"Experimental Investigation of Vibration Based Surface Roughness Prediction System"

Ravi Pathak[1], Ankur Kulshreshta[2]

[1] *M.Tech Scholar, Department of Mechanical Engineering, Pacific University, Udaipur (Raj.) India*

[2] *Associate Professor, Department of Mechanical Engineering, Pacific University, Udaipur (Raj.) India*

ABSTRACT

'Mass Customization' is an attempt to provide unique values to the customers in an efficient manner. In the present work, that unique value chosen is required surface quality instead of 'Best' quality which has become a choice of today's customized market.

Prediction of surface roughness is an essential requirement for any computer numeric controlled (CNC) machinery. Poor control on the desired surface roughness generates rebellious parts and results in increase in cost and loss of productivity due to rework. Surface roughness value is a result of several process variables among which vibration is of great significant.

In this study, full factorial design of experiment (DOE) approach is applied to find the optimum cutting parameters to obtain predicted surface roughness in turning at computer numeric controlled (CNC) cell. Dry turning is performed for aluminum alloy bars using diamond shaped carbide tool insert. The analysis of varianc e (ANOVA) and correlation technique are applied to study the performance characteristics of machining parameters with surface roughness and cutting tool vibrations.

Feed rate and bi-axial cutting tool vibrations are observed to be main parameters affecting surface roughness. Regression equation is formulated for estimating predicted values of surface roughness. Finally, to illustrate the effectiveness of the regression equation, the rate of error is found between the actual and predicted surface roughness values.

Keyword: - *DOE; ANOVA; CNC; Surface roughness; Regression*

---

1. INTRODUCTION

The turning process is considered to be most versatile operation as a large number of machining components passes through this process. A typical turning operation produces precision parts with critical features that may require specified surface roughness. Such applications include bearing surfaces on axles, bearings, races; ultra-clean surfaces in contaminant-sensitive components; and sealing surfaces on bores and pistons and many more. Producing these products with modern CNC turning equipment can potentially lead to numerous defects due to the lack of continuous operator monitoring. Considering that a typical minimally manned CNC cell is used for very high-volume production, a problem affecting surface roughness may go unnoticed for some time during the operation. Defects may therefore continue to be generated until either a setup person or a quality inspector notices the increase in surface roughness.

Thus present study focuses on developing such a regression model considering all major influencing parameters by which the operator can set in advance all the machining parameters according to predicted surface quality. There is no any chance for loss of productivity and increased cost due to better monitoring of parameters.

1.1. Metal Machining

Metal machining is a major concerning area in which a number of researchers are working throughout the world for evolving the new technologies. With the advancement and technical revolution, this segment has become the most challenging segment for industrialist and researchers. As discussed above, all the industries are moving towards increasing their production in conjunction with customer satisfaction with maximizing their profit which is the need of today's economy. The only solution to this problem is to use automated CNC cells with better controlling over the machining parameters.

In this global manufacturing environment, this is the need of market to produce the best quality product at least cost. it is only possible if the industries fulfill the following criterion like component according to need of customers, less wear, fast delivery, dimensional accuracy, better surface quality, high performance rates and reduced wastage etc. The mechanism behind the formation of surface roughness is very dynamic, complicated, and process dependent which need continuous operator monitoring else that may lead to defects.

There are various machined parts which may cause unusual behavior if surface quality is not maintained over those parts like couplings, aircraft fittings, valves, gaskets etc. These parts are such that they require specified surface roughness. If that specific value is not maintained over those parts then it may cause even failure of the system. Usually, these parts are made up of the material having durability and strength. Thus, mild steel is proven to be right material which matches the above discussed properties and applications. In industries, Mild steel is a widely used material for manufacturing of a large number of components.

Significant effects of cutting tool vibrations were also identified on the surface roughness. Effect of radial vibrations on surface roughness had been studied by many researchers and it was established that both amplitude and frequency of vibration has strong effect on surface topography.

Achieving a desired level of surface quality for CNC-turned parts needs practical knowledge and skill to properly set up this type of operation with the given specifications and conditions. A manufacturing engineer is often expected to utilize experience and published shop guidelines for determining the proper machining parameters to achieve a specified level of surface roughness.

Unfortunately, in most scenarios, time is limited thus the design of experiments (DOE) or Taguchi methodology can be used to minimize number of experiments to optimize the results.

We can use design of experiment (DOE) methodology for optimizing the results. Using that technique in minimum numbers of experiment we can get the optimized results. DOE may be full factorial design or fractional design. Along with that, numerous statistical methodologies like Correlation Techniques, Analysis of variance (ANOVA), Regression method and many more other techniques are most widely used by researchers for obtaining best set of results.

1.2 Objectives

Looking to the need of studies in the field of surface metrology for turning operation the following objectives are shortlisted:

- To study the effect of depth of cut, feed rate and spindle speed on surface roughness in CNC Turning process in conjunction with bi axial tool holder's vibration amplitudes.
- To perform the experimentation according to "Fractional or Full Factorial Design Approach" at different cutting parameters with differing values.
- To analyze the effect of machining vibrations on surface quality.
- To develop prediction system for required surface quality using "Regression Technique."

2. LIERATURE REVIEW

2.1. Current and Previous Studies

Current and previous studies are basically reviewed to analyze the gap between conventional technologies and current technologies. By in-depth analysis of these studies it can be easily judged that how the technology is moving ahead and still what is the research gap that can be a step ahead towards future extension of that particular work. Thus, that previous work and literatures provide a path and guidance for future work so that objectives can be planned.

2.1.1. Cutting Tool Holder's Vibration

There are several factors which affect directly the value of surface roughness which have been already considered and immense in-depth analysis have been done on those factors by numerous researchers. But, instead of all that, there are a few factors which indirectly affect the value of surface roughness. Vibrations of tool holder are one of those parameters. Such factors are known to be uncontrolled noise factor.

Various researchers investigated the effect of tool vibrations on surface roughness in turning process and they concluded that cutting tool vibrations play a vital role in affecting surface roughness as an uncontrolled factor. The features of vibration like its frequency, amplitude & time are highly correlated with various machining processes**.** Certain researchers stated vibration in single axis or double axes affect the roughness while a few stated that it has tri- axial effect**.** But third axis vibrations were found to be less affecting with respect to surface roughness so no need to be considered. A few researchers correlated their work with cutting tool vibrations for identification of surface roughness along with consideration of effect of tool length for inspecting the changes in tool vibrations.

Hence, numerous studies had proven cutting tool's vibration as a key parameter for studying about surface roughness.

2.1.2. Statistical Tools

A long ago, statistical techniques or mathematical techniques had become a choice of researchers. These techniques have been a part of all researches for optimizing the results and identifying the parameter effect relative to each other.

Such techniques may be as follows:

1. Design of experiment (DOE): Fractional or Full Factorial design,
2. Taguchi Method: Orthogonal Array Technique
3. Analysis of variance (ANOVA)
4. Artificial Neural Network (ANN) Technique
5. Pearson's Correlation Technique
6. Pareto Analysis
7. Work Study methods
8. Regression Technique etc.

For obtaining best set of results and for improving quality of work these techniques may be highly helpful which show the results in accurate manner. These techniques may explore the effect of all parameters affecting the results.

Design of experiment technique had proven to be a good methodology in management applications in comparison to Taguchi design which can optimize the results through setting of design parameters as per requirement effectively and this method can be operated consistently and optimally over a variety of conditions.

.Analysis of variance (ANOVA) technique is found to be best technique for obtaining the level of significance among various parameters involved in the study. In some studies, ANOVA was employed to develop empirical models to analyze response of the system**.** ANOVA is a best tool for recognizing most significant variables and their interaction effects along with their percentage contribution in affecting the response value .

A number of studies have been accomplished in which Regression technique was used for acquiring predicted results and it has proven to be a good tool for such applications with better approximation and minimum error.

3. METHODOLOGY

3.1. EXPERIMENTAL SETUP

Present study basically involves the use of 'Turning Operation' as it is most widely adopted method for machining. Thus, for accomplishment of the present work, the experimental setup is needed to select which involves a set of machineries which are used for completion of the work along with the material used for workpiece. The requirements of experimental setup are as follows:

- CNC Lathe machine
- Aluminum Alloy Workpieces
- Vibration Measurement Setup
- Surface Roughness Tester

A brief description of all these components has been presented below.

3.1.1. CNC Lathe

In accordance with objective of the present work, the machine selected for present experiment is CNC turning centre. The machine tool selection is a crucial factor which affects the outcome of experimental work. Thus, it should be selected in such a manner that it incorporates the basic needs of the present study like desired range of spindle speed, depth of cut and feed rate etc. Therefore, STALLION-100 HS CNC lathe machine was chosen for present work as shown in Figure 3.1.

This is a turner lathe which incorporates a 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 3.1. This experiment is performed with dry cutting i.e. without use of coolant.

Fig.3.1: Layout of CNC Lathe- STALLION-100 HS

Table 3.1: Technical Specifications of CNC Turning Centre

Sr. No.	Specifications	Range
1	Slant bed angle	35°

2	Spindle speed	50-3500 rpm
3	Spindle motor power	10 kW
4	Feed rate range	0.000001 – 4.000000 inch per revolution (ipr)
5	Least input movement increment	X 0.00005 inch, Z 0.0001 inch
4	Maximum Turning length	300 mm
5	Maximum turning diameter	200 mm
6	Controller	Fanuc- Siemens
7	Number of station of turret head	4
8	Weight	2500 kg

3.1.2. Material

For present experimental work, Aluminum alloy is chosen which is a most widely used alloy in the manufacturing industries for production of numerous components. There are different grades of aluminum alloy used in the industries out of that for present work Aluminum Alloy 5052 is chosen having good workability as well as good weldability.

The dimensions of the workpieces are as follows:

- Diameter: 1.0 inch (0.254 m)
- Length : 3.93 inch (10cm)

3.1.3. Vibration Measurement Setup

Instruments for measuring and analyzing machine's vibration are available in a wide range of features and capabilities. With the discovery of first musical instruments, probably drums or whistle, mankind got familiar with the concept of vibration. Since then, to understand the phenomenon of vibration, critical investigation has been applied by researchers.

➢ **Vibration Transducer**

This is the device that is held or attached to the machine to convert the machine's mechanical vibration into an electrical signal that can be processed by the associated instrument into measurable characteristics of the vibration amplitude, frequency and phase. Many different varieties of vibration transducers have been used over the years.

Typically, following three methods for mounting of accelerometer for vibration sensing applications are employed in rotating machines;

- Stud Mounting
- Adhesive Mounting
- Magnetic Mounting

In present work, a bi-axial piezoelectric accelerometer was employed. While machining, it measures the cutting tool's vibration signals along the two axes i.e. X (Radial) and Y (Feed) axes in which vibration signals are represented by G1 & G2.

3.1.4 Surface Roughness Tester

After completion of machining process on the workpieces, their surface roughness is measured for further analysis. There are various surface roughness measurement techniques, by which in-process and post-process measurements can be taken. Usually, the techniques of measuring roughness of machined parts can be classified into two categories:

- Non-Contact Surface Roughness Measurements Technique
- Contact Surface Roughness Measurements Technique

This instrument measures its surface roughness value by averaging the value in the cutoff. The stylus profiler is one of the most widely used instruments to measure surface roughness in industry and academic laboratories.

Fig 3.2: Mitutoyo Surface Roughness Tester: SJ-201P

The instrument used for present work was Mitutoyo Surftest SJ-201P as shown in Figure 3.2. The measurements were obtained with the help of movement of stylus with diamond tip over the surface. For measurement of the surface roughness linearly, the finished part is mounted over a specially designed V-shaped fixture at which the workpiece can be placed easily for movement of diamond tip stylus over the surface of workpiece.

3.2. Full Factorial Design of Experiment Approach

This section presents a detailed description about experimental work and data collection system for the present work as per full factorial approach.If the number of combinations in a full factorial design is too high to be logistically feasible, a fractional factorial design may be done, in which some of the possible combinations are omitted. But, Fisher in his book 'The Design of Experiments' stated that the factorial designs are more efficient than studying certain factors at a time in fractional design approach.

There are certain steps which should be followed to complete the task in a proper way as shown below by pictorial diagram in Flow Chart 3.1. These detailed steps are as follows:

i. Identify factors of interest and response variables.
ii. Determine appropriate levels for each independent variable.
iii. Determine a design structure according to full factorial design approach.
iv. Conduct the experiment and collect the data.
v. Analyze the data and organize the results in order to draw appropriate conclusions.

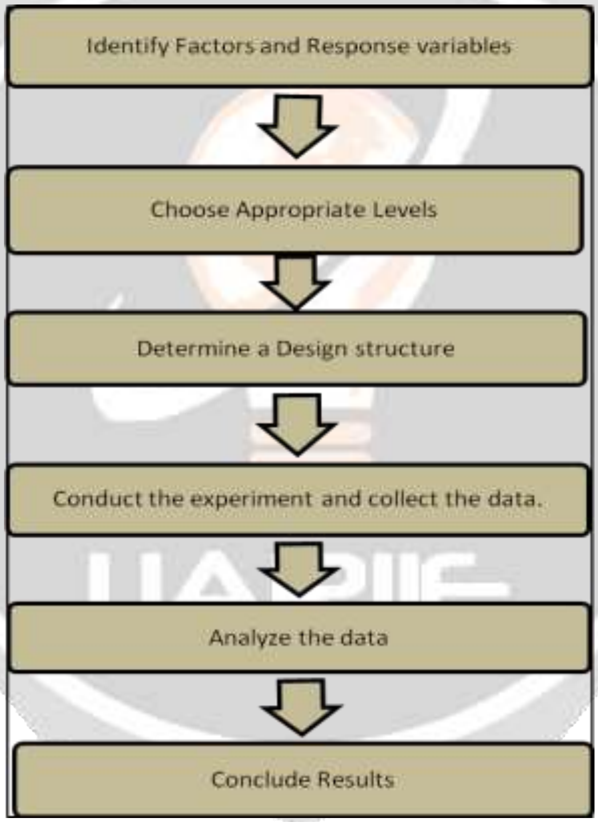
3.2.1. Parameter levels and Run selection

It is an attempt to experimentally examine the effect of various cutting parameters on the surface roughness along with its vibrations. The experiments will be performed according to full factorial design approach for all the possible sets of parameter levels being used in the experiment for required number of samples of work piece having same material and same dimensions.

The experiment will involve following variables:

- Independent variables:
  - i. Spindle speed(SS)
  - ii. Depth of cut (DC)
  - iii. Feed rate (FR)

- Dependent variables:
  - i. Surface roughness(R_a)
  - ii. Vibration Signal-1(G1)
  - iii. Vibration Signal-2(G2)



Flow Chart 3.1: Pictorial Depiction of Steps in Full Factorial design

The total numbers of experiments are divided in three groups each of 12 experiments. Each experimental set of experiment is conducted at specified spindle speed for varying values of depth of cut and feed rates. The full factorial design approach will include each and every combination of possible experimental run.

Table 3.2: Experimental Levels of Cutting Parameters

Cutting Parameters	Units	No. of Levels	Values For Each Level					
SS	rpm	3	1500		1800		2100	
FR	ipr	6	0.001	0.002	0.003	0.004	0.005	0.006
DC	inches	2	0.01			0.02		

Table 3.3: Number of Experimental Runs According to Full Factorial Deign

Spindle Speed		Level-1: 1500		Level-2: 1800		Level-3: 2100	
		Depth of Cut					
Feed Rate		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-1:0.001		**Exp. No.1**	**Exp. No.2**	**Exp. No.13**	**Exp. No.14**	**Exp. No.25**	**Exp. No.26**
L-2:0.002		**Exp. No. 3**	**Exp. No.4**	**Exp. No.15**	**Exp. No.16**	**Exp. No.27**	**Exp. No.28**
L-3:0.003		**Exp. No.5**	**Exp. No.6**	**Exp. No.17**	**Exp. No.18**	**Exp. No.29**	**Exp. No.30**
L-4:0.004		**Exp. No.7**	**Exp. No.8**	**Exp. No.19**	**Exp. No.20**	**Exp. No.31**	**Exp. No.32**
L-5:0.005		**Exp. No.9**	**Exp. No.10**	**Exp. No.21**	**Exp. No.22**	**Exp. No.33**	**Exp. No.34**
L-6:0.006		**Exp. No.11**	**Exp. No.12**	**Exp. No.23**	**Exp. No.24**	**Exp. No.35**	**Exp. No.36**
TOTAL EXPERIMENTS	**36 Nos**	**EXPERIMENTAL SET-I**		**EXPERIMENTAL SET-II**		**EXPERIMENTAL SET-III**	

- **Analysis Methodology**

After completion of experimentation, the measured performance characteristic from each trial can be used to analyze the relative effect of the different parameters. Firstly, analysis of variance (ANOVA) was applied for observing the effect of all the controlled factors over the response parameters. Analysis of variance frequently referred by the contraction ANOVA, is a collection of statistical models or statistical technique used to investigate and model the relationship between a response variable and one or more independent variables. It is also used to analyze differences between group means and their 'variation' among and between groups. Each explanatory variable called the factor and consists of two or more categories called the levels.

Pearson's correlation method basically follows the three steps

i. Determining whether a relation exists or not.
ii. Testing whether it is significant or not.
iii. Establishing the cause and effect relation, if any.

Furthermore, the regression technique was applied using MiniTab-17 software by entering the highly correlated values in the equation, and finally the rate of error was measured between the actual response values and the predicted response values.

The following equation was used to check the accuracy in terms of percentage error or rate of error:

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

4. Result and Discussion

In accordance with the strategy of the present work experimentation, in which a full factorial experimental runs were created as discussed.

4.1. Analysis of Variance (ANOVA)

It can be seen by the collected data that the amplitude of vibrations along both axes is affected by all the controlled factors i.e. spindle speed, feed rate and depth of cut because values of vibration are varying with respect to variations in controlled factors. All the factors have positive effect on vibration signals and shown to be increasing proportionally. But still just by observation, it is not clearly identified that which factor is affecting theses values in which manner.

Hence, to explore these observations, variance analysis (ANOVA) was performed using MiniTab statistical software. Separate variance analysis was performed two times for vibration data in X and Y axis as shown in Table 4.1 & 4.2 respectively in which analysis was performed for vibration signals taken as the response variable while the SS, DC and FR are taken as controlled factors.

Table 4.1: General Linear Model: G1 versus SP, FR & DC

Source	DF	Adj SS	Adj MS	F	P	% Contribution
SS	2	0.00621	0.00311	24.40	0.000	7.83
FR	5	0.00558	0.001116	87.66	0.000	70.31
DC	1	0.001391	0.001391	109.31	0.000	17.53
Residual error	27	0.000344	0.000013			4.33

Total	35	0.013423				100
S = 0.0035677 R-Sq = 95.67% R-Sq (adj) = 94.39%						

Table 4.2: General Linear Model: G2 versus SP, FR & DC

Source	DF	Adj SS	Adj MS	F	P	% Contribution
SS	2	0.01926	0.009632	21.75	0.000	18.84
FR	5	0.04145	0.008290	18.72	0.000	40.54
DC	1	0.02957	0.02956	66.77	0.000	28.92
Residual error	27	0.01196	0.000443			11.70
Total	35	0.013423				100
S = 0.0210437 R-Sq = 88.30% R-Sq (adj) = 84.84%						

The results acquired from the respective tables are as follows:

- It can be seen from the Tables 4.1 & 4.2; Spindle speed, Feed rate and Depth of cut all appear to significantly affecting the level of vibration. Each factor has their effect on the vibration amplitude in different manner explored from the results.

- As seen from the Table 4.1, the amplitude of vibration in x-direction i.e. G1 is strongly affected by Depth of cut because from the ANOVA table DC has highest F-value (109.31) which is much more greater than four indicating its strong level of significance. Spindle speed and feed rate also have their significant effect on G1 because their F- values are more than four. This model has the coefficient of determination (R-Sq) of 95.67%, which also indicates a strong relationship between the significant factors and response.

- As seen from the Table 4.2, the amplitude of vibration in y-direction i.e. G2 is strongly affected by depth of cut because from the ANOVA table DC has highest F-value (66.77). Spindle speed and feed rate also have their significant effect on G2. These parameters also have their F values more than four, so effect of all the variables are statistically significant. This model has the coefficient of determination (R-Sq) of 88.30%, which indicates a strong relationship between the significant factors and response.

- Thus the amplitude of vibrations in X and Y axis (i.e. G1 & G2) play a crucial role in affecting the surface roughness indirectly. Hence, these are the key factors for the present model.

4.2. Regression Analysis

Furthermore, Regression analysis was performed to formulate prediction equation for most significant data i.e. data having highest correlation coefficient to create more robust model as performed in Taguchi analysis. For that, Pearson's correlation coefficient was measured for each factor with respect to the surface roughness as shown in Table 4.3 and their contribution is shown by pie chart and histogram in Flow Chart 5.1 & 5.2 respectively.

Table 4.3: Pearson Correlation of Various Parameters with Surface Roughness

Sr. No.	Variables	Pearson's Correlation Coefficient
1	SS	-0.066
2	DC	0.048
3	FR	0.978
4	G1	0.826
5	G2	0.613

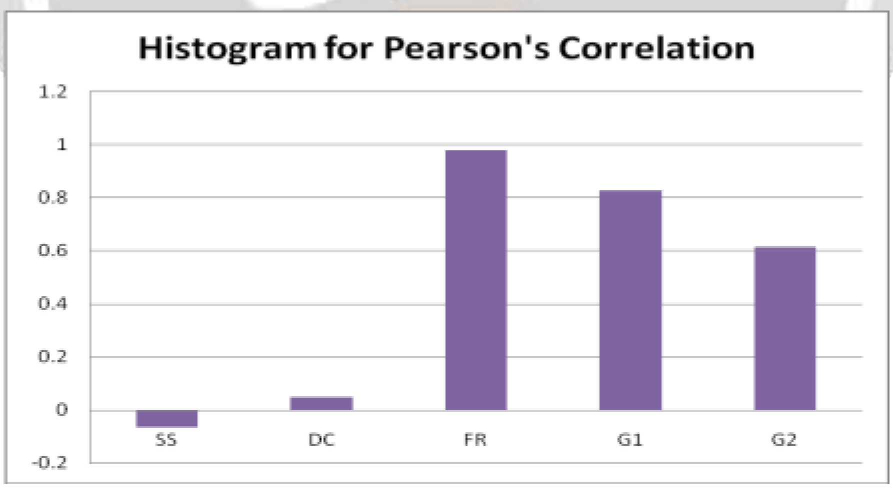
As it can be analyzed from Table 4.3 and Flow Chart 4.1 that, the feed rate, depth of cut and mean amplitude of vibrations in both axes i.e. x & y axes have positive correlation with the surface roughness so these most significant variables can be used in regression analysis to create the predictive equation. As seen from the Table 4.3, SS has the negative correlation thus no correlation exists between spindle speed and response variable.

By using these highly correlated factors and responses the predictive equation is found to be:

$$Ra_p = 6.57 + 9550\,FR + 352\,DC - 81\,G1 - 23.5\,G2$$

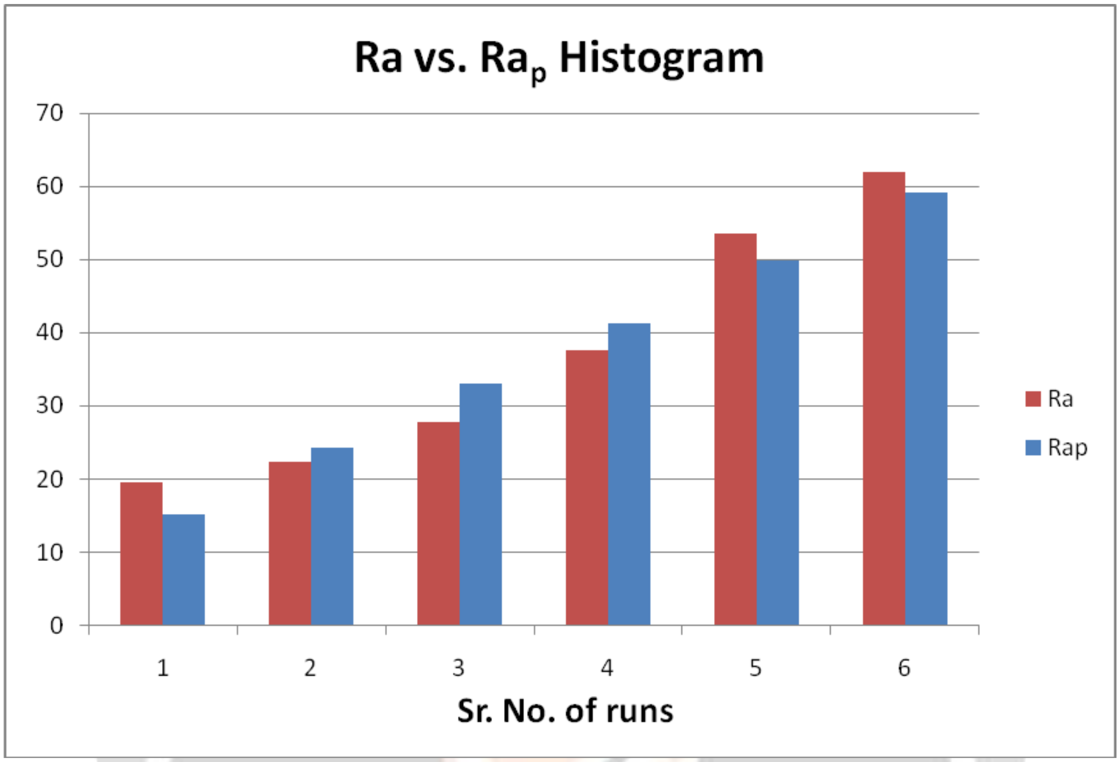
Where all the notations have their usual meaning. By using this predictive equation, values of surface roughness can be predicted before experimental run.

These predicted surface roughness values obtained by the regression equation for each run are collected. The rate of error for the experimental model is found to be 9.38%.

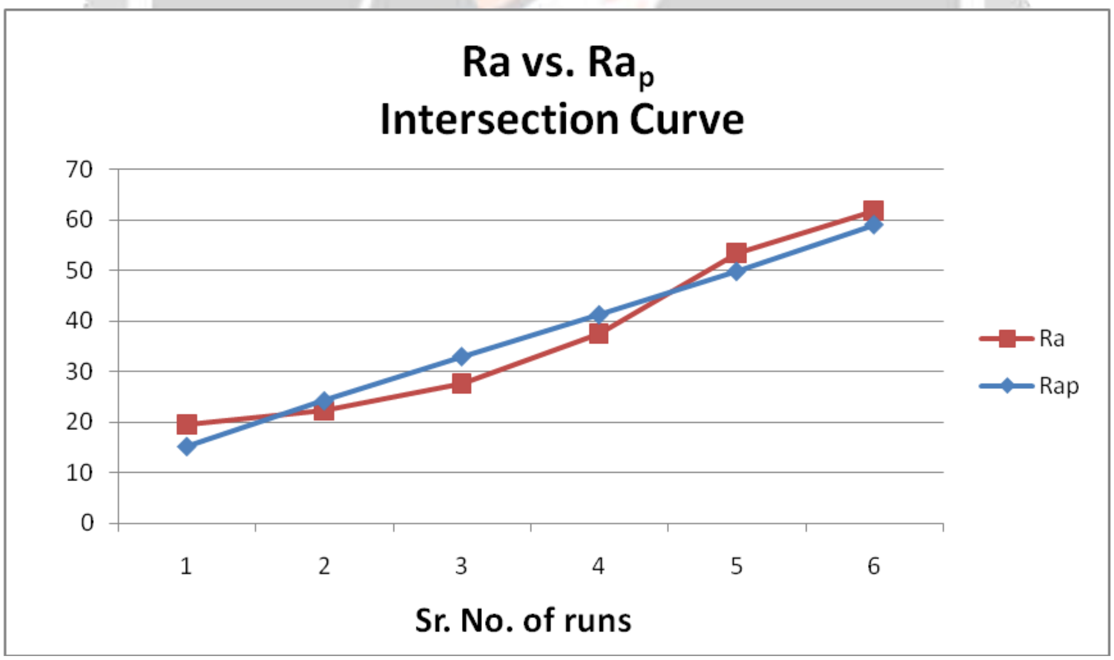


Flow Chart 4.1: Pearson's Correlation Histogram

The effectiveness of the system is further expressed by analyzing for measured versus predicted surface roughness data for experimental run as shown in Flow Chart 4.2 and Graph 4.1. As for each six set of experimental run, the spindle speed was kept constant, thus creates total six sets of experimentation (6x6=36). Each set of experiment shows the common results. As analyzed from the table, most of the points lie very close to the line for perfect prediction thus shows the accuracy of the regression model and present experimental setup.



Flow Chart 4.1: Histogram for Ra vs. Ra_p



Graph 4.2: Intersection Curve for Ra vs. Ra_p

5. CONCLUSIONS

The present investigation aimed at obtaining desired Surface roughness during CNC turning of aluminum work piece with carbide tool insert. Experiments were accomplished by taking into consideration the amplitude of bi-axial cutting tool's vibrations. This analysis was carried out by developing regression model of highly significant arithmetic values obtained by Pearson's correlation approach based on full factorial design of experiment approach. Main effect plots, histograms, cross relationship curves and various other manual curves were drawn which shows relationship among the collected data.

Finally, the following conclusions may be drawn for full factorial design of experiment:

- It is impossible to achieve surface roughness in controlled manner by 'Trial and Error' method. It needs an in-depth analysis of the parameters affecting it.
- Surface roughness and cutting parameters (i.e. SS, FR and DC) have highly non-linear relationships among them.
- Amongst the cutting parameters, surface roughness is strongly affected by feed rate while the depth of cut and spindle speed has least effect on surface roughness.
- While predicting the value of surface roughness major emphasis should be given to value of feed rate.
- Positive effect of amplitude of cutting tool's vibrations was identified on surface roughness. It shows that to achieve accurate value of required surface roughness, effect of vibration cannot be neglected.
- The full factorial run is proven to be a best choice because it involves all the possible combination of parameter values and gives minimum error rate hence shows accuracy of the experimental setup and statistical model and roughness values can be predicted up to close level of accuracy and precision.
- Cross relationship curves and Histograms drawn for actual vs. predicted surface roughness for both approaches show a close relationship among those roughness values proving effectiveness of 'Regression Model' with least rate of error.

REFERENCE

1. Safeen, Kassab Y., Younis and Khoshnaw K., 2007. The Effect of Cutting Tool Vibration on Surface Roughness of Work piece in Dry Turning Operation. Journal of Eng. & Technology, 25(7).

2. Lin S. C. and Chang M. F., 1998. Study on the Effects of Vibrations on The Surface Finish Using a Surface Topography Simulation Model for Turning. Int. J. of Machine Tools & Manuf., 38(7): 763-782.

3. Huang L. H. and Chen J. C., 2001. A Multiple Regression Model to Predict In-Process Surface Roughness in Turning Operation via Accelerometer. Journal of Industrial Technology, 17(2): 1-8.

4. Risbood K. A., Dixit U. S. and Sahasrabudhe A. D., 2003. Prediction of Surface Roughness and Dimensional Deviation by Measuring Cutting Forces and Vibrations in Turning Process. Journal of Materials Processing Technology, Elsevier. 132(1): 203-214.

5. Kassab Safeen Y. and Khoshnaw Younis K., 2007. The Effect of Cutting Tool Vibration on Surface Roughness of Workpiece in Dry Turning Operation. Jour. of Eng. & Technology, 25: 879-889.

6. Tobias, S.A. 1965. Machine-Tool Vibration, Blackie, London, pp. 286-295.

7. Cirstoiu C. A., 2005. Influence of Feed Rate on Surface Roughness in Turning Processes with Different Tool Inserts. UPB Scientific Bulletin, Series D: Mechanical Engineering, 67(2):63-70

8. Ozel T., Hsu T. K., & Zeren E., 2005. Effects of Cutting Edge Geometry, Workpiece Hardness, Feed Rate and Cutting Speed on Surface Roughness and Forces in Finish Turning of Hardened AISI H13 Steel. Journal of Advanced Manufacturing Technology, 25(3-4): 262-269.

9. Thomas M. and Beauchamp Y., 2003. Statistical Investigation of Modal Parameters of Cutting Tools in Dry Turning. International Journal of Machine Tools & Manufacture. 43; 1093–1106

10. Chelladurai H., Jain V. K. and Vyas N. S., 2008. Development of a Cutting Tool Condition Monitoring System for High Speed Turning Operation by Vibration and Strain Analysis. International Journal of Advance Manufacturing Technology 37:471–485.

11. Rawangwong S., Chatthong J., Burapa R. and Boonchouytan W., 2012. An Investigation of Optimum Cutting Conditions for Quality of Surface Roughness in Face Milling Mold Steel AISI P20 Using Carbide Tool. In Proceedings of the Asia Pacific Industrial Engineering & Management Systems Conference.

12. Henderson G.R. Six Sigma: Quality improvement with MINITAB, 2006. John Wiley and Sons, England, ISBN: 10: 0470011556, pp: 452.

13. Nalbant N., Gokkaya H. and Sur G., 2006. Application of Taguchi Method in the Optimization of Cutting Parameters for Surface Roughness in Turning. Jour. of Materials and Design. 127: 17–22.

14. Kriby D. E, Zhang Z. and Chen J. C., 2004. Development of an Accelerometer-Based Surface Roughness Prediction System in Turning Operations Using Multiple Regression Techniques. J. of Ind. Technol. 20(4):1–8.

15. Gopalsamy Bala M., Mondal B. and Ghosh S., 2009. Taguchi Method and Anova: An Approach for Process Parameter Optimization of Hard Machining While Machining Hardened Steel. Jour. of Scientific and Ind Res., 68: 686-695.