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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 the 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], EN 354 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 Aluminum Alloy AA6013 [18], Aluminum 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 criterian 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 criterian, 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^*_j and the worst value f^-_j of all criterian C_j (with j = 1,2, ... n).

Table 1: VIKOR decision matrix

No.	C_1	C_2	...	C_i	...	C_n
A_1	f_{11}	f_{12}	...	f_{1j}	...	f_{1n}
A_2	f_{21}	f_{22}	...	f_{2j}	...	f_{2n}
...	...	...	...	...	...	...
A_n	f_{m1}	f_{m2}	...	f_{mj}	...	f_{mn}
Max (f_j)	f^*_1	f^*_2	...	f^*_i	...	f^*_n
Min (f_j)	f^-_1	f^-_2	...	f^-_i	...	f^-_n
W	w_1	w_2	...	w_i	...	W_n

- If criterion j is a positive criterion, $f^*_j = \max f_{ij}$ and $f^-_j = \min f_{ij}$
- If criterion j is not a positive criterion (bad criterion), $f^*_j = \min f_{ij}$ and $f^-_j = \max f_{ij}$

Step 2: Standardizing the matrix and calculating S_i, R_i. Set:

$$r_{ij} = \left(|f^*_j - f_{ij}|\right)/\left(|f^*_j - f^-_j|\right) \qquad (2)$$

The value S_i (the convenience) and R_i (the separate regrets) were calculated by Eq. (3) and Eq (4).

$$S_i = \sum_{j=1}^{n} w_j(|f^*_j - f_{ij}|)/(|f^*_j - f^-_j|) = \sum_{j=1}^{n} w_j r_{ij} \qquad (3)$$

$$R_i = \max[w_j(|f^*_j - f_{i}j|)/(|f^*_j - f^-_j|)] = \max[w_j r_i j] \qquad (4)$$

Step 3: Calculating Q_i

The value Q_i was calculated by Eq (5).

$$Q_i = \frac{v(S_i - S^*)}{((S^- - S^*))} + (1-v)(R_i - R^*)/(R^- - R^*) \qquad (5)$$

with:

$0 \leq v \leq 1$

where:

v is the weight of the positive criterion group. Normally, v=0.5 [25].

$1-_v$ is the weight of the nonpositive criterion group.

And

$$S^* = \min S_i \qquad (6)$$
$$S^- = \max S_i \qquad (7)$$
$$R^* = \min R_i \qquad (8)$$
$$R^- = \max R_i \qquad (9)$$

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

Table 2: Equivalent symbols of EN 10503 steel

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

Table 3: Composition of EN 10503 steel

Element	%
C	0.44
Si	0.23
Mn	0.65
Cr	0.15
Ni	0.15
Mo	0.04
V	0.01
Ti	0.001
B	0.0004
Cu	0.21

Table 4: Properties of EN 10503 steel

Young's module (GPa)	210	Average CTE 20-300°C (µm/m°K)	12
Poisson´s ratio	0.3	Specific heat capacity 50/100°C (J/kg°K)	460 - 480
Shear module (GPa)	80	Thermal conductivity Ambient temperature (W/m°K)	40 - 45
Density (kg/m³)	7800	Electrical resistivity Ambient temperature (µΩm)	0.20 - 0.25

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

Figure 1: Workpieces in the experimental process

Figure 2: The setting of surface roughness measurement

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		
			1	2	3
Workpiece speed	n	rev/min	460	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	n (rev/min)	f (mm/rev)	t (mm)	r (mm)
1	1	1	1	1	460	0.08	0.20	0.4
2	1	2	2	2	460	0.194	0.35	0.6
3	1	3	3	3	460	0.302	0.50	1.2
4	2	2	3	3	650	0.08	0.35	1.2
5	2	3	1	1	650	0.194	0.50	0.4
6	2	1	2	2	650	0.302	0.20	0.6
7	3	3	2	2	910	0.08	0.50	0.6
8	3	1	3	3	910	0.194	0.20	1.2
9	3	2	1	1	910	0.302	0.35	0.4

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 dimentions 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).

$$MRR = \frac{1}{60} * n * \pi * d * f * t \, (mm^3 / s) \qquad (10)$$
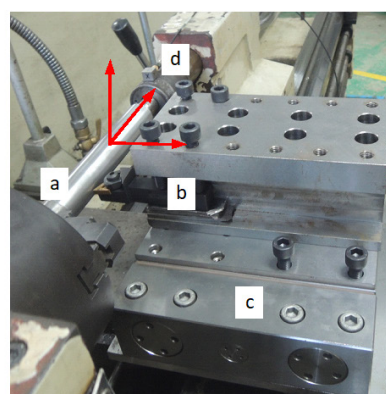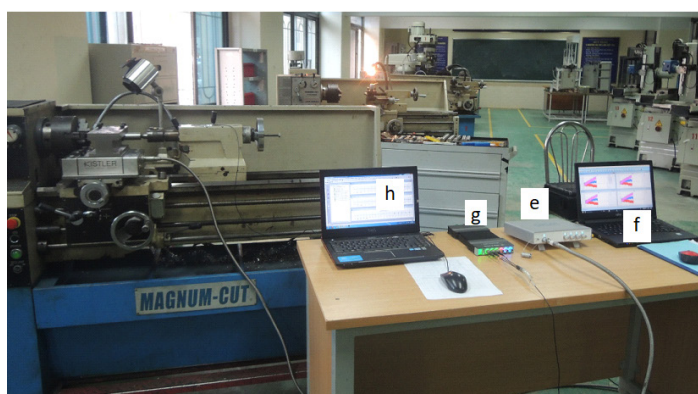
a. Workpiece b. Tool c. Dynamomster d. Acceleration sensor e. Cutting force signal processing system f. Laptop and DynoWare software g. Acceleration signal processing system h. PLUSE software

Figure 3: Cutting force and vibration measurement system

Table 7: Experimental results

No.	R_a (µm)	F_x (N)	F_y (N)	F_z (N)	A_x (µm)	A_y (µm)	A_z (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

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, minimum values of all three cutting force components, minimum values of all three vibration components, and the maximum 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 C_1, C_2, C_3, C_4, C_5, C_6, C_7, and C_8 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 A_7 had the smallest value of Q_7. So, this solution was the best solution in 9 solutions.

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

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
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_i)	1.122	563.73	153.285	965.227	6.2633	12.1603	16.2276	178.071
Min (f_i)	0.605	85.274	24.98	107.44	2.385	5.3594	5.5826	7.948

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Table 9: The calculated values of r_{ij}

	r_1	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	0.00000	1.00000
A_2	0.00000	0.16921	0.17585	0.14325	0.41168	0.46207	0.32287	0.72653
A_3	0.07544	1.00000	1.00000	1.00000	0.92182	1.00000	1.00000	0.00000
A_4	1.00000	0.27992	0.30429	0.26615	0.91643	0.51237	0.78963	0.70683
A_5	0.12379	0.14002	0.10602	0.09804	0.49694	0.33747	0.35485	0.79750
A_6	0.07350	0.18821	0.14939	0.12153	0.69626	0.67704	0.65064	0.86187
A_7	0.03095	0.22115	0.20846	0.22467	0.53624	0.31362	0.42603	0.69398
A_8	0.23985	0.26680	0.26606	0.23367	0.88786	0.45594	0.80911	0.84866
A_9	0.13540	0.08296	0.12131	0.06618	1.00000	0.70642	0.90987	0.82259

Table 10: Calculated values of S_i, R_i, and Q_i

	S_i	R_i	Q_i
A_1	0.72727	0.50000	0.50000
A_2	1.20573	0.36327	0.15851
A_3	2.99863	0.50000	1.00000
A_4	2.38781	0.50000	0.86554
A_5	1.22732	0.39875	0.27921
A_6	1.70922	0.43094	0.49047
A_7	1.32755	0.34699	0.13214
A_8	2.00398	0.44393	0.59783
A_9	1.92237	0.50000	0.76308

So, the optimized values of cutting velocity (or workpiece speed), feed rate, cutting depth, and insert nose radius were 76.82 m/min (or 910 rev/min, 0.08 mm/rev, and 0.5 mm, 0.6 mm, respectively. Use these values, the output parameters that were obtained were Ra of 0.621 μm, Fx, Fy, Fz of 191.084 N, 51.728 N, and 300.162N, respectively, Ax, Ay, Az of 4.465 μm, 7.492 μm, and 10.118 μm, respectively, and MRR of 60.009 mm³/s.

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

CONCLUSION

A new method that was proposed to solve the multi-objective optimization problem in the turning process of EN 10503 steel was presented in this study.

The conclusions of this study were drawn as follows:

- The multi-objective optimization problem was successfully solved using Taguchi and VIKOR methods in the external turning process of EN 10503 steel.

- By combining Taguchi and VIKOR methods, the optimal values of cutting velocity, feed rate, depth of cut, and insert nose radius were 78.62 m/min, 0.08 m/rev, 0.5 mm, and 0.4 mm, respectively.

- Using these optimized input parameters, the output paramerters including Ra, Fx, Fy, Fz, Ax, Ay, Az, and

MRR that were obtained 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.

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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