Original Research Article: full paper

(2021), «EUREKA: Physics and Engineering»
Number 2

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 L_9 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 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. 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.
1	2	3	4	5
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 0.0425 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; – Feed rate 0.15 mm/rev; – Depth of cut 1.25 mm	[11]
Polyethylen e	Minimum surface roughness	Taguchi	– Cutting velocity 213.88 m/min; – Feed rate 0.049 mm/rev; – Depth of cut 2.0 mm; – Tool nose radius 0.8 mm	[12]
Thermoplastic polymer-delrin 500AL	Minimum surface roughness	Taguchi	– Workpiece speed 250 rpm; – Feed rate 0.15 mm/rev; – Depth of cut 0.14 mm	[13]
	Maximum MRR		– Workpiece speed 300 rpm; – Feed rate 0.25 mm/rev; – Depth of cut 0.14 mm	
EN8 steel	Minimum surface roughness	Taguchi	– Workpiece speed 303 rpm; – Feed rate 0.067 mm/rev; – Depth of cut 0.2 mm	[14]
Aluminum 6063	Minimum power	Taguchi	– Workpiece speed 1750 rpm; – Feed rate 0.3 mm/rev; – Depth of cut 1.2 mm	[15]
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. – When using MQL, surface roughness was smallest. When using Dy cooling, the cutting forces were smallest	[16]
AM alloy	Minimum surface roughness	Taguchi	– Cutting velocity 160 mm/min; – Feed rate 0.1 mm/rev; – Depth of cut 0.5 mm	[17]
	Minimum cutting force		– Cutting velocity 115 mm/min; – Feed rate 0.1 mm/rev; – Depth of cut 0.5 mm	
AISI 1045	Minimum surface roughness	Taguchi	– Cutting velocity 200 m/min; – Feed rate 0.1 mm/rev; – Depth of cut 0.5 mm	[18]
S45C steel	Minimum surface roughness	Taguchi	– Cutting velocity 135 m/min; – Feed rate 0.08 mm/rev; – Depth of cut 1.1 mm	[19]
Aluminium	Minimum surface roughness	Taguchi	– Workpiece speed 160 rpm; – Feed rate 0.05 mm/rev; – Depth of cut 1.5 mm	[20]
Brass	Minimum surface roughness	Taguchi	– Workpiece speed 660 rpm; – Feed rate 0.1 mm/rev; – Depth of cut 1.0 mm	
Copper	Minimum surface roughness	Taguchi	– Workpiece speed 80 rpm; – Feed rate 0.1 mm/rev; – Depth of cut 1.5 mm	
Mild Steel	Minimum surface roughness	Taguchi	– Cutting velocity 60 m/min; – Feed rate 0.1 mm/rev; – Depth of cut 0.4 mm	[21]
EN 354 steel	Minimum surface roughness	Taguchi	– Cutting velocity 222 m/min; – Feed rate 0.015 mm/rev; – Depth of cut 1.2 mm	[22]
Titanium Alloy Ti-6Al-4V	Minimum surface roughness	Taguchi	– Cutting velocity 125 m/min; – Feed rate 0.12 mm/rev; – Depth of cut 0.6 mm	[23]

Continuation of Table 1

1	2	3	4	5
AISI 1020 MS	Minimum surface roughness	Taguchi	– Workpiece speed 630 rpm; – Feed rate 0.05 mm/rev; – Depth of cut 1.25 mm	[24]
Aluminum-2014 Alloy	Minimum surface roughness	Taguchi	– Workpiece speed 1700 rpm; – Feed rate 35 mm/min; – Depth of cut 0.4 mm	[25]
AISI 409 steel	Minimum surface roughness	Taguchi	– Cutting velocity 400 m/min; – Feed rate 0.2 mm/rev; – Depth of cut 2.0 mm	[26]
P20 steel	Minimum surface roughness	Taguchi	– Cutting velocity 120 m/min; – Feed rate 0.1 mm/rev; – Depth of cut 0.1 mm	[27]
DIN 1.2344 steel	Minimum surface roughness	Taguchi	– Cutting tool was DCT; – Cutting velocity 250 m/min; – Feed rate 0.12 mm/rev	[28]
	Minimum tool wear	Taguchi	– Cutting tool was DCT; – Cutting velocity 200 m/min; – Feed rate 0.15 mm/rev	
	– Minimum surface roughness; – Minimum tool wear	Taguchi+*GRA*	– Cutting tool was DCT; – Cutting velocity 200 m/min; – Feed rate 0.12 mm/rev	
Unidirectional glass fiber reinforced plastic (UD-GFRP) composite	– Minimum surface roughness; – Maximum MRR.	Taguchi+*GRA*	– Cutting environment was Cooled; – Tool nose radius 0.4 mm; – Tool Rake angle –6°; – Feed rate 0.2 mm/rev; – Cutting velocity 159.66 m/min; – Depth of cut 1.4 mm	[29]
EN-8, EN-31 and EN-36 steel	Minimum surface roughness	Taguchi+GRA	– EN-36 material; – Workpiece speed 598 rpm; – Feed rate 0.15 mm/rev; – Depth of cut.5 mm	[30]
DIN Ck45 steel	Minimum surface roughness	Taguchi+*GRA*	– Cutting velocity 400 m/min; – Feed rate 0.1 mm/rev; – Depth of cut 1.2 mm	[31]
Ti-6Al-4V alloy	Minimum surface roughness	Taguchi+*TOPSIS*	– Cutting velocity 80 m/min; – Feed rate 0.05 mm/rev; – Depth of cut 0.1 mm	[32]
	Minimum surface roughness	Taguchi+*SAW*	– Cutting velocity 80 m/min; – Feed rate 0.05 mm/rev; – Depth of cut 0.1 mm	
S45C steel	Minimum surface roughness	Taguchi+*GA*	– Cutting velocity 145.405 m/min; – Feed rate 0.0876 mm/rev; – Depth of cut 0.6057 mm	[33]
	Minimum surface roughness	Taguchi+*PSO*	– Cutting velocity 145 m/min; – Feed rate 0.08 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 $A=\{A_1, A_2,\ldots, A_m\}$ based on the set of criteria $C=\{C_1, C_2,\ldots, C_n\}$. In which, each crirerion C_j is assigned with a weight w_j ($j=1, 2, \ldots, n$), so that $SUM(w_j)=1$. A multiple-criteria decision making problem was presented by the matrix $D=[d_{ij}]_{m\times n}$.

$$\begin{matrix} A_1 \\ A_2 \\ \vdots \\ A_3 \end{matrix}\begin{bmatrix} d_{11} & d_{12} & d_{1n} & d_{1n} \\ d_{21} & d_{22} & d_{2n} & d_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ d_{m1} & d_{m2} & d_{mn} & d_{mn} \end{bmatrix},$$

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

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 $i=1, 2, \ldots, m$ and $j=1, 2, \ldots, n$ using Eq. (1):

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

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

$$e_j=-\sum_{i=1}^{m}\left[p_{ij}\,ln\left(p_{ij}\right)\right]-\left(1-\sum_{i=1}^{m}p_{ij}\right)\cdot ln\left(1-\sum_{i=1}^{m}p_{ij}\right). \quad (2)$$

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

$$w_j=\frac{1-e_j}{\sum_{j=1}^{n}\left(1-e_j\right)}. \quad (3)$$

The above equations will be used to maximize the multi-objective optimzation 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):

$$X=\left[X_{ij}\right]_{m\times n} \text{ with } X_{ij}=\frac{d_{ij}}{\sqrt{\sum_{i=1}^{m} d_{ij}^2}}. \quad (4)$$

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):

$$W_{ij}=w_j\cdot x_{ij}. \quad (5)$$

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

$$P_i=\frac{1}{|B|}\sum_{j\in B} W_{ij}, \quad (6)$$

$$R_i=\frac{1}{|NB|}\sum_{j\in NB} W_{ij}, \quad (7)$$

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).

$$Q_i=P_i-R_i. \quad (8)$$

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**.

Table 2

Equivalent symbols of EN 10503 steel according to several Standards

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

Table 3

Chemical composition of EN 10503 steel

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**.

Table 4
Properties of EN 10503 steel

Youngs module (GPa)	Poisson's ratio	Shear module (GPa)	Density (kg/m^3)
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 (μΩm)
12	460–480	40–45	0.20–0.25

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

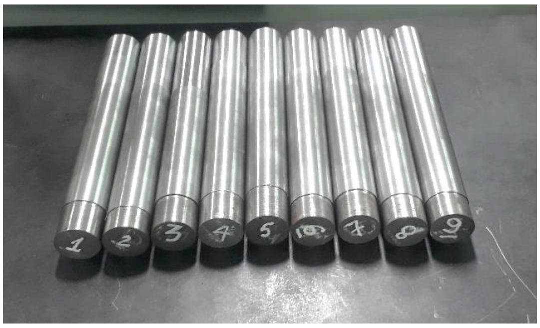

Fig. 1. Experimental workpieces

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		
			1	2	3
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.	Coded value			
	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

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.

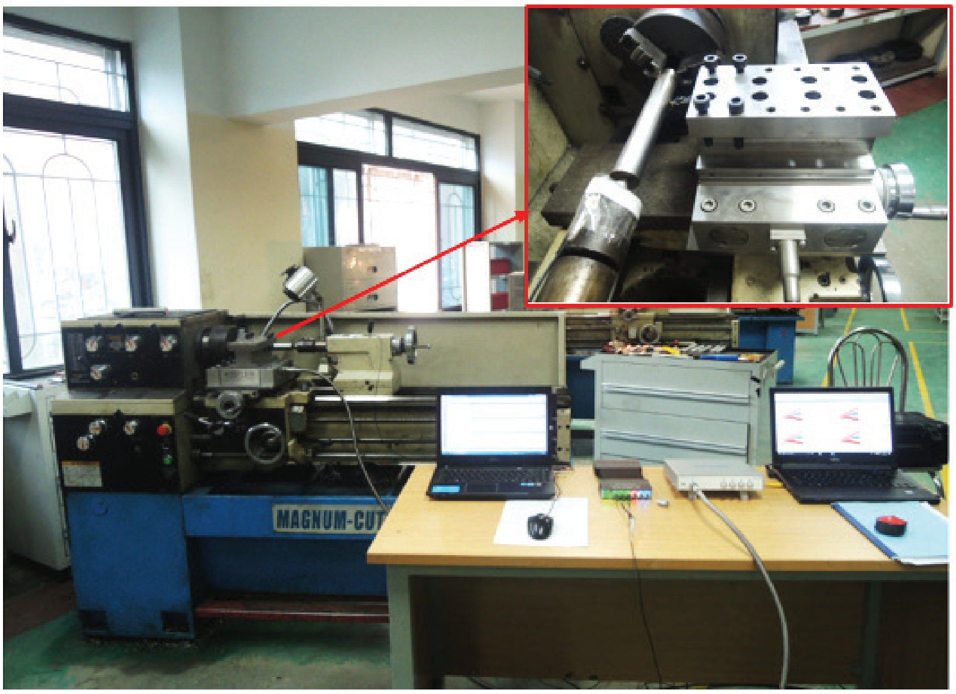

Fig. 3. Cutting force measurement setup

3. 4. 3. Calculation of Material Removal Rate

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

$$MRR = \frac{1}{60} \cdot n \cdot \pi \cdot d \cdot f \cdot a_p \ \text{(mm}^3\text{/s)}, \qquad (9)$$

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:

Table 7
Experimental Results

No.	*Ra* (µm)	*Fx* (N)	*Fy* (N)	*Fz* (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

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**.

Table 8

The evaluation criteria of the turning process

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**, M*OORA* 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**.

Table 9

The values of p_{ij}

No.	p_{ij}				
	C_1	C_2	C_3	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	0.003784
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	0.000117095	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.**

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 $X=[X_{ij}]_{m\times n}$ 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	–0.25505	202.05774	51.35507	350.03957	60.53168
A_4	–0.44436	78.56893	21.44929	121.75502	19.65577
A_5	–0.26495	54.57670	12.92646	69.46234	14.41235
A_6	–0.25465	62.84102	14.79057	76.76684	10.68978
A_7	–0.24594	68.49024	17.33010	108.85375	20.39886
A_8	–0.28871	76.31907	19.80597	111.65232	11.45360
A_9	–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	21.18306	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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Received date 28.01.2021
Accepted date 07.03.2021
Published date 31.03.2021

How to cite: *Trung, D. D., Nguyen, N.-T., Duc, D. V. (2021). Study on multi-objective optimization of the turning process of EN 10503 steel by combination of taguchi method and moora technique. EUREKA: Physics and Engineering, 2, 52–65. doi: https://doi.org/10.21303/2461-4262.2021.001414*