MULTI-OBJECTIVE OPTIMIZATION OF TURNING PROCESS USING A COMBINATION OF TAGUCHI AND VIKOR METHODS

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This study presents the solving process of the multi-objective optimization problem using VIKOR method when turning the EN 10503 steel. The cutting velocity, feed rate, depth of cut, and insert nose radius were chosen as the input parameters with three levels of each parameter. Taguchi L9 orthogonal array was used to design the experimental matrix with nine experiments. By the combination of Taguchi and VIKOR methods, the multi-objective optimization problem was successfully solved with optimal values (cutting velocity of 78.62 m/min, feed rate of 0.08 mm/rev, cutting depth of 0.5 mm, and insert nose radius of 0.6 mm). Using these optimized input parameters, the surface roughness, cutting force and vibration component amplitudes (in X, Y, Z directions), and material removal rate (MRR) were 0.621 µm, 191.084 N, 51.727 N, 300.162 N, 4.465 µm, 7.492 µm, 10.118 µm, and 60.009 mm³/s, respectively. This proposed method could be used to improve the quality and effectiveness of turning processes by improving the surface quality, reducing the cutting force and vibration amplitudes, and increasing the material removal rate.

Key words: EN 10503 steel, surface roughness, cutting force, vibrations, multi-objective optimization, Taguchi, VIKOR

INTRODUCTION

Turning is the most common machining process in the cutting methods. The work volume that is performed in turning processes is about 40% of the total workload of the machining processes. Besides, the number of turning machines is from 25% to 35% of the number of cutting machines in the cutting workshop [1].

The previous studies were conducted to reduce the machining surface roughness, cutting forces, and vibrations and to increase the MRR. To ensure the minimum value of surface roughness, Taguchi method was applied to obtain the optimal values of cutting velocity, feed rate, and depth of cut in the turning process of different materials such as aluminum [2], polyethylene [3], EN8 steel [4], EN354 steel [5], AM alloy [6], unidirectional glass fiber reinforced plastics (UD-GFRP) [7], titanium alloy [8], Brass and Copper [9], medium carbon steel [10], Titanium Alloy Ti-6Al-4V [11], AISI 1020 steel [12], Aluminium-2014 Alloy [13], AISI 409 steel [14].

To ensure the maximum value of MRR, Taguchi was also applied in the determination of the cutting parameters in turning processes of thermoplastic polymer-delrin 500AL [15] and in turning processes of the unidirectional glass fiber reinforced plastic (UD-GFRP) composite16. Taguchi was also applied in the determination of the cutting parameters to ensure the minimum of cutting forces when machining some materials such as AM alloy [6], AISI 316L stainless steel [17], etc. Several studies applied the Taguchi method to optimize the turning process of different materials such as Aluminium Alloy AA6013 [18], Aluminium Alloy AA2024 [19], and EN25 steel [20].

So, the Taguchi method was successfully applied in optimizing the turning processes for different materials. However, up to date, it seems that there have not been any studies that were performed to optimize the surface roughness, cutting forces, vibrations, and MRR in turning processes. VIKOR was a multi-objective optimization method that was applied in many different fields such as land management [21], Electrical Discharge Machine (EDM) [22, 23], milling process [24], etc. However, the studies that were performed to optimize the turning processes have not been mentioned. So, this study was performed to solve the multi-objective optimization problem in the turning process using Taguchi and VIKOR methods. The optimization problem was conducted with four input factors (machining velocity, feed rate, depth of cut, and insert nose radius) and with eight chosen evaluation criteria of the turning process (Surface roughness, three cutting force components in X, Y, Z directions, three vibration components in X, Y, Z directions, and material removal rate).

VIKOR method is a method of ranking priorities. The contents of this method is presented in the reference [25] as follows:

Assume that there are i solutions A = {A_i | i = 1, 2, 3, ..., m} and j criterion C = {C_j | j = 1, 2, 3, ..., n}; the evaluated value of solution i to the criterion j is F = {f_{ij} | i = 1, 2, 3, ..., m; j = 1, 2, 3, ..., n}; W is the weight of the criterion, W = {w_j | i = 1,2,...,m}. Then, the VIKOR decision matrix including four components was presented in Table 1.

The computational steps for ranking are presented as follows:

**Step 1:** Determining the best value \( f^* \) and the worst value \( f_j \) of all criterion \( C_j \) (with \( j = 1,2, ... n \)).
Table 1: VIKOR decision matrix

| No. | C₁ | C₂ | ... | Cᵢ | ... | Cₙ |
|-----|----|----|-----|----|-----|----|
| A₁  | f₁₁| f₁₂| ... | f₁ᵢ| ... | f₁ₙ|
| A₂  | f₂₁| f₂₂| ... | f₂ᵢ| ... | f₂ₙ|
| ... | ...| ...| ... | ...| ... | ...|
| Aᵢ  | fᵢ₁| fᵢ₂| ... | fᵢᵢ| ... | fᵢₙ|
| Aₙ  | fₙ₁| fₙ₂| ... | fₙᵢ| ... | fₙₙ|
| Max (fᵢ) | f*ᵢ | f*ᵢ | ... | f*ᵢ | ... | f*ᵢ |
| Min (fᵢ) | fᵢ⁻¹| fᵢ⁻²| ... | fᵢ⁻¹| ... | fᵢ⁻ⁿ|
| W   | w₁| w₂| ... | wᵢ| ... | Wᵦ |

Step 2: Standardizing the matrix and calculating \( S_i, R_i \). Set:
\[
\rho_j = \frac{|f_{i,j} - f_{j-1}|}{|f_{i,j} - f_{j}|} \quad (2)
\]
The value \( S_i \) (the convenience) and \( R_i \) (the separate regrets) were calculated by Eq. (3) and Eq. (4).
\[
S_i = \sum_{j=1}^{n} w_j (f_{i,j} - f_{j-1}) / (f_{i,j} - f_{j}) = \sum_{j=1}^{n} w_j \rho_j \quad (3)
\]
\[
R_i = \max \{w_j (|f_{i,j} - f_{j}| / (f_{i,j} - f_{j})) = \max \{w_j \rho_j \} \quad (4)
\]
Step 3: Calculating \( Q_i \)
The value \( Q_i \) was calculated by Eq (5).
\[
Q_i = \frac{v(S_i - S^-) + (1-v)(R_i - R^-)}{(S^+ - S^-) + (R^+ - R^-)} \quad (5)
\]
with:
\[
0 \leq v \leq 1
\]
where:
\[
v \text{ is the weight of the positive criterion group. Normally, } v=0.5 \quad [25].
\]
\[
1-v \text{ is the weight of the nonpositive criterion group.}
\]
And
\[
S^- = \min S_i \quad (6)
\]
\[
S^+ = \max S_i \quad (7)
\]
\[
R^- = \min R_i \quad (8)
\]
\[
R^+ = \max R_i \quad (9)
\]
Step 4: Ranking the solutions \( A_i \) based on the values of \( S_i, R_i, Q_i \) in order from small to large. The solution \( A_i \) that has the smallest value of \( Q_i \) is the best solution.

**MATERIAL AND METHOD**

**Experimental material**

In this study, the workpiece material was EN 10503 steel. This is common steel and is often used to manufacture the parts in machine manufacturers such as mechanical shafts, gears, mechanical levers, etc., because this steel has good machinability and low cost. According to several standards, the equivalent symbols of EN 10503 steel are presented in Table 2. Table 3 is the list of chemical compositions of EN 10503 steel. And Table 4 is the list of the properties of EN 10503 steel. The length and diameter of the workpiece are 300 mm and 27.5 mm, respectively, as shown in Fig 1.

**Turning machine and cutter**

The turning machine (FEL-1440GMW, MAGNUM-CUT, Taiwan) was used to conduct the experiments as shown in Fig 2. The inserts (Lungaloy, Japan) that were coated...
with titanium were used in the experimental process with three nose radius (0.4 mm, 0.6 mm, and 1.2 mm).

Experimental design
In this study, cutting velocity (V) or workpiece speed (n), feed rate (f), depth of cut (t), and insert nose radius (r) were the input parameters. These parameters were chosen as the controllable factors, and the levels of each parameter were presented in Table 5. Taguchi orthogonal array (L9) 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 |
|-----------------------|--------|-------|--------------------|
| Workpiece speed       | n      | rev/min | 1 60 650 910       |
| Feed rate             | f      | mm/rev | 0.08 0.194 0.302   |
| Depth of cut          | t      | mm    | 0.15 0.30 0.45     |
| Insert nose radius    | r      | mm    | 0.4 0.6 1.2        |

Table 6: Experimental matrix

| No. | Coded value | Actual value |
|-----|-------------|--------------|
| n   | f           | t           | r   |
| 1   | 1 1 1 1 1   | 460 0.08    | 0.4 |
| 2   | 1 2 2 2 2   | 460 0.194   | 0.6 |
| 3   | 1 3 3 3 3   | 460 0.302   | 1.2 |
| 4   | 2 2 3 3 3   | 650 0.08    | 0.35|
| 5   | 2 3 1 1 1   | 650 0.194   | 0.50|
| 6   | 2 1 2 2 2   | 650 0.302   | 0.20|
| 7   | 3 3 2 2 2   | 910 0.08    | 0.50|
| 8   | 3 1 3 3 3   | 910 0.194   | 1.2 |
| 9   | 3 2 1 1 1   | 910 0.302   | 0.35|

Measurement system
The surface roughness of the machined parts was measured by Mytutoyo SJ-210 tester (Japan) as described in Fig 2. For all surface roughness measurements, the standard length was fixed at 0.8 mm. For each measurement, the tool tip was moved parallel to the feed direction. The surface roughness was measured by repeating three times for each experiment.

Cutting force components in X, Y, and Z directions were measured using a cutting force measurement system, including a dynamometer (Kistler type 9139AA: force ranges: (-3KN÷3KN), a data processing system, and a Laptop with DynoWare software as described in Fig. 3. The vibrations of the machining system were measured by a system including a three dimensions acceleration sensor (type 4525-B-001), a data processing system, and the PLUSE software as illustrated in Fig. 3. The acceleration sensor is mounted at the shell of the center of the turning machine. The system vibrations were measured simultaneously in X, Y, and Z directions.

The material removal rate (MRR) was calculated by Eq (10).

\[
MRR = \frac{1}{60} \pi n d f t (mm^3/s)
\]

(10)
where:
n is the workpiece speed (rev/min).
d is the workpiece diameter (mm).
f is the feed rate (mm/rev).
t is the depth of cut (mm).

RESULTS AND DISCUSSION
Evaluation of experimental results
After performing the experiments in the Table 6, the results were obtained and listed in Table 7. The results in this Table show that it is difficult to determine the experiment, which simultaneously has the minimum value of surface roughness, the minimum values of cutting force components, the minimum values of vibration components, and the maximum value of MRR. It can be concluded that because with the results in Table 7, the value of surface roughness was the smallest value (equal to 0.605 µm) in experiment number 2, but the values of all three cutting force components and all three vibration components were the smallest values in experiment number 1. Besides, MRR was the largest value in experiment number 3.

From above analysis showed that it is not possible to choose one experiment from 9 performed experiments to simultaneously ensure the minimum value of surface roughness, the minimum values of cutting force components, the minimum values of vibration components, and the maximum value of MRR. Then, solving the multi-objective optimization problem is necessary to determine the cutting parameters and insert nose radius with small surface roughness, small cutting force components, small vibration component, and large MRR.

Multi-objective optimization using VIKOR method
To facilitate the use of the mathematical symbols in the optimization process, the surface roughness, cutting force amplitudes AFx, AFy, AFz, system vibration amplitudes Ax, Ay, Az, and MRR criteria were set as C1, C2, C3, C4, C5, C6, C7, and C8 as presented in Table 8.

The calculated results of r ij (with i=1÷16; j=1÷2) according to the Eq. (2) were listed in Table 9.
The calculated results of Si, Ri và Qi according to the Eq. (3) to Eq. (9) were listed in Table 10. The calculated results from Table 10 showed that solution A7 had the smallest value of Q7. So, this solution was the best solution in 9 solutions.

Table 7: Experimental results

| No. | Ra (µm) | Fx (N) | Fy (N) | Fz (N) | Ax (µm) | Ay (µm) | Az (µm) | MRR (mm³/s) |
|-----|---------|--------|--------|--------|---------|---------|---------|-------------|
| 1   | 0.840   | 85.2740| 24.9800| 107.4400| 2.3850  | 5.3594  | 5.5826  | 7.948       |
| 2   | 0.605   | 166.2340| 47.5420| 230.3210| 3.9816  | 8.5019  | 9.0195  | 54.471      |
| 3   | 0.644   | 563.7300| 153.2850| 965.2270| 5.9601  | 12.1603| 16.2276| 178.071     |
| 4   | 1.122   | 219.2030| 64.0220| 335.7370| 5.9392  | 8.8440  | 13.9882| 57.823      |
| 5   | 0.669   | 152.2660| 38.5830| 191.5410| 4.3123  | 7.6545  | 9.3600  | 42.398      |
| 6   | 0.643   | 175.3230| 44.1470| 211.6830| 5.0853  | 9.9639  | 12.5087| 31.447      |
| 7   | 0.621   | 191.0840| 51.7270| 300.1620| 4.4647  | 7.4923  | 10.1177| 60.009      |
| 8   | 0.729   | 212.9260| 59.1170| 307.8790| 5.8284  | 8.4602  | 14.1956| 33.694      |
| 9   | 0.675   | 124.9690| 40.5450| 164.2060| 6.2633  | 10.1637| 15.2682| 38.130      |

Table 8: VIKOR decision matrix for the turning process of EN 10503 steel

| C1 | C2 | C3 | C4 | C5 | C6 | C7 | C8 |
|----|----|----|----|----|----|----|----|
| 1  | 0.840 | 85.2740 | 24.9800 | 107.4400 | 2.3850 | 5.3594 | 5.5826 | 7.948       |
| 2  | 0.605 | 166.2340 | 47.5420 | 230.3210 | 3.9816 | 8.5019 | 9.0195 | 54.471      |
| 3  | 0.644 | 563.7300 | 153.2850 | 965.2270 | 5.9601 | 12.1603 | 16.2276 | 178.071     |
| 4  | 1.122 | 219.2030 | 64.0220 | 335.7370 | 5.9392 | 8.8440 | 13.9882 | 57.823      |
| 5  | 0.669 | 152.2660 | 38.5830 | 191.5410 | 4.3123 | 7.6545 | 9.3600 | 42.398      |
| 6  | 0.643 | 175.3230 | 44.1470 | 211.6830 | 5.0853 | 9.9639 | 12.5087 | 31.447      |
| 7  | 0.621 | 191.0840 | 51.7270 | 300.1620 | 4.4647 | 7.4923 | 10.1177 | 60.009      |
| 8  | 0.729 | 212.9260 | 59.1170 | 307.8790 | 5.8284 | 8.4602 | 14.1956 | 33.694      |
| 9  | 0.675 | 124.9690 | 40.5450 | 164.2060 | 6.2633 | 10.1637 | 15.2682 | 38.130      |

| C1 | C2 | C3 | C4 | C5 | C6 | C7 | C8 |
|----|----|----|----|----|----|----|----|
| 1  | 0.840 | 85.2740 | 24.9800 | 107.4400 | 2.3850 | 5.3594 | 5.5826 | 7.948       |
| 2  | 0.605 | 166.2340 | 47.5420 | 230.3210 | 3.9816 | 8.5019 | 9.0195 | 54.471      |
| 3  | 0.644 | 563.7300 | 153.2850 | 965.2270 | 5.9601 | 12.1603 | 16.2276 | 178.071     |
| 4  | 1.122 | 219.2030 | 64.0220 | 335.7370 | 5.9392 | 8.8440 | 13.9882 | 57.823      |
| 5  | 0.669 | 152.2660 | 38.5830 | 191.5410 | 4.3123 | 7.6545 | 9.3600 | 42.398      |
| 6  | 0.643 | 175.3230 | 44.1470 | 211.6830 | 5.0853 | 9.9639 | 12.5087 | 31.447      |
| 7  | 0.621 | 191.0840 | 51.7270 | 300.1620 | 4.4647 | 7.4923 | 10.1177 | 60.009      |
| 8  | 0.729 | 212.9260 | 59.1170 | 307.8790 | 5.8284 | 8.4602 | 14.1956 | 33.694      |
| 9  | 0.675 | 124.9690 | 40.5450 | 164.2060 | 6.2633 | 10.1637 | 15.2682 | 38.130      |

| Max (f) | 1.122 | 563.7300 | 153.2850 | 965.2270 | 6.2633 | 12.1603 | 16.2276 | 178.071     |
| Min (f) | 0.605 | 85.2740 | 24.9800 | 107.4400 | 2.3850 | 5.3594 | 5.5826 | 7.948       |
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Table 9: The calculated values of \( r_i \)

| \( r_i \) | \( r_2 \) | \( r_3 \) | \( r_4 \) | \( r_5 \) | \( r_6 \) | \( r_7 \) | \( r_8 \) |
|---|---|---|---|---|---|---|---|
| \( A_1 \) | 0.45455 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 1.00000 |
| \( A_2 \) | 0.00000 | 0.16921 | 0.17585 | 0.14325 | 0.41168 | 0.46207 | 0.32287 |
| \( A_3 \) | 0.12379 | 0.14002 | 0.10602 | 0.09804 | 0.49694 | 0.33747 | 0.35485 |
| \( A_4 \) | 0.07350 | 0.18821 | 0.14939 | 0.12153 | 0.69626 | 0.67704 | 0.65064 |
| \( A_5 \) | 0.23985 | 0.26680 | 0.26606 | 0.23367 | 0.88786 | 0.45594 | 0.80911 |
| \( A_6 \) | 0.13540 | 0.08296 | 0.12131 | 0.06618 | 1.00000 | 0.70642 | 0.90987 |

Table 10: Calculated values of \( S_i, R_i, \) and \( Q_i \)

| \( S_i \) | \( R_i \) | \( Q_i \) |
|---|---|---|
| \( A_1 \) | 0.72727 | 0.50000 |
| \( A_2 \) | 1.20573 | 0.36327 |
| \( A_3 \) | 2.99863 | 0.50000 |
| \( A_4 \) | 2.38781 | 0.50000 |
| \( A_5 \) | 1.22732 | 0.39875 |
| \( A_6 \) | 1.70922 | 0.43094 |
| \( A_7 \) | 1.32755 | 0.34699 |
| \( A_8 \) | 2.00398 | 0.44393 |
| \( A_9 \) | 1.92237 | 0.50000 |

MRR that were obtained were 0.621 \( \mu \)m, 191.084 N, 51.727 N, 300.162 N, 4.465 \( \mu \)m, 7.492 \( \mu \)m, 10.118 \( \mu \)m, and 60.009 mm/s, respectively.

By using proposed method in this study, the quality and effectiveness of turning processes can be improved by improving the surface quality, reducing the cutting force and vibration amplitudes, and increasing the material removal rate.

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