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Cutting Parameters Optimization for Surface Finish and Machining Time in turning of OHNS O1 grade Hardened Tool Steel for Near Dry Machining

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Abstract - *Near dry machining is the goal of today's metal cutting industry that tirelessly endeavors to reduce machining costs and impact from chemicals in the environment. Hard turning is a turning process done on materials with a Rockwell C hardness greater than 45. It is typically performed after the work piece is heat treated. The process is intended to replace or limit traditional grinding operations. Hard turning can be applied for purely stock removal purpose or finishing purpose. In Hard turning, high amount of heat is generated at the tool-chip interface which not only increase the tool wear but also deteriorates the job quality in terms of surface finish. In this study, MQL setup used for Near Dry Machining (NDM) in turning round bars of 25 mm diameter of Oil Hardening Non-Shrinking Die Steel (OHNS – AISI O1 grade) hardened to 53-57 HRC by TNMG 160404 MT TT5080 insert. The machining was carried out at three levels of Cutting Speed (v_c), Feed Rate (f), and Depth of cut (a_p) to investigates the performance of MQL setup on Surface Roughness (Ra) and Machining time(t_c) in hard turning of OHNS O1 grade. Full factorial (3^k) DOE was employed and 27 experiments were analyzed by using Response Surface Methodology (RSM) and regression equations were developed. ANOVA was used to find out the significant parameters. Feed rate is the most influential factor in increasing the surface roughness and decreasing machining time. Second influential factor for surface roughness is cutting speed which improves surface quality as speed increases and decreases machining time. Depth of cut has very less or no significance on both surface roughness and machining time. The optimum responses are at cutting speed of 190 m/min, feed rate of 0.0584616 mm/rev, 0.5 mm depth of cut and optimum machining time found to be 21.6065 sec producing surface roughness Ra to be 0.459032 µm.*

Key Words: Near Dry Machining (NDM), hard turning, MQL, Surface Roughness (Ra), Machining Time (t_c), RSM, ANOVA

1. INTRODUCTION

Dry machining has its advantages and associated drawbacks. The advantages of dry machining are obvious: cleaner parts, no waste generation, reduced cost of machining, reduced cost of chip recycling (no residual oil), etc. and most important is the better surface finish. However, these advantages do come at a cost. The most prohibitive part of switching to dry machining is the large capital expenditure required to start a dry machining operation. Machines and tools designed for Metal Working Fluids cannot be readily adapted for dry cutting. New, more powerful machines must be purchased, and special tooling is often needed to withstand the high temperatures generated in dry cutting. The quality of machined parts may be affected significantly as the properties of the machined surface are significantly altered by dry machining in terms of its metallurgical properties and residual machining stresses. High cutting forces and temperatures in dry machining may cause the distortion of parts during machining. Moreover, parts are often rather hot after dry machining so their handling, inspection gauging, etc., may present a number of problems. Near-dry machining (NDM) formerly known as minimum quantity lubrication (MQL) machining, was developed to provide at least partial solutions to the listed problems with dry machining.

In the continuous quest for reducing or eliminating the use of coolants in machining, only one process can offer a near-term solution for practical applications. This process uses a minimum quantity of lubrication and is referred to as "near-dry". In near-dry machining (NDM), an air–oil mixture called an aerosol is fed into the machining zone. Increasing the productivity and the quality of the machined parts are the main challenges of metal cutting industries. Compared to dry machining, NDM substantially enhances cutting performance in terms of increasing tool life and improving the quality of the machined parts. The growing demands for high productivity and quality of turned parts in terms of surface finish and less time for machining need use of high cutting velocity. Such machining inherently produces high cutting temperature, which not only reduces tool life but also impairs the product quality. Small oil droplets carried by the air fly directly to the tool working zone, providing the needed cooling and lubricating actions. Because MWF cannot be seen in the working zone, and because the chips look and feel dry, this application of minimum-quantity lubricant is called near-dry machining. In short, NDM delivers a very small amount of coolant to a cutter's edge in the form of an oil mist or aerosol, as opposed to traditional techniques of flooding the workpiece and tool with a substantial volume of liquid coolant. Just a tiny bit of that aerosol is left on the chips, workpiece and machine during the cutting operation.

2. LITRATURE REVIEW

Nikhil Ranjan Dhar and Sumaiya Islam [1] investigated the role of MQL on cutting temperature, tool wear, surface roughness and dimensional deviation in plain turning a 125 mm diameter and 760 mm long rod of AISI-4340 steel on a powerful and rigid lathe (Lehmann Machine Company, USA, 15hp) at different cutting velocities (Vc) and feeds (So) under dry, wet and minimum quantity lubrication (MQL) conditions. Results include significant reduction in tool wear rate, dimensional inaccuracy and surface roughness by MQL mainly through reduction in the cutting zone temperature and favourable change in the chip-tool and work-tool interaction.

Dhar NR, Islam S and Kamruzzaman M [1] studied the effect of NDM in tuning of 4340 steel using external nozzle and aerosol supply to the tool. They found that the temperature at the tool–chip interface reduced by 5–10% (depending upon the particular combination of the cutting speed and feed) in NDM compared to wet machining. As a result, tool life and finish of the machined surface improved by 15–20%. Interestingly, the authors found that the tool life is the same for dry and wet machining, which is in direct contradiction with common shop practice.

Yoshimura H, Itoigawa F, Nakamura T and Niwa K [2] found that, in machining of aluminium, the cutting force is lower and the surface finish is better with OoW NDM compared with dry, traditional NDM and wet machining.

Using a minimum quantity of lubricant (MQL) and a diamond-coated tool in the drilling of aluminium–silicon alloys, Braga DU, Diniz AE, Miranda GWA and Coppini NL [3] showed that the performance of the NDM process (in terms of forces, tool wear and quality of machined holes) was very similar to that obtained when using a large amount of water-soluble oil, with both coated and uncoated drills.

Ronan Autret and George W. [4] compared the mechanical performance of minimum quantity lubrication to completely dry lubrication for the turning of hardened bearing-grade steel materials based on experimental measurement of cutting forces, tool temperature, white layer depth, and part finish. The coolant used was a triglyceride and propylene glycol ester solution dispensed at a flow rate of 50 ml/hour under the nozzle pressure of 20psi. The workpiece material is high carbon steel bars hardened to 62 to 64 RHC. The cutting tool used was low content CBN tool (Kennametal KD5625) with rake angle of -6o, chamfer length of 0.12 mm, horn radius of 0.03 mm, and nose radius of 0.8 mm. During machining, cutting forces were measured with a tool post dynamometer. The results indicate that the use of minimum quantity lubrication leads to reduced surface roughness, delayed tool flank wear, and lower cutting temperature, while also having a minimal effect on the cutting forces.

Prianka B. Zaman and N. R. Dhar [5] in their research work studied the effects of minimum quantity lubrication (MQL) by different cutting fluids (soluble oil, vegetable oil and VG 68 cutting oil) on the cutting performance of hard turned part, as compared to completely dry cutting with respect to cutting temperature, chip thickness ratio, tool wear and machined surface quality have been studied. In the study, MQL is provided with a spray of air and cutting fluid. In this experiment Hardened AISI 4320 steel bars having surface hardness of 45 HRC with diameter and length of 74 mm and 230 mm respectively was turned in a lathe (China, 10 hp) by coated carbide inserts with ISO designation SNMG 120408 TN 4000. Tool holder used was PSBNR 2525 M 12 (WIDIA) and the working tool geometry was -6°, -6°, 6°, 6°,15°, 75° and 0.8mm. The experiment was carried out with different cutting velocities (V) of 82, 114, 163 m/min and feed rates (f) 0.10, 0.12, 0.14 mm/rev at a constant depth of cut 1.0 mm under dry and MQL by vegetable oil, cutting oil and soluble oil conditions to study effect of MQL on different machinability characteristics. Flow Rate of the MQL supply was 150 ml/hr, where air pressure and oil pressure was 23 bar and 25 bar, respectively. The results indicated that the use of MQL with VG 68 cutting oil performed better in comparison to other cutting fluids in respect of chips thickness ratio, cutting temperature, tool wear, surface roughness and dimensional deviation.

Khan M.M.A. and Dhar N.R [6] in their study deal with experimental investigation on the role of MQL by vegetable oil on cutting temperature, tool wear, surface roughness and dimensional deviation in turning AISI-1060 steel at industrial speed-feed combinations by uncoated carbide insert at different cutting velocities (Vc) and feed rates (So) under dry and MQL by vegetable oil conditions to study the role of MQL on the machinability characteristics of that work material mainly in the aspect of cutting temperature, cutting forces, tool wear, surface roughness and dimensional deviation. Results include significant reduction in tool wear rate, dimensional inaccuracy and surface roughness by MQL mainly through reduction in the cutting zone temperature and favorable change in the chip-tool and work-tool interaction.

M. M. Rahman and N. R. Dhar [7] focused on the effect of minimal quantity lubricant on chip-tool interface temperature under different cutting velocity and feed rate in turning of AISI 9310 steel. Chip-tool interface temperatures were measured for three different cooling types such as dry, wet and MQL conditions. An approach based on the process parameters were performed to identify the suitable MQL nozzle position for better cooling action. The minimum quantity lubrication was provided with a spray of air and oil. MQL machining was performed much superior compared to the dry and wet machining. It is clear from the obtained results that average chip-tool interface temperature increases with the increases in cutting velocity and feed rate for all three conditions. The chip-tool interface temperature values for MQL are lower than dry and wet conditions. The roles of variation of process parameters on percentage reduction of average interface temperature due to MQL have not been uniform. The effectiveness of the MQL was found to decrease with the increase in feed for more intimate chip-tool contact, but still more effective as compared to dry and wet conditions. Therefore, application of MQL at chip-tool interface is expected to improve upon the aforesaid machinability characteristics that play vital role on productivity, product quality and overall economy.

3. EXPERIMENTAL PROCEDURE AND SETUP

In NDM setup a 2 mm diameter thin flexible pipe which carries water soluble cutting oil runs co-axially in 8 mm diameter Pneumatic pipe carrying compressed air. Mist was made externally before tool tip by attaching a two wheeler carburettor nozzle to atomize the coolant oil coming from central co-axial pipe surrounded by compressed air jet, as shown in fig -1.

Fig -1: Co-axial pipe arrangement in NDM setup

The aerosol mixture was used in Near Dry Machining (NDM) in plan turning round bars of 25 mm diameter of Oil Hardening Non-Shrinking Die Steel (OHNS – AISI O1 grade) hardened to 53-57 HRC by TNMG 160404 MT TT5080 TaeguTec insert with WTJNL 2020 K1304 negative rake tool holder on MIDAS-O (Galaxy Machinery Pvt. Ltd, Coimbatore) model CNC lathe. The machining was carried out at three levels of Cutting Speed (v_c), Feed Rate (f), and Depth of cut (a_p) to investigates the performance of MQL setup in hard turning of OHNS O1 grade, Cutting velocity selected was 170 m/s, 180 m/s and 190 m/s, Feed rate as 0.05 mm/rev, 0.06 mm/rev and 0.07 mm/rev and Depth of cut as 0.5 mm, 0.6 mm, and 0.7 mm for the machining length of 50 mm by conducting the pilot experiments on similar cutting conditions and changing one variable at a time (OVAT). Aerosol mist is directed at tool tip at a distance of 10 mm above it by nozzle at approximate angle of 30^{o} with vertical as in Fig -2.

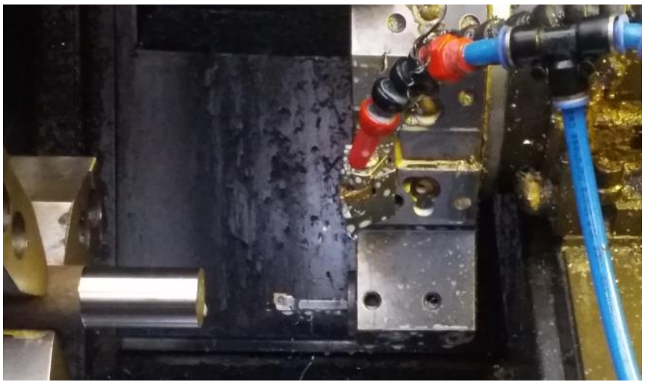

Fig -2: NDM setup installed on machine

The tool tip temperature was measured using BENTECH make digital infrared thermometer GM320 with measuring range from -50^{o}C to 380^{o}C as shown in fig -3.

Fig -3: Avg. tool-chip interface temperature measurement

The surface roughness was measured by surface roughness tester TIME make TR100 model for Ra in µm (λ1-0.25mm) as in Fig -4.

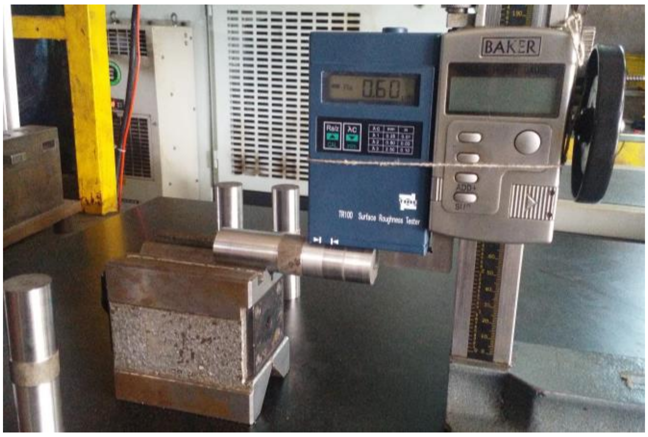

Fig -4: Testing of surface roughness (Ra)

The constant compressed air supply was taken from Chicago Pneumatic Make air compressor which delivers the air at max. final pressure of 10.2 Kg/cm^2 and 21.18 CFM which was controlled at 4 CFM at 6.9 bar before entering NDM setup.

DOE by Full Factorial design with uncoded value of input parameters of Cutting speed, Feed and depth of cut for Surface roughness (Ra) and Machining Time (Tc) as output under MQL condition and comparison of predicted values with experimental values and percentage error in experimental values and predicted values as shown in Table -1 were analysed by using Response Surface Methodology (RSM) and ANOVA to find out the significant parameters.

Table -1: DOE table, comparison of predicted values with experimental values and percentage error

Exp No	Input Variable Parameters			Experimental Values		Predicted Values		Error in Percentage	
	SPEED	FEED	DoC	Ra_{MQL}	T_c	Ra_{MQL}	T_c	Ra_{MQL}	T_c
	m/min	mm/rev	mm	μm	sec	μm	sec	%	%
1	190	0.05	0.6	0.35	24.8	0.34	24.8	2.2	0.1
2	170	0.06	0.7	0.50	23.1	0.53	23.5	5.8	1.8
3	190	0.05	0.7	0.37	24.8	0.35	24.8	5.3	0.0
4	190	0.06	0.5	0.47	20.6	0.48	21.0	2.4	2.0
5	170	0.07	0.7	0.70	19.8	0.68	19.8	3.1	0.2
6	180	0.07	0.6	0.65	18.7	0.65	18.5	0.7	1.0
7	180	0.07	0.7	0.66	18.7	0.66	18.5	0.5	0.9
8	190	0.05	0.5	0.34	24.8	0.33	24.8	2.0	0.1
9	190	0.07	0.6	0.65	17.7	0.64	17.3	1.7	2.4
10	170	0.05	0.5	0.39	27.7	0.36	27.3	7.0	1.6
11	180	0.07	0.5	0.65	18.7	0.65	18.5	0.7	1.0
12	180	0.06	0.5	0.48	21.8	0.50	22.3	3.5	2.1
13	170	0.05	0.7	0.40	27.7	0.38	27.3	4.6	1.6
14	180	0.06	0.6	0.48	21.8	0.51	22.3	5.2	2.1
15	180	0.05	0.7	0.36	26.2	0.37	26.0	1.9	0.7
16	180	0.06	0.7	0.49	21.8	0.52	22.3	4.9	2.2
17	170	0.07	0.6	0.69	19.8	0.67	19.8	3.0	0.2
18	190	0.07	0.5	0.64	17.7	0.63	17.3	1.6	2.4
19	190	0.06	0.6	0.48	20.7	0.49	21.0	2.2	1.6
20	190	0.06	0.7	0.49	20.7	0.50	21.0	1.9	1.6
21	170	0.07	0.5	0.67	19.8	0.66	19.8	1.3	0.2
22	170	0.05	0.6	0.40	27.7	0.37	27.3	7.1	1.6
23	170	0.06	0.6	0.50	23.1	0.52	23.5	4.2	1.8
24	180	0.05	0.6	0.35	26.2	0.36	26.0	2.2	0.7
25	190	0.07	0.7	0.67	17.7	0.65	17.3	3.4	2.4
26	180	0.05	0.5	0.35	26.2	0.35	26.0	0.3	0.7
27	170	0.06	0.5	0.49	23.1	0.51	23.5	4.5	1.7

4. RESULTS AND DISCUSSION

The above experimental data was analyzed by RSM for linear model of 95% confidence level of interval using Minitab 17 software and then the results obtained are analyzed in uncoded units and are discussed as below

4.1 Response Surface Regression: Ra_{MQL} versus SPEED, FEED, DoC

Table 2: Analysis of Variance for RaMQL versus SPEED, FEED, DoC

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	3	0.40183	0.13394	394.87	0.000
Linear	3	0.40183	0.13394	394.87	0.000
SPEED	1	0.00436	0.00436	12.84	0.002
FEED	1	0.39605	0.39605	1167.56	0.000
DoC	1	0.00142	0.00142	4.19	0.052
Error	23	0.0078	0.00034		
Total	26	0.40963			
Model Summary					
S	R-sq	R-sq(adj)	R-sq(pred)		
0.0184177	98.10%	97.85%	97.37%		

Table -3: Coded Coefficients for RaMQL versus SPEED, FEED, DoC

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	0.50630	0.00354	142.84	0.000	
SPEED	-0.01556	0.00434	-3.58	0.002	1.00
FEED	0.14833	0.00434	34.17	0.000	1.00
DoC	0.00889	0.00434	2.05	0.052	1.00

Regression Equation in Uncoded Units

$$Ra_{MQL} = -0.1570 - 0.001556\,SPEED + 14.833\,FEED + 0.0889\,DoC \quad ...(1)$$

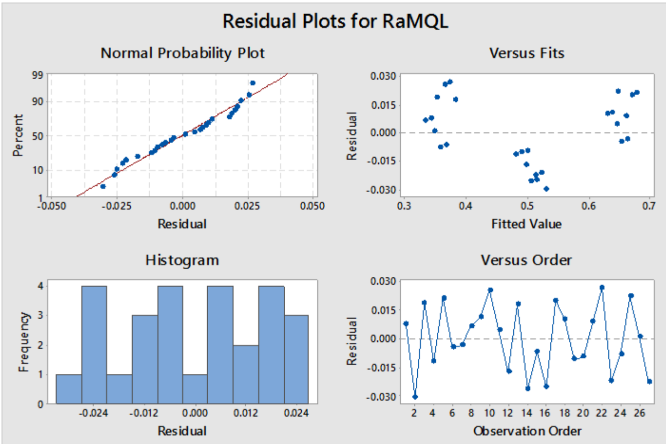

Chart -1: Residual Plots for RaMQL

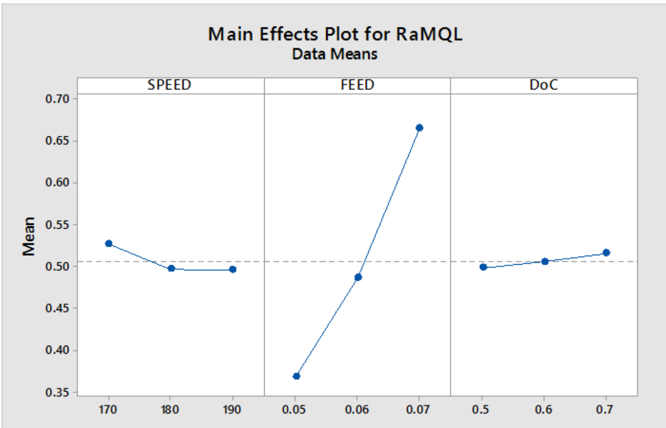

Chart -2: Main Effect Plots for RaMQL

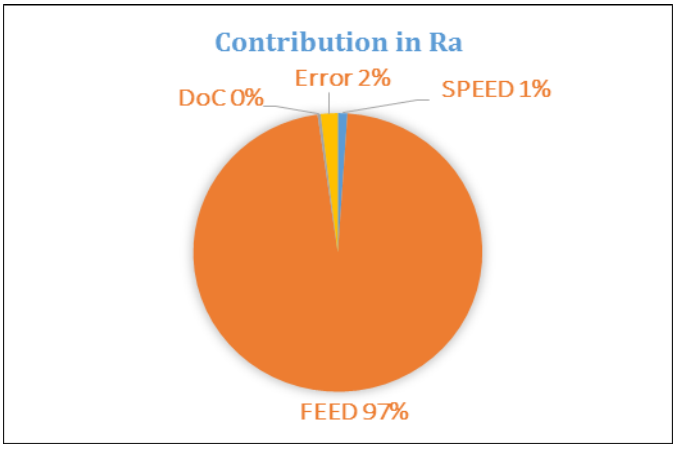

Chart -3: Percentage Contribution Chart for RaMQL

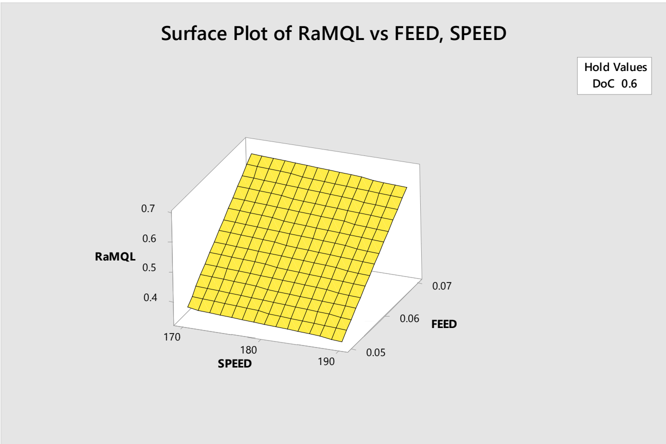

Chart -4: Surface plot of RaMQL vs FEED, SPEED

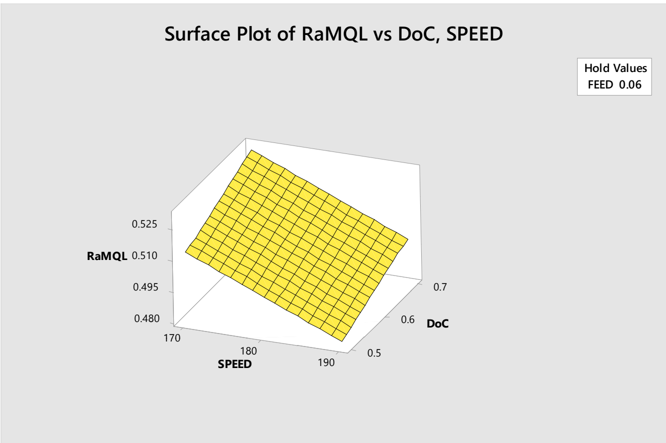

Chart -5: Surface plot of RaMQL vs DoC, SPEED

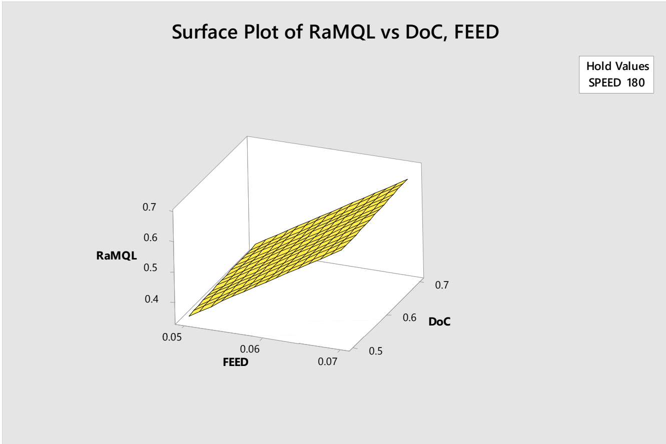

Chart -6: Surface plot of RaMQL vs DoC, FEED

From the above graphs it is observed that the surface roughness is having an increasing trend with the increase in feed rate and DoC. Surface finish improves with increase in cutting speed. The most important reason for increase in surface roughness is found to be feed rate having highest significance 96.68% contribution, least by cutting speed having only 1.06% contribution and DoC having only 0.35% contribution in MQL condition.

4.1 Response Surface Regression: Tc versus SPEED, FEED, DoC

Table 4: Analysis of Variance for Tc versus SPEED, FEED, DoC

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	3	280.753	93.584	747.61	0.000
Linear	3	280.753	93.584	747.61	0.000
SPEED	1	27.627	27.627	220.71	0.000
FEED	1	253.125	253.125	2022.13	0.000
DoC	1	0.001	0.001	0.00	0.947
Error	23	2.879	0.0125		
Total	26	283.632			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.353804	98.98%	98.85%	98.62%

Table -5: Coded Coefficients for Tc versus SPEED, FEED, DoC

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	22.2741	0.0681	327.13	0.000	
SPEED	-1.2389	0.0834	-14.86	0.000	1.00
FEED	-3.7500	0.0834	-44.97	0.000	1.00
DoC	0.0056	0.0834	0.07	0.947	1.00

Regression Equation in Uncoded Units

$$Tc = 67.04 - 0.12389\ SPEED - 375.00\ FEED + 0.056\ DoC \quad ...(2)$$

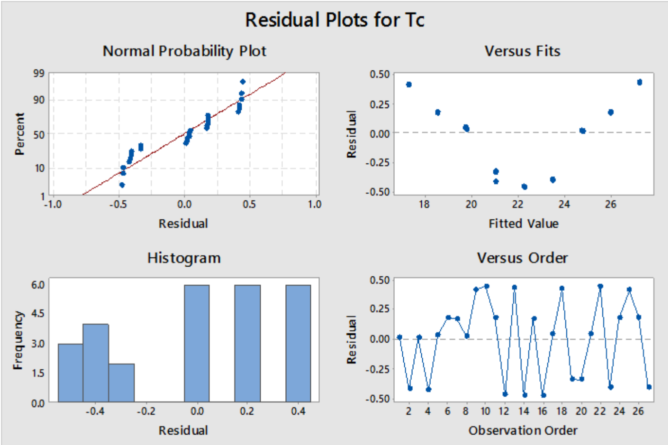

Chart -7: Residual Plots for Tc

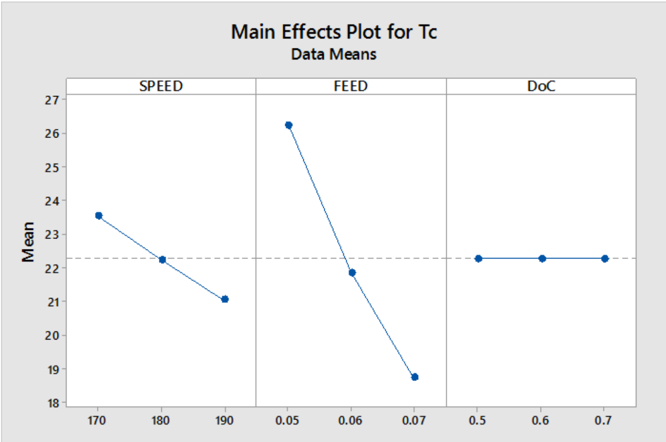

Chart -8: Main Effect Plots for Tc

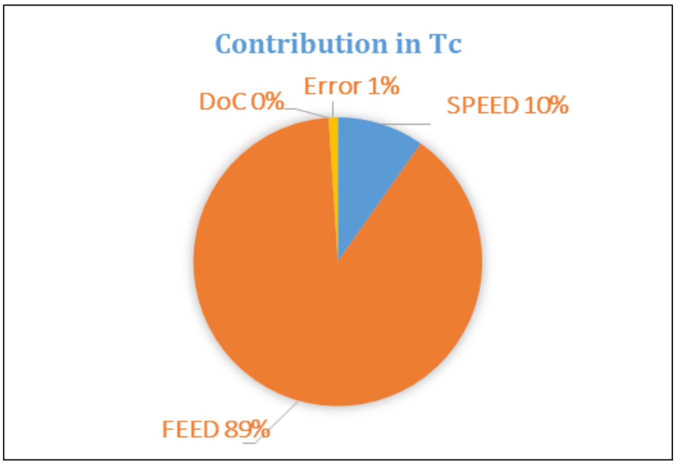

Chart -9: Percentage Contribution Chart for Tc

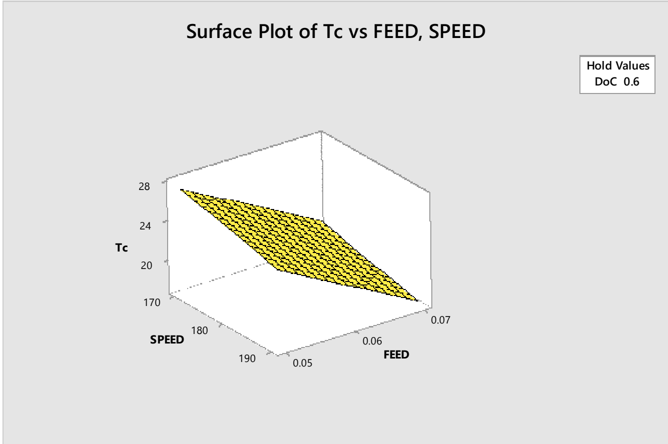

Chart -10: Surface plot of Tc vs FEED, SPEED

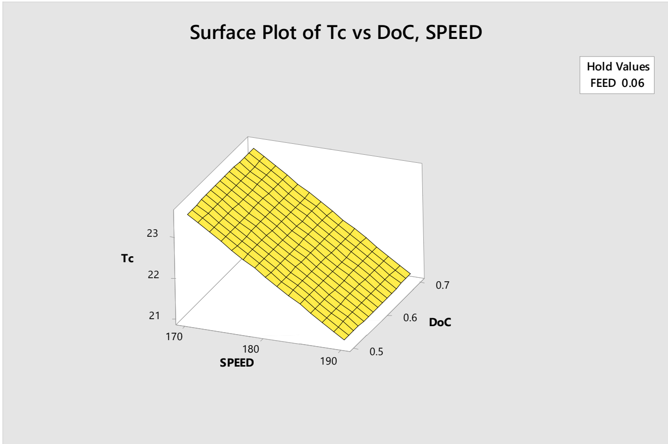

Chart -11: Surface plot of Tc vs DoC, SPEED

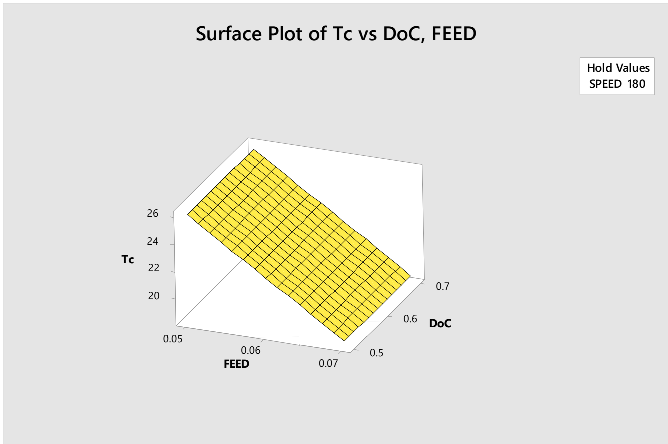

Chart -12: Surface plot of Tc vs DoC, FEED

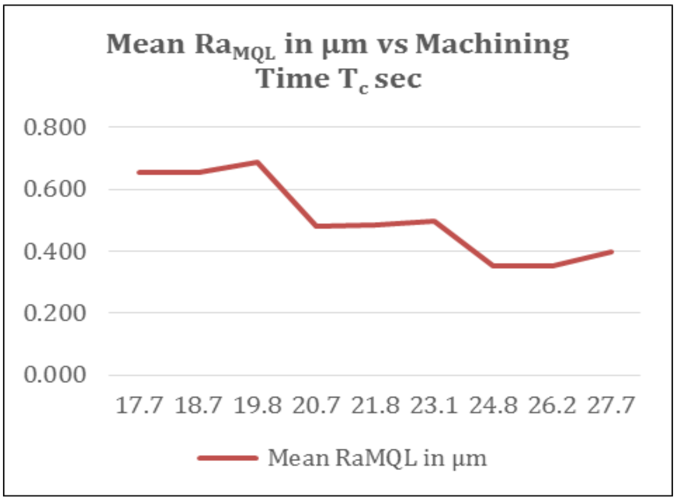

Chart -13: Surface roughness Ra_{MQL} vs Machining Time T_c

Similar observations were seen for machining time where it is having decreasing trend with the increase in cutting feed rate (most significant with 89.24 % contribution) and cutting speed (significant with 9.74% contribution) and at the same time DoC has very less or no effect on machining time. In turning, machining time mainly depends on the feed rate and then cutting speed. Also it is clear that with decrease in machining time (Tc decreases mainly with increase in feed rate and cutting speed) there is rise in the surface roughness value i.e. surface finish degrades as cutting time decreases due to increase in feed rate as shown in above graph.

4.3 Response Optimization: Tc, RaMQL

Response Optimization: Tc, RaMQL

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Parameters

Response  Goal      Lower  Target  Upper  Weight  Importance
Tc        Minimum           17.70   27.7       1           1
RaMQL     Minimum            0.34    0.7       1           1


Solution

                                   Tc     RaMQL    Composite
Solution  SPEED  FEED       DoC   Fit       Fit  Desirability
1         190    0.0584616  0.5  21.6065  0.459032     0.638647


Multiple Response Prediction

Variable  Setting
SPEED     190
FEED      0.0584616
DoC       0.5


Response      Fit   SE Fit        95% CI                95% PI
Tc         21.607    0.137  ( 21.324,  21.889)  ( 20.822,  22.391)
RaMQL     0.45903  0.00712  (0.44430, 0.47376)  (0.41818, 0.49988)
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Fig -5: Response Optimization by Minitab 17 for minimization of Tc (Machining Time) and Surface Roughness Ra by RSM Response Optimizer for SPEED, FEED and DoC

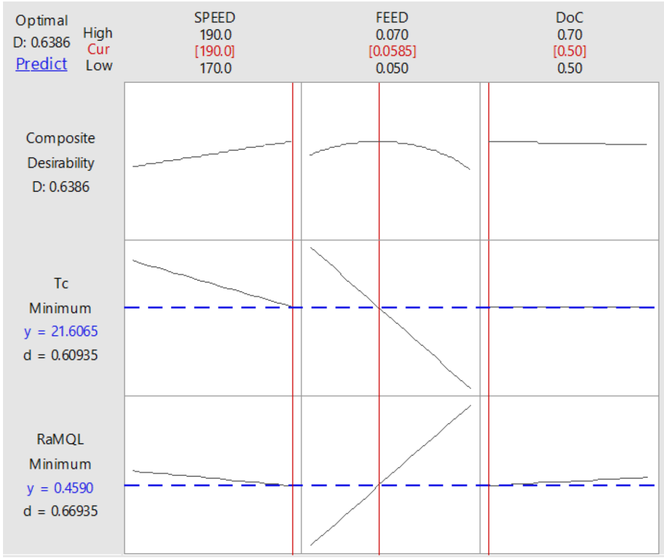

Chart -14: Response Optimization Plot for minimization of Tc (Machining Time) and Surface Roughness Ra under MQL condition by RSM Response Optimizer for SPEED, FEED and DoC

The process optimization was done using RSM's D-Optimal Test. The optimized values of input parameters for the minimization of responses are at cutting speed of 190 m/min, feed rate of 0.0584616 mm/rev, 0.5 mm depth of cut and optimum machining time found to be 21.6065 sec producing surface roughness Ra to be 0.459032 µm.

5. CONCLUSION

From the analysis of surface roughness Ra and machining time Tc in MQL condition in Near-Dry Machining the following conclusions can be drawn that feed rate is the most influential factor in increasing the surface roughness and decreasing machining time. Second influential factor for surface roughness is cutting speed which improves surface quality as speed increases and decreases machining time. Depth of cut has very less or no significance on both surface roughness and machining time. The optimum responses are at cutting speed of 190 m/min, feed rate of 0.0584616 mm/rev, 0.5 mm depth of cut and optimum machining time found to be 21.6065 sec producing surface roughness Ra to be 0.459032 µm.

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