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Multi-Criteria Decision of W-Powder Mixed Electro Discharge Drilling Parameters using TOPSIS Approach

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1. Introduction

With the increase of industrial and technological advancements in the domain of manufacturing and material science, every industry needs unconventional machining in all their applications. Among various Unconventional Manufacturing Processes, Electro Discharge Drilling (EDD) has drawn more attention in a wide spectrum of precision manufacturing sectors due to its ability for making fine holes in difficult to cut materials.

Electric Discharge Machining (EDM) drilling on Inconel 718 (INC718) superalloy is widely used in aircraft, liquid-fueled rockets, reciprocating engines, and cryogenic tank fasteners, etc. The major drawback of the traditional EDD process is low Material Removal Rate (MRR) and poor Surface Quality (SQ) which confine its applications in manufacturing sectors. Several research efforts have been made to find solutions to overcome these issues and improve process performance. In order to enhance the process performance, appropriate abrasive particles in powder form are impregnated with the dielectric medium. This hybrid method is called Powder-Mixed Electrical Discharge Machining (PMEDM) [1]. PMEDM is the recent development of EDM in which fine powders are mixed with the dielectric medium to improve its breakdown attributes. As the insulating strength of the dielectric decreases, the discharge distance between the tool and workpiece increases hence making flushing of debris even. Uniformity in flushing results in the enhancement of MRR and SQ.

However, at high concentration machining becomes unstable, which attributed to the frequent shorting of the electrode. Jeswani [2] explored the effects of addition of Graphite powder to kerosene and claimed that the MRR was increased about 60% and Tool Wear Rate (TWR) was decreased around 15% using the kerosene with 4 g/l Graphite (Gr) powder concentration. Wong et al. [3] investigated the near-mirror-finish phenomenon in machining of SKH-51 when Aluminium powder was added into the insulating medium at a concentration of 2 g/l.

In order to improve the performance of the EDD process, several researchers considered the optimization of the input variables as a single objective optimization problem. But in reality, the single objective optimization process does not help the purpose of enhancing performance and reduction of cost. Therefore, it is imperative to optimize all the objective functions concurrently. Among all the multi-objective optimization method, Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is found to be more efficient in solving Multi-Criteria Decision Making (MCDM) problems because it offers a simple computational technique, less computational time, and values are close to the ideal solution. TOPSIS is a method to estimate the performance of alternatives through the similarity with the ideal solution [4]. TOPSIS has been widely implemented in the manufacturing sectors for multi-criteria selection [5]. In composite product development, ideal subsystem selection was achieved using TOPSIS technique [6]. Thirumalai & Senthilkumaar [7] identified the best machining factors by means of combined TOPSIS and Analytical Hierarchy Process (AHP) approach in the machining of the INC718 alloy while turning of Titanium alloy [8]. Singaravel & Selvaraj [9] developed a multi-objective optimization approach based on TOPSIS and AHP methods to determine the simultaneous minimization of Microhardness, Surface Roughness (SR) while turning EN25 steel with coated carbide tools. A Taguchi based Orthogonal Array(OA) was utilized with the TOPSIS method for optimizing the process parameters of cryogenic cooling of micro EDM drilling (CμEDM) process on AISI 304 stainless steel [10]. Yuvaraj & Pradeep Kumar [11] optimized the process parameters during Abrasive Water Jet (AWJ) process with multi-response characteristics based on MCDM using the TOPSIS approach.

From the literature survey, it is observed that the Multi-attribute decision-making techniques like TOPSIS have not been implemented to find the optimal setting during Tungsten powder mixed drilling (W-PEDD) of INC718 alloy. An attempt to find out the best possible set of process variables through multi-objective optimization using TOPSIS to obtain maximum MRR and minimum SR using Tungsten powder mixed to the dielectric fluid has been made.

2. Materials and methods

INC718 superalloy was selected as machining material. It is a high strength temperature resistant (HSTR) Nickel-based superalloy and the exact chemical composition of INC718 superalloy is 54.04% Ni, 19.90 % Cr, 15.23% Fe, 5.12% Nb, 3.08% Mo, 0.88% Al, 0.75% Ti, 0.29% Mn, 0.24% Cu, 0.18% Si, 0.10% Co, 0.09 W, 0.06% V, 0.03% C, 0.01% P, 0.002% S.

Single channel hollow tubular copper electrodes having an external diameter of 12 mm and an internal diameter of 9 mm (with 99.9% purity) are employed as electrodes. Kerosene has been used as a dielectric for fine and medium fine machining. The powder material selected for this research was Tungsten (W). W-powder with the size of 4 microns is blended with kerosene in a concentration of

3g/l.

The literature review suggests that several process parameters greatly affect the response of the machining process. For the initial stage of the preliminary study, three important controllable parameters (i.e. I_p, T_{on}, and T_{off}) selected as input parameters and are given in Table 1.

Table 1

W-PEDD Process parameters and their levels

Sl. No.	Input variable	Levels		
1	Peak current (Amp)	10	12.5	15
2	Pulse-on time (μs)	500	1000	1500
3	Pulse-off time (μs)	200	500	800

In this study, MRR and SR were identified as the output responses and the MRR was calculated by equation (1). SR is an important performance measure for drilling processes which influence the product quality and cost.

$$\mathrm{MRR}(g./\min) = \frac{\text{Mass of workpiece removed}}{\text{Time of machining}}. \quad (1)$$

In the W-Powder mixed EDD (W-PEDD) process, experiments were carried out ELEKTRA M100 die sinking EDM in the presence of a Tungsten powder mixed kerosene dielectric medium. A specially designed tank was fabricated using 3mm mild steel sheet of size 330 mm length x 180 mm breadth x 187 mm height. The capacity of this small container is approximately 9 liters after deducting the volume of the fixture and other accessories. A motorized stirrer rotating at 1400 RPM was provided for the blending of powder particles. The W-PEDD process setup is shown in Fig. 1.

Fig. 1 Experimental setup

The Response Surface Methodology (RSM) based Central Composite Design with L_{20} Orthogonal Array (OA) was selected as the most suitable OA for the experimentation. The influence of input parameters on response variables like MRR and SR was examined. The average calculated MRR and SR for all the 20 experiments are given in Table 2.

Table 2

Experimental results

Run	I_p, Amp	T_{on}, μs	T_{off}, μs	Avg. MRR, g/min.	Avg. SR, μm
1	10	500	200	0.164	3.578
2	15	500	200	0.209	4.358
3	10	1500	200	0.289	4.429
4	15	1500	200	0.333	3.411
5	10	500	800	0.361	3.543
6	15	500	800	0.285	5.547
7	10	1500	800	0.247	3.432
8	15	1500	800	0.270	3.462
9	10	1000	500	0.244	5.823
10	15	1000	500	0.238	5.595
11	10	1000	800	0.247	4.138
12	12.5	500	200	0.269	3.688
13	12.5	1000	200	0.256	4.715
14	12.5	1500	200	0.278	4.787
15	12.5	500	500	0.246	5.123
16	12.5	1000	500	0.251	5.135
17	12.5	1500	500	0.244	5.153
18	12.5	500	800	0.248	5.099
19	12.5	1000	800	0.245	5.113
20	12.5	1500	800	0.248	5.037

3. Technique for order of preference by similarity to ideal solution (TOPSIS)

After finding the significant impact of input factors on process performance, an attempt was made to select the optimum parameters. Single objective optimization techniques often generate conflicts, when more than one response needs to be optimized concurrently. To minimize SR and to maximize MRR concurrently, multi-objective optimization method should be adopted. This research implements Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) Method to optimize the various input factors of the drilling process for INC718 alloy.

TOPSIS is one of multi-criteria decision-making techniques which is based on the concept that the selected solution is the nearest to the positive ideal (best) solution and the farthest from the negative ideal (worst) solution. The best solution is a hypothetical solution for which all attribute values correspond to the maximum attribute values in the database encompassing the satisfying solutions, the worst solution is the hypothetical solution for which all attribute values correspond to the minimum attribute values in the database. TOPSIS thus provides a solution that is not only nearest to the best, but also the farthest from the worst. In order to optimize the parameters, the TOPSIS was applied individually or three experimental runs and a comparison were made between them at the end. The optimization procedure includes the following steps:

Step 1: First step in TOPSIS method is to construct the decision matrix using the Eq. (2):

$$D_{20}\ x3 = [x_{ij}], \quad (2)$$

where: x_{ij} is the actual value of a j^{th} attribute of the i^{th} trial.

Step 2: Normalizing the decision matrix using the following Eq. (3):

$$R_{ij} = x_{ij} / \sum x_{ij}{}^2 \quad \text{for } i = 1, 2 \ldots m; \quad j = 1, 2 \ldots . n, \quad (3)$$

where: R_{ij} represents the corresponding normalized value.

Step 3: Constructing the weighted normalized matrix. The weights considered for this study were: MRR=0.50, SR=0.50. The weighted normalized decision matrix can be computed by multiplying the weights W_j of evaluated criteria with the values of normalized decision matrix R_{ij} as given in the Eq. (4) and presented in Table 3.

$$V_{ij} = W_j\ R_{ij}. \tag{4}$$

Table 3

Normalized and weighted normalized matrix

Run	Normalized matrix		Weighted normalized matrix	
	MRR, g/min	SR, µm	MRR, g/min	SR, µm
1	0.140063	0.172974	0.070031	0.086487
2	0.178573	0.210679	0.089286	0.105340
3	0.247035	0.214111	0.123517	0.107056
4	0.284689	0.164902	0.142345	0.082451
5	0.308651	0.171282	0.154326	0.085641
6	0.243612	0.268155	0.121806	0.134077
7	0.211092	0.165917	0.105546	0.082958
8	0.230775	0.167367	0.115388	0.083683
9	0.208525	0.281496	0.104262	0.140748
10	0.203390	0.270475	0.101695	0.135237
11	0.211092	0.200044	0.105546	0.100022
12	0.229919	0.178292	0.114960	0.089146
13	0.218794	0.227936	0.109397	0.113968
14	0.237621	0.231417	0.118811	0.115708
15	0.210236	0.247659	0.105118	0.123829
16	0.214515	0.248239	0.107258	0.124119
17	0.208525	0.249109	0.104262	0.124554
18	0.211948	0.246498	0.105974	0.123249
19	0.209381	0.247175	0.104690	0.123588
20	0.211948	0.243501	0.105974	0.121751

Step 4: Determination of Positive Ideal Solution (PIS) and Negative Ideal Solution (NIS) solution. The best and the worst solution are given by Eq. (5):

$$A^+ = \{V_1^+,...,V_n^+\}\ \&\ A^- = \{V_1^-,...,V_n^-\}. \tag{5}$$

Step 5: Computation of distance and the separation of each alternative from PIS and NIS are given by Eqs. (6), and is presented in Table 4:

$$S_i^+ = \left[\sum_{i=1,...m}\left(V_i^+ - V_{ij}^{\ 2}\right)\right]^{1/2}\ \&\ S_i^- = \left[\sum_{i=1,...m}\left(V_i^- - V_{ij}^{\ 2}\right)\right]^{1/2}. \tag{6}$$

Step 6: Estimation of Closeness Coefficient Index (CCI) which represents the relative closeness of a specific alternative is calculated by Eq. (7):

$$P_i = S_i^- / (S_i^+ + S_i^-);\ 0 < P_i < 1. \tag{7}$$

Step 7: Ranking the alternatives. The different alternatives are ranked according to the highest closeness coefficient index as shown in Table 4.

Table 4

Relative closeness value

Run	Separation measure		Relative Closeness	Order
	S^+	S^-		
1	0.084295	0.054261	0.391618	14
2	0.067717	0.040305	0.373121	18
3	0.037044	0.063214	0.630515	5
4	0.012643	0.092886	0.880195	2
5	0.000846	0.100709	0.991672	1
6	0.057640	0.052203	0.475250	9
7	0.048907	0.067830	0.581049	6
8	0.039039	0.072894	0.651229	3
9	0.073828	0.034231	0.316782	19
10	0.071740	0.032140	0.309396	20
11	0.050623	0.054036	0.516307	8
12	0.039456	0.068421	0.634249	4
13	0.052667	0.047612	0.474793	10
14	0.045992	0.054831	0.543837	7
15	0.061773	0.038953	0.386725	15
16	0.060263	0.040772	0.403542	12
17	0.062893	0.037869	0.375824	17
18	0.060740	0.039976	0.396919	13
19	0.061969	0.038675	0.384275	16
20	0.059845	0.040655	0.404524	11

4. Results and discussion

From Table 2, it was observed that the MRR was in the range from 0.164 to 0.361 g/min. In particular, Experiment number 5 with a set of input factors (I_p =10 Amp, T_{on} = 500 µs, T_{off} =800 µs) had produced the maximum MRR (0.361 g/min) due to high current and a medium level of T_{on}. It is expected that more discharge energy available at higher current for a longer duration will result in, more melting and vaporization of material. The minimum MRR (0.164 g/min) was observed in Experiment number 1 (I_p =10 Amp, T_{on} = 500 µs, T_{off} =200 µs) due to an insufficient amount of peak current and low pulse-on time. The measured SR was in the range of 3.411 to 5.823 µm. Higher I_p and higher T_{on} would increase the SR as in experiment number 9 (I_p =10 Amp, T_{on} = 1000 µs, T_{off} =500 µs).

From Table 4, it is clear that Experiment Number 5 provides the best multi-response characteristics as it represented the maximum CCI (0.992) and the optimal values are shown in Table 5.

Table 5

Optimal values of the input process parameters

Run	I_p, Amp	T_{on}, µs	T_{off}, µs	MRR, g/min.	SR, µm
5	10	500	800	0.362	3.543

After determining the optimum conditions and predicting the response under these conditions, a new experiment was conducted at the optimum levels of the machining parameters. Validation of the test results at the selected optimum conditions for MRR and SR when W powder was added into the dielectric fluid is shown in Table 6 and it can be observed that the calculated error is small. The error between experimental and predicted values for MRR and SR is 3.83% and 3.70%, respectively, which lie within the permissible limit (±10%). Obviously, this confirms excellent reproducibility of the experimental conclusions.

Table 6

Validation test results of W-PEDD

Run	I_p, A	T_{on}, μs	T_{off}, μs	MRR, g/min.			SR, μm		
				Pred	Act	% Error	Pred.	Act	% Error
5	10	500	800	0.36	0.37	3.83	3.54	3.41	3.70

To determine the effect of powder addition, experiment without powder was also performed at their optimal parametric settings (experiment no.5) without adding powder particles into the dielectric fluid. The data from the verification experiment is shown in Table 7.

Table 7

Verification test results without W-powder

Run	I_p, Amp	T_{on}, μs	T_{off}, μs	MRR, g/min.	SR, μm
5	10	500	800	0.164	5.823

From the validation and experimental results for exp. no. 5 presented in the Tables 6 and 7, it is observed that the W-PEDD process produces higher MRR and surface quality than conventional EDD process without adding powder particles into the dielectric medium.

5. Microstructure analysis

The micro-structural study of the drilled workpiece was carried out using a Scanning Electron Microscopy (SEM) analyzer. Micrograph in Fig. 2 shows the surface of the INC718 alloy which was drilled at I_p = 10 Amp, T_{on} = 500 μs and T_{off} = 800 μs using hollow tubular Cu electrode without adding W-powder. Drilling at high current I_p (10 Amp) produced deeper and larger craters on the surface because of high spark energy. This leads to an increase in MRR and reduced the surface quality and tool life. It was found that some part of the melted material was flushed out by the insulating liquid and the residual molten material re-solidified to form lumps of debris on the workpiece material. The rate of cracking of carbon from insulating liquid also increased which deposited on the surface (i.e. recast layer). The broader crack was found at T_{on} = =500 μs because spark energy was delivered for a longer time. Lumps of debris can be clearly realized for longer pulse off time (T_{off} = 800).

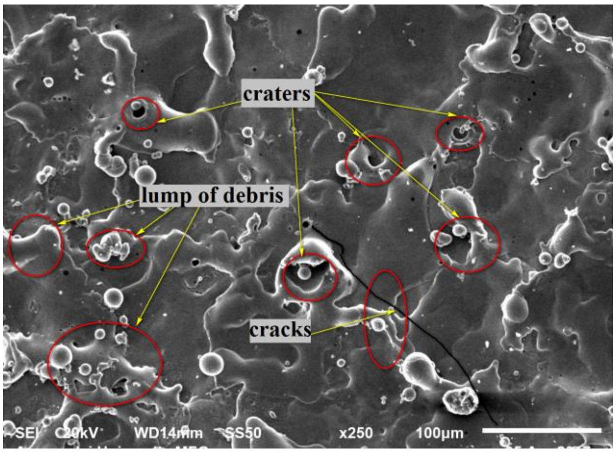

Fig. 2 SEM image of the workpiece without powder addition

Scanning Electron Microscope (SEM) analysis of machined surfaces has been studied for the addition of W powder is shown in Fig. 3. It can be observed that the W-powder suspended in dielectric produces the smooth surface. Traces of white oxide can also be observed due to the oxidation of W-powder in the insulating fluid. Due to low thermal energy, a small amount of cracked carbon from insulating fluid was transmitted to the surface. This causes deposition of carbon on the surface either in free or compound form. Deposition of suspended powder particles and decomposed carbon elements were observed on the machined specimens resulting in the formation of various compounds that significantly increase the surface smoothness.

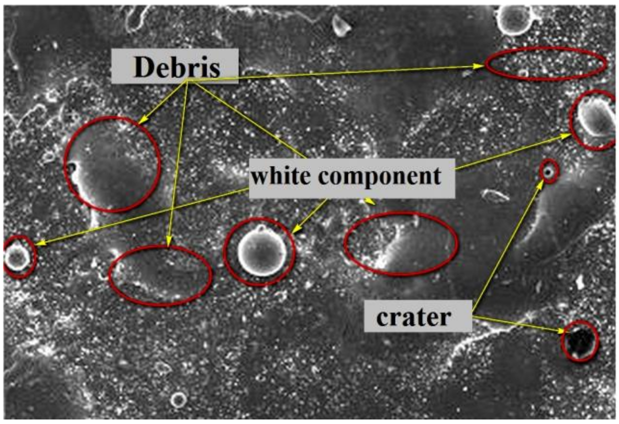

Fig. 3 SEM image of the workpiece with W-powder addition

6. Conclusions

This research implements TOPSIS method to optimize the various input factors of the drilling process on INC718 alloy using single channel hollow tubular Copper electrode under W-powder mixed in Kerosene dielectric. Through the TOPSIS optimization technique, it is recommended to use W-PEDD for obtaining better MRR and Surface Quality.

1. When 4 gm/l of W-powder is added the MRR value ranges from 0.164 g/min to 0.361 g/min and the SR value ranges from 3.411 μm to 5.823 μm.
2. Among the 20 trials, Experiment No. 5 is exhibited the best performance feature as it represents the maximum closeness coefficient value of 0.9916. Hence the optimal setting of process parameters is identified as I_p = =10 Amp, T_{on} = 500 μs and T_{off} = 800 by TOPSIS.
3. From the validation test, it is observed that the MRR is increased from 0.135 to 0.376 g/min, whereas SR is reduced from 7.885 to 3.412 μm for experiment no. 5 under with and without the addition of W powder. Confirmatory tests reveal that the improvement of preference values in the experimental and initial setting using TOPSIS, W-PEDD produces the greatest MRR and smooth surface than without addition of powder particles into the dielectric because spark efficiency during the W-PEDD process is improved.
4. From SEM analysis it can be observed that there are some surface defects such as cracks, craters, lumps of debris are presented during drilling on INC718 without adding the W-powder. But in the case of W-PEDD, less number of plucked materials, cracks, crates,

and elongated debris are found during the addition of W-powder mixed in a dielectric fluid. Hence the W-PEDD produces better surface finish than conventional EDD process.

5. The outcome of the present work will be a considerable aid to the industries for quality improvement in the drilling of INC718 superalloy using W-PEDD.

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MULTI-CRITERIA DECISION OF W-POWDER MIXED ELECTRO DISCHARGE DRILLING PARAMETERS USING TOPSIS APPROACH

S u m m a r y

In this study, Central Composite Design method in combination with Technique for Order of Preference by Similarity to the Ideal Solution has been implemented to estimate the efficiency of multi-objective characteristics for Electrical Discharge Drilling of Inconel 718 using hollow tubular copper electrode. The influence of input process variables such as peak current, pulse-on time and pulse-off time on Material Removal Rate and Surface Roughness have been investigated when Tungsten powder is mixed to the dielectric. Confirmatory test was conducted to verify the predicted results and it showed an improvement of 0.376 g/min and 3.412 using TOPSIS. The suggested settings of process parameters are found to be I_p =10 Amp, T_{on} = 500 μs and T_{off} = 800 from TOPSIS. The drilled surface properties were analyzed by Scanning Electron Microscope and it is observed that that good surface finish was obtained by W-PEDD rather than without the addition of powder to the dielectric fluid.

Keywords: Electrical Discharge Drilling, Inconel 718, TOPSIS, Analysis of variance, Scanning Electron Microscope.

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