A Perceptive Approach for Multi-objective Optimization of Die-Sinking EDM Process Parameters with Utility Concept and Taguchi Method for Sustainable Machining

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Abstract The present work attempts to assess the best parametric combination that satisfies multiple objectives of minimization of tool wear and surface roughness and maximization of material removal in electric discharge machining (EDM) of D2 steel. The study specifically focuses on influence of tool electrode material on machining performance. An electrode prepared by direct metal laser sintering (DMLS) has been chosen along with conventional electrodes like copper and brass to assess the feasibility of substituting the conventional electrodes with DMLS electrode which is a novel method. Very few attempts are being made to compare the performance of conventional electrodes with the electrodes prepared by non-conventional method. The study makes use of utility concept-based Taguchi method. Utility concept first finds out the overall utility index (OUI) which is a representative index of all the objectives considered in the study, and then, the problem can easily be solved by Taguchi method.

Keywords Multi-objective optimization · Overall utility index · Die-sinking EDM · Taguchi method

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1 Introduction

Electrical discharge machining (EDM) is a non-traditional machining process employed to remove material from any electrically conductive difficult-to-machine materials by the use of thermal energy. It can create any intricate shape irrespective of hardness of the materials. A sequence of spark generated between the tool and work helps in removing material. Simultaneous optimizations of vital performance measures like material removal rate (MRR), tool wear rate (TWR), and surface roughness (R_a) are extremely important to make the machined parts suitable for desired applications. One of the major objectives of a manufacturing engineer is to decrease the cost of tooling and time for product development for any manufacturing operation. In order to achieve both the objectives in EDM process, rapid prototyping (RP) technology may be explored to manufacture tool electrode. Arthur et al. [1] have employed thin metal coating on stereolithography (SL) models to machine-hardened tool steel. Those electrodes found to be useful in both semi-roughing and finishing operations in EDM. Rennie et al. [2] have manufactured EDM electrodes of complex geometry by employing electroforming on a die built through rapid prototyping process and found its performance comparable with the conventional copper electrode. Durr et al. [3] have manufactured simple cylindrical metal electrodes using nickel, bronze, and copper phosphite metal powder by direct metal laser sintering. Excessive tool wear and poor surface quality were observed in comparison with conventional electrodes. Dimla et al. [4] produced complex components having sloped surfaces and deep slots by electroplating on DMLS electrodes. Czyzewski et al. [5] have prepared EDM electrodes by 3-dimentional printing technology. Amorim et al. [6] have used tools made by selective laser sintering (SLS) using different powder materials. Czelusniak et al. [7] have focused on the choice of suitable materials to manufacture EDM electrode using selective laser sintering. Mohanty et al. [8] have carried out experiments using electrodes made of Direct-Metal20 prepared by DMLS. Reddy et al. [9] have produced electroless-coated EDM electrodes by coating materials prepared earlier by fused deposition modeling. Padhi et al. [10] found the suitability of electroplated ABS plastic electrode for semi-finishing and roughing operation. Singh and Pandey [11] prepared EDM electrode by utilizing 3D printing in combination with pressure-less sintering. Singh et al. [12] have employed loose powder sintering on polymer part prepared by 3D printing to prepare copper electrode for machining of D2 steel. Peak current is observed to be the most significant parameter on the responses like MRR, TWR, and cavity dimensional deviation.

In the present study, direct metal laser sintering is employed to prepare the electrode which has been chosen along with conventional electrode like copper and brass to assess the feasibility of substituting these conventional electrodes by the RP electrode considering different machining responses like MRR, TWR, and surface roughness (R_a).

The main objective of the present work is the multi-objective optimization of die-sinking EDM process of D2 steel using DMLS electrode. Under the *materials*

Table 1 Process parameters along with their levels

Levels	I_p (A)	T_{on} (μs)	T_{off} (μs)	F_p (kN/m^2)	TE
1	7.5	100	10	29.43	Brass
2	10	150	20	58.86	Copper
3	12.5	200	30	88.29	DMLS

and methods section, the materials for work piece and electrodes and the optimization method of various process parameters have been discussed. D2 steel has been selected as work piece, while brass, copper, and DMLS electrodes have been taken as tools. Utility concept-based Taguchi method has been used for optimizing various process parameters. Under the *results and discussion* section, DOE has been used to determine utility values of different quality attributes from the experimental results conforming L_{27} orthogonal array. Then, a confirmatory test has been performed to validate the experiment results. Also, a comparative study has been presented to assess the response using different electrodes. The *conclusions* section discusses the best response by optimizing various process parameters and recommendation for further work.

2 Materials and Methods

2.1 Materials

D2 steel has been chosen as work piece due to its widespread applications. Three cylindrical tools (20 × 20 mm) selected were brass electrode, copper electrode, and DMLS electrode using DirectMetal20. The selected process parameters (inputs) are peak current represented by I_p, on time represented by T_{on}, off time represented by T_{off}, flushing pressure represented by Fp, and tool electrode represented by TE. TWR, MRR, and R_a have been taken as response variables (outputs). Different process parameters along their levels while carrying out EDM are given in Table 1.

2.2 Methods

Taguchi Method. Taguchi method is an innovative method to solve single-objective optimization problems with less number of experimentation. It uses signal-to-noise (*S*/*N*) ratio [13] as a degree of performance. *S*/*N* ratio is the ratio between signal (mean) and noise (standard deviation). The *S*/*N* ratios for greater-the-better and lesser-the-better are presented by Eqs. (1–2). The best setting corresponds to the maximum *S*/*N* ratio.

$$\text{For greater - the - better (GB)},\ S/N \text{ ratio } = -10\ \log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \quad (1)$$

$$\text{For lesser - the - better (LB)},\ S/N \text{ ratio } = -10\ \log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}y_i^2\right) \quad (2)$$

In both the cases, n represents number of repetitions and y_i represents output.

Utility Concept-Based Taguchi Method. As per the utility theory [14, 15], if Z_i represents degree of usefulness of a quality characteristic i and n, number of attributes are involved in assessing the result; then, the combined utility function is represented as:

$$U(Z_1, Z_2, \ldots, Z_n) = f(U_1(Z_1)U_2(Z_2)\ldots U_n(Z_n)) \quad (3)$$

Here, $U_i(Z_i)$ is the utility corresponding to the ith attribute.

The overall utility function is the summation of different utilities by considering the attributes (qualities) to be independent of each other and is presented as follows:

$$U(Z_1, Z_2, \ldots, Z_n) = \sum_{i=1}^{n} U_i(Z_i) \quad (4)$$

The attributes (qualities) may be given weightages on the basic of their significances. The overall utility function can be represented as:

$$U(Z_1, Z_2, \ldots, Z_n) = \sum_{i=1}^{n} W_i U_i(Z_i) \quad (5)$$

Here, W_i represents the weightage allotted to the attribute i.

The summation of the weightages for all the attributes considered should be 1,

$$\text{i.e.,} \sum_{i=1}^{n} W_i = 1 \quad (6)$$

A scale is essential to fix the utility value of each characteristic. Two numbers 0 and 9 (chosen arbitrarily) represent just satisfactory and the finest possible value of the quality attribute, respectively. Now, P_i can be represented as follows:

$$P_i = A \times \ln\left(\frac{Z_i}{Z_i'}\right) \quad (7)$$

Z_i represents the value of any quality i represents Z_i' represents just acceptable value of quality i; A is a constant that can be calculated by the circumstance.

If $Z_i = Z^*$ (Z^* being the best value), then $P_i = 9$. Hence,

$$A = \frac{9}{\ln \frac{Z^*}{Z_i'}} \tag{8}$$

The overall utility index (OUI) can be presented as follows:

$$U = \sum_{i=1}^{n} W_i P_i \tag{9}$$

where W_i is the weightage given to attribute i.

As the utility function is greater-the-better category, by maximizing this, the quality attributes chosen for its evaluation will be optimized. OUI is the mean of the utility values of individual responses as equal weightage has been given to all the responses. Then, the OUI is optimized using Taguchi method.

DMLS Tool Preparation. DMLS is an advanced sintering procedure, which forms 3-dimentional geometries on layer-by-layer basis. The chosen material for preparation of tool is DirectMetal20. The machine employed for the purpose is EOSINT 250 extended machine.

3 Results and Discussion

Experimental results conforming to L_{27} orthogonal array, DOE (presented in Table 2), have been used to determine utility values of different quality attributes by using Eqs. (7)–(8). Lesser-the-better (LB) principle has been used for TWR and R_a, and greater-the-better principle has been used for MRR.

The utility values of the individual objectives have been calculated using Eqs. (7) and (8) and are presented in Table 3. Then, OUIs for each setting are calculated using Eq. 9 and are presented in the fifth column of Table 3. While calculating the OUI, equal weightage has been given to all the three responses (attributes). S/N ratios corresponding to the OUIs for all the 27 setting have been calculated and are presented in the last column of Table 3. The OUI has then been optimized using Taguchi's HB (Higher-the-better) criterion given by Eq. (1). Ideal setting has been found to be ($I_{p1}\ T_{\text{on}3}\ T_{\text{off}3}\ F_{p1}\ TE_1$) from Fig. 1. The process model for responses obtained through regression analysis is given by;

$$\text{OUI} = 7.45052 - 0.687056 I_p + 0.0379444 T_{\text{on}} + 0.516 T_{\text{off}} + 0.0400556 F_p - 1.09428 TE (\text{Coded units})$$

The predicted value for OUI is found to be 7.371. Finally, a confirmatory test was conducted to validate the experiment.

Table 2 Experimental results

S. N	L_{27} OA					Measured responses		
	I	T_{on}	T_{off}	F_p	Tool	TWR (mm^3/min)	MRR (mm^3/min)	R_a (μm)
1	1	1	1	1	1	10.229	9.166	2.14
2	1	1	1	1	2	5.275	9.775	2.97
3	1	1	1	1	3	6.54	5.871	3.73
4	1	2	2	2	1	8.211	12.862	1.957
5	1	2	2	2	2	4.995	13.025	3.06
6	1	2	2	2	3	7.431	6.65	4.397
7	1	3	3	3	1	7.265	11.875	1.93
8	1	3	3	3	2	3.875	11.925	2.697
9	1	3	3	3	3	5.878	6.753	3.17
10	2	1	2	3	1	7.585	12.568	2.313
11	2	1	2	3	2	5.195	12.862	3.603
12	2	1	2	3	3	4.114	2.309	4.82
13	2	2	3	1	1	9.102	17.088	2.377
14	2	2	3	1	2	5.215	17.663	3.377
15	2	2	3	1	3	5.624	9.872	5.163
16	2	3	1	2	1	11.785	12.375	2.34
17	2	3	1	2	2	7.795	12.275	3.56
18	2	3	1	2	3	8.082	5.191	4.007
19	3	1	3	2	1	11.865	18.307	2.34
20	3	1	3	2	2	9.365	19.075	3.487
21	3	1	3	2	3	10.469	12.706	5.287
22	3	2	1	3	1	13.965	17.075	2.813
23	3	2	1	3	2	10.495	15.695	3.93
24	3	2	1	3	3	11.081	9.613	5.113
25	3	3	2	1	1	15.245	19.875	2.677
26	3	3	2	1	2	10.345	20.175	3.963
27	3	3	2	1	3	11.305	12.514	4.603

The TWR, MRR, and R_a for the setting (I_{p1} T_{on3} T_{off3} F_{p1} $T\,E_1$) have been found to be 5.275 mm^3/min, 12.862 mm^3/min, and 2.14 µm, respectively, and the calculated OUI is 7.394 which is greater than the predicted value of 7.371. So, the quality has improved.

The ANOVA for OUI is shown in Table 4. R^2 value of 94.50% indicates the effectiveness of carrying out the experiments. I is found to be the most significant factor as found from Table 4. OUI is decreasing significantly with increase in I. OUI is in decreasing order for brass, copper, and DMLS electrodes.

Table 3 Utility values of different responses, OUI and *SN* ratio

S. N	Utility value (TWR)	Utility value (MRR)	Utility value (R_a)	OUI	*SN* ratio
1	2.622	5.724	8.078	5.475	14.7677
2	6.973	5.991	5.15	6.038	15.6179
3	5.561	3.875	3.115	4.184	12.4318
4	4.066	7.131	8.876	6.691	16.5098
5	7.332	7.183	4.884	6.466	16.2127
6	4.722	4.392	1.646	3.587	11.0946
7	4.87	6.799	9	6.890	16.7644
8	9	6.817	6.012	7.276	17.2379
9	6.262	4.456	4.568	5.095	14.1429
10	4.587	7.035	7.383	6.335	16.0349
11	7.074	7.131	3.425	5.877	15.3831
12	8.607	0	0.826	3.144	9.9497
13	3.389	8.31	7.14	6.280	15.9592
14	7.049	8.448	4.003	6.500	16.2583
15	6.552	6.032	0.212	4.265	12.5984
16	1.691	6.971	7.28	5.314	14.5084
17	4.407	6.937	3.532	4.959	13.9079
18	4.17	3.364	2.476	3.337	10.4671
19	1.647	8.597	7.28	5.841	15.3297
20	3.202	8.767	3.717	5.229	14.3684
21	2.47	7.08	0	3.183	10.0567
22	0.576	8.307	5.635	4.839	13.6951
23	2.453	7.957	2.649	4.353	12.7758
24	2.096	5.922	0.299	2.772	8.8559
25	0	8.938	6.078	5.005	13.9881
26	2.548	9	2.574	4.707	13.4549
27	1.965	7.017	1.237	3.406	10.6449

4 Conclusions and Future Work

Tool electrode and peak current have been found to be the most significant factors affecting the responses which are on the expected lines and prove the efficacy of conducting the experiments. Ideal setting for best performance has been found to be (I_{p1} $T_{\text{on}3}$ $T_{\text{off}3}$ F_{p1} TE_1) which has been verified by a confirmatory test. The performance of the copper electrode is found to be better than the performance of brass electrode whose performance is again found to be better than the DMLS electrode. Comparatively poor performance of DMLS electrode is owing to the higher porosity level and comparatively lower composition of copper. The future researchers should

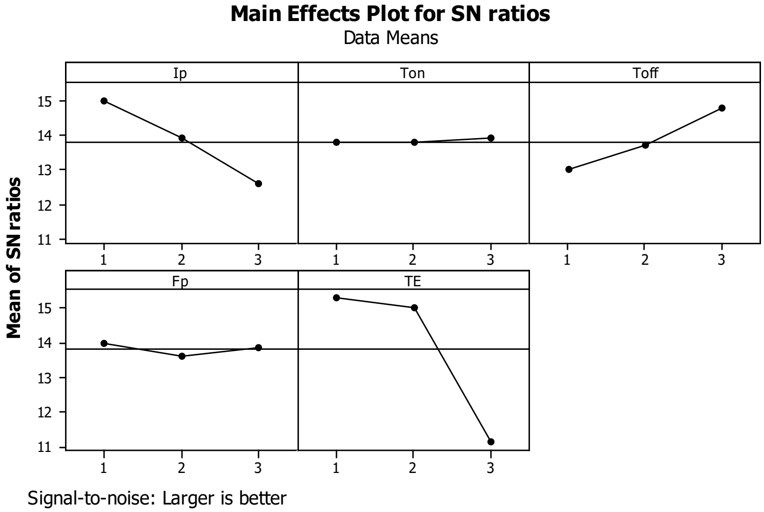

Fig. 1 Estimation of best setting

Table 4 ANOVA for OUI

Source	DF	Seq SS	Adj SS	Adj MS	*F*	*P*
I	2	8.5148	8.5148	4.2574	28.82	0.000
T_{on}	2	0.0267	0.0267	0.0134	0.09	0.914
T_{off}	2	4.8286	4.8286	2.4143	16.34	0.000
F_p	2	0.2217	0.2217	0.1109	0.75	0.488
TE	2	27.0115	27.0115	13.5058	91.42	0.000
Error	16	2.3637	2.3637	0.1477		
Total	26	42.9671				

$S = 0.384361$ $R^2 = 94.50\%$ R^2 (adj) $= 91.06\%$

reduce porosity levels of the DMLS electrode as well as increase in the copper composition in the powder mixture (which in turn would significantly improve the electrical conductivity) to make it possible to replace conventional electrodes. Thus, DMLS tool may be recommended for semi-finishing job.

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