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Optimisation of Machining Parameter of Cryotreated Titanium Alloy (Ti-6al-4v) Using Taguchi Method

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Abstract: *One of the most important kind of material used in engineering field is Titanium. Ti-6Al-4V alloy accounts for approximately 50% of the total world production of titanium alloys. This is due to their different properties like high strength to weight ratio, superior corrosion resistance and ability to withstand high temperature.They are known as "difficult to machine" materials because of their poor thermal property and poor machinability. The cryogenic-treatment is a method to change material properties. It can improve the plasticity of Ti-6Al-4V alloy but along with it reduces the strength to small extent.High-speed machining of the cryo-treated titanium and its alloys which is a highly reactive material is still far away uncertain. So, it is important to study the machining characteristics and optimization of the cutting parameters. In this paper Titanium alloy (Ti-6Al-4V) is cryo-treated and the dry turning experiment is performed in CNC lathe machine by using Coated Carbide cutting tool inserts.The Taguchi Technique is used for designing L_9 orthogonal array for three factors namely cutting speed, feed and depth of cut at three levels. The optimal machining conditions are acquired by Signal-Noise-ratio method with respect to surfaceroughness (Ra) and Cutting Force (F). The analysis of variance(ANOVA) and the percentage of contribution of feed,cutting speed and depth of cut for better surface roughness and minimum cutting force is validated using S/N-ratio.According to experimental results, for minimum roughness the depth of cut is a vital parameter followed by feed and then by cutting speed. Similarly, for minimum cutting force the feed is a vital parameter followed by cutting speed and then by the depth of cut. Optimum machining conditions for both resultant cutting forces and surface roughness were obtained. The worn-out surface ofinsert is examined by using the SEM and EDX.*

Keywords: *-Titanium alloy, Cryogenic treatment, Coated Carbide insert, Taguchi Design, Surface Roughness, Cutting Force, ANOVA, Tool Wear, Scanning Electron Microscope (SEM).*

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I. Introduction

Titanium and its alloys havevarious and important properties like high strength to weight ratio, highly resistant to corrosion and ability to withstand high temperature.The chemical composition of Titanium alloy grade 5 is shown in table 1 below.

Table1. Composition of Ti Grade 5 alloy (Ti-6Al-4V)

Material	Al	V	Fe	O	Ti
wt%	6.0%	4.0%	0.250%(max)	0.20%(max)	89.750%

Titanium dissipates heat within the workpiece which causes rise in temperature at the cutting edge of the tool and generates a rapid chipping at the cutting edge due to higher cutting speed which leads to catastrophic failure. The morphology of chips significantly influences the thermo and mechanical behavior at the workpiece/tool interface, which also affects the tool life. Generally, the machinability of material indicates the adaptability to manufacturing by a machining process. Good machinability depends on various parameters like cutting speed, feed rate, cutting depth, nose radius of the tool inserts, nose and flank wear, chatter, work-tool material properties. The surface quality of a part is the most important and critical one as it affects the mechanical properties. Many times, the poor surface quality of a mechanical part is a starting point where the failure starts taking place.An important aspect of machining is the force acting on a tool. Knowledge about the cutting force is necessary to estimate the power consumption and ensure that the machine tool elements, tool holder, and fixtures are adequately rigid and free from any vibrations. The cutting force vary with various factors like the cutting speed, feed rate, depth of cut, tool angle, approach angle, and accurate measurement of the tool forces are helpful in optimizing the tool design. With regarding quantity characteristics of turning parts, some of the problems include surface roughness, burr, and tool wear etc. The machining parameters such as cutting speed, feed rate, depth of cut, approach angle, work piece material, features of tools and coolant conditions will highly affect the response variables. It is necessary to select the appropriate machining settings to improve cutting efficiency, low cost process and produce highquality products. Hartung*etal.*[6] research work tells thattungsten carbide is one of the best tools insert material which can be used formachining titanium alloys.Venugopal *et al* [3] showed that uncoated tungsten carbidewith cobalt as binder is suitable for machining titaniumalloys. Cetin *et al.*[7] established the influence ofmachining variables and coolants on surface roughnessduring the turning of AISI 304L. Their work concluded thatcutting tool feed is the most influencing parameter onsurface roughness. Nithyanandam*et al.*[5] investigated theeffect of cutting variables on surface roughnessby employingtool insert with 0.8 mm nose radius. Their study revealsthat feed rate is the dominant factor having 41.69%contribution followed by cutting speed and then cutting depth.

Deng Jianxin*et al*.[9] performed different modes of tool failure including abrasive wear, adhesive wear and diffusion wear. These wears were observed during machining titanium alloy with WC/Co carbide tools. The diffusion of elements of titanium alloy to the WC/Co carbide tool via the tool- chip interface during machining processes leads to change of composition of the toolsubstrate, and it may also lead to tool wear. G.A.Ibrahimet*et al.*[8], showed thevarious wearmechanism observed on both the coated and uncoated cutting tools that caused more heat generation andcutting forces on the insert due to high depth of cut.

In this research work, the evaluation of machining parameters which affect thesurface roughness and cutting force in machining of titanium alloy and tool wear is carried out in details. The optimization of cuttingvariables investigated to get the minimum surfaceroughness using Taguchi Design during finish turning process of Ti-6Al-4V byemploying 0.8 mm nose radius insert at dry machiningcondition.

II. Experimental Details

2.1 Work Material

A bar of Titanium alloy Ti-6Al-4V having 50 mm diameter and 120 mm length is utilized as workpiece material for the experiment. Figure-1 shows the titanium alloy (grade 5) bar used in this work.

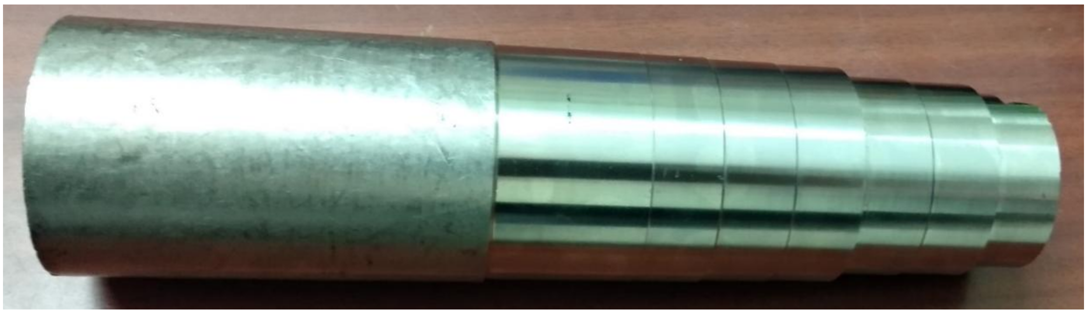


Fig-1 Rod of Ti-6Al-4V was used for turning experiment

2.2 Cutting Tool

The multilayer PVD Coated (TiAlN/TiN) Carbide Insert Grade TT5080 with ISO Geometry CCMT09T308 and nose radius of 0.8mmfrom Taegutec company as shown in figure was used.

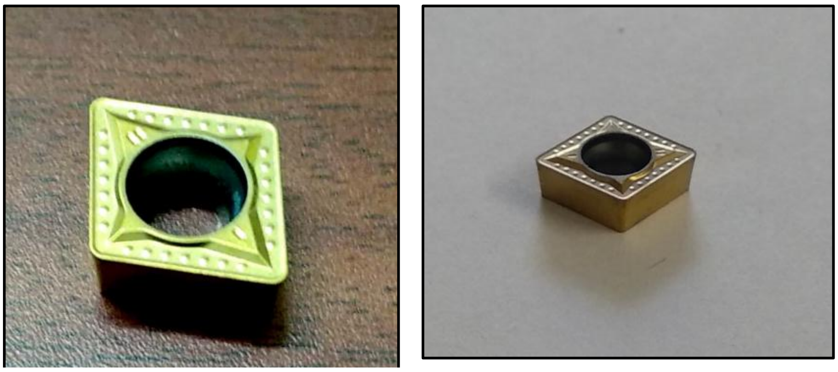
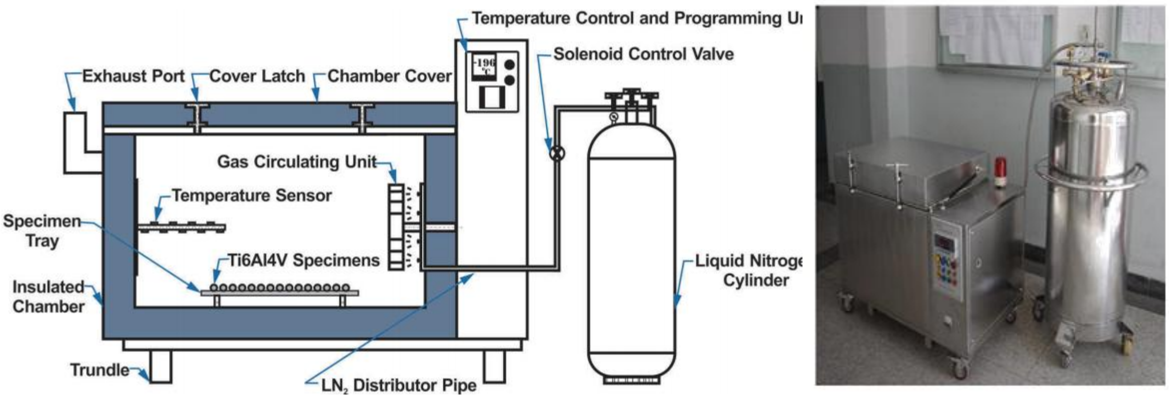


Fig-2 Coated Carbide Tool inserts

III. Experimental Procedure

For the experiment arod of Ti-6Al-4V alpha-beta titanium alloy was employed. The chemical composition of the titanium alloy is 5.5%-6.75% Al, 3.5%-4.5% V and the remaining is Ti. A program controlled cryogenic of SLX-80 cryogenic system is used for cryogenic treatment and the subsequent low temperature(-190^{o}C) temper which for the purpose of reducing cold shock.After cryogenic and temper treatment, machining is done to check and compare its machinability.



(a) (b)

Fig-3 CT setup (a) block diagram (b) SLX-80 cryogenic system

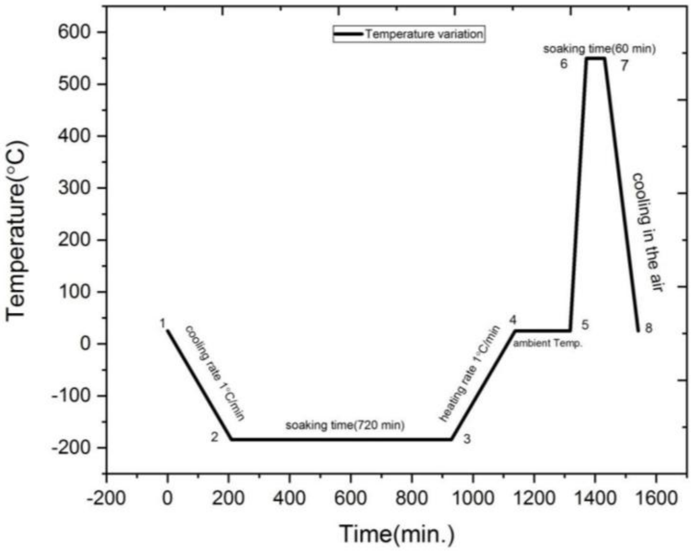


Fig-4 Stages of Cryogenic Treatment

The experimental work isdesigned by Taguchi L9 orthogonal array using Minitab18 and further signal-to-noise ratio analysis. The machining variables used were cutting speed, tool feed and cutting depth. These parameters are called control factors. Each machining parameter involves three levels, namely 1, 2, and 3. Table-2 gives the process parameters (factors) and their three levels. In the calculation of S-N ratio, minimum the better option is selected by theobjective of the research work. Then analysis of variancewasdone to know which machining variable havethe greatest influence on the output parameter (surfaceroughness, cutting force).

Table 2. Factors and levels of machining parameters

Parameters	units	Symbols	Level		
			1	2	3
cutting speed	m/min	V	80	120	150
feed rate	mm/rev	f	0.05	0.10	0.15
depth of cut	mm	d	0.8	1.0	1.2

The turning operation has been performed in order to obtain experimental data in the dry condition. The task is completed on run 16 TC CNC write architect machine with the greatest axle speeds of the 4000rpm. The cutting tool selected for machining titanium (Grade-5) alloy was PVD Coated Carbide Insert Grade TT5080 with ISO Geometry CCMT09T308 and nose radius of 0.8mm. The experiments were conducted to analyse the effect of cutting speed, feed rate and depth of cut on the surface roughness and cutting force. A strain gauge type KISTLER dynamometer in conjunction with XKM software and a computer were used to measure and record the experimental data.MITUTOYOSurface roughness tester was used to measure the surface roughness of the machined surface. Input parameters of the models are cutting speed (V), feed rate (f) and depth of cut (d). Output parameter of the models is their corresponding surface roughness (Ra), and Cutting force (Fc).

IV. Results And Discussion

4.1 Effect of Cryogenic treatment

Cryogenic treatment reduces the quantities of β phase particlesin material like Titanium and increases the particle size slightly, which is the main reason for the ductility improvement. Hardness is tested by digital Rockwell hardness tester. The Rockwell hardness of titanium alloy Ti-6Al-4V is 36 HRC before and after the cryogenic treatments the Rockwell hardness measured is 42.3 HRC and which is much more than that before cryogenic treatment. So, this is inferred from this that the Rockwell hardness of Ti-6Al-4V is increased by 17.5% after cryogenic treatment.

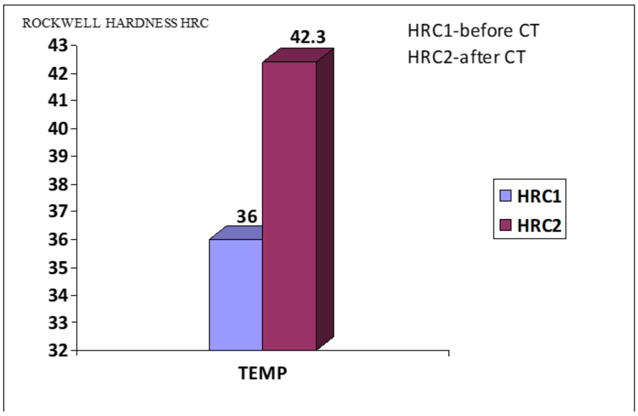


Fig-5 Comparison of HRC1 & HRC2

4.2 Analysis of Surface Roughness

The S-N ratios for the experimental resultswere obtained with the help of Minitab 18. Depending on thesignal-to-noise ratio analysis, the optimal processparameters for surface roughness are the cutting speed 120m/min, the feed rate 0.15mm/rev and depth of cut 1.2mm.Table-4represents the S-N ratio and mean value for surfaceroughness. Fig-4 (a) & (b) shows the main effectand means graph for S-N ratio of surface roughness. FromFig-4 (a), the factor level the largest S-N ratio isgiving the smaller values of surface roughness, and it isthe optimized parameters.

Table3. Response Table for Signal to Noise Ratios for Surface Roughness

Level	Average for Surface Roughness			S/N ratio for Surface Roughness		
	Cutting Speed(m/min)	Feed(mm/rev)	Depth of cut(mm)	Cutting Speed(m/min)	Feed(mm/rev)	Depth of cut(mm)
1	0.8700	0.6033	0.5533	2.8085	4.7675	5.5583
2	0.9233	0.8100	0.6200	1.1869	2.7747	4.1574
3	0.6433	1.0233	1.2633	4.0434	0.4965	-1.6769
Delta	0.2800	0.4200	0.7100	2.8564	4.2709	7.2352
Rank	3	2	1	3	2	1
Optimal Parameter	150	0.05	0.8	150	0.05	0.8

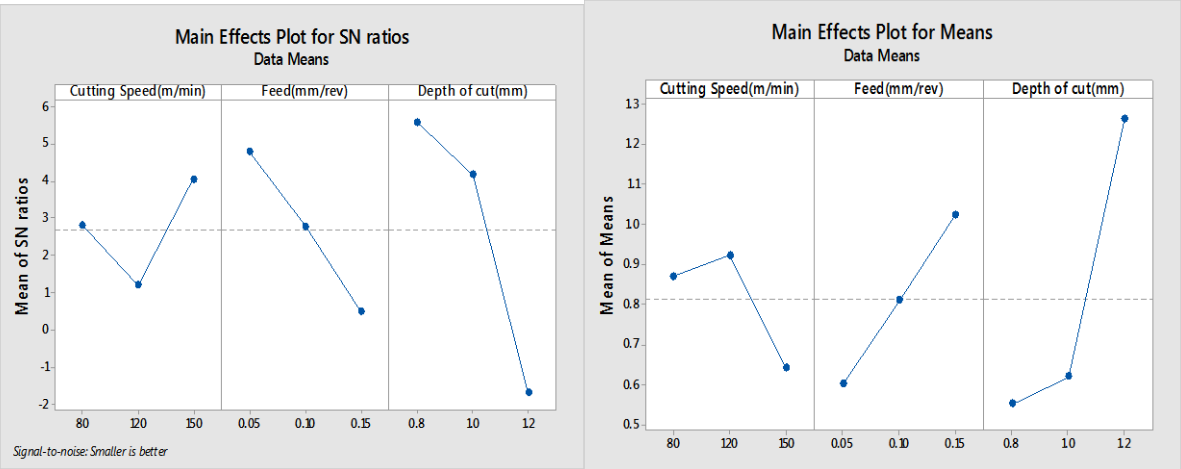


Fig-6(a) Main effects graph of S-N ratio with respect to cutting speed, feed and depth ofcut;(b) Main effects graph of Means with respect to cutting speed, feed and depth of cut.

4.3 ANOVA analysis for Surface Roughness

Based on ANOVA results, the machining variable Depth of cut(d) had more effect of 68.38% on the output variable surface roughness. Feed(f) had a contribution of 21.20%on the surface roughness. The Cutting speed (v) has less effect of 9.50% on the surface roughness. Table displays the result of ANOVA for the surface roughness. The error percentage is 0.87 % which is lesser than the allowable limit error value of 15%. This shows that design, observation, and analysis are in the right direction.

Table-4. Analysis of Variance for Surface Roughness

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**Percentage of Contribution**
Cutting Speed(m/min)	2	12.313	6.1567	10.89	9.50%
Feed(mm/rev)	2	27.402	13.7010	24.24	21.20%
Depth of cut(mm)	2	88.350	44.1752	78.14	68.38%
Error	2	1.131	0.5653	-	0.87%
Total	8	129.196	-	-	-

4.4 Confirmation Table

Table-5. Optimum value of Surface Roughness

Predicted Optimal S/N value from Taguchi: S/N Ratio	9.00997
Predicted Surface Roughness value corresponding to S/N Ratio	0.175556 µm
Experimental Surface Roughness value	0.185843 µm
Error %	5.86%

4.5 Analysis of Cutting Force

The S-N ratios for the experimental resultsobtained with the help of Minitab 17. Depending on thesignal-to-noise ratio analysis, the optimal processparameters for surface roughness are the cutting speed 120 m/min, the feed rate 0.15 mm/rev and depth of cut 1.00mm.Table-5 represents the S-N ratio and mean value for surfaceroughness. Fig-4 (a) & (b) display the main effectand mean graph for S-N ratio of surface roughness. FromFig-4 (a), the factor level having largest S-N ratio isgiving the smaller values of surface roughness, and it isthe optimized parameters.

Table-6. Response Table for Signal to Noise Ratios for Cutting Force

Level	Average for Surface Roughness			S/N ratio for Surface Roughness		
	Cutting Speed(m/min)	Feed(mm/rev)	Depth of cut(mm)	Cutting Speed(m/min)	Feed(mm/rev)	Depth of cut(mm)
1	147.33	88.33	140.00	-42.79	-38.83	-42.41
2	155.00	154.33	146.33	-43.54	-43.75	-43.11
3	132.33	192.00	148.33	-41.91	-45.65	-42.72
Delta	22.67	103.67	8.33	1.63	6.82	0.69
Rank	2	1	3	2	1	3
Optimal Parameter	150	0.05	0.8	150	0.05	0.8

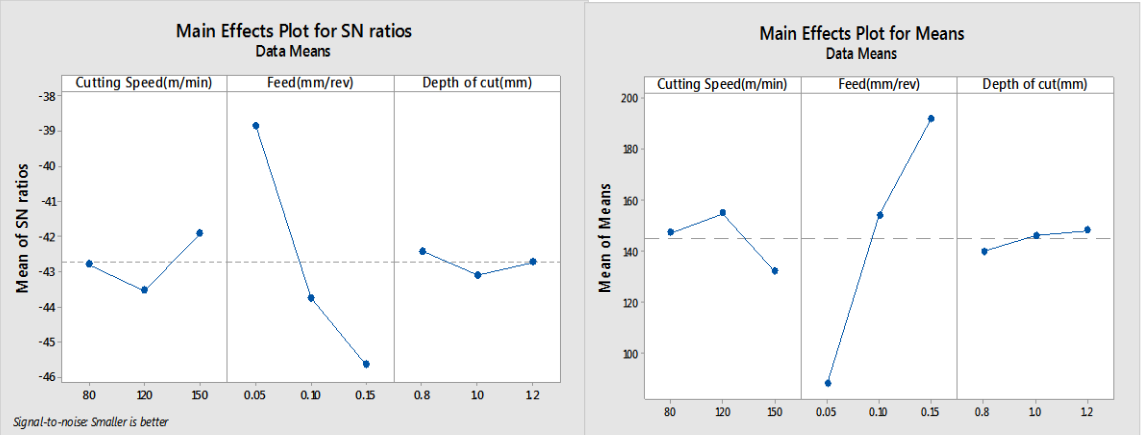


Fig-7(a) Main effects graph of S-N ratio with respect to cutting speed, feed and depth of cut;(b) Main effects graph of Means with respect to cutting speed, feed and depth of cut.

4.6 ANOVA analysis for Cutting Forces

Based on ANOVA results, the machining variable feed had more effect of 92.55% on the output variable surface roughness. Cutting speed had a contribution of 4.95%on the surface roughness. The depth of cut has less effect of 0.89% on the surface roughness. Table displays the result of ANOVA for the surface roughness. The error percentage is 1.58% which is lesser than the allowable limit error value of 15%. This shows that design, observation, and analysis are in the right direction.

Table-7. Analysis of Variance for Cutting Force

Source	DF	Adj SS	Adj MS	F-Value	Percentage of Contribution
Cutting Speed(m/min)	2	3.9795	1.9898	3.12	4.95%
Feed(mm/rev)	2	74.2868	37.1434	58.24	92.55%
Depth of cut(mm)	2	0.7223	0.3612	0.57	0.89%
Error	2	1.2756	0.6378	-	1.58%
Total	8	80.2642	-	-	-

4.7 Confirmation Table

Table-8. Optimum value of Surface Roughness

Predicted Optimal S/N value from Taguchi: S/N Ratio	-37.6657
Predicted Surface Roughness value corresponding to S/N	70.8889 N
Experimental Surface Roughness value	73.8875 N
Error %	4.22%

V. Tool Wear

Various tool wear such as crater wear, flank wear, abrasive wear, diffusion wear and nose wear areanalyzed using SEManalysis. It is proved that due to cryogenic treatment the hardness of Titanium is increased and is definitely more than cutting tool. The optimum parameter for cutting as determined i.e., cutting speed 150 m/min, feed 0.05 mm/rev and depth of cut 0.8 mm. So, by setting the machine at these parameters machining is done. In dry hard machining condition, the tool diffusion/Adhesion wear is not seen uniform.Diffusion wear is observed at the flank portion of the insertand the formation BUE was more at the cutting edge because of the adhesion. Turning at highspeed leads to heat generation which causes more cutting force on the insert.The toolwear is mostly high due to machining at high cutting speed. The wear patternmainly observed on the cutting insert was the crater wear in the nose region.

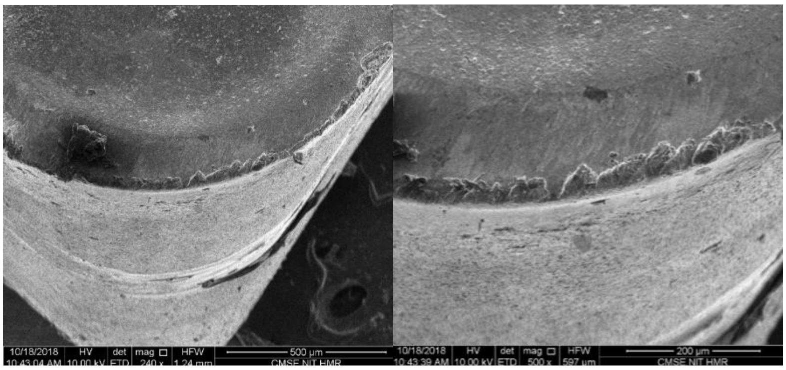


Fig-8 SEM micrograph of cutting tool insert under the following cutting conditions: v=150 m/min, f=0.05, d=0.8

5.1 Analysis of tool wear

The cutting surface of thetool inserts used for the machining were analyzed using the SEM(as shown above) and EDXtechniques to determine the nature of wear. Cuttingtools were multilayer coated cemented carbide inserts(Ti-Al-N).

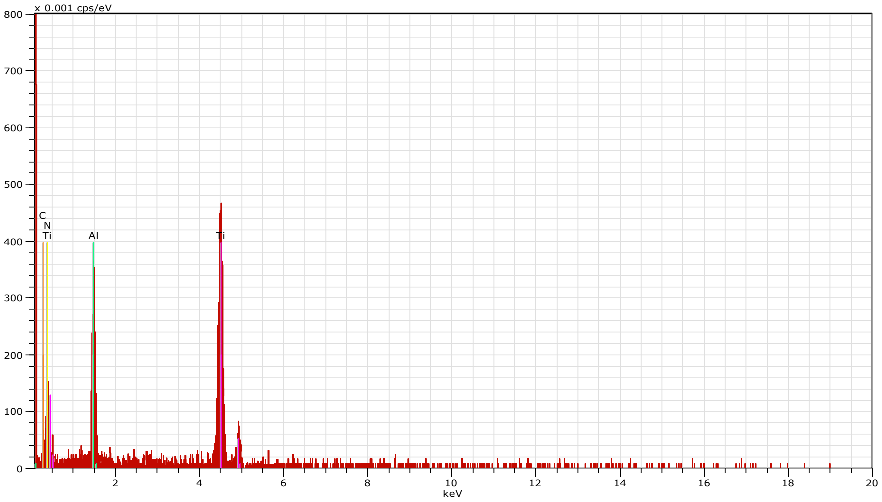
The EDX analysis of the new insertshows the presence of components at high levels of the original coating elements(TiAlN). On contrary, the analysis of components of worn inserts includes an extra element Tungsten(W) along with the original components as mentioned before in Table9

Table 9-EDX chemical composition analysis at flank face for new and worn cutting tool inserts

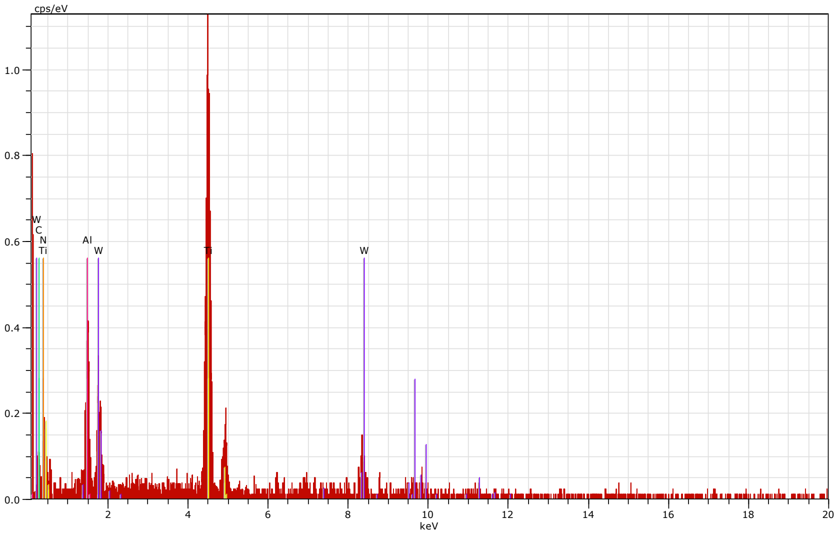
Element	New Insert		Worn out Insert at Cutting Speed					
			80m/min		120 m/min		150 m/min	
	Wt%	At%	Wt%	At%	Wt%	At%	Wt%	At%
Ti	38.81	16.31	31.39	14.13	33.69	14.73	33.18	13.97
N	37.02	53.20	27.22	41.87	28.14	42.05	31.60	45.08
C	13.40	22.45	20.18	36.19	19.50	33.98	18.91	31.60
Al	10.77	8.04	13.39	1.57	10.75	8.34	11.99	8.92
W	-	-	7.82	6.24	7.91	0.90	4.47	0.49
Totals	100		100		100		100	

5.1.1EDX of New and Worn-out Inserts

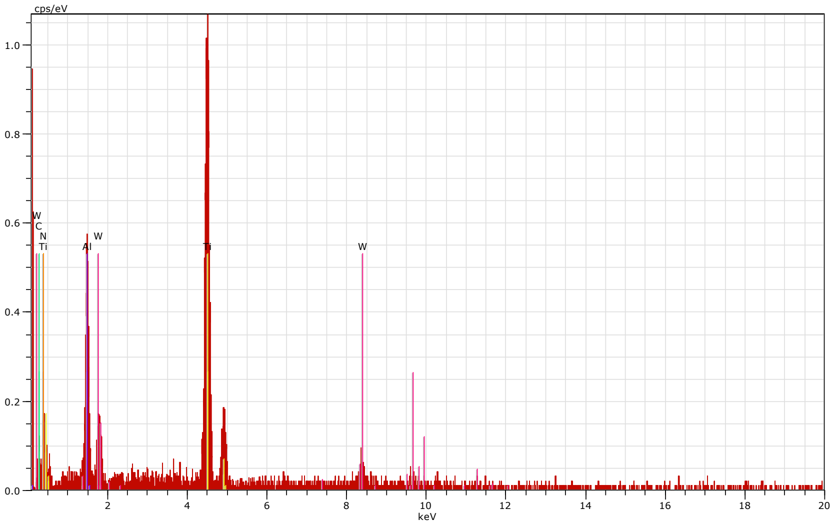
New Insert(Coated Carbide)



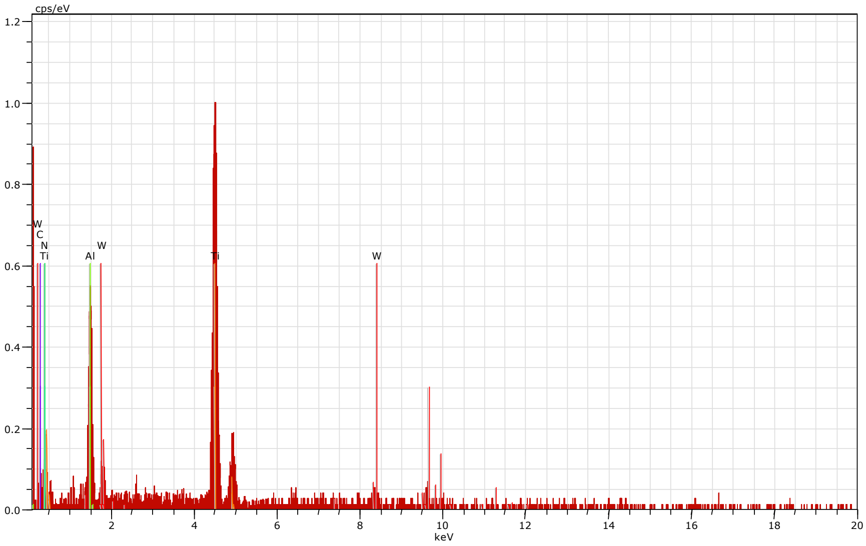
Insert at cutting speed 80 m/min



Insert at cutting speed 120 m/min



Insert at cutting speed 150m/min



VI. Conclusion

In this research work, investigation using Taguchi L9 orthogonal array is carried out and the influence of machining parameters on surface roughness and cutting force during dry turning of titanium alloy Ti-6Al-4V. The conclusions arrived from the experimental and analysis works are as follows

1) Due to the cryogenic treatment there is an improvement in the wear resistance and increase of Hardness of Ti–6Al–4V alloy from 36 to 42.3 HRC.
2) The optimal finish turning parameters have been obtained to produce minimum surface roughness and minimum cutting force.
3) The minimum surface roughness obtained using cutting speed of 150 m/min, the feed of 0.05 mm/rev and cutting depth of 0.8 mm.
4) The result of ANOVA analysis for surface roughness gives that cutting depth is the major factor that controls (68.38%) the surface roughness of the machined component. Next to depth of cut, the control factor tool feed affected the surface roughness by 21.20 %. The cutting speed showed a little contribution of about 9.5% to surface roughness. This shows that first cutting depth next feed rate need to be carefully controlled to have a better surface finish on the machined components.
5) The optimized value of surface roughness obtained is 0.1858 µm.
6) The minimum cutting force obtained using cutting speed of 150 m/min, the feed of 0.05 mm/rev and cutting depth of 0.8 mm.
7) The result of ANOVA analysis for Cutting Force gives that the cutting tool feed is the major factor that controls (92.55%) the Cutting Force of the machined component. Next to the feed, the control factor cutting speed affected the Cutting Force by 4.95%. The cutting depth showed a little contribution of about 0.89 % to Cutting Force. This shows that first cutting tool feed next cutting speed need to be carefully controlled to have a lesser cutting force on the machined components.
8) The optimized value of cutting force obtained is 73.88 N.
9) The built-up edges are found using SEM observation of the worn-out inserts and it is concluded that the tool wear is maximum at the flank side.
10) EDX of the flank portion is carried out and it is found that Tungsten(W) is diffused from working material to the insert.

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