Investigation of Experimental and Statistical (Respond Surface Method and Grey Relational Analysis) of Surface Roughness, Vibration and Energy consumption Values of Titanium Alloy During Machining

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Abstract. This study aims to explain the interaction between the results measured in the turning operation. For this purpose, Ti 6Al-4V alloy workpiece was machined on CNC lathe. Surface roughness (Ra), vibration and energy consumption values were determined by turning. Experimental results were analyzed statistically. Response surface method (RSM) and grey relational analysis were used statistical analysis. In RSM analysis, regression equations, ANOVA, contour graphs, pertubation graphs, real and prediction graphs, % contribution graphs, most significant factor, optimum parameters, it is determined that the effective parameter in surface roughness, vibration and energy consumption is feed rate. Grey relational analysis steps and results are examined.

Keywords: Ti 6Al-4V, Ra, Vibration, Energy consumption, RSM, grey relational analysis.

Nomenclature

RSM            Response Surface Method
Ra             Average Surface Roughness
ANOVA          ANalysis Of VAriance
ELI            Extra Low Interstitials
CNC            Computer Numerical Control
R²             Coefficient of determination
V              Cutting speed
f              Feed rate
a              Depth of cut

1. Introduction

Turning is the process of removing chips with a suitable cutting tool from a cylindrical material [1]. Turning is one of the most preferred methods in manufacturing today [2]. There are many studies on turning. New developments related to turning are increasing day by day [3]. This causes turning to remain popular in academia and industry.

There are many cutting parameters that affect the surface quality, vibration, energy consumption, material removal rate, wear, temperature, acoustic emission, sound intensity, cutting forces to be obtained during the turning process. The most important of these cutting parameters are primary motion cutting speed and secondary motion feed rate. Other important cutting parameters are depth of cut, workpiece material, material hardness, cutting tool geometry, cutting tool tip angle, cutting tool coating, workpiece length, cooling type etc. [4-7].
Surface roughness, which indicates the quality of a product, is a quality criterion that is effective in the combination of two parts [8-9]. Surface roughness measurement is an important parameter in many engineering applications [10-11]. There is time and material loss in determining the optimum surface roughness.

Vibration is present in almost all machining processes. Vibration is one of the most important factors affecting product quality [12-13]. Excessive vibration between the tool and the workpiece results in poor surface quality, rapid tool wear and work accidents [14]. Excessive vibration is caused by the cutting parameters not being selected appropriately. Appropriate cutting parameters must be selected to achieve optimum vibration values [15].

Energy consumption is increasing day by day in line with the developing technology. The importance of providing energy economically is increasing [16]. It is aimed to increase the efficiency of the energy. As in every field, ways to reduce energy consumption in machining and optimization of effective parameters are explored [17].

It is an important issue to evaluate the obtained test results correctly. Artificial intelligence methods, statistical methods, optimization methods are used for result evaluation [18]. RSM is a statistical method used in machining in recent years. The correct design of the experiment provides accurate data for optimum results [19]. It is provided to determine the optimum values among multiple parameters. In this way, the experience required for similar operations is realized in the form of computer learning. RSM is also used in academic studies because it reduces the number of experiments. RSM is a method that saves time and cost for both researchers and industry. Minitab, Design Expert are programs used for RSM analysis [20].

Grey relational analysis is a statistical approach used to eliminate uncertainty and obtain the most appropriate results when there are many results in one. Grey relational analysis has applications in machining [21, 22]. The term “grey” in grey relational analysis refers to deficiency and/or uncertainty, but is often used in relation to the concept of knowledge. In the white system, the information is fully known. In the black system, the information is unknown. The grey system is between these two systems [23]. Table 1 shows the comparison of white, black and grey systems.

Titanium is an engineering material with a wide range of uses due to its superior properties. Titanium is used in many fields, especially in the space, aviation, automobile, medical, chemical, defense industry. Titanium material machinability is difficult compared to other materials. Titanium material is processed with special tools or cutting fluids [24]. Today, the production volume of this material, called the space age metal, is hundreds of millions of dollars per year. Therefore, it is used in many studies and industries. Titanium has recently been the subject of many studies in the field of machinability (turning, milling, drilling, grinding, honing, etc.) [25, 26].

The aim of this study is to investigate the effect of cutting parameters on the surface roughness, energy consumption and vibration in the cutting tool while machining titanium 6Al-4V ELI (grade 5) alloy. RSM method will be used to reduce the number of experiments and optimize the results. Results will be evaluated by grey relational analysis. RSM and gray relational analysis were used together to contribute to the literature, to be original and to demonstrate the comparison of the results.

2. Experimentation

The experimental design, the experimental method, the devices used in the experiments and the acquisition of data at the end of the experiment are clearly stated below. Figure 1 shows the flow chart of my work.

Ti-6Al-4V (grade 5) alloy, also called TC4 or Ti64, was chosen as workpiece. Titanium alloy consists of approximately 90% titanium, 6% aluminum, 4% vanadium, 0.25% (max) iron and 0.2% (max) oxygen. Workpiece
dimensions are determined as Ø80x200 mm. Workpiece hardness was measured as 290 HB with Proceq equotip 3 hardness device. Turning operation was carried out with CNC Lathe LT-20C under dry cutting conditions. Sangeo DNMG 150608R is used as cutting tool and SMOXH TDJNR 2525 M15 is used as tool holder. The machining length has been determined as 120 mm. Experimental design was created with RSM. Design Expert program was used for RSM. Table 2 shows the parameters used for the experimental design. When turning titanium material, low cutting speeds or cutting fluid should be used. Otherwise high tool wear occurs.

Ra, vibration and energy consumption are determined as the result of the experiment. Ra were measured with Mitutoyo SJ-210. Vibration were measured with UT312 pocketable vibrometer. Vibration Acceleration (O-P) value of the device is 0.1~199.9 m/s² 'dir (Frequency response: 10~1500 Hz, Amplitude error: ≤±5%). Energy consumption were measured with Hioki Power Quality Analyzer PW3198. Ra was performed when the procedure was finished. Vibration and energy consumption was carried out when the machine was running. The vibrometer is fixed to the tool holder. The energy consumption meter is connected to the spindle power cable.

Experiment list has been created with RSM optimal (custom) design. A total of 15 experiments were created. The experiment list and results are given in Table 3.

3. Experimental Results

Experiments for Ra, vibration and energy consumption were performed in three replications and their average values were taken. Table 3 shows the Ra, vibration and energy consumption values.

Figure 2 shows the combined graph for Ra, vibration and energy consumption. When the Figure 2 is examined, it is seen that the three values affect each other. In other words, Ra, vibration and energy consumption are linear proportional.

It is seen in Figure 2 that vibration and energy consumption values measured on-line affect the surface roughness. This result shows the importance of real-time manufacturing. Thus, manufacturing can be achieved both with the best surface quality and at the lowest cost.

Azizi et al. concluded in their study that the surface roughness increases with increasing the feed rate [27]. They also concluded that surface roughness and tool vibration are linear proportional [25]. This causes an increase in vibration in the cutting tool and consequently affects negatively the surface roughness. Camoseco-Negrete stated that the most effective parameter in energy consumed per machining cycle is feed rate [28].

4. Applied statistical analysis

Statistical analysis were used to determine the interactions of parameters, effective parameters and optimum parameters. It is important to determine optimum values as there are multiple results. Therefore, RSM and grey relational analysis were used to examine the results.

4.1. RSM model

When the literature is examined, it is seen that the minimum values for Ra, vibration and energy consumption are desired in the analysis [29, 30].

RSM analysis was performed with Design Expert program for Ra, vibration and energy consumption. The quadratic regression model was created for Ra, vibration and energy consumption. Table 4 gives the obtained equations and coefficient of determination (R²). The R² value is between 0 and 1 [31]. If R² value is greater than
0.8, it indicates a good relationship between variables. When the $R^2$ values in Table 4 are examined; it is seen that there is a good result between cutting parameters for Ra, vibration and energy consumption.

When the equations for surface roughness, vibration and energy consumption are examined, the most effective factor is the B factor. It has been obtained that the most effective parameter for surface roughness, vibration and energy consumption is feed rate.

Table 5-7 presents the ANOVA results. The created quadratic regression models is meaningful since $P<0.05$ [31, 32]. When examining Table 5-7, the most effective parameter for Ra, vibration and energy consumption is feed rate. The contribution of feed rate to the results is 97.63% for Ra, 89.35% for vibration and 95.87% for energy consumption.

Percentage contribution rates in Table 5-7 are given graphically in Figure 3. Feed rate is seen as the most contributing parameter for Ra, vibration and energy consumption. If an optimum point is to be chosen for Ra, vibration and energy consumption, this is the optimum factor feed rate.

Figure 4 shows the contour graphs for Ra. The graphs show the effects of cutting parameters (V-f-a) on Ra. The line directions and dark colors on the graph show the directions where Ra increases. Feed rate is the cutting parameter that most affects Ra.

Figure 5 shows the contour graphs for vibration. The graphs show the effects of cutting parameters (V-f-a) on vibration. The line directions and dark colors on the graph show the directions where the vibration increases. Feed rate is the cutting parameter that most affects vibration.

Figure 6 shows the contour graphs for energy consumption. The graphs show the effects of cutting parameters (V-f-a) on energy consumption. The line directions and dark colors on the graph show the directions where energy consumption increases. Feed rate is the cutting parameter that most affects energy consumption.

It is seen in Figure 7 that the experimental (actual) and predicted values of RSM models created for Ra, vibration and energy consumption. When the Figure-7 are examined, it is seen that the actual and predicted results are in harmony.

Figure 8 presents perturbation graphs of RSM models created for Ra, vibration and energy consumption. When the graph for Ra, vibration and energy consumption is analyzed, it is seen that the B line is more open than the other factors. It is achieved that feed rate is more effective for Ra, vibration and energy consumption.

Figure 9 shows the optimum cutting parameters and results for Ra, vibration and energy consumption. Optimum cutting parameters were determined as $V=100$ m/min, $f=0.12$ mm/rev, $a=3.9$ mm. The values obtained for optimum cutting parameters are as follows: $Ra = 2.85$ µm, vibration = 86.71 m/s\(^2\), energy consumption = 12.7 kWh. Combined desirability ratio was obtained as 0.993. This high desirability ratio showed that the created RSM optimization model is reliable.

4.2. Grey relational analysis

Grey relational analysis consists of the basic steps found in multi-criteria (qualified) decision making methods [22, 23]. These steps are described below, respectively. At the last stage, calculated values are given in line with these steps.

**Step 1:** Decision matrices are created. Eq. (1) is formed as follows: m alternative and n criteria.
\[
X = \begin{bmatrix}
x_1(1) & x_1(2) & \cdots & x_1(n) \\
x_2(1) & x_2(2) & \cdots & x_2(n) \\
\vdots & \vdots & & \vdots \\
x_m(1) & x_m(2) & \cdots & x_m(n)
\end{bmatrix}
\]

(1)

**Step 2:** It is the normalization process of the data. In order for the criteria to be compared with each other, the unit differences between them must be eliminated. This step is carried out in three different ways for the purpose of the criteria. It is when the variable is maximum, minimum and ideal.

If the variable is desired to be at the maximum value, the Eq. (2) is as follows.

\[
x'_i(j) = \frac{x_i(j) - \min_{j} x_i(j)}{\max_{j} x_i(j) - \min_{j} x_i(j)} \quad i = 1, 2, \ldots, m \quad j = 1, 2, \ldots, m
\]

(2)

If the variable is desired to be at the minimum value, the Eq. (3) is as follows.

\[
x'_i(j) = \frac{\max_{j} x_i(j) - x_i(j)}{\max_{j} x_i(j) - \min_{j} x_i(j)} \quad i = 1, 2, \ldots, m \quad j = 1, 2, \ldots, m
\]

(3)

If the variable is desired to be at the ideal value, the Eq. (4) is as follows.

\[
x'_i(j) = 1 - \frac{|x_i(j) - x_0(j)|}{\max_{j} x_i(j) - x_0(j)} \quad i = 1, 2, \ldots, m \quad j = 1, 2, \ldots, m
\]

(4)

After normalization, unit differences between the variables disappear. Results take values between 0 and 1. In this way, the results become comparable.

**Step 3:** The step of creating the reference series. In the second step, the normalized decision matrix \((X')\) Eq. (5) of the values normalized:

\[
X = \begin{bmatrix}
x'_1(1) & x'_1(2) & \cdots & x'_1(n) \\
x'_2(1) & x'_2(2) & \cdots & x'_2(n) \\
\vdots & \vdots & & \vdots \\
x'_m(1) & x'_m(2) & \cdots & x'_m(n)
\end{bmatrix}
\]

(5)

The reference matrix \((X_0)\) for the reference values determined for each of the n criteria is the Eq. (6):

\[
X_0 = \{x_0(1), x_0(2), x_0(3), \ldots, x_0(n)\}
\]

(6)
**Step 4:** It is the step to obtain the difference matrix. Difference matrix values are obtained by calculating the difference between the values in the normalized decision matrix and the reference series calculated for each criterion using the Eq. (7).

\[
\Delta_{0i}(j) = |x_0(j) - x_i(j)| \quad i = 1, 2, \ldots, m \quad j = 1, 2, \ldots, m
\]  

**Step 5:** It is the step of obtaining grey relational coefficients. Grey relational coefficients are calculated according to Eq. (8). The grey relational coefficient between \(x_0(j)\) and \(x_i(j)\) is expressed as \(\varepsilon(x_0(j), x_i(j))\) and its value is calculated as equating between 0-1.

\[
\varepsilon(x_0(j), x_i(j)) = \frac{\Delta_{\text{min}} + \xi \Delta_{\text{max}}}{\Delta_{0i}(j) + \xi \Delta_{\text{max}}}
\]

\[
\Delta_{\text{min}} = \min_j \min_i |x_0(j) - x_i(j)|
\]

\[
\Delta_{\text{max}} = \max_i \max_j |x_0(j) - x_i(j)|
\]

\[
i = 1, 2, \ldots, m \quad j = 1, 2, \ldots, m
\]  

The expression \(\xi\) is expressed as the coefficient of separation and is a value between 0-1. It is usually taken as 0.5 in scientific articles.

**Step 6:** Grey relational degree expresses the weighted sums of grey relational coefficients for each criterion and is calculated as in Eq. (9).

\[
\gamma(x_0, x_i) = \sum_{j=1}^{n} \varepsilon(x_0(j), x_i(j)) \ast w_j(j)
\]  

The value of \(w_j(j)\) refers to the weights determined for each criterion. If the criteria have equal weight values, the formula in the Eq. (10) turns into the following.

\[
\gamma(x_0, x_i) = \frac{1}{n} \sum_{j=1}^{n} \varepsilon(x_0(j), x_i(j))
\]  

The grey relational degree measures the degree of similarity between the series for each alternative and the reference series. The more similar the alternative series is to the reference series, the greater the grey relational degree value. This way, each alternative is ranked from best to worst.
Table 8 shows the results calculated according to the stated steps. Minimum value equation is used for Ra, vibration and energy consumption. As a result of the grey relational analysis, it is seen that the experiment numbered 13 contains the optimum parameters. Optimum parameters according to the grey relational analysis is determined as cutting speed 55 m/min, feed rate 0.12 mm/rev, depth of cut 0.9 mm.

5. Conclusions, discussion and suggestions

In this study, Ti 6Al-4V alloy workpiece was machined on CNC lathe. The cutting parameters were selected with three factors (V-f-a) and four levels. RSM optimal (custom) design method was used to decrease the number of experiments. While we need to conduct 64 experiments with the full factorial experiment design, the number of experiments was reduced to 15 with the RSM. Ra, vibration and energy consumption values were determined. It is important to evaluate these results as much as the results obtained in the study. In our study, two statistical methods were used. Experimental results were evaluated by RSM and grey relational analysis method. Experimental and statistical results are as follows:

- When turning titanium material, low cutting speeds or cutting fluid should be used. Otherwise high tool wear occurs. As a result, vibration increases. Increasing vibration causes deterioration of surface quality and increase in energy consumption.
- This study is important as it examines the relationship between Ra, vibration and energy consumption on the machinability of titanium alloy.
- When the experimental results determined were examined, it was concluded that the Ra, vibration and energy consumption values were directly proportional. The increase in one affects the others. In the opposite case it is true.
- Regression equations have been created for Ra, vibration and energy consumption. $R^2$ value for Ra, vibration and energy consumption is 0.99. The $R^2$ values of the regression equations created showed the reliability of these models.
- ANOVA results were determined for effective parameter Ra, vibration and energy consumption. Feed rate is an effective parameter of about 98% for Ra, about 89% for vibration and 96% for energy consumption.
- When the contour charts, perturbation charts and% contribution charts are examined, it is concluded that Ra, vibration and energy consumption are more affected by the feed rate.
- Optimum cutting parameters were determined with RSM. Optimum cutting parameters for Ra, vibration and energy consumption have been determined as $V = 100$ m/min, $f = 0.12$ mm / rev, $a = 3.9$ mm. Optimized Ra, vibration and energy consumption were determined ($Ra = 2.85$ µm, Vibration = 86.71 m/s², Energy consumption = 12.7 kWh).
- The desirability ratio was obtained with RSM as 0.993. This desirability ratio has demonstrated to reliability of the optimization created.
- Optimum cutting parameters were determined with grey relational analysis. Optimum cutting parameters for Ra, vibration and energy consumption have been determined as $V=55$ m/min, $f=0.12$ mm/rev and $a=0.9$ mm. Optimized Ra, vibration and energy consumption were determined ($Ra = 0.75$ µm, Vibration = 58.30 m/s², Energy consumption = 9.82 kWh).
It is concluded that vibration and energy consumption can be controlled with Ra.

Since the results are positive, the methods used in the article can be applied to future studies (industrial and academic).

In future studies, different statistical approaches (Taguchi, artificial intelligence methods, etc.), different experimental designs (DOE, full factorial, Box Behnken, Taguchi etc.), different parameters (cutting tool, cutting speed, feed, chip depth, coolant, cutting tool angles, cutting tool material, etc.), different measurement results (wear, acoustic emission, vibration, cutting forces, sound, temperature, etc.) are recommended.

Acknowledgements

This study was supported by Amasya University Scientific Research Projects Coordination Unit with the project of FMB-BAP 19-0412.

Conflict of interest

The author declare that they have no conflict of interest.

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- Ramp function with values 55, 100, 0.12, 0.48, 0.9, 3.9, 0.7533, 8.9284, 58.3, 192.952, 9.82, 21.5086.

Desirability = 0.993
Solution 1 out of 79
### Tables

**Table 1.** Comparison of white, black and grey systems [23].

|                  | Black System | Grey System | White System |
|------------------|--------------|-------------|--------------|
| **Information**  | The exact unknown | Missing     | Certainly known |
| **View**         | Dark         | Grey        | Clear        |
| **Process**      | New          | Exchange of the old with the new | Old |
| **Feature**      | Chaos        | Difficulty (Complexity) | Tidy |
| **Methodology**  | Negative     | Change      | Positive     |
| **Behaviour**    | Tolerant     | Tolerant    | Seriously    |
| **Conclusion**   | No solution  | Many solutions | One solution |

**Table 2.** RSM factors.

| Factor | Unit     | Lowest Level | Highest Level | Level 1 | Level 2 | Level 3 | Level 4 |
|--------|----------|--------------|---------------|---------|---------|---------|---------|
| A      | Cutting speed | m/min        | 55            | 100     | 55      | 70      | 85      | 100     |
| B      | Feed rate  | mm/rev       | 0.12          | 0.48    | 0.12    | 0.24    | 0.36    | 0.48    |
| C      | Depth of cut | mm          | 0.9           | 3.9     | 0.9     | 1.9     | 2.9     | 3.9     |

**Table 3.** Experimental design and results.

| No | V (m/min) | f (mm) | a (mm/rev) | Ra (µm) | Vibration (m/s²) | Energy consumption (kWh) |
|----|-----------|--------|------------|---------|------------------|--------------------------|
| 1  | 85        | 0.12   | 2.9        | 2.23    | 72.62            | 11.91                    |
| 2  | 70        | 0.48   | 3.9        | 8.52    | 192.95           | 21.51                    |
| 3  | 55        | 0.12   | 3.9        | 1.43    | 190.82           | 11.05                    |
| 4  | 55        | 0.48   | 0.9        | 7.54    | 162.11           | 19.07                    |
| 5  | 100       | 0.24   | 3.9        | 4.95    | 129.38           | 15.96                    |
| 6  | 70        | 0.24   | 3.9        | 4.22    | 125.74           | 14.89                    |
| 7  | 55        | 0.36   | 2.9        | 5.60    | 154.19           | 16.66                    |
| 8  | 100       | 0.12   | 0.9        | 1.95    | 61.26            | 10.79                    |
| 9  | 55        | 0.24   | 1.9        | 3.28    | 101.74           | 13.46                    |
| 10 | 70        | 0.24   | 0.9        | 3.98    | 98.22            | 13.02                    |
| 11 | 55        | 0.48   | 0.9        | 7.54    | 160.11           | 19.57                    |
| 12 | 100       | 0.48   | 1.9        | 8.93    | 175.91           | 21.18                    |
| 13 | 55        | 0.12   | 0.9        | 0.75    | 58.30            | 9.82                     |
| 14 | 85        | 0.36   | 0.9        | 5.81    | 131.15           | 17.33                    |
| 15 | 70        | 0.36   | 1.9        | 5.70    | 142.67           | 17.99                    |

**Table 4.** Regression equations for Ra, vibration and energy consumption.

| Equations | R² |
\[ Ra = 5.14 + 0.61A + 3.28B + 0.33C - 0.003AB - 0.09AC - 0.02BC - 0.12A^2 + 0.02B^2 + 0.02C^2 - 0.9961 \]

\[ \text{Vibration} = 127.49 - 1.07A + 53.48B + 15.14C + 0.91AB - 1.61AC + 0.77BC + 3.06A^2 - 5.82B^2 + 2.56C^2 - 0.9981 \]

\[ \text{Energy consumption} = 16.35 + 0.75A + 4.83B + 15.14C + 0.05A\cdot B - 0.04B\cdot C - 0.41A^2 + 0.11B^2 - 0.19C^2 - 0.9953 \]

| Source | DF | Seq SS | Contribution | Adj SS | Adj MS | F-Value | P-Value |
|--------|----|--------|--------------|-------|--------|---------|---------|
| Regression | 9 | 94 | 99.61% | 93.8613 | 10.429 | 141.72 | 0 |
| A-v | 1 | 1 | 0.81% | 0.0834 | 0.0834 | 1.13 | 0.336 |
| B-f | 1 | 92 | 97.63% | 1.4747 | 1.4747 | 20.04 | 0.007 |
| C-a | 1 | 1 | 1.08% | 0.0004 | 0.0004 | 0 | 0.948 |
| A² | 1 | 0 | 0.02% | 0.0337 | 0.0337 | 0.46 | 0.528 |
| B² | 1 | 0 | 0.00% | 0.002 | 0.002 | 0.03 | 0.876 |
| C² | 1 | 0 | 0.01% | 0.0016 | 0.0016 | 0.02 | 0.887 |
| AB | 1 | 0 | 0.00% | 0.0001 | 0.0001 | 0 | 0.975 |
| AC | 1 | 0 | 0.05% | 0.0469 | 0.0469 | 0.64 | 0.461 |
| BC | 1 | 0 | 0.00% | 0.0028 | 0.0028 | 0.04 | 0.853 |
| Error | 5 | 0 | 0.39% | 0.3679 | 0.0736 | | |
| Total | 14 | 94 | 100.00% | | | | |

| Source | DF | Seq SS | Contribution | Adj SS | Adj MS | F-Value | P-Value |
|--------|----|--------|--------------|-------|--------|---------|---------|
| Regression | 9 | 24653.5 | 99.81% | 24653.5 | 2739.28 | 284.91 | 0 |
| A-v | 1 | 73.3 | 0.30% | 17.8 | 17.75 | 1.85 | 0.232 |
| B-f | 1 | 22070.5 | 89.35% | 662 | 661.97 | 68.85 | 0 |
| C-a | 1 | 2409.1 | 9.75% | 19.5 | 19.51 | 2.03 | 0.214 |
| A² | 1 | 1.1 | 0.00% | 21.3 | 21.31 | 2.22 | 0.197 |
| B² | 1 | 64.5 | 0.26% | 82.2 | 82.19 | 8.55 | 0.033 |
| C² | 1 | 9.4 | 0.04% | 15.4 | 15.43 | 1.6 | 0.261 |
| AB | 1 | 7.5 | 0.03% | 4.6 | 4.6 | 0.48 | 0.52 |
| AC | 1 | 14.8 | 0.06% | 13 | 13.04 | 1.36 | 0.297 |
| BC | 1 | 3.4 | 0.01% | 3.4 | 3.39 | 0.35 | 0.578 |
| Error | 5 | 48.1 | 0.19% | 48.1 | 9.61 | | |
| Total | 14 | 24701.6 | 100.00% | | | | |

| Source | DF | Seq SS | Contribution | Adj SS | Adj MS | F-Value | P-Value |
|--------|----|--------|--------------|-------|--------|---------|---------|
| Regression | 9 | 205.546 | 99.53% | 205.546 | 22.8385 | 118.86 | 0 |
| A-v | 1 | 0.91 | 0.44% | 0.514 | 0.5142 | 2.68 | 0.163 |
Table 8. Calculation results for grey relational analysis.

| No | B-f | C-a | A² | B² | C² | AB | AC | BC | Error | Total |
|----|-----|-----|----|----|----|----|----|----|-------|-------|
|    |     |     |    |    |    |    |    |    |       |       |
| 1  | 197.984 | 6.06 | 0.289 | 0.002 | 0.075 | 0.004 | 0.212 | 0.011 | 0.961 | 206.507 |
| 2  | 95.87% | 2.93% | 0.14% | 0.00% | 0.04% | 0.00% | 0.10% | 0.01% | 0.47% | 100.00% |
| 3  | 2.662 | 0.099 | 0.398 | 0.03 | 0.092 | 0.017 | 0.198 | 0.011 | 0.961 |
| 4  | 2.6617 | 0.0985 | 0.3983 | 0.03 | 0.0916 | 0.0171 | 0.1984 | 0.0106 | 0.1921 |
| 5  | 13.85 | 0.51 | 2.07 | 0.16 | 0.48 | 0.09 | 1.03 | 0.06 | 0.824 |
| 14 | 0.014 | 0.506 | 0.209 | 0.709 | 0.521 | 0.777 | 0.356 | 0.824 |       |

| No | Ra | Vibration | Energy | Ra | Vibration | Energy | Ra | Vibration | Energy | GRG | Rank |
|----|----|-----------|--------|----|-----------|--------|----|-----------|--------|-----|------|
| 1  | 0.819 | 0.894 | 0.821 | 0.181 | 0.106 | 0.179 | 0.734 | 0.825 | 0.736 | 0.765 | 4    |
| 2  | 0.050 | 0.000 | 0.000 | 0.950 | 1.000 | 1.000 | 0.345 | 0.333 | 0.333 | 0.337 | 15   |
| 3  | 0.917 | 0.758 | 0.895 | 0.083 | 0.242 | 0.105 | 0.858 | 0.674 | 0.827 | 0.786 | 3    |
| 4  | 0.169 | 0.229 | 0.208 | 0.831 | 0.771 | 0.792 | 0.376 | 0.393 | 0.387 | 0.385 | 12   |
| 5  | 0.486 | 0.472 | 0.475 | 0.514 | 0.528 | 0.525 | 0.493 | 0.486 | 0.488 | 0.489 | 8    |
| 6  | 0.576 | 0.499 | 0.566 | 0.424 | 0.501 | 0.434 | 0.541 | 0.500 | 0.536 | 0.525 | 7    |
| 7  | 0.407 | 0.288 | 0.414 | 0.593 | 0.712 | 0.586 | 0.458 | 0.413 | 0.461 | 0.444 | 10   |
| 8  | 0.854 | 0.978 | 0.917 | 0.146 | 0.022 | 0.083 | 0.774 | 0.958 | 0.858 | 0.863 | 2    |
| 9  | 0.691 | 0.677 | 0.689 | 0.309 | 0.323 | 0.311 | 0.618 | 0.608 | 0.617 | 0.614 | 5    |
| 10 | 0.605 | 0.704 | 0.726 | 0.395 | 0.296 | 0.274 | 0.559 | 0.628 | 0.646 | 0.611 | 6    |
| 11 | 0.169 | 0.244 | 0.165 | 0.831 | 0.756 | 0.835 | 0.376 | 0.398 | 0.375 | 0.383 | 13   |
| 12 | 0.000 | 0.127 | 0.028 | 1.000 | 0.873 | 0.972 | 0.333 | 0.364 | 0.340 | 0.346 | 14   |
| 13 | 1.000 | 1.000 | 1.000 | 0.000 | 0.000 | 0.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1    |
| 14 | 0.382 | 0.459 | 0.357 | 0.618 | 0.541 | 0.643 | 0.447 | 0.480 | 0.437 | 0.455 | 9    |
| 15 | 0.394 | 0.373 | 0.301 | 0.606 | 0.627 | 0.699 | 0.452 | 0.444 | 0.417 | 0.438 | 11   |
Biography

Dr. Harun AKKUS was born Osmaniye/Turkey in 1987. He received his B.S. degree in 2008, M.Sc. degree in 2010, and Ph.D. degree in 2017 from the Selçuk University. He worked as an academician at Amasya University between 2011-2021. He has been working as an academic at Nigde Omer Halisdemir University since 2021. He is working on automotive technology, machining, applied statistics, optimization.