INVESTIGATION OF TEMPERATURE IN ORTHOPAEDIC DRILLING USING RESPONSE SURFACE METHODOLOGY

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ABSTRACT: Rise in temperature is inevitable in orthopaedic drilling. Massive research had been done in the field of orthopaedic drilling to investigate the effect of cutting conditions, bone related parameters, and drill bit geometric parameters on heat generation and minimum surrounding tissues injury. In present research, contradictory conclusions regarding the cutting conditions and drill bit geometric parameters were observed. Minimum temperature of 31°C was achieved at speed of 186 rpm, feed of 0.196 mm/rev, drill diameter of 3.85mm, and drill tip angle of 110°. Response Surface Methodology (RSM) was used to develop a mathematical model to predict the type of relationship between inputs and response. It was concluded that the most influencing parameter was drill diameter.

Key words: Temperature, Orthopaedic drilling, Drill parameters, Response surface methodology.

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INTRODUCTION

Bone is a calcified connective tissue forming the major portion of skeleton of most vertebrates. Fractured bones are capable to heal themselves by producing new bone forming cells and blood vessels at the fractured site. Therefore, bones should connect properly to avoid permanent bending or other related issues. Major techniques for bone treatments are “Close Reduction (without cutting skin)” and “Open Reduction (with exposing skin). The open Reduction treatment involves ultrasonic drilling, conventional bone drilling, and laser beam drilling(Gill *et.al;* 2016and Alam *et.al;* 2011). Orthopaedicdrilling is a well-known step in bone fracture treatment and is used in surgery. In bone drilling, heat generation at tool-bone interface due to shearing of bone is inevitable. The friction causes thermal damage in the surrounding tissues which ultimately leads to failure at interface of screw with bone. The minimum temperature that may cause thermal necrosis is 47°Cif applied for more than one minute(Pandey and Panda, 2013 andAugustin*et.al;* 2012).

Bone material behaves like a brittle material and any crack formed, may propagate while performing drilling operation. Temperature can be kept in check by controlling different cutting conditions and drill geometry(Pandey and Panda, 2013).

Response Surface Methodology (RSM) is used to design experiments and analyze the individual and simultaneous effect on heat generation.

In drilling process, quality of the orthopaedic operation highly depends upon temperature control. Since 20th century, lot of efforts have been made to relate the temperature with cutting conditions, drill parameters and bone materials.The several statistical analysis are reported by(Karaca *et al;* 2011), finite element algorithm (FEA) reported by (Lughmani *et.al;*2015 and Sezek *et.al;* 2012), and other optimization methods, like RSM applied by (Pandey and Panda, 2014 andAugustin e*t.al;* 2012), Taguchi method used by (Gok *et al.* 2015 and Pandey and Panda, 2015), Full factorial Design Of Experiment (DOE) (Lee *et.al;* 2012) etc. are used to optimize the temperature.

Cutting speed is arrogated as most important parameter which leads to increase in temperature by increasing cutting speed. This is due to the fact that increase in cutting speed increases frictional force applied on rake face of drill bit which gets converted into heat and ultimately leads to increase in temperature.(Pandey and Panda, 2015, Sezek *et.al;* 2012,Karaca *et.al;* 2011 and Bağci and Ozcelik, 2006).Conversely, it is also found that temperature decreases as cutting speed increases above some specific range(Soriano *et.al;* 2014,Shakouri *et.al;* 2013 andAbouzgia and Symington, 1996). From these inferences,it isobserved that temperature increases with the increment in cutting speed up to some limit (above 30,000 rpm)and after that, it starts to reduce(Abouzgia and Symington, 1996).

Feed rate is found as most influencing factor which leads to variation I temperature during orthopaedic drilling(Pandey and Panda, 2013,Augustin *et.al;* 2012 andLee*et.al;* 2011), while the work of (Hillery and Shuaib,1999)reported feed rate as insignificant factor.Regarding the effect of feed rate on temperatures, it is observed that temperature reduces with the increase in feed rate due to decrease in drill time which results in less heat generation(Gok *et.al;* 2015,Sezek *et.al;* 2012 andBağci and Ozcelik, 2006).

The simultaneous effect of cutting speed and tool point angle on temperature has been investigated.

Since increment in drill point angle enhances the contact area of drill bit lips which results increase in volume of material removal per revolution and shearing of material which ultimately increases the temperature (Basiaga*et.al;* 2011).Drill diameter is highlighted as significant factor for heat generation than cutting speed and feed rate, because increase in surface contact area permits more heat transfer(Pandey and Panda, 2014). The study of (Saha*et.al;* 1982)mentioned direct relation of tool tip with temperature and find that point angle of about 118°is optimal drill bit geometry for minimum frictional heat generation.

In the present research work, an endeavor has been made to cover these differences with particular stress on cutting speed, feed, drill diameter and drill bit point angle. By resolving these issues, a relation is determined between cutting conditions and drill parameters against temperature. Optimal parametric values are determined for minimum temperature. Additionally, simultaneous effects of parameters have been studied at different conditions to investigated heat generation.

MATERIALS AND METHODS

The experimental detail includedComputer Numerical Control (CNC) setup, sample preparation, temperature measurement system, thermocouples, cutting conditions and drill bit parameters. Random test combinations were performed to avoid any unwanted results. During experimentation, tibia bone inserted in vice and adjustments were made to fit the thermocouples. The experimental setup along with schematic diagram is shown in Fig- 1.

A fresh calf tibia bone, with calcium = 73% and phosphorus = 27%, was obtained from butcher shop and marked with numbering at a specific distance to drill holes.The bone material's analogy with composite material (Sui *et.al;* 2014) and its mechanical properties areshown in Table (1).Density of bone was very close to gold, gravel and bricks.

The High Speed Steel (HSS) industrial tools of diameter of2–6.5mm and point angle of 90–130° were used. The machine tool used for the drilling was proLIGHT Intelitech CNC milling. The spindle speed of CNC milling varied between 180–850 rpm and feed between 0.14–0.25 mm/rev. A femoral tibia bone was fixed in the vice of CNC milling. Pilot hole was drilled up to 3mm depth and thermocouple was inserted 0.5mm away from the wall of the hole. A digital multi-meter was attached with thermocouple to collect the direct response.The values of response with corresponding input parameter combinations are shown in Table (3).

Central Composite Design (CCD) estimated the effect of uniform precision. CCD was used to run experiments randomly to avoid any manipulation. Thirty experiments were run with sixteen factorial points, eight alpha points and six center points. Factorial points were used to check the quadratic effect of parameters on response and zero points were used to measure pure error. The methodology applied for analysis of variance (ANOVA) was RSM. Itcombined the statistical and mathematical approaches to explore the response when the factors varied simultaneously.

Five levels and four parameters added with central, low, high, and alpha points (Table 2).Selected parametric levels were used to develop experimental design matrix using Design Expert 7.0.0™ (Table 3). Random combinations obtained from experimental design matrix were used to perform experimentation and temperature values were measured against these combinations (Table 3).

RESULTS AND DISCUSSION

The values were developed through design of experiments and results were modeled through either first order or second order by following two equations. Where β_0, β_i, β_{ii}, and β_{ij} were called parameters of approximating functions, f(x) was response, $x_i$was input variable, and ϵ was error term (Azam*et.al;* 2014).As has been given below.

$$f(x) = \beta o + y = \beta o + \beta_1 x_1 + \beta_2 x_2 + \beta_k x_k + \epsilon \quad (1)$$

$$f(x) = \beta o + \sum_{i=1} \beta_i x_i + \sum \beta_{ii} {x_i}^2 + \sum_{i<j} \sum \beta_{ij} x_i x_j + \epsilon \quad (2)$$

Different combinations were checked whether a trend was linear, quadratic or cubic. Linear behaviorwas suggested for the designed experiment (Table 4). In statistical analysis by checking the residuals, lack of fitness and error term, the model was significant. Results indicated that lack of fitness was not significant which clearly showed that model was correct (Table 5).

RSM was used to predict the temperature during drilling operation ofcalf tibia bone.The normal probability plot for residuals revealed independently and normal distribution (Fig- 2).The first order model for temperature was developed based on Equation (1).

$$\text{Temperature} = +36.89 + 0.9^{*} A + 0.83^{*} B + 3.50^{*} C + 0.70^{*} D$$

Table 5showed that the most influencing parameter was drill bit diameter. 3D-graphswere used to check the simultaneous effect of input parameters on response.

Alinear pattern was also shown in 3D plots as given below. The simultaneous effect of drill diameter and feed, as input parameterswere analyzed on heat generation as shown in Fig-3. From these plots, it was clear that by increasing feed rate, very small increase in temperature was observed while a small change in diameter resulted in greater variation in temperature values. Fig- 4 shows simultaneous effect of cutting speed and drill diameter on temperature which roseup to 41.6 °C.The diameter showed maximum influence on temperature. From these graphs,linear behavior of model was clearly indicated.

RSM was best technique to investigate the temperature as it provides best design for experiment(Pandey and Panda, 2014). There was clear inference from 3D graphs that there was linear relation between temperature and input parameters.

The contour plots(Fig- 5, 6) showedthat there was no significant interaction effect of the variables. These contour plots help to optimize the cutting parameters against temperature and play a key role in getting different combinations of input parameters for same temperature value. The target value of temperature on specific portions of a part may vary, depending upon the design and the functional requirements. It can be seen from the contour plots that thetemperature value varieswith changing the combination values of speed, feed, drill diameter and tip angle.

It was also evident from contour plots (Fig- 5, 6) that a target Tc value 36.27 °C can be achieved by setting the speed to350∼690 mm/rev, and feed 0.17∼0.22 mm; however, drill diameter should be set within 3.22∼3.60 mm. Contour plot combinations can be used to achieve minimum temperature with different cutting conditions.

Maximum value of 41.6 °C was produced using cutting speed of 200-850 rpm, feed 0.145-0.24 mm/rev, and drill diameter 2-6.5 mm. The ranges of process parameters were selected through trial runs in which temperature remained with in critical limit. Aforementioned ranges of process parameters were aimed to optimize (minimize) temperature during orthopaedic drilling and designed experimental combinations resulted in narrow range of temperature increase (about 10°C).The research work of (Sezek *et.al;* 2012 and Karaca*et.al;*2011)used same input parameters and maximum temperature produced was 67 °C and 45 °C respectively. Moreover, similar cutting conditions were employed by (Soriano *et.al;*2013) and temperature achieved was 35 °C, lower than previous results because drill diameter used in this case was 5mm.

Direct relationship of temperature was found with speed, drill diameter, and tip angle; whereas, feed showed inverse relation. Among four parameters (speed, feed, drill diameter, and tip angle), drill diameter was found as the most influencing parameter. However, the simultaneous effect of speed and drill diameter showed maximum influence on temperature in 3D graphs. The contribution of each parameter is better explained by the linear models developed through central composite design.

Table 1.Mechanical properties of composite bone material.

Tensile Strength	65MPa
Compressive Strength	200MPa
Elasticity	1.5%
Hardness	70.3HRC
Density	1800kg/m^3
Specific Heat	1300 J/kgK

Table 2. Levels and factors in Central Composite Design.

Parameters	**Units**	**-alpha**	**-1 level**	**0 level**	**+1 level**	**+alpha**
Speed	rpm	186	353	520	687	854
Feed	mm/rev	0.145	0.17	0.195	0.22	0.245
Drill diameter	mm	1.35	2.6	3.85	5.1	6.35
Tip angle	degree	90	100	110	120	130

Table 3. Design matrix with response.

	Factor 1	**Factor 2**	**Factor 3**	**Factor 4**	**Response**
Run No.	**A: Speed (rpm)**	**B: Feed (mm/rev)**	**C: Drill diameter (mm)**	**D: Tip angle (Degree)**	**Temperature (°C)**
13	353	0.17	5.1	120	40
12	687	0.22	2.6	120	37
6	687	0.17	5.1	100	40
29	520	0.195	3.85	110	33.2
22	520	0.195	6.35	110	46
11	353	0.22	2.6	120	34
25	520	0.195	3.85	110	35.5
4	687	0.22	2.6	100	35
14	687	0.17	5.1	120	43

28	520	0.195	3.85	110	35
23	520	0.195	3.85	90	35.5
17	186	0.195	3.85	110	31
27	520	0.195	3.85	110	35.5
19	520	0.145	3.85	110	32
30	520	0.195	3.85	110	38
7	353	0.22	5.1	100	39
21	520	0.195	1.35	110	32
24	520	0.195	3.85	130	39
26	520	0.195	3.85	110	38
3	353	0.22	2.6	100	32.5
20	520	0.245	3.85	110	39
15	353	0.22	5.1	120	41
9	353	0.17	2.6	120	32.5
8	687	0.22	5.1	100	42
5	353	0.17	5.1	100	40.6
2	687	0.17	2.6	100	32.5
1	353	0.17	2.6	100	34.5
18	854	0.195	3.85	110	35
16	687	0.22	5.1	120	43.5
10	687	0.17	2.6	120	35

Table 4. Model summary statistics

Source	Sum of Squares	Degree of Freedom (df)	Mean Square	F Value	p-value Prob> F	
Mean vs Total	40833.54	1	40833.54			
Linear vs Mean	343.085	4	85.77	21.2360	< 0.0001	Suggested

Table 5. ANOVA for RSM linear model

Analysis of variance table						
Source	**Sum of Squares**	**Degree of Freedom (df)**	**Mean Square**	**F Value**	**p-value Prob> F**	**Results**
model	343.08	4	85.77	21.24	<0.001	significant
A-speed	19.98375	1	19.98	6.852224021	0.0194	
B-feed	16.50041667	1	16.50	5.657824555	0.0311	
C-drill diameter	294.7004167	1	294.70	101.0497666	< 0.0001	
D-tip angle	11.90041667	1	11.90	4.080531479	0.0616	
Residual	43.74583333	15	4.04			
Lack of Fit	26.5125	10	4.19	0.76922147	0.6624	not significant
Pure Error	17.23333333	5	3.45			
Total	444.0586667	29				

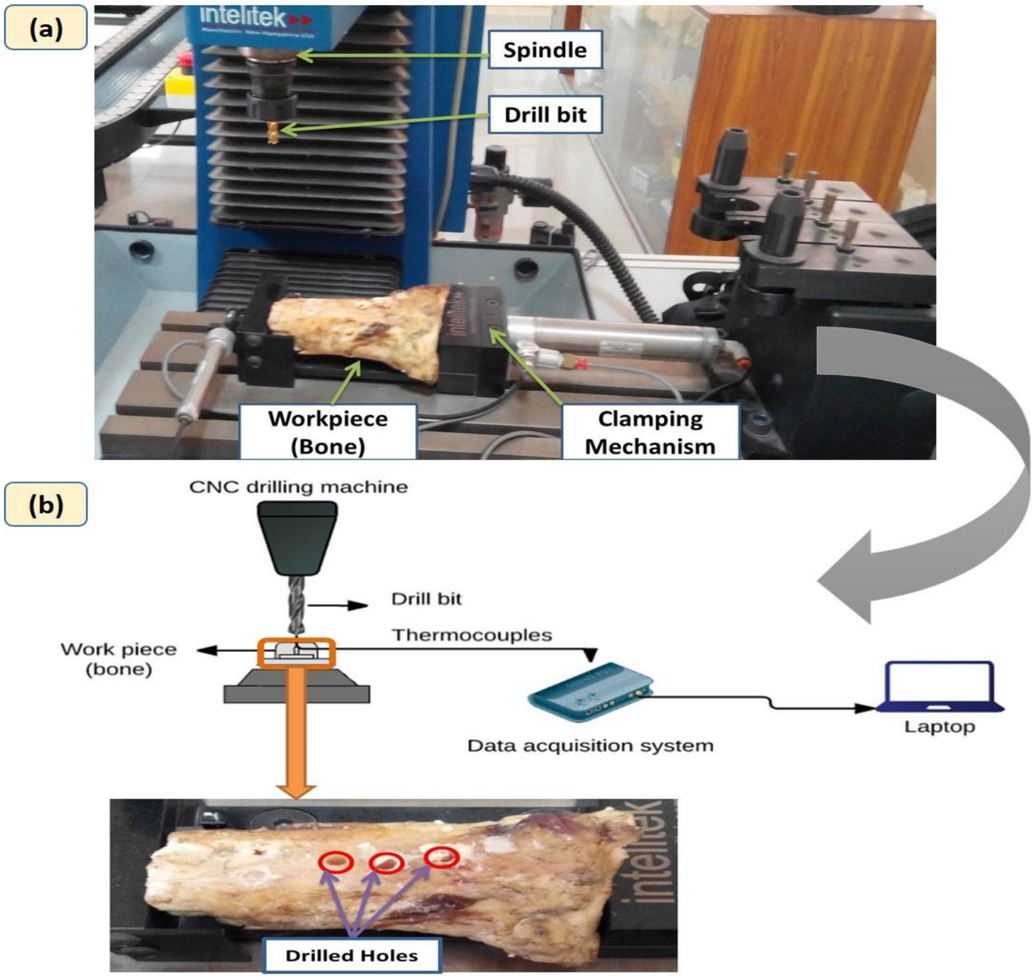

Fig-1: (a) Experimental setup (b) Schematic diagram

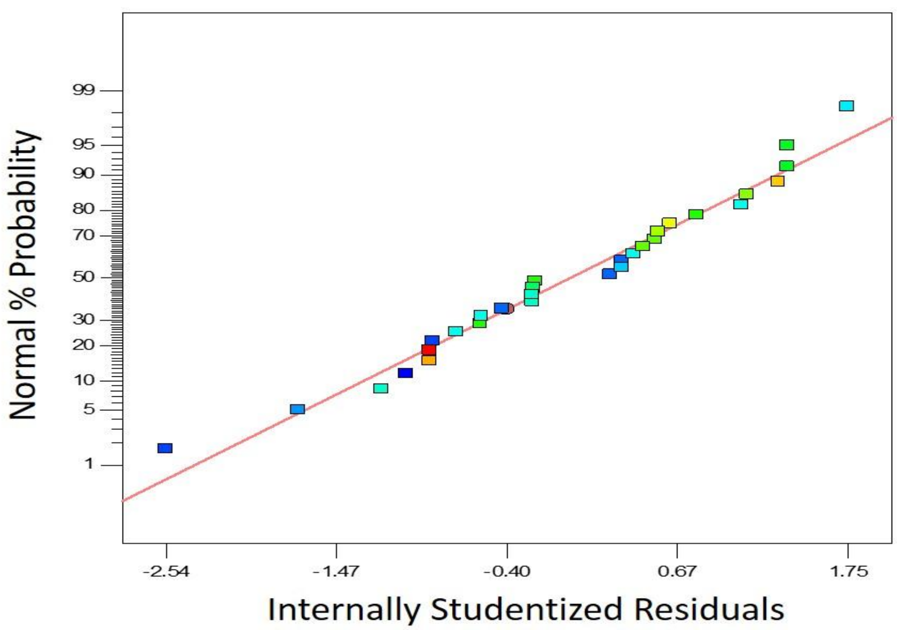

Fig-2: Normal probability plot of residuals

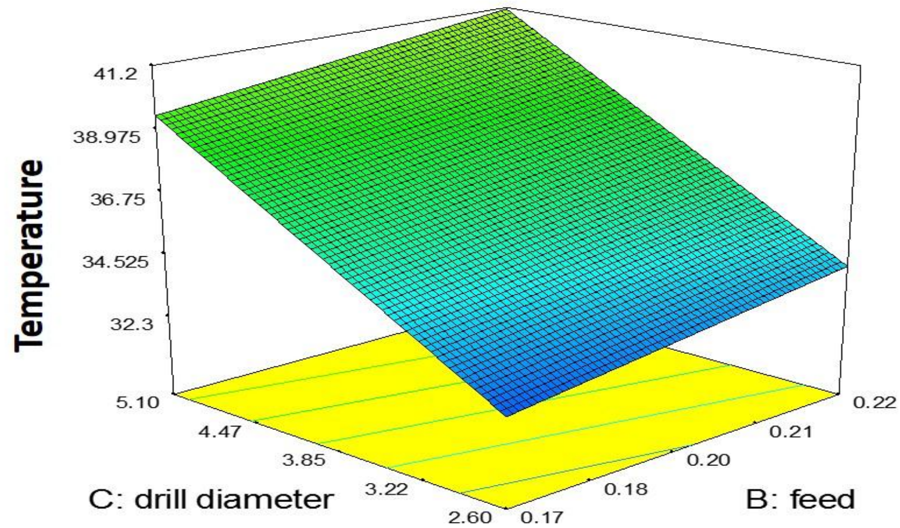

Fig-3. 3D-graph of temperature and input variables (Drill diameter and Feed)

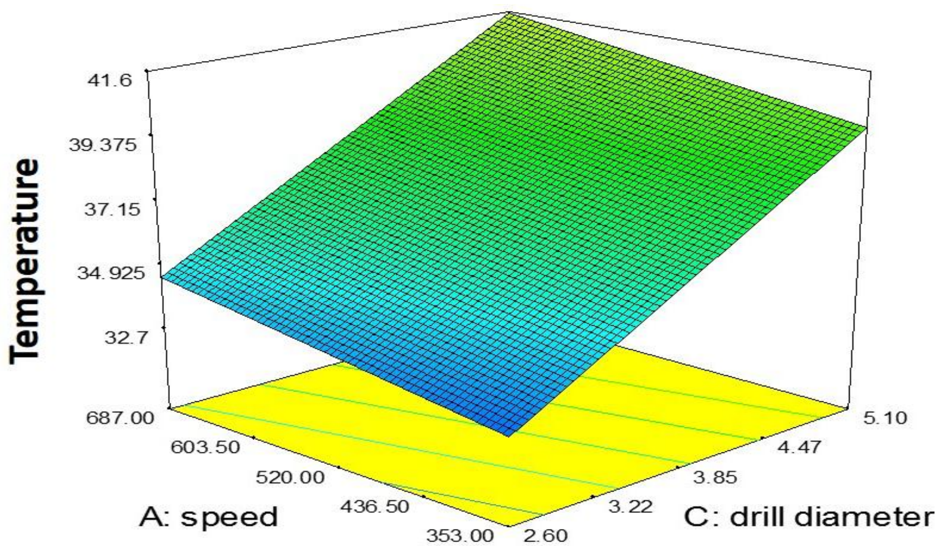

Fig-4: 3D-graph of temperature and input variables (Speed and Drill Diameter)

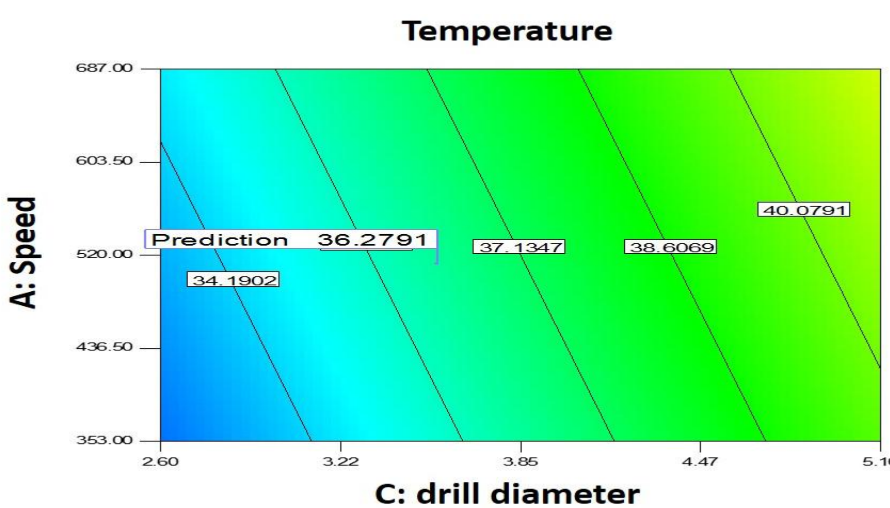

Fig-5. Contour Plot: Speed vs. Drill diameter

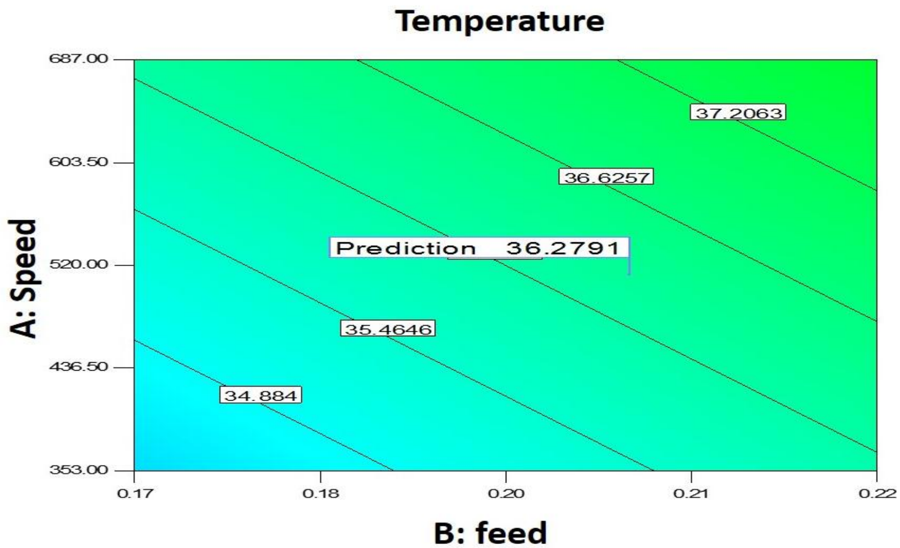

Fig-6. Contour Plot: Speed vs. Feed

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