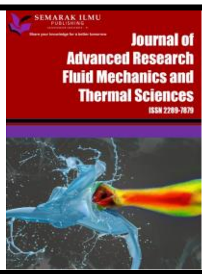
Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage:
https://semarakilmu.com.my/journals/index.php/fluid_mechanics_thermal_sciences/index
ISSN: 2289-7879



Optimization of Drill Bit Geometries for Minimum Thermal Damage in Bone Drilling

Mohd Faizal Ali Akhbar[1,*], Mohamad Faris Mohd Ashri[2], Ahmad Razlan Yusoff[2], Shahrizan Jamaludin[1], Rodianah Alias[3,5], Fatin Alias[1], Razhan Hassan[4], Muhammad Rizwan[6]

1 Department of Naval Architecture and Maritime Technology, Faculty of Ocean Engineering Technology (FTKK), Universiti Malaysia Terengganu, 21030, Kuala Nerus, Terengganu, Malaysia
2 Centre for Advanced Industrial Technology, Universiti Malaysia Pahang, 26600 Pekan, Pahang, Malaysia
3 Faculty of Innovative Design and Technology, Universiti Sultan Zainal Abidin, Campus Gong Badak, 21300 Kuala Nerus, Terengganu, Malaysia
4 Centre for Design & Innovation of Technology,Universiti Malaysia Pahang, 26600 Pekan, Pahang, Malaysia
5 Biomaterials & Nanomaterials Research Group, Smart Technology Cluster, Faculty of Innovative Design and Technology, Universiti Sultan Zainal Abidin, Campus Gong Badak, 21300 Kuala Nerus, Terengganu, Malaysia
6 Department of Metallurgical Engineering, Faculty of Chemical and Process Engineering, NED University of Engineering and Technology, 75270, Karachi, Pakistan

ARTICLE INFO

Article history:
Received 19 June 2024
Received in revised form 16 September 2024
Accepted 27 September 2024
Available online 20 October 2024

Keywords:
Bone drilling; osteonecrosis; Taguchi; point angle; helix angle; web thickness

ABSTRACT

Thermal injury is a common post-operative effect in bone drilling surgeries. The extreme heat generated during the drilling process kills bone cells, which causes irreversible bone death. This bone death loosens medical fixations—screws, plates, and implants—and subsequently refractures the bone. Research on drill bit geometries in bone drilling has attracted interest from engineering and medical researchers. However, previous research has mainly focused on the simulation of bone drilling, which could generate an incorrect approximation of thermal bone damage if the simulation model is not validated. For this reason, this study focuses on the optimization and parametric analysis of the bone temperature elevations induced by customized drill bit features—point angle (60-180°), web thickness (25-50 %), and helix angle (10-55°)—in comprehensive ex-vivo bone (bovine) experimental drilling tests. The L_9 Taguchi optimization method was then applied to determine the optimal design to minimize maximum bone temperature rise. Results from the parametric analysis revealed that the optimal setup for the drill point features can be obtained with the ranges of point angle of 160-180°, web thickness of 25-30 %, and helix angle of 30-40°. Based on the Taguchi optimization results, the minimum thermal damage is produced with the point angle of 180°, web thickness of 25 %, and helix angle of 35°. This work offers a promising solution for reducing thermal injury and preventing thermal osteonecrosis in bone drilling surgeries.

* *Corresponding author.*
E-mail address: mfaizalaa@umt.edu.my

https://doi.org/10.37934/arfmts.122.2.2237

1. Introduction

Bone drilling is a standard operation in medical departments, such as dentistry, otology, and orthopedics, to create holes in the bone for implant installation [1]. Excessive heat caused by shear deformation and friction in the drilling process could increase the bone temperature by more than 47 °C, the threshold for irreversible bone damage (thermal osteonecrosis) [2].

During the drilling process, friction—between the drill bit and bone—and the shear deformation of bone converts the mechanical process into heat [3,4]. Furthermore, bone chips from cutting could clog the drill flute and drilling hole [5]. In bone drilling, this phenomenon further increases the bone temperature, force, and torque, which could break the drill bit and kill the bone tissues (thermal osteonecrosis). The damaged bone tissues are exposed to severe infection and then could develop into bone sequestration, leading to bone absorption [1]. Thermal osteonecrosis loosens the screws and implants, leading to bone refracture and implant failure [1,2,6].

Drilling conditions and drill bit design are the two main parameters regulating heat generation in bone drilling [7]. Regarding drilling conditions, researchers have demonstrated the significant effects of rotational speed, feed rate, irrigation system, and drilling hole depth on bone temperature [8-12]. With the increased rotational speed, the friction energy generated per minute increases, thus elevating bone temperature. The feed rate significantly affects the thrust force during the drilling process; thrust force increases with the feed rate. As thrust force is directly involved in the heat generation process, increasing the feed rate will only enhance the heat generation and elevate the bone temperature. Adopting internal or external cooling systems during bone drilling prevents extreme bone temperature elevation [10,13]. However, these systems could initiate bacterial infections and disturb the surgeon's vision during the surgery [1]. Finally, increasing the drilling hole depth elevates bone temperature due to increased frictional and thrust forces because of the contact between bone debris and the drill bit in the drilling site.

1.1 Novel Contributions

Previous studies have focused on point angle, helix angle, and web thickness when designing surgical drill bits (Figure 1). However, contradictory findings have been reported in the literature. For example, the effects of point angle on bone temperature can be categorized into three groups: (1) increasing bone temperature, (2) reducing the bone temperature, and (3) insignificant effect [14-17]. Furthermore, the effect of helix angle on temperature rise is not unanimous [1]. However, only a few studies have researched the effect of drill web on bone's thermal damage. Sui *et al.,* [18] suggested a larger web thickness to reduce bone temperature. However, their simulation results are contradicted by their experimental results. Later, Akhbar and Yusoff [15,16] recommended a web thickness between 5 % and 40 % to minimize maximum bone temperature and osteonecrosis regions. The study focused on bone drilling simulation, and to date, no experimental study has investigated web thickness's effect on bone temperature in bone drilling. Furthermore, none have investigated the extended range of point angle (160-180°), web thickness (40-50 %), and helix angle (10-20° and 40-55°) in bone drilling research.

For these reasons, this research adopts experimental bone drilling tests to evaluate the effects of point angle, web thickness, and helix angle on bone temperature elevations. These effects yield crucial information regarding the suitable point angle, web thickness, and helix angle ranges for the optimization study. Next, the drill design is optimized using the Taguchi orthogonal array method based on these ranges. Finally, the confirmation test is performed to validate the results. The insight from the drill bit optimization will provide valuable information to tool manufacturers and engineers regarding the optimal drill design for thermal bone necrosis prevention.

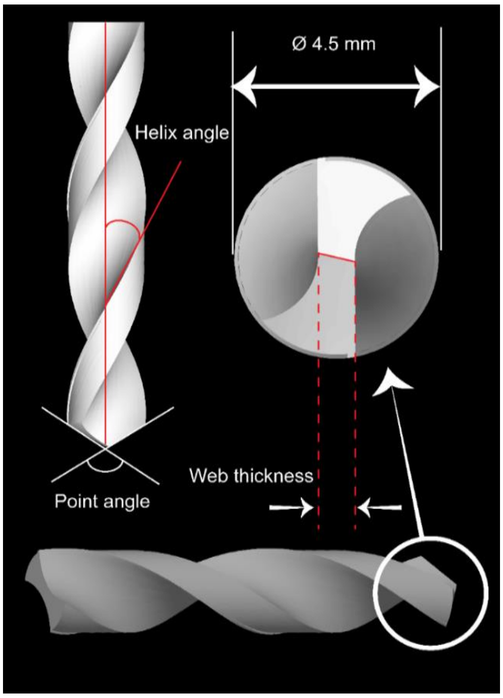


Fig. 1. Configuration of drill bit used in this study

2. Methodology

2.1 Preparation of Bone Specimens

Human bone is hard to acquire for experimental purposes; therefore, in this study, bovine (cow) bone was selected as the substitute in this research because of its closeness (bone temperature elevation) to human bone [19]. Furthermore, the average thickness of bovine bone (7.49 mm) is thicker than the average human cortical bone (5.5 mm) [20,21]. Therefore, the samples are sufficient to mimic the human bone drilling test. In our current location (Malaysia), bovine bones are abundantly available in the food chain. Therefore, no cows were slaughtered for the sole purpose of this study.

The bovine femurs were obtained from the local slaughterhouse four hours after the slaughter to ensure the freshness of the bone. These femurs were extracted from the male cows because they possessed thicker cortical bones than their female counterpart [20]. The thicker cortical bones are needed to ensure that a deeper drilling depth can be perforated for our test.

Figure 2 shows the fresh and processed bone for the bone drilling test. The meat, bone marrow, and tissues (periosteum) attached to the cortical bone were removed using a knife. This process is necessitated so that the meat and tissues do not interfere during drilling [7]. Their involvement could clog the drill flute, jam the drill bit, and cause a drill break [1]. After the bones were cleaned with water, the bone's end parts (epiphysis) were removed using a hacksaw to reduce the size of the femur for better clamping during drilling [8]. The final length of the bones was approximately 135 mm in length.

Regarding bone thickness, the bones with cortical thickness above 7.5 mm were selected for the drilling test to accommodate a drilling hole of 5.5 mm depth (Figure 2). A total of ten bovine femurs were used to complete the study design. All of these bones were used within seven hours after we obtained them to keep the freshness of the bone samples [22]. Furthermore, the samples were immersed in saline solution and placed in the refrigerator at -10 °C, strictly following the guidelines established by Sedlin and Hirsch [23]. The bones were then thawed (room temperature) for two hours before the bone drilling test [22].

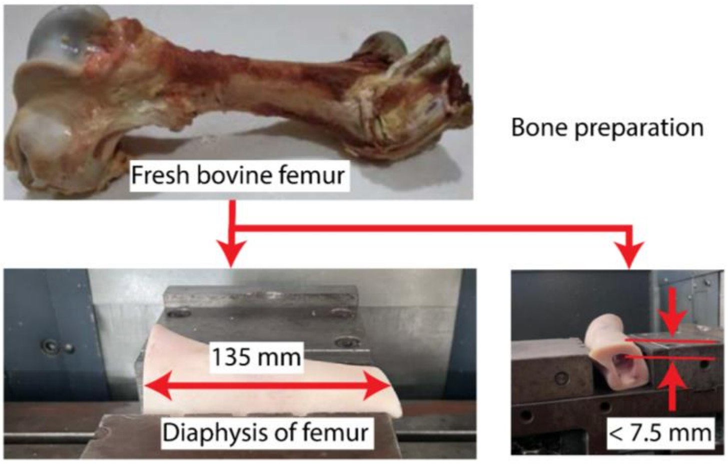


Fig. 2. Preparation of cortical bone samples

2.2 Bone Drilling Test Setup

The experimental bone drilling setup consists of a conventional milling machine, data measurement system, and customized stainless steel 316L drill bits with various point angles, web thicknesses, and helix angles. The photographic and schematic views of the bone drilling tests are presented in Figure 3.

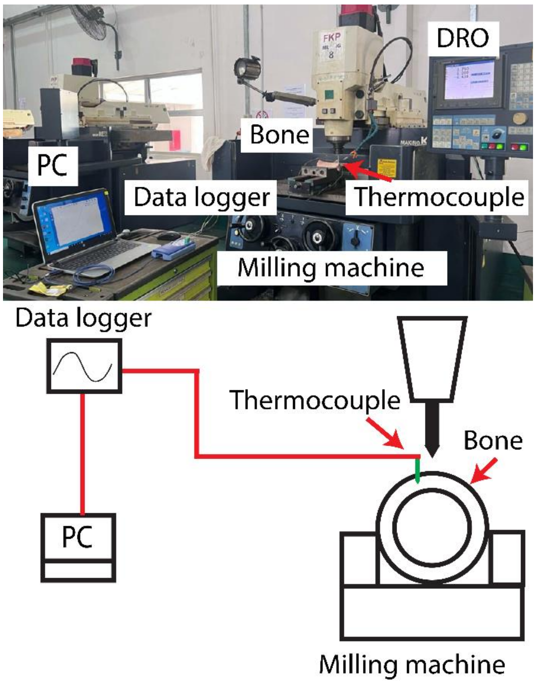


Fig. 3. Photographic and schematic views of the bone drilling experiment

The conventional milling machine, Makino KE55, with variable rotational speed (60–4000 rev/ min) and feed rate (1.0-5000 mm/ min), was used for the drilling process. This milling machine was chosen over the conventional drilling machine because it can adequately hold the bone and operate at high rotational speed without significant vibration, which will affect the accuracy of the drilling hole. For accurate hole positioning, a digital readout (DRO), ACU-RITE DRO 200S-3X-G, was used to locate the position of drilling and thermocouple holes with an accuracy of ±0.0001 mm. An adjustable vice was used to hold the femur on the drilling table during the drilling process. Before the drilling test, the top surface of the femur was milled with a 20 mm endmill to produce a flat surface. This surface eases the penetration of the drill bits and prevents the drill point from skidding the target location [7,8].

2.3 Bone Temperature Measurement

The heat in bone drilling is generated from three sources: (1) shear deformation of bone, (2) friction between bone debris and rake face, and (3) friction between bone surface and flank face of the drill bit [1]. Among these sources, shear deformation of bone and friction between the drill bit and bone debris produce most of the total heat [1,6]. In contrast, the heat from the friction of the bone surface and drill bit flank face is minimal and negligible if the new or sharp drill bit is used [1].

In bone drilling research, researchers have adopted two methods of measuring bone temperature: (1) using thermocouples and (2) using an infrared thermographic camera [8,22,24]. In previous studies, the thermographic camera has been successfully adopted to measure the heat distribution in bone drilling [24]. The temperature distribution helps predict heat-affected zones and real-time temperature profile records. However, the thermographic camera only measures the surface temperature of the bone and, therefore, is unable to produce an accurate maximum bone temperature reading [8,16]. For this reason, the thermocouples method was adopted in this study to measure the maximum bone temperature.

Figure 4 shows this study's bone temperature measurement using the thermocouple method (K-type thermocouples OMEGA Bare-24 K-12). A hole with a diameter of 1 mm and a depth of 3 mm was drilled 0.5 mm from the targeted drilling hole to house the thermocouple (Figure 5). The hole was then filled with a thermal paste to eliminate the air gap between the thermocouple and the housing wall. The recorded temperature readings were sent to a data logger, PICO TC-08, for temperature history profiling. These profiles identified the maximum bone temperature as the highest peak in the whole temperature history (Figure 4). Each experimental test was repeated five times [22,24]. The mean, standard deviation, and coefficient of variation a were calculated using Minitab software version 21.

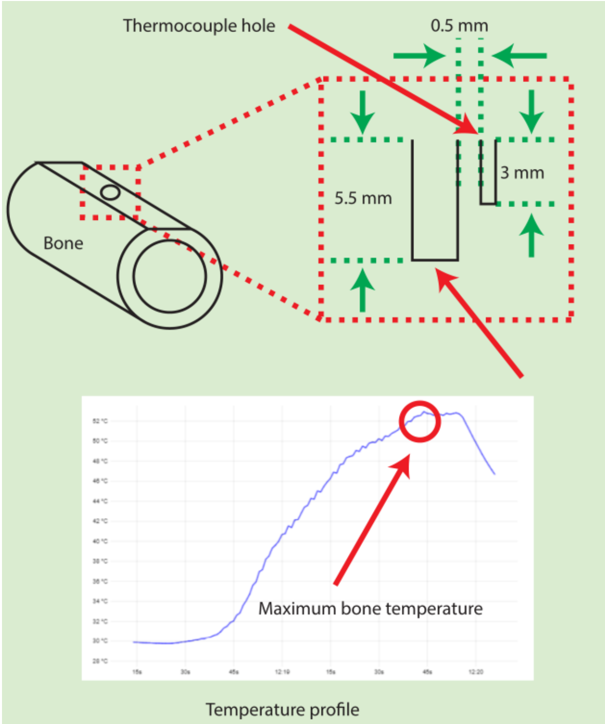


Fig. 4. Measurement and identification of maximum bone temperature methods

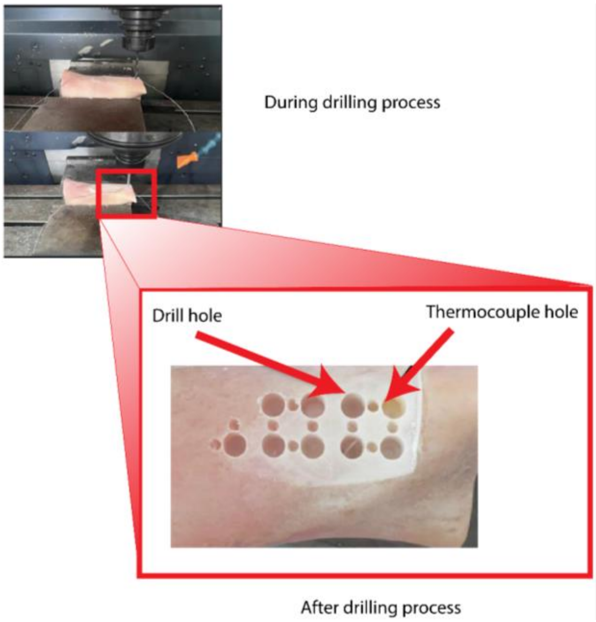


Fig. 5. The cortical bone during and after the bone drilling tests

2.4 Study Design
2.4.1 Parametric study

A parametric study was used to identify how (a) point angle, (b) web thickness, and (c) helix angle affect the thermal damage in bone-drilling surgery. The suitable ranges of point angle, web thickness, and helix angle will be selected based on the results from this parametric study for optimization analysis in the next section. The stainless steel 316L drill bits were customized with the desired designs because they mimic the real surgical drill bit [1].

Figure 6 shows the geometries of the customized drill bit used in this study. The diameter of all drill bits was fixed to 4.5 mm [8,9,15]. Regarding the variable parameters, the point angle was varied in five values: 60°, 100°, 118°, 160°, and 180° (Table 1). At the same time, the web thicknesses of 25 %, 30 %, 40 %, 45 %, and 50 % were selected to evaluate the web thickness's effect on temperature. Finally, the helix angle of 10°, 20°, 30°, 40°, and 55° was chosen to examine the helix angle's effects on temperature elevation. The values for point angle, helix angle, and web thickness were selected based on previous studies' reported drill bit design [1,2,6].

Fig. 6. Actual image of customized drill bits used in the study

Table 1
Customized drill bit design for the parametric study

Tool	Drill geometry		
	Point angle (°)	Web thickness (%)	Helix angle (°)
1	60	40	30
2	100	40	30
3	118	40	30
4	160	40	30
5	180	40	30
6	118	25	30
7	118	30	30
8	118	40	30
9	118	45	30
10	118	50	30
11	118	40	10
12	118	40	20
13	118	40	30
14	118	40	40
15	118	40	55

The machining parameters were fixed for the whole drilling process: rotational speed = 2000 rev/ min, feed rate = 0.13 mm/ rev, and hole depth = 5.5 mm. The targeted locations were drilled perpendicular to the long axis of the femur because the structure variations were minimized in this direction due to the oriental dependence of osteons in cortical bone [22].

When used repeatedly, the drill bit could produce extreme wear behavior, affecting the maximum bone temperature profile [22]. Therefore, each drill bit was only used to produce ten holes to eliminate the wear effect on maximum bone temperature. Initial bone and drill bit temperature can regulate maximum bone temperature [22]. Therefore, after each drilling test, the drill bit and bone sample were left to cool down to room temperature before the next drilling test (15 minutes) [22]. Furthermore, after each drilling run, the drill bit was cleaned thoroughly with a moist cloth and brush to avoid bone debris clogging the drill flute [22].

2.4.2 Optimization study with Taguchi L9 orthogonal array

The Taguchi method is a statistical technique that optimizes multiple parameters by identifying the optimal levels of control factors and analyzing their effects on the response [25]. It uses signal-to-noise (S/N) ratios to show the impact of input factors on the response function and is a valuable engineering tool for improving performance while minimizing the number of experiments required [26]. Furthermore, it employs an orthogonal series design to describe input factor effects on objective characteristics with reduced experimental cost. In the Taguchi method, the S/N (smaller-the-better) will be measured as

$$\frac{S}{N} = -10log\left(\frac{1}{n}\sum_{i=1}^{n} Y_i^2\right), \quad (1)$$

where n is the number of replications (in this study, n=3) and Y_i is the i_{th} measured value in the design array. This study adopted the criterion of lower being better for the S/N ratio to achieve minimum bone temperature elevation.

The results from the parametric study were used to determine the suitable levels of point angle (levels 1, 2, and 3), web thickness (levels 1, 2, and 3), and helix angle (levels 1, 2, and 3) for Taguchi L_9 orthogonal array design. This design consists of three factors with three levels. Nine experiments with three repetitions are performed to ensure the chance of variance. The design matrix for the L_9 Taguchi method in this study was designed and analyzed using Minitab 22 statistical software (Table 2).

Table 2
Design matrix for L9 orthogonal arrays used in this study

Orthogonal array	Point angle (°)	Web thickness (%)	Helix angle (°)
L_1	1	1	1
L_2	1	2	2
L_3	1	3	3
L_4	2	1	2
L_5	2	2	3
L_6	2	3	1
L_7	3	1	3
L_8	3	2	1
L_9	3	3	2

3. Results and Discussion

3.1 Parametric Study

3.1.1 Effect of point angle on maximum bone temperature

Figure 7 shows the maximum bone temperature elevations corresponding to various point angles (60°, 100°, 118°, 160°, and 180°). The web thickness and helix angle were fixed at 40 % and 30°, respectively. The maximum bone temperature increased with a point angle of 60° to 100° and peaked at 58.6 °C. The increasing bone temperature trend could be caused by the increased thrust force when increasing the point angle, which leads to increasing heat generation [1,27]. Sui *et al.,* [28] investigated the influence of point angles of 90°, 118°, and 150° on temperature rise when drilling bovine and artificial bones (Sawbones 3401). They discovered a decrease in normal rake angle with the increase of point angle; thus, more mechanical energy is converted into heat energy. However, their claim is still questionable because the rake angle only depends on the helix angle, and the point angle does not influence the rake angle [1].

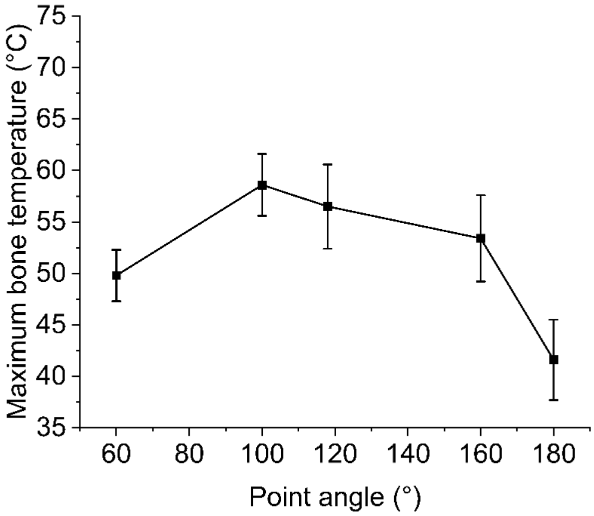


Fig. 7. Corresponding maximum bone temperature with a point angle of 60-180°

The maximum bone temperature decreased steadily with a more significant point angle of 100° to 180°. This trend could be because of the competing effect of thrust force and torque when increasing the point angle. Although the thrust force is increased with the point angle, the torque (twisting force) is reduced significantly [29]. For this reason, the heat generated during the drilling process is also reduced and minimizes bone temperature elevation. The larger point angle bites the material immediately after engaging; it prevents rubbing the bone's surface and reduces heat generation and temperature [1]. Moreover, a larger point angle produces smaller torque and high cutting efficiency [16].

The typical point angle for a surgical drill bit is 90°, which prevents the drill bit from skidding from the target drilling hole [16,29]. However, with a 90° point angle, the drill tends to get stuck in the drilling hole [29]. Furthermore, it produces excessive breakthroughs [15,16]. In bone drilling research, point angles of 60-160° have been investigated in the literature [1,6]. The narrower point angle (60°) produces an ellipsoidal hole unsuitable for screws or implant placement [1]. This study discovered that a larger point angle reduces maximum bone temperature elevation, which is consistent with previous studies [1].

Furthermore, a larger point angle produces smaller bone debris due to shorter cutting lips (Figure 8). For this reason, the bone chips were quickly evacuated from the drilling hole, preventing clogging of the drill flutes and drilling sites. These clogs increase the thrust force and drilling torque, which elevate bone temperature. Therefore, a larger point angle provides a better bone chip evacuation system and could minimize heat generation in bone drilling.

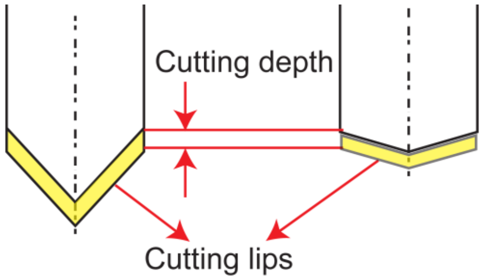


Fig. 8. Effect of point angle on the length of cutting lips

3.1.2 Effect of web thickness on maximum bone temperature

The influence of web thickness on bone temperature (maximum) is presented in Figure 9. Based on this figure, the maximum bone temperature was increased with the web thickness, varying from 25 % to 50 %. Increasing web thickness increases the thrust force by more than 50 % and increases the heat generation and maximum bone temperature [30]. Previous studies also reported this trend, where Sui *et al.,* [28] evaluated three different web thicknesses (0.42, 0.84, 1.26 mm) and discovered a direct relationship between web thickness and bone temperature rise [15,28]. The reason is that the length of the cutting lips increases with web thickness (Figure 10). As a result, more mechanical energy is converted into heat energy, which increases the bone temperature. Furthermore, increasing the web thickness reduces the locating ability of the drill bit and could cause the drill bit to skid from the target locations [15]. Therefore, this skidding adds unnecessary friction energy and heat generation due to the rubbing action between the drill tip and bone, resulting in higher bone temperature.

Web thickness is categorized into three groups: light (14-16 %), medium (17-22 %), and heavy (25-40 %) [1]. Previous researchers have recommended light (5 % 18) and medium web thickness (18 % 21) for minimum temperature and thrust force of bone drilling. Furthermore, a light web thickness minimizes the thermal osteonecrosis regions [15]. Results in this study point toward the effectiveness of using minimum web thickness (25 %) to reduce bone temperature elevation. When the web thickness was increased to 50 %, the elevation of maximum bone temperature was more than 12.8 % (61.9 °C).

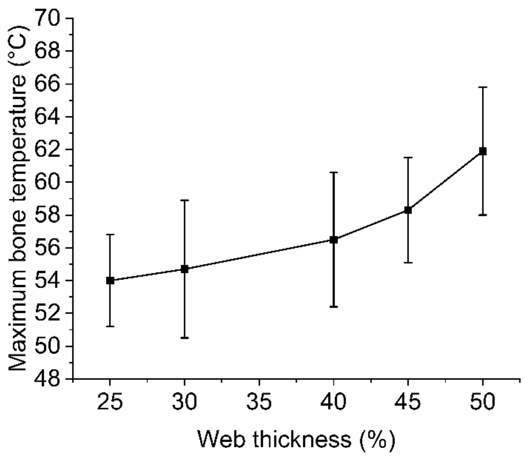


Fig. 9. Maximum bone temperature concerning the web thickness of 25-50 %

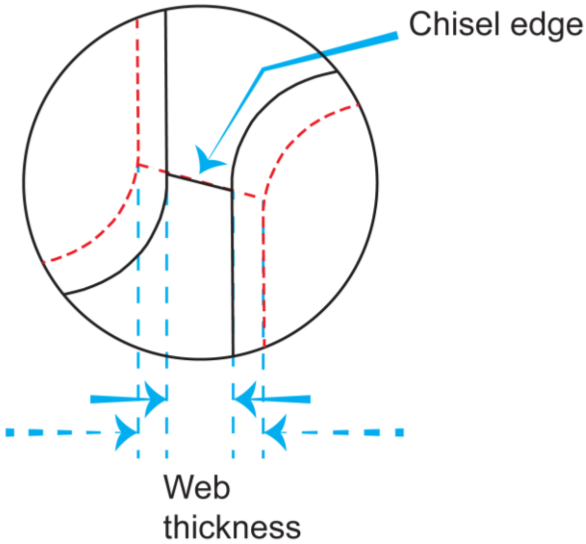


Fig. 10. The chisel edge increases with web thickness

3.1.3 Effect of helix angle on maximum bone temperature

Figure 11 depicts the maximum bone temperature corresponding to the different helix angles. The maximum bone temperature (64.6 °C) was reduced with helix angle and bottomed out (56.5 °C) at a helix angle of 30°. A higher helix angle evacuates bone debris quickly after shearing, preventing heat accumulation in the drilling hole [27]. Furthermore, a quicker bone debris evacuation could clear the drill flute and prevent flute clogging [22]. This action can prevent the increase in thrust force, contributing to heat generation [1]. This finding agrees with the previous study, which revealed a maximum torsional rigidity at a helix angle of 28°, and reduced mechanical and heat energy with increasing rake and helix angles [27,31].

The bone temperature was slightly increased by 3.4 % with a helix angle of 30° to 55°. This trend could be because a higher helix angle produces a smaller thrust force, which increases the drilling time; a longer drilling time generates more heat and increases the bone temperature [1,15]. A previous study suggested a helix angle of 12-14° for minimum drilling time and thermal damage [32].

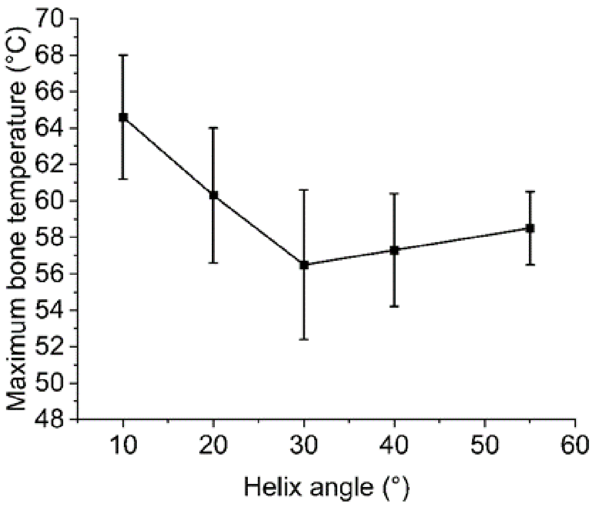


Fig. 11. Maximum bone temperature for helix angle of 10-55°

3.1.4 Optimal drill bit design

Results from the parametric study performed in the previous section revealed that the point angle of 160-180°, web thickness of 25-30%, and helix angle of 30-40° produce minimum bone temperature elevations. Therefore, these ranges are suitable for optimization using Taguchi L_9 and selected for further analysis (Table 3).

Table 3
Levels selected for Taguchi L9 orthogonal array

Level	Point angle (°)	Web thickness (%)	Helix angle (°)
1	160	25	30
2	170	27.5	35
3	180	30	40

In the Taguchi method, the S/N ratio is calculated to determine the best combination of point angle, web thickness, and helix angle [33]. "Signal" means the desirable value for the output or the product's quality change investigated in the study. Meanwhile, "Noise" means the undesirable value because numerous external factors are not considered when conducting the experiments [34]. Therefore, to simplify, the S/N ratio is the mean-to-standard deviation ratio.

The results of S/N ratios for each level of factors are listed in Table 4. Analysis shows that the helix angle level two has the highest S/N ratio value, followed by web thickness level one and point angle level three. The ranks of the factors influencing bone temperature have been included in the same table. Rank 1(helix angle) indicates the most influencing factor, and Rank 4(point angle) indicates the least influencing factor among the three factors. Using these S/N ratio values, the main effects for individual factors were computed and shown in Figure 12.

Analysis of variance (ANOVA) is performed to calculate the percentage distribution of each factor, and the results are shown in Table 5. The table shows that the helix angle has the highest contribution to maximum bone temperature elevation, with an F-ratio of 8.62. It is generally accepted that when the F-ratio is greater than four, any modification to the process parameter will substantially affect the characteristic's quality [35]. The percentage contribution of web thickness and point angle are 19.07 and 8.68, respectively. Therefore, the contributing factors from this table ranked as helix angle, web thickness, and point angle.

Table 4
Response table for S/N ratio of maximum bone temperature

Level	Point angle (°)	Web thickness (%)	Helix angle (°)
1	-33.45	-33.25	-33.33
2	-33.41	-33.40	-33.19
3	-33.29	-33.50	-33.64
Delta	0.16	0.25	0.46
Rank	3	2	1

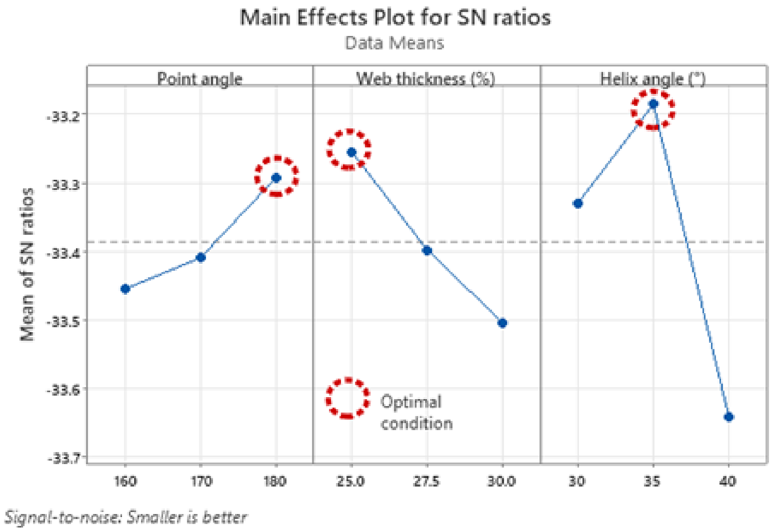


Fig. 12. Main effects plot for S/N ratios

Table 5
ANOVA results for maximum bone temperature

Factors	Degree of freedom	Sum of square	F-ratio	P-ratio	Percentage contribution
Point angle	2	1.282	1.16	0.464	8.68
Web thickness (%)	2	2.816	2.54	0.283	19.07
Helix angle (°)	2	9.562	8.62	0.104	64.74
Residual Error	2	1.109			7.51
Total	8	14.769			100

Altogether, from the S/N ratio and ANOVA analysis, the optimal set of parameters was found to be A3B1C2, corresponding to a point angle of 180°, web thickness of 25%, and helix angle of 35°. A confirmation test is the last step necessary to validate the results of the optimal conditions in terms of the actual and predicted results [25,26,35]. Therefore, the confirmation test for the optimum parameters A3B1C2(with a confidence level of 95%) was performed, and the results (maximum bone temperature) were compared with the predicted values (Table 6). Results showed that the percentage error between the experimental value (44.9 °C) and the predicted value (44.4 °C) was only 1.11 %. This small error shows that the experimental value is in good agreement with the predicted value. Therefore, the developed Taguchi optimization model was successfully validated.

Table 6
Results of the confirmation test

Optimum Parameter		Experiment	Prediction	Error (%)
PA (°)	180	44.9 °C	44.4 °C	1.11%
WT (%)	25			
HA (°)	35			

3.1.5 Limitations

Although the experimental tests used in this study closely mimic the actual surgeries in bone drilling compared with the simulation study, there are some limitations

i. The ex vivo animal bones were used to substitute the human bone, which could produce different results due to the effects of blood flow in the medullary canal and different cortical bone structures between humans and cows. However, the blood flow effect is negligible, and bovine bone produces close similarity with human bone in terms of bone temperature elevations [2,6,19].

ii. The temperature elevations were measured using thermocouples, which can only record the maximum temperature of 0.5 mm from the circumference of the drilling hole. However, this method gives acceptable results and is adopted in most bone drilling research [1].

4. Conclusions

This work assessed the influences of drill bit design—point angle, web thickness, and helix angle—on the maximum bone temperature of cortical bone in a bone drilling experiment. The following key insights are drawn from this study

i. Point angle has a parabolic effect on maximum bone temperature. When varying the point angle from 60° to 100°, the maximum bone temperature was increased by 17.7 %. However, a higher point angle from 118-180° decreases the bone temperature elevation by up to 40.9 %.
ii. A higher web thickness (25-50 %) increases the maximum bone temperature to 12.8 %.
iii. The helix angle in the 10-30° range decreases the maximum bone temperature up to 14.3 %. However, the maximum bone temperature slightly increases (3.4 %) with a helix angle of 30-55°.
iv. The optimal setting of 180° point angle, 25 % web thickness, and 30° helix angle produces a minimum bone temperature elevation of 44.9 °C.

Declaration of competing interests

The authors declare no conflicts of interest.

Acknowledgment

The author gratefully acknowledged the financial support of Universiti Malaysia Terengganu through a research grant UMT/TAPE-RG/2022/55402. We also thank Universiti Malaysia Pahang for support through grants PDU 213213 and PDU213204.

References

[1] Akhbar, Mohd Faizal Ali, and Akmal Wani Sulong. "Surgical drill bit design and thermomechanical damage in bone drilling: a review." *Annals of Biomedical Engineering* 49, no. 1 (2021): 29-56. https://doi.org/10.1007/s10439-020-02600-2
[2] Islam, Md Ashequl, Nur Saifullah Kamarrudin, Ruslizam Daud, Siti Noor Fazliah Mohd Noor, Azwan Iskandar Azmi, and Zuradzman Mohamad Razlan. "A review of surgical bone drilling and drill bit heat generation for implantation." *Metals* 12, no. 11 (2022): 1900. https://doi.org/10.3390/met12111900
[3] Othman, Maisarah Kursus, Pay Jun Liew, Siang Yee Chang, Mohd Shukor Salleh, Raja Izamshah, and Jingsi Wang. "Experimental study of quarry dust and aluminium oxide suspension as cutting fluid for drilling of titanium alloy." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 91, no. 2 (2022): 145-153. https://doi.org/10.37934/arfmts.91.2.145153
[4] Kalvin, Roman, Juntakan Taweekun, Muhammad Waqas Mustafa, Saba Arif, and Abdullah Javed. "Investigation of Chip Formation and its Grain Structure using Vegetable Oil Based Lubricants." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 84, no. 2 (2021): 92-97. https://doi.org/10.37934/arfmts.84.2.9297
[5] Wiggins, K. L., and S. Malkin. "Drilling of bone." *Journal of Biomechanics* 9, no. 9 (1976): 553-559. https://doi.org/10.1016/0021-9290(76)90095-6
[6] Lee, JuEun, Craig L. Chavez, and Joorok Park. "Parameters affecting mechanical and thermal responses in bone drilling: A review." *Journal of Biomechanics* 71 (2018): 4-21. https://doi.org/10.1016/j.jbiomech.2018.02.025
[7] Akhbar, Mohd Faizal Ali. "Thermomechanical damage in cortical bone caused by margins of surgical drill bit: A finite element analysis." *Computer Methods and Programs in Biomedicine* 231 (2023): 107361.

https://doi.org/10.1016/j.cmpb.2023.107361

[8] Akhbar, Mohd Faizal Ali, and Ahmad Razlan Yusoff. "Fast & Injurious: Reducing thermal osteonecrosis regions in the drilling of human bone with multi-objective optimization." *Measurement* 152 (2020): 107385. https://doi.org/10.1016/j.measurement.2019.107385

[9] Akhbar, Mohd Faizal Ali, and Ahmad Razlan Yusoff. "Drilling of bone: thermal osteonecrosis regions induced by drilling parameters." *Biomedical Physics & Engineering Express* 5, no. 6 (2019): 065003. https://doi.org/10.1088/2057-1976/ab42f2

[10] Gok, Kadir, Arif Gok, and Yasin Kisioglu. "Optimization of processing parameters of a developed new driller system for orthopedic surgery applications using Taguchi method." *The International Journal of Advanced Manufacturing Technology* 76 (2015): 1437-1448. https://doi.org/10.1007/s00170-014-6327-0

[11] Akhbar, Mohd Faizal Ali, and Ahmad Razlan Yusoff. "Optimization of drilling parameters for thermal bone necrosis prevention." *Technology and Health Care* 26, no. 4 (2018): 621-635. https://doi.org/10.3233/THC-181221

[12] Akhbar, Mohd Faizal Ali, Mukhtar Malik, and Ahmad Razlan Yusoff. "Effects of drilling parameters in numerical simulation to the bone temperature elevation." In *AIP Conference Proceedings*, vol. 1948, no. 1. AIP Publishing, 2018. https://doi.org/10.1063/1.5030881

[13] Gok, Kadir, Arif Gok, and Yasin Kisioglu. "Computer aided finite element simulation of the developed driller system for bone drilling process in orthopedic surgery." *Journal of Advanced Manufacturing Systems* 18, no. 04 (2019): 583-594. https://doi.org/10.1142/S0219686719500318

[14] Zhang, Yue, Linlin Xu, Chengyong Wang, Zhihua Chen, Shuai Han, Bin Chen, and Jacky Chen. "Mechanical and thermal damage in cortical bone drilling in vivo." *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine* 233, no. 6 (2019): 621-635. https://doi.org/10.1177/0954411919840194

[15] Akhbar, Mohd Faizal Ali, and Ahmad Razlan Yusoff. "Drilling of bone: Effect of drill bit geometries on thermal osteonecrosis risk regions." *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine* 233, no. 2 (2019): 207-218. https://doi.org/10.1177/0954411918819113

[16] Akhbar, Mohd Faizal Ali, and Ahmad Razlan Yusoff. "Multi-objective optimization of surgical drill bit to minimize thermal damage in bone-drilling." *Applied Thermal Engineering* 157 (2019): 113594. https://doi.org/10.1016/j.applthermaleng.2019.04.004

[17] Esteves, Jônatas Caldeira, Elcio Marcantonio Jr, Ana Paula de Souza Faloni, Fernanda Regina Godoy Rocha, Rosemary Adriana Marcantonio, Katarzyna Wilk, and Giuseppe Intini. "Dynamics of bone healing after osteotomy with piezosurgery or conventional drilling-histomorphometrical, immunohistochemical, and molecular analysis." *Journal of Translational Medicine* 11 (2013): 1-13. https://doi.org/10.1186/1479-5876-11-221

[18] Sui, Jianbo, Naohiko Sugita, Kentaro Ishii, Kanako Harada, and Mamoru Mitsuishi. "Mechanistic modeling of bone-drilling process with experimental validation." *Journal of Materials Processing Technology* 214, no. 4 (2014): 1018-1026. https://doi.org/10.1016/j.jmatprotec.2013.11.001

[19] Akhbar, Mohd Faizal Ali, and Ahmad Razlan Yusoff. "Comparison of bone temperature elevation in drilling of human, bovine and porcine bone." *Procedia CIRP* 82 (2019): 411-414. https://doi.org/10.1016/j.procir.2019.03.220

[20] Choi, Sung-Jin, Jong-Il Lee, Nam-Soo Kim, and In-Hyuk Choi. "Distribution of cortical bone in bovine limbs." *Journal of Veterinary Medical Science* 68, no. 9 (2006): 915-921. https://doi.org/10.1292/jvms.68.915

[21] Treece, Graham M., Andrew H. Gee, P. M. Mayhew, and Kenneth ES Poole. "High resolution cortical bone thickness measurement from clinical CT data." *Medical Image Analysis* 14, no. 3 (2010): 276-290. https://doi.org/10.1016/j.media.2010.01.003

[22] Lee, JuEun, O. Burak Ozdoganlar, and Yoed Rabin. "An experimental investigation on thermal exposure during bone drilling." *Medical Engineering & Physics* 34, no. 10 (2012): 1510-1520. https://doi.org/10.1016/j.medengphy.2012.03.002

[23] Sedlin, Elias D., and Carl Hirsch. "Factors affecting the determination of the physical properties of femoral cortical bone." *Acta Orthopaedica Scandinavica* 37, no. 1 (1966): 29-48. https://doi.org/10.3109/17453676608989401

[24] Gholampour, Seifollah, Hossein Haghighi Hassanalideh, Mansore Gholampour, and David Frim. "Thermal and physical damage in skull base drilling using gas cooling modes: FEM simulation and experimental evaluation." *Computer Methods and Programs in Biomedicine* 212 (2021): 106463. https://doi.org/10.1016/j.cmpb.2021.106463

[25] Shakir, Safa Waleed, Sarah Saad Mohammed Jawad, and Zainab Abdulmaged Khalaf. "Analysis of the Impact of Nanofluids on the Improvement in CO_2 Absorption using Taguchi Method." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 115, no. 1 (2024): 83-98. https://doi.org/10.37934/arfmts.115.1.8398

[26] Idrus, Muhammad Abdul Mun'aim Mohd, Aniq Danish Azli, Md Redzuan Zoolfakar, Raa Khimi Shuib, Abdul Hafidz Yusoff, and Asmalina Mohamed Saat. "Optimization of the Effect of Hydraulic Hot-Pressing-Process Parameters on Tensile Properties of Kapok Fiber Nonwoven Web Based on Taguchi Experimental Design." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 115, no. 1 (2024): 156-165.

https://doi.org/10.37934/arfmts.115.1.156165

[27] Sui, Jianbo, and Naohiko Sugita. "Experimental study of thrust force and torque for drilling cortical bone." *Annals of Biomedical Engineering* 47 (2019): 802-812. https://doi.org/10.1007/s10439-018-02196-8

[28] Sui, Jianbo, Chengyong Wang, and Naohiko Sugita. "Experimental study of temperature rise during bone drilling process." *Medical Engineering & Physics* 78 (2020): 64-73. https://doi.org/10.1016/j.medengphy.2020.01.007

[29] Farnworth, G. H., and J. A. Burton. "Optimization of drill geometry for orthopaedic surgery." In *Proceedings of the Fifteenth International Machine Tool Design and Research Conference*, pp. 227-233. Macmillan Education UK, 1975. https://doi.org/10.1007/978-1-349-01986-1_27

[30] Saha, S., S. Pal, and J. A. Albright. "Surgical drilling: design and performance of an improved drill." *Journal of Biomechanical Engineering* 104, no. 3 (1982): 245-252. https://doi.org/10.1115/1.3138356

[31] Narasimha, K., M. O. M. Osman, S. Chandrashekhar, and J. Frazao. "An investigation into the influence of helix angle on the torque-thrust coupling effect in twist drills." *The International Journal of Advanced Manufacturing Technology* 2 (1987): 91-105. https://doi.org/10.1007/BF02601495

[32] Fuchsberger, Alfred. "The damaging temperature at the machining of bone." *Unfallchirurgie* 14 (1988): 173-183. https://doi.org/10.1007/BF02770032

[33] Agarwal, Raj, Vishal Gupta, Jaskaran Singh, and Vivek Jain. "Prediction of surface roughness and cutting force induced during rotary ultrasonic bone drilling via statistical and machine learning algorithms." *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science* 236, no. 23 (2022): 11123-11135. https://doi.org/10.1177/09544062221110407

[34] Ahmad, Saif Nawaz, and Om Prakash. "Optimization of ground heat exchanger of the ground source heat pump system based on exergetic analysis using Taguchi technique." *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science* 235, no. 21 (2021): 5892-5901. https://doi.org/10.1177/0954406221991183

[35] Shafie, Bunyami, Huei Hong Lee, Phene Neoh Pei Nee, Fatin Hana Naning, Tze Jin Wong, Lee Feng Koo, and Yiu Pang Hung. "Heat Moisture Modified Rice Flours as Additive in Drilling Fluids." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 80, no. 1 (2021): 62-72. https://doi.org/10.37934/arfmts.80.1.6272