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OPTIMIZATION OF INPUT CUTTING PARAMETERS OF SURFACE ROUGHNESS OF Ti–6Al–4V TURNING BY MQL MACHINING

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Abstract: The analysis of optimum cutting conditions to get the lowest surface roughness in CNC turning of Ti–6Al–4V. To study the effect of cutting speed (Vc), feed rate (f) and depth of cut (DOC) on surface roughness during machining of titanium alloy on CNC turning for minimum quantity lubrication (MQL). While working with cutting tool by using different cooling condition on this material more heat is develop because of high strength, hardness and its low thermal conductivity It was found that higher machining parameter gives more cutting force that affects to surface finish, for optimization the parameters Taguchi method (L27 design) was used for the experiments. Analysis of variance with an adjusted approach has been adopted. The results have been shown that the various input parameters give a more significant effect on surface roughness, which is observed under SEM and EDS. Feed rate and speed have more effect on the surface roughness in MQL condition.
Keywords: Taguchi design; ANOVA, MQL, Surface roughness, S/N Ratio,SEM, EDS

1. INTRODUCTION

The conventional turning operations are performed using single–point cutting tools like silicon nitrides, ceramic, polycrystalline diamonds, sintered carbides, boron nitrides, and polycrystalline cubic boron nitrides, etc. These cutting tools are expensive; to reduce the cost of the operation and to enhance tool life, it is necessary to maintain the machining parameters such that desired surface quality can be obtained along with increased tool life. It is also observed that the tool life depends on the selection of appropriate process parameters, their range and optimal combination of cutting speed (Vc), feed rate (f) and depth of cut (DOC).

To obtain a better surface quality of the product and increase tool life along with cutting parameters and material properties that majorly influence the cutting force. The physical and material Titanium alloy is usually used in high–temperature applications. Titanium alloy has a high strength to weight ratio. The other properties that are advantageous in many engineering applications are high corrosion resistant, high toughness, and biocompatibility. With the discussed properties of titanium alloys, it is suitable in a variety of applications like automotive, medical, aerospace, marine and chemical industries.

Surface roughness consists of the fine irregularities of surface textures including feed marks generated by the machining process the quality of a surface is a significantly important factor in evaluating the productivity of the machine tool and machined part. Where SEM and EDS used for observation of surface texture. Surface roughness has to bear on heat transmission, ability to hold lubricant, surface friction, wearing, etc. varying from various material to tool combinations and the machining conditions.

Taguchi's signal–to–noise(S/N) ratio was introduced to this experiment to determine the significant control factor out of cutting speed(Vc), feed rate(f) and depth of cut(DOC) for all three machining processes in parallel with determining the optimal control factor combination for procuring minimum surface roughness value.

An orthogonal array L_{27} was formed out of the control factors. Minitab 17 was used to determine the S/N ratio values for all the different interactions by incorporating "smaller the better" characteristic.

2. LITERATURE REVIEW

Mainly thrust research areas include improvement in surface finish, machinability of titanium alloys, tool wear, Surface roughness minimization, thermal analysis during machining. Wang and Lan et al [1] used Orthogonal Array of Taguchi method coupled with grey relational analysis considering four parameters viz. speed (Vc), depth of cutting (DOC), feed rate (f), and tool nose run etc. for optimizing three responses: surface roughness, tool wear and material removal rate in precision turning on an ECOCA–3807 CNC Lathe. Zang et al [2]. Used Minimum Quantity Cooling Lubrication and Minimum Quantity Lubrication as a cooling method. Tool life increases by 1.57 times under MQCL. Low Surface roughness were enhanced cooling performance. Feng and Wang et al [3] investigated the effect on surface roughness by developing an experimental model with variables like work piece hardness, feed, rake angle, depth of cut, cutting speed and time. Andriya et al [4]. Specified that the range of Vc and f was the most important factor for Ra value in turning Ti–6Al–4V. M. Rahman and N. R. Dhar et al [5] concentrated on the effect of MQL on chip–tool interference temperatures under different Vc and feed rates in turning of AISI9310 steel. Chip–tool interference was measured for three different cooling types such as dry, wet MQL conditions. Application of MQL at the chip– tool interface is expected to improve machinability characteristics. Bermingham et al [6].reported that high–pressure cryogenic coolants are effective coolants for increasing the tool life for machining.

Lalwani et al. [7] studied the effect of various parameters on Surface roughness in turning of MDN250 steel. The coated ceramic tool was used for RSM and Sequential Approach to face cantered composite design. It is observed that the DOC is the most significant factor for feed force and feed rate. Lin et al. [8] the surface roughness and cutting force could be predicated by the regression analysis model. Adopted an abdicative network to construct a prediction model for surface roughness and cutting force. Aouic et al. [9] have applied response surface methodology (RSM) to optimize the effect of cutting parameters (v, f, d) at the different levels of work piece hardness on surface roughness and cutting force components in the hard turning of AISI H11 with CBN tool results showed that the Surface roughness component was influenced principally by DOC and work piece hardness. D.Philip Sevaraj et al [10].Applied dry turning on cast DSS ASTM A 955 grade5A work material. TiC and TiCN coated carbide cutting tool inserts are used. S/N ratio and Analysis of Variance were applied to optimize the cutting parameters.

Ronan Autret et al. [11] compared the mechanical performance of MQL to completely dry lubrication for turning of hardened bearing–grade steel materials based on experimental measurement of Surface roughness, tool temperature, white layer depth, and part finish. The coolant used was a triglyceride and propylene glycol ester solution. The work piece material is HSS bars hardened to 62 to 64 RHC. The cutting tool used was a low content CBN tool with a rake angle of –6 degree, and nose radius of 0.8mm. The results indicate that the use of MQL leads to reduced surface roughness, delayed tool flank wear, a lower cutting temperature. Suresh et al. [12] focused on machining mild steel by TiC–coated tungsten carbide cutting tools for developing a surface roughness prediction model by using RSM.

Ozel et al. [13] conducted a set of analyses of variance and performed a detailed experimental investigation on the surface roughness and cutting force in the finish hard turning of AISI H13 steel. Their results indicated that the effects of two factors interactions of the edge geometry and the feed rate, and the Vc and the feed rate (f) are important. Sing and Rao et al [14] studied on optimization of feed force through the setting of the optimal value of process parameters (v, f, d) in turning of EN24 steel with TiC coated tungsten carbide inserts. Fnides et al. [15] studied on machining of X38CrMoV5–1 steel treated at HRC by a mixed ceramic tool (insert CC650) to reveal the influence of cutting parameters (v, f, d) and flank wear on cutting forces as well as on surface roughness.

Nikhil Ranjan Dhar et al [16] investigated the role of MQL on cutting temperature, tool wear, surface roughness and dimensional deviation in the plain turning of AISI–4340 steel on a powerful and rigid lathe at different cutting velocities (Vc) and feed under dry, wet, minimum quantity lubrication (MQL) conditions. Results include a significant reduction in tool wear rate, dimensional inaccuracy and surface roughness by MQL mainly through a reduction in the cutting zone temperature and a favorable change in the chip–tool and work–tool interaction. Boucha et al. [17]

stated the effect of cutting parameters on surface roughness and cutting forces. A three–level factorial design was used to study the machining behavior of AISI52100 steel. Feed rate (f) and Vc are the major affecting parameter for surface roughness. Where the DOC governs major for the Surface roughness. A. Zawada–Tomkiewicz et al. [18] studied the multi–parameter characterization of the surface in turning operation on an EN41Cr4 low chromium alloy steel. Polycrystalline cubic boron nitride tools were used for machining the material.

Kaplan B et al. [19] studied the tool wear is studied by using X–ray diffraction and electron microscopy. To check the Performance each cemented carbide grade was used for the interface of the cemented carbide/work–piece. It is observed that with decreasing binder volume % a slower wear progression and longer tool life is observed. The microstructure of the adhered layer is also dependent on the binder volume %, and diffraction peaks corresponding to cubic (Ti,V)C are also occasionally observed. Tao Chen et.al [20] studied the optimization of cutting force on the turning of GCr15 steel by setting the optimal value of process parameters Suárez, A et al. [21] worked on nickel–based alloy 718 turning by using the HPC and flood cooling. Tool wear and Surface roughness were noted. HPC reduced Surface roughness s by more than 10%. Jafarian, G et al [22] the major effect of machining time at the different cutting parameters was mostly investigated on the surface roughness. For this, the neural network model was used. Non–dominated Sorting Genetic Algorithm was applied to enhance tool life and surface roughness. Pervaiz, S et al [23] Machinability for hard material was studied for different parameters like cutting tool materials, wear mechanisms, modes of failure, and new tooling techniques. Surface integrity defects were studied on residual stresses, cracking, microstructural alterations, and work hardening layer formation. Guo Y.B et al [24] geometrically defined tools are used to study the features of residual stresses formed in the machining of hardened steels. Correlations between residual stresses, microstructures, and tool–wear were studied by using the Finite element method.

Many researchers have proposed that surface roughness is a function of heat transmission, the ability to hold lubricant, surface friction, wear, etc. Presently to cool the tool and work piece different types of coolants, cryogenic fluids and compressed air are used. The above literature review visualizes that researchers have carried out a study on different materials by focusing on different traditional cooling systems with a different combination of coolants on surface finish, cutting force and other performance parameters.

3. MATERIALS AND MACHINE

Annealing heat treatment followed by air cooling Ti–6Al–4V material alloy used for this research study. These bars (20 mm in diameter and 100 mm in length) were machined under MQL condition. This grade offers good toughness and wears resistant against titanium alloy. The turning operation was conducted using TC35 Industrial type of CNC lathe machine with a range of spindle speed from 50 rpm to 3500 rpm, and a 10 KW motor drive. The chemical composition of the material used in this work is given table1.

Figure 1. Experimental setup of MQL Machining

Table 1: Chemical composition work piece alloy.

C	Al	O	Fe	V	H	N	Ti	Y
0.010	5.86	0.12	0.200	4.02	0.0023	0.007	Bal.	<0.0050

The work piece material selected for study is titanium alloy (Ti–6Al–4V) for its good mechanical properties like strength, hardness and modules of elasticity.

Table 2: Mechanical properties of Ti–6Al–4V.

Property	UTS	Fatigue strength	Rockwell Hardness	Modulus of Elasticity	Elongation
Value	1020 MPa	600 MPa	33 HRC	120 GPa	14%

— Cutting tool insert

The insert type was TNGA 160408–KY1615. It is a ceramic–based cutting tool. It is excellent for machining most of the steel, stainless steel, Ni–hard alloy nonferrous materials, Inconel 718, EN–31, Ti alloy. Under the stable condition, it also performs well machining hardened and short chipping materials. The tool code TNGA160404 indicates that the insert is of triangular geometries the length of cutting edge is 16 mm, with thicknesses 4 mm and Nose Radius is of 4mm.

— **Surface roughness measurement**

The instrument used for the measurement of surface roughness was surf test SJ–201P manufactured by Mitutoyo company which is a stylus probe–type instrument measuring range –200µm to 150µm, stylus tip radius 5µm and roughness parameter Ra, Rq, Rz.

— **Cutting condition**

Here for this experimentation MQL cooling is used. The cooling strategies are studied against a mix of the high and low levels of cutting parameters (v, f, d) which have been selected to present a challenge to machining. MQLis provided using an external setup where compressed air and vegetable oil is mixed, a nominal oil flow rate of 3 ml/ min is to be supplied by this MQL unit through the contact point of tool and work piece. Vegetable oil consists of biodegradable substances and it is fit for industrial use.

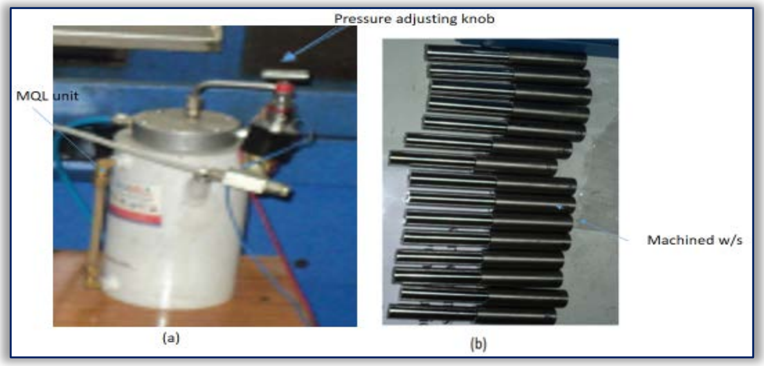

Figure 2. Experimental setup (a) MQL Unit (b) Machined work pieces

Table 3: Factors and their Levels

Factor	Level 1	Level 2	Level 3
Speed (rpm)	1000	1200	1500
Feed (mm/rev.)	0.1	0.15	0.20
Depth of cut (mm)	0.5	1	1.2

4. TAGUCHI'S DESIGN

Taguchi design L–27 for three levels and three factors (3^k) yielded 27 experiments and two replicates were carried out. For this input parameter level are considered for experimentations. It is shown in Table –3.

— **Experimentation and analysis for MQL**

Taguchi design L_{27} for three levels and two replicates were carried out. The run order, cutting parameters and responses in the design of experiments are given Table–4

Table 4: Design matrix with responses (surface roughness) for MQL

Run order	Speed RPM	Feed mm	Depth of cut mm	RA For MQL µm	SNRA1	MEAN1
1	1000	0.10	0.5	0.81667	1.75910	0.81667
2	1000	0.10	1.0	0.86833	1.22627	0.86833
3	1000	0.10	1.2	0.94900	0.45468	0.94900
4	1000	0.15	0.5	1.14830	–1.20111	1.14830
5	1000	0.15	1.0	1.23447	–1.82959	1.23447
6	1000	0.15	1.2	1.32500	–2.44432	1.32500
7	1000	0.20	0.5	1.49713	–3.50521	1.49713
8	1000	0.20	1.0	1.51333	–3.59869	1.51333
9	1000	0.20	1.2	1.69537	–4.58527	1.69537
10	1200	0.10	0.5	0.83467	1.56974	0.83467
11	1200	0.10	1.0	0.83800	1.53512	0.83800
12	1200	0.10	1.2	0.86133	1.29657	0.86133
13	1200	0.15	0.5	1.23863	–1.85886	1.23863
14	1200	0.15	1.0	1.28200	–2.15776	1.28200
15	1200	0.15	1.2	1.19267	–1.53038	1.19267
16	1200	0.20	0.5	1.18770	–1.49414	1.18770
17	1200	0.20	1.0	1.18780	–1.49487	1.18780
18	1200	0.20	1.2	1.29403	–2.23891	1.29403
19	1500	0.10	0.5	0.81933	1.73079	0.81933
20	1500	0.10	1.0	0.84900	1.42185	0.84900
21	1500	0.10	1.2	0.85860	0.36725	0.95860
22	1500	0.15	0.5	1.29967	–2.27664	1.29967
23	1500	0.15	1.0	1.34110	–2.54922	1.34110
24	1500	0.15	1.2	1.79300	–5.07161	1.79300
25	1500	0.20	0.5	1.82038	–5.20324	1.82038
26	1500	0.20	1.0	1.95667	–5.83034	1.95667
27	1500	0.20	1.2	1.94600	–5.78286	1.94600

Table 5: Signal to Noise Ratios

LEVEL	Speed	Feed	DOC
1	-1.5249	1.2624	-1.1644
2	-0.7082	-2.3244	-1.4752
3	-2.5771	-3.7482	-2.1705
Delta	1.8689	5.0105	1.0061
Rank	2	1	3

— **Taguchi Analysis: RA versus Speed, Feed, DOC**

Response table for Signal to Noise Ratio – Smaller is the better condition

— **Response Surface Regression: RA versus Speed, Feed, DOC**

The ANOVA results very clearly support the hypotheses, indicating that both feed and depth of cut have a significant influence on surface roughness (Table 6). This can be seen in the main effect plot of surface roughness.

Table 6: Analysis of Variance and regression Coefficients

Source	DF	Adj SS	Adj MS	F–Value	P–Value
Model	6	2.93905	0.48984	25.56	0.000
Linear	3	2.53008	0.84336	44.00	0.000
Speed	1	0.16746	0.16746	8.74	0.008
Feed	1	2.27740	2.27740	118.82	0.000
DOC	1	0.08523	0.08523	4.45	0.048
Square	2	0.30462	0.15231	7.95	0.003
Speed*Speed	1	0.24353	0.24353	12.71	0.002
Feed*Feed	1	0.06109	0.06109	3.19	0.089
2–Way Interaction	1	0.12188	0.12188	6.36	0.020
Speed*Feed	1	0.12188	0.12188	6.36	0.020
Error	20	0.38335	0.01917		
Total	26	3.32240			
Model Summary	S	R=SQ	R=SQ(adj)	R–SQ(Pred)	
	0.138445	94.12%	91.00%	89.87%	

Table 7: Coded Coefficients

Term	Effect	Co–efficient	SE Co– efficient	T–Value	P–Value	VIF
Constant	—	1.1704	0.0616	18.99	0.000	——
Speed	0.1929	0.0965	0.0326	2.96	0.008	1.01
Feed	0.7137	0.3569	0.0327	10.90	0.000	1.01
DOC	0.1336	0.0668	0.0317	2.11	0.048	1.00
Speed*Speed	0.4225	0.2113	0.0593	3.56	0.002	1.01
Feed*Feed	–0.2018	–0.1009	0.0565	–1.79	0.089	1.00
Speed*Feed	0.2002	0.1001	0.0397	2.52	0.020	1.01

It can be observed that the interaction effect of feed rate & depth of cut and the interaction of all three cutting parameters have a significant influence on surface roughness. The R–square and adjusted R–square values (94.12 and 91 %) above 90%, indicates that the model is fit.Which is on the higher side of the acceptable limit. The regression coefficients of surface roughness for MQL are given in table 7. The regression equation for surface roughness is as follows.

$$MQL\ RA = 5.71 - 0.00978\ S + 39.2\ F - 6.15\ DOC + 0.000004\ S*S - 64.4\ F*F$$
$$+ 2.34\ DOC*DOC - 0.0051\ S*F + 0.00260\ S*DOC - 3.72\ F*DOC \quad \ldots (1)$$

5. RESULTS & DISCUSSIONS

The main effect of S/N ratio and the average surface roughness of Ti–6Al–4V machining for MQL cooling. The graph shows the surface roughness of Ti–6Al–4V affected by all the three process parameters here S/N Ratio affected by speed, feed, and depth of cut and main effect Ratio affected to the process parameters are shown in Figure 3(a–b).

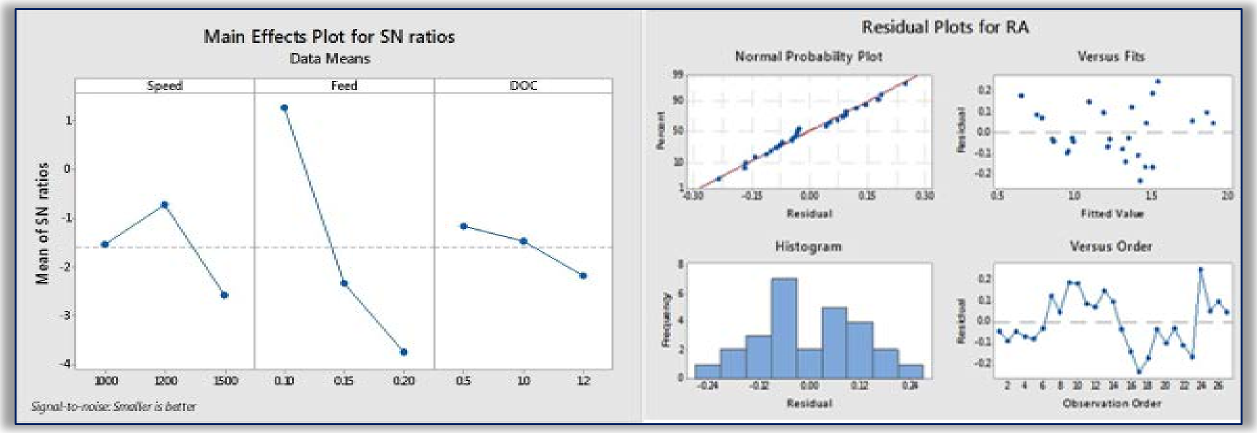

Figure 3. (a) S/N Ratio verses process parameter (b) Mean effect Ratio verses process parameter

The contour plot shows in fig4 (a)–(c) that depicts the minimum surface roughness less than 0.6μm occurs at less than 0.1mm/rev feed rate,depth of cut in the range of 0.3 to 0.8 mm, and speed between 1050rpm to1450 rpm respectively.

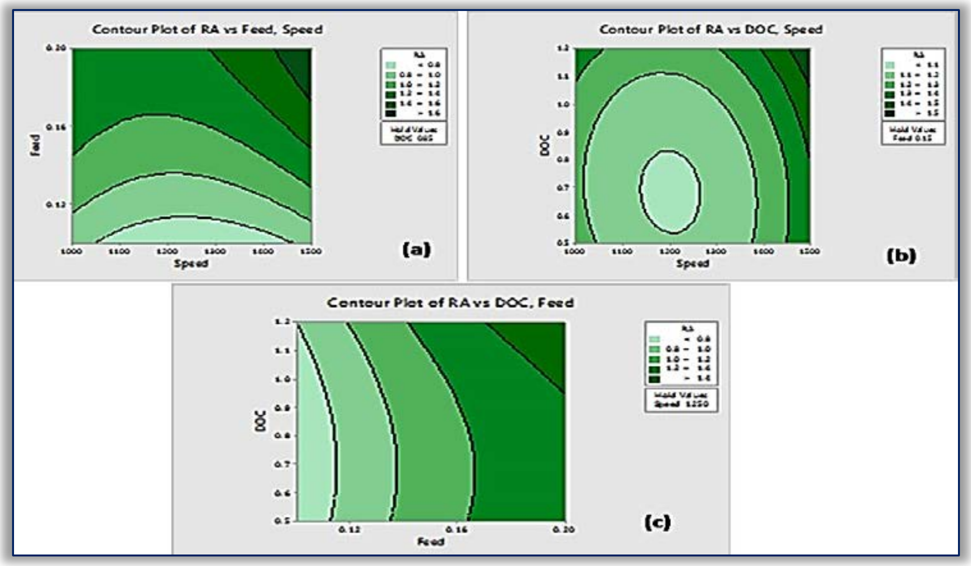

Figure 4: Contour Plots (a) RA vs. speed, feed, (b) RA vs. speed, Doc, (c) RA vs. feed, Doc

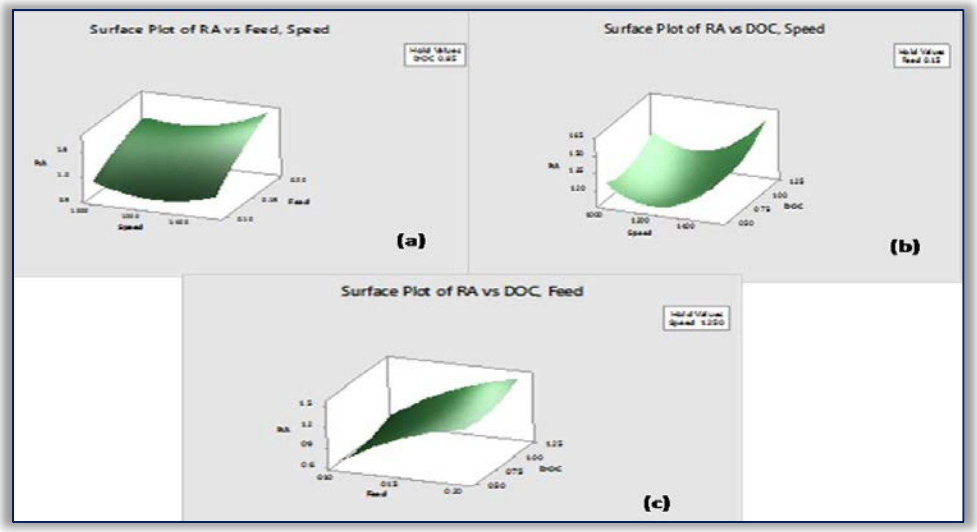

Fig 5: Surface plot (a) RA vs. speed, feed, (b) RA vs. speed, Doc, (c) RA vs. feed, Doc

The main effect of the response surface method and average of the surface roughness of Ti–6Al–4V Machining for MQL cooling. The graph shows the surface roughness of Ti–6Al–4V affected by all the three process parameter (v, f, d) response surface methods. The surface response parameter developed from the empirical relationship is presented in the graphical form to analyze the effect of parameter on response. The input process parameters are assigned on the X–axis and Y–axis and response on Z–axis. The response surface indicates the optimal surface roughness is showed by the apex of the response surface shown in fig.5(a)–(c) the surface roughness is 1.4 μm exhibited by the apex of the response surface for the values of feed, depth of cut and speed are 0.16mm/rev; 0.8mm, and 1450rpm respectively. The feed rate and depth of cut have a major significant influence on the surface roughness. The regression model with the P values indicated that the three cutting parameters and the two–level interaction of speed & feed and feed & depth of cut. The most significant among all these is the feed rate which is very much in the deal with the analysis of variance. One more parameter that is nose radius also affect to surface roughness, the theoretical surface roughness [$Ra=f^2/(32r)$] is mainly a function of the feed rate.

6. SURFACE ANALYSIS OF WORK PIECE

Titanium oxides developed during the turning process by the metal oxidation reaction and its influence in the micro compositional and microstructural work piece material changes to be studied by applying scanning electron microscopy (SEM) methods combined with this energy dispersive spectroscopy (EDS) analysis. Where changes in different parts of work piece material surface were characterized by SEM and EDS. The microstructure of the machined surface of the titanium work–piece was obtained for each machined sample by using a scanning electron microscope (SEM). The microstructure of each machined sample was obtained in order to study of the machined surface. Fig 6 show the SEM images of Ti–6Al–4V under MQL cooling. the surface generated under the cutting speed of 1000rpm, feed of 0.1mm/rev, and depth of cut of 1.2 mm and the recorded surface roughness of 0.949µm.

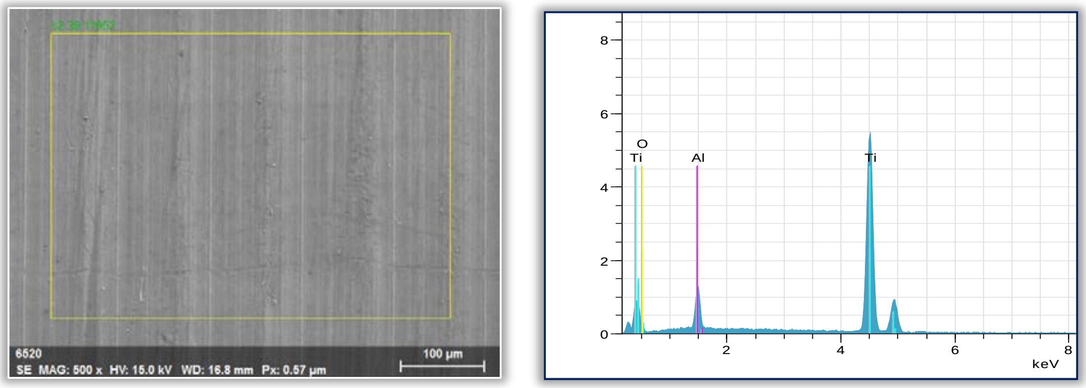

Figure 6. Surface generated during machining of titanium alloy (Ti–6Al–4V) with MQL condition (cutting speed: 1000rpm, feed: 0.10 mm/rev, and depth of cut: 1.2 mm).

Figures 7 show the SEM images of Ti–6Al–4V under MQL cooling. the surface generated under the cutting speed of 1000rpm, feed of 0.1mm/rev, and depth of cut of 1.2 mm and the recorded surface roughness of 0.86133µm.

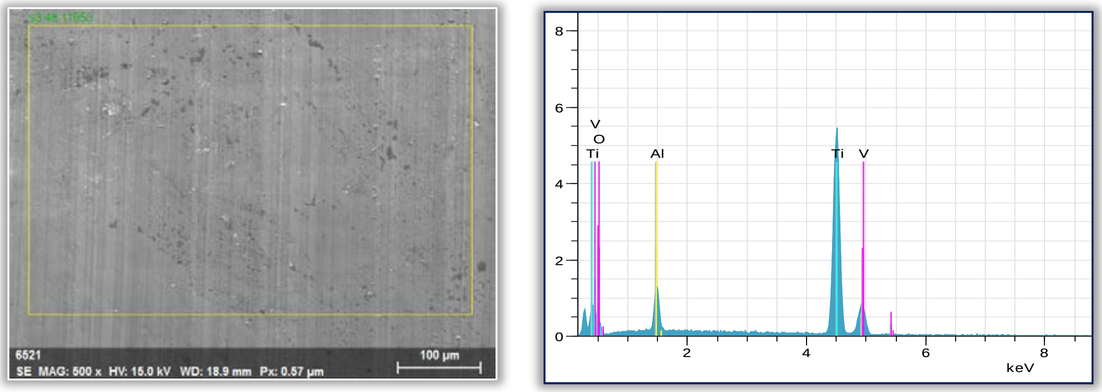

Figure 7. Surface generated during machining of titanium alloy (Ti–6Al–4V) with MQL condition (cutting speed: 1200rpm, feed: 0.10 mm/rev, and depth of cut: 1.2 mm).

Figures 8 show the SEM images of Ti–6Al–4V under MQL cooling the surface generated under the cutting speed of 1000rpm, feed of 0.1mm/rev, and depth of cut of 1.2 mm and the recorded surface roughness of 0.85860µm.

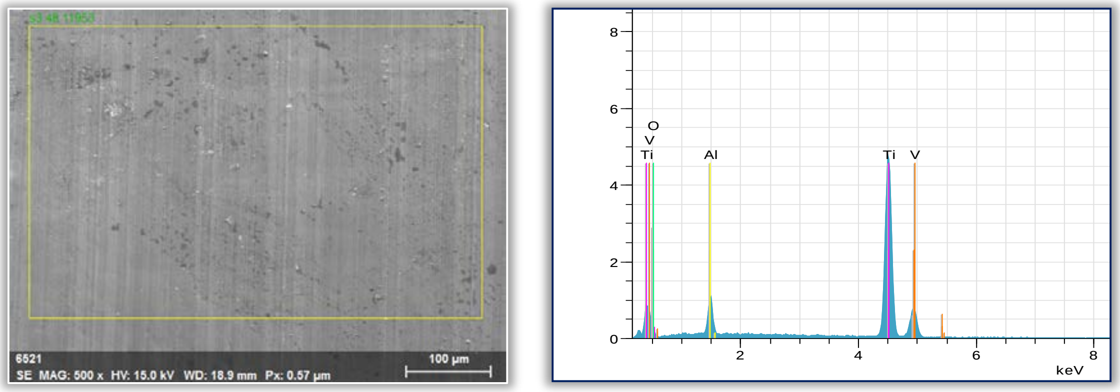

Figure 8. Surface generated during machining of titanium alloy (Ti–6Al–4V) with MQL condition (cutting speed: 1500rpm, feed: 0.10 mm/rev, and depth of cut: 1.2 mm).

Table 8: EDS–analysis of the Ti–6Al–4V grains reveals for different speed

E1	AN	Norm. C Wt.%for 1000rpm speed	Norm. C Wt.%for 1200rpm speed	Norm. C Wt.%for 1500rpm speed
Ti	22	84.88	90.59	91.58
Al	13	5.86	6.14	5.91
V	23	1.86	3.27	2.51
O	8	7.40	0.00	0.00

SEM and of the turned off the Ti–6Al–4V material produced during high cutting speed at 1500 rpm revealed a relatively smooth surface with compare to 1200rpm and 1000rpm speed at constant 0.1mm/rev feed and 1.2mm depth of cut. Which is shown in Fig7–9. The better surface finish is attributed due to MQL condition, low feed, and high cutting speed. A large number of defects were observed on the surface during the experimental trials conducted. The SEM images of the machined surfaces show that micro–pits and re–deposited work material were the main damages to the surfaces. Microstructural examination of the machined surfaces revealed no plastic deformation after finish machining at the cutting conditions investigated. EDS–analysis of the Ti–6Al–4V grains reveals for different speeds shows increasing the contents of Ti with an increase in speed which is shown in table 8. While the results declared through this experimental work may be generalized to a considerable extent while working on Ti–6Al–4V using cutting tools, the study is limited to the extreme range of values of the cutting parameters specified. In this experimentation cutting condition(MQL) enables to reduce the main surface roughness due to improved and near chip tool interaction, the cutting fluid has mainly reduced the amount of heat and friction at the contact point of tool and work piece. The most probable reason can be explained as the cutting speed increases, the heat generated at the deformation zone increases as a result of adiabatic heating due to high strain rate deformation and friction between the tool and work piece. This heat generated cannot dissipate into the work piece because of the poor thermal conductivity of titanium alloys leading to unfriendly conditions to cut the material. In machining of Ti–6A1–4V, tool wear had a greater influence on the surface roughness rather than the thermal softening characteristics of the titanium alloy as surface roughness did not decrease with speed, but it is increased.

7. CONCLUSIONS

The following conclusions were drawn based on the research work carried out by employing MQL Cooling conditions.

From the analysis of variance, it is observed that the feed is the most influencing parameter to surface roughness followed by the depth of cut and cutting speed in turning by using MQL Cooling condition:

- The minimum surface roughness of 0.8μm is obtained at 1000–1350 rpm of cutting speed, 0.12 mm/rev of feed and less than 1.0 mm of the depth of cut by using MQL cooling condition.
- Surface roughness estimated using the regression equation developed for MQL cooling condition predicts 1.32 μm optimal cutting conditions.
- The feed is the most influencing parameter for surface roughness. The higher feed rate led cutting tools to traverse the work piece too rapidly resulting in deteriorated surface quality.
- SEM and of the turned off the Ti–6Al–4V material produced during high cutting speed at 1500 rpm revealed a relatively smooth surface with compare to 1200rpm and 1000rpm speed at constant 0.1mm/rev feed and 1.2mm depth of cut.

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