R + \frac{k\sqrt{t\alpha_1}\, e^{\frac{a^2}{4t\alpha_1}} \left(1.775 - \sqrt{\pi} * erf\left(\frac{a}{2\sqrt{t\alpha_1}} \right) \right)}{\eta * 40 \left[\frac{\pi N^2}{150 f \sin(p)(\tan\alpha + \cot\phi)} \right]^{0.06} \left(\frac{ft(D - d_0)}{\Delta z * R * \cos(90 - p)\cos\phi} \right) a^2}$$

In this section, comparisons are made for temperature rise between human bone and PMMA theoretically, also experimental results are compared for different drilling conditions.

5.2.1 Comparison for PMMA and human bone

Temperature rise obtained from the equation is compared for PMMA and human bone by substituting thermal conductivity and thermal diffusivity values for drilling conditions of 1200

Table 5.1 Values substituted for PMMA and Bone

Properties	Bone	PMMA
Thermal conductivity (W/m K)	0.2	0.2
Thermal diffusivity (m^2/sec)	$0.3*10^{-6}$	$0.11*10^{-6}$

RPM speed, 2mm diameter drill, 16 mm depth and at a feed rate of 0.00508 m/sec. Results obtained by substituting the above values are compared in the figure 5.7. We can observe in the figure that temperature rise in human bone is pretty similar to the temperature rise as in the case of PMMA. But the maximum temperature obtained during drilling is more for Bone as compared to that of the PMMA. This rise is due to the fact that thermal diffusivity of Bone is more than that of the PMMA that is in fact due to higher density values of bone. Bone has density values of

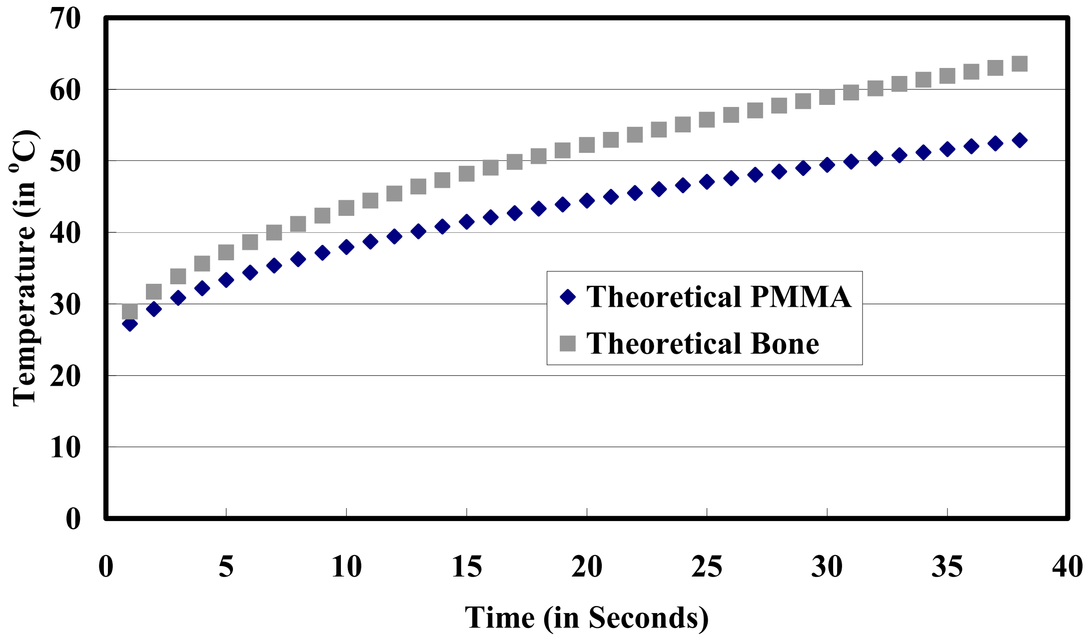

Figure 5.7 Comparison of Results for PMMA and Human bone

1800 kg/m^3 where as for PMMA it is about 1400 kg/m^3. We can see about 15 to 20% increase in final temperature for human bone as compared to that of PMMA.

5.2.2 Comparison of experimental &theoretical results for pmma

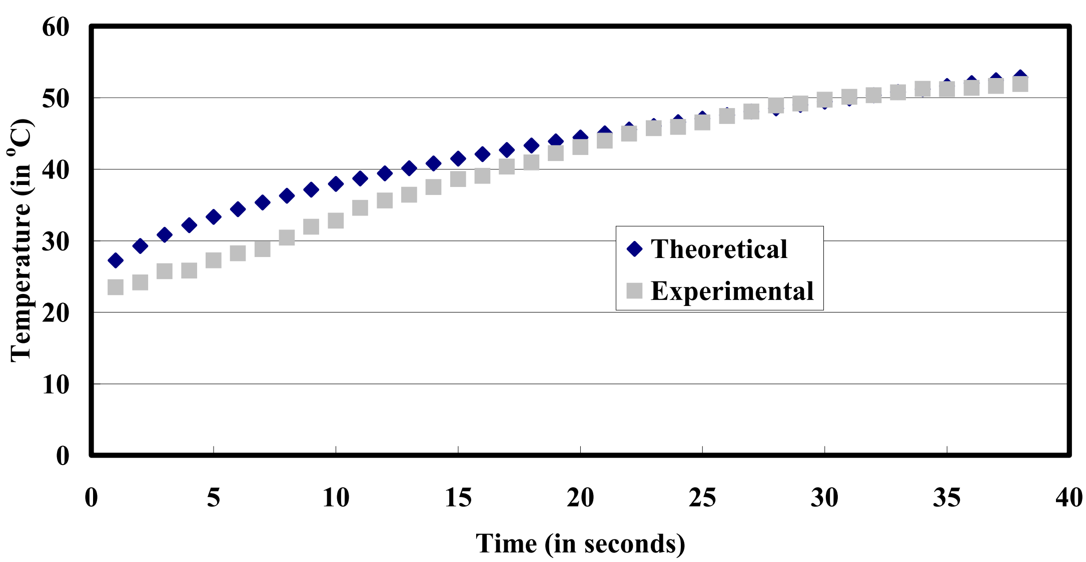

Figure 5.8: Comparison of Results from model and experiments for PMMA

The above figure shows the comparison of results obtained for PMMA from experiments and theoretical model. The experiments are performed with 2-mm diameter drill, at a feed rate of 0.00508 m/sec, speed of 1200 RPM and for drilling depth of 16-mm. Experimental results shown above are the temperatures obtained after taking average of values obtained for the three PMMA samples. We can observe that the maximum temperatures obtained by experiments and theoretically match each other.

5.2.3 Comparison for drilling parameters

Temperatures obtained from experiments for variable drilling parameters are compared with the temperatures obtained from model by substituting the drilling conditions. Following figures show comparison of temperatures obtained from model and experiments for drilling depth, feed rate and drill diameters.

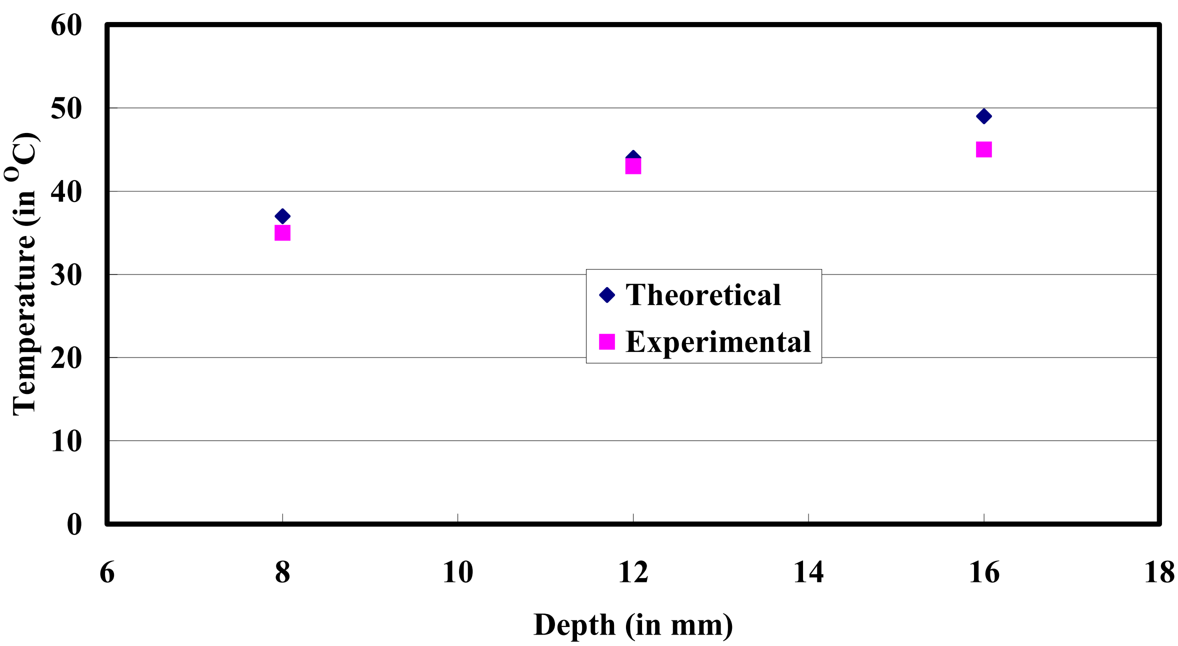

Figure 5.9: Comparisons for Drilling Depth

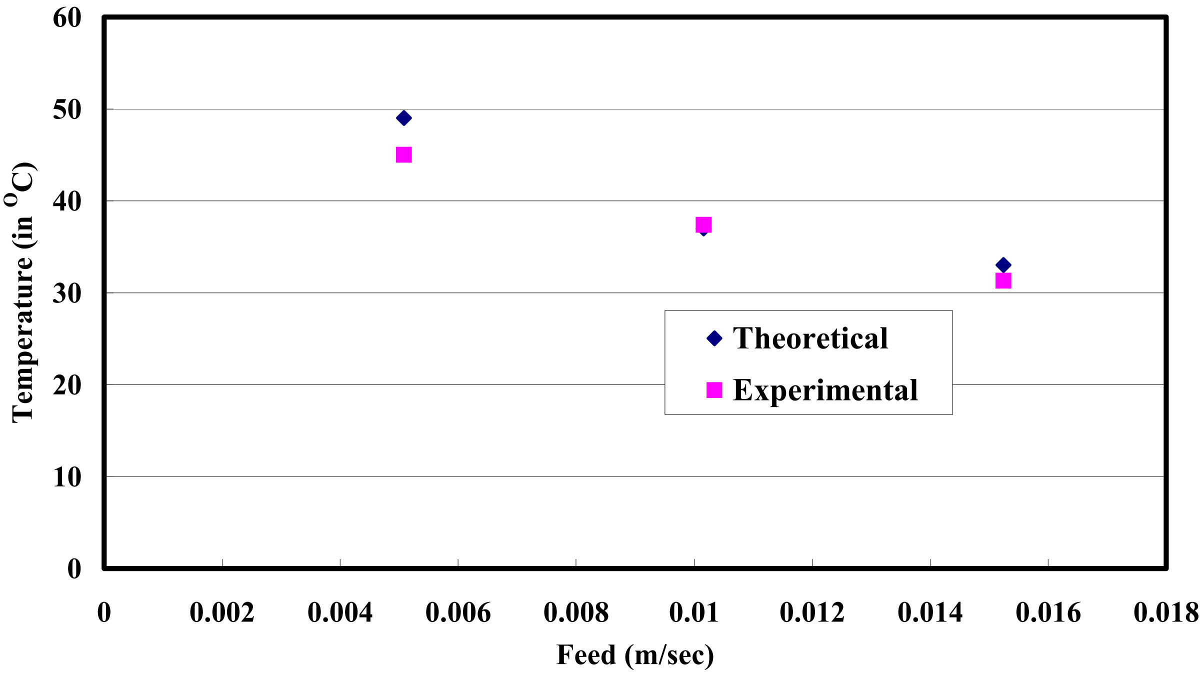

Figure 5.10: Comparison of results for Feed rates

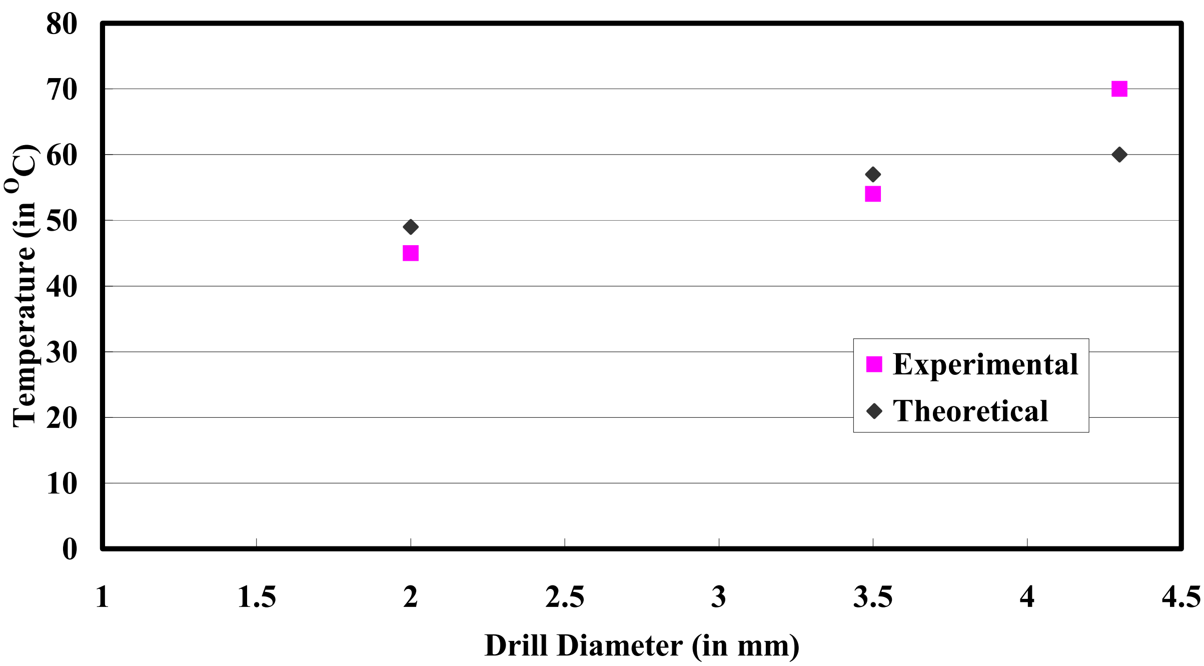

Figure 5.11: Comparison of results for drill diameter

Comparisons in these graphs show that experimental results with the temperatures obtained from thermal model for that particular drilling conditions. Similarly comparisons of temperatures for PMMA and human bone show that temperature profiles are same for both of them. The thermal model derived in the previous chapter can be used for predicting temperatures during drilling process. This equation can help makers of drills for dental implant surgery to optimize drill design resulting in lesser heat during drilling operation and also can help in reducing the amount of implant failures due to excess temperatures in Osseo integration process.

CHAPTER 6
SUMMARY AND CONCLUSIONS

6.1 SUMMARY

This study mainly concentrates on reducing the amount of temperature rise during the implant surgery procedure that results in reducing the number of failures that occur during the Osseo integration process. Earlier investigations have indicated that there are many factors, which affect the temperature rise during the drilling process. However investigators had different opinions on how these factors affect the temperature rise. Also all the observations made are reported from experimental study but they haven't explained theoretically why and how these factors affect heat generation during drilling process.

It has been found that there are many factors, which affect temperature rise during drilling process. In order to check how these factors affect temperature increase during drilling process series of experiments are carried out. Bone cement or PMMA is being considered for the experiments as replacement of human bone. In this thesis study, an attempt is made to explain theoretically in the form of equation about how the heat flux is generated during the drilling process conducts inside the bone and how it is dependent on many drilling parameters like speed, feed rate, etc. Theoretical equation developed in this study is based on two assumptions.

The assumptions can be listed as follows:

- Heat distribution in the body is in a radial direction.
- Body is considered to be semi-infinite solid.

Based upon the following assumptions temperature rise during the drilling process can be summarized as following:

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} = \frac{1}{\alpha_1}\frac{\partial T}{\partial t} \qquad \text{For} \quad a \le r < \infty$$

Where temperature T, is a function of radius r and time t. α_1 is the thermal diffusivity of the material.

Boundary conditions:

At $r = a$, $\frac{\partial T}{\partial r} = -\frac{q}{k}$ q is the constant heat flux being generated.

At $r = \infty$, $\frac{\partial T}{\partial r} = 0$ we assume heat flux is zero at infinite boundary.

Initial condition:

For $t = 0$, $T = T_R$ T_R is the room temperature.

Solution for the above problem is

$$T = T_R + \frac{k\sqrt{t\alpha_1}\, e^{\frac{a^2}{4t\alpha_1}} \left(1.775 - \sqrt{\pi} * erf\left(\frac{a}{2\sqrt{t\alpha_1}} \right) \right)}{\eta * 40 \left[\frac{\pi N^2}{150 f \sin(p)(\tan\alpha + \cot\phi)} \right]^{0.06} \left(\frac{ft(D - d_0)}{\Delta z * R * \cos(90 - p)\cos\phi} \right) a^2}$$

This final equation summarizes the reasons for temperature increase in drilling process as a function of thermal properties of the material (thermal conductivity and thermal diffusivity) and also as a function of various drilling parameters like speed, diameter, feed rate, and drilling depth.

Comparisons of temperature rise obtained by substituting experimental conditions in the above equation and from experimental results were made for PMMA. Comparisons show that the equation developed in this study can accurately predict how the temperature rise takes place during the drilling process. This can be of a great help for dentists in reducing the excess heat generation by optimizing the drilling parameters, which they will be using for performing dental surgery.

6.2 CONCLUSIONS

1. Thermal model developed in this study can help in optimizing drill design and also drilling parameters to reduce the amount of heat generated during drilling process. This can reduce the chance of dental implant failures and gum inflammation occurring in the initial process of dental implant surgery.

2. Experiments during this study show how variable drilling parameters like drilling speed, depth, bit diameter, and feed rate affect the heat generation. Graphs shown in the chapter 5 explain the trend in temperature rise or decrease as the parameters are changed. These results are also confirmed with the results obtained from theoretical model.
3. This study also suggests that the drilling process carried out step-by-step increase of diameter rather than drilling in a single step with the same drill would reduce the temperature rise thus reducing risk of death tissue.
4. Use of external coolant is also suggested for avoiding higher temperatures.
5. This study provides good information for the dentist in avoiding the drilling conditions that can lead to temperatures causing gum inflammation and death tissue.

6.3 FUTURE WORK

Experiments performed here are under in vivo conditions and are also performed on PMMA. To accurately predict the exact temperatures during dental implant surgery experiments are to be conducted on live specimen using infrared camera and these results should be compared with the temperatures obtained from the model developed in this study. Also experiments are to be performed to study the impact of internal irrigation and different coolants on temperatures produced during drilling operations. Also the model cannot predict the affect of drill sharpness on temperature rise.

APPENDIX 1
NOMENCLATURE

T	Final temperature after drilling
α_1	Thermal diffusivity of the material.
T_R	Room temperature
k	Thermal conductivity of the material.
q	Heat flux generated during drilling.
t	Time taken for drilling in sec.
N	Drill speed in R.P.M.
F	Drill feed rate in m/sec.
Δz	Height of the element where the heat flux is applied or Drilling Depth (m)
a	Radius of the hole (m).
η	Fraction of heat that enters the work piece.
D	Drill diameter (m),
d_0	Chisel edge diameter of the tool (m),
θ	Helix angle of the cutting tool,
p	Half-angle at the point.
α	Rake angle of the cutting tool.

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