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Nhu-Tung Nguyen
Faculty of Mechanical Engineering,
Hanoi University of Industry,
Hanoi city, Vietnam

Do Duc Trung
Faculty of Mechanical Engineering,
Hanoi University of Industry,
Hanoi city, Vietnamv

Key words: *multi-objective optimization, surface grinding, SKD11 Steel, MOORA, COPRAS, Taguchi, surface roughness, MRR*

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COMBINATION OF TAGUCHI METHOD, MOORA AND COPRAS TECHNIQUES IN MULTI-OBJECTIVE OPTIMIZATION OF SURFACE GRINDING PROCESS

*Nhu-Tung Nguyen, Do Duc Trung**

Faculty of Mechanical Engineering, Hanoi University of Industry, Hanoi city, Vietnam

This study presentes a combination method of several optimization techniques and Taguchi method to solve the multi-objective optimization problem for surface grinding process of SKD11 steel. The optimization techniques that were used in this study were Multi-Objective Optimization on basis of Ratio Analysis (MOORA) and Complex Proportional Assessment (COPRAS). In surface grinding process, two parameters that were chosen as the evaluation creterias were surface roughness (Ra) and material removal rate (MRR). The orthogonal Taguchi L_{16} matrix was chosen to design the experimental matrix with two input parameters namely workpiece velocity and depth of cut. The two optimization techniques that mentioned above were applied to solve the multi-objective optimization problem in the grinding process. Using two above techniques, the optimized results of the cutting parameters were the same. The optimal values of workpiece velocity and cutting depth were 20 m/min and 0.02 mm, respectively. Corresponding to these optimal values of the workpiece velocity and cutting depth, the surface roughness and material removal rate were 1.16 μm and 86.67 mm^3/s. These proposed techniques and method can be used to improve the quality and effectiveness of grinding processes by reducing the surface roughness and increasing the material removal rate.

Key words: multi-objective optimization, surface grinding, SKD11 Steel, MOORA, COPRAS, Taguchi, surface roughness, MRR

INTRODUCTION

In the machining methods, grinding method are the most common method to machine the surfaces that requires high precision and high surface gloss. The efficiency of the grinding process is evaluated through many parameters such as surface roughness, material removal rate (MRR), cutting forces, cutting heat, system vibrations, ... Many studies have been done to determine the optimum value of the machining parameters to achieve one or more objectives.

Mahajan et al. [1] determined the optimal value of wheel grit size, the grinding wheel speed, the feed rate per revolution, and depth of cut in surface grinding process of D2 steel. Taguchi method was applied to design and optimize the machining surface roughness and material removal rate. To obtain the minimum value of surface roughness, the optimal value of wheel grit size, the grinding wheel speed, the feed rate per revolution, and depth of cut were 46 (mesh), 2300 (rev/min), 0.834 (mm/rev), and 0.05 (mm), respectively. Besides, to obtain the maximum value of MRR, the optimal value of wheel grit size, the grinding wheel speed, the feed rate per revolution, and depth of cut were 36 (mesh), 1650 (rev/min), 0.834 (mm/rev), and 0.075 (mm), respectively. However, this method has not yet given a set of values of input parameters to ensure simultaneously the minimum value of surface roughness and maximum value of MRR.

Rai et al. [2] used Taguchi method to optimize the surface grinding process of AISI410 steel. The wheel grit size, the feed rate per revolution, and depth of cut were chosen the input parameters to design the experimental matrix. The aim of this study was determination of the input parameters to ensure the average surface roughness and mean square of surface roughness having the minimum values. Using this method, the average surface roughness and mean square of surface roughness have also the minimum values when the wheel grit size, the feed rate per revolution, and depth of cut were 54 (mesh), 0.5 (mm/rev), and 0.06 (mm), respectively.

Atish et al. [3] used Taguchi to optimize the surface grinding process of the mild steel. The aim of this study was determination of values of the depth of cut, the workpiece velocity, and cross feed rate to achieve the minimum value of surface roughness and maximum of MRR. This study found that to obtain the minimum of surface roughness, the depth of cut, the workpiece velocity, and cross feed rate were 0.1 (mm), 20 (strokes/min), and 10 (strokes/min), respectively. To obtain the maxinmum of MRR, the depth of cut, the workpiece velocity, and cross rate were 0.1 (mm), 30 (strokes/min), and 30 (strokes/min), respectively.

Aravind et al. [4] combined the Taguchi method and response surface method (RSM) to optimize the surface grinding process of ASIS 1035 steel. The wheel grain size, the grinding wheel speed, depth of cut, and feed rate were selected as the input parameters to design the experimental matrix. This study showed that to obtain

*doductrung@haui.edu.vn

the minimum values of both Ra and Rz, the wheel grain size, the grinding wheel speed, depth of cut, and feed rate were 54 (mesh), 0.05 (mm), and 0.45 (mm/stroke), respectively.

Hamid Reza FAZLI SHAHRI et al. [5] combined Taguchi method and regression analysis to optimize the surface grinding process of AISI 1045 AISI 1045. This study showed that to achieve the maximum of machining surface hardness, the grinding wheel must be fine dressed, and the optimal values of depth of cut, cutting velocity, workpiece velocity, cross feed were 0.03 (mm), 32 (m/s), 10 (m/min), and 5 (mm/rev), respectively.

Prashant et el. [6] combined the Taguchi method and grey relational analysis (GRA) technique to optimize the surface grinding process of EN8 steel. The parameters that were selected as the input parameters were depth of cut, type of lubricant, feed rate, grinding wheel speed, coolant flow rate, and nanoparticle size. This study showed that to obtain the minimum of surface roughness, the type of lubricant was the water containing the CuO particles with the grain size of 100 (nm), concentration of 2%, and flow of 5 (ml/min), and the depth of cut, feed rate, grinding wheel speed were 5 (μm), 2000 (mm/min), and 35(m/s), respectively.

Luu Anh Tung et al. [7] also combined Taguchi method and GRA to determine the optimal values of the grinding wheel dressing parameters in grinding process of 9CrSi tool steel. The purpose of this study was assurance of the minimum value of machining surface roughness and minimum value of the flatness tolerance. In this study, the optimal values of the dressing parameters were determined including: The coarse dressing depth was 0.025 (mm), the coarse dressing times were 3 times, the fine dressing depth was 0.005 (mm), the fine dressing times were 2 times, and the dressing feed rate was 1.6 (m/min).

In other study, the multi-objective optimization in surface grinding process of 90CrSi tool steel was also performed by Nguyen Thi Hong et al. [8]. This study aimed to determine the dressing parameters to simultaneously ensure the minimum values of surface roughness and tangential cutting force, and maximum value of tool life. In this study, Taguchi method and GRA were combined to determine the optimal values of dressing parameters as following. The coarse dressing depth was 0.015 (mm), the coarse dressing times were 2 (times), the fine dressing depth was 0.005 (mm), the non-feeding dressing times were 3 (times), and the dressing feed rate was 1.6 (m/min).

The combination of Taguchi method and GRA was also applied to solve the multi-objective optimization problem in the surface grinding process of AISI D2 steel [9]. In this study, three different coolant conditions were applied in surface grinding process including dry conditions, flood cooling condition, and minimum quantity lubrication (MQL) condition. This study showed that to simultaneously ensure the minimum values of machining surface roughness, cutting heat, and normal cutting forces, the grinding process was performed with a cutting depth of 15 (μm), a workpiece velocity of 3 (m/min), cutting velocity of 25 (m/s), and with flow rate 250 (mL/h) of MQL condition.

Prashant J. Patil et al. [10] also combined Taguchi method and GRA to solve the multi-objective optimization problem in surface grinding process of EN-24 steel in MQL condition. The input parameters that were selected in this study included the nanoparticles in the lubricating solution (Al2O3, CuO, water), the concentration of particles, particle size, flow rate of solution, depth of cut, feed rate, and cutting velocity. The obtained results showed that to simultaneously achieve the minimum values of mormal cutting force, tangential cutting force, and cutting heat, the grinding process must be performed in the lubricating solution using CuO nanoparticle with a concentration of 2%, a nanoparticle size of 100 (nm), a coolant flow rate of 5 (ml/minute), and with a cutting depth of 5 (μm), a feed rate of 2000 (mm/min), and a grinding wheel speed 35 (m/s).

The combination of Taguchi method and GRA to solve the multi-objective optimization problem in grinding process of OCR12VM material was performed by Hendri Jumianto et al. [11]. This study showed that to ensure the minimum values of system vibrations, the cutting velocity, workpiece velocity, and cross feed rate were 3000 (rpm), 11 (mm/s), and 5 (mm/stroke), respectively.

From above studies, it shows that the Taguchi method has been successfully applied in solving the optimization of the surface grinding process in many specific cases. Among published studies, the cutting parameters are often chosen as the input parameters for the experimental process. This issue could be explained that the adjustment of these parameters during machining is more easily done by the operator than by adjusting other parameters such as the rigidity of the machine system, the vibrating factors transmitted into the system, etc. However, with each specific case about the machining material, the optimal values of cutting parameters were different. So, for each machining material and each specific machining condition, the experimental and optimization studies must be performed under specific conditions. Besides, if only using Taguchi method, only one evaluation criteria is optimized (the single objective optimization), if the multi-objective optimization problem is solved, the Taguchi method must be combined with other methods or techniques.

MOORA and COPRAS are two of the famous optimization methods that were applied into different research fields. Gadakh [12] combined Taguchi and MOORA technique to optimize the cutting parameters of the milling process. The purpose of this study was determination of the optimal values of spindle speed, feed rate per flute, tool diameter, tool nose radius, and the machining time to ensure the minimum of the tool wear, and to ensure the maximum of MRR.

Mesran et al. [13] applied the MOORA technique to investigate the division of the students into each class when entering the universities. This study proposed the best method to divide the students into the class based on the parameters of each student (UN Average Score, Psychotest Value, IPA Value, Mathematics Value, Interview Value). Nguyen et al. [14] used the MOORA to optimize the Powder mixed electrical discharge machining (PMEDM). The aim of this study to determine the optimal values of the workpiece material, tool material, polarity, peak current, pulse-on-time, pulse-off-time, and titanium powder concentration to ensure the minimum values of surface roughness and electrode wear. Tran et al. [15] applied MOORA and COPRAS techniques to determine the optimal values of the materials (straw, corn cobs, sawdust, rice bran, and CaCO3) for growing mushrooms, and so on. However, up to now, there have not been any published studies on the application of these two techniques to solve the multi-objective optimization problem in the machining process in general or the surface grinding processes in particular.

Surface roughness has a significant influence on the workability and life of the product. While MRR is a parameter that reflects machining productivity, energy consumption, grinding wheel consumption, so the efficiency of grinding process also can be evaluated through this parameter. Therefore, these two parameters are often chosen as indicators of evaluating the efficiency of grinding processes in general and the surface grinding process in particular.

In this study, SKD11 steel was grinded on a surface grinder. The experiments were designed according to the Taguchi method including 16 experiments. In which, the workpiece velocity and cutting depth were selected as the input parameters for each experiment. The surface roughness and MRR were chosen as the two output parameters. Two techniques MOORA and COPRAS have been applied to solve the multi-objective optimization problem. The results showed that these techniques have determined the same set of values of workpiece velocity and depth of cut to ensure the minimum value of surface roughness and maximum value of MRR. The two techniques MOORA and COPRAS not only successfully applied in solving the multi-objective optimization problem of the surface grinding process in this study, but also opened up a very potential research direction in multi-objective optimization of other machining processes.

EXPERIMENTAL METHOD

Experimental system

The experiments were conducted in the surface grinding APSG-820/2A machine. The grinding wheel aluminum oxide APSG-820/2A was used in this study. The workpiece material that was used in the experimental process was heat treated SKD11 with the hardness of 60 HRC. The length, width, and height of workpiece were 80 (mm), 40 (mm), and 10 (mm), respectively. The surface roughness tester SJ-301 (Japan) was used to measure the surface roughness of machining parts. Each experiment, the surface roughness was measured at least three consecutive times. The average value of surface roughness was used for evaluation and analysis process.

The material removal rate RMM was calculated by equation $MRR = v_w \times b \times t$ (mm^3/s). Where v_w, b, and t are the workpiece velocity (m/s), the width of the grinding wheel (mm), and the depth of cut (mm), respectively.

Experimental design

The Taguchi method was applied to design the experimental matrix. The cutting parameters that were chosen as the input parameters were workpiece velocity and depth of cut. The orthogonal L_{16} matrix with 16 experiments was used and listed in Table 1.

Table 1: Experimental matrix

No.	v_w (m/min)	t (mm)
1	5	0.005
2	5	0.001
3	5	0.015
4	5	0.002
5	10	0.005
6	10	0.001
7	10	0.015
8	10	0.002
9	15	0.005
10	15	0.001
11	15	0.015
12	15	0.002
13	20	0.005
14	20	0.001
15	20	0.015
16	20	0.002

Grinding conditions

The experiments were conducted with the controllable factors in Table 1 and with the grinding conditions as following:

- The cutting velocity: 26 m/s.
- The dressing depth of cut: 0.01 mm.
- The dressing feed rate: 100 mm/min
- Cooling fluid: emulsion 10%, overflow irrigation method.

MULTI-OBJECTIVE OPTIMIZATION PROCESS USING MOORA AND COPRAS TECHNIQUES

Multiple-Criteria Decision Making (MCDM)

The multiple criteria decision making – MCDM can be used to select the best solution from the solutions $A = \{A_1, A_2, \ldots, A_m\}$ based on the criterias $C = \{C_1, C_2, \ldots, C_n\}$.

In which, each crireria C_j is assigned with a weight w_j (j = 1, 2, …, n), so that $\sum_{j=1}^{n} w_j = 1$. A MCDM problem can be presented by the matrix $D = [d_{ij}]_{m\times n}$ [16].

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

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

In this study, in the MOORA and COPRAS techniques, 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 [17, 18]:

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

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

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

$$e_j = -\sum_{i=1}^{m}\left[p_{ij}\ln\left(p_{ij}\right)\right] - \left(1 - \sum_{i=1}^{m} p_{ij}\right) \times \ln\left(1 - \sum_{i=1}^{m} p_{ij}\right) \tag{2}$$

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

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

MOORA technique

MOORA $(1-e_j)$ technique was introduced the first time in 2004 by Brauers [19]. This multi-objective optimization technique can be successfully appliec 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)

$$X = \left[X_{ij}\right]_{m\times n} \text{ với } X_{ij} = \frac{d_{ij}}{\sqrt{\sum_{i=1}^{m} d_{ij}^2}} \tag{4}$$

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).

$$W_{ij} = w_j \times x_{ij} \tag{5}$$

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

$$P_i = \frac{1}{|B|}\sum_{j\in B} W_{ij} \tag{6}$$

$$R_i = \frac{1}{|NB|}\sum_{j\in NB} W_{ij} \tag{7}$$

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 by Eq. (8).

$$Q_i = P_i - R_i \tag{8}$$

Step 8: Ranking the solutions $A_k > A_i$ if $Q_k < Q_i$ with i, k = 1, 2, …, m.

COPRAS technique

COPRAS technique was introduced by Zavadskas et al. [18]. This is a famous multi-objective optimization method. The COPRAS 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. (9)

$$X_{ij} = \frac{d_{ij}}{\sum_{i=1}^{m} d_{ij}} \tag{9}$$

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. (10).

$$W_{ij} = w_j \times d_{ij} \tag{10}$$

Step 6: Calculating P_i and R_i by Eq. (11) and Eq. (12).

$$P_i = \frac{1}{|B|}\sum_{j\in B} W_{ij} \tag{11}$$

$$R_i = \frac{1}{|NB|}\sum_{j\in NB} W_{ij} \tag{12}$$

Step 7: Calculating the priority value with i = 1, 2, …, m by Eq. (13).

$$Q_i = P_i + \frac{\sum_{i=1}^{m} R_i}{R_i \times \sum_{i=1}^{m} \frac{1}{R_i}} \tag{13}$$

Step 8: Ranking the solutions $A_k > A_i$ if $Q_k < Q_i$ with i, k = 1, 2, …, m.

MULTI-OBJECTIVE OPTIMIZATION RESULTS OF SURFACE GRINDING PROCESS OF SKD11 STEEL

Experimental results

The experiments were conducted according to the experimental matrix in Table 1. The experimental results were listed in Table 2. To facilitate for the using of the mathematical symbols when optimizing according to MOORA and COPRAS techniques, the surface roughness criterion and the MRR criterion were set as C1 and C2 as presented in Table 3.

Table 2: Experimental results

No.	v_w (m/min)	t (mm)	Ra (μm)	MRR (mm^3/s)
1	5	0.005	0.59	5.42
2	5	0.001	0.66	1.08
3	5	0.015	0.53	16.25
4	5	0.002	0.38	21.67
5	10	0.005	0.85	10.83
6	10	0.001	0.83	2.17
7	10	0.015	0.77	32.50
8	10	0.002	0.64	43.33
9	15	0.005	1.01	16.25
10	15	0.001	1.22	3.25
11	15	0.015	1.02	48.75
12	15	0.002	0.90	65.00
13	20	0.005	1.23	21.67
14	20	0.001	1.29	4.33
15	20	0.015	1.26	65.00
16	20	0.002	1.16	86.67

Table 3: Surface roughness and MRR with the different values of input parameters

No.	C1	C2
A1	0.59	5.42
A2	0.66	1.08
A3	0.53	16.25
A4	0.38	21.67
A5	0.85	10.83
A6	0.83	2.17
A7	0.77	32.50
A8	0.64	43.33
A9	1.01	16.25
A10	1.22	3.25
A11	1.02	48.75
A12	0.90	65.00
A13	1.23	21.67
A14	1.29	4.33
A15	1.26	65.00
A16	1.16	86.67

The optimized results using MOORA technique

From the data in Table 3, MOORA technique was used to calculate the values as following:

Step 1: Calculating the values p_{ij} by Eq. (1). The calculated results were listed in Table 4.

Step 2: Calculating the values e_j by Eq. (2). The calculated results were listed in Table 5.

Step 3: Calculating the values w_j by Eq. (3). The calculated results were also listed in Table 5.

Step 4: Calculating the matrix $X = [X_{ij}]_{m \times n}$ by Eq. (4). The calculated results were listed in Table 6.

Step 5: Calculating the matrix W by Eq. (5). The calculated results were listed in Table 7.

Step 6: Calculating the values P and Ri by Eq. (6) and Eq. (7). The calculated results were listed in Table 8.

Step 7: Calculating the values Q_i by Eq. (8). The calculated results were also listed in Table 8.

The calculated results from Table 8 showed that the solution A_{16} was the best solution in 16 solutions. If considering only the surface roughness criteria or only the MRR, A_{16} is not the best solution (Table 2). However, when considering the two parameters of surface roughness and MRR at the same time, this solution was considered to be the best solution.

Table 4: Value of p_{ij}

No.	C1	C2
A1	0.011377	0.000236
A2	0.014478	4.72E-05
A3	0.009303	0.000708
A4	0.004826	0.000945
A5	0.024013	0.000472
A6	0.022727	9.45E-05
A7	0.019925	0.001417
A8	0.013682	0.001889
A9	0.034146	0.000708
A10	0.049468	0.000142
A11	0.034506	0.002125
A12	0.027017	0.002834
A13	0.050043	0.000945
A14	0.054886	0.000189
A15	0.053023	0.002834
A16	0.044805	0.003779

Table 5: Weight of the criterias

	C1	C2
Entropy	1.911441	0.140969
Weigth	17.39053	-16.3905

Table 6: Standardized matrix using MOORA technique

No.	C1	C2
A1	0.1559	0.0358
A2	0.1758	0.0072
A3	0.1410	0.1073
A4	0.1015	0.1431
A5	0.2265	0.0716
A6	0.2203	0.0143
A7	0.2063	0.2147
A8	0.1709	0.2862
A9	0.2700	0.1073
A10	0.3250	0.0215
A11	0.2715	0.3220
A12	0.2402	0.4293
A13	0.3269	0.1431
A14	0.3424	0.0286
A15	0.3365	0.4293
A16	0.3093	0.5725

Table 7: Combination of standardized matrix using MOORA technique and weight

No.	C1	C2
A1	10.1746	-88.7819
A2	11.4777	-17.7564
A3	9.2007	-266.3456
A4	6.6270	-355.1275
A5	14.7820	-177.5638
A6	14.3808	-35.5128
A7	13.4649	-532.6913
A8	11.1578	-710.2550
A9	17.6270	-266.3456
A10	21.2164	-53.2691
A11	17.7198	-799.0369
A12	15.6793	-1065.3825
A13	21.3393	-355.1275
A14	22.3480	-71.0255
A15	21.9654	-1065.3825
A16	20.1916	-1420.5100

Table 8. Calculated results of Pi, Ri, Qi and the ranked results using MOORA technique

No.	Pi	Ri	Qi	Ranking
A1	10.1746	-88.7819	98.9565	12
A2	11.4777	-17.7564	**29.2341**	16
A3	9.2007	-266.3456	275.5464	10
A4	6.6270	-355.1275	361.7545	8
A5	14.7820	-177.5638	192.3457	11
A6	14.3808	-35.5128	49.8936	15
A7	13.4649	-532.6913	546.1562	6
A8	11.1578	-710.2550	721.4128	5
A9	17.6270	-266.3456	283.9727	9
A10	21.2164	-53.2691	74.4856	14
A11	17.7198	-799.0369	816.7567	4
A12	15.6793	-1065.3825	1081.0618	3
A13	21.3393	-355.1275	376.4668	7
A14	22.3480	-71.0255	93.3735	13
A15	21.9654	-1065.3825	1087.3479	2
A16	20.1916	-1420.5100	**1440.7016**	1

The optimized results using COPRAS technique

From the data in Table 3, COPRAS technique was applied according to the steps in above section. The results were calculated and listed in Table 9, Table 10, and Table 11.

The calculated results from Table 11 also showed that the solution A16 was the best solution in 16 solutions. The ranking order of the solutions in Table 11 also coincided with the ranking order of solutions in Table 8. Thus, in this case, the MOORA and the COPRAS techniques gave a unified result when determining the optimal solution. That further confirms the correctness of the implemented methods. So, in surface grinding process of KSD11 steel, to ensure the minumum value of surface roughness and maximum value of material removal rate, the optimal values of the workpiece velocity and cutting depth were 20 m/min and 0.02 mm.

Table 9: Standardized matrix using COPRAS technique

No.	C1	C2
A1	0.0415	0.0002
A2	0.0468	0.0000
A3	0.0376	0.0007
A4	0.0270	0.0009
A5	0.0603	0.0005
A6	0.0587	0.0001
A7	0.0550	0.0014
A8	0.0455	0.0019
A9	0.0719	0.0007
A10	0.0866	0.0001
A11	0.0723	0.0021
A12	0.0640	0.0028
A13	0.0871	0.0009
A14	0.0912	0.0002
A15	0.0897	0.0028
A16	0.0824	0.0038

Table 10: Combination of Standardized matrix using COPRAS technique

No.	C1	C2
A1	10.17462	-88.7819
A2	11.47775	-17.7564
A3	9.20075	-266.346
A4	6.626951	-355.128
A5	14.78195	-177.564
A6	14.38081	-35.5128
A7	13.46491	-532.691
A8	11.15776	-710.255
A9	17.62704	-266.346
A10	21.21645	-53.2691
A11	17.71979	-799.037
A12	15.6793	-1065.38
A13	21.33934	-355.128
A14	22.34799	-71.0255
A15	21.9654	-1065.38
A16	20.19156	-1420.51

Table 11: Calculated results of Pi, Ri, Qi and the ranked results using using COPRAS technique

No.	Pi	Ri	Qi	Ranking
A1	10.17462	-88.7819	-520.6382	12
A2	11.47775	-17.7564	**-2642.5861**	16
A3	9.20075	-266.346	-167.7368	10
A4	6.626951	-355.128	-126.0762	8
A5	14.78195	-177.564	-250.6244	11
A6	14.38081	-35.5128	-1312.6511	15
A7	13.46491	-532.691	-75.0039	6
A8	11.15776	-710.255	-55.1938	5
A9	17.62704	-266.346	-159.3106	9
A10	21.21645	-53.2691	-863.4715	14
A11	17.71979	-799.037	-41.2594	4
A12	15.6793	-1065.38	-28.5551	3
A13	21.33934	-355.128	-111.3639	7
A14	22.34799	-71.0255	-641.1680	13
A15	21.9654	-1065.38	-22.2690	2
A16	20.19156	-1420.51	**-12.9842**	1

CONCLUSIONS

This study was performed using Taguchi method, MOORA and COPRAS techniques to solve the multi-objective optimization problem for surface grinding process of SKD11 steel. The conclusions of this study were drawn as following:

- Taguchi method, MOORA and COPRAS techniques were successfully applied to solve the multi-objective optimization problem for surface grinding process of SKD11 steel. Using these above techniques, the optimized results of the cutting parameters were the same.
- The optimal workpiece velocity and cutting depth were 20 m/min and 0.02 mm. Corresponding to these optimal values of the workpiece velocity and cutting depth, the surface roughness and material removal

rate were 1.16 μm and 86.67 mm^3/s, respectively.

- hese proposed techniques and method can be used to improve the quality and effectiveness of grinding processes by reducing the surface roughness and increasing the material removal rate.

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