Optimisation of Cutting Parameters for Minimal Surface Roughness in Single Point Diamond Turning of TI6AL4VELI

Nitish Chandra, Sukhdeep singh Dhami

Abstract*: *In this study the effect and optimisation of machining parameters on surface roughness in a facing operation of Ti6Al4VELI by single point diamond machining have been investigated. The experimental studies carried under varying cutting speeds, feed rates, different tool nose radius and depths of cut. The orthogonal array, signal-to-noise ratio (S / N) and variance analysis (ANOVA) were used to examine the performance characteristics of the Ti6Al4VELI alloy turning by using single-point diamond cutting tool. The influential factors on the surface roughness after machining are feed rate and cutting speed after the conclusions revealed. Whereas the feed rate had the most significant effect on tool life. Minimal surface roughness achieved after machining is in nano-level which is better than other conventional precision machining.

Keywords: Taguchi method, Analysis of variance (ANOVA), Ti6Al4VELI, Signal-to-noise (S/N) ratio, Surface roughness.

I. INTRODUCTION

The use of Titanium alloys (Ti6Al4VELI) in a variety of fields, such as biomedical, aviation and automotive makes it a versatile material[1]. It is a α+β two-phase alloy, aluminium as α and vanadium as a β stabiliser. The exceptional resistance to corrosion and superior biocompatibility of titanium and its alloys are due to their outstanding mechanical characteristics and the thin oxide layer of the surface[2][3]. As it is having low density and good elastic modulus which makes these metals mechanically closer to those of bones. Titanium and its alloys are one of the few materials that naturally meet the human body's implantation demands due to their lightness, strength and biocompatibility[4].Ti-6Al-4V (grade 5) and pure titanium (cp Ti, grade 2) alloys are used as commercial material in the biomedical field among all the titanium and its alloys [5]. They are commonly used in artificial bones, joints and dental implants. An articulating bearing consisting of Femoral head and cup which is the part of Artificial hip joints and stem are one of the most common applications of titanium alloys [6][7].

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In such demands, Titanium alloys parts have tribological contact made from different material like dissimilar metal, polymers and other media under different conditions like dynamic or stationary loading along with various temperatures[8]. These interactions can cause numerous negative impacts on titanium parts, such as corrosion, elevated friction and even seizures such as galvanic and crevice corrosion, leading to early failure of implanted devices[9]. Improving surface quality for titanium and its alloys are, therefore to control or prevent these effects and to extend the lifetime of the implant[10]. Ultra-precision machining seeks to produce high-quality products for sophisticated components in terms of shape precision, surface finish and dimensional integrity [11]. In Ultraprecision machining Diamond turn machining have been used[12]. In Diamond Turn machining Single point diamond tool is used to machine the workpiece. When conventional precision machines can generate surfaces with accuracy level better than 1 μm, diamond turn machines can produce a similar surface within a few tens of nm accuracy[13][14].

II. MATERIAL AND METHODS

Workpiece material, Tool material and methods have been discussed below.

A. Workpiece material

Titanium is available in several different grades. Titanium alloys are categorized into three primary groups, such as α-phase, β-phase and α-β phase. Workpiece material before machining is shown in Figure 2.1.1.

Figure2.1.1 Workpiece material before machining

Ti6Al4VELI alloy is an alpha-beta wrought alloy.Ti6Al4VELI (grade 23) is very similar to Ti6Al4V (Grade 5), except that Ti6Al4VELI contains lower concentrations of oxygen and carbon where ELI stands for "Extra Low Interstitials", and These reduced interstitials provide enhanced ductility [15].Ti6Al4VELI alloy with a diameter of 2mm was utilized as the raw material. Physical and Chemical Properties of Workpiece are shown in Table 2.1.1.

Table 2.1.1 Physical and Chemical Properties of Workpiece

Physical Properties of workpiece				
Part Density	**Ultimate Tensile Strength**	**Yield Strength**	**Elongation at Break**	**Vickers hardnes s[HV]**
4.41g/cm^3	1290 ± 80 MPa	1150 ± 80 MPa	8 ± 4%	320 ± 15

Chemical Properties of Workpiece						
Element	**Ti**	**Al**	**V**	**C**	**O**	**S**
Weight %	88.49	6.10	3.89	1.13	0.28	0.16
Atomic %	79.59	9.32	4.45	5.40	1.15	0.09

B. Tool Material

Single crystal diamond instrument has a small affinity to the materials used in ultra-precision cutting and can be rendered with a very sharp cutting edge. It is recognized to be an ideal ultra-precision cutting tool. Exact contoured surfaces and highly accurate devices are to be produced by diamond cutting tool.For ultra-precision machining of targeted workpiece single point diamond tool with nose radius of 1mm and 5mm with zero rake angle used for facing operation. Different tool nose radius of diamond tool is shown in fig 2.1.1.

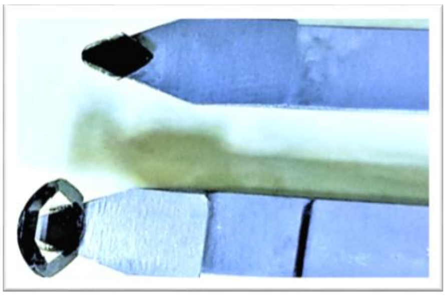


Figure 2.1.1 Single point diamond tool with different nose radius

C. Experimental Procedure

On a two-axis CNC (Nanoform 200 from Precitech) ultra-precision machine, all Diamond cutting tests were carried out .Wide literature survey have been carried out to select cutting parameters on diamond turning. MINITAB 17 Software is used to analyse the variance and for making the design of experiments. After machining all combination the Surface roughness of workpieces was measured using CCI optical profilers (Non-contact type).

D. Design of experiments (DoE) and observations

DoE is the most efficient technique for optimizing process parameters where various parameters are employed. Numbers of trials reduced by utilizing the Taguchi method [16]. It will be too expensive and time-consuming to machine all combinations of tests, thus avoiding all these combinations, an orthogonal array with the minimum amount of tests have been performed. An orthogonal matrix is selected for this study, L18, which is a multilevel experiment. So, cutting speed, feed rate, depth of cut and nose radius was selected as input parameters whose values were selected from the existing literature. Three levels of each parameter were chosen for testing in the current research. The chosen range of cutting speed was (2000 to 4000 rpm), the feed rate was (1 to 5 mm/min) and depth of cut was (1 to 10 µm). There are two levels for tool nose radius so for this we are going for mixed-level for making DOE. To compare the machining of Ti6Al4VELI is done with a single point diamond tool in cutting mentioned above conditions. Machining parameters and observation are shown in Table 2.2.1.

Table 2.2.1 shows the machining parameters and observation

Cutting parameter	Units	Level 1	Level 2	Level 3
Nose Radius	(mm)	1	5	-
Spindle Speed	(rpm)	2000	3000	4000
Feed rate	(mm/min)	1	3	5
Depth of cut	(µm)	1	5	10

Table 2.2.2 Experimental Observation

Order of Run	TNR	SS	FR	DoC	Ra	SNRA2	FITS1
1	1	2000	1	1	108.76	-40.73	4.51239
2	1	2000	3	5	16.50	-24.35	3.47301
3	1	2000	5	10	13.86	-22.839	2.39721
4	1	3000	1	1	158.33	-43.991	4.8443
5	1	3000	3	5	33.36	-30.466	3.80492
6	1	3000	5	10	24.50	-27.783	2.72912
7	1	4000	1	5	127.00	-42.076	5.03053
8	1	4000	3	10	58.30	-35.313	3.95473
9	1	4000	5	1	28.00	-28.943	3.3888
10	5	2000	1	10	118.33	-41.462	4.59179
11	5	2000	3	1	80.53	-38.12	4.02586
12	5	2000	5	5	15.53	-23.825	2.98648
13	5	3000	1	5	152.66	-43.675	5.10579
14	5	3000	3	10	44.63	-32.993	4.02999
15	5	3000	5	1	27.10	-28.659	3.46406
16	5	4000	1	10	173.66	-44.794	5.25561
17	5	4000	3	1	145.66	-43.267	4.68968
18	5	4000	5	5	37.70	-31.527	3.65029

SS-Spindle speed (RPM), FR-Feed rate (mm/min) Ra-Avg. surface roughness (nm), DoC-depth of cut (µm)

The signal-to-noise ratio (S / N) is calculated for each factor level combination .S/N ratio Smaller-is-better using base 10 log the formula for this is

$$S/N = -10*\log(\Sigma(Y^2)/n)$$

Where Y = factor level combination response
n = number of factor-level combination responses

III. ANALYSIS AND THE DISCUSSION OF EXPERIMENTAL RESULTS

After machining, the roughness of the machined workpiece is evaluated by coherence correlation interferometer (CCI) taylor hobson which is a type of Non-Contact Optical Profiler

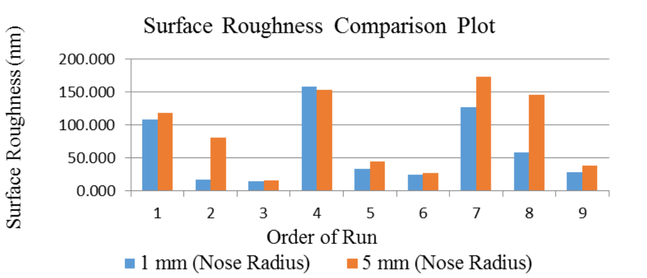
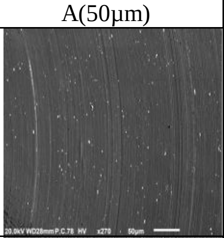
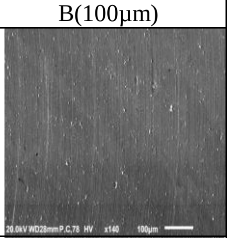
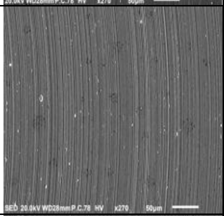
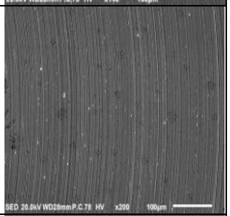
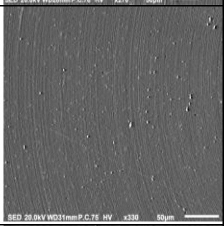
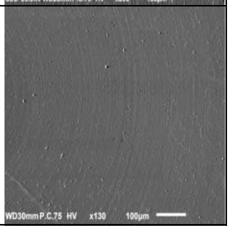
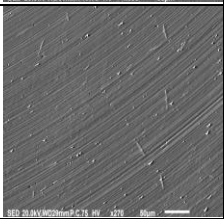
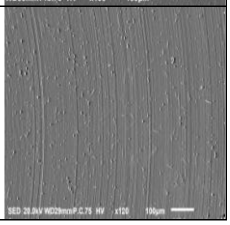


Figure 3.1 Surface Roughness Comparison Plot

Table 2.2.2 Shows the best surface roughness plots obtained from the optical profiler in 3rd run i.e. by tool of 1 mm nose radius at a speed of 2000 rpm, 5mm/min feed rate and 10 µm depth of cut. Table 3.1 shows the comparison of surface roughness among 1 mm nose radius and 5 mm nose radius of tool.

Table 3.1 Surface Roughness of workpiece SEM image

OoR	R_a	A(50µm)	B(100µm)
3rd	13.867		
4rd	158.33		
12rd	15.333		
16rd	173.67		

OoR-Order of Run, R_a-Average Roughness (nm-nanometer)

A. Taguchi's Analysis of Surface Roughness

Taguchi analysis is used to design the experiments and then to research the findings obtained on MINITAB 17. It is easier to approach S / N ratio for the evaluation purpose and it has been observed that the smaller approach is better [18]. The S / N ratio describes the impacts of uncontrollable variables on the response factors. In the response charts delta is the change from the highest limit to the lower limit. and rank is the sequence in which variables influence the response parameter[19]. Tables 3.1.1 indicate the mean surface roughness response table and table 3.1.2 indicates the response table of S/N Ratio for Surface Roughness.

Table 3.1.1: Response Table for Mean for Surface Roughness

Level	Nose Radius(mm)	Spindle Speed	Feed Rate	DoC
1	63.18	58.92	139.79	91.40
2	88.43	73.43	63.17	63.79
3		95.06	24.45	72.22
Delta	25.24	36.13	115.34	27.61
Rank	4	2	1	3

Table 3.1.2: Response Table of S/N Ratios for Surface Roughness

Level	Nose Radius(mm)	Spindle Speed	Feed Rate	DoC
1	-32.94	-31.89	-42.79	-37.29
2	-36.48	-34.59	-34.08	-32.65
3		-37.65	-27.26	-34.20
Delta	3.54	5.77	15.53	4.63
Rank	**4**	**2**	**1**	**3**

These charts indicate that feed rate has the greatest impact on surface roughness, accompanied by machining, then spindle speed and depth of cut, but nose radius has the lowest impact on surface roughness. Figure 3.1.1 show Main effects plots for means and figure 3.1.2. Shows S/N ratios of the surface roughness.

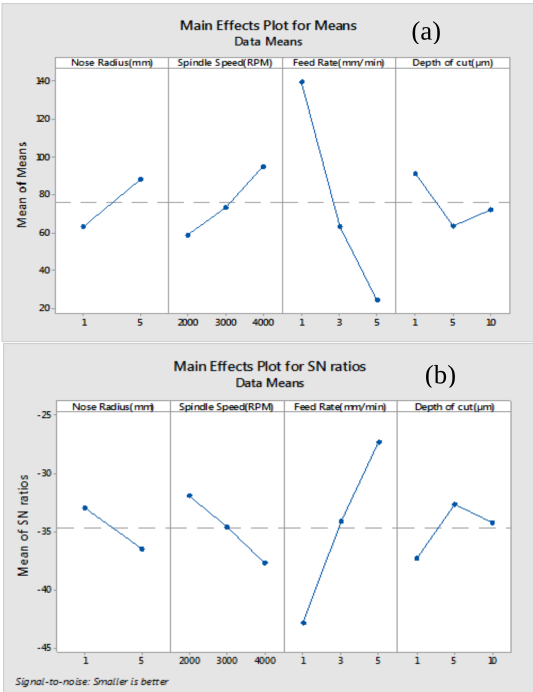


Figure 3.1.1 (a) Main effects plots for means (b) S/N ratios of the surface roughness

It can be interpreted from the plots that by machining of 1 mm tool nose radius, minimum surface roughness is obtained. In the situation of Depth of cut, it can be seen that the surface roughness first reduces with an increase in DoC and then rises. At 5 µm depth of cut surface roughness is minimum. For feed rate, the surface roughness reduces with a rise in feed rate and at 5 mm / min feed the finest surface finish is achieved. Spindle speed model with surface roughness variation is just contrary to feed rate, i.e. surface roughness increases with spindle speed rise. The minimum surface roughness is acquired at 2000 rpm from the result. From the above assessment, it can be stated that machiningofTi6Al4VELI workpiece with 1 mm tool nose radius at a reduced velocity with intermediate feed rate with a higher cutting depth in order to achieve minimum surface roughness.

B. Regression Analysis of Surface Roughness

Table 3.2.1 demonstrates the actual surface roughness scores acquired after the tests, the fit characteristics forecast by the ANOVA system and the distinction between the actual value and fits shown by residue. The average error measured from experiment is 3.03289% from Table 3.2.1.

Table 3.2.1: Actual and Predicted Values of Surface Roughness

Order of Run	Ra (nm)	Fits	Residue	%Error
1	108.767	91.1392	17.627	16.2067
2	16.500	32.2335	-15.734	-95.355
3	13.867	10.9924	2.874	20.7276
4	158.333	127.014	31.319	19.7807
5	33.367	44.9214	-11.555	-34.63
6	24.500	15.3193	9.181	37.4721
7	127.000	153.014	-26.014	-20.483
8	58.300	52.1814	6.119	10.4949
9	28.000	29.6303	-1.630	-5.8224
10	118.333	98.6709	19.662	16.6161
11	80.533	56.0284	24.505	30.4283
12	15.533	19.8158	-4.282	-27.569
13	152.667	164.975	-12.308	-8.0623
14	44.633	56.2606	-11.627	-26.051
15	27.100	31.9465	-4.847	-17.884
16	173.667	191.638	-17.971	-10.348
17	145.667	108.818	36.849	25.2967
18	37.700	38.486	-0.786	-2.0849
Average	**75.8037037**	**73.5047**	**2.299**	**3.03289**

Figure 3.2.1 shows the experimental and the predicted values of the surface roughness by the ANOVA model and gives a comparison between both of them. In the plot order of run is shown on the horizontal axis while on vertical axis surface roughness. Figure 3.2.1 reflects and compares the test and expected surface roughness results from the ANOVA model.

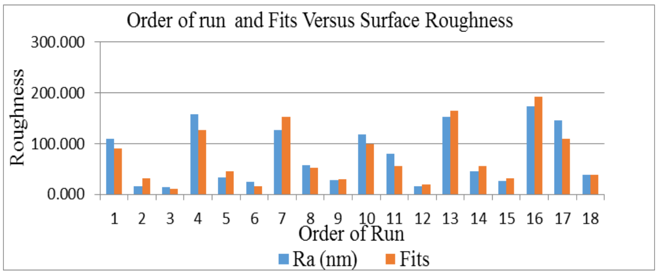


Figure 3.2.1 Experimental and Fitted Values for Surface Roughness

Figure 3.2.2 shows the Residue Chart for Surface Roughness. In this plot Zero is the reference line and variations is described above and below this line.

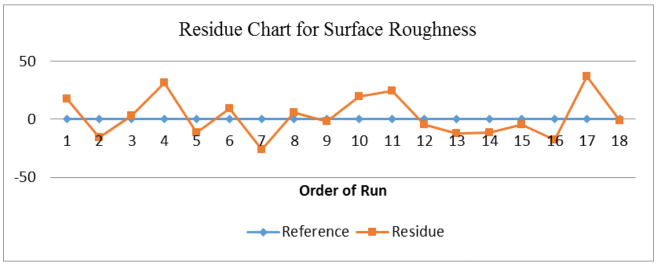


Figure 3.2.2: Residue Chart for Surface Roughness

In this chart, Residue is represented on the vertical axis while order of run on the horizontal. Analysis of surface roughness is shown by the ANOVA table mentioned in Table 3.2.2.

Table 3.2.2: ANOVA Table for Surface Roughness

Source	Adj SS	Adj MS	F-Value	P-Value	% PCR	Remark
Regression	11.97	2.994	28.89	0		
Spindle Speed	1.322	1.322	12.76	0.003	9.922	2
Feed Rate	9.584	9.584	92.49	0	71.93	1
DoC	0.323	0.323	3.12	0.101	2.428	4
Nose Radius	0.746	0.746	7.2	0.019	5.599	3
Error	1.347	0.103				
Total	13.32					

1-most significant, 2-moderate significant, 3-least significant, 4-non significant

Model is significant when the p value should be less than 0.05. From the table it is shown that that feed rate is a most valuable parameter for the surface roughness while Tool nose radius is less significant source ,there is not any significace of depth of cut means to say that not much effect by changing DoC and most significant is feed rate which will effect the surface roughness more. Table 3.2.3 shows that R-sq is 95.08% which is compared with the predicated value of 90.00% about its mean from the model summary for surface roughness.

Table 3.2.3: Model Summary for Surface Roughness

S	R-Sq.	R-Sq.(Adj)	R-Sq.(Pre)
0.0193210	95.08 %	93.56%	90.00%

Table 3.2.4 shows Unusual Run for Surface Roughness which indicates that one usual fit should be observed on the first run from the analysis of model.

Table 3.2.4: Unusual Run Data for Surface Roughness

S	R-sq	R-sq(adj)	R-sq(pred)
0.321911	89.89%	86.78%	81.94%

Regression equations acquired by the Taguchi model are shown in equation 4.1 and 4.2.

Regression Equation for 1mm tool nose radius

ln(Ra) = 4.332 + 0.000332 Spindle Speed(RPM)
- 0.4469 Feed Rate(mm/min) - 0.0364 Depth of cut(µm)
……………………..equation 4.1

Regression Equation for 5mm tool nose radius

ln(Ra) = 4.739 + 0.000332 Spindle Speed(RPM)
- 0.4469 Feed Rate(mm/min)
- 0.0364 Depth of cut(µm)……....……………...equation 4.2

IV. CONCLUSION

In this study, the optimisation of turning operations has been investigated and presented on the surface roughness based on the parameter design of the Taguchi method. Based on the analysis of results it may be concluded that the 3^{rd} Order of run for 1mm tool nose radius and 12^{th} order of run for 5mm tool nose radius settings are the optimal machining parameters for surface roughness, respectively. Based on the analysis of variance (ANOVA) results and from the experimental results and derived analysis, one can conclude that feed Rate has the most dominant effect on the observed surface roughness, followed by cutting speed, depth of cut and effect of tool nose radius. Tool nose radius has the least effect whose influences on surface roughness are smaller. Minimal surface roughness achieved after machining is 13 nm. There is improvement of 300 % in surface roughness after optimal machining.

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