PCA based hybrid Taguchi philosophy for optimization of multiple responses in EDM

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Abstract. The present study is aimed at a multi-response optimization problem by applying Principal Component Analysis (PCA) combined with Taguchi method. The investigation has been carried out through a case study in Electric Discharge Machining (EDM) of D2 steel by using copper, brass and Direct Metal Laser Sintered (DMLS) electrode produced by direct metal laser sintering using Directmetal20. The research work has been carried out to evaluate the best parametric combination which could fulfill multiple responses like lower Tool Wear Rate (TWR), higher Material Removal Rate (MRR) and lower Surface Roughness (R_a). Unlike the use of single-objective optimization problem in traditional Taguchi method, a hybrid Taguchi method has been developed in combination with PCA to solve multi-objective problem. Taguchi method assumes that the quality characteristics should be uncorrelated or independent which is not always fulfilled in actual condition. PCA is applied to remove response correlation and to calculate independent (uncorrelated) quality indices known as principal components. These principal components combined with weighted principal component analysis (WPCA) are used to calculate overall quality index denoted as Multi-response Performance Index (MPI). This investigation combines WPCA and Taguchi method for forecasting optimal setting. The predicted result by this method was validated through confirmatory test proving the efficacy of the process. Out of five input process parameters considered, tool electrode has been found to be the most significant factors through the Analysis of Variance (ANOVA).

Keywords. Multi-objective optimization; weighted principal component analysis; multi-response performance index; Taguchi method; electric discharge machining; direct metal laser sintering.

1. Introduction

EDM is a commonly used as a non-conventional machining process which can effectively machine electrically conductive metals irrespective of their geometry and hardness by use of thermal energy. It is used to manufacture a number of automotive and aerospace components, dies and molds. As no physical contact occurs between the tool electrode and work electrode during machining, mechanical stresses are eliminated. EDM is carried out with an arrangement consisting of a machine tool and a power supply. The machine tool while holding a shaped electrode progresses towards the work piece and generates the desired shape. The power supply by producing a series of electrical spark discharge between the tool electrode and work electrode removes material from the work electrode by thermal erosion. The most common performance measures for EDM are MRR measured in mm^3/min , TWR

measured in mm^3/min , and R_a of the eroded cavity measured in μm . Optimization of the process parameters is essential to get the desired performance in EDM.

2. Literature review and motivation of the present research

Optimization of the process parameters is necessary to obtain the desired performance in EDM. The above factor necessitates the production of more than one separate electrode of a specific geometry. Complexity of eroded cavity increases the cost of EDM machining. Therefore, for minimizing cost of EDM tool as well as product development time, rapid prototyping (RP) technology has been developed. This includes a group of manufacturing methods, in which addition of material on layer-by-layer basis produces the shape of the desired part. Rapid tooling (RT) is an evolution from RP. RT techniques can be broadly

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classified into direct, indirect and patterns of casting [1]. The direct methods utilize a RP-based process for direct production of tools, whereas the indirect methods utilize the RP process to produce a pattern from which the tools are prepared. Rapid casting utilizes RP patterns to manufacture the required components. The most common of RP techniques is Stereo Lithography, which makes plastic parts using photo-curable resins. Laser Sintering offers an alternative, which can create parts by using different powders (metal, ceramic, plastic or a combination of the two). Laser beam is used both in Stereo Lithography and Laser Sintering manufacturing processes. It is observed that Stereo Lithography offers greater dimensional accuracy (± 0.15 mm) and surface finish (from 1 to 5 μm) compared to Laser Sintering while Laser Sintering offers greater mechanical strength of prototypes compared to Stereo Lithography [2, 3] specifically when it uses metal powders. Apart from the above two, the other well-known RP techniques are Laminated Object Manufacturing (LOM), Fused Deposition Modeling (FDM), 3D printing, Thermo Jet Printing (TJP), etc. Many researchers [4–6] attempted to produce electrodes employing these methods. In EDM mechanism, both the work and tool electrodes are eroded simultaneously. It is found that spark on time, spark off time, peak current have maximum influence on EDM performance. The tool electrode material should possess desirable qualities to minimize the TWR and to maximize the MRR. Apart from that, owing to high temperature and pressure generated during EDM machining, the electrode material should have reasonable mechanical strength and melting point in order to decrease the TWR.

It is observed that the EDM cycle for mold and dies manufacturing may consume in the range of 25 to 40% of the total lead-time and half of the manufacturing cost [7]. The manufacturing of electrode itself accounts for over half of the total cost in EDM. Most of the dies and molds to be manufactured require more than one cavity and each requires a different electrode of definite shape. An efficient additive technology to produce single-piece electrode in quick time with less human intervention would significantly reduce lead-time as well as cost of tooling. Expenses will be reduced with greater part complexity with the use of additive technologies. RP is a novel method for quick creation of physical models from CAD models. RT is usually connected with fast tooling manufacturing with the help of prototypes made by RP. Researchers associated with process development are now paying their attention to minimize lead-time and development costs. During nineties [8–10] efforts were made to develop methods for RP-EDM tooling by the use of Stereo Lithography models directly. It was observed that the thin-coated Stereo Lithography-EDM electrodes present wear and failure mechanisms. Previously, researchers at the Modeling Prototypes Laboratory of the Instituto Superior Técnico, Portugal have indirectly manufactured EDM electrodes with SL patterns for investment casting technology. A direct or an indirect

production route is desired to manufacture RT-EDM electrodes using RP models. These RT-EDM electrodes must ensure sizable material removal rate along with low tool wear rate.

In University of Chemnitz [11], manufacturing of metal electrodes by DMLS was first carried out. The electrode produced was of simple cylindrical shape from Ni, bronze and copper phosphite metal powder. Copper phosphite is first intermingled with bronze as low melting material followed by second sintering. It was observed that the laser power, laser speed, sintering strategy and hatch distance were the factors having the maximum influence on the porosity of the electrodes produced by DMLS. Subsequently the electrodes were penetrated by a silver-containing brazing metal as well as of a tin-containing plumb bob to bring about an improvement in their performance. The MRR achieved with the help of the electrodes was up to $12.5 \text{ mm}^3/\text{min}$ and resulted in greater TWR and poor surface quality than conventional electrodes. Then, it was recommended that the performance of the electrodes need to improve significantly for practical use. In National University of Singapore (NUS), efforts were made [12] to fabricate metal electrodes by DMLS by using the powder metal comprising of copper, tin, nickel and phosphorus. In the University of Bournemouth researchers [13] concentrated on the shell thickness of copper shell electroplated DMLS electrodes. The shape of the component was complex with sloped surfaces, deep slots which is not easy to be machined by CNC milling. Sizable differences in the copper shell thickness were noticed. The minimum deposition was observed in the inner cavities (about 10 μm), while the upper and outer faces had a copper deposition between 40 and 180 μm . They observed that electroplated DMLS electrodes were not suitable for industrial use due to the unevenness in copper shell thickness. A SLS/RAP-I system was used by National University of Aeronautics and Astronautics, China [14] to manufacture direct RT electrodes. The powders used for the purpose were steel, polyester and phosphate. Laser sintering was done to fabricate the green part which was followed by treatment in three phases. Sintering was done at low temperature (between 260 and 300°C) to decompose the polyester in the first phase. Then sintering was done at high temperature (between 760 and 1,040°C) and a rigid inorganic compound was formed due to phosphate-steel reaction. In the last phase to improve the quality, copper infiltration was done at 1,120°C. It was observed that electrodes manufactured by the above method were appropriate for finishing operations in EDM.

Meena and Nagahanumaiah [15] applied Taguchi method to examine the effects of EDM parameters on the performance of DMLS electrode. These researchers used an EOSINT M250 machine and an EOS DirectMetal50 metal powder system. It was found that the peak current is the main parameter as with conventional electrodes. They also noticed that the electrode wear at the front edge was higher

than the side wear due to the porosity of the DMLS electrodes. Ferreira *et al* [16] have applied indirect rapid tooling (RT) technology to create EDM copper electrodes from investment casting with wax prototypes made by Thermo Jet 3D printing, a rapid prototyping (RP) technique. The reverse engineering (RE) method was employed to transform the point cloud data of an object surface, obtained from 3D digitizing, in a 3D CAD surface model data set. Based on a case study, some functional conclusions were made for the application of RT in manufacturing EDM electrodes aided by 3D digitizing and RE, validating the accomplishment by the integration of these technologies and methodologies in EDM manufacturing processes. Czyzewski *et al* [17] described a method of rapid prototyping of electrically conductive components based on 3D printing technology. The prototyped model is made of plaster-based powder bound on layer-by-layer by an inkjet printing of a liquid binder. To obtain the electric conductivity, the model has been impregnated by a dispersion of carbon nano fibers (CNF) in epoxy resin. Amorim *et al* [18] used electrodes made with SLS utilizing pure copper, bronze-nickel alloy, copper-bronze-nickel alloy and steel alloy powders for finishing, semi-finishing and roughing operations. The bronze-nickel powder electrode showed the best EDM performance followed by those made by the mixture of copper and bronze nickel powder. Pawar *et al* [19] performed EDM operation using special electrode prepared by electro-less copper coating of nonconductive ABS material which was made by fused deposition modeling (one of the rapid prototyping techniques). Like conventional electrodes Pulse current was found to be the significant factor affecting MRR, TWR and R_a .

In the present study, multi-objective optimization problem has been performed to choose the best process environment for optimizing multiple quality characteristics of D2 steel in EDM. Due to insufficiency of traditional Taguchi approach to solve a multi-response optimization problem, WPCA has been tied with Taguchi method in the present investigation. Optimization of various manufacturing processes highlighted in literature assumed that individual quality indices are independent to each other i.e., they are not correlated. But in practice the assumption may not be valid always. Therefore, hybrid Taguchi based optimization approaches like grey Taguchi [20], desirability function based Taguchi [21], and utility concept based Taguchi methods [22, 23] and which neglect response correlation may lead to inaccurate results. To overcome this limitation, the study proposes application of WPCA to eliminate response correlation and to convert correlated responses into uncorrelated quality indices called principal components. These principal components have been aggregated further to calculate the composite principal component called multi-response performance index (MPI) [24]. In this way the multi-objective optimization problem has been converted into an equivalent single objective optimization situation which has been

solved by Taguchi method. Detailed methodology of the proposed optimization technique has been presented in the paper.

3. Weighted principal component analysis (WPCA)

In applying the PCA method, the main processes of dealing with the multi-response problem are:

- (1) To measure each response for each setting
- (2) To normalize each response for each setting
- (3) To convert these normalized responses into a multi-response index
- (4) To get the best combination of factors/levels, and
- (5) To carry out a confirmation experiment

Processes 2 and 3 are the essence of the WPCA. Data normalization is using the following equations.

- (a) SB (Smaller-the-Better)

$$Y_i(k) = \min X_i(k) / X_i(k) \quad (1)$$

Here, $i = 1, 2, \dots, m$; $k = 1, 2, \dots, n$ and $Y_i(k)$ is the normalized value.

- (b) LB (Larger-the-Better)

$$Y_i(k) = X_i(k) / \max X_i(k) \quad (2)$$

where the number of experimental runs in Taguchi's orthogonal array (OA) design as m and the number of quality characteristics as n , $Y_i(k)$ represent the normalized data of the k th element in the i th sequence. After data normalization, the value of $Y_i(k)$ will be between 0 and 1.

To compute PCA, $k(k \leq p)$ components will be obtained to explain the variance in the p responses. Principal components are independent of each other. Simultaneously, the explained variance of each principal component for the total variance of responses is also gained. The j th principal component obtained is a linear combination $Z_j = \sum_{i=1}^p a_{ji} Y_i$, for $j = 1, \dots, k$ subjecting to $\sum_{i=1}^p a_{ji}^2 = 1$; where the coefficient a_{ji} is called eigen vector.

This paper uses the WPCA method to overcome the deficiencies of multi-response problem in the PCA method [25]. First to achieve the objective, all principal components are to be used in this WPCA method describing the explained variance in all responses. Secondly, as different principal components have their own variance to account for the total variance, the variance of each principal component is regarded as the weight. Because these principal components are independent to each other (which means that these principal components are in an additive model), the multi-response performance index is given as $MPI = \sum_{j=1}^k W_j Z_j$, where W_j is the weight of the j th principal components. The larger MPI indicates better quality. Finally, significant factors in this quality index and their

contribution percentage for total variation in MPI will be obtained with application of ANOVA.

4. Taguchi philosophy

Taguchi method was suggested by Genichi Taguchi, a Japanese quality management consultant. The method explores the concept of quadratic quality loss function and uses a statistical measure of performance called signal-to-noise (S/N) ratio [26]. It is the ratio of the mean (signal) to the standard deviation (Noise). The ratio relies on the quality characteristics of the product/process to be optimized. The standard S/N ratios commonly used Larger-the-Better (LB), Smaller-the-Better (SB) and Nominal-the-Best (NB) as given in Eqs. (3)–(5). The optimal setting is the parameter combination, which has the highest S/N ratio.

4.1 Larger-the-better (LB)

$$S/N \text{ ratio} = -10 \log_{10} \left(\frac{1}{n} \sum_{i=1}^n \frac{1}{y_i^2} \right) \quad (3)$$

where n is number of replications and y is the observed data

This is applied for problems where maximization of the performance characteristic of interest is desired. This is referred to as the larger-the-better type problem.

4.2 Smaller-the-Better (SB)

$$S/N \text{ ratio} = -10 \log_{10} \left(\frac{1}{n} \sum_{i=1}^n y_i^2 \right) \quad (4)$$

This is applied for problems where minimization of the performance characteristics is intended. This is termed as Smaller the Better type problem.

4.3 Nominal the Best (NB)

$$S/N \text{ ratio} = -10 \log_{10} \left(\frac{\mu^2}{\sigma^2} \right) \quad (5)$$

where μ = and σ = standard deviation.

Based on the S/N analysis, the S/N ratios for each level of process parameters are computed. Larger S/N ratio corresponds to better performance characteristics regardless of their category of performance. It means that the level of process parameters with the highest S/N ratio corresponds to the optimum level of process parameters. Taguchi recommends orthogonal array (OA) for conducting experiments as a result number of experiments are reduced

significantly. These OAs are generalized Graeco-Latin squares. Finally, a confirmatory experiment is conducted to authenticate the optimal processing parameters obtained from the parameter design.

5. Proposed optimization methodology

Traditional Taguchi approach is developed to solve single-response optimization problems. It is then essential to transform these multiple objectives into an equivalent single objective function which can be treated as the representative index for multiple quality characteristics. In this situation, application of PCA proves to be very useful. PCA

Table 1. Composition D2 steel workpiece.

Composition (weight %)					
C	Si	Cr	Mo	V	Fe
1.50	0.30	12.00	0.80	0.90	Balance

Figure 1. Direct metal laser sintering process.

Table 2. Chemical composition of tool electrodes.

Electrode used (% of material composition)		
Copper	Brass	DMLS
P-0.052	Cl-0.346	Si-0.239
S-0.065	Ca-0.027	P-1.076
Cl-0.338	Mn-0.049	S-0.027
K-0.029	Fe-0.339	Cl-0.406
Fe-0.084	Ni-0.229	Ca-0.034
Ni-0.114	Cu-57.999	Cr-0.082
Cu-99.173	Zn-37.172	Fe-0.544
As-0.019	Nb-0.081	Ni-19.03
Sr-0.009	Sn-0.444	Cu-72.598
Sn-0.033	Yb-0.377	Sn-5.963
Hg-0.05	Pb-2.837	
Tl-0.019		
Pb-0.016		

Table 3. Process parameters and domain of experiments.

Levels	I_p (A)	T_{on} (μ s)	T_{off} (μ s)	F_p (kgf/cm ²)	TE
1	8	100	10	0.3	Brass
2	10	150	20	0.6	Copper
3	12	200	30	0.9	DMLS

Table 4. Results obtained along with design matrix.

Sl. no.	L ₂₇ OA					Measured responses		
	Ip	Ton	Toff	Fp	Tool	TWR	MRR	Ra
1	1	1	1	1	1	10.384	9.29	2.11
2	1	1	1	1	2	5.43	9.9	2.94
3	1	1	1	1	3	6.695	5.996	3.7
4	1	2	2	2	1	8.366	12.99	1.927
5	1	2	2	2	2	5.15	13.15	3.03
6	1	2	2	2	3	7.586	6.775	4.367
7	1	3	3	3	1	7.42	12	1.9
8	1	3	3	3	2	4.03	12.05	2.667
9	1	3	3	3	3	6.033	6.878	3.14
10	2	1	2	3	1	7.74	12.693	2.283
11	2	1	2	3	2	5.35	12.987	3.573
12	2	1	2	3	3	4.609	2.434	4.79
13	2	2	3	1	1	9.257	17.213	2.347
14	2	2	3	1	2	5.37	17.788	3.347
15	2	2	3	1	3	5.779	9.997	5.133
16	2	3	1	2	1	11.94	12.5	2.31
17	2	3	1	2	2	7.95	12.4	3.53
18	2	3	1	2	3	8.237	5.316	3.977
19	3	1	3	2	1	12.02	18.432	2.31
20	3	1	3	2	2	9.52	19.2	3.457
21	3	1	3	2	3	10.624	12.831	5.257
22	3	2	1	3	1	14.12	17.2	2.783
23	3	2	1	3	2	10.65	15.82	3.9
24	3	2	1	3	3	11.236	9.738	5.083
25	3	3	2	1	1	15.4	20	2.647
26	3	3	2	1	2	10.5	20.3	3.933
27	3	3	2	1	3	11.46	12.639	4.573

eliminates response correlation and transforms correlated responses into uncorrelated quality indices (principal components). The principal component which has the maximum accountability proportion (AP) is normally considered as overall performance index. But in the situation when more than one principal component has considerable value of accountability proportion which can not be ignored; the problem of computing composite principal component is required. Literature review indicates that different researchers recommended different approaches to compute the composite principal component [25, 27, 28].

Among the different approaches suggested, weighted principal component analysis recommended by Liao [27] has been found to be very useful. The study provided viable

Table 5. Normalized data.

Sl. no.	Normalized TWR	Normalized MRR	Normalized R _a
1	0.388	0.458	0.9
2	0.742	0.488	0.646
3	0.602	0.295	0.514
4	0.482	0.64	0.986
5	0.783	0.648	0.627
6	0.531	0.334	0.435
7	0.543	0.591	1
8	1	0.594	0.712
9	0.668	0.339	0.605
10	0.521	0.625	0.832
11	0.753	0.64	0.532
12	0.874	0.12	0.397
13	0.435	0.848	0.81
14	0.75	0.876	0.568
15	0.697	0.492	0.37
16	0.338	0.616	0.823
17	0.507	0.611	0.538
18	0.489	0.262	0.478
19	0.335	0.908	0.823
20	0.423	0.946	0.55
21	0.379	0.632	0.361
22	0.285	0.847	0.683
23	0.378	0.779	0.487
24	0.359	0.48	0.374
25	0.262	0.985	0.718
26	0.384	1	0.483
27	0.352	0.623	0.415

Table 6. Eigen value, eigen vector and accountability proportion.

Principal component	PC ₁	PC ₂	PC ₃
Eigen value	1.5803	0.8844	0.5353
Eigen vector	−0.606	0.482	0.633
	0.662	−0.135	0.737
	0.441	0.86	−0.238
AP	0.527	0.295	0.178
CAP	0.527	0.822	1.000

means for calculation of composite principal component. Values of individual principal components multiplied by their priority weight were added to determine the composite principal component defined as MPI which was maximized with the help of Taguchi method.

6. Experimentation

The selected process parameters for current research include peak current (I_p), spark on time (T_{on}), spark off time (T_{off}), flushing pressure (F_p) and tool electrode (TE) while other parameters have been kept constant. It is observed

Table 7. Calculated three major principal components.

Sl. no.	Z ₁	Z ₂	Z ₃	Sl. no.	Z ₁	Z ₂	Z ₃
1	0.465	0.9037	0.369	15	0.0665	0.5896	0.7157
2	0.1583	0.8506	0.6756	16	0.5659	0.7917	0.4721
3	0.0572	0.6949	0.4761	17	0.3345	0.6273	0.6432
4	0.5664	0.9988	0.5421	18	0.0879	0.6138	0.3889
5	0.231	0.8323	0.824	19	0.761	0.7508	0.6854
6	0.0912	0.5871	0.4788	20	0.6125	0.5519	0.8341
7	0.5032	1.0469	0.5413	21	0.3479	0.4096	0.6198
8	0.1012	1.0177	0.9013	22	0.6892	0.6138	0.6421
9	0.0864	0.7995	0.5287	23	0.5014	0.4983	0.6975
10	0.4649	0.8864	0.5924	24	0.2651	0.4317	0.492
11	0.202	0.7367	0.8217	25	0.8099	0.6144	0.7209
12	−0.275	0.7485	0.5472	26	0.6423	0.4679	0.8651
13	0.655	0.7958	0.7076	27	0.3821	0.4445	0.5832
14	0.3759	0.7346	0.9852				

Table 8. MPI and S/N ratio.

Sl. no.	MPI	SN ratio	Sl. no.	MPI	SN ratio
1	0.5773	−4.7644	15	0.3364	−9.4526
2	0.4546	−6.8417	16	0.6158	−4.2098
3	0.3199	−9.8943	17	0.4758	−6.4460
4	0.6896	−3.2218	18	0.2966	−10.5536
5	0.5139	−5.7774	19	0.7445	−2.5604
6	0.3065	−10.2686	20	0.6341	−3.9568
7	0.6704	−3.4668	21	0.4145	−7.6411
8	0.514	−5.7740	22	0.6586	−3.6249
9	0.3755	−8.5009	23	0.5354	−5.4199
10	0.6119	−4.2565	24	0.3546	−9.0052
11	0.47	−6.5580	25	0.7364	−2.6530
12	0.1733	−15.2290	26	0.6305	−4.0022
13	0.7059	−3.0239	27	0.4363	−7.1983
14	0.5902	−4.5771			

that previous experimental or analytical research works carried out in EDM [29] mostly consider TWR, MRR and R_a as response variables. In this present investigation, these three responses variables have also been selected. The experiment was performed with D2 steel work piece. The composition of D2 steel is presented in table 1.

In the experiment, three tools such as brass, copper and DMLS part using DirectMetal20 are used as EDM electrode. All the three electrodes are cylindrical in shape with length and diameter 20 mm each. The schematic diagram of the direct metal laser sintering process is shown in figure 1. DMLS is a liquid phase sintering process which can build 3D geometries layer-by-layer. The material used to prepare the tool is DirectMetal20. The machine used is EOSINT M250 Extended machine which has a laser unit, a control computer, a powder dispenser, a build chamber and a wiper blade. 3D CAD model of the cylindrical specimen

was modeled using “Magic RP software”. CAD model in STL format was sliced using “EOS RP Tools”. The layer thickness was maintained constant at 40 μ m. The sliced data was transferred to the process computer of DMLS machine where laser path was generated with PSW software. A base plate made of steel was mounted on building platform. The building platform was heated to a temperature of 80°C. Laser power, layer thickness, hatch width, hatch spacing and laser scan speed were maintained constant at 228 W, 40 μ m, 5 mm, 0.2 mm and 200 to 500 mm/s respectively.

Sintering was done in nitrogen atmosphere with oxygen level below 1.5%. The building platform was removed from the base plate using wire electrical discharge machining. The chemical composition for the three tools as obtained from XRF Analyzer (Epsilon-1, PANalytical) is shown in table 2.

The design factors with their corresponding values on different levels are shown in table 3. There are constraints in selecting the values of the variables due to the capacity of the machine used in experimental work. L_{27} Orthogonal Array (OA) design has been chosen for experiments in the study.

The DMLS part was prepared with the help of EOSINT M250 Extended machine. The EDM machine used is ECOWIN M/C, Taiwan Make, and MIC 432CS Model. The coolant used during machining is EDM 30. All the twenty seven experiments were carried out using the above machine. The surface roughness has been measured thrice for each specimen using the stylus-type profilometer, Talysurf and the mean values are taken as R_a .

After each experiment, the material removal and tool wear were calculated by weight loss method which calculates the loss of weight by considering the weight before and after the machining. To measure the weight, digital weighing balance with a least count of 0.1 mg was

Figure 2. Factorial plot.**Table 9.** ANOVA for MPI.

Source	DF	Seq SS	Adj SS	Adj SS	F	P	% Contribution
<i>I</i>	2	0.048127	0.048127	0.024064	23.06	0.000	7.802
<i>T_{on}</i>	2	0.007839	0.007839	0.003919	3.76	0.046	1.2708
<i>T_{off}</i>	2	0.027331	0.027331	0.013665	13.10	0.000	4.4307
<i>F_p</i>	2	0.010970	0.010970	0.005485	5.26	0.018	1.7784
TE	2	0.505893	0.505893	0.252946	242.40	0.000	82.0117
Error	16	0.016696	0.016696	0.001044			
Total	26	0.616855					

S = 0.0323036 R-Sq = 97.29% R-Sq (adj) = 95.60%.

employed. Then the material removal and tool wear were converted into mm³/min by dividing the weight loss in each case with corresponding density value.

7. Results and analysis

Table 4 shows the parametric setting under which each experiment has been conducted and the measured responses such as TWR, MRR and R_a. In order to avoid biasness, experiments have been conducted in a random order.

Experimental data from table 4 (responses) has been normalized as presented in table 5. For TWR and R_a, SB

(Smaller-the-Better) criterion is used whereas LB (Larger-the-Better) criteria for MRR has been selected using Eqs. (1) and (2), respectively.

Principal component analysis (PCA) has been carried out on normalized responses using MINITAB 14 software. The results of PCA (eigenvalue, eigenvector, accountability proportion and cumulative accountability proportion) have been shown in table 6. It is observed that accountability proportions by three responses are 0.527, 0.295 and 0.178 for MRR, TWR and R_a, respectively. The Eigen vector for each principal component can be used to transform normalized responses into principal component. The relationship between principal components and responses are:

$$Z_1 = -0.606 \times TWR (Normalized) + 0.662 \\ \times MRR (Normalized) + 0.441 \times R_a (Normalized)$$

$$Z_2 = 0.482 \times TWR (Normalized) - 0.135 \\ \times MRR (Normalized) + 0.865 \times R_a (Normalized)$$

$$Z_3 = 0.663 \times TWR (Normalized) + 0.737 \\ \times MRR (Normalized) - 0.238 \times R_a (Normalized)$$

Accountability proportion of individual principal components has been taken as individual priority weights [27]. Then, the responses have been transformed into quality indices called major principal components (Z_1 , Z_2 , and Z_3) which have been furnished in table 7. Then, Multi-performance index (MPI) has been calculated using the following equation:

$$MPI = 0.527 \times Z_1 + 0.295 \times Z_2 + 0.178 \times Z_3 \quad (6)$$

Values of MPI and the corresponding S/N ratio for all experimental runs have been listed in table 8. The MPI is then optimized (maximized) using Taguchi method. The predicted optimal setting becomes $I_{p3}T_{on3}T_{off3}F_{p1}TE_1$ (subscript represents optimal level of corresponding factors) as observed from figure 2. After assessing the optimal parameter settings, the optimal result was tested using the confirmatory test.

R-Sq value of 97.29% shows the efficacy of performing the experiments. In PCA based Taguchi method, the optimal setting was found to be $I_{p3}T_{on3}T_{off3}F_{p1}TE_1$. The confirmatory test was found to be in agreement with the predicted settings which confirms usefulness of the hybrid Taguchi method. The ANOVA for MPI as presented in table 9 shows that the tool electrode (TE) is the most significant factor. Direct metal laser sintered part is more porous than copper and brass as it is being produced by sintering. Due to this, DMLS is presenting poor performance in comparison to the brass and copper electrode. If porosity levels can be reduced, it can present performance comparable with other conventional electrodes. In addition, the performance of EDM electrode relies heavily on its electrical conductivity. The electrical conductivity of copper electrode is highest followed by brass followed by DMLS electrode. Copper enrichment of DMLS electrode would bring about an improvement in its performance. The conductivity of DMLS tool decreases because of porous structure. However, DMLS tool can be used for semi-finishing operation as tool fabrication time is greatly reduced.

8. Conclusions

The following conclusions may be drawn from the results of the experiments and study of the experimental data in connection with multi-response optimization (Lower TWR, Higher MRR and Lower R_a) with (1) peak current, (2)

pulse-on time, (3) pulse-off time, (4) flushing pressure and (5) tool electrode as process parameters in electric discharge machining of D2 steel:

1. Optimum parameter setting can be evaluated by combining PCA with Taguchi method which proves its effectiveness in handling multi-response problems.
2. Confirmatory experiment has been performed to validate the optimal parametric setting ($I_{p3}T_{on3}T_{off3}F_{p1}TE_1$) obtained by the cited method.
3. Tool electrode is found to be the most significant factors from the analysis of variance.
4. This method can be recommended to solve other multi objective optimization problems.
5. The performance electrode prepared by DMLS is presenting poor performance in comparison to the brass and copper electrode. The performance may improve if porosity levels are considerably reduced. Copper enrichment of DMLS electrode is also essential as would increase its electrical conductivity which would improve electric discharge machining.
6. Peak current is the most significant factor next to tool electrode.

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