Effect of Process Parameters during Turning of Ti6Al4V-ELI in Dry and MQL Environments

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Abstract - This research article explores the influence of machining process input variables on cutting force, and surface roughness in dry and minimum quantity lubrication (MQL) environment with PVD coated TiAlN insert. Full factorial design of experiment L18 was used for the experimentation. Two machining process parameters with three levels and one machining parameter with two levels. Turning process input variables studied were cutting speed (80, 125, 170 m/min), feed (0.08, 0.15, 0.20 mm/rev), machining environment (dry, MQL), PVD TiAlN cutting tool and depth of cut was 0.5 mm constant. Turning performance is better in MQL environment as compared to dry turning. Feed is the dominant process parameter for cutting force and surface roughness.

Keywords - Ti6Al4V-ELI, PVD TiAlN, Cutting force, Surface roughness

I. INTRODUCTION

Researchers observed that Ti6Al4V-ELI has low carbon, iron, and oxygen [1,2]. It is used in biomedical field such as bone fixation devices, cryogenic vessels, surgical clips, because of its better properties such as low modulus of elasticity and high fatigue strength. It is the ideal Ti alloy for aerospace and marine applications. The interstitial elements of iron and oxygen are carefully controlled to enhance ductility and fracture toughness.

Surface roughness of machined surface is utmost significant necessities in machining process because surface roughness is an index of quality of product. Achieving the desired machined surface superiority is significant for the functional behaviour of a part. The performance of mechanical components and their cost of manufacturing is depending on the surface finish because it affects parameters such as, geometrical tolerances, thermal conductivity, ease of holding lubricant, friction, geometrical tolerances, thermal and electrical conductivity etc. The ability of a machining process to manufacture a desired surface roughness of machined surface depends on various factors. Cutting speed, feed, depth of cut, nose radius of tool, tool wear, cutting fluid, machine vibrations, properties of tool and workpiece material these are the significant input factors affecting on surface finish and cutting force. So, it is significant for the researchers to model and quantify the relationship of input and output factors. Properties of tool material, workpiece, and machining conditions influencing on surface roughness [3,14]. It is explored that the lubrication, cooling, and help in chip flow are the major functions of cutting fluids. Hence, the effect dry machining is the high thermal and mechanical effect on the cutting tool and the surface roughness of machined surface, and increased tool wear [4].

Several researchers have commented on the poor machinability of Titanium alloys. It was found that in spite of the most use of Ti alloy in several applications, it possesses various cutting problems and consider as difficult to machine material [5]. It was found that maximum heat developed during machining of titanium alloy transmitted to the cutting tool insert due to its low thermal conductivity, therefore a major concentration of heat on the principal cutting edge of the tool, which decreases tool life [6]. It was explored that the feed rate was the dominant machining process factor influencing cutting force and surface roughness. Surface roughness with 97.34% influence during machining of Ti6Al4V-ELI with PVD coated TiAlN tool in a dry turning [1,7,8].

The cutting force increases while machining with dull edge or not properly ground edges. It was also observed that cutting force increases while machining with high depth of cut [9,10,11]. As cutting speed increases, the magnitude of cutting forces increases.

Machining of Titanium alloys involves different dominant process parameters that affect the performance of machining which is based on various output parameters. It is evident from the various literatures and to the perception of the researcher that not properly analyzed the machining of Ti6Al4V-ELI with PVD TiAlN inserts in terms of surface roughness and cutting force in dry and MQL environments.

II. MATERIAL AND METHOD

Work Material: The cylindrical work material used during the experimentation. The chemical composition of the Ti6Al4V-ELI is shown in Table 1.

Table 1 Chemical composition of Ti6Al4V-ELI

Element	**C**	**Si**	**Fe**	**Al**	**N**	**V**
Wt%	0.08	0.03	0.22	6.1	0.006	3.8
Element	**S**	**O**	**H**	**Ti**		
Wt%	0.003	0.12	0.003	Balance		

The work material has a microstructure consisted of an elongated alpha-phase surrounded by fine, dark etching of beta matrix. Ti6Al4V-ELI has high strength and depth hardenability (32 HRC). Ultimate tensile strength and yield strength of work material is 860 MPa and 795 MPa respectively. Modulus of elasticity is 114 GPa. Figure 1 shows the microstructure of work material i.e. Ti6Al4V-Extra low interstitial. HF + HNO_3+H_2O etchant was used. Figure 2 shows the machining setup with dynamometer.

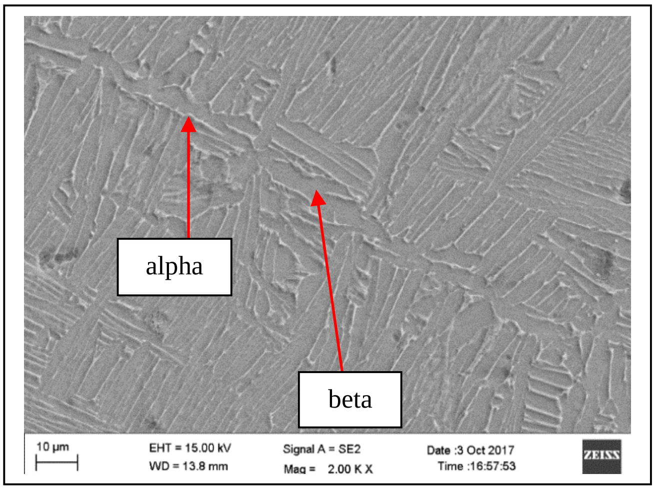


Figure 1 Microstructure of Ti6Al4V-Extra low interstitial

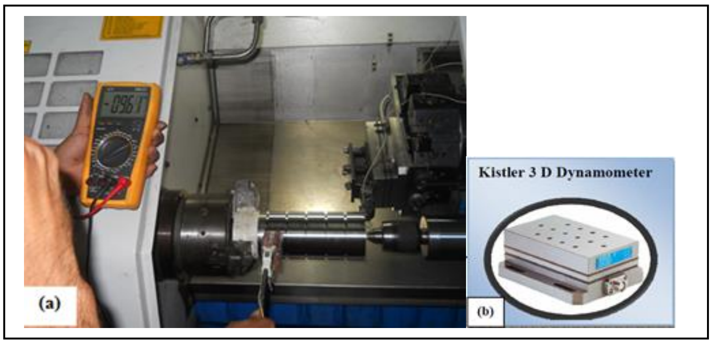


Figure 2 Photographic view of machining setup with dynamometer.

Cutting tool:
CNMG120408 SF 1105 PVD coated TiAlN insert Sandvik make, were selected for turning of Ti6Al4V-ELI. During experimental work PCLNL 2525 M12 tool holder was used. The quality of both the substrate and coating of the coated tool is significant for machining performance. Therefore, it is vital to characterize the selected cutting insert. Critical load for adhesion strength obtained for PVD TiAlN is 78. Figure 3 shows fractured cross-section indicating the coating thickness of the PVD TiAlN coated tools observed under a scanning electron microscope. The average value of coating thickness is 1.37 µm of PVD TiAlN coated tool.

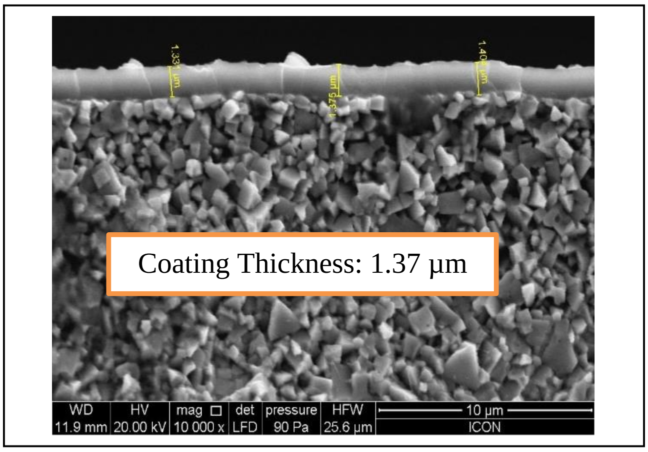
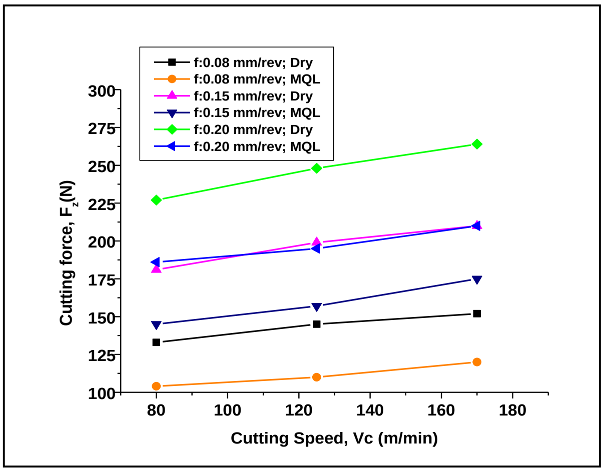


Figure 3 Coating Thickness of PVD TiAlN Coated Tool

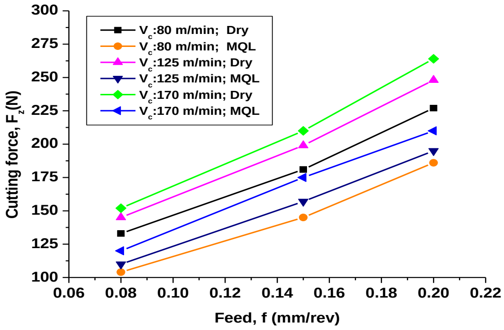
Machining Tests: Turning experimentations were performed CNC Lathe. The number of experiments were designed by using the full factorial design of experiment for the turning experiments. Number of experiments based on the number of machining process parameters and its levels. L18 orthogonal array was used. The turning process were performed in a dry and MQL environments by using PVD TiAlN cutting tool insert. Randomization concept has been incorporated for selection of sequence of experiments. To avoid undesirable errors the material was removed before conducting of turning experiments. Each experiment performed with new edge of cutting tool insert.

III RESULTS AND DISCUSSION

Cutting Force:
The cutting forces acting on the tool are the significant characteristic of machining. Cutting force measurement is significant for the estimation of power required for machining, design of machine tool parts etc. The cutting forces vary as per the tool geometry. Main cutting force increases when cutting speed increases from 80 to 125 m/min and 125 m/min to 170 m/min due to strain gradient induced material strengthening effects which is shown in Figure 4 [12]. This makes it difficult to increase the cutting speed when machining Ti alloy. It was found that the influence of cutting speed on the cutting force is nonlinear. Cutting forces increases due to strain rate hardening at high cutting speed.
An increase in feed rate increases cutting force which is shown in Figure 4 due to an increase in the area of undeformed chip cross section which increases the friction between the cutting edge and workpiece [12]. Increase in feed also increases the chip load, which causes excessive cutting force. Friction increases between the cutting edge and workpiece while turning of Ti6Al4V-ELI in a dry environment, results in increasing cutting force as compared to MQL environment.



(a)



(b)

Figure 4 Influence of (a) cutting speed and (b) feed on cutting force

Main effects plot for cutting force is shown in Figure 5.

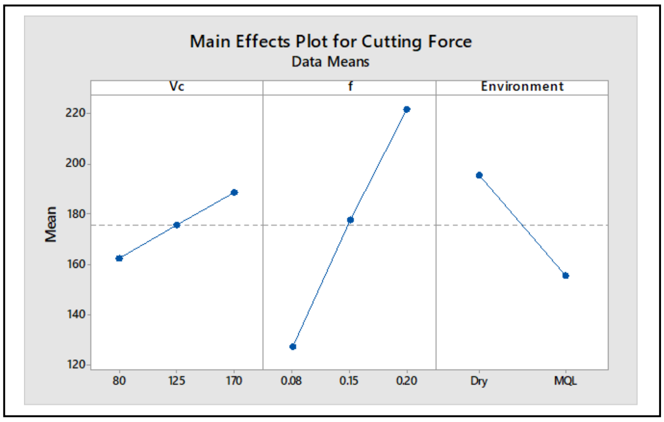


Figure 5 Main effects plot for cutting force

Cutting force generated during machining of Ti6Al4V-ELI were analyzed by statistical methods using main effects plots (MEPs) and analysis of variance (ANOVA). The P value analysis revealed that (see Table 2) the cutting speed, feed rate, and Environment has statistical significance on cutting force at a 95% confidence interval.

Table 2 ANOVA for cutting force

Cutting force, F_z						
Source	**DF**	**SOS**	**MS**	**F-value**	**P-value**	**% contribution**
V_c	1	1935.6	1935.6	194.43	**0.000**	5.39
f	1	26696.3	26696.3	2681.67	**0.000**	74.32
Environment	1	6882.9	6882.9	691.39	**0.000**	19.16
$V_c X V_c$	1	0.0	0.0	0.0	0.959	0.00
f X f	1	81.3	81.3	8.16	**0.019**	0.23
V_c *X f*	1	91.8	91.8	9.22	**0.014**	0.26
V_c *X Environment*	1	18.7	18.7	1.88	0.203	0.05
f X Environment	1	214.8	214.8	21.57	**0.001**	0.59
Error	9	89.6	10.0			
Total	17	36238.3				
R^2 = 99.75 %						

ANOVA of the data showed that cutting speed, feed, and machining environment are the most significant parameters for cutting force. Furthermore, ANOVA indicated that the interaction between cutting speed and machining environment is not significant for cutting force.

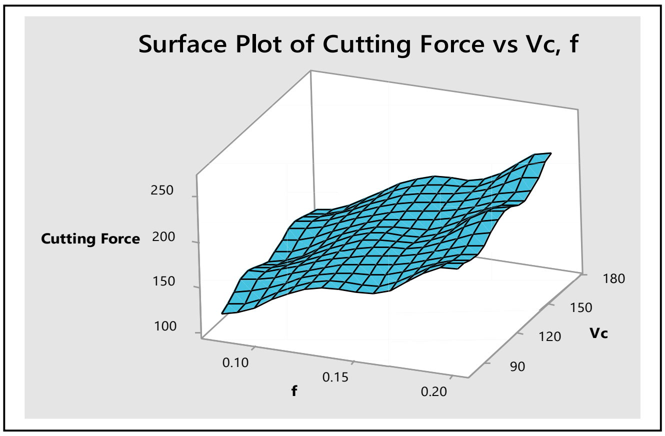
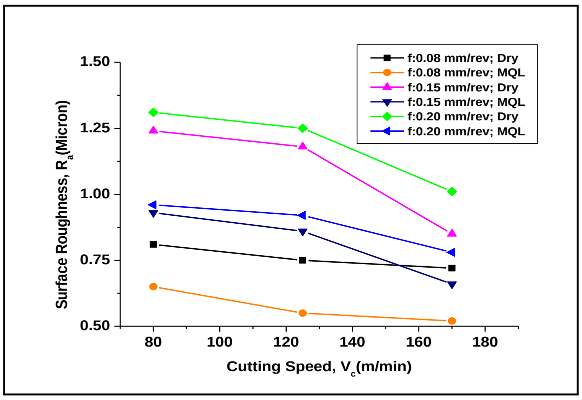


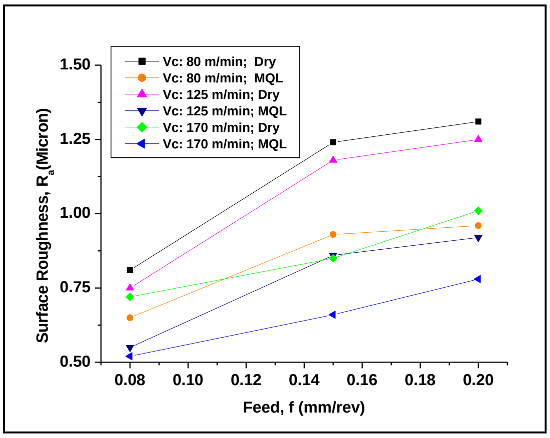
Figure 6 Surface plot for cutting force

Surface Roughness:

Surface finish is the most significant parameter of machinability. Surface roughness influencing on the performance and service life of the machined product. Input factors of turning process such as cutting speed, feed, and machining environment have a significant effect on the surface roughness of machined surface [3]. Ti6Al4V-ELI is mostly used for parts needful the utmost reliability so, the surface roughness of machined surface must be controlled [13]. Surface roughness of machined surface decreases all of a sudden with the increase in cutting speed for a given value of feed, which is shown in Figure 7. As cutting speed increases, the cutting temperature also increases due to that material becomes soft thus reduces the surface roughness [3]. The coefficient of friction of the PVD TiAlN insert is low. This leads to tool life increases resulting in decreases the surface roughness.



(a)



(b)

Figure 7 Influence of (a) cutting speed and (b) feed on surface roughness

It is observed from the ANOVA that the feed, machining environment, and the cutting speed are statistically significant at 95% confidence interval effect on the variability of the performance characteristics of turning Ti6Al4V-ELI. In addition, from the Figure 8 it is observed that, feed is the most dominating factor followed by machining environment, and the cutting speed during turning of Ti6Al4V-ELI.

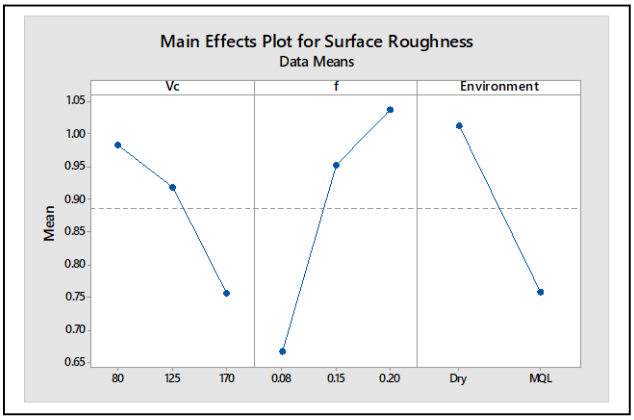


Figure 8 Main effects plot for surface roughness

The ANOVA is performed to determine the machining process parameter, which significantly affects the multi-response characteristics in turning of Ti6Al4V-ELI in different cutting condition using PVD TiAlN coated tools. The results of ANOVA for surface roughness values with contribution percentage and F-value and P-value are shown in Table 3.

Table 3 ANOVA for surface roughness

Surface Roughness, R_a						
Source	**DF**	**SOS**	**MS**	**F-value**	**P-value**	**% contribution**
V_c	1	0.147993	0.147993	41.63	**0.000**	16.47
f	1	0.414408	0.414408	116.57	**0.000**	46.13
Environment	1	0.282540	0.282540	79.48	**0.000**	31.45
$V_c X V_c$	1	0.009344	0.009344	2.63	0.139	1.04
$f X f$	1	0.019343	0.019343	5.44	**0.045**	2.15
$V_c X f$	1	0.010738	0.010738	3.02	0.116	1.20
V_c *X Environment*	1	0.003333	0.003333	0.94	0.358	0.37
f X Environment	1	0.010668	0.010668	3.00	0.117	1.18
Error	9	0.031994	0.003555			
Total	17	0.966628				
$R^2 = 96.69$ %						

ANOVA of the data showed that cutting speed, feed, and machining environment are the most significant factors for surface roughness. Furthermore, ANOVA indicated that the interaction between cutting speed and feed, cutting sped and environment, feed and machining environment are not significant for the surface roughness. Surface plot for surface roughness is shown in Figure 9.

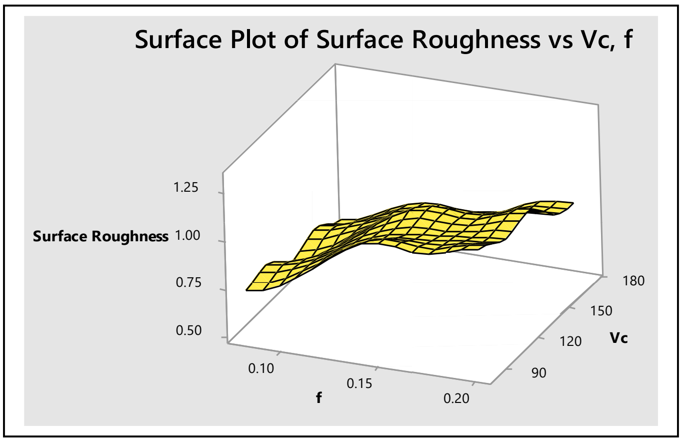


Figure 9 Surface plot for surface roughness

IV CONCLUSIONS

- The highest cutting force was recorded under the dry environment with a cutting force 264 N at the 170 m/min cutting speed and 0.20 mm/rev feed. However, the lowest cutting force was recorded under MQL environment with a cutting force 104 N at the 80 m/min cutting speed and 0.08 mm/rev feed while turning by PVD TiAlN tool.
- Appreciable reduction in cutting force was obtained with PVD coated TiAlN insert with 20 % in MQL as compared to a dry environment.
- The highest surface roughness of machined surface was recorded under the dry environment with an average surface roughness 1.31 µm at cutting speed of 80 m/min and feed of 0.20 mm/rev. However, the lowest surface roughness was recorded under MQL environment with an average surface roughness 0.52 µm at cutting speed of 170 m/min and feed of 0.08 mm/rev while machining carried out by PVD TiAlN tool.
- The feed has more dominating factor than cutting speed on the surface roughness of machined surface as well as on cutting force.

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