Dry Machining of Ti-6Al-4V using PVD Coated TiAlN Tools

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Abstract—**This paper deals with machining Ti6Al4V material. The experimental analysis was carried out using Response Surface Methodology (RSM). The detailed experiments under dry conditions using the PVD coated TiAlN tools. In the present work the relationship of Ti6Al4V's surface roughness and cutting forces with critical machining parameters and conditions, based on experimental input and output data, has been derived during the turning operation. It has been found through design of experiments technique that linear model is best fitted for predicting feed force and surface roughness dry cutting environment. Linear model is also fitted for thrust force prediction during dry cutting. 2FI (2 Factor Interaction) model is found to be fitted for cutting force prediction under dry cutting environment**

Index Terms— **Ti6Al4V-alloy, PVD Coating, TiAlN tool, RSM, Dry Machining**

I. INTRODUCTION

TITANIUM and its alloys are considered as extremely difficult to machine materials. Titanium and its alloys have several promising inherent properties (like low strength-weight ratio, high corrosion resistance etc.) but their machinability is generally considered to be poor. Titanium and its alloys have high chemical reactivity with most of the available cutting tool materials. Also due to the low thermal conductivity of these alloys the heat generated during machining remains accumulated near the machining zone. Consequently the cutting tools are more prone to thermal related wear mechanism like diffusion, adhesion wear. Hence, on machining, the cutting tools wear out very rapidly due to high cutting temperature and strong adhesion between tool and workpiece material. Additionally, the low modulus of elasticity of titanium alloys and its high strength at elevated temperature makes the machining further difficult [1-3]

To a large extent, machining of titanium and its alloys follow criteria that are also applied to common metallic materials. Compared to high strength steels, however, some restrictions have to be recognized, which are due to the unique physical and chemical properties of titanium and its alloys. The lower thermal conductivity of titanium alloy hinders quick dissipation of the heat caused by machining. This leads to increased wear of the cutting tools. The lower modulus of elasticity of titanium leads to significant spring back after deformation under the cutting load. This causes titanium parts to move away from the cutting tool during machining which leads to high dimensional deviation in the workpieces. The lower hardness of titanium and its higher chemical reactivity leads to a tendency for galling of titanium with the cutting tool and thereby changing the important tool angles like the rake angles.

Titanium alloy machining performance can be increased by selecting improved cutting tool materials and coated tools [4-5]. Nowadays, most of the carbide cutting tools come with hard coatings deposited on them either by the CVD or PVD technique. PVD coated tools have been found to be better performing compared to their CVD counterparts. Also in PVD thinner coatings can be deposited and sharp edges and complex shapes can be easily coated at lower temperatures [6]. PVD–TiAlN-coated carbide tools are used frequently in metal cutting process due to their high hardness, wear resistance and chemical stability. Also, they offer higher benefits in terms of tool life and machining performance compared to other coated cutting tool variants.

Currently in machining industries hard turning process is being used to obtain high material removal rates. For successful implementation of hard turning, selection of suitable cutting parameters for a given cutting tool - workpiece material and machine tool are important steps. Study of cutting forces is critically important in turning operations [7] because cutting forces co-relate strongly with cutting performance such as surface accuracy, tool wear, tool breakage, cutting temperature, self-excited and forced vibrations, etc. The resultant cutting force is generally resolved into three components, namely feed force (Fx), thrust force (Fy) and cutting force (Fz).

Machining of titanium and its alloys differs from conventional turning of engineering materials like steel, in several key ways, mainly because the thermal conductivity of the material is very low when compared to the steel (K_{Ti} is 7.3W/mK and K_{Steel} is 50.7W/mK). This low thermal conductivity results in high heat accumulation at the machining zone (shear zone) and heat dissipation is very less when compared to conventional turning of steels.

II. LITERATURE REVIEW

CNC Turning is widely used for machining of symmetrical components in a variety of industries such as automotives, aerospace, chemical, biomedical, textile and other manufacturing industries. In the machining process, errors may occur due to the problems in the machine tool, machining methods and the machining process itself. Of these, the errors that arise due to high cutting forces are the

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major problems for machining process. In turning, cutting forces and surface finish are important parameters by which the performance can be assessed. Hence it is important to minimize the cutting forces and maximize the surface finish.

Sun et al [8-9] studied the characterization of cutting forces in dry machining of titanium alloys considering input parameters like cutting speed (60-260 m/min) , feed (0.12 to 0.3 mm/rev) and depth of cut (0.5 to 2 mm) using uncoated inserts and they have reported that cutting forces increases with increase in feed and increase in depth of cut. Venugopal et al [10], Hong et al [11-13], have studied the cutting forces under dry and wet cutting environment for machining of Ti-6Al-4V using uncoated inserts and they compared the results with cryogenic machining. Jawaid et al [3, 14-16] have studied the machining of titanium alloys using PVD TiN coated and CVD coated ($TiCN+Al_2O_3$) in wet cutting environment and they assessed the wear mechanism of coated inserts. Nalabant et al [9, 17] have investigated extensively the effects of uncoated, PVD and CVD coated cutting inserts and the various cutting process parameters on surface roughness and they have found that the best average surface roughness values were obtained at cutting speed of 200 m/min with a feed of 0.25 mm/rev using a 2.3 μm thickness PVD coated TiAlN-coated cutting tool [18].

Recently Yuan et al [19] studied the machining of titanium alloys using uncoated cemented carbide inserts under three different cutting environments such as dry, wet, MQL with room temperature and MQL with varying temperature of cooling air. Fang et al [20] did a comparative study of the cutting force in high speed machining of Ti-6Al-4V and Inconel 718 and they have explained the similarities and differences both quantitatively and qualitatively in terms of force related quantities.

Most of the experimental investigations on titanium machining have been conducted using two-level factorial design (2k) for studying the influence of cutting parameters on cutting forces and surface roughness[11, 20-21]. In two-level factorial design, one can identify and model linear relationships only. For studying the nonlinearity present in the output characteristics at least three levels of each factor are required (i.e. three-level factorial design, 3k). A central composite design which requires fewer experiments than alternative 3k design is usually better. Again, sequential experimental approach in central composite design can be used to reduce the number of experiments required. Keeping the foregoing in mind, the present work is focused on investigations of cutting forces and surface roughness as a function of cutting parameters in titanium machining using sequential approach in central composite design technique. The study was conducted on Ti-6Al-4V alloy using coated tools under dry environment to analyze and compare the measured output parameters. Regression equations correlating input parameters viz., Cutting speed, feed, depth of cut and effective rake angle with output like forces and surface roughness were established based on experimental data.

The review of literature suggests that for the machining titanium alloys most researchers have used the input machining parameters like cutting speed, feed and depth of cut. But there are hardly any papers where researchers have used different rake angles as also an input parameter. In the current paper the effective rake angle is considered as another input parameter. The major objective of the present work is to experimentally find the magnitude of the cutting forces and the surface roughness of the turned components under dry conditions.

III. EXPERIMENTAL DETAILS

The details of experimental conditions, instrumentations and measurements and the procedure adopted for the study are described in this section.

A. *Workpiece Material*

Titanium alloys have found wide applications owing to its unique characteristics like low density or high strength to weight ratio (density of titanium is about 60% of that of steel or nickel-based super alloys) and excellent corrosion resistance (for biomedical, chemical and other corrosion-resistant environments). Titanium is an expensive metal to extract, melt, fabricate and machine. Titanium alloys are considered to be difficult-to-machine materials. This is due to certain inherent metallurgical characteristics of these alloys that make them more difficult and expensive to machine than steels of equivalent hardness. Titanium alloys have low thermal conductivity due to which the heat generated in the cutting zone cannot be rapidly conducted away into the fast-flowing chip.

In the present study Ti-6Al-4V alloy bars of 60 mm diameter and length 200 mm were used. They were annealed and their chemical compositions are given in the Table I.

TABLE I
CHEMICAL COMPOSITION OF Ti-6Al-4V

% of Element	Actual Values
C	0.027
V	3.89
Fe	0.11
Al	5.81
Ti	Balance

B. *Cutting tool*

In the present experiments, 5 levels of rake angle were used. The -6 degree default rake angle tool holder for CNMG tool inserts was used and for VNMG inserts the tool holder default rake angle -10 degrees was used. The details of the cutting inserts are given in the Table 2. So, the rake angles obtained by such combination of inserts and tool holders are -10, -6, 0, 7 and 14 degrees.

TABLE II
CUTTING INSRTS SPECIFICATION

Insert Grade	Rake Angle
VNMG 160408 - SM 1105	0
CNMG 120408- MM 1115	0
CNMG 120408- MP KC 5025	6
CNMG 120408- MS KC 5510	13
CNMG 120408- FF KC 5010	20

C. *Machine Tool*

A rigid, high precision T-6 (Leadwell, Taiwan) lathe equipped with specially designed experimental setup was used for carrying out the experiments. For increasing rigidity of machining system, workpiece material was held between chuck (three jaws) and tailstock (revolving center).

D. *Cutting conditions*

The experiments have been conducted using tool holders with -6 and -10 degree default rake angle. In this study the input parameters and their levels are shown in Table III.

TABLE III
THE LEVELS AND INPUT PARAMETERS

S No	Parameters	Levels Units	1	2	3	4	5
1	Cutting Speed	m/min	60	80	100	120	140
2	Feed	mm/rev	0.04	0.08	0.12	0.16	0.2
3	Depth of Cut	mm	0.5	0.8	1.1	1.4	1.7
4	Effective Rake Angle	degree	-10	-6	0	7	14

E. *Cutting Force Measurement*

The cutting forces were measured using Kistler® piezoelectric dynamometer (model 9257B) mounted on specially designed fixture. Kistler® tool holder (model: 9129AA) was used for holding the 20×20 shank size cutting tool. The charge generated at the dynamometer was amplified using three-charge amplifier (Kistler®, Model: 5070A). The input sensitivities of the three-charge amplifiers were set corresponding to the output sensitivity of the force dynamometer in the *x*, *y* and *z* directions. The amplified signal was acquired and sampled using USB data acquisition system and stored in computer using Dynaware software for further analysis. The sampling frequency of data was kept at 300 samples/s per channel and the average value of steady-state force was used in the analysis.

F. *Surface Roughness Measurement*

The measurements of average surface roughness (Ra) were made on the Taylor Hobson Surface roughness measuring machine with Ultra Surface Finish Software V5 version. Three measurements of surface roughness were taken at different locations and the average value was used in the analysis.

G. *Response Surface Methodology*

Response surface methodology (RSM) is a collection of mathematical and statistical techniques that are useful for the modeling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimize this response [22].

H. *Experimental Plan Procedure*

Planning of experiments is an important stage. Number of experimental runs was decided by using the response surface methodology. In this study, cutting experiments are planned using five-levels of each of the input parameters. Cutting experiments are conducted considering four input parameters or factors: Cutting Speed, feed, depth of cut and rake angle. A total of 30 experiments were performed on a CNC turning center (T-6 Lead well). The cutting experiments involved in the machining of Ti–6Al–4V with TiAlN-PVD coated carbide tools, five levels of cutting speeds, feeds, and depth of cut and effective rake angles.

IV. RESULTS AND DISCUSSION

The results are analyzed in Design Expert V8.0.6 software. An ANOVA summary table is commonly used to summarize the test of the regression model, test of the significance factors and their interaction and lack-of-fit test. If the value of 'Prob > *F*' in ANOVA table is less than 0.05 then the model, the factors, interaction of factors and curvature are said to be significant. Finally, % contribution column is added in ANOVA summary table and it often serves as a rough but an effective indicator of the relative importance of each model term [22]

A. *Force components: the cutting force, thrust force and feed force against Input parameters*

Anova analysis shows that the model is significant and feed (B) and depth of cut (C) are only the significant factors (terms) in the model. All other terms are insignificant. In default the central composite design the curvature is insignificant which says that the model is linear. The lack of fit also confirms the insignificance as depicted from Anova analysis thereby indicating that the model fits well with the experimental data.

The various R^2 statics (i.e. R^2, adjusted $R^2$and Predicted R^2) of the cutting force are exported for Anova table for dry cutting environment. The value $R^2 = 0.9748$ for Dry of Fz force indicates that 97.48% for dry of the total variations are explained by the model. The adjusted R^2 is a static that is adjusted for the size of the model. The value of the adjusted $R^2 = 0.9719$ for Dry cutting environment indicates that 97.19 % of the total variability is explained by the model after considering the significant factors. Predicted $R^2 = 0.967$ for dry cutting environment is in good agreement with adjusted R^2 and shows that the model would be expected to explain 96.7% for Dry of the variability in new data [22]. 'C.V.' stands for the coefficient of variation of the model and it is the error expressed as a percentage of the mean ((S.D./Mean)×100). Lower value of the coefficient of variation (C.V. = 8.20%) indicates improved precision and reliability of the conducted experiments.

The response surface eqauations as obtained from the Anova analysis and are follows

$$Fx = 96.49+387.437*feed \tag{1}$$

$$Fy = 15.397 + 160.7861 * doc \tag{2}$$

$$Fz = 15.89+61.833*f+62.58*doc+1548*f*doc \tag{3}$$

The normal probability plot of the residuals (i.e.error = predicted value from model−actual value) cutting force is shown in Fig 1 and reveal that the residuals lie reasonably close to a straight line, giving support that terms mentioned in the model are the only significant [22].

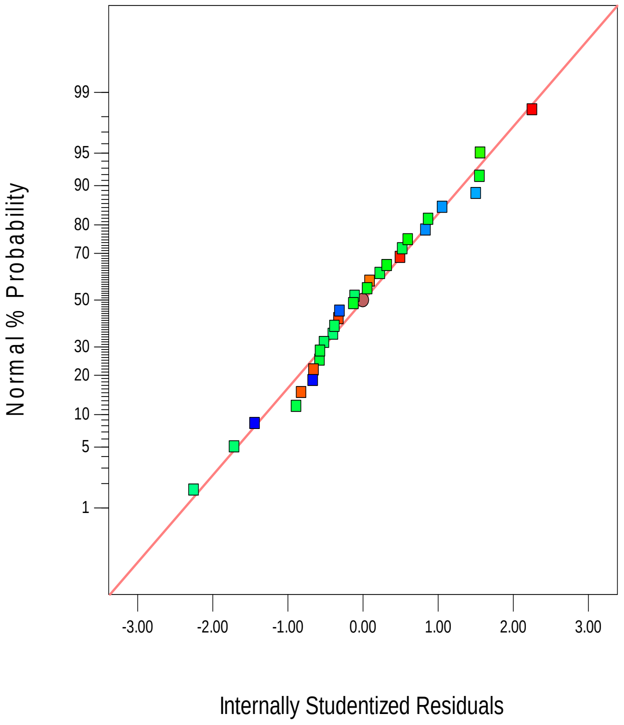

Fig 1 Normal Probality & Residuals

Fig 2 explains the comparision of the significant factors with the input parameters and explains that the most significant factors for the inrease in the cutting force are feed and depth of cut and shows that the significant factor for feed force is feed and as feed increases the feed force also increases and as shown in Fig 3 feed is also the most significant factor for increase in the surface roughness.

Fig 5 shows the scanning electron microscope (SEM) images under the different input parameters. SEM images are obtained to study the rake face and cutting edge behaviour for the extreme cutting conditions. Fig 5.1 shows the 14 degrees rake angle with a fresh cutting edge.

The same insert is shown in Fig 5.2 & Fig 5.3 after machining. Fig 5.2 shows the extreme coniditions of all the input parameters (cutting speed (140m/min), feed (0.2 mm/rev), depth of cut (1.7 mm) and rake angle (14 degrees)), it can be observed that from Fig 5.2 the formation of built up edge is more and also it can be observed that peeling off of the coating from the rake face has occured resulting in the tool failure. It is also observed from the Fig 5.4 to Fig 5.6 that wear of the nose radius has taken place and also sizeable crater wear is seen on the rake face (Fig 5.5 and Fig 5.6).

A. *Surface Roughness and Input Parameters*

The normal probability plot of the residuals for surface roughness in dry condition is shown in Fig 6 The Figures prove that the residuals lie reasonably close to a straight line, giving support that terms mentioned in the model are the only significant [22].

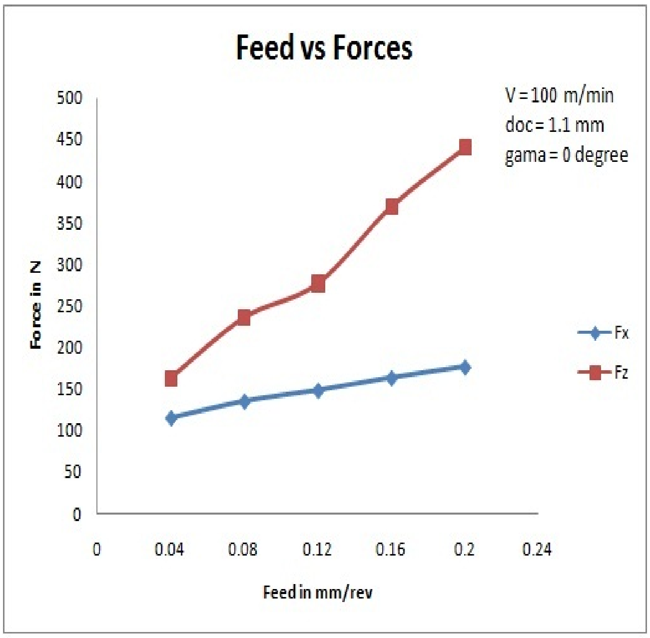

Fig 2 Comparing the significant factors for forces

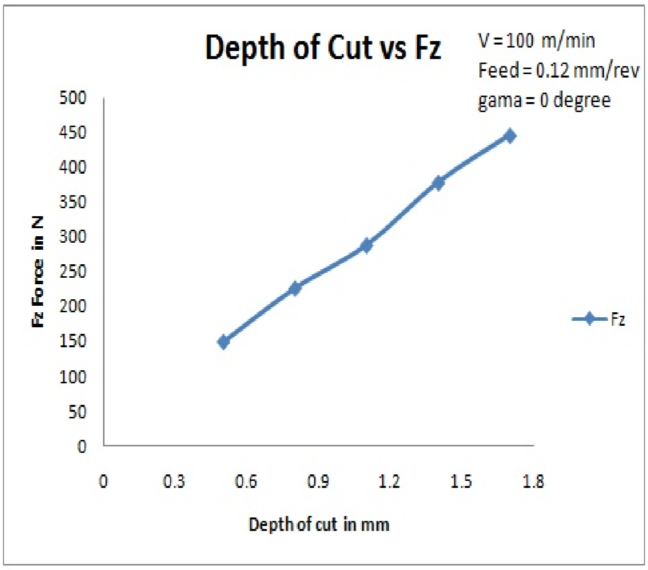

Fig 3 Comparing the significant factors for forces

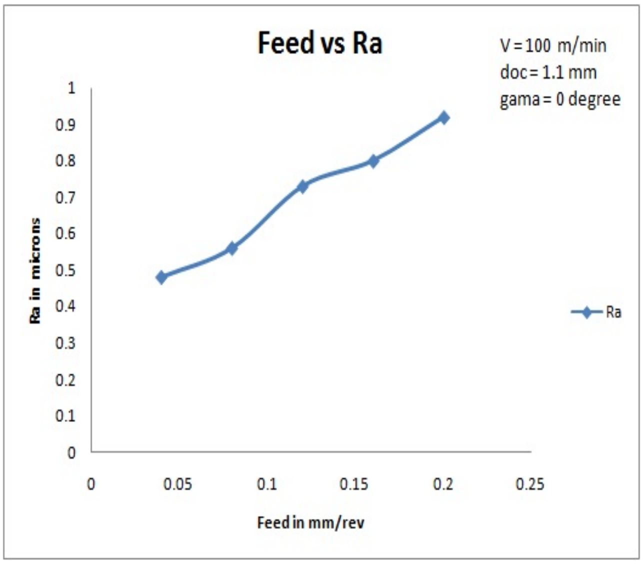

Fig 4 Comparing the significant factor for surface roughness

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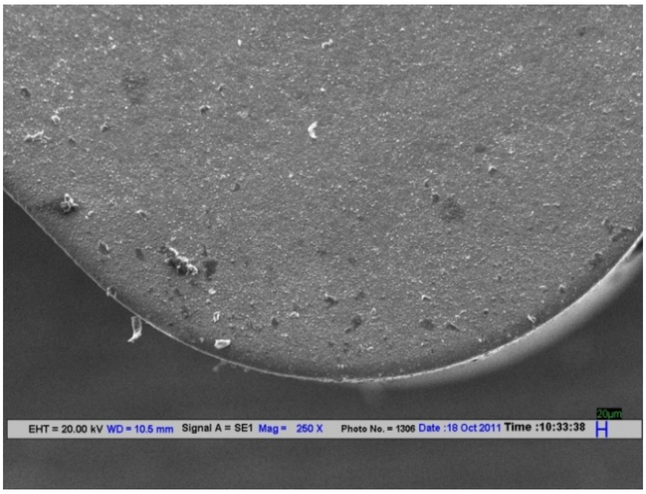

Fig 5.1 SEM micrographs of a fresh cutting edge of 14 degess rake angle cutting tool inserts

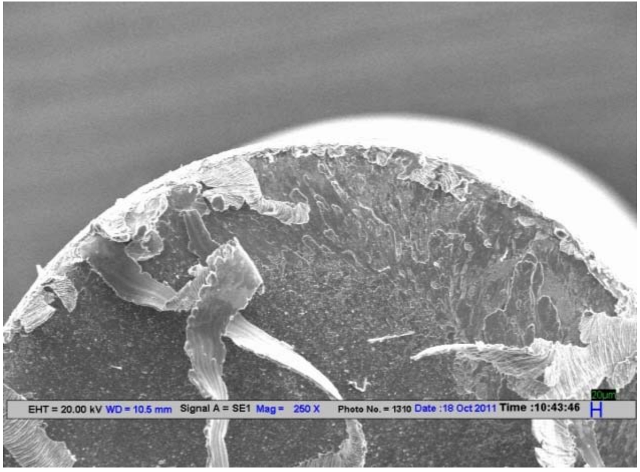

Fig 5.2 SEM micrograph of cutting tool insert under the following cutting conditions: V=140 m/min; f = 0. 2 mm/rev and doc =1.7 mm and 14 degess rake angle

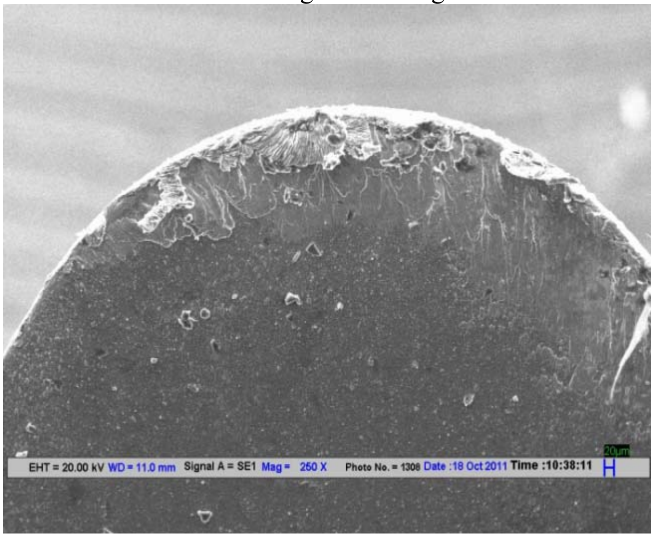

Fig 5.3 SEM micrograph of cutting tool insert under the following cutting conditions: V=100 m/min; f = 0.12 mm/rev and doc =1.1 mm and 14 degress rake angle

V CONCLUSION

The following main conclusions are drawn from the comparative study of the effect of cutting speed, feed, depth of cut and effective rake angle on the feed force (Fx), thrust force (Fy), cutting force (Fz) and surface roughness (Ra) in the machining of Ti-6Al-4V using PVD TiAlN coated inserts.

- The central composite design is beneficial as it saves number of experimentations required when

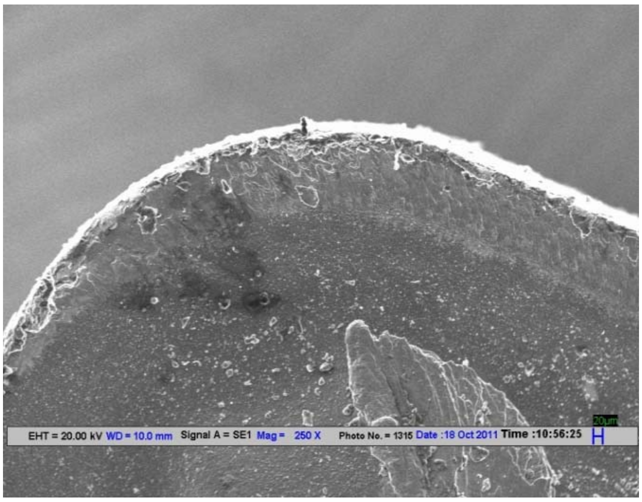

Fig 5.4 SEM micrograph of cutting tool insert under the following cutting conditions: V=100 m/min; f = 0.12 mm/rev and doc =1.7 mm and 0 degess rake angle

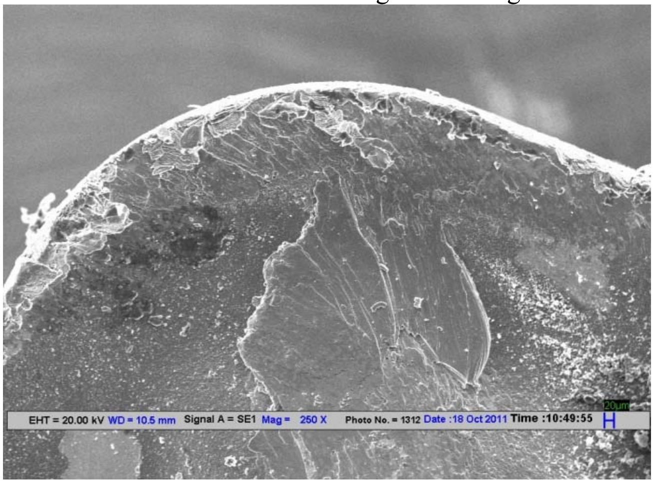

Fig 5.5 SEM micrograph of cutting tool insert under the following cutting conditions: V=100 m/min; f = 0.2 mm/rev and doc =1.1 mm and 0 degress rake angle

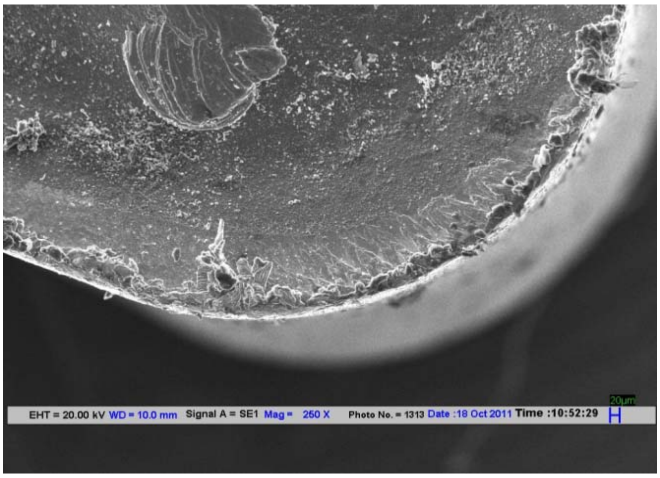

Fig 5.6 SEM micrograph of cutting tool insert under the following cutting conditions: V=140 m/min; f = 0.12 mm/rev and doc =1.1 mm and 0 degress rake angle

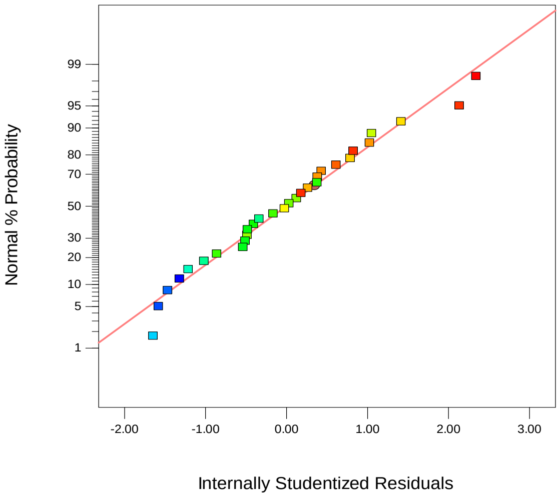

Fig 6 Normal Probality & Residuals

compared with the full factorial design for the same factors and for the same levels.

- Linear model is fitted for thrust force, feed force and surface roughness in dry cutting and 2FI (2 Factor Interaction) model is fitted for cutting force.
- For the feed force model: feed is most significant factor with 41.04% contribution in the total variability of model whereas depth of cut has a secondary contribution of 5.11% in the model.
- For the thrust force model: feed and the depth of cut are significant factor with 1.5% and 66.77% contribution in the total variability of model, respectively
- For the cutting force model: the feed and depth of cut are the most significant factors affecting cutting force and account for 46.88% and 47.59% contribution in the total variability of model, respectively. The interaction between these two provides a secondary contribution of 1.28%.
- For the Surface roughness model: the cutting velocity and the feed provides primary contribution and influences most significantly on the surface roughness.

From conclusions drawn from the analysis of the results for Ti-6Al-4V machining using PVD coated TiAlN inserts the Dry environment is also best suited environment for the selected process parameters. Such detailed experimental work enable researchers to choose the optimized process parametric conditions including cutting tool geometry (rake angle mainly) to machine Ti alloy material effectively and efficiently without sacrificing on the material removal rate.

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