STUDY ON MULTI-OBJECTIVE OPTIMIZATION OF THE TURNING PROCESS OF EN 10503 STEEL BY COMBINATION OF TAGUCHI METHOD AND MOORA TECHNIQUE

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Abstract
In this study, the multi-objective optimization problem of turning process was successfully solved by a Taguchi combination method and MOORA techniques. In external turning process of EN 10503 steel, surface grinding process, the orthogonal Taguchi L9 matrix was selected to design the experimental matrix with four input parameters namely insert nose radius, cutting velocity, feed rate, and depth of cut. The parameters that were chosen as the evaluation criteria of the machining process were the surface roughness (Ra), the cutting force amplitudes in X, Y, Z directions, and the material removal rate (MRR). Using Taguchi method and MOORA technique, the optimized results of the cutting parameters were determined to obtain the minimum values of surface roughness and cutting force amplitudes in X, Y, Z directions, and maximum value of MRR. These optimal values of insert nose radius, cutting velocity, feed rate, and cutting depth were 1.2 mm, 76.82 m/min, 0.194 mm/rev, and 0.15 mm, respectively. Corresponding to these optimal values of the input parameters, the surface roughness, cutting force amplitudes in X, Y, Z directions, and material removal rate were 0.675 µm, 124.969 N, 40.545 N, 164.206 N, and 38.130 mm³/s, respectively. The proposed method in this study can be applied to improve the quality and effectiveness of turning processes by improving the surface quality, reducing the cutting force amplitudes, and increasing the material removal rate. Finally, the research direction was also proposed in this study.

Keywords: Multi-Objective Optimization, Taguchi, Moora, Turning process, EN 10503 Steel.

DOI: 10.21303/2461-4262.2020.001414

1. Introduction

Turning is one of the most common machining processes in the cutting methods. The work volume that the lathes perform about 40 % of the total workload of the machining processes, and the number of lathes accounts about 25–35 % of the total number of machine tools in the cutting workshop [1].

Many studies were performed to improve the accuracy and productivity of machining processes [1–12]. In which, most studies focus on determining the optimal values of the cutting parameters to ensure the surface roughness with the smallest value, the force components with the smallest values, and the material removal rate with greatest value.

The response surface method (RSM) was applied to optimize the turning process of AISI 410 [2], turning process of Inconel 718 Nickel-base super alloy [3, 4]. RSM and Genetic Algorithm (GA) were also combined to optimize the turning process of AISI 1040 [5], turning process of martensitic stainless steel [6], and turning process of EN8 steel [7].

Particle swarm optimization (PSO) algorithm was applied to optimize the turning process of AISI D2 [8]. The regression analysis method was used to optimize the turning process of PM nickel-based superalloy [9]. Weighting factor method and GA algorithm were applied to optimize the turning process of 52100 steel [10].
Taguchi method was applied to optimize the turning process with different materials such as aluminum [11], polyethylene [12], thermoplastic polymer-delrin 500 AL [13], EN 8 steel [14], aluminum 6063 [15], AISI 316L stainless steel [16], AM alloy [17], AISI 1045 steel [18], S45C steel [19], Aluminum, Brass, and Copper [20], Mild Steel [21], EN 354 steel [22], Titanium Alloy Ti-6Al-4V [23], AISI 1020 MS steel [24], Aluminium-2014 Alloy [25], AISI 409 steel [26], P20 steel [27], and so on. A combination method of Taguchi and Grey relational analysis (GRA) was used to optimize the turning process of DIN 1.2344 steel [28], turning the unidirectional glass fiber reinforced plastic (UD-GFRP) composite rods [29], turning the EN-8, EN-31 steel and EN-36 steel [30], turning the DIN Ck45 steel [31]. Taguchi was combined to TOPSIS and SAW method to optimize the turning process of Ti-6Al-4V alloy under minimum quantity lubrication (MQL) [32]. Taguchi was also combined to GA and PSO algorithm to optimize the turning process of S45C steel [33].

The summary of the reviewed literatures about the optimization of the turning processes including the materials, the aims, the methods, and the optimized results of each study as listed in Table 1.

Table 1
Summary of the reviewed literatures about the optimization of turning process

| Workpiece material | Aims                                      | Optimization method/algorithms | Input values and their value                      | Ref. |
|--------------------|-------------------------------------------|--------------------------------|--------------------------------------------------|------|
| AISI 410           | Minimum surface roughness                 | RSM                            | – Cutting velocity 255.75 m/min; – Feed rate 0.1 mm/rev; – Depth of cut 0.3 mm; – Tool nose radius 1.2 mm | [2]  |
| Inconel 718 Nickel-base super alloy | Minimum surface roughness | RSM                            | – Cutting velocity 70 m/min; – Feed rate 0.09 mm/rev; – Tool nose radius 0.4 mm | [3]  |
| Inconel 718 Nickel-base super alloy | – Minimum surface roughness; – Minimum cutting force; – Minimum power; – Maximum tool life; – Maximum MRR | RSM                            | – Cutting velocity 40 m/min; – Feed rate 0.1 mm/rev; – Depth of cut 1.0 mm | [4]  |
| AISI 1040 steel    | Minimum main cutting force \( P_z \)     | RSM+GA                         | – Cutting velocity 142.284 m/min; – Feed rate 0.029 mm/rev | [5]  |
| Martensitic stainless steel | Minimum surface roughness | RSM+GA                         | – Cutting velocity 119.93 m/min; – Feed rate 0.15 m/min; – Depth of cut 0.5 mm | [6]  |
| EN28 steel         | Minimum surface roughness                 | RSM+GA                         | – Workpiece speed 800 rpm; – Feed rate 0.3 m/min; – Depth of cut 0.3 mm | [7]  |
| AISI D2 steel      | – Minimum surface roughness; – Minimum tool wear | PSO                            | – Cutting velocity 67.5 m/min; – Feed rate 0.0345 mm/rev | [8]  |
| PM nickel-based superalloy | Minimum cutting force | Regression analysis           | – Cutting velocity 20 ± 40 m/min; – Feed rate 0.08 ± 0.1 mm/rev; – Depth of cut 0.1 ± 0.15 | [9]  |
| 52100 steel        | Minimum surface roughness                 | Weighting factors+GA           | – Cutting velocity 100 ± 300 m/min; – Feed rate 0.15 mm/rev; – Depth of cut 1.0 mm | [10] |

Minimum power

– Cutting velocity 100 m/min; – Feed rate 0.15 mm/rev; – Depth of cut 1.0 mm

Minimum cutting times

– Cutting velocity 300 m/min; – Feed rate 0.45 mm/rev; – Depth of cut 1.0 mm

Minimum cutting force \( F_z \)

– Cutting velocity 300 m/min; – Feed rate 0.15 mm/rev; – Depth of cut 1.0 mm
Continuation of Table 1

| 1            | 2                              | 3                              | 4                                          | 5                      |
|--------------|---------------------------------|---------------------------------|---------------------------------------------|------------------------|
| Aluminum     | Minimum surface roughness       | Taguchi                         | – Cutting velocity 35 m/min;                | [11]                   |
|              |                                  |                                 | – Feed rate 0.15 mm/rev;                    |                        |
|              |                                  |                                 | – Depth of cut 1.25 mm                      |                        |
| Polyethylene | Minimum surface roughness       | Taguchi                         | – Cutting velocity 213.88 m/min;            | [12]                   |
|              |                                  |                                 | – Feed rate 0.049 mm/rev;                   |                        |
|              |                                  |                                 | – Depth of cut 2.0 mm;                      |                        |
|              |                                  |                                 | – Tool nose radius 0.8 mm                   |                        |
| Thermoplastic| Minimum surface roughness       | Taguchi                         | – Workpiece speed 250 rpm;                 | [13]                   |
| polymer-delin |                                  |                                 | – Feed rate 0.15 mm/rev;                    |                        |
| 500AL        | Maximum MRR                     |                                 | – Depth of cut 0.14 mm                      |                        |
| EN8 steel    | Minimum surface roughness       | Taguchi                         | – Workpiece speed 303 rpm;                 | [14]                   |
|              |                                  |                                 | – Feed rate 0.067 mm/rev;                   |                        |
|              |                                  |                                 | – Depth of cut 0.14 mm                      |                        |
| Aluminum 6063| Minimum power                   | Taguchi                         | – Workpiece speed 1750 rpm;                | [15]                   |
|              |                                  |                                 | – Feed rate 0.3 mm/rev;                     |                        |
|              |                                  |                                 | – Depth of cut 1.2 mm                       |                        |
| AISI 316L stainless steel | Minimum surface roughness; – Minimum cutting force | Taguchi | – Increasing the feed rate and depth of cut, the surface roughness and cutting forces increased. | [16]                   |
|              |                                  |                                 | – When using MQL, surface roughness was smallest. |                        |
|              |                                  |                                 | – When using Dy cooling, the cutting forces were smallest |                        |
| AM alloy     | Minimum surface roughness       | Taguchi                         | – Cutting velocity 160 mm/min;              | [17]                   |
|              |                                  | Minimum cutting force           | – Feed rate 0.1 mm/rev;                     |                        |
|              |                                  |                                 | – Depth of cut 0.5 mm                       |                        |
| AISI 1045    | Minimum surface roughness       | Taguchi                         | – Cutting velocity 200 m/min;              | [18]                   |
|              |                                  |                                 | – Feed rate 0.1 mm/rev;                     |                        |
|              |                                  |                                 | – Depth of cut 0.5 mm                       |                        |
| S45C steel   | Minimum surface roughness       | Taguchi                         | – Cutting velocity 135 m/min;              | [19]                   |
|              |                                  |                                 | – Feed rate 0.08 mm/rev;                    |                        |
|              |                                  |                                 | – Depth of cut 1.1 mm                       |                        |
| Aluminium    | Minimum surface roughness       | Taguchi                         | – Workpiece speed 160 rpm;                 | [20]                   |
|              |                                  |                                 | – Feed rate 0.05 mm/rev;                    |                        |
|              |                                  |                                 | – Depth of cut 1.5 mm                       |                        |
| Brass        | Minimum surface roughness       | Taguchi                         | – Workpiece speed 660 rpm;                 | [21]                   |
|              |                                  |                                 | – Feed rate 0.1 mm/rev;                     |                        |
|              |                                  |                                 | – Depth of cut 1.0 mm                       |                        |
| Copper       | Minimum surface roughness       | Taguchi                         | – Workpiece speed 80 rpm;                  | [22]                   |
|              |                                  |                                 | – Feed rate 0.1 mm/rev;                     |                        |
|              |                                  |                                 | – Depth of cut 1.5 mm                       |                        |
| Mild Steel   | Minimum surface roughness       | Taguchi                         | – Cutting velocity 60 m/min;               | [23]                   |
|              |                                  |                                 | – Feed rate 0.1 mm/rev;                     |                        |
|              |                                  |                                 | – Depth of cut 0.4 mm                       |                        |
| EN 354 steel | Minimum surface roughness       | Taguchi                         | – Cutting velocity 222 m/min;              | [24]                   |
|              |                                  |                                 | – Feed rate 0.015 mm/rev;                  |                        |
|              |                                  |                                 | – Depth of cut 1.2 mm                       |                        |
| Titanium Alloy Ti-6Al-4V | Minimum surface roughness | Taguchi | – Cutting velocity 125 m/min; | [25]                   |
|              |                                  |                                 | – Feed rate 0.12 mm/rev;                    |                        |
|              |                                  |                                 | – Depth of cut 0.6 mm                       |                        |
From the summary of the reviewed literatures in Table 1, it is clear that many methods and algorithms were applied in optimization of turning processes. However, with different machining material, the obtained values of cutting parameters were different. So, the optimization process should be performed with each specific material. Taguchi method has been successfully applied to optimize the turning processes with different cases. Besides, Taguchi was also successfully combined with one or two of algorithms (GRA, GA, TOPSIS, SAW, PSO, etc.) to optimize the turning processes.
Up to date, it seems that the combination of Taguchi method and MOORA technique in optimization of the turning processes have not mentioned. Besides, in previous studies, the surface roughness or cutting forces or MRR or two parameters of them were chosen as the output parameters. It also seems a study that was performed in consideration of all five output parameters (Surface roughness, cutting force in X, Y, Z directions, and MRR) have not been mentioned. EN 10503 steel is a steel type widely used to manufacture the parts in the machine manufacturing. Because this steel has good machinability and low cost. The optimization of turning process of the EN 10503 steel with five above output parameters have been not mentioned and this is a necessary study.

The aim of this research is simultaneously determining the values of four parameters including the tool insert radius, cutting speed, feedrate, and depth of cut to ensure simultaneously output criteria including the minimum value of surface roughness, the minimum values of three cutting force components, and maximum value of MRR when turning the EN 10503 steel. To solve this problem, Taguchi method was applied to design the experimental matrix and MOORA technique was applied to solve the multi-objective optimization problem.

2. Multi-Objective Optimization using MOORA Technique

2.1. Multiple-Criteria Decision Making (MCDM)

The Multiple-Criteria Decision Making (MCDM) was used to choose the best solution from the set of solutions $A = \{A_1, A_2, ..., A_m\}$ based on the set of criteria $C = \{C_1, C_2, ..., C_n\}$. In which, each criterion $C_j$ is assigned with a weight $w_j$ ($j = 1, 2, ..., n$), so that $\sum_{j=1}^{n} w_j = 1$. A multiple-criteria decision making problem was presented by the matrix $D = [d_{ij}]_{m \times n}$.

$$
A_1 \begin{bmatrix} d_{11} & d_{12} & d_{1n} \\ d_{21} & d_{22} & d_{2n} \\ \vdots & \vdots & \vdots \\ d_{m1} & d_{m2} & d_{mn} \end{bmatrix}
$$

where $d_{ij} \in R^+$ with $i = 1, 2, ..., m$ and $j = 1, 2, ..., n$.

In the MOORA technique, the weights were calculated using measurement of Entropy, because this method can get the high accuracy. The steps of the weight calculation process will be performed as following [34, 35]:

**Step 1:** Calculating the values $p_{ij}$ with $i = 1, 2, ..., m$ and $j = 1, 2, ..., n$ using Eq. (1):

$$
p_{ij} = \frac{d_{ij}}{m + \sum_{i=1}^{m} d_{ij}^2}.
$$

**Step 2:** Calculating the measurement entropy $e_j$ of each criterion $C_j$ with $j = 1, 2, ..., n$ by Eq. (2):

$$
e_j = -\sum_{i=1}^{m} [p_{ij} \ln(p_{ij})] - \left(1 - \sum_{i=1}^{m} p_{ij}\right) \ln \left(1 - \sum_{i=1}^{m} p_{ij}\right).
$$

**Step 3:** Calculating the weight $w_j$ of each criterion $C_j$ with $j = 1, 2, ..., n$ by Eq. (3):

$$
w_j = \frac{1 - e_j}{\sum_{j=1}^{n} (1 - e_j)}.
$$

The above equations will be used to maximize the multi-objective optimization in next part of this paper.

2.2. MOORA technique

MOORA technique was introduced the first time in 2004 by Brauers [36]. This multi-objective optimization technique can be successfully applied to solve the complex decision problems...
in the production environment with the together conflicting objectives. The MOORA technique includes the steps as following:

**Step 1:** Calculating the values \( p_{ij} \) with \( i = 1, 2, ..., m \) and \( j = 1, 2, ..., n \) using Eq. (1).

**Step 2:** Calculating the measurement entropy \( e_j \) of each criterion \( C_j \) with \( j = 1, 2, ..., n \) by Eq. (2).

**Step 3:** Calculating the weight \( w_j \) of each criterion \( C_j \) with \( j = 1, 2, ..., n \) by Eq. (3).

**Step 4:** Calculating the standardized matrix \([X_{ij}]_{m \times n}\) with \( i = 1, 2, ..., m \) and \( j = 1, 2, ..., n \) by Eq. (4):

\[
X = [X_{ij}]_{m \times n} \quad \text{with} \quad X_{ij} = \frac{d_{ij}}{\sqrt{\sum_{i=1}^{m} d_{ij}^2}}.
\]

**Step 5:** Calculating the decision matrix after standardizing with the weight \( W = [W_{ij}]_{m \times n} \) with \( i = 1, 2, ..., m \) and \( j = 1, 2, ..., n \) by Eq. (5):

\[
W_{ij} = w_j \cdot x_{ij}.
\]

**Step 6:** Calculating \( P_i \) and \( R_i \) by Eq. (6) and Eq. (7):

\[
P_i = \frac{1}{|B|} \sum_{j \in B} W_{ij},
\]

\[
R_i = \frac{1}{|NB|} \sum_{j \in NB} W_{ij},
\]

where \( B \) and \( NB \) are the set of benefit criteria and the set of non-beneficial criteria with \( i = 1, 2, ..., m \).

**Step 7:** Calculating the priority value with \( i = 1, 2, ..., m \) (8).

\[
Q_i = P_i - R_i.
\]

**Step 8:** Ranking the solutions \( A_k > A_i \) if \( Q_k < Q_i \) with \( i, k = 1, 2, ..., m \).

### 3. Material and Experimental Method

#### 3.1. Material

In this study, EN 10503 was used in the external turning process. This is common steel and is often used to manufacture the parts in the machine manufacturing such as mechanical shafts, gears, mechanical levers, etc. The equivalent sign of EN 10503 steel according several standards is described in Table 2.

The specimen is analyzed for spectrum and its chemical composition is introduced in Table 3.

| Germany  | United States | Europe | China   | Italy  | Japan |
|----------|---------------|--------|---------|--------|-------|
| DIN      | SAE           | EN     | BS      | UNI    | JIS   |
| EN 10503 | 1045          | C45    | 060A4   | C45    | S45C  |

| Element | C | Si | Mn | Cr | Ni | Mo | V  | Ti | B  | Cu |
|---------|---|----|----|----|----|----|----|----|----|----|
| %       | 0.44 | 0.23 | 0.65 | 0.15 | 0.15 | 0.04 | 0.01 | 0.001 | 0.0004 | 0.21 |
The properties of EN 10503 steel are listed in Table 4.

| Properties of EN 10503 steel |
|-----------------------------|
| Youngs module (GPa)         | Poisson’s ratio | Shear module (GPa) | Density (kg/m³) |
| 210                         | 0.3             | 80                 | 7800            |

Average CTE
20–300 °C (µm/m⋅°K)
Specific heat capacity
50/100 °C (J/kg⋅K)
Thermal conductivity
Ambient temperature (W/m⋅°K)
Electrical resistivity
Ambient temperature (µΩ⋅m)

The length and diameter of workpiece were 300 mm and 27.5 mm, respectively, as shown in Fig. 1.

Fig. 1. Experimental workpieces

3.2. Experimental Machine and Cutter
The manual lathe (FEL-1440GMW, MAGNUM-CUT, Taiwan) was used to conduct the experiments. Three insert types (Lungaloy, Japan) with the nose radius of 0.4 mm, 0.6 mm, and 1.2 mm were used in the experimental process. The cutting inserts are coated with titanium.

3.3. Experimental Matrix
In this study, the Taguchi method was used to design the experimental matrix. Four input parameters were insert nose radius ($r$), cutting speed ($n$), feed rate ($f$), and depth of cut ($a_p$). Three selected values of the insert nose radius are those commonly used in turning processes. The values for cutting speed, feedrate, and depth of cut are chosen based on the cutting tool manufacturer’s recommendation for turning steel in general and EN 10503 steel in particular and also based on the adjustment ability of these parameters of the experimental machine. These parameters were selected as the controllable factors, and their levels were presented in Table 5. The orthogonal array ($L_9$) with 9 experiments was selected to design the experimental matrix as listed in Table 6.

Table 5
Input parameters and their levels

| Parameters          | Symbol | Unit  | Value at the level |
|---------------------|--------|-------|--------------------|
| Insert nose radius  | $r$    | mm    | 0.4 0.6 1.2        |
| Cutting speed       | $n$    | rev/min | 460 650 910       |
| Feed rate           | $f$    | mm/rev | 0.08 0.194 0.302   |
| Depth of cut        | $a_p$  | mm    | 0.15 0.30 0.45     |
Table 6
Experimental Matrix

| No. | r  | n  | f  | a_p |
|-----|----|----|----|-----|
| 1   | 1  | 1  | 1  | 1   |
| 2   | 1  | 2  | 2  | 2   |
| 3   | 1  | 3  | 3  | 3   |
| 4   | 2  | 1  | 2  | 3   |
| 5   | 2  | 2  | 3  | 1   |
| 6   | 2  | 3  | 1  | 2   |
| 7   | 3  | 1  | 3  | 2   |
| 8   | 3  | 2  | 1  | 3   |
| 9   | 3  | 3  | 2  | 1   |

According to this experimental matrix form, there will be 9 experiments to be performed. At each experiment, the five input parameters will be changed simultaneously.

3. 4. Measurement system and Calculation of MRR

3. 4. 1. Surface roughness measurement system

The MITUTOYO-Surftest SJ-210 surface roughness tester was used to measure the surface roughness of the machined parts. The evaluation length was fixed at 0.8 mm (The standard length) as described in Fig. 2.

![Fig. 2. Surface roughness measurement setup](image)

The surface roughness was measured perpendicular to the cutting velocity direction and repeated three times following three repeated times of each cutting test. The average value of surface roughness of three measurement consecutive times was used for analysis and evaluation of surface roughness.

3. 4. 2. Cutting force measurement system

Cutting forces in three directions (X, Y, and Z) were measured using a dynamometer (Kistler Type 9139AA: Force Ranges: (–3KN÷3KN), a data processing box, and a PC with DynoWare software as described in Fig. 3.

The data-processing devices were connected to the computer and they processed the results of the measurement of the component forces by the dynamometer. The value of the forces at each experiment is the average during the machining operation.
3. 4. 3. Calculation of Material Removal Rate

The material removal rate ($MRR$) was calculated by Eq (9).

$$MRR = \frac{1}{60} \cdot n \cdot \pi \cdot d \cdot f \cdot a_p \text{ (mm}^3/\text{s}),$$

where $n$ is cutting speed (rev/min); $d$ is diameter of workpiece (mm); $f$ is feed rate (mm/rev); $a_p$ is depth of cut (mm).

4. Results and Discussion

4. 1. Experiment results

The experimental results were listed in Table 7. The experimental results in this table show that it is difficult to determine which of the experiment in 9 performed experiments have simultaneously the minimum value of surface roughness, minimum values of all three cutting force components, and the maximum of $MRR$. This is explained as follows:

| No. | $Ra$ (µm) | $F_x$ (N) | $F_y$ (N) | $F_z$ (N) | $MRR$ (mm$^3$/s) |
|-----|-----------|-----------|-----------|-----------|------------------|
| 1   | 0.840     | 85.274    | 24.980    | 107.440   | 7.948            |
| 2   | 0.605     | 166.234   | 47.542    | 230.321   | 54.471           |
| 3   | 0.644     | 563.730   | 153.285   | 965.227   | 178.071          |
| 4   | 1.122     | 219.203   | 64.022    | 335.737   | 57.823           |
| 5   | 0.669     | 152.266   | 38.583    | 191.541   | 42.398           |
| 6   | 0.643     | 175.323   | 44.147    | 211.683   | 31.447           |
| 7   | 0.621     | 191.084   | 51.727    | 300.162   | 60.009           |
| 8   | 0.729     | 212.926   | 59.117    | 307.879   | 33.694           |
| 9   | 0.675     | 124.969   | 40.545    | 164.206   | 38.130           |

![Fig. 3. Cutting force measurement setup](image-url)
With the results in Table 7, for example, in the experiment 2, the surface roughness was the smallest value (equal to 0.605 µm), but in this experiment, the values of all three cutting force components were not the smallest values. Besides, MRR in this experiment was also not the maximum value. Another example is experiment 3, in this experiment, MRR was the largest value, but also in this experiment, the value of the cutting force components also were the maximum values. Besides, the surface roughness was not the smallest in this experiment.

From above analysis showed that, it is not possible to choose one experiment from 9 performed experiments to ensure simultaneously the minimum value of surface roughness, the minimum values of cutting force components, and the maximum value of MRR. So that, it is necessary to solve the multi-objective optimization problem to determine the experiment with small surface roughness, small cutting force components, and large MRR. This issue will be presented in next section.

4.2. Multi-Objective Optimization of Turning Process using MOORA Technique

To facilitate for the using of the mathematical symbols when optimizing according to MOORA techniques, the surface roughness, cutting force in \( X \) direction, cutting force in \( Y \) direction, cutting force in \( Z \) direction, and \( MRR \) criteria were set as \( C_1, C_2, C_3, C_4, \) and \( C_5 \) as presented in Table 8.

| No. | \( C_1 \) | \( C_2 \) | \( C_3 \) | \( C_4 \) | \( C_5 \) |
|-----|----------|----------|----------|----------|----------|
| \( A_1 \) | 0.840    | 85.274   | 24.980   | 107.440  | 7.948    |
| \( A_2 \) | 0.605    | 166.234  | 47.542   | 230.321  | 54.471   |
| \( A_3 \) | 0.644    | 563.730  | 153.285  | 965.227  | 178.071  |
| \( A_4 \) | 1.122    | 219.203  | 64.022   | 335.737  | 57.823   |
| \( A_5 \) | 0.669    | 152.266  | 38.583   | 191.541  | 42.398   |
| \( A_6 \) | 0.643    | 175.323  | 44.147   | 211.683  | 31.447   |
| \( A_7 \) | 0.621    | 191.084  | 51.727   | 300.162  | 60.009   |
| \( A_8 \) | 0.729    | 212.926  | 59.117   | 307.879  | 33.694   |
| \( A_9 \) | 0.675    | 124.969  | 40.545   | 164.206  | 38.130   |

From the data in Table 3, MOORA technique applied to calculate the values according to the following steps:

**Step 1:** Using Eq. (1), the values \( p_{ij} \) were calculated and listed in Table 9.

| No. | \( C_1 \) | \( C_2 \) | \( C_3 \) | \( p_{ij} \) | \( C_4 \) | \( C_5 \) |
|-----|----------|----------|----------|------------|----------|----------|
| \( A_1 \) | 0.084177 | 0.000154 | 0.000599 | 0.000076616 | 0.000169 |
| \( A_2 \) | 0.060628 | 0.000301 | 0.001139 | 0.000164242 | 0.001157 |
| \( A_3 \) | 0.064536 | 0.001021 | 0.003673 | 0.000688304 | 0.0003784 |
| \( A_4 \) | 0.112437 | 0.000397 | 0.001534 | 0.000239414 | 0.001229 |
| \( A_5 \) | 0.067041 | 0.000276 | 0.000924 | 0.000136588 | 0.000901 |
| \( A_6 \) | 0.064436 | 0.000318 | 0.001058 | 0.000150951 | 0.000668 |
| \( A_7 \) | 0.062231 | 0.000346 | 0.001239 | 0.000214046 | 0.001275 |
| \( A_8 \) | 0.073054 | 0.000386 | 0.001416 | 0.000219549 | 0.000716 |
| \( A_9 \) | 0.067642 | 0.000226 | 0.000971 | 0.000170955 | 0.00081 |

**Step 2:** Using Eq. (2), the values \( e_j \) of each criterion \( C_j \) were calculated and listed in Table 10.

**Step 3:** Using Eq. (3), the values \( w_j \) of each criterion \( C_j \) were calculated and listed in Table 10.

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Table 10
Weight of the criteria

| Parameter | $C_1$  | $C_2$  | $C_3$  | $C_4$  | $C_5$  |
|-----------|--------|--------|--------|--------|--------|
| Entropy   | 2.07193| 0.02986| 0.09320| 0.01843| 0.07993|
| Weight    | -0.39604| 0.35843| 0.33503| 0.36265| 0.33993|

Step 4: Using Eq. (4), the standardized matrix $X=[X_{ij}]_{m×n}$ was calculated and listed in Table 11.

Step 5: Using Eq. (5), the decision matrix $W$ after standardizing with the weight was calculated and listed in Table 12.

Step 6: Using Eq. (6) and Eq. (7), the values $P_i$ and $Q_i$ were calculated and listed in Table 13.

Step 7: Using Eq. (8), the values $Q_i$ were calculated and listed in Table 13.

Table 11
Standardized matrix

| No. | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ |
|-----|-------|-------|-------|-------|-------|
| $A_1$ | 0.37645 | 0.11476 | 0.12228 | 0.09073 | 0.03664 |
| $A_2$ | 0.27114 | 0.22372 | 0.23273 | 0.19450 | 0.25110 |
| $A_3$ | 0.28861 | 0.75866 | 0.75036 | 0.81509 | 0.82086 |
| $A_4$ | 0.50283 | 0.29500 | 0.31340 | 0.28351 | 0.26655 |
| $A_5$ | 0.29982 | 0.20492 | 0.18887 | 0.16175 | 0.19544 |
| $A_6$ | 0.28817 | 0.23595 | 0.21611 | 0.17876 | 0.14496 |
| $A_7$ | 0.27831 | 0.25716 | 0.25321 | 0.25347 | 0.27662 |
| $A_8$ | 0.32671 | 0.28655 | 0.28939 | 0.25999 | 0.15532 |
| $A_9$ | 0.30251 | 0.16818 | 0.19848 | 0.13866 | 0.17577 |

Table 12
Combination of Standardized matrix and Weight

| No. | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ |
|-----|-------|-------|-------|-------|-------|
| $A_1$ | -0.33267 | 30.56476 | 8.36905 | 38.96312 | 2.70176 |
| $A_2$ | -0.23960 | 59.58325 | 15.92800 | 83.52591 | 18.51633 |
| $A_3$ | -0.44436 | 78.56893 | 21.44929 | 121.75502 | 19.65577 |
| $A_4$ | -0.26495 | 54.57670 | 12.92646 | 69.46234 | 14.41235 |
| $A_5$ | -0.25465 | 62.84102 | 14.79057 | 76.76684 | 10.68978 |
| $A_6$ | -0.24594 | 68.49024 | 17.33010 | 108.85375 | 20.39886 |
| $A_7$ | -0.28871 | 76.31907 | 19.80597 | 111.65232 | 11.45360 |
| $A_8$ | -0.26733 | 44.79264 | 13.58379 | 59.54931 | 12.96153 |

Table 13
Calculated results of $P_i$, $R_i$, $Q_i$ and the ranked results

| No. | $P_i$ | $R_i$ | $Q_i$ | Ranking |
|-----|------|------|------|--------|
| $A_1$ | 19.39106 | 2.70176 | 16.68930 | 2     |
| $A_2$ | 39.69939 | 18.51633 | 21.8306 | 4     |
| $A_3$ | 150.79933 | 60.53168 | 90.26766 | 9     |
| $A_4$ | 55.33222 | 19.65577 | 35.67645 | 7     |
| $A_5$ | 34.17514 | 14.41235 | 19.76279 | 3     |
| $A_6$ | 38.53594 | 10.68978 | 27.84617 | 5     |
| $A_7$ | 48.60704 | 20.39886 | 28.20818 | 6     |
| $A_8$ | 51.87216 | 11.45360 | 40.41856 | 8     |
| $A_9$ | 29.41460 | 12.96153 | 16.45307 | 1     |
The calculated results from Table 13 showed that the solution $A_9$ was the best solution in 9 solutions because this is the solution having the smallest value of $Q_i$. If considering only the surface roughness criterion or only the cutting force components or only $MRR$, $A_9$ is not the best solution (Table 7). However, when simultaneously considering five parameters including the surface roughness, three cutting force components, and $MRR$, the solution $A_9$ was the best solution. In this experiment, the surface roughness was smaller than that ones in Experiments 1, 4, and 8. The cutting force components in $x$ and $z$ directions both have very small values and these cutting force components are at position number 2 (these cutting force component values were only larger than that ones in experiment 1); the force component in $Y$ direction also has very small value and it was ranked at position number 3 (this cutting force component value was only larger than that ones in experiment 1 and 5), in this experiment, $MRR$ was ranked at position number 6 (this $MRR$ value was smaller than ones in experiment 2, 3, 4, 5, and 7). So, these optimal values of insert nose radius, cutting velocity, feed rate, and cutting depth were 1.2 mm, 76.82 m/min, 0.194 mm/rev, and 0.15 mm, respectively. Using these optimal values of the input parameters, the surface roughness, cutting force amplitudes in $X$, $Y$, $Z$ directions, and material removal rate were 0.675 µm, 124.969 N, 40.545 N, 164.206 N, and 38.130 mm$^3$/s, respectively. The proposed method in this study can be applied to improve the quality and effectiveness of turning processes by improving the surface quality, reducing the cutting force amplitudes, and increasing the material removal rate.

In this study, only four input parameters are considered, have not considered the material and shape of the cutting tool (insert). Besides, other factors of the turning process affect the output parameters such as workpiece material, workpiece hardness, cooling lubrication conditions, etc. also have not considered in this study. These are issues that need to be done in the next research to evaluate the turning process in a more comprehensive way.

4. Conclusions

In this study, Taguchi method and MOORA technique were applied to solve the multi-objective optimization problem for external turning process of EN 10503 steel. The conclusions of this study were drawn as following:

- Taguchi method and MOORA techniques were successfully used to solve the multi-objective optimization problem for external turning process of EN 10503 steel.
- These optimal values of the insert nose radius, cutting velocity, feed rate, and cutting depth were 1.2 mm, 76.82 m/min, 0.194 mm/rev, and 0.15 mm, respectively. Using these optimal values of the input parameters, the surface roughness, cutting force amplitudes in $X$, $Y$, $Z$ directions, and material removal rate were 0.675 µm, 124.969 N, 40.545 N, 164.206 N, and 38.130 mm$^3$/s, respectively.
- The proposed method in this study can be applied to improve the quality and effectiveness of turning processes by improving the surface quality, reducing the cutting force amplitudes, and increasing the material removal rate.

Acknowledgements

The authors thank Faculty of Mechanical Engineering, Hanoi University of Industry for the support during the implementation of this research.

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