Multi-objective Optimization of EDM Process on ZE41 Magnesium Alloy with Copper, Brass and EN8 Electrodes Using AHP-TOPSIS Method

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Abstract. ZE41 Magnesium (Mg) alloys are widely employed in the automotive and aerospace industries because of their advantageous qualities like lightest structural metal, corrosion resistant and better mechanical properties. Since it is highly cumbersome to machine this alloy of complex shapes using conventional machining processes, it can be machined by unconventional machining process i.e. EDM process. It employs electro-thermal energy to remove the material and there is no contact between material and electrode. In the present study, three electrodes such as copper, brass and EN8 were utilized because they have dominant effect on machining performance. An effort was made to carry out multi-objective optimization of various objectives viz. Metal removal rate, surface roughness and radial overcut considering the input parameters like type of electrode, peak current, pulse on time and pulse off time. Experiment were conducted based on Taguchi's L_{27} orthogonal array. Analytical hierarchy process coupled with TOPSIS is used for multi-objective optimization and derive better process parameters. The results indicated that the best solution obtained by proposed method corresponds to brass electrode, peak current of 18A, pulse on time of 100 (μs) and pulse of time of 100 (μs) and the worst solution corresponds to copper electrode, peak current of 6A, pulse on time of 500 (μs) and pulse of time of 100 (μs). The metal removal rate, surface roughness and radial overcut corresponding to best solution are 282.075mg/min, 6.031μm and 0.122mm respectively.

Keywords: Electrical discharge machining · Magnesium alloy ZE41 · AHP-TOPSIS method

1 Introduction

EDM is a novel method of machining that is widely utilized for intricate components and hard materials in a variety of sectors. It contains a conducting tool and a conductive work piece that are immersed in a dielectric medium. According on the characteristics of the work item, positive or negative polarity might be applied. A minuscule distance of about 50 micron separate them. When electric current is passed, it creates a succession of

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electrical sparks between the work piece and the electrode submerged in a liquid dielectric media, the EDM technique severely heats the work piece and erodes material from it. The material is melted and vaporized in this process, and is then expelled and washed away by the dielectric fluid. Thus the material removal takes place as long as electric current is passed for specific period of time [1]. Mg-alloys have been employed in military products ranging from ground vehicles to aircraft parts. The main factors influencing use were accessibility and light weighting of military technology [2]. However, traditional production procedures such as turning, drilling, milling, and so on produce built-up edges and chatter when cutting Mg alloys. While machining Mg alloys, extreme caution should be exercised because the formation of chips and dust is extremely combustible. In such cases, EDM can be used to machine complex parts made of magnesium alloys such as AZ21, AZ31, AZ91, and ZE41 [3]. Nyugoon et al. did parametric optimization on a variety of input factors like servo voltage, pulse on time, current, pulse off time and duty cycle. The work applied AHP-TOPSIS method for optimization and were of the opinion that this combined method can optimize a variety of unconventional manufacturing process parameters [1, 4]. Vasu et al. applied Taguchi- TOPSIS method for parametric optimization of micro EDM of titanium alloy with tungsten carbide. Their work evaluated output responses like machining depth, overcut and tool wear considering input process parameters such as voltage, capacitance and electrode rotational speed. And concluded that The optimal process parameters produced better surface finish and machining accuracy [5].

It is observed from literature that less work was done on optimization of EDM process on magnesium alloys. Hence, it is decided to perform multi-objective optimization of EDM process on specific magnesium alloy ZE41 using AHP-TOPSIS method.

2 Experimentation Details

2.1 Materials

Mg alloy ZE41 is selected as work piece material and purchased from the supplier Magnesium Elecktron Limited, Hyderabad, India. İt has the hardness of 55–70 BHN and density 1.84 g/cm^3. The work piece dimensions were cut to exact sizes 75 x 500 x 12 mm^3 and were polished and ground before conduction of experiments. The chemical composition of ZE-41 Mg alloy (%Wt.) is: Ce/Tr-50.4, Cu- $>$ 0.005, Fe-0.003, Mn-0.02, Ni- $<$ 0.0005, Si- $<$ 0.005, Tr-1.2, Zn-4.2, Zr-0.54, Oe- $<$ 0.050, To- $<$ 0.05 Mg-Balance [7]. Different electrodes provide different machining performance due to different properties and proper selection of electrodes for EDM is very important. In the present study, electrode materials like copper, brass and EN8 were considered as they are frequently used in industries due to economy. All three electrodes with diameter 12 mm are employed in experimentation.

2.2 Design of Experiments and EDM Process Parameter Levels

Taguchi method is a very simple statistical technique, economical and allows less number of experiments to be carried out instead of full factorial experiments. Based on pilot

Table 1. Levels of process parameters

Process Parameters	Symbol	1	2	3
Electrode type	A	Cu	Br	EN-8
Current (Amp)	B	6	12	18
Ton (μs)	C	100	200	500
Toff (μs)	D	20	50	100

experimentation, the operating ranges of peak current, pulse on time, and pulse off time were selected. Further, the levels of parameters were selected by examining the surface damage caused on the work piece and specifications of the EDM machine. The levels of process parameters are shown in Table 1. An L_{27} (3^4) orthogonal array was selected to accommodate four input parameters and is shown in Table 2.

2.3 Conduction of Experiments and Measurement of MRR, SR and ROC

Experiments were performed on die-sink EDM machine (Make: ASKAR, Model: V3525) at constant voltage of 30V. Experiments were conducted randomly according to L_{27} orthogonal array. Each experiment was repeated twice for four minutes each. The weights of machined specimen and electrode were measured with digital weighing balance (Mitutoyo, Japan) with capacity of 200 gm and an accuracy 0.1mg. For measurement of metal removal rate (MRR), weight difference between the work piece plate and electrode tool before and after machining was divided by machining time. The surface roughness tester (Mitutoyo, Japan) was used to measure the SR of machined surfaces using center line technique and cut-off length of 0.8mm. The average of five readings (Ra values) was considered for the measurement of SR. The ROC values were computed using optical microscope with image analysis software (Make- Olympus stream basic, Japan). The radial overcut was calculated as half the difference of the diameter of the hole (D_O) produced on the surface and the tool diameter (Di) as shown in Eq. (1). The average values of output responses were used for analysis.

$$ROC = \frac{D_0 - D_i}{2} \tag{1}$$

3 Multi-objective Optimization of MRR, SR and ROC

The machining performance generally involves higher productivity, surface quality and accuracy of the component/product/process are very important simultaneously and influenced by many input process parameters. EDM is one such a process which is stochastic in nature and has dominant process parameters and many output responses. Hence, multi-objective optimization approaches have become increasingly popular in various fields over the past several years. Among them, AHP and TOPSIS are two popular, adequately accurate [1, 4] and same are used for multi-objective optimization of MRR, SR & ROC in present study.

Table 2. Experimental results of MRR, SR and ROC

Expt. No	A	B	C	D	MRR (mg/min)	SR (um)	ROC (mm)
1	Cu	6	100	20	16.7000	3.4663	0.4565
2	Cu	6	200	50	18.4000	4.0620	0.4650
3	Cu	6	500	100	25.8750	4.3707	0.5150
4	Cu	12	100	50	55.2750	4.2660	0.5253
5	Cu	12	200	100	121.0500	6.1323	0.5253
6	Cu	12	500	20	82.8750	5.5413	0.5650
7	Cu	18	100	100	179.3750	5.7823	0.6553
8	Cu	18	200	20	232.8250	5.5460	0.6173
9	Br	18	500	50	196.1000	5.7867	0.6605
10	Br	6	100	20	28.5000	3.4267	0.1075
11	Br	6	200	50	41.6500	3.5007	0.1180
12	Br	6	500	100	32.9250	3.9140	0.1602
13	Br	12	100	50	176.9750	4.3797	0.4778
14	Br	12	200	100	163.8500	5.9473	0.2538
15	Br	12	500	20	129.7250	5.7230	0.2128
16	Br	18	100	100	282.0750	6.0317	0.1220
17	Br	18	200	20	262.8000	5.7367	0.3408
18	Br	18	500	50	243.0750	5.0570	0.4790
19	EN-8	6	100	20	13.3500	4.0990	0.3093
20	EN-8	6	200	50	35.7750	3.2333	0.4563
21	EN-8	6	500	100	25.3500	3.7610	0.3430
22	EN-8	12	100	50	95.1500	5.3180	0.4715
23	EN-8	12	200	100	116.0100	5.1907	0.5020
24	EN-8	12	500	20	66.6250	3.2613	0.5675
25	EN-8	18	100	100	183.1500	5.1413	0.4850
26	EN-8	18	200	20	72.6250	4.7140	0.5802
27	EN-8	18	500	50	77.4250	4.7607	0.7518

3.1 AHP Method for Calculation of Weights

In this, a decision making problem is decomposed into a system of hierarchies of objectives or alternatives. The greatest advantage of AHP is that it calculates the weight of each output response with the choice of decision maker and the ease with which it handles multi-objectives. In AHP, Saaty's nine-point preference scale is utilized as shown in Table 4. The calculation of weight in AHP has following steps [6, 8],

Step 1: Formulation of Hierarchal structure.

Step 2: Construction of pair wise comparison matrix by considering relative importance of different responses with respect to the goal or priority according to Satty's nine-point scale. The same is depicted in the Table 3.

Step 3: Measurement of weights of responses using Eq. (2) & shown in Table 4.

$$\omega = \frac{\left\{\prod_{j=1}^{N} C_{ij}\right\}^{\frac{1}{N}}}{\sum_{i=1}^{N}\left\{\prod_{j=1}^{N} C_{ij}\right\}^{\frac{1}{N}}}, \mathrm{i} = 1, 2, \ldots\ldots\ldots\mathrm{N} \quad (2)$$

Step 4: Consistency ratio (CR) is measured to find out the variation in responses and is given by Eq. (3),

$$\mathrm{CR} = \frac{CI}{RI} \quad (3)$$

Here, RI is the random consistency index and its value depends upon the number of responses considered. CI is consistency index and is given by following Eq. (4).

$$\mathrm{CI} = \frac{\lambda_{max} - N}{N - 1} \quad (4)$$

Here, λ_{max} can be determined by taking the average of ratios between sum value and criteria weights. If the final value of CR exceeds the maximum received limit of 0.1, the procedure must be repeated in order to achieve better consistency. Here, assessment of λ_{max} is 3.068 and ratio of consistency CR = 0.059. CR should be less than 0.1 and found satisfactory.

4 TOPSIS Method

TOPSIS is a multi-objective decision making process and uses relative distance measurements between a decision-making alternative and the ideal solution to evaluate the alternatives. It provides a simple and practical way to evaluate complex decisions by ranking the alternatives based on similarity to the ideal solution. It has following steps,

STEP-1: Normalization of the data and calculation of normalized matrix. The data is normalized by following Eq. (5) and shown in Tables 4 and 5. Here, X_{ij} is the result of i^{th} experiment for j^{th} performance.

$$\overline{x_{ij}} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{n} X_{ij}^2}} \quad (5)$$

STEP-2: Determination of weighted normalized matrix by multiplying each column of the normalized matrix with corresponding criteria weight. The normalized matrix is shown in Table 6.

STEP-3: Calculation of the ideal worst and best values. Higher MRR and lower SR and ROC are desirable. Therefore, for MRR, the highest value of all $\mathrm{V_j}$ values is taken

Table 3. Saaty's 9-point scale of relative importance

Scale	Definition	Explanation
1	Equally Important	Indifferent
3	Weakly Important	Slightly better
5	Strongly Important	Better
7	Very Strongly Important	Much better
9	Extremely Important	Definitely much better
2,4,6,8	Intermediate value	When compromise needed

as the ideal best and the lowest as the ideal worst. The highest value of V_j is treated as the ideal worst for both ROC and SR, while the lowest value of V_j is treated as the ideal best. The ideal best solution (V_j^+) and the ideal worst solution (V_j^-) for each response are measured using Eqs. (6) and (7),

$$V_j^+ = \left\{ \sum_{i=1}^{max} V_{ij}/j \in J, \sum_{i=1}^{min} V_{ij}/j \in J^1 \right\} \quad (6)$$

$$V_j^- = \left\{ \sum_{i=1}^{min} V_{ij}/j \in J, \sum_{i=1}^{max} V_{ij}/j \in J^l \right\} \quad (7)$$

STEP 4: Calculation of Euclidean distances (Si^+ and Si^-) from ideal best and worst. They are calculated by using the Eq. (8) and (9) respectively,

$$S_i^+ = \left[\sum_{j=1}^{m} \left(V_{ij} - V_j^+ \right)^2 \right]^{0.5} \quad (8)$$

$$S_i^- = \left[\sum_{j=1}^{m} \left(V_{ij} - V_j^- \right)^2 \right]^{0.5} \quad (9)$$

Ideal best and ideal worst solutions are shown Table 7.

Step 5: Calculation of the performance score. It can be computed using the Eq. (10) and are depicted in Table 7.

$$P_i = \frac{S_i^-}{S_i^+ + S_i^-} \quad (10)$$

5 Conclusions

In the present study, an effort was made to carry out multi-objective optimization of EDM process parameters on machining ZE41 magnesium alloy using combined AHP-TOPSIS method. Type of electrode, peak current, pulse on time and pulse off time were considered

Table 4. Pair wise comparison matrix and normalized pairwise matrix

	Pair wise comparison matrix			Normalized pair wise matrix			
	MRR	SR	ROC	MRR	SR	ROC	Weights
MRR	1	3	2	0.55	0.64	0.44	0.54
SR	1/3	1	3/2	0.18	0.21	0.33	0.24
ROC	½	2/3	1	0.27	0.14	0.22	0.21
SUM	1.83	4.66	4.5				

Table 5. Consistency matrix

	0.54	0.24	0.21	Weight sum value	WSM/W
	MRR	SR	ROC		
MRR	0.54	0.72	0.42	1.68	3.111
SR	0.18	0.24	0.32	0.73	3.05
ROC	0.27	0.158	0.21	0.64	3.04

as process parameters to optimize MRR, SR and ROC. Taguchi's L_{27} orthogonal array was utilized to conduct experiments on ZE41 magnesium alloy with three electrodes i.e. copper, brass and EN-8. The results indicate that that the relative closeness is maximum i.e. ideal best solution at experiment No.16 with brass electrode, current of 18A, pulse on time of 100 µs and pulse of time of 100 µs. The relative closeness is minimum i.e. ideal worst solution for experiment No. 3 with copper electrode, current of 6A, pulse on time of 500 µs and pulse of time of 100 µs. Experiment No. 16 is repeated twice to confirm the results and found to be satisfactory.

Table 6. Normalized matrix

Expt. No.	MRR	SR	RO
1	0.023	0.138	0.188
2	0.026	0.162	0.191
3	0.036	0.174	0.212
4	0.077	0.17	0.216
5	0.169	0.244	0.216
6	0.116	0.22	0.232
7	0.251	0.23	0.269
8	0.326	0.221	0.254
9	0.274	0.23	0.272
10	0.04	0.136	0.044
11	0.058	0.139	0.049
12	0.046	0.156	0.066
13	0.248	0.174	0.196
14	0.229	0.237	0.104
15	0.181	0.228	0.088
16	0.395	0.24	0.05
17	0.368	0.228	0.14
18	0.34	0.201	0.197
19	0.019	0.163	0.127
20	0.05	0.129	0.188
21	0.035	0.15	0.141
22	0.133	0.212	0.194
23	0.162	0.206	0.206
24	0.093	0.13	0.233
25	0.256	0.205	0.199
26	0.102	0.188	0.239
27	0.108	0.189	0.309

Table 7. Normalized decision matrix

Expt. No.	MRR	SR	ROC	Si+	Si−	Pi	Ranking
1	0.013	0.033	0.039	0.2172	0.0365	0.1439	25
2	0.014	0.039	0.04	0.2188	0.0323	0.1285	26
3	0.02	0.042	0.044	0.2283	0.0285	0.1109	**27***
4	0.042	0.041	0.045	0.2225	0.0416	0.1574	24
5	0.091	0.059	0.045	0.2086	0.0838	0.2866	14
6	0.063	0.053	0.049	0.2248	0.0554	0.1976	17
7	0.136	0.055	0.057	0.2268	0.1259	0.3569	12
8	0.176	0.053	0.053	0.2145	0.1664	0.4369	8
9	0.148	0.055	0.057	0.2260	0.1384	0.3798	11
10	0.022	0.033	0.009	0.0711	0.0627	0.4686	5
11	0.031	0.033	0.01	0.0787	0.0642	0.4492	7
12	0.025	0.037	0.014	0.1112	0.0575	0.3409	13
13	0.134	0.042	0.041	0.1885	0.1271	0.4028	10
14	0.124	0.057	0.022	0.1262	0.1217	0.4910	3
15	0.098	0.055	0.018	0.1151	0.0997	0.4640	6
16	0.213	0.058	0.011	0.0501	0.2103	0.8077	**1***
17	0.199	0.055	0.029	0.1468	0.1919	0.5666	2
18	0.184	0.048	0.041	0.1836	0.1756	0.4889	4
19	0.01	0.039	0.027	0.1777	0.0431	0.1954	18
20	0.027	0.031	0.039	0.2115	0.0417	0.1646	22
21	0.019	0.036	0.03	0.1843	0.0432	0.1900	19
22	0.072	0.051	0.041	0.2009	0.0670	0.2500	16
23	0.088	0.05	0.043	0.2038	0.0812	0.2848	15
24	0.05	0.031	0.049	0.2287	0.0516	0.1840	20
25	0.138	0.049	0.042	0.1897	0.1308	0.4081	9
26	0.055	0.045	0.05	0.2302	0.0493	0.1764	21
27	0.058	0.045	0.065	0.2625	0.0503	0.1610	23
Vj+	0.213	0.031	0.009				
Vj−	0.01	0.059	0.065				

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