Scientia Iranica B (2015) 22(2), 487–492

SCIENTIA IRANICA

Sharif University of Technology
Scientia Iranica
Transactions B: Mechanical Engineering
www.scientiairanica.com

Experimental measurements of temperatures in drilling cortical bone using thermocouples

K. Alam*

Department of Mechanical and Industrial Engineering, College of Engineering, Sultan Qaboos University, P.O. Box 33, Al-Khoud 123, Sultanate of Oman.

Received 23 February 2014; received in revised form 2 June 2014; accepted 6 September 2014

KEYWORDS
Orthopaedics;
Bone drilling;
Thermocouples;
Drilling temperatures;
Thermal damage.

Abstract. A high speed cutting process of bone such as drilling produces heat, and can result in thermal damage (death) of bone tissue. Temperature measurement in bone drilling is a primary step in establishing threshold level for thermal damage (necrosis). Advanced understanding of techniques for acquiring reliable thermal data on bone drilling is important to avoid traumatic incision. Currently, thermocouples are the main source in the experimental determination of temperature elevation during bone drilling. In an effort to overcome uncertainties in temperature measurements with thermocouples, a new approach was used which includes inserting a thermocouple either attached to the cutting edge of a drill or inserted into the bone. The leading idea in this study was to investigate how temperature data obtained from the two mentioned systems are inherently different. Temperature measurements were observed to vary considerably with both types of measurement systems. Experimental results identified drilling speed and depth of drilling as the critical parameters for inducing higher temperatures in bone drilling. The results presented in this study can be used to select the right method for acquiring temperature data for shallow and deep drilling in bone.

1. Introduction

Bone drilling is a well-known procedure in orthopaedic and dental surgery and is typically performed for correcting bone fractures and attaching prosthetics. Heat generation, which could induce significant trauma to the tissue through osteonecrosis, is a common problem in bone drilling. The meticulous use of drilling parameters can avoid thermal injury to the bone tissue and associated postoperative complications [1]. Exact data on temperature rise in bone material during drilling is of fundamental importance for investigating and improving the procedure.

Several experimental methods have previously been used to evaluate temperature distribution during bone drilling [2-7]. Researchers have also developed Finite Element (FE) and analytical models to predict the level of temperature rise in bone cutting [8-10]. Among those methods, measurement with thermocouples was the most frequent choice of practice [2,3,7,9,11]. Heterogeneous structure and the highly non-conductive material property of bone can dramatically affect certainty in temperature measurements with the thermocouple inserted into bone [12]. Similarly, measurements with thermocouples placed near the cutting edge of a drill necessitate additional accessories to avoid rotation of the thermocouple wire. In addition to these difficulties, thermocouples have not been used to measure temperature in deep drilling of bone such as in Anterior Cruciate Ligament (ACL) reconstruction surgery, where the drill may penetrate into femur up to 30 mm deep [13]. Also, the drill may go deeper when drilling parallel to the longitudinal axis

*. *Tel.: +968 24143751; Fax: +968 24141316*
E-mail address: kalam@squ.edu.om (K. Alam)

of bone. To my knowledge, no research has been carried out previously to investigate the magnitude of drilling temperature for a penetration depth larger than the average thickness of the cortical wall (6-9 mm).

In fact, no published data is available containing an analysis of temperature measurements in drilling operation using the two techniques described earlier (measurements with thermocouples attach to bone and with thermocouple placed in the drill) on the same bone. This research investigated uncertainty in temperatures inevitably occurring in bone drilling with a penetration depth equal to an average cortical wall thickness, followed by a study to acquire a saturation temperature at drilling larger depths. This study demonstrates how thermocouples in different attachments drastically affect the results and provide a guideline for the selection of the right scheme for acquiring reliable temperature data in drilling bone or other biomaterial.

2. Material and methods

2.1. Specimen preparation

Drilling tests were performed on cortical specimens excised from the central portion of a cow femur. The age of the animal was between three to four years, with an average thickness of cortical wall of 9-10 mm. Fresh femurs were obtained from a local slaughter house and used in experiments within four to five hours after the slaughter. Specimens were refrigerated at -10°C before the experiments to preserve their properties. Specimens were cut with a rotary hacksaw and flattened along the longitudinal axis using a milling machine. The specimens were then placed on each other to make a stack of bones for deep drilling. A thin layer of glue was applied between the smooth surfaces to provide strong contact. The author hopes that this thin layer will produce negligible error in the acquired data. The thin layer of glue also provided an insulated medium to heat transfer along the plane of contact of the glued surfaces. The anatomical location and dimensions of the specimen are shown in Figure 1. A total of 15 specimens were prepared, and each could accommodate around twenty holes. The final dimensions of the specimen were 50 mm × 40 mm × 35 mm.

2.2. Drill-embedded thermocouple system (Scheme I)

Experimental arrangement for measuring bone temperature with thermocouple embedded in the drill is shown in Figure 2(a). The drill was held fixed in the tool post of a conventional lath machine and the bone piece was rotated in the chuck. This arrangement avoided thermocouple wire rotation during cutting. In this system, the thermocouple probe was attached close to the cutting lips of a drill, as shown in Figure 2(b). The distance between the thermocouple bead and cutting lip was 1.2 mm. The thermocouple wire was passed through the hole along the longitudinal axis of the drill.

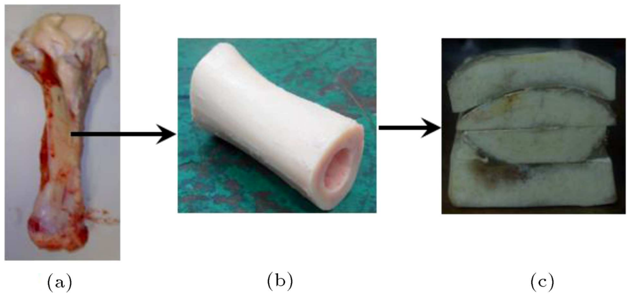

Figure 1. (a) Fresh bovine bone. (b) Sample cut from middle diaphysis. (c) Stack of bones for drilling longer depths.

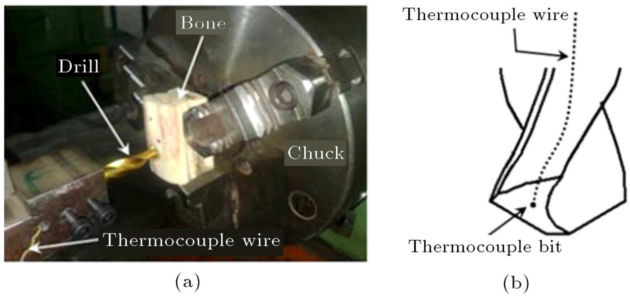

Figure 2. (a) Experimental arrangement for drilling bone in Scheme I. (b) Schematic of drill design and thermocouple location.

2.3. Bone-embedded thermocouple system (Scheme II)

In this arrangement, thermocouples beads were placed in the bone 1 mm away from the drilling track in order to avoid crushing of thermocouples by the cutting edges of the drill. Five wells were prepared perpendicular to the axis of the drilling path for inserting thermocouples. The Experimental set up used in this system is shown in Figure 3(a). Five thermocouples were placed along the drilling track to measure temperatures at various points along the drilling path. The distance between each thermocouple was kept to 6 mm which was sufficient to avoid voltage

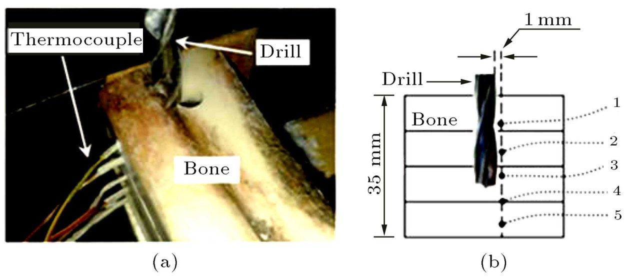

Figure 3. Experimental arrangement for drilling bone in Scheme II: (a) Bone with thermocouples; and (b) schematic of thermocouple locations along drilling depth.

jamming and reduce noise in the acquired data (see Figure 3(b)).

2.4. Experimental equipment and procedure

A conventional lathe machine and vertical drilling machine with multiple speed control were used in Scheme I and Scheme II, respectively. Standard K type insulated thermocouples with a wire diameter of 127 μm were used for temperature measurements. The K type thermocouple can take measurement values up to 500°C with a response time of 10 μsec. The data logger FMSDL48 (Glasgow, UK) was used for temperature acquisition. An instrument calibration of the entire system was performed before the experiments against a standard mercury thermometer, and an error of ±1°C was found in measurements. Thermocouples beads were coated with thermo-conductive paste (Omega, OT-201-2) to ensure good contact of the thermocouple with the drill and bone. A standard twist drill of 5 mm diameter was used for drilling.

Drilling speed and depth were changed in the experiments to investigate their effect on temperature rise in bone. All experiments were performed without irrigation (cooling) at the drilling site, as the cooling fluid may be a potential biohazard to the operator. Drilling was conducted in the direction perpendicular to the longitudinal axis of bone (femur). The initial temperature of bone and drill were measured and found to be 25°C. Experiments were conducted for spindle speed ranging between 600 rpm and 3000 rpm, and a constant feed rate of 50 mm/min. The choice of drilling speed and feed rate was based on the data widely reported in literature [2,3]. Each experiment was repeated five times for a particular set of parameters to evaluate repeatability in the data set.

3. Results and discussions

Each data point on the subsequent plot represents the average value of five tests. The value on the ordinate ΔT of the subsequent plots represents the rise in bone temperature above 25°C.

3.1. Drilling speed vs. bone temperature

In Scheme I, specimens were rotated in the chuck of the lathe machine to measure change in bone temperature with different drilling speeds for up to 6 mm thickness (depth). Temperature values at each drilling speed were recorded when the drill tip penetrated 6 mm. The effect of drill speed on temperature rise in the bone is shown in Figure 4. The dependence of temperature rise on drilling speed was significant; as an increase of 38°C was recorded when drilling speed was changed from 600 rpm to 3000 rpm. The rise in temperature was obvious since the shearing energy in bone material and, the friction between the drill and bone increased with higher drilling speeds. Higher shearing velocities

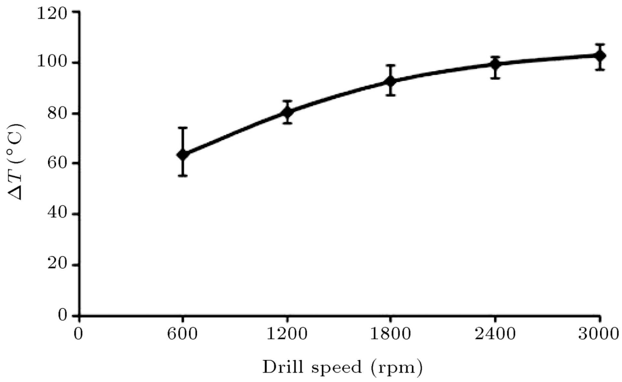

Figure 4. Temperature rise vs. drilling speed in Scheme I (drilling depth: 6 mm).

at the cutting edge of the drill developed chips more quickly, which resulted in a larger heat flux generated in the drilling zone. The results of temperature measurements in these experiments are comparable with two and three dimensional numerical studies on drilling temperatures in bone [14,15]. In those studies a nonlinear increase of bone temperature was reported with increasing drilling speed, which is similar to this study.

The increase in temperature was sharp up to a drilling speed of 1800 rpm, and the rate of increase dropped when the drilling speed was further increased. A similar trend was also reported in drilling human and bovine cortical bone [2] with drilling speed exceeding 1200 rpm. An increase in thermal conductivity of bone with increasing temperatures as reported in [16] may be the reason for producing heat at a lower rate at higher drilling speeds. The increase in temperature at higher drilling speed caused the thrust force to drop and this was attributed to a softening of the bone with a rise in temperature [17]. Interestingly, the temperature was not seen to tend towards saturation point for the range of drilling speeds used in this study when the drilling depth was 6 mm.

This section describes temperature measurements using Scheme II. The response of thermocouple was not similar to what it was in Scheme I, because the thermocouple bead was placed below the top surface of the specimen. No significant temperature rise was recorded using this scheme of measurement until the cutting edge of the drill approached the location where thermocouple was placed. The temperature rose very quickly up to a maximum value and decreased as the cutting edge of the drill passed the thermocouple bead, as shown in Figure 5.

Similar to Scheme I, temperature measurement was strongly influenced by the drilling speed, as shown in Figure 6. Each data point in Figure 6 corresponds to the maximum temperature recorded by the thermocouple when the tip of the drill was just passing it. The bone temperature rose with increase in drilling

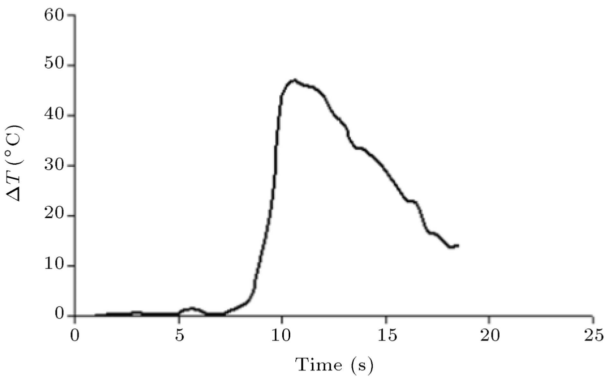

Figure 5. Typical response of thermocouple placed 6 mm below the top surface (drill speed: 1800 rpm).

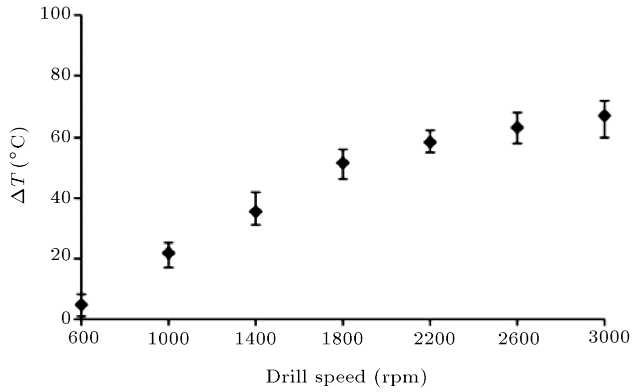

Figure 6. Temperature rise vs. drilling speed in Scheme II (drilling depth: 6 mm).

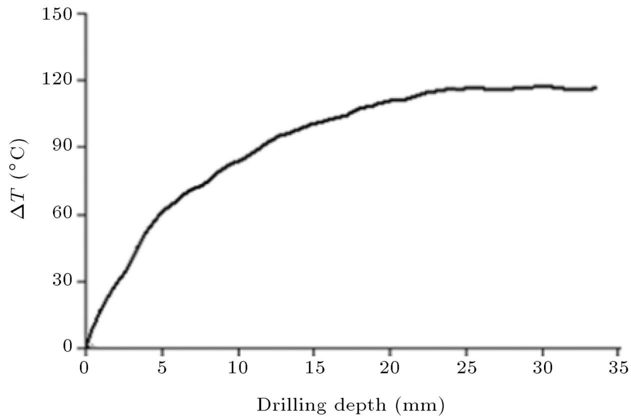

Figure 7. Temperature evolution in deep drilling of bone using Scheme I (drill speed: 1800 rpm).

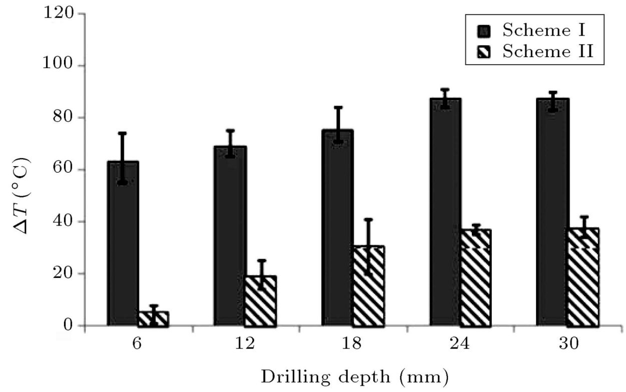

Figure 8. Temperatures rise in bone at different drilling depths (drill speed: 600 rpm).

speed in a fashion similar to that observed in Scheme I. The change in temperature was observed to increase from a mean value of 6°C to 51°C when the drilling speed was changed from 600 rpm to 1800 rpm, and the relationship was linear. The drop in increasing rate at the higher drilling speed was similar to that noted in Scheme I. The results of temperature measurements in our experiments contradicted those reported in [18], where a nonlinear decrease of bone temperature was reported with increasing drilling speed. The obvious reasons responsible for these differences were the use of a 2.5 mm diameter drill and significantly higher speeds (from 20000 rpm to 100000 rpm) in that study.

3.2. Acquiring saturation temperature

It is obvious from the previous results that the temperature would have increased further if there had been more penetration depth available for the drill. In the next set of experiments, the drill penetrated through the entire depth of the specimens at both drilling speeds. One of the objectives of the present study was to investigate the maximum temperature and depth where it saturated. Initially, tests were performed to find the approximate depth of drilling where temperature stabilised with Scheme I. The study was further extended to relate depth of drilling with minimum and maximum drilling speeds using both drilling schemes. A typical thermal history in bone as the drill penetrated up to 35 mm in bone using Scheme I is shown in Figure 7. The saturation temperature was achieved at drill penetration of around 20 mm and above. Similar results were also obtained using Scheme II.

Temperature variation at various drilling depths using both types of measurement systems for the two values of drilling speeds are displayed in Figures 8 and 9. The drilling depth was calculated from the feed rate (50 mm/min) when the drill started touching the top surface of the bone in Scheme I. In Scheme II, it was calculated from the response of the thermocouples near the drilling track. Drilling through longer depths has been shown to elongate the exposure time to the heat generation and propagate thermal effect to further distances in the specimen [4,5,19]. At longer depths, the accumulation of heat may be attributed to the decrease in convection heat transfer caused by ambient air in the cutting zone. It was not possible to establish the relationship between a single thermocouple reading and time due to quick temperature rise to a maximum value followed by sharp drop as the drill approached

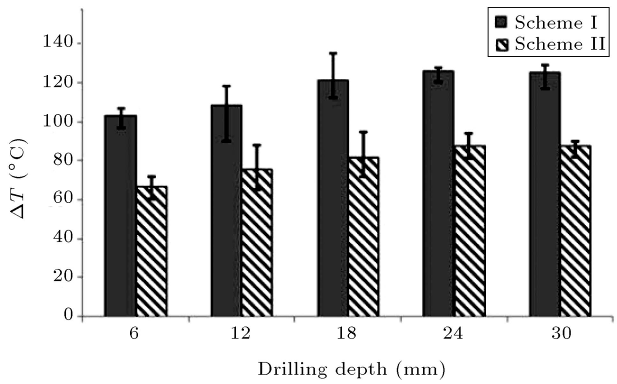

Figure 9. Temperatures rise in bone at different drilling depths (drill speed: 3000 rpm).

and passed the thermocouple location. The data points in Figure 9 represent thermocouple measurements at locations placed along the drilling path (see Figure 3(b)). The results of this study were similar to those published on thermal response of bone in drilling, using analytical and computational analysis [20,21].

3.3. Comparison of numerical and experimental results

The maximum temperature rise in bone was found to increase with depth of drilling and was measured to saturate at a specified distance from the top surface of the specimens in both systems of measurements. Unexpectedly, the temperature values measured using Scheme I were found to be much higher than those acquired with Scheme II. An obvious reason for the difference was that measurements in Scheme II were obtained from thermocouples placed at a distance of 1 mm from the cutting edge of the drill. Another reason was the nonconductive response of bone to heat transport in Scheme II. The standard error at longer drilling depths was lower compared to drilling shallower depths. This may be due to the effective convection by the surrounding air since the drill was more exposed to the air at shallower drilling depths. The percentage difference in both systems of measurements was more at lower drilling speeds. The exact reasons for these variations were unknown to the author at this stage of investigation, and are assumed to be the mechanics of chip formation, which greatly influenced temperature rise in drilling using different speeds. The difference may also be due to the friction at the drill-bone interface at different drilling speeds. However, given all of the inherent complexities in the systems and the process itself, the trend in both types of measurement systems was similar.

4. Conclusions

Measurement of temperature in bone drilling is notoriously uncertain due to complex nature of the bone tissue as well as the process itself. The drilling experiments allowed the quantification of temperature levels in bone using drill-embedded and bone-embedded thermocouples, and allowed a comparison of the two techniques. The level of temperatures in bone was observed to be strongly influenced by the system of measurement. The drilling speed and drilling depth were identified as crucial for affecting bone temperatures. Both systems measured saturation temperature at a depth above 25 mm for all drilling speeds. Measurements with thermocouples embedded in the bone provided lower temperatures compared to the system where the thermocouple was attached to the drill. Higher temperature at deep drilling was due to the inability of the bone to conduct heat away from the drilling zone. An effect not considered in the current experimental setup was the moderating thermal effect of irrigation and blood flow which can decrease locally elevated temperature. This study suggests the application of efficient cooling system when drilling the bone longer than 10 mm.

Acknowledgment

The author wishes to thank Prof. Vadim Silberschmidt for providing guidance and help in experimental work.

References

1. Brisman, D.L. "The effect of speed, pressure, and time on bone temperature during the drilling of implant sites", *Int. J. Oral. Maxillofac. Impl.*, **11**, pp. 35-37 (1996).
2. Hillery, M.T. and Shuaib, I. "Temperature effects in the drilling of human and bovine bone", *J. Mater. Proc. Technol.*, **92-93**, pp. 302-308 (1999).
3. Bachus, K.N., Rondina, M.T. and Hutchinson, D.T. "The effects of drilling force on cortical temperatures and their duration: An in vitro study", *Med. Eng. Phys.*, **22**, pp. 685-691 (2000).
4. Eriksson, A.R., Albrektsson, T. and Albrektsson, B. "Heat caused by drilling cortical bone. Temperature measured in vivo in patients and animals", *Acta. Ortho. Scand.*, **55**, pp. 629-631 (1984).
5. Lee, J., Ozdoganlar, O.B. and Rabin, Y. "An experimental investigation on thermal exposure during bone drilling", *Med. Eng. Phys.*, **34**, pp. 1510-1520 (2012).
6. Augustin, G., Davila, S., Udiljak, T., Vedrina, D.S. and Bagatin, D. "Determination of spatial distribution of increase in bone temperature during drilling by infrared thermography: preliminary report", *Arch. Orthop. Trauma. Surg.*, **129**, pp. 703-709 (2009).
7. Karaca, F., Aksakal, B. and Kom, M. "Influence of orthopaedic drilling parameters on temperature and histopathology of bovine tibia: An in vitro study", *Med. Eng. Phys.*, **33**, pp. 1221-1227 (2011).

8. Sezek, S., Aksakal, B. and Karaca, F. "Influence of drill parameters on bone temperature and necrosis: A FEM modelling and in vitro experiments", *Comput. Mater. Sci.*, **60**, pp. 13-18 (2012).

9. Tu, Y.K., Chen, L.W., Ciou, J.S., Hsiao, C.K. and Chen, Y.C. "Finite element simulations of bone temperature rise during bone drilling based on a bone analog", *J. Med. Biol. Eng.*, **33**, pp. 269-274 (2013).

10. Lee, J., Rabin, Y. and Ozdoganlar, O.B. "A new thermal model for bone drilling with applications to orthopaedic surgery", *Med. Eng. Phys.*, **33**, pp. 1234-1244 (2011).

11. Abouzgia, M.B. and James, D.F. "Temperature rise during drilling through bone", *Int. J. Oral. Maxillofac. Impl.*, **12**, pp. 342-353 (1997).

12. Benington, I.C., Biagioni, P.A., Crossey, P.J., Hussey, D.L., Sheridan, S. and Lamey, P-J. "Temperature change in bovine mandibular bone during implant site preparation: An assessment using infra-red thermography", *J. Dent.*, **24**, pp. 263-267 (1996).

13. Webb, J.M., Corry, I.S., Clingeleffer, A.J., Leo, A. and Pinczewski, L.A. "Endoscopic reconstruction for isolated anterior cruciate ligament rupture", *J. Bone. Joint. Surg.*, **80-B**, pp. 288-294 (1998).

14. Alam, K., Mitrofanov, A.V. and Silberschmidt, V.V. "Thermal analysis of orthogonal cutting of cortical bone using finite element simulations", *Int. J. Exp. Comput. Biomech.*, **1**, pp. 236-251 (2010).

15. Alam, K., Khan, M. and Silberschmidt, V.V. "3D finite element modeling of drilling cortical bone: Temperature analysis", *J. Med. Biol. Eng.* (December 18, 2013) (In Press). Doi: 10.5405/jmbe.1585

16. Moses, W.M., Witthaus, F.W., Hogan, H.A. and Laster, W.R. "Measurement of the thermal conductivity of cortical bone by an inverse technique", *Exp. Therm. Fluid Sci.*, **11**, pp. 34-39 (1995).

17. Alam, K., Mitrofanov, A.V. and Silberschmidt, V.V. "Experimental investigations of forces and torque in conventional and ultrasonically-assisted drilling of cortical bone", *Med. Eng. Phys.*, **33**, pp. 234-239 (2011).

18. Abouzgia, M.B. and Symington, J.M. "Effect of drill speed on bone temperature", *Int. J. Oral. Maxillofac. Surg.*, **25**, pp. 394-399 (1996).

19. Toews, A.R., Bailey, J.V., Townsend, H.G.G. and Barber, S.M. "Effect of feed rate and drill speed on temperatures in equine cortical bone", *Am. J. Vet. Res.*, **60**, pp. 942-944 (1999).

20. Tu, Y.K., Chen, L.W., Ciou, J.S., Hsiao, C.K. and Chen, Y.C. "Finite element simulations of bone temperature rise during bone drilling based on a bone analog", *J. Med. Biol. Eng.* (January 17, 2013) (In Press). Doi: 10.5405/jmbe.1366

21. Sezek, S., Aksakal, B. and Karaca, F. "Influence of drill parameters on bone temperature and necrosis: A FEM modelling and in vitro experiments", *Comput. Mat. Sci.*, **60**, pp. 13-18 (2012).

Biography

Khurshid Alam is Assistant Professor in the department of Mechanical and Industrial Engineering, Sultan Qaboos University, Sultanate of Oman. He received his PhD degree in Mechanical Engineering from Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, UK. He received his BEng degree in Mechanical Engineering from University of Engineering and Technology, Peshawar, Pakistan and his MSc degree in Design and Manufacturing from GIK Institute of Engineering Sciences and Technology, Topi, Pakistan. His current research is focused on the experimental measurements and computational analysis of bone cutting forces in conventional and vibrational mode. His other areas of research are experimental and computational modeling and analysis of biomechanical components and systems.