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# Effect of Machining Parameters on Tool Wear and Nodal Temperature in Hard Turning of AISI D3 Steel

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## Abstract

**Present day metal cutting industry has to meet the challenges of productivity and the quality of the machined parts during the turning processes economically. In the present work, an attempt has been made to develop a model and predict the tool wear and nodal temperature of hard turned AISI D3 hardened steel using Response Surface Methodology (RSM). The combined effects of cutting speed, feed rate and depth of cut are investigated using contour plots. RSM based Central Composite Design (CCD) is applied as an experimental design. $Al_2O_3$/TiC mixed ceramic tool with a corner radius of 0.8 mm is employed to accomplish 20 tests with six centre points. The adequacy of the developed models is checked using Analysis of Variance (ANOVA). Main and interaction plots are drawn to study the effect of process parameters on output responses.**

## Keywords

**Hard Turning, Tool Flank Wear, Nodal Temperature, AISI D3, RSM**

**Subject Areas: Industrial Engineering, Mechanical Engineering**

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## 1. Introduction

Hard turning is the process of single point cutting of hardened ferrous material with a hardness value of more than 45 HRC in order to obtain finished workpieces directly from hardened parts. Increasingly, the growth of hard turning process has been indebted to the advent of new advanced tools such as Ceramic, Cubic Boron Nitride (CBN) and Polycrystalline Cubic Boron Nitride (PCBN) tools since 1970. Reduction in machining costs,

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elimination of cutting fluids, increase in the flexibility and efficiency, reduction in part-handling costs and finally decrease in the set-up times, when compared to grinding process, are the advantages of hard turning [1]-[3]. The advantage of hard turning is its dry environment; it is mostly carried out in the absence of lubricants. Aspects such as tool life and wear, surface finish, cutting forces, material removal rate, power consumption and cutting temperature (on tool and workpiece interface) decide the productivity, product quality and overall economy in manufacturing by machining. During machining, the consumed power is largely converted into heat resulting in high cutting temperature near the cutting edge of the tool. The amount of heat generated varies from the type of material being machined and machining parameters, especially cutting speed, which has great influence on the temperature [4]. Many of the economic and technical problems of machining are caused directly or indirectly by this heating action. In actual practice, there are many factors which affect these performance measures, such as tool variables workpiece variables and cutting conditions. Excessive temperatures directly influence the temperatures of tool face and tool flank and induce thermal damage to the machined surface [5].

Earlier researchers have published works based on experiments to study the effect of cutting parameters on surface roughness [6] [7]. Jarah A. G. *et al*. [8] investigated machinability of FCD 500 ductile castiron using coated carbide tool in dry machining condition. Lalwani D. I. *et al*. [9] experimentally found that cutting parameters have influence on cutting forces and surface roughness of MDN 250 steel. Kaladhar *et al*. [10] optimised material removal rate during machining of AISI 304 austenitic stainless steel CVD coated cutting insert. It is necessary to select the most appropriate machining settings in order to improve cutting efficiency. Hence statistical Design of Experiments (DOE) and statistical or mathematical models are used quite extensively. Statistical DOE refers to the process of planning the experiments so that the appropriate data can be analyzed by statistical methods, resulting invalid and objective conclusions [11]. Davim J. P. and Figueira L. [12] have investigated the machinability evaluation in hard turning of cold work AISI D2 steel with ceramic tools using statistical techniques. It has been identified that the tool wear is highly influenced by the cutting velocity and in a smaller degree by cutting time. The specific cutting pressure is strongly influenced by the feed rate.

The optimum parameter selection is determined by the operators' experience, knowledge or the previous recorded data. If it was not done properly, it leads to decrease in productivity due to sub-optimal use of machining capability; this causes high manufacturing cost and low product quality [13] [14]. Sahin Y. [15] has compared the tool life of CBN and ceramic inserts in turning hard steels using Taguchi method. The effects of cutting parameters (cutting speed, feed, tool hardness) on tool life were determined by using ANOVA. As a result, it was concluded that the effects of cutting speed, tool hardness and feed rate on tool life were 41.63%, 32.68% and 25.22%, respectively. Adeel H. Suhail *et al*. [16] conducted experiments to optimize the cutting parameters on workpiece surface temperature and surface roughness by employing Taguchi technique and ANOVA. The results showed that the workpiece surface temperature can be sensed effectively as an "in-process signal" for cutting parameters optimization. As a result, it was seen that the $V_b$ value decreased as the cutting speed and the depth of cut increased; however, it has first decreased and then increased as the feed rate increased. On the other hand, the surface roughness decreased as the cutting speed increased. In contrast, surface roughness increased when the feed rate increased.

Anirban Bhattacharya *et al*. [17] investigated the effect of cutting parameters on surface finish and power consumption during high speed machining of AISI 1045 steel using Taguchi design and ANOVA. The result showed a significant effect of cutting speed on surface roughness and power consumption, while the other parameters have not substantially affected the response.

Zou *et al*. [18] used $Al_2O_3$/TiN-coated tungsten carbide tools for finish-turning of $NiCr_{20}TiAl$ nickel-based alloy under various cutting conditions and cutting forces, surface integrity and tool wear are investigated and the inter-diffusing and transferring of elements between $Al_2O_3$/TiN-coated tungsten carbide tool and $NiCr_{20}TiAl$ nickel-based alloy are studied.

In the present study, an attempt has been made to investigate the effect of process parameters (cutting speed, feed rate and depth of cut) on the performance characteristics (tool life and tool temperature) in finish hard turning of AISI D3 steel hardened at 62 HRC with Ceramic tool. The combined effects of the process parameters on performance characteristics are investigated while employing ANOVA. The relationship between process parameters and performance characteristics are modelled using RSM.

## 2. Experimentation

The work piece material used for experimentation is AISI D3. Test sample is trued, centred and cleaned by removing a 2 mm depth of cut from the outside surface, prior to actual machining tests. A bar of diameter 68 mm × 360 mm long is prepared. The chemical composition of the work piece material is given in **Table 1**. The workpiece is oil-quenched from 980˚C (1800˚F), hardened by tempering at 200˚C to attain 62 HRC. **Figure 1** shows image of insert CC6050. Experimental set up is shown in **Figure 2**.

The lathe used for machining is a *Kirloskar* make model Turn Master-35, spindle power 6.6 KW. A roughness meter Surftest SJ 201 *Mitutoyo* make is used to measure surface roughness ($R_a$) of turned surface as shown in **Figure 3**. Temperature is measured with the help of IR thermometer and tool maker's micro scope is used for measuring tool flank wear.

**Figure 1.** Image of ceramic cutting insert CC6050.

**Figure 2.** Experimental set up.

**Figure 3.** Mitutoyo Surface Roughness tester SJ 210.

**Table 1.** Chemical composition of AISI D3 (wt %).

| C | Si | Mn | P | S | Cr | Ni | Mo | Al | Cu | Zn | Fe |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2.06 | 0.55 | 0.449 | 0.036 | 0.056 | 11.09 | 0.277 | 0.207 | 0.0034 | 0.13 | 0.27 | Balance |

The cutting insert used is a mixed ceramic one, of square form with eight cutting edges and having the designation of SNGA 120408 T01020 *Sandvik* make CC6050 is a mixed ceramic grade based on alumina with an addition of titanium carbide. The high hot-hardness, the good level of toughness makes the grade suitable as first choice for hardened steel (50 - 65 HRC) in applications with good stability or with light interrupted cuts. The inserts are mounted on a commercial tool holder of designation PSBNR 2525 M 12 (ISO) with the geometry of active part characterized by the following angles: $\chi = 75^\circ$; $\alpha = 6^\circ$; $\gamma = -6^\circ$; $\lambda = -6^\circ$. Three levels are defined for each cutting variable as given in **Table 2**. The variable levels are chosen within the intervals as recommended by the cutting tool manufacturer. Three cutting variables at three levels led to a total of 20 tests.

## Measurement of Tool Wear and Nodal Temperature

The nodal temperature of the machined samples were measured by the use of infrared the rmometer (make: Amprobe IR750) having temperature range of −50˚C to 1500˚C and with optical resolution of 10:1 and emissivity 0.1 - 1 (adjustable). During the course of experimentation the tool flank wear of worn out inserts are measured with the help of a tool maker’s microscope.

## 3. Analysis of Results

**Table 3** gives the experimental results of Tool flank wear ($V_b$) and Temperature of Tool in accessible region (Nodal Temp) and work piece interface for various combinations of cutting conditions (cutting speed, feed rate and depth of cut) as per the design matrix. The Temperatures are of the order of 700˚C - 900˚C at the cutting zone during machining.

The raw data presented in **Table 3** for which analysis has to be graphically represented. The following sections present the detailed discussion.

### 3.1. Statistical Analysis

In RSM, the quantitative form of the relationship between the desired response and independent input process parameters can be represented by [19].

$$Y = f\left(\mathrm{Vc}, \mathrm{f}, \mathrm{d}\right) \tag{1}$$

where Y is the desired response and *f* is the response function. In the present investigation, the RSM-based mathematical models for tool wear and Nodal temperature have been developed with cutting speed “Vc”, feed rate “f” and depth of cut “d” as the process parameters. The response surface equation for three factors is given by [19].

$$\mathrm{Y} = \mathrm{a_o} + \mathrm{a_1 Vc} + \mathrm{a_2 f} + \mathrm{a_3 d} + \mathrm{a_{12} Vcf} + \mathrm{a_{13} Vcd} + \mathrm{a_{23} fd} + \mathrm{a_{11} v^2} + \mathrm{a_{22} f^2} + \mathrm{a_{33} d^2} \tag{2}$$

where Y is desired response and $\mathrm{a_o}$, $\mathrm{a_1} \cdots \mathrm{a_{33}}$ regression coefficients to be determined for each response. The regression coefficients of linear, quadratic, and interaction terms of RSM-based mathematical models are determined by [19].

**Table 4** and **Table 5** show estimated regression co-efficient for tool wear ($V_b$) and Nodal temperature after removing the insignificant terms. **Table 6** and **Table 7** present the ANOVA results which are performed to evaluate the statistical significances of the fitted regression model and factors involved therein for the response factors namely $V_b$ and surface temperature. ANOVA table is used to summarize the test for significance of regression model, test for significance for individual model coefficient. Output reveals that regression model is statistically significant for the selected response. Significant model terms are identified at 95% significance level. Goodness of fit was evaluated from R-Sq in order to check the reliability and precision of the model. In this case speed, feed, depth of cut, speed × feed, speed × depth of cut and feed × depth of cut are significant model terms. **Table 4** shows the R-Sq value to be 96.5%. This value illustrates that there is variability in the data and it can

**Table 2.** Process parameters and their levels.

| Parameters | Levels | | |
|---|---|---|---|
| | −1 | 0 | +1 |
| Speed (m/min) | 145 | 155 | 165 |
| Feed (mm/rev) | 0.05 | 0.075 | 0.1 |
| Depth of cut (mm) | 0.3 | 0.6 | 0.9 |

**Table 3.** Experimental results for tool wear and nodal temperature.

| Experiment. No. | Un Coded Form | | | Tool Flank Wear | Nodal Temperature |
|---|---|---|---|---|---|
| | Speed (m/min) | Feed (mm/rev) | Depth of Cut (mm) | $V_b$ (mm) | T (˚C) |
| 1 | 145 | 0.05 | 0.3 | 0.1740 | 80.000 |
| 2 | 165 | 0.05 | 0.3 | 0.1480 | 95.200 |
| 3 | 145 | 0.1 | 0.3 | 0.1560 | 87.500 |
| 4 | 165 | 0.1 | 0.3 | 0.1630 | 93.200 |
| 5 | 145 | 0.05 | 0.9 | 0.1730 | 81.400 |
| 6 | 165 | 0.05 | 0.9 | 0.1840 | 97.700 |
| 7 | 145 | 0.1 | 0.9 | 0.1720 | 86.100 |
| 8 | 165 | 0.1 | 0.9 | 0.2230 | 109.500 |
| 9 | 145 | 0.075 | 0.6 | 0.1750 | 79.200 |
| 10 | 165 | 0.075 | 0.6 | 0.1775 | 92.000 |
| 11 | 155 | 0.05 | 0.6 | 0.1680 | 86.500 |
| 12 | 155 | 0.1 | 0.6 | 0.1700 | 89.780 |
| 13 | 155 | 0.075 | 0.3 | 0.1630 | 86.000 |
| 14 | 155 | 0.075 | 0.9 | 0.1860 | 91.000 |
| 15 | 155 | 0.075 | 0.6 | 0.1780 | 92.000 |
| 16 | 155 | 0.075 | 0.6 | 0.1710 | 86.500 |
| 17 | 155 | 0.075 | 0.6 | 0.1780 | 90.700 |
| 18 | 155 | 0.075 | 0.6 | 0.1700 | 87.900 |
| 19 | 155 | 0.075 | 0.6 | 0.1690 | 90.400 |
| 20 | 155 | 0.075 | 0.6 | 0.1720 | 85.630 |

**Table 4.** Estimated regression coefficients for tool wear $V_b$ (mm) after removing the insignificant terms.

| Term | Coef | SE Coef | T | P |
|---|---|---|---|---|
| Constant | 0.172945 | 0.001289 | 134.136 | 0.000 |
| Speed (m/min) | 0.004550 | 0.001186 | 3.836 | 0.003 |
| Feed (mm/rev) | 0.003700 | 0.001186 | 3.120 | 0.011 |
| Depth of cut (mm) | 0.013400 | 0.001186 | 11.298 | 0.000 |
| Speed (m/min) × Feed (mm/rev) | 0.009125 | 0.001326 | 6.882 | 0.000 |
| Speed (m/min) × Depth of cut (mm) | 0.010125 | 0.001326 | 7.636 | 0.000 |
| Feed (mm/rev) × Depth of cut (mm) | 0.005125 | 0.001326 | 3.865 | 0.003 |
| S = 0.003750 R-Sq = 96.5% R-Sq (adj) = 93.4% | | | | |

**Table 5.** Estimated regression coefficients for Nodal temperature after removing the insignificant terms.

| Term | Coef | SE Coef | T | P |
|---|---|---|---|---|
| Constant | 87.8667 | 1.0390 | 84.567 | 0.00 |
| Speed (m/min) | 7.3400 | 0.9558 | 7.680 | 0.000 |
| Feed (mm/rev) | 2.5280 | 0.9558 | 2.645 | 0.025 |
| Depth of cut (mm) | 2.3800 | 0.9558 | 2.490 | 0.032 |
| S = 3.022 R-Sq = 89.3% R-Sq (adj) = 79.7% | | | | |

**Table 6.** Analysis of variance for tool wear $V_b$ (mm).

| Source | DF | Seq SS | Adj SS | Adj MS | F | P |
|---|---|---|---|---|---|---|
| Regression | 9 | 0.003898 | 0.003898 | 0.000433 | 30.79 | 0.000 |
| Linear | 3 | 0.002140 | 0.002140 | 0.000713 | 50.70 | 0.000 |
| Square | 3 | 0.000062 | 0.000062 | 0.000021 | 1.47 | 0.280 |
| Interaction | 3 | 0.001696 | 0.001696 | 0.000565 | 40.20 | 0.000 |
| Residual Error | 10 | 0.000141 | 0.000141 | 0.000014 | | |
| Lack-of-Fit | 5 | 0.000061 | 0.000061 | 0.000012 | 0.76 | 0.616 |
| Pure Error | 5 | 0.000080 | 0.000080 | 0.000016 | | |
| Total | 19 | 0.004039 | | | | |

**Table 7.** ANOVA Nodal temperature.

| Source | DF | Seq SS | Adj SS | Adj MS | F | P |
|---|---|---|---|---|---|---|
| Regression | 9 | 764.29 | 764.29 | 84.921 | 9.30 | 0.001 |
| Linear | 3 | 659.31 | 659.31 | 219.770 | 24.06 | 0.000 |
| Square | 3 | 44.95 | 44.95 | 14.984 | 1.64 | 0.242 |
| Interaction | 3 | 60.02 | 60.02 | 20.008 | 2.19 | 0.152 |
| Residual Error | 10 | 91.35 | 91.35 | 9.135 | | |
| Lack-of-Fit | 5 | 58.81 | 58.81 | 11.761 | 1.81 | 0.266 |
| Pure Error | 5 | 32.54 | 32.54 | 6.508 | | |
| Total | 19 | 855.64 | | | | |

be analysed.

$$\begin{aligned} V_b &= 0.172945 + 0.004550 \times Vc + 0.003700 \times f + 0.013400 \times d \\ &\quad + 0.009125 Vc \times f + 0.010125 Vc \times d + 0.005125 f \times d \end{aligned} \tag{3}$$

$$T = 87.8667 + 7.3400 \times Vc + 2.5280 \times f + 2.3800 \times d \tag{4}$$

### 3.2. Main Effect Plots and Interaction Plots for Tool Flank Wear and Nodal Temperature

**Figure 4** shows main effects plot for tool flank wear. It is observed that the depth of cut strongly influences the flank wear. Speed and Feed rate also has an increasing effect. For the depth of cut, influence value is that highest and it has much higher levels of contribution. However, low depth of cut should be used in order to reduce the tendency to chatter. Therefore, if the tool work system is not very rigid, such as in cutting slender parts, very fine depth of cut should be employed to avoid chatter.

**Figure 5** shows interaction of tool flank wear with input parameters. From the above figure flank wear is decreasing at low speed, feed and depth of cut. At high levels of speed and feed as well as speed and depth of cut

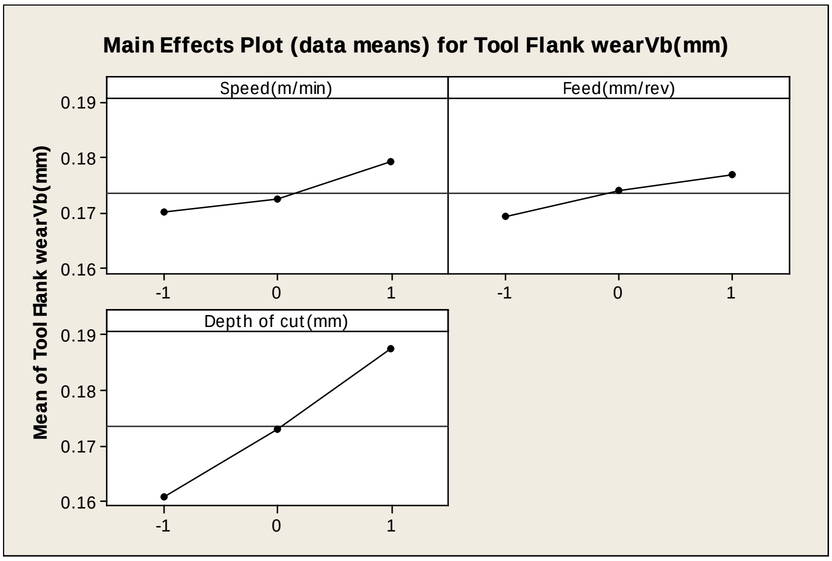


Figure 4. Main effects plot for mean tool flank wear.

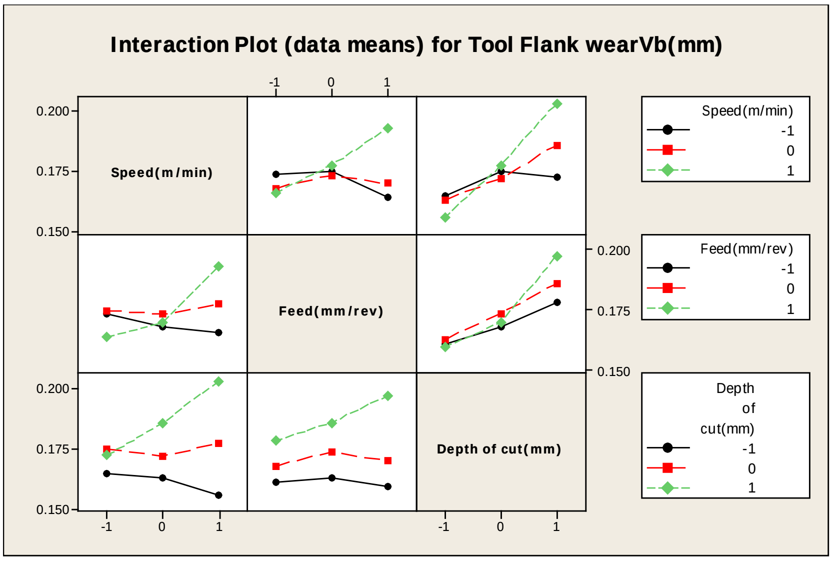


Figure 5. Interaction plot for mean tool flank wear.

flank wear is high. The combined effect of feed and depth of cut is also following the same trend as above. The combined effect of depth of cut on flank wear is more even with small changes in speed or feed.

The main effects plot for Nodal temperature is shown in **Figure 6** and it concludes that with speed Nodal temperature increases drastically as the amount of material removal is more. Where as feed and depth cut shows small change at low and medium levels but drastic change at higher level. The surge is seen in the graph as again one material removal is more.

From the interaction plots shown in **Figure 7** it is evident that the Nodal temperature increases when speed combined with feed and depth of cut irrespective of low level or high level. The combined effect of feed and depth of cut with the other variables decreases first and then increases against low level to high level.

### 3.3. Contour Plots for Tool Flank Wear and Nodal Temperature vs Speed, Feed and Doc

Contour plots play a very important role in the study of the response surface. By creating contour plots for response surface analysis, the optimum is located by characterising the shape of the surface. Circular shaped con-

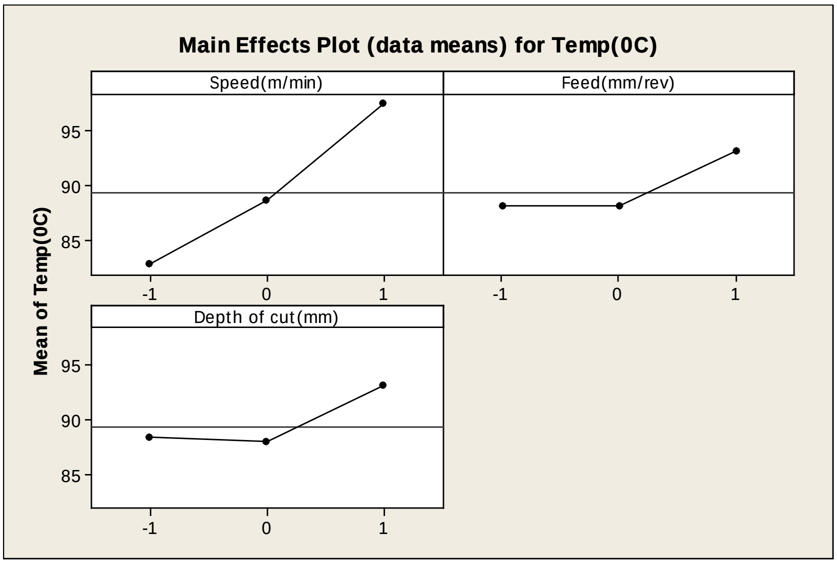


**Figure 6.** Main effects plot for mean Nodal temperature.

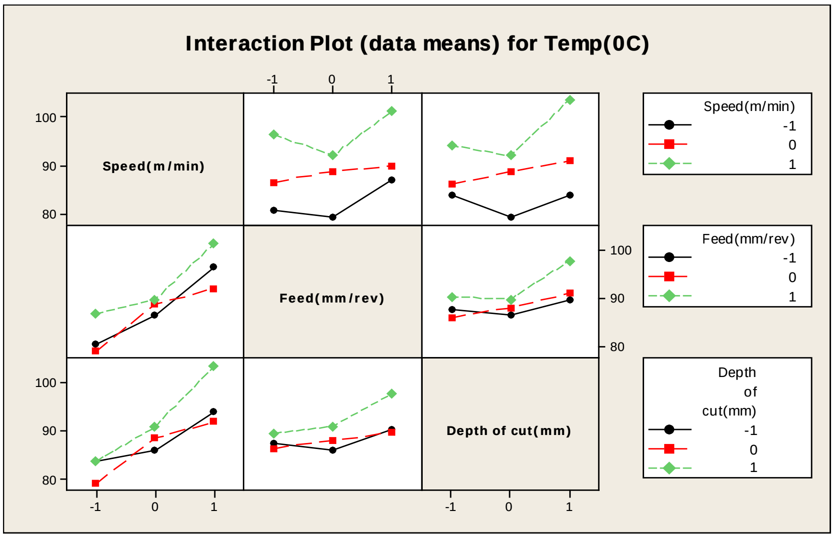
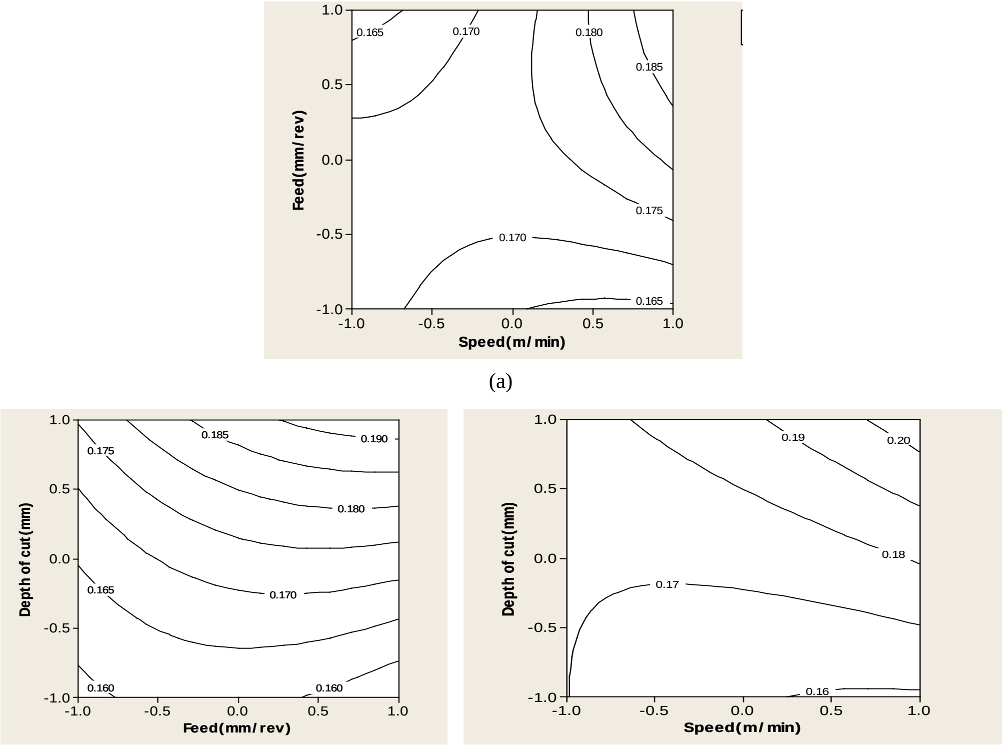


**Figure 7.** Interaction plot for mean Nodal temperature.

tour represents the independence of factor effects and elliptical contours may indicate factor interaction. The contours of the responses are shown in **Figures 8(a)-(c)** for flank wear, it almost to be low at low levels of feed, depth of cut and mid level of speed. But, it is very sensitive against depth of cut and speed, flank wear is drastically increases even at low values. The contour plots of Nodal temperature are shown in **Figures 9(a)-(c)**. Nodal temperature increases when feed and speed increases from the low level to high level. The interaction of depth of cut and feed is more on Nodal temperature. Higher interaction on temperature is shown by depth of cut and speed.

### 3.4. 3D Surface Plots

3D Surface plots of Tool flank wear vs. different combinations of cutting parameters are shown below. **Figure 10(a)** presents the influence of depth of cut and feed rate on the tool flank wear, while the speed is kept at the middle level. **Figure 10(b)** shows the estimated response surface in relation to the depth of cut and cutting speed while feed is kept at the middle level. **Figure 10(c)** shows surface plot of speed and feed while the depth of cut is kept at the middle level. **Figure 11(a)** presents influence of depth of cut and feed on Nodal temperature,

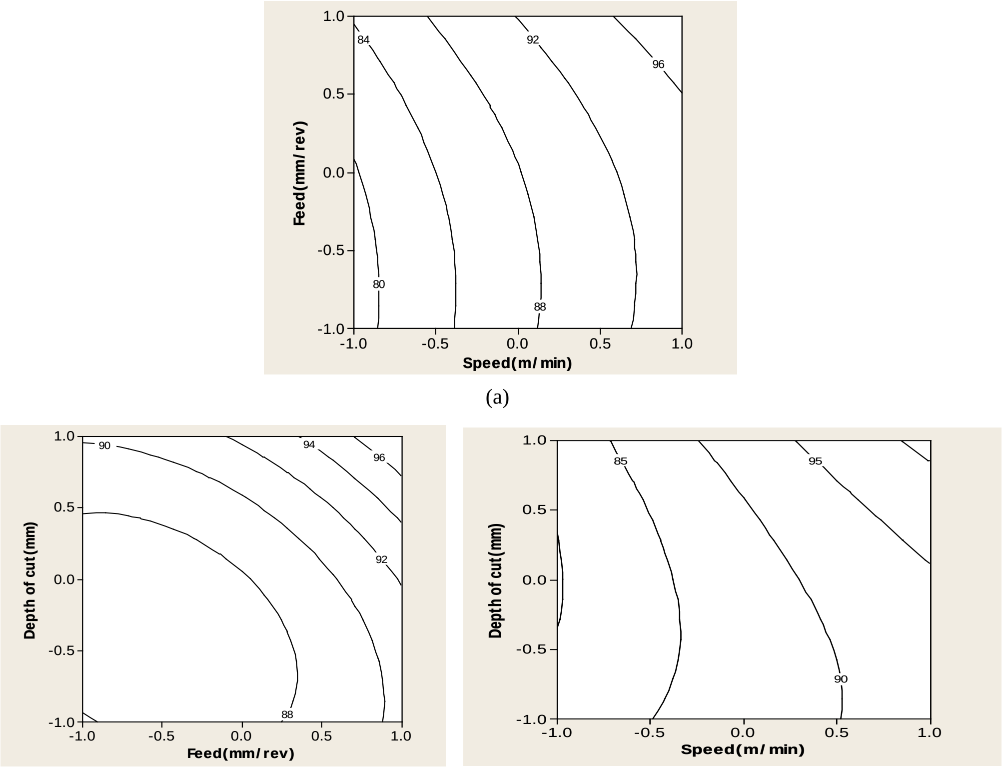


(a)

(b)

(c)

**Figure 8.** Contour plots for flank wear vs input parameters.

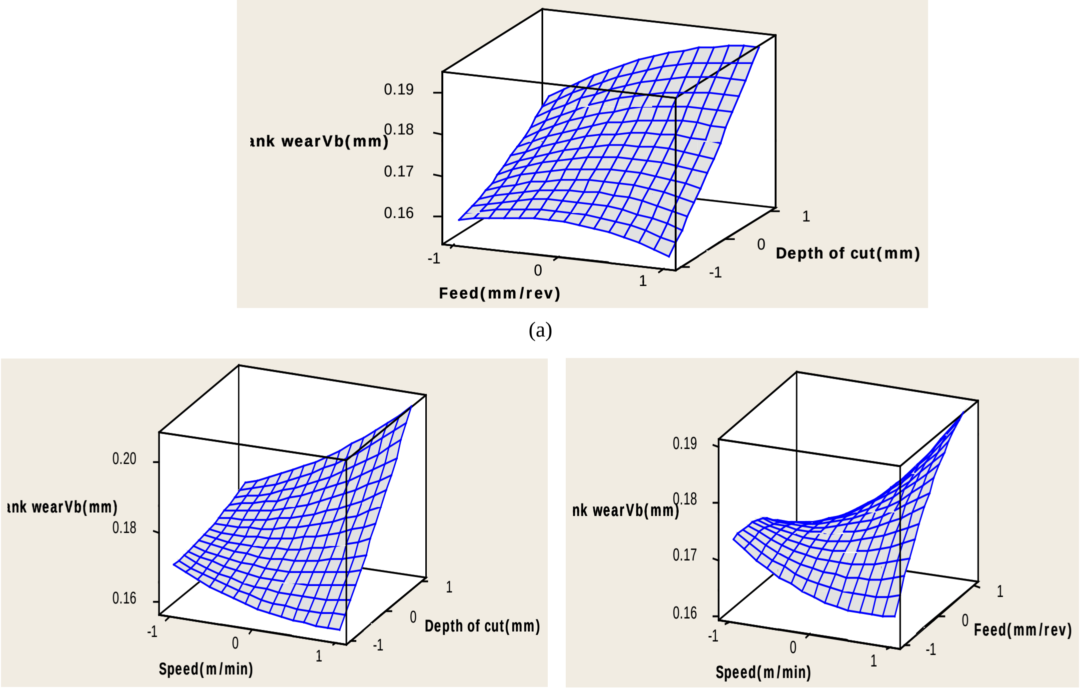


(a)

(b)

(c)

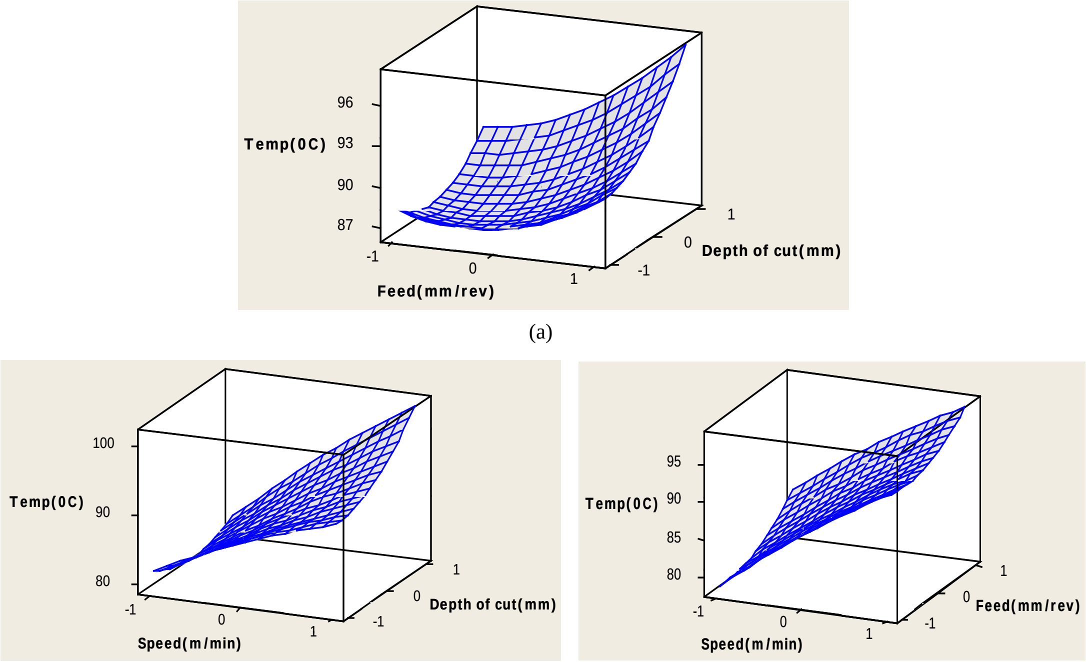
**Figure 9.** Contour plots for nodal temperature vs input parameters.



(a)

(b) (c)

**Figure 10.** Surface plot for Flank wear vs input parameters.



(a)

(b) (c)

**Figure 11.** Surface plot of nodal temperature vs input parameters.

where speed kept at middle level. **Figure 11(b)** shows effect of depth of cut and speed when feed is kept at the middle level. **Figure 11(c)** plots influence of feed and speed while the depth of cut is kept at the middle level. For each plot, the variables not represented are held at a constant value (the middle level). These 3D plots confirm the nodes observed during the main effects plots analysis.

## 4. Conclusions

In this work, tool wear and workpiece temperature are analyzed to study the effects of cutting speed, feed rate and depth of cut in hard turning of AISI D3 cold work tool steel using CC6050 ceramic inserts. The conclusions are as follows.

1) The experimental results showed that the RSM design is an effective way of determining the optimal cutting parameters for achieving low tool wear and low Nodal temperature.

2) The significant parameters for Nodal temperature are cutting speed (145 m/min) and Depth of cut (0.6 mm). The feed has a little influence of the total variation.

3) The relationship between cutting parameters (cutting speed, depth of cut, feed) and the performance measures (tool wear and Nodal temperature) is expressed by multiple regression equation which can be used to estimate the expressed values of the performance level for any parameter levels.

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