

Identifying Optimal Cutting Parameters in Drilling of Titanium Aluminum Vanadium Using Finite Element Analysis

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Abstract

Titanium alloys are widely used in the aerospace industries because of their excellent strength-to-weight ratio, high resistance to corrosion, high chemical reactivity and low thermal conductivity and ability to withstand high temperatures. However, these properties make titanium alloys difficult to machine. Drilling of titanium alloy may generate high temperature and high cutting forces. This paper is aimed at determining the suitable cutting parameters in the drilling of titanium alloys to minimize the cutting temperature and cutting forces. A finite element 3D model of the drilling process is simulated in this research. A combination of drilling speeds and feed rates are simulated to obtain the resulting responses of cutting force and temperature. The central composite design (CCD) is used to generate different combinations of cutting parameters to reduce the number of experiments and optimize the temperature and cutting force responses. Results show at the drilling speed of 5000 rpm with a feed rate of 0.1 mm/rev, temperature and cutting force significantly reduced.

Keywords

Titanium Alloys, Design of Experiments, Drilling, Cutting Force

1. Introduction

Titanium is known to be very difficult to machine, despite its excellent properties and wide usage. The reason for this is due to their poor thermal conductivity [1]. The heat generated while machining does not dissipate because of the weak thermal conductivity and this will cause a definite reduction in tool life. Heat is

build-up around the cutting edge and tool face. When the temperature escalates during machining, it causes tool wear or failure due to galling, smearing as well as welding. Chip formation also occurs and is caused by dissimilarity of the shear strains in the chip and is bounded by a narrow band that forms serrated chips [2]. Conventional cutting tools that work for other traditional industrial materials do not work with Titanium even at normal cutting speeds. Most researches focused on turning and end milling operations and not much work has been done on drilling of Titanium alloys. Yang *et al.* [1] has covered different areas of machining such as turning, milling and grinding. Therefore, it is important to participate in contributing research to identifying important parameters in drilling of Titanium and further optimize it as Titanium has shown to be thriving in aerospace industry, and continues to gain favor when it comes to the choosing of materials. Among other applications, titanium and its alloys are also widely used in chemical industries, manufacturing of turbine blades, bio-medical engineering and as bone supplement in bone grafting [3]. Isbiliar *et al.* [4] presented that FE model of drilling could accurately predict the cutting force, torque and stresses with respect to drilling parameters. Parameters of machining that are essential include cutting speed, feed rate and depth of cut. Experimental work was conducted by Sultan *et al.* [5] to identify the optimum cutting speed and feed rate for discontinuous chip formation with a drilling process. It was found that the lowest cutting speed as well as feed rate produced the best performance in regards to chip formation. Besides that, the material chosen for the cutting tool is vital when machining of titanium is concerned. The important and influential parameters are only considered for this research paper. The influence of cutting parameters such as cutting speed, feed rate are considered to estimate the cutting force and cutting temperature. These parameters were tested and then optimized using Response Surface Methodology with the Design Expert. The research performed here is aimed at reducing the cutting temperature and cutting force which is pre-determined by the parameters tested to further improve cost and machining efficiency with regards to tool life and workpiece surface integrity. At the same time, this research looks to ultimately determine the utmost optimal parameters for Titanium drilling that can be used as reference in all future drilling activities of the Titanium material.

2. Experimental Details

2.1. Workpiece Material

The workpiece used is the *Titanium Aluminum Vanadium* (Ti6Al4V) with the dimensions of $12 \times 3 \times 12$ mm for width, height and length respectively.

Cutting Tool

In this study, the cutting tool used is the standard carbide drill commonly used in industrial. The carbide drill is coated with one layer of TiAlN with a thickness of 0.007 mm. The cutting tool has a drill diameter of 6 mm and a helix angle of 30° .

2.2. Design of Experiment

The experiment was conducted to study and analyze the cutting parameters in drilling. The influence of the parameters was investigated to identify its correlation to the response, temperature and cutting force. A simulation of a TiAlN coated carbide tool drilling a Ti6Al4N workpiece material is conducted to identify the maximum cutting temperature and cutting force acting on the workpiece. The testing parameters were generated using Central Composite Design which will help in reducing the number of experiments necessary. A two-level factorial is selected for the design of this experiment. CCD uses a coded factor of -1, 0 and 1 to produce varied iterations to determine their various interactions as shown in **Table 1**. The drilling parameters tested are the spindle speed and feed rate. In total, 13 number of runs were generated by the software shown in **Table 2**. The software uses 5 center point replicates with the other 8 points being an independent interaction. The drilling parameters and CCD matrix for design and responses are shown below:

3. Results and Discussion

3.1. Simulation

The simulation was conducted using the *ThirdWave Systems AdvantEdge* software.

Table 1. Drilling Parameters used for study.

Parameters	Values		
Factorial Level	-1	0	1
Spindle Speed (rpm)	1000	3000	5000
Feed Rate (mm/rev)	0.1	0.55	1.0

Table 2. CCD design matrix and responses.

Test No.	Parameters		Response	
	Speed (m/min)	Feed (mm/rev)	Temperature (°C)	Cutting Force (N)
1	-1	-1	330	969
2	0	0	320	1753
3	1	-1	135	407
4	0	0	850	3796
5	-1	1	720	6137
6	0	0	1150	4192
7	1	1	700	5926
8	0	0	850	3903
9	0	1	750	6756
10	0	-1	750	873
11	-1	0	800	4157
12	1	0	950	5883
13	0	0	1050	3743

The responses obtained from the simulation were interpreted graphically and its numerical values were extracted to discuss and compare the different variables. From the responses obtained, 3 graphs (Figures 1-3) were plotted to obtain an approximate analysis of the results. The graphs are shown below:

From the graphs shown above, the lowest feed rate, 0.1 mm/rev shows the lowest responses for temperature and cutting force. The values steadily decrease as the speed increases. This coincides with previous researches that state the optimal parameters for drilling require a low feed rate but high cutting speed.

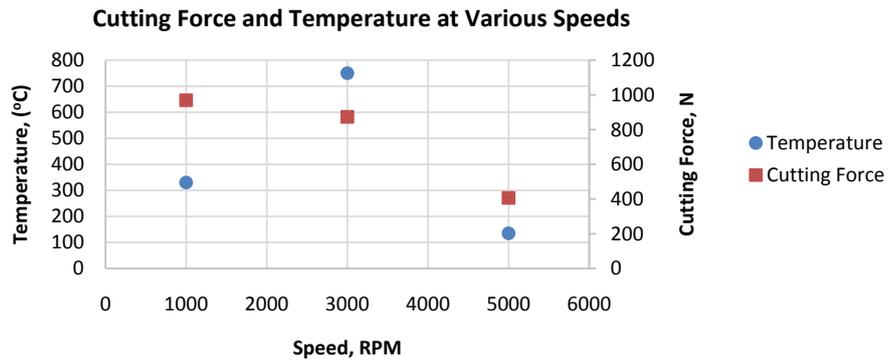


Figure 1. Cutting force and temperature at 0.1 mm/rev feed rate.

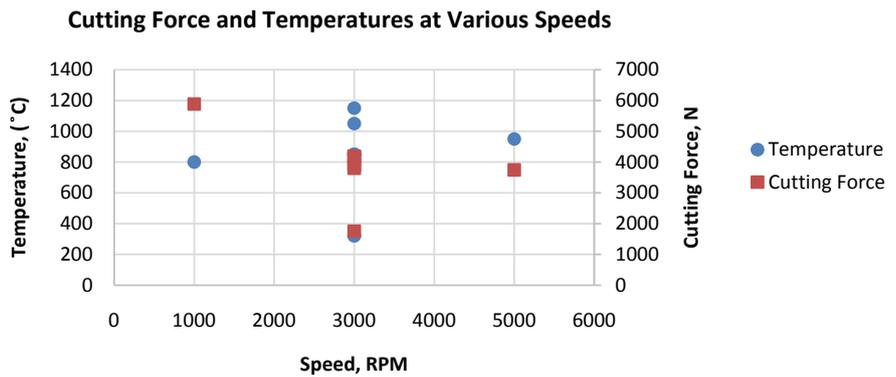


Figure 2. Cutting force and temperature at 0.55 mm/rev feed rate.

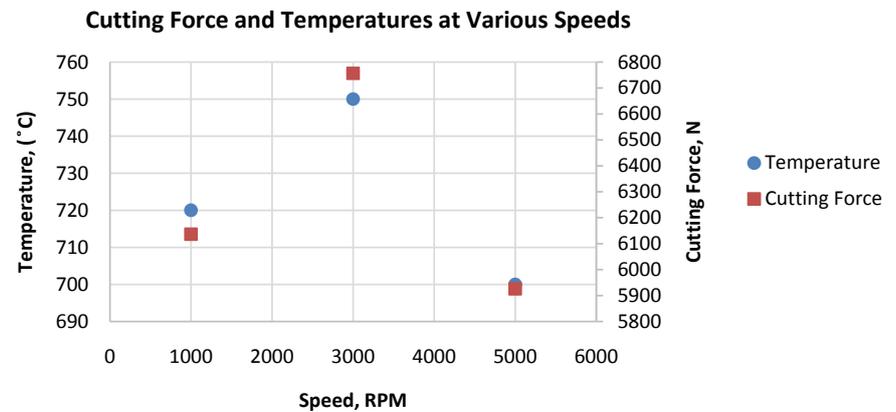


Figure 3. Cutting force and temperature at 1.0 mm/rev feed rate.

3.2. Analysis of Variance (ANOVA)

The Model F-value of 23.76 implies (Table 3) that the model is significant. There is only a 0.02% chance that an F-value this large could occur due to noise. Values of “Prob > F” less than 0.05 indicates that the model terms are significant. In this case, the feed rate is a significant model term.

3.3. Residual Plots

The residual plot (Figure 4) is used to examine the goodness-of-fit in regression and ANOVA. Examining residual plots helps determine where the assumptions are being met. If the assumptions are met, there will be minimal variance. The plots above show minimum variance as the points are aligned closely to the predicted line.

3.4. Optimizing Cutting Force and Temperature

After analyzing the variance, it is important to identify the most suitable parameters for cutting speed and feed rate. These values should be optimized to produce the smallest value for cutting force and temperature. Table 4 below shows the optimized values that meet the requirement of minimizing the responses. The confidence level was maintained at 92% with desirability of 0.92.

The graph (Figure 5) shows the relationship between the feed rate and drilling speed with the temperature and cutting force responses. The temperature graph showed minimal changes in temperature with the various parameters. A significant drop in temperature can be observed in the graph when the feed rate is 0.1 mm/rev and the cutting speed is 94.25 m/min. As for the cutting force response, a more significant change can be observed with the various parameters.

Table 3. ANOVA table for cutting force.

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	4.591E+007	2	2.296E+007	23.76	0.0002
A-Speed	1.515E+005	1	1.515E+005	0.16	0.7005
B-Feed	4.576E+007	1	4.576E+007	47.36	<0.0001
Residual	9.663E+006	10	9.663E+006		
Lack of fit	5.826E+006	6	9.709E+005	1.01	0.5198
Pure Error	3.873E+006	4	9.594E+005		
Cor Total	5.558E+007	12			

Table 4. Optimum cutting parameters for temperature and cutting force.

No.	Speed	Feed	Temperature	Cutting Force	Desirability
1	94.25	0.100	310.91	1127.64	0.92
2	94.25	0.104	316.68	1150.81	0.92
3	93.378	0.100	317.59	1123.97	0.92

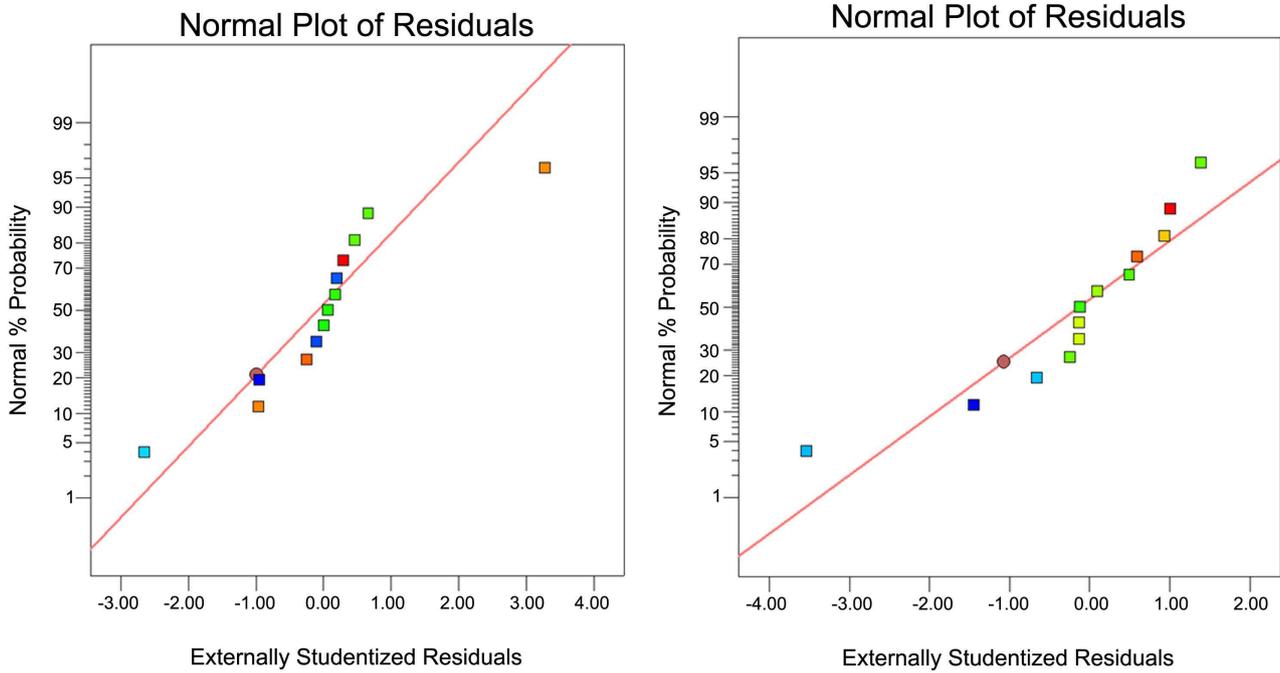


Figure 4. Residual plots.

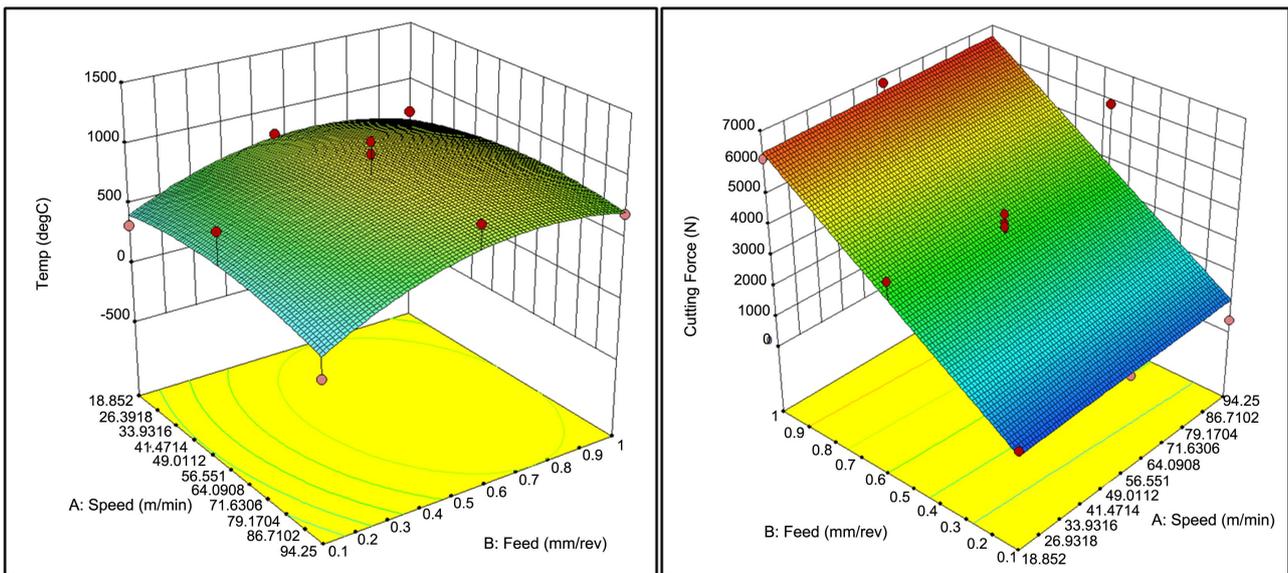


Figure 5. 3D plots of temperature and cutting force.

The lowest feed rate and cutting speed produce significantly lower temperature compared to the highest feed rate and cutting speed. However, to reduce both responses, the feed rate was chosen to be the lowest value at 0.1 mm/rev whilst the cutting speed has the maximum value of 94.25 m/min.

The cutting force and temperature graph above further depict the predicted response with respect to the drilling parameters. The contour plots in Figure 6 helps to understand the relationship between the parameters and the responses. While other combinations of parameters may produce lower responses, CCD

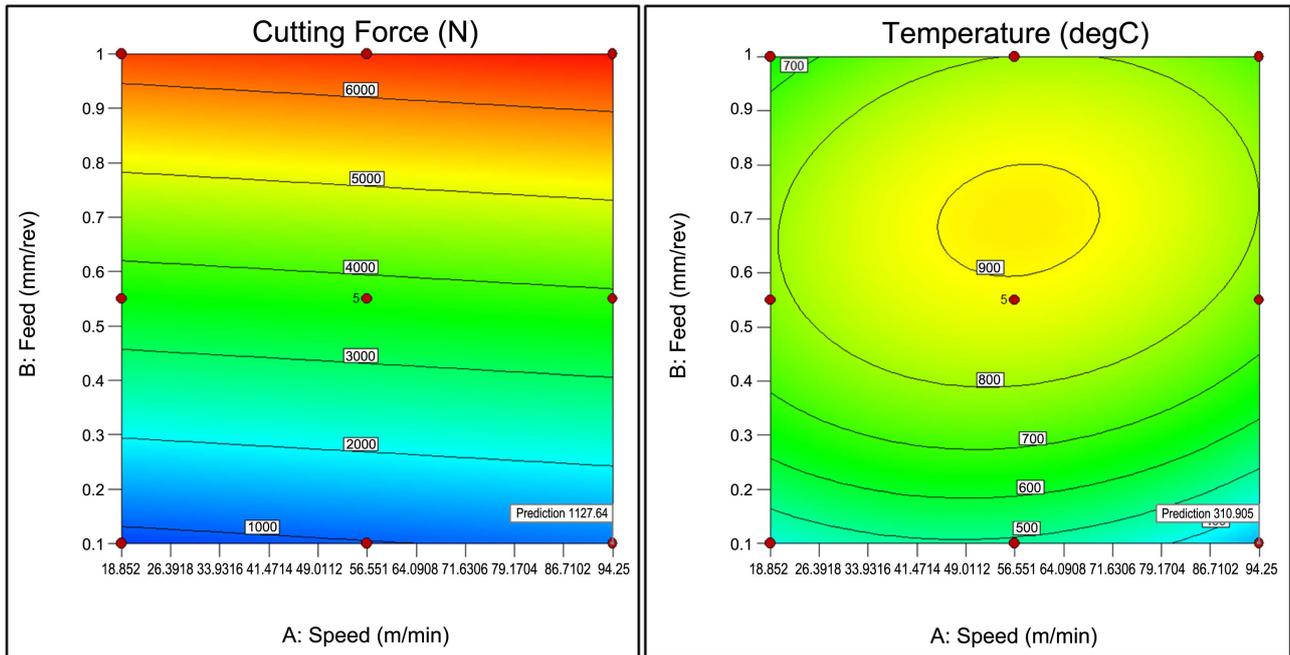


Figure 6. Contour plots of temperature and cutting force.

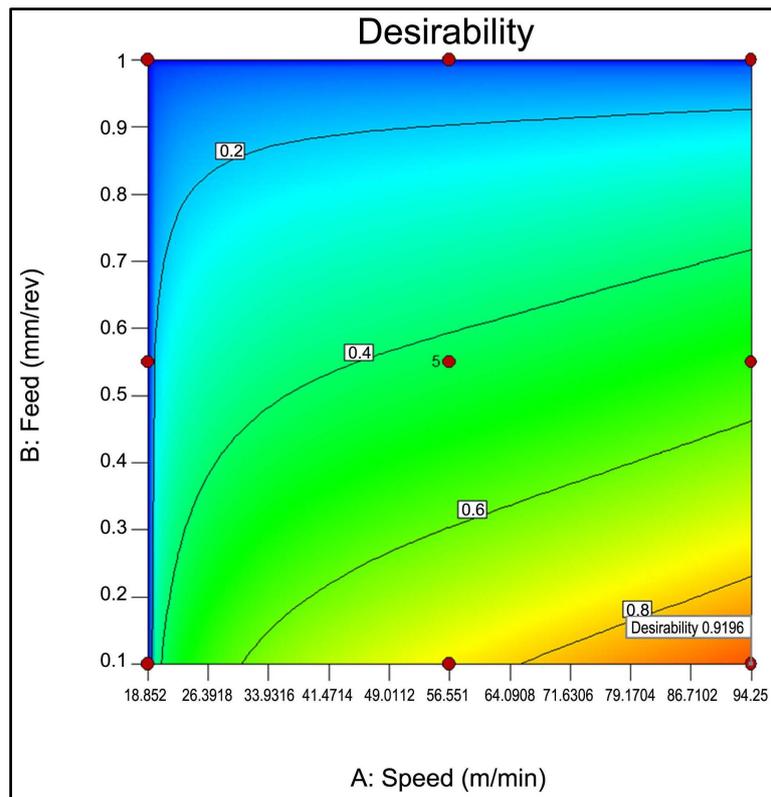


Figure 7. Desirability of the responses.

uses the selection criteria of lowering the responses to determine the best result for both temperature and cutting force simultaneously. At 94.25 m/min and 0.1 mm/rev, the desirability of the responses (Figure 7) is highest at 92.1%. The

yellow zone in the graph (Figure 7) shows that the predicted values are in range of the desired criteria.

4. Conclusions

To conclude this research paper, the optimal parameters for the drilling of titanium have been found through the simulation and optimization done for this research.

1) A Central Composite Design (CCD) of response surface methodology (RSM) has been adopted to determine the parametric combination (treatment) for conducting the experiments and obtain maximum process-related information with the least number of experimental runs.

2) Finite element analysis has been used to develop 3D model and perform the drilling simulation using Advant Edge.

3) The lowest responses for the temperature and cutting force obtained from the simulation are 310.91 °C and 1127.64 N with the optimal cutting parameters at 94.25 m/min and 0.1 mm/rev for drilling speed and feed rate respectively.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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