Parameter Selection to Ensure Multi-Criteria Optimization of the Taguchi Method Combined with the Data Envelopment Analysis-based Ranking Method when Milling SCM440 Steel

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Abstract-SCM440 steel is a commonly used material for making plastic injection molds and components such as gears, transmission shafts, rolling pins, etc. Surface roughness has a direct influence on the workability and durability of the parts and/or components, while the Material Removal Rate (MRR) is a parameter that is used to evaluate the productivity of the machining process. Furnished products with small surface roughness and large MRR is the desired result by all milling processes. In this paper, the determination of the values of input parameters is studied in order to ensure that during the process of milling SCM440 steel, it will have the smallest surface roughness and the largest MRR. There are five parameters that are required to be determined, namely the cutting insert material, the tool nose radius, the cutting speed, the feed rate, and the cutting depth. The Taguchi method was applied to design the experimental matrix with a total of 27 experiments. Result analysis determined the influence of the input parameters on surface roughness and MRR. The Data Envelopment Analysis-based Ranking (DEAR) method was applied to determine the optimal value of the input parameters, which were used to conduct the milling experiments to re-evaluate their suitability.

Keywords-milling; SCM440 steel; surface roughness; MRR; optimization; Taguchi; DEAR

I. INTRODUCTION

Milling is a very common machining method in the mechanical engineering industry. It is considered to be the cutting method with the highest productivity. With the development of the cutting tool manufacturing technology as well as the emergence of the modern CNC machines, this method is capable of ensuring very high accuracy. Research of solutions that improve the accuracy of milling machines and milling cutters is continuously conducted [1]. Therefore, in some cases, this method is used as the final machining method for surfaces requiring high precision [2]. To make the most use of the achievements in the mechanical engineering technology and the cutting tool manufacturing technology, many researchers carried out experimental studies to determine the optimal value of parameters related to the machining process. The purpose of these studies is to determine the value of the machining process's parameters to ensure minimum surface roughness and maximum Material Removal Rate (MRR). This problem is known as milling operations optimization. When studying the milling operations optimization, many authors used the Taguchi method to design the experimental matrix. When comparing the Taguchi-based matrix design method with some other matrix design methods, it was found that the Taguchi method requires a smaller number of experiments. An advantage that only the Taguchi method possesses is that it can design a matrix with the input parameters being a qualitative (not a quantitative) parameter [3, 4].

In [5], the Taguchi method was applied to design the experimental matrix when milling the AA6082T6 material by a tungsten carbide cutting tool. Signal-to-Noise (S/N) ratio was analyzed to determine the optimal values of spindle speed, feed rate, and depth of cut to ensure the minimum value of surface roughness. The Taguchi method was also used to design the experimental matrix when milling AA6082T6 with PVD-coated and CVD-coated cutting tools. The determination of cutting speed, feed rate, and tool material type to ensure tool wear was similarly performed for surface roughness in [6]. In [7], the authors applied the Taguchi method to design the experimental matrix when milling D2 steel with the carbide inserts cutting tool. Cutting parameters including spindle speed, feed rate, and depth of cut were selected as input parameters for each experiment. The S/N ratio analysis method was applied to determine the optimal value of the cutting parameters to ensure the minimum value of surface roughness. When milling AISI P20 steel with the carbide inserts cutting tool, the authors in [8] used the Taguchi method to design an experimental matrix with spindle speed, feed rate, and depth of cut as input parameters [8]. They also used S/N ratio analysis to determine the optimal value of the input parameters to ensure the minimum value of surface roughness. To determine the optimal value of parameters including cutting speed, feed, radial depth, and axial depth to ensure the minimum value of surface roughness when milling 1.2738 steel with the WNHU 04T310 cutting tool

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(manufactured by Palbit), the authors in [9] also applied the Taguchi method to design the experimental matrix. The S/N ratio analysis method was applied to determine the optimal value of the cutting parameters. Authors in [10] also designed the experimental matrix according to the Taguchi method when milling 7075T6 aluminum alloy with an AlTiN PVD-coated cutting tool. The optimal values of cutting speed, feed rate, radial depth, and axial depth were also determined by the analysis of the S/N ratio. This study also aimed to ensure the minimum value of surface roughness. To determine the optimum value of cutting speed, feed rate, depth of cut, and coolant flow to ensure the minimum value of surface roughness when milling AISI 1040 MS steel with the carbide inserts cutting tool, the authors in [11] also designed the experimental matrix according to the Taguchi method and the S/N ratio analysis method was also used to determine the optimal value of the input parameters. Authors in [12] also designed the experimental matrix according to the Taguchi method when milling 7075 T6 aluminum alloy with a High-Speed Steel (HSS) cutting tool. They also applied the S/N ratio analysis method to determine two sets of optimal values of cutting speed, feed rate, and depth of cut, one set that ensures the smallest surface roughness and another set that ensures the largest MRR.

The experimental matrix design based on the Taguchi method has been successfully applied in a number of studies to ensure a certain criterion of the machining process. However, if only the Taguchi method is applied for the experimental design and the S/N ratio analysis to determine the optimal value of the machining process parameters, only one criterion of the machining process can be guaranteed. In order to resolve this shortcoming of the Taguchi method, many studies combined the Taguchi method with other methods to optimize the multi-objectives of the milling process: in [13], the Taguchi method has been combined with ANOVA to determine the values of the spindle speed, the feed rate and the cutting depth to ensure the minimum surface roughness and the maximum MRR when milling AISI 1005 steel with the TiN coated cutting tool. In [14], the Taguchi method and the Weighted Principal Component Analysis (WPCA) were combined to determine the milling type and the values of milling parameters to simultaneously ensure minimum surface roughness and maximum MRR when milling Al 6061 aluminum alloy with a high speed steel cutting tool. The Taguchi method and the Gray Relational Analysis (GRA) method were combined to determine the values of cutting speed, feed rate, and cutting depth to ensure simultaneously minimum surface roughness and maximum MRR when milling Inconel 718 super alloy by an uncoated tungsten carbide cutting tool in [15]. A combination of the Taguchi method, TOPSIS method, and ANOVA analysis was performed to determine the optimal values of cutting speed, feed rate, and depth of cut to ensure simultaneously the minimum value of surface roughness and maximum value of MRR when milling Ti-6Al-4V titanium alloy with TiN coated cutting tools in [16]. Through the above studies, it is shown that the cutting tool parameters are commonly selected as the input parameters of the milling experiment process. These parameters can be easily adjusted by the operators. However, to the best of our knowledge, there have been no studies that consider all the 5 parameters of the cutting tool material, i.e. the insert material, the tool nose radius, the cutting speed, the feed rate, and the depth of cut.

SCM440 steel is a type of steel used quite commonly to make plastic injection molds and components such as gears, transmission shafts, and rolling pins [17]. Due to the high content of Cr, Mo and Mn elements, this steel has a low thermal conductivity. When machining this steel, the tool wears out quickly, thus it is required to select the right cutting tool [18-20]. A number of studies on milling steels equivalent to this steel have been carried out [17-23]. However, to the best of our knowledge, there are no published studies on milling SCM440 (or equivalent) steel that consider all 5 parameters. DEAR is a method used for multi-criteria decision making that was introduced in 2002 [24]. This method has been used for the multi-objective optimization of the AISI 1055 steel turning process [25], the Ti-6Al-4V alloy turning process [26], the SAE420 steel grinding with a segmented grinding wheel [27], of the Electrical Discharge Machining (EDM) with the material type AA 6082 [26], etc. However, to the best of our knowledge, there have been no published studies on the application of this method in multi-criteria decision making for milling methods in general and for milling SCM440 steel in particular.

In this study, milling parameters such as the cutting tool material, the tool nose radius, the cutting speed, the feed rate, and the cutting depth will be determined to simultaneously ensure the optimization of two criteria, minimum surface roughness and maximum MRR when milling this type of steel. A combination of the Taguchi method and the DEAR method was used to solve this problem.

II. THE DEAR METHOD

The purpose of the experimental process of this study is to ensure that surface roughness (*Ra*) has the smallest value and the *MRR* reaches the maximum value. Thus, it is required to determine the values of the input parameters that ensure the set out objectives. The DEAR method will be applied in this study to carry out the above-stated work [24]. The DEAR method's steps are [24]:

- Determine the weight of each response for all experiments. This value is calculated as the ratio of the value of each response to the sum of all responses.
- Transfer the response data to the weight data by multiplying the observed data by their respective weight.
- Divide the inversed data by the sum of all inversed data.
- The Multi Response Performance Index (MRPI) is calculated by (1):

$$MRPI = W_{R_a} * R_a + W_{MRR} * MRR \quad (1)$$

The weights of the responses are calculated as:

$$W_{R_a} = \frac{R_a}{\sum R_a} \quad (2)$$

$$W_{MRR} = \frac{\frac{1}{MRR}}{\sum \frac{1}{MRR}} \quad (3)$$

III. EXPERIMENTS ON MILLING SCM400 STEEL

A. *Experimental System*

A CNC milling machine with the HAA5 serial was used to carry out the experiments (Figure 1). The experimental sample is SCM400 steel with length, width, and height of 80mm, 40mm, and 30mm respectively. The steel's chemical composition conducted with a spectrometer was: 0.43% C, 0.28% Si, 0.72% Mn, 1.05% Cr, 0.23% Mo, 0.024% P, and 0.026% S.

Fig. 1. The milling machine.

TABLE I. PARAMETERS OF THE CUTTING INSERTS

Parameter	**Cutting insert**		
	R390-11T303M-PM1025	**R390-11T305M-PM1025**	**R390-11T305M-PM1025**
Tool nose radius (mm)	0.3	0.5	0.8
Back edge length (mm)	0.8	0.9	1.2
Weight (kg)	0.0022	0.0026	0.003
Coating material	TiN; TiCN; TiAlN		
Cutting thickness (mm)	3.59		
Main cutting angle (degree)	90		
Maximum cutting depth (mm)	10		
Shape style of cutting piece	L		
Edge width (mm)	6.8		
Effective length of edge (mm)	10		

Three types of cutting pieces were used in the experiment namely the TiN-, TiCN-, and TiAlN-coated pieces. These cutting pieces have high thermal resistance, and have been proven to be very suitable for machining SCM440 steel. Each cutting piece was used with 3 tool nose radius values of 0.3mm, 0.5mm, and 0.8mm. On the tool shank with 12mm diameter, 2 symmetrical cutting pieces were installed. Each cutting insert was used only once for the purpose of eliminating the influence of tool wear on the output parameters of the milling process. In other words, the number of cutting inserts used in the experiment is twice the number of experiments to be carried out. The milling process has been carried out according to the method of symmetric milling, which means that the milling width was equal to the diameter of the milling cutter. Table I shows some basic parameters of the cutting inserts used.

The surface roughness was measured with a Mitutoyo - Japan SJ301 surface roughness tester of 0.8mm standard length. The surface roughness of each experimental sample was determined by averaging at least three consecutive measurements. The MRR was calculated according to:

$$MRR = V_f \cdot a_p \cdot b_w \text{ (mm}^3\text{/min)} \quad (4)$$

where V_f is the feed rate (mm/min), a_p is the cutting depth (mm), and b_w is the cutting width (mm). In this case the cutting width is just equal to the diameter of the milling cutter.

B. *Experimental Design*

The Taguchi method was applied to design the experimental process in this study. Five parameters were selected as the input parameters of the experimental process,. Each selected parameter has three levels of values (corresponding to three encoding degrees of 1, 2, and 3). The values of the experimental parameters, selected within their range as recommended by the cutting tool manufacturer [29], are shown in Table II.

TABLE II. INPUT PARAMETERS

Parameter	**Symbol**	**Unit**	**Value at level**		
			1	**2**	**3**
Insert material	***IM***	**-**	**TiN**	**TiCN**	**TiAlN**
Tool nose radius	r	mm	0.3	0.5	0.8
Cutting speed	V_c	m/min	80	120	160
Feed rate	V_f	mm/min	250	320	390
Depth of cut	a_p	mm	0.20	0.30	0.40

The Taguchi method was used to design the experimental matrix. When comparing the matrix design method by the Taguchi method with some other matrix design methods, it can be found that it requires a smaller number of experiments. For example, with 5 input parameters, in which each parameter has 3 levels of values, the Taguchi method only needs 27 experiments while the Box-Behnken design needs at least 46 experiments and the Central Composite Design (CCD) method needs a minimum of 43 experiments. An advantage that only the Taguchi method obtains is that it allows designing the experimental matrix with input parameters that are not quantitative parameters. In this case the qualitative parameter is just the cutting insert material type. So, the experimental matrix was designed according to the Taguchi method with a total of 27 experiments, as shown in Table III.

IV. RESULTS AND DISCUSSION

The experiments in Table III are given in accordance with the results shown in Table IV. Figure 2 shows the influence of the input parameters on surface roughness. The comparison of the difference at the lowest and highest levels, i.e. between level 1 and level 3 of the parameter line graph (red broken line) shows that the tool nose radius is the parameter that has the greatest influence on surface roughness, followed by the influence of the cutting insert material and the feed rate. The difference of the line graph of cutting speed and cutting depth is very small, showing that these two parameters have negligible influence on surface roughness.

TABLE III. EXPERIMENTAL MATRIX

No.	**Code value**					**Actual value**				
	IM	***r***	V_c	V_f	a_p	***IM***	***r (mm)***	V_c ***(m/min)***	V_f ***(mm/min)***	a_p ***(mm)***
1	1	1	1	1	1	TiN	0.3	80	250	0.2
2	1	1	1	1	2	TiN	0.3	80	250	0.4
3	1	1	1	1	3	TiN	0.3	80	250	0.6
4	1	2	2	2	1	TiN	0.5	120	320	0.2
5	1	2	2	2	2	TiN	0.5	120	320	0.4
6	1	2	2	2	3	TiN	0.5	120	320	0.6
7	1	3	3	3	1	TiN	0.8	160	390	0.2
8	1	3	3	3	2	TiN	0.8	160	390	0.4
9	1	3	3	3	3	TiN	0.8	160	390	0.6
10	2	1	2	3	1	TiCN	0.3	120	390	0.2
11	2	1	2	3	2	TiCN	0.3	120	390	0.4
12	2	1	2	3	3	TiCN	0.3	120	390	0.6
13	2	2	3	1	1	TiCN	0.5	160	250	0.2
14	2	2	3	1	2	TiCN	0.5	160	250	0.4
15	2	2	3	1	3	TiCN	0.5	160	250	0.6
16	2	3	1	2	1	TiCN	0.8	80	320	0.2
17	2	3	1	2	2	TiCN	0.8	80	320	0.4
18	2	3	1	2	3	TiCN	0.8	80	320	0.6
19	3	1	3	2	1	TiAlN	0.3	160	320	0.2
20	3	1	3	2	2	TiAlN	0.3	160	320	0.4
21	3	1	3	2	3	TiAlN	0.3	160	320	0.6
22	3	2	1	3	1	TiAlN	0.5	80	390	0.2
23	3	2	1	3	2	TiAlN	0.5	80	390	0.4
24	3	2	1	3	3	TiAlN	0.5	80	390	0.6
25	3	3	2	1	1	TiAlN	0.8	120	250	0.2
26	3	3	2	1	2	TiAlN	0.8	120	250	0.4
27	3	3	2	1	3	TiAlN	0.8	120	250	0.6

TABLE IV. EXPERIMENTAL RESULTS

No	***IM***	***r*** **(mm)**	V_c **(m/min)**	V_f **(mm/min)**	a_p **(mm)**	***Ra*** **(µm)**	***MRR*** **(mm^3/min)**
1	TiN	0.3	80	250	0.2	0.771	600
2	TiN	0.3	80	250	0.4	1.457	1200
3	TiN	0.3	80	250	0.6	1.697	1800
4	TiN	0.5	120	320	0.2	1.538	768
5	TiN	0.5	120	320	0.4	0.905	1536
6	TiN	0.5	120	320	0.6	0.986	2304
7	TiN	0.8	160	390	0.2	2.205	936
8	TiN	0.8	160	390	0.4	1.582	1872
9	TiN	0.8	160	390	0.6	0.863	2808
10	TiCN	0.3	120	390	0.2	1.024	936
11	TiCN	0.3	120	390	0.4	1.112	1872
12	TiCN	0.3	120	390	0.6	0.801	2808
13	TiCN	0.5	160	250	0.2	1.076	600
14	TiCN	0.5	160	250	0.4	2.908	1200
15	TiCN	0.5	160	250	0.6	1.014	1800
16	TiCN	0.8	80	320	0.2	0.985	768
17	TiCN	0.8	80	320	0.4	3.019	1536
18	TiCN	0.8	80	320	0.6	1.549	2304
19	TiAlN	0.3	160	320	0.2	0.927	768
20	TiAlN	0.3	160	320	0.4	0.877	1536
21	TiAlN	0.3	160	320	0.6	0.892	2304
22	TiAlN	0.5	80	390	0.2	1.234	936
23	TiAlN	0.5	80	390	0.4	1.929	1872
24	TiAlN	0.5	80	390	0.6	0.824	2808
25	TiAlN	0.8	120	250	0.2	0.545	600
26	TiAlN	0.8	120	250	0.4	1.549	1200
27	TiAlN	0.8	120	250	0.6	1.601	1800

Because the cutting insert material, the tool nose radius and the cutting speed do not exist in the MRR calculation formula (4), they have no influence on MRR. Figure 3 shows the influence of the feed rate and the cutting depth on MRR. The difference between level 1 and level 3 of cutting depth line graph is greater than the one of the feed rate line graph. This shows that the cutting depth has a greater influence on MRR than the feed rate. Thus, we see that the influence of the input parameters on surface roughness and MRR is different, even adverse, e.g. the tool nose radius has a great influence on surface roughness without any influence on MRR, the feed rate and the cutting depth are two parameters needed for calculating the MRR, but they do not significantly affect surface roughness, etc. Thus, it can be said that being based only on the two graphs of Figures 2 and 3, limits the determination of the values of the input parameters to ensure minimum surface roughness and maximum MRR. Table IV shows that surface roughness has the smallest value in experiment #25, while MRR has the maximum value in experiments #9, #12 and #24. Thus, if we only observe Table IV, it is not possible to determine the value of the input parameters to ensure both minimum surface roughness and maximum MRR. The DEAR method will be used to solve this problem in the next section.

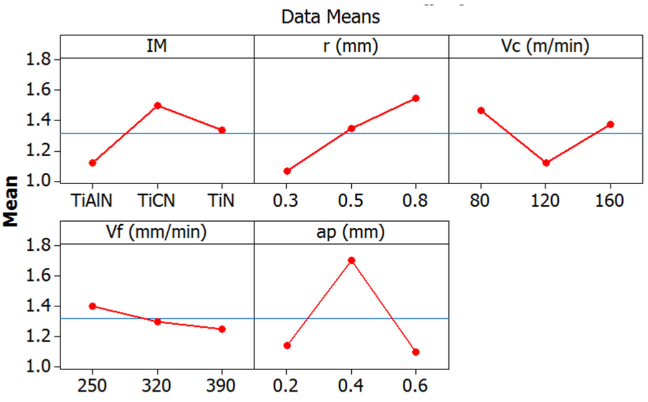

Fig. 2. Main effect plot for surface roughness.

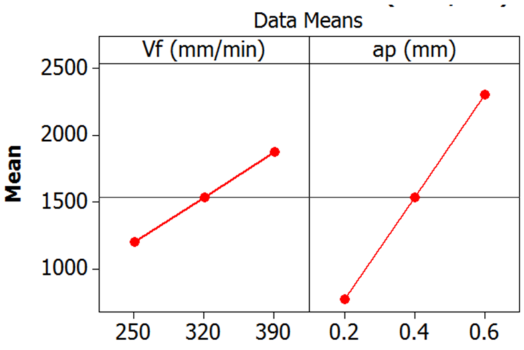

Fig. 3. Main effect plot for MRR.

V. SELECTION OF THE VALUE OF THE INPUT PARAMETERS

From the experimental data in Table IV, the weights of the responses and the MRPI value at each experiment are calculated according to (1) - (3), as shown in Table V. From the data in Table V, the MRPI values of all input parameters at all degrees were calculated. This value is calculated as the sum of the MRPI value of each parameter at the respective degree, as shown in Table VI. From the data in Table VI, it can be seen that the cutting insert material (*IM*) has the smallest value of MRPI corresponding to level 3, tool nose radius (*r*) has the smallest value of MRPI corresponding to level 1, cutting speed (V_c) corresponding to level 2, and feed rate (V_f) and cutting depth (a_p) corresponding to level 3. Thus, the optimal value of the parameters of the cutting insert material, the tool nose radius, the cutting speed, the feed rate, and the cutting depth are TiAlN, 0.3mm, 120m/min, 390mm/min, and 0.6mm respectively [24]. The MRPI value with the maximum Max-Min of 0.52972 is the cutting depth. Thus, the cutting depth is the parameter that has the greatest influence, followed by the tool nose radius, the cutting insert material, the cutting speed, and the feed rate [24].

TABLE V. EXPERIMENTAL RESPONSE WEIGHT AND MRPI

No.	W_{R_a}	W_{MRR}	MRPI
1	0.02168	0.07506	45.05364
2	0.04096	0.03753	45.09661
3	0.04771	0.02502	45.11789
4	0.04324	0.05864	45.10343
5	0.02544	0.02932	45.05996
6	0.02772	0.01955	45.06426
7	0.06199	0.04812	45.17362
8	0.04448	0.02406	45.10729
9	0.02426	0.01604	45.05787
10	0.02879	0.04812	45.06641
11	0.03126	0.02406	45.07169
12	0.02252	0.01604	45.05497
13	0.03025	0.07506	45.06948
14	0.08175	0.03753	45.27467
15	0.02851	0.02502	45.06584
16	0.02769	0.05864	45.06421
17	0.08487	0.02932	45.29317
18	0.04355	0.01955	45.10439
19	0.02606	0.05864	45.06109
20	0.02466	0.02932	45.05855
21	0.02508	0.01955	45.05930
22	0.03469	0.04812	45.07974
23	0.05423	0.02406	45.14154
24	0.01473	0.01604	45.04465
25	0.01532	0.07506	45.04528
26	0.04355	0.03753	45.10439
27	0.04501	0.02502	45.10899

TABLE VI. TOTAL MRPI

Parameter	Level			Max - Min
	1	2	3	
IM	405.83457	406.06482	405.70353	0.36129
r	405.64016	405.90357	406.05920	0.41904
V_c	405.99584	405.67938	405.92771	0.31646
V_f	405.93679	405.86835	405.79778	0.13901
a_p	405.71690	406.20787	405.67815	0.52972

VI. EXPERIMENTS WITH THE OPTIMAL VALUES OF THE PARAMETERS

The optimal set of the 5 input parameters defined above was used to experiment on the milling process with 3 steel samples. The surface roughness of each experimental sample is shown in Table VII. The MRR value at each experiment has also been calculated and is included in this Table. The average value of surface roughness in these cases is 0.724μm. If compared with the surface roughness values in Table IV, it can be seen that although 0.724μm is still larger than the value of surface roughness at experiment #25, this value is very small when compared to the total of 27 experiments that were carried out. For MRR, when calculated according to (4), in the three test samples, the MRR is equal to 2808mm^3/min, which is also larger than the data in Table IV. From that, it can be seen that when machining with the optimal values of the input parameters, MRR reaches its maximum value and surface roughness is also significantly improved. This result ensures the reliability when using the optimal value of the input parameters and proves the success in using the DEAR method in this study.

TABLE VII. OUTPUT PARAMETERS WHEN EXPERIMENTING WITH THE OPTIMAL VALUES OF THE INPUT PARAMETERS

No.	**Optimization value**					***Ra*** **(µm)**	***MRR*** **(mm^3/min)**
	IM	***r*** **(mm)**	**V_c (m/min)**	**V_f (mm/min)**	**a_p (mm)**		
1	TiAlN	0.3	120	390	0.6	0.726	2808
2						0.721	2808
3						0.725	2808
Mean						0.724	2808

VII. CONCLUSION

An experimental process of milling SCM 440 steel was carried out in this study. Three types of cutting inserts were used, coated with TiN, TiCN, and TiAlN. The tool nose radius, the cutting speed, the feed rate, and the cutting depth were also determined as input parameters of the experimental process. The DEAR method was applied to determine the optimal value of the input parameters. Some of the conclusions drawn from this study are:

- The tool nose radius is the parameter that has the greatest influence on surface roughness, followed by the influence of the cutting insert material and the feed rate. The cutting speed and the cutting depth have no significant influence on surface roughness.
- Only the feed rate and the cutting depth have an influence on MRR, and the influence of the cutting depth on MRR is greater than the one of the feed rate.
- The parameter set that ensures simultaneously the two objectives is: TiAlN cutting insert material, 0.3mm tool nose radius, 120mm/min cutting speed, 390mm/min feed rate, and 0.6mm cutting depth.
- DEAR method was not only successful in determining the optimal values of the input parameters in this study as well as in [25-28] but it is also quite promising to being successful in the future when applied to determine the value of input parameters to simultaneously ensure multi-criteria optimization of the machining process.

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