Optimization of turning process parameters of SS-321 using taguchi based grey relational analysis

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Abstract. Tool wear, high surface roughness & MRR (Material Removal Rate) are the major problems associated with turning of SS-321. The turning parameters such as feed rate, depth of cut and cutting speed have the major effects on surface roughness, MRR, and cutting forces. An increase in magnitude of cutting forces leads to increase in the power requirements and simultaneously it decreases efficiency, which is the great concern in current scenario. In this turning work on SS-321, Taguchi based L\textsubscript{27} orthogonal array was designed and experiments were performed accordingly. The data analysis was done by Taguchi, ANOVA and Grey relational analysis. The optimized results and improvements by using this method were also validated by a verification test. Results revealed that turning process with parameters such that feed rate, depth of cut and cutting speed at 0.3 mm/rev, 0.3 mm and 120 m/min respectively yields the optimum multi-performance characteristics. However, it was determined by ANOVA (Analysis of Variances) that depth of cut is a process parameter that affect most the multi-function features with percentage contribution of 64.86% followed by feed (16.84%) and speed (10.20%). Under these circumstances, the optimum parameters set seems to favorably affect the average values of all the three response parameters (surface roughness, cutting forces, MRR) so that the average values of output characteristics arrive at optimum level.

1. Introduction

Turning is a method of a method of machining used for extracting excess material. The metal removal is the removal of a piece of metal from the workpiece to produce a finished product with the desired dimensions, shapes and characteristics of the surface roughness. Engineers are always involved in determining the best suitable parameters with optimized output and performance with the minimum use of resources [1].

In general, the selection of appropriate process parameter is not so easy because it depends mostly on the expertise of operator and the machining process parameters given for the material by the machine tool manufacturers. Therefore, optimization of process parameters is very important because it plays a key role in economy and efficiency of machining process [2].

Surface roughness is very crucial to evaluate the accuracy of machining processes [3]. The system vibration directly affects the work material surface finish. In turning process vibrations are obtained due to different forces acting on cutting tool [4]. Our main concern now is to reduce costs and time, improve
quality and economic productivity. Better surface finish and less tool wear are challenges when using materials of high strength and resistance to wear while turning. Optimized cutting parameters should be used for overcoming the above problems [5]. Multi-response optimization in industrial applications is therefore important. It is better than optimizing single-response technology as all factors are influenced by all input factors at once. Taguchi technique with GRA (Grey Relational Analysis) is being used to optimize the process parameters of turning on CNC lathe with surface roughness, cutting forces and MRR as multi-performance characteristics. It has been used effectively in developing high quality in the field of automotive, aerospace etc. at low cost [6]. Goel et al. [7] provided a successful methodology for optimizing the HSLA steel slab milling process based on Taguchi with GRA for multi-function features. Siddiquee et al [8] performed the experiments on AISI 321 steel using Taguchi method for optimizing deep drilling process parameters.

Literature surveys have shown a plethora of work on the effects of process parameters on surface roughness, material removal rate and cutting forces has been reported. There is, however, little literature on the effect on SS-321 of the turning process parameters. Many researchers have noted that the Taguchi approach and grey relationship analysis have become powerful tools for increasing productivity in the development process and have found a wide range of applications through different machining processes. High quality goods can therefore be manufactured easily and at low cost.

In this study 27 experiments were conducted by using taguchi and GRA for optimization of three turning parameters (depth of cut, speed and feed) for machining of SS-321 on CNC lathe machine and the multi-function features were surface roughness, material removal rate and cutting forces as radial force, cutting force and feed force.

2. Experimental Details

As per designed L27 orthogonal array 27 turning experiments were completed using CNC lathe machine and to obtain the optimum parameters for multi-function features ANOVA was applied. The all three turning parameters (speed, depth of cut, feed) and their different value selected for experiments is shown in table 1.

| Table 1. Machining parameter and their levels |
|---|---|---|---|
| Notation | Parameter | Level 1 | Level 2 | Level 3 |
| A | Depth of cut | .5 | 1 | 1.5 |
| B | Speed (m/min.) | 60 | 90 | 120 |
| C | Feed (mm/rev) | .2 | .25 | .3 |

The various performance parameters for experimental investigations were measured by using Mitotoyo surface roughness tester. It is a stylus and skid-type instrument in which the profile of surface irregularities is traced through a sharply pointed stylus. The stylus movement cut-off length was .8 mm. In this experiment Kistler made 3-component 9129AA dynamometer with charge amplifier are used for measuring the cutting forces i.e., radial force (F_1), cutting force (F_c) and feed force (F_f).

The metal removal rate is an important factor for productivity. The metal removal rate was calculated in turning process by formula as shown below:

\[ \text{Material Removal Rate} = \frac{1000 \times f \times V_c \times d}{60} \text{ mm}^3/\text{sec} \]  

Where:

- \( V_C \) = Cutting speed in m/min,
- \( f \) = Feed in mm/rev,
- \( d \) = Depth of cut in mm

The measured values of surface roughness (Ra), MRR, radial force, cutting force and feed force see in table 2.

| Table 2. Values of response variables |
Experiments | A | B | C | Ra (µm) | MRR (mm³/s) | Radial Force (F_r) | Cutting Force (F_c) | Feed Force (F_f) |
--- | --- | --- | --- | --- | --- | --- | --- | --- |
1. | 1 | 1 | 1 | 1.57 | 100.0 | 187.40 | 220.40 | 95.35 |
2. | 1 | 1 | 2 | 0.98 | 125.0 | 194.4 | 274.8 | 121.6 |
3. | 1 | 1 | 3 | 1.05 | 150.0 | 231.6 | 435.9 | 134.2 |
4. | 1 | 2 | 1 | 0.96 | 150.0 | 205 | 282.8 | 99.58 |
5. | 1 | 2 | 2 | 1.32 | 187.5 | 226.8 | 261.1 | 121.8 |
6. | 1 | 2 | 3 | 1.28 | 225.0 | 256 | 496.5 | 134 |
7. | 1 | 3 | 1 | 1.02 | 200.0 | 214.5 | 301.5 | 114.9 |
8. | 1 | 3 | 2 | 1.12 | 250.0 | 233.3 | 279.6 | 117.3 |
9. | 1 | 3 | 3 | 0.95 | 300.0 | 269 | 597.7 | 147.1 |
10. | 2 | 1 | 1 | 2.00 | 200.0 | 189.1 | 355 | 175.7 |
11. | 2 | 1 | 2 | 2.06 | 250.0 | 213.5 | 511.7 | 191.4 |
12. | 2 | 1 | 3 | 2.66 | 300.0 | 237.4 | 786.6 | 198.7 |
13. | 2 | 2 | 1 | 1.54 | 300.0 | 201.5 | 450.2 | 174.8 |
14. | 2 | 2 | 2 | 2.07 | 375.0 | 198.2 | 345.3 | 178.5 |
15. | 2 | 2 | 3 | 3.09 | 450.0 | 239 | 435.2 | 188.9 |
16. | 2 | 3 | 1 | 1.82 | 400.0 | 214.5 | 454.5 | 176.7 |
17. | 2 | 3 | 2 | 2.14 | 500.0 | 269.6 | 820.5 | 219.3 |
18. | 2 | 3 | 3 | 2.45 | 600.0 | 243.8 | 501.9 | 193 |
19. | 3 | 1 | 1 | 2.41 | 300.0 | 208.2 | 526.9 | 455.9 |
20. | 3 | 1 | 2 | 2.44 | 375.0 | 241.6 | 772.3 | 499 |
21. | 3 | 1 | 3 | 3.39 | 450.0 | 236.4 | 988 | 798 |
22. | 3 | 2 | 1 | 2.10 | 450.0 | 222.8 | 610.6 | 484.1 |
23. | 3 | 2 | 2 | 2.60 | 562.5 | 231.1 | 899.9 | 450.7 |
24. | 3 | 2 | 3 | 3.16 | 675.0 | 265.4 | 1268 | 768.7 |
25. | 3 | 3 | 1 | 1.69 | 600.0 | 249.5 | 709.8 | 558.5 |
26. | 3 | 3 | 2 | 2.94 | 750.0 | 268.6 | 904.4 | 752.2 |
27. | 3 | 3 | 3 | 3.15 | 900.0 | 271.9 | 1397 | 852.5 |

3. Calculations (Analysis Method)

3.1. Signal to noise (S/N) ratio and Data pre-processing

Taguchi offers a systematic, simple and efficient optimization technique. Depending on the features, the three S/N ratios used in taguchi method are of three types, first one is smaller is good, second greater is good, and the third is nominal is good [9,10].

Smaller is good:

\[ \eta_{ij} = -10 \log \left[ \frac{1}{n} \sum_{j=1}^{n} y_{ij}^2 \right] \]  

(2)

Greater is good:

\[ \eta_{ij} = -10 \log \left[ \frac{1}{n} \sum_{j=1}^{n} \frac{1}{y_{ij}^2} \right] \]  

(3)

Nominal is good:

\[ \eta_{ij} = -10 \log \left[ \frac{1}{ns} \sum_{j=1}^{ns} y_{ij}^2 \right] \]  

(4)

Where,

\( y_{ij} \) means the “\( i^{th} \) experiment at ‘\( j^{th} \)’ test, \( \text{“n” is Total number of test and “s” refers to standard deviation. Some other formulations of the S/N ratio are also available, which can be obtained in references.}

As per above discussion criterion smaller is good was selected for the S/N ratios of roughness and cutting forces, whereas the greater is good for MRR [11].
Data pre-processing is used to convert the original series in number which can be compare. So, the results of experiments were processed and normalized in between 0 to 1. There are three different approaches to achieve normalization. Normalization information found at [12,13,14,15].

3.2. Grey relational coefficient and grey relational grade
Grey relational coefficient is determined to demonstrate the relationship between ideal and actual effects of the normalized experiments. It can reflect as follows:

\[ \xi_i(k) = \frac{\Delta_{\text{min}} + \xi \cdot \Delta_{\text{max}}}{\Delta_{0i}(k) + \xi \cdot \Delta_{\text{max}}} \]  

(5)

Where \( \Delta_{0i}(k) \) is the deviation sequence of the reference sequence \( x^*_0(k) \) and the comparability sequence \( x^*_i(k) \), called as,

\[ \Delta_{0i}(k) = \|x^*_0(k) - x^*_i(k)\| \]  

(6)

\[ \Delta_{\text{max}} = \max_{\forall j \in \mathcal{I}, \forall k} \|x^*_0(k) - x^*_i(k)\| \]  

(7)

\[ \Delta_{\text{min}} = \max_{\forall j \in \mathcal{I}, \forall k} \|x^*_0(k) - x^*_i(k)\| \]  

(8)

Generally, identification faction \( \xi \) is taken as 0.5 and it ranges from 0 to 1.

3.3. Analysis of mean (ANOM)
The average of multi-function features i.e., grey relational grade is calculated using ANOM to identify the effect of every parameter individually. Grey relational grades are discussed below:

\[ \gamma_i = \frac{1}{n} \sum_{k=1}^{n} \xi_i(k) \]  

(9)

However, since in realistic implementations the effect of each element on the device isn't exactly the same, equation (8) may be changed to:

\[ \gamma_i = \frac{1}{n} \sum_{k=1}^{n} w_k \cdot \xi_i(k) \sum_{k=1}^{n} w_k \]  

(10)

where \( w_k \) represents the normalized weight of factor k. Equations (9) and (10) given the same weight, are identical.

4. Results and discussion
4.1. Optimal parameter combination
Grey relational coefficient and grades calculated for all three multi performance features (i.e., roughness, cutting forces, MRR) and the combination of parameters which give the optimum results for turning is obtained by grey relational analysis. Grey relational grades and their responses for different turning parameters at their different values shown in figure 1. As we can see from figure 1, A3, B3 and C3 display the maximum value of grey relational grades for each turning process parameter. Thus, the optimized multi-function features are obtained at combination A3B3C3 for each turning parameter.

| Symbol | Turning Parameter | Machining | Level 1 | Level 2 | Level 3 | Max – Min |
|--------|-------------------|-----------|---------|---------|---------|-----------|
| A      | Depth of Cut      | 0.41444   | 0.518433| 0.738   | 0.323101|           |
The differences in maximum and minimum value of grey relational grades are shown in Table 3 and which depict that difference for factor A (depth of cut) is highest followed by C (Feed rate) and B (cutting speed) as 0.323101, 0.163212 and 0.126817 respectively. This shows that factor A has major impact on multi-function features. Figure 1 demonstrates the effect of multi-function features on turning parameter levels.

4.2. Analysis of variance
ANOVA is an approach to statically determine the influencing effects of different factors individually. As it is a complex design and performance of process is to be determine for roughness, cutting forces and material removal rate simultaneously and it is not possible by taguchi method only so ANOVA is also applied to find the contribution of each parameter. ANOVA also include F test to indicate the impact of a parameter on multi-function features. If value of F test less than four then the effects of particular parameter is insignificant. Here as shown in table 4 all the process parameters are significant because their F test value is more than four and out of which parameter A (depth of cut) is most effective with F test value 115.60.

Table 4. Result of Analysis of Variance

| Symbol | Parameters      | DF  | SS    | Mean square | F ratio | Contribution (%) |
|--------|-----------------|-----|-------|-------------|---------|------------------|
| A      | Depth of Cut    | 2.00| 0.489 | 0.377       | 115.60  | 64.86            |
| B      | Speed           | 2.00| 0.077 | 0.038       | 11.79   | 10.20            |
| C      | Feed rate       | 2.00| 0.122 | 0.061       | 18.81   | 16.27            |
| Error  |                 | 20.00| 0.065 | 0.003       |         | 8.65             |
| Total  |                 | 26.00| 0.754 | 0.003       |         | 100              |

Figure 1. Grey relational grade graph

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So, it is very clear from ANOVA results as shown in table 4 that turning parameter A (depth of cut) is a most important parameter with 64.86% contribution, where as in decreasing order C (feed rate) and B (speed) have their contributions 16.27% and 10.20% respectively. Contribution of all the turning parameters is also shown in figure 2.

4.3. Verification test
A verification test was completed to compare and validate the optimized turning parameters results. As the increase in grey relational grades represent the improvement in multi-function features for turning parameters and it was observed that the grey relational grades increase from 0.899 (predicted value) to 0.979 (experimental value) which indicate an improvement of 8.899% (see table 5).

| Level             | Optimal Machining Parameter | Prediction | Experiment | % Change |
|-------------------|-----------------------------|------------|------------|----------|
| Surface roughness |                            | A_3B_3C_3  | 0.897      |          |
| Material Removal Rate |                       | A_3B_3C_3  | 1.000      |          |
| Radial Force      |                            | A_3B_3C_3  | 1.000      |          |
| Cutting Force     |                            | A_3B_3C_3  | 1.000      |          |
| Feed Force        |                            | A_3B_3C_3  | 1.000      |          |
| Grey relational grade |                     | A_3B_3C_3  | 0.899      | 0.979    | 8.899    |

5. Conclusion
The optimized machining parameters are obtained as A_3B_3C_3 where depth of cut 1.5mm, speed-120m/min. and feed rate-0.30mm/rev. As the % contribution of depth of cut is higher (64.86%) followed by speed (10.20%) and feed rate (16.27%) respectively under these circumstances, the parameter set A_3B_3C_3 seems to be favorably affecting the average values of all response parameters (Surface roughness, Material removal rate, radial force, cutting force and feed force) so that the average values of output characteristics arrive at optimum level. This method achieves a multi-performance improvement of 8.89.

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