Effects of Tool Material on the Machinability of Titanium (Grade-5) Alloy using RSM

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Abstract: This paper presents the findings of experimental investigations into the effects of cutting speed, feed rate, depth of cut and approach angle on the machinability of titanium (Grade-5) alloy. The comparison for two different cutting materials inserts, i.e. polycrystalline diamond (PCD) and cubic boron nitride (CBN) with similar tool geometry for similar machining parameters is also carried out. Design of experiment technique i.e. response surface methodology (RSM) has been used to accomplish the objectives of the experimental study. The experimental plan for four factors at three levels using face centre, and centred composite design (CCD) was employed. The results approved the approach angle as a dominant factor on the surface roughness and the tangential force evaluation as machinability criteria. In comparison to CBN cutting insert, the PCD insert showed better surface finish and smaller cutting force in association with the parameters considered for investigation in machinability study of Titanium (Grade-5) alloy.

Keywords: CCD Design, Response Surface Methodology (RSM), Surface Roughness (p_{ie}), Tangential Force (f_c), Turning Process

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1 INTRODUCTION

The term machinability is quite commonly used in machining operation for removal of the material. The machinability means a complex physical property of a metal which involves true machinability, finish ability or ease of obtaining a good surface finish and abrasiveness or abrasion undergone by the tool during cutting. Noordin et al. explained the term machinability as “Machinability of a material provides an indication of its adaptability to be manufactured by a machining process” [1]. In general, machinability can be defined as an optimal combination of factors such as low cutting force, high material removal rate, good surface integrity, accurate and consistent work-piece geometrical characteristics, low tool wear rate and good curl or chip breakdown of chips.

It is taken for granted by the researchers and engineers that cutting conditions such as cutting speed, feed rate, depth of cut, tool geometry and tool materials in machining operations may optimize the economics of the machining operation considering productivity, total machining costar and unit cost. Computer numerical control (CNC) machine tools require huge investment compared to conventional counterparts which necessitate operating CNC machines as efficiently as possible in order to obtain required payback. This is particularly true in case of machining like titanium alloy at higher machining parameters. During the machining of titanium alloy, tool wear progresses rapidly because of high cutting temperature and strong adhesion between the tool and the work material, owing to their low thermal conductivity and high chemical reactivity.

Many researchers have studied the machinability of titanium alloys in the past researches [2-5]. The cost associated with titanium machining is high as machining is carried at lower cutting speeds (< 60 m/min) and also due to shorter tool life (found by Rahman et al. [6]). The machinability of titanium and its alloys is generally considered to be poor owing to several inherent properties of the materials. Titanium is very reactive chemically; thus, it has a tendency to weld to the cutting tool during machining, and lead to chipping and premature tool failure.

Ezugwu and Wang found that the low thermal conductivity of titanium alloy increases the temperature at the tool/work-piece interface which affects the tool life adversely [7]. The fact that how product quality as well as efficiency affect machining has been well examined, and international focus has also been on surface roughness. Suleyman et al. observed that a good quality turning surface can lead to improvement in strength features such as fatigue strength, corrosion resistance and thermal resistance [8].

Kramer and Hartung found that the analysis of the data during manufacturing by using suitable statistical designs is highly important for precise evaluation of the process [9]. In machinability studies statistical design of experiments is widely used, where the statistical design of experiments refers to the process of planning the experiment so that appropriate data can be analyzed by statistical methods, resulting in valid and objective conclusions as found by Montgomery [10].

Noordin et al. investigated the application of response surface methodology in evaluating the performance of coated carbide tools when turning AISI 1045 steel [11]. The factors investigated were cutting speed, feed and the side cutting edge angle. Thiele and Melkate used a three-factor complete factorial design to determine the effects of work-piece hardness and cutting tool edge geometry on surface roughness and machining forces [12]. He also used four factors and two-level fractional factorial designs to find out the effect of cutting edge geometry, work-piece hardness, feed rate and cutting speed on surface roughness and resultant forces in the finish hard turning of AISI H13 steel.

Antony carried out a case study for multi-response optimization in industrial experiments using Taguchi’s quality loss function in conjunction with principal component analysis [13]. Arbizu and Perez presented a surface roughness prediction model using RSM to determine surface quality in turning processes [14]. Sahin and Motorcu developed the surface roughness model in terms of main cutting parameters such as cutting speed, feed rate and depth of cut using RSM [15]. Thomas et al. used a full factorial design considering six factors to investigate the effects of cutting and tool parameters on the resulting surface roughness and built-up edge formation in the dry turning of carbon steel [16]. Suresh et al. investigated response surface method and genetic algorithm for predicting the surface roughness and optimizing process parameters [17].

Choudhary and EI-Baradie used RSM and 2^3 factorial designs to estimate the surface roughness for turning process of high strength steel [18]. Davim investigated the influence of cutting conditions on the surface finish during turning process on the Taguchi design of experiment [19]. Yang and Tang studied optimal cutting parameters using Taguchi method in turning [20]. Dhar et al. studied the effect of cryogenic cooling on machining of AISI 1040 steel and AISI 4320 steel and reported similar findings [21]. Daim also conducted a more detailed study using orthogonal array to acquire the optimal machining parameters for turning of metal matrix composites [22]. Kopac and Bahor examined the changes in surface roughness of AISI 1060 and AISI 4140 steels and analyzed the effect of cutting parameters by using RSM [23].

Erzurumlu and Oktem [24] discussed the effect of cutting parameters on surface roughness. On the other hand Lin et al. [25] used an adductive network to construct a prediction model for surface roughness and cutting force. Al-Ahmari [26] investigated that empirical model for predicting of machinability models (tool life, cutting force and surface roughness) were developed based on the cutting experiments on austenitic AISI 302 steels. The developed computational neural networks (CNN), response surface methodology (RSM) and multiple linear regression analysis (Ra) are compared and evaluated.

From the literature mentioned above it can be deduced that most of the researcher have considered cutting speed, feed rate and depth of cut as primary factors. Whereas tool nose radius, tool length, edge part of tool, work-piece length and work-piece hardness were assumed as secondary factors. The parameters such as approach angle find no references which are very important in case of using tool inserts for the machining of the material like titanium alloy. The above-mentioned literature evidently shows that statistical techniques such as RSM are effective for study of machinability of various metals, alloys and metal-matrix composites.

However there is very little mention of RSM application in study of machining parameters using PCD and CBN tool inserts of Titanium Ti-64 alloy. Considering these points, this work has been carried out by adopting RSM methodology. In this reported work, machining parameters such as cutting speed, feed rate, depth of cut and approach angle are considered as independent variables. Based on the preliminary experiments the effects of these machining parameters on surface roughness (R_a**)** and tangential force (f_c) are tested through the set of planned experiments based on the four factors at three levels**.**

The RSM with Face centre, centred composite design (CCD) of experiments to explore the quadratic response and to construct the second order quadratic model are used. In this study, machining experiments on Titanium Ti-64 alloy are conducted with (PCD) and (CBN) cutting tools inserts to assess the machinability responses as surface roughness and tangential force.

2 EXPERIMENTAL PROCEDURE

2.1. Material, Machine tool and cutting tool inserts used

The main objective of the experimental investigation is to establish a relationship between the machining parameters and the machinability performance as surface roughness and tangential force. The cutting performance tests were performed on Titanium Ti-64 alloy in round bars. The work-piece material used has a dimension of 200 mm in length and 15 mm in diameter. The chemical composition of the work piece is 6%Al, 4%V, 0.20%O, 0.015%P and 89.75%Ti. The hardness of the bar is 35 HRC.

The mechanical characteristics of Titanium Ti-64 alloy are such as ultimate tensile strength, 950 MPa, percentage elongation, 14%, and shear strength, 550 MPa. These are suitable for a wide variety of aerospace, medical and automotive type of applications. The machining experiments were carried out in order to obtain experimental data under dry condition on a SPRINT 16TC CNC Turning Centre. The CNC turning Centre has spindle speed of 40-4000 rpm, maximum turning diameter of 225 mm, a maximum turning length of 325 mm, and spindle nose of A 2-5. The full power range of the machine is 1000-3000 rpm. The arrangement of experimental set up is shown in the Figure 1.

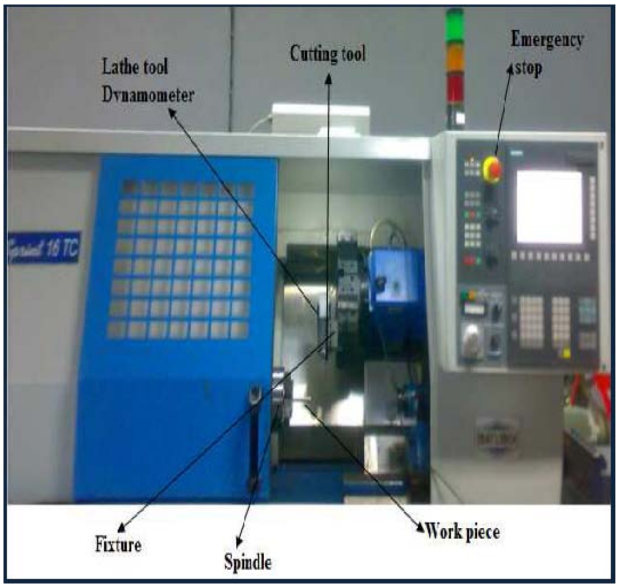

Fig. 1 The arrangement of experimental set up

A lathe tool dynamometer (TeLCDKM 2010, Germany) in conjunction with XKM software and a computer were used to measure and record the cutting forces. Surface roughness tester (SJ-301, manufactured by Mitutoyo) was used to measure the surface roughness of the machined surface. The cutting tool selected for machining Titanium Ti-64 alloy was polycrystalline Diamond (PCD) type of (CCGW 09T308 FST KD1425) and cubic boron nitride (CBN) type of (CCGW 09T308 S01015MT B1610) of Kennametal make having 0.8 nose radius. The microstructure (LEICA DFC 280, Type 090-136-003, and Germany) of titanium Ti-64 is shown in the Figure 2.

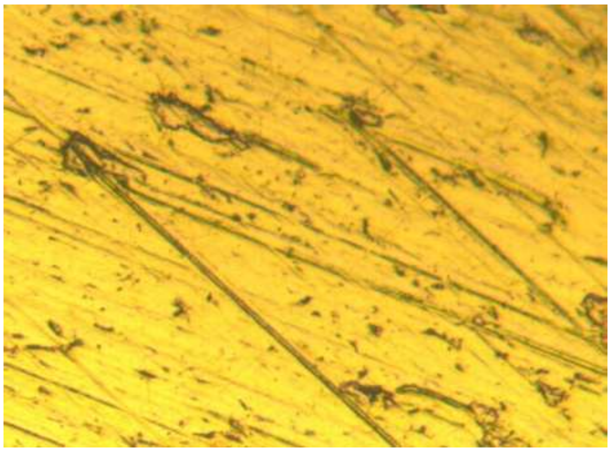

Fig. 2 Microstructure of titanium (Grade-5) alloy

2.2. Experimental design

In order to find out the effect of machining parameters on the surface roughness and tangential force, four principal machining parameters including the cutting speed (v_c), feed rate (f), depth of cut (u_p), and approach angle (u_a), were used. In this study, these machining parameters were chosen as the independent input variables. The RSM was employed for modeling and analysis of machining parameters in dry turning process in order to obtain the machinability performances for surface roughness (R_c) and tangential force (F_c).

Response surface methodology (RSM) is a collection of mathematical and statistical techniques that are useful for modeling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimize this response. The Design Expert Software version 8.0.4.1 was used to develop the experimental plan for RSM. The software was also used for the analysis of the related data collected, and the following are the steps used for analysis of experimental data obtained:

1- Choose a transformation if desired, otherwise leave the option at "none".
2- Select the appropriate model to be used. The Fit Summary buttons display the sequential F-test, lack-of-fit tests and other adequacy measures that could be used to assist in selecting the appropriate model.
3- Perform the analysis of variance (ANOVA).
4- Inspect the various diagnostic plots to statistically validate the model.
5- If the model looks good, generate model graphs, i.e. the contour and 3D graphs, for interpolation.

The analysis and inspection performed in steps 3 and 4 will show whether the model is good or otherwise, a good model must be significant and the lack-of-fit must be insignificant. After analyzing each response, multiple response optimizations is performed, either by inspection of the interpretation plots or with the graphical and numerical tools provided for this purpose. In RSM the quantitative form of relationship between desired response and independent input variables can be represented in the following:

$$Y = f(A, B, C, D) \qquad (1)$$

Where 'Y' is the desired response and 'f' is the response function (or response surface). In the procedure of analysis, the approximation of 'Y' is proposed using the fitted second–order polynomial regression model which is called the quadratic model.

$$Y = b_0 + \sum_{i=1}^{k} b_i X_i + \sum_{i=1}^{k} b_{ii} X_i^2 + \sum_{i=1}^{k-1}\sum_{j=1}^{k} b_{ij} X_i X_j + e \qquad (2)$$

Where 'bo' is constant and i, j are linear, quadratic coefficients, respectively. While 'b' is regression coefficient, 'k' is the number of factors investigated and optimized in the experiments; 'e' is random error. When developing the quadratic equation, the test factors were coded according to the following equation:

$$x_i = \frac{x_i - x_0}{\Delta x_i} \quad \text{Where } i = 1, 2, 3 .... K \qquad (3)$$

Where:

x_i : is the dimensionless value of an independent variable.

x_0 : is the real value of the independent variable at the centre point.

Δx_i : is the step change value.

Using this quadratic model of 'Y' in this study is not only to investigate over the entire factor space, but also to locate the region of being desired target where the response approaches its optimum or near optimal value. The necessary data for the quadratic models are collected by the machining experiments based on response surface methodology (RSM) via using face centered, central composite design. The central composite design is of first-order (2^n) designs augmented by additional centre and axial points to allow estimation of the tuning parameters of a second order model.

The factorial portion of the CCD is the full factorial design with all combinations of the factors at two levels (low -1 and high +1) and composed of the eight star points, six central points which is the midpoint between the high and low levels. The star points at the face of the cubic portion on the design and tangential force. The star points at the face of the cubic portion on the design correspond to α value of 1, where this type of design is commonly called the face centered. Four machining parameters at three levels with their ranges are presented in Table 1.

3 RESULTS AND DISCUSSION

The design matrix (actual values) and response (Surface roughness and Tangential force) test for lack-of-fit were performed to verify the goodness of fit for the obtained quadratic model. The analysis of variance (ANOVA) was applied to summarize the performance of the above mentioned tests. Without performing any transformation on the response examination of the Fit and Summary, output revealed that the quadratic model is statistically significant for both responses and therefore it is used for further analysis.

Table 1 Design layout of machining parameters and their levels

Parameters	Units	Low level (-1)	Medium level (0)	High level (+ 1)
Cutting speed $A(V_a)$	m/min	30	50	70
Feed rate B (f)	mm/rev	0.05	0.10	0.15
Depth of cut C (a_p)	mm	0.15	0.20	0.25
Approach angle D (a_a)	Deg (º)	60	75	90

Table 2 Design layout matrix and experimental results

Run					Responses			
	Machining parameters				For PCD tool		For CBN tool	
	v_c	f	a_p	a_a	F_a(μm)	F_c(N)	F_a(μm)	F_c(N)
1	30	0.05	0.15	60	1.15	90	1.58	48
2	50	0.10	0.20	75	1.68	250	1.32	79
3	70	0.10	0.15	60	1.85	120	2.60	103
4	50	0.10	0.20	60	1.81	138	1.50	90
5	50	0.10	0.20	75	1.67	248	1.17	92
6	50	0.05	0.20	75	1.68	259	1.29	96
7	70	0.05	0.25	90	0.90	122	0.95	75
8	70	0.05	0.25	60	1.12	80	1.35	71
9	30	0.15	0.25	60	1.43	75	1.82	70
10	30	0.10	0.15	90	1.02	130	1.56	77
11	70	0.15	0.20	75	1.79	247	1.10	108
12	30	0.15	0.15	60	1.71	80	2.35	96
13	30	0.15	0.25	60	1.87	126	2.55	95
14	70	0.15	0.15	90	0.95	142	2.20	86
15	50	0.05	0.20	75	1.55	243	0.95	67
16	50	0.10	0.20	75	1.74	240	1.20	90
17	50	0.10	0.15	75	1.53	203	1.85	105
18	50	0.10	0.20	75	1.48	257	1.30	90
19	70	0.15	0.25	60	1.45	157	1.80	142
20	30	0.05	0.25	90	0.80	85	1.20	63
21	30	0.05	0.15	90	0.83	83	1.25	52
22	30	0.10	0.20	75	1.81	231	1.22	105
23	70	0.05	0.15	90	1.10	82	1.51	48
24	50	0.15	0.20	75	1.76	247	1.70	98
25	50	0.10	0.20	75	1.31	238	1.41	92
26	70	0.05	0.15	60	1.56	95	1.63	72
27	70	0.15	0.25	90	1.01	156	2.35	140
28	50	0.10	0.25	75	1.82	230	1.85	97
29	30	0.15	0.25	90	1.00	138	2.00	85
30	50	0.10	0.20	90	1.01	112	1.15	65

Table 3 The results of ANOVA Table for reduced quadratic model for surface roughness (R_a) and tangential force (F_c) by using CBN cutting

(a) The results of ANOVA Table for reduced quadratic model (surface roughness R_a, μm)

Source	Sum of Squares	Degree of freedom	Mean square	F-value	Prob. > F
Model	5.69	7	0.81	33.97	< 0.0001 Significant
A	8.889E-005	1	8.889E-005	3.712E-003	0.9520
B	2.62	1	2.62	109.59	< 0.0001
C	0.024	1	0.024	1.01	0.3257
D	0.50	1	0.50	21.02	< 0.0001
AC	0.34	1	0.34	14.05	0.0011
AD	0.23	1	0.23	9.62	0.0052
C^2	1.98	1	1.98	82.61	< 0.0001
Residual	0.53	2	0.024		
Lack of fit	0.49	17	0.029	3.84	0.0715 Not significant
Pure error	0.037	5	7.497E-003		
Cor total	0.22	29			
S. D.	0.15	R-Squared	0.9153		
Mean	1.59	Adj R-Squared	0.8884		
C. V.%	9.73	Pred R-Squared	0.7844		
PRESS	1.34	Adeq. precision	21.090		

(b) The results of ANOVA Table for reduced quadratic model (tangential force F_c, N)

Source	Sum of Squares	Degree of freedom	Mean square	F-value	Prob. > F
Model	1224.60	8	1530.33	14.19	< 0.0001 Significant
A	1317.56	1	1317.56	12.22	0.0022
B	7040.89	1	7040.89	65.29	<0.0001
C	1266.72	1	1266.72	11.75	0.0022
D	512.00	1	512.00	4.75	0.0409
AB	451.56	1	451.56	4.19	0.0535
AC	390.06	1	390.06	3.62	0.0710
A^2	370.47	1	370.47	3.44	0.0779
D^2	1195.36	1	1195.36	11.08	0.0032
Residual	2264.76	21	0.024		
Lack of fit	2099.93	16	131.25	3.98	0.0669 Not significant
Pure error	0.037	5	7.497E-003		
Cor total	0.22	29			
S. D.	10.38	R-Squared	0.8439		
Mean	86.57	Adj R-Squared	0.7844		
C. V.%	12.00	Pred R-Squared	0.6573		
PRESS	4972.09	Adeq. precision	15.383		

3.1. ANOVA analysis

In the ANOVA analysis the test for significance of the regression model, test for significance of individual model coefficients and test for lack-of-fit are needed to be performed. The Table 3(a-b) is the ANOVA table for the reduced quadratic model for surface roughness and tangential force using CBN cutting tool insert. The value of "Prob.>*F*" in Table 3 for model is less than 0.05 which indicates that the model is significant; this is desirable as it indicates that the terms in the model have significant effects on the response. The determination coefficient R^2 in Table 3(a-b) is a measure for the degree of fit. When R^2 approaches to unity, the response model fits better to the actual data. The difference between the predicted and actual values is minor. From Table 3(a) the Model F-value of 33.97 implies that model is significant. There is only 0.01% possibility for occurrence of "Model F-Value" at this range due to noise. Values of "Prob>F" less than 0.0500 indicate that model terms are significant. Tables 4(a-b) indicates the reduced quadratic model for surface roughness and tangential force using PCD. This model can be used to navigate the significant design model terms which in this case are *B, D, AC, AD,* space. Similarly from the Table 3(b), the Model F_c are significant model terms. Values greater than 14.19 imply that the model is significant, where 0.1000 indicates that model terms are not significant.

Table 4 The results of ANOVA Table for reduced quadratic model for surface roughness (R_c, µm) and tangential force (F_a, *N*) by using PCD cutting tool

(a) The results of ANOVA Table for reduced quadratic model (surface roughness R_c, µm)

Source	Sum of Squares	Degree of freedom	Mean square	F-value	Prob. > F
Model	3.21	7	0.46	19.81	< 0.0001 Significant
A	6.722E-004	1	6.722E-004	0.029	0.8661
B	0.26	1	0.26	11.42	0.0027
C	5.00E-003	1	5.00E-003	0.22	0.6464
D	1.58	1	1.58	68.28	< 0.0001
AC	0.12	1	0.12	5.08	0.0346
BD	0.10	1	0.10	4.36	0.0486
C^2	1.14	1	1.14	49.29	< 0.0001
Residual	0.51	22	0.023		
Lack of fit	0.37	17	0.022	0.81	0.6643 Not significant
Pure error	0.14	5	0.027		
Cor total	3.71	29			
S. D.	0.15	R-Squared	0.8631		
Mean	1.41	Adj R-Squared	0.8195		
C. V.%	10.76	Pred R-Squared	0.7516		
PRESS	0.92	Adeq. precision	13.234		

(b) The results of ANOVA Table for reduced quadratic model (tangential force F_a, N)

Source	Sum of Squares	Degree of freedom	Mean square	F-value	Prob. > F
Model	1.317E+005	6	21946.63	104.64	< 0.0001 Significant
A	1476.06	1	1476.06	7.04	0.0142
B	6460.06	1	6460.06	30.80	< 0.0001
C	1152.00	1	1152.00	5.49	0.0281
D	440.06	1	440.06	2.10	0.1610
C^2	1664.67	1	1664.67	7.94	0.0098
D^2	44359.58	1	44359.58	211.51	< 0.0001
Residual	4823.69	23	209.73		
Lack of fit	4456.36	18	247.58	3.37	0.0916 Not significant
Pure error	367.33	5	73.47		
Cor total	0.22	29			
S. D.	14.48	R-Squared	0.9647		
Mean	163.47	Adj R-Squared	0.9554		
C. V.%	8.86	Pred R-Squared	0.9344		
PRESS	8958.44	Adeq. precision	27.926		

If there are many insignificant model terms (regardless of those required to support hierarchy), model reduction may improve the model respectively. The "Lack of Fit F-value" of 3.84 implies the Lack of Fit is not significant relative to the pure error. There is a possibility of 7.15% for occurrence of "Lack of Fit F-value" at this range due to noise. The "Pred R-Squared" of 0.7844 is in reasonable agreement with the "Adj R-Squared" of 0.8884. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. The ratio of 21.090 in the model indicates adequacy. There is only 0.01% chance for occurrence of a "Model F-Value" at this range due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant, which in this case are *A, B, C, D,* and D^2. Values greater than 0.1000 indicate that the model terms are not significant. The "Lack of Fit F-value" of 3.98 implies that there is a 6.69% chance for occurrence of a "Lack of Fit F-value" at this range due to noise. The "Pred R-Squared" of 0.6573 is in reasonable agreement with the "Adj R-Squared" of 0.7844. "Adeq Precision" measures the signal to noise ratio. Ratio of 15.383 in the model indicates an adequate signal, and this model can be used to navigate the design space.

Similarly, for the PCD cutting tool insert the response (R_c) from the Table 4(a) the Model F-value of 19.81 implies that the model is significant. There is only a 0.01% chance for occurrence of a "Model F-Value" at this range due to noise. Values of "Prob > F" less than 0.0500 indicate that the model terms are significant, which in this case are *B, D, AC, BD,* and D^2.

Values greater than 0.1000 indicate that the model terms are not significant. The "Lack of Fit F-value" of

0.81 implies that the Lack of Fit is not significant relative to the pure error. There is a 66.43% chance for occurrence of a "Lack of Fit F-value" at this range due to noise. The "Pred R-Squared" of 0.7516 is in reasonable agreement with the "Adj R-Squared" of 0.8195. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. The ratio of 13.234 in the model indicates an adequate signal. This model can be used to navigate the design space.

Also for the response (F_a) from the Table 4(b) the Model F-value of 104.64 implies that the model is significant. There is only 0.01% possibility that a "Model F-Value" occurs due to noise at this range. Values of "Prob > F" less than 0.0500 indicate that the model terms are significant which in this case are *A, B, C*, C^2, and D^2. Values greater than 0.1000 indicate the model terms are not significant. The "Pred R-Squared" of 0.6573 is in reasonable agreement with the "Adj R-Squared" of 0.7844. "Adeq Precision" measures the signal to noise ratio. The ratio of 15.383 in the model indicates an adequate signal. This model can be used to navigate the design space.

The following equations are the final quadratic model for surface roughness and tangential force using CBN cutting tool in terms of actual factors shown as follows:

$$\text{Surface Roughness } (R_a) = +9.93750-1.11111E\text{-}003\times V_c + 7.63333\times f -77.35000\times a_F\ 0.031148 \times a_p - 0.14500 \times V_c\times a_p+4.00000E\text{-}004\times V_c\times a_c+209.66667\times a_p^z \quad (4)$$

$$\text{Tangential force } (F_c) = -301.28159-3.68371 \times V_c + 129.93056\times f -79.0972\times a_p+12.06380\times a_z+5.31250\times V_c\times f +4.93750\times V_c\times a_p + 0.025927 \times V^2_c -0.082796 \times a^2_a \quad (5)$$

Also the final equations of the quadratic model for surface roughness and tangential force using PCD cutting tool in terms of actual factors are shown as follows:

$$\text{Surface Roughness } (R_c) = -8.65306 + 0.017431 \times V_z + 10.35972 \times f + 3.94792 \times a_z + 0.25603 \times a_a - 0.085625 \times V_a\times a_p-1.76790E\text{-}003 \times a^2_a \quad (6)$$

$$\text{Tangential force } (F_a) = -3061.34140 + 0.45278 \times V_c + 378.88889 \times f + 3677.41935 \times a_z + 75.98554 \times a_a - 0.085625 \times a_p^z - 0.50437 \times a^2_a \quad (7)$$

3.2. Effect of independent parameters on response variables for CBN and PCD cutting tool inserts

Regarding the results of the ANOVA Tables in 3 and 4 an adequacy checking model was performed in order to verify that the quadratic model of surface roughness (R_a) and tangential force (F_c) of the regression analysis is not violated. The normal probability plot of the residual for the surface roughness and tangential force is shown in Figures 3 & 4 (CBN cutting tool) and Figs. 5 & 6 (PCD cutting tool) which show no sign of the violation of the independence or constant assumption, since each point in the plot follows a straight line pattern implying that the errors are distributed normally. The above obtained model can be used to predict the surface roughness and tangential force (within the limits of the factors studied).

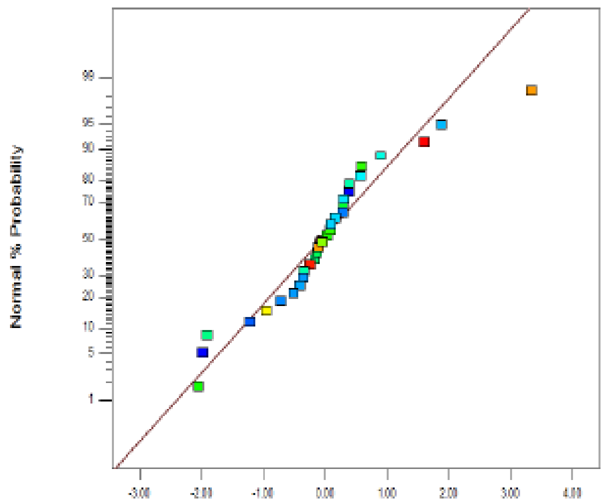

Fig. 3 Normal probability plot of residuals for surface roughness (Ra, μm) with CBN tool

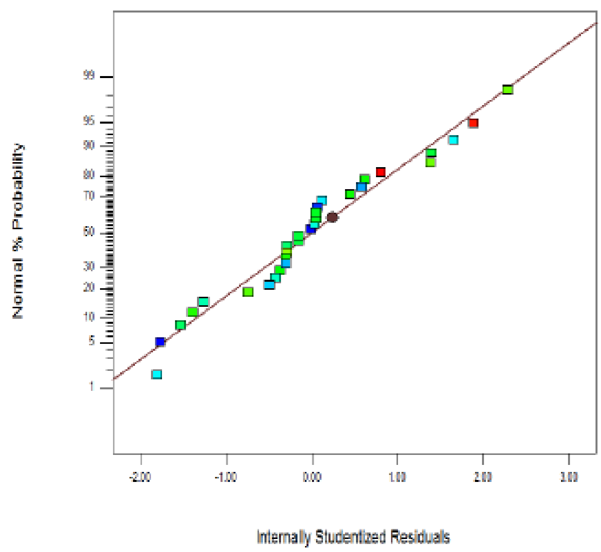

Fig. 4 Normal probability plot of residuals for tangential force (Fc, N) with CBN tool

In order to investigate the effect of independent parameters on response variables for CBN cutting tool inserts, the three-dimensional (3D) response surfaces plots are drawn and shown in Figures 7 & 8, 9 & 10 respectively.

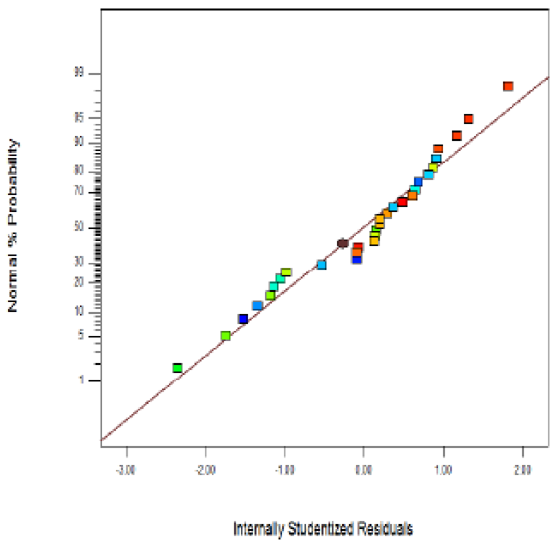

Fig. 5 Normal probability plot of residuals for surface (R_a, µm) with PCD tool

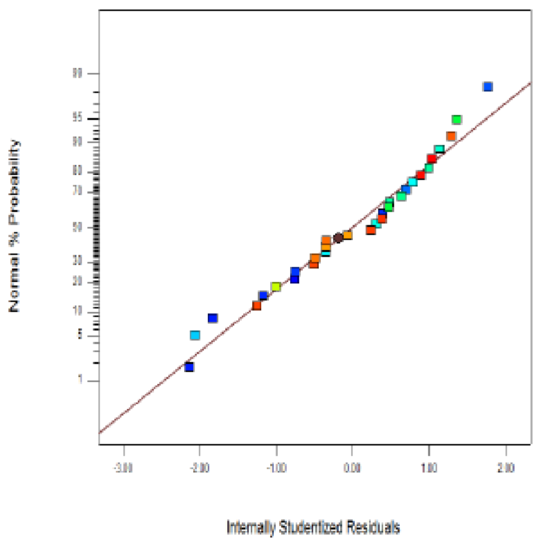

Fig. 6 Normal probability plot of residuals for tangential force (Fc, N) with PCD tool

The Figures 7 & 8 present the effect of cutting speed and approach angle, depth of cut and feed rate on the surface roughness. Figures 9 & 10 present the effect of depth of cut and approach angle, cutting speed and feed rate on the tangential force. The results from the Figures 7 & 8 shows that the surface roughness increases with increase in the cutting speed and depth of cut, however, surface roughness decreases with increase in the approach angle and decrease in the feed rate.

The results of the figures 9 & 10 show that the tangential force increases with increase in the depth of cut and feed rate, however, tangential force decreases with increase in the approach angle and cutting speed. This could be due to the effect of chatter or vibration which usually occurs at these cutting conditions when turning titanium alloy. It is also observed that there are plenty of friction effects for chipping in the scope of high cutting speed, feed rate and depth of cut.

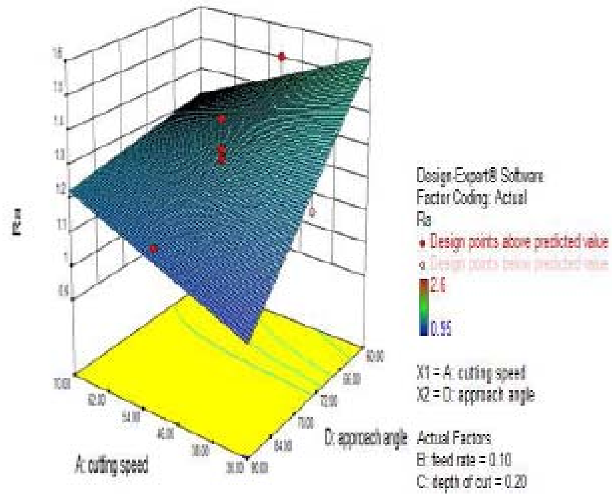

Fig. 7 The 3D response plot for surface roughness (Ra, µm) according to change of approach angle and cutting speed with CBN tool

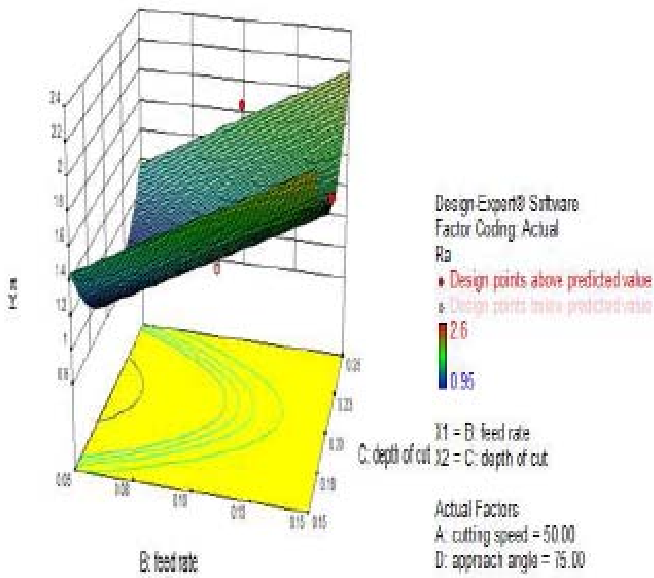

Fig. 8 The 3D response plot for surface roughness (Ra, µm) according to change of depth of cut and feed rate with CBN tool

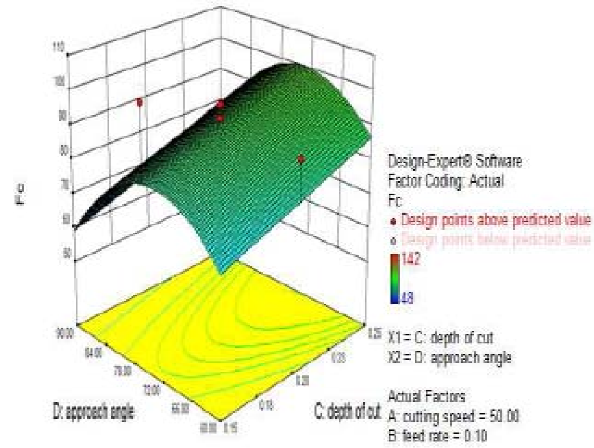

Fig. 9 The 3D response plot for tangential force (Fc, N) according to change of depth of cut and approach angle with CBN tool

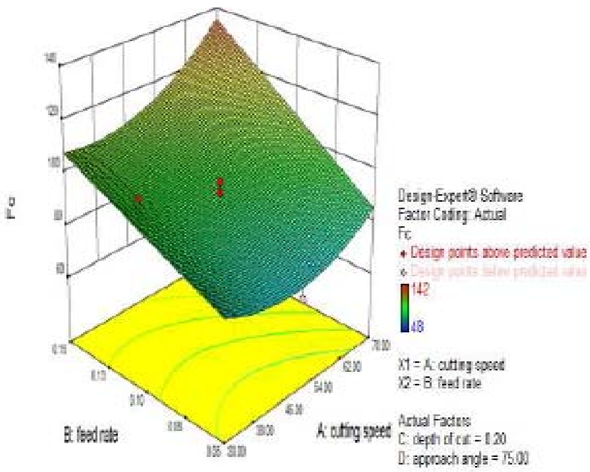

Fig. 10 The 3D response plot for tangential force (Fc, N) according to change of depth of cutting speed and feed rate with CBN tool

Moreover, in order to investigate the effect of independent parameters on response variables for PCD cutting tool inserts, the three-dimensional response (3D) surfaces plots are drawn and shown in Figures 11, 12 & 13. The Figures 11 & 12 present the effect of approach angle and feed rate, depth of cut and cutting speed on the surface roughness respectively. In Figures 11 & 12 it is clear that the surface roughness decreases with increase in the approach angle and increase in the cutting speed surface roughness and tangential force increases. However, surface roughness decreases with decrease in the cutting speed and feed rate. Figure 13 presents the effect of approach angle and cutting speed whereas the depth of cut and the feed rate are kept at middle level. The result shows that the tangential force increases with increase in the cutting speed and decreases with increase in the approach angle.

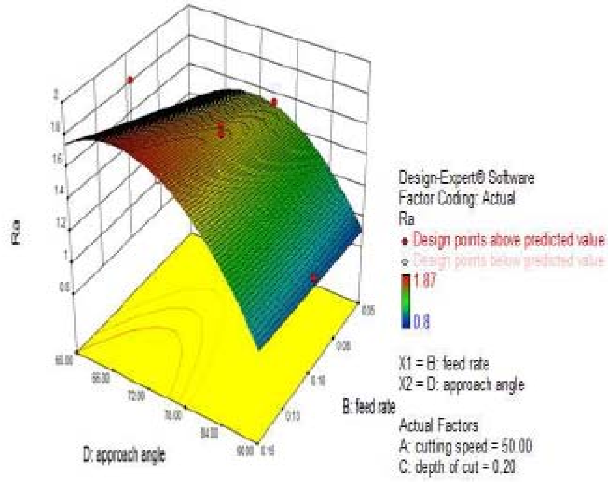

Fig. 11 The 3D response plot for surface roughness (Ra, µm) according to change of approach angle and feed rate with PCD tool

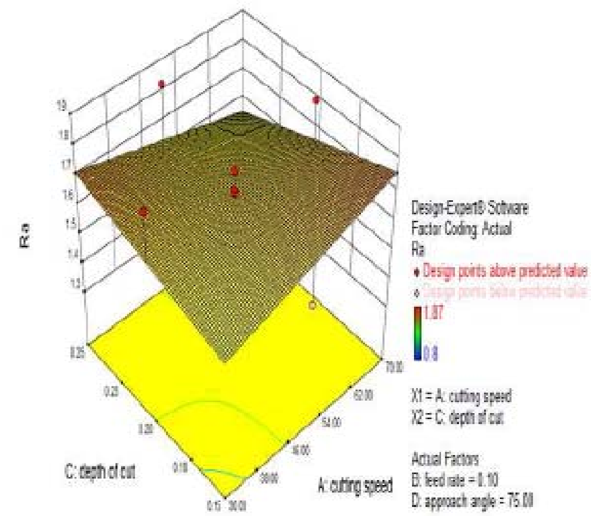

Fig. 12 The 3D response plot for surface roughness (Ra, µm) according to change of depth of cut cutting speed with PCD tool

Also it is found that the polycrystalline diamond (PCD) leads to better results in comparison to the cubic boron nitride (CBN) cutting tool inserts. This is because of the fact that the PCD tools are harder than CBN tools, and also during the machining of titanium alloy using CBN tool exhibits deformation at the cutting nose, as the speed and feed increases the cutting temperature and stress prevailing over the cutting edge increases. A limit is finally reached at which tool material can no longer resist the combined effect of stress and temperature and beings to deform at the nose radius of the tool.

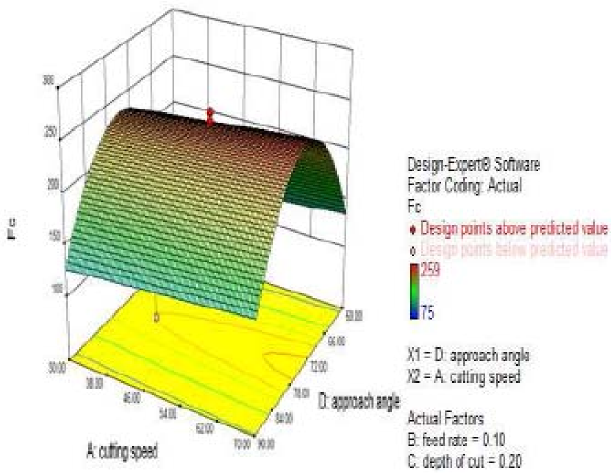

Fig. 14 The 3D response plot for tangential force (Fc, N) according to change of cutting speed and approach angle with PCD tool

4 CONFIRMATION TEST

In order to verify the adequacy of the model developed, the twelve confirmation experiments were performed for the surface roughness (R_c) and tangential force (F_c). The predicted value and the actual experimental value were compared and the residual and the percentage error were calculated. Using the point prediction capability of the software, the surface roughness and tangential force of the selected experiments were predicted together with 95% prediction interval. The predicted values and the associated prediction interval are based on the model developed.

The results of the confirmation test and their comparisons with the predicted values for the surface roughness and tangential force are shown in Table 5 (a&b). The results show that both the residual and percentage error are small. From Table 5(a) the percentage error range between the actual and the predicted value of surface roughness lies between the range of -6.19 to 3.54 and for tangential force between the range of -0.53 to 1.35%. From the Table 5(b) the percentage error range between the actual and the predicted value of surface roughness lies in range of -2.01 to 4.42% and for tangential force in the range of -0.52 to 0.98% respectively. All the experimental values of confirmation test are within 95% prediction interval. Therefor it obviously demonstrates that the obtained Eqs. (4,5) and (6,7) are the highly accurate quardatic models for machinability study of Titanium Ti-64 alloy for the selected level of input variables.

Table 5 The results of the confirmation test for surface roughness (Ra, µm) and tangential force (F_a, N)

(a) For surface roughness (R_a, µm) by using CBN cutting tool								
No.	**Machining parameters**				**Actual**	**Predicted**	**Residual**	**Error (%)**
	V_c	f	a_p	a_a				
1	30	0.05	0.15	60	1.58	1.61	-0.03	2.65
2	50	0.10	0.20	75	1.31	1.27	0.04	3.54
3	70	0.15	0.25	90	2.35	2.28	-0.07	-6.19
For tangential force (F_a, N) by using CBN cutting tool								
1	30	0.05	0.15	60	48	53	5	1.35
2	50	0.10	0.20	75	91.52	85	6.52	2.16
3	70	0.15	0.25	90	140	143.25	-3.25	-0.53
(b) For surface roughness (R_a, µm)by using PCD cutting tool								
1	30	0.05	0.15	60	1.15	1.10	0.05	4.42
2	50	0.10	0.20	75	1.67	1.65	0.02	1.77
3	70	0.15	0.25	90	1.01	1.07	-0.06	-2.01
For tangential force (F_a, N) by using PCD cutting tool								
1	30	0.05	0.15	60	90	86	4	0.98
2	50	0.10	0.20	75	241	235	5.63	1.72
3	70	0.15	0.25	90	156	159	-3	-0.53

5 CONCLUSION

In this paper the reduced quardatic model for surface roughness and tangential force has been developed so as to investigate the influences of machining parameters in turning of Titanium Ti-64 alloy. The experimental plan is of face centre, centred composite design (CCD). The effect of machining parameters such as cutting speed, feed rate, depth of cut and approach angle have been evaluated by using RSM with centered composite design method. The following conclusions are drawn based on the experimental investigations.

1- RSM is successfully used for design of experiment and analysis of experimental data for machining of Titanium Ti-64 alloy using CBN and PCD cutting tool inserts. The RSM model developed, predicted and implemented successfully in order to study the machinability.
2- With the CBN cutting tool insert, the surface roughness increases with increasing the cutting speed and depth of cut, while decreases with increasing by the approach angle and decrease in the feed rate.
3- With the CBN cutting tool insert, the tangential force increases with increase in the depth of cut and feed rate, and decreases with increase in the approach angle and decrease in the cutting speed.
4- With the PCD cutting tool, the surface roughness increases with decrease in the approach angle and also the depth of cut, and decreases with decrease in the feed rate and cutting speed.
5- The tangential force in case of PCD cutting tool increases with decrease in the approach angle and decreases with decrease in the depth of cut.
6- Based on the above findings, the polycrystalline diamond (PCD) provides better results in comparison to the cubic boron nitride (CBN) cutting tool inserts.
7- The ANOVA results revealed that approach angle is the most significant factor influencing the response variables investigated.

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