Optimization of Roundness, MRR and Surface Roughness on Turning Process using Taguchi-GRA

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Abstract. This research was conducted to optimize the turning process on several quality characteristics with the Taguchi-GRA method. Some of the quality characteristics that are optimized are roundness, material removal rate (MRR) and surface roughness. These three quality characteristics are then converted to a GRG value. The independent variables used in this study are the depth of cut (0.5; 0.75; 1 mm), feed rate (0.045; 0.065; 0.085 mm/rev) and cutting speed (37.68; 56.52; 75.36 m/min). The experimental design used is the L9 orthogonal array. The experimental results show that the turning process can be effectively improved through the Taguchi-GRA method. The optimal combination for obtaining maximum GRG values can be reached at a depth of cut of 1 mm, feed rate of 0.085 mm / rev and cutting speed of 75.36 m / min. The GRG value increased to 34% from 0.7017 to 0.9403.

1. Introduction

The manufacturing industries are expected to be able to create high-quality products and achieve high productivity in order to remain competitive in today's industry competition [1]. Turning is any of the most widely used and important machining processes in the manufacturing industry. Surface quality is a very significant performance characteristic in machining process. The productivity of machine components and machine tools needs to be evaluated. Roundness and surface roughness are critical quality indicators for machine surfaces. Roundness and surface roughness are the most important quality parameters for measuring machine surface quality. Good quality turning surfaces can result in increased material strength properties such as assembly tolerance, fatigue strength, heat and aesthetic resistance, corrosion resistance, friction coefficient, wear rate, cleanliness, etc. [2]. On the other hand, the high material removal rate (MRR) value is more desirable in the manufacturing industry, because it can be applied to mass production in a shorter time without sacrificing product quality. MRR improvement can be reached through increasing turning process variables such as feed rate, depth of cut and cutting speed. However, higher cutting speeds result in greater power induction that can exceed the availability of power in machine tools. Thus, selecting the right parameters in the turning process is very important role in the effectiveness, efficiency, and economics of manufacturing in order to produce good product quality and higher material removal rates [1].

Therefore, the development of procedures for selecting the right turning parameters is absolutely necessary. Optimization of turning parameters that affect surface quality is needed to increase the quality of surface turning. The method for conducting research with a lot of variables but few experiments can use the Taguchi method in the form of an orthogonal array [3]. The use of orthogonal arrays can reduce the number of experimental configurations that will be studied. In addition, the result and conclusion
derived from a small number of experiments apply to all experimental areas stretched by setting factors and levels [4]. The Taguchi method just can be used to optimize with one response. Taguchi method must be combined with other methods as well as methodology of response surface, grey relational analysis (GRA), fuzzy logic and neural networks so that it can be used to optimize multi-response simultaneously [5]. The grey system theory explained that to analyse the correlation between variables can be used the grey relational analysis. Grey relational analysis uses less data and many factors [6]. It is considered more profitable than regression statistical analysis. This method is proposed to optimize the turning process. In this study the Taguchi method is composited with GRA to optimize multi-response in turning process on St 40 bar steel.

2. Experimental Work and Result

2.1. Material Testing and Specification
The material used in this study is St 40 steel which has dimensions of 200 mm in length and 25 mm in diameter. St 40 bar steel includes low carbon steel with a carbon composition of less than 0.3%. St 40 shows that this steel has a maximum tensile strength of 40 kg/mm$^2$. This material is widely used in the manufacturing industry such as bush slave, shaft, piston, extrusions, doors, irrigation tubing and window frames. Turning machine is used for machining. The specification of cutting tool is HSS cutting tool. The angles which form the tools point are the same for all the tested. The surface roughness is measured by the Mitutoyo Surf test Sj-210 and roundness was measured using dial indicator then the data obtained is inserted into the radar graph. The turning process runs in the condition of dry machining without cooling liquid. Lathe machine, cutting tools, measuring instruments and materials were used in this study shown in Figure 1.

![Figure 1. Lathe machine and measuring instruments](image)

2.2. Design of Experiments
Design experiment in the study was conducted using the Taguchi’s method which is an effective instruments in experimental design [7]. Experimental design use Taguchi method, specifically orthogonal array $L_9$ with three factors and three levels. The benefit of using the Taguchi method is to be able to study the entire range of parameters using only a small number of experiments. This method can reduce drastically the number of experiments needed in modelling the response function when compared to the conventional method approach [8]. The assignment of the levels and factors used is given in Table 1. The experimental results are given in Table 2.

| No | Factors       | Unit | Symbol | Level 1 | Level 2 | Level 3 |
|----|---------------|------|--------|---------|---------|---------|
| 1  | Depth of cut  | mm   | a      | 0.5     | 0.75    | 1       |
| 2  | Feed rate     | mm/rev | f     | 0.045   | 0.065   | 0.085   |
| 3  | Cutting speed  | m/min | $v_c$ | 37.68   | 56.52   | 75.36   |
3. Optimization using Grey Relational Analysis

The Taguchi method in this study uses an orthogonal array design to study the variables of experiment in small quantities. Grey relational grade (GRG) is used to convert multiple response problems into one response. The scope of this research is to recognize the optimal combination of process variables that simultaneously minimized roundness and surface roughness, as well as maximized material removal rate (MRR). To achieve the goal, Taguchi is used in combination with grey relational analysis. The steps be used to implement an optimization using Taguchi grey relational analysis are shown on Figure 2.

Figure 2. Steps for optimization using Taguchi grey relational analysis

3.1. S/N Ratio Calculation

S/N ratio in the Taguchi method is an assessment of quality characteristics and a value of deviation. There are three classification of quality characteristic in the S/N ratio analysis, namely the smaller is better, the larger is better and the nominal is better. The S/N ratio of roundness response and surface roughness is calculated using the smaller is better characteristics, while the S/N ratio of the MRR is calculated using the larger is better characteristics. The S/N ratio of all responses was tabulated in Table 3.

3.2. Normalization of S/N Ratio

In the Grey relational analysis, data pre-processing is used to normalize the initial data. The experimental results of roundness, surface roughness and MRR have been performed in the range between 0 and 1 by using linear normalization. In the present work, as roundness and surface roughness were to be minimized (smaller is better), the Table 3 shows the data that has been calculated since grey relational generating, GRC and GRG. The Greater normalization value interpreting better performance of response. The best normalized result should be equal to aggregation.

3.3. Coefficient of Grey Relational

The correlation in the results of best and actual experiments is represented by grey relational coefficients (GRC). The formula to obtain the grey relational coefficient ($\xi_i(k)$) is given below:

$$\xi_i(k) = \frac{\Delta_{min} + \zeta \Delta_{max}}{\delta_0(k) + \zeta \Delta_{max}}$$

(1)
By $\Delta_0(i)(k)$ is the deviation between reference sequence $x_0^*(k)$ and comparability sequence $x_i^*(k)$. $\zeta$ is the distinctive coefficient ($\zeta \in [0, 1]$). $\zeta$ is used to organize the distinction of the relational coefficient. In this experiment $\zeta$ was taken as 0.5 and the grey relational coefficient calculated by using Eq (1) was shown in table 3.

3.4. Grey Relational Grade (GRG)

The formula to calculate GRG is as follows:

$$a_I = \frac{1}{n} \sum_{k=1}^{n} \xi_i(k)$$

(2)

By n is the amount of quality characteristics. If the relational GRG value is greater, then the combination of process variables used is close to the optimal value.

3.5. Grey relational ordering

Equation 2 was used to calculate the GRG value and then the GRG sequence is presented in table 3. The first order in the order column in Table 3 is the largest grey relational grade value. From table 3, it can be seen that the 9th parameter setting (experiment 9) has the highest GRG value. This shows that in experiment 9, the turning process variable is the most optimal to minimize roundness and surface roughness, and to maximize MRR simultaneously. The larger is better characteristics of multi-response are the targets of this study. The level of the process variable on the highest S/N ratio generates the value of optimal combination. Then it can be seen that the setting of the process variables for the optimal multi-response characteristics is $a_3f_3v_3$.

Main effect plot for the GRG average is shown in Figure 3. From Figures 3 it can be seen that the optimal combination to maximize GRG is depth of cut at level 3 by 1 mm, feed rate at level 3 by 0.085 mm / put and cutting speed at level 3 by 75.36 m / min. The ANOVA results from GRG are presented in Table 5. Based on the analysis in this table, it can be known that the depth of cut is followed by cutting speed and rate generate a significant effect on grey relational grade.

| Trial No. | S/N Ratio Normalization of S/N Ratio Grey relational coefficient | GRG Order |
|-----------|---------------------------------------------------------------|-----------|
|           | Round MRR Ra Round MRR Ra Round MRR Ra Round MRR Ra | 9         |
| 1         | -20.000 -5.301 -7.332 0.000 0.000 0.000 0.333 0.333 0.333 | 3333      |
| 2         | -26.021 5.282 -8.831 0.333 0.595 0.233 0.429 0.555 0.395 | 4585      |
| 3         | -29.542 8.556 -10.224 0.528 0.779 0.450 0.515 0.693 0.476 | 5613      |
| 4         | -29.542 5.610 -10.438 0.528 0.613 0.483 0.515 0.564 0.492 | 52333     |
| 5         | -33.979 11.302 -12.024 0.774 0.933 0.730 0.689 0.882 0.649 | 7398      |
| 6         | -32.041 7.612 -12.004 0.667 0.726 0.727 0.600 0.646 0.647 | 63075     |
| 7         | -38.062 12.496 -12.013 1.000 1.000 0.728 1.000 1.000 0.648 | 8826      |
| 8         | -33.979 9.173 -13.154 0.774 0.813 0.906 0.689 0.728 0.841 | 7527      |
| 9         | -36.902 11.326 -13.761 0.936 0.934 1.000 0.886 0.884 1.000 | 9233      |

| Source | DF | Seq SS   | Adj MS   | F     | P     | % contribution |
|--------|----|----------|----------|-------|-------|----------------|
| a      | 2  | 48.7236  | 24.3618  | 168.38| 0.006 | 74.05          |
| f      | 2  | 7.4078   | 3.7039   | 25.6  | 0.038 | 10.88          |
| v_c    | 2  | 8.9856   | 4.4928   | 31.05 | 0.031 | 13.30          |
| Error  | 2  | 0.2894   | 0.1447   | 1.77  |       |                |
| Total  | 8  | 65.4064  | 100.00   |       |       |                |

S = 0.3804 R-Sq = 99.6% R-Sq(adj) = 98.2%
3.6. Prediction Optimal Multiple Performance and Confirmation Experiments

The prediction of multiple performance characteristic is purposed for calculate the prediction of GRG which is resulted from optimal combination of turning process. Equation 3 is used for the calculation of predicted grey relational grade.

\[
\gamma = \gamma_m + \sum_{i=1}^{n} (\gamma_i - \gamma_m)
\] (3)

By \(\gamma_m\) is the total means of GRG, \(\gamma_i\) is the mean of the GRG at optimal level, \(n\) is the amount of main design parameters that affect the performance characteristics. The confirmation experiment purpose is to verify the improvement of performance characteristics. Using equation (3) it can be seen that the optimal combination prediction is \(a_3-f_3-v_{c3}\) and the predicted GRG value is 0.9957.

The validation of experimental results is conducted by confirmation experiment. Confirmation experiment results are presented on Table 5. The confirmation experiments were replicated 3 times and the average of this experiment then used to validate the prediction.

| Trial No. | Turning Parameters | Roundness (\(\mu m\)) | MRR (\(cm^3/min\)) | Ra (\(\mu m\)) |
|-----------|--------------------|------------------------|---------------------|----------------|
| 1         | 3                  | 3                      | 3                   | 70             | 3.921          | 4.887          |
| 2         | 3                  | 3                      | 3                   | 70             | 3.901          | 4.821          |
| 3         | 3                  | 3                      | 3                   | 70             | 3.948          | 4.920          |
| Average   | 70                 | 3.924                  | 4.876               |                |                |

The GRG value from confirmation experiments is 0.9403. Comparisons between optimum and initial combinations are used to generate value of quality improvements resulting from the optimization process. The initial combination experiment is an experiment carried out using level 2 for all parameters that have 3 levels. For experiments that have 2 levels, the level is selected from the optimum conditions. The results of experiment of initial combination are tabulated in Table 6.

The GRG value calculated from the initial combination experiment is 0.7017. Comparison of Roundness, MRR, Ra and GRG from experiments of initial and optimal combination was calculated by an equation 2 and shown in Table 6.

| Table 6. Results of initial combination |
|-----------------------------------------|
| Initial | Optimum | Improvement |
| Roundness | 60 | 70 | 17% | Increase |
| MRR      | 2.149 | 3.924 | 83% | Increase |
| Ra       | 4.218 | 4.876 | 16% | Increase |
| GRG      | 0.7017 | 0.9403 | 34% | Increase |
Table 6 shows that GRG representing the characteristics of multi-response increased by 34% from 0.7017 to 0.9403. MRR increased by 83% from 2,149 cm$^3$/minute to 3,924 cm$^3$/minute. Roundness and surface roughness that should have been lowered, turned out to increase. Roundness increased by 17% from 60 μm to 70 μm, and surface roughness increased by 16% from 4,218 μm to 4,876 μm. This is consistent with the greater the better the characteristics used as targets to measure the characteristics of multi-response quality in this experiment.

4. Conclusion
This study presents multi-response optimization on the turning process with independent variables including depth of cut, feed rate and cutting speed. Taguchi method combined with grey relational analysis is used to do multi-response optimization. The conclusions of this study are as follows:

1. The percentages of contribution from the depth of cut, feed rate and cutting speed in reducing the total variance of multi-response characteristics in sequence are 74.05%, 10.88% and 13.35%.
2. In order to obtain optimum roundness, MRR and surface roughness in the turning process, the independent variables need to be regulated as follows: depth of cut at level 3 (1 mm), feed rate at level 3 (0.085 mm / put) and cutting speed at level 3 (75.36 m / min).
3. The experimental results show that the performance of the turning process can be improved effectively through this method.
4. Method of analysis of Taguchi grey relational can simplify optimizing of variables in turning process with various characteristics of performance.

5. References
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