SEMARAK ILMU PUBLISHING
202103268166(003316878-P)

Journal of Advanced Research in Applied Mechanics

Journal homepage:
https://semarakilmu.com.my/journals/index.php/appl_mech/index
ISSN: 2289-7895

Quantifying the Impact of Drilling Parameters on Temperature Elevation within Bone during the Process of Implant Site Preparation

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ARTICLE INFO

Article history:
Received 14 December 2023
Received in revised form 9 February 2024
Accepted 23 February 2024
Available online 30 April 2024

Keywords:
Orthopaedics; bone drilling; thermal bone damage; ANOVA analysis; optimizing drilling conditions

ABSTRACT

This study aimed to elucidate the influences of several drilling parameters on bone temperature during drilling, as excessive heat generation can cause thermal bone damage and affect post-surgery recovery. In vitro drilling tests were conducted on bovine femoral shaft cortical bone specimens. The parameters considered included tool rotational speed (s), feed rate (f), tool diameter (d), and drill tip angles of 118° and 135°. Drilling temperatures were studied across a range of 800–2000 rpm rotational speeds, 20–40 mm/min feed rates, and 2–4 mm drill diameters. A predictive statistical model was constructed using the response surface methodology (RSM). Analysis of variance (ANOVA) at a 95% confidence level (α = 0.05) revealed that rotational speed significantly impacted temperature increase, contributing to 59.74% of observed temperature rises. Drill diameter accounted for 16.21% of temperature variations, while feed rate contributed to 10.04% of the temperature rises. The study provides valuable insights into the predominant factors affecting bone temperature during drilling. Understanding these parameters and their interplay is pivotal for optimizing drilling conditions and minimizing potential thermal damage to bones.

1. Introduction

Orthopaedic surgeons commonly use bone drilling as a surgical procedure to repair fractures or reconstruct bones. Among various cutting techniques in orthopaedics, drilling is the most widely used and extensively discussed in medical literature. This process involves the utilization of mechanical twist drills to create holes in the bone, which are then used to secure fixative devices with screws for stabilization. Controlling drilling force, temperature elevation, and microcracking in the bone are critical factors for a successful and safe drilling operation.

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https://doi.org/10.37934/aram.116.1.112

Medical literature emphasises that bone temperature should not exceed 47°C for more than sixty seconds, indicating a low thermal dosage threshold [1]. Excessive heat accumulation during drilling can cause severe thermal damage at the drill site, potentially leading to early loosening of the fixture [2]. The surgeon must apply precise pressure when drilling the compact part of the bone, but this can result in overheating and potential death of osteocytes. The bone's low thermal conductivity and specific heat capacity contribute to an elevated likelihood of thermal osteonecrosis occurring at the drilling site. This presents a significant obstacle in effectively regulating heat generation during the procedure.

Numerous research studies have explored the effects of drilling conditions, bone type, density, drill-bit shape, and irrigation on maximum temperatures and exposure periods during bone drilling, with the aim of identifying factors to prevent thermal osteonecrosis [3-5]. However, some studies have reported contradictory results, which might be attributed to sources of measurement uncertainty rather than the analytical methodologies employed [6-8].

The present investigation is centred on examining the impacts of rotating speed, feed rate, and drill bit diameter on the distribution of temperature during the drilling process of bovine femur bones. This research adopts a unique approach to measure temperature during bone drilling, using multiple thermocouples and CNC machining technology. The study systematically investigates the parametric variations in rotational speed, feed rate, drill bit diameter, and thermocouple positions to gain deeper insights into the temperature dynamics during bone drilling. By shedding light on the crucial parameters influencing temperature distribution, this study contributes valuable knowledge to the field of bone drilling and its associated challenges in orthopaedic surgery.

2. Materials and Methods

2.1 Bone Specimen Preparation

In this experimental investigation, bovine (cow) femur bones were deliberately chosen as the test material due to their properties' close resemblance to human bones [3]. The main section of interest in the femur bones was the middle diaphysis, which contains the most compact bone compared to other regions of the skeletal system. This compact bone, commonly known as cortical bone, coexists with a less dense and more porous section called trabecular bone [4]. To this study, the researchers specifically focused on the cortical bone obtained from the femoral shaft of young cows aged between two and three years [5]. The selection of cortical bone from this specific age group ensured consistency and relevance to the human bone characteristics under examination.

To preserve the physical properties of the bone specimens with minimal alteration, they were carefully stored at -20 °C before the drilling tests [21]. The cylindrical bone specimens were thoroughly examined, and they exhibited no visible signs of disease or significant porosity, ensuring the integrity of the study material [3].

Prior to conducting the drilling tests, the bone specimens were thawed at room temperature for a standardized period of 2 hours [9]. This thawing process ensured uniformity in the bone's temperature across the experiments. The temperature of each test specimen was measured before the experiments and was found to be approximately at room temperature, further ensuring the consistency and reliability of the experimental conditions [11]. By employing these precise preparation and storage procedures, the researchers aimed to maintain the bone specimens' structural and thermal characteristics, providing a sound basis for the drilling tests and subsequent data analysis.

2.2 Experimental Procedure

Figure 1 exhibits the drill bits employed in this experimental study, fabricated from HSS-6542, with sizes of 2mm, 3mm, and 4mm. These drill bits were equipped with a standard cutting point head geometry encompassing an angle range of 118 to 135°. The trials were conducted at different rotational speeds (1000, 1500, and 2000 revolutions per minute) while employing drilling feed rates of 20, 30, and 40 mm/min.

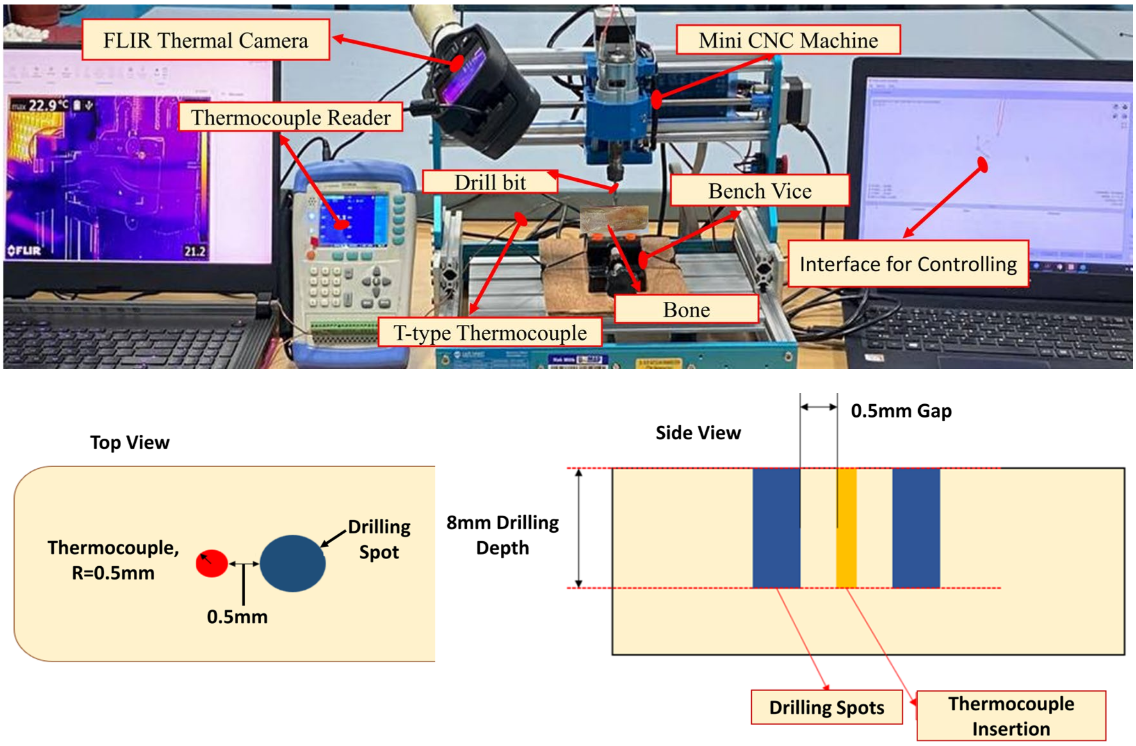

Fig. 1. Customized test bench apparatus setup for bone drilling process and bone drilling plan design

Before commencing the drilling process, precise bone measurements were taken using a vernier calliper scale. Thermocouples were inserted into the bone for temperature measurement, and to ensure consistent spacing, a 1.2mm drill bit was employed to pre-drill the bone, maintaining a fixed 1mm spacing between the midpoints of the drilling holes and the thermocouple pre-drilled holes. The temperature readings were recorded using a multi-channel temperature meter connected to a T-type thermocouple. The temperature data were saved in a pen drive attached to the thermocouples for subsequent analysis.

To control the drilling process, a mini-CNC machine was utilized, providing a controlled and precise drilling environment. The response surface method, a statistical technique, was employed to analyse the collected data and draw meaningful conclusions from the experimental results.

The bones used in the study were sourced from a local butcher and were studied within a few days of procurement to preserve their mechanical and thermo-physical properties. To maintain consistent conditions, all trials commenced at room temperature, approximately 23 °C. The data collection system allowed sufficient time between trials to allow the bone and drill bit to recover to room temperature before initiating the next trial, ensuring reliable and consistent data acquisition.

3. Results

Figure 2 depicts the influence of drilling process factors on the mean maximum temperature. The peak temperature is attained shortly after the initiation of bone penetration by the drill. When the point angle is held constant, an increase in rotational speed from 1000 to 2000 rpm and a corresponding increase in feed rate from 20 to 40 mm/min led to a proportionate rise in temperature. Nevertheless, when the diameter of the drill bit is augmented from 2 to 4mm, there is an initial elevation in temperature followed by a marginal decline in its impact. The measurement of the highest bone temperature is conducted during each set of drilling parameters, whereby the cutting lips of the drill bit are completely submerged into the bone tissue. Nevertheless, a significant decline in temperature is noticed with the removal of the drill bit subsequent to penetrating the cortical layer of the bone.

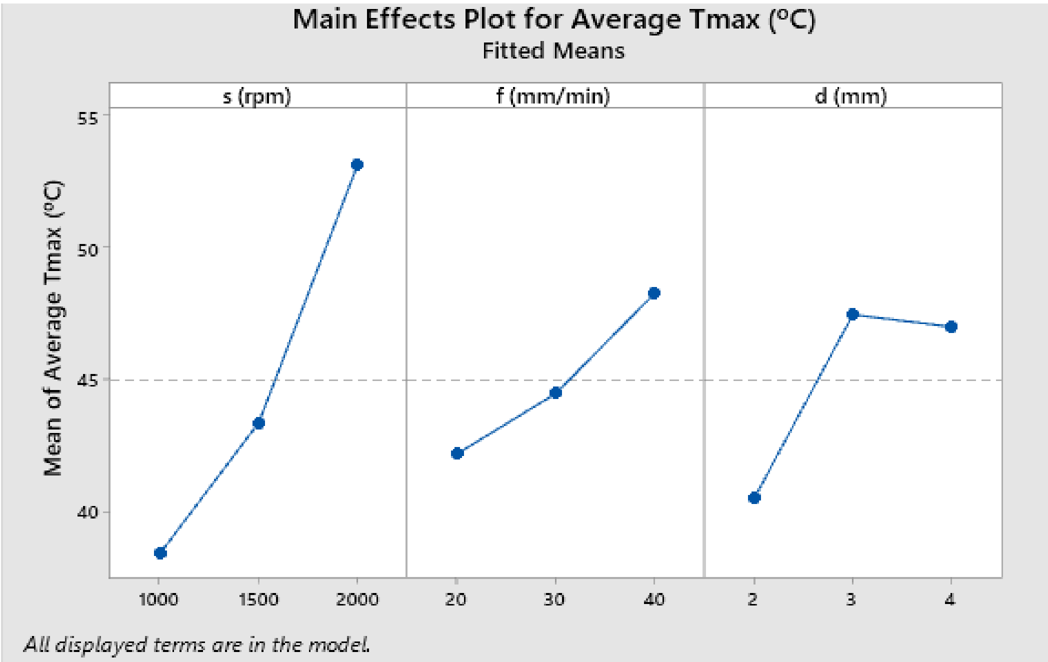

Fig. 2. Drilling average maximum temperature as a function of feed rate, diameter, and rotating speed

Figure 3 presents the sensitivity analysis conducted to assess the impact of various drill bit sizes (2, 3, and 4 mm), rotational speeds (800 and 1000 rpm), and point angles (118 and 135°) on temperature elevation. The figures unambiguously demonstrate that the point angle of 135° exerts the most pronounced impact on the increase in temperature. Conversely, the drill bit diameters exhibit comparatively less effect compared to the other parameters.

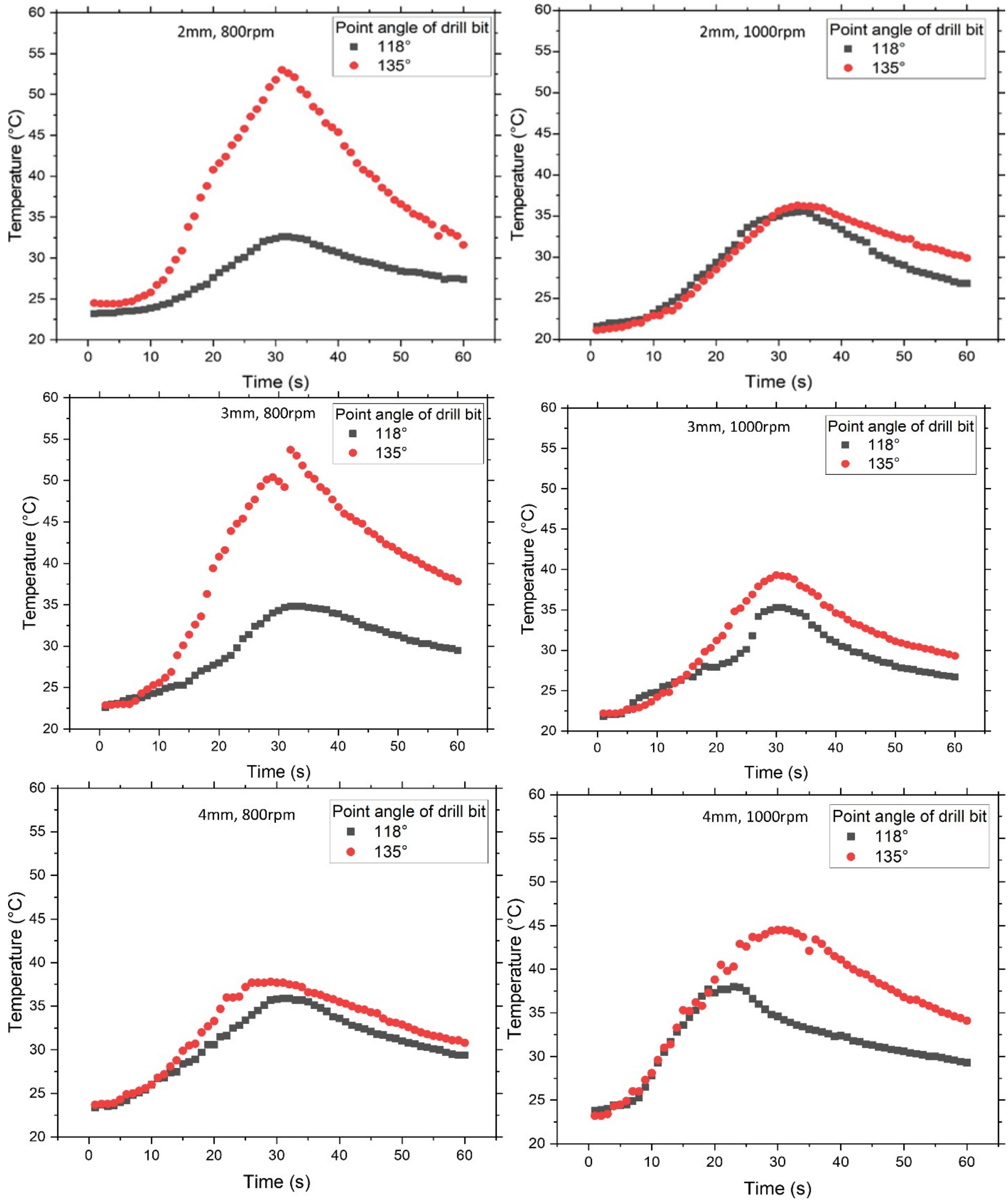

Fig. 3. Temperature vs Time graph for all the parameters

3.1 Effect of Combinations of Parameters on Temperature

Figure 4(a) demonstrates a substantial increase in temperature as the rotational speed gradually rises from 1000 to 2000 rpm, and the feed rate increases from 20 to 40 mm/min. Higher rotational speeds lead to a reduction in the maximum force exerted on the bone during drilling. This effect is due to improved chip evacuation, decreased friction between the tool and the workpiece, and reduced chances of chip blockage. Consequently, higher rotational speeds can contribute to lower process temperatures and forces. This observation is currently being further investigated in laboratories [10].

In Figure 4(b), the combined influence of rotational speed and drill bit diameter on temperature rise is illustrated. It is evident that the rotational speed and drill bit diameter together have the most significant effect on temperature rise as shown in Figure 4(a). However, the effect of drill bit diameters 3mm and 4mm on temperature is similar when compared to the impact of rotational speed. This indicates that spindle rotational speed has a more pronounced effect on temperature than the drill bit diameter. Notably, drill bit diameter plays a critical role in generating heat and thermal necrosis, as supported by the p-value and regression equation coefficients. From a medical perspective, using thinner drill bits can not only reduce heat and force imposed on the bone tissue but also lead to shorter recovery periods [11].

Finally, in Figure 4(c), the temperature's effect is relatively lower (53.67 ℃) compared to the other two combinations of parameters. This suggests that the particular combination of parameters represented in Figure 4(c) has a lesser impact on temperature elevation.

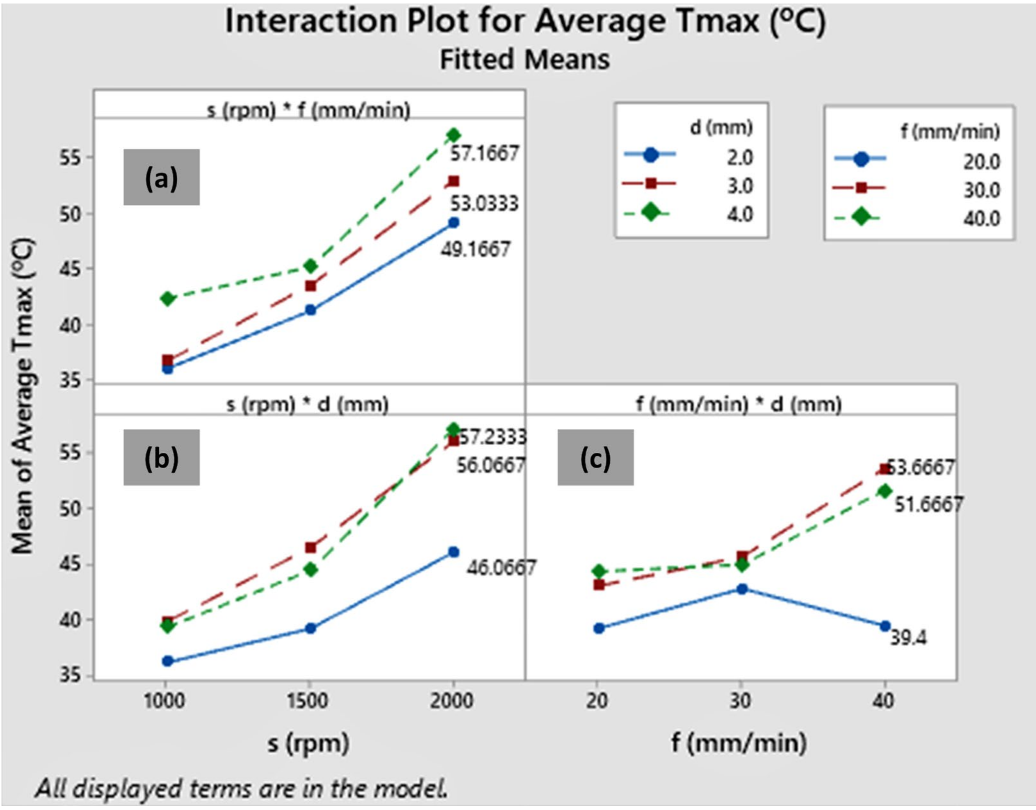

Fig. 4. Interaction effect of (a) rotational speed and feed (b) rotational speed and diameter (c) feed and diameter on average maximum temperature

To examine the significance level and potential interactions among geometrical parameters, the use of analysis of variance (ANOVA) is presented inside the framework of Factorial design. Hence, it is commonly observed in the design and analysis of trials. Table 1 elucidates the impact of individual input parameters and their interactions on the response of the system [12-14].

Table 1
ANOVA of process temperature based on all factors of the bone drilling process

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Result
Model	18	1678.88	93.271	44.09	0.000	-
Linear	6	1458.08	243.013	114.86	0.000	-
s (rpm)	2	1013.01	506.507	239.41	0.000	<Significant
f (mm/min)	2	170.26	85.130	40.24	0.000	<Significant
d (mm)	2	274.81	137.403	64.95	0.000	<Significant
2-Way Interactions	12	220.80	18.400	8.70	0.002	
s (rpm) * f (mm/min)	4	21.54	5.385	2.55	0.121	<Non-significant
s (rpm) * d (mm)	4	59.92	14.980	7.08	0.010	<Significant
f (mm/min) * d (mm)	4	139.34	34.835	16.47	0.001	<Significant
Error	8	16.93	2.116	-	-	-
Total	26	1695.81	-	-	-	-

Table 1 presents the comprehensive model data, encompassing both effective and ineffective parameters. On the other hand, Table 2 includes only the effective parameters, which have P-values lower than 0.05, as derived from the modified model. The selection of a P-value less than 0.05 is based on a reliability threshold of 95%, which is generally deemed acceptable for most engineering problems. Parameters meeting this criterion are considered effective in influencing the model's outcomes.

The fitted model helps evaluate the established model's correctness, especially in design of tests. A lower fitted model value suggests better system output prediction. In temperature analysis, regression Eq. (1) of experimental findings is second-order linear, minimising total squared error. The regression Eq. (1) controls bone drilling temperature and helps explain how factors affect temperature.

$$Temperature\ (°C) = 44.948 + 8.174s(rpm) + 3.296f\left(\frac{mm}{min}\right) + 2.019d(mm) - 0.748s(rpm) * f\left(\frac{mm}{min}\right) - 2.093s(rpm) * d(mm) + 1.404f\left(\frac{mm}{min}\right) * d(mm) \quad (1)$$

Table 2
ANOVA of process temperature based on only effective parameters in the bone drilling process

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Contribution
s (rpm)	2	1013.01	506.507	158.02	0.000	59.74%
f (mm/min)	2	170.26	85.130	26.56	0.000	10.04%
d (mm)	2	274.81	137.403	42.87	0.000	16.21%
s (rpm) * d (mm)	4	59.92	14.980	4.67	0.017	3.53%
f (mm/min) * d (mm)	4	139.34	34.835	10.87	0.001	8.22%
Error	12	38.46	3.205	-	-	2.26%
Total	26	1695.81	-	-	-	100%

Based on the observed values of R-squared (R-sq) at 97.73%, predicted R-squared (R-sq (pred)) at 88.52%, and adjusted R-squared (R-sq (adj)) at 95.09%, together with the favourable distribution of residuals depicted in Figure 5, it can be deduced that the suggested model exhibits a satisfactory level of accuracy. The R-squared goodness-of-fit statistic (R-sg) is a significant indicator that quantifies the accuracy of a model. It may be calculated using Eq. (2).

$$R^2 = \frac{SS_R}{SS_r} = 1 - \frac{SS_{Res}}{SS_T} \quad (2)$$

As the parameter approaches 100% or unity, it signifies a greater level of accuracy in the fitted model and a more exact ability to anticipate outcomes [13,15]. Another factor that is associated with the accuracy of the fitted model is the residual fitted value. The ideal fitted model should closely align with the data points, exhibiting minimal and stochastic deviations from them. The distance between data points may be determined by the coefficient of determination, commonly referred to as R-squared (R-sq). The random distribution of this distance is visually represented in Figure 5. The distribution depicted in the analysis demonstrates that the R-squared values indicate a precise and flawless fit of the model to the observed data points in this investigation.

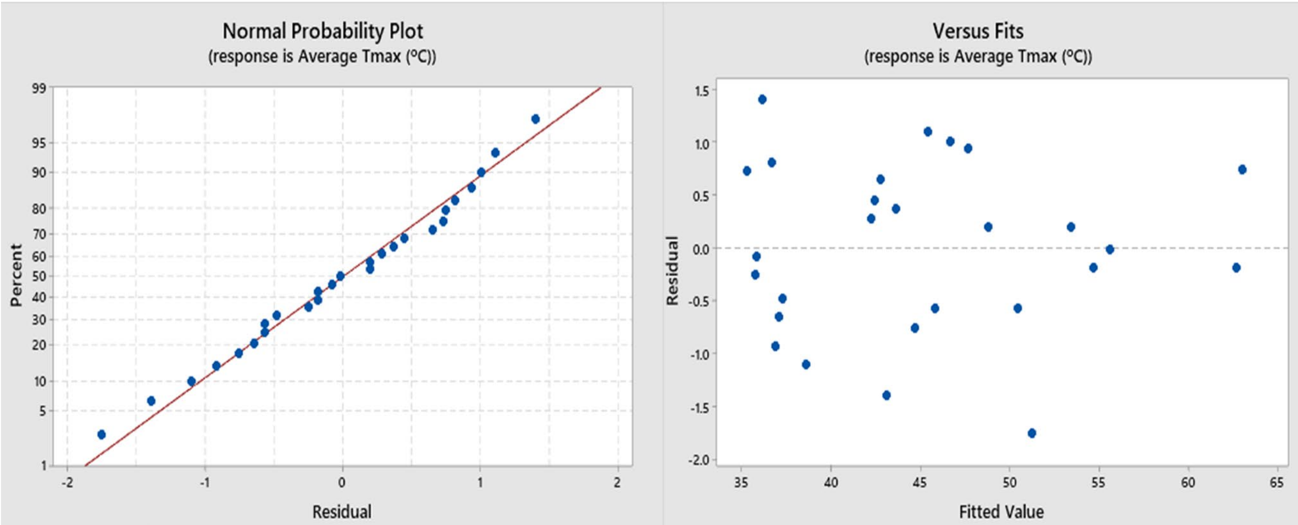

Fig. 5. Residual distribution versus normal and fitted value of drilling temperature

Figure 6 illustrates the temperature behaviour during bone drilling while examining various input parameters and different tool diameters, employing the RSM method. The combination of feed (f), rotational speed (s), and drill bit diameter (d) has been utilized to assess their influence on the temperature rise. The contour plot progresses from the left to the right, representing low to high temperature concentrations. The temperature is significantly impacted by changes in drill bit diameter and feed rate, resulting in a notable rise. Meanwhile, adjustments in feed and rotational speed, as well as drill bit diameter and rotational speed, contribute to a more gradual increment in the temperature.

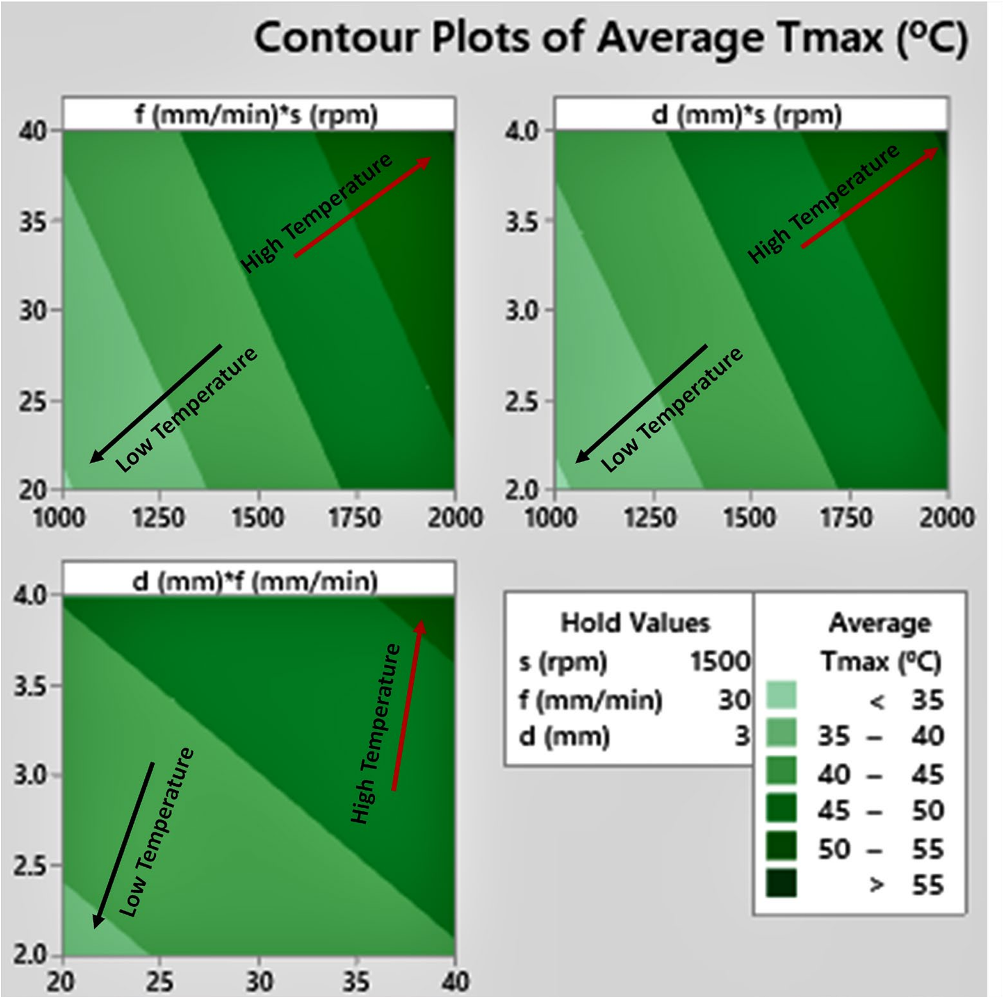

Fig. 6. Interaction diagrams of rotational speed (s), feed (f) and tool diameter (d) effect on average temperature in bone drilling

3.2 Optimization of Process Temperature in Bone Drilling

Through data analysis, we used an optimization method to identify the most favourable combination of input factors that would yield the lowest process temperature. The optimization process, considering the achieved minimum process temperature from the proposed model and incorporating desirability limits, is visually presented in Figure 7. Validation results, along with a comparison to experimental data, are summarized in Table 3. Remarkably, the modelling error is only 0.45%, indicating an exceptionally high accuracy of the model.

Within the investigated range of various input values, it is feasible to reduce the process temperature to a minimum value of 35.05 °C. The temperature that yields the best results aligns with a tool diameter of 2 mm, a feed rate of 40 mm/min, and a rotating speed of 1000 rpm. Figure 7 presents an extensive array of configurable input parameters that guarantee the application of a safe temperature to the bone, hence preventing any potential harm to the bone tissue.

It is crucial to emphasize the significance of reliable bone surgeries, especially in robot-assisted procedures [16-20]. This research highlights the potential of the proposed model in achieving precise temperature control during bone drilling, which could significantly contribute to the success and safety of such surgical interventions.

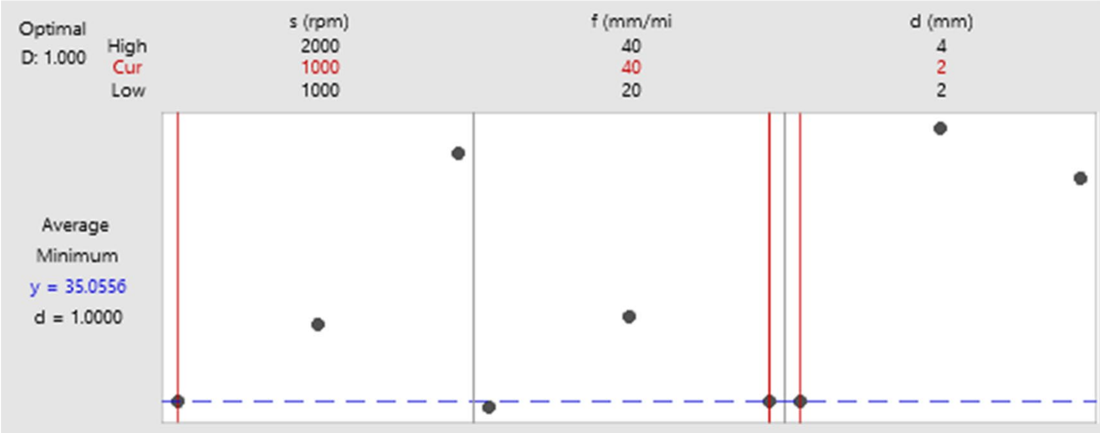

Fig. 7. Optimization to achieve minimum temperature

Table 3
Optimization to achieve the lowest temperature

Optimization	s (rpm)	f (mm/min)	d (mm)	Average Tmax (ºC)
experimentation	1000	40	2	35.50
model	1000	40	2	35.05
Error percentage	-	-	-	0.45%

4. Discussion and Limitations

The complexity of measuring heat transfers during bone drilling arises from the bone tissue's inhomogeneous, thermally anisotropic nature, coupled with the intricate kinematics of the drilling process. The delay in temperature rise after the drill's penetration into the bone is attributed to the bone's low thermal transport capability and the time taken for the heat to reach the thermocouple bead, causing a delay in temperature sensing. The temperature increase in bone primarily results from the cutting of bone material at a higher rate, with the heat generation being augmented by increased friction in the drilling zone. Higher drill rotational speeds lead to elevated bone temperatures due to the increased friction at the drill and bone interface. Similarly, higher feed rates result in increased friction, leading to higher bone temperatures.

This study aimed to determine the optimal process parameters for bovine bone drilling. The identified parameters included a rotational speed of 1000 rpm, a feed rate of 40 mm/min, and a tool diameter of 2 mm. However, it's important to note that these optimal values might not directly apply to in vivo orthopaedic surgery. In practical orthopaedic surgeries, larger drill diameters are often used, which might deviate from the optimal diameter of 2 mm found in this study. The feed rate of 40 mm/min, which proved to be optimal in our experiments, may result in drilling times of approximately 0.5 to 1 minute. In real orthopaedic practice, the drilling time may differ from this average. Additionally, this study presented different parameter sets, such as varying tool diameters and their associated temperatures. Surgeons can customize the drilling process by adjusting the tool parameters according to their requirements.

It is essential to consider that the temperatures observed in bone drilling might differ from previous reports due to variations in bone types, sizes, and drilling conditions used in different studies. The study showed lower temperatures during bone drilling compared to other research [20–23], likely influenced by the specific experimental setup and parameters. Despite its limitations, this study's results can serve as a useful starting point to guide the selection of optimal drilling parameters in orthopaedic surgery. Surgeons can use these findings as references and adjust the parameters based on specific surgical requirements and conditions.

5. Conclusions

The aim of this study was to provide surgeons and personnel who conduct osteotomy using a mechanical drill with engineering-based knowledge about the temperature generated during bone drilling. Analysing the impact of rotating speed, feed rate, and drill diameter on the temperature of the drilling process.

One notable achievement of this work is the establishment, to the best of our knowledge, of a second-order linear regression equation that demonstrates the correlation between temperature and input parameters in the context of bone drilling. The study employed optimisation approaches to determine the ideal temperature values under certain conditions, including a rotating speed of 1000 rpm, a feed rate of 40 mm/min, and a tool diameter of 2 mm. As a consequence of this analysis, the determined optimal temperature was found to be 35.05 °C.

The findings hold potential implications for the development of automatic bone surgical drilling machines and the optimization of bone cutting procedures. Additionally, given the similarities in geometry, composition, and strength between bovine and human bone, the outcomes of this study may be justifiably extrapolated to human bone drilling applications.

The study's implications extend to healthcare systems involved in bone drilling procedures, as the acquired knowledge can aid in enhancing drilling practices, contributing to improved surgical outcomes.

Acknowledgement
The author would like to acknowledge the support from the Fundamental Research Grant Scheme (FRGS) under a grant number of FRGS/1/2018/TK03/UNIMAP/02/8 from the Ministry of Higher Education Malaysia.

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