Optimization of Surface Finish in Turning Operation by Considering the Machine Tool Vibration using Taguchi Method

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RECEIVED ON 02.06.2009 ACCEPTED ON 18.11.2009

ABSTRACT

Optimization of surface roughness has been one of the primary objectives in most of the machining operations. Poor control on the desired surface roughness generates non conforming parts and results into increase in cost and loss of productivity due to rework or scrap. Surface roughness value is a result of several process variables among which machine tool condition is one of the significant variables. In this study, experimentation was carried out to investigate the effect of machine tool condition on surface roughness. Variable used to represent machine tool's condition was vibration amplitude. Input parameters used, besides vibration amplitude, were feed rate and insert nose radius. Cutting speed and depth of cut were kept constant. Based on Taguchi orthogonal array, a series of experimentation was designed and performed on AISI 1040 carbon steel bar at default and induced machine tool's vibration amplitudes. ANOVA (Analysis of Variance), revealed that vibration amplitude and feed rate had moderate effect on the surface roughness and insert nose radius had the highest significant effect on the surface roughness. It was also found that a machine tool with low vibration amplitude produced better surface roughness. Insert with larger nose radius produced better surface roughness at low feed rate.

Key Words: Taguchi Method, Surface Roughness, Vibration Amplitude, ANOVA, Optimization.

1. INTRODUCTION

Every machine tool user is familiar with vibration in metal cutting operations. This phenomenon is especially recognized in cutting operations carried out on turning and milling machines. There are several reasons for occurrence of this problem including machine tool condition, job clamping, tool and workpiece geometry, and cutting parameters used for machining [1-3]. Machine tool's condition is one of the most important factors causing vibration. Vibration level of machine tool may change with the passage of time due to its uses and the wear/tear. Kirby [3] found that turning centre spindle running with used or damaged jaws, for example, has a different level of vibration than with new jaws. Vibration level would certainly depend upon the speed of the spindle and condition of the used jaws. Lin and Chang [4] studied the effect of radial vibrations on surface finish during cutting, and they found that the vibration amplitude and frequency both have strong effects on the surface roughness. Improper tool geometry can also produce vibration in cutting. Vibration may also generate during turning if the insert nose radius being used is greater than the depth of cut [5]. Control of vibration during machining is very important, as it has an adverse effect on machining performance such as surface

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roughness, tool wear, and cutting forces [6]. It may also increase the production cost due to an increase in consumption of energy [7]. Some research work carried out on achieving or controlling desired response variables, like surface roughness and tool wear, involve either automatic reduction of controlled cutting parameters or stabilization of relative position of cutting tool and work piece [8-9]. The most readily controlled parameters in cutting operations are cutting speed, feed rate, depth of cut, and insert nose radius. Cutting speed, feed rate, and insert nose radius have a significant influence on surface roughness, where depth of cut has shown either little or no effect on it [10-13].

Literature reviewed shows that investigation of effect of vibration has been mainly carried out by taking into account the vibration produced during cutting operations. In the current study, an attempt has been made to relate the surface roughness with the dry run vibration level. The dry run vibration level indicates the machine tool condition. Therefore, the machine tool condition may be related to the surface roughness. Machine tool's vibration amplitude measurement can be done by considering any one among displacement, velocity, and acceleration. The spindle speed selected for the present study was around 3500 revolution per minute. The most appropriate variable for measurement of vibration amplitude suggested at this spindle speed is velocity as in the Entek IRD vibration manual [14]. Therefore, the experimentation was carried out by measuring velocity amplitude. Controlled parameters considered along with vibration amplitude were feed rate and insert nose radius. Controlled parameters cutting speed and depth of cut were kept constant. Surface roughness was selected as the response variable to be investigated. Taguchi orthogonal array L_9 [15] with the objective of fewest experiment was used. S/N (Signal-to-Noise) ratio and variance (ANOVA) analyses were employed to find the optimal levels of the controlled cutting parameters for optimization of surface roughness.

2. TAGUCHI TECHNIQUE FOR DESIGN OF EXPERIMENT

The Taguchi method is one of the popular statistical techniques used in research [15-17]. The past work shows that this technique is indeed an effective and quick tool in developing a robust and quick model that has a wide range of applications in engineering. In traditional full factorial DoE (Design of Experiment), a large number of experiments have to be carried out when the number of process parameters and their levels increase. Taguchi method uses a special technique called orthogonal arrays to solve this problem. Orthogonal Array is a useful tool to decrease the number of experiments resulting in decreasing the time and cost of experimentation and analysis.

For conducting the tests, the orthogonal array L_9(3x4) has been selected. Orthogonal array L_9(3x4) has four columns (i.e. factors or parameters) and 9 rows (i.e. runs) as shown in Table 1. The Column-1 of the Table 1 was assigned to vibration amplitude, Column-2 was assigned to feed rate, and Column-3 was assigned to insert nose radius as shown in the Table 2. Fourth column of the orthogonal array, L_9, was left empty for the error of experiments. Orthogonality is not lost by letting one column of the array remain empty. Table 2 shows the input parameters and their levels used in the present study.

TABLE 1. TAGUCHI L_9(3X4) ORTHOGONAL ARRAY

Test No.	1	2	3	4
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

2.1 Machine Tool's Vibration Amplitude Levels Measurement

Three levels of vibration amplitude were recorded, one default and two induced, during dry run, i.e. without machining. The default level of vibration was recorded by running the spindle at different speeds, as shown in Table 3. The first induced level (i.e. second level) of vibration was achieved by fastening a mild steel ring on the chuck of the machine as shown in Fig. 1. Unbalance mass weighing 57gm, was attached to this ring for generating this induced vibration level. The second induced level (i.e. third level) of vibration was achieved by attaching unbalance mass weighing 85gm. Unbalance masses were the small pieces of steel that were attached to the mild steel ring, fastened on the chuck of the lathe, at a radial distance of 107mm from the centre. Vibration amplitude readings, for three levels, were recorded using vibration analyzer RBM collector 2117-A series. The magnetic type accelerometer of the vibration analyzer was attached to the spindle bearing housing for recording the readings for vibration amplitude.

2.2 Fixed Parameters

The workpiece material used in this series of experiments was AISI 1040 carbon steel bar of one inch diameter, which has wide range of applications in manufacturing especially in automobile industry. The major applications include crankshafts, coupling, and cold heated parts. As the initial

TABLE 3. MACHINE TOOL'S VIBRATION AMPLITUDE LEVELS READINGS

Serial No.	Spindle Speed (rpm)	Vibration Amplitude, a (mm/min)		
		Level-1 Default	Level-2 Induced	Level-3 Induced
1.	1000	0.07	0.17	0.22
2.	1500	0.09	0.27	0.46
3.	2000	0.12	0.34	1.11
4.	2500	0.13	1.16	1.81
5.	3000	0.15	1.47	2.32
6.	3500	0.19	1.69	3.29
7*.	3521	0.20	1.80	3.40
8.	4000	0.23	1.95	6.33
9.	4500	0.25	2.08	**
10.	5000	0.28	2.45	**
11.	5500	0.32	2.83	**
12.	6000	0.33	3.01	**

*Vibration amplitude levels taken at cutting speed of 250 m/min for this study are shown in Table 4.

**Vibration amplitude levels at higher spindle speeds were not taken for machine tool safety.

TABLE 2. EXPERIMENTAL RESULTS FOR SURFACE ROUGHNESS USING DESIGN OF L_9(3X4) EXPERIMENT FOLLOWING ORTHOGONAL ARRAY AT CONSTANT CUTTING SPEED=250 M/MIN

Test No.	a (mm/min)	f (mm/rev)	r (mm)	R_a (μm)	Average R_a at Three Vibration Levels (μm)	S/N Ratio (η)
1	0.2	0.100	0.4	0.753	0.616	2.464
2	0.2	0.125	0.8	0.501		6.003
3	0.2	0.150	1.2	0.593		4.538
4	1.8	0.100	0.8	0.563	0.818	4.989
5	1.8	0.125	1.2	0.571		4.867
6	1.8	0.150	0.4	1.320		-2.411
7	3.4	0.100	1.2	0.691	0.937	3.210
8	3.4	0.125	0.4	1.220		-1.727
9	3.4	0.150	0.8	0.901		0.906
Overall Means				0.790		2.538

surface roughness condition of the job could influence the surface quality of the final product [18]. So in order to ensure a clean surface before experimentation, each workpiece was machined at nominal diameter of 25mm. This also helped to have the same depth of cut of 1.2mm in each run during experimentation. In order to assure the necessary stiffness of the workpiece, the overall cutting length of each workpieces was kept 65mm. This fixed the length to diameter ratio to 2.9/1. Cutting speed range defined in the Cutting Tool Catalogue by KYOCERA, was 160-250 m/min. In this study constant cutting speed at higher level of 250 m/min was chosen, as higher cutting speed generates low values of surface roughness [11-12]. Although as described earlier, depth of cut has shown insignificant or little effect on the surface roughness. Even than it was kept constant at a value of 1.2mm which is equal to the maximum insert nose radius being used.

2.3 Experimental Setup

The experimentation was carried out on slant bed EMCO Concept turn 345-series CNC lathe machine having maximum power of 21KW, maximum spindle speed of 6000 rpm, and maximum feed rate of 8000 mm/min. The three input variables used in this study were vibration amplitude, feed rate, and insert nose radius as shown in Table 4. As by Groover, M.P. [19], the surface roughness, feed rate, and insert nose radius are important parameters having the following relationship:

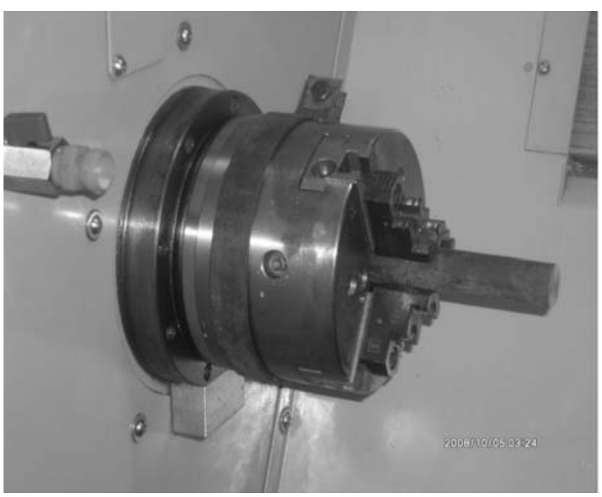

FIG. 1. UNBALANCED MASS ATTACHED TO MILD STEEL RING FASTENED ON THE CHUCK FOR GENERATING INDUCED LEVEL OF VIBRATION

$$R_a = f^2/(32 \times r) \quad (1)$$

Where R_a is average surface roughness (μm or μ-in), f is feed (mm/rev or inch/rev) and r is non-zero insert nose radius (mm or inch).

The spindle speed (rpm) corresponding to cutting speed 250 m/min at a cutting diameter of 22.6mm was 3521. The recommended feed rate given for the AISI carbon steel 1040, in the cutting tools catalogue, ranges from 0.1-0.2 mm/rev. As low feed produces good surface roughness [5-6], therefore, feed rate range selected for this study was 0.10-0.15 mm/rev. The hardness of the workpiece materials, AISI 1040 carbon steel, was tested and the average value was found to be 27.2 HRC. The working was done with C type negative, multi layers coated inserts CNMG 120404, CNMG 120408 and CNMG 120412 each having grade CA5525 [20]. These inserts have chip breaker geometry of type CQ, which has a broader range of applications. The insert has rake angle of -6º and inclination angle of -6º as shown in Fig. 2. The tool holder used for the inserts was PCLNL2020K12.

TABLE 4. INPUT PARAMETERS AND THEIR LEVELS

Level	Vibration Amplitude a, (mm/min)	Feed Rate f, (mm/rev)	Insert Nose Radius r, (mm)
1	0.20	0.100	0.4
2	1.80	0.125	0.8
3	3.40	0.150	1.2

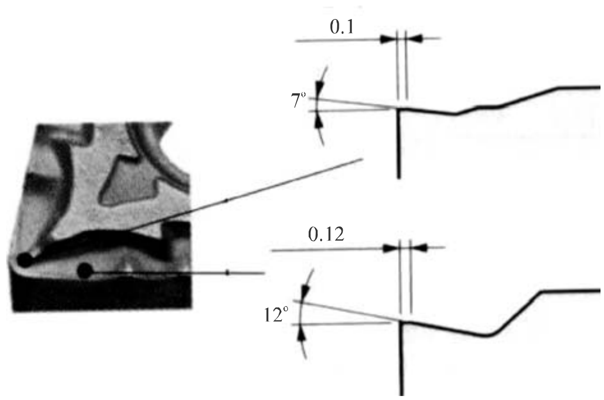

FIG. 2. CQ TYPE INSERT CHIP BREAKER GEOMETRY

The workpieces were machined at default level and two induced levels of vibrations. The surface roughness was measured with surface texture meter by Taylor Hobson, UK as shown in Table 2. For measurement of the surface roughness of the machined work pieces, cut off length and evaluation length were set to 0.8 and 4mm respectively. A total of three reading for each run of surface roughness were taken. Then average surface roughness, R_a, for each run was calculated.

3. EXPERIMENTAL RESULTS AND DISCUSSION

Statistical treatment of the data has been made into three phases Following sub-sections describe S/N ratio analysis, ANOVA, and optimization applied to the experimental results. In the 1st phase, S/N ratio analysis was carried out for knowing the optimal levels of the controlling variables. In the 2nd phase ANOVA has been carried out for knowing the significant factors. In the 3rd and final phase, based on the results of the S/N ratio and ANOVA analyses, optimal setting of the parameters for surface roughness were obtained and verified through confirmation test.

3.1 Analysis of the Signal-to-Noise Ratio

Taguchi recommends the use of S/N ratio to measure the quality characteristic deviation from the desired values. The term 'Signal' represents the desired value (i.e. mean) for the response and the term 'Noise' represents the undesired value (i.e. SD). Therefore, S/N ratio is the ratio of the mean to SD. Usually there are three categories of quality characteristic in the analysis of S/N ratio, i.e. the larger-the-better, the smaller-the-better, and the nominal-the-better. Regardless of the category of the quality characteristic, a greater S/N ratio corresponds to better quality characteristic. In this experiment, the S/N ratio for each level of process parameter was computed based on the smaller-the-better S/N analysis for the surface roughness. The experiments were conducted aiming at determining the effect of machine tool condition, in term of vibration amplitude, on surface roughness of the workpiece. Table 2 shows the values of S/N ratio, η, corresponding to the average surface roughness of each run calculated using the Equation (2) [21]:

$$\eta = -10 \log [(\Sigma y_i^2)/n] \quad (2)$$

Where η is the S/N ratio, y_i is surface roughness measurements in a run, and n is the number of replicates.

In this case the S/N ratio is based on the Taguchi smaller-the-better loss function, as the idea is to minimize the response, i.e. surface roughness. The S/N ratio is a summary statistic which indicates the value and dispersion of the response.

Since the experimental design is orthogonal, it is then possible to separate out the effect of each parameter at different levels. For example, the mean S/N ratio for the vibration amplitude at levels 1-3 can be calculated by averaging the S/N ratio for the Experiments 1-3, 4-6 and 7-9, respectively. The mean S/N ratio for each of the other parameter can be computed in the similar manner. The mean S/N ratio for each level of the cutting parameters is summarized and called the mean S/N response table for the surface roughness. The S/N response table and S/N response graph are shown in Table 5 and Fig. 3, respectively.

3.2 ANOVA Analysis for Average Surface Roughness, R_a

The response values of R_a range from 0.501-1.320µm as shown in Table 2 and provide the ratio of maximum to

TABLE 5. S/N RESPONSE TABLE FOR SURFACE ROUGHNESS

Symbol	Cutting Parameter	Mean S/N Ratio (dB)			
		Level-1	Level-2	Level-3	Max-Mini
A	Vibration Amplitude	4.335	2.482	0.796	3.539
B	Feed Rate	3.555	3.048	1.011	2.544
C	Insert Nose Radius	-0.558	3.966	4.206	4.764

minimum that is equal to 2.635. In order to obtain a better fit with coefficient of correlation, R^2=85.55%, a linear model for ANOVA was used. Table 6 presents the ANOVA detail for this linear model. From Table 6 it is clearly observable that the effect of factors vibration amplitude (A) and insert nose radius (C) are significant. Feed rate (B) has also shown significant effect on the R_a as 'Prob> F' value is less than 0.1 [22]. It is also observable from Table 6 that the effect of insert nose radius is about 2 times more significant than that of the vibration amplitude and 3 times more significant than the feed rate. Hence it is concluded that machine tool condition, i.e. vibration amplitude and feed rate have moderate effect on surface roughness and the insert nose radius has the highest significant effect on the response.

It is also evident from the Table 2 that average surface roughness value has been increased by 33% as the machine tool vibration amplitude increases from level 1-2. Similarly average surface roughness value has been increased by 15% as the machine tool vibration amplitude increases from level 2-3. It is expected that due to increase in vibration

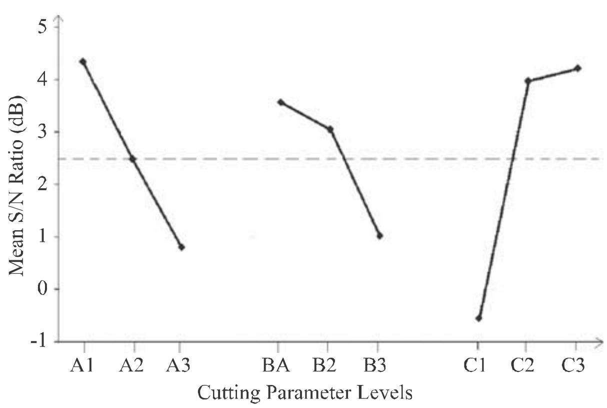

FIG. 3. S/N RATIO GRAPH FOR SURFACE ROUGHNESS

amplitude of the machine tool, the distance of workpiece centerline varies with reference to cutting edge. Therefore, this variation results into more crests and troughs on the surface, i.e. surface roughness. So it can be said that a machine tool having low level of vibration amplitude produces better surface roughness. Similarly low surface roughness value is achieved with the larger nose radius of insert and low feed rate. It is just a preliminary study in this area and further research is needed by considering more input parameters like material hardness, insert chip breaker geometry, and output parameter tool life along with surface roughness.

3.3 Optimization Followed by Confirmation Tests

The statistical method, NOVA, is performed to see which process parameters are statistically significant. Further, the optimal level of the significant process parameters is the level with the greatest S/N ratio. With ANOVA and the S/N ratio analyses, the optimal combination of the process parameters then can be predicted. Therefore, based on the ANOVA, and S/N analyses, the optimal cutting parameters for the surface roughness are the vibration amplitude at level 1, feed rate at level 1, and insert nose radius at level 3. As the optimal level of the design parameters has been selected, the final step is to predict and verify the improvement in the surface roughness using the optimal level of the design parameters. The predicted S/N ratio, η_{pred}, using Taguchi method [16, 21], with the optimal levels of the input parameters can be calculated as:

$$\eta_{pred.} = \eta_m + (\eta_A - \eta_m) + (\eta_B - \eta_m) + (\eta_C - \eta_m) \quad (3)$$

TABLE 6. RESULTS OF ANOVA FOR SURFACE ROUGHNESS

Source	Sum Squares	df	Mean Squares	F-Value	Prob>F	Significance
A-a	0.16	2	0.080	7.55	0.0404	Significant
B-f	0.11	2	0.055	5.28	0.0699	Significant
C-r	0.34	2	0.170	16.78	0.0094	Significant
Error	0.10	2	0.050			
Total	0.70	8				

Where, η_m is the overall mean S/N ratio and η_A, η_B, η_C, are the S/N ratios of the factors A, B, and C respectively at their optimal levels. The predicted S/N ratio for the surface roughness at the optimal cutting parameters levels can then be obtained. The corresponding surface roughness to this predicted S/N ratio can be calculated by using the Equations (2-3). Table 7 shows comparison of the predicted surface roughness with the actual surface roughness at the optimal cutting parameters levels. The increase in value of the S/N ratio from the initial cutting parameters levels to the optimal cutting parameters levels is 4.623dB. Therefore, the surface roughness value is improved by about 2.05 times of the initial predicted surface roughness. In other words, the experimental results confirm the suitability of Taguchi design for analyses and optimization of the response variable and cutting parameters. Therefore, surface roughness in straight turning operation is greatly improved through this technique.

4. CONCLUSIONS

This study provided the profound analysis of dependence of surface roughness on machine tool condition, through the use of the Taguchi parameter design process. The following conclusions can be summed up on the basis of the experimental results obtained in this study.

(i) The use of L_9 orthogonal array, with three control parameters required only nine runs to conduct the experiment, one third the runs required for a full factorial design.

(ii) Machine tool condition, i.e. vibration amplitude and feed rate have moderate effect on the surface roughness.

TABLE 7. RESULTS OF CONFORMATION EXPERIMENT FOR R_a

Initial Cutting Parameters Levels		Optimal Cutting Parameters Levels	
		Prediction	Experiment
Level	A2B2C2	A1B1C3	A1B1C3
R_a (μm)	0.601	0.446	0.353
S/N Ratio (dB)	4.421	7.020	9.044
Improvement of S/N Ratio =4.623 dB			

(iii) Insert nose radius has shown the highest effect on surface roughness.

(iv) Low level of vibration amplitude of machine tool produced a good surface finish and got deteriorates as the vibration amplitude increases.

(v) Insert with larger nose radius has shown better results for obtaining low surface roughness at low feed rate.

(vi) This design had yielded an optimum condition for the input parameters using ANOVA and S/N ratio. The verification process was then performed using the predictive equation, which indicated that deviation between actual and predicted S/N ratio of surface roughness was small.

(vii) The improvement of the surface roughness from initial cutting parameters to the optimal cutting parameters was about 100%.

ACKNOWLEDGEMENTS

The authors are indebted to the Department of Industrial & Manufacturing Engineering, University of Engineering & Technology Lahore, and HEC (Higher Education Commission), Pakistan, for having made this research possible. The authors are also thankful to the Dr. Afzaal Malik, National University of Science & Technology, Pakistan, for his valuable suggestions and comments.

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