
M2D2017
Albufeira, 11-15 June 2017


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Shaker A. Meguid
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EURASEM-European Society for Experimental Mechanics

SEM-American Society for Experimental Mechanics

JSME-Japanese Society of Mechanical Engineering

IMEKO-International Measurement Confederation

AFM-Association Française de Mécanique

DYMAT-European Association for Dynamics of Materials

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Editors Preface

M2D2017 is the seventh international gathering of a prestigious series of conferences coordinated by the International Scientific Committee of Mechanics and Materials in Design. This series of conferences is wholy devoted to advances in mechanics, materials, structural integrity and design. M2D2017 is sponsored by the University of Porto, the University of Toronto and the University of Algarve. The conference attracted over 230 participants with 360 accepted submissions from 40 countries out of 416 submissions. These papers were presented in June 11-15, 2017 in the magnificent city of Albufeira/Algarve, Portugal. The conference themes which address novel and advanced topics in Mechanics and Materials in Design focused on computational mechanics, experimental mechanics, fatigue and fracture mechanics, composite and advanced materials, nanotechnologies and nanomaterials, tribology and surface engineering, mechanical design and prototyping, biomechanical applications, civil engineering applications, impact ant crashworthiness, energy and thermo-fluid systems, and industrial engineering and management.

The conference also included an Open Forum on *The Challenges Facing Engineering Education*, where an expert panel with over 100 years of collective and active researchers and educators addressed the roles of professors that they meet, the obligations of their stakeholders and current challenges facing engineering education.

We believe that the meeting offered our delegates a forum for the dissemination of their recent work in mechanics and materials and their applications in engineering design, 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 more than 360 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 discussions. We are also indebted to the outstanding keynote speakers who highlighted the conference themes with their contributions. We also take this opportunity to thank the members of the International Scientific Committee, the members of the Advisory 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, M2D2017 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 (Integrity, Reliability and Failure - IRF2018) will take place in Lisbon, the capital city of Portugal, in July 2018. Undoubtedly, we expect IRF2018 to be as stimulating and interesting as M2D2017, as evidenced by the excellent contributions offered in this current event. We look forward to seeing all of you in Lisbon in 2018.

Shaker A. Meguid and J.F. Silva Gomes

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INFLUENCE OF DRILL BIT DIAMETER ON DRILLING OF POLYURETHANE FOAMS

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ABSTRACT

Drilling is one of the most common processes involved in machining operations. The usual requirement is the efficient material removal. However, when it comes to the living tissues, drilling assumes greater attention to ensure a minimally invasive procedure. This work describes conventional drilling experiments performed on solid rigid polyurethane foams with similar mechanical properties to the human bone. An extensive experimental study was conducted to evaluate the effects of different drill diameters (4, 5 and 6 mm) on the temperature rise and stresses generation during drilling process. Different experimental tests were performed to assess their repeatability. Results from the experiments suggest that both drilling temperatures and stress level increased with increase in the drill tool diameter.

Keywords: polyurethane foam, drilling, drill diameter, temperature, stress, damage.

INTRODUCTION

Drilling is a mechanical process in which a drill bit revolving on its own axis that is called the drilling axis creates a cylindrical cavity in the material by applying axial load on the rotating drill. This mechanical action between the drill and that material affects the surface properties in different aspects (Shingh et al. 2016). It is a known fact that this process generates high mechanical efforts and high temperatures due to high contact friction between the drill bit and the material (Franssen et al. 2008; Bertollo et al 2010). An excessive increase in this values can endanger the integrity of the material and the quality of the process. Nevertheless, when the drilling concepts are applied on the living tissues, the precautions for a minimally aggressive technique requires augmented attention.

Currently, bone drilling is increasingly demanded in various types of surgery operations. Every day around the world, drilling procedures are carried out in hospitals across most medical surgeries like orthopedic surgery, ear surgery, maxillofacial surgery, neurosurgery, and many others. Only in dentistry, more than 700,000 implants are inserted every year, increasing these numbers (Haswell 2009; Soriano et al. 2014). The postoperative success of this surgeries is largely dependent on the damage degree induced by the drilling process. It is known that the most common problems associated to the bone drilling are mechanical damage (Brett et al. 2004; Kendoff et al. 2007), heat generation (Augustin et al. 2008), crack formation (Alam et al. 2016), irregular surface topography of drilled walls and even bone necrosis (Singh et al. 2016). These damages may lead to failure of the joint and the implant.

For instance, recent publications have indicated that the implant failure rate for thermal osteosynthesis of lower leg is 2.1%-7.1% (Augustin et al. 2008; Augustin et al. 2009; Augustin 2012). Therefore, the importance of reducing the bone damage risk is becoming clearer and it is visible in the large increase of recent published works (Fernandes et al. 2015; Fernandes et al 2016; Singh et al. 2016; Fernandes, Fonseca et al. 2017; Fernandes, Natal et al. 2017).

Despite the efforts and the progress in the improvement of drilling processes, bone drilling continues to be undertaken by hand drills, which means a blind operation with unknown hole depth and a feed-rate manually controlled by the surgeon. The scientific developments in this area have shown some remarks on bone drilling processes, particularly as regards of the drilling parameters. For instance, in dental practice is recommended the use of irrigation during implant site preparation and the drill speed is recommended by the manufacturer of the implant system (Bogovič et al. 2016). However, the drilling force depends on the dentist sensitivity and experience. The drill bit diameter is, to a large extent, the only parameter that can be more or less chosen by the surgeon, according to the quality and quantity of the bone and the size of implant that is to be inserted.

According to Pandey and Panda (2014), the drill diameter is highlighted as significant factor for heat generation than cutting speed and feed rate, because increase in surface contact area permits more frictional heat generation (Jamil et al. 2016). Frictional heat generation induces temperature gradients and thermal stresses in the bone and surrounding tissue. Therefore, it is critical to understand and explore appropriate drill diameters to minimize bone damage for safe and efficient bone cutting.

Experimental, analytical and numerical studies have been used by many researches to study the influence of drill bit diameter (Sener 2009; Pandey and Panda 2014; Bogovič et al. 2015; Pandey and Panda 2015; Bogovič et al. 2016). However, most of the published work accounts only the effect on the heat generation. There is a lack of information with regard to the strain and thermal stresses distribution during bone drilling. Even about the thermal damage, there still remains a lack of consensus in the literature regarding critical temperature values and their durations (Bertollo N and Walsh 2011).

The main focus of the present study is to contribute in the reduction of the mechanical and thermal damage during bone drilling procedures. Therefore, the goal was to measure the influence of drill bit diameter, relative to the known influence of drill speed and feed-rate on the heat and stress generation during drilling. An experimental procedure was conducted on solid rigid polyurethane foam materials as an alternative for human bone. The foams were instrumented with strain gauges to measure the level of strains on the surface during the drilling process. Simultaneous, the temperature distribution inside of the foam and on the external surface of the drill bit was measured with thermocouples and thermography equipment.

The findings of this study complement the previous researches developed by the authors of this work (Fernandes, Fonseca et al. 2015; Fernandes, Fonseca and Jorge 2015; Fernandes, Fonseca and Natal, 2016; Fernandes, et al. 2016; Fernandes, Fonseca and Jorge 2017; Fernandes, Natal et al. 2017; Lopes, Fernandes et al. 2017). The used experimental methodologies to analyse the effect of drill bit diameter are an important contribution in the improvement of drilling processes and in the development of numerical models.

EXPERIMENTAL TESTS

Bone model

The workpiece used in this study was polyurethane foam, as an artificial bone block (from Sawbones, Pacific Research Laboratories, Inc., Vashon. WA, USA) used as an alternative material to cortical bone due its consistent and homogeneous structural properties (Kim et al. 2012; Liu et al. 2016). These blocks are approved by the American Society for Testing and Materials and are recognized as a standard material for testing orthopaedic devices and instruments, making them ideal to replace human bone in the drilling tests. The sample was supplied in rectangular shape with the dimension of 130x180x40 mm and the material has a closed cell with density of 0.80 g/cm^3.

Methodologies and equipment

In order to study the influence of different drill bit diameters in the temperature and stress generation during drilling, two different measurement systems were applied. In the first one, a set of linear strain gauges (1-LY18-6/120, 120Ω ± 0.35% from HBM) were installed on the surface of the foam block to measure the level of strains during the drilling. The surface of block was properly clean and the locations of the holes were marked to keep a distance of 3.5 mm, between the edge of the hole and the strain gauge (Fig. 1). The strain gauges were properly connected to the quarter bridge in a data acquisition system (Vishay Micro Measurements P3 Strain Indicator and Recorder), which made it possible to read the strains on different material positions along the time, for each used twist drill diameter (4, 5 and 6 mm).

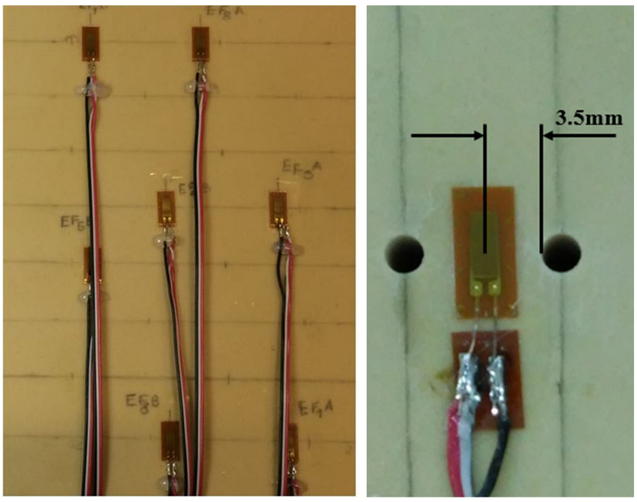

Fig. 1 - Location of the linear strain gauges

The other system consists in the use of one K-type thermocouple to measure the bone block temperature and a thermal camera to measure the drill bit surface temperature. The thermocouple was inserted into a hole (Ø2 mm and 4 mm in depth) and placed at distance of 2 mm from the edge of drilling track (Fig 3 (a)). By using a data logging thermometer (Extech SDL200: 4-Channel Datalogging Thermometer) the temperature monitoring inside of bone block was performed during machining process.

A factory-calibrated Thermal Imaging Camera (ThermaCAM 365, FLIR Systems) was rigidly fixed to a tripod at distance of 1.5 m from the drilling zone and allowed to record two thermal images for each drilling event. The first image was taken of the site immediately prior to the beginning of drilling. A second image was taken at the point where the drill bit penetrated the 30 mm of depth. The thermal images were analysed using an appropriate software (FLIR QuickReport Software, FLIR Systems).

Experimental setup and drilling parameters

The experimental trials have been designed to analyse the influence of different drill bit diameters on the heat and stresses generation during drilling. For this purpose, three different drill diameters (4, 5 and 6 mm) were selected. All drills used in these experiments were conventional twist drill bits (stainless steel) with point angles equal to 118º and helix angles of 30º (Fig. 2). A drilling depth of 30 mm was set for each diameter.

Fig. 2 - Drill bit diameters used in this study: (a) 4 mm, (b) 5 mm and (c) 6 mm.

The remaining drilling parameters were chosen based on our previous studies, where it was concluded that the higher feed-rate and lesser drill speed lead to a decrease in temperature and stresses on bone tissue (Fernandes, Fonseca et al. 2015; Fernandes, Fonseca and Jorge 2017). Thus, the drill speed was kept at 600 rpm and the feed-rate was 1.25 mm/s (equal to 75 mm/min) with perforations of 30 mm depth. The processing parameters are summarized in Table 1.

Table 1 - Working conditions

Diameter drill head (mm)	4, 5 and 6
Point angle (º)	118
Helix angle (º)	30
Drill speed, *n* (rpm)	600
Feed-rate, *f* (mm/s)	1.25
Hole depth (mm)	30
Cooling system	No coolant
Machine-tool	CNC controller

All drilling tests were performed in Mechanical Laboratory at Polytechnic Institute of Bragança using a computer numerically controlled machine system. Experiments were performed at room temperature without any cooling method. The overview of the experimental setup used in this study is shown in Fig. 3 (b).

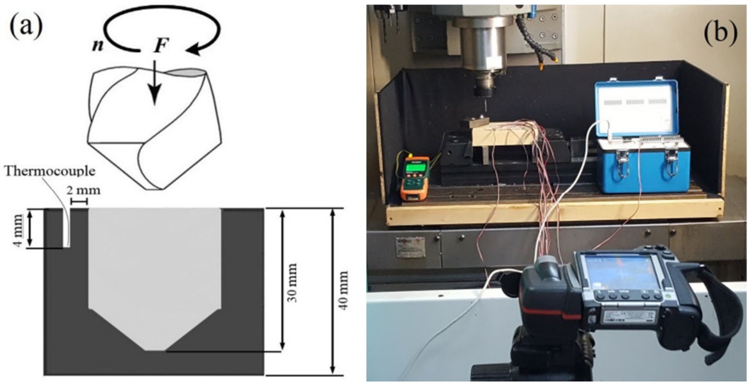

Fig. 3 - (a) Scheme of the block sample during the drilling process and (b) general experimental setup

RESULTS AND DISCUSSION

Measured strains and stress calculation

Strain measurements were taken continuously during each step of the drilling until the drill bit reached the 30 mm of depth. The strain measurements were recorded and the mean values were evaluated for each strain gauge based on the different drill bit diameters. Fig. 4 shows the typical curves of strain versus hole depth measurements.

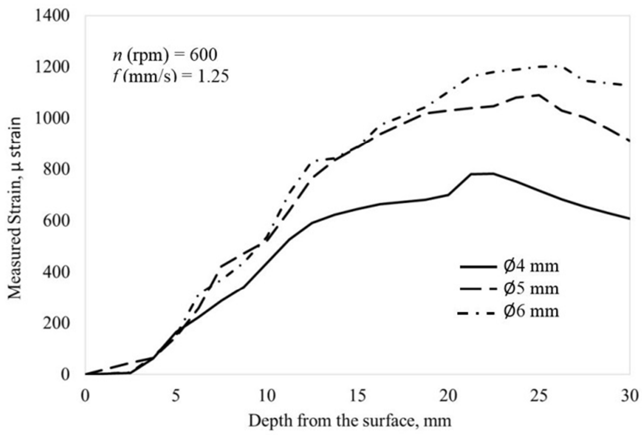

Fig. 4 - Variation of strains vs. hole depth according to the different drill diameters

Results showed that all drill bit diameters presenting similar trends of strain vs. hole depth curves. The generated strains in the bone block increased with tool penetration, reaching a maximum value when the drill bit penetrated completely the hole. It can therefore be concluded that the greater of the drilled hole depth produces high strain values generated in the block.

After analysing the profile of strain vs. hole depth from the block surface, it is also important to analyse the generated stress according each drill diameter. The stresses were calculated using the Hooke law equation, considering the Young modulus equal to 0.987 GPa. The mechanical properties of the bone block were obtained from the uniaxial tensile tests and have been comprehensively defined in our previous studies (Fernandes et al. 2015). Fig. 5 presents the calculated average of the maximum stress for all experiments.

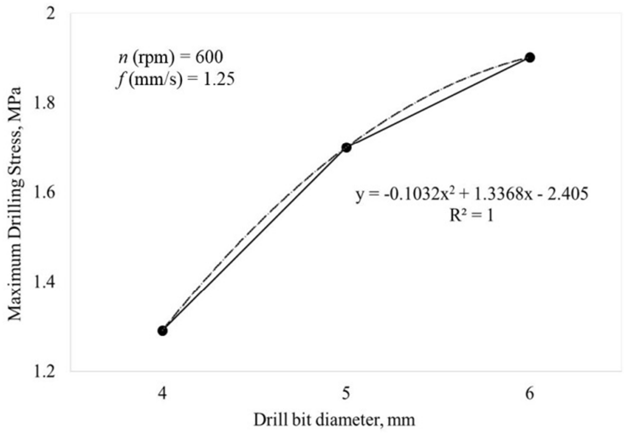

Fig. 5 - Maximum stresses (MPa) according to the drill diameters.

Fig. 5 shows the effect of drill bit diameter on the average maximum stress. It can be concluded from the polynomial trendline (order 2) that smaller drill diameter at constant feed-rate (1.25 mm/s) and drill speed (600 rpm) leads to a decrease in the stresses generation in bone block during drilling. Comparing the levels of stress, it was observed that when the drill diameter was increased from 4 to 5 mm the stress increased by 31.61% and when the drill diameter was increased from 5 mm to 6 mm the stress increased by 11.88%. With the R-squared = 1 is guaranteed a good approximation for any drill bit diameter in the observation range.

Measured temperatures

The recorded temperatures inside of bone block and drill bit surface are given under this section. As regards the heat generated inside of bone block, temperature measurements were also taken continuously during each step of the drilling procedure and for 56 s afterwards. This time allowed stabilization of any temperature fluctuations caused by the drilling process. The Fig. 6 represents the temperatures obtained over time for three holes in the bone block, considering the three different drill diameters.

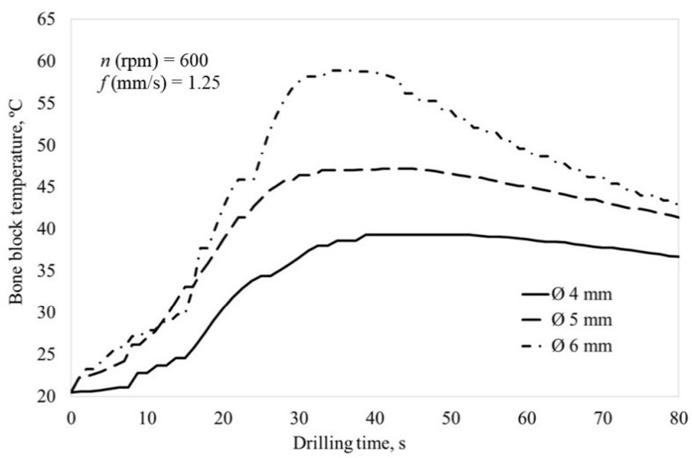

Fig. 6 - Bone block temperature vs. drilling time, according to the different drill bit diameters

It can be observed from Fig.6 that the maximum temperature decreases with the decreasing of drill bit diameter. Maximum temperature of 58.9 ºC is found at drill diameter of 6 mm for a constant drill speed of 600 rpm, and a feed-rate equal to 1.25 mm/s. It is known that high temperatures on the living tissue causes damage and even cell death. It has been shown that heating above 55°C for a period longer than 30 seconds causes irreversible change to the physical bone properties (Hillery and Shuaib 1999). However, an effect not simulated by the current experimental setup is the moderating thermal effect of blood flow, where blood perfusion tends to lower the locally elevated temperature. Based on the thermal histories, it was found that all curves show a similar trend with time; first an increase in time, reaching a peak (maximum) value, and then a slow decay.

The maximum values average of bone block temperature for all test were also calculated, as well as, the temperature variation on the external surface of drill bit. In the Fig. 6, graph (a) represents the mean values of maximum generated temperature inside of bone block and graph (b) represents the recorded temperature variation (ΔT) on the drill bit surface. The ΔT was calculated and compared, subtracting to the recorded temperature, the initial temperature of the drill bit.

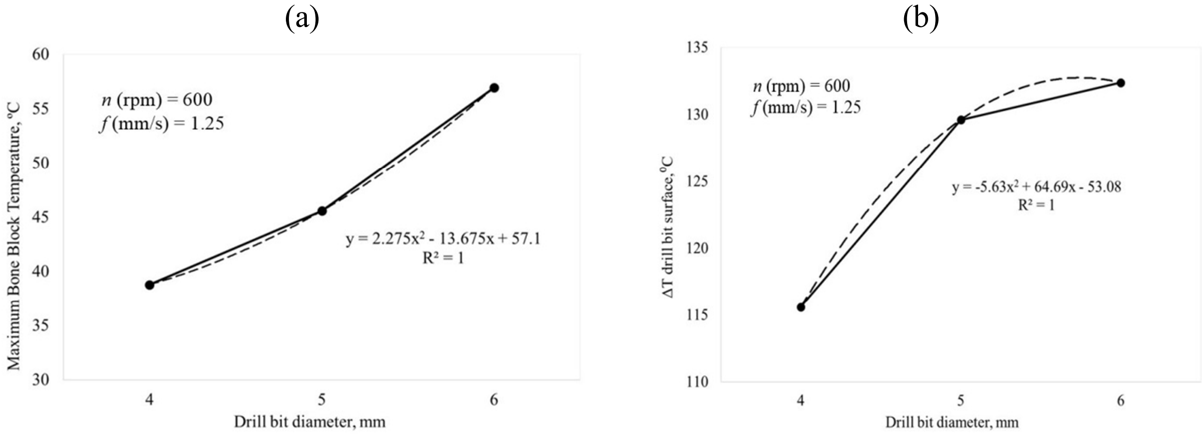

Fig. 7 - Recorded temperatures: (a) inside of bone block and (b) temperature variation on drill bit

In terms of recorded temperatures, it was also noted that the higher drill diameter leads to an increase of the drilling temperatures on the bone block and drill bit, following the same trend of the stresses analysed before.

In Fig. 7(a), bone block temperature increased 17.53% with increased drill diameter from 4 to 5 mm and when the drill diameter was increased from 5 to 6 mm the bone block temperature increased by 24.89%.

In Fig. 7(b), ΔT increased 12.13% with increased drill diameter from 4 to 5 mm and 2.19% with increased drill diameter from 5 to 6 mm.

Also in this case, an order 2 polynomial trendline illustrate a good relationship between the drill bit diameter and the recorded temperatures obtained from the tests. The same trend can be found in others studies using bovine and porcine bones (Bogovič et al. 2015; Gupta and Pandey 2016).

CONCLUSIONS

Thermal and mechanical damage can significantly affect the bone tissue and compromise the success of the drilling surgeries. It is important the development of methodologies that analyse not only the thermal effects but also the strains and generated stresses during bone drilling. This paper presents an experimental methodology that includes strains, stresses and temperatures determination during the bone machining process, using different drill bit diameters.

The findings of the study can be summarized as follows:

- the strains and stresses increase with the tool penetration and, consequently, with increasing of hole depth;
- the maximum values of stresses are found for the higher drill bit diameter;
- an increase in drill bit diameter increases the contact surface between the tool and the material, which leads to a higher energy input for cutting the material and, consequently, an increase of heat generated on the bone block and drill bit.

The topics dealt in this study bring an important role to help in the safety enhancement and quality of the drilling surgeries and support the specialists or surgery robot systems to their automated assist solution.

ACKNOWLEDGMENTS

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