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ANALYSIS & OPTIMIZATION OF PROCESS PARAMETERS IN CNC TURNING FOR MINIMIZING SURFACE ROUGHNESS

Vikas Bohra [1], Dr. Pankaj Mohan Rastogi[2], Dr. Naveen Kumar[3]

Research Scholar, Mechanical Department, Sir Padampat Singhania University, Udaipur, India[1]

Mechanical Department, Sir Padampat Singhania University, India[2]

Mechanical Department, Sir Padampat Singhania University, India[3]

Abstract: Prediction of surface roughness and dimensional inaccuracies is an essential prerequisite for any unmanned computer numeric controlled (CNC) machinery. This prediction technique is also important for optimization of machining process. In the present work, it is observed that, using Taguchi approach, the quality of surface finish can be predicted within a reasonable degree of accuracy by taking the amplitude of vibration of tool holder into account. Surface roughness and tool vibrations are the critical factors which influence the quality of the machined parts.
In this research paper, an attempt has been made to optimize the cutting conditions to get predicted surface roughness in turning of 6061-T6511 Aluminium alloy rod. The experiment was designed using Taguchi method and 36 experimental runs were conducted for various combinations of cutting parameters. The orthogonal array, signal to noise ratio and analysis of variance (ANOVA) were employed to study the performance characteristics at different conditions. In order to analyse the response of the system, experiments were carried out at various spindle speeds, depth of cut and feed rate. The results obtained by this research will be useful for various industries and researchers working in this field.

Keywords: CNC; Surface roughness; Taguchi method; orthogonal array; ANOVA

I. INTRODUCTION

In today's global manufacturing environment, all the companies are competing to produce high quality product at lowest cost. In order to achieve this goal, there is a trend of companies towards technical revolution or modernization to machine variety of materials to fulfil companies need [1]. The companies are tending towards automated unmanned CNC cells for increasing the production rate and decreasing labour cost. However, due to lack of continuous operator monitoring it can cause defects in the machined parts.
Turning is the most common machining operation which is specially being used for the finishing of machined parts. In a typical turning operation, certain machine parts may require specified surface roughness. It is an important parameter in mechanical applications that influence widely the performance of the parts and it is one of the major quality attribute of the machined parts [2]. Such parts may be bearing surfaces, sealing surfaces etc. which need continuous operator monitoring else that may lead defects. In turning operation, it is crucial task to select cutting parameters for achieving better performance.
Tool wear is a major factor which affects the surface roughness but the operator can hear the chattering sound of the worn out tool and see the tool condition or can use tool condition monitoring system to measure the tool wear. Researchers and engineers are already trying to evolve a highly reliable cutting tool condition monitoring system. Hence, in the present study it is not considered as a key factor which affects the surface roughness. [3}

Robust design for the engineering is a better methodology for obtaining best set of results which are minimally sensitive to the numerous causes of variation to produce best quality products at least cost. Taguchi and ANOVA parameters are important tool for such kind of robust design which offers simple and systematic approach to optimize the design data. These techniques can be employed for optimizing the desired results by controlling the design parameters in several experimental runs. Taguchi design can optimize the results through setting of design parameters as per requirement. On the other hand, ANOVA is employed to recognize the most significant variables and their interaction effects along with their percentage contribution. [5]
The present research work describes about how to select the controlled factors (spindle speed, depth of cut and feed rate) that can minimize the effect of noise factor on the response (surface roughness). Along with that the effect of tool vibrations along all the axes is also considered which affect the amount of surface finish. In order to analyse the response

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of the system, experiments were carried out for various spindle speeds, depth of cut, feed rates. To decrease the number of runs, Taguchi orthogonal array of design was used instead of full factorial design. [11]

Vibration data in form of mean amplitude are recorded during the machining process using tri-accelerometer based

vibration measurement setup. In the previous research work in this field, tool vibrations have been correlated well with the surface roughness. The previous studies found that while predicting surface roughness, there is positive effect of vibrations in single direction as well as the various cutting parameters. Although, it has been shown that during cutting process vibrations occur in all the directions and it also affect the cutting conditions. In this study the effect of vibrations along all the axes has been considered.[20]

MATERIALS AND METHODS

Material & its specifications

The work piece material for this experiment was Aluminium Alloy 6061-T6511. It is the commonly used wrought alloy in all the industries for manufacturing of durable, light weight and corrosion resistive parts. Mechanical properties and chemical composition of 6061- T6511 Aluminium Alloy is as shown in Table 1 & 2 respectively. The work pieces were cut from 1.0-inch diameter rod. Each work piece was roughly cut prior to the final finish cut in order to maintain dimensional inaccuracies and proper measurement of vibrations at varying cutting parameters.

Experimental Design and Setup

This experiment involves a basic Taguchi design in which an orthogonal array design is used to perform experimental runs at various cutting parameters. The experiment involves three controlled factors and two response variables. The controlled factors are spindle speed, depth of cut and feed rate while the response variables are surface roughness and amplitude of vibrations along three axes.

Table-1: Mechanical Properties of 6061- T6511 Aluminium Alloy

Hardness	Elongation	Tensile Strength	Yield Strength	Young's Modulus	Thermal Conductivity
95 BHN	12-17 %	310 MPa	276 MPa	69 GPa	167 W/mK

Table-2: Chemical Composition of 6061- T6511 Aluminium Alloy, % Weight

Al	**Cr**	**Cu**	**Fe**	**Mg**	**Mn & Ti**	**Zn**
95.8-98.6	0.04-0.35	0.15-0.4	Max 0.7	0.8-1.2	Max 0.15 each	0.25

Table-3: Experimental Levels of Cutting Parameter

Cutting Parameters	**Units**	**No. of Levels**	**Values For Each Level**					
SS	rpm	3	2000		2500		3000	
FR	inches	6	0.001	0.002	0.003	0.004	0.005	0.006
DC	ipr	2	0.01			0.02		

As shown in Table-3, all the three controlled factors i.e. spindle speed (SS), depth of cut (DC) and feed rate (FR) has variable levels. This results in total of 36 randomized runs to be conducted to test all the combinations of the parameter level according to Taguchi L_{36} orthogonal array design will result in total of (3x6x2) 36 runs (i.e. full factorial design) to be conducted to test all the possible combinations of parameter levels.

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Spindle Speed (rpm):		**L-1: 2000**		**L-2: 2500**		**L-3: 3000**	
FR (ipr)	**DC (in.)**	L-1: 0.01	L-2: 0.02	L-1: 0.01	L-2: 0.02	L-1: 0.01	L-2: 0.02
L-1:0.002		Run #1	Run #2	Run #13	Run #14	Run #25	Run #26
L-2:0.003		Run #3	Run #4	Run #15	Run #16	Run #27	Run #28
L-3:0.004		Run #5	Run #6	Run #17	Run #18	Run #29	Run #30
L-4:0.005		Run #7	Run #8	Run #19	Run #20	Run #31	Run #32
L-5:0.006		Run #9	Run #10	Run #21	Run #22	Run #33	Run #34
L-6:0.007		Run #11	Run #12	Run #23	Run #24	Run #35	Run #36

All the required data are collected from the experimental setup for individual run. The experimental setup includes CNC Lathe, sample work pieces, surface roughness measurement setup and vibration data collection system.

The experiment was performed using CNC turning centre DX-200 Series slant bed CNC lathe. This is a bi-directional turner lathe which incorporates a 30° slant bed setup and some other special features that help in better machining and surface finish. The major technical specifications of the CNC Turning centre are given in Table-5. In order to maintain constant machining and vibration condition, this experiment was performed with dry cutting i.e. without use of coolant. The selected parameters values were set using the NC program and data were stored in CNC's control unit. The machining process was conducted using a new diamond shaped carbide tool insert. The in process vibration data collection system was used which measures the mean amplitude of tool vibrations at various cutting parameters. The system was comprised of a tri-axial accelerometer which measures and amplifies the vibration signals in the three axes of the lathe i.e. X, Y and Z axes. The tri-axial accelerometer sensor used was PCB Piezotronics 356-B-08 sensor which amplifies the signal. All the signal data were recorded and digitized for analysis purpose.

After final finish cut, the surface roughness was measured for each work piece at each 90° incremental intervals along the circumference as shown in fig.1. The measurements were taken using Mitutoyo Surface roughness measuring tester SJ-210 as shown in fig.2. The measurements were obtained with the help of movement of stylus with diamond tip over the surface along the z axis. The instrument measures various forms of surface roughness amplitudes according to the particular industrial use i.e. Arithmetic mean of roughness (Ra), Mean squares of roughness (Rq), and Maximum Peak to valley values of roughness (Rz) etc.

For this experiment, Arithmetic mean of roughness (Ra) was calculated for each work piece. The average roughness (Ra) is the area between the mean line and its roughness profile or the integral of the absolute value of the roughness profile height over the evaluation length. Thus, Ra can be specified by the following equation:

$$Ra= \frac{1}{L} \int_0^L |Y(x)| dx \qquad \text{...(1)}$$

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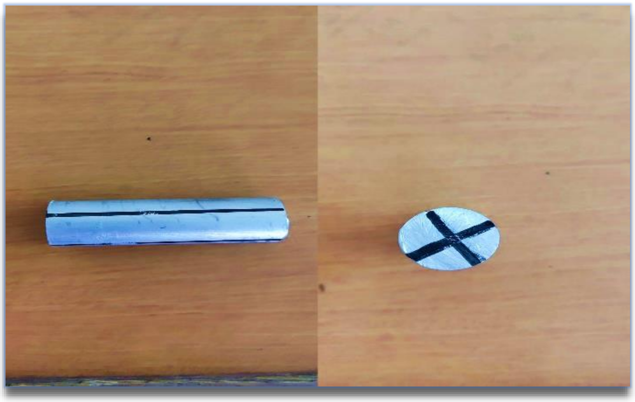

Fig.1 Measurement Section of Surface Roughness

Fig.2 Mitutoyo Surf Roughness Tester: SJ-210

Experimental Procedure

A randomized schedule of runs was created at various combinations according to Taguchi design of experiments as shown in Table-2. The work pieces from the bar were cut and turned with specified cutting conditions. The dry turning was performed for each run in order to get accurate vibration signals. During the finish turning vibration data were collected on each axes using vibration data collection system. After completion of all the runs, the surface roughness of all the work pieces was measured. Surface roughness was measured at each 90° increment around the circumference i.e. four times for each work piece and finally their average value is stored in the data table. Data processing and its analysis were performed through MINITAB-21 statistical software.

The parameters and results of each individual run including mean vibration signals and surface roughness were collected as shown in Table-6.

Table-6: Factors and Response Data for Individual Experimental Run

Sr. No.	**Factors**			**Response**			
					Amplitude of Vibrations		
	SP	**FR**	**DC**	**Ra**	**Vx**	**Vy**	**Vz**
1	2000	0.001	0.01	20.03	0.0508	0.0916	0.04
2	2000	0.002	0.01	22.06	0.0565	0.098	0.049
3	2000	0.003	0.01	29.8	0.0697	0.1259	0.51
4	2000	0.004	0.01	40.02	0.073	0.1396	0.55
5	2000	0.005	0.01	56.23	0.0752	0.158	0.514
6	2000	0.006	0.01	64.1	0.082	0.159	0.578
7	2000	0.001	0.02	23.5	0.0658	0.104	0.0431
8	2000	0.002	0.02	24.2	0.0701	0.1129	0.0596
9	2000	0.003	0.02	31.4	0.0766	0.1357	0.0627
10	2000	0.004	0.02	45.03	0.0845	0.1628	0.0658
11	2000	0.005	0.02	54.32	0.0929	0.1859	0.0718
12	2000	0.006	0.02	68.88	0.108	0.2199	0.0769
13	2500	0.001	0.01	20.3	0.0527	0.0988	0.0413
14	2500	0.002	0.01	22.45	0.07	0.13	0.049
15	2500	0.003	0.01	30.2	0.0739	0.1416	0.0514
16	2500	0.004	0.01	40.3	0.089	0.1528	0.0607

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17	2500	0.005	0.01	50.02	0.0908	0.1865	0.0698
18	2500	0.006	0.01	62.22	0.0919	0.1866	0.0726
19	2500	0.001	0.02	15.32	0.0717	0.11	0.0429
20	2500	0.002	0.02	23.05	0.0838	0.153	0.057
21	2500	0.003	0.02	29.25	0.0925	0.171	0.0627
22	2500	0.004	0.02	38.09	0.11	0.208	0.0787
23	2500	0.005	0.02	48.2	0.1154	0.22	0.0858
24	2500	0.006	0.02	61.08	0.1207	0.229	0.0927
25	3000	0.001	0.01	17.04	0.0689	0.119	0.0419
26	3000	0.002	0.01	20.53	0.0749	0.128	0.0456
27	3000	0.003	0.01	28.67	0.0759	0.15	0.0519
28	3000	0.004	0.01	41.03	0.0898	0.1495	0.062
29	3000	0.005	0.01	52.9	0.0929	0.1658	0.0693
30	3000	0.006	0.01	65.7	0.1121	0.1989	0.0749
31	3000	0.001	0.02	19.8	0.0842	0.1452	0.0612
32	3000	0.002	0.02	21.65	0.0935	0.1668	0.0658
33	3000	0.003	0.02	30.05	0.1023	0.1762	0.0697
34	3000	0.004	0.02	36.09	0.1129	0.1957	0.0798
35	3000	0.005	0.02	48.08	0.12	0.2437	0.0928
36	3000	0.006	0.02	60.5	0.1263	0.2663	0.1045

Analysis of S/N Ratios & Analysis of Variance (ANOVA)

For Taguchi analysis, experimental results of surface roughness are transformed into Signal to Noise (S/N) ratio (η) as shown in Table 6. Here the signal is representing the desirable value i.e. mean of the output characteristics while the noise represents the undesirable value i.e. squared deviation of output characteristics. Usually, there are three categories for analysis of S/N Ratio i.e. the smaller is better, the larger is better, the nominal is best. The S/N ratio for each level of process parameter is computed by S/N analysis. Regardless of the category, the larger S/N ratio is recommended for better performance. Thus, the optimal parameter for any factor is the level having highest S/N ratio. Usually, the objective of the first category is to optimize the system when the response is as small as possible while the second category is used when the response is as large as possible and the objective of the third category is to reduce the variability around the specific target.

For this experimental analysis, the first category i.e. "The smaller is better" was employed to calculate S/N ratio and its main effect plots are generated for S/N Ratio using MiniTab-21 statistical software as shown in figure 3. The first category was chosen to obtain the optimization conditions for minimization of surface roughness which is the desired condition for turned machined parts. The following equation was used to calculate S/N ratio

$$\eta = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \qquad \ldots(2)$$

Where η is the Signal to Noise ratio, n is the no. of repetitions of the experiment and y_i is the measured value of the quality characteristics. The S/N ratios are expressed on the decibel scale.

While applying Taguchi design analysis to these experimental data, the data tables for analysis of S/N ratios (η) was generated as shown in Table 7 by which rank value of the factors can be obtained for S/N ratios.

Table -7: Response Table for S/N Ratios with Cutting Parameters

LEVEL	SS	FR	DC
1	-31.26	-25.65	-30.75
2	-30.50	-26.96	-30.75
3	-30.48	-29.51	

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4		-32.04	
5		-34.24	
6		-36.08	
Delta	0.78	10.43	0.00
Rank	2	1	3

It can be seen by the collected data that the amplitude of vibrations on all the three axes is affected by both feed rate and depth of cut. Both the factors have positive effect on vibration signals and shown to be increasing proportionally. Hence, ANOVA is used to explore these observations as shown in Table 8.

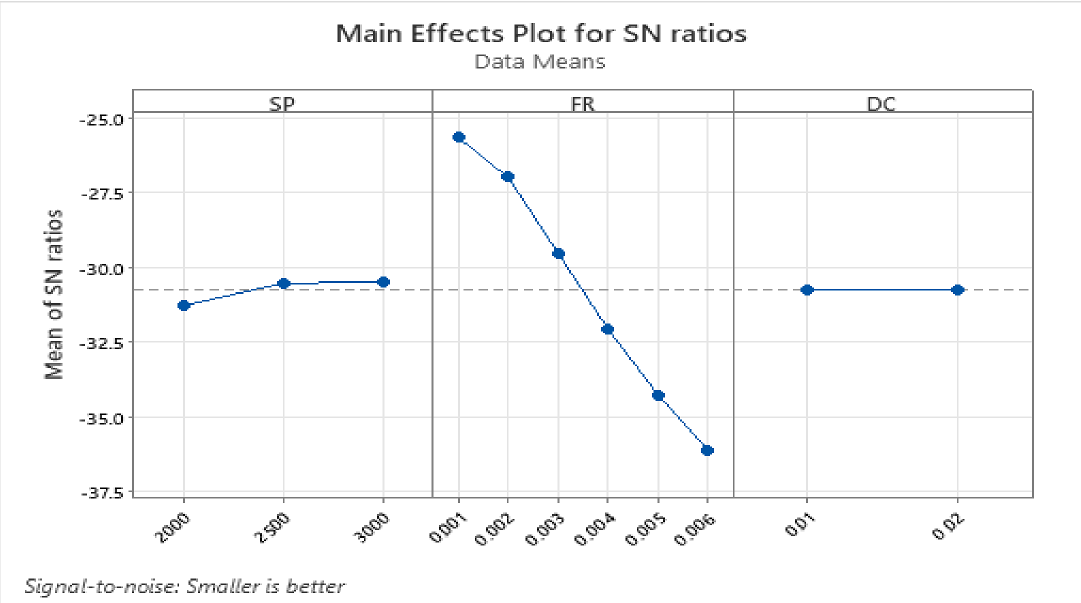

Fig-3: S/N Ratios vs. Cutting Parameters (SS, DC, FR) Plots

Table- 8: Analysis of Variance for S/N Ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Percentage Contribution
Regression	6	8888.53	8888.53	1481.42	109.38	0	95.77%
SP	1	58.69	0.64	0.64	0.05	0.829	0.63%
FR	1	8786.93	986.17	986.17	72.81	0	94.67%
DC	1	0.73	17.77	17.77	1.31	0.261	0.01%
Vx	1	31.95	21.52	21.52	1.59	0.218	0.34%
Vy	1	0.03	0.02	0.02	0	0.972	
Vz	1	10.21	10.21	10.21			
Error	29	392.77					4.23%

In ANOVA, there is a tool i.e. F-Test which is named after Fisher which is used to analyze that which process parameters have a significant effect on the performance. Usually, the larger the F- values, there will be the greater effect on the performance due to varying cutting parameters.

Furthermore, Regression analysis was performed for most significant data i.e. data having highest correlation coefficient so that it will create more robust model. For that, Pearson's correlation coefficient was measured for each factor with respect to the surface roughness as shown in Table-9. Regression model was created with those highly correlated factors to get prediction equation.

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Regression Equation

As it can be analysed from Table 9 that feed rate and mean amplitude of vibrations in y & z axes have positive correlation with the surface roughness so these most significant variables can be used in regression analysis to create the predictive equation. By using these factors, the predictive equation is found to be:

$$Ra = 11.62 + 0.00074\ SP + 11036\ FR + 344\ DC - 222\ Vx + 2.3\ Vy - 4.40\ Vz \quad \ldots\ldots(3)$$

This equation was used to test the accuracy of the prediction model using both the experimental data results and validation run. Initially, the equation was applied for experimental data for each run as given in Table 3 to check the accuracy of the predictive equation. The following equation was used to check the accuracy in terms of percentage error or rate of error.

$$\text{Rate of Error } (\delta) = \frac{1}{n} \sum_{i=1}^{n} \left[\frac{Ra - Ra_p}{Ra} \text{ x } 100\ \% \right] \quad \ldots(4)$$

Where R_a is the measured surface roughness for specific run, Ra_p is the Predicted surface roughness for specific run, n is the total number of measurements and i is the measurement being done for specific run.

DISCUSSIONS

It can be seen from the Table 7 and the corresponding Rank value for each factor that the feed rate (Rank 1) is the highest influencing factor which has strongest effect on the surface roughness followed by spindle speed (Rank 2) and last by depth of cut (Rank 3).

CONCLUSION

The development of practical and reliable system for obtaining desired surface roughness in turning operation is essential for today's global and intelligent manufacturing system. In this study, the problem of obtaining controlled surface roughness has been studied using vibration measurement method. Based on the current study, the following conclusions can be drawn. Predicted surface roughness can be obtained in a controlled manner if we control the values of feed rate which has highest impact on surface roughness. In future, further research in this field of turning for controlled surface roughness is recommended because it is vital for precision industries. Further research may include any other statistical approach. consideration of different variables, variation in experimental setup to improve prediction model accuracy and to decrease rate of error. This kind of improved research may be more adaptable to the industries.

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