HEAT FLUX ANALYSIS GENERATED DURING THE BONE CUT IN TIBIA OSTEOTOMY SURGERY

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Abstract. *For the bones cut in orthopaedic surgeries, tools as mountain ranges and saws are used. The friction between the tool and the bone generates heat, that must be controlled. During the surgical procedure, the bone temperature must be controlled to prevent the bone necrosis due to high temperature, what makes essential the knowledge of the temperature value in the cut region, mainly if the surgery is carried out through the automation aids, such as specially designed robot and saw. To determine the temperature distribution during the bone cut, it is necessary to know the heat flux generated due to during the cut process. To calculate the heat flux, some operational parameters of the automatic saw (shear speed and force) and a bone physical parameter (shear tension for both cortical and trabecular sections), must be known. The objective of this paper is to present a model to calculate the saw/bone heat flux during the bone cutting in a tibia osteotomy surgery. Then, the heat flux is used as one of the boundary conditions for the numerical simulation of the bone temperature distribution.*

Keywords: *Mechatronics, Bioengineering, Tibia Osteotomy, Heat Flux, Thermal Necrosis*

1. INTRODUCTION

When machining cutting tools as saws and mountain ranges are used, heat is produced, which raises the temperature of the tool and also of the material that is being cut. In orthopaedics, the drilling and cutting tools are frequently used in bone cut, and the heat produced by these procedures might result in thermal necrosis of the bone, according to Lundskog (1972). Due to the fact that the thermal necrosis has a negative impact on the result of a drilling and cutting procedure, the temperature of the bone must be kept bellow the threshold that results in necrosis.

Within the context of knee orthopaedic surgery, the tibia osteotomy is a surgical procedure implemented in three stages: surgery planning (image capitation and registration); surgical cut (1st and 2nd cut); and realignment. The focus of this paper is at the surgical cutting stage, because it is during this stage that the heat - which raises the bone temperature - is generated. The heat flux is caused by the friction between the cutting tool (saw) and the working piece (bone).

In order to maintain the bone temperature bellow the threshold that results in necrosis, it is necessary to determine the temperature distribution during the cut, and, for that reason, the heat generated due to the saw/bone friction must be determined. To calculate the heat flux, some operational parameters of the robotic equipment, such as cutting speed and force of the tool as well as the bone shear tension (for both cortical and trabecular sections) must be known.

This paper presents a model to obtain the behavior of the saw/bone heat flux during the bone cut in a tibia osteotomy surgery. In a complementary analysis, the heat flux study is going to be used as one of the boundary conditions for the numerical simulation of the bone temperature distribution.

The problem formulation is state as follows: which is the heat flux generated by the saw blade for a determined set of cutting parameters, and which percentage of this heat is transferred to the bone?

To answer these questions it is necessary to first investigate the structure and proprieties of the bone tissue as described below.

2. STRUCTURE AND PROPRIETIES OF THE BONE TISSUE

The human skeleton is composed mostly of bone tissue, the most resistant tissue of the human body that performs the following mechanics and dynamics functions in a healthy body: sustentation of the mass index, protection from the external solicitations, locomotion, besides the fact it is the repository of calcium and cells, according to Shimano (1994).

The bone tissue is composed of collagen fibers and organic components. It may be distinguished basically two types of bone tissue: the trabecular or spongy and the cortical, as shown in Fig. 1.

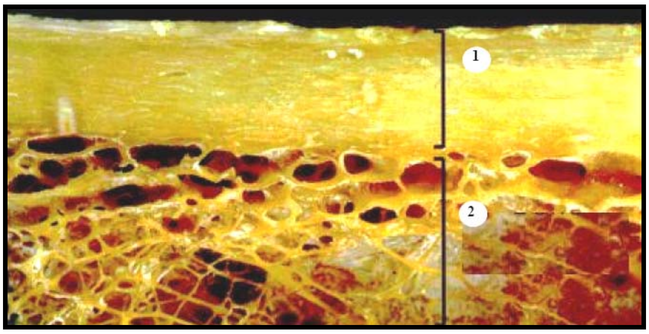

Figure 1. Components of the bone tissue
1 – Cortical Bone / 2 – Trabecular Bone

The cortical bone composes 80% of the skeleton: it is hard, dense and is the external part of many bones and the body of long bones. According to Rodrigues (2003), it has a porosity considered low, from 5 to 30%; it is rigorous, compact and contains microscopic vascular canals connected.

The spongy bone composes 20% of the skeleton. It is a highly porous structure found in vertebral bodies and at the final end of the long bones. According to Rodrigues (2003), it has a porosity considered high, from 30 to 90%; it is composed of a net of trabeculas interconnected with empty spaces filled by the bone marrow. The bones are classified basically in four types: long, short, flat and irregular. The bone analyzed herein is the tibia, classified as long.

One of the types of tibia osteotomy surgery is done at the end of the tibia, also called epiphysis. This region has as characteristic to be composed, in its central part, with trabecular bone with a thin external layer of cortical bone. The bone presents many structural variations, what makes it more difficult to make an accurate geometrical analysis. For that reason, in this paper, the bone was considered as being a non porous cylinder, with 0.05m of diameter, composed of a trabecular region with a diameter of 0.047m and a cortical region with thickness of 0.0015m, as shown in Fig. 2.

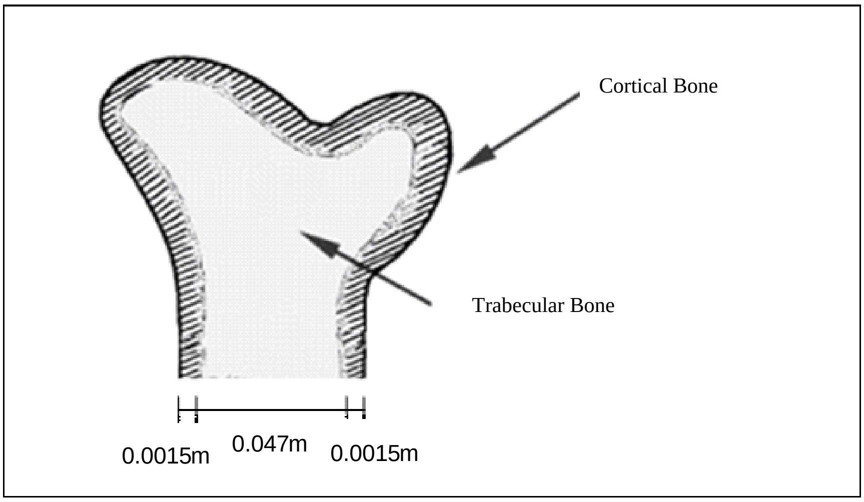

Figure 2. Bone geometry (cortical and trabecular)

According to Shimano (2001), the bone tissue is an anisotropic material, i.e. its mechanical characteristics vary, depending on the direction of the application of the load. The bone is also viscoelastic, which means it responds in different ways depending on the speed in which the load is applied and the duration of the load.

In this paper, the average values of the characteristics needed for modeling purposes are used: this a simplifying hypothesis, adopted in a primary analysis. Thus, the bone is ideally considered a homogeneous and isotropic material.

This supposition was also based on recent experiments from David *et al.* (2000) that investigated some peculiarities of the bone and showed characteristic variations of no more than 10% in different directions.

The bone characteristic necessary for the formulation of the problem is the tension of the shear of the cortical bone, 45.000.000 Pa and from the trabecular bone, 1.000.000 Pa. These values were obtained by James *et al.* (2003) through experimental tests. After presenting the bone characteristics, the cutting procedure is detailed as follows.

2.1. Cutting Procedure

The cutting procedure is illustrated in Fig. 3. The tool blades move with the progress speed (v_a) and rotational or angular speed (v_r) through the working material (bone), removing a layer of the material (bone). It bas been considered that the cutting procedure is executed in a single pass of the tool through the bone. This explains why the dimension of the saw is bigger than the bone's.

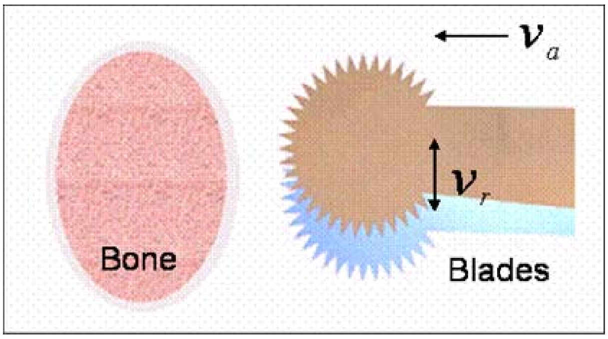

Figure 3. Cutting procedure

In order to formulate the problem, it is convenient divide the cutting procedure in four stages, as depicted in Fig. 4. At the first stage, the saw is positioned to begin the cut. At the second stage, the saw cuts through the cortical bone, only. Then, at the third stage, the saw travels through the cortical bone region, where the blades hit the trabecular part and then both, trabecular and cortical sections of the bone. Finally, at the fourth and last stage, there is only cortical bone to be cut.

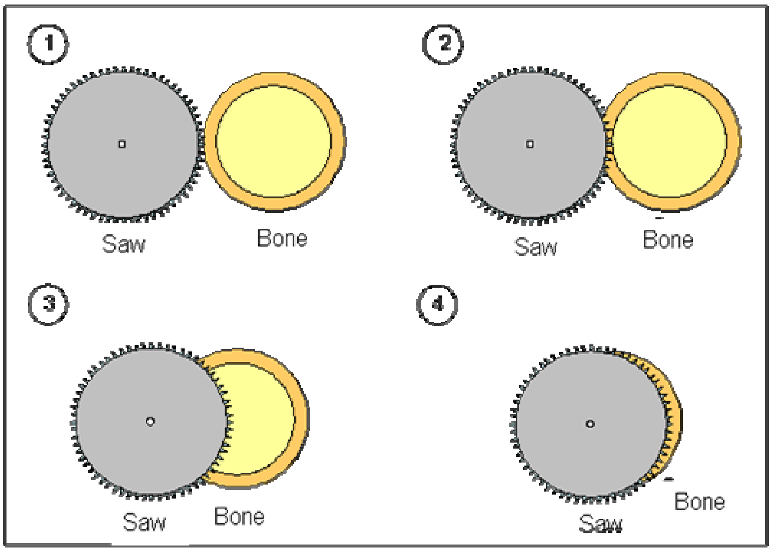

Figure 4. A four stage cutting procedure

2.2. Modeling of the Heat Flux Generated by the Cutting Process

Part of the necessary energy for bone shearing is converted into heat generated by the attrition between the saw blades and the bone. There could be identified two forms of attrition in this process: frontal and lateral.

The frontal attrition is generated by the friction of the frontal part of the saw tooth of the blades with the bone. The lateral attrition is generated by the contact of the lateral (superior and inferior surfaces) between the blade and the bone.

According to Slade *et al.* (2003), the manipulation of the saw by a robot guarantees the cut is done in a superficial and plain way, thus the lateral attrition was not taken into account for the heat generation model.

According to Merehant (1945), almost all the energy used in the removal of the material is converted into heat. The heat generated during the cut may, then, be determined by the magnitude of the mechanical work, calculated according to James et *al.* (2003), as:

$$\frac{\partial Q}{\partial t} = F_C . v_C \tag{1}$$

where: Q is the heat generated by the cutting action; t is the cutting time; F_C is the shear force; v_C is the shear speed.

2.2.1. Shear Speed

To determine the shear speed (v_C) it is necessary to analyze the progress speed (v_a) and the rotation speed (v_r) of the saw. Fig. 5 shows the vectors that indicate the trajectory of the speeds present in the bone cutting procedure.

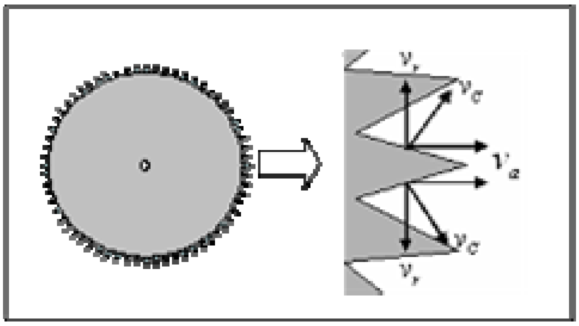

Figure 5. Trajectories procedure stages

The progress and rotation speeds are taken as steady during the cutting process; thus the shear speed is calculated as:

$$v_C = \sqrt{v_a^2 + v_r^2} \tag{2}$$

2.2.2. Shear Force

Due to the presence of both regions (cortical and trabecular) constituted of materials with different characteristics, the assessment of the total shear force on the material that is being removed by the cutting tool, has been modeled separately, as follows:

Shear force of the cortical region (F_{Cc}):

$$F_{Cc} = \tau_{Cc} . A_{Cc} \tag{3}$$

where: τ_{Cc} is the shear tension and A_{Cc} is the area of the cortical bone that is being sheared.

Shear force of the trabecular region (F_{Ct}):

$$F_{Ct} = \tau_{Ct} . A_{Ct} \tag{4}$$

where: τ_{Ct} is the shear tension and A_{Ct} is the area of the trabecular bone that is being sheared.

After the determination of the shear forces of the cortical and trabecular regions, the total shear force (F_{CT}) can then be calculated as:

$$F_{CT} = F_{Cc} + F_{Ct} \quad (5)$$

2.2.3. Shear Area

Just as the shear force, the assessment of the shear area has been obtained separately for the cortical and trabecular portions. Initially, the total area of the circular sector of the saw that is in contact with the bone has been calculated, as shown in Fig. 6a. Then, this figure is multiplied by the (f) factor, that corresponds to a percentage of the area of all the circular section of the saw. This is a necessary correction, because only the saw teeth of the blade actually shears (see Fig. 6b). The value used in this paper for this factor is 0.5.

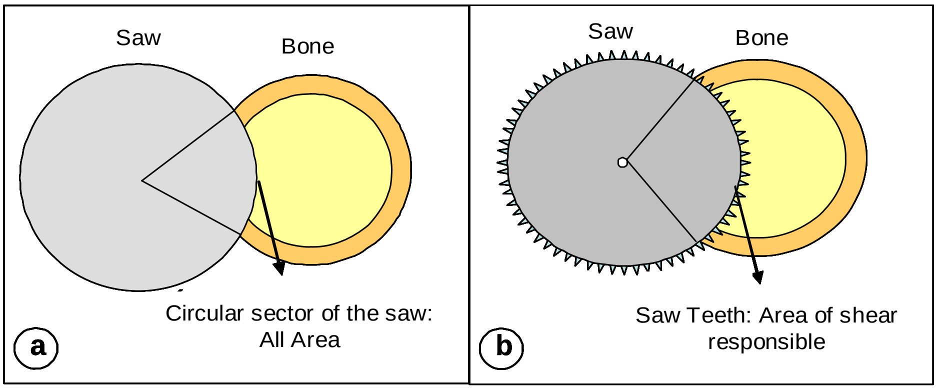

Figure 6. Bone shear area

The shear area of the cortical region (A_{Cc}) is calculated as:

$$A_{Cc} = r_s.\theta_c.e_l.f \quad (6)$$

where: r_s is the radius of the saw; θ_c is the angle of the circular section in relation to the diameter of the cortical bone; e_l is the thickness of the blade; f is the factor that represents the contact area between the blade and the bone.

Similarly, the shear area of the cortical region shear (A_{Ct}) can be obtained as:

$$A_{Ct} = r_s.\theta_t.e_l.f \quad (7)$$

where: θ_t is the angle of the circular section in relation to the diameter of the trabecular bone.

2.2.4. Heat Flux Generated in the Bone

The heat generated by the cutting process is conducted through the

- ✓ tool (saw blades);
- ✓ material removed (bone);
- ✓ atmosphere and
- ✓ the working material/piece (bone).

It is extremely difficult to determine the fraction of heat, η , that goes to the bone from the mechanics bases and heat conduction. Alternatively, the empiric approximation was proposed by James *et al.* (2003), and the fraction was determined by comparing the temperatures previewed by the analyses of James *et al.* (2003), with the temperatures measured in five different tests in vivo of the bone perforation, done by Abouzgia (1995). The perforations parameters of these in vivo tests were used as input data for thermal simulations and the values of the maximum temperature were compared. The value of η , found by James et *al.* (2003), that better related the experimental values with the theoretical values was 0.5, the value also used in this paper.

Combining the previous equations, the final equation for the heat tax, $\frac{\partial Q_o}{\partial t}$, that goes to the bone during the cutting procedure is:

$$\frac{\partial Q_o}{\partial t} = \eta.\frac{\partial Q}{\partial t} = \eta.A_C.\tau_C.v_C \tag{8}$$

The heat flux, q, is calculated as:

$$q = \frac{\partial Q_o}{\partial t}.\frac{\Delta t}{A_{CT}} \tag{9}$$

where: Δt is the time step; A_{CT} is the total shear area.

3. RESULTS AND DISCUSSION

In this first analysis, the data used for the simulations were: v_a = 0.001 m/s and v_r = 5 rad/s. Afterwards, when it is implemented a numerical simulation of the temperature distribution in the bone, these speeds are modified in order to evaluate how they influence the temperature alteration of the bone during the cutting procedure.

Figure 7 shows the shear force applied on the trabecular bone due to the displacement of the saw in relation to the bone. It can be observed that from 0 to 0.0015 m and from 0.0485 to 0.05 m there is no force being applied on the trabecular bone as this region is the cortical bone.

The force applied in the 0.0015 to 0.0485 m range has shown the expected behavior: the bigger the area sheared, the bigger the necessary force to shear it.

The highest shearing force on the trabecular bone during the whole cutting procedure was 54 N, applied on the centre of the bone (0.025m).

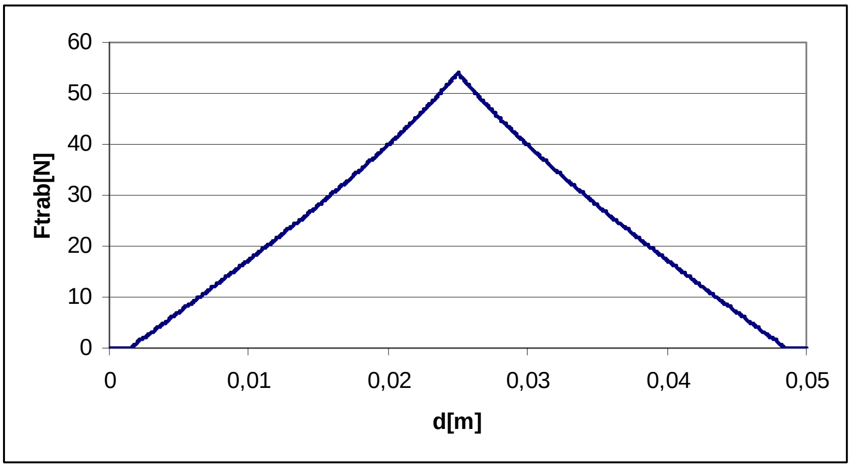

Figure 7. Shear strength on the trabecular bone (F_{trab}) x Displacement on the bone (d)

Figure 8 shows the shearing force applied on the cortical bone. Differently from the trabecular, the cortical bone is always in contact with the saw blades, that is why there is force being applied during the whole cutting procedure.

It may be observed that from 0 to 0.0015 m and from 0.0485 to 0.05 m there are two regions where the highest shear force is applied, 857.5 N. It happens because this two are the regions where there is only cortical bone, so the area is bigger.

While the cut is getting bigger, until the centre of the bone, the shear strength is reducing, getting to 229.8 N, and from the centre of the bone to the end of the cutting procedure it gets higher again. This behavior is due to the reduction of the shear area, followed by a reverse behavior.

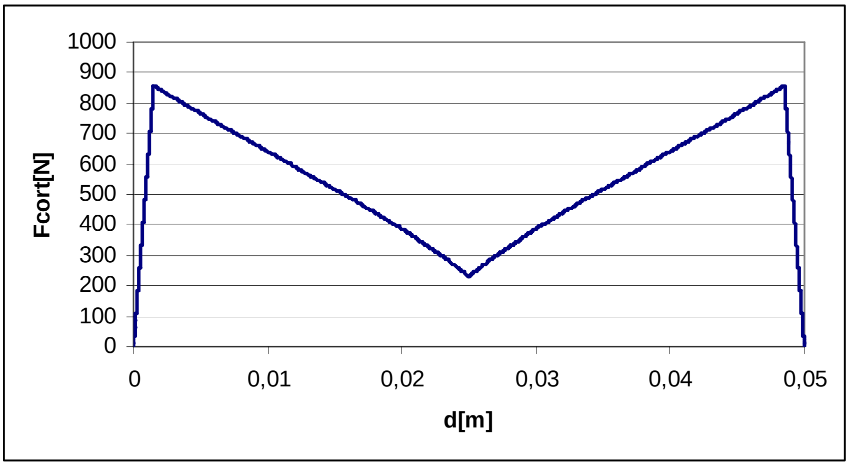

Figure 8. Shear force on the cortical bone (F_{cort}) x Displacement on the bone (d)

Figure 9 shows the total shear force due to the displacement of the saw in relation to the bone. This total shear strength is the result of the sum between the shear force on the trabecular bone – Fig. 7 – and the shear force on the cortical bone – Fig. 8.

As it has been pointed out before, one of the principal differences between the two types of bone tissue is that the cortical one is dense and hard whilst the trabecular is tender. These characteristics can be easily visualized on Fig. 9, because the highest force, 857.5 N, applied during the whole cutting procedure is at the regions where there is only cortical bone. Just as the shear area of the bone gets smaller, the force necessary to shear also gets smaller, getting to its lower value, 283.8 N, in the middle of the cutting procedure.

The shear area of the trabecular bone has a low influence in the determination of the total cutting strength.

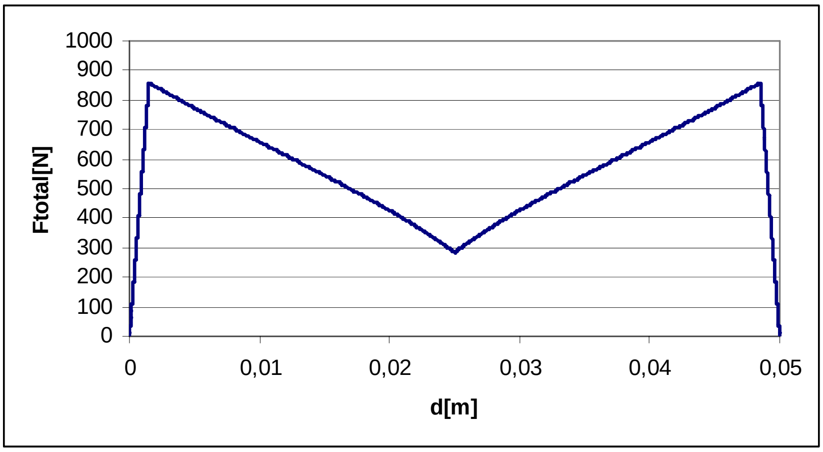

Figure 9. Total shear force (F_{total}) x Displacement on the bone (d)

Figure 10 shows the heat flux due to the displacement of the saw in relation to the bone. This heat flux is a result of the frontal attrition of the saw blades with the bone during the cutting procedure.

It may be observed that the highest heat flux, 208,173.9 cal/m^2, was generated in the region where the area where both cortical and trabecular bone are present, as already expected.

The analysis of the heat flux generated in this region, where both cortical and trabecular bone are present, it is possible to notice that the bigger the shear area of the trabecular bone and, consequently, the smaller the area of the cortical bone is and, consequently, the heat quantity gets bigger.

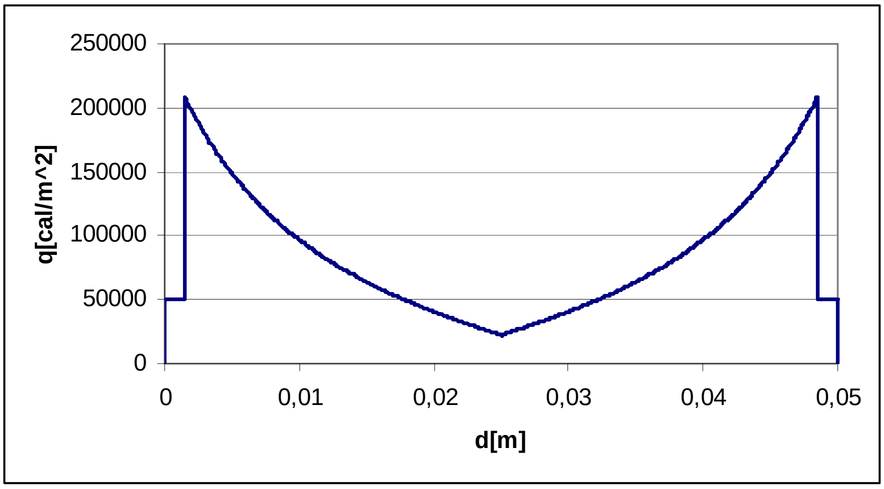

Figure 10. Heat flux (q) x Displacement on the bone (d)

4. CONCLUSIONS

For a preliminary analysis, the calculations presented for the determination of the heat generated due to the attrition saw/bone, during the cutting procedure, were representative and satisfactory, considering that the physical behavior difference of the of the trabecular and cortical bone - when submitted to a perforation process - is similar (qualitatively) to the results found in the literature.

The next step of this research is to use this heat flux as one of the boundary conditions for the numerical simulation of the distribution of the temperature in the bone. By determining the temperatures of the bone during the whole cutting may change the procedure variables of the cutting process, such as progress and rotation speed of the saw, avoiding, consequently the thermal bone necrosis.

5. ACKNOLEDGEMENTS

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