EFFECT OF DIFFERENT FEED-RATE IN BONE DRILLING: EXPERIMENTAL AND NUMERICAL STUDY

EFEITO DA VELOCIDADE DE AVANÇO NA FURAÇÃO ÓSSEA: ESTUDO EXPERIMENTAL E NUMÉRICO

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ABSTRACT

The behaviour of bone tissue during drilling has been subject of recent studies due to their importance. However, there is still a lack information with regard to the distribution of mechanical and thermal stresses during bone drilling. The present paper describes a sequentially coupled thermal-stress analysis to assess the mechanical and thermal stress distribution during bone drilling. A three-dimensional thermo-mechanical model was developed using ANSYS/LS-DYNA as finite element code under different drilling conditions. The model incorporates the dynamic characteristics of drilling process, as well as the thermo-mechanical properties of the involved materials. Experimental tests in polyurethane foam materials were also carried out. It was concluded that the use of high feed-rate leads to a decrease of normal stresses and strains in the foam materials. The experimental and numerical results were compared and showed good agreement. The proposed numerical model could be used to predict the better drilling parameters to minimize the bone injuries.

RESUMO

O comportamento do tecido ósseo durante processos de furação tem sido objeto de recentes estudos devido à sua importância. No entanto, ainda existe uma falta de informação no que diz respeito à distribuição de tensões de origem térmica e mecânica, durante a furação do osso. O presente estudo descreve uma análise sequencial termomecânica acoplada para avaliar a distribuição de tensões durante a furação óssea. Através do código de elementos finitos ANSYS/LS-DYNA foi desenvolvido um modelo termomecânico tridimensional, assumindo diferentes condições de furação. O modelo incorpora as características dinâmicas do processo de furação, bem como as propriedades térmicas e mecânicas dos materiais envolvidos. Foram também realizados testes experimentais em materiais de espuma de poliuretano. Concluiu-se que a utilização de velocidades de avanço maiores conduz a uma diminuição das tensões e deformações normais nas espumas de poliuretano. Os resultados experimentais e numéricos foram comparados e apresentaram boa concordância. O modelo numérico proposto pode ser utilizado para prever os melhores parâmetros de furação e dessa forma minimizar possíveis as lesões ósseas.

1. INTRODUCTION

Drilling operations applied on the bone tissue as a part of surgical intervention are similar to those performed on the structural materials. It is known in production technology the importance of manufacturing processes, which include surface integrity, low cost and short time work. These concepts are adaptable to the bone drilling processes, since it is required to conjugate low drilling time (in order to diminish the total time of the surgery) and surface quality (related with thermal and mechanical bone damage). Therefore, the success of these interventions depends largely on precision of the operation and the damage level on the surrounding tissues (Li et al. 2014; Hou et al. 2015; Gehrke et al. 2016). A clear example is the osseointegration of the implants. There are basic requirements to the successful osseointegration, particularly the atraumatic surgical technique and the initial stability of the implant during the surgery. These aspects are directly related to the bone drilling procedure for preparing the site prior to installation of the implant (Cardemil et al. 2009; Gehrke et al. 2015).

Among the many problems associated to the bone drilling, thermal damages are the most important consequence of an aggressive bone drilling (Santiuste et al. 2014). The overheating of surrounding bone in drilling process can cause a local bone necrosis, which means irreversible death of the bone cells. This phenomenon occurs when the temperature increases above a threshold supported by bone (Sezek et al. 2012). Eriksson and Albrektsson indicated that thermal necrosis in cortical bone tissue from living rabbits occurred when this one reached a temperature of 47 ºC for 1 minute (Eriksson and Albrektsson 1983). Other authors showed that temperature values above 55 ºC for a period longer than 30 seconds can cause great irreversible lesions in bone tissue (Hillery and Shuaib 1999; Tu et al. 2013). No less important is the bone mechanical damage. It is well known that the high speed drilling with higher cutting forces and tool vibrations can also cause damages to the bone microstructure, which can lead to the formation of microcracks and fracture of bone tissue (Staroveski et al. 2015; Li et al. 2014). The presence of the injuries mentioned above is often associated with the delay of healing process, bone regeneration, reduction of stability and strength of the fixation implant and in some cases even the failure of implant (Pandey and Panda 2013; Pandey and Panda 2015).

The importance of this surgical intervention on the recovery of the patients has motivated the study of bone drilling. Several studies have been performed to analyse the effect of drilling parameters on the outcome of the process and its effect on bone. Currently it is known that level of bone damage is directly related to the drilling parameters (Fernandes et al. 2015; Fernandes et al. 2016). For better performance of the drilling procedures, it is essential to understand the thermal and mechanical behaviour of the bone tissue, their failures and consequently improve the cutting conditions.

This paper presents a realistic thermo-mechanical finite element (FE) model that incorporates the dynamic characteristics involved in the process. The numerical model was used to investigate the effect of the feed-rate on the thermal and mechanical behaviour of the bone tissue. A sequentially coupled thermal-stress analysis was conducted in ANSYS/LS-DYNA, first solving the thermal analysis, then reading the temperature solution, and finally obtain the level of stress. An experimental approach was developed using polyurethane foam materials with properties similar to the human bone. The foams were instrumented with strain gauges to measure the strain during the drilling. Thermography was used during the tests to measure the temperature on the surface of the foams and cutting tool.

2. METHODOLOGIES

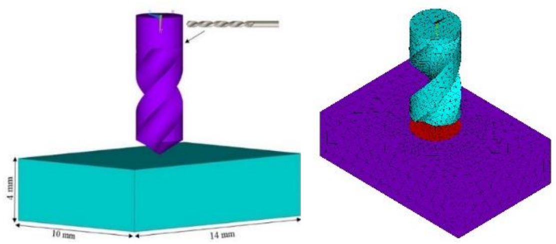
In the bone drilling, keep the deformation and temperature rise to a minimum level is an extremely important matter. Different models have been developed with the aim of reproducing the behaviour of bone tissue. In this work, polyurethane foams with mechanical properties similar to the human bone were used as a reference and the numerical results are compared with the experimental data. The detailed methodlogies are described in following subsections.

2.1 Finite element model of drilling

A sequentially thermo-mechanical coupled FE model of the bone drilling process was developed using an explicit dynamic analysis with ANSYS/LS-DYNA (LSTC, Livermore, CA, United State). To simulate the drilling process were built a bone block and a drill bit. The drill was built with geometry similar to the conventional HSS twist drill bit (Ø4 mm, point angle of 118° and helix angle of 30°), reproducing the shape of the drill bit used in the experimental tests. Bone block was modelled as rectangular shape with dimensions: 10x14x4 mm and material properties similar to the polyurethane foams (Fig.1 (a)). The model was meshed using 3D SOLID 164 elements (8 nodes with three degrees of freedom at each node in X, Y, Z directions), only used for explicit dynamic analyses. Several meshes convergence study were carried out to obtain a more suitable model for this kind of simulation. In the last model was applied a mesh discretisation in the drilled zone, with an element size equal to 0.5 mm. In the remaining block was used a coarse mesh, as shown in Fig. 1 (b).

In order to include the effects of thermally induced stresses, sequentially coupled approach was used for thermo-mechanical problem which is divided into two parts: thermal transient analysis and dynamic thermal stress analysis (Fig. 2).

The transient thermal analysis was performed to calculate the temperature inside the material during the drilling process. The analysis was conducted by using ANSYS Multiphysics software Version 14.5 (ANSYS, Inc., Canonsburg, PA, USA). The boundary conditions considered in this analysis are the convection in the upper bone surface and a prescribed temperature inside of the hole drill, according to the real experimental conditions. The progress of drill bit



(a) (b)

Fig. 1-3D model: (a) geometric representation and (b) finite element model

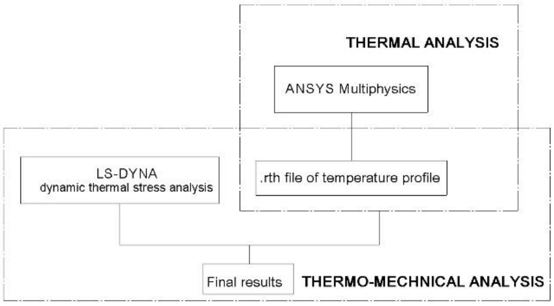


Fig. 2-Working steps for sequentially coupled analysis.

temperature was recorded with the thermal camera. An average of the registered temperature values in the different holes was considered as a prescribed condition in the numerical model. The model is assumed with an initial temperature equal to 19 °C.

The thermal stress analysis, which is the focus of this study, is followed using the explicit dynamic analysis. To simulate the drilling process, a set of boundary conditions were imposed on the model. Bone block was kept fixed in all vertical faces and the drill bit was constrained to move only about its own longitudinal axis with a specified drill speed and feed-rate downwards into the block. To explore the effects of feed-rate on the generated thermal stresses, the simula-tions were performed using three feed-rates (25, 50 and 75 mm/min) and a constant drill speed of 800 rpm.

The structure of the cortical bone tissue was approximated as an isotropic equivalent homogeneous material. Materials subject to drilling are highly affected by large and high strain rates, which finally lead to failure. To define the material block submitted to high impact deformation and the expansion due to the temperature increase, different components of the model were created and appropriate materials were implemented.

An elastic-plastic material with kinematic isotropic hardening was chosen (*MAT_PLASTIC_KINEMATIC) to simulate the thermo-elastic material behaviour of bone block. The strain rate effect is considered and the yield stress is defined with the following equation (Cowper and Symonds, 1957; ANSYS/LS-DYNA User's Guide, 2009):

$$\sigma_y = \left[1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{\frac{1}{p}}\right]\left(\sigma_0 + \beta E_p \varepsilon_p^{eff}\right) \qquad (1)$$

where σ_y is the yield stress, σ_0 the initial yield stress, $\dot{\varepsilon}$ the strain rate, β the hardening parameter (between 0 for kinematic hardening and 1 for isotropic hardening), C and P are the Cowper–Symonds strain rate parameters, ε_p^{eff} the effective plastic strain and Ep the plastic hardening modulus which is dependent of the E Young's modulus and the E_{tan} tangent modulus given by:

$$E_p = \left(\frac{E_{\tan} E}{E - E_{\tan}}\right) \qquad (2)$$

In addition, a temperature dependent model (*MAT_ELASTIC_PLASTIC_THERMAL) was used to define the material with a thermal expansion coefficient. This model allows the definition of temperature dependent material coefficients in a thermo-elastic-plastic material. The drill bit was assumed to be a rigid body, since its stiffness is much higher than the bone. Mechanical properties of the polyurethane foams were obtained from the uniaxial tensile tests and have been comprehensively defined in our previous studies (Fernandes et al. 2015). The remaining thermal and mechanical properties were taken from literature (Li et al. 2010; Fonseca et al. 2012; Huang et al. 2010; Sawbones Worldwide, 2013; Ranu 1987). All material properties for bone block and drill bit are summarized in Table 1.

The hole generation during the drilling process was simulated by the element deletion that occurs when the plastic strain of an element reached the limit. Based on the bone properties, the failure strain reaching 0.05 is adopted as the criterion in the erosion algorithm implementation for the numerical

Table 1 – Material properties used in numerical analysis.

Properties		Block	Drill
Density (kg/m^3)		800	7850
Young's Modulus (GPa)		0.987	200
Poisson's ratio		0.3	0.3
Heat Conductivity (W/K.m)		0.4	53.3
Specific heat (J/kgK)		1260	440
Thermal expansion coefficient (1/ºC)		2.75e-5	
Initial Yield Stress (MPa)		22.59	
Tangent Modulus (MPa)		0.91	
Hardening Parameter		0.1	
Cowper-Symonds model			
	C	2.5	
	P	7	
Failure Strain		0.05	

simulation. To this happen is also important to define an appropriate contact between the surfaces during the process. In this analysis, a contact algorithm *CONTACT_ERODING_SURFACE_TO_SURFACE was chosen. This type of contact is used when a surface of one body penetrates the surface of another body, with eroding of the elements. The frictional contact between the drill bit and the bone block was assumed to be governed by Coulomb's friction law, with a constant coefficient of friction of 0.3 (Tu el al. 2013; Mellal et al. 2004). Dynamic analysis was used with the simulation range subdivided into 15000 time increments of 8.0×10-4 seconds. LS-DYNA requires very small time steps with many iterations to ensure stability of solution.

2.2 Validation of FE model

Before the implementation of the numerical simulations, the developed numerical model was validated using experimental data obtained for a feed-rate of 25, 50 and 75 mm/min and a constant drill speed of 800 rpm. The drilling tests were performed on polyurethane foam blocks (from Sawbones; Pacific Research Laboratories Inc., Vashon Island, WA, USA) as an alternative to the cadaveric human bone because of its consistent and homogeneous structural properties (Kim et al. 2012; Liu et al. 2016) (Fig. 3). The experiments were performed in Mechanical Laboratory at Polytechnic Institute of Bragança. In total 18 holes with 30 mm of depth were made at room temperature (without cooling) using a standard Ø4 mm twist drill

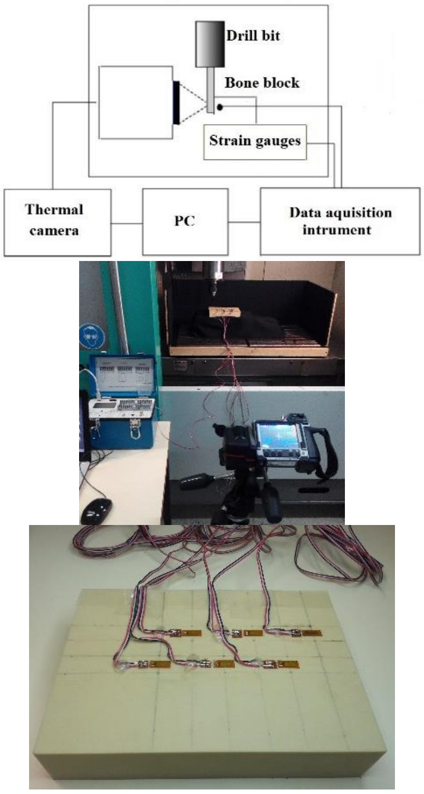


Fig. 3 – Experimental setup.

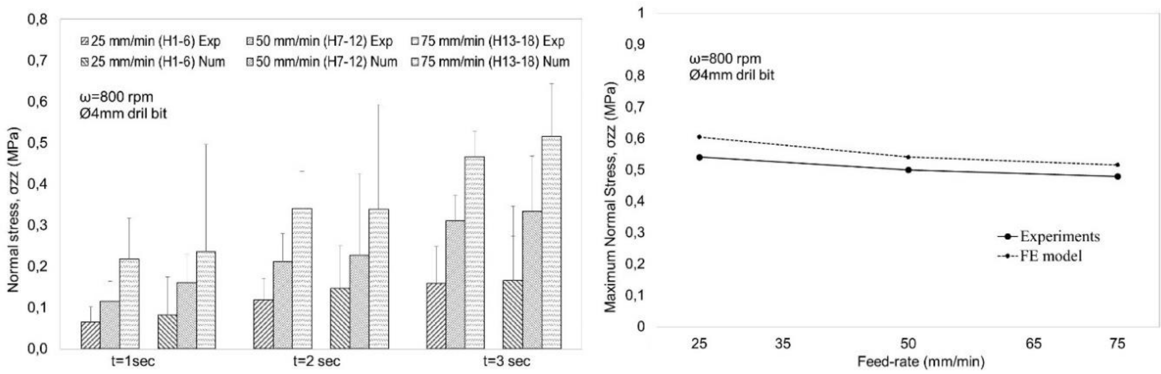
bit with a point angle equal to 118º and helix angle of 30º. A control of the drilling parameters was provided by a CNC machine. For each combination of parameters, the average of six drillings was used to present the results.

The experimental setup is shown in Fig.3. A set of linear strain gauges (1-LY18-6/120, 120 ± 0.35% from HBM) were installed on the block surfaces at 3.5 mm from the edge of drilled hole. The strain gauges were connected to the data acquisition system (Vishay Micro Measurements P3 Strain Indicator and Recorder) to read the strains on the block surfaces during drilling time. Temperature measurement was carried out using a thermal camera ThermaCAM 365, FLIR Systems) with the lens located at distance of 1.5 m from the drilling area. This method allowed to obtain thermal images of the block surface and the drill bit surface, before and immediately after drilling.

3. RESULTS AND DISCUSSION

In order to evaluate the feed-rate parameter and determining the safe zones, thermo-mechanical stresses were recorded experimentally and compared with numerical results. Different numerical simulations were performed with an appropriated drilling time, considering the complete depth of the block (4 mm) and the respective feed-rate (25, 50 and 75 mm/min). In both methods, the average of normal stress at differrent feed-rates were calculated and compared at different time instants of the drilling. The calculated distance between the edge of the drilled hole and the strain gauge was also considered in both methodologies. Fig. 4(a) shows the mean and the standard deviation of normal stresses located near of each hole obtained in both methods, at three different drilling times (1, 2 and 3 seconds), while the Fig. 4(b) shows the average of maximum normal stress, at final of the drilling process.

Based on the results presented on the Fig. 4(a), normal stress in the polyurethane foam materials increase with the increase of the



(a) (b)

Fig. 4- Comparison of normal stress (MPa) in numerical and experimental models: (a) at different drilling times and (b) at the end of the drilling

feed-rate, for the same time instant. Also in both methods, it can be observed that the normal stresses increase with the drill penetration, reaching a maximum value when the drill bit penetrated completely the block due the higher produced effort at the end of the process. Therefore, it can be concluded that the greater the drilled hole depth the greater will be the generated normal stress on the bone block surface.

Using the average of maximum normal stress at the end of the drilling was observed that the normal stress decreased with the increase of feed-rate. Although at the start of drilling, the generated normal stresses are higher for higher feed-rates (75 mm/min), in the entire process are found higher stresses for lowest feed-rate (25 mm/min) because the drilling time also increases. Both methodologies show similar results, validating the numerical model.

3.1 Recorded temperature in drill bit

The recorded temperature on the drill bit under the three different feed-rates was also examined. Fig. 5 displays the final drill bit temperature of each hole function of the applied feed-rate.

Also in the drill bit temperature analysis can be seen that the maximum temperature increases with decreasing feed-rate. This results are normal and expected, since the increase of feed-rate leads to a decrease in drilling time and, in turn, less time of contact between drill bit and material.

4. CONCLUSIONS

In this paper, bone drilling is analysed using a numerical approach based on finite element method. Analyse the effect of drilling parameters on the bone damage is crucial for improvement to these surgical interventions. A sequentially thermo-mechanical coupled FE model of bone drilling was developed to predict the thermo-mechanical stresses evolution in bone tissue. The numerical model allowed to evaluate the stresses distribution during bone drilling at different feed-rates and was validated by experimental tests.

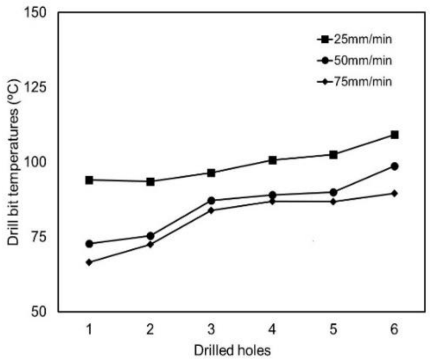


Fig. 5 – Drill bit temperature variation with feed-rate.

It was found that lower levels of feed-rate lead to an increase of the normal stresses on the surface of the bone blocks. The thermo-mechanical stress generated in the material increasing with tool penetration and, consequently, with increasing of hole depth. The thermal stresses calculated using the developed numerical model agree well with the experimental results.

Based on the results, appropriate magnitudes of feed-rates should be used to prevent the damage on bone tissue. The thermo-mechanical stresses analysis is crucial to predict the behaviour of bone tissue during drilling and to help in developing predictive capabilities by verifying models.

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