ORTHOPEDIC DRILLING & THERMAL INJURY ANALYSIS

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ABSTRACT

Orthopedic Drilling & Thermal Injury Analysis

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In orthopedic surgery, fixation pins are used to provide stability of bone segments to ensure proper healing. The drilling process to implant these pins can generate a considerable amount of heat. Raising the temperature of bone tissue above 47°C for a prolonged amount of time can cause cell death in a process called thermal osteonecrosis. Should bone tissue surrounding implants like fixation pins die and begin to break-down, the stability of said implants becomes at risk for failure. The failure of a surgical implant can be costly, resulting in additional surgery for repairs and prolonged recovery time. Reducing the amount of heat generated during drilling can greatly lessen the potential for thermal injury.

This study aims to evaluate the effect of varying drilling parameters on heat generation, namely examining if internal temperatures be reduced by varying the rotational velocity and feed rate in orthopedic drilling, and thus reduce the probability of thermal osteonecrosis.

Experiments were performed comparing combinations of feed rates and spindle speeds for the drilling process parameters, specifically feed rates of 1.5, 3.0, 5.0, 9.0, and 12.0 mm/s and spindle speeds of 1000, 2000, and 3000 rpm. The tests used traditional
smooth-shaft fixation pins, with trocar tips, that were drilled into 20 PCF synthetic bone. A Flir T440 infrared camera was used to record thermal video of the drilling process.

Data acquired from the infrared camera shows that lower spindle speeds resulted in lower maximum temperatures while varying feed rates had only a moderate effect. With these results orthopedic drilling can be optimized for reduced heat generation and the prevention of thermal osteonecrosis.
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<th>Description</th>
<th>SI Units</th>
</tr>
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<tr>
<td>CEM</td>
<td>Cumulative Equivalent Minutes</td>
<td>minutes</td>
</tr>
<tr>
<td>Δt</td>
<td>Time difference</td>
<td>seconds</td>
</tr>
<tr>
<td>R</td>
<td>Temperature Dependent Rate of Cell Death</td>
<td>Dimensionless</td>
</tr>
<tr>
<td>T</td>
<td>Temperature Dependent Rate of Cell Death</td>
<td>°C</td>
</tr>
<tr>
<td>$E_{store}$</td>
<td>Energy Stored in System</td>
<td>joules</td>
</tr>
<tr>
<td>$E_{in}$</td>
<td>Energy into the System</td>
<td>joules</td>
</tr>
<tr>
<td>$E_{out}$</td>
<td>Energy out of System</td>
<td>joules</td>
</tr>
<tr>
<td>q</td>
<td>Energy Generation in System</td>
<td>watts</td>
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<tr>
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<td>W/(m·K)</td>
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<tr>
<td>ρ</td>
<td>Density</td>
<td>kg/m³</td>
</tr>
<tr>
<td>Cp</td>
<td>Specific Heat Capacity</td>
<td>J/(kg·K)</td>
</tr>
<tr>
<td>α</td>
<td>Thermal Diffusivity</td>
<td>m²/s</td>
</tr>
<tr>
<td>Ti</td>
<td>Initial Temperature</td>
<td>°C</td>
</tr>
<tr>
<td>Ts</td>
<td>Source Temperature</td>
<td>°C</td>
</tr>
<tr>
<td>h</td>
<td>Convective Heat Transfer Coefficient</td>
<td>W/(m²·K)</td>
</tr>
<tr>
<td>Δx</td>
<td>Distance Increment, planar coordinates</td>
<td>meters</td>
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<tr>
<td>Δr</td>
<td>Distance Increment, radial coordinates</td>
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CHAPTER 1 - INTRODUCTION

1.1 Background

In orthopedic surgery, “open reduction” is a technique for mending bone fractures that involves the close alignment and compression of the broken segments. This process requires a high degree of stability and precise arrangement. To this end, “internal fixation” is a system of rigid hardware that are embedded into the bone to provide the needed stability.

Bone drilling is a critical component of internal fixation. Steinmann pins (larger diameter) and Kirschner wires (smaller diameter) are drilled into bone to temporarily align and reconnect broken segments. This ensures proper mending during the healing process.

![Figure 1.1-1: Methods of internal 1.25mm Kirschner wire fixation for Bennett fracture repair: A) Transfixion of the base of the first metacarpal to the trapezium, B) Transfixion of the thumb base to the second metacarpal, C) Combination of both (modified from Fricker, Kastelec, Nuñez, & Axelrod, 2008)]
The drilling process and subsequent use of various hardware helps to ensure for a clean and reliable installation so that a bone can properly heal and quickly return to its normal function.

1.2 Problem Statement

During the drilling process, the cutting of chips and the friction of the bit against the bone tissue can generate a considerable amount of heat. Too much heat can cause bone cells to die in a process called thermal osteonecrosis. This dead bone tissue will than begin to break-down and be reabsorbed by the body. Should bone tissue surrounding implants like fixation pins and hip replacements begin to break-down, the stability of said implants becomes at risk for failure. The failure of a surgical implant can be very costly, resulting in additional surgery for repairs and prolonged recovery time.

1.3 Scope of Research

Outside of the medical world, there are a number of technologies and practices utilized for reducing the heat generated by a drill bit. This thesis seeks to find the optimal combination of spindle speed and feed rate that will produce the least amount of heat during orthopedic drilling, thus reducing the risk of thermal injury.

Using numerical models, in conjunction with infrared imaging, this study also seeks to create a new technique for predicting internal temperatures during drilling using an inverse methodology. Finally, using the results of the new inverse technique, a thermal injury analysis can be performed to predict thermal osteonecrosis.
CHAPTER 2 – LITERATURE REVIEW

2.1 Thermal Osteonecrosis

Excessive heat can have very damaging effects on bone tissue. Bone that experiences elevated temperatures can result in a loss of blood supply to the tissue. Extended periods without blood will result in tissue death (Pandey & Panda, 2013). If the temperature of bone is raised above 47°C for 60 seconds, the cells will die, a process called thermal osteonecrosis, and the bone tissue will breakdown (Eriksson, Albrektsson, & Magnusson, 1984).

Bone death and breakdown in the drill-hole could cause the hole to enlarge, resulting in a less secure hold for the pins/bits that are holding the bone together and thus improper healing/alignment, additional surgery for repairs, prolonged recovery etc.

2.2 Thermal Damage Analysis

As discussed in Section 2.1, thermal injury is found to occur when a critical temperature has been exceeded for a given amount of time. In the case of thermal osteonecrosis, the accepted threshold is 47°C for the duration of 60 seconds. However, temperatures that exceed 47°C must also be considered.

The Cumulative Equivalent Minutes (CEM) methodology is an equation that considers a given temperature and duration of exposure and produces an equivalent number of minutes at the accepted critical temperature threshold.

\[
\text{CEM}_{47} = \int_{0}^{t} R^{(47-T(\tau))} dt
\]

EQUATION 1
Where

- $\Delta t$ is the duration of exposure
- $R$ is related to the temperature dependence of rate of cell death: for temperatures below the critical value of 47°C, $R = 0.25$, and for temperatures at or above the critical value, $R = 0.5$
- $T(t)$ is the temperature of the bone at time $t$

This model considers a given thermal dose and determine how it compares to the established critical values to determine whether or not necrosis would occur (Chang, 2010) (van Rhoon, et al., 2013).

### 2.3 Heat Generation during Drilling

To create a hole, drill bits utilize a spinning wedge design to cut into and remove the material. Heat is generated from the plastic deformation of the material as it is cut away by the wedge and the friction of the tool rubbing against the material (Davidson & James, 2003).

*Fig. 2.3-1: Areas of heat generation and dissipation in the drilling process (from Davidson & James, 2003)*
As seen in Figure 2.2-1 at label “A”, as the tool edge cuts into the material, the material is sheared away and plastically deforms into the chips that are generated in drilling. Zone “A” is called the primary deformation zone in which heat is generated via the plastic deformation of the material.

Heat generated via friction can be seen at labels “B” and “C”. At zone “B”, friction from the chips against the face of the cutting tool results in some heat. Similarly, zone “C” shows heat that is generated from the friction of the cutting tool against the uncut base-material.

Due to the angle of the wedge as it cuts into the base material, there is an area behind the cutting edge where no contact is made between the tool and base material. As such, no additional heat is generated and this area, labeled zone “D” in Figure 2.2-1.

### 2.4 Heat Mitigation in Drilling – Bit Geometry

To reduce the heat generated in drilling, the geometry of the bit is an important design consideration. Heat from both friction and material deformation can be reduced through optimizing the shape of the drill bit.

![Drill Bit Terminology](image)

**Fig. 2.4-1: Drill Bit Terminology - (A) Full Length (B) Drill Point (C) Angles**
As the tool section that does the material cutting, and thus is the generator of the majority of heat, the Drill Point is a critical focus. Chacon examined the effect from varying the relief, clearance, and edge angles\(^1\) of the drill point cutting edge in specially designed bits that have a two-step design following the cutting edge.

![Diagram of a Drill Point with Two Steps of Clearance, First the Relief Angle and Then the Clearance Angle](modified.png)

**Fig. 2.4-2: Diagram of a Drill Point with Two Steps of Clearance, First the Relief Angle and Then the Clearance Angle (Modified from Chacon, Bower, Larsen, McGlumphy, & Beck, 2006)**

They found that a larger relief angle had less flank rubbing against the workpiece. It was generally found that a larger relief angle (6°-13°) and a larger clearance angle (22° – 43°) maintained drilling temperatures below 47°C, even after completing twenty-five tests with the same drill bit, when wear of the tool would usually set in and greatly reduce cutting effectiveness and increase friction (Chacon, Bower, Larsen, McGlumphy, & Beck, 2006).

\(^1\) It should be noted that in some cases the terms “edge angle”, “rake angle”, and “helix angle” are used interchangeably to mean the angle of the cutting edge face relative to the workpiece. Sometimes these terms are in fact referring to the same physical phenomenon, but that is not always the case and so will be noted accordingly.
Looking at other angels and key drill point variables, Noorazizi focused on point angle, the helix angle, and web thickness, all at different penetration angles (0°, 15°, and 30°). It was found that, second only to the thermal effects of penetration angle (discussed here in Section 2.5), the point angle was critical in keeping temperatures lower, with a point angle of 140° (Noorazizi, Izamshah, & Kasim, 2017).

![Drill Point Terminology](image)

**Fig. 2.4-3: Drill Point Terminology – (Modified from Natali, Ingle, & Dowell, 1996)**

Natali compared traditional orthopedic bits against commercial ones and found the commercial bits were less thermally damaging. They went on to show that an orthopedic bit with a drill point of 118°, a large helix angle, and a split point (or split chisel edge) was the most thermally efficient, producing the lowest temperatures (Natali, Ingle, & Dowell, 1996).

Hein also found that a commercial drill bit generated less heat than its orthopedic counterparts. They theorized that the commercial bit’s large helix angle is more efficient at clearing hot chips from the workpiece, decreasing friction, and generating less heat (Hein, Inceoglu, Juma, & Zuckerman, 2017).

Similarly, Soriano found the rake angle to be the most influential variable in preventing thermal damage to the bone. As secondary methods of reducing heat, Soriano
also concluded that narrow margin thicknesses and body thinning were effective in preventing thermal damage to the bone (Soriano, Garay, Aristimuno, & Arrazola, 2014).

Also called a back-taper, body thinning is the reduction of diameter size from the drill point backwards to the shank. The back-taper provides additional clearance between the bit and workpiece, reducing friction and heat generation.

**FIG. 2.4-4: BACK-TAPER (Saporetti, 2005)**

### 2.5 Heat Mitigation in Drilling – Drilling Practices

Equally important to heat mitigation as the geometry of the drill bit is how the surgeon uses the drill assembly. As mentioned in the previous section, Noorazizi found that more than any other parameter, the angle at which the drill bit penetrated the bone had the greatest influence on heat generation, concluding that a fixation pin drilled directly normal to the bone would result in the lowest temperature increase (Noorazizi, Izamshah, & Kasim, 2017).

In Cseke, it was found that there is a direct correlation between the duration of the drilling process and the average peak temperature reached. They concluded that a shorter duration of drilling would have a positive effect in reducing average peak temperatures. It was also noted that how the shorter drilling duration was achieved is not critical, via either increased spindle speed, increased feed rate, or even an increase in both parameters would help to reduce peak temperatures (Cseke & Heinemann, 2017).
However, while in agreement that an increased feed rate will result in lower peak temperatures, Augustin contends that increased spindle speeds will result in higher peak temperatures (Augustin, et al., 2008).

Comparatively, Matthews concludes that an increase in drilling force (also known as feed rate) results in lower average peak temperatures, and that change in spindle speed had no impact on heat generation. Matthews determines that the heat generated in drilling is due to friction, and so fewer rotations needed for a given hole would equate to a lower peak temperature. Thusly, a greater feed rate would remove more material in a single rotation and complete the whole in fewer rotations (Matthews & Hirsch, 1972).

Another possible drilling practice proposed by Matthews involves the use of an initial, smaller diameter pilot hole followed by a second drilling with the larger bit to reach the desired diameter. Matthews notes that while likely successful at limiting the amount of heat generated in a given drilling, two drillings would be inconvenient (Matthews & Hirsch, 1972).

### 2.6 Heat Mitigation in Drilling – Active Cooling Methods

A technique frequently used in other industries that utilize drilling is active cooling during the drilling process. In a thermal efficiency evaluation of drill bit design that also incorporated external irrigation, Augustin found that independent of the influences from all other drill bit variables, external irrigation kept the temperature of the bone sample below the 47°C threshold. Augustin concluded that external irrigation is the most important parameter for preventing thermal injury to bone (Augustin, et al., 2008).
In another study, Augustin looked at a new drill bit design equipped with internal cooling and irrigation. This new design contained channels for the flow of coolant through the center of the bit and out of the drill point. Again, Augustin determined that with the use of internal cooling, all other drilling parameters were insignificant for thermal influence (Augustin, et al., 2012).
## 2.7 Summary of Literature Review

<table>
<thead>
<tr>
<th>Reference</th>
<th>Research Method</th>
<th>Data Collection</th>
<th>Drill Speed (rpm)</th>
<th>Feed Rate (mm/s)</th>
<th>Drill Diameter (mm)</th>
<th>Drill Shape</th>
<th>Cooling Method</th>
<th>Drilling Depth (mm)</th>
<th>Bone Type</th>
<th>Temp Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Chacon, Bower, Larsen, McGlumphy, &amp; Beck, 2006)</td>
<td>Experimental</td>
<td>Network of thermocouples</td>
<td>2500</td>
<td>2.4 kg</td>
<td>2.0 - 4.2</td>
<td>Relief, Clearance Edge Angle</td>
<td>Saline solution bath to irrigate chips</td>
<td>n/a</td>
<td>Bovine Cortica</td>
<td>T(max)</td>
</tr>
<tr>
<td>(Hein, Inceoglu, Juma, &amp; Zuckerman, 2017)</td>
<td>Experimental</td>
<td>Network of thermocouples</td>
<td>990</td>
<td>5</td>
<td>3.97 - 4.0</td>
<td>Fluted</td>
<td>Helical</td>
<td>n/a</td>
<td>20</td>
<td>Porcine femora</td>
</tr>
<tr>
<td>(Natali, Ingle, &amp; Dowell, 1996)</td>
<td>Experimental</td>
<td>Network of thermocouples</td>
<td>800</td>
<td>Done by Hand</td>
<td>2.5</td>
<td>Fluted</td>
<td>Helical</td>
<td>n/a</td>
<td>n/a</td>
<td>Human tibiae</td>
</tr>
<tr>
<td>(Noorazizi, Izamshah, &amp; Kasim, 2017)</td>
<td>Experimental</td>
<td>Infrared Camera</td>
<td>1000</td>
<td>1.667</td>
<td>4.3</td>
<td>Fluted</td>
<td>Helical</td>
<td>n/a</td>
<td>4</td>
<td>Bovine cortical femur</td>
</tr>
<tr>
<td>(Soriano, Garay, Aristimuno, &amp; Arrazola, 2014)</td>
<td>Experimental</td>
<td>Infrared Camera</td>
<td>50-500</td>
<td>.05mm per tooth</td>
<td>5.3</td>
<td>Fluted</td>
<td>Helical</td>
<td>n/a</td>
<td>4</td>
<td>Bovine femoral diaphysis</td>
</tr>
<tr>
<td>(Cseke A, 2017)</td>
<td>Experimental</td>
<td>Network of thermocouples</td>
<td>700rpm &amp; 0.12mm/rev, 1000rpm &amp; 0.15 mm/rev, and 1500rpm &amp; 0.2mm/rev</td>
<td>3</td>
<td>Fluted</td>
<td>Helical</td>
<td>n/a</td>
<td>10</td>
<td>SawBones, Bovine &amp; Porcine Cortical</td>
<td>T(max)</td>
</tr>
<tr>
<td>(Matthews &amp; Hirsch, 1972)</td>
<td>Experimental</td>
<td>Network of thermocouples</td>
<td>345, 885, 2900</td>
<td>2, 6, 12 kg</td>
<td>3.2</td>
<td>Fluted</td>
<td>Helical</td>
<td>Manual, external irrigation</td>
<td>5</td>
<td>Human Femoral diaphysis</td>
</tr>
<tr>
<td>(Augustin, et al., 2008)</td>
<td>Experimental</td>
<td>Single thermocouple</td>
<td>188, 462, 1140, 1820</td>
<td>0.4, 0.933, 1.4, 3.266</td>
<td>2.5, 3.2, 4.5</td>
<td>Fluted</td>
<td>Helical</td>
<td>External irrigation, water</td>
<td>4 - 5</td>
<td>porcine femur diaphysis</td>
</tr>
<tr>
<td>(Augustin, et al., 2012)</td>
<td>Experimental</td>
<td>Single thermocouple</td>
<td>1.18, 10.68, 33.61, 56.55, &amp; 66.05m/min</td>
<td>0.02, 0.04, 0.10, 0.16, &amp; 0.18 mm/rev</td>
<td>3.4, 4.5</td>
<td>Fluted</td>
<td>Helical</td>
<td>Internal cooling, water</td>
<td>4 - 5</td>
<td>porcine femur diaphysis</td>
</tr>
<tr>
<td>(Davidson &amp; James, 2003)</td>
<td>Numerical</td>
<td>n/a</td>
<td>100 - 200000</td>
<td>0.45 - 4.5</td>
<td>1.0 - 3.5</td>
<td>Fluted</td>
<td>Helical</td>
<td>n/a</td>
<td>9</td>
<td></td>
</tr>
</tbody>
</table>

**Table 2.7-1: Summary of Literature Review**
CHAPTER 3 - THEORETICAL ANALYSIS & NUMERICAL MODELS

The experimental results from drilling of the synthetic bone block show the effect of varying spindle speed and feed rate on maximum temperatures at the surface of the sample. However, this only shows the temperature at the exterior of the sample where temperature is the lowest due limited thermal diffusion through the material and convection of heat away to ambient. The highest temperature in the bone will occur internally next to the drill hole where friction occurs and heat is generated. To find the maximum internal temperature of the sample, a computer model can be created that mimics experimental setup and produces the same result.

To begin, we can apply the Law of Conservation of Energy to a closed system:

\[ E_{\text{store}} = E_{\text{in}} - E_{\text{out}} + q \]

Where:
- \( E_{\text{store}} \) = rate of energy storage in the system
- \( E_{\text{in}} \) = rate of energy entering the system
- \( E_{\text{out}} \) = rate of energy leaving the system
- \( q \) = rate of energy generation within the system

In the case of drilling, there is no heat generation within the closed system being evaluated and so the energy generation term can be dropped, leaving:

\[ E_{\text{store}} = E_{\text{in}} - E_{\text{out}} \]

Equation 2
For small increments of drilling in the $z$-direction, the drilling and heating process occur much more quickly than the rate of thermal diffusion. For this reason, the present numerical model can be accurately described with a one dimensional approximation where heat diffuses in a single direction from the drill hole to the external surface of the sample. We must also select a suitable coordinate system to apply to Equation 2. For an initial calculation, the case of a one dimensional problem in planar coordinates will be reviewed.

3.1 Finite-Difference Method - 1D Planar Model with Constant Temperature Heat Source

The general equation for heat diffusion is:

$$\dot{q} = \rho c_p \frac{\partial T}{\partial t} - \nabla \cdot (k \nabla T)$$  \hspace{1cm} \text{EQUATION 3}
Where:

- $\dot{q}$ = Energy Generation in System, watts
- $\rho$ = Density, kg/m$^3$
- $C_p$ = Specific Heat Capacity, J/(kg-K)
- $T$ = Temperature, °C
- $t$ = Time, seconds
- $\kappa$ = Thermal Conductivity, W/(m-K)

Figure 3.1-1 depicts the internal nodes of the established system. Conduction is the mode of heat transfer between nodes.

**Fig. 3.1-1: Schematic of One Dimensional FDM Heat Diffusion for Internal Nodes, Conduction (Modified from (Bergman, Lavine, Incropera, & Dewitt))**

For an initial approximation, this equation can be simplified by assuming a constant-temperature heat source at the drill hole. Thus, when there is zero heat generation, Equation 3 becomes:
\[ \rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) \]  

**Equation 4**

To solve this differential equation, the Finite-Difference Method (FDM) is a useful numerical approximation. As such, Equation 4 can be rewritten to approximate the temperature in the x-direction at intervals between the constant source temperature at the drill hole and ambient temperature at the block surface:

\[ \rho c_p \Delta x \left( T_{m+1}^{P} - T_{m}^{P} \right) = \frac{k(T_{m+1}^{P} - T_{m}^{P})}{\Delta x} + \frac{k(T_{m-1}^{P} - T_{m}^{P})}{\Delta x} \]  

**Equation 5**

Rearranging variables and solving Equation 5 for the unknown temperature at an interior node “m” and time step “P+1”:

\[ T_{m}^{P+1} = \left( \frac{\Delta t + k}{\rho c_p \Delta x^2} \right) (T_{m+1}^{P} - T_{m}^{P}) + \left( \frac{\Delta t + k}{\rho c_p \Delta x^2} \right) (T_{m-1}^{P} - T_{m}^{P}) + T_{m}^{P} \]  

**Equation 6**

Equation 6 can also be written as:

\[ T_{m}^{P+1} = F_o * (T_{m+1}^{P} - T_{m}^{P}) + F_o * (T_{m-1}^{P} - T_{m}^{P}) + T_{m}^{P} \]

And after rearranging terms:

\[ T_{m}^{P+1} = F_o * (T_{m+1}^{P} + T_{m-1}^{P}) + (1 - 2 * F_o) * T_{m}^{P} \]  

**Equation 7**
Equation 7 is an explicit method to finding the unknown temperature. As such, the stability criterion of the explicit method requires that the coefficient in front of the 
\( T_m \) term in Equation 7 always be greater than zero. To this end, Equation 7 makes use of the Fourier number, Fo, a dimensionless parameter that describes transient heat conduction by combining the physical properties of the subject material with the parameters of the numerical model, namely \( \Delta t \) and \( \Delta r \), the time and space discretizations. The Fourier number is defined as:

\[
Fo = \left( \frac{\Delta t \times k}{\rho c_p \Delta x^2} \right)
\]

For Equation 7 to remain stable, the Fourier number must be below 0.5. As such, it is evident that care must be taken when selecting the \( \Delta t \) and \( \Delta r \) for this problem. A time step of 0.5 seconds and a length discretization of 0.001 meters were selected and give a Fourier number of 0.055. These values for \( \Delta t \) and \( \Delta r \) also keep the number of calculations low and are granular enough to provide accurate data. Smaller values for the time and length steps were tested without any significant change in the results.

Equation 7 is applicable to interior nodes where heat diffuses through the block from one node to the next via conduction. At the surface of the block, convection becomes the primary form of heat transfer to the surrounding environment. Figure 3.1-2 depicts heat transfer at the surface of the system. Convection is the mode of heat transfer external nodes.
FIG. 3.1-2: SCHEMATIC OF ONE DIMENSIONAL FDM HEAT DIFFUSION FOR EXTERNAL NODES, CONVECTION (MODIFIED FROM (BERGMAN, LAVINE, INCROPERA, & DEWITT))

Taking into consideration this convective heat transfer, the equation for temperature at the external surface node “M”, at time step “P+1” is:

\[ T_{M}^{P+1} = \left( \frac{2h\Delta t}{\rho c_p \Delta x} \right) (T_\infty - T_{m}^{P}) + \left( \frac{2k\Delta t}{\rho c_p \Delta x^2} \right) (T_{M-1}^{P} - T_{M}^{P}) + T_{M}^{P} \]  

**EQUATION 8**

Where “h” is the Convective Heat Transfer Coefficient, measured in W/(m²-K).

Equation 8 can be written as:

\[ T_{M}^{P+1} = (2 \ast Fo \ast Bi) (T_\infty - T_{m}^{P}) + (2 \ast Fo \ast Bi) (T_{M-1}^{P} - T_{M}^{P}) + T_{M}^{P} \]

Or:

\[ T_{M}^{P+1} = (2 \ast Fo) (T_{M-1}^{P} + Bi \ast T_\infty) + (1 - 2 \ast Fo - 2 \ast Fo \ast Bi) T_{M}^{P} \]  

**EQUATION 9**
Equation 9 is also an explicit method to finding the unknown temperature at the surface node. Again, the stability criterion requires that the coefficient in front of the \( T_m^P \) term in Equation 9 always be greater than zero. Equation 9 makes use of the Fourier number and introduces another dimensionless parameter called the Biot number, \( \text{Bi} \), defined as:

\[
\text{Bi} = \left( \frac{h \Delta x}{\kappa} \right)
\]

The Biot number is a relation of convection to conduction in heat transfer. A small Biot number indicates that convective heat transfer is small compared to the rate of heat transfer via conduction.

With equations 7 and 9, we can create a model that uses the properties of the artificial bone to simulate heat diffusion from the drill hole to the surface of the block as a function of the source-temperature.

The synthetic bone is made of polyurethane foam (P.U.F.). Table 3.1-1 below summarizes the material properties for polyurethane foam, as well as other parameters relevant for the numerical model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Conductivity</td>
<td>( K )</td>
<td>W/(m·K)</td>
<td>0.052</td>
</tr>
<tr>
<td>Density</td>
<td>( \rho )</td>
<td>kg/m³</td>
<td>320</td>
</tr>
<tr>
<td>Specific Heat Capacity</td>
<td>( C_p )</td>
<td>J/(kg·K)</td>
<td>1477</td>
</tr>
<tr>
<td>Thermal Diffusivity</td>
<td>( \alpha )</td>
<td>m²/s</td>
<td>1.1002E-07</td>
</tr>
<tr>
<td>Initial Temperature</td>
<td>( T_i )</td>
<td>°C</td>
<td>23</td>
</tr>
<tr>
<td>Source Temperature</td>
<td>( T_s )</td>
<td>°C</td>
<td>73.5</td>
</tr>
<tr>
<td>Convective Heat Transfer Coefficient</td>
<td>( h )</td>
<td>W/(m²·K)</td>
<td>10</td>
</tr>
<tr>
<td>Time Step</td>
<td>( \Delta t )</td>
<td>seconds</td>
<td>0.5</td>
</tr>
<tr>
<td>Distance Step</td>
<td>( \Delta r )</td>
<td>meters</td>
<td>0.001</td>
</tr>
<tr>
<td>Fourier Number</td>
<td>( F_o )</td>
<td>-</td>
<td>0.055</td>
</tr>
<tr>
<td>Biot Number</td>
<td>( \text{Bi} )</td>
<td>-</td>
<td>0.192</td>
</tr>
</tbody>
</table>

**Table 3.1-1: One Dimensional Model of Synthetic Bone – Material & System Properties**
A convective heat transfer value of $10^\text{W/(m}^2\text{ * K)}$ was selected to replicate free convection of air from the surface of the block. The ambient temperature was set to average room temperature.

Assume the sample is initially at ambient temperature, 23°C, and experiences a constant heat source of 73.5°C. This generates the temperature versus time profile seen in Figure 3.1-1.

![1D Planar, Constant Temperature Source](image)

**Fig. 3.1-3: Transient, One Dimensional Planar Heat Diffusion: Source-Temp = 73.5 °C**

In Figure 3.1-2, each curve represents the temperature profile at a particular node, with the node at 5 mm being the surface node that experiences convection. Represented by the pink line, the maximum temperature at this surface node after 60 seconds is 36°C.
By adjusting the source-temperature to achieve a desired temperature at the surface node, this model can be used inversely to find the maximum internal temperature of a given experimental trial. In the above case, the surface temperature of 36°C was targeted to validate the results of Trial #1 of the experimental drilling. After a few adjustments, 73.5°C was found to be the maximum internal temperature at the drill hole that produced 36°C at the surface node.

The thermal penetration depth is the distance into the material at which the temperature has increased significantly. We use the below equation to define a significant increase in temperature:

\[
\left( \frac{T(t) - T_s}{T_i - T_s} \right) = 90\% \tag{Equation 10}
\]

Where

- \(T(t)\) is the temperature at time “t”,
- \(T_s\) is the source-temperature in the drill hole (73.5°C), and
- \(T_i\) is the initial temperature of the material (23°C)

For our one dimensional planar case, this temperature is 28.05°C. Using our FDM model, we can select a depth into the material and measure at what timestamp that location reached 28.05°C. Table 3.1-2 presents these results.
A exact solution for the thermal penetration depth is also available. For a one-dimensional semi-infinite medium, the equation for thermal penetration depth is:

$$
\Delta \delta = 2.3\sqrt{\alpha t}
$$

**Equation 11**

Where "\( \alpha \)" is the thermal diffusivity, in \( \text{m}^2/\text{s} \), of the material, defined as:

$$
\alpha = \frac{\kappa}{\rho c_p}
$$

**Equation 12**

Using equation 9 and the timestamps measured in Table 3.1-2, the thermal penetration depths for the exact solution can be found.

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Exact Thermal Penetration Depth (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.763</td>
</tr>
<tr>
<td>6</td>
<td>1.869</td>
</tr>
<tr>
<td>14.5</td>
<td>2.905</td>
</tr>
<tr>
<td>24.5</td>
<td>3.776</td>
</tr>
<tr>
<td>31</td>
<td>4.248</td>
</tr>
</tbody>
</table>

**Table 3.1-3 Thermal Penetration Depth for Exact Solution**
Figure 3.1-4 summarizes the results of the thermal penetration depth comparison.

We can see that the FDM model matches well with the Exact solution.

![Thermal Penetration Depth, Numerical vs. Analytical](image)

**FIG. 3.1-4: THERMAL PENETRATION DEPTH, NUMERICAL VS. ANALYTICAL**

However, while a useful way to demonstrate the transfer of heat, the planar model only shows how heat diffuses in a single direction. This is not indicative of drilling operations, where heat will diffuse out radially from the drill hole. To make our model more accurate we must create a model of heat diffusing in the radial direction.

### 3.2 Finite-Difference Method - 1D Radial Model with Constant Temperature Heat Source

To create a one dimensional model with radial heat diffusion to better simulate drilling of the synthetic bone block, we must convert Equation 5 into radial coordinates:
\[ \rho c_p (r_\Delta r 2\pi) \frac{T_{m+1} - T_m}{\Delta t} = \frac{k(r_i + \frac{\Delta r}{2})2\pi(T_{m+1} - T_m)}{\Delta r} + \frac{k(r_i - \frac{\Delta r}{2})2\pi(T_{m-1} - T_m)}{\Delta r} \] 

EQUATION 13

Rearranging variables and solving Equation 13 for the unknown temperature at an interior node “m” and time step “P+1”:

\[ T_{m+1}^P = T_m^P + \left( \frac{\Delta t + k}{\rho c_p \Delta r^2} \right) \left( \frac{r_i + \frac{\Delta r}{2}}{r_i} (T_{m+1}^P - T_m^P) + \frac{r_i - \frac{\Delta r}{2}}{r_i} (T_{m-1}^P - T_m^P) \right) \] 

EQUATION 14

Equation 14 written in dimensionless form:

\[ T_{m+1}^P = T_m^P + F_O \left( \frac{r_i + \frac{\Delta r}{2}}{r_i} (T_{m+1}^P - T_m^P) + \frac{r_i - \frac{\Delta r}{2}}{r_i} (T_{m-1}^P - T_m^P) \right) \] 

EQUATION 15

Equation 15 is applicable to interior nodes where heat diffuses through the block from one node to the next via conduction. At the surface of the block, convection becomes the primary form of heat transfer to the surrounding environment. Taking into consideration this convective heat transfer, the equation for temperature at the external surface node “M”, at time step “P+1” is:

\[ T_{M+1}^P = T_M^P + \left( \frac{2\Delta t}{\rho c_p \Delta r^2} \right) \left( \frac{r_i}{r_i - \frac{\Delta r}{2}} (T_{\infty} - T_M^P) \right) + \left( \frac{2k\Delta t}{\rho c_p \Delta r^2} \right) \left( \frac{r_i - \frac{\Delta r}{2}}{r_i - \frac{\Delta r}{4}} (T_{M-1}^P - T_M^P) \right) \] 

EQUATION 16

Equation 16 written in dimensionless form:
\[ T_{M}^{P+1} = T_{M}^{P} + (2 \times Fo \times Bi) \left( \frac{r_{i}}{(r_{i} - \frac{\Delta r}{4})} (T_{\infty} - T_{M}^{P}) \right) + (2 \times Fo) \left( \frac{r_{i}}{(r_{i} - \frac{\Delta r}{4})} (T_{M-1}^{P} - T_{M}^{P}) \right) \text{ \textbf{Equation 17}} \]

Using equations 15 and 17, and the same material properties from Table 3.1-1, we can create a second constant source-temperature model for heat diffusion in the radial direction. The results of this radial model are presented below in Figure 3.2-1.

**Fig. 3.2-1:** Transient, 1D Radial Heat Diffusion: Source-Temperature = 73.5°C

For validation of these results, a three dimensional model was created in SolidWorks. With the SolidWorks Simulation tool, a 3D approximation of the constant temperature heat source model was constructed using the same boundary conditions as those in the one dimensional radial model. Table 3.2-1 provides the temperature
measurements at set distances from the drill hole in each model after 60 seconds of diffusion.

<table>
<thead>
<tr>
<th>Distance from Drill Hole (mm)</th>
<th>3D SolidWorks Model (°C)</th>
<th>1D FDM Model (°C)</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>73.5</td>
<td>73.5</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>55.2</td>
<td>54.63</td>
<td>1.04%</td>
</tr>
<tr>
<td>2</td>
<td>44.2</td>
<td>42.53</td>
<td>3.85%</td>
</tr>
<tr>
<td>3</td>
<td>36.4</td>
<td>35.42</td>
<td>2.72%</td>
</tr>
<tr>
<td>4</td>
<td>32.2</td>
<td>31.90</td>
<td>0.92%</td>
</tr>
<tr>
<td>4.75</td>
<td>30.3</td>
<td>30.89</td>
<td>1.92%</td>
</tr>
</tbody>
</table>

**Table 3.2-1 Temperature, 60 seconds of diffusion: 3D CAD vs. 1D FDM**

As can be seen in above, with a maximum percent difference between the two models of only 3.85%, our radial one dimensional FDM model has strong reliability to a 3D model of the same boundary conditions.

For comparison to the planar model, the source-temperature for the radial was set to 73.5°C. After 60 seconds the temperature at the surface node reached 30.9°C. This surface node temperature is 5.1°C lower than the planar case with the same source temperature, supporting the expectation that heat diffuses more quickly in the radial direction.

Additionally, comparing the temperature profile for the 1mm node between the planar and radial models, we can see that the curve in the planar model increases in temperature more rapidly, indicating slower heat diffusion.
Unfortunately, the constant source-temperature models presented here in sections 3.1 and 3.2 are not indicative of how heat is actually generated during the drilling process. In cases where the feed rate is lower, the drilling process will last longer and thus generate heat for a long amount of time. Conversely, for higher feed rates the drilling process will finish more quickly and generate heat for a shorter period of time. In each of these cases the rate of heat generation is a considerable factor.

While our initial assumption in Equation 3 of a constant-temperature heat source and zero heat generation made for a simpler equation, it does not sufficiently describe our system. In this case, the appropriate tool to model the drilling process is a heat flux boundary condition at the drill hole.
3.3 Finite-Difference Method - 1D Radial Model with Time Dependent Heat Flux

To create a one dimensional radial model with heat flux source to simulate drilling of artificial bone, we return to Equation 3:

$$\dot{q} = \rho c_p \frac{\partial T}{\partial t} - \nabla \cdot (k \nabla T)$$  \hspace{1cm} \text{Equation 3}

The volumetric heat generation term, $\dot{q}_V$, can also be written as:

$$\dot{q}_V = q''(2\pi r_i \Delta z)$$  \hspace{1cm} \text{EQUATION 18}

Where:

- $q''$ is the input heat flux
- $r_i$ is the diameter of the drill hole
- $\Delta z$ is the distance drilled, 31.75 mm

Adding the volumetric heat generation term to Equation 3 and applying the Finite Difference Method:

$$\rho c_p (r_i \Delta r 2\pi) \frac{T_m^{P+1} - T_m^P}{\Delta t} = k \left( \frac{r_i + \Delta r}{2} \right) \frac{2\pi (r_{m+1}^P - r_m^P)}{\Delta r} + q''(2\pi r_i)$$  \hspace{1cm} \text{EQUATION 19}

Solving Equation 19 for the unknown temperature:

$$T_m^{P+1} = T_m^P + \frac{q''r_i + \left( \frac{\Delta r^2}{r_i} \right) + \left( \frac{r_i + \Delta r}{2} \right) (r_{m+1}^P - r_m^P)}{\rho c_p \left( \frac{r_i + \Delta r}{2} \right)^2}$$  \hspace{1cm} \text{EQUATION 20}
Equation 20 is the applicable at the first node where there is a heat flux source. Similar to the one dimension radial FDM model in Section 3.2, interior nodes can be described using Equation 15, for radial conduction through medium, and Equation 17 for the surface node, where convection transfers heat from the surface to ambient. Using Equations 15, 17, and 20, and the parameters from Table 3.1-1, we can generate a one dimension radial FDM model with a time dependent heat flux as the source.

Referring again to Trial #1, a feed rate of 1.5 millimeters per second over the distance of the block height, 31.75 millimeters, will result in a drilling time of roughly 21.5 seconds. As such, our model will apply a heat flux at the drill hole for 21.5 seconds, after which the input heat flux will turn off. Figure 3.3-1 presents the results of this simulation.

**Fig. 3.3-1: Transient, 1D Radial Heat Diffusion; Heat Flux = 3675 W/m²**
Just as before, by adjusting the heat flux source to achieve the desired temperature at the surface node, this model can be used inversely to find the internal temperature profile. From Trial #1, a surface temperature of 36°C was targeted. The source heat flux was applied for 21.5 seconds, after which the heat flux was reduced to zero and the residual heat diffused to the surface for the remaining 38.5 seconds. After a few adjustments, 3675 W/m² was found to be the required heat flux at the drill hole to produce 36°C at the surface node. For a drill hole of 1.6 millimeters in radius and 31.75 millimeters in depth, this heat flux equates to a total of 1.173 watts of energy generated during the drilling process of Trial #1. Table 3.3-1 below summarizes the required heat flux in each trial and the resulting energy generated during drilling.

<table>
<thead>
<tr>
<th>Trial #</th>
<th>q&quot; (w/m²)</th>
<th>q (w)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3,675</td>
<td>1.173</td>
</tr>
<tr>
<td>2</td>
<td>4,150</td>
<td>1.325</td>
</tr>
<tr>
<td>3</td>
<td>9,100</td>
<td>2.905</td>
</tr>
<tr>
<td>4</td>
<td>12,750</td>
<td>4.070</td>
</tr>
<tr>
<td>5</td>
<td>14,500</td>
<td>4.628</td>
</tr>
<tr>
<td>6</td>
<td>3,650</td>
<td>1.165</td>
</tr>
<tr>
<td>7</td>
<td>5,450</td>
<td>1.740</td>
</tr>
<tr>
<td>8</td>
<td>10,750</td>
<td>3.431</td>
</tr>
<tr>
<td>9</td>
<td>17,900</td>
<td>5.713</td>
</tr>
<tr>
<td>10</td>
<td>29,500</td>
<td>9.416</td>
</tr>
<tr>
<td>11</td>
<td>4,825</td>
<td>1.540</td>
</tr>
<tr>
<td>12</td>
<td>7,550</td>
<td>2.410</td>
</tr>
<tr>
<td>13</td>
<td>13,300</td>
<td>4.245</td>
</tr>
<tr>
<td>14</td>
<td>25,000</td>
<td>7.980</td>
</tr>
<tr>
<td>15</td>
<td>33,500</td>
<td>10.693</td>
</tr>
</tbody>
</table>

**Table 3.3-1: Heat Flux and Total Energy Generated in Drilling**
Comparing two of the established FDM models, the radial model with heat flux versus the planar model with constant temperature heat source, the temperature at node r=0 in Figure 3.3-1 reaches a maximum temperature of 116.4°C, which is 42.9°C higher than the maximum temperature for the same location in the planar model. However, at the surface node (r=4.75 mm), the temperature profiles for the two models are very similar to one another, as seen in Figure 3.3-2.

![Surface Node Temperature Comparison](image)

**FIG. 3.3-2: SURFACE NODE TEMPERATURE COMPARISON: RADIAL WITH HEAT FLUX VS. PLANAR WITH CONSTANT TEMPERATURE**

With surface node temperature profiles that are nearly identical, but internal maximum temperatures that differ by as much as 43°C, it is evident that modeling the heat source correctly is critical for creating an accurate simulation. As such, we will now examine modeling the heat source as a moving heat flux in a two dimensional radial model, analogous to a fixation pin being drilled into the artificial bone block.
3.4 Sensitivity Analysis

When performing a numerical analysis, it is important to evaluate the influence of each given independent variable upon the dependent variable. In this case our independent variables are: the source temperature, the thermal conductivity of the material, the convection coefficient at the surface boundary, the material’s density, and the specific heat capacity of the material. The dependent variable is the temperature of the surface node after sixty seconds of diffusion.

Unless otherwise noted, all sensitivity analysis calculations were performed using the material properties of synthetic bone and under the following conditions:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source Temperature, $T_s$</td>
<td>°C</td>
<td>73.5</td>
</tr>
<tr>
<td>Thermal Conductivity, $K$</td>
<td>w/(m·K)</td>
<td>0.052</td>
</tr>
<tr>
<td>Convection Coefficient, $h$</td>
<td>w/(m²·K)</td>
<td>10</td>
</tr>
<tr>
<td>Density, $\rho$</td>
<td>(kg/m³)</td>
<td>320</td>
</tr>
<tr>
<td>Specific Heat Capacity, $c_p$</td>
<td>J/(kg·K)</td>
<td>1477</td>
</tr>
</tbody>
</table>

Table 3.4-1: Sensitivity Analysis Model Parameters

3.4.1 Temperature Source

In the one dimensional models created in sections 3.1 and 3.2, a constant source temperature was used at the first node and how the heat diffused through the material was observed. To evaluate the influence of source temperature, $T_s$, on the model, Figure XYZ contains three curves of the resulting surface temperature for three different starting values:

- 73.5 °C, the lowest source temperature observed in Trial #1
98 °C, the median temperature of the trials

123 °C, the maximum source temperature observed in Trial #15

**Fig. 3.4.1-1: Sensitivity Analysis - Temperature Source Variance**

As expected, increased source temperatures results in increased temperatures at the model’s surface node.

**3.4.2 Thermal Conductivity**

How efficiently heat diffuses through a material will have a major influence on the maximum temperatures seen. As such, the following model evaluates three different thermal conductivities: 0.05, 0.1, and 0.15 w/(m-K).
In curve number three, the temperature at the model’s surface node was considerably higher even though it experienced the same source temperature of 73.5 °C. This is because the higher thermal conductivity means the material is much more efficient at diffusing heat and thus its surface node will have more heat conducted to it over the same diffusion time period.

**3.4.3 Convective Heat Transfer Coefficient**

Similar to the thermal conductivity, how efficiently heat is removed from the surface node will also have a major influence on the temperature at the source node. In this test, the three values of convection coefficient evaluated were:

- 10 w/(m^2-K), to simulate convection to low flow, ambient air
- 100 w/(m^2-K), to simulate convection to moderate flow, ambient air

![Figure 3.4.2-1: Sensitivity Analysis – Source Temperature Variance](image-url)
500 w/(m^2-K), to simulate water cooling at the surface node

As is expected, the curve with the largest convection coefficient experienced the greatest amount of heat removal via convection, and thus saw the smallest increase in temperature at the surface node.

### 3.4.4 Density

To assess the impact of density on our model, multiples of polyurethane foam’s density were evaluated, namely: 320, 640, and 960 kg/m^3.
As can be seen in Figure 3.5.4-1, as the density of the material increased, the temperature at the surface node decreased. This is because as density increases, and all other parameters remain constant, the material’s thermal diffusivity, $\alpha$, will decrease. A ratio of thermal conductivity over thermal storage ability, a decreasing thermal diffusivity means that the material will store thermal energy more instead of conducting heat through the material. This is why the second and third surface node temperature curves are so much lower than the first; the heat has not yet diffused through to the surface.

### 3.4.5 Specific Heat Capacity

Specific heat capacity, $C_p$, indicates a material’s ability to store thermal energy relative to its mass and temperature. For this sensitivity analysis, the following values of $C_p$ were used: 1477, 2000, and 2500 J/(kg*K).
Similar to effects seen with increasing density, increasing the specific heat capacity of a material will also result in a decreased thermal diffusivity. Referring to Figure 3.4.5-1, we can see that as the specific heat capacity increased in the second and third curves, less thermal energy was conducted away from the heat source to the surface node. The first curve, however, had a lower specific heat capacity and thus more thermal energy was able to diffuse to the surface node, increasing its temperature over time.

**Fig. 3.4.5-1: Sensitivity Analysis - Specific Heat Capacity Variance**
CHAPTER 4 - EXPERIMENTAL APPARATUS & PROCEDURE

4.1 Experimental Methods

To evaluate the influence of spindle speed and feed rate on heat generation, experiments were performed comparing combinations of the two parameters, specifically feed rates of 1.5, 3.0, 5.0, 9.0, and 12.0 mm/s and spindle speeds of 1000, 2000, and 3000 rpm. The bits used in testing are traditional Steinmann pins used in orthopedic surgery. They had a smooth shaft with a pyramidal point, called a Trocar tip, and were 3.2 millimeters in diameter.

![Traditional Smooth-shaft Steinmann Pin with Trocar Tip](image)

To mimic the properties of human bone, a synthetic bone material was procured, called SawBones, composed of 20 PCF solid rigid polyurethane foam (P.U.F.). Each sample had a 1.25 inch x 1.25 inch square cross-section with a circular void space, 0.63 inches in diameter.
Drilling was performed at a depth of 0.25 inches from the face of the synthetic bone block to accommodate the 3.2 mm pin diameter. Other depths closer to the face were tested, but these resulted in cracking of the bore hole and failure of the material. A distance of 0.25 inches from the face provided the right balance between maintaining the structural integrity of the drill hole, as well as limiting the distance the heat must diffuse from the drill hole to the face of the material for measurement by the infrared camera.

To prevent potential thermal contamination during drilling, two additions were made to the drilling set up. The first is a plug that blocks hot chips and the drill bit from being picked up by the infrared camera as the pin passes out of the first cortex and through the void space. This plug fits into the void space of the synthetic bone block while allowing drilling to still be performed.

**Fig. 4.1-2: Diagram of Synthetic Bone Block**
The second is a thermal shield that fits around the block. The shield frames the block in the infrared camera and prevents contamination from the spray of hot chips as the pin first makes contact with the block at the surface.

The Thermal Shield is made from aluminum sheet-metal, and so was also covered in a layer of tape to eliminate the aluminum’s reflectivity that would otherwise skew the infrared recordings, as can be seen Figure 4.1-4. Figure 4.1-5 shows the final assembly.
of the P.U.F. block with void space plug and thermal shield installed and ready for drilling.

![Image of bone block assembly](image)

**FIG. 4.1-5: FINAL SYNTHETIC BONE BLOCK ASSEMBLY FOR DRILLING**

For the drilling process, a CNC router was utilized. A programmed CNC router ensures accurate drilling with precise repeatability of procedure execution between tests. A strobe-light tachometer was used to validate the spindle speed of each set of trials.

Upon completion of drilling, the CNC router was programed to immediately stop at the bottom of the hole without withdrawing the bit. This most accurately mimics the orthopedic drilling of Steinmann pins since these fixation pins are being embedded into the bone, not drilling a hole that could then be cooled via convection of a fluid (blood, air, etc.) through the hole.

For data acquisition, a Flir T440 infrared camera was used to record thermal video of the drilling process. The Flir T440 is a long-wavelength camera, detecting infrared light in the range of 7 – 13.5 microns. It has a thermal sensitivity of 0.045°C at 30°C.
All thermal videos were recorded at a rate of thirty hertz to ensure accurate capture of temperature change.

The camera has a graphics display resolution of 320x240 pixels, where each pixel is embedded with infrared information. At a rate of thirty hertz, and with each frame containing 320x240 pixels of infrared information, the thermal recordings generate a considerable amount of data. As such, the infrared camera must be connected to a computer running the proprietary Flir ResearchIR software.

Following completion of the drilling, the ResearchIR software has a number of tools that enable thorough and comprehensive analysis of the thermal video. Primary among these tools is a feature that enables post-experiment calibration for emissivity and proximity. In this case, polyurethane foam was found to have an emissivity of 0.87 and all recordings were taken at a distance of 15 cm from the sample.

**Figure 4.1-6: Experimental Schematic**

Figure 4.1-6 shows an overview of the experimental set-up.
4.1.1 Thermography & Surface Emissivity

A critical parameter for proper calibration of infrared images, surface emissivity is a measure of a material’s efficiency at emitting energy as thermal radiation. Emissivity is calculated as the ratio of the energy radiated by a material at a given temperature, divided by the energy radiated by an ideal blackbody at the same temperature. For example, human skin as a very good emitter of thermal radiation and so has a high emissivity of 0.98. A highly polished and reflective mirror, on the other hand, has an emissivity of less than 0.1.

In many cases the surface emissivity of a material can be found in material data sheets. For the synthetic bone blocks used in these experiments however, polyurethane foam is a less common material and a calibration test was performed to find its surface emissivity.

1. Finding Reflected Apparent Temperature
   a. The reflected apparent temperature was found to account for possible ambient light reflecting from the surface of the polyurethane foam.
   b. The camera was calibrated to an emissivity of 1.0. This enables the camera to sense any possible light from the surface as thermal radiation.
   c. The reflected apparent temperature was found to be 23.2 °C
   d. It should be noted that for all trials shades placed around the drilling site were used to limit the level of ambient light during drilling.

2. Finding Emissivity
a. A sample of black electrical tape, with a known emissivity value of 0.97, was placed halfway over the face of the P.U.F. block, leaving half of the face exposed.

b. Next, this same surface was warmed to a high temperature, roughly 70 °C, using a hot plate.

c. With the camera calibrated to the 0.97 emissivity of the black electrical tape, a surface temperature reading was taken for the tape.

d. With this temperature in mind, a second reading was measured for the polyurethane foam. Due to the difference in emissivity between the two surfaces, black electrical tape and polyurethane foam, the temperature reading for the polyurethane foam was much lower.

e. As such, the emissivity of the camera was adjusted until the temperature of the polyurethane foam matched the previously recorded temperature of the black electrical tape.

f. This operation was repeated four times the below table presents each of these results.

<table>
<thead>
<tr>
<th>Test</th>
<th>Emissivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test #1</td>
<td>0.89</td>
</tr>
<tr>
<td>Test #2</td>
<td>0.86</td>
</tr>
<tr>
<td>Test #3</td>
<td>0.91</td>
</tr>
<tr>
<td>Test #4</td>
<td>0.83</td>
</tr>
<tr>
<td>Average</td>
<td>0.8725</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>0.0303</td>
</tr>
</tbody>
</table>

**Table 4.1.1-1 Emissivity Calibration Results**
With these results, the polyurethane foam used in this experiment’s drilling operations has an emissivity of 0.87.

### 4.2 Experimental Schedule

The parameters tested in these experiments were rotational velocity and feed rate. Considering the data from previous studies, as seen in Section 2.6, a broad range of values were selected for evaluation. Table 4.3-1 compiles all of the parameters according the trial.

<table>
<thead>
<tr>
<th>Trial</th>
<th>Bit Diameter (mm)</th>
<th>Speed (rpm)</th>
<th>Feed Rate (mm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.2</td>
<td>1050 ±0.21</td>
<td>1.5 ±0.11</td>
</tr>
<tr>
<td>2</td>
<td>3.2</td>
<td>1050 ±0.21</td>
<td>3.0 ±0.10</td>
</tr>
<tr>
<td>3</td>
<td>3.2</td>
<td>1050 ±0.21</td>
<td>5.0 ±0.37</td>
</tr>
<tr>
<td>4</td>
<td>3.2</td>
<td>1050 ±0.21</td>
<td>9.0 ±0.96</td>
</tr>
<tr>
<td>5</td>
<td>3.2</td>
<td>1050 ±0.21</td>
<td>12.0 ±0.7</td>
</tr>
<tr>
<td>6</td>
<td>3.2</td>
<td>2040 ±0.408</td>
<td>1.5 ±0.11</td>
</tr>
<tr>
<td>7</td>
<td>3.2</td>
<td>2040 ±0.408</td>
<td>3.0 ±0.10</td>
</tr>
<tr>
<td>8</td>
<td>3.2</td>
<td>2040 ±0.408</td>
<td>5.0 ±0.37</td>
</tr>
<tr>
<td>9</td>
<td>3.2</td>
<td>2040 ±0.408</td>
<td>9.0 ±0.96</td>
</tr>
<tr>
<td>10</td>
<td>3.2</td>
<td>2040 ±0.408</td>
<td>12.0 ±0.7</td>
</tr>
<tr>
<td>11</td>
<td>3.2</td>
<td>3070 ±0.614</td>
<td>1.5 ±0.11</td>
</tr>
<tr>
<td>12</td>
<td>3.2</td>
<td>3070 ±0.614</td>
<td>3.0 ±0.10</td>
</tr>
<tr>
<td>13</td>
<td>3.2</td>
<td>3070 ±0.614</td>
<td>5.0 ±0.37</td>
</tr>
<tr>
<td>14</td>
<td>3.2</td>
<td>3070 ±0.614</td>
<td>9.0 ±0.96</td>
</tr>
<tr>
<td>15</td>
<td>3.2</td>
<td>3070 ±0.614</td>
<td>12.0 ±0.7</td>
</tr>
</tbody>
</table>

**Table 4.2-1 Trial Schedule**

To ensure reliable data, the CNC router’s accuracy is critical. The spindle speed was validated using a strobe-light tachometer and the feed rate was checked using a stopwatch and drilling over a known distance.
4.3 Experimental Procedure

The process for each trial was performed in three phases. The first phase was the start-up of the CNC router. After powering on the machine, the program specific to these trials was uploaded to the CNC router’s computer. Using a collet wrench the fixation pin was installed into the appropriately sized collet, making note of the bit’s length after installation to ensure proper zeroing of the pin tip relative to the drilling program.

To prepare the P.U.F. block, the void space plug must be pushed into the void space of the block, taking care that it is sufficiently embedded to prevent chips from blowing out, but also without interfering with the travel of the drill bit. Double-faced tape ensures that the block is adequately secured to the CNC router platform. Using the laser guide on the router-head, the drill hole location was set on the top surface of the P.U.F. block, offset from the corner by 0.625 inches lengthwise and 0.25 inches offset from the face. Figure 4.3-1 provides a diagram of the drill hole location.

![Diagram of Drill Hole Location on Top Face](image)

**Fig. 4.3-1: Diagram of Drill Hole Location on Top Face**
Next, the thermal shield was placed around the block with adequate clearance for the drill collet. Additional shielding was placed around the sample to ensure that no pollution from external sources of infrared light.

Phase two of the experiment pertains to the start-up of the infrared camera. After powering on the Flir T440 camera, a USB cable was used to connect it to the computer. Flir’s ResearchIR software was opened and the camera was installed so all input can be viewed on the computer monitor.

With the camera properly installed on its tripod and placed 15 centimeters from the P.U.F. block, the camera’s control toggle was used to focusing the image, ensuring a clear resolution and thus accurate data.

The final phase of the experiment was drilling of the sample. First, the camera was started recording, followed shortly by execution computer program to begin drilling. The router drilled through sample at the preordained spindle speed and velocity, stopping precisely one millimeter from the bottom of the block. The camera continued to record for a total time of sixty seconds as heat from the drill hole diffused to the face of the block.
4.4 Drilling Process Time-Lapse

The thermal shielding and void space plug are very important components to the P.U.F. block assembly that enable accurate data recording and reliable results. As a result, they also preclude viewing the drilling process as it happens. As such, Figure 4.4-1 is a time-lapse of the drilling process with the removal of the thermal shielding and void space plug. Each image indicates the elapsed time, depth drilled, and general point in the drilling process.
**Table 4.4-1: Time Lapse Of Drilling Process Without Thermal Shielding**
In image A of Table 4.4-1, the drill bit has just begun rotating and will soon start traveling downward to the synthetic bone block. In image B, the bit has made contact with the surface of the synthetic bone and commenced drilling. The bright yellow surrounding the point of contact between the bit and synthetic bone surface is due to hot chips produced during drilling. These hot chips are not representative of internal temperatures and serve only to obfuscate the drilling recording with thermal pollution, proving the necessity of a thermal shield.

In images C and D, the drill bit has cut through the first cortex of the synthetic bone and passes through the void space. Hot chips can also be seen here spraying out of the drill hole, followed by the heated tip of the bit. These images demonstrate the necessity for the void space plug to prevent contamination of data. Image E shows the bit it first cuts into the second cortex, again producing hot chips at the juncture point.

In image F, the drilling process has end and the bit stops rotating. Images G and H were taken at set time intervals after the bit stopped rotating, 5 seconds and 10 seconds respectively, and show how the heat inside the drill hole diffuses to the surface.
CHAPTER 5 - RESULTS & DISCUSSION

For analysis of the infrared drilling videos, temperature measurements were taken at four primary locations on the face of the synthetic bone block:

- Position 1 indicates the temperature of the bone at the initial entrance of the pin into the bone,
- Position 2 measures the temperature as the pin exits the first cortex,
- Position 3 is for the temperature of the bone as the pin enters the second cortex,
- Position 4 measures the temperature of the bone at the bottom of the second cortex, where the tip of the pin comes to rest after drilling ends.

![Schematic of Synthetic Bone Block with Locations of Temperature Measurement]

**FIG. 5-1: SCHEMATIC OF SYNTHETIC BONE BLOCK WITH LOCATIONS OF TEMPERATURE MEASUREMENT**

This method allows for the comparison of temperature at an established point between different sets of testing criteria. For instance, we can now evaluate the temperature profile over time at Position 2 for Trial #3 (1050 rpm & 5.0 mm/s) versus...
Trial #12 (3070 rpm & 3.0 mm/s). These location specific temperature plots will be referred to as “Four-Point Temperature Plots”.

In addition, “Maximum Temperature Plots” will display the maximum temperature seen on the surface of the block over time. In most cases these two plots of data match up well. However, there are a few instances where temporary spikes are seen when hot chips from the drilling process flash across the camera’s field of view.

5.1 Drilling at Low Rotational Velocity, $\omega = 1050$ rpm

The following sections contain the “Four-Point Temperature Plot” and the “Maximum Temperature Plot” for each of Trials 1 through 5, which were all performed at 1050 rpms. For each of the following “Four-point Temperature Plots,” the alphabetical labels mean the following:

- Point A: the drill bit first makes contact with the surface of the block
- Point B: the drill bit has exited the first cortex of the block and begins moving through the void space
- Point C: the drill bit has entered the second cortex
- Point D: the drill bit has come to a stop

5.1.1 Trial #1: $\omega = 1050$ rpm & $V = 1.5$ mm/s

Looking at Figure 5.1.1-1, we can see that there is little change in temperature for the curves of Positions 1 and 2 until well after Point B, when the bit has exited the first cortex. After this, the Positions 1 and 2 curves climb as the bit enters the second cortex
and they continue to increase until shortly after Point D when the bit has stopped rotating and thus no more friction occurs. Following Point D the Position 1 and 2 curves level off.

**FIG. 5.1.1-1: FOUR-POINT TEMPERATURE PLOT: TRIAL #1, 1050 RPM AND 1.5 MM/S**

In a similar but more exaggerated display, the curves for Positions 3 and 4 also see little temperature change until Point C when the drill bit enters the second cortex. Here, Position 3 begins to slowly increase in temperature while Position 4 stays level. This is because the drill bit is already quite hot from having drilled through the first cortex and thus Position 3 will increase in temperature more quickly than Position 4. As the drill bit hits Point D, the drilling process comes to a stop and there is no more heat generation. After Point D though, both the Position 3 and the Position 4 curves see a
large increase in temperature as the heat that was previously generated diffuses to the surface and in sight of the infrared camera.

In Figure 5.1.1-2, the Maximum Temperature Plot for Trial #1, the temperature curve matches well with the maximum points for each of the four positions curves seen in Figure 5.1.1-1. However, there is a large spike at the 12 second mark that differs greatly from Figure 5.1.1-1. This is due to a hot chip generated during drilling that quickly flashes across the camera’s field of view. Aberrations aside, the peak temperature experienced in Trial #1 was 36.0 °C.

**Fig. 5.1.1-2: Max Temperature Plot: Trial #1, 1050 rpm and 1.5 mm/s**
5.1.2 Trial #2: $\omega = 1050$ rpm & $V = 3.0$ mm/s

In Trial #2, Figure 5.1.2-1 shows that across all four curves there is no temperature change until after Point D when the drilling process has ended. The curves for Position 1 and Position 2 show a small increase in temperature for the remainder of the recording as heat generated while drilling the first cortex diffuses to the surface.

The Position 3 and Position 4 curves both show a comparably larger increase in temperature as the drill bit was already hot from drilling the first cortex. Position 3 sees a larger temperature increase than Position 4 because Position 4 is at the bottom of the sample and experienced less friction from drilling.

![Graph showing temperature changes for different positions](image)

**Fig. 5.1.2-1: Four-point Temperature Plot: Trial #2, 1050 rpm and 3.0 mm/s**
In Figure 5.1.2-2, the Maximum Temperature Plot for Trial #2, the temperature curve matches very well with the maximum points for each of the four positions curves seen in Figure 5.1.2-1. The peak temperature experienced in Trial #2 was 31.8 °C.

![Figure 5.1.2-2: Max Temperature Plot: Trial #2, 1050 rpm and 3.0 mm/s](image)

**5.1.3 Trial #3: $\omega = 1050$ rpm & $V = 5.0$ mm/s**

In Figure 5.1.3-1, the curve of Position 3 is the first to show a temperature increase, occurring right after Point C when the drill bit entered the second cortex. This large temperature increase at Position 3 is due to a combination of a pre-heated drill bit from the first cortex, and from friction via drilling into the second cortex.
Positions 1, 2, and 4 did not show any increase in temperature until after Point D, when drilling has finished. For the Position 4 curve, this is again due to the limited amount of friction that is experienced with the conclusion of drilling near Position 4. For the curves of Positions 1 and 2, the larger feed rate of 5.0 mm/s results in faster drilling of the block, meaning fewer total rotations of the drill bit and thus less friction.

**FIG. 5.1.3-1: FOUR-POINT TEMPERATURE PLOT: TRIAL #3, 1050 RPM AND 5.0 MM/S**

In Figure 5.1.3-2, the maximum temperature curve matches well with the four-point temperature plot in Figure 5.1.3-1, but hot chips again caused a large temperature spike at the 7 second mark. Discounting the spike due to the hot chips, the maximum temperature experienced in Trial #3 was 33.1 °C.
5.1.3-2: **Max Temperature Plot: Trial #3, 1050 rpm and 5.0 mm/s**

5.1.4 **Trial #4: \( \omega = 1050 \) rpm & \( V = 9.0 \) mm/s**

Similar to the trend seen in Figure 5.1.3-1, the temperature curves in Figure 5.1.4-1 show that Position 3 experiences the earliest and largest increase in temperature. The Position 4 curve follows a similar arc soon after Position 3. Positions 1 and 2 show only a slight increase in temperature.
Fig. 5.1.4-1: Four-point Temperature Plot: Trial #4, 1050 rpm and 9.0 mm/s
The maximum temperature plot in Figure 5.1.4-2 closely matches the four-point temperature plot in Figure 5.1.4-1. The maximum temperature experienced in Trial #4 was 32.0 °C.

**FIG. 5.1.4-2: MAX TEMPERATURE PLOT: TRIAL #4, 1050 RPM AND 9.0 MM/S**
5.1.5 Trial #5: $\omega = 1050$ rpm & $V = 12.0$ mm/s

For Trial #5, Figure 5.1.5-1 shows that the Position 3 curve was the earliest and largest increase in temperature, Position 4 follows a similar arc soon after Position 3, and Positions 1 and 2 show only a slight increase in temperature.

**FIG. 5.1.5-1: Four-point Temperature Plot: Trial #5, 1050 rpm and 12.0 mm/s**
Figure 5.1.5-2 shows that the maximum temperature experienced in Trial #5 was 29.9 °C.

**Fig. 5.1.5-2: Max Temperature Plot: Trial #5, 1050 rpm and 12.0 mm/s**
5.2 Drilling at Moderate Rotational Velocity, $\omega = 2040$ rpm

The following sections contain the “Four-Point Temperature Plot” and the “Maximum Temperature Plot” for each of Trials 6 through 10, which were all performed at 2040 rpms.

For each of the “Four-point Temperature Plots,” the drill bit first makes contact with the surface of the synthetic bone block at Point A. At Point B, the drill bit has exited the first cortex of the block and is moving through the void space. Point C indicates when the drill bit has entered the second cortex, and at Point D the drill bit has come to a stop.

5.2.1 Trial #6: $\omega = 2040$ rpm & $V = 1.5$ mm/s

For Trial #6, Figure 5.2.1-1 shows that there is no change in temperature until after Point B when the drill bit has exited the first cortex. As the drill bit crosses the void space from cortex one to cortex two, the curves of Positions 1 and 2 begin to rise in temperature. In addition, the temperature at Position 3 also begins to increase at this time, even though the drill bit has not yet begun to cut into the material of the second cortex. It is theorized that hot chips from drilling of the first cortex fell and landed on the surface of the second cortex, heating the surface prior to drilling.

Once drilling of the second cortex begins at Point C, the temperature curves of Positions 3 and 4 increases steeply as heat diffuses from the drill hole to the surface of the sample.
The maximum temperature plot in Figure 5.2.1-2 deviates moderately from the four-point temperature plot during the 11 second to 19.5 second mark. This indicates a location of higher maximum temperature in the first cortex that is not aligned with Positions 1 or 2. For the remainder of the recording however, the two plots are in agreement and show a maximum temperature of 37.1 °C.
**FIG. 5.2.1-2: MAX TEMPERATURE PLOT: TRIAL #6, 2040 RPM AND 1.5 MM/S**
5.2.2 Trial #7: $\omega = 2040 \text{ rpm} \& V = 3.0 \text{ mm/s}$

Figure 5.2.2-1 shows zero change in temperature until after Point D, when the drilling process has ended. Approximately 4 seconds after Point D, each of the four Position curves begins to increase in temperature as heat generated during drilling diffuses to the surface: the curves for Position 1 and Position 2 show a small increase in temperature, while the Position 3 and Position 4 curves both show a comparably larger increase in temperature.
Figure 5.2.2-1 shows that the maximum temperature experienced in Trial #7 was 34.6 °C.

**Fig. 5.2.2-2: Max Temperature Plot: Trial #7, 2040 rpm and 3.0 mm/s**
5.2.3 Trial #8: \( \omega = 2040 \text{ rpm} \) & \( V = 5.0 \text{ mm/s} \)

In Figure 5.2.3-1, the curve of Position 3 is the first to show a temperature increase, occurring right after Point C when the drill bit entered the second cortex. This large temperature increase at Position 3 is due to a combination of a pre-heated drill bit from the first cortex, and from friction via drilling into the second cortex.

Positions 1, 2, and 4 did not show any increase in temperature until after Point D, when drilling has finished. For the Position 4 curve, this is again due to the limited amount of friction that is experienced with the conclusion of drilling near Position 4. For the curves of Positions 1 and 2, the larger feed rate of 5.0 mm/s results in faster drilling of the block, meaning fewer total rotations of the drill bit and thus less friction.

![Four-point temperature plot: Trial #8, 2040 rpm and 5.0 mm/s](image)

**Fig. 5.2.3-1: Four-point Temperature Plot: Trial #8, 2040 rpm and 5.0 mm/s**
The maximum temperature plot in Figure 5.2.3-2 deviates some from the four-point temperature plot during the 7 second to 22 second mark. This indicates a location of higher maximum temperature in the first cortex that is not aligned with Positions 1 or 2. For the remainder of the recording however, the two plots are in agreement and show a maximum temperature of 36.0 °C.

FIG. 5.2.3-2: MAX TEMPERATURE PLOT: TRIAL #8, 2040 RPM AND 5.0 MM/S
5.2.4 Trial #9: $\omega = 2040 \text{ rpm} & V = 9.0 \text{ mm/s}$

Similar to the results seen in Trial #8, Figure 5.2.4-1 shows zero change in temperature until after Point D, when the drilling process has ended. The Position 3 curve was the earliest and largest increase in temperature, Position 4 follows a similar arc soon after Position 3, and Positions 1 and 2 show only a slight increase in temperature.

![Four-point temperature plot: Trial #9, 2040 rpm and 9.0 mm/s](image)

**Fig. 5.2.4-1: Four-point Temperature Plot: Trial #9, 2040 rpm and 9.0 mm/s**
The maximum temperature plot in Figure 5.2.4-2 deviates some from the four-point temperature plot during the 6.5 second to 20 second mark. This indicates a location of higher maximum temperature in the first cortex that is not aligned with Positions 1 or 2. For the remainder of the recording however, the two plots are in agreement and show a maximum temperature of 35.5 °C.

**Fig. 5.2.4-2: Max Temperature Plot: Trial #9, 2040 rpm and 9.0 mm/s**
5.2.5 Trial #10: $\omega = 2040$ rpm & $V = 12.0$ mm/s

Figure 5.2.5-1 shows zero change in temperature until after Point D, when the drilling process has ended. Approximately 4 seconds after Point D, each of the four Position curves begins to increase in temperature as heat generated during drilling diffuses to the surface: the curves for Position 1 and Position 2 show a moderate increase in temperature, while the Position 3 and Position 4 curves both show a comparably larger increase in temperature.

**FIG. 5.2.5-1: FOUR-POINT TEMPERATURE PLOT: TRAIL #10, 2040 RPM AND 12.0 MM/S**
The maximum temperature plot in Figure 5.2.5-2 indicates a maximum temperature of 36.9 °C.

**FIG. 5.2.5-2: MAX TEMPERATURE PLOT: TRIAL #10, 2040 RPM AND 12.0 MM/s**
5.3 Drilling at High Rotational Velocity, ω = 3070 rpm

The following sections contain the “Four-Point Temperature Plot” and the “Maximum Temperature Plot” for each of Trials 11 through 15, which were all performed at 3070 rpms.

For each of the “Four-point Temperature Plots,” the drill bit first makes contact with the surface of the synthetic bone block at Point A. At Point B, the drill bit has exited the first cortex of the block and is moving through the void space. Point C indicates when the drill bit has entered the second cortex, and at Point D the drill bit has come to a stop.

5.3.1 Trial #11: ω = 3070 rpm & V = 1.5 mm/s

For Trial #11, Figure 5.3.1-1 shows no change in temperature until after Point B when the drill bit has exited the first cortex. While the drill bit crosses the void space from cortex one to cortex two, the heat generated at Positions 1 and 2 begins to reach the surface of the synthetic bone block. In addition, the temperature at Position 3 also begins to increase at this time, even though the drill bit has not yet begun to cut into the material of the second cortex. As previously stated for Trial #6, it is theorized that hot chips from drilling of the first cortex fell and landed on the surface of the second cortex, heating the surface prior to drilling.

Once drilling of the second cortex begins at Point C, the temperature curves of Positions 3 and 4 increases steeply as heat diffuses from the drill hole to the surface of the sample.
FIG. 5.3.1-1: FOUR-POINT TEMPERATURE PLOT: TRIAL #11, 3070 RPM AND 1.5 MM/S
The maximum temperature plot in Figure 5.3.1-2 indicates a maximum temperature of 40.1 °C.

**Fig. 5.3.1-2: Max Temperature Plot: Trial #11, 3070 rpm and 1.5 mm/s**
5.3.2 Trial #12: $\omega = 3070$ rpm & $V = 3.0$ mm/s

In Figure 5.3.2-1, there is little change in temperature for Positions 1 and 2 until after the bit has exited the first cortex. Just prior to Point C, when the drill bit enters into the second cortex, temperatures at Positions 1 and 2 begin to increase and continue until shortly after Point D when the bit has stopped rotating and thus no more friction occurs. Following Point D the Position 1 and 2 curves level off.

Similarly, the curves for Positions 3 and 4 experience little temperature change until Point D when the drill bit has reached its maximum depth and comes to a stop. Here, Positions 3 and 4 begin to increase in temperature, with Position 3 increasing more quickly. As the drill bit hits Point D, the drilling process comes to a stop and there is no more heat generation. Both the Position 3 and 4 curves see a large increase in temperature as the heat that was previously generated diffuses to the surface and in sight of the infrared camera.
**FIG. 5.3.2-1: FOUR-POINT TEMPERATURE PLOT: TRIAL #12, 3070 RPM AND 3.0 MM/S**
The maximum temperature plot in Figure 5.3.2-2 indicates a maximum temperature of 38.6 °C.

**FIG. 5.3.2-2: MAX TEMPERATURE PLOT: TRIAL #12, 3070 RPM AND 3.0 MM/S**
5.3.3 Trial #13: \( \omega = 3070 \text{ rpm} \& V = 5.0 \text{ mm/s} \)

Figure 5.3.3-1 shows very similar trends to the results in Trial #12, but with greater temperatures due to the increased feed rate and thus faster drilling process.

**Fig. 5.3.3-1:** **Four-point Temperature Plot: Trial #13, 3070 rpm and 5.0 mm/s**
The maximum temperature plot in Figure 5.3.3-2 indicates a maximum temperature of 40.2 °C.

**Fig. 5.3.3-2: Max Temperature Plot: Trial #13, 3070 rpm and 5.0 mm/s**
5.3.4 Trial #14: $\omega = 3070$ rpm & V = 9.0 mm/s

For Trial #14, Figure 5.3.4-1 shows that temperatures maintain level until after Point D, when the drilling process has ended. The high feed rate results in a shorter drilling process, such that heat diffuses to the surface nearly simultaneously for each Position curve. The Position 3 curve shows the largest increase in temperature, with Position 4 following almost exactly the same trend, and Positions 1 and 2 showing slightly lower increases in temperature.

![Temperature Plot: Trial #14, 3070 rpm and 9.0 mm/s](image)

**FIG. 5.3.4-1: FOUR-POINT TEMPERATURE PLOT: TRIAL #14, 3070 RPM AND 9.0 MM/S**
The maximum temperature plot in Figure 5.3.4-2 indicates a maximum temperature of 40.1 °C.

**FIG. 5.3.4-2: MAX TEMPERATURE PLOT: TRIAL #14, 3070 RPM AND 9.0MM/S**
5.3.5 Trial #15: $\omega = 3070$ rpm & $V = 12.0$ mm/s

Figure 5.3.5-1 shows that Trial #15 had very similar results to Trial #14, with no temperature change until after Point D, when heat diffuses to the surface almost simultaneously for each Position curve. The high feed rate of 12 mm/s results a rapid drilling of the sample and thus near uniform heat generation through the entire depth of the drill hole.

FIG. 5.3.5-1: FOUR-POINT TEMPERATURE PLOT: TRIAL #15, 3070 RPM AND 12.0 MM/S
In Figure 5.3.5-2, hot chips again caused a temperature spike around the 5 second mark. The maximum temperature for Trial #15 was 40.9 °C.

**FIG. 5.3.5-2: MAX TEMPERATURE PLOT: TRIAL #15, 3070 RPM AND 12.0MM/S**
5.4 Experimental Results Summary

Table 5.4-1 below summarizes the maximum temperatures at the surface of the synthetic bone block for each combination of spindle speed and feed rate. In addition, the ambient temperature at each trial is indicated. This allows us to normalize the maximum temperatures relative to the initial of the block to show increase in temperature from drilling.

<table>
<thead>
<tr>
<th>Feed Rate (mm/s)</th>
<th>1050 rpm</th>
<th></th>
<th>2040 rpm</th>
<th></th>
<th>3070 rpm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Max. Temp. (°C)</td>
<td>Ambient Temp. (°C)</td>
<td>Δ (°C)</td>
<td>Max. Temp. (°C)</td>
<td>Ambient Temp. (°C)</td>
</tr>
<tr>
<td>1.5</td>
<td>36.0</td>
<td>24.0</td>
<td>12.0</td>
<td>37.1</td>
<td>25.2</td>
</tr>
<tr>
<td>3.0</td>
<td>31.8</td>
<td>24.6</td>
<td>7.2</td>
<td>34.6</td>
<td>25.1</td>
</tr>
<tr>
<td>5.0</td>
<td>33.1</td>
<td>23.6</td>
<td>9.5</td>
<td>36.0</td>
<td>24.8</td>
</tr>
<tr>
<td>9.0</td>
<td>32.0</td>
<td>24.8</td>
<td>7.2</td>
<td>35.5</td>
<td>25.4</td>
</tr>
<tr>
<td>12.0</td>
<td>29.9</td>
<td>24.0</td>
<td>5.9</td>
<td>36.9</td>
<td>25.0</td>
</tr>
</tbody>
</table>

**Table 5.4-1 Peak Temperature on synthetic bone surface for each Trial**
Figure 5.4-1 below presents the maximum temperature for each spindle speed at varying feed rates.

![Diagram showing maximum surface temperature for each spindle speed at the respective feed rates]

**Fig. 5.4-1: Maximum surface temperature for each spindle speed at the respective feed rates**

Taking into account the initial temperature of the synthetic bone block, Figure 5.4-2 presents the increase in temperature for each of the trials performed.
While slightly different graphs from one another, both Figure 5.4-1 and Figure 5.4-2 show that increasing spindle speed will result in higher maximum temperatures for each of the five feed rates. While direct comparisons with results from literature are not possible due to differences in important parameters, these results show qualitative trends that are reflected in other studies. Using a newly devised numerical model, Davidson and James concluded that the maximum temperatures seen in orthopedic drilling increased directly with increasing spindle speed (Davidson & James, 2003). The model created by Lee, Rabin, and Ozdoganlar also showed that increasing spindle speed resulted in increased maximum temperatures during drilling.

When evaluating the effect of feed rate on maximum temperature, the results from these experiments are less definitive. Figures 5.4-1 and 5.4-2 show mostly stagnant temperature change relative to feed rate, with a small decreasing trend in temperature.
with as feed rate increases. Davidson and James showed that while increasing the feed rate up to 1.8 mm/s caused an increase in maximum temperatures, feed rates above 1.8 mm/s resulted in a general flattening of the maximum temperature, with some slight decreases (Davidson & James, 2003). While the feed rates used in the experiments for this thesis never went below 1.5 mm/s, and so direct comparison with Davidson and James is not possible, the feed rates examined did show a similarly small effect on maximum temperature, with occasional decreases. A clear answer on feed rate cannot be drawn from these results.

5.5 Experimental vs. Numerical Analysis

To test the validity of the numerical analysis, the model’s results can be compared against the real-world data from experiment. Measuring the time it takes for thermal energy to diffuse from the beginning of the drilling process to the surface of the synthetic bone provides a time delay for heat diffusion, which can be compared between the two systems. Figure 5.5-1 shows the time delay for heat diffusion from Trial #1 of experiment.
Table 5.4-2 evaluates three trials and compares the time delay for heat diffusion between the experimental results and the one dimension radial model with a heat flux source. The three trials chosen for this comparison, trials #1, #9, and #15, were selected because they cover the broadest range in maximum temperature, and thus the broadest range in heat generated during drilling.

<table>
<thead>
<tr>
<th>Trial</th>
<th>$q$ (w)</th>
<th>Experimental Time Delay (s)</th>
<th>Numerical Model Time Delay (s)</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.173</td>
<td>10.25</td>
<td>10.00</td>
<td>2.50%</td>
</tr>
<tr>
<td>9</td>
<td>5.713</td>
<td>7.19</td>
<td>7.50</td>
<td>4.16%</td>
</tr>
<tr>
<td>15</td>
<td>10.693</td>
<td>6.91</td>
<td>7.00</td>
<td>1.31%</td>
</tr>
</tbody>
</table>

**Table 5.5-1: Time Delay Comparison - Experimental vs. Numerical**
As seen in Table 5.4-2, there is close agreement between the two systems with a maximum difference in time delay of 4.16%. With this degree of confidence in the numerical model, further analysis can be made.

Combining the maximum surface temperatures from experiment with the one dimensional radial model with a heat flux source, an inverse approach for estimating the maximum internal temperature due to drilling is created. With the spindle speed constant at 1050 rpm, Figure 5.5-2 shows the maximum temperature in the synthetic bone block as a function of the feed rate of the drill bit. Each curve corresponds to a set distance from the drill hole, as indicated in the legend.

![Graph](image_url)

**Fig. 5.5-2: Maximum Temperature vs. Feed Rate: 1050 rpm**

As can be seen, with the exception of the zero millimeter mark, the temperature profiles remain relatively flat as feed rate increases. This is a trend that continues at the
higher spindle speeds. Figure 5.5-3 corresponds to a constant spindle speed of 2040 rpm and Figure 5.5-4 to a constant spindle speed of 3070 rpm.

**Fig. 5.5-3: Maximum Temperature vs. Feed Rate: 2040 rpm**

**Fig. 5.5-4: Maximum Temperature vs. Feed Rate: 3070 rpm**
Similarly, to show the influence of spindle speed on internal temperatures, Figure 5.5-5 indicates the maximum temperature in the synthetic bone block as a function of the rotational velocity of the drill bit at a constant feed rate of 3.0 mm/s.

![Max Temperature vs. Spindle Speed: 3.0 mm/s](image)

**Fig. 5.5-5: Max Temperature vs. Spindle Speed: 3.0 mm/s**

In Figure 5.5-5 it can be seen that for each distance from the drill hole, as spindle speed increased, the maximum temperature increased as well.

The results identified in Figures 5.5-2 through Figure 5.5-5 show that the established inverse technique for predicting the maximum internal temperature matches well with expectations from literature. Now, combining the inverse technique with the Cumulative Equivalent Minutes equation for determining the likelihood of necrosis, an approximation of thermal damage from drilling can be found.
5.6 Thermal Injury Analysis

As previously established in Section 2.2, the Cumulative Equivalent Minutes technique is an established and effective methodology for predicting the occurrence of thermal necrosis.

\[ \text{CEM}_{47} = \int_0^t R^{(47-T(t))} \, dt \]  

Equation 1

Combined with the inverse technique for approximating the internal temperature during drilling established in Section 5.5, equation 1 can be utilized to predict thermal osteonecrosis during drilling of human bone.

First, an inverse analysis must be performed to find the maximum internal temperatures during drilling of human bone. Similar to the process used in Section 3.3, Finite Difference Method - One Dimensional Radial Model with Time Dependent Heat Flux, this analysis will be a one dimension radial model with a heat flux source. Using the results from experiment, Table 3.3-1 established the total amount of heat generated during drilling of the synthetic bone block. Assuming a similar amount of heat generation during drilling of human bone, the heat flux derived from the spindle speed and feed rate used in Trial #1 will be reviewed first. Table 5.6-1 summarizes the material properties and system parameters for this numerical model.
<table>
<thead>
<tr>
<th>Property</th>
<th>Symbol</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Conductivity</td>
<td>$K$</td>
<td>W/(m·K)</td>
<td>0.540</td>
</tr>
<tr>
<td>Density</td>
<td>$\rho$</td>
<td>kg/m$^3$</td>
<td>1800</td>
</tr>
<tr>
<td>Specific Heat Capacity</td>
<td>$C_p$</td>
<td>J/(kg·K)</td>
<td>1260</td>
</tr>
<tr>
<td>Thermal Diffusivity</td>
<td>$\alpha$</td>
<td>m$^2$/s</td>
<td>2.3810E-07</td>
</tr>
<tr>
<td>Initial Temperature</td>
<td>$T_i$</td>
<td>°C</td>
<td>37</td>
</tr>
<tr>
<td>Heat Flux</td>
<td>$q$</td>
<td>W/(m$^2$)</td>
<td>3,675</td>
</tr>
<tr>
<td>Convective Heat Transfer Coefficient</td>
<td>$h$</td>
<td>W/(m$^2$·K)</td>
<td>10</td>
</tr>
<tr>
<td>Time Step</td>
<td>$\Delta t$</td>
<td>seconds</td>
<td>0.5</td>
</tr>
<tr>
<td>Distance Step</td>
<td>$\Delta r$</td>
<td>meters</td>
<td>0.001</td>
</tr>
<tr>
<td>Fourier Number</td>
<td>$F_o$</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Biot Number</td>
<td>$B_i$</td>
<td></td>
<td>0.018518519</td>
</tr>
</tbody>
</table>

**Table 5.6-1: One Dimensional Model of Human Bone – Material & System Properties**

Figure 5.6-1 presents the numerical results for maximum internal temperatures achieved during drilling of human bone under the parameters of Trial #1.

![Graph of temperature over time](image)

**Fig. 5.6-1: Transient, 1D Radial Heat Diffusion, Human Bone: Heat Flux = 3675 W/m$^2$ from Trial #1**

Using the temperature profiles from each Trial, Equation 1 can be applied to find the Cumulative Equivalent Minutes of exposure to the critical temperature of 47 °C.
Evaluating the level of thermal damage of as a function of the source heat flux, CEM models were created using the heat flux data from six trials: Trial #1, Trial #3, Trial #4, Trial #9, Trial #14, and Trial #5. These trials were chosen to cover the widest range possible of drilling parameters and thus the widest range of heat flux. Table 5.6-2 below summarizes the results of this CEM analysis.

<table>
<thead>
<tr>
<th>Spindle Speed (rpm)</th>
<th>Trial 1</th>
<th>Trial 3</th>
<th>Trial 4</th>
<th>Trial 9</th>
<th>Trial 14</th>
<th>Trial 15</th>
</tr>
</thead>
<tbody>
<tr>
<td>1050</td>
<td>1050</td>
<td>1050</td>
<td>2040</td>
<td>3070</td>
<td>3070</td>
<td></td>
</tr>
<tr>
<td>Feed Rate (mm/s)</td>
<td>1.5</td>
<td>5</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>12</td>
</tr>
<tr>
<td>Duration of Drilling (s)</td>
<td>21.16</td>
<td>6.35</td>
<td>3.53</td>
<td>3.53</td>
<td>3.53</td>
<td>2.65</td>
</tr>
<tr>
<td>Heat Flux (w/m²)</td>
<td>3675</td>
<td>9100</td>
<td>12750</td>
<td>17900</td>
<td>25000</td>
<td>33500</td>
</tr>
<tr>
<td>q (watts)</td>
<td>1.173</td>
<td>2.905</td>
<td>4.07</td>
<td>5.713</td>
<td>7.98</td>
<td>10.693</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Distance from Drill Hole (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
<tr>
<td>0.1</td>
</tr>
<tr>
<td>0.2</td>
</tr>
<tr>
<td>0.3</td>
</tr>
<tr>
<td>0.4</td>
</tr>
<tr>
<td>0.5</td>
</tr>
<tr>
<td>0.6</td>
</tr>
<tr>
<td>0.7</td>
</tr>
<tr>
<td>0.8</td>
</tr>
<tr>
<td>0.9</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>4.75</td>
</tr>
</tbody>
</table>

**Table 5.6-2: CEM Analysis of Six Trials**
Figure 5.6-2 below presents the thermal damage as a function of proximity to the drill hole. As distance from the drill hole increases, the risk of thermal damage decreases considerably, as expected. To better visualize the trend and greater distances from the drill hole, the vertical axis has been scaled logarithmically.

**FIG. 5.6-2: THERMAL DAMAGE VERSUS DISTANCE FROM DRILL HOLE**

To evaluate the level of thermal damage of as a function of the source heat flux, Figure 5.6-2 presents thermal damage risk as a function of the source heat flux at two points in the sample: 0 mm and 1 mm from the drill hole site. Again, the vertical axis has been scaled logarithmically for easier viewing.
As can be seen above, thermal damage is very much influenced by the source heat flux. As such, a drilling process that produces the least amount of heat will result in the least thermal damage.

**Fig. 5.6-3:** Thermal Damage versus Source Heat Flux, at the 0 and 1 mm Nodes
CHAPTER 6 – CONCLUSIONS & FUTURE WORK

The goal of this work was to evaluate if varying drilling parameters would have an impact on reducing internal temperatures during orthopedic drilling and thus reducing the likelihood of thermal osteonecrosis. Traditional smooth-shaft Steinmann pins were drilled into a synthetic bone material at varying combinations of spindle speed and feed rate. It was found that reducing the spindle speed had the effect of generating less heat, while feed rate had a less impactful effect on heat generation.

An inverse technique was established to estimate internal temperatures. Using surface temperatures measured in experiment, a one dimensional heat diffusion model was created to approximate the temperature profiles experienced inside the subject material. Finally, using the results of this inverse technique, a thermal damage model was created to predict bone tissue damage from heating.

These experiments show that the orthopedic drilling can be optimized for reduced heat generation and the prevention of thermal osteonecrosis. It can be seen from Figure 5.6-2 that Trial #4, which combined a slow spindle speed of 1050 rpm and a moderate feed rate of 9 mm/s, resulted in the lowest probability of thermal damage. Further work should be done to further evaluate the influence of feed rate on heat generation. In particular, feed rates below 1.5 mm/s should be reviewed.
REFERENCES


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