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Prediction of Surface Roughness in CNC Turning of Aluminum 6061 Using Taguchi Method and ANOVA for the Effect of Tool Geometry

Ranganath M Singari[1], Vipin[2], Sanchay Gupta[3]

[1,2,3](Department of Mechanical, Production and Industrial Engineering,Delhi Technological University, Delhi, India)
[1] ranganathdce@gmail.com

Abstarct : *Surface Roughness is one of the major attributes that define and evaluate the quality characteristics of the product after it is machined. Consequently, it is an important criterion of determining the quality of the product post machining processes and analysis of the response becomes important. The paper delves the parameters that affect the surface roughness in CNC Turning of Aluminum 6061.The process factors taken are rake angle, nose radius, cutting speed, feed rate and depth of cut and the analysis of influence of these parameters is carried out using Taguchi Method. An L27 orthogonal array has been employed to carry out the analysis and the influence of the factors are studied using Analysis of Variance (ANOVA) method. Feed Rate is found to be the most influential and significant factor followed by rake angle of the tool.*

Keywords: *Surface Roughness, CNC Turning, Taguchi Method, Orthogonal Array, ANOVA, rake angle*

I. INTRODUCTION

Surface roughness is an important characteristic used to determine and evaluate the quality of a turned product. However, the study and optimization of surface roughness is not as easy as determining any other variation. The study of Surface Roughness is harder to achieve as it depends on various variables. These variables are both controllable and uncontrollable. The controllable variables being tool rake angle, feed rate, spindle speed, depth of cut etc. while factors such as wearing of tool, material friction, tool degradation 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 [1]. Thus, achieving an optimal roughness response has become vital for industries to improve their quality and merit. Identifying the most influential and important parameter allows proper selection of tool material that prolongs the life of tool and minimizes the surface roughness. Consequently, A recent advent of Design of Experiments has given vent to various methods such as Taguchi Method, Response Surface Methodology, etc., that have not only allowed scholars and industrialists to efficiently organize the process of optimizing roughness but has also given way to several techniques to reduce the number of trials that have to be carried out to obtain optimal response. The Taguchi Method is a statistical tool that allows creation of a design by choosing the most optimal path in an operation environment. Since noise factors are also present in the process that cannot be controlled, this method identifies the values of controllable factors that minimizes the effect of noise factors and provide an optimal response. Thus design of experiments by Taguchi method was adopted for analyzing the surface roughness and Analysis of Variance (ANOVA) was used for finding the most significant factor that affects the surface response.

Prajwalkumar M. Patil et al. [7] 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. Ranganath M S et al. [15] developed a prediction model of surface roughness for turning EN-8 steel with uncoated carbide inserts using Response Surface Methodology (RSM). A multiple regression model was developed in the form of correlating dependent parameter surface roughness with cutting speed, feed rate and depth of cut, in a turning process. The Box Behnken Design was used to plan the experiment. The Analysis of variance (ANOVA) was done to test for significance of regression model. The control parameter of cutting speed was found out to have the strongest effect on the surface roughness among the selected parameters; and varied inversely with response. Also surface Roughness was inversely proportional to depth of cut. Murat Sarikaya et al. [5] used Taguchi design and RSM Technique under 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 R^2 value. Ranganath M S et al. [12] presented a paper on analysis of the effect of the cutting speed, feed rate and depth of cut on surface roughness.

The author employed an L27 orthogonal array to carry out the analysis. The ANOVA values proved that speed is the most significant factor, the next significant factor was depth of cut followed by feed. The response tables for S/N ratios and the means showed that feed is the dominant factor followed by depth of cut and speed. It was concluded that increase in cutting speed decreases the surface up to a certain level but as speed increases beyond a certain level the surface roughness increases. The optimal combination of process parameters for the work with regard to minimum surface roughness were speed at 1900 rpm, depth of cut 0.25 mm and feed of 0.12 mm/rev. Ilhan Asiltürk et al. [4] used the Taguchi method and L9 orthogonal array were used to reduce number of the experiments. Analysis of Variance (ANOVA) was applied to investigate effects of cutting speed, feed rate and depth of cut on surface roughness. Results indicated that the feed rate had the most significant effect on Ra and Rz. The effects of two factor interactions of the feed rate-cutting speed and depth of cut-cutting speed appeared to be important. Chinnasamy Natarajan et al. [2] predicted and analyzed surface roughness factors of a non-ferrous material using Artificial Neural Network (ANN). A model was developed to predict the surface roughness of material (Brass C26000) through Artificial Neural Networks technique by utilizing feed-forward back propagation training algorithm using Matlab (2009a) software for the data obtained. As the spindle speed increases, for lower feed rates, the surface roughness decreases, for higher feed rates, the surface roughness changes considerably. The depth of cut influences the surface roughness considerably for a given feed rate. The increase in feed rate causes the surface roughness to increase and then decrease. For lower depth of cut, surface roughness decreases and then increases.

This paper presents the experimental approach for studying the effects of machining parameters on the surface roughness of the machined work-piece. The experimentation produced strong interactions between the various control factors. The analysis of variance (ANOVA) technique and the study of F-test statistics revealed strong interactions between the tool geometry and the various turning parameters undertaken. For different levels of the factors, different output values of surface roughness were obtained. The most influential and significant interactions were obtained between the tool geometry and cutting parameters. A systematic and organized study of the response values and the control factors in the experiment were tabulated for the design table with maximum utility of the resources.

II. TAGUCHI METHOD

Taguchi Method is an important tool for robust design based on Orthogonal Array which gives much reduced variance for the experiments with the optimum setting of the control parameters. Taguchi method provides a way of developing a robust design that reduces the number of experimentations by creating a design table of the levels for the control factors. The inherent principle of orthogonality in the technique provides a simple, effective and systematic qualitative optimal design to a lower relative cost. Taguchi designs estimate the effects of factors on the response mean and variation. An orthogonal array means the design is balanced so that the factor levels are weighted equally. Because of this, each factor can be assessed independently of all the other factors, so the effect of one factor does not affect the estimation of a different factor. This reduces the time and cost associated with the experiment when fractionated designs are used. In this paper Taguchi approach is used to study and analyze the effect of control parameters viz. rake angle, nose radius, cutting speed, feed rate and depth of cut on the roughness of Aluminum 6061 using cemented carbide tool inserts in CNC turning to achieve optimal setting. To find the most influential and significant factor Analysis of variance (ANOVA) is used by fitting a general linear model. The steps involved in Taguchi technique are:

1. Determination of main function to be optimised, side effects and failure mode.
2. Determination of noise factor, testing condition and quality characteristics.
3. Determination of the control factor and their levels.
4. Choosing the orthogonal array and matrix experiment and conducting the matrix experiment.
5. Carrying out the analysis of the data and predicting the optimum level and performance.
6. Performing the verification experiment and planning the future action.

III. EXPERIMENTAL SETUP

CNC Lathe

The entire turning was carried out on CNC Lathe LMW LL20TL3 which consists of the machining unit with a three jaw self-centering independent chuck and a computer numerically controlled tool slide containing 8 tool posts. The tool post assembly can move in x and z directions where x axis represents the movement in vertical direction which provides the depth of cut. The movement in z direction represents vertical displacement of the tool post assembly and is responsible for the feed of the tool to the work piece and also gives the location of the tool slide. The offset or the zero with respect to the work-piece, in both the x and z directions, is defined and the commands for the turning program are provided in the form of a program which is fed into the system. The machine is also provided with a automatic lubrication motor for its slides.

Cutting Tool material

Cemented Carbide Insert type Tools were used as the cutting tool in the turning operation. The Carbide cutting tool provided with the CNC lathe Trainer was a 30 mm square tool with 60 mm length having the same tool angles as for a normal turning tool. The tool used was cemented carbide insert type. The geometry of tool is: Rake angle 60(+ve), 50 (+ve) clearance angle, 600 (+ve) major cutting edge angle, 600 (+ve) included angle and 00 cutting edge inclination angle [8]. All the three elements-tungsten, molybdenum and cobalt help in achieving high hot hardness; the first two do so by forming complex carbides and the cobalt forms an alloy by going into solid solution in the ferrite matrix and thus raising the recrystallization temperature [8]. Vanadium in high speed steels increases the wear resistance of tool at all operating temperatures. Vanadium also helps to inhibit grain growth at the high temperatures required in heat treatment [8].

Work piece Material

Industry grade Aluminium 6061 was used as the work-piece material for the turning operation. Standardized material was selected to ensure consistency of the alloy, and is a common wrought alloy used in industries. Aluminum 6061 marks as one of the most extensively used aluminium in the series 6000. This structural alloy is one of the most versatile of the heat-treatable alloys, is popular for medium to high strength requirements and has good toughness characteristics. Several applications of this structural alloy range from transportation components to machinery and equipment applications to recreation products and consumer durables. It is also widely used in turning processes for producing various automotive components.

It has excellent atmospheric corrosion resistance to atmospheric conditions and sea water. This alloy also offers good finishing characteristics and responds well to anodizing. Alloy 6061 can be easily welded and joined by various commercial methods. Alloy 6061 has adequate machinability characteristics in the heat-treated condition in screw machine applications. The control inputs were fed in the form of part program including dimensions of the work piece, cutting parameters viz., depth of cut in mm, feed rate and the Speed which was available from 50-3500 rpm and feed in mm/min.

The elemental composition of the aluminium 6061 alloy is given in table 1.

Table 1: Elemental Composition of work-piece

Composition	**% weight**
Magnesium (Mg)	0.8 to 1.2
Silicon (Si)	0.4 to 0.8
Iron (Fe)	0 to 0.7
Copper (Cu)	0.15 to 0.4
Chromium (Cr)	0.04 to 0.35
Zinc (Zn)	0 to 0.25
Manganese (Mn)	0 to 0.15
Titanium (Ti)	0 to 0.15
Residuals	0 to 0.15

IV. EXPERIMENTATION AND ANALYSIS

Table 2 gives the various control factors taken and the subsequent levels defined for the parameters during the experiment. The first column specifies the codes assigned to each factors during the analysis, the second column names the corresponding factor for the code while the last three columns instantiate the three levels specified for each control factor.

Table 2: Cutting parameters and levels

Code	**Cutting Parameter**	**Level 1**	**Level 2**	**Level 3**
A	Rake Angle	16	18	20
B	Nose Radius	0.4	0.8	1.2
C	Cutting Speed (rpm)	175	225	275
D	Feed Rate (mm/rev)	0.05	0.10	0.15
E	Depth of Cut (mm)	0.1	0.2	0.3

The surface roughness of the machined surface has been measured Taylor Hobson Tally surf instrument, Surtronic 3, is a portable, self-contained instrument for the measurement of surface texture and is suitable for use in both the workshop and laboratory. The evaluation of parameters and other functions of the instrument are microprocessor based. The measurement values of surface texture of the work-piece are displayed on the LCD screen or the output can be further produced by connected the tally surf to the computer.

Surface Roughness being a dependent variable has been analyzed by designing an L27 orthogonal array. Table 3 shows a standard L27 (3^5) orthogonal array of Taguchi design with experimental results and various levels of control factors.

The objective of the present work is to minimise the surface roughness of the machined work-piece, thus 'Smaller is better' type classification of Taguchi technique for analysing surface roughness is exploited. The main effects plot for means is given in fig.1. They depict the variation of individual response with the five control parameters viz., rake angle, nose radius, cutting speed, feed rate and depth of cut. The value of each process parameter and the response value are represented by the x and y-axis respectively. The central horizontal line indicates the mean value of the surface response. The subsequent plot gives information on the individual dependency of response on each control parameter and is used to determine the optimal design for experiments to minimise surface roughness.

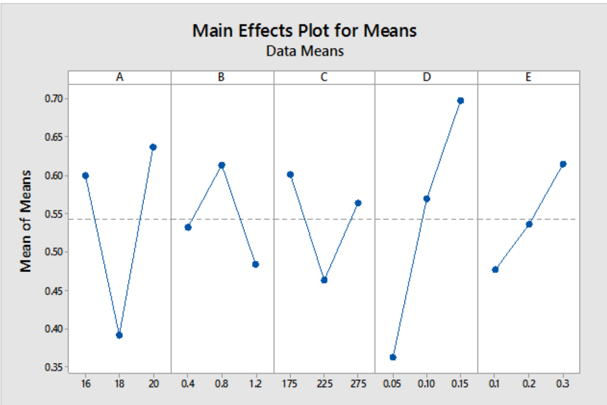

Figure 1: Main Effect Plot for Means

Table 3: Design Table and Response readings

Expt No.	Control Factors A	B	C	D	E	Ra (μm) Mean	S/N Ratio
1	1	1	1	1	1	0.42	7.5350
2	1	1	1	1	2	0.47	6.5580
3	1	1	1	1	3	0.51	5.8486
4	1	2	2	2	1	0.57	4.8825
5	1	2	2	2	2	0.62	4.1522
6	1	2	2	2	3	0.66	3.6091
7	1	3	3	3	1	0.65	3.7417
8	1	3	3	3	2	0.71	2.9748
9	1	3	3	3	3	0.79	2.0475
10	2	1	2	3	1	0.42	7.5350
11	2	1	2	3	2	0.45	6.9357
12	2	1	2	3	3	0.5	6.0206
13	2	2	3	1	1	0.26	11.700
14	2	2	3	1	2	0.31	10.172
15	2	2	3	1	3	0.34	9.3704
16	2	3	1	2	1	0.36	8.8739
17	2	3	1	2	2	0.41	7.7443
18	2	3	1	2	3	0.48	6.3752
19	3	1	3	2	1	0.6	4.4370
20	3	1	3	2	2	0.68	3.3498
21	3	1	3	2	3	0.74	2.6154
22	3	2	1	3	1	0.75	2.4988
23	3	2	1	3	2	0.87	1.2096
24	3	2	1	3	3	1.14	-1.138
25	3	3	2	1	1	0.27	11.372
26	3	3	2	1	2	0.31	10.172
27	3	3	2	1	3	0.37	8.6360

As is evident from the graph, since the ordinates represent the measured response values and abscissa denotes the various levels for the variables, surface roughness is minimum for rake angle (A) at level 2 (18), nose radius (B) at level 3 (1.2), cutting speed (C) at level 2 (225 rpm), feed rate (D) at level 1 (0.1 mm/rev) and depth of cut (E) at level 1 (0.1 mm). Table 4 is the response table for means and gives the ranking of various parameters as achieved by Taguchi analysis.

Main effects plot for S/N ratio of surface roughness for the data means is as depicted in fig. 2. The S/N ratio plot provides the information on degree of performance of the control parameters in the presence of the Noise factors. The aim of using this plot is to develop a product insensitive to the variance factor. Since the effect of noise should be minimum on the design parameters, the control factor with the maximum signal to noise ratio finds the optimal value. Thus, the ideal conditions for minimum Surface Roughness as depicted by the plot is level 2 (18) of rake angle (A), level 3 (1.2) of nose radius (B), level 2 (225 rpm) of cutting speed (C), level 1 (0.05 mm/rev) of feed rate, level 1 (0.1 mm) of depth of cut.

Table 4: Response table for Means

Level	A	B	C	D	E
1	0.600000	0.5322	0.6011	0.3622	0.4778
2	0.392200	0.6133	0.4633	0.5689	0.5367
3	0.636700	0.4833	0.5644	0.6978	0.6144
Delta	0.244400	0.1300	0.1378	0.3356	0.1367
Rank	2	5	3	1	4

Table 5 is the response table for S/N ratio and gives the ranking of various parameters as achieved by Taguchi analysis on the basis of SN ratio.

Table 5: Response table for S/N ratio

Level	A	B	C	D	E
1	4.594	5.648	5.056	9.041	6.953
2	8.303	5.162	7.035	5.115	5.919
3	4.795	6.882	5.601	3.536	4.821
Delta	3.709	1.720	1.979	5.505	2.133
Rank	2	5	4	1	3

Regression Equation:
Roughness = 0.037 + 0.0092 rake angle - 0.0611 nose radius - 0.000367 cutting speed + 3.356 feed rate + 0.683 depth of cut

The purpose of the analysis of variance (ANOVA) is to investigate which design parameter significantly affects the surface roughness [18]. A better feel for the relative effect of the different factors can be obtained by the decomposition of the variance, which is commonly known as analysis of variance (ANOVA) [7]. ANOVA and the F-test are applied to analyze the experimental data. ANOVA table shows that the percentage contribution of feed Rate is Maximum followed by rake angle. The most significant control parameter is feed rate and the second most significant factor is rake angle. The significance of other three factors is similar and much lower.

Table 6: Analysis of Variance

Source	DF	Adj	SS	Adj	MS
A	2	0.31281	0.156404	59.66	0.000
B	2	0.07761	0.038804	14.80	0.000
C	2	0.09165	0.045826	17.48	0.000
D	2	0.51576	0.257881	98.36	0.000
E	2	0.08459	0.042293	16.13	0.000
Error	16	0.04195	0.002622		
Total	26	1.12436			

Table 7: Model Summary

S	R-sq	R-sq (adj)	R-sq (pred)
0.0512031	96.27%	93.94%	89.38%

The interaction plots for mean are depicted in fig. 3. Fig.4 gives the interaction plot for S/N for the controlling factors.

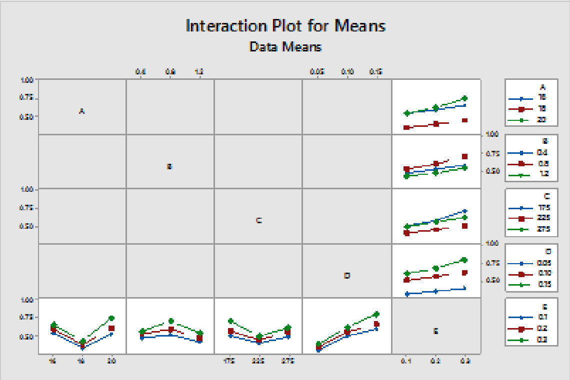

Figure3:Interaction plot for means

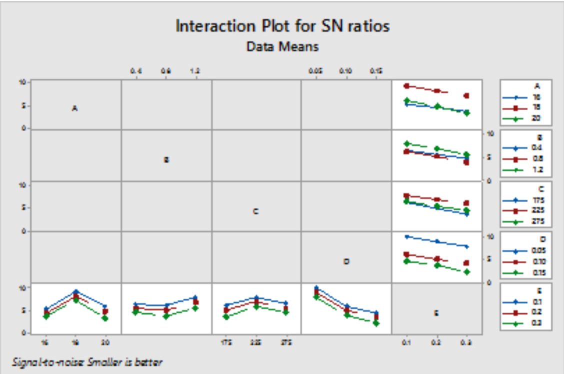

Figure 4: Interaction plot for SN ratio

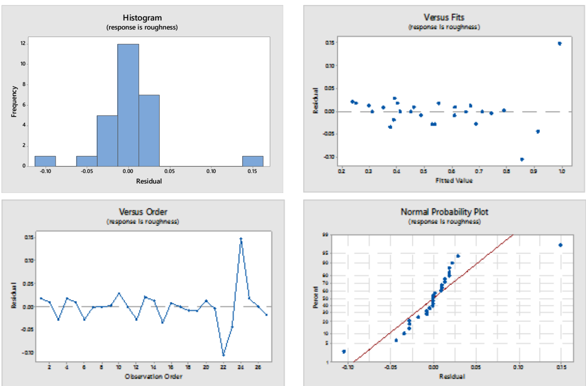

Figure 5: Residuals plot for mean

The diagnostic checking has been performed through residual analysis for the developed model. The Residual plots for surface roughness are shown in Fig.5. These fall on a straight line implying that errors are distributed normally. From figure 5 it can be further concluded that all the values are within the control range, indicating that there is no obvious pattern and unusual structure and also the residual analysis does not indicate any model inadequacy. The four plots shown in the fig. 5 are residual versus fits plot, residual as a plot of frequency (histogram), Residuals versus order graph and the normal probability plot.

V. CONCLUSIONS

The following are the conclusions drawn based on the experimental investigation conducted at three levels of the five turning parameters by employing Taguchi technique to determine the optimal level of the factors.

- From the data collection and the subsequent analysis, it is found that increase in feed rate increases surface roughness and the finish becomes poor. Hence lower the feed rate, higher is the surface finish.
- The surface roughness first decreases with the rake angle and the minimum surface roughness is achieved at the second level (18) of the rake angle. Roughness then increases from second level to the third level and hence the optimal surface finsh is achieved at the second level of the rake angle.
- The optimal combination of control variables for minimum Surface Roughness is level 2 (18) of rake angle (A), level 3 (1.2) of nose radius (B), level 2 (225 rpm) of cutting speed (C), level 1 (0.05 mm/rev) of feed rate, level 1 (0.1 mm) of depth of cut.
- ANOVA table and F-test of the variables show that the feed rate is the most dominant factor with the highest percentage contribution followed by the rake angle. The other three factors namely nose radius, cutting speed and the depth of cut have similar and much lower contribution.
- Taguchi gives systematic simple approach and an efficient robust design method for the optimum operating conditions.

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