A Fuzzy Multi-criteria Decision-making Model for Green Electrical Discharge Machining

Jagadish and Amitava Ray

Abstract This paper aims to combine fuzzy and technique for order preference by simulation of ideal solution (TOPSIS) to solve the multi-response parameters optimization problem in green manufacturing. From the viewpoint of health and environment, tap water is used as working fluid, since it does not release the harmful gases. This work considers discharge current, pulse width/pulse interval ratio, gap voltage, and lifting height are the input parameters and output parameters have been identified as material removal rate (MRR), electrode wear ratio (EWR), and surface roughness (SR). In this paper, initially, an experiment was performed using Taguchi experimental technique. Thereafter, fuzzy-TOPSIS is used to convert multi-response parameters into a single response parameter. Finally, the ranking of the parameter decides the best experimental setup and optimized the input-process parameters. In this work, weighting factors for the output parameters are determined using triangular fuzzy number which influences correlation coefficient values for finding the finest experimental setup. Additionally, an attempt has been made to compare the proposed methodology with the gray relational analysis (GRA). The numerical result shows that the optimum process parameters are A_1 (4.5 A), B_1 (30:70 μs), C_3 (30 V), and D_4 (6 mm) and using tap water machining Ti-6Al-4V material can produce high MRR, decrease the machining cost, and have no harmful to the operators and environment.

Keywords Fuzzy · TOPSIS · Green manufacturing (GM) · Process parameters

Jagadish (✉)
Department of Mechanical Engineering, National Institute of Technology Silchar, Silchar 788010, Assam, India
e-mail: jagadishbaridabad.s@gmail.com

A. Ray
Department of Training and Placement, Jalpaiguri Government Engineering College, Jalpaiguri 735102, India
e-mail: amitavaray.siliguri@gmail.com

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1 Introduction

EDM is non-traditional machining process, which is extensively used in machining hard, high strength, and complex geometry in a contact less manner. The material is removed from the workpiece by generating the electric spark between electrode tool and workpiece [1–5]. Ti-6Al-4V is widely used in aerospace, automobile, chemical, and biomedical fields, because it has exceptional merits such high strength to weight ratio, good temperature-resistance, and prominent corrosion resistance. However, it is a hard to cut material with high melting point and low thermal conductivity, and it is not suitable for cutting by traditional machining. Therefore, non-traditional machining process has been used to machine this alloy.

Green manufacturing deals with environmental principle and plays an important role in reduction of environmental burdens [6, 7]. Friction during the machining process of Ti-6Al-4V alloy results in the heat generation. The effect of this heat generated decrease the MRR, increase the SR, and increase the electrode wear ratio (EWR) and also releases numerous amounts of harmful components in the form of solid, liquid, and gas wastes resulting in serious occupational health and environmental issues. These toxic substances are very harmful and create serious problems to the operator through ingestion, inhalation, and skin contact. The amount of waste generated and its output parameters of process are strongly affects the input-process parameters. Therefore to mitigate this, optimization of process parameters is a key role to improve the EDM, MRR, SR, reduce the EWR, and look for optimal machining parameters attains the green EDM. Green manufacturing not only improves the efficiency but also saves the resources.

The selection of optimum process parameters is a multi-criteria decision-making (MCDM) selection problem. The literature survey [8–15] reveals the use of various MCDM methods employed in solving engineering problems. Authors suggested that in all these MCDM methods, the ranking of the alternatives is influenced by the criteria weights. Several researchers [16–23] used these MCDM methods for optimization in green manufacturing. Much research has been conducted to attempt green manufacturing parameters for EDM using different types of dielectric fluid. Several researchers have proposed in the literature to study the influence of various process parameters on EDM operation [24–29]. The machining D2 tool steeled in tap water and deionized water with brass and bronze electrode, and the results reveal that by using 75 % tap water and 25 % deionized water mixture, the dielectric can obtain the maximum MRR and the minimum EWR [30]. Study has been conducted on EDM with dielectric-water-in-oil, kerosene, a urea with water, and low-sensitivity deionized water to attempt high MRR and low EWR [31–33]. Graphite, electrolytic copper, aluminum, and copper–tungsten material were researched as EDM electrodes in order to obtain surface integrity of Ti-6Al-4V [34, 35, 36]. The fundamental study on the Ti-6Al-4V alloy properties and improving the capabilities of EDM using Powder-mixed EDM has been made to improve the MRR [37, 38]. The relationship between residual stresses and white layer has been made with different types of EDM dielectric [39, 40]. A comparative study on different machining techniques [41–44] such as ultrasonic, vibratory, and rotary and magnetic field has been made to determine the optimal machining parameters in EDM. Machining performance in the EDM process can be improved effectively through optimal machining parameters [45–48]. Using kerosene in the machining releases numerous amounts of harmful components in the form of solid, liquid, and gases wastes resulting in serious occupational health and environmental issues. These toxic substances are very harmful and create serious problems to the operator through ingestion, inhalation, and skin contact [49].

Tang et al. [50] developed a combined method of Taguchi coupled with GRA to optimize the process parameters and machining of Ti-6Al-4V alloy under tap water as dielectric medium. In this work, an author has determined the optimal parameters and improves the green manufacturing parameters without considering the relative weights of the response parameters. But in actual practice, the response parameters are solely dependence on the input parameters with their relative importance. The effect of weights on the performance parameters will lead to error in decision making and methodology will not produce the optimal result. Therefore, in this paper, fuzzy theory [51, 52] has been used to overcome this. Fuzzy set theory deals effectively with this type of uncertainty data, thus allowing linguistic variables (such as low, high, very high, and very low) to be employed for approximate reasoning. Generally, triangular and trapezoidal fuzzy numbers are used for representing linguistic variables.

Among the MCDM methods, TOPSIS [49, 53], which can handle multi-response problems with both continuous and discrete data, is the most suitable technique in engineering applications. The basic principle of TOPSIS is to select the best alternative that has the shortest distance from the positive ideal solution and the farthest distance from the negative ideal solution.

The objective of this research is to optimize the process parameters of Ti-6Al-4V alloy green EDM. In this paper, an integrated approach has been projected to handle the multi-response parameters optimization problems. The experiments are designed using Taguchi (L9) orthogonal array and optimized the process parameters by developing methodology. Weighting factors associated with each of the output parameters are determined using triangular fuzzy number and the most paramount factor level combination is identified utilizing TOPSIS approach. The goal was to attain high efficiency; high quality and pollution-free environment during the machining meets the modern industrial requirements.

The rest of the following sections are organized as follows: Section 2 explores the input-process-output parameters for green EDM; Sect. 3 describes the materials and research design in detail; In Sect. 4, result and discussion have been highlighted. Finally, conclusions are described in Sect. 5.

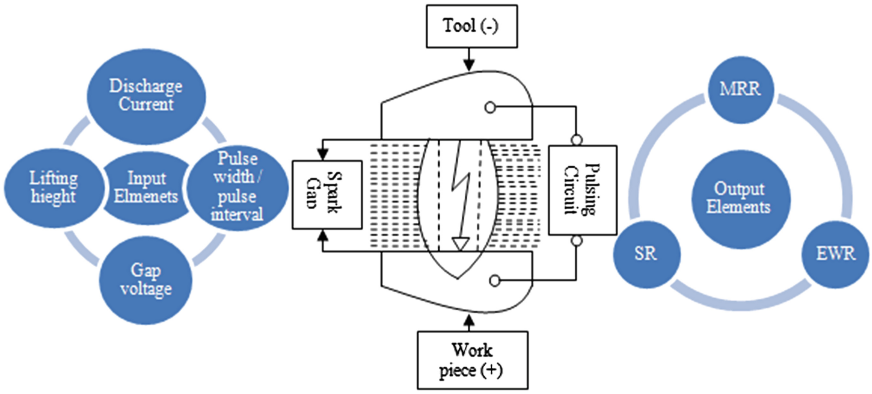


Fig. 1 Input-process-output for Green EDM

2 Input-Process-Output Diagram of Green EDM

The main theory of the EDM process is an electric arc struck between two electrodes produces the energy required for the material removal [6]. The relationship between input and output parameters is shown in Fig. 1.

3 Materials and Methods

3.1 Determination of Response Parameters

The response parameters are determined by means of valid experiential setup on CNC ACTSPARK EDM machine. The detailed explanation of experimental setup and material chemical composition has been explored in the literature [50]. The work considers four input parameters and three output parameters. The number of experimental runs is carried out using L9 (3^4) orthogonal array. The input-process parameters and three levels for the design are shown in Table 1. The results of the experiments are depicted in Table 2.

Table 1 Input parameters and their levels [50]

Symbol	Control parameters	Level 1	Level 2	Level 3
A	Discharge current (A)	11	16	20
B	Pulse width/pulse interval (Ton/Toff) (μs)	30:70	50:50	70:30
C	Gap voltage (V)	20	25	30
D	Lifting height (mm)	3	6	9

Table 2 Experimental results [50]

Exp. No.	Input parameters				Output parameters		
	A	B	C	D	MRR (mm^3/min)	EWR (mm^3/min)	SR(μs)
1	1	1	1	1	2.96	0.21	2.17
2	1	2	2	2	1.28	0.14	2.37
3	1	3	3	3	1.73	0.16	2.83
4	2	1	2	3	3.27	0.30	2.19
5	2	2	3	1	4.30	0.30	2.61
6	2	3	1	2	4.07	0.28	2.86
7	3	1	3	2	5.90	0.41	2.15
8	3	2	1	3	6.62	0.41	2.65
9	3	3	2	1	6.36	0.41	4.27

3.2 Optimization Using Fuzzy-TOPSIS

In this paper, fuzzy coupled with TOPSIS is developed to compute the optimal process parameters for green EDM. The relative weights of the output parameters are assigned in terms of linguistic variables as shown in Table 3. The triangular fuzzy number is used to describe the linguistics variables. A committee with four experts is made to act as decision maker. Each decision maker rated each attribute weights with respect to linguistics variables, and aggregated fuzzy weights are tabulated in Table 4.

Thereafter, TOPSIS method is used for optimizing the process parameters. This method begins with normalized performance matrix. The normalized performance matrix is expressed using the following equation:

$$p_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \tag{1}$$

where x_{ij} represents the actual values of ith attributes with jth experimental run, p_{ij} represents the corresponding normalized performance values, and m indicates the

Table 3 Linguistic variables for each output criterion

Importance	Fuzzy weight
Extremely low (EL)	(0, 0, 0.1)
Very low (VL)	(0, 0.1, 0.3)
Low (L)	(0.1, 0.3, 0.5)
Medium (M)	(0.3, 0.5, 0.7)
High (H)	(0.5, 0.7, 0.9)
Very high (VH)	(0.7, 0.9, 1)
Extremely high (EH)	(0.9, 1, 1)

Table 4 Importance of output responses and Fuzzy weights

Output response	Decision maker				Fuzzy weights
	DM1	DM2	DM3	DM4	
MRR	H	H	VH	H	0.55, 0.75, 0.925
EWR	VL	L	L	VL	0.05, 0.2, 0.4
Ra	M	H	M	L	0.75, 0.925, 1

number of experimental runs. The normalized performance values are then multiplied with respective relative weights of each output parameter thus yielding the weighted normalized matrix N. The weighted normalized matrix is expressed as follows:

$$N_{ij} = p_{ij} \times w_j \quad j = 1, 2, \ldots n \;\; i = 1, 2, \ldots m \tag{2}$$

The ideal and nadir ideal solutions are determined using Eqs. (3) and (4), respectively:

$$N_j^+ = \left\{ \left(\underset{i}{\text{Max}} N_{ij} \middle| j \in K \right), \left(\underset{i}{\text{Min}} N_{ij} \middle| j \in K^1 \right) \right\} \tag{3}$$

$$N_j^- = \left\{ \left(\underset{i}{\text{Min}} N_{ij} \middle| j \in K \right), \left(\underset{i}{\text{Max}} N_{ij} \middle| j \in K^1 \right) \right\} \tag{4}$$

where K is the index set of benefit criteria and K^1 is the index set of non-benefit criteria.

The distances from the ideal and nadir solutions are measured. The two Euclidean distances for each alternative are determined as given in Eqs. (5) and (6), respectively:

$$V_i^+ = \left\{ \sum_{j=1}^{n} \left(N_{ij} - N_j^+ \right)^2 \right\}^{0.5} \quad j = 1, 2, \ldots n \quad i = 1, 2, \ldots m \tag{5}$$

$$V_i^- = \left\{ \sum_{j=1}^{n} \left(N_{ij} - N_j^- \right)^2 \right\}^{0.5} \quad j = 1, 2, \ldots n \quad i = 1, 2, \ldots m \tag{6}$$

The closeness coefficient to the ideal solution is calculated as shown in following equation

$$CC_i = \frac{V_i^-}{V_i^+ + V_i^+} \quad i = 1, 2, \ldots m \quad 0 \le CC_i \le 1 \tag{7}$$

The higher values of CC_i mean that the rank is better.

4 Results and Discussion

At first, closeness coefficient values for each of the experiments of the (L9) orthogonal array are calculated as discussed in the previous section (Table 5). The result reveals that experiment No. 2 yields the highest clones coefficient value. Therefore, the experiment No. 2 has the optimal machining parameters setting for the desirable output responses among the nine experiments.

Additionally, this research also analyzes the response of input parameters using the response table obtained from Taguchi method by calculating the average closeness coefficient for each level of the input parameter. The process consists of two major steps, as follows: (i) Group the closeness coefficient values by factor level for each column in the orthogonal array and (ii) average of closeness coefficient values. The mean closeness coefficient values for each of the process parameters are shown in Table 6.

The influence of each input parameters can be clearly presented by means of closeness coefficient graph. It shows that the change in the response when value of the parameters factor goes for their level 1–3. The response graph is shown in Fig. 2.

The higher closeness coefficient values show the optimum input parameters for the green EDM. The optimal comparability sequence is obtained as $A_1B_1C_3D_2$ and they are shown in Table 6. Therefore, the optimal parameters that minimize the manufacturing and environmental components are the A_1 (4.5 A), B_1 (30:70 μs), C_3

Table 5 Closeness coefficient values

Exp. No	A	B	C	D	Closeness coefficient (CC_i)	Rank
1	1	1	1	1	0.7225	3
2	1	2	2	2	0.9594	1
3	1	3	3	3	0.8548	2
4	2	1	2	3	0.6620	4
5	2	2	3	1	0.4903	6
6	2	3	1	2	0.5077	5
7	3	1	3	2	0.3443	7
8	3	2	1	3	0.2498	8
9	3	3	2	1	0.0434	9

Table 6 Response table of closeness coefficients

	Average closeness coefficients			Max–Min	Rank
Input parameters	Level 1	Level 2	Level 3		
A	**0.84557**	0.55333	0.21250	0.63307	1
B	**0.57627**	0.56650	0.46863	0.10763	3
C	0.49333	0.55493	**0.56313**	0.06980	4
D	0.41873	**0.60380**	0.58887	0.18507	2

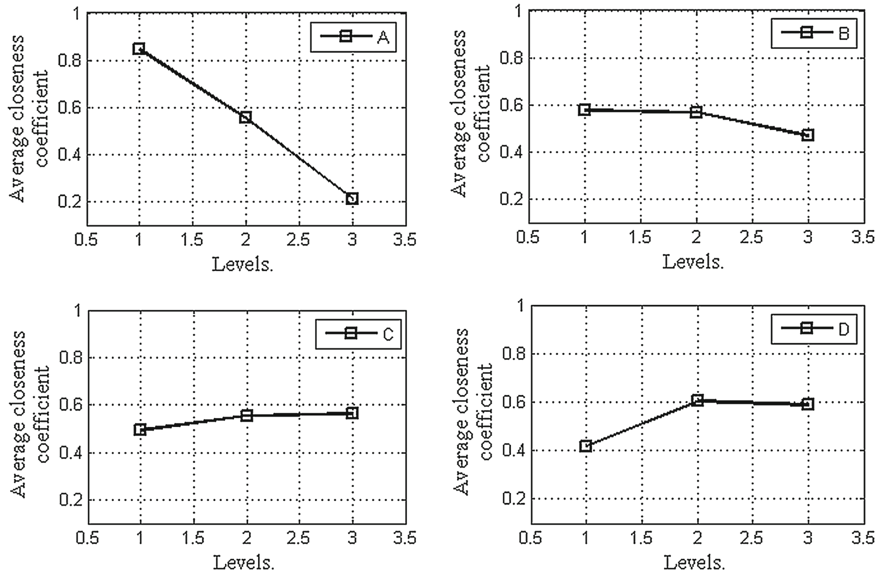
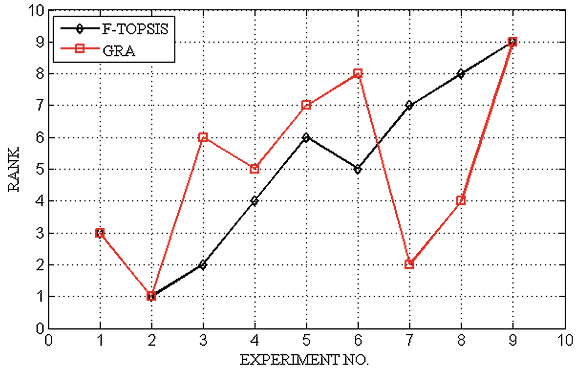


Fig. 2 Effects of process parameters on closeness coefficient

Fig. 3 Comparison of the results



(30 V), and D_4 (6 mm). The most significant factor is identified (Table 6) by determining the difference between the maximum and the minimum values of the closeness coefficient of the EDM parameters. The value indicated that discharge current (A) has strong effect on the output parameters. Finally, Fuzzy-TOPSIS result is compared with the results of GRA [50] model. The observed results are same for all the cases which are as shown in Fig. 3.

5 Conclusion

The present manufacturing industries is considered as one of the main sources of environmental pollution. How to minimize the environmental pollution is an important topic for the entire manufacturer. The novel Ti-6Al-4V with tap water is explored in this paper. The fuzzy-TOPSIS is used to optimize the process parameters and to improve the multiple performances of the EWR, MRR, and SR in the EDM. There are three conclusions gained as follows:

- The result shows that experiment No. 2 yields the highest closeness coefficient value. Therefore, experiment No. 2 has the optimal machining paramagnets setting for the desirable output responses among the nine experiments.
- The optimal parameters that minimize the manufacturing and environmental components are the A_1 (4.5 A), B_1 (30:70 μs), C_3 (30 V), and D_4 (6 mm). The most significant factor is identified by determining the difference between the maximum and the minimum values of the closeness coefficient of the EDM parameters. The value indicated that discharge current (A) has strong effect on the output parameters.
- The fuzzy-TOPSIS result is compared with the published results of GRA model and indicated that the proposed methodology is validated and it can be used for multi-objective parameters optimization in green electrical discharge machining Ti-6Al-4V alloy with tap water.

Using tap water machining, Ti-6Al-4V alloy has high MRR, has less environmental pollution, and the also decrease the machining cost.

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