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Design optimization of cutting parameters for turning operations on CNC lathe using AISI 316L stainless steel.

First Author
Hammad Khan
Production Technology Dept.
Community College A.M.U Aligarh
Email: khanhammad46@gmail.com

Second Author
Kr. Mohd Salman
Production Technology Dept.
Community College A.M.U Aligarh
Email: slmn9358@gmail.com

Third Author
Mohd Mohsin Khan
University Polytechnic
Faculty of Engineering, AMU, Aligarh
Email: mosink123@rediffmail.com

Abstract

The current research focuses on the study of processing parameters for Turning the AISI 316 L. The main aim of the research is to optimize the parameters to achieve the minimum surface finish in a turning process of 316 L. The study is done using the Taguchi method, to conduct a series of experiments with specific parameters. ANOVA technique was utilized to determine a correlation between the processing parameters.

Introduction

316 L is known for its high corrosion resistance and high strength at elevated temperature. This is the reason it has found its wide application in marine industry, exhaust systems, heat exchangers, jet engine parts, aerospace and automobile sector. It contains less carbon in comparison to similar grade of steels (316, 304, 304 L etc.). The chemical composition of stainless steel is given in table 1.

Generally, the stainless steel is manufactured using casting, forging and final elements are machined or welded into the final format. And annealing is required to increase its ductility and reduce hardness before service period.

Turning is a common process used in industries to shape the raw metal bars to final cylindrical dimensions. However, care should be taken to keep the final dimensions within tolerance and surface roughness within acceptable limits. The current study focuses on the optimization of cutting parameters in a turning process on particular type of milling machine. The parameters are optimized to keep the surface roughness value (Ra and Rz) as minimum as possible.

Earlier Kopac et al. [1] considered cutting speed, cutting tool materials, feed rate and depth of cut as cutting parameters in machining C15 E4 steel on a lathe. They used the Taguchi orthogonal array of L16 (25), which has two levels and a degree of freedom of 13 in the experimental design. Wang and Lan [2] used orthogonal array of Taguchi method coupled with the Grey Relational Analysis (GRA) in considering the four parameters of cutting speed, depth of cut, feed rate and tool nose radius. Ilhan Asilturk conducted a similar study by optimizing cutting speed, feed rate and depth of cut to reduce surface roughness in a turning process[3]. They had chosen the L9 orthogonal array for the selection of processing parameters in Taguchi design. In addition, they have also conducted the ANOVA analysis for the evaluation of correlation of parameters. Neseli et al. [4] observed on the influence of tool geometry on the surface finish obtained in turning of AISI 1040 steel. Their study focused on the effect of tool geometry parameters on the surface roughness during turning. The intension of this study is to conduct an experimental analysis to evaluate the effect of processing parameters (feed rate, depth of cut and cutting speed) on surface roughness achieved for a particular type of milling machine. G. Basmaci[5] has investigated the effect of cooling system, feed rate and depth of cut for optimizing cutting force and surface roughness via Taguchi design. They divided processing parameters each at 3 levels and utilized the ANOVA to determine the optimal parameter levels.

The aim here is to identify parameters levels that can lead to minimum surface roughness. Later, ANOVA statistical analysis is being used to recognize the important parameters.

Material and methodology

This particular study is conducted for 316 L, low carbon steel generally used in industries. Its chemical composition is displayed in table 1.

Table 1: Chemical Composition of 316 L

Component	C	Cr	Ni	Mn	Mo	Fe
Percentage	<0.03	17.5	11.5	< 2	2.3	Balance

This steel has a very high hardness in comparison to other conventional materials. The samples are machined on ACE designers' JOBBER LM type CNC machine. Carbide tip cutting tool is used for turning operation and dry cutting is performed. Nine round bars of 1-inch diameter and five-inch length are selected for this purpose and shown in figure 1. Almost half of the length is machined (around 2.5 inches), which is enough for all kind of roughness measurements.

Figure 1: a) JOBBER LM, CNC Machine from ACE designer b) 316 L samples after turning operation.

The roughness was measured using ZEISS, type HANDYSURF E-35 A portable instrument, measuring nearly 1-inch length of sample with automatic movement once started. Three locations which are 120^o apart are selected for roughness measurement as marked in the figure 2 b. And the average of these three values is taken for the analysis.

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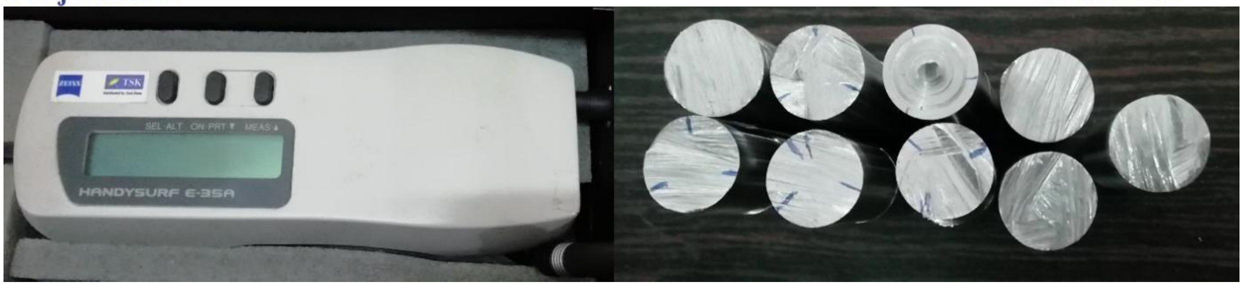

Figure 2: ZEISS's roughness measurement instrument b) Samples marked for roughness measurements.

Three operating parameters cutting speed, feed rate and depth of cut are selected for optimization. Each parameter is set at three levels as shown in Table 2. In order to limit the number of experiments for optimization, Taguchi method was utilized. And combination is set according to L9 orthogonal array for 3 parameters at 3 levels.

Table 2: Processing parameters for turning operation

Cutting speed (m/min)	Feed rate (mm/rev)	Depth of Cut (mm)
100	0.2	0.1
125	0.3	0.3
150	0.4	0.5

Taguchi design and experimentation

The conventional methods of experimental designs require a series of experiments. It utilizes all possible combinations of parameters to analyze the control factors effect on experimental data. As well it takes into consideration all possible combinations to study any possible interaction within control factors.

Taguchi ensures cost reduction and identifies significant factors in comparatively lesser time. It is effective in robust design and minimizing noise. Unlike conventional method, Taguchi utilizes a completely different approach. It reduces the number of experiments significantly, with the use of orthogonal arrays. These arrays are combinations of control factors, which evaluates the contribution of factors and assess the best combination of parameters for desired results. The method is based on the signal-to-noise (S/N) ratio. It is the ratio of desired signal with respect to the noise in the background. The higher the ratio, the less is the contribution of noise.

Taguchi method identifies the best combination of parameters by the value of S/N ratio. For our case surface roughness need to be minimized. Therefore, any combination of control factors that gives the minimum S/N ratio is desirable.

Taguchi have defined the optimal value of S/N ratio for 3 kinds of situations.

- Nominal the better

$$\frac{S}{N} = 10\ log\ \frac{\bar{y}}{S_y^2}$$

- Smaller the better

$$\frac{S}{N} = -10 log \frac{1}{n} (\sum y^2)$$

- Larger is better

$$\frac{S}{N} = -log\frac{1}{n}\left(\sum\frac{1}{y^2}\right)$$

Where,

y_i is the measured value of response variable i.

In summary, the complex method of Taguchi can be summarized in the following steps

- Identifying control factors and set their number of levels.
- Evaluate the response function.
- Based on the number of control factors and levels, select an appropriate orthogonal array (L9) and assign the control factors, run the experiments.
- Evaluate the data generated via Taguchi and ANOVA analysis.
- The effect of control factors on response function is evaluated.

ANOVA analysis is being performed on experimental results for investigating the contribution of every control factors.

Table 3: The results of experiments and S/N ratio values

Experi no	A	B	C	Ra	Rz	Ra for S/N	Rz for S/N
1	1	1	1	0.463	1.883	6.6884	-5.497
2	1	2	2	1.730	5.733	-4.7609	-15.167
3	1	3	2	3.000	10.200	-9.5424	-20.172
4	2	1	2	0.523	2.320	5.6300	-7.309
5	2	2	2	1.766	6.330	-4.9398	-16.028
6	2	3	1	2.693	9.700	-8.6047	-19.735
7	3	1	3	0.316	1.390	10.0063	-2.860
8	3	2	1	0.190	0.850	14.4249	1.411
9	3	3	2	0.223	0.926	13.0339	0.667

Table no. 2 is the L 9 orthogonal array for the current study, where A, B, C are cutting speed(m/min), feed rate(mm/rev) and depth of cut(mm) respectively. In column A, B and C levels marked as 1, 2 and 3 denotes the level of control factors. Ra and Rz are the surface roughness achieved that is the response variable, that needs to be minimized. The Value of Ra and Rz achieved is being further investigated to study the contribution of every control factors via ANOVA analysis in the next section.

4. Analyzing and evaluating results of the experiments using the Taguchi method

The most essential criterion in the Taguchi method for analyzing experimental data is signal/noise ratio. In this study, the S/N ratio should have a maximum value to obtain optimum cutting conditions, according to the Taguchi method.

Table 4 : Response Table for Signal to Noise Ratios

Smaller is better

Level	Cutting speed	Feed rate	Depth of cut
1	-2.538	7.442	4.170
2	-2.638	1.575	4.634
3	12.488	-1.704	-1.492
Delta	15.127	9.146	6.126
Rank	1	2	3

Thus the optimum condition was found as -4.7609 for Ra in L9 orthogonal array table. The Optimum cutting conditions are 100 m/min , feed rate 0.3 mm/rev and depth of cut 0.3 mm (1 2 2 orthogonal array) were obtained for the best Ra values . Level values of factors obtained for Ra according to taguchi design are given in Table 4.The average S/N ratio for every level of experiment is calculated based on the recorded value as shown in Table 4.

The different values of S/N ratio between maximum and minimum are (main effect) also shown in Table 4. The feed rate and the cutting speed are two factors that have the highest difference between values, 9.146 and 15.127 respectively. Based on the Taguchi prediction that the larger different between value of S/N ratio will have a more significant effect on surface roughness (Ra). Thus, it can be concluded that increasing the feed rate will increase the Ra significantly and also the cutting speed. The results of data analysis of S/N ratio for Ra values, which The results of data analysis of S/N ratio for Ra values, which are calculated by Taguchi method, are shown in Table 5 (where df is degree of freedom, F variance ratio, and P significant factor). Thus, it is seen in Fig. 3 and Table 4 that the third level of A factor (cutting speed), the first level of B factor (feed rate) and the second level of C factor (depth of cut) are higher. Consequently, the optimum cutting conditions determined under the same conditions for the experiments to be conducted will be 150 m/min for the cutting speed, 0.20 mm/rev for the feed rate and 0.3 mm for the depth of cut.

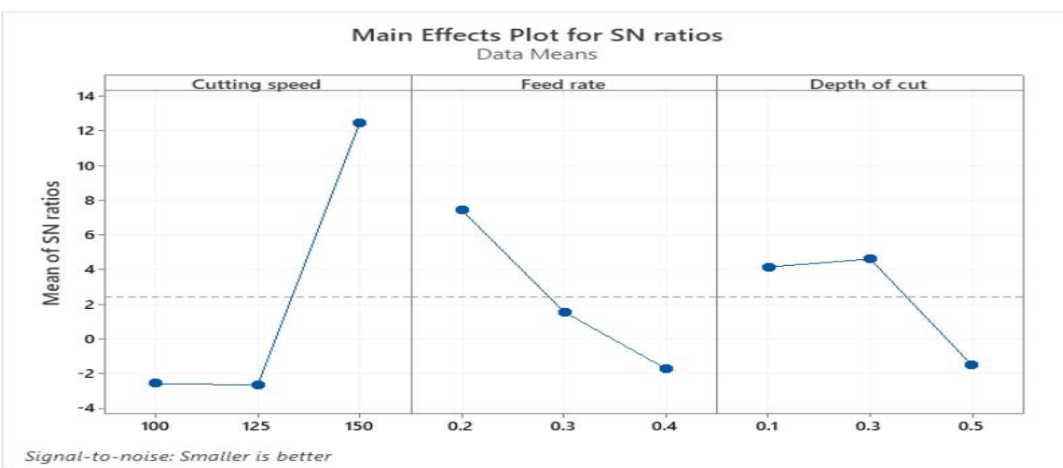

Fig. 3. The graphic of mean of S/N ratios versus factor levels (Ra).

5. ANOVA (Analysis of Variance)

The Taguchi method was used in determining optimum cutting conditions according to the S/N ratio, while the interaction between the cutting parameters was determined with the help of the variance analysis. Variance analyses of S/N ratios were conducted through the MINITAB 19.0 Program and the interactions between the S/N-cutting speed, the S/N-feed rate and the S/N-depth of cut were evaluated. The results of the conducted S/N-variance analyses (ANOVA) are given in Tables 5.

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Regression	3	7.3717	75.02%	7.3717	2.4572	5.00	0.058
Cutting speed	1	3.3212	33.80%	3.3212	3.3212	6.76	0.048
Feed rate	1	3.5482	36.11%	3.5482	3.5482	7.23	0.043
Depth of cut	1	0.5023	5.11%	0.5023	0.5023	1.02	0.358
Error	5	2.4550	24.98%	2.4550	0.4910		
Total	8	9.8267	100.00%				

Table 5. Interactions between the S/N-cutting speed, the S/N-feed rate and the S/N-depth of cut

Table 5 shows the interaction between the S/N and the cutting speed , feed rate and depth of cut considering that, according to P (significant) values; Depth of cut does not produce a significant level within the reliability interval of 95%. In other words, Depth of cut has no effect on S/N ratio. According to Table 5, The P value is effective at the reliability level of 95% for Cutting speed and feed rate because the results are lower than 0.05.

5. Regression Model

The regression model to predict the surface roughness have derived from the experimental data by using MINITAB 19 software, the equation given below and also from the analysis the residual plot can be drawn.

S.R = 2.19 - 0.0298 cutting speed + 7.69 feed rate + 1.45 Depth of Cut.

7. The 3D surface plots for the surface roughness :

The 3D surface plots can be used for estimating the surface roughness values for any suitable combination of the input parameters namely cutting speed, feed rate and depth of cut.These are shown in Figure 4. Figure 4 shows the surface and contour plots for surface roughness at 0.3 mm depth of cut. It is clear from Figure that the surface roughness increases with increase in feed rate. It is observed that the surface roughness increases with increase in cutting speed at lower feed rate, while at higher feed rate the surface roughness decreases with increase in cutting speed.

Figure also shows the surface plots for surface roughness at cutting speed of 125 m/min. It reveals that surface roughness increases with increase in feed rate and depth of cut has no significant effect.

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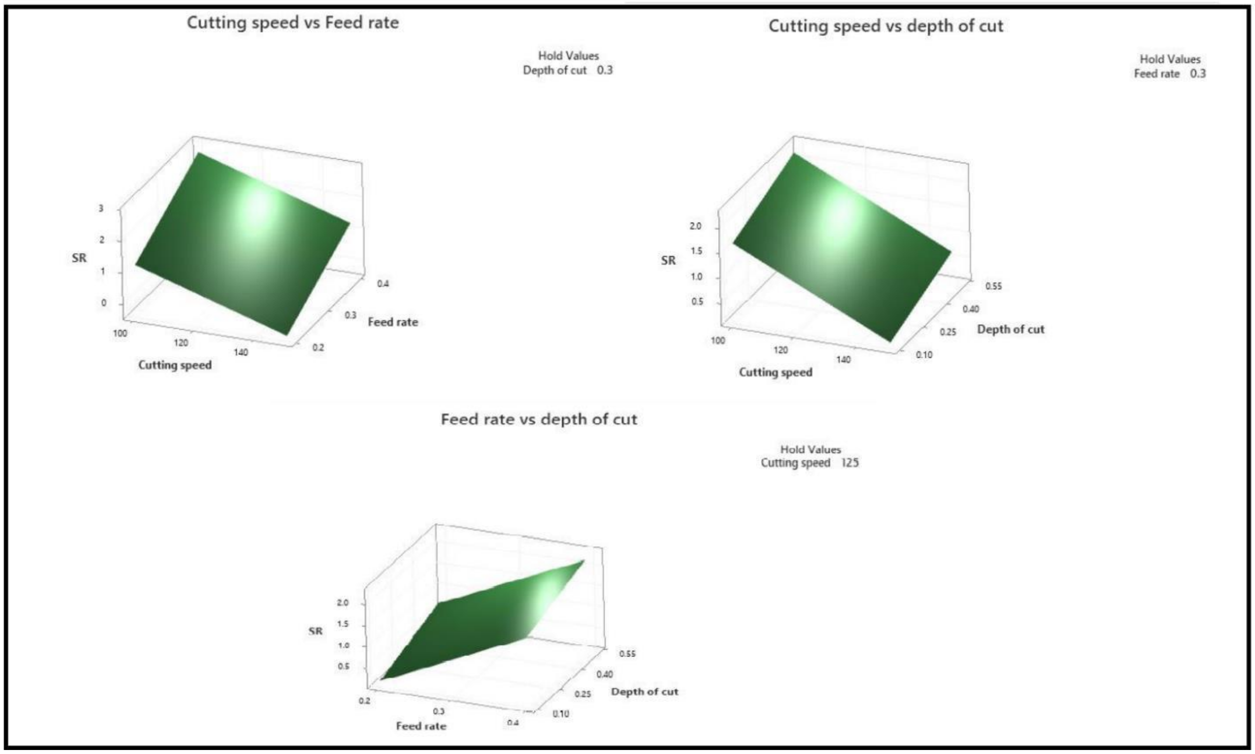

Fig. 4 : 3D Surface Plots of Surface Roughness at different values of Feed rate, speed & Depth of cut.

8. Conclusion:

The Taguchi experimental design was used to obtain optimum cutting parameters on turning. Experimental results were analyzed using ANOVA.

Orthogonal array was selected for three different levels of cutting speed, feed rate and depth of cut, which were cutting factors, by using the Taguchi method. As a result, 9 experiments were conducted . Ra ,S/N ratio were found as a result of experiments conducted according to the L9 orthogonal array. The maximum value was found by using the S/N ratio equation of ‘‘the smaller-the better,’’ the maximum S/N ratio yielded optimum cutting parameters. 3D surface plots are generated and effect of parameters on Surface Roughness was studied.

The following conclusion are drawn based on the performance of machining characteristics studies:

(a) Optimum Cutting Conditions which Corresponds to -4.7609 for smaller surface roughness in turning operation (1 2 2) were found to be 150 m/min for the cutting speed, 0.20 mm/rev for the feed rate and 0.3 mm for the depth of cut.

(b) Variance analysis was applied to S/N ratios to discover interactions between cutting parameters relating to Ra and Rz. According to the ANOVA analysis, the feed rate and cutting speed has an effect on Ra at a reliability level of 95%. Any significant difference (variance) was not observed for the depth of cut at the reliability level of 95%.

For Surface Roughness from the all selected parameters, Feed rate is the most significant input factor affecting the Turning of AISI 316L followed by Speed and Depth of Cut.

(c)The contribution of Cutting Speed ,Feed Rate and Depth of Cut is33.8%, 36.11%, 5.11% respectively.

(d) From the 3D surface plots shows that surface roughness increases with increase in feed rate. It is also observed that the surface roughness increases with increase in cutting speed at lower feed rate, while at higher feed rate the surface roughness decreases with increase in cutting speed. Feed rate and spindle speed has significant effect on surface roughness.

9. Scope of Work

(a) The CNC turning optimization can be done by considering tool wear, nose radius , different cutting tools into account
(b) The multi objective optimization can be done with Fuzzy/grey relation analysis.
(c) The Micro structure analysis can be done through scanning electron microscopy

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