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# APPLICATION OF GREY RELATIONAL ANALYSIS FOR MULTI-CRITERIA OPTIMIZATION OF CUTTING PARAMETERS IN TURNING AISI 4340 STEEL

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## ABSTRACT

This paper deals with the optimization of cutting parameters in turning AISI 4340 steel with the aim of minimizing the output responses flank wear and surface roughness using Grey Relational Analysis (GRA). Wear developed at the flank face of the cutting tool insert reduces the life of the cutting tool and surface roughness at the machined surface reduces the quality of the component, which makes this study essential. Cutting parameters viz. cutting speed, feed rate and depth of cut are varied through three levels, for which a $L_9$ Orthogonal Array (OA) is chosen based on Taguchi's Design of Experiments (DoE). A combined grey relational grade is calculated from the determined grey relational coefficient of the output responses and the optimum control parameters are obtained. Relationship between the input parameters are studied using interaction plots. Analysis of Variance (ANOVA) performed shows that depth of cut is the most significant parameter that contributes towards the output responses. Confirmation experiment conducted shows a reduction in output responses.

**Keywords:** *Machining parameters, Taguchi's DOE, Grey Relational Analysis and ANOVA.*

## 1. Introduction

Turning is a general term for a group of machining operations in which the workpiece carries out the prime rotary motion while the tool performs feed motion. These are used for the external and internal turning of surfaces. Turning is used for machining cylindrical surfaces. The primary motion is the rotary motion of the workpiece around the turning axis. The secondary motion is the translational motion of the tool, known as the feed motion. In any machining operation, the cutting speed is the rate at which the workpiece surface is passed by the cutting edge. It is measured in meters per minute. The feed motion is provided to the tool or the workpiece, and when added to the primary motion leads to a repeated or continuous chip removal and the formation of the desired machined surface. The cutting feed is the distance in the direction of feed motion at which the cutting tool advanced into the workpiece per one revolution and thus the feed is measured in millimeters per revolution. The feed rate is the velocity of the tool in the feed direction. It measures in millimeters per minute. Fig. 1 shows the various parameters and motions involved in an turning operation [21].

Aslan et al. [5] analyzed the effects of machining parameters over flank wear and surface roughness while machining hardened steels using $Al_2O_3$ based ceramic tool and developed an empirical relationship between them. Aouici et al. [6] investigated the effects of cutting parameters on flank wear and surface roughness using CBN tool during turning hardened AISI H11 steel and found that surface roughness of workpiece is influenced by the feed rate. Lalwani et al. [8] had analyzed the effect of machining parameters over cutting forces and surface roughness in turning MDN250 steel using coated ceramic tool and developed a linear model for feed force, thrust force and cutting force whereas for surface roughness a quadratic model is fitted. Palanikumar et al. [12] studied the influence of cutting parameters on various surface roughness values and developed an empirical model for it while turning FRP material with PCD tool. Senthilkumar et al. [15] applied Taguchi's DoE for designing the experimental layout for varying level values of machining parameters and cutting tool geometry and applied artificial neural network technique for predicting the flank wear and surface roughness. Senthilkumar et al. [17] determined the optimum grinding parameters using weighted S/N ratio of Taguchi's technique for optimizing multiple responses simultaneously.

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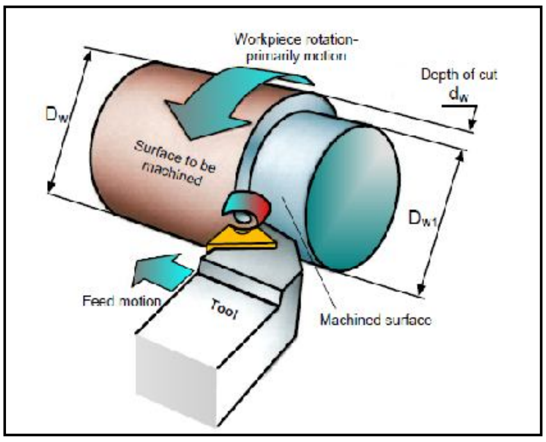


**Fig. 1 Parameters and Motions in Turning**

## 2. Workpiece and Cutting Tool Material

The workpiece material chosen for this analysis is AISI 4340 steel; a high tensile strength, shock resistance, good ductility and resistance to wear steel, used in construction of aircrafts and heavy vehicle crankshaft, gear shaft, camshaft and propeller shaft etc. The chemical composition of the workpiece material is shown in Table 1, whose hardness is 217 BHN.

**Table 1: Chemical Composition of AISI 4340 Steel**

| Sl. No | Elements Present | Alloying % |
|---|---|---|
| 1 | Carbon | 0.372 |
| 2 | Silicon | 0.278 |
| 3 | Manganese | 0.570 |
| 4 | Phosphorus | 0.030 |
| 5 | Sulphur | 0.026 |
| 6 | Chromium | 1.106 |
| 7 | Molybdenum | 0.320 |
| 8 | Nickel | 1.467 |
| 9 | Aluminum | 0.023 |
| 10 | Copper | 0.14 |
| 11 | Niobium | 0.064 |
| 12 | Vanadium | 0.033 |
| 13 | Ferrous | Remainder |

The SEM image of the workpiece material is shown in Fig. 2. The microstructure shows fine pearlite grains in a matrix of ferrtie, with fine dispersion of the chromium carbides. The size of the grains shows that the material is in mild annealed condition and the hardness measured is in agreement with it.

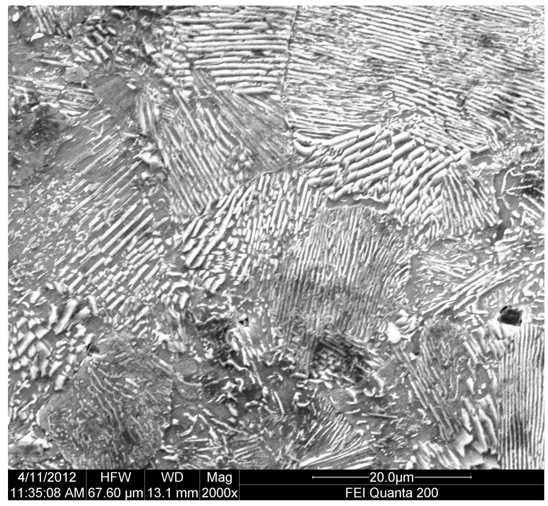


**Fig. 2 SEM Image of AISI 4340 Steel**

The cutting tool insert used in this study is uncoated cemented carbide cutting tool insert, whose ISO designation is CNMG 120404 and Brinell hardness is 1433 BHN. The chemical composition of the cutting tool insert is given in Table 2.

**Table 2: Chemical Composition of Cutting Tool Insert**

| Sl. No | Elements/compound | Alloying % |
|---|---|---|
| 1 | Tungsten carbide | 96.4 |
| 2 | Titanium carbide | 0.5 |
| 3 | Tantalum carbide | 0.8 |
| 4 | Cobalt | 2.19 |

## 3. Experimental Setup / Methodology

The experiments are conducted on a CNC Turning centre, Lokesh make two axes CNC TL-20 lathe. After performing the machining process, the flank wear is measured and recorded by using a Mitutoyo digital tool makers microscope of specifications, eyepiece 15X, view field diameter 13mm, objective 2X, working distance 67mm, total magnification 30X. Surface roughness values of the machined surfaces are recorded by using a Kosaka Laboratory Ltd make Surfcorder SE1200; with a vertical measuring range of 520µm, horizontal measuring range of 25mm, vertical resolution of 0.008µm, cutoff value of 0.8 mm with Gaussian filter.

 

### 3.1 Taguchi's design of experiment

Taguchi's technique is a powerful tool in quality optimization. Taguchi's technique makes use of a special design of orthogonal array (OA) to examine the quality characteristics through a minimal numbe`r of experiments [14]. Taguchi's DOE [1,7,16,18] is used to design the orthogonal array for three parameters varied through three levels. The control parameters and their levels chosen [4] are shown in Table 3.

**Table 3: Control Parameters and its Levels**

| Parameter / Level | Symbol | Level I | Level 2 | Level 3 |
|---|---|---|---|---|
| Cutting Speed (m/min) | A | 136 | 122 | 108 |
| Feed Rate (mm/rev) | B | 0.203 | 0.330 | 0.432 |
| Depth of Cut (mm) | C | 0.1 | 0.2 | 0.3 |

The various combinations of cutting speed, feed rate and depth of cut based on which the experiments are conducted is presented in Table 4.

**Table 4: Inner Array of Taguchi $L_9$ Orthogonal Array**

| Sl. No | Cutting Speed (m/min) | Feed Rate (mm/rev) | Depth of Cut (mm) |
|---|---|---|---|
| 1 | 136 | 0.203 | 0.1 |
| 2 | 136 | 0.330 | 0.2 |
| 3 | 136 | 0.432 | 0.3 |
| 4 | 122 | 0.203 | 0.2 |
| 5 | 122 | 0.330 | 0.3 |
| 6 | 122 | 0.432 | 0.1 |
| 7 | 108 | 0.203 | 0.3 |
| 8 | 108 | 0.330 | 0.1 |
| 9 | 108 | 0.432 | 0.2 |

### 3.2 Grey relational analysis

In order to determine the optimum condition of various input parameters to obtain the best quality characteristics, Grey Relational Analysis (GRA) [2,9] is carried out. GRA has been broadly applied in evaluating or judging the performance of a complex project with meager information. However, data to be used in grey analysis must be preprocessed into quantitative indices for normalizing raw data for another analysis. Preprocessing raw data is a process of converting an original sequence into a decimal sequence between 0.00 and 1.00 for comparison. If the expected data sequence is of the form "higher-the-better", then the original sequence can be normalized as,

$$x_i^*(k) = \frac{x_i^0(k) - \min x_i^0(k)}{\max x_i^0(k) - \min x_i^0(k)} \quad (1)$$

where $x^o_i$ $(k)$ is the original sequence, $x^*_i$ $(k)$ the sequence after the data preprocessing, max $x^o_i$ $(k)$ the largest value of $x^o_i$ $(k)$, and min $x^o_i$ $(k)$ implies the smallest value of $x^o_i$ $(k)$.When the form "smaller-the-better" becomes the expected value of the data sequence, the original sequence can be normalized as,

$$x_i^*(k) = \frac{\max x_i^0(k) - x_i^0(k)}{\max x_i^0(k) - \min x_i^0(k)} \quad (2)$$

Following data pre-processing, a grey relational coefficient is calculated to express the relationship between the ideal and actual normalized experimental results. The grey relational coefficient can be expressed as follows,

$$\zeta_i(k) = \frac{\Delta_{\min} + \zeta.\Delta_{\max}}{\Delta_{0i}(k) + \zeta.\Delta_{\max}} \quad (3)$$

where $\Delta_{oi}(k)$ is the deviation sequence of the reference sequence which is given by,

$$\Delta_{0i}(k) = \left\| x_0^*(k) - x_i^*(k) \right\| \quad (4)$$

$$\Delta_{\max} = \max_{\forall j \varepsilon i} \max_{\forall k} \left\| x_0^*(k) - x_j^*(k) \right\|, \quad (5)$$
$$\Delta_{\min} = \min_{\forall j \varepsilon i} \min_{\forall k} \left\| x_0^*(k) - x_j^*(k) \right\|.$$

$\zeta$ is distinguishing or identification coefficient: $\zeta \in [0, 1]$. $\zeta = 0.5$ is generally used. After obtaining the grey relational coefficient, we normally take the average of the grey relational coefficient as the grey relational grade. The grey relational grade is defined as follows.

$$\gamma_i = \frac{1}{n} \sum_{k=1}^{n} {}_i\zeta_i(k) \quad (6)$$

### 3.3 Analysis of variance

ANOVA is a statistical tool which is used to evaluate the size of the difference between inputs when applied to a data set. In performing ANOVA, it is essential to identify which variables are assigned as dependent and independent variables. Dependent variables reflect the outcome of the process, and independent variables reflect the factors that influence the dependent variables. Dependent and independent variables are related to each other. For analyzing the effect of categorical factors on a response, ANOVA is an important technique. The individual effect and their contribution on output responses are determined by this analysis [3,10].

 

## 4. Results and Discussion

Experiments are conducted based on the $L_9$ Orthogonal array designed using Taguchi's DoE. In this study, nine different workpiece are taken and for each level a separate workpiece is used. The output responses such as flank wear and surface roughness [11,13,19,20] are measured using equipment's mentioned, which are given in the Table 5.

**Table 5: Measured Output Responses**

| Sl. No | Flank wear (mm) | Surface roughness (µm) |
|---|---|---|
| 1 | 0.126 | 2.46 |
| 2 | 0.067 | 2.34 |
| 3 | 0.144 | 3.71 |
| 4 | 0.079 | 1.43 |
| 5 | 0.086 | 2.44 |
| 6 | 0.058 | 3.37 |
| 7 | 0.112 | 2.18 |
| 8 | 0.023 | 2.57 |
| 9 | 0.045 | 3.45 |

From the measured output responses, it is observed that, when cutting speed is increased from 108 m/min to 122 m/min, flank wear increases by 18.92% and surface roughness decreases by 13.14%. When it is further increased to 136 m/min, flank wear increases by 33.93% and surface roughness increases by 14.95%. A decrease of flank wear by 79.66%, increase of surface roughness by 17.43% is observed when feed rate is increased from 0.203 mm/rev to 0.33 mm/rev. When feed rate is further increased to 0.432 mm/rev, flank wear increases by 28.05% and surface roughness increases by 30.2%. Decrease in flank wear by 7.81% and surface roughness by 16.33% is observed when depth of cut is changed from 0.1 mm to 0.2 mm. But, when depth of cut is increased from 0.2 mm to 0.3 mm, increase in flank wear by 43.86% and surface roughness by 13.32% is observed.

In order to analyze the output responses using GRA, first the data pre-processing is carried out and then the deviation sequence is determined, which are given in Table 6.

For calculating the weighted grey relational grade, the output quality characteristics; flank wear and surface roughness are given equal weightage of 50%. Hence, the average of the grey relational coefficient of flank wear and surface roughness will be the weighted grey relational grade, which is shown in Table 7.

**Table 6: GRA Normalized Sequence after Data pre-Processing and Deviation Sequences**

| Sl. No | Data Pre-Processing | | Deviation Sequence | |
|---|---|---|---|---|
| | Flank wear | Surface roughness | Flank wear | Surface roughness |
| 1 | 0.14876 | 0.54825 | 0.85124 | 0.45175 |
| 2 | 0.63636 | 0.60088 | 0.36364 | 0.39912 |
| 3 | 0 | 0 | 1 | 1 |
| 4 | 0.53719 | 1 | 0.46281 | 0 |
| 5 | 0.47934 | 0.55702 | 0.52066 | 0.44298 |
| 6 | 0.71074 | 0.14912 | 0.28926 | 0.85088 |
| 7 | 0.26446 | 0.67105 | 0.73554 | 0.32895 |
| 8 | 1 | 0.5 | 0 | 0.5 |
| 9 | 0.81818 | 0.11404 | 0.18182 | 0.88596 |

**Table 7: Grey Relational Coefficient and Weighted Grey Relational Grade**

| Sl. No | Grey Relational Coefficient | | Weighted Grey Relational Grade |
|---|---|---|---|
| | Flank Wear | Surface Roughness | |
| 1 | 0.370 | 0.525 | 0.448 |
| 2 | 0.579 | 0.556 | 0.568 |
| 3 | 0.333 | 0.333 | 0.333 |
| 4 | 0.519 | 1.000 | 0.760 |
| 5 | 0.490 | 0.530 | 0.510 |
| 6 | 0.634 | 0.370 | 0.502 |
| 7 | 0.405 | 0.603 | 0.504 |
| 8 | 1.000 | 0.500 | 0.750 |
| 9 | 0.733 | 0.361 | 0.547 |

The best levels of various parameters are identified by calculating the average values of weighted grey relational grade, corresponding to each level of parameters as consolidated in Table 8.

**Table 8: Response Table for Weighted Grey Relational Grade**

| Level / Parameter | Cutting speed | Feed rate | Depth of cut |
|---|---|---|---|
| Level 1 | 0.45 | 0.571 | 0.567 |
| Level 2 | 0.591 | **0.609** | **0.625** |
| Level 3 | **0.600** | 0.461 | 0.449 |

 

From the response table of weighted grey relational grade, the optimal parameter levels are identified as, cutting speed of 108 m/min, feed rate of 0.33 mm/rev and depth of cut of 0.2 mm. Hence, the optimum conditions are represented as $A_3B_2C_2$. From the response table of surface roughness, the main effects plot is drawn as shown in Fig. 3.

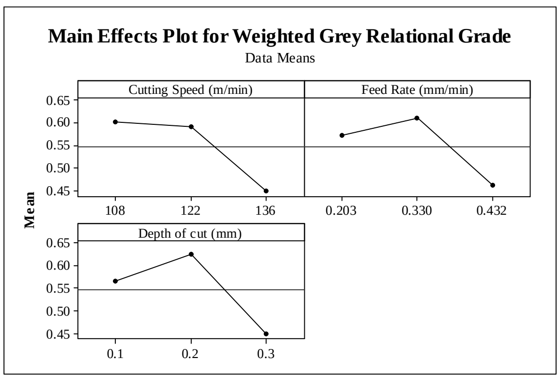


**Fig. 3 Main Effects plot for Weighted Grey Relational Grade**

The interaction plot of control parameters for weighted grey relational grade is shown in Fig. 4. Interaction plot is a graphical tool for interpreting the interaction effects, providing a better understanding of interactions among the chosen control variables. A moderate interaction effect is observed between cutting speed and feed rate but a higher interaction exists when the cutting speed is 122 m/min. For a cutting speed of 108 m/min, the interaction effect is higher between cutting speed and feed rate, for other values, it is lower. In between feed rate and depth of cut, a higher level of interaction exists between all the values of feed rate.

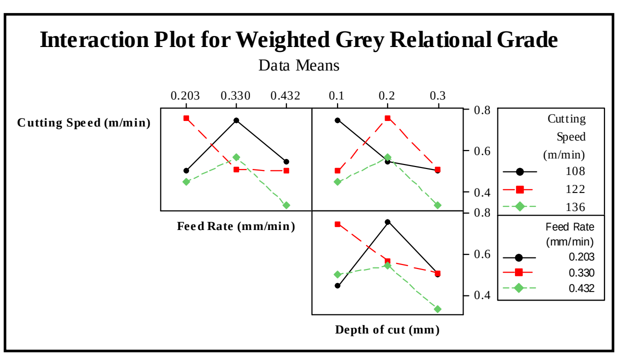


**Fig. 4 Interaction plot for Weighted Grey Relational Grade**

Using Minitab-16, statistical software, ANOVA is performed for the weighted grey relational grade; the results are shown in Table 9.

**Table 9: Analysis of Variance for Weighted Grey Relational Grade**

| Source | DOF | Seq SS | Adj MS | F | P | % Contribution |
|---|---|---|---|---|---|---|
| Cutting Speed | 2 | 0.04267 | 0.02134 | 2.01 | 0.333 | 28.86 |
| Feed Rate | 2 | 0.03570 | 0.01785 | 1.68 | 0.373 | 24.14 |
| Depth of Cut | 2 | 0.04822 | 0.02411 | 2.27 | 0.306 | 32.61 |
| Error | 2 | 0.02126 | 0.01063 | | | 14.38 |
| Total | 8 | 0.14786 | | | | |

From the ANOVA, it is evident that the depth of cut is the significant factor, which contributes by 32.61%, followed by cutting speed; 36.37% and feed rate by 24.14%. Fig. 5 shows the percentage contribution of machining parameters and error on weighted grey relational grade.

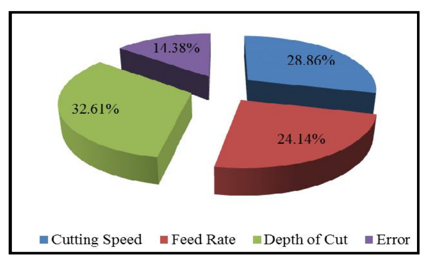


**Fig. 5 Percentile Contribution of Machining Parameters**

### 4.1 Confirmation experiment

With the determined optimum conditions of cutting speed: 108 m/min, feed rate: 0.330 mm/rev and depth of cut: 0.2 mm a confirmation experiment is performed with the same experimental setup and the output obtained is flank wear of 0.037 mm and surface roughness of 2.61 μm. A reduction in flank wear by 55% and surface roughness by 1.92% is observed which shows an improvement in the turning process.

## 5. Conclusion

In this work, Grey relational analysis is used to optimize the cutting parameters cutting speed, feed rate and depth of cut in the process of minimizing flank wear and surface roughness. Some of the outcomes of this analysis are,

 

i. Experiments are designed using Taguchi's DoE and the output responses are optimized simultaneously using multi-objective optimization technique, GRA.
ii. The optimum condition obtained is cutting speed of 108 m/min, feed rate of 0.33 mm/rev and depth of cut of 0.2 mm.
iii. The most significant factor that contributes to the output quality characteristics is depth of cut by 32.61%, cutting speed by 36.37% and feed rate by 24.14%.
iv. Confirmation experiment shows a reduction in flank wear by 55% and surface roughness by 1.92% with that of the average values obtained from the nine experiments.
v. A significant interaction exists between feed rate and depth of cut and from the analysis; it is evident that when the flank wear increases, surface roughness also increases with a correlation existing between them.
vi. Hence, in order to achieve lower flank wear and surface roughness during turning AISI 4340 steel, lower cutting speed with moderate feed rate and depth of cut is essential. This technique is further applied to other machining process for achieving better results and in future GRA may be coupled with other techniques for supremacy.

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