Experimental Investigation of Cutting Parameters influence on Surface Roughness in turning of Alloy Steel ASTM A182, Grade F91

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Abstract

The purpose of this experimental investigation was to analyze the effect of controlled cutting parameters (Cutting Speed, Feed rate, Depth of cut, Insert radius) on surface roughness (R_a) in turning of ASTM A182, Grade F91 alloy steel. The surface was evaluated in term of surface roughness. Taguchi method (L_9 design with 4 factors and 3 levels) has been employed in the optimization of cutting parameters for surface roughness. L_9 orthogonal array, signal-to-noise ratio and analysis of variance have been implemented to study the performance characteristics in turning using carbide insert. Validation tests with optimal levels of parameters were performed to demonstrate the effectiveness of Taguchi optimization. The analysis reveals that feed rate has the most significant effect on surface roughness accounting 74.44% contribution, whereas insert radius is another significant parameter which accounts for 16.83% contribution on surface roughness.

Keywords

Turning process, ASTM A182, Gr.F91, Surface Roughness, Taguchi Method

I. Introduction

ASTM A182, Gr.F1 finds its application in Oil & Gas, Petrochemical, Chemical & Fertilizers, and Power Generation components such as Pipe Flanges, Forged Fittings, and Valves and Parts for High-Temperature Service. Predicting process of machinability models and determining the optimum values of controlled process parameters in manufacturing system have been areas of interest for researchers and manufacturing engineers. The surface roughness of machined parts is a significant design specification that is known to have considerable influence on mechanical properties such as wear resistance, fatigue strength and refers to deviation from the nominal surface. This material is attractive because of its properties such as high hardness, toughness, yield strength, excellent ductility and compatibility at high-temperature service. But machining of this material is difficult than carbon and low alloy steel because of high strength, and a higher degree of ductility and work hardenability [1, 2]. The problems such as poor surface finish and higher tool wear are common while machining these materials. In the machining process, one of the most notable mechanical requirements of the customers is surface finish. To improve the fatigue strength, wear resistance, and aesthetic appeal, a good surface finish is required. A substantial amount of studies have investigated the general effect of process parameters (cutting speed, feed rate, depth of cut, insert radius) on process functions such as surface roughness, tool life, cutting forces etc. [3, 4]. Most of these models are based on the regression analysis (RA), very few researchers used computational neural networks techniques (CNN) [5-9]. In this paper our main objective is to study the influence of cutting parameters on ASTM A182, Gr.F91 alloy steel workpiece surface roughness by employing design of experiments via Taguchi methods and Analysis of Variance (ANOVA) using carbide insert on CNC lathe machine. Four machining parameters were considered (Cutting speed (v, m/min.), Feed rate (f, mm/rev.), Depth of cut (d, mm), Insert radius (r, mm)). Therefore this paper presents the following contributions: at first, it applies Taguchi concept to design the process for machining using an orthogonal array. Secondly, it applies response to perform analysis of mean (ANOM) and analysis of variance (ANOVA) to optimize and reveal significant cutting parameters to improve surface roughness using Minitab15 software [10]. Finally, the resulting models are compared against each other to illustrate the most appropriate approach for predicting the best model of the considered response.

Several experimental investigations have been carried over the years in order to study the influence of various cutting parameters on the surface finish of the workpiece, tool life using workpieces of different materials.

M.Nalbant et al. [11] implemented the Taguchi method to find out optimum cutting parameters for surface roughness in turning. ANOVA method was employed to study the performance characteristics in turning of AISI 1030 steel bar using TiN-coated tools. The study reveals that the feed rate and the insert radius were the main machining parameters that affect the surface roughness in turning of AISI 1030.

Ilhan Asilturk et al. [12] focuses on optimization of turning parameters based on Taguchi method to minimize surface roughness (Ra&Rz). Experimental have been carried out using L9 orthogonal array in CNC turning. Dry turning tests were carried out on hardened AISI 4140 with coated carbide tools. It has been observed that feed rate has the most significant effect on the surface roughness.

M. Antony Xavior et al. [13] carried out an experiment to determine the influence of cutting fluids on tool wear and surface roughness during turning of AISI 304 with carbide tool. Further, an attempt was made to identify the influence of coconut oil in reducing the tool wear and surface roughness during the turning process. The performance of coconut oil was compared with another two cutting fluids namely an emulsion and a neat cutting oil (immiscible with water). The experiment results indicated that coconut oil as a cutting fluid performed better than the other two cutting fluids by improving the surface finish and reducing the tool wear.

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A. Taguchi Design of Experiment

Taguchi Method is a qualitative statistical approach to optimize the process parameters and improve the quality of parts that are manufactured. In the early 1950s, Dr. Genichi Taguchi, "the father of Quality Engineering", established the concept of off-line Quality control techniques known as Taguchi process parameter design [14]. Off-line Quality control techniques are those activities executed during the product or process design and development phases. Taguchi parameter design is completely based on the concept of fractional factorial design [15]. Taguchi design of experiment is a powerful methodology designed for finding the optimum levels of the control process parameters (cutting parameters in machining) to make the product or process impervious to the noise factors [16, 17]. The Taguchi method for quality is based on matrix experiments, and these experimental matrices are special orthogonal arrays (OA's), which allow the effects of several process parameters to be studied simultaneously[16, 17]. The motive of conducting an orthogonal experiment is to determine the most optimum level for every single process parameter and to evaluate the relative significance of individual parameter on performance characteristics [16, 17]. Classical experimental design methods are too complex, time-consuming and not simple to implement. A large number of experimental trials have to be performed when more parameters or factors are involved. To resolve this problem, the Taguchi methodology uses a special purpose design of orthogonal arrays (OA's) to study the complete parameter space with the lesser number of experimentations. Taguchi conveys that signal-to-noise (S/N) ratio (for loss function) is the main objective function for orthogonal matrix trials [16, 17]. The signal-to-noise ratio for each sample is used to measure performance characteristics and shows the degree of expectable performance in the existence of noise factors. Taguchi categorizes the S/N ratio into three different types "smaller the better", "larger the better" and "nominal the best" based on the nature of objective functions. The "Analysis of Means" (ANOM) established on the Signal-to-Noise ratio is used to determine the optimum levels of the process parameters in Taguchi's design of experiment. The optimal level for a process parameter is the level of outcomes with the maximum value of signal-to-noise ratio in the experimental region. The "Analysis of Variance" (ANOVA) in Taguchi constraint design creates the comparative significance of various process parameters and is performed on the S/N ratios to find the percentage contribution of each process parameter [16, 17].

II. Experimental Details

The details of experimental conditions, equipment, instruments, measurements and the procedure adopted for the study are described in this section.

A. Materials and Methods Used

Turning is a popular material removal process in which a cutting tool removes the unwanted outer layer of material from the rotating cylindrical workpiece. The Computer Numerical Controlled (CNC) machine plays a critical function in current machining industry to improve an item quality and profitability [18]. The workpiece material selected for investigation is ASTM A182, Gr. F91 alloy steel round bar. In the present work, we have used a round workpiece of dimensions 100 mm length and 25 mm diameter. The chemical composition, mechanical and physical properties of ASTM A182, Gr. F91 alloy steel are shown in Table-1 and Table-2 respectively.

Table 1: Chemical Composition of ASTM A182, Gr. F91

Element	%	Element	%
C%	0.087	Cu%	0.062
Si%	0.486	Al%	0.019
Mn%	0.500	S%	0.008
Cr%	8.156	P%	0.017
Ni%	0.192	Ti%	0.002
Mo%	0.970	Nb%	0.0060
V%	0.223	Fe%	89.200

Table 2: Mechanical and Physical Properties of ASTM A182, Gr. F91

Properties	**Metric**
Tensile strength, ultimate	585 MPa
Tensile strength, yield	415 MPa
Bulk modulus (typical for steel)	140 GPa
Poisson's ratio (calculated)	0.27 – 0.35
Elongation at break (in 50 mm)	40 %
Hardness, Brinell	250

The experimental studies were carried out on CNC lathe model LMW LL20T L5. The experiments were carried out under full flooded coolant conditions. The tool holder was the model: WIDAX ID 01 MTJNR 2525M16 and carbide inserts TungaloyT9025 TNMG 160412, Widia Tn2000 – 160408, Kennametal K10P – 160404 were used as a cutting tool material. The surface roughness (R_a) was measured using a Mitutoyo Surf test SJ-201P portable Surface Roughness Tester with sampling length 2.5 cm. The values of the cutting parameters and cutting parameter range were chosen from the research paper for the tested material. The selected cutting parameters are shown below.

Table 3: Selected Cutting Parameters

Code	Control Factor	Level		
		1	2	3
A	Cutting Speed, (m/min)	90	110	130
B	Feed, (mm/rev)	0.10	0.15	0.20
C	Depth of Cut (mm)	0.25	0.50	0.75
D	Insert Radius (mm)	0.4	0.8	1.2

The Taguchi method and L_9 orthogonal array were used to reduce the number of experiments. The design of experiment and measured surface roughness (R_a) are shown in table 4. The experiments were conducted three times for each combination of process parameters.

Table 4: Orthogonal array with R_a Value

Experiment No	A	B	C	D	R_a (µm)
1	90	0.10	0.25	0.4	0.69556
2	90	0.15	0.50	0.8	0.87556
3	90	0.20	0.75	1.2	1.38889
4	110	0.10	0.50	1.2	0.64444
5	110	0.15	0.75	0.4	1.43222
6	110	0.20	0.25	0.8	1.31333
7	130	0.10	0.75	0.8	0.70000
8	130	0.15	0.25	1.2	0.86444
9	130	0.20	0.50	0.4	2.37556

The experiments are conducted with four controllable factors and three levels. Table-3 presents three controlled factors of the cutting speed (i.e., A (m/min)), the feed rate (i.e., B (mm/rev)), the depth of cut (i.e., C (mm) and the insert radius (i.e., D (mm)) with three levels of each factor.

Taguchi uses the signal-to-noise (s/n) ratio as a quality characteristic. The higher the ratio of the desired signal to the background noise, the lesser prominent the background noise. In the other words, the standard deviation cannot be minimized first the mean should be brought to the target value [19]. The S/N ratio can be classified into three categories given by equation when the characteristic is continuous:

The S/N ratio with a lower-the-better characteristic can be expressed as:

$$\eta_{ij} = -10\log\left(\frac{1}{n}\sum_{j=1}^{n} y_{ij}^2\right) \qquad (1.1)$$

The S/N ratio with a higher-the-better characteristic can be expressed as:

$$\eta_{ij} = -10\log\left(\frac{1}{n}\sum_{j=1}^{n} \frac{1}{y_{ij}^2}\right) \qquad (1.2)$$

The S/N ratio with a nominal-the-better characteristic can be expressed as:

$$\eta_{ij} = -10\log\left(\frac{1}{ns}\sum_{j=1}^{n} y_{ij}^2\right) \qquad (1.3)$$

This implicates that the system behaves in such a way that the manipulated production factor can be divided into three categories: where yij is the ith response of jth experiment, n is the total number of the tests and 's' is the standard deviation. With the above S/N ratio transformation smaller the value of S/N ratio better the result if we are considering tool wear, cutting forces, surface roughness etc. The deviation between experimental and desired value is known as loss function in Taguchi method. This loss is converted into signal-to- noise ratio [17]. In the Taguchi concept, the optimum parameter which gives minimum surface roughness can be obtained by using above equations and the "smaller-the-better" S/N ratio and desired level can be calculated by using equation (1.1). Since the objective function (Surface Finish) is the smaller-the-better type of control function, was used in calculating the S/N ratio. The S/N ratios of all the experiments were calculated with MINITAB15 [10] and tabulated as shown in Table-5.

Table 5: Calculated S/N Ratios for R_a

Experiment No.	Surface Roughness (R_a) (µm)	S/N Ratio (dB)
1	0.69556	3.124050
2	0.87556	1.114378
3	1.38889	-2.898680
4	0.64444	3.747104
5	1.43222	-3.224283
6	1.31333	-2.377857
7	0.70000	3.051739
8	0.86444	1.261758
9	2.37556	-7.585654

III. Data Analysis and Results

The most important data in Taguchi method for analyzing the experiment data is signal-to-noise ratios. The "Analysis of Means" (ANOM) based on the "S/N ratio" was used to determine the optimal levels of process parameters. The parameter level that corresponds to the highest value of S/N ratio is the best level of Combination. The optimum cutting parameters are found to be A_1, B_1, C_1, D_3, which were Cutting speed (A) 90m/min, Feed rate (B) 0.10mm/rev, Depth of cut (C) 0.25mm and Insert radius (D) 1.2mm were obtained for the best Ra values. Level values of the factor obtained for Ra according to the Taguchi design are given in Table-6 below. Figure-1 shows the graphical representation of the level values A, B, C and D factors given in Table-6 and assist in determining the optimum cutting parameters of the experiment constructed under the same conditions.

Table 6: ANOM for R_a values based on S/N ratios

Parameters	Level 1	Level 2	Level 3	Opt. Level
Cutting Speed (A)	0.447	-0.618	-1.091	1
Feed (B)	3.308	-0.283	-4.287	1
DOC (C)	0.669	-0.908	-1.024	1
Insert Radius (D)	-2.562	0.596	0.703	3

A. Main Effect Plots Analysis

The main effect plots analysis is made with the assistance of software package MINITAB-15 [10]. The main effect of the plot is shown in Figure-1. It demonstrates the variation of every single response with four parameters i.e. Cutting speed, Feed rate, Depth of cut and Insert radius distinctly. In the plot, x-axis signifies the value of each process parameter and y-axis signifies the response value. The mean of the response is indicated by the horizontal line. The main effect plots are utilized to determine the optimal design conditions to get the ideal surface finish. As indicated by main effect plots, the ideal conditions for least surface roughness (R_a) are Cutting speed at level 1 (90 m/min), Feed rate at level 1 (0.10 mm/rev), Depth of cut at level 1 (0.25 mm) and Insert Radius at level 3 (1.2 mm).

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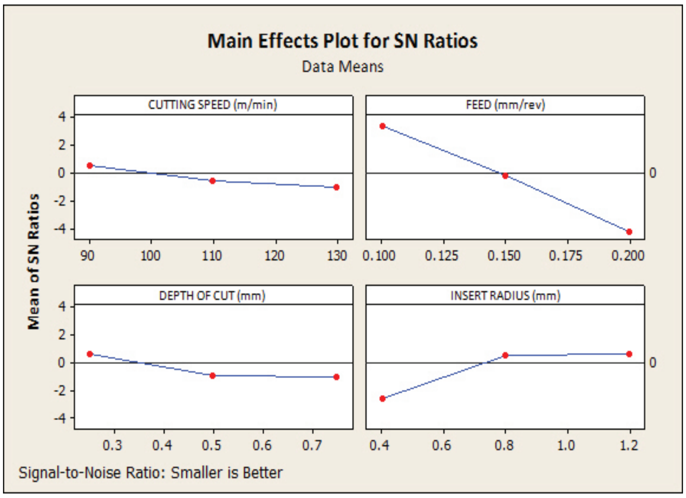

Fig. 1: Main Effect Plot for SN Ratios

B. Analysis of Variance

The "Analysis of Variance" (ANOVA) based on S/N ratio has been implemented to study the effects of turning process parameters quantitatively [16, 17]. The summary of results ANOVA for surface roughness (R_a), is given Tables-7. It can be observed from the ANOVA tables that feed rate (74.44%) and insert radius (16.83%) make major contributions in minimizing the surface roughness; whereas cutting speed and depth of cut have least effects in minimizing the surface roughness. Thus it can be concluded that with the decrease in the value of feed rate and increase in the value of insert radius, the value of surface roughness (R_a) will decrease. The result for data analysis for R_a values which is calculated with the help of Taguchi method are shown in the table-7 below where (SS is the sum of squares, DF is the degree of freedom, F is variance ratio, PC is percentage contribution and MS is the mean of sum of squares). Thus it seems that in both Table-6 and Figure-1 that first level of factor A (Cutting speed), the first level of B (Feed rate), the first level of C (Depth of cut) and third level of D (Insert Radius) are the optimum cutting parameters for the current turning process.

Table 7: Analysis of Variance for R_a

Factors	DF	SS	MS	F	PC
Cutting Speed	2	3.721	1.860	3.490	3.19
Feed	2	86.613	43.306	81.253	74.44
DOC	2	5.368	2.684	5.036	4.61
Insert Radius	2	19.581	9.791	18.370	16.83
Error	2	1.066	0.533		0.916
Total	10	116.348	11.635		100.00

The optimum condition for carrying out the final experiment will be A1 B1 C1 D3 i.e. Cutting speed 90m/min, Feed rate 0.10mm/rev, Depth of cut 0.25mm and Insert radius 1.2mm.

IV. Validation Test of Optimal Results

After selecting the optimal level of process parameters, the last step is to predict and confirm the performance characteristics. The predicted optimum value of S/N ratio (is given by [15]):

$$\eta_{opt} = m + \sum_{j=1}^{p}\left[(m_{i,j})_{max} - m\right]$$

Where $(m_{i,j})_{max}$ is the S/N ratio of the optimum level of parameter j, m is the overall mean of S/N ratio and p is the number of parameters that affect the machinability characteristics.

Table 8: Results of Validation test

Performance Measures	R_a
Optimum Levels (A, B, C, D)	A1, B1, C1, D3
Experimental Value (R_a) (µm)	0.61194
S/N Experimental (dB)	4.20383
S/N Predicted (dB)	3.93940
Improvement in Prediction (dB)	0.26442

Good agreement has been found between the predicted machining performance and actual machining performance. The 0.26442(dB) improvement of the S/N ratio for the individual performance characteristics is needed. The confirmation experiment result confirms the optimum cutting parameters with performance characteristics in turning operation.

V. Conclusion

The following are the conclusions drawn based on the experimental investigation conducted on turning ASTM A182, Gr. F91 alloy steel using Carbide insert at three levels by employing Taguchi technique to determine the optimal level of process parameters.

- The L_9 Orthogonal array has been selected for three different levels of process parameters i.e. insert radius, cutting speed, feed rate, depth of cut by using Taguchi's concept, as a result, nine experiments were conducted instead of 27 experiments. Surface roughness and S/N ratio for the surface roughness were measured and calculated respectively according to the L_9 orthogonal array. The maximum value of S/N ratio is calculated using the smaller is the better equation. The optimum cutting condition which responds to maximum 4.20383(dB) S/N ratio value of the R_a value 0.61194(µm) for the surface roughness in turning were found to be cutting speed 90m/min, feed rate 0.10mm/rev, depth of cut 0.25mm, and insert radius 1.2 mm.
- Variance analysis was applied to S/N ratio to find out the effect of cutting parameters on surface roughness. According to the ANOVA analysis, it was found the feed rate influence the surface roughness the most at the reliability level of 95%.
- The improvement of the S/N ratio from optimum cutting parameters to the experimental cutting parameters is about 0.26442(dB).
- The surface roughness is improved by 6.71% with optimum parameters.

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