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TOOL LIFE PERFORMANCE OF COATED CARBIDE TOOL ON TITANIUM ALLOY EXTRA LOW INTERSTITIALS

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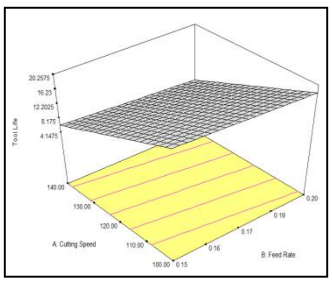
Graphical abstract



Abstract

The Titanium alloys (Ti-6Al-4V) has been employed in a variety of applications, particularly in the aerospace, automotive, medical and chemical industries, primarily because of its high strength to weight ratio, high resistance to fracture, and exceptional anti-corrosion property. However, Ti-6Al-4V cannot be easily machined even at a high temperature as it has a low thermal conductivity and low elastic modulus, and may react chemically with the coating on the cutting tool. The objective of this study was to investigate the cutting tool life performance in the turning of Ti-6Al-4V Extra Low Interstitials (ELI) using a Chemical Vapor Deposition (CVD) carbide cutting tool in dry conditions. The Factorial method was used as the basis for the experimental design of this study. A factorial design with two levels was chosen for the arrangement of the cutting parameters, which comprised a cutting speed of between 100 to 140 m/min, a feed rate of between 0.15 to 0.20 mm/rev, and a fixed depth of cut of 0.35 mm. A three-axis microscope was used to measure the flank wear for every 20 mm on the workpiece until the ISO criterion was arrived at by the flank wear (Vb). The results indicated that the maximum tool life of 20.68 minutes was achieved at a cutting speed of 100 m/min and a feed rate of 0.15 mm/rev.

Keywords: CVD coated carbide, tool life, titanium alloy, Ti-6Al-4V ELI, factorial method

Abstrak

Aloi titanium (Ti-6Al-4V) digunakan secara meluas terutamanya dalam bidang aeroangkasa, automotif, perubatan dan kimia, ini disebabkan Ti-6Al-4V memiliki sifat nisbah kekuatan terhadap berat yang tinggi, rintangan patah yang tinggi, dan rintangan kakisan yang sangat baik. Walau bagaimanapun, Ti-6Al-4V adalah bahan yang sukar dimesin walaupun pada suhu tinggi kerana ia mempunyai keberairan terma yang rendah, modulus kenyal rendah dan mudah bertindak balas dengan bahan mata alat. Tujuan kajian ini adalah untuk mengkaji prestasi jangka hayat mata alat semasa pelarikan bahan Ti-6AL-4V ELI menggunakan mata alat karbida (CVD) dalam keadaan kering. Reka bentuk eksperimen kajian ini adalah berdasarkan kaedah pemfaktoran. Reka bentuk Two Level Factorial digunakan untuk mengatur parameter eksperimen iaitu laju pemotongan dengan julat dari 100 hingga 140 m/min, kadar suapan dari 0.15 hingga 0.20 mm/rev dan kedalaman pemotongan adalah malar iaitu 0.35 mm. Haus rusuk diukur menggunakan mikroskop mudah alih tiga paksi di mana bacaan diambil dan direkod bagi setiap 20 mm pelarikan pada benda kerja sehingga nilai haus rusuk purata (Vb) mencapai kriteria ISO. Berdasarkan kepada keputusan eksperimen, nilai hayat maksimum dihasilkan oleh laju pemotongan 100 m/min dan kadar suapan 0.15 mm/rev.

Kata kunci: CVD bersalut karbida, hayat mata alat, aloi titanium, *Ti-6Al-4V ELI,* kaedah faktorial

1.0 INTRODUCTION

Titanium alloys are used extensively in the aerospace industry in view of their exceptional high specific strength or strength-to-weight ratio, which remains steady at high temperatures as well as their resistance to fracture and corrosion at extreme temperatures [1-2]. The main features of the super alloys used in aerospace applications are their austenitic matrix, which facilitates rapid work hardening, and their reactivity with cutting tool materials under atmospheric conditions. This will result in a build-up-edge that will be attached to the cutting tool because of the low thermal conductivity, and abrasive carbide will be introduced into the microstructures, thus reducing the quality of the surface [2-3]. One of the most essential and complicated aspects of the machining process is the cutting tool wear. The tool life can usually be determined by the tool failure modes, with the tool wear being identified according to the area where it occurs, such as the flank wear, crater wear, nose wear, cutting edge chipping, plastic deformation, and catastrophic failure [4]. Arrazola *et al*. [5] used uncoated WC/Co cutting tools for the machining of the titanium alloy Ti-6Al-4V and Ti555.3. According to the results, a protective built-up layer was formed at low cutting speeds, but this layer was eliminated as the cutting speed was increased, and high wear rates were recorded.

Dry machining is vital with regard to the environment, and environmental protection laws are expected to be enforced soon requiring industries to resort to this method in compliance with occupational safety and health regulations. Dry machining is preferable for several reasons. For example, it does not pollute the atmosphere or water; it leaves no swarf residue, thus reducing disposal and cleaning costs; it is not hazardous to health; it is not harmful to the skin, and is non-allergenic [6]. In addition, dry machining is cheaper in terms of machining costs as it does not require the use of cutting fluids, which are much more expensive than manpower and overhead costs. Hence, less manufacturing costs will be incurred with the introduction of dry machining [7].

Ibrahim *et al*. [8] also investigated the progression of CVD carbide tools for the machining of Ti-64Al-4V ELI at low cutting speeds ranging from 55 to 95 m/min, and discovered that the insert tool life was reduced by a high feed rate and depth of cut.

In this study, the Two-Level Factorial design was used to determine the machining conditions necessary to obtain the optimum CVD carbide tool life during the turning of the titanium alloy, Ti-6Al-4V ELI, under dry condition.

2.0 EXPERIMENTAL

The chemical properties of the low interstitial Ti-6Al-4V with 32 HRC / 317 HV that was selected for the machining process, are shown in Table 1. CVD-coated carbide inserts, made from sandwich and rhombus-shaped CNGG 120408 SGF S05F, were used as the cutting tool.

The CNGG 120408 SGF S05-coated carbide tool together with its geometrical scheme is shown in Figure 1.

Table 1 Chemical composition of Ti-6Al-4V ELI (% wt)

Composition	C	Si	Fe	Ti	Al	N	V	S	O	H	Y
Wt%	0.11	<0.03	0.18	Bal.	6.1	0.007	4.0	<0.003	0.11	0.0031	<0.005

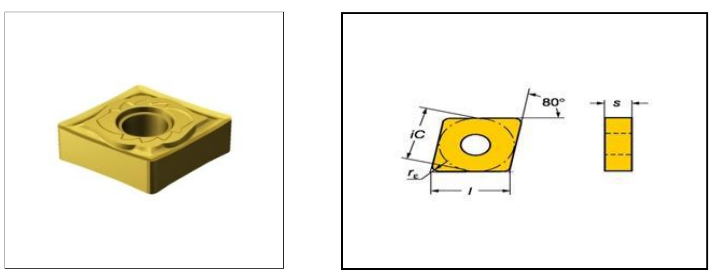


Figure 1 (a) CNGG 120408 SGF S05F insert (b) Schematic geometry of CNGG 120408 SGF S05F insert

Before the actual experiment was conducted, the flank wear and tool life were recorded by means of CNC programming. Since the literature indicated that most of the carbide tools had a cutting speed of 30 – 70 m/min, a cutting speed of 100 m/min was selected for this experiment [9-10]. Table 2 presents the cutting parameters and their combination levels that were employed in the experiments. The centre point runs were conducted twice in order the repeat the experiment so as to obtain an estimation of the pure error or noise. The machine runs based on the Two-Level Factorial design are shown in Table 3. The machining experiments were carried out in dry conditions. A Mitutoyo optical microscope was used to measure both the average (Vb_{avg}) and maximum (Vb_{max}) flank wear. The data was also recorded at every cutting length of 20 mm. The experiment ended once the following tool life criteria based on ISO 3685 were attained: (i) Average flank wear (Vb_{avg}) of ≥ 0.3 mm; (ii) Maximum flank wear (Vb_{max}) of ≥ 0.6 mm; (iii) Brittle fracture occurs that can potentially damage the workpiece. An average flank wear (Vb_{avg}) of 0.3 mm was fixed for all the inserts that were tested in this study.

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

Factors	Level	
	-1	**1**
Cutting speed, *v* (m/min)	100	140
Feed rate, *f* (mm/rev)	0.15	0.20
Depth of cut, *d* (mm)	0.35	

Table 3 The cutting parameters combination arranged by Two Level Factorial

Run	*v* (m/min)	*f* (mm/rev)	*d* (mm)
1	100	0.20	0.35
2	120	0.17	
3	140	0.20	
4	100	0.15	
5	140	0.15	
6	120	0.17	

3.0 RESULTS AND DISCUSSION

3.1 Tool Life

According to the results of the tool life experiments shown in Table 4, the maximum tool life of 20.48 minutes was attained at a cutting speed of 100 m/min and feed rate of 0.15 mm/rev, while the minimum tool life of 4.37 minutes was attained at a cutting speed of 140 m/min and a feed rate of 0.20 mm/rev. The main factor for the determination of the tool life was the flank wear which, unlike the crater wear, can be easily measured by means of an optical microscope. The optical microscope images of the CVD tool indicated that the flank wear occurred in Zone C, i.e. in the nose region, because of the low depth of cut of 0.35 mm, which was smaller than the nose radius of 0.8 mm that was applied during the hard turning. Figures 2 to 5 show the progression of tool wear for different cutting speeds and feed rates at every 20 mm length of cutting. There were three stages to the pattern of tool wear progression; (i) an early stage, where the wear rate was rapid; (ii) a middle stage, where the tool wear began gradually and then increased steadily; and (iii) a final stage where the wear rate increased drastically and damaged the surface of the flank wear.

Table 4 Experimental results for tool life

Run	Factor 1	Factor 2	Responses
	A: Cutting Speed (m/min)	**B: Feed Rate (mm/rev)**	**Tool Life (minute/s)**
1	120	0.17	8.68
2	100	0.20	18.02
3	140	0.20	4.37
4	100	0.15	20.48
5	140	0.15	5.94
6	120	0.17	8.77

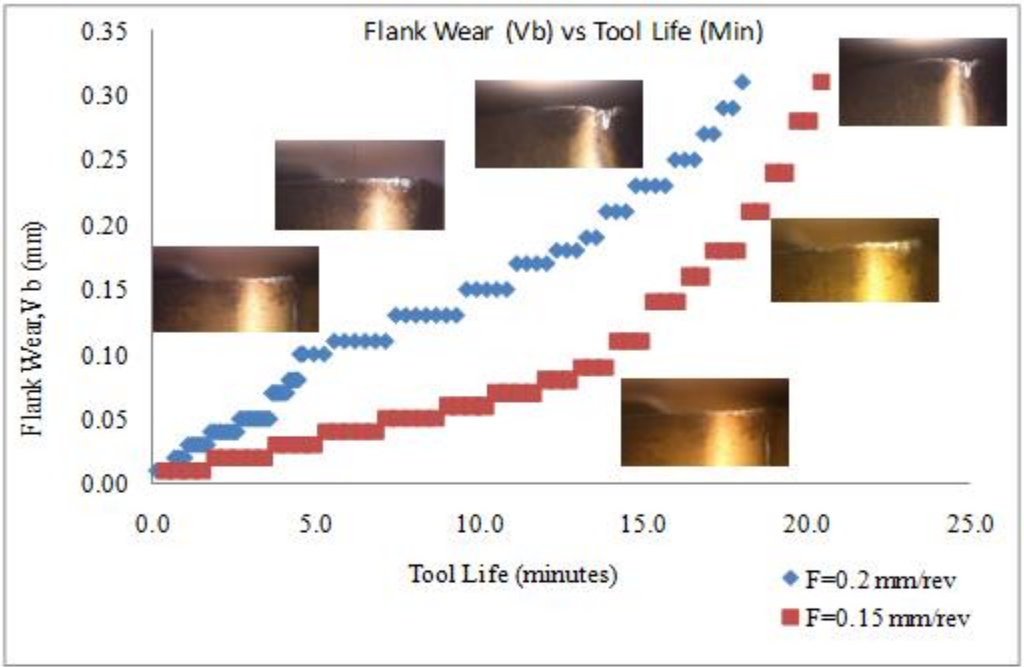


Figure 2 Effect of feed rate on tool life with cutting speed of 100 mm/min and depth of cut 0.35 mm

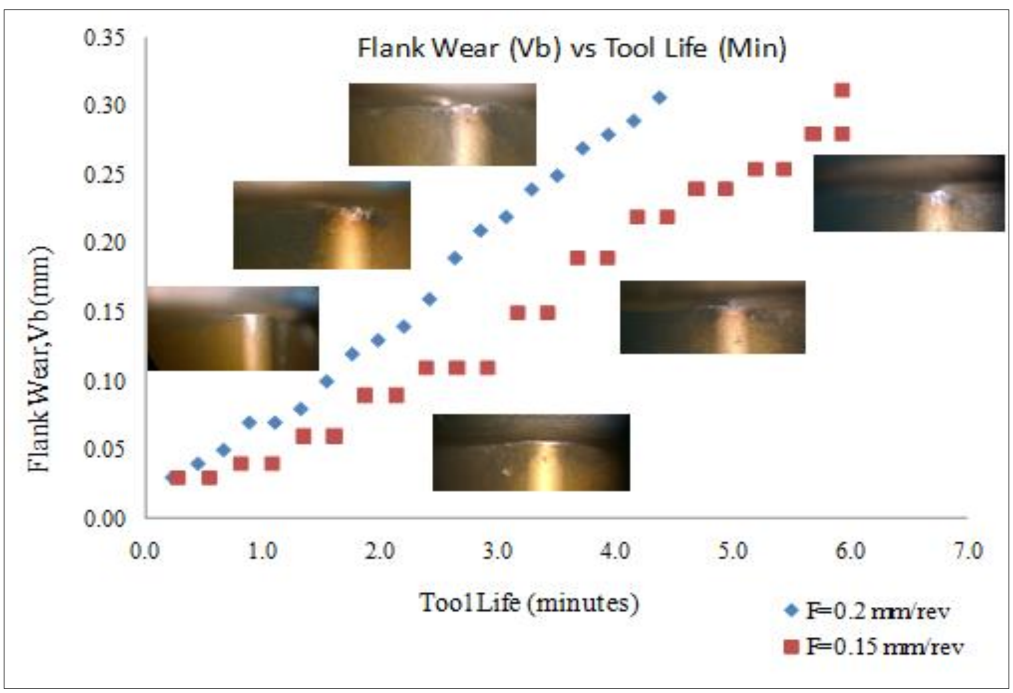


Figure 3 Effect of feed rate on tool life with cutting speed of 140 mm/min and depth of cut 0.35 mm

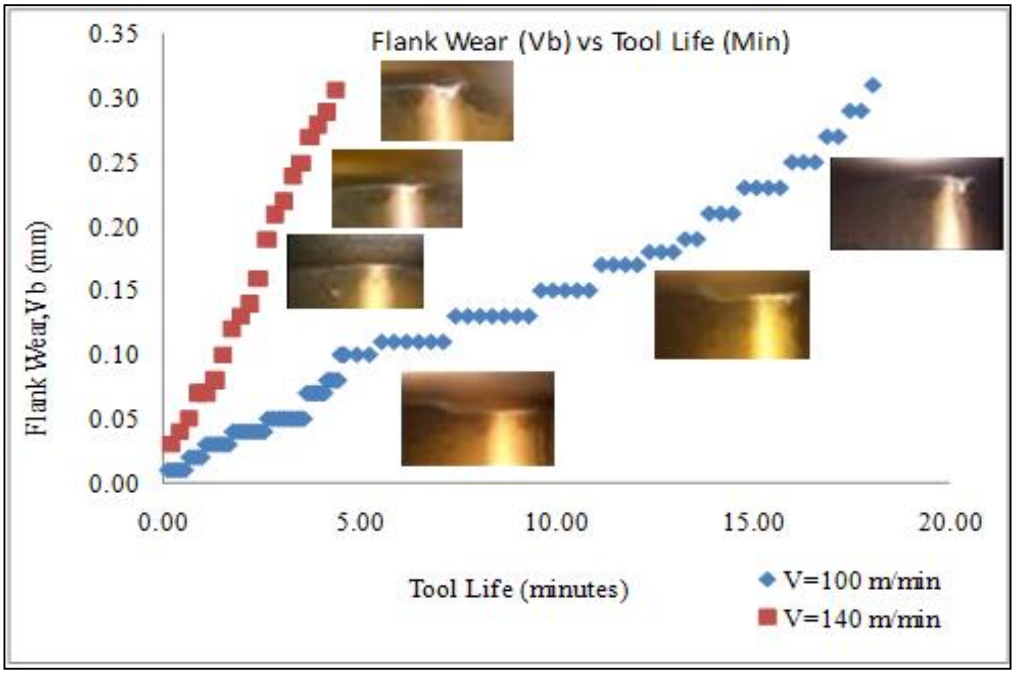


Figure 4 Effect of cutting speed on tool life with feed rate of 0.20 mm/rev and depth of cut 0.35 mm.

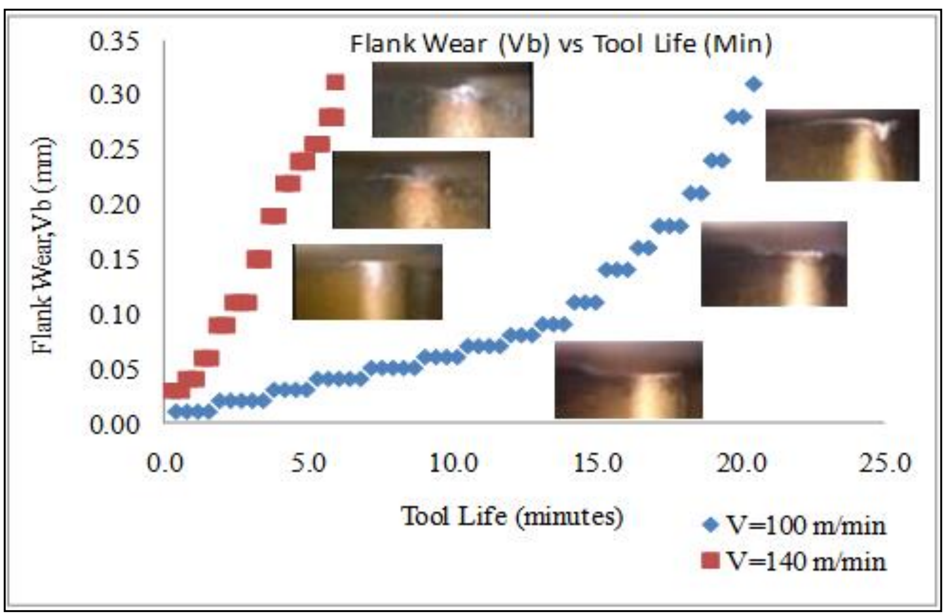


Figure 5 Effect of cutting speed on tool life with feed rate of 0.15 mm/rev and depth of cut 0.35 mm

Figures 2–5 indicate that the tool life in relation to the flank wear was reduced as the cutting speed and feed rate increased. The higher cutting speed and feed rate caused the temperature to rise, thus increasing the wear on the flank, which in turn led to a rapid rise in the tool wear and a reduction in the tool life. Luo *et al*. [12] noted that a very high cutting speed will cause the temperature to rise and soften the tool face, thus rendering it susceptible to abrasions from hard particles in the work material, leading to acceleration in the tool wear. The coating will be rapidly worn away at high cutting speeds and feed rates, leaving the substrate exposed, thus resulting in higher wear rates. In addition, a faster cutting speed and feed rate will not only raise the temperature but will also subject the tool to greater stress, thus combining to weaken the tool. Sulaiman *et al*. [13] used uncoated carbide inserts to explore various cutting parameters for the machining of Ti-6Al-4V ELI and discovered that a high cutting speed, greater feed rate and depth of cut resulted in a maximum flank wear rate. They also noted that a rapid flank wear rate was achieved at higher cutting speeds and feed rates [14]. Previous results have shown an increase in cutting speed will lead to an increase in the flank wear, whereby the flank wear advanced more rapidly at the maximum cutting speed of 220 m/min, followed by 170 m/min and 120 m/min [15-16]. It was also observed that the coating on the cutting tool had been stripped off, and that the tools had been evenly abraded as evidenced by the smooth and clean grooves of the worn region.

3.1 Analysis of Variance (ANOVA)

Once the model from the sequential model sum of squares had been selected, the next step was to analyse the model by means of the analysis of variance (ANOVA). The ANOVA for the tool life model is shown in Table 5. The prob > F is < 0.001 was much lower than the significant value of 0.05, thus indicating that the model terms, i.e. both A and B, were significant, where A is the cutting speed and B the feed rate. The "Lack of Fit" value of 48.9 suggested that the lack of fit was not significant compared to the pure error, thus indicating that the tool life model fitted.

Table 5 ANOVA for tool life model

Sources	Sum of Squares	Degree of Freedom	Mean Square	F Value	Prob > F	Condition
Model	202.73	2	101.36	1003.24	0.001	Significant
A	198.67	1	198.67	1966.29	0.001	-
B	4.06	1	4.06	40.19	0.024	-
Curvature	16.12	1	16.12	159.58	0.006	Significant
Residual	0.2	2	0.1	-	-	-
Lack of Fit	0.2	1	0.2	48.9	0.09	Not significant
Pure Error	3.78	1	3.78	-	-	-
Total	219.06	5	-	-	-	-

From the resultant ANOVA table it could also be seen that the F value of the cutting speed, A (1966.29) was greater than the F value of the feed rate, B (40.19), thus indicating that the cutting speed was a more significant factor than the feed rate in the determination of the tool life. At the same time, the Model F-value of 1003.24 suggested that the model was significant, with only a 0.10% probability that such a large "Model F-Value" could be the result of noise. "Prob > F" values that are below 0.05 indicate that the model terms are significant, while values above 0.1 indicate that the model terms are insignificant [17]. Therefore, A and B were regarded as significant model terms. This model may be improved by model reduction if there are many insignificant model terms (excluding those needed to support the hierarchy).

The "Curvature F-value" of 159.58 suggested that there was significant curvature (the average of the centre points minus the average of the factorial points) in the design space. There was only a 0.62% probability that such a large "Curvature F-value" could have been caused by noise. The "Lack of Fit F-value" of 48.9 suggested that there was a 9.04% probability that such a large "Lack of Fit F-value" could have been caused by noise. A large Lack of Fit F-value is not good and it must be significant if the model is to fit.

Table 6 shows the regression statistic where the value "Pred R-Squared" of 0.9855 is in reasonable agreement with the "Adj R- Squared" of 0.998. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable and ratio of 62.073 indicates an adequate signal. This model can be used to navigate the design space. The tool life data from experimental result can be compared with predicted data from mathematical model where predicted data was calculated by using Equation 2.

The final equation in terms of coded factors:

$$\textit{Tool Life} = 12.2 - 7.05*A - 1.01*B \quad (1)$$

The final equation in terms of actual factors:

$$\textit{Tool Life} = 61.54 - 0.35238*\text{Cutting Speed} - 40.3*\text{Feed Rate} \quad (2)$$

Table 6 Regression Statistic

Std. Dev.	0.32	R-Squared	0.999
Mean	11.04	Adj R-Squared	0.998
C.V.	2.88	Pred R-Squared	0.986
PRESS	3.18	Adeq Precision	62.073

The differences between the regression model and the actual experimental results are presented in Table 7 and Figure 6. It is obvious that on the whole most of the deviations between the experimental data and the predicted data, with the exception of experiment numbers 1 and 6, were ≤ 10%. The highest deviation of 43% between the actual data and the predicted data occurred at a cutting speed of 120 m/min and a feed rate of 0.17 mm/rev. Moreover, experiment numbers 1 (at a cutting speed of 100 m/min and feed rate of 0.15 mm/rev) and 2 (at a cutting speed of 100 m/min and feed rate of 0.20 mm/rev) resulted in the lowest deviation of 1%.

The plots for the cutting speed and feed rate as separate factors for tool life are shown in Figures 7 and 8. According to these graphs, the cutting speed had a steeper slope than the feed rate, thus indicating that the cutting speed had a greater impact on the tool life than the feed rate. The 3D plot for the tool life model is shown in Figure 10. The conclusion that can be drawn from all these figures is that an increase in the cutting speed and feed rate will lead to a reduction in the tool life.

Table 6 Comparison of actual tool life and predicted tool life

Run	Cutting Speed	Feed Rate	Tool Life, T		
	(m/min)	(mm/rev)	Actual (min)	Predicted (min)	Error (%)
1	120	0.17	8.68	12.40	43%
2	100	0.20	18.02	18.24	1%
3	140	0.20	4.37	4.15	5%
4	100	0.15	20.48	20.26	1%
5	140	0.15	5.94	6.16	4%
6	120	0.17	8.77	12.40	41%

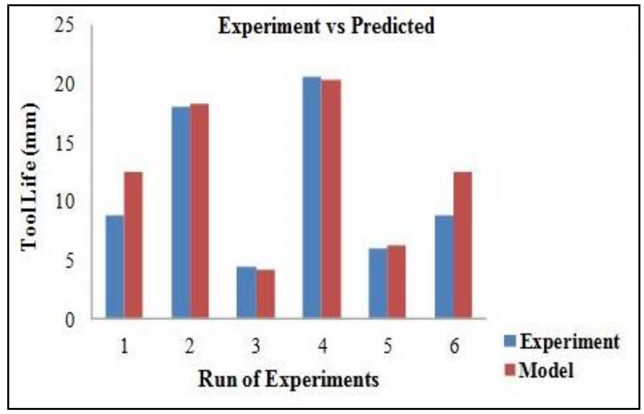


Figure 6 Comparison of actual tool life and predicted tool life

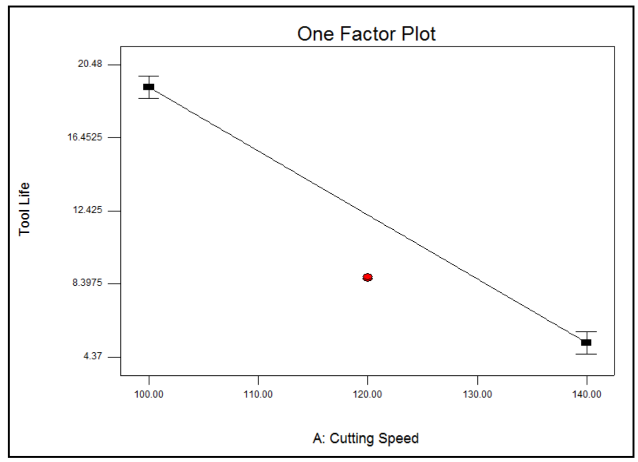


Figure 7 One factor plot of cutting speed versus tool life

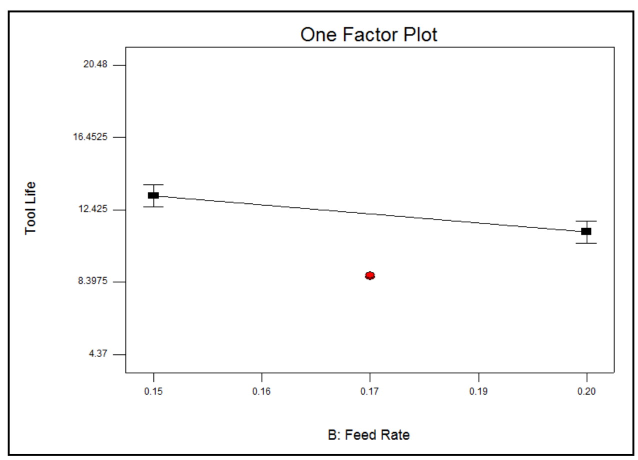


Figure 8 One factor plot of feed rate versus tool life

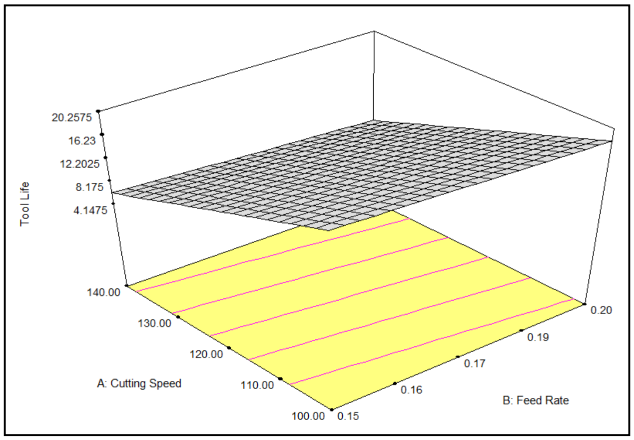


Figure 9 3D plot for tool life model

3.2 Optimization of Parameter for Tool Life

According to the numerical optimization for the improvement of the tool life of the model shown in Table 8, the target or goal of this optimization was at a maximum. In other words, the optimization of the tool life was conducted until the maximum value was attained. From the experiment, the minimum limit for the tool life was fixed at 4.37 minutes and the maximum limit was fixed at 20.48 minutes, while the cutting speed and feed rate ranged from 100 to 140 m/min and from 0.15 to 0.20 mm/rev, respectively.

Based on the solutions generated by the Design Expert software as shown in Table 9, two solutions, ranking from the highest to the lowest tool life, were proposed. In other words, the best solution was solution number one and the next was solution number two. Solution number one, which had a higher desirability, was selected to undergo the validation test. The current results were in good agreement with those obtained through similar investigations by other researchers [18-19]. The selected historical data together with the experimental validation are shown in Table 10. In the experiment, the error was also computed as a measurement of the noise (uncontrollable factors). The response surface contour, where the predicted tool life value was 20.26 minutes, is shown in Figure 10, while the ramps for each factor and the response requirements in relation to the factors and the response contributions are shown in Figure 11.

Table 8 Comparison of actual tool life and predicted tool life

Factors	Target	Lower Limit	Upper Limit
A: Cutting speed, m/min	In range	100	140
B: Feed rate, mm/rev	In range	0.15	0.20
Tool Life, min	Maximum	4.37	20.48

Table 9 Solution suggested

No	A: Cutting speed, m/min	B: Feed rate, mm/rev	Tool Life, min
1	100	0.15	20.26
2	100	0.16	20.12

Table 10 Optimum data selected for experiment validation with the error

Cutting speed (m/min)	Feed Rate (mm/rev)	Tool Life (min)	Description
100	0.15	20.26	Data selected
100	0.15	20.48	Experiment validation
		1%	Error, %

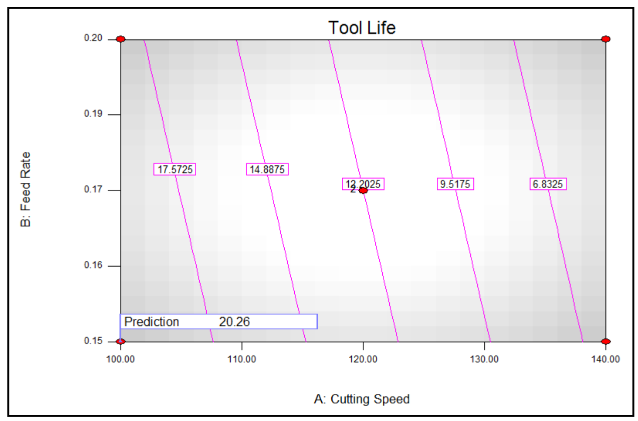


Figure 10 Response surface contours for prediction tool life value

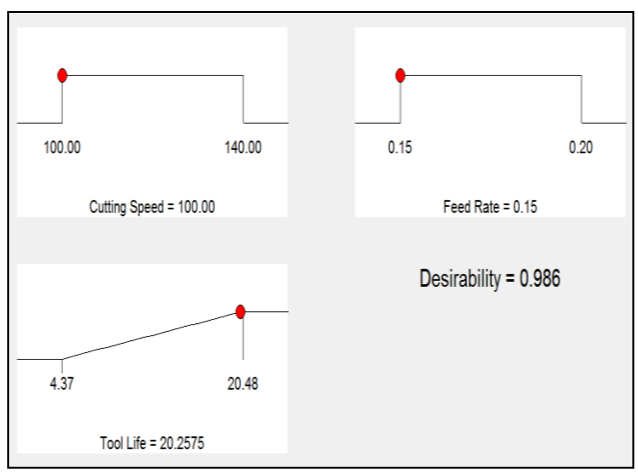


Figure 11 Ramps for each factors and response combination selected

4.0 CONCLUSION

An examination of the impact of cutting speed (V), feed (f), and depth of cut (d) on tool life during the turning of the titanium alloy, Ti-6Al-4V ELI, under dry conditions has been described in detail in this paper.

a. According to the results, the titanium alloy, TI-6A1-4V ELI, can be machined by a CVD carbide tool at a medium cutting speed in dry conditions.
b. The tool wear progression increases drastically when the flank wear (V_b) is between 0.20 mm to 0.30 mm. The tool wear progression is also affected by a high cutting speed and feed rate, while the tool life is shortened over time. On the other hand, the tool life is extended by a low cutting speed and feed rate.
c. The ANOVA analysis also suggests that the cutting speed is a more significant factor than the feed rate in the determination of the tool life. The tool life model is generated as follows:
   Tool Life = 61.54 – 0.35238*Cutting Speed – 40.3*Feed Rate
d. According to the optimizations of the parameters, a maximum tool life of 20.26 minutes is attained at a cutting speed of 100 m/min and a feed rate of 0.15 mm/rev.

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References

[1] Ezugwu, E. O. and Wang, Z. N. 1997. Titanium Alloys and Their Machinability-A Review. *Journal of Materials Processing Technology*. 68(3): 262-274.
[2] Ezugwu, E. O. 2005. Key Improvements in the Machining of Difficult-To-Cut Aerospace Superalloys. *International Journal of Machine Tools and Manufacture*. 45(12-13): 1353-1367.
[3] Che Haron, C. H., Ginting, A. and Goh, J. H. 2001. Wear of Coated and Uncoated Carbides in Turning Tool Steel. *Elsevier Journal of Material Processing Technology*. 116(33): 49-54.
[19] Palanisamy, S., McDonald, S. D. and Dargusch, M. S.2009. Effects of Coolant Pressure on Chip Formation While Turning Ti6Al4V Alloy. *International Journal of Machine Tools and Manufacture.* 49: 739-743.
[4] Kalpakjian, S., and S. R. Schmid. 2001. *Manufacturing Engineering and Technology*. 4th ed. New Jersey: Prentice Hall.
[5] Arrazola, P. J., Garay, A., Iriarte, L. M., Armendia, M., Marya, S. and Maitre, F. L. 2009. Machinability of Titanium Alloys (Ti6Al4V and Ti555.3). *Journal of Materials Processing Technology*. 209: 2223-2230.
[6] Sreejith, P. S. and Ngoi, B. K. A. 2000. Dry Machining: Machining of the Future. *Journal of Materials Processing Technology.* 101: 287-291.
[7] Bryne, G., Dornfield, D. and Denkena, B. 2003. Advancing Cutting Technology. *Annals of the CIRP*. 52(2): 483-507.
[8] Ibrahim, G. A., Che Haron, C. H. and Ghani, J. A. 2009. Progression and Wear Mechanism of CVD Carbide Tools in Turning Ti-6Al-4V ELI. *International Journal of Mechanical and Materials Engineering*. 4(1): 35-41.
[9] Armendia, M., Garay, A., Iriarte, L. M. And Arrazola, P.J. 2010. Comparison of the Machinabilities of Ti6Al4V and TIMETAL® 54M using Uncoated WC–Co tools. *Journal of Materials Processing Technology*. 210: 197-203.
[10] Zheng, X. H., Liu, Z. Q. And Chen, M. 2013. Experimental Study on Micro-Milling of Ti6Al4V with Minimum Quantity Lubrication. *International Journal of Nanomanufacturing.* 9: 570-582.
[11] ISO (International Organization for Standardization). 1993. *Testing with Single Point Turning Tools (ISO 3685)*. 2nd ed.
[12] Luo, S. Y., Liao, Y. S. and Tsai, Y. Y. 1999. Wear Characteristic in Turning High Hardness Alloy Steel by Ceramic and CBN Tools. *Elsevier Journal of Materials Processing Technology*. 88: 114-12.
[13] Sulaiman, M. A., Che Haron, C. H., Ghani, J. A. and Kasim, M. S. 2013. Optimization of Turning Parameters for Titanium Alloy Ti-6Al-4V ELI Using the Response Surface Method (RSM). *Journal of Advanced Manufacturing Technology*. 7(2): 11-28.
[14] Sulaiman, M. A., Che Haron, C. H., Ghani, J. A. and Kasim, M. S. 2012. The Study of Wear Process on Uncoated Carbide Cutting Tool in Machining Titanium Alloy. *Journal of Applied Sciences Research*. 8(9): 4821-4827.
[15] Germain, G., Morel, A. and Bouchnak, T. B. 2013. Identification of Material Constitutive Laws Representative of Machining Conditions for Two Titanium Alloys: Ti6Al4V and Ti555-3. *Journal of Engineering and Materials Technology.* 135: 1-11.
[16] Sulaiman, M. A., Che Haron, C. H., Ghani, J. A. and Kasim, M. S. 2014. Effect of High-speed Parameters on Uncoated Carbide Tool in Finish Turning Titanium Ti-6Al-4V ELI. *Sains Malaysiana.* 43(1): 111–116.
[17] Cho, J. H., Hwang, M. J., Han, M. K., Han, O. S., Song, H. J. and Park, Y. J. 2014. Eutectoid Nanostructure Formation in $T_{i\text{-}x}$pd Alloys and Its Effects on Mechanical Properties and Cytotoxicity. *Journal of Alloys and Compounds.* 610: 74-81.
[18] Antonysamy, A. A., Meyer, J. and Prangnell, P. B. 2013. Effect of Build Geometry on the B-Grain Structure and Texture in Additive Manufacture of Ti6Al4V by Selective Electron Beam Melting. *Materials Characterization*. 84: 153-168.