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Optimization of Cutting Variables for Minimum Surface Roughness in Orthogonal Turning of AISI-304 Alloy Steel Using Taguchi

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ABSTRACT

Optimization of cutting variables for minimum surface roughness in orthogonal turning of AISI-304 alloy steel under dry and wet environments were carried out and statistical analysis was also carried out. The workpiece material used for the investigation was AISI 304 alloy steel while the cutting tool used was tungsten carbide coated tool insert with right hand cutting tool holder. Experimental design was based on Design of Experiment (DOE) via Taguchi and minitab 17 statistical software was used in analysing the results of the experiment. The signal to noise (S/N) based on Taguchi experimental technique was used for surface roughness. Analysis of variance (ANOVA) was also conducted to investigate effects of the cutting variables on surface roughness. It was observed that for both dry turning and wet turning with mineral oil-based cutting fluid, cutting speed has the most significant effect on surface roughness with 40.04% and 38.50% contributions respectively. Feed rate was found to be least significant parameter in both environments with contribution of 23.87% and 20.77% in dry and wet environment respectively.

Keywords: cutting variables, cutting speed, feed rate, depth of cut, surface roughness.

1. INTRODUCTION

Surface roughness is the mean height or depth (usually in μm) of the hills and valleys respectively on the real surface of machined component. It is the shorter frequency of real surfaces relative to the troughs. This property affects component's appearance and also produces texture or tactile differences. Texture and appearance can influence a product's added value such as customers' satisfaction and class. It is also very vital when a machine component is to fit properly with another mating component and almost in all finish turning processes. The roughness of surfaces is considered an essential parameter in many industries because it is an indication of surface quality of the machined part. (Ashvin *et al*, 2013). The requirement of products with good quality in terms of high strength, good surface finish, lower cost and less environmental effects is the challenge of the manufacturing industries (Hartem, 2011).

Surface finish is one of the responses by which machinability of materials is judged (Khan *et al*, 2006). Surface roughness grows quite fast under dry machining due to more intense temperature and stresses at the tool-tip while minimum quantity lubrication, MQL appear to be effective by vegetable oil improve surface finish depending on workpiece-tool materials and mainly through controlling the deterioration of the auxiliary cutting edge by abrasion, chipping and formation of built-up edge (Khan *et al*, 2006). Orthogonal turning is the type of turning where the cutting tool's motion is perpendicular to the cutting edge (Olaiya, 2021).

In turning operations, surface roughness is a function of cutting speed, feed rate, depth of cut, tool's nose radius, tool's lubrication, machine vibrations, tool wear, mechanical and other properties of the material being machined (Yang *et al*, 1998), (Kirby *et al,* 2006) and (Lan *et al*, 2009). Surface roughness is now one of the most significant technical requirement and important index of assessing product quality (Ravindra, 2008). A good surface finish is desired in order to improve the tribological properties, fatigue strength, corrosion resistance and asthetic appeal of a mechanical component.

Consequently, the manufacturing industries specifically, are focusing attention on dimensional accuracy and surface finish (Patel, 2014). In order to obtain optimal cutting variables to accomplish the best possible surface finish, manufacturing industries have resorted to the use of hand-book information and operators experience. This traditional practice leads to improper surface finish and decrease in productivity due to sub-optimal use of machining capability (Ranganath *et al.,* 2015).

Sub-optimal use of machining capability brings about high cost of manufacturing and low product quality (Upadhye and Keswani, 2012). The high challenges force the manufacturing sectors to make components of better quality within a short period at minimal cost (Ramasamy *et al.,* 2018) and (Selfam *et al.,* 2012). Achieving desired quality on a machined surface itself is itself a common problem for engineers and scientists. Specifically, achieving the desired quality within the prescribed machine tool's limitation, machining time and cost is not often achieved (Benardos and Vosniakos, 2003).

Improper selection of cutting variables results in increase in machining cost and a decrease in quality (Rao and Venkatasubbaiah, 2016). Components can be produced to precise specifications when machines are used under optimal cutting conditions (Ramasamy *et al.,* 2018) and (Selvan *et al.,* 2012). Surface roughness is very essential in accessing accuracy of machining (Sarosh *et al.,* 2016), (Chales *et al.,* 2004) and (Shin *et al.,* 1995).

2. MATERIALS AND METHODS

2.1 Materials

2.1.1 Workpiece

The workpiece material for this research is an austenitic chromium-nickel stainless steel categorised as AISI 304 by American Iron and Steel Institute (AISI). The material has excellent corrosion resisting property and consequently find very useful applications in food, pharmaceutical, marine, petrochemical and similar industries. The chemical composition of the material is presented in Table I as revealed by material composition test via optical emission spectrometer (OES). The initial dimension of the workpiece is Ø25mm by 60mm length.

2.1.2 Machine tool

The research was conducted on Colchester conventional centre lathe machine located in the department of mechanical engineering, Lagos state university of science and technology, LASUSTECH, Ikorodu. The characteristics of the machine is presented in Table 1, and the machine is shown on plate I.

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Table1: Characteristics of experimental lathe

Manufacturer	Colchester Lathe, Hythe, England
Rated Power	7.5HP
Voltage	415V, 3 phases
Speed (Motor)	5000
Current	8.7 – 12 Amps
Spindle speed	25 - 2000rpm
Bed size	2 meters
Controls	Electric buttons and levers
Bed width	300mm
Spindle hollow	55mm
Model	Triumph 2000
Machine number	537/0798

Plate I: Colchester Lathe

2.1.3 Cutting tool

Tungsten-coated tool insert (Widia model CNMG 1204082H) was used. It is shown in plate II.

Plate II: Cutting tool insert

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2.1.4 Tool holder

The cutting tool holder used was a straight hand cutting tool insert (indexable) holder produced by Widia tools, India. It is shown in plate III. It the following specification:
Model: DCLWR 2020 K/2
Brand: Widia
Cross-section: 20 by 20mm^2
Shank length: 120mm.

Plate IV: Tool holder

2.1.5 Surface roughness tester

For measurement of surface roughness, digital surface roughness tester shown in plate V was used. The specification the measuring tool is as follows:
Model: TMR 120 with portable stylus
Manufacturer: TMTECH Instrument co Limited
Accuracy: ±5%

Plate V: Surface roughness tester

2.2 Method

2.2.1 Design of experiment

Design of experiment (DOE) is a strong tool for planning of experiment and analysis of experimental results. It is defined as the process of planning experiments to facilitate statistical analysis of appropriate data to obtain valid objectives and conclusions (Montgomery, 2009) and (Masounave *et al.,* 1997).

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Statistical design of experiment is used in this investigation. Statistical design of experiments refers to the process of planning the experiments so that the appropriate data can be analysed by statistical methods, resulting in valid conclusions (Kaladhar *et al*, 2012) and (Varma *et al*, 2012). Taguchi design of experiment was used for three variables which include cutting speed, feed rate and depth of cut while the output dependent variable or response is surface roughness in dry and wet condition using mineral oil-based cutting fluid. The cutting parameters and their levels are presented in Table 2 while Table 3 shows the L_{27} orthogonal array of experimental runs as generated via minitab 17 statistical software. The experiments were conducted in dry and wet conditions.

Table 2: Machining variables (factors) and their Levels

Factor	Unit	Level 1	Level 2	Level 3
		Low (-1)	Medium (0)	High (+1)
Cutting Speed	rev/min	625	840	1120
Feed Rate	mm/min	0.50	0.75	1.00
Depth of Cut	Mm	0.25	0.35	0.50

Table 3: L_{27} Orthogonal Array Matrix

Runs	Cutting speed	Feed Rate	Depth of cut
	(rev/min)	(mm/min)	(mm)
1	625	0.50	0.25
2	625	0.50	0.25
3	625	0.50	0.25
4	625	0.75	0.35
5	625	0.75	0.35
6	625	0.75	0.35
7	625	1.00	0.50
8	625	1.00	0.50
9	625	1.00	0.50
10	840	0.50	0.35
11	840	0.50	0.35
12	840	0.50	0.35
13	840	0.75	0.50
14	840	0.75	0.50
15	840	0.75	0.50
16	840	1.00	0.25
17	840	1.00	0.25
18	840	1.00	0.25
19	1120	0.50	0.50
20	1120	0.50	0.50
21	1120	0.50	0.50
22	1120	0.75	0.25
23	1120	0.75	0.25
24	1120	0.75	0.25
25	1120	1.00	0.35
26	1120	1.00	0.35
27	1120	1.00	0.35

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2.2.2 Experimental procedure

The workpiece used is cylindrical rods of AISI 304 alloy steel of dimension, with diameter 25 x 200mm. The workpiece was fixed on the Lathe such that a length of 175mm was hung. Centre-drilling operation was carried out and the workpiece was then supported with tailstock. The support is consequent upon Lawal *et al* (2011), which revealed that when l/d > 4, the workpiece must be supported.

For this work, l/d =175/25 = 7, hence the need for tail stock support.

l = length of workpiece, and
d = diameter of workpiece.

Orthogonal turning operations of L_{27} experimental runs was then carried out at ambient temperature based on L_{27} Orthogonal arrays of Table 3.

3. RESULTS AND DISCUSSION

3.1 Material Composition Test Result

The result of the composition test of the workpiece material conducted via Optical Emission Spectrometer (OES) is presented in Table 4.

Table 4: AISI 304 Alloy Steel Workpiece Composition

Element	Fe	Cr	Ni	Mn	Si	Cu	Co	C	V	N
Composition (%)	70.7	18.04	8.33	1.36	0.408	0.329	0.199	0.096	0.0729	0.0409

The composition agrees with the expected composition of AISI 304 as reported by NAS, 2016

3.2 Experimental Results

The DOE applied in this research was Taguchi. Experiment was conducted in each of the two environments – dry and wet (with mineral oil-based cutting fluid) to make a total of 54 experimental runs. The results obtained were analysed using analysis of variance (ANOVA). The measured values of the surface roughness for various experimental runs and cutting environments are presented in Table 8.

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Table 5: Experimental Process Parameters and Results in dry and wet environments

EXP NO	Cutting speed(rpm)	Feed rate(mm/min)	Depth of cut(mm)	Surface roughness Dry(μm)	Surface roughness Wet (μm)
1	625	0.50	0.25	0.77	1.48
2	625	0.50	0.25	0.83	0.77
3	625	0.50	0.25	1.08	0.88
4	625	0.75	0.35	0.77	1.24
5	625	0.75	0.35	0.61	1.27
6	625	0.75	0.35	0.50	1.43
7	625	1.00	0.50	0.63	1.35
8	625	1.00	0.50	0.78	1.85
9	625	1.00	0.50	0.89	1.65
10	840	0.50	0.35	0.66	1.35
11	840	0.50	0.35	0.64	1.43
12	840	0.50	0.35	0.66	1.76
13	840	0.75	0.50	0.76	0.87
14	840	0.75	0.50	1.08	1.95
15	840	0.75	0.50	0.71	1.80
16	840	1.00	0.25	1.37	2.18
17	840	1.00	0.25	0.91	1.30
18	840	1.00	0.25	1.62	1.29
19	1120	0.50	0.50	1.34	1.99
20	1120	0.50	0.50	1.17	1.27
21	1120	0.50	0.50	1.42	1.52
22	1120	0.75	0.25	0.76	0.49
23	1120	0.75	0.25	1.20	1.24
24	1120	0.75	0.25	0.99	1.23
25	1120	1.00	0.35	0.85	0.79
26	1120	1.00	0.35	0.98	0.84
27	1120	1.00	0.35	1.33	0.91

3.3 Analysis of Experimental Results

3.3.1 Signal to Noise (S/N) ratio

In view of unavoidable disturbances present in the experimental system which may include backlash on the machine slides, vibrations from machine base and possible fluctuations of electric current which cannot be easily controlled, signal to noise (S/N) ratio is evaluated and shown also in Table 9. The smaller, the better criterion was used to accomplish optimization for surface roughness.

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Table 9: Signal to Noise (S/N) ratio for experimental results in all environments

Run order	Cutting speed(rpm)	Feed rate(mm/min)	Depth of cut(mm)	Surface roughness dry(μm)	S/N ratio dry (db)	Surface roughness Wet (μm)	S/N ratio wet (db)
1	625	0.50	0.25	0.77	2.2702	1.48	-3.405
2	625	0.50	0.25	0.83	1.6184	0.77	2.270
3	625	0.50	0.25	1.08	-0.669	0.88	1.110
4	625	0.75	0.35	0.77	2.2702	1.24	-1.868
5	625	0.75	0.35	0.61	4.2934	1.27	-2.076
6	625	0.75	0.35	0.50	6.0206	1.43	-3.107
7	625	1.00	0.50	0.63	4.0132	1.35	-2.607
8	625	1.00	0.50	0.78	2.1581	1.85	-5.343
9	625	1.00	0.50	0.89	1.0122	1.65	-4.350
10	840	0.50	0.35	0.66	3.6091	1.35	-2.607
11	840	0.50	0.35	0.64	3.8764	1.43	-3.107
12	840	0.50	0.35	0.66	3.6091	1.76	-4.910
13	840	0.75	0.50	0.76	2.3837	0.87	1.210
14	840	0.75	0.50	1.08	-0.669	1.95	- 5.801-
15	840	0.75	0.50	0.71	2.9748	1.80	5.106
16	840	1.00	0.25	1.37	-2.734	2.18	-6.770
17	840	1.00	0.25	0.91	0.8192	1.30	-2.279
18	840	1.00	0.25	1.62	-4.190	1.29	-2.212
19	1120	0.50	0.50	1.34	-2.542	1.99	-5.977
20	1120	0.50	0.50	1.17	-1.364	1.27	-2.076
21	1120	0.50	0.50	1.42	-3.046	1.52	-3.637
22	1120	0.75	0.25	0.76	2.384	0.49	6.196
23	1120	0.75	0.25	1.20	-1.584	1.24	-1.868
24	1120	0.75	0.25	0.99	0.0873	1.23	-1.799
25	1120	1.00	0.35	0.85	1.4116	0.79	2.048
26	1120	1.00	0.35	0.98	0.1755	0.84	1.514
27	1120	1.00	0.35	1.33	-2.477	0.91	0.819

According to Onuoha (2015), Performance characteristics using S/N ratio are commonly applied as follows:

1. Bigger – the – better, S/N = $-10\log\left[\frac{1}{n}\sum_{i=1}^{n} 1/y_i^2\right]$ 1
2. Nominal – the better, S/N = $10\log\left[\frac{y^2}{5^2}\right]$ 2
3. Smaller – the better, S/N = $10\log\left[\frac{1}{n}\sum_{i=1}^{n} y_i^2\right]$ 3

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Where S/N is the signal to noise; y_i = individual responses; n = number of responses for the given factor combination; and S = Responses standard deviation for the given factor level combination. The main effect plots of the signal to noise (S/N) ratio for dry and wet with mineral oil-based cutting fluid are presented in Figures 1 and 2 respectively.

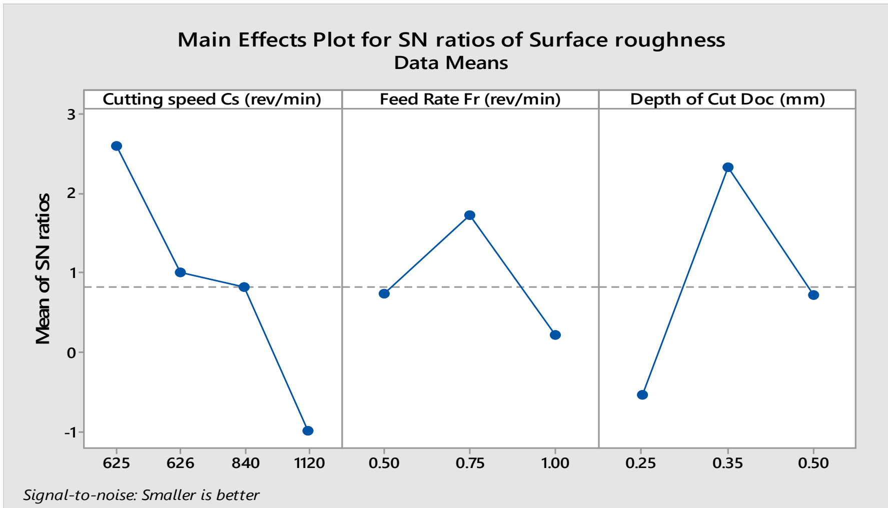

Figure 1: Main effects plots for S/N ratio in dry environment

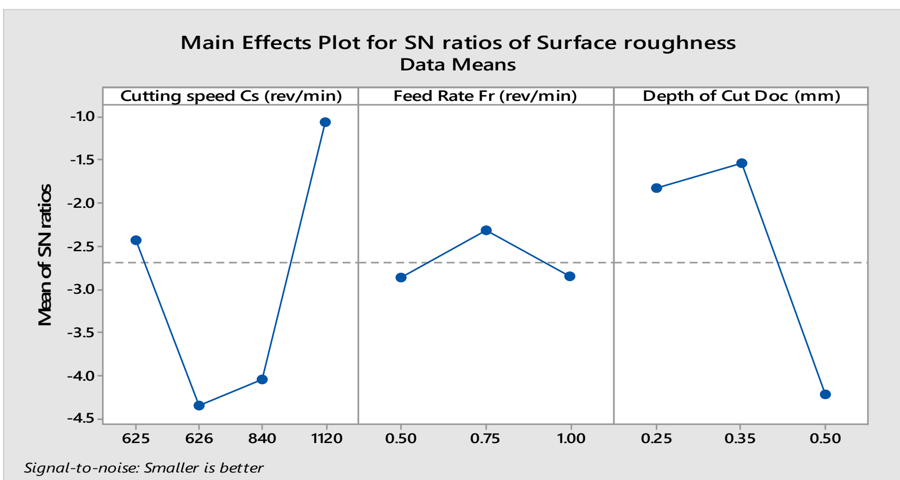

Figure 2: Main effects plots for S/N ratio in wet environment

3.3.2 Analysis of variance (ANOVA)

Analysis of variance (ANOVA) is a statistical tool used to detect differences between experimental group means (Sawyer, 2017). Analysis of variance (ANOVA) was performed as given in Tables 9 through 11 for various cutting environments. ANOVA was conducted to determine the significant effects of the cutting variables for significant level of $\propto$= 0.05 and a confidence level of 95%. The Sum of Square (SS), Degree of Freedom (DOF), Mean Square (MS), F –values and Percentage contribution (P) are calculated using equations 4 – 9.

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$SOS_{\tau} = \sum_{i=1}^{n}(y_i)^2 = -\frac{1}{n}\sum_{i=1}^{n} y_i^2$ 4

DOF = number of levels – 1 5

MS = $\frac{SS\ (individual)}{DOF}$ 6

f –value = $\frac{SS\ (individual)}{MS\ _{(error)}}$ 7

Contribution = $\frac{SS\ (individual)}{SS\ _{\tau}}$ 8

Error = Total - $\sum DOF$ 9
(Montgomery *et al.,* 1998; Montgomery, 2009)

The significant effects of cutting variables on the surface roughness during dry cutting is shown in Table 10.

Table 10: ANOVA Table for surface roughness in dry turning

Factor	DOF	SS	MS	F	P
Cutting speed	2.0	0.8903	0.4452	79.830	40.040
Feed rate	2.0	0.5308	0.2654	47.595	23.872
Depth of Cut	2.0	0.6853	0.3427	61.449	30.821
Error	21.0	0.1171	0.0056		5.266
Total	27.0	2.2235	0.0824		100.0

From Table 10, It is observed that cutting speed has the highest significant effect of 40.04%, followed by depth of cut with 30.82%. The least significant factor is feed rate with 23.87% significance. The percentage error is 5.266%.
The significance of each of the variables in wet turning with mineral oil-based cutting fluid is presented in Table 11.

Table 11: ANOVA Table for surface roughness in wet turning

Factor	DOF	SS	MS	F	P
Cutting speed	2	1.7619	0.8810	122.695	38.503
Feed rate	2	0.9503	0.4752	66.178	20.767
Depth of Cut	2	1.7130	0.8565	119.290	37.434
Error	21	0.1508	0.0072		3.295
Total	27	4.5760	0.1695		100.000

In wet turning environment with mineral oil-based cutting fluid, Figure 11 revealed that cutting speed (38.50%) specifies the most significant parameter, followed by depth of cut (37.43%) and feed rate (20.77%) being the least significant.

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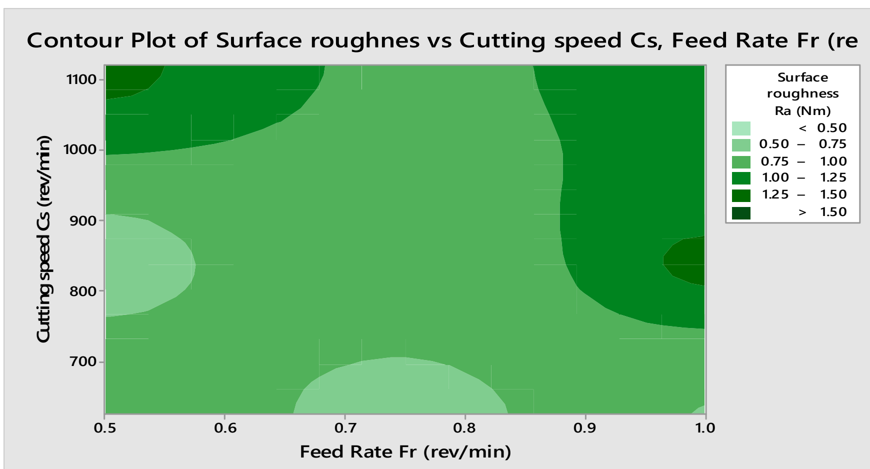
The significant effects of each of the cutting variables- cutting speed, feed rate and depth of cut on surface roughness in each of the two investigated cutting environments are summarily presented in Table 12.

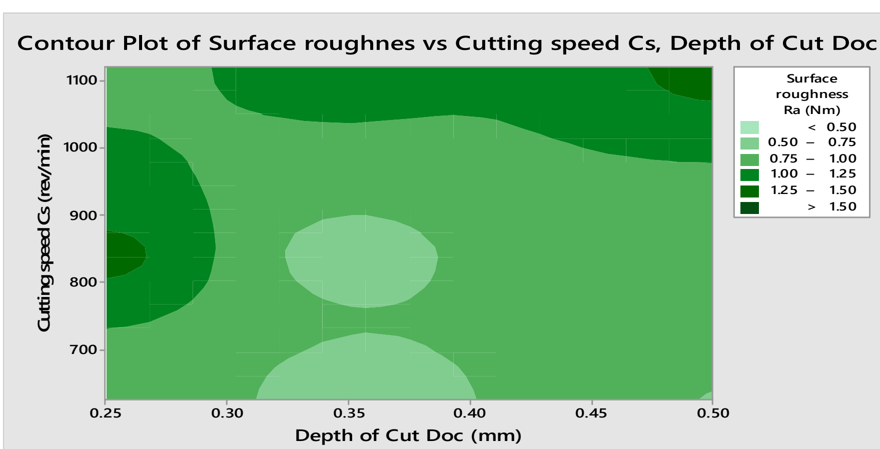
Table 12: Significant Effects of the cutting variables on surface roughness in various environments

Cutting Environment		Cutting Variables	
	Most Significant	More Significant	Significant
Dry	Cutting speed	Depth of cut	Feed rate
Wet, mineral oil	Cutting speed	Depth of cut	Feed rate

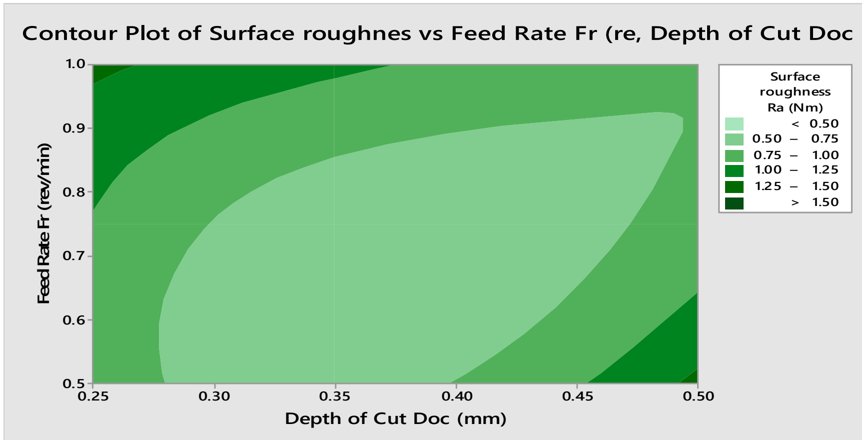
From Table 12, in both dry and wet turning environments, the order of significance of the cutting variables for minimum surface roughness is cutting speed, depth of cut and feed rate.The contour plot of Figure 4 indicates how cutting speed and feed rate affect the surface roughness when the depth of cut is kept constant in dry turning. Other contour plots for surface roughness in dry turning are presented in Figures 5 and 6, while the contour plots of Figures 7 through 9 show the surface roughness in wet turning with mineral oil-based cutting fluid.



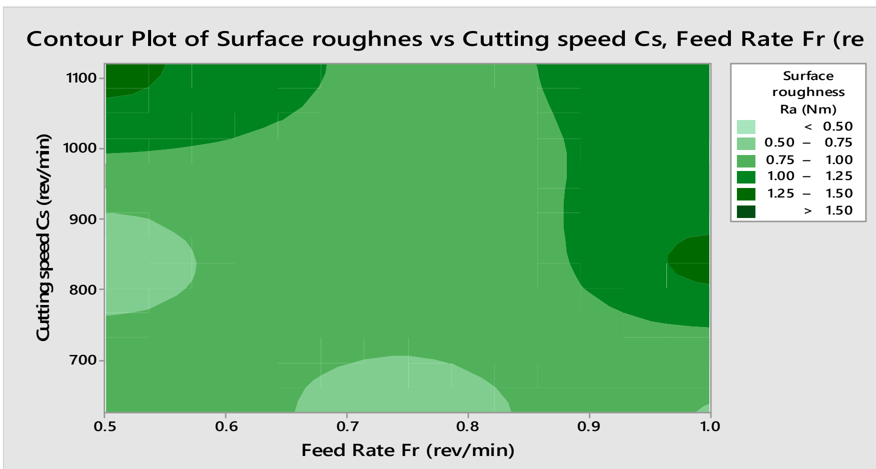
Figures 4 : Contour plots of Surface roughnes in dry turning



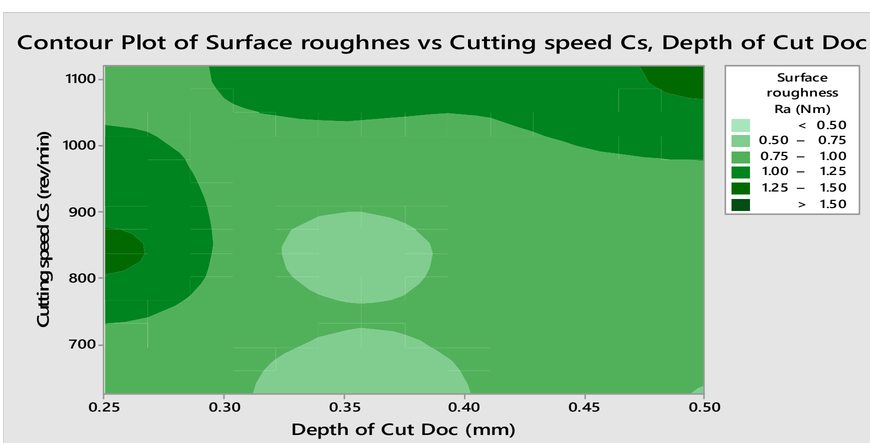
Figures 5 : Contour plots of Surface roughnes in dry turning



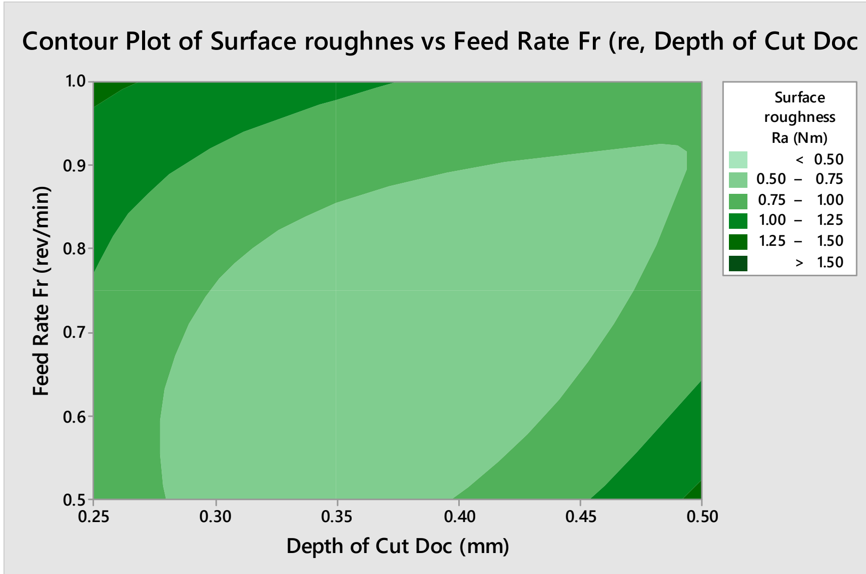
Figures 6 : Contour plots of Surface roughnes in dry turning



Figures 7: Contour plots of Surface roughnes in wet turning

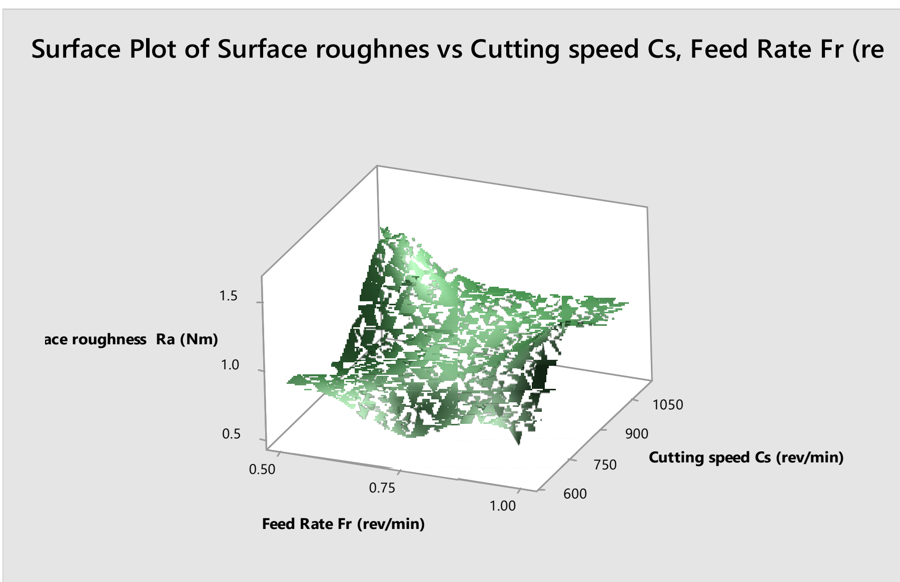


Figures 8 : Contour plots of Surface roughnes in wet turning



Figures 9 : Contour plots of Surface roughnes in wet turning

The Contour plots reveal the interaction of input variables and response in two dimensions, but the 3D Surface plots show the interactions in three dimensions. The 3D Surface plots of input variables and the response in dry turning are shown in Figures 10 to 12 while that of wet turning environments are presented in Figures 13 to 15.



Figures 10 - :3D plots of Surface roughnes in dry turning

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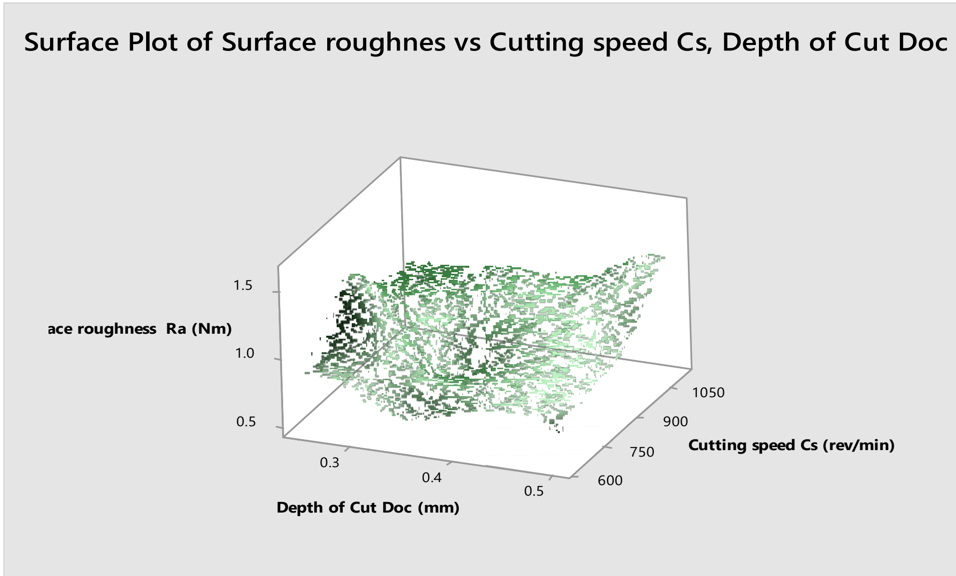
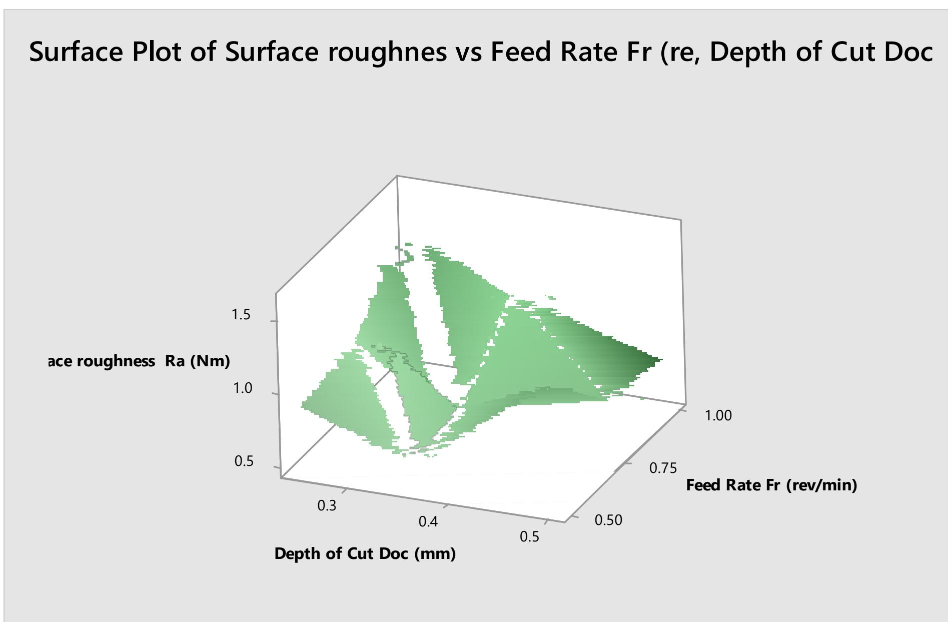
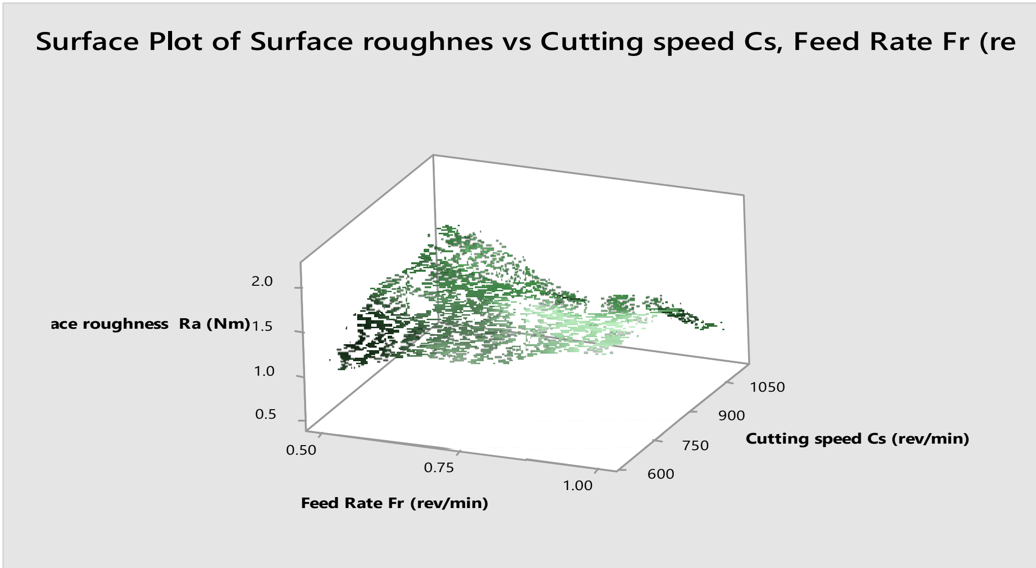


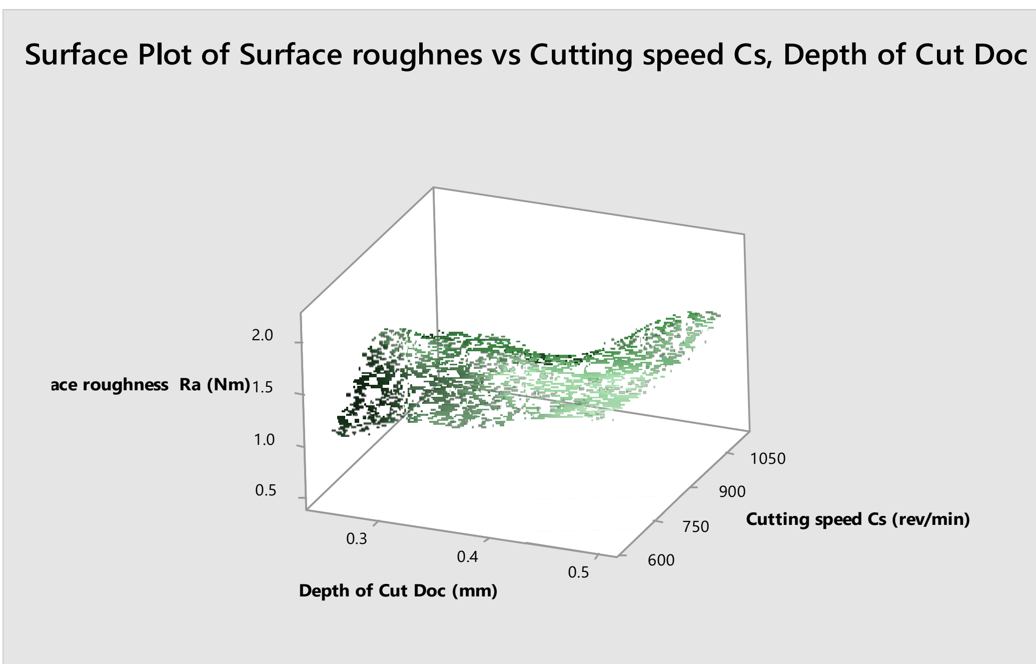
Figures 11 - :3D plots of Surface roughnes in dry turning



Figures 12 - :3D plots of Surface roughnes in dry turning



Figures 13-:3D plots of Surface roughnes in wet turning



Figures 14 -:3D plots of Surface roughnes in wet turning

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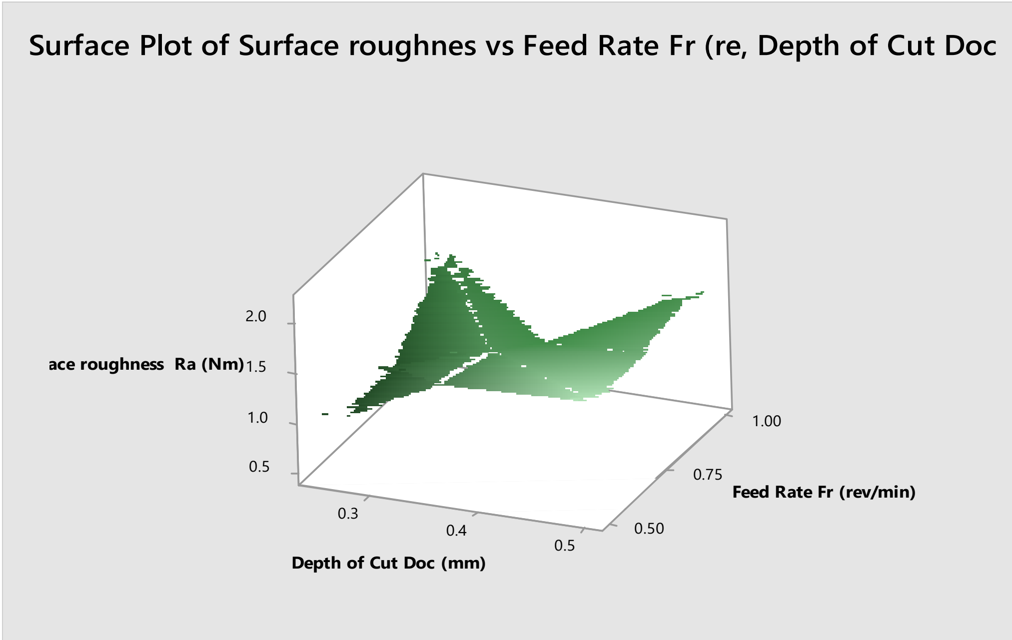

Figures 15 - 3D plots of Surface roughnes in wet turning

The the interaction plots for surface roughnesses in dry and wet turning environments are presented in Figures 16 and 17.

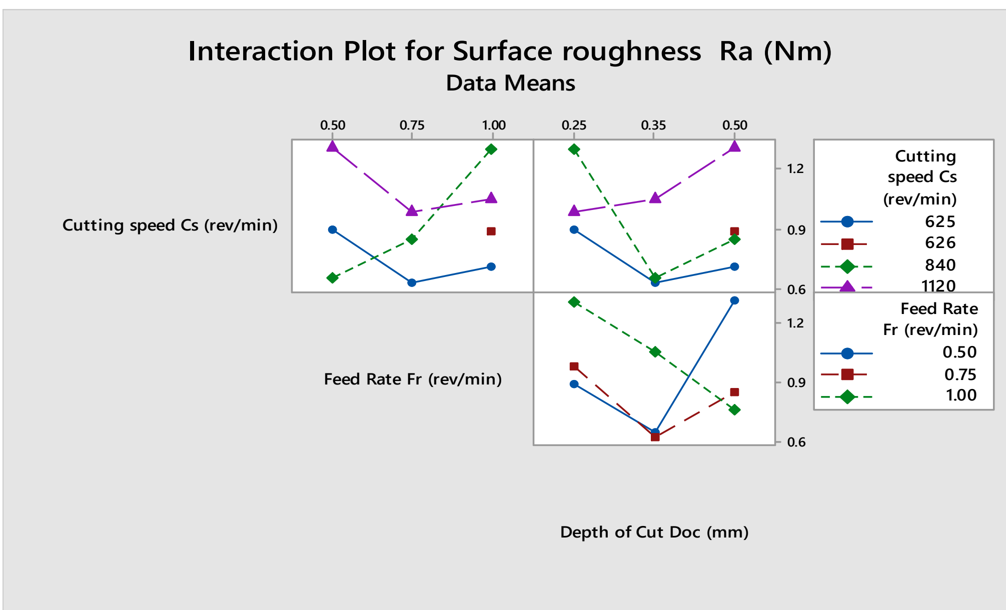

Figure 16: Interaction plots of Surface roughnes in dry turning

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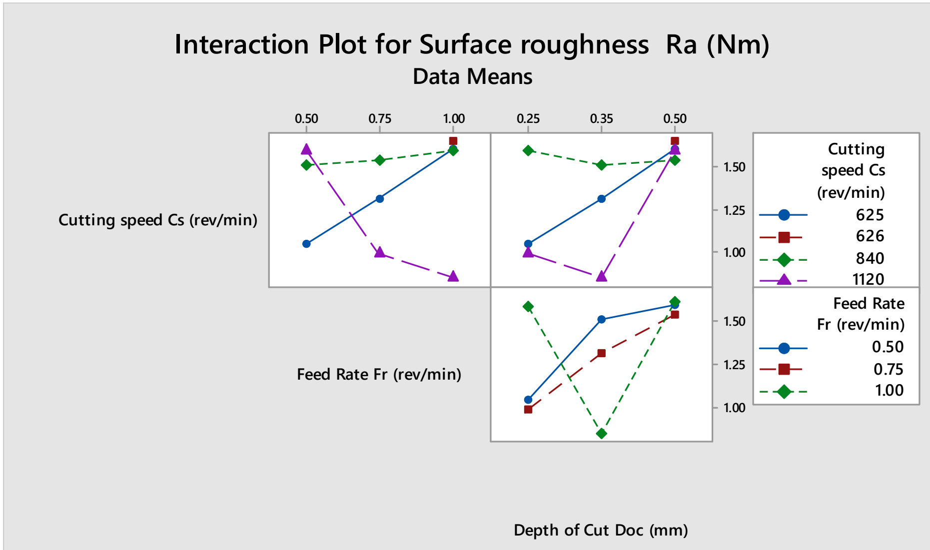

Figure 17: Interaction plots of Surface roughnes in wet turning

3.4 Regression Equations

Regression models were developed using minitab 17 statistical software. This regression equation can be applied to predict the values of the experimental response (surface roughness) for values of cutting variables.

For dry turning, the regression equation obtained is presented as equation 10, while that of wet turning is presented as equation 11.

Surface roughness Ra (μm) = -88 + 0.346 CS + 264 Fr - 936 Doc - 0.000202 CS*CS - 176 Fr*Fr - 553 Doc*Doc - 0.293 CS*Fr + 0.77 CS*Doc + 824 Fr*Doc 10

R-sq = 67.73% and R-sq (adj) = 52.18%

Surface roughness Ra (Nm) = -29 + 0.104 CS + 74 Fr - 245 Doc - 0.000059 CS*CS - 46 Fr*Fr – 152Doc*Doc- 0.083 CS*Fr + 0.21 CS*Doc + 219 Fr*Doc 11
R-sq = 67.91% and R-sq (adj) = 50.33%

The regression equations for both cutting environments are full quadratic equations.

4. CONCLUSION

The effects of cutting of cutting variables on surface roughness in dry and wet condition with mineral oil-based cutting fluids has been investigated. From the experimental results' analysis, the following conclusions are hereby drawn. In dry and wet cutting environment with mineral oil-based cutting fluid, cutting speed has the most significant effect in accomplishing minimum surface roughness. Feed rate was found to be least significant variables for accomplishing minimum surface roughness in both dry and wet environments with mineral oil-based cutting fluid.

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