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Experimental Analysis and Statistical Prediction of Tissue Temperature in High-Speed Cortical Bone Drilling Process

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Abstract: The drilling process in surgery is used for joining the pins and prostheses to the human body. Proper drilling can improve the strength of the joint. In this article, the drilling of cortical bone is experimentally investigated at high-speed ranges. For this purpose, the effects of input process variables, including the rotational speed, feed rate, and drill diameter, on the maximum temperature of bone tissue are studied. The response surface methodology (RSM) method is employed for designing the experiments (15 experiments). The results show that the temperature of the tissue first decreases until it reaches a minimum value by increasing the rotational speed, and then the temperature of the tissue begins to increase with the further increase of the rotational speed. Also, the maximum value of tissue temperature was reduced by increasing the feed rate of the tool in the drilling process. In addition, with an increase in the drill diameter, the maximum temperature of the tissue is reduced. The temperature of the bone tissue is predicted using a regression equation as a function of process variables.

Keywords: Feed Rate, High-Speed Bone Drilling Process, Response Surface Methodology, Rotational Speed, Tissue Temperature

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Research paper

1 INTRODUCTION

The drilling of human bone is one of the most important objects of health science that is extensively used in orthopedic surgery, dentistry, fracture treatment, and bone sampling. Today, in bone drilling, the goal is to achieve the lowest amount of mechanical and thermal damage to the bone tissue. This process is one of the most important, sensitive, and widely used mechanical processes in the field of medical engineering due to the complexity and special conditions of the bone material. Bone fracture treatment is performed by restoring the original location of the organ and fixing it with implantable components. Through the operation of bone drilling, screws and implants can be placed inside the broken parts to fix the damaged parts to each other. It should be noted that the term bone, as the main member and constituent of the skeleton of the human body and other vertebrates, refers to a family of materials that have a complex and organized structure. Bone tissue is a non-homogeneous, anisotropic, and porous substance whose porosity is between 5% and 95%, depending on factors such as location, function, and performance conditions. Bone tissue is a smart tissue and changes its structure when a crack occurs, depending on the conditions. The most effective parameters process in the drilling of the bone can be divided into two groups related to process control and parameters related to the geometry and characteristics of the drill. The rotational speed, the feed rate of the tool, the cooling condition, the depth of drilling, and the pre-drilling diameter are the most important parameters related to the control of the drilling process. The drill diameter, helix angle, chisel edge angle, point angle of the drill, rake angle, and the criteria of tool life (erosion of the tool) are the most geometrical variables of the drill tool. Also, the temperature increases in the drilling process, the axial force applied to the bone tissue, the torque created in the drilling process, and the surface roughness can be mentioned as the most important output responses of the bone drilling process. The most important parameter of an automated drilling process is the rotational speed. The next effective parameter is the feed rate. Research in the field of bone piercing is continuously progressing and expanding. One of the most important parameters that must be considered and constantly checked during the drilling is the amount of heat generated due to the frictional contact in the bone tissue. The generated heat transfers according to the conductivity of the bone, and the thermal conductivity measurement shows that the thermal conductivity coefficient is as low as 0.38-2.3 W/(m.°K) [1]. So, the generated heat transfers very slowly, and most of the heat remains in the drilling location. This is undesired because this heat changes the nature of the bone. This provides the basis for the phenomenon of thermal necrosis, bone tissue death, cell death, and reducing strength in the drilling location [2]. The strength of the remaining drilled material is very important in orthopedic surgery. Reducing the strength leads to insufficient supporting of installed automatic screws in the next step, and consequently, problems to restrain the support equipment and stabilize the fracture position in this hole appear. The main problem is weak bone welding in the desired direction due to the lack of strength in the retaining screw and the bone (the drilling area). The rate of failure in plaque implantation in leg fractures has been reported up to 7.1% [3-4]. By studying rabbit bone, Lundskog [5] concluded that bone undergoes cell death when exposed to a temperature of 55°C for 30 seconds. By conducting microscopic studies on rabbit bone, Erickson et al. [6] concluded that a temperature of 47°C for 60 seconds causes thermal necrosis in cortical bone. Two factors that affect thermal necrosis are the specified temperature magnitude and exposure time to that temperature. A threshold limit of temperature to prevent thermal necrosis has been reported by some researchers; the temperature has no significant effect on bone tissue below the threshold temperature, but at higher temperatures, the bone cells are affected by the generated heat. The threshold limit of temperature was reported as 47°C for 60 seconds time duration. According to the tests carried out, the tolerable time for the bone decreases exponentially for a rise in temperature above 47°C. At 48°C, this period is reduced to 30 seconds, while at 53°C, the thermal necrosis happens immediately [7-8]. Brisman [9] reported that an independent increase in speed or axial force increases the temperature in the bone, while increasing the combination of these two parameters improves the cutting efficiency without causing a significant temperature change. Histological studies focusing on the effect of high-speed drilling in the orthopedic surgery process have been carried out by Boyne [10], Moss [11], and Spartz [12]. In these studies, it has been suggested that high-speed drilling has less harmful effects than conventional (low-speed) drilling. Abouzgia et al. [13] by experimenting on cow bone at a speed of 49000 rpm without cooling reported that by increasing force up to 4 N, the temperature increases first, and then it decreases by increasing the force above 4 N. However, increasing the axial force may cause micro-cracks around the hole and damage the bone or lead to the drill breaking inside the bone. Iyer et al. [14] conducted a study on the rabbit tibia. The generated heat during bone cutting in living tissue was measured at three levels: low speed (2000 rpm), medium speed (30000 rpm), and high speed (400000 rpm). An inverse relation between the drilling speed and the generated heat was observed.

Li et al. [15] studied the heat transfer of the drilling process on bones by developing a 3D finite element model in ANSYS software. The maximum temperature of bone has been measured according to varying the influencing process parameters (spindle speed, feed rate, and drill diameter). The results show an increase in maximum temperature by increasing any of the process inputs. The maximum temperature is predicted by developing an empirical equation, and it can be optimized to obtain the minimum temperature. Ying et al. [16] investigated the variation of temperature and force during the cutting by conventional cutting and ultrasonic vibration-assisted cutting experimentally and numerically. A finite element model is developed in ABAQUS software using the Johnson-Cook material model. The results show that the ultrasonic vibration decreases the cutting force while it increases the temperature. Also, the cutting force decreases with decreasing cutting speed, while the temperature increases. Dahibhate et al. [17] investigated the temperature variation during bone drilling of sheep rib bone. The experiments have been conducted for process parameters including the drill diameter (2.5, 3.2, 4.5 mm), feed rate (50, 60, 70 mm/min), and spindle speeds (1000, 1500, 2000 rpm). A linear regression equation was developed for the prediction of bone drilling temperature. The analysis of experimental results by statistical tools shows that the most effective parameter is the drill diameter. The second affecting parameter is feed rate.

Also, the rate and quality of postoperative healing in the jawbone were measured. The results show that the healing rate and quality of the bone formed in drilled holes at high speed are better than using the low and medium speeds in the first 6 weeks after drilling [18]. Reingewirtz et al. [19] by studying the high-speed drilling of the beef femur, concluded that the temperature increases directly in the range of 400-7000 rpm rotational speed, and it decreases by increasing the rotational speed in the range of 7000-24000 rpm. It was also concluded that changes in the feed rate from 80 to 200 mm/min have a negligible effect on the temperature in the range of low speeds, such as 400-800 rpm. Udiljak et al. [20] investigated the study of high-speed porcine bone drilling. The drilling machine was prepared with 10000 to 16000 rpm rotational speeds, and a standard surgical drill was used. It was concluded that the rate of temperature increase at high speeds has decreased compared to low speeds, and no significant effect on temperature changes at speeds above 10000 rpm was observed. Li et al. [21] investigated experimentally the effects of cutting speed and feed rate during the drilling of beef femurs. The results show that the maximum temperature increases by increasing the cutting speed and decreasing the feed rate. By studying the cow femur in two different speed ranges of 500-1000 rpm (low speed) and 3000-18000 rpm (high speed), Shakoori et al. [22] reported that the temperature decreases with increasing the rotational speed in conventional drilling. Tahmasbi et al. [23] developed a regression equation using response surface methodology to find the temperature in the bone drilling process according to the process variables (rotational speed, feed rate, and tool diameter).

As the literature survey shows, obtaining a good hole quality in the drilling of bones is important and has several advantages in surgery and patient life. In recent years, attention has been drawn to the high-speed drilling of bones. In this research, the effect of drilling process parameters on the generated heat will be investigated experimentally. The experimental tests have been planned according to response surface methodology (RSM). The effective parameters will be determined by analysis of the variance (ANOVA). The attitude of the current study is to find a reliable equation for predicting the temperature in bone drilling at high speeds.

2 MATERIALS AND METHODS

In the experiments, fresh femur bovine bone aged about 3-4 years was used [23]. A 100 mm length diaphysis part of the cow thigh (middle part) has been used in the experimentation. The cortical bone has about 8-10 mm thickness. Also, to make things easier in the experimentations, the beginning and end parts of the femur were cut with a saw. In “Fig. 1”, a fresh femur bovine bone that was used in the experiments can be seen.

Fig. 1 A fresh femur bovine bone was used in the experiments.

It should be noted that the experimentations have been carried out on the bovine cortical femur because its physical and mechanical characteristics are very similar to the human long bones [24]. Therefore, many researchers have used cow femur to investigate the cortical bone drilling process. For carrying out this research, a long time should not have passed since the bone tissue was alive, so that the thermomechanical and physical properties and density of the new bone tissue are preserved and resemble the living tissue undergoing surgery. The thermomechanical and physical properties of the bone change widely over time and will no longer have the necessary similarity with the conditions of surgery [25]. Also, if the fresh bone is not used (for about 3-4 hours) to preserve its properties, the fresh bone should be quickly placed in the freezer at -25℃. In this study, the femur of the cow, which was removed from its body immediately after slaughter, has been used. Due to the time gap between slaughtering and drilling, to keep the bones fresh after removing the excess meat that remained on its surface, the bones were immediately frozen to keep them fresh and placed in the open air for a few hours before the experiment. The thickness of the outer cortex of the bone wall, which is the cortical part of the bone, is about 8-10 mm. Before performing the experiments, the surface of the bone is completely cleaned of the remaining meat and fats on the surface of the bone, because the presence of these complications causes problems in the way of draining the chips and increases the possibility of clogging the drill grooves. To facilitate the measurement of bone temperature and the proper placement of bone on the load cell to read the drilling force, samples with a width of about 15 to 20 mm have been created using a milling machine. By doing this cutting, smooth pieces that can be drilled and tested are better selected. These tests have been done at room temperature without using any coolant liquid.

In this research, to perform high-speed experiments, a high-speed motor with a wide range of rotational speeds is used. The maximum available rotational speed of the motor is 18,000 rpm. This motor is installed on the head of the milling machine using a base so that the drilling tool can be installed on it. K-type thermocouples have been used for measuring the temperature while drilling. The thermocouple is placed at a 3 mm depth, 0.5 mm distance from the wall of the hole created in the bone tissue to measure the temperature. The position is determined based on the investigations that have been done in previous research [26]. Also, to measure the force in this research, single base load cells were used; the maximum amount of force that can be measured is up to 30 kg with an accuracy of 0.01 kg. The standard high-speed steel (HSS) drills have been selected for performing the drilling process. The diameters of the drills are 2, 4, and 6 mm, respectively. Of course, the other geometrical characteristics of the drills, such as point angle, helix angle, and other characteristics, are the same in all of the experiments. The experiments have been carried out according to the design of experiments (DOE) planning, which determines the optimal number of experiments to find the proper equation between the output variable and input variable. The response surface methodology (RSM) is one of the DOE techniques that predict the output carriable with good correlation. This method is suitable for finding the effect of the interaction of process parameters. In this research, three process parameters, including feed rate, rotational speed, and drill diameter, are selected as input variables. According to “Table 1”, the rotational speed is adjusted between 10000-18000 rpm, the feed rate is adjusted between 10-50 mm/min, and the drill diameters are set between 2-6 mm. “Table 2” displays the experiments that should be performed.

Table 1 The levels of each input parameter for the high-speed bone drilling process

Input Variables	Symbol	Min Value	Mid Value	Max Value
Rotational speed (rpm)	N	10000	14000	18000
Feed rate (mm/min)	F	10	30	50
Drill diameter (mm)	D	2	4	6

Table 2 The designed experiment plan according to RSM

Experiment number	N(rpm)	F(mm/min)	D(mm)
1	10000	10	2
2	18000	10	2
3	10000	50	2
4	18000	50	2
5	10000	10	6
6	18000	10	6
7	10000	50	6
8	18000	50	6
9	10000	30	4
10	18000	30	4
11	14000	10	4
12	14000	50	4
13	14000	30	2
14	14000	30	6
15	14000	30	4

3 RESULTS AND DISCUSSION

According to the analysis of the maximum temperature values obtained from the experiments, the analysis of variance (ANOVA) results for the data of the experiments are shown in “Table 3”. The ANOVA determines the effect of the input variables and their interactions on the output variable.

Table 3 Analysis of variance of the maximum temperature

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	8	1199.59	149.949	42.08	0.000
Linear	3	317.77	105.925	29.72	0.000
N	1	171.23	171.230	48.05	0.000
F	1	138.53	138.533	38.87	0.000
D	1	8.01	8.010	2.25	0.162
Square	2	232.36	116.178	32.60	0.000
N*N	1	48.31	48.314	13.56	0.004
F*F	1	44.66	44.656	12.53	0.005
2-Way Interaction	3	649.46	216.486	60.75	0.000
N*F	1	35.96	35.955	10.09	0.009
N*D	1	116.43	116.434	32.67	0.000
Error	11	39.20	3.564		
Lack-of-Fit	6	30.59	5.098	2.96	0.127
Pure Error	5	8.61	1.723		
Total	19	1238.79			

Considering the confidence level of 95% in the experiments, the input variables with a P-value less than 0.05 are considered effective parameters on the tissue temperature in the high-speed bone drilling process. The results of Table 3 show that the rotational speed, feed rate, and the diameter of the drill are the effective parameters of the output variable (tissue temperature).

Equation 1 expresses the tissue temperature in high-speed bone drilling, which, of course, is appropriate for the range considered for the input parameters in “Table 2”.

$$
\begin{aligned}
T \;=\; & 97.7 - 0.00513N - 1.164F \\
& + 0.32D + 0.000000N^2 + 0.00934F^2 \\
& - 0.000027\,N \times F - 0.000477\,N \times D \\
& + 0.1971\,F \times D
\end{aligned} \tag{1}
$$

The coefficient of determination “R^2” is used to show the quality of curve fitting. It is the amount of agreement between predicted data by the regression (statistical) model and experimental data. The value of R^2 is 1 for a theoretically perfect statistical model. The coefficient of determination (R^2) was 0.9453 for the response of tissue temperature, which means that the proposed equation can predict 94.53% of the experimental data. Considering the value of R-sq=94.53% and also the appropriate dispersion of residual analysis according to “Fig. 2”, it can be said that the modelling done has acceptable accuracy.

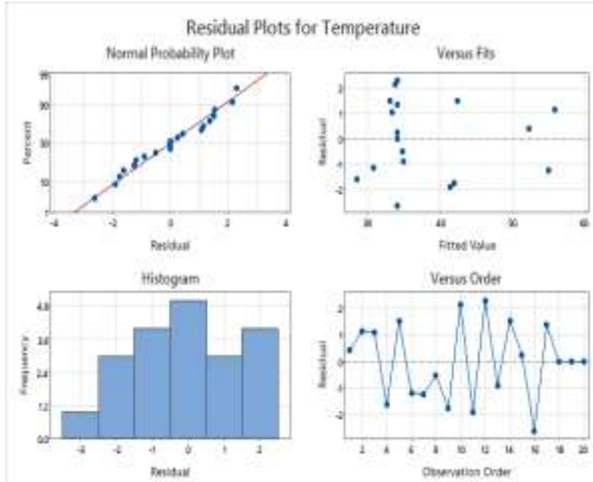


Fig. 2 The residual plots for the model in the high-speed bone drilling process.

To describe the effect of variation in input parameters on the output variable (tissue temperature), the diagram of the mean effect plot and the interaction plot were utilized. In “Fig. 3”, the effect of rotational speed on the maximum value of tissue temperature is presented. It is obvious that by increasing the rotational speed, the tissue temperature first decreased until it reached a minimum value, and then the temperature of the tissue began to increase.

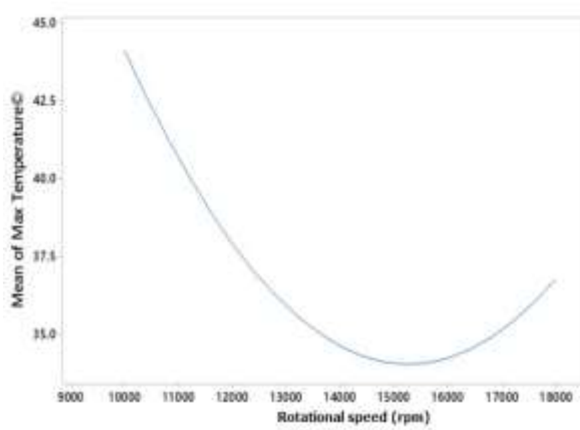


Fig. 3 The effect of rotational speed on the maximum value of tissue temperature in the high-speed bone drilling process.

In this research, the choice of high-speed drilling was in the range of 10,000 to 18,000 rpm. It should be noted that in the high-speed bone drilling process, the size of the deformed chips in the form of powder becomes smaller by increasing the rotational speed, which leads to the ease and better removal of the chips from the drilled hole which is the reason for the decreasing slope of the temperature graph from the speed of 10,000 to the range of 15,000 rpm. But after passing the range of 15,000 rpm, despite the constant force, the temperature shows an increasing trend. Considering the three sources of heat generation in the drilling process, i.e. chip formation force, chip accumulation in the flute, and the frictional contact between the chip, drill, and bone, it can be assumed that with increasing the rotational speed of the drill, the generated heat due to the friction between the chip or the drill body and the hole wall will increase and this heat generation factor, from a certain rotational speed onward overcomes the positive effect of force loss and reduction of chip accumulation and leads to a further increase in temperature.

In “Fig. 4”, the effect of feed rate on the maximum value of tissue temperature is shown. As can be seen, the maximum value of tissue temperature reduces with an increase in the feed rate of the drill. The reason is that with an increase in the drill feed rate, the drilling time decreases, and consequently, the generated heat due to the friction is reduced, and as a result, the temperature also decreases. In addition, in “Fig. 5”, the effect of drill diameter on the maximum value of tissue temperature is shown.

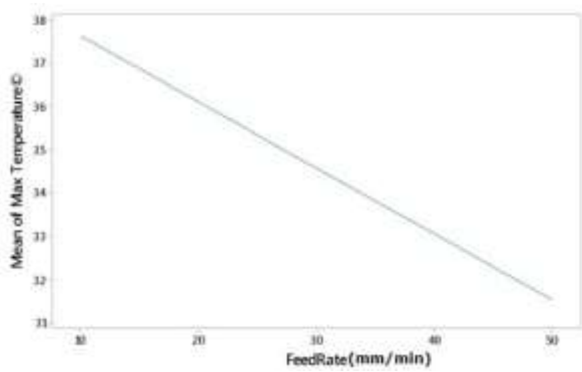


Fig. 4 The effect of feed rate on the maximum value of tissue temperature in the high-speed bone drilling process.

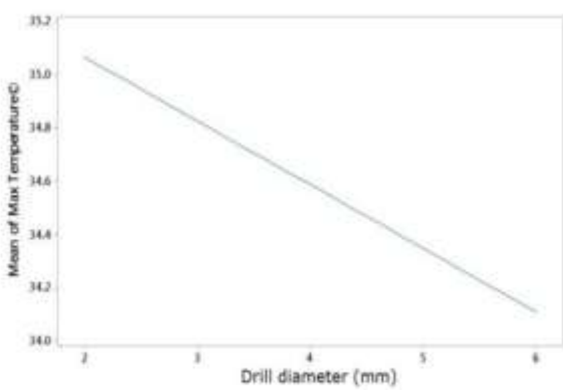
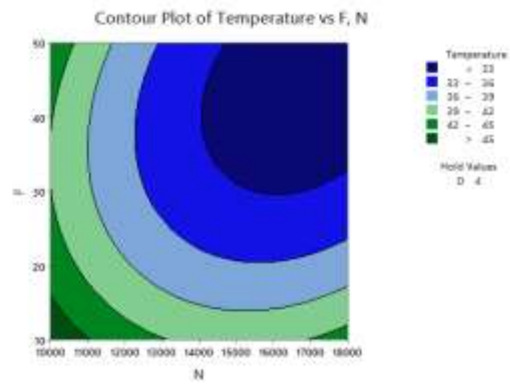


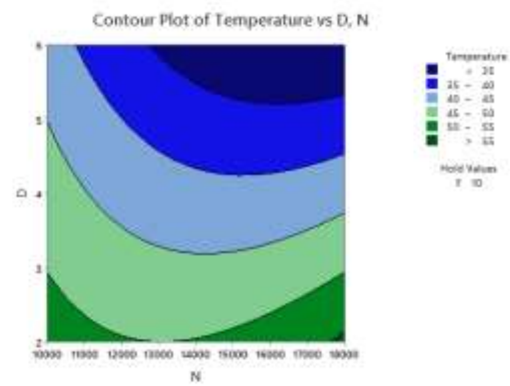
Fig. 5 The effect of drill diameter on the maximum value of tissue temperature in the high-speed bone drilling process.

As it is concluded from “Fig. 5”, with an increase in the drill diameter, the maximum value of tissue temperature is reduced. The reason is that by increasing the drill diameter, the exit channel of the chips in the drill will be bigger, which leads to a decrease in tissue temperature.

Figure 6 shows the interactions of process parameters on the tissue temperature in a high-speed bone drilling process, which again confirms the effects of input variables on the maximum value of tissue temperature. The results show that the minimum temperature occurs at a high feed rate and high rotational speed, while at a low feed rate, the temperature is generally higher and it is undesired. Also, the temperature decreases by increasing the tool diameter and increasing the rotational speed. From “Fig. 4 and Fig. 5”, it is obvious that the interaction of tool diameter and feed rate is descending.



(a)



(b)

Fig. 6 The interactions of: (a): rotational speed, feed rate, and (b): drill diameter on the tissue temperature in the high-speed bone drilling process.

4 CONCLUSIONS

In this work, the drilling process of cortical bone at high-speed ranges was investigated experimentally, and by using statistical tools (ANOVA), the effects of input process parameters including the rotational speed, feed rate, and drill diameter on the maximum temperature of bone tissue were studied. To perform a comprehensive study, containing the effect of each input parameter and their interaction effects of parameters on the tissue temperature, the design of experiment (DOE) method was employed. The main findings of the research can be listed as follows.

- The ANOVA analysis shows that the rotational speed, feed rate, and drill diameter were effective parameters of the tissue temperature.
- The coefficient of determination (R^2) was 0.9453 for the response of tissue temperature which indicated that the regression equation can predict the temperature with good accuracy.
- The ANOVA results showed that by increasing the rotational speed, the temperature of the tissue first decreased until it reached a minimum value, and then with the further increase of the rotational speed, the tissue temperature began to increase.
- It was concluded that the maximum value of tissue temperature was reduced by increasing the feed rate of the drill. The reason was that by increasing the drill feed rate, the contact time between the bone tissue and the drill was reduced, and consequently, the amount of heat generated due to friction was reduced, so the temperature was also decreased.
- It was proved from the results that with an increase in the drill diameter, the maximum value of tissue temperature was reduced. The reason was that by increasing the drill diameter, the exit channel of the chips in the drill would be bigger, which would lead to a decrease in tissue temperature.

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