OPTIMIZATION OF TURNING PARAMETERS FOR TITANIUM ALLOY TI-6AL-4V ELI USING THE RESPONSE SURFACE METHOD (RSM)

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ABSTRACT: Titanium alloys are attractive materials due to their uniquely high strength–weight ratio, which is maintained at elevated temperatures. Due to the low machinability of titanium alloys, optimization of machining conditions is crucial. Uncoated carbide tool (CNGG 120408-SGF-H13A) was used to turn the titanium alloy Ti-6Al-4V ELI. In this study, the effects of cutting speed, feed rate, and depth of cut parameters were examined. Cutting-speed range of 120–220 m/min was used under flooded conditions. Response surface method (RSM) with a Box-Behnken design was utilized to set the 17 parameter runs. Analysis shows that cutting speed had the greatest effect on tool life, followed by feed rate and depth of cut. Meanwhile the feed rate was most significant factor for surface roughness, Ra of machined surface rather than cutting speed and depth of cut. Additionally, the optimum machining conditions were determined using RSM for both tool life and Ra to be a high cutting-speed of 220 m/min and a low depth of cut and feed rate of 0.4 mm and 0.1 mm/rev, respectively. Here the tool life gave 14.55 min for predicted value, but the validation thru experimental work produced 13.05 min, and the error about 10.65%. Moreover the surface roughness, Ra value for predicted was 0.529μm, meanwhile the validation gave 0.489 μm. This error was calculated to 7.56%.

KEYWORDS: *Uncoated carbide, Titanium alloy, Ti-6Al-4V ELI, RSM – Box Behnken, Optimum cutting.*

1.0 INTRODUCTION

The aerospace industry has encompassed the majority of titanium applications, but a shift in market trends from military to commercial and aerospace to industry has been reported. Titanium and its alloys, however, are notorious for their poor thermal properties and are classified as difficult-to-machine materials. Machinability is defined as the ease with which a workpiece can be machined under specific operating conditions, including cutting speed, feed rate, and depth of cut. Machinability of a workpiece is assessed by measuring the cutting-tool life, machined-surface quality, and the component forces during cutting [1 - 2]. Titanium and titanium alloys are extensively used in the aerospace industry because of their high specific strength (strength-to-weight ratio), which is retained at elevated temperatures, as well as their fracture resistance and exceptional corrosion resistance at high temperatures [2 - 5]. In machining, however, these properties can exacerbate wear on the cutting tool, a detrimental factor that limits tool life. Various types of wear can occur, and these are taken into account in this study's optimization of machining conditions. Wear on the flank of a cutting tool, caused by friction between the machined surface and the tool contact area, plays a significant role in determining the tool life. Venkatesh [6] performed an investigation on wear of some cutting tool materials, and plotted tool life vs. flank wear curves. The findings showed that the tool life of carbides rapidly decreases at high cutting speeds. Rapid cratering and/or plastic deformation of the cutting edge occurs when titanium alloys are cut at high speeds due to the heat generated, which concentrates on the cutting edge closest to the nose of the insert. Similar effects have been reported when high-speed steel and carbide tools are used [7]. Tool failures are mainly due to adhesion and diffusion, wear on the rake face, and attrition wear-mechanisms on the flank face.

RSM is a collection of mathematical and statistical techniques for empirical model building that uses quantitative data from appropriate experiments to determine and simultaneously solve multivariable equations, allowing for optimization of the responses [8]. Initially, RSM was developed to model experimental responses and then migrated into the modeling of numerical experiments [9]. The application of RSM in design optimization is aimed at reducing the cost of expensive methods of analysis. In this study, the Box-Behnken design (BBD) was employed because it excludes corners where all variables are simultaneously maximized – therefore, BBD permits a wider variety of individual ranges. It can be further used to study the quadratic effect of factors after identification of the significantly influential factors using screening factorial experiments. BBD does not contain any points at the vertices of the experimental region. This is advantageous, as points at the cube corners contain combinations of factors at levels that are prohibitively expensive or are impossible to test due to physical process constraints [10].

Another advantage of the BBD is that it does not contain combinations where all factors are simultaneously at their highest or lowest levels, so it is useful in avoiding experiments performed under extreme conditions, for which unsatisfactory results might occur.This paper investigates the machining conditions required for optimum tool life and surface roughness when turning titanium alloy Ti-6Al-4V ELI under a high-speed machining regime using RSM. Not only were the machining factors that affect tool life and surface roughness investigated and discussed, but so were the detailed progression of tool wear and the wear mechanisms involved.

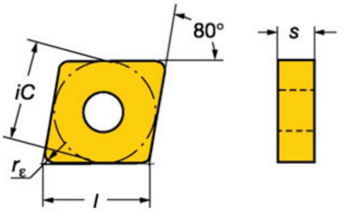
II. METHODOLOGY

The workpiece material used in these experiments was a cylindrical bar of alpha-beta (α-β) titanium alloy Ti-6Al-4V extra-low interstitial (ELI), which consists of equiaxed α-phase surrounded by α-β in the grain boundary. The nominal composition of the alloy (in wt%) is given in Table 1. The workpiece has a microstructure consisting of an elongated α-phase surrounded by a fine, dark etching of the β matrix. This material has high strength and hardenability (32 HRC). At least 3 mm of material on the top surface of the workpiece were removed to eliminate any surface defects and residual stresses that could adversely affect the machining results [11].

Table 1. Chemical compositions of Ti-6Al-4V ELI (% wt) referred by TSI Titanium.

Composition	C	Si	Fe	Ti	Al	N	V	S	O	H
Weight, %	0.08	0.03	0.22	Bal.	6.1	0.006	3.8	0.003	0.12	0.0031

A carbide insert with the International Standards Organization (ISO) designation of CNGG 120408-SGF-H13A was used in the machining experiments. The cutting tools used were uncoated, straight tungsten carbide chip breakers with a rhombic shape, shown in Figure 1. The insert consisted of 82.6 wt% tungsten carbide and WC with 16.4 wt% cobalt, as well as Co as the binder. Straight tungsten carbide (WC/Co) cutting tools have proven their superiority in almost all machining processes of titanium alloys.



Note: s = 0.13 mm, l = 12 mm, iC = 12.7 mm and rε = 0.8 mm

Fig. 1. Schematic of the geometry of the carbide insert used in this study.

All machining experiments were performed on a Tornado T4 CNC lathe, with a GE Fanuc Series 21i-TB as the controller. The cutting parameters and their combination levels used in the experiments are shown in Table 2. Table 3 shows the machine run according to the Box-Behnken design. The machining experiments were performed in flooded conditions using a water-based mineral oil. The cutting parameters tested were in the range of high-speed finish turning-processes for the alloy. A 3 mm pre-cut entry was made for every new cutting pass to prevent a concentrated impact load that could trigger chipping during machining [11]. After pre-cutting, the insert being tested was used according to the machining conditions listed in Table 3. The cutting operation was stopped at 20 mm intervals, at which point, the insert was then dismounted from the tool holder and tool wear was measured. The experiment for a particular insert was stopped when the average flank wear (Vbavg) reached 0.3 mm. These steps were repeated for all machining conditions. The flank wear (Vb) was measured using a Perthometer 3D optical microscope, and the data were analyzed.

The experiment was conducted in accordance with ISO 3685 [12]: (i) when the average flank wear reached 0.3 mm or the maximum flank wear reached 0.6 mm, (ii) when the notch at the depth of cut reached 1.00 mm, (iii) when the crater wear depth reached 0.14 mm, (iv) when the surface finish on the work material exceeded the 6 mm center line average; or (v) when flaking or fracture occurred; the cutting process was stopped. Cutting was abandoned and the tools were discarded when catastrophic fracture at the edge was observed. In this experiment, an average flank wear (Vbavg) of 0.3 mm was set as the tool life criterion for all inserts tested.

Table 2. The cutting parameters and their levels used in the experiment.

Level	-1	0	1
Cutting speed, V	120	170	220
Feed rate, F	0.1	0.15	0.2
Depth of cut, doc	0.4	0.5	0.6

Table 3. Cutting parameter combinations arranged by Box Behnken.

Run	Factor 1 A:V m/min	Factor 2 B:f mm/rev	Factor 3 C:d mm
1	1	0	-1
2	0	1	1
3	1	0	1
4	-1	-1	0
5	0	0	0
6	1	-1	0
7	-1	0	-1
8	0	0	0
9	0	-1	-1
10	0	-1	1
11	1	1	0
12	0	1	-1
13	-1	1	0
14	0	0	0
15	-1	0	1
16	0	0	0
17	0	0	0

III. RESULTS

A. Tool Life and Surface Roughness

The experimental results for tool life and surface roughness are shown in Table 4. In this work, the shortest cutting time, or tool life, is 1.2 min, whereas the longest cutting time is 42.2 min. According to ISO 3685 [12], a tool life of 2 min or more is an acceptable value for machining expensive materials. For surface roughness, the smallest Ra measured was 0.380 μm.

Tool life is mainly affected by the heat generated and force exerted at the cutting edge of the tool. Changing the cutting speed, feed rate, and depth of cut will directly affect the cutting force and heat generated. Figure 2 shows the progression of flank wear for a CNGG 120408-SGF-H13A uncoated carbide insert at various cutting parameter settings when machining Ti-6Al-4V ELI. Table 5 shows in detail that the flank wear rate was fastest at high cutting speed, with a cutting time of less than 2 min, followed by the wear rates produced by greater feed rate and depth of cut.

The contact area at the chip-tool interface decreased at high cutting speeds, which resulted in the concentration of heat generation very close to the cutting edge. Increased cutting speeds and feed rates caused a significant increase in temperature at the cutting edge of the tools, which again resulted in a loss of strength as well as plastic deformation, weakening the cutting tool material. Jawaid [13] also showed that plastic deformation of the tool occurs during titanium alloy turning, even at low cutting speeds of approximately 45 m/min. In addition, greater depth of cut directly affected the cutting force due to the increased contact area between the cutting tool and the workpiece. It also directly caused a rapid increase in wear progression. These findings are in accordance with the results obtained by Ibrahim [14].

Table 4. Experimental results for tool life and surface roughness.

Run	Factor 1 A:V m/min	Factor 2 B:f mm/rev	Factor 3 C:d mm	Tool life min	Ra µm
1	1	0	-1	8.019	0.922
2	0	1	1	1.709	1.770
3	1	0	1	1.218	0.914
4	-1	-1	0	42.24	0.806
5	0	0	0	2.994	1.142
6	1	-1	0	9.507	0.380
7	-1	0	-1	22.742	1.473
8	0	0	0	4.117	1.102
9	0	-1	-1	9.259	0.934
10	0	-1	1	5.887	0.775
11	1	1	0	1.406	1.868
12	0	1	-1	4.189	1.444
13	-1	1	0	10.337	1.534
14	0	0	0	3.801	1.244
15	-1	0	1	11.255	1.603
16	0	0	0	4.380	1.013
17	0	0	0	3.245	1.425

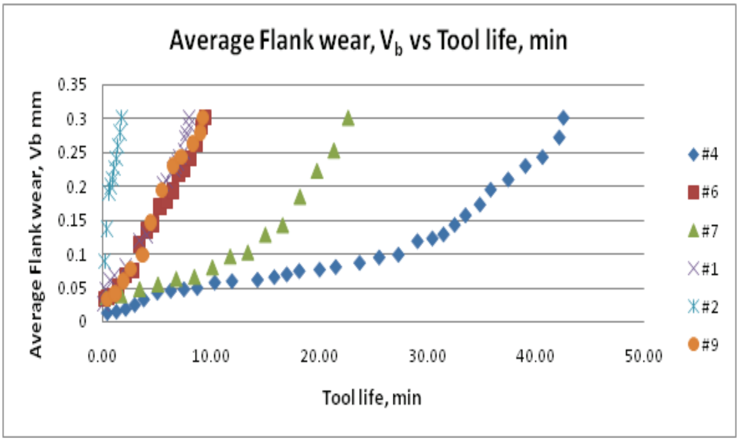


Fig. 2. Average flank wear for multiple uncoated carbide tools each with different cutting parameter settings.

Table 5. Cutting parameters and ultimate tool life values for average flank wear tests.

Insert #	Cutting speed, Vc	Feed rate, f	Depth of cut, d	Tool life, min
4	120	0.1	0.5	42.53
7	120	0.15	0.4	22.74
9	170	0.1	0.4	9.26
2	170	0.2	0.6	1.71
6	220	0.1	0.5	9.51
1	220	0.15	0.4	8.02

B. ANOVA Analysis

ANOVA is normally used to summarize the tests performed. Table 6 shows the ANOVA table for the reduced quadratic model for tool life. The "Prob.> F" value for this model is less than 0.05, indicating that the model is statistically significant, which is desirable as it indicates that the terms in the model have a significant effect on the response. In other words, cutting speed (A), feed (B), depth of cut (C), square of cutting speed (A2), and the two-level interactions of A and C (AC) are significant model terms. The highest value for F, 77.89, indicates that cutting speed has the greatest effect on tool life compared to other factors. This is because the cutting speed directly controls the elevated temperatures generated during the machining process. This conclusion is strongly supported by Venkatesh [6], who stated that tool life decreased as the cutting speed increased and is confirmed by many others [14, 16, 17]. Therefore, the factor with the greatest effect on tool life and wear progression is cutting speed.

Adequate Precision in Table 6 measures the signal to noise ratio; a ratio greater than 4 is desirable. Here a ratio of 20.731 indicates adequate signal to noise; thus the regression model in (1) can be used to navigate the design space. The regression modeling in (1) was also used to verify the accuracy of the experimental data. Comparison of 17 experimental and modeled tool life tests are shown in Figure 3 for experiment validation. The following regression model for tool life H13A was developed based on the experiment design:

$$\text{Ln (Tool life)} = 11.305 - 0.078*V - 13.389*f + 5.485*d + 0.000268*V2 - 0.0616*V*d \quad (1)$$

Table 6. ANOVA table (partial sum of squares) for Response Surface Reduced Quadratic Model (response: Tool Life, min).

ANOVA for Response Surface Reduced Quadratic Model						
Analysis of variance table [Partial sum of squares]						
Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Model	13.66	5	2.732	36.70	< 0.0001	significant
A	5.80	1	5.797	77.89	< 0.0001	
B	3.59	1	3.586	48.18	< 0.0001	
C	1.99	1	1.988	26.71	0.0003	
A^2	1.91	1	1.908	25.64	0.0004	
AC	0.38	1	0.379	5.10	0.0453	
Residual	0.82	11	0.074			
Lack of Fit	0.72	7	0.102	4.00	0.0992	not significant
R-Squared	0.9434					
Adjusted R-Squared	0.9177					
Prediction R-Squared	0.8206					
Adequate Precision	20.731					

Meanwhile Table 7 shows the ANOVA of a surface linear model for surface roughness, Ra. As in the tool life analysis, the value "Prob. > F" is less than 0.05 indicating that the model is statistically significant. In this analysis, however, the effects of feed (B), cutting speed (A), and depth of cut (C) are the significant model terms. In addition, for the highest F value of 40.57, feed (B) is the most significant factor that affects surface roughness, rather than cutting speed or depth of cut. This is due to the increased friction and contact between the workpiece and tool interface, which eventually increases the temperature in the cutting zone [15, 16]. This also agrees by (2), which clearly shows that surface roughness is primarily dependent on the feed and nose radius [17, 18]:

$$h = f^2 / 8R \text{ OR } h_{CLA} = f^2 / 18\,(3R)^{1/2} \qquad (2)$$

where h is the peak-to-valley height, hCLA is the centerline average roughness, f is the feed rate and R is the nose radius of the cutting tool. Adequate Precision in Table 7 measures the signal to noise ratio. A ratio greater than 4 is desirable. Here the ratio of 12.608 indicates an adequate signal; thus the regression model in (3) can be used to navigate the design space.

Table 7. ANOVA table (partial sum of squares) for Response Surface Linear Model (response: Surface Roughness, Ra, µm).

ANOVA for Response Surface Linear Model						
Analysis of variance table [Partial sum of squares]						
Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Model	1.96	3	0.654	15.34	0.0001	significant
A	0.22	1	0.222	5.20	0.0401	
B	1.73	1	1.731	40.57	< 0.0001	
C	0.01	1	0.010	0.24	0.6291	
Residual	0.55	13	0.043			
Lack of Fit	0.46	9	0.051	2.04	0.2572	not significant
R-Squared	0.780					
Adjusted R-Squared	0.729					
Prediction R-Squared	0.577					
Adequate Precision	12.608					

The regression modeling in (3) was used to verify the accuracy of the experimental data once all seventeen experiments were performed. The predicted and experimental values were compared, and the percentage error was calculated. These values are presented in Figure 4. As a result, as shown in Tables 8 and 9, the percentage errors for tool life range from 2 to 14 percent, while the surface roughness errors range from 4 to 14 percent. These error ranges show that the experimental data were reasonably accurate, particularly with respect to tool life. Almost all the experimental values for the confirmation runs are within the 95% prediction interval. The 95% prediction interval is the range in which we can expect any individual value to fall 95% of the time.

$$Ra = 0.1871 - 0.00333*V + 9.3025*f + 0.36125*d \tag{3}$$

Table 8. Percentage error for tool life values.

No.	Experiment	Predicted	Error %
1	1.213	1.243	2
2	3.896	3.996	3
3	3.562	3.368	5
4	1.339	1.490	11
5	7.012	6.520	7
6	11.435	12.849	12
7	1.589	1.709	8
8	4.572	3.996	13
9	23.897	22.161	7
10	3.801	3.996	5
11	38.657	35.775	7
12	8.019	7.476	7
13	5.234	4.741	9
14	10.337	9.377	9
15	4.38	3.996	9
16	3.685	3.996	8
17	13.235	15.138	14

Table 9. Percentage error for surface roughness values.

No.	Experiment	Predicted	Error %
1	1.770	1.698	4.22
2	1.142	1.197	4.59
3	1.444	1.626	11.19
4	0.914	1.067	14.31
5	0.489	0.565	13.51
6	0.624	0.696	10.31
7	1.624	1.496	8.58
8	1.102	1.197	7.94
9	1.473	1.327	10.97
10	1.244	1.197	3.93
11	0.806	0.898	10.28
12	0.922	0.994	7.28
13	0.775	0.768	0.91
14	1.678	1.829	8.24
15	1.264	1.197	5.60
16	1.321	1.197	10.36
17	1.534	1.400	9.60

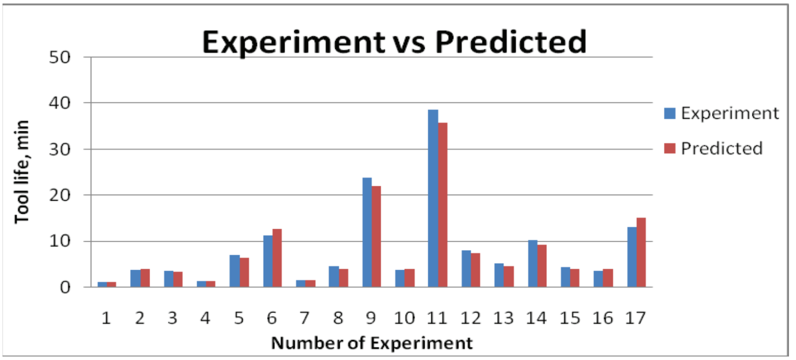


Fig. 3. Comparison between experimental and modeled tool life values.

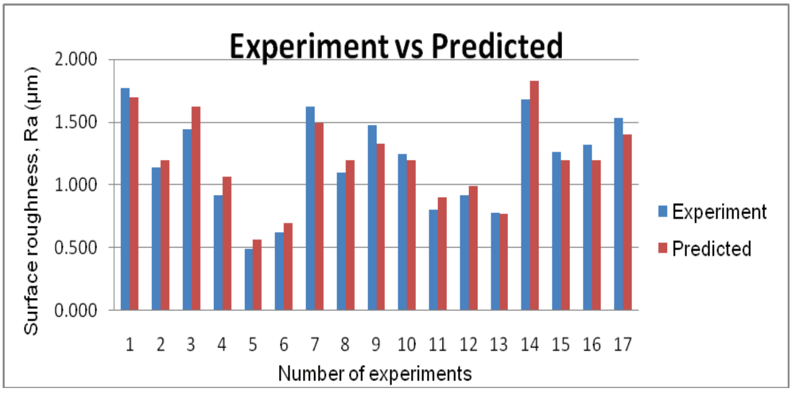


Fig. 4. Comparison between experimental and predicted surface roughness values.

C. Optimization of Cutting Conditions for Tool Life and Surface Roughness

The most important factor in machining processes is productivity, achieved by cutting the greatest quantity of material in the shortest period of time using tools with the longest lifespan. This must be balanced with the need for a low surface roughness value to ensure quality surfaces on machined titanium parts. Through RSM and careful design of the experiments, a maximized cutting tool lifetime and low surface roughness can be efficiently achieved by the optimization of a response (output variable) that is influenced by several independent variables (input variables). Based on the optimization in Table 10, the optimum set of cutting parameters for this study is a 220 m/min cutting speed, feed of 0.1 mm/rev, and depth of cut of 0.4 mm, providing a tool life of 13.05 minutes for the experimental and 14.55 minutes for the predicted value. Comparison of these lifetimes shows an error of only 10.65%. The surface roughness, Ra, at these parameters is 0.529

µm for the predicted and 0.489 µm for the experimental, with an error of almost 7.6%.

The contours of the response surfaces for predicting Ln (tool life) is shown in Figure 5 meanwhile the tool life value is shown in Figure 6. It is clear that at cutting speed, V = 220 m/min, feed, F = 0.1 mm/rev, depth of cut, doc = 0.4 mm; the predicted optimum points are Ln (tool life) = 2.68 (Figure 5) and tool life value = 14.55 min (Figure 6). The contour of the response surface for surface roughness is shown in Figure 7. At the optimum condition, V = 220 m/min; f = 0.1 mm/rev; d = 0.4 mm, the predicted surface roughness is 0.53 µm. The 3D surface graphs show the interaction among the cutting parameters for tool life and surface roughness are shown in Figure 8 and 9. Tool life has a curvilinear profile in accordance with the quadratic model fit. The surface roughness has a linear profile due to the generated surface linear model.

Table 10. Optimization of cutting parameters determined by RSM and validated through experiments also the error percentage.

V	F	doc	Ln (Tool life)	Tool life, min	Ra, µm	
220	0.1	0.4	2.681	14.55	0.529	Predicted by RSM
220	0.1	0.4	-	13.045	0.489	Validated by Experiment
				10.649	7.56	% error between Predicted and Experiment

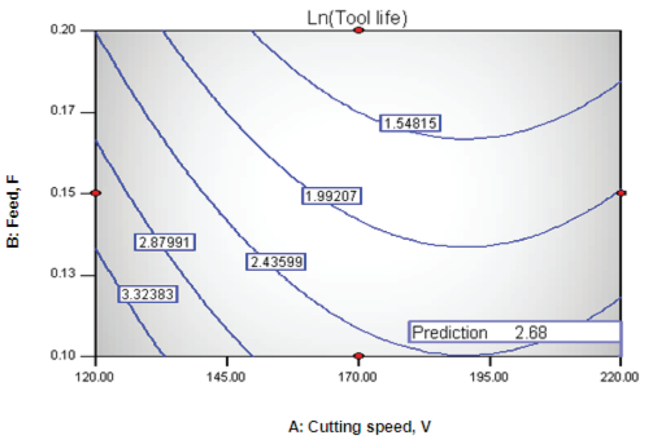
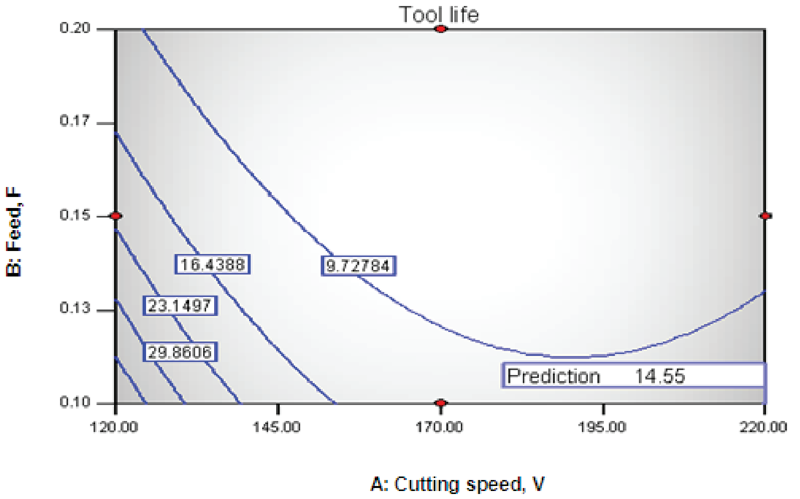


Fig. 5. Optimization of Ln (tool life) contours in Feed – Cutting speed plane at a cut depth of 0.4 mm.



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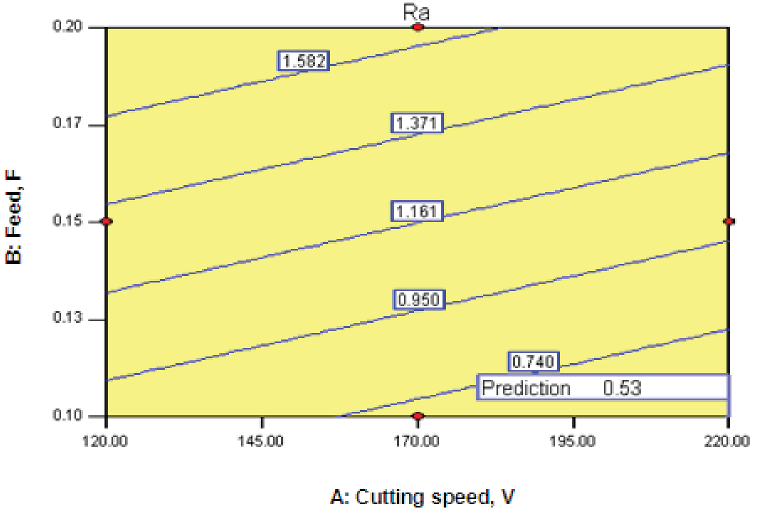

Fig. 7. Optimization of surface roughness contours in Feed – Cutting Speed plane at a cut depth of 0.4 mm.

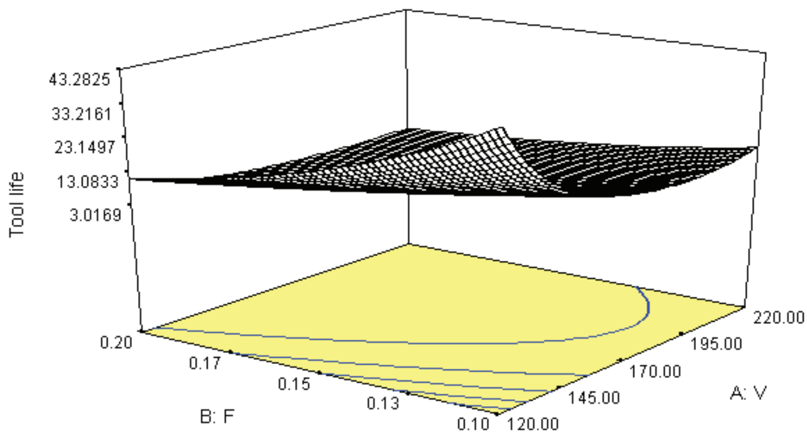

Fig. 8. Interaction effect between cutting speed and feed rate for tool life (optimization).

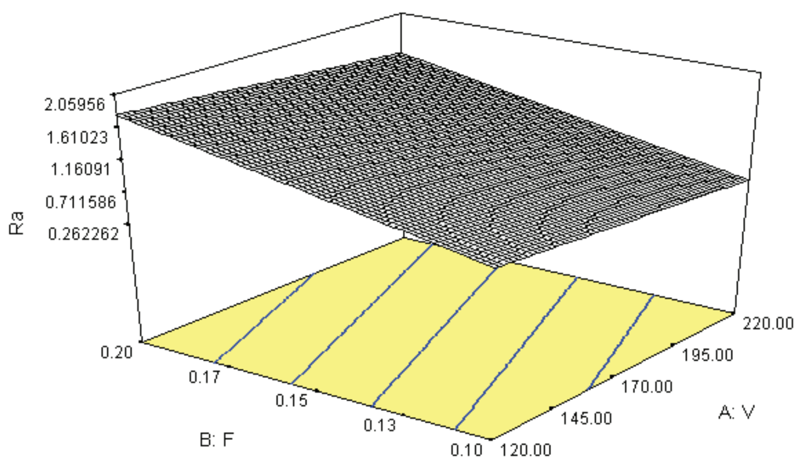

Fig. 9. Interaction effect between cutting speed and feed rate for surface roughness (optimization).

IV. CONCLUSIONS

This paper details an investigation into the effect of cutting speed (V), feed (f), and depth of cut (d) on tool life and surface roughness when turning the titanium alloy Ti-6Al-4V Ti6Al4V ELI under flooded coolant condition.

1. The tool life for uncoated carbide tool suggested that cutting speed, V, and feed rate, F, are the most significant

factor influencing the response variables investigated. The V2, depth of cut and V interaction factors contributed secondarily to the responses investigated. The prediction model for uncoated carbide tool is shown below;

$$\text{Ln (Tool life)} = 11.30 - 0.077{*}V - 13.39{*}f + 5.48{*}d + 0.000268{*}V2 - 0.0616{*}V{*}d$$

2. The surface roughness ANOVA analysis showed that feed rate has the greatest effect, followed by cutting speed contributed most to the surface roughness. The prediction model for the surface roughness when using uncoated carbide tool is shown below;

$$Ra = 0.187 - 0.0033{*}V + 9.30{*}f + 0.361{*}d$$

3. The process used in this study resulted in the following optimized cutting parameter settings: V= 220 m/min, f = 0.1 mm/rev, and d = 0.4 mm. The tool life and surface roughness, Ra, at these settings were determined to be 13.045 min and 0.489 μm respectively.
4. The reduced quadratic model and surface linear model developed using RSM were reasonably accurate and can be used for prediction within the limits of the parameters investigated.
5. According to ISO 3685, a tool life of 2 min or more is acceptable for the machining of expensive materials. Therefore, the tool life and cutting parameter values derived from this work can be considered acceptable for Ti6Al4V ELI machining.

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