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STUDY OF CUTTING FORCES AND SURFACE ROUGHNESS IN TURNING OF TI-6AL-4V UNDER FLOOD COOLING BASED ON TAGUCHI METHOD

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Keywords:
Ti-6Al-4V;
Cutting force;
Surface roughness;
Flood cooling;
Taguchi method;
Analysis of variance.

Abstract

Titanium and its alloys are used extensively in aerospace industry because of their excellent combination of high specific strength which is maintained at even elevated temperature, their fracture resistant characteristics, and their exceptional resistance to corrosion. They are also being used increasingly in other industrial and commercial applications, ranging from petroleum refining to pulp and paper and nuclear waste storage to food processing. The Ti-6Al-4V comprises about 45% to 60% of total titanium production. In this experimental study, the effect and optimization of machining parameters on surface roughness and cutting forces in a turning of Ti-6Al-4V alloy under flood cooling was investigated by using the Taguchi method. The studies were conducted under different process parameters, (viz. cutting speeds, feed rates, and depths of cut) under flood cooling by vegetable oil based water miscible metal cutting fluid. It was found that feed rate is the most significant parameter for lowering surface roughness where as depth of cut has the maximum effect on higher cutting forces. The ANOVA also confirms that contribution of cutting speed is minor in case of cutting force generation where as inverse effect of cutting speed on surface roughness is observed.

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1 Introduction

Titanium alloys have become established engineering materials available in a range of alloys and in all the wrought forms, such as billet, plate, sheet, strip, hollows, extrusions, wire, etc.

Even after increased usage and production of titanium and its alloys, they are still considered as costly metals because of the complexity of the extraction process, difficulty of melting, and problems during fabrication and machining. On the other hand, the extensive service lives and excellent properties counterbalance the higher production costs.

Titanium sometimes is classified as difficult to machine metal by traditional methods. Many authors like, Ezugwu and Wang, Machado and Wallbank have attributed in part to the physical, chemical, and mechanical properties of Titanium alloys. A brief summary of the causes of poor machinability of titanium alloys as claimed by several authors is given below. [Ezugwu and Wang, 1997; M. Rahman et al., 2003; Mathew and Donachie, 2003; Machado and Wallbank, 1990 H. Siekman, 1955; Komanduri and Turkovich, 1981]

i. High strength is maintained at elevated temperatures that are generated in machining and this opposes the plastic deformation needed to form a chip.

ii. Titanium is a poor conductor of heat. Heat, generated by the cutting action, does not dissipate quickly. Ezugwu and Wang mentioned that high cutting temperatures are generated when machining titanium alloys and the fact that the high temperatures act close to the cutting edge of the tool are the principal reasons for the rapid tool wear. As illustrated in Figure 1, a large proportion, about 80% of the heat generated when machining titanium alloy Ti-6Al-4V is conducted

iii. into the tool because it cannot be removed with the fast flowing chip or into the workpiece due to the low thermal conductivity of titanium alloys, which is about 1/6 that of steels.

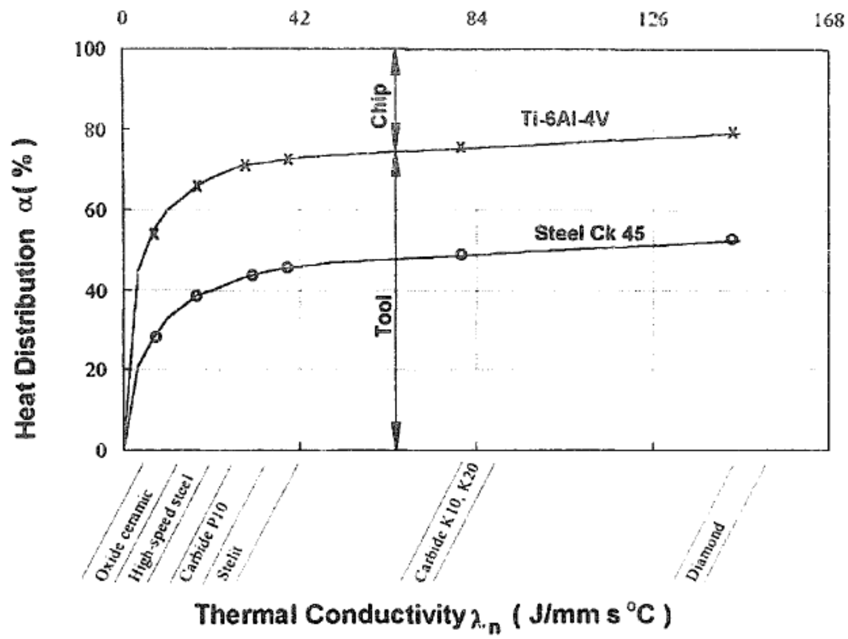

Figure 1 Distribution of thermal load when machining titanium and steel [Ezugwu and Wang, 1997]

iv. Machado and Wallbank observed that Titanium's chip is very thin which causes an unusually small contact area between the chip and tool. (one third that of the contact area in case of steel at the same feed rate and depth of cut.) This causes high stresses at tool tip, although cutting forces are reported to be similar to steel.

v. The 'catastrophic thermoplastic shear' process by which titanium chips are formed. Titanium's low volumetric specific heat and relatively small contact area along with the presence of a very thin flow zone between the chip and the tool (approximately 8 μm compared with 50 μm when cutting iron under the same cutting conditions) cause high tool-tip temperatures of up to about 1100°C [Machado and Wallbank, 1990; H. Siekman, 1955]

vi. Titanium has a strong alloying tendency or chemical reactivity with materials in the cutting tools at tool operating temperatures. This causes galling, welding, and smearing along with rapid destruction of the cutting tool.[M. Rahman et al. 2003]

vii. Titanium has a relatively low modulus of elasticity, thereby having more "springiness" than steel. Work has a tendency to move away from the cutting tool unless heavy cuts are maintained or proper backup is employed. Slender parts tend to deflect under tool pressures, causing chatter, tool rubbing, and tolerance problems.

viii. Titanium’s fatigue properties are strongly influenced by a tendency to surface damage. Care must be exercised to avoid the loss of surface integrity, especially during grinding and finish machining.

ix. Titanium’s work-hardening characteristics are such that Ti-alloys demonstrate a complete absence of “built-up edge.” But with high bearing force it results in a great increase in heat on a very localized portion of the cutting tool.

x. Machado and wallbank also mentioned that care must be taken about titanium’s tendency to ignite during machining because of the high temperature involved.

In view to such difficulties, machining of titanium alloys has been investigated through extensive experimental work under different conditions (i.e. flood cooling, minimum quantity lubrication, high pressure jet cooling, cryogenic cooling and hot machining). Also machining of Titanium alloys with different tool geometry and tool materials has also been explored.

Hascalik and Caydas, 2008; has reported that the feed rate parameter is the main factor that has the highest influence on the surface roughness and this factor is about 1.72 times more important than the second ranking factor (depth of cut). Cutting speed does not seem to have much of an influence on surface roughness.

Doshi et al., 2013; reported in his review paper that nanofluid looks promising and improve performance of machining if used as cutting fluid during machining of difficult to cut materials.

State of the art detailed research articles and plenty of experimental studies are available on Ti-6Al-4V turning under different conditions. It was also stated that the force generation during the turning of Ti-6Al-4V is similar that of Steel and hence power consumption. But exclusive primary study on the force analysis and surface finish in turning of Ti-6Al-4V under flood cooling condition is rare. In respect to the observed gap this experimental study is performed.

The objective of this experimental study is to investigate the effect of cutting parameters (viz. cutting speed, feed rate and depth of cut) on the performance characteristics (viz. surface roughness and cutting force components) in the environment of flood cooling with vegetable oil based metal cutting fluid during turning of Ti-6Al-4V. For the experimental study Taguchi approach is followed.

2 The Taguchi method and design of experiment

As per the Taguchi method, three major process parameters with three levels of each are identified as the control factors such that the levels are sufficiently far apart. The process parameters and their ranges are finalized based on the literature and machine operator's experience. The three control factors selected are Cutting Speed (A), Feed (B) and Depth of Cut (C). Table 1 shows the control factors and their levels.

Table 1 - Control factors and levels

Level number	Control factors		
	Cutting speed m/min	Feed mm/rev	DOC mm
	A	B	C
1	50	0.16	0.75
2	70	0.2	1.25
3	90	0.24	1.75

Based on the number of factors, levels of each factor and total degrees of freedom as mentioned below, particular orthogonal array $L_9(3^4)$ is selected from the standard list of orthogonal array.

i. Number of control factors = 3
ii. Number of levels for each control factor = 3
iii. Total degrees of freedom of factors = 8

Orthogonal array $L_9(3^4)$ can accommodate a maximum of four number of control factors, in this case one column in this orthogonal array is left empty which is also permitted by the principles of robust design methodology. Table 2 indicates the 9 experiments with its process parameters and their values.

Table 2 – Experimental design as per $L_9(3^4)$ Orthogonal array

Exp. No.	Cutting speed m/min	Feed rate mm/rev	DOC mm	Empty
1	50	0.16	0.75	-
2	50	0.2	1.25	-
3	50	0.24	1.75	-
4	70	0.16	1.25	-
5	70	0.2	1.75	-
6	70	0.24	0.75	-
7	90	0.16	1.75	-
8	90	0.2	0.75	-
9	90	0.24	1.25	-

3 Experimental Study

An experimental setup is developed for turning Ti-6Al-4V rod on centre lathe. Rigid, high power precision lathe equipped with specially designed experimental set up and data acquisition system is used for experimental work. The experimental system can be divided in to two subsystems.

i. Machine tool subsystem.

ii. Data acquisition subsystems.

3.1 Machine tool subsystem

Ti-6Al-4V grade 5 rod with diameter 26mm and 35mm length is used as work piece material. Rigid, high power precision lathe - model: NH22, HMT make is used to turn the Ti- 6Al-4V rod. In order to impart the rigidity to the machining system, the work piece is held between three jaw chuck and revolving centre.

Sandvik make right hand tool holder, DCBNR 2525 M12 is used to hold the tool bit of uncoated Tungsten carbide of ISO S-grade, CNMG 120408 H13A, sandvik make. Uncoated tungsten carbide tool bit is used because literature revealed that uncoated tungsten carbide tool produce better surface finish compared to coated tungsten carbide tool.

Cutting fluid employed is VASCO 1000, vegetable oil based water miscible metal working fluid with 3ltr/min flow rate on the rake surface during turning process.

3.2 Data Acquisition subsystem

For the study of machinability, it is paramount to have accurate data acquisition system. For measuring performance parameters, namely cutting force and surface roughness following are used.

i. Kistler dynamometer with dnyoware software for force measurement.

ii. Surface profilometer for measurement of surface finish.

4 Results and discussion

Ti-6Al-4V rod machining carried out with water miscible vegetable oil based metal cutting fluid with 5% concentration. Cutting forces can be divided into three components: feed force (Fx), radial force (Fy) and tangential cutting force (Fz). Usually the tangential cutting force is the largest of the three components, though in finishing the radial thrust force is often larger, while the feed force is minimal. Cutting forces are measured by the Kistler dynamometer and surface roughness measured with surface profilometer. Surface roughness is measured four times and its average is indicated in results for each experiment. Table 3 indicates the summary of results.

Table 3 Summary of results

Exp. No.	Fx (N)	Fy (N)	Fz (N)	SF (μ)
1	160	136	231	1.41
2	233	112	400	2.17
3	313	283	705	2.90
4	240	220	392	1.74
5	325	241	600	2.46
6	150	203	345	2.84
7	202	145	502	1.98
8	134	184	279	2.15
9	229	228	496	2.63

4.1 Analysis of Variance

The machining performance for each experiment of the L9 can be calculated by taking the observed values of the surface roughness and cutting forces from table 3. In the table of ANOVA, $F_{0.05,n1,n2}$ is mentioned from statistical table. If the calculated F-ratio values exceed $F_{0.05,n1,n2}$, then the contribution of the input parameters, such as feed rate, is defined as significant as depicted in Table 4 by **, and subsignificant parameter is depicted by *, i.e. cutting speed and depth of cut.

Similarly tables 5, 6 and 7 summarize the results of ANOVA and indicate the significant and subsignificant parameters in evaluating the cutting force components feed force (Fx), radial force (Fy) and tangential cutting force (Fz) respectively.

Table 4 – Analysis of variance for Surface roughness

Parameter	DOF (f_z)	Sum of Square (Sz)	Variance (Vz)	F-ratio (Fz)	$F_{0.05,\ n1,n2}$	Pure Sum (Sz')	Percent (Pz) %
Cutting Speed	2.00	0.38	90.42	1953.32*	3.32	0.29	3.09
Feed	2.00	6.75	93.60	2022.12**	3.32	6.66	70.91
Depth of Cut	2.00	0.91	90.68	1959.06*	3.32	0.82	8.75
Error	29.00	1.34	0.05				17.25

Moreover, Table 4 presents the results of ANOVA on performance characteristic. To minimize the surface roughness, feed has major contribution i.e. 70.91% in optimizing the performance characteristic followed by depth of cut and cutting speed. Further, it is also observed the ANOVA has resulted in 17.25% of error contribution.

To minimize the cutting force components Fx and Fz, depth of cut has major contribution i.e. 96.61% and 83.16% respectively in optimizing the performance characteristic followed by feed rate as shown in Table 5 & 7. Further, cutting force component Fy showed mixed contribution of cutting speed, feed and depth of cut. Also, it is observed from Table 5 & 7 that depth of cut is significant factor for lowering cutting force component Fx and Fz. In contrast cutting speed and feed rate is significant factor for cutting force component Fy as depicted in table 6.

Table 5 – Analysis of variance for Cutting force Fx

Parameter	DOF (f_z)	Sum of Square (Sz)	Variance (Vz)	F-ratio (Fz)	$F_{0.05, n1,n2}$	Pure Sum (Sz')	Percent (Pz) %
Cutting Speed	2.00	1920.48	998586.13	8864.99*	3.32	1695.20	0.83
Feed	2.00	1514.44	998383.11	8863.19*	3.32	1289.15	0.63
Depth of Cut	2.00	197422.99	1096337.38	9732.79**	3.32	197197.70	96.61
Error	29.00	3266.67	112.64				1.93

Table 6 – Analysis of variance for Cutting force Fy

Parameter	DOF (f_z)	Sum of Square (Sz)	Variance (Vz)	F-ratio (Fz)	$F_{0.05, n1,n2}$	Pure Sum (Sz')	Percent (Pz) %
Cutting Speed	2.00	80257.79	566211.51	273.71*	3.32	76120.55	32.60
Feed	2.00	70950.55	561557.89	271.46*	3.32	66813.31	28.62
Depth of Cut	2.00	22270.92	537218.07	259.70**	3.32	18133.68	7.77
Error	29.00	59990.02	2068.62				31.01

Table 7 – Analysis of variance for Cutting force Fz

Parameter	DOF (f_z)	Sum of Square (Sz)	Variance (Vz)	F-ratio (Fz)	$F_{0.05, n1,n2}$	Pure Sum (Sz')	Percent (Pz) %
Cutting Speed	2.00	14752.19	3402871.82	4380.64*	3.32	13198.60	1.74
Feed	2.00	88900.60	3439946.03	4428.37*	3.32	87347.01	11.52
Depth of Cut	2.00	632317.90	3711654.67	4778.15**	3.32	630764.30	83.16
Error	29.00	22527.12	776.80				3.58

4.2 Optimum set of control factors

The main effects analysis is used to study the trend of the effects of each of the factors, as shown in figures 6. Table 8 presents the corresponding S/N ratio for surface roughness and cutting forces for experimental results summarized in table 3.

Table 8 S/N ratio for performance characteristics

Exp. No.	S/N Ratio SF	S/N Ratio Fx	S/N Ratio Fy	S/N Ratio Fz
1	-3.01	-42.59	-45.25	-48.86
2	-6.82	-47.39	-40.99	-52.04
3	-9.26	-49.90	-48.99	-56.93
4	-4.81	-47.73	-46.83	-51.85
5	-7.83	-50.09	-47.50	-55.41
6	-9.08	-42.97	-45.60	-50.16
7	-6.13	-50.80	-34.81	-54.13
8	-6.64	-44.12	-31.05	-47.25
9	-8.44	-47.13	-47.08	-53.83

In order to find the optimum set of conditions, the individual level averages of S/N ratios are calculated in table 9.

Table 9 Summary of S/N ratios

Surface Roughness			
Factor	Level		
	1	2	3
Cutting speed (A)	**-6.37**	-7.24	-7.07
Feed (B)	**-4.65**	-7.10	-8.93
Depth of cut (C)	**-6.24**	-6.69	-7.74

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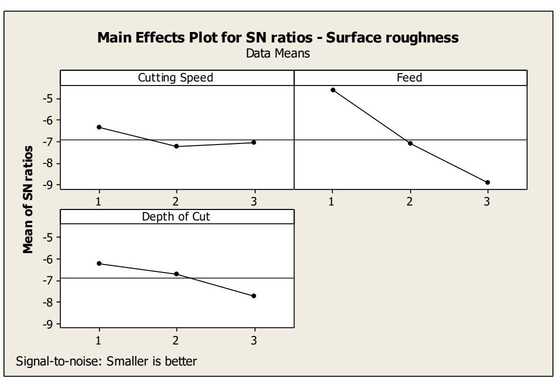
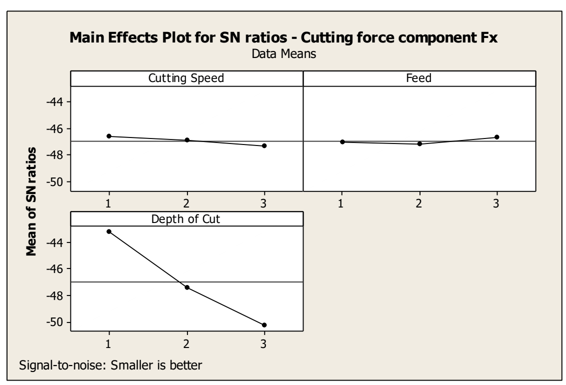
Cutting force Fx			
Factor	Level		
	1	2	3
Cutting speed (A)	**-46.63**	-46.93	-47.35
Feed (B)	-47.04	-47.20	**-46.67**
Depth of cut (C)	**-43.23**	-47.42	-50.27

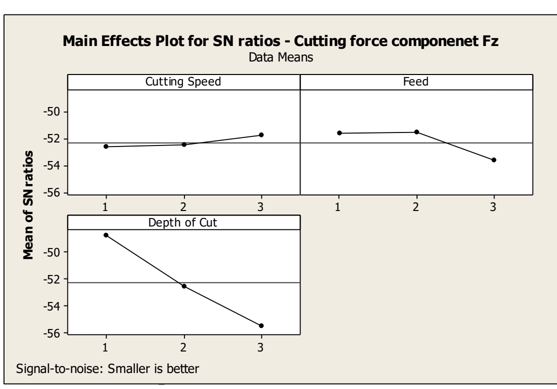
Cutting force Fy			
	Level		
Factor	1	2	3
Cutting speed (A)	-45.07	-46.64	**-37.65**
Feed (B)	-42.30	**-39.85**	-47.22
Depth of cut (C)	**-40.63**	-44.97	-43.77

Cutting force Fz			
	Level		
Factor	1	2	3
Cutting speed (A)	-52.61	-52.47	**-51.74**
Feed (B)	**-51.61**	-51.56	-53.64
Depth of cut (C)	-48.76	**-52.57**	-55.49

Figure 6 shows the main effects plot for S/N ratio for the different levels and control factors. S/N ratio is calculated with the help of MINITAB15 and its output is shown in the following graph.







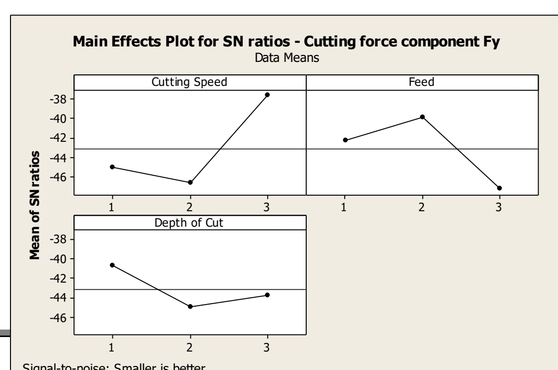


Figure 6 Main effects plot for S/N ratio for the different levels and control factors

The objective is to maximize the S/N ratio values. Thus, the optimized conditions choose for different conditions are as follows.

Optimum parameters combination for Surface roughness – A1B1C1

Optimum parameters combination for Cutting force Fx – A1B3C1

Optimum parameters combination for Cutting force Fy – A3B2C1

Optimum parameters combination for Cutting force Fz – A3B1C2

It is observed that feed rate has major contribution on surface finish compare to cutting speed and depth of cut. It is also observed that at higher cutting speed with lower feed rate, surface finish is better.

For cutting force component Fx and Fz, depth of cut has major impact compare to cutting speed and feed rate. On increasing depth of cut cutting forces increased significantly. For cutting force component Fy, chart depicts combination effect of all three control factors.

5 Conclusion

This paper has discussed the turning of Ti-6Al-4V with uncoated tungsten carbide bit on centre lathe in the environment of flood cooling. Taguchi method has been used to determine the main effects, significant factors and optimum machining condition to the performance of Ti-6Al-4V rod turning operation. Based on the results presented herein, it can be conclude that, the feed rate mainly affects the surface finish. The depth of cut largely affects the cutting force component feed force (Fx) and tangential cutting force (Fz).

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