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Optimization of Surface Finish in Orthogonal Turning of Al-Si Aluminium Alloy Using Taguchi Method

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ABSTRACT
This paper presents an experimental investigation of the optimization of surface roughness of Aluminium-Silicon (Al-Si) alloy in orthogonal turning using Taguchi Method. In manufacturing using machining operation, the surface finish of the machined product is a measure of quality and also reduces production cost. In order to obtain good surface finish from the products, the process parameters (cutting speed, feed rate and depth of cut) must be carefully selected during orthogonal turning. Machining is a manufacturing process whereby metals are shaped by way of chip removal in order to produce new components. This study investigates the effect of cutting parameters (cutting speed, feed rate and depth of cut) on surface roughness. An experiment was conducted using Taguchi Design of Experiment (DOE). Each machining parameters is considered at three levels. The experimental data was obtained after machining the Al-Si material with HSS cutting tool. The surface roughness was measured using TMR 120 surface roughness tester. MINITAB 16 software was used to analyse the data set so as to reduce manipulations and machining trials. The result of the analysis shows that cutting feed has the largest effect on the surface roughness followed by the depth of cut and the spindle speed has the smallest effect on the surface roughness. A regression equation was obtained for optimal surface roughness to be Ra = - 1.50 + 0.00142 Speed + 8.02 Feed rate + 1.60 Depth of cut.
Keywords: *cutting speed, depth of cut, feed rate, optimisation, surface roughness, Taguchi.*

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I. INTRODUCTION

The quality of surface finish is an important attribute that is used to determine and evaluate the quality of a product in machining operation Adeel et al. (2010). However, the study and optimization of surface roughness is not as easy as determining any other variable. The study of Surface Roughness is harder to achieve as it depends on both controllable and uncontrollable factors. The controllable variables include tool rake angle, feed rate, spindle speed, depth of cut etc. while wearing of tool, material friction, tool degradation etc. factors are much harder to control. Surface roughness of a machined product could affect several of the product's features such as surface friction, wearing, light reflection, heat transmission. Ability of distributing and holding a lubricant, coating, and resisting fatigue Sanchay et al. (2017)

Adedeji et al. (2020), worked on modelling and simulation of orthogonal metal cutting of Aluminium 6061-T6 using ANSYS 19.2 software to investigate the effects of depth of cut, cutting speed and tool rake face angle on cutting variables such as cutting forces, chip morphology, temperature and stress distributions using the Johnson-Cook and Johnson-Cook damage models.

Prajwalkumar M. Patil et al. (2015), observed and analyzed the effect of cutting parameters on the surface roughness and hardness. Taguchi method was analyzed by the authors in the optimization of cutting parameters. L9 orthogonal array was employed to carry out the analysis. The analysis of means (ANOM) and Analysis of variance (ANOVA) were carried out to determine the optimal parameters level and obtain level of importance of each parameter. From the ANOVA, the feed had maximum significance in case of Ra and Rz. Murat Sarikaya et al. (2014), used Taguchi design and Response Surface Methodology (RSM) Technique under Minimum Quantity Lubrication (MQL) for analyzing CNC turning parameters. The results were analyzed using 3D surface graphs, signal to noise ratios and main effect graphs of means. Also mathematical model output showed that the developed RSM model was statistically significant and suitable for all the cutting conditions because of higher R2 value. In modern manufacturing industries related to turning process, controlling and optimization of surface quality and material removal rate (MMR) are the most important performance and quality measures which are considered as the main response Sanjit et al. (2010).

Surface finish is an important parameter in manufacturing engineering. A characteristic can influence the performance of mechanical parts and production costs. Roughness plays an important role in determining how a real object will interact with its environment. Rough surfaces usually wear more quickly and have higher friction coefficient than smooth surfaces. Roughness is often a good predictor of the performance of a mechanical component, since irregularities in the surface may form nucleation sites for cracks and corrosion Kadirgama et al. (2008).

Various failures, sometimes catastrophic, leading to high costs, have been attributed to the surface finish of the components in question. For these reasons, there have been research developments with the objective of optimizing the cutting conditions to obtain a good surface finish Ramesh and Elvin (2011). Determination of optimal cutting conditions for surface finish obtained in turning using the techniques of Taguchi and a correlation between cutting velocity, feed and depth of cut with the roughness evaluating parameters Ra and Rt was established using multiple linear regression by Davim (2001). Also, John et al. (2001) demonstrated a systematic procedure of using Taguchi parameter design in process control in order to identify the optimum surface roughness performance with a particular combination of cutting parameters in an end milling operation. Kopac et al. (2002) described the machining parameters influence and levels that provide sufficient robustness of the machining process towards the achievement of the desired surface roughness for cold pre-formed steel workpieces in fine turning. The objective of this research is to optimize surface roughness during orthogonal turning of Al-Si with the use of Taguchi techniques. Adedeji and Lamidi (2021) studied helps to determine the best process parameter (cutting speed, feed rate and depth of cut) that will minimise the effect of noise factors on the response (surface roughness) using Taguchi Design of Experiment (DOE).

II. METHODS AND MATERIALS

2.1 Workpiece Material

Aluminium alloy Al-Si has been selected for the experimental investigation. Al-Si contains aluminum and silicon as the main alloying element while other alloying elements are copper, magnesium, manganese, calcium, silicon, tin, zinc and iron. The most important cast aluminum alloy system is Al-Si, where the high level of silicon contributes to give good casting characteristics. These alloys contains silicon (89.79%) and aluminum (8.23%) as the main alloying ingredients but contain very little copper or magnesium. Their main use stems from their lower melting points which confers good casting qualities.

2.2 Chemical composition of Aluminium-Silicon Alloy

Table 1: Percentage composition of the elements

Elements	% Composition
Aluminium	89.79
Silicon	8.23
Calcium	1.24
Magnesium	0.38
Copper	< 0.001
Zinc	0.01
Iron	0.18
Sodium	0.01
Manganese	0.01
Tin	0.14

2.3 Experimental area

The experiment was conducted in the machine workshop of Mechanical Engineering Department, Lagos State University Epe Campus and Lagos State Polytechnic Ikorodu, Southwest Region of Nigeria.

2.4 Equipment and materials required for the study

The materials used for this research work are Colchester l880 lathe machine with rated power of 28kVA, High Speed Steel (HSS) cutting tools, hacksaw, vernier caliper, meter rule, Aluminum-Silicon (Al-Si) alloy, TMR 120 surface roughness tester, The purchase of Al-Si aluminium alloy was done at available market within Nigeria precisely from OwodeOnirin market, Lagos.

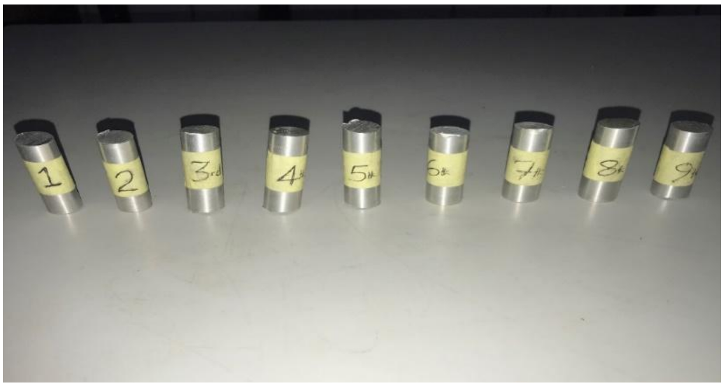

Fig. 1: Photograph of sample specimen of Al-Si Aluminium Alloy. (Adedeji and Lamidi 2021)

2.5 Experimental Flow chart/Procedure

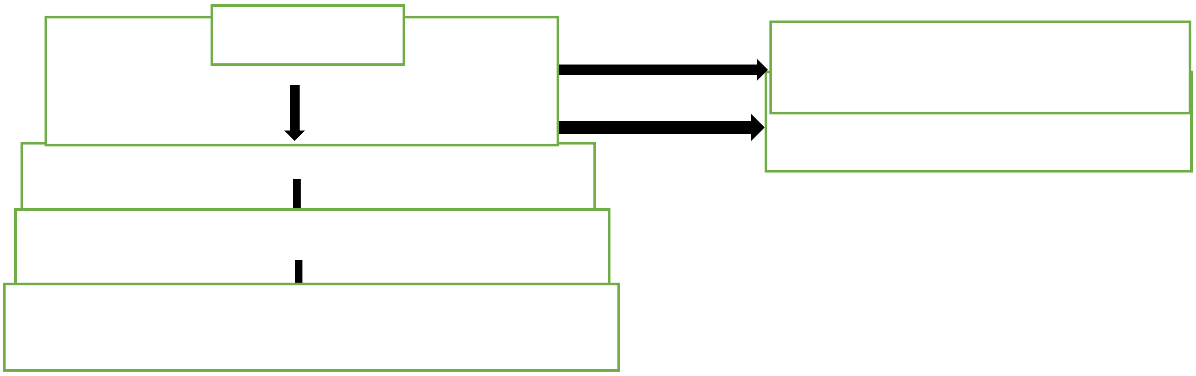

Fig 2. Organogram showing sequence of operation flow

2.6 Process parameters and their limits

Table 2: Process Parameter Levels

Process Variable	Unit	Level 1	Level 2	Level 3
Cutting Speed	m/min.	350	470	625
Feed rate	mm/rev.	0.2	0.225	0.25
Depth of cut	mm	0.2	0.4	0.6

2.7 Detailed experimental procedure

A lathe machine Colchester 1800 with rated power of 28kVA was used for the machining trial and for all the experimental works. The Lathe was checked and prepared ready for performing the machining operations. The Al-Si aluminium rod was cut by hacksaw and initial turning operation was performed on the lathe to get desired dimension of the workpieces (length–50mm; diameter–20mm). Twenty seven numbers of samples of same material and same dimension have been made. The length of each specimen is 50mm and has a diameter of 20mm. Weight of each specimen was measured by the high precision digital balance meter before machining. Straight turning operation was performed on the specimens in various cutting environments involving various combinations of process control parameters like: cutting speed (350, 470 and 625 m/min), feed (0.2, 0.225, and 0.25 mm/rev) and depth of cut (0.2, 0.4, and 0.6 mm). After machining the surface roughness of the work piece at different cutting conditions were measured using TMR 120 surface roughness tester.

III. RESULTS AND DISCUSSIONS

MINITAB 16 software was used to perform the experimental design and explore to analyse the main effects of plots, signal to noise (S/N) ratio, regression, mean and ANOVA in order to achieve the optimization analysis for surface roughness. These experimental results were explored in the determination of direct effect of each of the machining parameters on the response.

3.1 Regression analysis

It is used to investigate and model the relationship between a response variable and one or more predictors. Minitab provides least square, partial least square, and logistic regression procedures.

Table 3: Table of Results

Experiment no.	Cutting Speed (m/min)	Feed rate (mm/rev)	Depth of cut (mm)	Ra (µm)
1	350	0.2	0.2	0.50
2	350	0.2	0.2	0.52
3	350	0.2	0.2	0.55
4	350	0.225	0.4	1.85
5	350	0.225	0.4	1.89
6	350	0.225	0.4	1.82
7	350	0.25	0.6	1.31
8	350	0.25	0.6	1.32
9	350	0.25	0.6	1.30
10	470	0.2	0.4	1.43
11	470	0.2	0.4	1.40
12	470	0.2	0.4	1.42
13	470	0.225	0.6	2.65
14	470	0.225	0.6	2.77
15	470	0.225	0.6	2.87
16	470	0.25	0.2	1.90
17	470	0.25	0.2	1.75
18	470	0.25	0.2	1.62
19	625	0.2	0.6	1.60
20	625	0.2	0.6	1.65
21	625	0.2	0.6	1.80
22	625	0.225	0.2	1.69
23	625	0.225	0.2	1.59
24	625	0.225	0.2	1.40
25	625	0.25	0.4	1.70
26	625	0.25	0.4	1.84
27	625	0.25	0.4	1.74

3.1 Interactive effect of machining parameter on Surface roughness

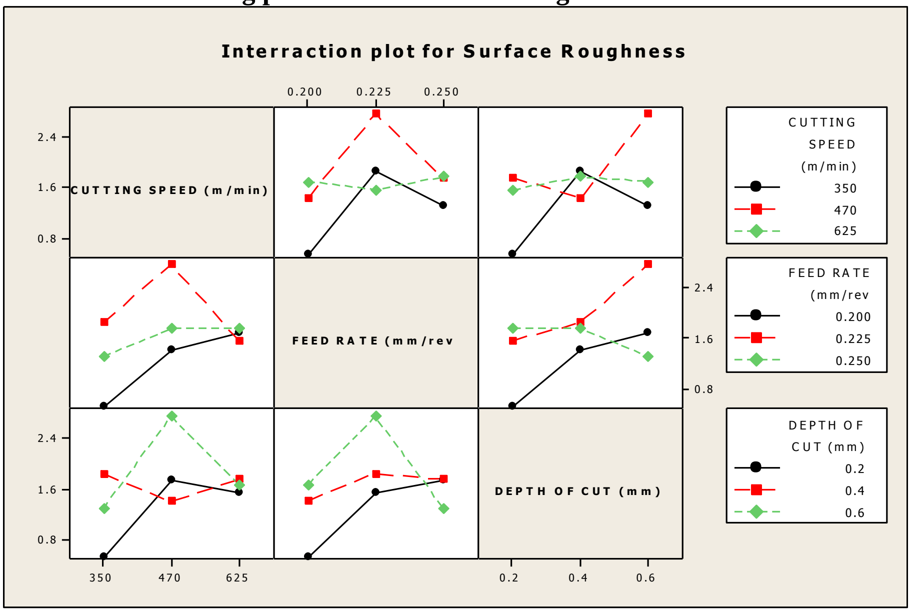

Figure 3: Interaction plot for surface roughness

The results above display full interaction plot matrix for the surface roughness. The interaction plot as displayed above shows the mean surface roughness versus cutting speed for each of the three factors. The nonparallel lines on the interaction plot indicates that the relationship between surface roughness and the three variables, feed rate and depth of cut depends on cutting speed. This plot displays means for the levels of one factor on the x-axis and a separate line for each level of another factor. This combines all the effects of all the independent variables in a single plot as shown below. It can be seen that there are significant interactions and thus significant effects between the cutting parameters and the surface roughness.

Table 4: Main effect plot analysis for signal-to-noise (S/N) ratio and Surface roughness

Process parameters	Level	Response Value
Cutting speed	1	350 m/min)
Feed rate	1	(0.200 mm/rev)
Depth of cut	2	(0.4 mm)

Table 4: Response Table for Signal to Noise Ratios (Larger is better)

Table 5: **Dynamic Response**

Level	**Cutting Speed (m/min.)**	**Feed rate (mm/rev.)**	**Depth of cut (mm)**
1	25.85	23.95	21.42
2	19.21	17.61	24.83
3	20.52	24.03	19.33
Delta	6.64	6.42	5.49
Rank	1	2	3

3.4 Regression Analysis (Ra) versus cutting speed, feed rate and depth of cut.

Ra = **-** 1.50 + 0.00142 Speed + 8.02 Feed rate + 1.60 Depth of cut.

Table 6: ANOVA table for Ra.

Predictor	**Coef SE**	**Coef**	**T**	**P**
Constant	-1.505	1.101	-1.37	0.185
Cutting speed	0.0014246	0.0008074	1.76	0.091
Feed rate	8.022	4.453	1.80	0.085
Depth of cut	1.5972	0.5566	2.87	0.009

S = 0.472298 R-Sq = 38.8% R-Sq(adj) = 30.8%

3.5 Table 7: Analysis of Variance on Ra.

Source	**df**	**ss**	**ms**	**f**	**P**
Regression	3	9587.60	3195.87	116.323	0.0000000
Residual error	23	386.73	386.73	14.076	0.0010398
Total	26	4637.85	4637.85	168.808	_

Analysis of Variance table

3.5.1 Table 8: **Sequencial sum of squares**

Source	**df**	**Seq ss**
Speed	1	386.7
Feed	1	4637.9
DOC	1	4563.0

Table 8

Table 9: Unusual Observation

Observation	**Speed**	**Ra**	**Fit**	**SE fit**	**Residual**	**St resid**
15	470	2.87	1.9280	0.1440	0.9420	2.09R

Table 9. R denotes observation with large, standardised residual

3.7 Residual plot for surface roughness

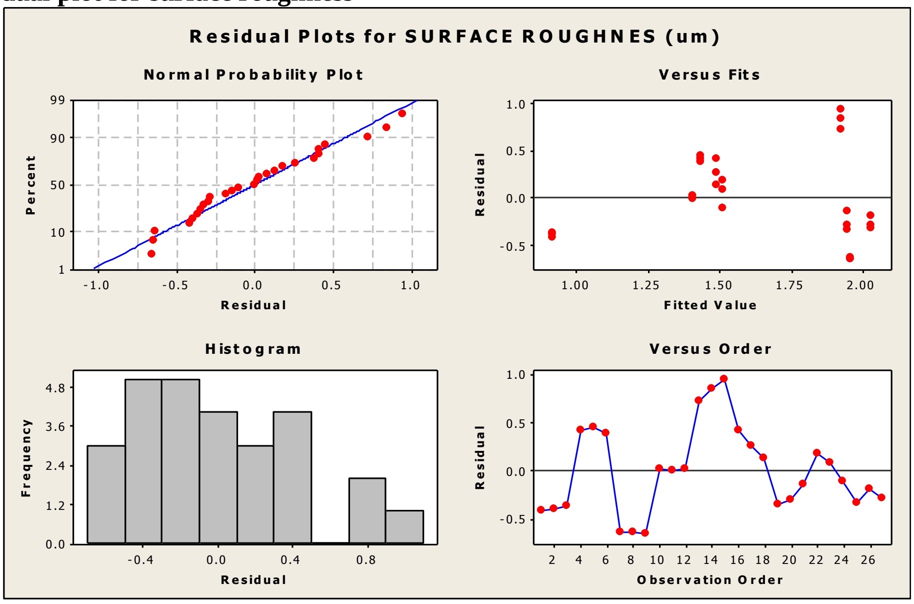

Fig. 4: Residual plots for surface roughness

From fig. 4. the histogram shows two potential outlier in the data. The normal probability plot shows an approximately linear pattern consistent over a wide range. However, there were good fit between the outlier observed. The plot of residual versus the fitted values shows a random pattern, which suggests that the residuals have constant variance. This plot also shows two potential outlier.

The residuals versus order plot is used to verify the assumption that the residuals are independent from one another. Independent residuals show no trends or pattern when displayed in time order. Patterns in the points may indicate that residuals near each other may be correlated, and thus, not independent.

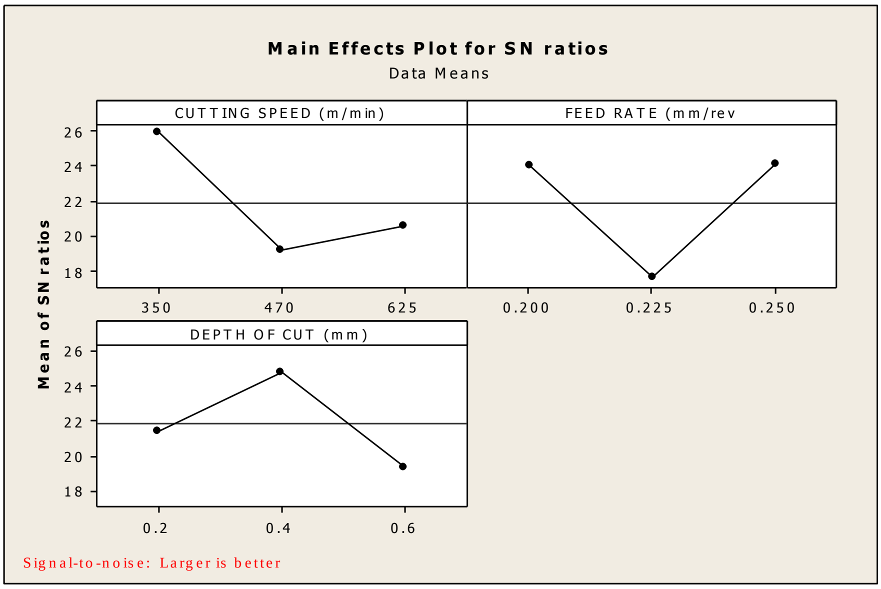

Fig. 5: Main effects plots for signal-to-noise (S/N) ratio

From fig.5 above, the effect of each of this factor is calculated by determining the range (delta). As shown in table 3.4 the S/N response table and response table for means. The cutting feed has the largest effect on the surface roughness followed by the depth of cut and the spindle speed has the smallest effect on the surface roughness. This agrees with Kaladhar *et al*. (2012) which had earlier discovered that depths of cut and feed rate are the significant factors on surface roughness. This analysis was made with the aid of MINITAB16 software package. From results table 4,5,6,7,8 and 9 and Figure 4 and 5, the main effect plots are discussed as follows; It shows the variation of individual response variable with three parameters i.e cutting speed, feed rate and depth of cut separately. Minitab creates the main effects plot by plotting the means for each variable parameters. A line connects the points for each variable, the x-axis indicates the factor while the y-axis indicates the response. In the plots, the X-axis indicates the value of each process parameter, and the Y-axis indicates the response value. Horizontal lines indicate the mean value of the response. The main effect plots are used to determine optimal design conditions, to obtain optimum material removal rate. According to the main effect plots shown above, the optimal condition for surface roughness are shown in table 4 above.

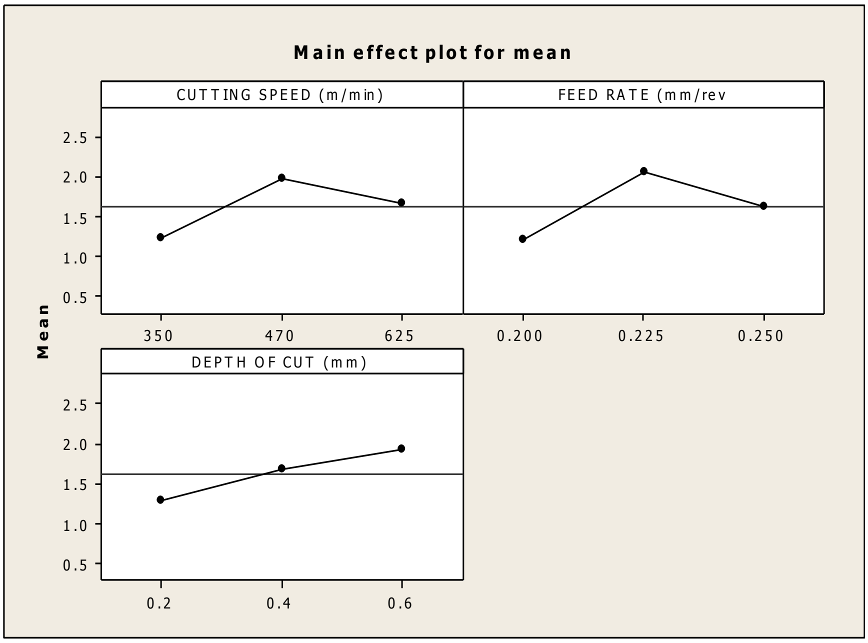

Fig. 6: S/N ratio main effect plot for surface roughness

The figure above shows the effect of each of factor calculated by determining the range (delta). As shown in table 4.3b the S/N response table and response table for means. The cutting feed has the largest effect on the surface roughness followed by the depth of cut and the spindle speed has the smallest effect on the surface roughness. This agrees with Kaladhar *et al*. (2012) which had earlier discovered that depths of cut and feed rate are the significant factors on surface roughness. This analysis was made with the aid of MINITAB16 software package. From results table 4.3a, 4.3b and Figure 4.6a and 4.6b, the main effect plots are discussed as follows; It shows the variation of individual response variable with three parameters i.e cutting speed, feed rate and depth of cut separately. Minitab creates the main effects plot by plotting the means for each variable parameters. A line connects the points for each variable, the x-axis indicates the factor while the y-axis indicates the response. In the plots, the X-axis indicates the value of each process parameter, and the Y-axis indicates the response value. Horizontal lines indicate the mean value of the response. The main effect plots are used to determine optimal design conditions, to obtain optimum material removal rate. According to the main effect plots shown above, the optimal condition for surface roughness is 350m/min, o.200mm/rev and 0.4mm for cutting speed, feed rate and depth of cut respectively.

IV. CONCLUSION

The regression equation is

1. Ra = **-** 1.50 + 0.00142 Speed + 8.02 Feed rate + 1.60 Depth of cut.

This implies that the depth of cut showed a very weak regression coefficient for surface roughness while both cutting speed and feed rate showed a very strong regression against surface roughness.

2. From the graphical analysis it can be depicted that the cutting feed has the largest effect on the surface roughness followed by the depth of cut and the cutting speed has the least effect on the surface roughness.

3. The optimal condition for surface roughness is 350m/min, 0.200mm/rev and 0.4mm for cutting speed, feed rate and depth of cut respectively.

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