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ANALYSIS OF DRY LUBRICATION STRATEGIES FOR SUSTAINABLE MACHINING DURING TURNING OF TITANIUM TI-6AL-4V ALLOY

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Abstract: The machining of titanium alloy is very difficult, expensive and during machining it lead wear and tear of tool tip. To improve tool life and obtain better surface quality of work piece, it is necessary to set up optimal process parameters during machining. This work aims to evaluate the effect of input process parameters on cutting force in Dry Machining of Titanium Alloy. The CNC turning on titanium alloy material were conducted as per Taguchi L_{27} orthogonal array design matrix Turning parameters studied were cutting speed (1000, 1200, 1500 rpm), feed rate (0.1, 0.15, 0.2 mm/rev) and depth of cut (0.5,1.0,1.2 mm) respectively. The Dry Machining has been adopted to study the effect of parameters on cutting force and surface quality, the significantly affecting process parameters are identified using ANOVA and optimal response parameters. Also proposed a mathematical model to estimate optimum cutting force. The results reveals that depth of cut is most significantly affecting process parameters and the cutting force estimated from proposed model is in close agreement with each other. This study helps to identify the Dry condition and cutting force which leads to the optimal solution.
Keywords: Taguchi design, ANOVA, S/N Ratio, RSM, Cutting force

1. INTRODUCTION

The conventional turning operations are performed using single point cutting tool like silicon nitrides, ceramic, polycrystalline diamonds, sintered carbides, boron nitrides, and polycrystalline cubic boron nitrides etc. These tools are expensive, to reduce the cost of the operation and increase the tool life it is very necessary to maintain the operating condition of the tool to obtain the desired surface quality. There are many cutting parameters like feed rate, speed, Depth of cut, tool geometry and material properties are influencing on cutting force. The material and its physical and chemical properties of the materials are also affects to the surface accuracy, tool wear, chip formation, cutting temperature etc. A Bhattacharya et al. [1] investigated the effect of cutting parameters on surface roughness and power consumption during high speed machining of AISI 1045 steel using Taguchi design and ANOVA. The result shows that the cutting speed is significant parameter affecting on surface roughness and power consumption. A Kacal and Yildirim et al [2] carried out experiment on high speed hard turning of AISI S1 cold work tool steel. The results show that good surface roughness obtained with CBN tools. A surface roughness value of approximately 0.2 µm was obtained. Andriya et al [3].stated the range of cutting forces and surface roughness in turning Ti-6Al-4V. For surface roughness cutting velocity and feed were the most significant factor. Asiltürk et al. [4] investigated that the main effect of the feed rate was the most significant factor on the work piece surface roughness (Ra and Rz) with the percent impact of 85.5% in bringing down the average roughness values in both Taguchi and response surface analysis. It was also found that RSM to be effective for the identification and development of important relationships between cutting parameters. B. Fnides et al. [5] studied on machining of X38CrMoV5-1 steel treated at HRC by a mixed ceramic tool (insert CC650) to reveal the influence of cutting parameters and flank wear on cutting forces as well as on surface roughness.

Bermingham et al [6].studied turning of Ti-6Al-4V using cryogenic coolants and high pressure emulsions are most effective coolants extending the tool life. However, the high pressure water based emulsion offered a better tool life. D. Lalwani et al. [7] attempted to investigate the effect of cutting parameters on cutting forces and surface roughness in finish hard turning of MDN250 steel using coated ceramic tool through response surface methodology (RSM) and sequential approach using face centered central composite design. The results show that the depth of cut is most significant factor for feed force and feed rate is most significant factor for surface roughness. D.Philip Sevaraj et al [8]. Stated the dry turning operation on cast DSS ASTM A 955 grade5A using TiC and TiCN coated carbide cutting tool inserts. Taguchi's S/N ratio ANOVA were implemented to optimize the cutting parameters. Cutting speed 100m/min and a feed rate of 0.04mm/rev gave an outcome of lowest surface roughness values for both the grades of duplex stainless steel. A cutting speed set at 120m/min with a feed rate of 0.01mm/rev secured the lowest cutting force for both grades of duplex stainless steel.

Feng and Wang et al [9] investigated the influence on surface roughness in finish turning operation by developing an empirical model through considering exogenous variables work piece hardness (material), feed, cutting tool point angle, depth of cut, spindle speed, and cutting time. Fratila D et.al. [10] used Orthogonal Array of Taguchi method coupled with grey relational analysis considering four parameters viz. speed, depth of cutting, feed rate, tool nose run off etc. for optimizing three responses: surface roughness, tool wear and material removal rate in precision turning on CNC. G. Akhyar et al. [11] analyzed optimization of cutting parameters in turning Ti-6Al-4V extra low interstitial with coated and uncoated cemented carbide tools under high cutting speed with dry cutting condition. Taguchi's robust design method is suitable to optimize the surface roughness in turning Ti-6Al-4V ELI. The significant factors of surface roughness in turning Ti-6Al-4V ELI were feed rate and tool grade, with contribution of 47.14% and 38.88% respectively. Ginting. A et al [12] studied is focused on the machined surface integrity of titanium alloy under the dry milling process. The result of surface roughness shows that the CVD-coated carbide tool fails to produce better Ra value compared to the uncoated tool. It was concluded that for titanium alloys, dry machining can be carried out with uncoated carbide tools as far as cutting condition is limited to finish and/or semi-finish operations. H. Aouic et al. [13] 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 cutting force component were influenced principally by depth of cut and work piece hardness. Haron et al. [14] found that the feed was the most dominant factor influencing the surface roughness. Acceptable surface roughness achieved when cutting speed was 160 m/min; feed was 0.18 mm/rev and depth of cut was 1 mm. Ibrahim et al.[15] explored that machining of titanium alloy at the high feed rate produced the high and uneven surface roughness but when the cutting speed increases surface roughness decreases. J. Senthilkumar et al. [16] carried out experimental investigation of surface roughness and flank wear in finish turning and facing of Inconel 718 using taguchi technique. The percentage error between experimental and predicated result is 4.67% for turning process and 2.63% for facing process. Results showed that cutting speed and depth of cut are the dominant factors of turning process while cutting speed and feed are dominant factors of facing process. K. Vikram and Ratnam et al [17] developed an empirical model for surface roughness in hard turning based on analysis of machining parameters and hardness values of various engineering materials. The process parameters like cutting speed and feed are primary influencing factors of surface finish. The results indicate that feed is the dominant factor affecting on surface roughness followed by cutting speed and material hardness.

K. Boucha et al [18] investigated the effect of cutting speed, feed rate and depth of cut on surface roughness and cutting speed, feed rate and depth of cut on surface roughness and cutting forces using three level factorial design (3^3) during machining of bearing steel (AISI52100) with CBN tool. Results show how much surface roughness is mainly influenced by feed rate and cutting speed and that the depth of cut exhibits maximum influence on the cutting forces as compared to feed rate and cutting speed. Lin et al. [19] the surface roughness and cutting force could be predicated by regression analysis model. Adopted an abdicative network to construct a prediction model for surface roughness and cutting force Gunay and Yucel et al [20] analyzed optimization of cutting conditions for the average surface roughness obtained in machining of high alloy white cast iron (Ni-Hard50 HRC and 62 HRC) at two different hardness levels. The effects of the cutting parameters and tool material on surface roughness were evaluated by the analysis of variance. The statistical analysis indicated that the cutting speed and feed rate are significant parameters effect on surface roughness. Pawade and Joshi et al [21] analyzed multi-objective optimization of cutting force and surface roughness in the high speed turning of Inconel 718. A commercially available low cubic boride nitride (CBN) content inserts were used as cutting tool. Results showed that depth of cut had statistical significance on overall turning performance. Rotella G. et.al. [22] Studied of machining of Ti6Al4V alloy under dry, minimal quality lubrication, and cryogenic cooling conditions using coated tools at varying cutting speeds and feed rates. Results show that cooling conditions affect surface integrity of the product signifying the benefits of cryogenic cooling in improving the overall product performance. Suresh et al. [23] focused on machining mild steel by TiC-coated tungsten carbide (CNMG) cutting tools for developing a surface roughness prediction model by using Response Surface Methodology (RSM). T Ozel et al. [24] conducted a set of analysis of variance (ANOVA) and performed a detailed experiment 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 cutting speed and the feed rate are also important.

The above literature review study that many researchers have carried out study on different materials by focused on different traditional cooling systems with different combination of coolants on surface finish, cutting force and other performance parameters. Also there is a continuous need to extend this study for the different combinations of input process parameters during machining of Ti-6Al-4V material with dry Cooling system to determine the optimal process parameters to obtain the desired cutting force and surface conditions.

2. MATERIALS AND MACHINE

The Ti-6Al-4V material rod annealed, heat treated and followed by air cooled material is used in the research work. This grade 5 material offers good toughness and wear resistant as compared to the other materials alloys. The 20 mm diameter titanium alloy rod is cut into a work pieces of 100 mm length. 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. The titanium alloys is one of the material which has desired properties helpful for variety of applications like automotive, medical, aerospace, marine and chemical industries. The chemical and mechanical properties of the material is given in Table 1.

Table 1: Chemical and Mechanical properties of the material.

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

The ceramic based cutting tool inserts were used. These insets have excellent capability for machining stainless steel, Ni-alloy nonferrous, Inconel 718, EN-31, and Ti alloy materials under stable conditions to perform machining of hardened and short chipping materials. The triangular geometry insert (TNGA160404) selected for the experimental work specifications and geometry dimensions are given in Table 2 and Figure 1 respectively.

Table 2: Insert specifications

Size mm	Grade	Chip groove	r mm	l mm	d mm	s mm	d1 mm
16	TNGA160404	M42	0.4	16.5	9.52	4.76	3.81

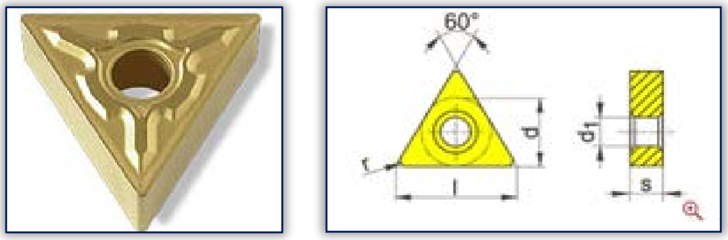

Figure 1. Cutting Tool Insert geometry

The TC35 Industrial type of CNC lathe machine with a range of spindle speed varies from 50 - 3500 rpm, and maximum operating power of 10 KW used for turning of Ti-6Al-4V material. The experiments were conducted as per Taguchi's L_{27} orthogonal array design matrix to study the main effect of cutting parameters and process parameters on responses. The experimental setup used for conducting experiments is shown in Figure 3.

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

The experiments were conducted under dry cooling system to cool work piece and cutting tool during machining. The effect of cooling on machining parameters such as surface finish and Cutting force were analyzed. The range of levels of cutting speed, feed and depth of cuts selected for experimentation are presented in Table 3.

Figure2 Experimental setup of dry Machining

3. CUTTING FORCE MEASUREMENT

The three dimensional tool dynamometer is used for measurement of cutting force. It comprises of three independent digital display units and calibrated to display force directly. The cutting force measuring unit comprise with independent strain gauge bridges arrangement for measuring strain in independent directions, signal processing system and independent display of respective axis data. Instrument operates on 230V, 50Hz AC mains supply. The Taguchi design matrix L_{27} for three levels and three factors (3^k) yielded 27 experiments were carried out. The run order (runs), cutting input process parameters and responses of average of three tangential cutting force measured using dynamometer is given in Table 4.

Table 4: cutting force measurement

Runs	speed	feed	DOC	Force	Runs	speed	feed	DOC	Force
1	1000	0.10	0.5	17.6667	15	1200	0.15	1.2	41.0000
2	1000	0.10	1.0	30.0000	16	1200	0.20	0.5	35.6667
3	1000	0.10	1.2	33.6667	17	1200	0.20	1.0	46.0000
4	1000	0.15	0.5	24.6667	18	1200	0.20	1.2	56.3333
5	1000	0.15	1.0	40.3333	19	1500	0.10	0.5	25.6667
6	1000	0.15	1.2	52.3333	20	1500	0.10	1.0	41.6667
7	1000	0.20	0.5	27.0000	21	1500	0.10	1.2	65.3333
8	1000	0.20	1.0	45.0000	22	1500	0.15	0.5	38.0000
9	1000	0.20	1.2	54.0000	23	1500	0.15	1.0	40.3333
10	1200	0.10	0.5	19.3333	24	1500	0.15	1.2	49.6667
11	1200	0.10	1.0	23.6667	25	1500	0.20	0.5	32.6667
12	1200	0.10	1.2	28.0000	26	1500	0.20	1.0	56.0000
13	1200	0.15	0.5	23.0000	27	1500	0.20	1.2	57.0000
14	1200	0.15	1.0	32.0000					

4. STATISTICAL ANALYSIS OF EXPERIMENTAL DATA

The effect of control parameters like speed, feed, and depth of cut are varied as per orthogonal array of L_{27} and the surface roughness are measured and analyzed using MINITAB 17 software.

The significantly affecting process parameters ranks are identified through Analysis of Variance is presented in Table 6 the table reveals that depth of cut affects significantly on cutting force feed affects lesser.

Table 5: Ranking of process parameters

Level	Speed	Feed	Depth of Cut
1	-30.63	-29.34	-28.39
2	-30.12	-31.28	-31.67
3	-32.76	-32.89	-33.46
Delta	2.65	3.55	5.07
Rank	3	2	1

The analysis of mean effect plot for means and S/N ratio obtained from Taguchi's analysis the optimum combination of control factor for predicting minimum surface roughness along with the prominent control factors are shown in Figure 3 and Figure 4. A Smaller is the better characteristics feature was chosen for analysis to determine the optimum surface roughness under Vortex tube jet assisted air cooling conditions.

Statistical approaches such as RSM can be employed to minimize the cutting force in special titanium alloy material by optimization of operational factors like cutting speed, feed and depth of cut. In contrast to conventional methods, the interaction among process variables can be determined by statistical techniques as well as interaction effect of feed rate & depth of cut and the interaction of all the three cutting parameters have significant influence on cutting force. The ANOVA technique enables us to perform this simultaneous test and as such is considered to be an important tool of analysis in the hands of a researcher. The P-vale represented in Table 8 depicts the quadratic effect of speed is more prominent as compared to other inputs since the p-value is less than 0.001, the table reveals that they are within acceptable range.

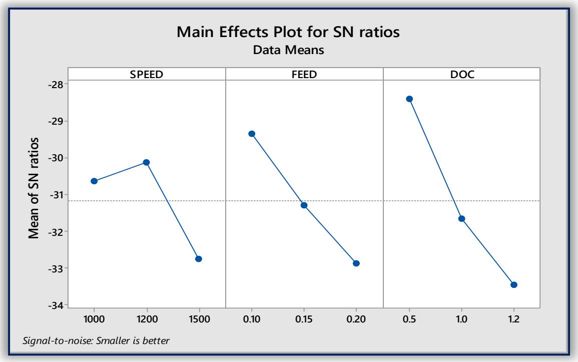

Figure 3: Main Effect Plot for Means

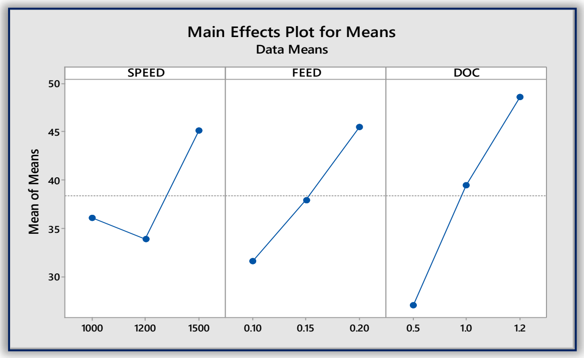

Figure 4: Main Effect Plot for S/N Ratios

Table 6: ANOVA of cutting force

Sources	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	3732.99	414.78	10.50	0.000
Linear	3	3210.41	1070.14	27.10	0.000
SPEED	1	348.47	348.47	8.82	0.009
FEED	1	754.92	754.92	19.12	0.000
DOC	1	2084.35	2084.35	52.78	0.000
Square	3	253.75	84.58	2.14	0.133
SPEED*SPEED	1	200.20	200.20	5.07	0.038
FEED*FEED	1	2.67	2.67	0.07	0.798
DOC*DOC	1	50.88	50.88	1.29	0.272
2-Way Interaction	3	125.96	41.99	1.06	0.391
SPEED*FEED	1	111.10	111.10	2.81	0.112
SPEED*DOC	1	3.55	3.55	0.09	0.768
FEED*DOC	1	11.31	11.31	0.29	0.599
Error	17	671.30	39.49		
Total	26	4404.30			
Model Summary	S	R-sq		R-sq(adj)	R-sq(pred)
0.0788802	6.28398	94.76%		86.69%	84.37%

The regression coefficients for cutting force, R-square and adjusted R-square values obtained from regression analysis are 94.76% and 86.69% respectively. The mathematical model presented the regression equation for cutting force that indicates the model fit is on the higher side of the acceptable limit. This is as given below. However, it can be observed that in the regression equation, the regression equation is as follows.

$$CF = 108.6 - 0.193\,S + 308\,F - 35.7\,D + 0.000097\,S*S + 267\,F*F + 30.0\,D*D - 0.242\,S*F + 0.0060\,S*D + 54\,F*D \ldots \quad (1)$$

An influential point greatly affects the slope of the regression line, the residual plot shown in Figure5 fairly random pattern and distributed around the horizontal in positive and negative sides of the plots this pattern indicates that a model provides a decent fit to the data. If the points in a residual plot are randomly dispersed around the horizontal axis hence model is appropriate for non-linear model. Residual plots show the good linearity, normality and residually for the response, which indicate that the data considered for the regression analysis are reliable and the regression model generated is validated.

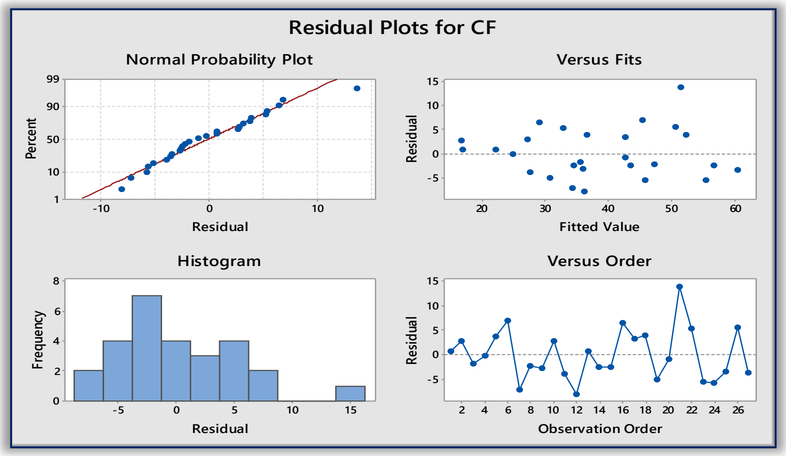

Figure 5. Residual Plots for Cutting Force

5. RESULT AND DISCUSSIONS

It is apparent from the figures 6 that cutting force increases with the increase of feed rate and cutting force decreases with the increase of cutting speed. It is also seen that increase in depth of cut might result in improvement of cutting force to a slight amount sometimes but that is insignificant. Variation of cutting force with progress of machining time at lower speed and feed (V=1000rpm, f=0.10 mm/rev) and higher speed and feed (V=1500rpm, f=0.20 mm/rev) with two depth of cut (d=1.0mm and 1.2 mm) under dry it is seen that cutting force is increasing with machining time in dry environment.

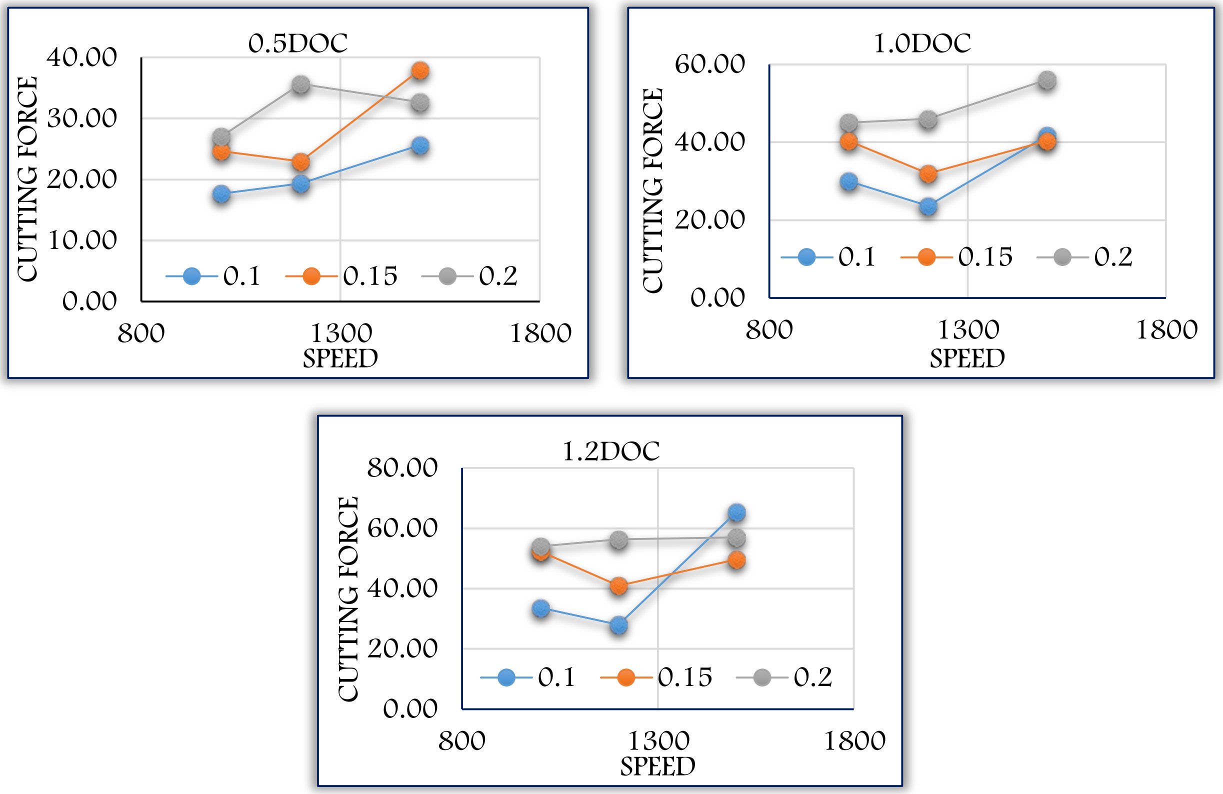

Figure 6: Surface plot of cutting force verses speed, feed, and depth of cut

The contour plots generated under dry shows the effect of cutting force on Ti-6Al-4V is affected by all the three process parameter. The minimum power consumption by machine tools is obtained, when cutting tool is subjected to the minimum cutting force. The contour plots shown in Figure 7 are obtained from RSM method helps to predict the minimum required cutting force. The appropriate input process parameters can be selected by referring contour plots to obtain the desired cutting force. It is observed from Figure 6 that minimum cutting force can be obtained by setting cutting speed less than 1400rpm, feed rate less than 0.12 mm/rev, and depth of cut less than 0.60 mm irrespectively. The range of process parameters selected for the study reveals that depth of cut plays an important role to obtain minimum cutting force.

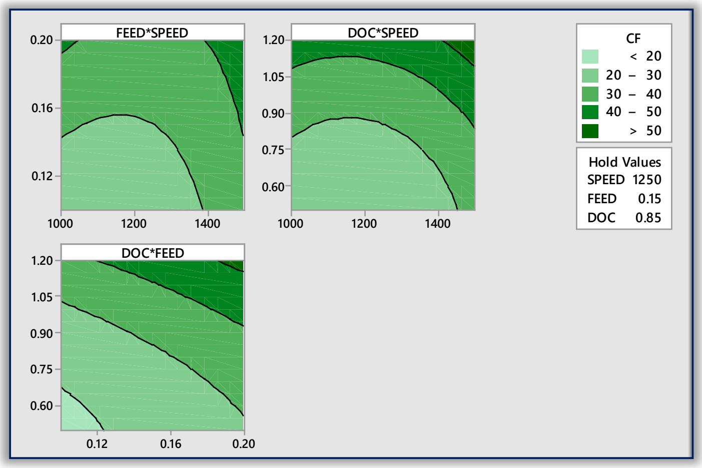

Figure 7: Contour plot represents relation between speeds, feed, Doc ad CF

The Surface Plots help to visualize the response surface in 3-D plot drawn in a 3D Space. The plot determining optimum operating conditions reaching minimum from the best-fitted model with a map of contour lines, follows a direction of movement along the path of minimum response from a reference point. The process parameters hold at constant at speed of 1350 rpm, depth of cut at 0.65 mm and feed of 0.15 mm/rev the surface plots are drawn.

The Figure 7 reveals that the cutting force was observed as increasing in non-linear fashion with the increase in both feed and speeds, The cross referencing to ANOVA Table 6 confirms that the interaction between feed and depth of cut was found very significant for getting desired cutting force in Ti-6Al-4V machining under Dry cooling environment. While the results declared through this experimental work may be generalized to a considerable extent while working on Ti-6Al-4V using cutting tool, the study is limited to the extreme range of values of the cutting parameters specified.

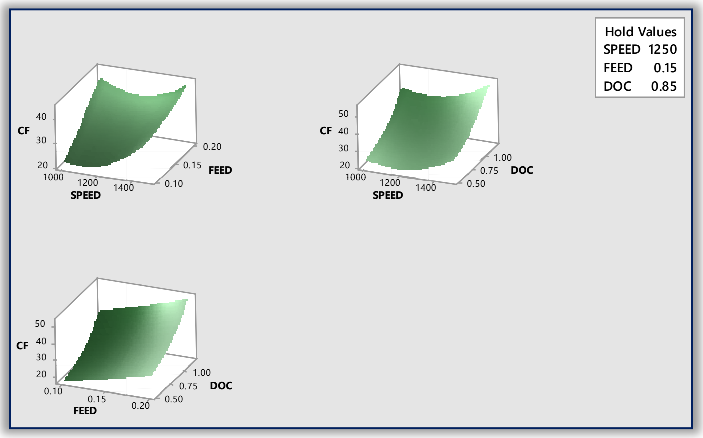

Figure 8: Surface plot of cutting force verses speed, feed, and depth of cut

— Analysis of hardness

During machining, the surface of the material become harder due to work hardening. The internal work hardening developed due to heating occurs with the contact of tool and work piece at the time of machining. The hardness value of the surface is much higher than the machined material hardness. The hardness of titanium material before machining was 285 Hv and after the machining for different cutting parameters are varied between 311 Hv (minimum) to 407 Hv (maximum). The low thermal conductivity of titanium alloy also caused the temperature below the machined surface to be retained. Rapid heating and cooling may have contributed to the work hardening effect during machining it is seen that the depth of the work hardening layer varies depending on the type of mechanical and thermal interaction. The surface hardness value increases with the increase in depth of cut and cutting speed because of increased cutting forces.

Figure 9: Micro Hardness measuring Device

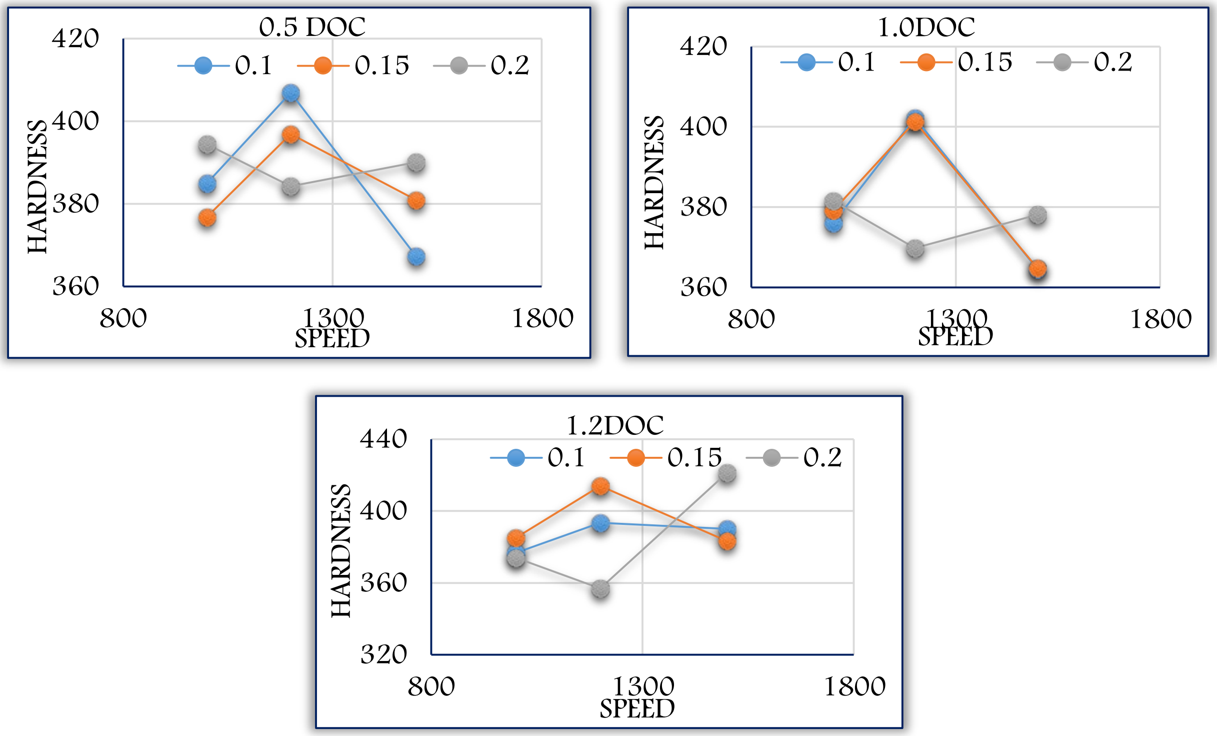

Figure 10: Surface plot of cutting force verses speed, feed, and depth of cut

Hardness value does not vary much with the feed rate. Heat generation is decreased and consequently lower temperatures and plastic flow, resulting in lesser hardening effect. The surface generated under dry mode with cutting speed of 1200rpm, feed of 0.2mm/rev, and depth of cut of 0.5 mm and the recorded surface hardness of 356.9Hv.

6. CONCLUSIONS

The presented research work focused on the study of the process parameters in the presence of Dry cooling systems to estimate the optimal cutting force by implementing Taguchi and RSM. The following conclusions are drawn based on experiment and statistical methods.

- The depth of cut is the most influencing parameter on turning single point cutting tool whereas least affected by cutting speed under dry Cooling condition.
- The proposed analytical model predicts the optimal solution within the accuracy of 16.65 % as compared to the experimental results.
- Response surface methodology analysis shows that less than 20 Kgf cutting force obtained at less than 0.13mm/rev feed rate, less than 0.65 mm depth of cut, and less than 1200rpm speed. Whereas by experimentation minimum cutting force obtained is 17.66Kgf at 1000rpm speed, 0.1mm/rev feed, and 0.5mm depth of cut.
- The surface hardness value increases with the increase in depth of cut and cutting speed because of increased cutting forces.

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