
IRF2016
(Porto/Portugal, 24-28 July 2016)


Proceedings of the
5th International Conference on
INTEGRITY-RELIABILITY-FAILURE
Editors
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FEUP/U.Porto
Portugal
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MADL/U.Toronto
Canada
ISBN: 978-989-98832-5-3
INEGI/FEUP
(2016)

PROCEEDINGS

IRF2016

5th International Conference

INTEGRITY-RELIABILITY-FAILURE

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Editors Preface

IRF2016 is the fifth international gathering of a prestigious series of Integrity-Reliability-Failure conferences coordinated by the International Scientific Committee of Mechanics and Materials in Design. This series of conferences are wholy devoted to advances in mechanics, materials, structural integrity and design. IRF2016 is jointly sponsored by the University of Porto and the University of Toronto, and it took place in the facilities of FEUP-Faculty of Engineering of University of Porto, in the beautiful city of Porto/Portugal, from 24 to 28 July 2016. The conference attracted over 200 participants with 220 accepted submissions involving 510 authors from 38 different countries around the world. The conference themes which address novel and advanced topics on Integrity, Reliability and Failure focused on Computational Mechanics, Experimental Mechanics, Fracture and Fatigue, Composite and Advanced Materials, Tribology and Surface Engineering, Mechanical Design and Prototyping, Biomechanical Applications, Civil Engineering Applications, Energy and Thermo-Fluid Systems, and Industrial Engineering and Management, among other topics.

We believe that the meeting offered our delegates a forum for the discussion and dissemination of their recent work in assessing the integrity, reliability and failure of engineering structures, components and systems, fostered research that integrates mechanics and materials in the design process, and promoted exchange of ideas and international co-operation among scientists and engineers in this important field of engineering.

We are particularly indebted to the authors and special guests for their presentations. Each of the 220 contributions offered opportunities for thorough discussions with the authors. Particularly, we acknowledge the excellent contributions of the participants, their innovative ideas and research directions, the novel modeling and simulation techniques, and the invaluable critical comments. We are also indebted to the outstanding keynote speakers who highlighted the conference themes with their contributions and covered the main topics of the conference. We also take this opportunity to thank the members of the International Scientific Committee and the reviewers for their time, effort and helpful suggestions.

We offer our sincere gratitude to the symposia organisers for their efforts and valuable contributions to the success of the event, and the local organising committee for attending to the conference demands and delegates needs.

All in all, IRF2016 was a great success and the credit must go to all the participants for their significant contributions and lively discussions, the keynote speakers for bridging the gap between the different disciplines and the organizing committee for an absolutely superb organization of the meeting in this magnificent city. To all of you, we offer our gratitude.

Given the rapidity with which science is advancing in all areas of mechanics and materials, the next conference in this series (Mechanics and Materials in Design - M2D2017) will take place in Algarve, Portugal in June 2017. Undoubtedly, we expect M2D2017 to be as stimulating and interesting as IRF2016, as evidenced by the excellent contributions offered in this current event. We look forward to

IAP 2016, as evidenced by the excellent contributions offered in this current event. We look forward to seeing all of you in Algarve 2017.

Shaker A. Meguid and J.F. Silva Gomes
Porto / Portugal, July 2016

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IMEKO-International Measurement Confederation

AFM-Association Française de Mécanique

DYMAT-European Association for Dynamics of Materials

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Proceedings of the 5th International Conference on Integrity-Reliability-Failure, Porto/Portugal 24-28 July 2016
Editors J.F. Silva Gomes and S.A. Meguid
Publ. INEGI/FEUP (2016)

PAPER REF: 6356

INFLUENCE OF BONE DRILLING PARAMETERS ON THE THERMAL STRESS DISTRIBUTION

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ABSTRACT

The material removal through the drilling involves two important processes. The first one is the drilling of material by cutting edges of the drill bit and the second is the friction generated by the contact between the drill bit and the hole wall of the material. Both processes lead to heat generation during drilling. In clinical practice, drilling procedures with high-speed cutting tools are often applied on bone tissue. These operations are associated to complications such as thermal osteonecrosis due to the excessive heat generation and mechanical damage due to the excessive levels of penetration force. The development of additional tools for accurately simulate the drilling is essential to predict the risk of thermo-mechanical damage during bone drilling. This paper investigates the thermal and mechanical damage in bone tissue induced by different parameters. An experimental and numerical approach of bone drilling has been conducted. A three-dimensional dynamic numerical model was developed to predict the thermo-mechanical stress generated during the drilling. The numerical model incorporates the geometric and dynamic characteristics involved in the drilling processes, as well the developed temperature inside the material. The numerical analysis has been validated by experimental tests using polyurethane foam materials with similar mechanical properties to the human bone.

Keywords: Bone drilling, damage, finite element analysis, temperature.

INTRODUCTION

The drilling process is one of the most frequent conventional mechanical procedures in machining operations. The industrial concepts of productivity and surface integrity in material removal processes can be translated to medical applications. In the surgical context, the reduced drilling time is related to a short surgery in global time and the bone integrity is related to the absence of drilling induced damage (Marco el al. 2015).

In recent years, numerous studies on bone drilling have been conducted, mainly focused to determine the effect of drilling parameters on the outcome of the process and its effect on bone tissue (Augustin et al. 2008; Lee et al. 2012; Sezek et al. 2012; Fonseca et al. 2008; Fernandes et al. 2015). The most frequent drilling induced problems are thermal and mechanical damage due the excessive heat and the cut effort achieved during the process. The generated heat occurs due to the friction between the drill bit and the bone tissue, transforming the applied drilling energy into heat energy (Staroveski et al. 2015). Depending on the magnitude of the temperature rise and the exposure time in the drilling zone, heat generated may lead to hyperthermia and even combustion of bone tissue, resulting in cell death (thermal osteonecrosis) (Lee et al. 2011; Karaca et al. 2011). Besides of the negative thermal impact, 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. These situations cause mechanical bone damages, which also have negative impact on the post-operative progress (Li et al. 2014; Staroveski et al. 2015). Experimental and numerical investigations have indicated that many microcracks are generated during bone drilling (Wang et al. 2013; Alam 2014; Lughmani et al. 2015). It is know that the microcracks occur when the bone strain exceeds the threshold. The process of microcrack accumulation in the bone, eventually leads to a reduction of bone stiffness, resulting in damage by cracks of the material (Taylor D and Kuiper 2005; O'Brien et al. 2005; Wang et al. 2013). The presence of the injuries mentioned above may delay healing, increase the risk of infection and in some cases even the failure of implant (Tomislav et al. 2015; Pandey and Panda 2015). Piattelli et al. (1998) reported 8 cases of failed implants due to suspected thermally induced bone necrosis. Recently, Abayazid et al. (2010) reported that the failure rate of dental implant in the lower jaw is 7.65% in 10 years period and three times higher in the maxilla. According to the authors Augustin et al. (2008) the implant failure rate for leg osteosynthesis ranges between 2.1% and 7.1% and it is higher than the failure rate upper limbs due to physiological stress during locomotion.

The growing increase of the use of bone drilling as a medical intervention and the importance of the associated problems have motivated the development of different methodologies to find the optimal drilling conditions that minimize the bone injuries. However, there is still a lack information with regard to the strain and thermal stresses distribution in bone tissue during drilling. Although in several methodologies have been proposed estimated values for bone temperature and cutting forces, none of them include the thermal stress distributions on the bone. The large number of significant drilling parameters makes the study of bone drilling, through experiments, impractical. It is necessary the development of accurate numerical models in order to reproduce the factors influencing the output variables (mainly temperature, drilling forces and surface integrity). Only a few numerical models in the literature have attempted to model bone drilling. Recently, Marcos et al. (2015) has made a bibliographic review of the main contributions on the field of numerical modelling of bone cutting, including bone drilling. They found that the numerical models are still far from clinical application and there is a clear necessity of improvement of models available for drilling simulation. Most of the models presented in the literature were executed with limited parameters and using 2D simulations, furthermore the analysis was not validated comparatively with experimental tests (Sugita et al. 2009; Sezek et al. 2012). Experimentally, various measurement techniques have been developed to obtain the deformations during the drilling processes in industrial applications, but have not widely used for medical applications (Mainjot et al. 2011). Usually, the deformations are measured on the surface, typically using strain gages, from which the stresses can be calculated.

This study was designed for the evaluation of thermo-mechanical stress generated during bone drilling, as function of different drilling parameters and temperature changes during the process. ANSYS explicit dynamic analysis software solutions are capable of solving short-duration, large-strain, large-deformation, fracture, material failure, and structural problems with complex contact interactions. ANSYS/LS-DYNA module takes advantage and provides simulations with all these capabilities. For this purpose, a three-dimensional (3D) dynamic finite element (FE) model with the element removal scheme was developed to simulate the thermo-mechanical behaviour of the contact region between the drill bit and the bone. The simulations were executed using ANSYS/LS-DYNA, which incorporates the dynamic characteristics involved in the process with the accurate geometrical considerations, as well the developed temperature inside the material. An experimental approach was developed using polyurethane foam materials with properties similar to the human bone. The foam materials 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. The temperature distribution inside of the foams was also obtained using thermocouples at different distances from the drilling area. The results of numerical simulations are discussed and compared with experimental results.

MATERIALS AND METHODS

Experimental Approach

Polyurethane foam materials, as synthetic blocks (from Sawbones; Pacific Research Laboratories Inc., Vashon Island, WA, USA) were used as an alternative to the cadaveric human bone because of its consistent and homogeneous structural properties (Kim et al. 2012; Liu et al. 2016). The samples were supplied in rectangular shape (test block) with the dimension of 130x180x40 mm and the material has a closed cell with density of 0.80 g/cm^3.

To carry out the tests, a set of drilling parameters were chosen in order to study the influence of drill speed and feed-rate on the thermo-mechanical stress generated during drilling. The blocks were divided in two groups. For the first group, the holes were performed at drill speeds of 600 rpm, 800 rpm and 1200 rpm with a constant feed-rate equal to 50 mm/min. In the second group, three different feed-rates (25, 50 and 75 mm/min) were applied throughout the drilling procedures, with a constant drill speed of 800 rpm. All drilling parameters considered in the experimental tests are listed in Table 1.

The experiments were performed in Mechanical Laboratory at Polytechnic Institute of Bragança. In total 30 holes with 30 mm of depth were made at room temperature (without cooling) using a twist drill bit of 4 mm diameter, point angle equal to 118º and helix angle of 30º. A control of the drilling parameters was provided by a computer numerically controlled (CNC) system. All drills were used no more than fifteen times before being replaced with a new one. For each combination of parameters, the average of six drillings was used to present the results.

Table 1 - Drilling parameters used in experimental tests

Study groups	Drill speed (rpm)	Feed-rate (mm/min)	Drill-bit	Hole depth (mm)
Group I	600, 800, 1200	50	HSS, Ø4 mm, point angle 118º	30
Group II	800	25, 50, 75		

Strain gauge installation and measurement system

Before the drilling tests, a set of flexible linear strain gauges (1-LY18-6/120, 120Ω ± 0.35% from HBM) were installed on the blocks surface. To promote the uniformity of results, the locations of the holes were properly marked to maintain the same distance of 3.5 mm between the hole and the strain gauge (Figure 1).

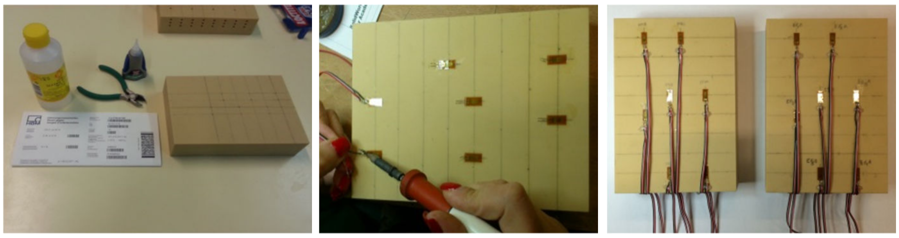


Fig. 1 - Linear strain gauges installed in the blocks

The strain gauges were identified for each channel and attached with bonding adhesive following the instructions of the manufacturer, as indicated in Figure 1. Strains over time were taken continuously during each step of the drilling, using an acquisition data software (Vishay Micro Measurements P3 Strain Indicator and Recorder) at once per second. The corresponding profiles of stress in block surface versus drilling depth were calculated.

Drilling temperature control

Temperature measurement was carried out using two methods. In the first method, thermography (ThermaCAM 365, FLIR Systems) was used 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. The measured temperature is function of the surface conditions, represented by their emissivity. The imposed parameters to the camera during image acquisition are listed in Table 2.

Table 2 - Parameters used for thermal images acquisition

Parameters	Value
Distance camera-block	1.5 m
Room temperature	20 ºC
Emissivity ε	$\varepsilon_{\text{stainless steel}} = 0.70$; $\varepsilon_{\text{skin human}} = 0.98$
Relative humidity	50%

In the second method, a set of chromel-alumel K-type thermocouples (Omega Engineering Inc., USA) installed close to the hole surface were used for measuring the temperature inside of block. The thermocouples with wire diameter of 3.5 mm were installed in two opposite sides of the block and at the same distance from the hole for all tests, as shown in Figure 2. After the thermocouples have been placed, the entrance of each hole was appropriately sealed with glue to fix the thermocouples and isolate them from external heat.

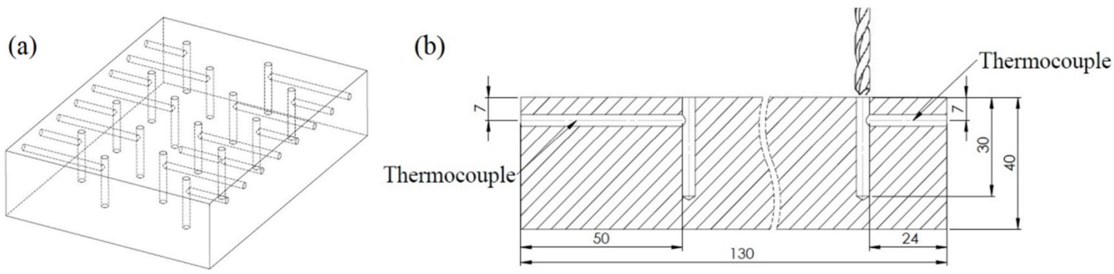


Fig. 2 - Geometrical model: (a) entire block and (b) thermocouples position

All thermocouples were connected to a data acquisition system (HBM MGCplus) for the acquisition of temperature along the drilling time. The temperature data were transferred to a PC in simultaneous during the process. Each block was prepared to accommodate eight holes with a distance between them of 20 mm.

The complete experimental setup is shown in Figure 3. In this setup the position of the drill is fixed and a CNC machine was used to perform the holes.

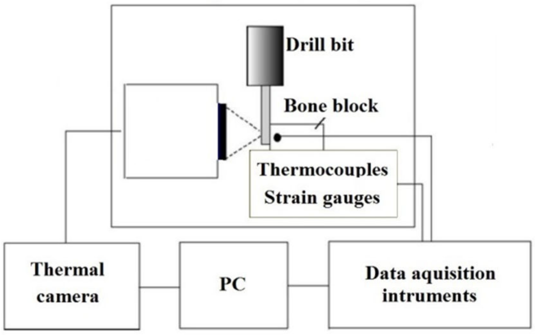


Fig. 3 - Experimental setup

All experiments started from room temperature (approximately 20 ºC - 23 ºC) and the drilling direction was perpendicular to the block axis (Figure 4). Between successive experiments, sufficient time was allowed for the block and the drill bit to return to initial conditions.

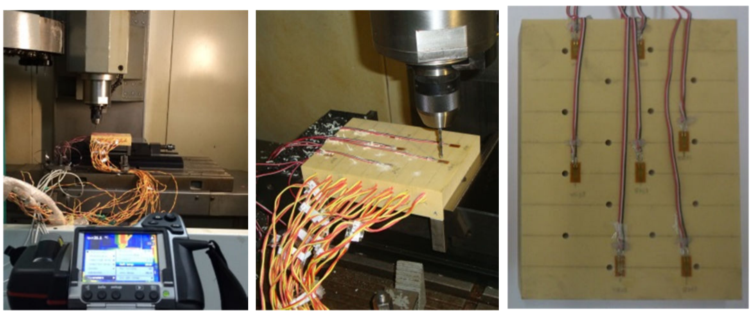


Fig. 4 -Drilling tests on blocks

FE model of drilling

Model overview and boundary conditions

A 3D FE model of the block drilling was established through the explicit dynamic finite element code, LS-DYNA (LSTC, Livermore, CA, United State), to calculate the thermo-mechanical stress of the bone during drilling. The first step of the solid model generation consisted in the construction of the cutting tool. The drill bit geometry was designed through the CAD software SolidWorks® (Dassault Systems S.A., France), considering the shape of the drill bit used in the experiments (Ø4 mm and point angle of 118º). The CAD model was later imported into ANSYS software for mesh generation. The bone was modelled with rectangular shape with the following dimensions: 14x10x4 mm and material properties similar to the blocks used in the experimental tests. The whole model is shown in Figure 5.

This kind of simulations involves high deformations and nonlinear material behaviour. It is important to consider a mesh sensitivity to obtain accurate results. The priority in this type of analysis was the bone region located in the immediate vicinity of the drilled hole. In order to reduce the computational cost, only this part was configured as a circular disc with 6 mm of diameter. A mesh discretisation was applied with a size equal to 0.5 mm for the finite elements edge in this area. In the remaining block was used a coarse mesh. The element type chosen for the numerical model was the 3D Solid 164 (8 nodes with three degrees of freedom at each node in X, Y, Z directions), only used for explicit dynamic analysis. The final model of the block and the drill bit was meshed with 20477 elements (Figure 5).

Following the experimental tests, boundary conditions were imposed on the block and the drill bit. The drill bit movement was explicitly simulated via a dynamic FE approach to rotate and move only about its own longitudinal axis (Y axis) with a specific drill speed (ω) and feed rate (V) vertically downwards into the block, as shown in Figure 5. Table 3 presents the drilling parameters used in all numerical simulations. The magnitudes for drilling speed and feed rate were varied over ranges used in the experimental tests. In order to include the effects of thermally induced stresses, the input temperature distribution as a load was defined during the explicit dynamic analysis. Through the temperature data obtained with thermocouples, the time temperature history was applied to a specific nodal component as a prescribed thermal load, producing the heating source effect inside of the block. The initial temperature of the block was set as 19 °C.

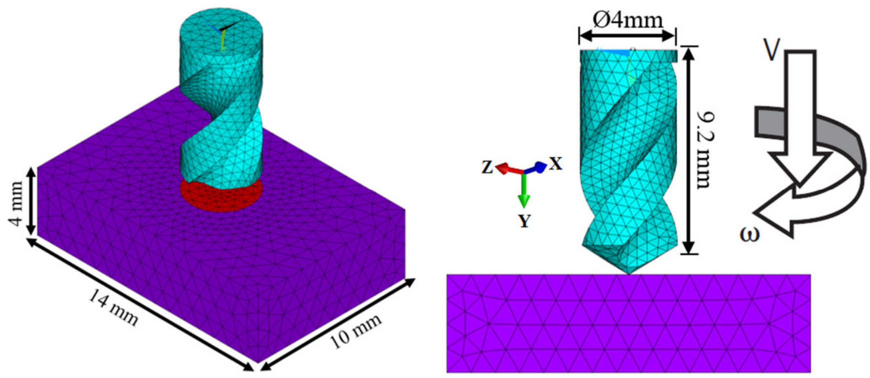


Fig. 5 - FE model of bone drilling

Table 3 - Parameters used in numerical simulations

Parameters	
Drill bit	Ø 4 mm, point angle 118º
Drill speed (ω)	600, 800, 1200 rpm
Feed rate (V)	25, 50, 75 mm/min
Initial temperature of block	19 ºC

Material models

It is well known that the FE simulation results are very sensitive to the material properties, and thus it is important to choose the most suitable material models in accordance with the analysis type. Materials subject to drilling are highly affected by large and high strain rates, which finally leads 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 the block. The strain rate effect is considered using the Cowper-Symonds model and the yield stress is defined with the following equation (Cowper and Symonds, 1957; ANSYS/LS-DYNA User's Guide, 2009):

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

where σy is the yield stress, σ0 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 Etan tangent modulus given by:

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

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 mechanical properties of the block material were obtained from the uniaxial tensile tests and have been comprehensively defined in our previous studies (Fernandes et al. 2015). The remaining material properties were taken from literature (Li et al. 2010; Sawbones Worldwide, 2013; Ranu 1987). The drill bit was assumed to be a rigid body, since its stiffness is much higher than the bone. This is a practice way to reduce computational cost and resources involved in the drilling simulation. All the material properties used in the numerical analysis are listed in Table 4.

Table 4 - Material properties used in drilling simulations

Properties		**Block**	**Drill bit**
Density (kg/m^3)		800	7850
Young's Modulus (GPa)		0.987	200
Poisson ratio		0.3	0.3
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	

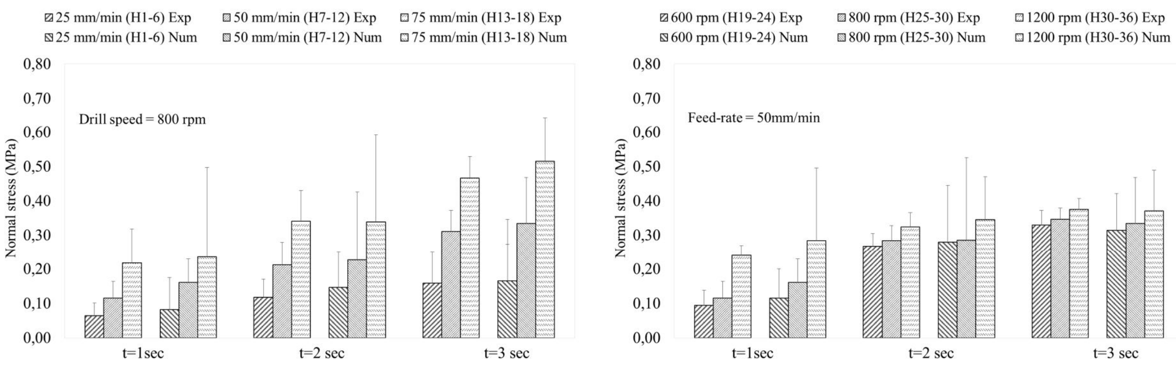
Contact interaction and failure criteria

The contact algorithm was *CONTACT_ERODING_SURFACE_TO_SURFACE, which is accessible in the LS-DYNA code (ANSYS/LS-DYNA User's Guide, 2009). This type of contact is used when a surface of one body penetrates the surface of another body. Eroding contact forms are suggested when solid elements involved in the contact definition are subject to erosion (element deletion) due to material failure criteria. The surface of the drill bit was classified as the contact surface. The target surfaces include all the block surfaces that will be contacted with drill bit. The friction behaviour between the drill bit and the block is assumed to be governed by Coulomb's friction law. In this case, for the frictional contact between the drill bit and the block a constant coefficient of friction of 0.3 was used (Tu el al. 2013; Mellal et al. 2004).

A failure criteria was applied to simulate the element removal and hole generation. As it was mentioned above, the approach of element erosion can be used to simulate the perforation when any element exceeds a specified plastic strain. These elements are deleted from the solution after they fail. Based on the bone properties, the failure strain reaching 0.05 is adopted as the criterion in the erosion algorithm implementation for the numerical simulation. Dynamic analysis was used with the simulation range subdivided into 15000 time increments of 8.0×10^{-4} seconds. ANSYS/LS-DYNA requires very small time steps with many iterations to ensure stability of solution. Each simulation took about 68 hours to execute on a workstation with a quad-core Intel I7-4790k with 16 GB RAM.

RESULTS AND DISCUSSION

The ability to measure the thermo-mechanical stress is crucial to predict the behaviour of bone tissue during drilling and also to aiding in developing predictive capabilities by verifying models. Most of numerical methods, which are not well-known in the drilling fields, are based on simplistic models and do not incorporate the dynamic characteristics involved in the process. The results presented in this study provide information on the thermo-mechanical stress, considering the effect of drill speed and feed-rate. In the numerical model different simulations with the same parameters used in the experimental tests were performed. For each feed-rate were chosen different drilling times, considering the complete depth of the block (4 mm). In order to evaluate and compare the bone drilling results in both methods, the average of normal stresses was calculated experimentally and compared with the numerical results at different times instant of drilling. The distance between the edge of the drilled hole and the linear strain gauge was considered on the selection of the nodal points in the numerical model. Figure 6 shows the mean and standard deviation of normal stresses obtained in both methods (stress component in Z direction for numerical model and stress from the linear strain experimentally measured), at different times of drilling. The drill speed was fixed at the value of 800 rpm to measure the effect of feed-rate and fixed at the value of 50 mm/min to measure the effect of drill speed.



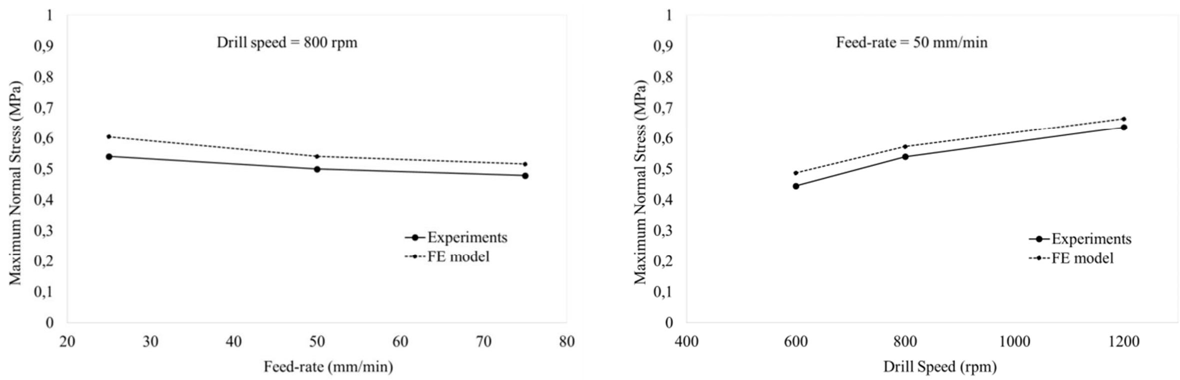
(a) (b)

Fig. 6 - Variation of normal stress (MPa) with (a) feed-rate and (b) drill speed, at different times of drilling

Experimental and numerical results indicate that the normal stress in drilling process increases with the increasing of feed-rate and drill speed, for the same time instant. It can also be observed from Figure 6 (a) and (b) that the level of normal stresses increases with the tool penetration, reaching a maximum value when the drill bit penetrated completely the block.

The greater of the drilled hole depth, the greater the normal stress in the bone block. However, this difference was more evident with regard to the feed-rate (Figure 6 (a)). This may be explained in part by the differences between drilling depths at different feed-rates. For the same time instant, the holes made with a feed-rate equal to 75 mm/min reach a higher depth than feed-rates equal to 25 and 50 mm/min. Most important than analyse the behaviour of the bone tissue at different drilling times is the analysis of its behaviour at final of the process.

The effect of feed-rate and drill speed for the complete penetration of the block was examined. The average of maximum normal stress was calculated and compared for different feed-rates and drill speeds, as represented in Figure 7 (a) and (b), respectively.



(a) (b)

Fig. 7 - Variation of maximum normal stress (MPa) with (a) feed-rate and (b) drill speed

Analysing the entire process, it was observed that the maximum normal stress maintained the same behaviour with respect to the drill speed. Regarding to the feed-rate, 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 experimental and FE models gave similar results.

The drilling depth of 3 mm was chosen to show the von-Mises stress distribution at different feed-rates and drill speeds in the numerical simulations. Figures 8 shows the contours of von-Mises stress distribution in the bone drilling for the feed-rate 25, 50 and 75 mm/min and drill speeds of 600, 800 and 1200 rpm, respectively.

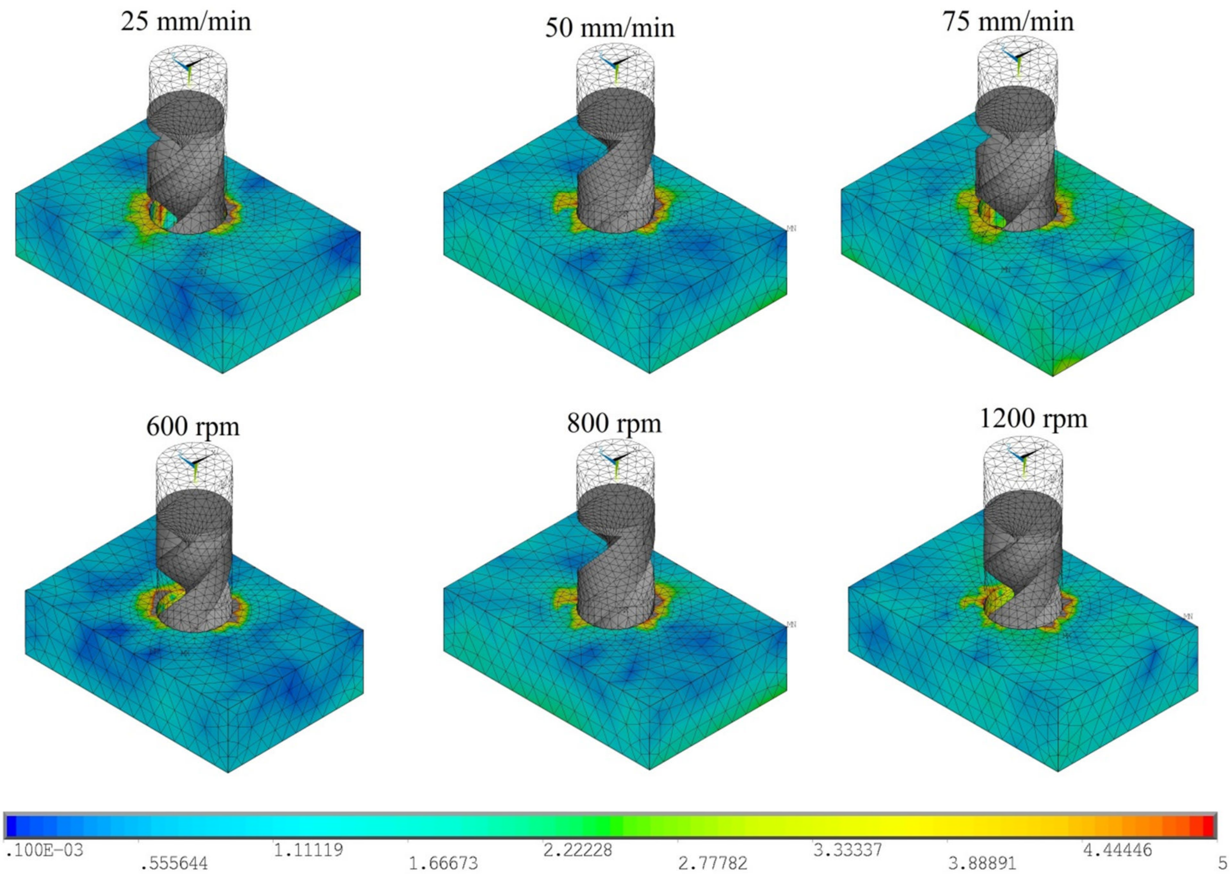


Fig. 8 - Distribution of von-Mises stresses (MPa) at different feed-rates and drill speeds (3 mm of depth)

It can be seen from Figure 8 that the maximum values of the von-Mises stress obtained from the different drilling parameters are around 5 MPa and maintained the same trend. It is also important to point out that the maximum values of von-Mises stress, for all numerical simulations, were verified in the drilled zone and its immediate vicinity, exceeding the 5 MPa. During the simulation, the elements in the drilled hole were removed when the yield stress and the plastic strain failure in the material were reached.

CONCLUSIONS

A three-dimensional thermo-elastic-plastic dynamic model to simulate the drill bit penetration into the bone tissue was developed. Thermo-mechanical stress involved in the drilling processes were obtained and compared with experimental tests. The effect of the generated temperatures has been taken into account in the numerical simulations. Based upon the obtained results, the following conclusions can be drawn:

- The thermo-mechanical stress generated in the material increasing with tool penetration and, consequently, with increasing of hole depth.
- The normal stresses tend to decrease when the feed-rate is higher and increase when the drill speed is higher.
- The maximum values of von-Mises stress are found in the drilled zone and its immediate vicinity for all situations.

- The results presented here demonstrate that the experimental methodology coupled to the developed numerical model are an effective procedure for evaluating thermo-mechanical behaviour of the contact region between the drill bit and bone.

ACKNOWLEDGMENTS

This research was supported by the Portuguese Foundation of Science and Technology under the research project UID/EMS/50022/2013. The third author acknowledges the funding of Project NORTE-01-0145-FEDER-000022 - SciTech - Science and Technology for Competitive and Sustainable Industries, cofinanced by Programa Operacional Regional do Norte (NORTE2020), through Fundo Europeu de Desenvolvimento Regional (FEDER).

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