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TEMPERATURE ASSESSMENT IN THE DRILLING OF COMPOSITE MATERIALS AND EX-VIVO PORCINE BONES

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Abstract. *This study presents different experimental methodologies for analysis and temperature evaluation during the drilling process of composite materials and ex-vivo porcine bones. In the experimental methodologies were evaluated the influence of different parameters on the bone temperature rise. The combinations of different parameters produced temperatures far below the critical values. It was concluded that drill temperature decreases when the feed-rate is higher and, independently, increases with the increasing of hole depth. The influence of drill speed is not clear. In the composite materials the temperature decreases in the drill bit when the drill speed is higher, and in ex-vivo porcine bones happens the opposite. The animal models recorded lower temperature values than composite materials.*

1 INTRODUCTION

The bone cutting is a procedure widely used in medicine, including orthopaedic, dental and neuro surgeries. The success of this surgeries is dependent of many factors and also in temperature generation during the drilling bone. When an excessive heat is produced during the drilling bone the thermal necrosis can occur, and the bone suffers injuries. Eriksson and Albrektsson indicated that thermal necrosis in cortical bone from living rabbits occurred when this one reached a temperature of 47 ºC for 1 minute. Other authors showed that temperature values above 55 ºC for a period longer than 30 seconds can cause great irreversible lesions in bone tissue. The main goal of many researchers has been finding one way for reducing the heat generated in drilling processes. Studies have shown that the increased temperature is directly related with the cutting parameters, particularly, the drill speed, feed-rate, applied force, the hole depth, the geometry of the drill bit, the use or not of a cooling system and also the type of bone. The heat generated from the contact between the cutting tool and the bone tissue, during the bone drilling in surgical operations has been a known problem for years. The increase of heat is caused by friction of the cutting surface of the drill bit in contact with the bone tissue and converts the applied cutting energy into heat energy that causes necrosis and combustion of bone tissue, which means the irreversible death of bone cells [1]. The post-operative success of these surgeries is widely conditioned by the temperature generation and the level of damage in the bone tissue during the drilling operation [2]. The reduction of damage in bone surgeries is very important to the reduction of rejected implants, to increase the capacity of bone regeneration and decrease the patient recovery time [3, 4]. Currently, it is known that the heat generation in the drilling process is associated to drilling parameters. Thus, it is important to understand and to improve the drilling conditions and all the involved variables, to reduce the heat generated and consequently minimize the bone damage. The analysis of the temperature changes during drilling has been examined in animal models and in specific materials with similar properties to the human bone tissue [5]. Several studies have focused on measuring temperature distribution during bone drilling, where thermocouple measurements is most frequently choice. However, the uncertainty in sensor placement and the heat conduction within the sensor, where the thermal conductivity of the bone is two orders of magnitude smaller than that of the thermocouple wires, can be a problem [6]. An alternative method of measurement is the thermography technique that allows surface measurements in the cutting tool and bone.

In this study, the combined of two experimental methodologies has been executed by considering the effects of drill speed, feed-rate and hole depth on the maximum temperature during drilling of several fresh porcine bones and composite materials. Different drill speed were used in the experimental tests: 600, 800 and 1200 rpm; feed-rates of 25, 50 and 75 mm/min and a drill bit with 4 mm of diameter. In both methodologies, a thermographic camera was used to capture the surface temperature in the drill bit.

2 EXPERIMENTAL METHODOLOGIES

In order to keep the bone necrosis to a minimum level, two experimental methodologies were used to evaluate the temperature during the drilling processes of different materials with different drilling parameters. In the first methodology, composite materials with similar density to the human bone were used and in the second one, an *ex-vivo* study was performed by considering the porcine femur bones. Both methods were performed in the Mechanical Laboratory at IPB-ESTiG (Polytechnic Institute of Bragança), using a computer numerically controlled (CNC) machine system with total control of the involved parameters.

2.1 Drilling process of composite materials

To the drilling operations in composite materials, three composite blocks were chosen with similar mechanical properties to the human bone. The composite blocks have the following dimensions: 130x180x40mm [7].

In order to evaluate the temperature in cutting tool, a thermographic camera (ThermaCAM 365, FLIR Systems) at a distance of 1.5 m from the drilling area was used. The thermal camera allowed to obtain thermal images before and after of drilling process (Figure 1) [8]. Several holes were made using a conventional drill bit with 4 mm of diameter, 30 mm of depth and a point angle equal to 118º. In order to evaluate the influence of the drill parameters, a set of three different drill speeds and three different feed-rates were considered (Table 1). The other parameters were considered as a constant in all experiments.

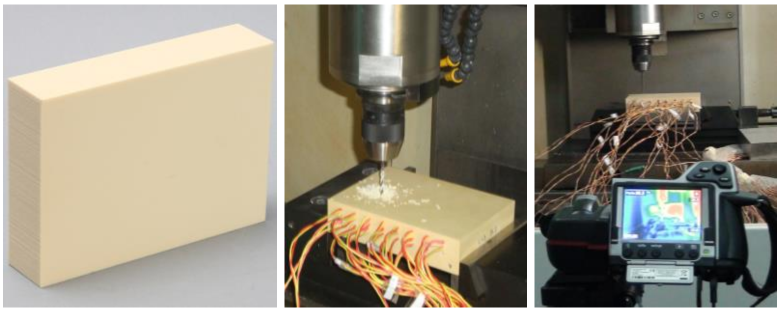

Figure 1: Drilling operations of composite materials.

2.2 Drilling process of *ex-vivo* porcine bone

Through three samples of porcine femur was elaborated an *ex-vivo* study to evaluate the temperature in the cortical bone tissue. The fresh porcine bone was chosen due to its mechanical properties similar to human bone [9]. The bone samples were obtained from a local butchery, after animal death from animals processed for food industry (no animals were sacrificed specifically for the purpose of the current study). The samples have been previously cleaned (muscle removed), as shown in Figure 2.

In order to retain the mechanical and thermo-physical properties, the samples were prepared according to the guidelines established by Yuehuei and Robert [10]. All samples were kept moist in saline solution with gauze swabs and stored in plastic bags at -4ºC, before the tests. To realize the experiments, the periosteum was removed from the outer surface of the bone samples, as it clogs the drill flutes [11]. All the epiphysis were removed and the mid-diaphysis columns were obtained using a hacksaw (Figure 2). Also the bone marrow was removed, leaving only the cortical tissue [12].

(a) (b) (c)

Figure 2: (a) fresh bone; (b) sample cut from mid-diaphysis and (c) sample with gauze swabs.

The porcine samples present the approximate dimensions of 7-9 mm in length with an average thickness of the cortical wall of 4-6 mm. All samples were divided to accommodating several drilled holes.
In order to compare the obtained results in composite materials with *ex-vivo* bones, the same parameters and cutting tool were used during the tests (Table 1).

Table 1: Parameters of drilling.

Parameters	**Composite materials**	***Ex vivo* porcine bones**
Drill diameter (mm)	4	4
Drill point angle (degrees)	118	118
Depth of the holes (mm)	30	5
Drill speed (rpm)	600, 800, 1200	600, 800, 1200
Feed rate (mm/min)	25, 50, 75	25, 50, 75

As it was tested in the composite materials, only the thermographic camera was used to measure the temperature in drill bit, before and after of drilling process in *ex-vivo* porcine bones. The holes were carried out at room temperature without cooling.

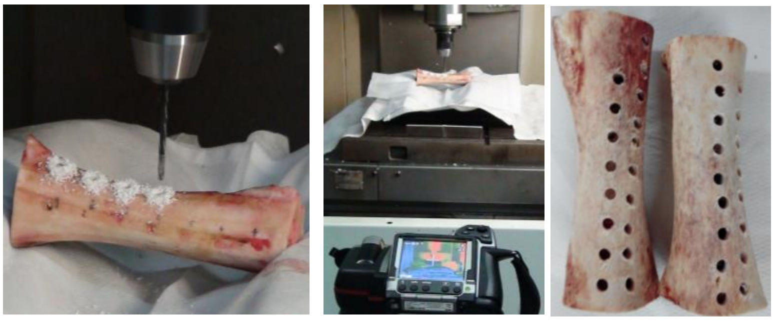

Figure 3: Experimental setup of bone drilling.

3 RESULTS AND DISCUSIONS

To evaluate the generation of temperature in bone tissue it is important to take into account that the inherent variation in mechanical and thermal properties of specimens taken from different bones in the animal, and from different animals of the same species, results in variations in the measured temperature subject to virtually identical drilling conditions in repeated experiments [6]. In this study three samples of femurs porcine bone from three different animals and three composite blocks were used to measure the temperature. During drilling of the bone, the cortical tissue is the main part of the bone that generates higher temperatures. The current study aims to realize an experimental investigation of the effects of drill speed, feed-rate and hole depth, on the temperature distribution in the cutting tool during drilling of the cortical section of the porcine femurs and composite materials.

Evaluation tests were performed under two representative sets of drilling conditions: the first one, the holes were performed with feed-rates of 25, 50 and 75 mm/min and a constant drill speed of 800 rpm and the second one with drill speeds equal to 600 and 1200 rpm and a constant feed-rate of 50 mm/min. The tests were repeated several times for each set of conditions and for both methodologies. The Tables 2 and 3 present the mean values of the temperature in the tool cutting, obtained in different tests.

Table 2: Temperature variation from drill bit, before and after drilling, in composite materials.

Composite materials				
Drill speed [rpm]	Feed-rate [mm/min]		ΔT [ºC]	
			Mean ± SD	[Range]
600	50	(n=6)	102.75 ± 14.16	[77.80-115.80]
1200	50	(n=6)	87.45 ± 7.25	[76.20-97.0]
800	25	(n=8)	86.81 ± 9.20	[76.70-102.60]
	50	(n=7)	72.73 ± 9.69	[55.80-84.40]
	75	(n=8)	63.69 ± 6.63	[51.20-70,80]

n number of the holes, *SD* Standard deviation, *ΔT* Temperature variation

Table 3: Temperature variation from drill bit, before and after drilling, in *ex-vivo* porcine bones.

***Ex vivo* porcine samples**				
Drill speed [rpm]	Feed-rate [mm/min]		ΔT [ºC]	
			Mean ± SD	[Range]
600	50	(n=7)	28.22 ± 6.20	[20.4-34.20]
1200	50	(n=7)	36.60 ± 3.49	[31.0-41.20]
800	25	(n=7)	26.42 ± 6.51	[15.90-33.90]
	50	(n=5)	18.36 ± 1.82	[16.10-21.10]
	75	(n=7)	18.87 ± 1.46	[16.80-20.80]

n number of the holes, *SD* Standard deviation, *ΔT* Temperature variation

Comparing the results obtained in the Tables 2 and 3, it was found that the temperature in the cutting tool is higher in holes made in composite materials, when compared with holes in *ex-vivo* porcine femurs. These results were expected, since the holes depth in the composite materials (30 mm) is higher than in *ex-vivo* bones (5 mm). In addition, the composite materials have a constant geometry over the whole model while the samples of porcine femur have an irregularly geometry, with different cortical thickness along its diaphysis.

In both studies it can be observed that maximum temperature in the cutting tool decrease with the increasing feed-rate. This observation is consistent with the literature, where increased of feed-rate was seen to reduce the drilling temperatures during bone drilling [5, 6, 8, 12]. Regarding the drill speed it was found there is not agreement between composite materials and bone samples. In composite materials, the maximum temperature in the cutting tool decreases with the increase of drill speed but in the porcine samples it is just the inverse. Also, in the literature it is not found agreement among different authors [13]. This can be explained by the fact that the increase of drill speed increases the friction energy generation due to the friction forces acting on the rake face of the drill bit (close to the cutting edges). Since a majority of this energy is converted into heat, it is reasonable to expect increased temperatures at higher drill speeds [14], as it is supported by the results from *ex-vivo* study. However, with higher drill speeds, the chips are moving faster away from the cutting zone, which results in a higher heat transfer rate from this zone with the stream of chips; this stream generates an apparent cooling effect [6]. While this cooling effect is not sufficient to reverse the trend due to the increased friction energy, it may be responsible for different results with different materials.

4 CONCLUSIONS

In the present study were used experimental methods to investigate the effects of feed-rate, drill speed and hole depth on temperature generation of cutting tool during drilling in porcine femur models and composite materials using a thermography technique. In general, it was found that the maximum drill temperature increased with the increasing of hole depth and, independently, decreases with the increasing feed-rate.

Comparing the results for different drill speeds, it was verified does not exist a consistent trend. In the composite materials was found that higher drill speed produces lower drill temperatures and in the porcine femur models happens the opposite. In this study the obtained values of temperature in the drilling process of *ex-vivo* cortical tissue from porcine femurs were lower than the drilling process of composite material.

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