International Journal of Current Engineering and Technology
E-ISSN 2277 – 4106, P-ISSN 2347 - 5161

Available at http://inpressco.com/category/ijcet

Research Article

Surface Roughness Analysis during Turning of Ti-6Al-4V under Near Dry Machining using Statistical Tool

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Accepted 31 May 2014, Available online 16 June2014, **Vol.4, No.3 (June 2014)**

Abstract

Ti-6Al-4V components are the most widely used titanium alloy products in aircraft. Ti-6Al-4V is known as a difficult-to-machine material. When Ti-6Al-4V is being chosen for high volume and machine-intensive components, it is crucial that the machinability of these materials be understood. The machinability of Ti-6Al-4V has been investigated actively worldwide since 1980s and most researchers have found that polycrystalline cubic boron nitride (PCBN) and polycrystalline diamond (PCD) tools can be used to machine Ti-6Al-4V effectively. Driven by the high cost of these tools, it is still desirable to optimize the cutting conditions. The main objective of this paper is to determine the favourable machining conditions for Ti-6Al-4V. Conventional finish cutting (turning) using PCBN tool based on design of experiments has been conducted to achieve this goal. The first part of the paper concentrates on experimentally identifying the effect of dry, oil-water emulsion and NDM (Coconut Oil) on surface roughness under different cutting condition using Taguchi's design of experiments on turning of Ti-6Al-4V. The second part of the paper concentrates on identifying optimum cutting condition for improving surface integrity. A second-order model has been established between the cutting parameters and surface integrity using response surface methodology for turning of Ti-6Al-4V under near dry machining.

Key words:*-Near Dry Machining, Polycrystalline Cubic Boron Nitride, Titanium alloy, Design of Experiments*

1. Introduction

The aerospace industry is the single largest market for titanium products primarily due to the exceptional strength-to-weight ratio, elevated temperature performance and corrosion resistance. Titanium applications are most significant in jet engine and airframe components. Titanium and its alloys are classified as difficult-to-machine materials. The main problems in machining them are the high cutting temperatures and the rapid tool wear. Most tool materials wear rapidly even at moderate cutting speeds (Field.W *et al*, 1968; Williams D.N *et al*, 1971; Zareena *et al*, 2001). To minimize tool wear, current machining practice limits the cutting speed to less than 1 m/s. The machining characteristics for titanium and its alloys are well defined (Machado *et al*, 1990; Hartung *et al*, 1982; Donachie *et al*, 1982).In metal cutting processes; the use of cutting fluids is the most common strategy to improve the tool life, the product surface finish and the size accuracy. Cutting fluids also makes chip-breaking and chip-transport easier. However, the introduction of cutting fluids often produces airborne mist, smoke and other particulates in the shop floor air quality. These products bring in the environmental, health and safety concerns. In addition the cost of using cutting fluids is several times higher than tool costs (Klocke *et al*, 1997). The economical and environmental concerns on the use of cutting fluids lead to the research of Near Dry Machining (NDM) several years ago (Heisel*et al*, 1994). In order to alleviate the economical and environmental impacts, NDM was addressed as an alternative to the traditional flood cooling application a decade ago. NDM refers to the use of a small amount of cutting fluid, typically in the order of 100 ml/hr or less, which is about ten-thousandth of the amount of cutting fluid used in flood–cooled machining (Machado *et al*, 1997).Vegetable oils were found to be promising alternative for mineral based oils due to their environmental friendly characteristics. These were utilized to develop biodegradable lubricants for various industrial applications. The trend was extended to formulate environmental friendly metal working fluids (Y.M. Shashidhar *et al*, 2010). Among the selected lubricating conditions, they have found surface roughness to have considerably reduced with coconut oil compared to SAE 40 oil. The cutting temperature, tool flank wear and surface roughness decreased significantly with coconut oil (Vamsi Krishna *et al*, 2010).They found that all vegetable-based oils produced better results than the reference mineral oil. Polycrystalline cubic boron nitride (PCBN) is the second hardest material next to diamond. PCBN

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cutting tool is formed by high temperature, high pressure processing on a cemented tungsten carbide substrate (Collier et al, 1999). PCBN is thermally stable up to 1200^0c and has high resistance to chemical attack. Many parameters, such as the composition and hardness of the workpiece and of the tool material, the environment and the machining parameters influence the different degradation mechanisms, which will eventually affect the workpiece surface finish and tool life (Ljubodrag T *et al*, 2011).

The NDM technique suggests several advantages in machining processes. Most of the experimental investigations on machinability aspects are limited to the role and effectiveness of NDM over dry and wet machining. But, in order to achieve good surface quality on a machined surface the cutting conditions should be carefully selected with an optimum amount of NDM. As per knowledge, no systematic research work has been reported to determine the optimum quantity of lubricant with appropriate cutting conditions for achieving better machinability. Hence, an attempt has been made in this paper to enhance the machinability characteristics in turning of Ti-6Al-4V.

2. Experimental

The experiments were carried out in PSG A141 lathe (2.2 KW). The turning experiments were carried out initially using Polycrystalline Cubic Boron Nitride inserts KB-90 (ISO code) in dry, oil water emulsion and Near Dry Machining lubricating conditions(Figure 2.1)followed by Near Dry Machining under different cutting parameters. In NDM application, the Coconut oil is supplied to the cutting zone by a specially developed oil mist lubrication system. This test rig consists of a Reservoir of the Mist Lubricator which is made of imported acrylic (2 Liters) and a Pneumatic Piston Pump to inject oil in line. Filter regulator is fitted in airline to regulate air used in mist System. Float switch is provided which indicates minimum oil level electrically. Oil filter is used to filter oil for about 149 microns. Pressure Switch is used to regulate air pressure coming to the system. Solenoid Valve is used for working of Pneumatic Piston pump and air Regulator controls the air Pressure in both lines with Electronic timer to control frequency of oil Piston pump.

Ti-6Al-4V work piece specimens popularly known as Titanium alloy in the form of cylindrical bars of length 300mm and diameter 70 mm is used for machining test. The Figure 2.2 shows the microstructure and the chemical composition is shown in Table 2.1.Turning method as machining process was selected. Specification and mechanical properties of test sample is shown in Table 2.2.The ISO codes of cutting tool insert and tool holder are shown in Table 2.3 respectively. Each experiment was repeated three times and three measurements were taken from each experiment and the averages were obtained. Taguchi L_{27} orthogonal array is employed to identify the optimal cutting parameters for minimum responses. The factors and levels chosen for the turning tests are summarized in Table 2.4 and the experimental layout of Taguchi L_{27} orthogonal array is given in Table 2.6.The central composite design (CCD) of RSM is used for establishing empirical relationships among the process parameters. The number of experiments used in this case is 30 and the number of turning parameter considered is four. The factors and levels chosen for the turning tests are summarized in Table 2.5. The surface profile traces of the machined workpiece were obtained using Taylor/Hobson Surtronoic 3+ surface roughness measuring instrument shown in Figure 2.3.

Table 2.1 Nominal chemical composition of Ti-6Al-4V

Elements	Weight (%)
Ti	Bal
Al	6.1
V	4
Fe	0.16
O	0.11
C	0.02
N	0.01
Y	0.001
H	0.001

Table 2.2 Specification and mechanical properties of test sample

Tensile Strength (MPa)	955
Yield Strength (MPa)	900
Reduction of Area (%)	42
Elongation in 4D(%)	18
Hardness [HV]	305

Figure2.1.NDM setup

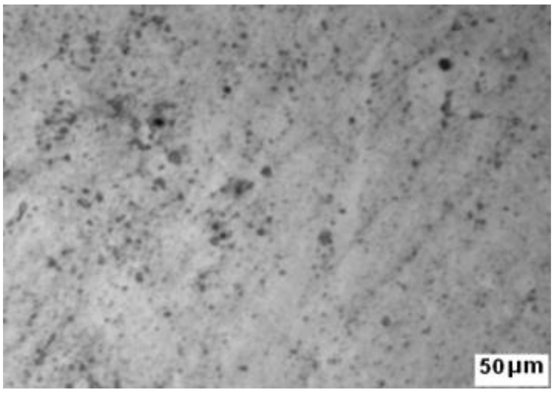

Figure2.2 Microstructure of Ti-6Al-4V

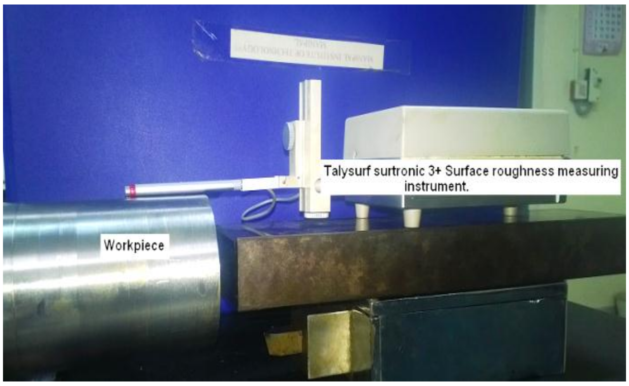

Figure2.3 Surface Roughness measurement equipment layout

Table 2.3 Details of cutting tool and tooling system used for experimentation

Tool holder Specification	STGCR 2020 K-16
Tool geometry Specification	Approach angle:91^0 Tool nose radius:0.4 mm Rake angle: 0^0 Clearance angle: 7^0
Tool insert PCBN (KB-90) Specification	TPGN160304-LS

Table 2.4 Levels and factors(Taguchi)

Levels	**(A)Lubricating Condition**	**(B)Feed (mm/rev)**	**(C)Depth of cut(mm)**	**(D)Cutting speed(m/min)**
1	Dry Machining	0.11	0.10	50
2	Oil water Emulsion	0.18	0.15	75
3	Near Dry Machining	0.25	0.20	100

Table 2.5 Levels and factors (RSM)

Levels	**(A)Cutting speed (m/min)**	**(B)Feed (mm/rev)**	**(C)Depth of cut(mm)**	**(D)Volume flow rate(ml/hr)**
1	50	0.11	0.10	10
2	100	0.25	0.20	20

Table 2.6 Taguchi L_{27} orthogonal array

Test No	**A**	**B**	**C**	**D**
1	-1	-1	-1	-1
2	-1	-1	-1	0
3	-1	-1	-1	1
4	-1	0	0	-1
5	-1	0	0	0
6	-1	0	0	1
7	-1	1	1	-1
8	-1	1	1	0
9	-1	1	1	1
10	0	-1	0	-1
11	0	-1	0	0
12	0	-1	0	1
13	0	0	-1	-1
14	0	0	-1	0
15	0	0	-1	1
16	0	1	1	-1
17	0	1	1	0
18	0	1	1	1
19	1	-1	-1	-1
20	1	-1	-1	0
21	1	-1	-1	1
22	1	0	0	-1
23	1	0	0	0
24	1	0	0	1
25	1	1	1	-1
26	1	1	1	0
27	1	1	1	1

Table 2.7 Experimental layout of RSM

Test No	**A**	**B**	**C**	**D**
1	-1	-1	-1	-1
2	1	-1	-1	-1
3	-1	1	-1	-1
4	1	1	-1	-1
5	-1	-1	1	-1
6	1	-1	1	-1
7	-1	1	1	-1
8	1	1	1	-1
9	-1	-1	-1	1
10	1	-1	-1	1
11	-1	1	-1	1
12	1	1	-1	1
13	-1	-1	1	1
14	1	-1	1	1
15	-1	1	1	1
16	1	1	1	1
17	0	0	0	0
18	0	0	0	0
19	0	0	0	0
20	0	0	0	0
21	-1	0	0	0
22	1	0	0	0
23	0	-1	0	0
24	0	1	0	0
25	0	0	-1	0
26	0	0	1	0
27	0	0	0	-1
28	0	0	0	1
29	0	0	0	0
30	0	0	0	0

3. Design of Experiments

The analysis is made using the popular software specifically used for design of experiment applications known as MINITAB 15. Before any attempt is made to use this simple model as a predictor for the measures of performance, the possible interactions between the control factors must be considered. In order to understand a concrete visualization of impact of various factors and

Table 4.1 Analysis of Variance for S/N ratios for Surface roughness

Source	DF	Seq SS	Adj SS	Adj MS	F	P	P (%)
(A)Lubrication condition	2	155.485	155.485	77.7427	107.14	0.000	95.108
(B)Cutting speed(m/min)	2	0.228	0.228	0.1142	0.16	0.858	0.1420
(C)Depth of cut(mm)	2	3.122	3.122	1.5609	2.15	0.198	1.9085
(D)Feed(mm/rev)	2	4.459	4.459	2.2293	3.07	0.121	2.725
A×D	4	.308	.308	0.0770	0.11	0.976	.09764
B×D	4	.016	.016	0.0039	0.01	1.000	.00008
C×D	4	.016	.016	0.0039	0.01	1.000	.00008
Residual Error	6	4.354	4.354	0.7256			
Total	26	167.987					100

Table 4.2 Response table for Signal to Noise ratios Smaller is better (Surface roughness)

Level	Lubrication condition	Cutting Speed(m/min)	Depth of Cut(mm)	Feed (mm/rev)
1	-5.3828	-2.1497	-2.2701	-1.7773
2	-1.8792	-2.2818	-1.8512	-2.2557
3	0.4566	-2.3739	-2.6841	-2.7724
Delta	5.8393	0.2241	0.8329	0.9951
Rank	1	4	3	2

their interactions, it is desirable to develop analysis of variance (ANOVA) table to find out the order of significant factors as well as their interactions.

3.1Taguchi's method

Taguchi techniques have been used widely in engineering design (Ross, 1996; Ghani *et al*, 2004; Phadke, 1989). The main trust of the Taguchi techniques is the use of parameter design, which is an engineering method for product or process design that focuses on determining the parameter settings producing the best levels of a quality characteristic (performance measure) with a minimum variation. Taguchi designs provide a powerful and efficient method for designing processes that operate consistently and optimally over a variety of conditions. To determine the best design requires the use of a strategically designed experiment which exposes the process to various levels of design parameters.

3.2Response surface methodology

The surface finish of difficult to machine materials is important in aerospace applications which have considerable effect on some properties such as wear resistance, light reflection, heat transmission, coating and fatigue resistance. While machining, quality of the parts can be achieved only through proper cutting conditions. In order to know the surface quality and dimensional properties in advance, it is necessary to employ theoretical models making it feasible to predict in terms of the function of operation conditions. Response surface methodology (RSM) is a 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 (Montgomery, 2005).

4. Results and Discussion

The analysis is made using the popular software specifically used for design of experiment applications known as MINITAB 15. Before any attempt is made to use this simple model as a predictor for the measures of performance, the possible interactions between the control factors must be considered. In order to understand a concrete visualization of impact of various factors and their interactions, it is desirable to develop analysis of variance (ANOVA) table to find out the order of significant factors as well as of interactions.

The results of the ANOVA with the surface roughness will be shown in table below (Table 4.1). This analysis was carried out for a significance level of $\alpha = 0.05$, i.e. for a confidence level of 95%. Tables below shows the P-values, that is, the realized significance levels, associated with the F-tests for each source of variation. The sources with a P-value less than 0.05 are considered to have a statistically significant contribution to the performance measures. Also, the last columns of the tables show the percent contribution of each source to the total variation indicating the degree of influence on the result.

4.1 Effect of control parameters on Surface roughness using Taguchi's design of experiments under different lubrication conditions

The orthogonal array for four factors at three levels was used for the elaboration of the plan of experiments the array L_{27} was selected, which has 27 rows corresponding to the number of tests (26 degrees of freedom).The first column was assigned to the lubrication condition (A), the second column to cutting speed (m/min) (B), and the third column to the feed mm/rev (C) and remaining were assigned to interactions. The output to be studied was the surface roughness. The selected levels and factors in machining of Ti-6Al-4V is shown in Table 2.4.

The calculated S/N ratio for four factors on the surface roughness in machining of Ti-6Al-4V for each level is shown in Figure 4.1.As shown in Table 4.2and Figure 4.1lubricating condition (near dry machining using coconut oil) is a dominant parameter on the surface roughness followed by feed. The cutting speed had a lower effect on the surface roughness compared to other factors. Lower surface roughness is always preferred. The quality characteristic considered in the investigation is smaller the better characteristics. In the present investigation, when the cooling technique is NDM the surface roughness is minimized.The reason being, the near dry machining decreases the heat generation which results in less surface roughness. Based on the main effects plot for SN ratios mean S/N graph for surface roughness is made Figure 4.1, the optimum conditions for the surface roughness can be established at, lubrication condition (A): NDM Cutting speed (B): 50 m/min, Feed (C): 0.11mm/rev and Depth of cut(D): 0.15mm. Figure 4.2 shows the Trinocular inverted metallurgical microscope images of machined surface under different cooling techniques dry, oil water emulsion and near dry machining.

On the examination of the percentage of contribution (P%) of the different factors (Table 4.1), for surface roughness it can be seen that lubricating condition has the highest contribution of about 95.108%, thus lubrication condition is an important factor to be taken into consideration while machining Ti-6Al-4V alloy followed by feed D (P = 2.725 %), depth of cut C(P = 1.9085 %). Interactions do not present a statistical significance, nor a percentage of physical significance of contribution to the surface roughness. Interaction S/N graph for Surface roughness is shown in Figure 4.3. Response table for Signal to Noise ratios Smaller is better (surface roughness) is shown in Table 4.1.

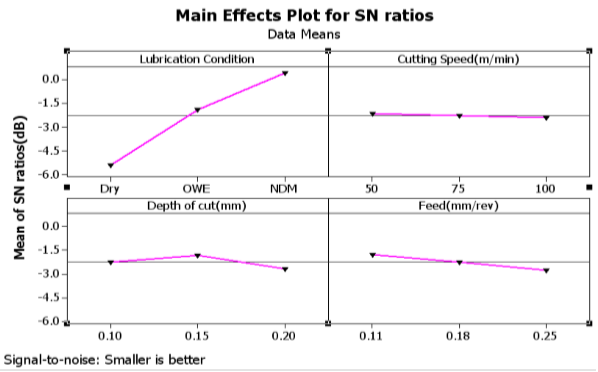

Figure 4.2: Trinocular inverted metallurgical microscope images of machined surface under different Lubrication Condition (a) NDM (b) Oil water Emulsions(c) Dry

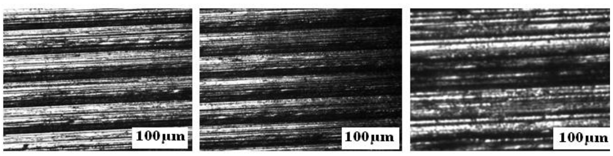

Figure 4.1: Mean S/N graph for Surface roughness

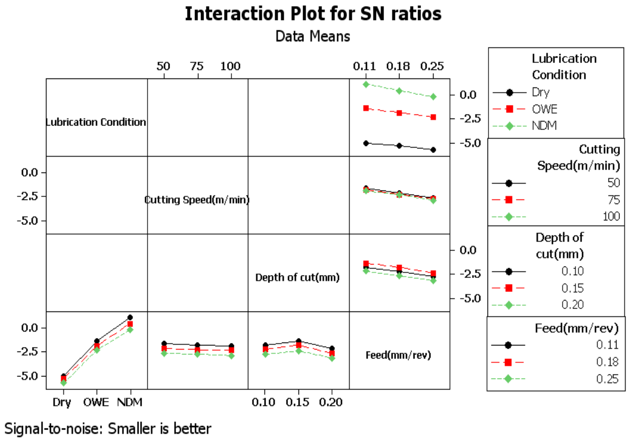

Figure 4.3: Interaction S/N graph for Surface roughness

4.2Response Surface Analysis for Surface Roughness under Near Dry Machining Approach

In response surface methodology, 30 sets of experiments are sorted using the standard ordering and are carried out according to experimental design matrix, shown in Table 2.7.A second-order model has been established for surface roughness using response surface methodology. The selected levels and factors in machining of Ti-6Al-4V using response surface methodology are shown in Table 2.5.

The second order response surface representing the surface roughness (Ra) can be expressed as a function of cutting parameters such as cutting speed m/min (A), feed mm/rev (B), depth of cut mm(C), and volume flow rate ml/hr(D). The relationship between the surface roughness and machining parameters has been expressed as follows:

$$R_a = \beta_0 + \beta_1(A) + \beta_2(B) + \beta_3(C) + \beta_4(D) + \beta_5(A^2) + \beta_6(B^2) + \beta_7(C^2) + \beta_8(D^2) + \beta_9(AB) + \beta_{10}(AC) + \beta_{11}(AD) + \beta_{12}(BC) + \beta_{13}(BD) + \beta_{14}(CD) \quad (4.1)$$

From the observed data for surface roughness, the response function has been determined in uncoded units as:

Surface Roughness$= 1.85606 - 0.0170447A + 2.82895B - 1.29380C - 0.0342872D + 9.55152\times10^{-5}A^2 - 11.2863B^2 - 2.12121C^2 + 0.000587879D^2 + 0.0157143A\times B - 0.0040A\times C - 8.000\times10^{-5}A\times D - 7.14286B\times C - 0.0142857B\times D + 0.0800C\times D \quad (4.2)$

Result of ANOVA for the response function surface roughness is presented in Table 4.3. This analysis is carried out for a level of significance of 5%, i.e., for a level of confidence of 95%. From the analysis of Table 4.3, it is apparent that, the F calculated value is greater than the F-table value ($F_{0.05}$, 14, 14=2.48) and hence the second order response function developed is quiet adequate. From equation (5.2) contour and surface plot for each of the response surfaces at different depth of cut and volume flow rate is plotted (Figure 4.4).These response contours and surface plot can help in the prediction of the

Table 4.3ANOVA table for response function of the surface roughness

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Blocks	1	0.003840	0.000955	0.000955	0.83	0.377
Regression	14	0.215537	0.215537	0.015396	13.43	0.000
Residual Error	14	0.016053	0.016053	0.001147		
Total	29	0.235430				

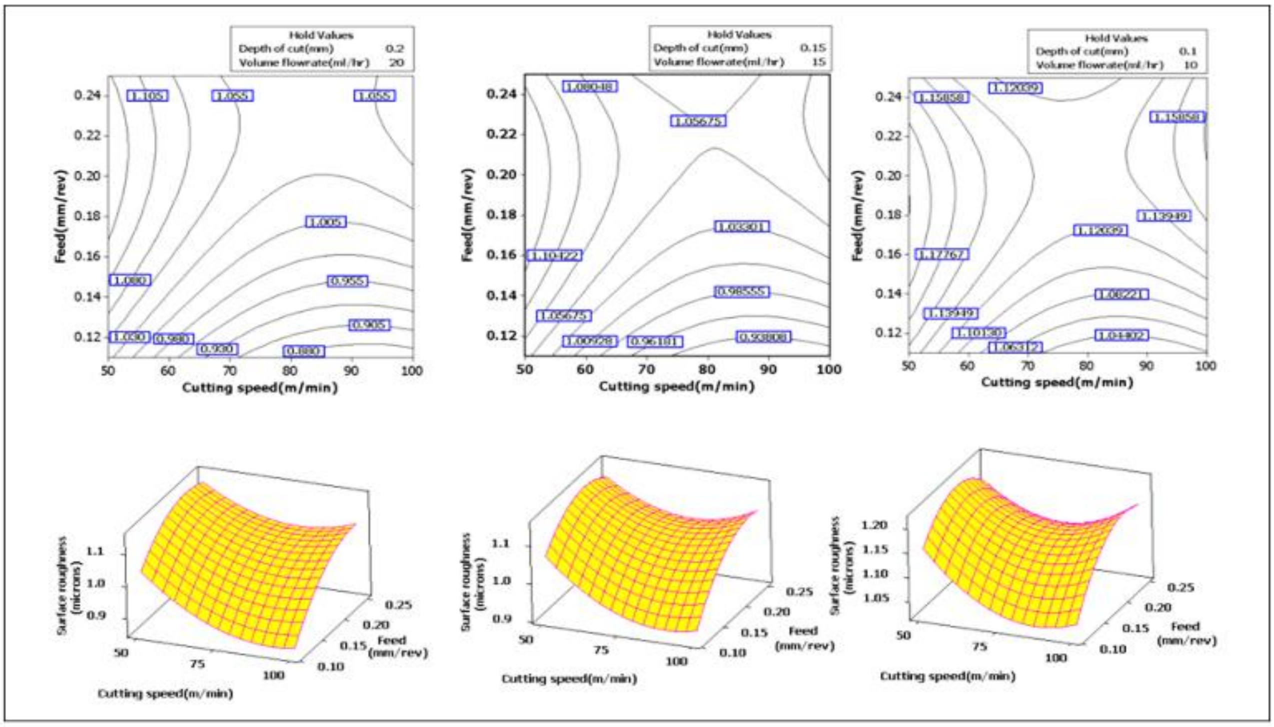

Figure 4.4: Surface roughness contour plot and surface plot in cutting speed- feed planes at different Depth of cut and Volume flow rate

surface roughness at any zone of the experimental domain. It is clear from these figures that the surface roughness falls with the increase of cutting speed and decrease of feed rate; however, it increases with the decrease of volume flow rate of the lubricant (coconut oil).

Conclusions

The surface roughness has been measured in the turning of Ti-6Al-4V alloy under different cutting conditions using Taguchi's design of experiments and response surface methodology. Based on the results, the following conclusions are drawn:

- The effect of machining parameters on the surface roughness has been evaluated with the help of Taguchi's design of experiments and optimal machining conditions to minimize the surface roughness have been determined.
- The effect of lubrication condition is found to be having highest physical as well as statistical influence on surface roughness of about 95.1%.

- The feed is found to be the cutting parameter that affects surface roughness by about 2.72%.\
- A second-order response surface model for surface roughness has been developed from the data. The predicted and measured values are fairly close, which indicates that the developed model can be effectively used to predict the surface roughness on machining of Ti-6Al-4V alloy with 95% confidence intervals. Using such model, one can obtain a remarkable savings in time and cost.
- The result obtained shows that with a proper selection of machining parameters, it is possible to obtain a better performance in turning of Ti-6Al-4V alloy.

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