



Prediction of optimality and effect of machining parameters on Surface Roughness based on Taguchi Design of Experiments

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Abstract: Quality is the prime requirement for most of the customers and hence it is always a challenging and upcoming task in industries. This work focus on Surface Roughness produced in hard turning process on Lathe. The process of hard turning is done on AISI 1040 Steel material under dry conditions using coated Carbide Inserts and High Speed Steel (HSS) Tools. Spindle Speed and Feed are chosen as control factors. The control factors are adopted to analyze significance and contribution on the Surface Roughness of the machined parts.

Taguchi methodology based on Orthogonal Arrays (OA) is used to Design the Experiments. Signal-to-noise Ratio (S/N ratio) of the generated Roughness values is used to evaluate the optimal machining parameter combinations. Later Analysis of Variance (ANOVA) is used to analyze the influences and contribution of the machining parameters on the Roughness values based on F-Statistic Test.

Regression Model analysis was developed for predicting the Average Surface Roughness (Ra) as a function of Speed and Feed. Confirmation experiments are yielding an error of max 8.55% and 0.46% in Regression, while machining with Carbide and HSS tools respectively.

Keywords: Roughness, Dry machining, Taguchi, Two-Way ANOVA, Hard Turning.

I. INTRODUCTION

To have high surface finish, one has to machine a component in multiple cuts. The machining concept of multiple cuts machining increases the processing time, production cost and high setup time. Hence, hard turning operation where components are machined with single cut operation came into existence to focus on reduction in processing time, production cost and setup time with high surface finish [5,6,10].

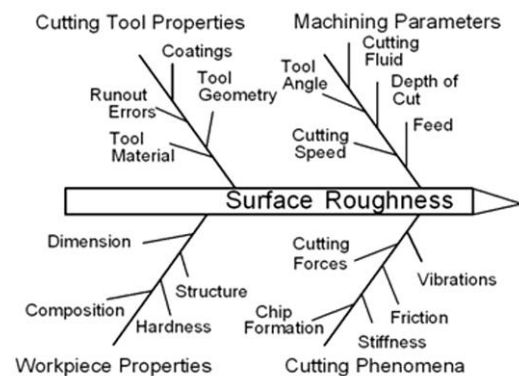


Fig.1. Machining Parameters Influencing Surface Roughness

Surface roughness is one of the most important customer requirements and is an indicator of quality in metal cutting machining process. Surface Roughness is not just a single property, because it plays a major role in focusing attention on the product appearance, functionality and assembly.

Surface Roughness of a machined part depends on many machining factors as shown in figure 1. In this paper, machining parameters like Speed and feed with 25mm constant depth of cut and each time new tool inserts were used to overcome the tool wear with single hard turning operation under dry conditions were considered.

II. TAGUCHI PHILOSOPHY

In order to produce any product with desired quality by machining, proper selection of process parameters is essential. This can be accomplished by Taguchi approach.

Taguchi's philosophy supports the approach that asserts that higher quality resulting in lower cost and furthermore, it leads to move quality improvement upstream and thereby helps design engineers to build quality into products and processes [1-3].

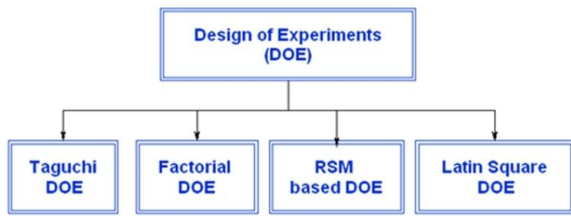


Fig.2. Classification of Design of Experiments

Many of the DOE are widely in use, as shown in figure 2, but Taguchi DOE are now widely used in many industries to efficiently optimize the manufacturing process and also to allow multiple complex properties to be rapidly optimized at minimal cost.

III. LITERATURE REVIEW

In LATHE machining processes like turning, a proper selection of cutting conditions generates high surface roughness finish and less dimensional error parts subject to fatigue loads, precision fits and aesthetic requirements. Hence many researchers focused on the literature on the measurement of surface roughness using single (lathe) and multi-point (milling) cutting tool using different machining parameters like feed, speeds, depth of cut and tool geometry are well documented. Totally the researches in this field can be divided in four groups [8]:

1. Trends based on machining theories.
2. Trends based on experimental tests.
3. Trends based on designed tests (TAGUCHI based).
4. The trends based on intelligent neural networks.

Samir Khrais et al.[1] focused on evaluating surface roughness and developed a multiple regression model for surface roughness as a function of cutting parameters during the machining of flame hardened medium carbon steel with TiN- Al_2O_3 -TiCN coated inserts. Taguchi methodology was adapted for experimental plan of work and signal-to-noise ratio (S/N) were used to relate the influence of turning parameters to the workpiece surface finish and the effects of turning parameters were studied by using the ANOVA. Ali Motorcu Riza [2], studied the surface roughness in the turning of AISI 8660 hardened alloy steels by ceramic based cutting tools with cutting parameters such as cutting speed, feed rate, depth of cut in addition tool's nose radius, using a statistical approach. An orthogonal design, signal-to-noise ratio and analysis of variance were employed to find out the effective cutting parameters and nose radius on the surface roughness.

W.H. Yang and Y.S. Tarng [3], studied the Taguchi method as a powerful tool to design optimization for quality and used to find the optimal cutting parameters for turning operations based on orthogonal array, signal-to-noise (S/N) ratio, and the analysis of variance (ANOVA) to investigate the cutting characteristics of S45C steel bars using tungsten carbide cutting tools. Through this study, they found not only the optimal

cutting parameters for turning operations can be obtained, but also the main cutting parameters that affect the cutting performance in turning operations. Experimental results are provided to confirm the effectiveness of this approach.

A.E. Diniz et al. [4] focused on working to find cutting conditions more suitable for dry cutting, i.e., conditions which make tool life in dry cutting, closer to that obtained with cutting with fluid, without damaging the Workpiece surface roughness and without increasing cutting power consumed by the process.

Dilbag Singh et al. [5] investigated the effects of cutting conditions and tool geometry on the surface roughness in the finish hard turning of the bearing steel (AISI 52100) with Mixed ceramic inserts made up of aluminum oxide and titanium carbo-nitride (SNGA). A mathematical model for the surface roughness was developed using RSM. T. Tamizharasan et al. [6] analyzed the process of hard turning and its potential benefits compared to the conventional grinding operation. Additionally, tool wear, tool life, quality of surface turned, and amount of material removed are also predicted.

Turnad L. Ginta et al. [7] focused on developing an effective methodology to determine the performance of uncoated WC-Co inserts in predicting minimum surface roughness in end milling of titanium alloys Ti-6Al-4V under dry conditions. Response surface methodology was employed to create an efficient analytical model for surface roughness in terms of cutting parameters and Surface roughness values were measured using Mitutoyo Surftest model SV-500 Surface Roughness Tester.

R.A. Mahdavejad et al. [8] highlighted the methods of predicting the surface roughness, like based on the trends of machining theories, based on the designed tests, based on Artificial intelligence such as Neural networks, GA, Fuzzy etc and based on lab research such as statistics and regression model analysis. The combination of adaptive neural fuzzy intelligent system is used to predict the roughness of dried surface machined in turning process.

Development of Regression models based on experimental tests of turning operations are widely in exercise for predicting the behaviour and effects of machining parameters on surface roughness of the components or to aid the selection of working parameters given a required surface roughness. C. X. (Jack) Feng et al. [9] developed an empirical model for the prediction of surface roughness in finish turning basing on Workpiece hardness (material), cutting parameters, tool geometry and cutting time by means of nonlinear regression with logarithmic data transformation and their applications in determining the optimum machining conditions. A. Manna. B. Bhattacharyya [10] investigated influence of cutting conditions on surface finish during turning of Al/SiC-MMC with a fixed rhombic tooling system using

Taguchi method for optimizing the cutting parameters for effective turning. Multiple linear regression mathematical models relating to surface roughness were established.

Researchers applied Taguchi method not only for lathe machining but also for Wire-cut electric discharge machining (WEDM) of various materials [11] basing on Taguchi's orthogonal array under different conditions of parameters.

This paper focuses on study of combination of two cutting parameters with Taguchi full factorial study in turning operation. The Surface Roughness and Regression models are considered for Analysis, while machining with two types of cutting tool (like HSS and Carbide) based on machining parameters (Speed and Feed) with constant depth of cut.

IV. EXPERIMENTAL DESIGN AND CONDITIONS

In this work, turning operations conducted on fully automated all geared headstock lathe machining center under dry conditions.

Each turning operation were carried out with new carbide inserts and HSS tools for avoiding impact of tool geometry wear and crater impact on disturbing the surface roughness finish in hard turning operations.



Fig.3. Setup of Carbide and HSS Machining on Lathe respectively

The material like EN8 (AISI 1040) steel was chosen for studying the impact of feed and speed with 25mm constant depth of cut. The influence of these parameters on the Surface Roughness and Regression model while machining with Taguchi Orthogonal Array DOE are analyzed.

Surface roughness tester as shown in figure 4a of Mitutoyo SURFTEST SJ-301, range of traverse 0.25-0.5mm, Stylus (Diamond) differential induction method detection unit, measuring in the range of -200 to 150microns is used to measure the surface roughness on the four diametrical points of the machined surfaces and average is considered as Surface Roughness value.



(a): Roughness Tester (b): Cutting Tools
Fig.4. Roughness tester and Cutting Tools

A. Workpiece material and cutting inserts

EN8 (AISI 1040) is an unalloyed medium carbon steel and finds application in the manufacture of various items like Shafts, stressed pins, studs, keys etc is taken as work piece material for hard turning operation.

Commercially available Cemented carbides coated with multi layer of TiN-Al₂O₃-TiCN-TiN from WIDIA with an ISO Designation: CNMG120408-Grade: TN4000 were used.

High-speed steels (HSS) tools are not a new material, but are basic tools generated with innovative heat treatment procedures were been used for hard machining, as shown in figure 4b.

B. Taguchi DOE based on Orthogonal Arrays

This work postulates the model for the Surface Roughness prediction in the turning operations on AISI 1040 steel material in terms of two independent variables are investigated using Taguchi DOE based on Orthogonal Arrays. Two control factors like feed (0.14mm/rev, 0.17mm/rev and 0.20mm/rev) and spindle speed (560 rpm, 900rpm and 1250rpm) with 25mm constant depth of cut with three levels each are considered, as shown in Table 1.

Taguchi's approach was built on traditional concepts of design of experiments (DOE), such as factorial and fractional factorial designs, orthogonal arrays, signal-to-noise ratios to minimize the number of experiments required to determine the effect of process parameters upon performance characteristics while investigating a minimum number of possible combinations of parameters or factors [1,2,3,11,12].

Taguchi recommends a loss function to measurement measure the performance characteristic deviating between experimental and the desired value.

Taguchi proposed optimization of process of product in three step approaches, like System design, Parameter design and Tolerance design. The parametric design is to optimize the settings of process parameters and improve the quality characteristic with insensitivity in noise factors [3].

Table 1: Taguchi DOE of L9 based on Orthogonal Array

Exp. No.	Control factors		Actual setting values	
	A	C	Spindle Speed (rpm)	Feed (mm/rev)
1	1	1	560	0.14
2	1	2		0.17
3	1	3		0.20
4	2	1	900	0.14
5	2	2		0.17
6	2	3		0.20
7	3	1	1250	0.14
8	3	2		0.17
9	3	3		0.20

According to the Taguchi quality design concept an L_9 orthogonal array has been used to determine the S/N ratio (dB). The statistical measure of performance called signal-to-noise (S/N) ratio developed by Taguchi is applied to determine the effects of individual parameters on surface roughness and to identify the best set of parameters for the hard-turning operations. The S/N equation depends on the optimization of the quality characteristics.

In this analysis, surface roughness is required to be minimum and so the smaller-is-better (for minimize) formula for S/N ratio is selected.

C. Analysis of Variance

ANOVA is used to investigate the significant effect of design parameters on the quality characteristic of the response and thereby finding the optimal parametric setting value that directly influence the response for determining the minimum cost at the optimal policy [2]. It also depicts the contribution of parameters on generating the required responses.

Two-Way ANOVA was used to determine the significances of the factors and their interaction using the formulae mentioned:

$$SS_{Total} = \sum X^2 - \frac{(\sum X)^2}{N} \text{ \& } DF = N - 1 \quad (1)$$

$$SS_{Between} = \frac{(\sum X_1)^2}{n_1} + \frac{(\sum X_2)^2}{n_2} + \dots + \frac{(\sum X_{AC})^2}{n_{AC}} - \frac{(\sum X)^2}{N} \quad (2)$$

$$SS_A = \sum \frac{(\sum \text{for each row})^2}{n \text{ for each row}} - \frac{(\sum X)^2}{N} \quad (3)$$

$$SS_C = \sum \frac{(\sum \text{for each column})^2}{n \text{ for each column}} - \frac{(\sum X)^2}{N} \quad (4)$$

$$SS_{Within} = SS_{Total} - SS_{Between} \quad (5)$$

$$\%Contribution = MS/MS_{Total} \quad (6)$$

Where 'SS' is sum of squares, 'DF' is degree of freedom, 'N' is total observations, 'n' is size of population.

D. Regression model

$$R_a = C * f^a * v^b \quad (7)$$

Where R_a is Average Surface Roughness (μm), v is the spindle speed (rpm) and f is the feed (mm/rev). C, a, b are model parameters to be estimated from experimental results. Converting the exponential form of surface roughness ' R_a ' to linear model with help of logarithmic transformation and modeled as

$$\log R_a = \log C + a * \log f + b * \log v \quad (8)$$

The proposed second order model developed from the above functional relationship is:

$$Y = \beta_0 x_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_1^2 + \beta_4 x_4^2 + \epsilon \quad (9)$$

Where Y is the true response of surface roughness on a logarithmic scale $x_0=1$ (dummy variable), x_1, x_2, x_3, x_4 are logarithmic transformations of feed and cutting speed respectively, while $\beta_0, \beta_1, \beta_2, \beta_4$ are the parameters to be estimated.

E. Experimentations setup

Work piece material of $\Phi 50\text{mm}$ and length 210mm was divided into 3 equal parts (i.e. 3 x 70mm). Basing on the Orthogonal Array of Taguchi DOE, combination of the feeds and speeds with constant depth of cut are generated as mentioned in table 1.

As the work surface is cylindrical, surface roughness was measured on the three diametrical end points and average of them was considered.

In this paper, 9 cutting experiments are done and Surface Roughness values were measured using surface roughness tester, as tabulated in the Table 2.

The surface roughness values are used to find the parametric Non-Linear regression equation basing on the least square method with help of commercially available data mining technique.

Table 2: Experimental values of Turning AISI 1040 using TiN-Al₂O₃-TiCN-TiN Carbide insert and HSS Tools

Exp No.	A: Speed (rpm)	C: Feed (mm/rev)	Carbide insert			HSS Tools		
			Surface Roughness Ra (microns)	Average Ra (microns)	S/N ratio	Surface Roughness Ra (microns)	Average Ra (microns)	S/N Ratio
1	1	1	2.80 2.82 2.81	2.81	-8.9741	4.48 4.50 4.46	4.48	-13.0256
2	1	2	3.13 3.11 3.12	3.13	-9.9109	4.53 4.54 4.52	4.53	-13.1220
3	1	3	3.46 3.52	3.46	-10.7815	4.61 4.59	4.61	-13.2678

			3.40			4.62		
4	2	1	1.45 1.42 1.48	1.45	-3.2274	4.40 4.42 4.44	4.42	-12.9085
5	2	2	1.53 1.55 1.51	1.53	-3.6938	4.45 4.43 4.46	4.45	-12.9607
6	2	3	2.12 2.15 2.09	2.12	-6.5267	4.53 4.53 4.54	4.53	-13.1284
7	3	1	0.87 0.85 0.89	0.87	1.2096	4.29 4.28 4.31	4.29	-12.6559
8	3	2	1.52 1.53 1.51	1.52	-3.6369	4.33 4.33 4.35	4.33	-12.7431
9	3	3	2.20 2.21 2.19	2.20	-6.8485	4.36 4.37 4.35	4.36	-12.7897

V. DATA ANALYSIS AND DISCUSSIONS

Table 3 and 5 present the ANOVA result of machining parameters as main effects on Surface Roughness generated with Carbide inserts and HSS tools, respectively. Table 4 and 6 present the ANOVA result of machining parameters as Interactions on Surface Roughness generated with Carbide inserts and HSS tools, respectively. Table(s) 3 and 5 indicates that the spindle speed is highly significant with 80% contribution. Table(s) 6 and 8 indicates the spindle speeds is highly significant and feeds is relatively less significant, while the interactions are relatively not significant.

Table 3: Two-Way ANOVA for CARBIDE Inserts: Roughness Vs SPEED, FEED Excluding Interactions

Source	Df	SS	MS	F	P	%Contribution & Significance	
A	2	13.9	6.95	283	0.00	80	Highly Significant (HS)
C	2	3.56	1.78	72.7	0.00	20	Significant (S)
Error	22	0.54	0.03				
Total	26	18.0				100	
S = 0.1566 R-Sq = 97.01% R-Sq(adj) = 96.46% F-Critical for Df (2,22) is 3.44							

Table 4: Two-Way ANOVA for CARBIDE Inserts: Roughness Vs SPEED, FEED including Interactions

Source	Df	SS	MS	F	P	%Contribution & Significance	
A	2	14	6.9	9478	0.00	78.5	HS
C	2	3.6	1.8	2430	0.00	20.0	HS
A*C	4	0.5	0.1	179	0.00	1.5	Not Significant (NS)
Error	18	0.0					
S = 0.02708 R-Sq = 99.93% R-Sq(adj) = 99.89% F-Critical for Df (2,18) is 3.55 and Df (4,18) is 2.93							

Table 5: Two-Way ANOVA for HSS: Roughness Vs SPEED, FEED Excluding Interactions

Source	Df	SS	MS	F	P	%Contribution & Significance	
A	2	0.20	0.10	267	0.00	79	Highly Significant (HS)
C	2	0.05	0.02	63	0.00	21	Significant (S)
Error	22	0.01	0.004				
Total	26	0.26					
S = 0.0195 R-Sq = 96.78% R-Sq(adj) = 96.20% F-Critical for Df (2,22) is 3.44							

Table 6: Two-Way ANOVA for HSS: Roughness Vs SPEED, FEED including Interactions

Source	Df	SS	MS	F	P	%Contribution & Significance	
A	2	0.20	0.10	488	0.00	77	HS
C	2	0.05	0.02	115	0.00	17	S
A*C	4	0.005	0.001	5.5	0.00	6	NS
Error	18	0.004					
S = 0.0144 R-Sq = 98.56% R-Sq(adj) = 97.92% F-Critical for Df (2,18) is 3.55 and Df (4,18) is 2.93							

A. Regression results analysis

A Non-Linear equation is generated and used to predict the regression constants and exponents. The regression equation of Surface Roughness generated as, as shown in table(s) 7 and 8 for Carbide and HSS tools respectively:

Table 7: Regression Analysis for Roughness with CARBIDE Inserts

Source	Df	SS	MS	F	P	F-critical	Remarks
Regression	2	14.9	7.47	58.5	0.00	3.40	S
Error	24	3.06	0.13				
S = 0.357 R-Sq = 83.0% R-Sq(adj) = 81.6% and Ra=8.68-0.012*A-21.16*B+5.39*10 ⁻⁶ *A2+105.55*B2							

Table 7: Regression Analysis for Roughness with CARBIDE Inserts

Source	Df	SS	MS	F	P	F-cri	Remarks
Regression	2	14.9	7.47	58.5	0.00	3.40	S
Error	24	3.06	0.13				
S = 0.357 R-Sq = 83.0% R-Sq(adj) = 81.6% and Ra=8.68-0.012*A-21.16*B+5.39*10 ⁻⁶ *A ² +105.55*B ²							

Table 8: Regression Analysis for Roughness with HSS Tools

Source	Df	SS	MS	F	P	F-cri	Remarks
Regression	2	0.24	0.12	198	0.00	3.4	S
Error	24	0.02	0.00				
S = 0.0247692 R-Sq = 94.3% R-Sq(adj)=93.8% Ra =4.58+0.00016*A-2.49*B-2.58*10 ⁻⁷ *A ² +12.35*B ²							

Table(s) 7 and 8 present the analysis of Roughness Regression models generated with roughness values with Carbide and HSS machining respectively and indicates that the model depicts a significance more than 95% confidence level ($P < 0.05$).

B. Confirmation experiments

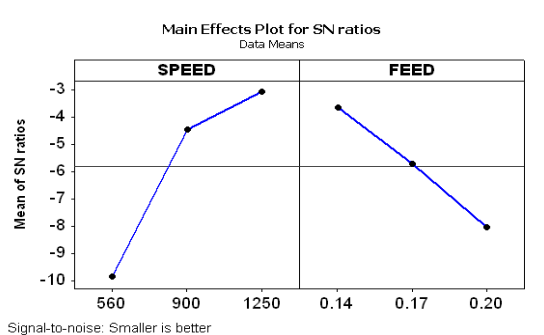
Table 9 shows the error determined using the experimental value and the regression equation(s) values. The results show the calculated error with maximum 8.55% and minimum 0.94% while machining with CARBIDE and maximum of 0.46% and minimum 0.03% while machining with HSS respectively.

Table 9: Confirmation tests and Foreseen results of Roughness With HSS Tools

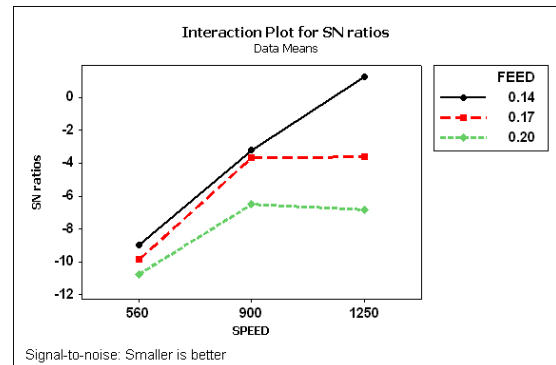
Exp. No.	Feed	Speed	Experimental Roughness	Predicted	Error %
5	0.17	900	4.45	4.45	0.03
7	0.14	1250	4.29	4.27	0.46
With Carbide Inserts					
5	0.17	900	1.53	1.54	0.94
9	0.2	1250	2.20	2.01	8.55

C. Discussions on graphs

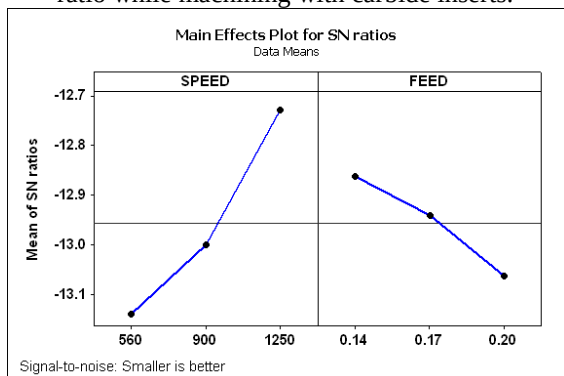
Graph(s) 1a, 1b, 2a and 2b interprets main effects plot and interaction plots based on SN ratios of Roughness while machining with CARBIDE and HSS respectively. Based on the smaller is better characteristic of S/N ratios, the graphs propose Highest spindle speed (1250rpm) and lowest value of feed (0.14mm/rev) as optimal combination should be selected (A3B1) for higher surface finish.



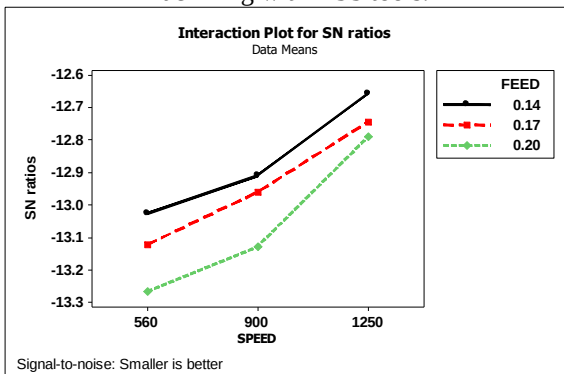
Graph 1a: Effect of main parameters on S/N ratio while machining with carbide inserts.



Graph 1b: Effect of Interaction of parameters on S/N ratio while machining with carbide inserts.

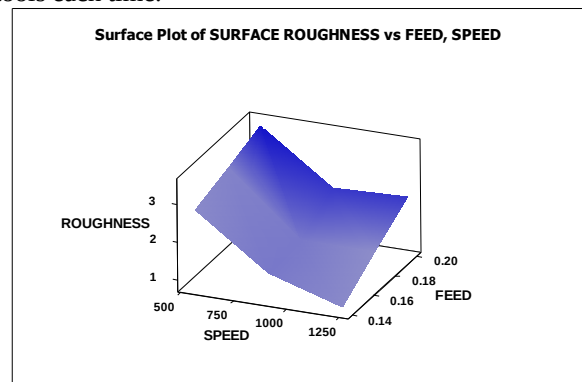


Graph 2a: Effect of main parameters on S/N ratio while machining with HSS tools.

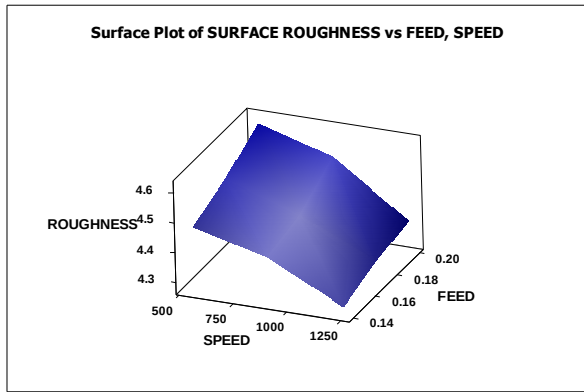


Graph 2b: Effect of Interaction of Parameters on S/N ratio while machining with HSS tools.

The optimum combination of spindle speed and feed gives a roughness of 0.87 μ m and 4.27 μ m for Carbide and HSS machining respectively, using new inserts and tools each time.



Graph 3a: Surface Plots of parameters on Roughness while machining with carbide.



Graph 3b: Surface Plots of parameters on Roughness while machining with HSS.

Graph(s) 3a and 3b predicts that the Higher the spindle speeds, lower the Surface Roughness values and Higher the feeds, higher the Surface Roughness values.

VI. CONCLUSIONS

The investigation of this study indicates that the optimum combination of machining parameters is A3B1 (i.e. Speed 1250RPM and Feed 0.14mm/rev).

The result graphs shows that the spindle speeds to be directly proportional and feeds to be indirectly proportional to the generated Surface Roughness values.

From ANOVA and %contribution evaluation, the spindle speeds seem to be very highly significant and predominant factor in producing the Surface Roughness while machining with both type of tools.

The experimental results conclude that they are very compromising and correlating with the regression model generated through nonlinear regression data mining technique by using MINITAB software. The confirmation tests show an error of maximum 0.46% and 8.55% while machining with HSS and Carbide tools respectively.

The regression models can be used to estimate the values of surface roughness at certain turning parameters (speed and feed). They are also useful in the selection of optimal combination of machining parameters for a required surface roughness.

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