# Machining of Titanium Alloy and Optimization of Machining Parameters using Response Surface Method

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***Abstract-*** *Titanium alloys have been generally defined as difficult to cut materials due to their natural properties. The main drawbacks in machining titanium alloys are high cutting temperatures and tool wear due to high adhesion of tool work interface. This paper presents a finite-element modeling (FEM) of cutting tool temperature during turning of Titanium alloy Ti-6Al-4V under dry machining. Cutting temperature during machining plays a very important role in the overall performance of machining processes. Since in the current investigation, it was a very difficult task to measure the tool temperature correctly. Thus, Finite Element Modeling was used as a modeling tool to predict cutting temperature. The ANSYS software was used to determine the cutting temperature at tool nose. The Design of Experiments (DOE) was carried out using response surface methodology in Minitab 2018 software. The process parameters considered for design of experiments are spindle speed, feed rate, depth of cut and tool type used for operation. Response Surface Methodology (RSM) was used to analyse the machining effect on tool material in this study. The purpose of performing an orthogonal array experiment is to determine the optimum level for each of the process parameters and to establish the relative significance of each parameter.*

***Keywords***- Titanium alloys, Cutting temperature, Turning, Research Surface Methodology (RSM), dry machining, Thermal modelling.

## I. INTRODUCTION

Aluminium and aluminium alloys were previously the preferred materials of the aerospace industry. But newer aircraft designs are increasingly using of titanium and titanium alloys. Titanium alloys are classified as difficult-to-cut materials since they pose an utmost challenge to manufacturing engineers due to the high temperatures and stresses generated during machining. Titanium and its alloys have gained widespread applications in aerospace, biomedical industries due to their following favourable properties: They are light weight, possess high strength, have excellent fatigue performance and offer high resistance to an aggressive environment [1]. Due to low thermal conductivity heat generated in the cutting zone stay near the cutting interface resulting in poor tool life and in accurate workpiece dimensions [2]. The main drawbacks in machining titanium alloys are high cutting temperatures and tool wear due to high adhesion of tool work interface. Titanium and its alloys have very high chemical reactivity when temperature exceeds 500 °C [3]. Ti-6Al-4V which is among the most extensively utilized alpha-beta (α+β) titanium alloys for producing compressor blades in aerospace industries [4].

In machining processes, the temperature in the cutting zone is one of the most important key point affecting machinability [5]. The cutting temperature have a major impact on rapid tool wear development. As measurement of cutting tool temperature in machining is a very difficult task, many researchers' uses analytical models to study regarding the temperature distribution in the cutting zone. During the machining of difficult-to-cut metals like Titanium alloy (Ti6Al4V), temperatures with very high values are generated due to their high thermal and mechanical properties. When the cutting temperature reaches the value above 600 – 700 °C, atmospheric oxygen and nitrogen diffuses into the top most layers of workpiece and results in higher hardness level [6]. Accordingly, the tool temperature issue is a major concern to be considered when machining this kind of difficult-to-cut metals because this can seriously affect the overall performance of the machining process.

Finite Element Modeling (FEM) proves to be very effective tool for the modeling of machining processes. FEM techniques have been applied to solve problems related to structural and thermal analysis in machining as these approaches are known to provide accurate and precise solutions for many complex phenomena. All machining processes involve the interaction between the cutting tool insert and the work piece, which is a particularly complicated phenomenon. Moreover, the properties and condition of the workpiece, insert material, insert geometry, cutting parameters, machine tool dynamic performance, and clamping conditions are also important aspects that must be taken into account [7]. This indicates that analysis of a machining process is a very difficult task, and FEM modeling can provide the correct solution to this complex problem [7]. During machining, numerical methods can predict temperatures using Finite Element (FE) analysis and analytical methods. Due to progress in analysis of numerical methods, the ability of FE models has been improved to predict machining processes, including machining forces, temperatures, residual stress, and chip morphology [8]. FE modeling is nowadays a very essential tool in current industrial practice for machining process as it can be used to model and simulate the metal cutting process before costly and time consuming experimental trials [9].

In this study, the focus was on finding out the predicted values of cutting tool temperature using regression analysis method and to form Model equations of responses. Then plot the graph to understand the impact of process parameters visually, also find out optimum process parameters for turning of Titanium alloy using RSM (Response Surface Methodology).

## II. EXPERIMENTAL ANALYSIS

PVD TiAlN coated tungsten carbide inserts are used during turning of titanium alloy Ti-6Al-4V under dry environment. PVD TiAlN coated carbide tools are used frequently in metal cutting process due to their high hardness, wear resistance and chemical stability [10]. Cutting inserts with ISO specification TNMG 160408 are used for turning operations. For the present work Ti-6Al-4V (grade 5) which is widely used among all the titanium alloys is considered as workpiece material. All the tests were carried out under dry machining condition with combination of different process parameters like cutting speed, feed and depth of cut.

Table 1. Selected Process Parameters

| Machining Parameters | Unit | Level 1 | Level 2 | Level 3 |
|---|---|---|---|---|
| Cutting speed | m/min | 120 | 180 | 240 |
| Feed rate | mm/rev | 0.1 | 0.15 | 0.2 |
| Depth of cut | mm | 0.5 | 0.75 | 1 |

Turning experiments were conducted as per scheme of runs determined by full factorial design of experiments and cutting forces calculated by Neelesh Kumar Sahu et al [11] are taken as reference.

Table 2. Experimental Results

| Experiment Number | Speed (V) (m/min) | Feed (f) (mm/rev) | Depth of cut (d) (mm) | Feed Force ($F_Q$) (N) | Cutting Force ($F_P$) (N) | Resultant Force (F) (N) |
|---|---|---|---|---|---|---|
| 1 | 180 | 0.15 | 1 | 234.6 | 256.3 | 347.4 |
| 2 | 180 | 0.1 | 0.75 | 101.9 | 146.1 | 178.1 |
| 3 | 120 | 0.2 | 1 | 296.5 | 336.4 | 448.4 |
| 4 | 180 | 0.2 | 0.75 | 214.6 | 375.7 | 432.7 |
| 5 | 120 | 0.1 | 1 | 148 | 139.4 | 203.3 |
| 6 | 240 | 0.1 | 0.75 | 117 | 156.3 | 195.2 |
| 7 | 120 | 0.2 | 0.5 | 196 | 365.1 | 414.4 |
| 8 | 180 | 0.2 | 1 | 323 | 379.8 | 498.6 |
| 9 | 180 | 0.1 | 1 | 169.4 | 145.7 | 223 |
| 10 | 180 | 0.15 | 0.75 | 156.2 | 264.3 | 307 |
| 11 | 180 | 0.1 | 0.5 | 90.2 | 182.3 | 203.4 |
| 12 | 120 | 0.2 | 0.75 | 215.4 | 328.2 | 392.6 |
| 13 | 240 | 0.15 | 0.5 | 135.8 | 333.3 | 359.9 |
| 14 | 180 | 0.15 | 0.5 | 132.4 | 306.1 | 333.5 |
| 15 | 120 | 0.15 | 0.75 | 155.7 | 234.6 | 281.5 |
| 16 | 240 | 0.2 | 0.5 | 157.6 | 438.1 | 465.6 |
| 17 | 120 | 0.15 | 1 | 229.2 | 245.7 | 336 |
| 18 | 240 | 0.15 | 1 | 270.3 | 299 | 403 |
| 19 | 240 | 0.2 | 0.75 | 210.8 | 445.8 | 493.2 |
| 20 | 120 | 0.15 | 0.5 | 137.7 | 272.6 | 305.4 |
| 21 | 180 | 0.2 | 0.5 | 189.6 | 415 | 456.2 |
| 22 | 120 | 0.1 | 0.75 | 91.2 | 166.8 | 190.1 |
| 23 | 120 | 0.1 | 0.5 | 101.4 | 165.2 | 193.9 |
| 24 | 240 | 0.2 | 1 | 332.7 | 456.1 | 564.6 |
| 25 | 240 | 0.1 | 0.5 | 87.8 | 186.3 | 206 |
| 26 | 240 | 0.15 | 0.75 | 156.4 | 287.1 | 326.9 |
| 27 | 240 | 0.1 | 1 | 183.6 | 169 | 249.5 |

## III. FINITE ELEMENT MACHINING SIMULATION

In turning operations, heat generation takes place in three regions during the material removal process as shown in figure. These three regions are named as Primary Shear Deformation Zone (PSDZ), Secondary Shear Deformation Zone (SSDZ) and Tertiary Shear Deformation Zone (TSDZ). The total heat generation in machining is given by Equation (1):

Total Heat Generated = Heat Generated in (PSDZ + SSDZ + TSDZ)

$$\text{Total Heat} = Q = Q_s + Q_f + Q_r \quad (1)$$

The heat generated in the tertiary zone is very small in comparison to the heat of the primary and secondary deformation zones which almost equal to 99% of the total heat generated during cutting. By neglecting the heat generated in the tertiary shear deformation zone, the total heat generation can be given by Equation (2):

$$\text{Total Heat} = Q = Q_s + Q_f \quad (2)$$

From the heat generated by shear and friction region, the total heat generated during machining can be given by Equation (3) [12]:

$$Q = \left(\frac{\cos\alpha_n}{\cos(\varphi-\alpha_n)}\right)\left(\frac{\cos i}{\cos\eta_s}\right)V * \sqrt{[(F_P\cos i + F_R\sin i)\cos\varphi - F_Q\sin\varphi]^2 + (F_P\sin i - F_R\cos i)^2} + \left(\frac{\sin\varphi}{\cos(\varphi-\alpha_n)}\right)V \sqrt{[(F_P\cos i + F_R\sin i)\sin\alpha_n + F_Q\cos\alpha_n]^2 + (F_P\sin i - F_R\cos i)^2} \quad (3)$$

The total heat estimated by Equation (3) is taken as input to obtain the cutting temperature distribution on the cutting tool during steady state thermal analysis with the ANSYS software.

For every finite element model, boundary conditions play a very important role to get accurate results. The following boundary conditions are applied during this analysis:

1) The internal surfaces of the insert are assumed to be smooth and in perfect contact, which are in contact with the holder and the shim seat.
2) For the exterior region, boundaries of the tool insert which are exposed to the air, a heat transfer coefficient of h = 20 $W/m^2$ is considered.
3) Initially, the whole model is kept at an ambient temperature of 20°C.

Temperature views, distribution of temperature on different faces of the tools, and temperature variation with respect to time for some combination of process parameters in dry machining are shown in Figures 1,2&3 given below:

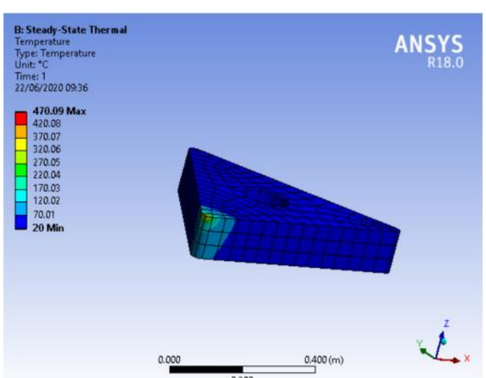


Figure 1. Temperature distribution of tool at Speed = 120m/min, Feed = 0.1mm/rev, Depth of Cut = 1mm.

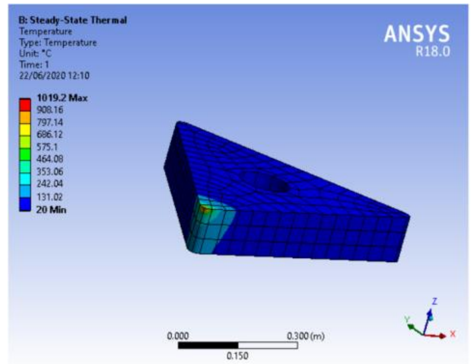


Figure 2. Temperature distribution of tool at Speed = 240m/min, Feed = 0.1mm/rev, Depth of Cut = 1mm.

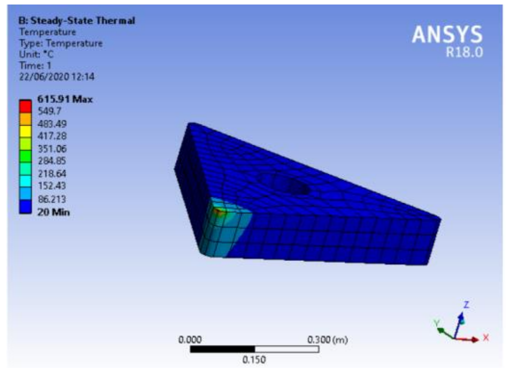


Figure 3. Temperature distribution of tool at Speed = 240m/min, Feed = 0.2mm/rev, Depth of Cut = 0.5mm.

Table 3. Orthogonal array and Simulation results

| Experiment Number | Speed (V) (m/min) | Feed (f) (mm/rev) | Depth of cut (d) (mm) | Temperature (°C) |
|---|---|---|---|---|
| 1 | 120 | 0.1 | 0.5 | 255.04 |
| 2 | 120 | 0.1 | 0.75 | 248.16 |
| 3 | 120 | 0.1 | 1 | 234.55 |
| 4 | 120 | 0.15 | 0.5 | 454.13 |
| 5 | 120 | 0.15 | 0.75 | 341.5 |
| 6 | 120 | 0.15 | 1 | 360.4 |
| 7 | 120 | 0.2 | 0.5 | 559.53 |
| 8 | 120 | 0.2 | 0.75 | 455.49 |
| 9 | 120 | 0.2 | 1 | 470.09 |
| 10 | 180 | 0.1 | 0.5 | 424.59 |
| 11 | 180 | 0.1 | 0.75 | 298.26 |
| 12 | 180 | 0.1 | 1 | 455.49 |
| 13 | 180 | 0.15 | 0.5 | 760.46 |
| 14 | 180 | 0.15 | 0.75 | 566.08 |
| 15 | 180 | 0.15 | 1 | 543.37 |
| 16 | 180 | 0.2 | 0.5 | 1019.2 |
| 17 | 180 | 0.2 | 0.75 | 780.57 |
| 18 | 180 | 0.2 | 1 | 769.45 |
| 19 | 240 | 0.1 | 0.5 | 615.91 |
| 20 | 240 | 0.1 | 0.75 | 428.41 |
| 21 | 240 | 0.1 | 1 | 551.18 |
| 22 | 240 | 0.15 | 0.5 | 1083.1 |
| 23 | 240 | 0.15 | 0.75 | 854.91 |
| 24 | 240 | 0.15 | 1 | 831.99 |
| 25 | 240 | 0.2 | 0.5 | 1511.3 |
| 26 | 240 | 0.2 | 0.75 | 1341.6 |
| 27 | 240 | 0.2 | 1 | 1158.5 |

## IV. OPTIMISATION

### *A. Development of prediction model*

With the experimental data a nonlinear regression model is obtained using Response Surface Methodology (RSM). Response surface methodology (RSM) is defined as collection of mathematical and statistical techniques that are useful for the modeling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimize this response [13]. Regression Analysis is performed using MINITAB software. RSM also quantifies the relationship between the controllable input parameters and the obtained response surfaces [14].

Model Equations from Regression Analysis,

$$\text{Temperature (T)} = -306 - 0.39\,V - 94\,f + 812\,d + 46.35\,V*f - 2.58\,V*d - 4251\,f*d$$

### *B. Effect of process parameters*

The effect of process parameters on cutting temperature have been studied with the help of main effect plot and analysis of variance. ANOVA tells about the significance of process parameter influencing the output responses. Usually, the change of the turning process parameter has a significant effect on the performance characteristics when the F value is large. The F-test has been carried out at 95 % confidence level. F-value is defined as the ratio of mean square deviations of each parameter to the mean square error. If probability of significance (P-value) is less than 0.05 at 95% confidence level, then the factors are said to be statistical significance on responses [15]. The percentage contribution defines the relative power of a factor used to reduce the variation. There is a great influence on the performance for a factor with a high percentage contribution. The percentage contributions of the cutting parameters on the cutting temperature are shown in Table 4.

Table 4. ANOVA Results for cutting temperature

| Source | DF | Seq SS | Contribution | Adj SS | Adj MS | F-Value | P-Value |
|---|---|---|---|---|---|---|---|
| Model | 6 | 2919004 | 97.41% | 2919004 | 486501 | 125.17 | 0.000 |
| Linear | 3 | 2635099 | 87.93% | 2635099 | 878366 | 225.98 | 0.000 |
| V | 1 | 1387784 | 46.31% | 1387784 | 1387784 | 357.04 | 0.000 |
| f | 1 | 1152233 | 38.45% | 1152233 | 1152233 | 296.44 | 0.000 |
| d | 1 | 95083 | 3.17% | 95083 | 95083 | 24.46 | 0.000 |
| 2-Way Interaction | 3 | 283905 | 9.47% | 283905 | 94635 | 24.35 | 0.000 |
| V*f | 1 | 232002 | 7.74% | 232002 | 232002 | 59.69 | 0.000 |
| V*d | 1 | 18017 | 0.60% | 18017 | 18017 | 4.64 | 0.044 |
| f*d | 1 | 33885 | 1.13% | 33885 | 33885 | 8.72 | 0.008 |
| Error | 20 | 77737 | 2.59% | 77737 | 3887 | | |
| Total | 26 | 2996741 | 100.00% | | | | |

The main effect plot of cutting temperature is shown in figure 4 given below,


Figure 4. Main Effects Plot for Temperature(T).

The cutting speed was found to be the major factor affecting the cutting temperature, whereas the feed and the depth of cut were found to be the second and third ranking factors respectively. At higher cutting speed, cutting temperature is high enough to soften the work material and reduces material shear strength [16]. The estimated response surfaces for the cutting temperature components are illustrated in Figures (5,6,7).

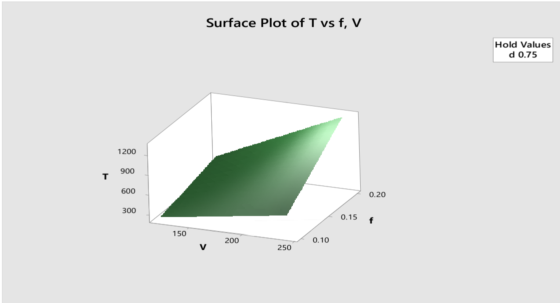


Figure 5. Surface Plot of Temperature(T) vs Speed(V), Feed rate(f).

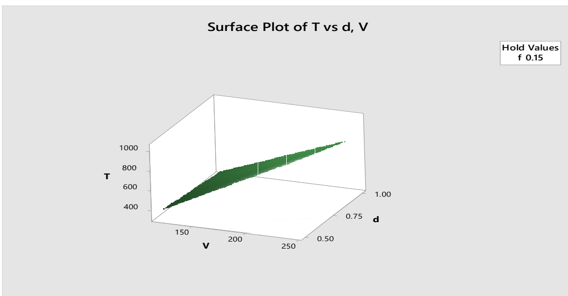


Figure 6. Surface Plot of Temperature(T) vs Speed(V), Depth of cut(d).

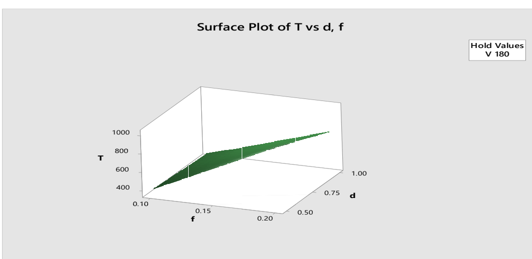


Figure 7. Surface Plot of Temperature(T) vs Feed rate(f), Depth of cut(d).

From the response surface and contour plots (Figures 8,9& 10), it is noted that cutting speed increases cutting temperature also increases drastically, also increase in feed and depth of cut will lead to produce more cutting temperature.

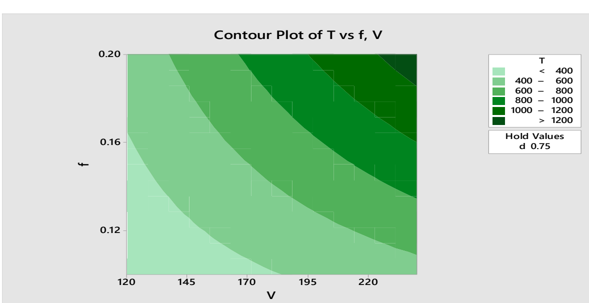


Figure 8. Contour Plot of Temperature(T) vs Speed(V), Feed rate(f).

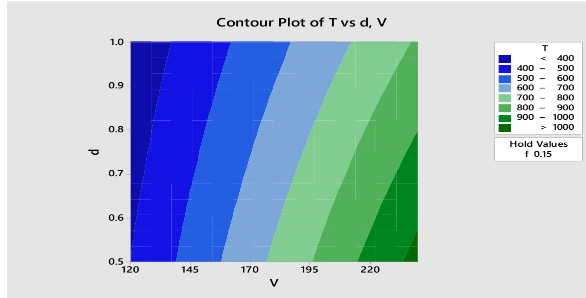


Figure 9. Contour Plot of Temperature(T) vs Speed(V), Depth of cut(d).

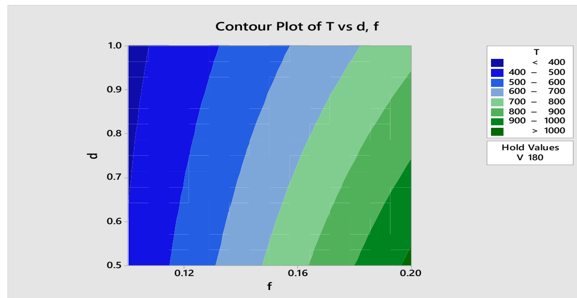


Figure 10. Contour Plot of Temperature(T) vs Feed rate(f), Depth of cut(d).

## V. RESULT AND DISCUSSION

Finite Element Modeling (FEM) was carried out to obtain the cutting temperature distribution on the tool insert in reducing the cutting temperature during turning of Titanium alloy (Ti-6Al-4V). Though actual temperature was not measured during this investigation, the total heat generations in three regions (primary, secondary and tertiary respectively) were calculated from cutting force components which were measured with a dynamometer.

The influences of cutting parameters on the cutting responses were studied using ANOVA. For turning operation with PVD TiAlN coated tungsten carbide inserts, cutting speed (46.31%) is the most influential on cutting temperature followed by feed rate (38.45%) and depth of cut (3.17%). For turning with PVD TiAlN coated tungsten carbide inserts, it was found through interaction plot as depicted in figure 11 that the resultant cutting temperature increases with an increase in cutting speed.

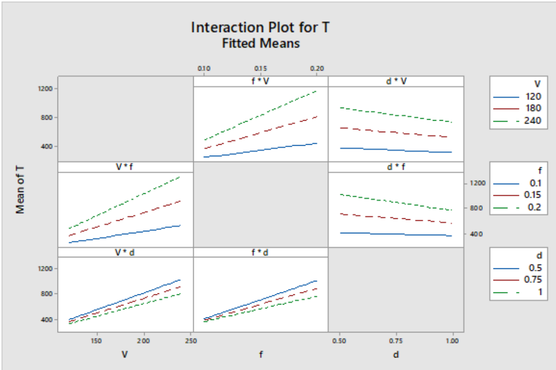


Figure 11. Interaction Plot for Temperature(T).

Confirmation test is done to check the adequacy of the model developed by RSM. The optimal levels for turning of titanium alloy (Ti-6Al-4V) to obtain minimum temperature is possible at a cutting speed of 120 m/min, depth of cut of 0.5 mm and feed rate of 0.1 mm/rev. The figure 12 shows the combined desirability at the optimum conditions. The outcomes of the confirmation test and their comparisons with the predicted values for the cutting temperature are listed in table 5 below.

Table 5. Optimal parameters for the turning operations

| Cutting Speed | Feed | DOC | Temperature Value | | Composite Desirability |
|---|---|---|---|---|---|
| | | | Predicted | Experimental | |
| 120 | 0.1 | 0.5 | 232.6166 | 255.04 | 1 |

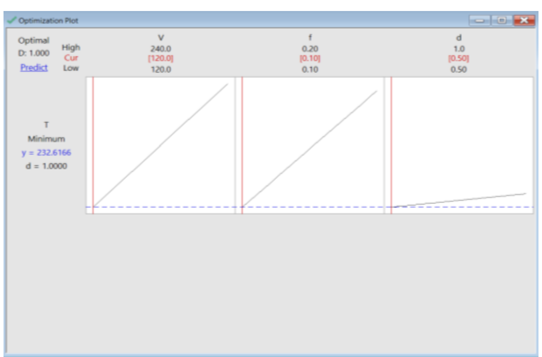


Figure 12.Optimization Plot.

## VI. CONCLUSION AND FUTURE SCOPE

1) Finite element simulations proved to be very useful in predicting temperature distribution on cutting inserts in dry turning of the Ti-6Al-4V as measurement of actual temperature is not possible.
2) In this, the quadratic model for cutting temperature has been developed so as to investigate the influences of machining parameters in turning of titanium alloy.
3) From the ANOVA, the study concludes that cutting speed is the most influential parameter on the temperature distribution.
4) The results of ANOVA (Analysis of Variance) confirm that mathematical model obtained of cutting temperature is well fitted with the experimental values.
5) It is clear from the plot for overall desirability function that cutting speed of 120 m/min, feed rate of 0.10 mm/rev and depth of cut of 0.5 mm are desirable for getting optimal conditions.
6) Three variables such cutting velocity, feed rate and the depth of cut are considered for the experimental part, for getting the response parameter. This research work can be extended by increasing the number of variables. The new variable may be spindle speed and tool nose radius.
7) The procedure can be used for the prediction of cutting temperature at various points of cutting tool.

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