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Modelling and optimization of temperature in orthopaedic drilling: An in vitro study

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This present investigation uses the Taguchi and response surface methodology (RSM) for modelling and optimization of the temperature produced during bone drilling. The drilling of bone is a common procedure in orthopaedic surgery to produce hole for screw insertion to fixate the fracture devices and implants. A major problem which is encountered during such a procedure is the increase in temperature of the bone due to the plastic deformation of chips and the friction between the bone and the drill. The increase in temperature can result in thermal osteonecrosis which may delay healing or reduce the stability and strength of the fixation. The drilling experiments are conducted on poly-methyl-meth-acrylate (PMMA) (as a substitute for bone) using Taguchi's L_{27} experimental design technique. The cutting parameters used are drill diameter, feed rate and cutting speed. The optimum cutting parameters for minimum temperature are determined by using S/N ratios and the effect of individual cutting parameters on temperature produced is evaluated using analysis of variance (ANOVA). A second-order model is established between the drilling parameters and temperature using RSM. The experimental results show that the drill diameter is the most significant drilling parameter affecting the temperature during drilling followed by cutting speed and feed, respectively. The values predicted and the values obtained from experiment are fairly close, which indicates that the developed RSM model can be effectively used to predict the temperature in orthopaedic drilling.

Key words: *analysis of variance (ANOVA), orthopaedic surgery, response surface methodology, Taguchi method, thermal osteonecrosis*

1. Introduction

Preparation of an implant site through the drilling of bone is a common procedure during orthopaedic surgery. The increase in temperature during such a procedure increases the chances of thermal invasion of bone which can cause thermal osteonecrosis, i.e., irreversible death of the bone cells when the temperature increases above a threshold [1]–[3]. There is no consensus among the researchers on the exact threshold temperature for the death of the human bone. However, majority of the authors believe an average temperature of 47 °C for 1 min as threshold, above which the thermal necrosis of the human bone will take place [1], [4]–[7]. The necrosis of bone reduces the stability of the fixation due to the rapid bone absorption in the necrotic region [8], also the presence of the necrotic tissue delays the healing of the fractured bone. Therefore, the drilling of bone with minimum temperature is a major challenge for orthopaedic fracture treatment.

In recent years, researchers have successfully employed the statistical tools for modeling and optimization of the manufacturing process. Taguchi method and response surface methodologies can be conveniently used for these purposes [9]–[14]. In comparison with the other optimization tools Taguchi method has been widely used because it is a powerful technique for design of experiments and is very effective in dealing with the response influenced by multivariables [15], [16]. RSM is a very useful tool for the modeling of a process to develop a relationship between the response and process variables yield and the process variables [17]. The present work uses Taguchi method to find the optimal setting of drilling parame-

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ters to achieve minimum temperature during bone drilling. This paper also intends to present an approach to develop a mathematical relationship between the temperature produced during bone drilling with drilling parameters such as spindle speed, feed rate, and drill diameter using RSM.

2. Materials and methods

2.1. Taguchi method

Taguchi methodology is a powerful tool which provides simple and efficient means to examine the process control parameters to optimize the designs for performance, quality and cost. The experimental design methods used traditionally are tangled and difficult to use [18]. In comparison to it, the Taguchi method provides a significant reduction in the number of experiments to be performed for the same number of process control factors [16]. Orthogonal arrays (OAs) and the signal to noise ratio (S/N) are the two important tools used by the Taguchi method. OAs greatly reduce the number of experiments by considering, for each level of any one factor, all the levels of other factors occurring an equal number of times, thereby giving a balanced design. OAs allow the researcher or designer to study many process control factors simultaneously and can be used to evaluate the effect of each factor independent of the other factors [16]. Signal to noise ratio is a quality indicator that indicates the scattering around a target value. Signal represents the effect on the average response while the noise is a measure of the influence on the deviation from the average response [16]. A high S/N ratio is desirable as the signal level is much higher than the random noise level, so represents the best performance [15], [16]. The contribution of each factor and their interactions on the response value are obtained by performing ANOVA [17], [18].

2.2. Response surface methodology

During orthopaedic drilling, minimization of the temperature is necessary for reducing the thermal injury of the bone and to facilitate its faster recovery. A theoretical model to predict the drilling temperature as a function of the operating conditions can be very useful for selecting the drilling parameters so that the drilling temperature can be minimized.

RSM is an aggregation of mathematical and statistical tools that are efficacious for the modeling and analysis of process in which a response is influenced by several variables and the objective is to optimize that response [17], [18]. It employs statistical design of experiments and least square fitting in the model generation phase. The relationship between the desired response and the independent process variables can be represented as [14], [17], [18]

$$Y = f(A,B,C) + \varepsilon \quad (1)$$

where Y is the desired response and f is the response function, ε represents the noise or error observed in the response. Therefore, the first step in RSM is to find a suitable approximation for true functional relationship between Y and set of independent process variables. Generally, a second order model is employed if the response function is unknown or nonlinear [9], [14], [17], [18],

$$Y = \beta_o + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_i \sum_j \beta_{ij} x_i x_j + \varepsilon \quad (2)$$

where β represents the coefficients which are evaluated using least square method.

2.3. Experimental details

The experiments are conducted following the steps in Taguchi design of experiment methodology, as shown in Fig. 1.

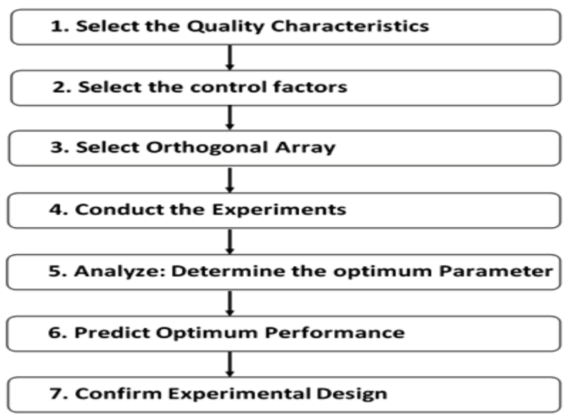

Fig. 1. Steps in Taguchi design of experiments [16]

Selection of quality characteristics

Three types of quality characteristics are used in Taguchi methodology: Lower is better, nominal is better and higher is better. As the temperature produced during orthopaedic drilling should be minimum therefore lower is better (LB) quality characteristic is selected to obtain the optimal combination of the control factors. The LB quality characteristic S/N ratio of each trial is expressed as [16]

$$\frac{S}{N} = -10\log\left(\frac{1}{m}\sum_{i=1}^{m} Y_i^2\right) \tag{3}$$

where Y is the experimental value in the i-th test and m is the number of repeated test.

Selection of control factors

In Taguchi method the process parameters are divided into two categories: control factors and noise factors. The control factors are the controllable parameters which affect the process significantly whereas noise factors are the special variables that affect the process and are either uncontrollable or too expensive to control [16]. In this study, the drill diameter, feed rate and spindle speed are considered as the control factors as these parameters can significantly affect the temperature generated during drilling. The control factors along with the levels used are given in Table 1.

Selection of orthogonal array (OA)

The orthogonal array is utilized for determining the combination of various levels of different control factors for which the experiments are to be carried out. The optimal combination of the levels of control factors for the process is determined by analyzing the data acquired using OA. Taguchi's OA is selected on condition that the total degrees of freedom (DOF) of the OA must be greater than or equal to the total DOF required for the experiment [16], [19]. DOF is defined as the number of comparisons needed to determine which level is better [16], [19]. For each control factor the DOF is one less than the total number of levels (DOF of a factor = Total no of levels of factor –1). Taguchi's orthogonal array of L_{27} is most suitable for this experiment. It requires 27 runs and has 26 degrees of freedom (DOFs). The DOF for three control factors, each at three levels is 6(3 × (3–1)) for main

Table 1. Factors and levels considered for drilling

	Control factor	Level 1	Level 2	Level 3
A	Drill diameter (mm)	6	8	10
B	Feed rate (mm/min)	35	40	45
C	Spindle speed (rpm)	1500	2000	2500

Table 2. Comparison of the properties of bone and PMMA

Properties	Bone	PMMA
Thermal conductivity (W/mK)	0.1–0.35	0.15–0.4
Specific heat (J/KgK)	1300	1400
Thermal diffusivity (m^2/sec)	$0.3*10^{-6}$	$0.11*10^{-6}$
Density (Kg/m^3)	1800	1400

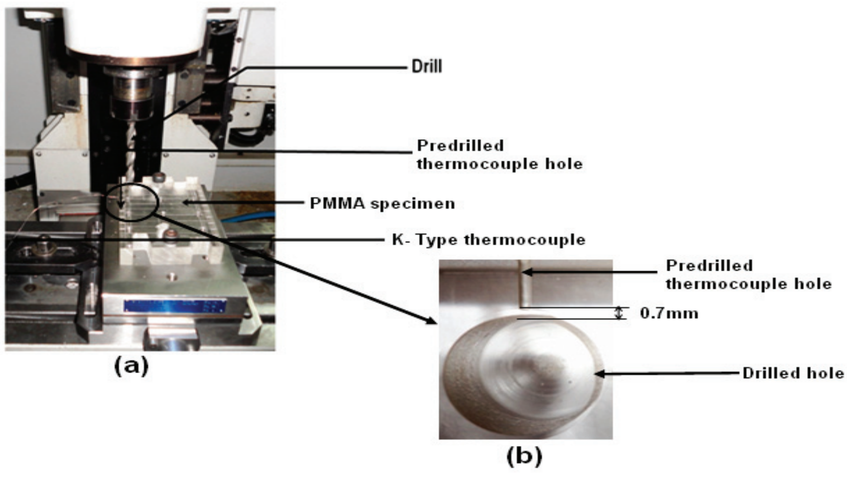

Fig. 2. Experimental set up (a) and enlarged view of the predrilled thermocouple hole and drilled hole (b)

factors [19]. Square effects and interaction between parameters take the remaining DOFs [16], [19].

Experimental work

The work material used is Poly-methyl-methacrylate (PMMA). Human bones are not easily available, also they vary widely in density, cortical thickness and other parameters of interest [20]. A more uniform and consistent material was desirable having properties similar to bone, allowing the results to be extrapolated for real surgical processes. PMMA has the properties comparable to the bone and is an acceptable surrogate for bone in such studies [20]. Many researchers have used PMMA as a substitute for bone in their studies [6], [20]. The properties of bone and PMMA are shown in Table 2. Specimens were made by using PMMA block of size 12 cm × 7.5 cm × 2 cm. A hole of 1 mm diameter is made at a depth of 5 mm to accommodate a thermocouple 0.7 mm from the edge of test drill hole [19] (shown in Fig. 2b).

The experiments were conducted using the 3 axis MTAB Flex mill. *X* axis 250 mm, *Y* axis 150 mm, and *Z* axis 200 mm. The table size is 420 × 180 mm. An Omega K-type thermocouple was used for temperature sensing. NI-DAQ 9219 was used with LABVIEW Software for the acquisition of the data. The experimental set up is shown in Fig. 2. Figure 2a shows the complete experimental setup and Fig. 2b shows the enlarged view of the predrilled thermocouple hole and drilled hole.

3. Results

The values of the levels of the drilling parameters in coded form and the actual setting values for the experiment along with the obtained temperature results are shown in Table 3. The average temperature produced is used for the analysis.

3.1. Taguchi analysis

S/N ratio for each response is calculated by using (3), shown in the last column of Table 3. By utilizing the S/N ratios computed from the experimental results the average S/N ratios for every factor at each level is

Table 3. Experimental conditions and results

Experiment No.	Coded values			Actual setting value			Temperature (°C)	S/N ratio (dB)
	A	B	C	A	B	C		
1	1	1	1	6	35	1500	41.3391	–32.3272
2	1	1	2	6	35	2000	46.7783	–33.4009
3	1	1	3	6	35	2500	48.0000	–33.6248
4	1	2	1	6	40	1500	45.1756	–33.0981
5	1	2	2	6	40	2000	45.0246	–33.0690
6	1	2	3	6	40	2500	51.3897	–34.2175
7	1	3	1	6	45	1500	46.7180	–33.3897
8	1	3	2	6	45	2000	50.5785	–34.0793
9	1	3	3	6	45	2500	51.1552	–34.1778
10	2	1	1	8	35	1500	46.3431	–33.3197
11	2	1	2	8	35	2000	50.5280	–34.0706
12	2	1	3	8	35	2500	49.7903	–33.9429
13	2	2	1	8	40	1500	44.5953	–32.9858
14	2	2	2	8	40	2000	46.1804	–33.2892
15	2	2	3	8	40	2500	47.1815	–33.4754
16	2	3	1	8	45	1500	46.1920	–33.2913
17	2	3	2	8	45	2000	48.6203	–33.7363
18	2	3	3	8	45	2500	51.4934	–34.2350
19	3	1	1	10	35	1500	53.7469	–34.6071
20	3	1	2	10	35	2000	55.8367	–34.9384
21	3	1	3	10	35	2500	54.7636	–34.7698
22	3	2	1	10	40	1500	50.1228	–34.0007
23	3	2	2	10	40	2000	57.1087	–35.1340
24	3	2	3	10	40	2500	56.8153	–35.0893
25	3	3	1	10	45	1500	49.1733	–33.8346
26	3	3	2	10	45	2000	51.1272	–34.1730
27	3	3	3	10	45	2500	55.9826	–34.9611

Table 4. Average S/N ratio of all factors at each level

Level	Drill diameter	Feed rate	Spindle speed
1	–33.49	–33.89	–33.43
2	–33.59	–33.82	–33.99
3	–34.61	–33.99	–34.28
Delta	1.12	0.17	0.85
Rank	1	3	2

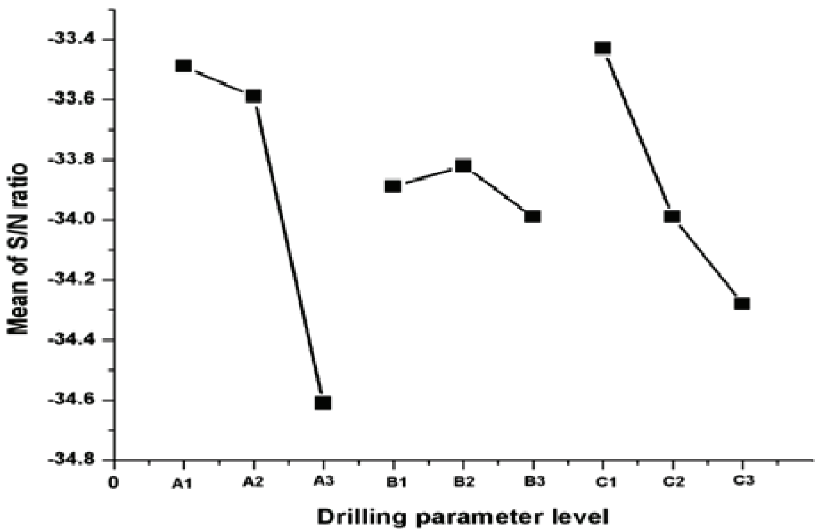

Fig. 3. Main effect plot for S/N ratio (mean)

Table 5. ANOVA table of S/N ratios for the temperature produced during drilling

Source	DOF	SS	MS	*F*-value	*P*-value	Contribution (%)
Drill diameter (A)	2	6.94	3.47	30.6	0.0002	51.946
Feed rate (B)	2	0.13	0.065	0.57	0.5870	0.97
Spindle speed (C)	2	3.35	1.68	14.78	0.0021	25.07
A*B	4	1.66	0.42	3.66	0.0558	12.425
A*C	4	0.1443	0.04	0.32	0.8581	1.08
B*C	4	0.2231	0.06	0.49	0.7425	1.669
Error	8	0.907	0.113			6.788
Total	26	13.36				100

calculated and is presented in Table 4. Based on the Δ (Delta) statistics which is the highest minus the lowest average of S/N ratio for each factor, the rank of the parameters affecting the temperature produced during drilling of PMMA is listed [15], [16]. It is found that the diameter has the highest influence on temperature produced during drilling PMMA, followed by the spindle speed and feed rate, respectively. These values are plotted in Fig. 3 as response graph for drilling parameters.

The level of a factor with the highest signal-to-noise ratio is the optimum level [15], [16]. Therefore, from the above analysis the optimal level of parameter setting for drilling is identified as: level 1 of drill diameter (A1), level 2 of feed rate (B2) and level 1 of drill speed (C1). The effect of each parameter on drilling of PMMA is analyzed by ANOVA. The ANOVA result for temperature is presented in Table 5. The analysis is carried out at a significance level of $\alpha = 0.05$ (confidence level of 95%).

From the analysis of Table 5 it is observed that the drill diameter is the parameter which mainly affects the temperature produced in drilling of PMMA. Drill diameter (most significant factor) contributed 51.94% to the temperature generated followed by spindle speed (25.07%). Feed rate (.97%) was the least significant parameter and shows very little effect on the temperature in drilling of PMMA. Among the interactions considered, the interaction between the drill diameter and feed rate A*B (12.425) only shows some effect on the temperature produced during drilling in PMMA.

3.2. Response surface analysis

Response surface model of second order representing the temperature (T, °C) as a function of drill diameter (A, mm), feed rate (B, mm/min) and spindle speed (C, rpm) is shown below

$$T = \beta_0 + \beta_1(A) + \beta_2(B)$$
$$+ \beta_3(C) + \beta_4(A^2) + \beta_5(B^2)$$
$$+ \beta_6(C^2) + \beta_7(AB) + \beta_8(AC) + \beta_9(BC). \quad (4)$$

From Table 6 it is clear that the quadratic model is best suited model for prediction of the temperature during drilling. For a model, low standard deviation, R-squared near 1 is best. RSM's Box-Behenken design consisting of 17 experiments is calculated for developing the mathematical model [18].

The mathematical relationship for correlating the temperature and the drilling parameters considered (drill diameter, feed rate, and spindle speed) is obtained using the Design Expert software 8.0.1. The relationship between the temperature and machining parameters is expressed in uncoded unit as follows

Table 6. Model summary statistics

Source	Std. deviation	R-squared	Adjusted R-squared	Predicted R-squared	
Linear	2.69	0.5351	0.4278	0.2122	
2FI	2.74	0.6289	0.4062	–0.1363	
Quadratic	**0.65**	**0.9853**	**0.9663**	**0.7641**	**suggested**

Table 7. ANOVA table for response surface quadratic model

Source	SS	DOF	MS	F-value	P-value	
Model	199.90	9	22.21	51.97	< 0.0001	significant
A – drill diameter	*49.90*	1	*49.90*	116.76	< 0.0001	
B – feed rate	0.052	1	0.052	0.12	0.7384	
C – spindle speed	*58.62*	1	*58.62*	137.16	< 0.0001	
AB	18.10	1	18.10	42.36	0.0003	
AC	*0.057*	1	*0.057*	0.13	0.7253	
BC	0.86	1	0.86	2.01	0.1991	
A^2	*56.42*	1	*56.42*	132.01	< 0.0001	
B^2	*6.47*	1	*6.47*	15.13	0.0060	
C^2	*4.51*	1	*4.51*	10.55	0.0141	
Residual	2.99	7	*0.43*			
Total	202.89	16				

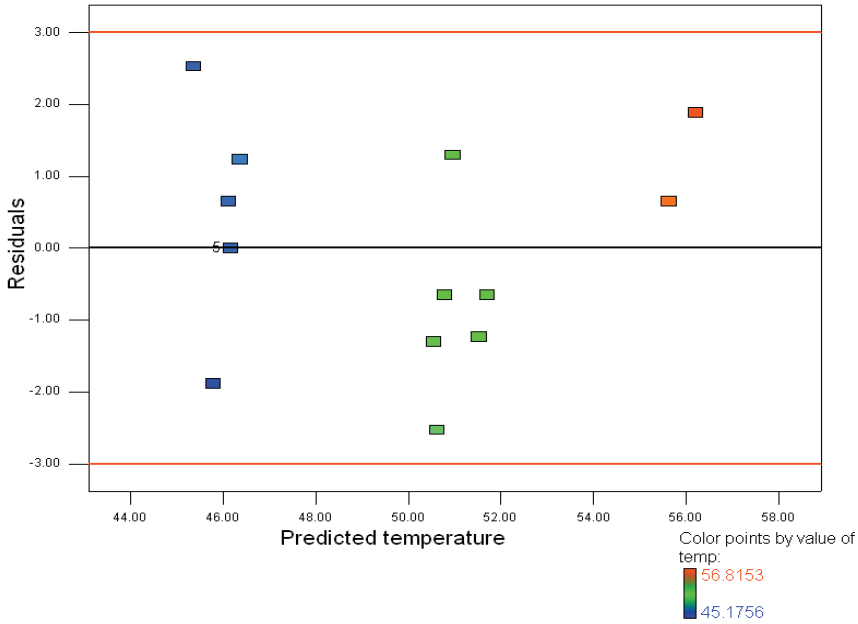

Fig. 4. Plot of the residuals with respect to the predicted temperature

$$T = 127.83295 - 5.12261 * A - 2.61863 * B - 0.019520 * C + 0.91512 * A^2 + 0.049572 * B^2 + 4.13995E - 6 * C^2 - 2.12744(A * B) - 1.19600E - 4 * (A * C) + 1.85420E - 4(B * C). \quad (5)$$

The above mathematical model can be used to predict the values of the temperature within the limits of the factors studied. The ANOVA results for the response surface model are given in Table 7. The *P* value of the model is <0.1000 which implies that the model is significant. In this case A, C, AB, AC, A^2, B^2 are significant model terms, the other model terms are insignificant.

The plot of the residuals against the predicted temperature is shown in Fig. 4. From the plot it can be stated that the model proposed predicts the temperature with reasonable accuracy and can be effectively used for the prediction of temperature during bone drilling.

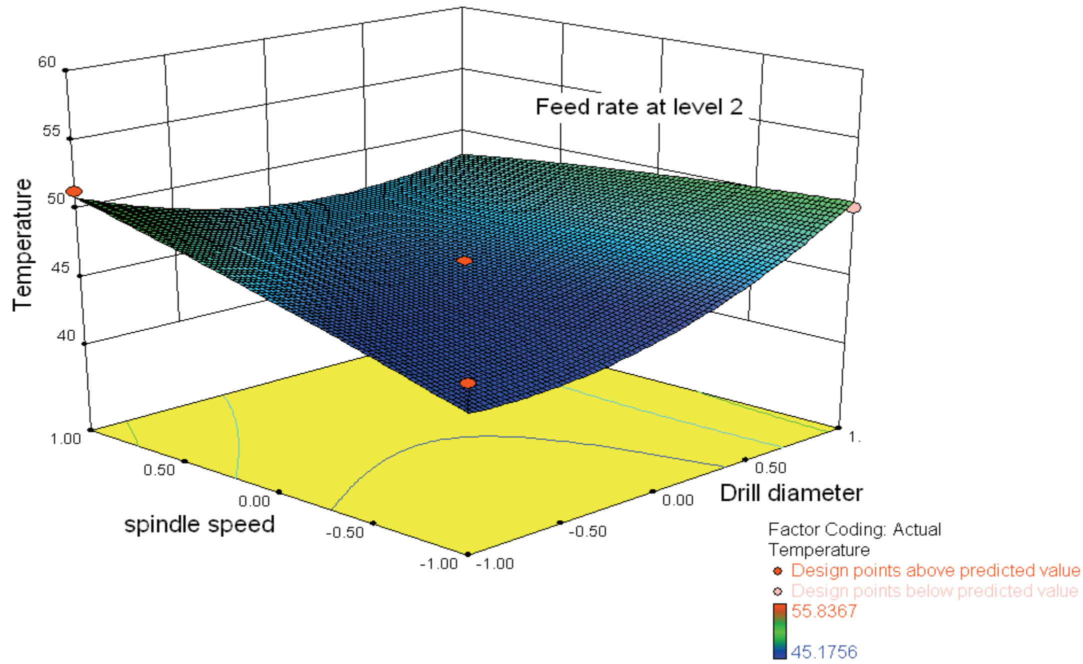

Fig. 5. Response surface plot of the temperature during drilling of PMMA as a function of drill diameter and spindle speed

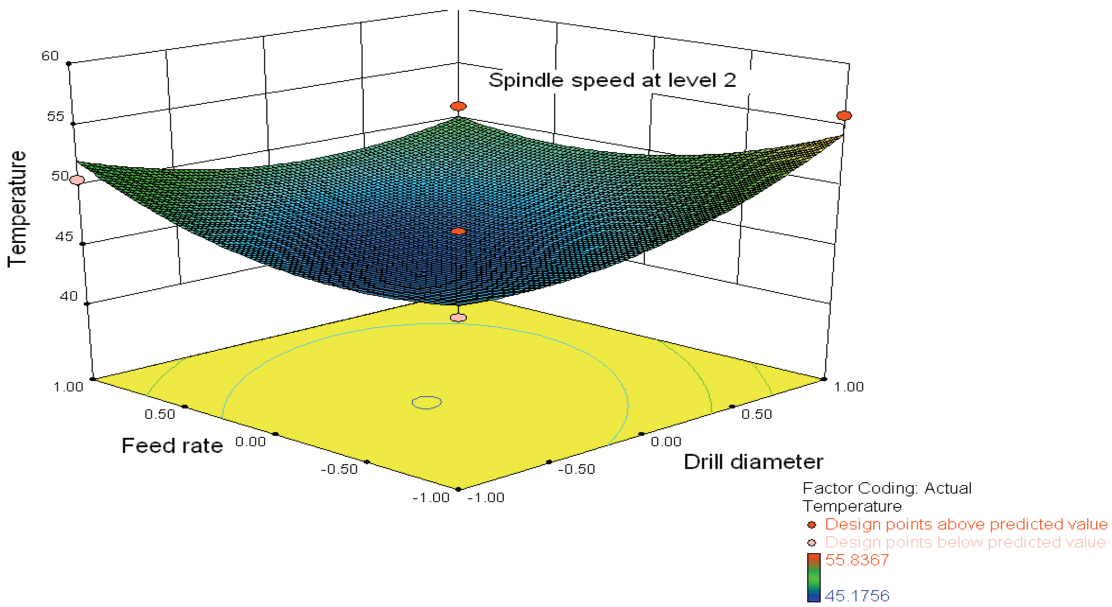

Fig. 6. Response surface plot of the temperature during drilling of PMMA as a function of drill diameter and feed rate

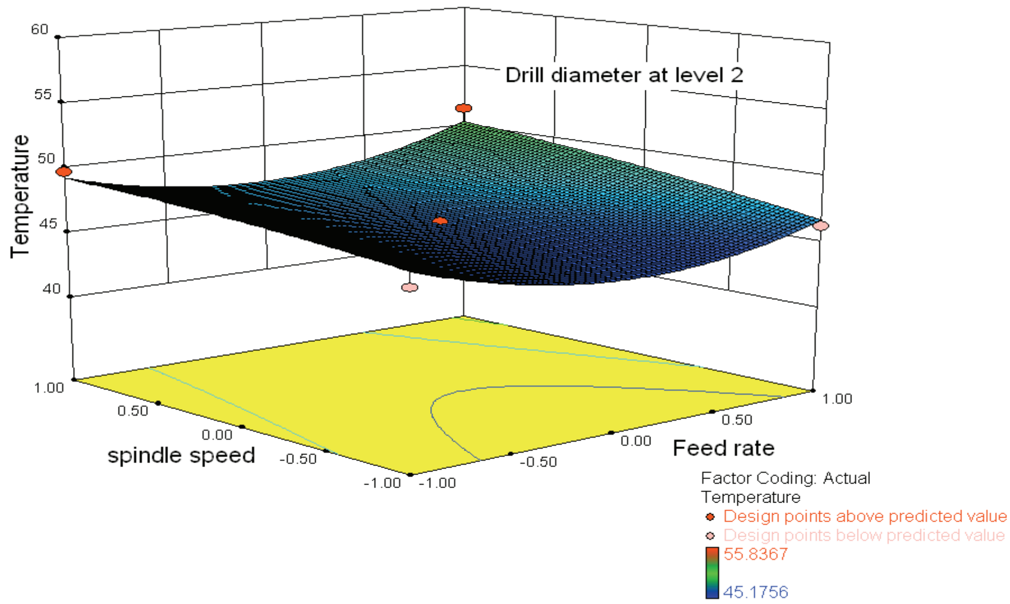

Fig. 7. Response surface plot of the temperature during drilling of PMMA as a function of feed rate and spindle speed

The response surface plots obtained by the modeling of temperature in drilling of PMMA are shown in Figs. 5, 6 and 7. The figures are drawn with respect to two different parameters by keeping the third parameter constant at the middle level [18]. Figures 5 and 6 show the effect of drill diameter on the temperature during drilling at different spindle speed and feed rate, respectively. Figure 7 indicates the effect of the speed and feed on the temperature produced during drilling of PMMA.

3.3. Confirmation of the experimental results

For the confirmation of the results obtained from the Taguchi analysis and response surface modeling, the validation experiments are performed. The predicted optimum value of the S/N ratio ($\eta_{\text{predicted}}$) is calculated from the following expression

$$\eta_{\text{predicted}} = \eta_m + \sum_{i=1}^{k} (\eta_i - \eta_m) \qquad (6)$$

where η_m is the total mean of the S/N ratio, η_i is the mean of S/N ratio at the optimal level, and k is the number of main drilling parameters that affect the response [9], [15], [16]. The confirmation experiments were carried out at four selected levels (one at optimal level, i.e., experiment number 4 and three at experimental conditions selected randomly, corresponding to experiment numbers 6, 18 and 25 in Table 3, and is designated as verification test number 1, 2, 3 and 4, respectively). The predicted value of S/N ratio obtained from (6) is –33.3115. At the optimal setting, the S/N ratio of the temperature obtained from the confirmation experiment is –33.1556 which is greater than the predicted value. Thus, a gain in S/N ratio is obtained, which implies that the Taguchi method can be successfully utilized for the optimization of the temperature in bone drilling process. The confirmation for the response surface model is shown in Fig. 8.

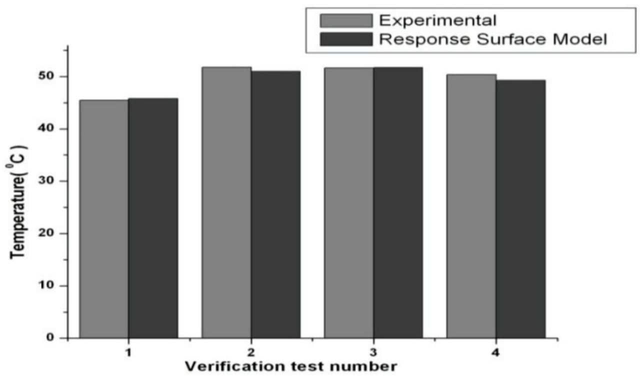

Fig. 8. Verification test results

4. Discussion

Several researchers have carried out many investigations on PMMA to study the effect of drilling parameters on temperature produced during bone drilling. Kalidindi [20] performed a series of experiments on PMMA to show how the various drilling parameters such as drilling speed, feed rate and drill bit diameter affect the heat generation during bone drilling and developed a theoretical model for predicting the temperature. It was found that with an increase in speed and drill diameter the temperature increases whereas an increase in feed rate decreases the temperature. Lee et al. [6] reported similar results while performing drilling experiments on PMMA. In the present studies similar effect is visualized except for the feed rate in which minimum temperature is reported at intermediate level, as shown in Figs. 5, 6 and 7. From Figs. 5, 6 and 7 it can be stated that the temperature increases with an increase in the drill diameter and the cutting speed whereas the feed at the middle level produces the better result. This event is attributed to the increase in the friction effect when the drill diameter, speed and feed rate increases resulting in high temperatures. Low feed increases the drilling time thereby increasing the duration for the heat propagation from tool to the work piece which results in higher temperature. Basiaga et al. [21] studied the effect of drilling speed and suggested similar trend of increase in temperature with drill speed. Recently, Pandey and Panda [22] proposed a BPNN model to predict temperature bone drilling based on their investigations. Previous investigations performed by the researchers were aimed to study only the effect of the various drilling parameters and drill geometries on the temperature generated during bone drilling but there is a lack of studies reporting the statistical modelling and optimization of the bone drilling process. Ueda et al. [19] used Taguchi method to establish the optimum settings of drill geometry for minimum temperature during bone drilling but they did not account for the drilling parameters such as spindle speed and feed rate, neither the modelling of the temperature as a function of drill geometry and drilling parameters was reported. Taguchi and RSM are the two well-known statistical techniques which have been widely used for modelling and optimization of the complex machining problems. In this study, PMMA is used as the surrogate for bone to carry out the drilling investigations and the use of Taguchi with RSM have been discussed to model and optimize the process of bone drilling. The effect of drilling parameters on the temperature produced during orthopaedic drilling is analyzed with the help of Taguchi method and the optimal cutting condition for minimum temperature is A1B2C1, i.e., drill of diameter 6 mm, feed rate of 35 mm/min and spindle speed of 1500 rpm. It is emphasized that the use of these conditions will minimize the temperature during orthopaedic drilling. The drill diameter has the highest influence on temperature produced during drilling, followed by the spindle speed and feed rate, respectively. The contribution of each factor and their interaction (by percentage) on the temperature produced during orthopaedic drilling is evaluated using ANOVA. Among all the interactions, the interaction between the drill diameter and feed rate (A*B) only shows some effect on the temperature. A second order response surface model is developed to predict the temperature during orthopaedic drilling. The predicted values and the values obtained from the experiments are very close to each other, which indicates that the use of the above suggested model for selecting the level of drilling parameters can be very effective to reduce the risk of thermal osteonecrosis. Confirmation tests are performed and the results reveal that the determined optimal combination of parameters satisfies our objective of minimum temperature during drilling. It also shows that the proposed RSM model predicts the temperature with high accuracy.

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