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1           **An analytical modelling with experimental validation of bone**  
2                                   **temperature rise in drilling process**

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16

17

18 **ABSTRACT**

19

20 Predicting the bone thermal response in a surgical operation remains a major  
21 challenge. In the previous works, metal machining theory has frequently been used to  
22 predict bone temperature in drilling process. However, several experimental studies  
23 demonstrate that the chip formation process is very complex compared to metal  
24 cutting. In the present study, a simplified analytical model based on the moving heat  
25 source approach combined with the method of image sources is developed. The heat  
26 source due to the drill-bit tip was supposed to be proportional to the cutting energy.  
27 The friction at the tool-hole contact was also considered. An experimental study was  
28 performed on fresh femur pig bone for cutting speeds from 2 to 20 m/min. Temperature  
29 rise, drilling forces and bone volume fraction were measured. The experimental  
30 validation showed that the model reproduces satisfactorily the increase in temperature  
31 up to the maximum value while it overestimates the temperature during the cooling  
32 stage. A parametric study (thermal boundary conditions, lateral friction) was also  
33 performed. From the predicted results, it appears that the model can be improved by  
34 considering the effects of the bone volume fraction which can present a significant  
35 variation in the bone sample.

36 **Keywords**

37 Bone drilling, Bone necrosis, Bone temperature rise, Thermal model for bone drilling,  
38 Moving heat source, Axial drilling force and torque, Bone volume fraction.

39

40 **1. INTRODUCTION**

41 Bone cutting is a common step in bone fracture treatment and implantology.  
42 Notwithstanding that bone cutting method includes grooving, sawing, drilling, and  
43 milling, the most discussed process in the literature is bone drilling [1]. The reason of

44 this increasing interest among researchers comes from the fact that drilling process  
45 generates significant heat that may lead to thermal injury of bone [2-4]. Hillery and  
46 Shuaib [5] report that, for exposure time greater than 30 s, the necrosis threshold in  
47 human and bovine bones is 55 °C. According to Bertollo *et al.* [6], Pandey and Panda  
48 [1], bone necrosis can appear for very small exposure time when the bone temperature  
49 is 70 °C. In spite of the fact that there is no consensus concerning the critical values of  
50 exposure duration and temperature magnitude, the typical value of 47 °C during at  
51 least 60 s is often used as a reference threshold for the thermal injury apparition [3,7].  
52 Pioneering works related to bone drilling deal about the prevention of osteonecrosis.  
53 The key step of these investigations is the assessment of the cutting temperature by  
54 using experimental and/or theoretical techniques [1,3,8-10]. Due to the variability of  
55 bone samples properties and experimental conditions and to the large number of  
56 drilling parameters, these investigations often do not converge towards general  
57 conclusions about the temperature rise with respect to the drilling parameters. So, it  
58 appears necessary to develop realistic thermo-mechanical models of bone drilling  
59 operation to investigate the effect of each parameter, on temperature elevation.

60 Metal machining theory has frequently been used to calculate drilling heat generated  
61 during bone drilling [8,11,12]. The authors assumed that bone behaves like metal when  
62 it is machined. Therefore, the deformation in the chip was supposed to be  
63 characterized by three zones; the primary deformation zone where the required energy  
64 in material shearing is converted into heat; the secondary zone where heat is  
65 generated by shearing along the tool rake face and the third zone where friction  
66 between the tool clearance face and the new surface of bone produces heat. A similar  
67 assumption has been taken by Lee *et al.* [8] to suggest a thermal model for bone  
68 drilling. In their investigation, the heat generated in the third zone was assumed to be

69 negligible for a sharp cutting tool, exactly as in the case of metal cutting. This theory  
70 has been extended further upon by Maani *et al.* [12] to develop a mathematical model  
71 for predicting the thermal response in the surgical drilling of bone. To determine the  
72 temperature rise during drilling, Kalidindi [13] also used the approach developed by  
73 Oxley [14].

74 Other authors investigated the cutting and chip formation mechanism of bone cutting  
75 and suggested an alternative view. Jacob *et al.* [15] analysed, through microscopic and  
76 SEM images, bone chips shape during orthogonal cutting. They showed that Merchant  
77 [16] analysis of orthogonal cutting, commonly used in material cutting, has limited  
78 applicability to bone material. Further investigations done by Wiggins and Malkin [17]  
79 on the mechanics of orthogonal machining of bone showed that the chip formation  
80 process occurred by a series of discrete fractures. Recently, Liao and Axinte [18]  
81 identified three different chip formation modes related to the uncut chip thickness.  
82 Feldman *et al.* [19] corroborated the observations of Liao and Axinte [18]. They found  
83 the bone cutting behaviour changed from a ductile to a fracture cutting mode as cutting  
84 depth increases. The threshold cutting depth inducing cracks with chips formation was  
85 shown to be 20  $\mu\text{m}$  [20].

86 Thus, within these experimental investigations, it appears that the chip formation  
87 process is very complex compared to metal cutting and that during bone cutting  
88 process, chips are formed more by fracture mode than shear mode, regardless of  
89 cutting direction, as shown in Fig. 1. Consequently, it seems more realistic to assume  
90 that bone behaves like a quasi-brittle material in drilling process. Therefore, whereas  
91 for metal cutting the heat sources in the chip are clearly associated to the plastic  
92 deformation in the shear zones, the temperature elevation inside bone can clearly not  
93 be associated to the same physical mechanisms. As a consequence, analytical models

94 based on metal machining theory cannot be considered as an appropriate approach to  
95 predict the bone temperature rise in drilling. In addition, the source of the heat  
96 generated during bone drilling is not clearly defined for a wide range of drilling  
97 conditions and needs further investigation.

98 Recently, new thermal models for bone drilling, based on the moving heat source  
99 approach of Jaeger [21], have been introduced by Feldmann *et al.* [19,22]. The  
100 interactions between drill tip and bone are modeled by a moving heat source  
101 assimilated to a disk source with the size of the drill bit diameter. The authors [19,22]  
102 expressed the thermal energy as a function of bone density distribution. With the  
103 Green's function of time-dependent moving point source, they determined the  
104 temperature distribution in function of time. It can however be noted that the model  
105 [19,22] presents different limitations: (i) the bone has been assimilated to an infinite  
106 medium (i.e. the bone material fills all the space). As it will be shown in the present  
107 work, this assumption may induce an underestimation of bone temperature if the feed  
108 rate is not large enough. (ii) during the drill bit penetration into the bone, the distance  
109 between the heat source, which moves with the tool, and the measurement position of  
110 temperature has been taken constant for a fixed time  $t$ , (iii) the heat sources induced  
111 by the bone-tool interactions are restricted to the tool tip effect.

112 As indicated previously, the bone behaves as a quasi-brittle material during cutting  
113 process. Therefore, friction between the drilled hole and the tool can affect the bone  
114 temperature. In the present work, a simplified analytical model is developed using the  
115 following assumptions: (i) bone temperature rise results from two main sources  
116 corresponding to the interaction between the drill-bit tip and bone and the friction  
117 between the drill-bit side and the drilled hole, (ii) the effect of the point angle is  
118 neglected and the heat source associated to the tool tip is assimilated to a disk. The

119 model was used to analyze the influence of spindle speed which affects the heat  
120 generation and the heat transfer through the exposure time. Experimental tests of bone  
121 drilling have also been conducted on porcine samples. After a validation study of the  
122 model with temperature experimental data, a parametric study has been performed  
123 and compared with the results of the experimental campaign.

124

## 125 **2. MATERIALS AND METHODS**

### 126 *2.1 Experimental study*

127 Bone samples used in these experiments were extracted from the diaphyseal part of a  
128 porcine femoral bone aged of 6 months. The bone was obtained from a local  
129 slaughterhouse just after the slaughter of the animal and directly frozen (-20°C). There  
130 was no animal sacrifice specifically for this study. Experiments were conducted on  
131 bones devoted to food industry. Before sample preparation, bone was thawed to a  
132 temperature between 3 and 6 degrees during 24 hours. Bone samples were finally  
133 machined at room temperature to get dimensions of approximately 70 mm-long and  
134 10 mm-wide. Fig. 2(a) shows the final state of the sample to drill.

135

136 Each bone sample was scanned by X-ray micro-computed tomography ( $\mu$ CT) machine  
137 EasyTom (RX Solutions, Chavanod, France) before drillings tests. The scanning  
138 parameters are the following ones: voltage 100 keV, current 50  $\mu$ A, exposure time 2.6  
139 s and voxel size  $15 \times 15 \times 15 \mu\text{m}^3$ . Microtomography was conducted on several bone  
140 samples but the most homogeneous sample in terms of microstructure (i.e. with a  
141 cortical layer of quite constant thickness along the whole specimen) and presenting

142 the highest thickness of cortical bone was kept for the drilling process and the  
143 comparison with the analytical model.

144 After image acquisition of the bone sample, the drilling experiments were performed  
145 on it. A feed per tooth of 0.02 mm was chosen and cutting velocities varying between  
146 2 to 20 m/min were tested. The drilling tests were performed on a three axes CNC  
147 milling machine Roeders RP600. A Nobel Biocare twist drill of 3.2 mm diameter with a  
148 point angle of  $118^\circ$  and an helix angle of  $30^\circ$  was used. The drilling depth was 4 mm.  
149 Drill is made of stainless steel with a diamond-like carbon (DLC) coating. The whole  
150 machine, sample, and tool are considered perfectly rigid so that the cutting vibrations  
151 are negligible.

152 Samples were clamped and mounted on a Kistler 9256C2 piezoelectric dynamometer  
153 to measure the feed force  $F$  and the cutting torque  $M$ , see Fig. 2(b). The signal was  
154 amplified by a Kistler 5017B charge amplifier and recorded by a National Instrument  
155 data acquisition system coupled with a Labview software. Signals obtained were  
156 filtered by a Butterworth type filter, traditionally used during the machining data  
157 processing.

158 Temperature data were recorded by two K-type thermocouples OMEGA KMTSS-  
159 IM025U-150 with a wire diameter of 0.25 mm implanted in pre-drilled holes. The  
160 measuring junctions were positioned precisely at 1.5 mm depth and 0.5 and 0.9 mm  
161 from the wall, see Fig. 2(c). A conductor paste was injected through the holes to  
162 optimise the conduction from bone to thermocouples.

163 After drilling tests, microtomography of drilled bone was performed with the parameters  
164 presented previously. The reconstruction process of bone sample volume was  
165 conducted via RX Solutions X-ACT software. The resetting of drilled and undrilled bone



166 tomograms was done on Avizo 9 software. By subtracting tomographic images before  
 167 and after drilling tests, the 3D volume of the drilling zones of bone was obtained to  
 168 represent our volume of interest. To facilitate the post-treatment, these zones were  
 169 approximated by the addition of a cylinder and a cone, Fig. 3(a). Bone volume fractions  
 170 (BV/TV) were then determined within these zones. BV/TV is extracted from each slice  
 171 through drilling direction of the whole stack of the volume of interest.

172  
 173

## 174 2.2 Analytical modelling of bone temperature rise

175 The temperature distribution in the bone can be obtained from the approach  
 176 developed by Carslaw and Jaeger [23]. A fixed coordinate system  $(x, y, z)$  is associated  
 177 to the bone sample where the beginning of the drilled hole is located at position  $x=0$   
 178 , Fig. 4. Heat is liberated at time  $t'$ , from  $0$  to  $t$  ( $0 \leq t' \leq t$ ), at point  $Q(x', y', z')$  where the  
 179 heat rate  $q_c ds$  ( $q_c$  ( $w/m^2$ )) is associated to an elementary surface  $ds$  and due to the  
 180 cutting process. During drilling, the heat source moves with a constant speed  $V$  in  $x$ -  
 181 direction so that  $x' = Vt'$  as shown in Fig. 4. When the bone sample is assimilated to  
 182 an infinite medium (i.e. the bone is supposed to occupy all the space  
 183  $-\infty < x, y$  and  $z < +\infty$ ) and according to Carslaw and Jaeger [23], the temperature  
 184 elevation  $\Delta T$  at a point  $M(x, y, z)$  for time  $t$  is given by:

$$185 \quad \Delta T(x, y, z, t) = \frac{q_c ds}{8\rho c(\pi a)^{3/2}} \int_0^t (t-t')^{-3/2} e^{-\{(x-Vt')^2+(y-y')^2+(z-z')^2\}/4a(t-t')} dt' \quad (1)$$

186 where  $\rho$ ,  $k$ ,  $c$ , and  $a$  represent respectively the density, the thermal conductivity,  
 187 the specific heat and the thermal diffusivity. Note that in (1),  $q_c$  is time independent.

188 According to Tu *et al.* [24], the thermal properties and the density of pig bone are given  
 189 by:  $k = 0.45 \text{ W/Km}$ ,  $c = 1640 \text{ J/kg K}$  and  $\rho = 1640 \text{ kg/m}^3$ .

190 A similar approach has been proposed by Feldmann *et al.* for the tool tip contribution  
 191 [19,22]. However, there is a difference between the two models. Indeed, during the  
 192 heat source displacement for  $0 \leq t' \leq t$ , its vertical position  $x'$  was supposed to be equal  
 193 to  $Vt$  in Feldmann *et al.* work [19,22]. This is equivalent to consider that the distance  
 194 between the heat source  $Q(x', y', z')$  and the measurement position  $M(x, y, z)$  is  
 195 constant for  $0 \leq t' \leq t$ .

196 Eq. (1) means that elevation temperature distribution at time  $t$  is obtained by adding  
 197 the rise temperature caused by the amount of heat liberated during the source  
 198 displacement namely when it was at the positions  $(x' = Vt', y', z')$  with  $0 \leq t' \leq t$ .

199 By introducing the variable  $\tau = t - t'$ , (1) is reduced to

$$200 \quad \Delta T(x, y, z, t) = \frac{q_c ds}{8\rho c(\pi a)^{3/2}} e^{-V(x-Vt)/2a} \int_0^t \tau^{-3/2} e^{-\left(\frac{d^2}{4a\tau} + \frac{V^2\tau}{4a}\right)} d\tau \quad (2)$$

201 where  $d = \sqrt{(x-Vt)^2 + (y-y')^2 + (z-z')^2}$  is the distance from the heat source as reported  
 202 in Fig. 4.

203

204 From the close form of the time integral term, we get:

$$205 \quad \Delta T(x, y, z, t) = \frac{q_c ds}{8\rho c \pi a} e^{-V(x-Vt)/2a} f(d, t) \quad (3)$$

206 with

$$207 \quad f(d, t) = \frac{1}{d} \left\{ e^{Vd/2a} \operatorname{erfc}\left(d/2\sqrt{at} + V\sqrt{at}/2a\right) + e^{-Vd/2a} \operatorname{erfc}\left(d/2\sqrt{at} - V\sqrt{at}/2a\right) \right\} \quad (4)$$

208 The temperature distribution, due to the drill-bit tip contribution, is obtained by adding  
 209 the temperature rise caused by each elementary heat source  $q_c ds$  ( $q$  [ $w/m^2$ ]) over the  
 210 disk surface, see Fig. 4(a):

211 
$$T_{tip}(x, y, z, t) = \frac{1}{8\rho c \pi a} e^{-V(x-Vt)/2a} \int_0^R \int_0^{2\pi} q_c f(d, t) d\theta r dr \quad (5)$$

212 where  $R$  is the drill bit radius and  $d$  is expressed in polar coordinates  
 213  $d = \sqrt{(x-Vt)^2 + (y-r\cos\theta)^2 + (z-r\sin\theta)^2}$ . In (5), the bone is considered as an infinite  
 214 medium.

215 For drilling operation, the bone can be assimilated to a half space (i.e. the bone sample  
 216 occupies the half space  $x \geq 0$  and its top surface is located at position  $x=0$ ). To obtain  
 217 the temperature distribution in a semi-infinite medium with adiabatic surface, the image  
 218 sources  $q_{im} ds$  (with  $q_{im} = q_c$ ) are introduced as in Komanduri and Hou [25-27]. These  
 219 fictive sources move with a constant speed  $-V$  in  $x$ -direction such as  $q_{im} ds$  is located  
 220 at  $Q_{im}(x' = -Vt', y', z')$  where heat is liberated at time  $t'$ , from  $0$  to  $t$  ( $0 \leq t' \leq t$ ), see Fig.  
 221 4(a). The temperature distribution due to  $Q_{im}$  is deduced from (5) by replacing  $d$  with  
 222  $d_{im} = \sqrt{(x+Vt)^2 + (y-r\cos\theta)^2 + (z-r\sin\theta)^2}$  and  $V$  with  $-V$ . Finally, for the bone  
 223 assimilated to a half space, we obtain:

224 
$$T_{tip}(x, y, z, t) = \frac{1}{8\rho c \pi a} \left\{ e^{-V(x-Vt)/2a} \int_0^R \int_0^{2\pi} q f(d, t) d\theta r dr + e^{V(x+Vt)/2a} \int_0^R \int_0^{2\pi} q f(d_{im}, t) d\theta r dr \right\} \quad (6)$$

225 The integral terms in (6) are calculated numerically by using Gauss quadrature method.  
 226 To account for the friction between the drill-bit side and the drilled hole, the depth  $H$  of  
 227 the hole is divided into  $N$  small differential elements having ring shape. The height of  
 228 each element  $j$  ( $1 \leq j \leq N$ ) is given by  $\Delta h = H/N$ , Fig. 4(b).

229 When the drill bit penetrates deeper into the bone, frictional heat is liberated at time  $t'$   
 230 , from  $t_{0j}$  to  $t$  ( $t_{0j} \leq t' \leq t$ ), at point  $Q_f(x', y', z')$  where the heat rate  $q_f ds$  ( $q_f$  ( $w/m^2$ )) is  
 231 associated to an elementary surface  $ds = R d\theta \Delta h$ , see Fig. 4(b). The heat source moves  
 232 with a constant speed  $V$  in  $x$ -direction so that  $x' = Vt'$  as shown in Fig. 4(b). Following

233 the drill bit penetration, each source at  $Q_f$  is activated at  $t' = t_{0j}$  with  
 234  $t_{0j} = j\Delta h/V + R/V \tan(\psi/2)$ . In this equation, the term  $R/\tan(\psi/2)$  represents the height  
 235 of the drill-bit tip and  $\psi$  is the point angle, see Fig. 4(a). Thus, at time  $t$ , the number of  
 236 differential elements (elementary rings of Fig. 4(b)) forming the total friction zone is  
 237 given by the integer part of the ratio  $Vt/\Delta h$ .

238 Applying the foregoing approach, the temperature distribution in the bone (modeled as  
 239 a half space), due to the side drill bit contribution (frictional heat), is as follows:

$$240 \quad T_{side}(x, y, z, t) = \frac{R \Delta h}{8\rho c \pi a} \sum_j^N \left\{ e^{-V(x+h_j-Vt)/2a} \int_0^{2\pi} q_f f(d, t-t_{0j}) d\theta + e^{V(x-h_j+Vt)/2a} \int_0^{2\pi} q_f f(d_{im}, t-t_{0j}) d\theta \right\}$$

241 (7)

242 with

$$243 \quad \begin{cases} h_j = (j-1/2)\Delta h \\ d = \sqrt{(x+h_j-Vt)^2 + (y-R\cos\theta)^2 + (z-R\sin\theta)^2} \\ d_{im} = \sqrt{(x-h_j+Vt)^2 + (y-R\cos\theta)^2 + (z-R\sin\theta)^2} \end{cases} \quad (8)$$

244 The length  $h_j$  is defined in Fig. 4(b) and the integral terms in (7) are calculated  
 245 numerically by using Gauss quadrature method. Note that in (7),  $q_f$  is time  
 246 independent.

247 The temperature distribution in the bone, resulting from the two contributions, is given  
 248 by:

$$249 \quad T(x, y, z, t) = T_0 + T_{tip}(x, y, z, t) + T_{side}(x, y, z, t) \quad (9)$$

250 where  $T_0$  is the initial bone temperature.

251 During cutting operation, the tool-bone interaction changes due to the variation of the  
 252 bone behavior from the cortical part to the cancellous bone. Consequently to estimate  
 253 the heat source, we propose to use the average of the maximum and minimum values

254 of feed force  $F$  and cutting torque  $M$  denoted by  $\bar{F}$  and  $\bar{M}$  respectively, see the  
255 Results section. Following this approach, the heat source relative to the tool tip is  
256 assumed to be constant during drilling, and equal to a fraction  $0 < \eta < 1$  of the mean  
257 value of the mechanical energy :

$$258 \quad q_c = \eta (\bar{F} V + \bar{M} \omega) / (\pi R^2) \quad (10)$$

259 where  $V$  and  $\omega$  represent respectively the feed rate and the rotational speed ( $rad/s$ ).  
260 Eq. (10) corresponds to a heat source which is time independent as in the present  
261 thermal model.

262 The frictional heat induced by the contact between the drill-bit side and the drilled hole  
263 is given by:

$$264 \quad q_f = \mu_f p V_c \quad (11)$$

265 with  $\mu_f$  the friction coefficient,  $p$  the contact pressure and  $V_c$  the cutting velocity  
266 ( $V_c = \omega R$ ).

267 It should be noted that before applying the analytical model to analyse the thermal  
268 problem in the bone, we have to calibrate the parameters  $\eta$  and  $p$ . The calibration  
269 procedure will be presented and discussed in the Discussion section.

270

### 271 **3. RESULTS**

272 Fig. 3(a) shows an example of obtained 3D volume rendering. Each curve reported in  
273 Fig. 3(b) joins bone volume fractions determined on each slice of the drilled zones in  
274 the drilling direction. The typical evolution of bone volume fractions confirms the drilling  
275 of two different types of bone. The relatively flat part of the curve denotes drilling  
276 through cortical bone whose bone volume fraction is relatively stable (greater than 0.9).  
277 The highly sloped part of bone volume fraction curve represents the entrance into

278 spongy bone where BV/TV can drop to 0.4 at the end of the drilling process. It is also  
279 visible that the bone volume fraction highly varies from a drilled site to another, even  
280 inside the cortical part of the bone.

281 The variation of the feed force and cutting torque during drilling is observed in parallel.  
282 The curves obtained are reported in Figs. 5(a) and 5(b). The force rapidly increases at  
283 the entrance into bone samples to reach a maximum value. Then, the values slightly  
284 decrease until the end of the drilling process where the values drop to zero. This  
285 diminution trend is similar to the one observed on the BV/TV curves (Fig. 3b).  
286 Therefore, it can be deduced that a relationship exists between the evolution of feed  
287 force and bone density. Concerning the torques, their evolution with the drilling depth  
288 depends on the cutting speed considered. No general trend can be observed.

289 In order to evaluate the heat source at the drill tip, given by Eq. (9), the average values  
290 of feed force  $\bar{F}$  and cutting torque  $\bar{M}$  are extracted on the curve profiles from the  
291 drilling maximal and minimum values, see Figs. 5(a) to 5(d). These figures reveal that  
292  $\bar{F}$  varies only slightly with cutting speed  $v_c$  while  $\bar{M}$  is larger for  $v_c \geq 10 \text{ m/min}$  than  
293 for  $v_c \leq 5 \text{ m/min}$ . The obtained values  $\bar{F} = 18 \text{ N}$  and  $\bar{M} = 0.08 \text{ N.m}$  (mean value for  $v_c$   
294 from 2 to 20 m/min) have been used to estimate the heat source (9).

295

296 After model calibration (described and discussed in the Discussion section), the  
297 predicted temperature of the model and measurement are compared. Fig. 6 shows the  
298 comparison for both positions of thermocouples and for each cutting velocity. All curves  
299 present two phases with a first one where the bone temperature increases because of  
300 the drilling process and a second one illustrating the cooling phase. The culmination of  
301 the curve coincides with the end of the drilling stage.

302

303

304 The influence of the heat source due to the lateral friction is reported in Fig. 7(a). As  
305 expected, the lateral friction induces an increase in the temperature rise. A modification  
306 of the position of the maximum temperature is also observed mainly for the small value  
307 of cutting velocity 2 m/min. Thus, the duration of the temperature increase becomes  
308 larger. Fig. 7(b) shows how the predicted temperature changes when the bone is  
309 assimilated to an infinite or semi-infinite medium. When a semi-infinite medium with an  
310 adiabatic surface is considered (i.e. the bone sample occupies the half space  $x \geq 0$   
311 and its top surface is located at position  $x=0$ ), the temperature rises obtained are  
312 higher but the global profiles of the temperature curves remain unchanged. Concerning  
313 the comparison of the maximal temperature rises, the increase with  $v_c$  from 2 to 10  
314 m/min is reproduced by the model, Fig. 7(c). From 10 to 20 m/min, the predicted values  
315 tend to saturate while the temperature measurements show a decrease, Fig. 7(c).

316

317

#### 318 **4. DISCUSSION**

319 Heat generation, due to the conversion of fraction of cutting energy into thermal energy,  
320 is a critical parameter for thermal modelling of bone drilling. As discussed before, the  
321 application of the metal machining theory assumes that the cutting mechanisms are  
322 similar in bone and metal: in particular, the shear angle can be estimated from the  
323 Merchant law [16]. For instance, Davidson and James [11], Maani *et al.* [12], Lee *et al.*  
324 [8] have supposed that a fraction of shearing energy, due to the primary shear zone,  
325 goes into the bone. In Maani *et al.* [12], Lee *et al.* [8], this fraction was deduced from

326 the metal machining theory of Oxley [14] and Davidson and James [11] supposed that  
327 it is equal to 0.5.

328 In the present approach, bone temperature rise results from two main sources: the  
329 drill-bit tip (cutting process) and the friction between the drill-bit side and the drilled  
330 hole. The values of both sources  $q_c$  and  $q_f$  are obtained thanks to relationships (10)

331 and (11). Expression (10) requires the determination of average values of feed force

332  $\bar{F}$  and cutting torque  $\bar{M}$  which are provided in Fig. 5. As shown in Fig. 5(c), the drilling

333 force  $\bar{F}$  is almost constant as a function of the cutting speed. Fig. 5(d) shows two

334 distinct levels for the torque  $\bar{M}$ : one for the smallest cutting velocities 2 and 5 m/min

335 and a higher value for velocities 10 and 20 m/min. The values used in this work are:

336  $\bar{F} = 18 N$  and  $\bar{M} = 0.08 N.m$  (average value of  $\bar{M}$  for  $v_c$  from 2 to 20 m/min). Further

337 investigations with higher values of cutting velocities would have to be conducted in

338 order to complete these first results. Finally, the determination of  $q_c$  and  $q_f$  requires

339 the values of parameters  $\mu_f$ ,  $\eta$  and  $p$ . The value of  $\mu_f$  was fixed to 0.3 according to

340 data from the literature. Indeed, Rancourt *et al.* report that  $\mu_f = 0.3$  for tibial cancellous

341 bone sliding against stainless steel surface [28]. Davim and Marques [29] analyzed the

342 influence of sliding velocity on  $\mu_f$  for bovine bone-steel contact pair. They indicate that

343  $\mu_f = 0.25$  for sliding velocities from 0.02 m/s to 0.1 m/s. More recently, Zhu *et al.* [30]

344 examined the variation of  $\mu_f$  in function of contact pressure and sliding velocity with

345 water lubrication for bovine femoral cortical bone-316 L stainless steel contact pair. For

346 sliding velocity of 0.44 m/s and contact pressure of 0.42 MPa, Zhu *et al.* [30] showed

347 that  $\mu_f = 0.25$ .



348 Concerning parameters  $\eta$  (fraction of mechanical energy resulting from the tool tip-  
 349 bone interaction converted into heat) and  $p$  (contact pressure between the drill-bit side  
 350 and the drilled hole), a calibration procedure was carried out. From the parametric  
 351 study reported in Fig. 7(a), it appears that the time  $t_c$ , corresponding to the maximum  
 352 temperature rise  $\Delta T_{\max}$  ( $t_c$  is time during which temperature increases), is mainly  
 353 dependent on the side heat source (11) (via the contact pressure  $p$ ) especially for  
 354 small cutting velocities. Based on this trend, the calibration of  $p$  and  $\eta$  was performed  
 355 with respect to the time  $t_c$  and  $\Delta T_{\max}$  respectively. Thus, the calibration procedure is  
 356 based on the following iterative approach. First, the two parameters were varied within  
 357 a defined range (for instance  $\eta \in [0.1, 0.7]$  and  $p[MPa] \in [0, 20]$ ). Secondly, for each value  
 358 of  $\eta$ , pressure  $p$  is selected so that the condition  $t_c^{model} \approx t_c^{exp}$  is satisfied. Finally, among  
 359 all values of  $\eta$  and for each calibrated pressure, the chosen value of  $\eta$  must satisfy  
 360 the condition  $\Delta T_{\max}^{model} \approx \Delta T_{\max}^{exp}$  ( $t_c^{exp}$  and  $\Delta T_{\max}^{exp}$  represent the experimental measurements).  
 361 According to this approach,  $\eta$  and  $p$  were calibrated such as the experimental  
 362 temperature and the model prediction are as close as possible for the smallest cutting  
 363 speed  $v_c = 2 \text{ m/min}$  as reported in Fig. 6(a) (temperature was measured at 0.5 mm from  
 364 the drilled hole, see Fig. 2). The values of parameters  $\eta$  and  $p$  obtained with this  
 365 calibration are  $\eta = 0.35$  and  $p = 1 \text{ MPa}$ . Besides, Fig. 7(c) indicates that the difference  
 366 between the temperature elevation when the bone is assimilated to a semi-infinite  
 367 medium with adiabatic surface or considered as an infinite medium is more significant  
 368 for  $v_c = 2 \text{ m/min}$  than for  $v_c = 20 \text{ m/min}$ . This can be explained by the fact that the feed  
 369 rate  $V$  increases with the cutting speed  $v_c$  and, at low feed rate, conduction

370 overcomes the convection of heat (thanks to the heat source displacement) so that  
371 heat diffusion will extend deep into the infinite medium.

372 In order to dissociate the effect of the feed rate per tooth  $f_t$  from the influence of  $v_c$ ,  
373  $f_t$  is kept constant  $f_t = 0.02 \text{ mm/tooth}$ . Fig. 6. shows the effect of cutting speed  $v_c$  on  
374 the bone temperature elevation over time at depth 1.5 mm and for the two  
375 thermocouples placed at 0.5 and 0.9 mm from the hole (denoted respectively by 'T<sub>h1</sub>'  
376 and 'T<sub>h2</sub>', see Fig. 2). As expected, the model results indicate that the temperature is  
377 an increasing function of  $v_c$  (i.e. the rotational speed  $\omega$ ) while the exposure time  
378 decreases with  $v_c$ . This temperature growth is more significant for 'T<sub>h1</sub>' than for 'T<sub>h2</sub>'.

379 Overall, the model correctly reproduces the evolution of temperature rise with time  $t$   
380 from 0 to  $t_c$  (i.e.  $0 \leq \Delta T \leq \Delta T_{\max}$ ). The low heat conductivity and the high heat capacity  
381 of the bone result in lower temperatures at the location of the second thermocouple  
382 'T<sub>h2</sub>', Figs. 6(e)-6(h). Because of keeping  $f_t$  constant ( $f_t = 0.02 \text{ mm/tooth}$ ), the feed  
383 rate  $V$  increases with cutting speed  $v_c$  ( $V = f_t v_c / (\pi R)$ ). Consequently, the heat  
384 sources increase with  $v_c$  while the duration of heat exchange (exposure time) with the  
385 bone is reduced. These two opposite effects result in a slowing down in the increase  
386 of the maximum temperature with  $v_c$  as reported in Fig. 7(c) (the heat sources  $q_c$  and  
387  $q_f$  are proportional to  $v_c$ , see Eq. (10) and (11), but the evolution of the maximum  
388 temperature results from the two opposite effects). The model predictions reveal that  
389 the growth of cutting speed  $v_c$  from 2 to 5 m/min induces an increase of temperature  
390 of thermocouple 'T<sub>h1</sub>' of about 16 °C (8 °C for 'T<sub>h2</sub>') while it is about 2°C for a variation  
391 from 10 to 20 m/min (2 °C for 'T<sub>h2</sub>'). These tendencies are close to the temperature  
392 measurements, Fig. 7(c). It can also be observed from Fig. 7 that the analytical model  
393 predicts the maximum temperature rise with a maximum error of 18% for 'T<sub>h1</sub>' whereas

394 we have 28% for 'T<sub>h2</sub>', which is logical as the model was calibrated for the closest  
395 position of the thermocouple. The difference between model results and  
396 measurements can be attributed to several parameters which are not considered in  
397 the present model: (i) the evolution of the bone density during cutting, (ii) the  
398 relationship between the bone thermal properties and its density, (iii) the influence of  
399 the presence of both thermocouples on the bone temperature distribution, and (iv) the  
400 effect of cutting conditions on the model parameters :  $\eta$  ,  $p$  ,  $\bar{M}$  and  $\mu_f$  .

401 During bone drilling, the temperature rise depends on the bone density (through  
402 BV/TV). Fig. 3(b) shows that the ratio BV/TV is much higher for the cutting tests with  
403  $v_c = 2$  and  $5$  m/min than for  $v_c = 10$  and  $20$  m/min . Note also that the thermal conductivity  
404 depends on the bone density, see Feldmann *et al.* [31]. These variations are not taken  
405 into account in the present approach where the heat sources are supposed to be  
406 constant. To improve the model predictions, the effect of BV/TV on the heat generation  
407 and on the thermal conductivity have to be considered. Additionally, the model does  
408 not reproduce correctly the cooling stage. Indeed to reduce the computational time,  
409 the cooling process was estimated from the moving heat source solution by keeping it  
410 to zero during the cooling step (i.e. when  $t_c \leq t$  ). To reproduce the bone cooling  
411 process when  $t_c < t$  , we have to consider the numerical solution of the heat problem  
412 where the initial temperature distribution corresponds to the solution given by the  
413 present model at  $t = t_c$  .

414 The thermal damage of the bone is mainly dependent on two factors: exposure time  
415 and temperature magnitude. Several parameters affect these two critical factors:  
416 drilling conditions, drilling strategies, cooling and thermomechanical bone properties.  
417 From the foregoing comparison between the model predictions and the experimental

418 results, it appears that despite the model simplicity, it can be helpful to examine the  
419 bone necrosis in terms of drilling conditions for  $0 \leq t \leq t_c$  (i.e.  $0 \leq \Delta T \leq \Delta T_{\max}$ ).

420

## 421 **5. CONCLUSION**

422 In the present study, a simplified analytical model based on the moving heat source  
423 approach is developed. Besides, to be closer to the boundary conditions of the thermal  
424 problem, the method of image sources has been applied. Because of the complexity  
425 of the chip formation mechanisms in bone cutting process, the heat source due to the  
426 drill-bit tip has been supposed to be proportional to the cutting energy. The friction  
427 between the drill-bit side and the drilled hole was also taken into account. Drilling  
428 experiments were conducted on fresh femur pig bone. The distribution of bone volume  
429 fraction through the drilled hole was determined by microtomography for the bone  
430 samples. The present model requires the calibration of two parameters. The  
431 experimental validation has shown the model reproduces satisfactorily the increase in  
432 temperature up to the maximum value while it overestimates the temperature during  
433 the cooling stage. A parametric study, concerning the thermal boundaries conditions  
434 (infinite or finite medium) and the lateral friction, was also performed. The results show  
435 that the difference of temperature rise between semi-infinite or infinite medium is more  
436 pronounced for small cutting velocities. The lateral friction has a direct influence on the  
437 duration of the temperature increase, especially for small cutting velocities. Finally, the  
438 present simplified approach can be improved by considering the effects of the bone  
439 volume fraction which can present a significant variation in the bone sample.

440

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442

443

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445

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452

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