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Optimization of Surface Roughness in CNC Turning Using Taguchi Method and ANOVA

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Abstract

*Now a day's achieving a good Surface Finish is the main challenge in the metal cutting industry during turning processes. The present work is to investigate the effect of cutting parameters (speed, feed and depth of cut) in CNC (Computer Numerical Control) turning of AA7075 to achieve low Surface Roughness using tungsten carbide insert. The experiments were designed as per the Taguchi's L9 (3 levels * 3 parameters) Orthogonal array technique. Analysis of variance (ANOVA) was performed to find the significance of the cutting parameters on the Surface roughness. The results showed that feed and cutting speed are the most important parameters influencing the surface roughness. From Taguchi analysis the minimum surface roughness are found at cutting speed of 1000 rpm (Level 1), feed of 0.2 mm/rev (Level 1) and depth of cut of 0.5 mm (Level 1) respectively. Thereafter, optimal range of surface roughness values was predicted. Finally, the relationship between cutting parameters and response was developed by using the MINITAB-16 software and regression analysis has been done. The predicted values were compared with the experimental values and it is observed that both the values were very nearer and hence the models prepared were more accurate and adequate.*

Key words: *AA7075, Surface Roughness (R_a), Taguchi, ANOVA, Regression Analysis*

1. Introduction

Aspects such as Material Removal Rate, Surface Roughness, tool life, wear and cutting forces decide the productivity, product quality of machining. During machining, heat will be generated near the cutting edge of the tool. The amount of heat generated varies with the type of material being machined and machining parameters especially at high cutting speeds. [1-2] Increase in temperatures directly influences the tool wear and flank wear properties and induce thermal damage to the machined surface. All these conditions lead to low material removal rate and poor surface finish. In actual practice, there are many factors affect the surface roughness like cutting conditions (speed, feed and depth of cut), tool variables (tool material, nose radius, rake angle, cutting edge geometry, tool vibration, tool overhang, tool point angle *etc.*,) and workpiece variables (material, hardness and other mechanical properties *etc.*). So, to achieve good surface finish, it is necessary to select the most appropriate machining setting in order to improve cutting efficiency. [3-6] Generally, this optimum parametric selection is determined by the operator's experience or by design data books, but which leads to decrease in productivity due to sub optimal use of machining capabilities this causes an increase in machining cost and a decrease in quality. Hence statistical design of experiments and statistical/mathematical models are

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used for decreasing the machining cost and time. [7-10] Statistical design of experiments refers to the process of planning the experiments so that the appropriate data can be analyzed by statistical methods, resulting in valid conclusions. [11-12] The Taguchi experimental design method is a one of the well known, unique and powerful technique for product or process quality improvement. It is widely used for analysis of experiment and in optimization problems. Taguchi has developed a factorial design of experiments called an orthogonal array which covers the entire parametric space with less number of experiments. [13-15] Taguchi introduces his concepts to:

- Quality should be designed into a product and not inspected into it.
- Quality is best achieved by minimising the deviation from a target.
- The cost of quality should be measured as a function of deviation from the standard and the losses should be measured system wide.

Taguchi recommends a three stage process to achieve desirable product quality by design, including system design, parameter design and tolerance design. The system design helps to identify working levels of the designed parameters. Parameter design seeks to determine parameter levels that provide the best performance of the product under study. The optimum condition is selected so that the influence of uncontrollable factors causes a minimum variation of system performance. Orthogonal arrays, variance and signal to noise analysis are the essential tools of parametric design. Tolerance design is a step to fine tune the results of parametric design. [16-20]
Signal-to-Noise characteristics given by Taguchi are

(a) Larger-the-better: it is used where the larger value of response is desired.
S/N ratio = $-10 \log_{10} [1/Y_i^2]$
(b) Smaller-the-better: it is used where the smaller value of response is desired.
S/N ratio = $-10 \log_{10} [Y_i^2]$
Where, Y_i is observed response.

The aim of the present investigation is to find the effect of cutting parameters on AA7075 steel workpiece surface roughness by employing Taguchi's orthogonal array design and analysis of variance (ANOVA).

2. Experimental Details

2.1. Work Piece Material

The workpiece material was Aluminium alloy 7075 shown in the figure1 taken in the form of round bars each of 30 mm dia. and 60 mm length. AA7075 has a wide range of applications in the field of manufacturing and aerospace applications. The chemical composition and mechanical properties of AA7075 are given in the Tables 1 and 2.

Figure 1. AA7075 Workpiece

Table 1. Chemical Composition of AA7075

element	Al	Zn	Cu	Cr	Fe	Mg	Mn
Wt %	87.1-91.4	5.1-6.1	1.2-2.0	0.18-0.28	0.5 max	2.1-2.9	0.3 max

Table 2. Mechanical Properties of AA7075

parameter	Ultimate Tensile Strength (psi)	Yield Strength (psi)	Brinell (BHN)	Rockwell	Density (gm/cm^3)
Value	83000	73000	150	1387	2.8

2.2. Cutting Insert

In tests, Tungsten carbide insert of ISO designation DNMG160404 has been used for the experiment. The cutting insert was clamped onto a tool holder having ISO designation PDJNL2525M16 and shown in the Figure 2. Viscool 5096 was used as a coolant during machining.

Figure 2. Tungsten Carbide Insert with Tool Holder

2.3. Experimental Procedure

The turning tests on the workpiece were conducted under wet conditions on a CNC (Computer Numerical Control) lathe (DX 200, JOBBER XL) having maximum spindle speed of 4000 rpm and maximum power of 7.5 KW. Prior to actual machining, the rust layers were removed by 0.5 mm depth of cut in order to minimize any effect of homogeneity on the final results. Machined components after machining were shown in the Figure 3.

Figure 3. Machined Components of AA7075

2.4. Measurement of Surface Roughness

The surface roughnesses of the machined components were measured at three different points by the use of Mitutoyo SJ301 as shown in the Figure 4. (Measuring range: 350μm, Tip radius: 5μm, shape stylus: Diamond).

Figure 4. Experimental Setup for Measuring Surface Roughness

2.5. Design of Experiments

The aim of the experiments was to analyze the effect of cutting parameters on Surface roughness in turning of AA7075. The experiments were planned as per Taguchi's L9 Orthogonal array given in the Table 3. The surface roughness depends on several parameters like cutting conditions (speed, feed and depth of cut), tool conditions (Tool nomenclature, nose radius) and mechanical properties (hardness, tensile strength) *etc*. It is well known that the number of experiments to be conduct will get increased with the increase in the number of parameters. So, to reduce the experiments, the cutting speed, feed and depth of cut were used as inputs at three different levels. The control parameters and the levels used in experiment, experimental setup and conditions are given in the Table 4.

Table 3. Taguchi L9 Orthogonal Array

S. No.	Speed (rpm)	Speed	Feed (mm/rev)	Feed	Doc (mm)	Doc
1	1	1000	1	0.2	1	0.5
2	1	1000	2	0.3	2	0.75
3	1	1000	3	0.4	3	1
4	2	1500	1	0.2	2	0.75
5	2	1500	2	0.3	3	1
6	2	1500	3	0.4	1	0.5
7	3	2000	1	0.2	3	1
8	3	2000	2	0.3	1	0.5
9	3	2000	3	0.4	2	0.75

Table 4. Parameters with Levels

Parameter	Units	Levels		
		1	2	3
Speed, v	rpm	1000	1500	2000
Feed, f	mm/rev	0.2	0.3	0.4
Depth of cut, d	mm	0.5	0.75	1

Experimental Setup and Conditions

Machine tool: CNC lathe (DX 200, JOBBER XL)
Workpiece material: AA7075
Size: 30 mm diameter, 60 mm Length
Cutting insert: DNMG160404
Tool holder: PDJNL2525M16
Surface roughness Gauge: SJ301 (Mitutoyo)
Cutting environment: wet
Coolant: Viscool 5096

3. Results and Discussions

A series of experiments are conducted on AA7075 with a tungsten carbide insert. S/N ratios for Surface roughness values were calculated using Smaller-the-better characteristic proposed by Taguchi and given in the Table 5.

Table 5. Experimental Results of Surface Roughness

S.No.	R_a (µm)	S/N value
1	3.25	-10.2377
2	7.45	-17.4431
3	12.71	-22.0829
4	3.75	-11.4806
5	7.87	-17.9195
6	12.59	-22.0005
7	3.69	-11.3405
8	7.97	-18.0292
9	12.37	-21.8474

3.1. Analysis of Variance (ANOVA)

The experimental results of surface roughness values were analyzed with Analysis of variance (ANOVA), used to identify the factors significance on the response. The result of ANOVA of surface roughness was given in the Table 6. This analysis was carried out for a significance level of $\alpha = 0.5$ *i.e.*, for a confidence level of 95%. The sources with a P-value less than 0.05 are considered to have a statistically significant contribution to the performance measures.

Table 6. ANOVA Results of Surface Roughness

Source	DOF	SS	MS	F	P
v	2	0.117	0.059	0.74	0.575
f	2	121.496	60.748	764.02	0.001
d	2	0.084	0.042	0.53	0.653
Error	2	0.159	0.080		
Total	8	121.857			

S = 0.281977, R-Sq = 99.87%, R-Sq (Adj) = 99.48%

Table 6 shows the results of ANOVA for surface roughness. From the results, it is observed that the feed is the most significant parameter followed by cutting speed and depth of cut has less significance in controlling the surface roughness values. From the analysis of the Table 6, p-value of feed (0.0001) which is less than 0.05. It means that feed's influence significantly on workpiece surface roughness between three cutting parameters.

3.2. Main Effect Plots Analysis

The data were further analyzed to study the effect of cutting parameters on surface roughness. From the S/N ratios given in the Tables 7 and 8 main effect plots were drawn using MINITAB-16 software and shown in the Figures 5 and 6 respectively. The plots show the variation of response with the change in cutting parameters. In the plots 5 and 6, the X-axis indicates the value of each process parameters at three levels and y-axis the response value. These main effect plots are used to determine the optimal design conditions to obtain the low surface roughness.

Table 7. Response Table for S/N Ratios of R_a

level	v	f	d
1	-16.59	-11.02	-16.76
2	-17.13	-17.80	-16.92
3	-17.07	-21.98	-17.11
Delta	0.55	10.96	0.36
Rank	2	1	3

Table 8. Response Table for Means of R_a

level	v	f	d
1	7.803	3.563	7.937
2	8.070	7.763	7.857
3	8.010	12.557	8.090
Delta	0.267	8.993	0.233
rank	2	1	3

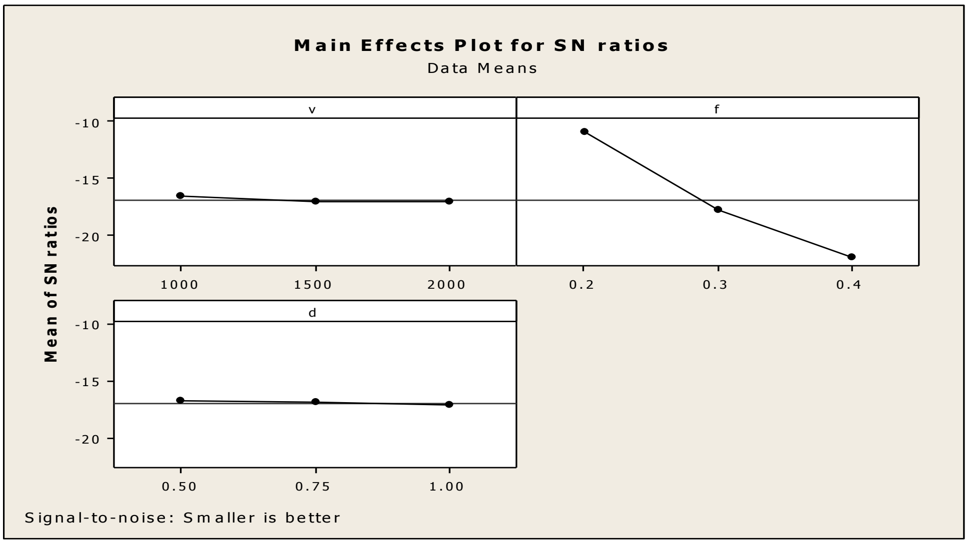

Figure 5. Main Effects Plot for S/N Ratios of R_a

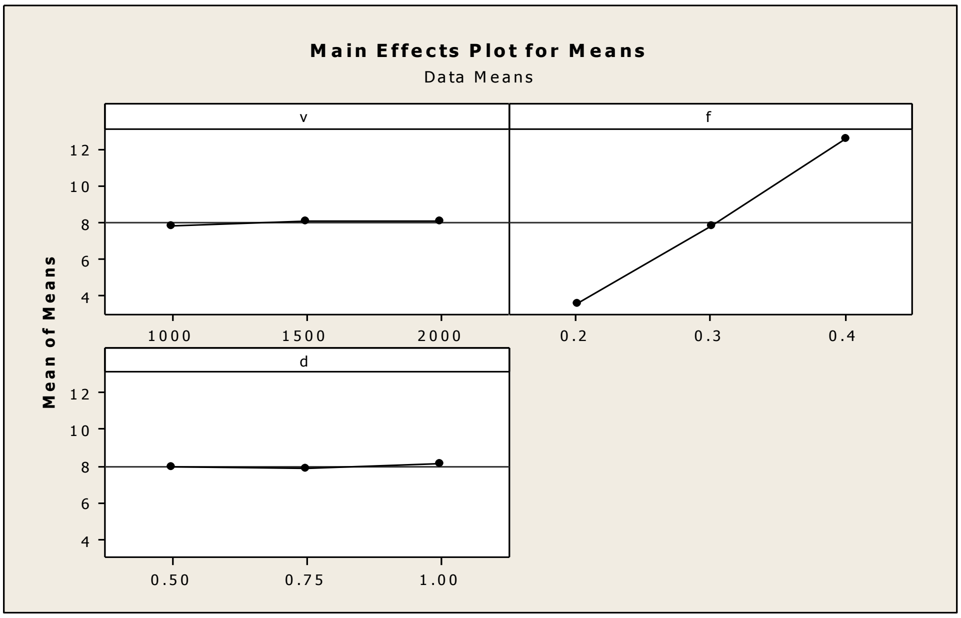

Figure 6. Main Effects Plot for Means of R_a

From the Figures 5 and 6, it is observed that with the increase in cutting speed and depth of cut levels there is a less change in response. But with the increase in the levels of feed significant change in the response can be observed. Based on the analysis the low value of surface roughness was obtained at cutting speed of 1000 rpm (level 1), feed of 0.2 mm/rev (Level 1) and depth of cut of 0.5 mm (level 1).

Table 9. Optimum Conditions for Surface Roughness

Parameter	Best level	value
Speed, rpm	1	1000
Feed, mm/rev	1	0.2
Depth of cut, mm	1	0.5

3.3. Prediction of Optimal Design

Optimal design

Performance of R_a when the two most significant factors (feed and speed) are at their better level (based on estimated average).

$\mu_{A1B1} = A_1 + B_1 - T$

$A_1 = 3.563$, $B_1 = 7.803$ (From Table 8)

$T = 7.961$ (From Table 5)

$\mu_{A1B1} = A_1 + B_1 - T$

$= 3.563 + 7.803 - 7.961 = 3.405$

$CI = \sqrt{((F_{95\%,1,doferror} V_{error})/(\eta_{efficiency}))}$

Where, $\eta_{efficiency} = N/(1+dof)$ of all parameters associated to that level.

$\eta_{efficiency} = N/(1+dof) = 9/(1+2+2) = 9/5 = 1.8$

$V_{error} = 0.08$, (From Table 6)

$F_{95\%,1,2} = 18.5128$ (From standard F-table)

$CI = \sqrt{((18.5128 \times 0.08) / 1.8)} = 0.907$

The predicted optimal range of R_a at 95% ($\alpha = 0.05$) confidence level is obtained as,

$\mu_{A1B1} - CI \leq \mu_{A1B1} \leq \mu_{A1B1} + CI$

$3.405 - 0.907 \leq \mu_{A1B1} \leq 3.405 + 0.907$

$2.498 \leq \mu_{A1B1} \leq 4.312$

3.4. Regression Equation

The relationship between cutting parameters (speed, feed and depth of cut) and the response (Surface roughness) was modeled by linear regression using the MINITAB-16 software.

$R_a = - 6.07 + 0.000207 v + 45.0 f + 0.307 d$

S = 0.2958, R-Sq = 99.6%, R-Sq (Adj) = 99.4%

Inspection of some diagnostic plots of the model was done to test the statistical validity of the models. The residuals could be said to follow a straight line in normal plots of residuals implying that the errors were distributed normally shown in Figure 7. This gives the support that the models prepared were significant and accurate. The residuals were randomly scattered within one constant variance across the residual versus the predicted plot shown in Figure 8. Figures 7 and 8 indicate that there is no obvious pattern and unusual structure present in the data which implies that the residual analysis does not indicate any model inadequacy.

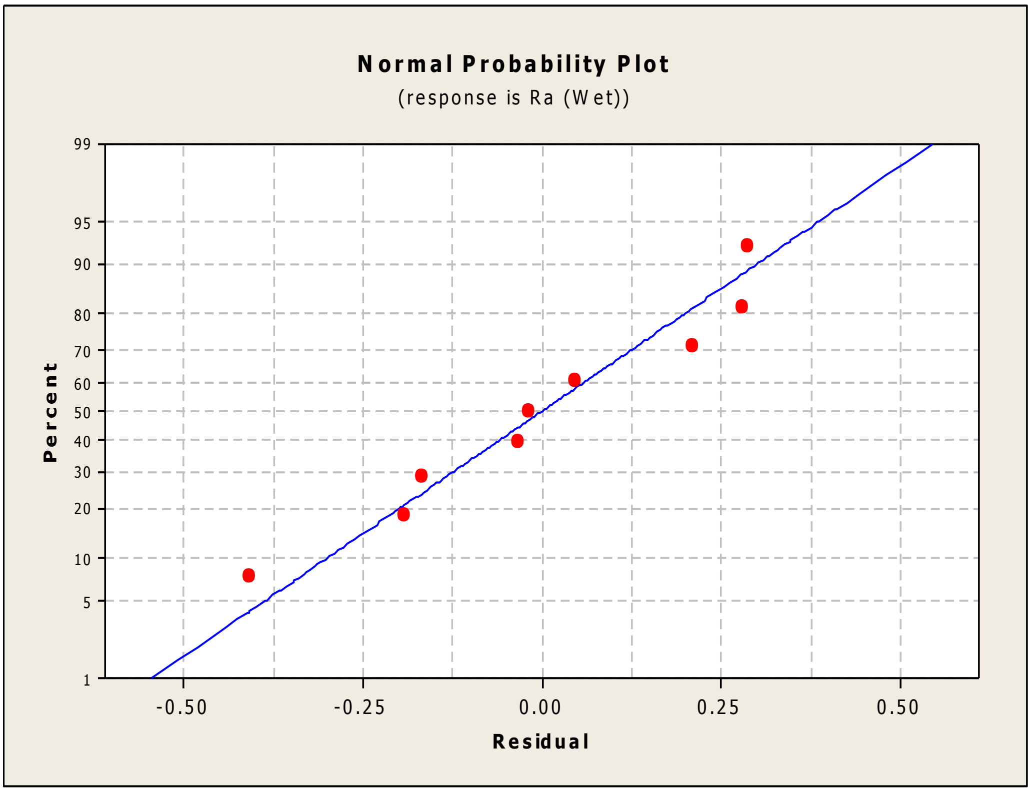

Figure 7. Normal Probability Plot for R_a

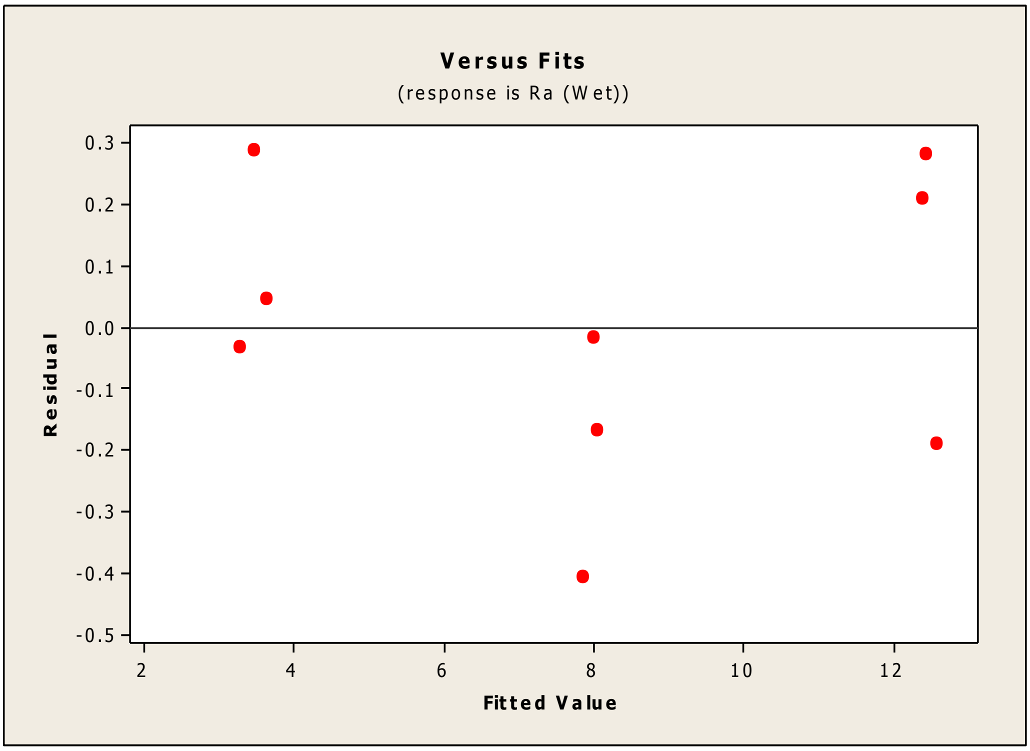

Figure 8. Versus Fits Plot for R_a

The surface plots were drawn by using MINITAB-16 software to find the relation between Response variable and cutting parameters and shown in Figures 9 and 10. Surface plots shows how a response variable relates to two factors based on model equation. From the Figures 9 and 10, it is observed that the low roughness values can be achieved by maintaining low levels of three cutting parameters.

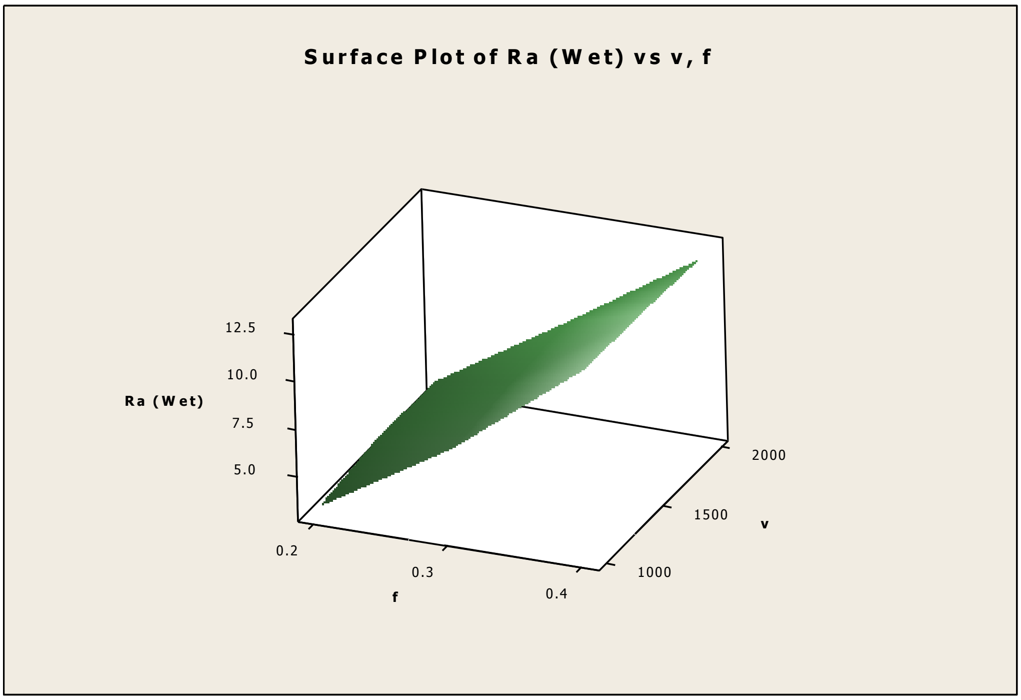

Figure 9. Surface Plot for R_a Vs Speed, Feed

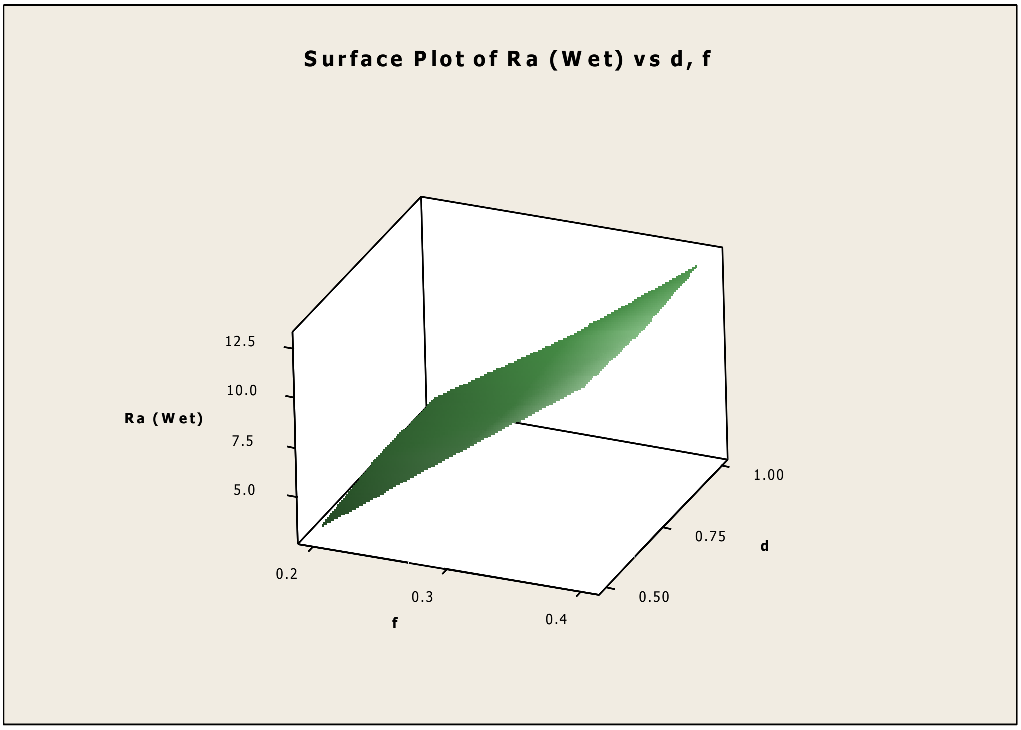

Figure 10. Surface Plot for R_a Vs Feed, Depth of Cut

3.5. Comparison of Experimental and Regression Values of Surface Roughness

The experimental and the regression values of surface roughness were compared and the comparison graph was plotted using EXCEL by taking experiment number on X-axis and surface roughness value on Y-axis and shown in the Figure 11. From the Figure 11, it is observed that both experimental and regression values were close to each other hence, the models prepared were more accurate and can be used for the prediction of surface roughness values. %errors between experimental and regression values of surface roughness were calculated as

% of Error = ((Experimental-Predicted)/(Experimental))*100

Table 10. Comparison of Experimental and Predicted Values of Surface Roughness

S.No.	R_a (EXP)	R_a (REG)	% Error
1	3.25	3.29	-1.24
2	7.45	7.87	-5.60
3	12.71	12.44	2.09
4	3.75	3.47	7.44
5	7.87	8.05	-2.25
6	12.59	12.39	1.55
7	3.69	3.65	1.05
8	7.97	7.99	-0.34
9	12.37	12.57	-1.65

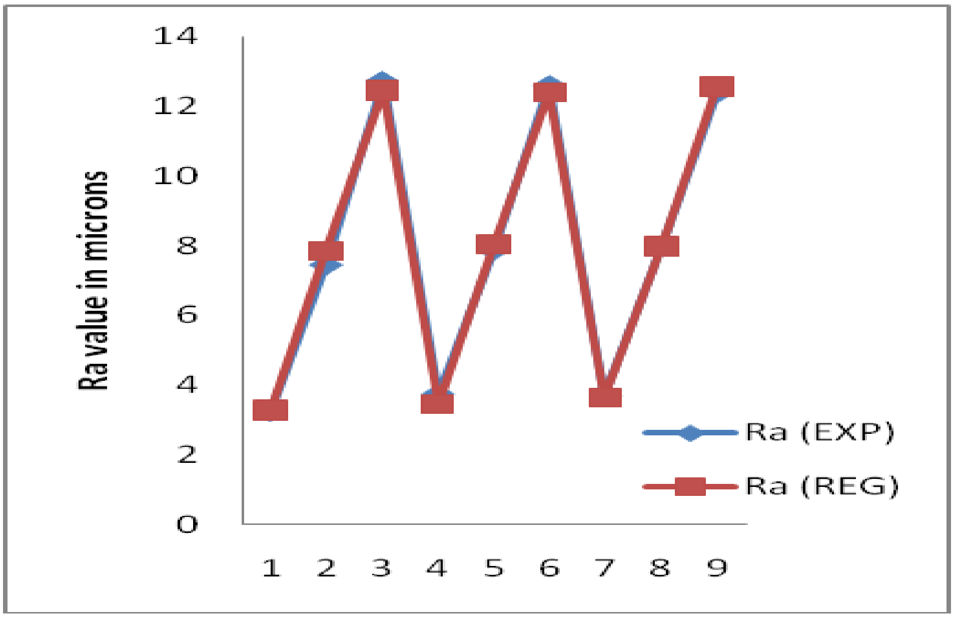

Figure 11. Comparison of Experimental and Regression Values of R_a

4. Conclusions

From the experimental and predictd results the following conclusions can be drawn

- From Taguchi results, the optimal combination of cutting parameters for low surface roughness was found at v1-f1-d1 *i.e.*, speed at 1000 rpm, feed at 0.2 mm/rev and depth of cut at 0.5 mm.
- From ANOVA results, for achieving minimum surface roughness values, feed has high influence (F = 764.02) followed by speed (F = 0.74) and depth of cut (F = 0.53) has low influence.

- The Regression model prepared is more accurate and adequate because of high coefficient of determination (R-Sq = 99.6%) and it can be used for the prediction of surface roughness.
- %Errors between experimental and regression values are within the acceptable range (±7).

5. Future Scope of Work

- The present work can be extended further for different conditions of process parameters at different levels for different materials.
- The present work can be done by taking PVD or CVD coated tools rather than tungsten carbide.

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