Optimization of Multiple Surface Roughness Characteristics of Electric Discharge Machined D2 Steel with the help of a Tool Produced by Rapid Prototyping using Weighted Principal Component Analysis and Taguchi Method

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***Abstract**: The present study highlights a multi-objective optimization problem by applying Weighted Principal Component Analysis (WPCA) coupled with Taguchi method through a case study in Electric Discharge Machining of D2 Steel by using Electrode produced by Direct Metal Laser Sintering using Directmetal20. The study aimed at evaluating the best process environment which could simultaneously satisfy multiple Surface Roughness requirements. In view of the fact, that traditional Taguchi method fails to solve a multi-objective optimization problem; to overcome this limitation, WPCA has been coupled with Taguchi method. Furthermore, to follow the basic assumption of Taguchi method i.e. quality attributes should be uncorrelated or independent; which is not always satisfied in practical situation; the study applied Principal Component analysis (WPCA) to eliminate response correlation and to evaluate independent or uncorrelated quality indices called Principal Components which were aggregated by WPCA to compute overall quality index denoted as Multi-Response Performance Index (MPI).. The larger the MPI is, the higher the quality. The study combined Principal Component Analysis and Taguchi method for predicting optimal setting. Optimal result was verified through confirmatory test. This indicates application feasibility of the aforesaid methodology proposed for multi-response optimization in Electric Discharge Machining.*

.Key words: Multi-objective optimization; Principal Component Analysis; Taguchi method; Electric Discharge Machining, Direct Metal Laser Sintering. .

1. Introduction

Electrical discharge machining (EDM) is one of the most extensively used non- conventional material removal processes. It uses thermal energy to machine electrically conductive hard material parts regardless of their geometry. It is used to manufacture many automotive and aerospace components as well as moulds and dies. Electrical discharge machining is accomplished with a system comprising two major components: a machine tool and a power supply. The machine tool holds a shaped electrode, which advances into the work piece and produces a shaped cavity. The power supply produces a high frequency series of electrical spark discharges between the electrode and the work piece, which remove metal from the work piece by thermal erosion or vaporization. A relatively soft graphite or metal electrode can easily machine hardened tool steels or tungsten carbide. In any machining operation surface quality of the finished part is very important. The most common surface quality is Ra. But Ra alone is not sufficient to express surface quality.. Because of the nature of the EDM process, optimization of the process parameters is required, in order to achieve the desirable performance specifications. The above factors often lead in the manufacturing of more than one separate electrode of a specific geometry, which run sequentially, in order to manufacture dies and moulds. So, the cost of EDM tooling is increased by the complexity of the eroded cavity. So as to reduce the product development time and the cost of tooling, layered manufacturing techniques were developed commonly known as rapid prototyping (RP) technology. This technology encompasses a group of manufacturing techniques, in which adding the material layer-by-layer generates the shape of the physical part. Many of these techniques are based on either the selective solidification of the liquid or the bonding of solid particles. Rapid tooling (RT) is a progression from RP. It is the ability to build prototype tools directly, as opposed to prototype products directly from the CAD model, resulting in compressed time to market solutions. The three broad classifications of the RT techniques are direct, indirect and patterns for casting. The direct approaches use a RP-based process to manufacture tooling inserts directly, whereas the indirect methods use the RP process to generate a pattern from which the tooling inserts are made. Finally, rapid casting uses RP patterns to produce final metal parts. The most widespread of RP techniques is Stereo-lithography (SL), which produces accurate plastic prototypes from photo-curable resins. Laser Sintering (LS) is an alternative technique, which uses powders (metal, ceramic, plastic, or a combination) to produce parts. Both of them incorporate a laser beam to manufacture prototypes. In general, it is reported that SL gives better dimensional accuracy (±0.15 mm) and surface finish (between 1and 5 μm, Ra on horizontal and vertical surfaces) while LS gives better mechanical strength of prototypes especially when it uses metal powders. In addition to the above two techniques there are a number of RP techniques which can produce both prototypes and functional parts: Laminated Object Manufacturing (LOM), Fused Deposition Modeling (FDM), 3D Printing, Thermo Jet Printing (THJ), etc. Although these techniques are oriented on RP, many researchers attempted to manufacture electrodes, too. Furthermore, since the shaped electrode defines the area in which spark erosion will occur, the dimensional accuracy of the produced part depends on the dimensional accuracy and the surface texture of the electrode. Finally, shape details and recesses affect the electrode performance since they define the electric field in which machining takes place. Electrodes manufactured using RP techniques should have high dimensional accuracy and appropriate surface roughness in order to meet EDM specifications. Thus, post-processing of RP parts for EDM applications (roughing, semi-roughing, and finishing) is necessary. It includes several stages according to the material electric properties (nonconductive, conductive, pattern for casting) and quality characteristics (dimensional accuracy, surface roughness). Post-processing of non-conductive materials includes surface finishing, primary metallization to change the conductivity and secondary metallization to reinforce the final electrode properties. The above three sub-processes can be applied on a positive or a negative RP part (direct or indirect electrode). In a negative shape case, two more steps must be applied: Backfilling the metal shell cavity with an appropriate material, and RP pattern (mandrel) removal process. Conductive materials such as metal powders, metal powder resins, and metal matrix ceramics (MMC) powders need special post-processing according to each RP process. Metal parts made from RP cast patterns need finishing to improve surface quality & eliminate the stair stepping phenomenon.

Typically, the EDM cycle for mould and die production in the tool room can take 25-40% of the total lead-time. The electrodes production itself accounts for over 50% of the total machining costs. Many dies and moulds require multiple cavities and each requires a separate electrode of specific geometry that is run sequentially. This methodology has often been adopted as owing the difficulty to fabricate complex electrode profiles by subtractive technologies. An accurate additive technology to manufacture one-piece electrodes quickly with minimum manual intervention would considerably reduce lead-time and tooling costs. With additive technologies, savings will increase with greater part complexity. Rapid prototyping (RP) is an innovative additive technology for quickly creating physical models and functional prototypes directly from CAD models. RT generally, is related with fast tooling production using prototypes made by RP. Technologists involved in RT processes development are now focusing to reduce lead-times and development costs through manufacturing additively production tooling via RP. Between 1991 and 1996, attempts were made to develop applications and techniques for RP-EDM tooling by using stereo lithography (SL) models directly. sIn previous years, investigations at the Modeling Prototypes Laboratory (LMP) of the Instituto SuperiorTécnico (IST), Portugal, have also been undertaken to indirectly manufacture EDM electrodes with stereo lithography patterns for investment casting technology. To manufacture RT-EDM electrodes using RP models, a direct or an indirect manufacturing route is required. These RT-EDM electrodes must realize substantial metal removalvolume combined with low tool wear. It would have double the effect to unlock the EDM die sinking process potential and to expand the RP/RT role in the metal working Industry.

Direct metal laser sintering to fabricate metal sintered electrodes was first carried out the University of Chemnitz. The DLMS electrode shape was simple (cylindrical) and the metal powder system consisted of Ni, bronze and a few percent of copper phoshite. Copper phoshite interacted with bronze as low melting material.

Then a second thermal sintering followed. Optimization of the process indicated that the laser power, laser speed, sintering strategy and hatch distance had the biggest impact on the porosity of the sintered electrodes. Then, the electrodes were infiltrated by a silver-containing brazing metal as well as of a tin-containing plumb bob in order to improve rapid electrode performance. Finally, it was suggested that the performance of the electrodes as well as the dimensional accuracy and surface roughness might be further improved for manufacturing use. Direct metal laser sintering was also used by the National University of Singapore (NUS) to fabricate metal electrodes by using scopper, tin, nickel and phosphorusas metal powder. The University of Bournemouth investigated the shell thickness of copper shell electroplated DLMS electrodes. The shape of the part was complex with sloped surfaces, deep slots and details; a model which is difficult to be manufactured by CNC milling. Big differences in the copper shell thickness were found depending on the position of measurement. The least deposition tended to occur in the inner cavities (about 10 µm), while the upper and outer faces had a copper deposition between 40 and 180 µm. It was concluded that electroplated DLMS electrodes were unsuitable for industrial use due to the uneven copper shell thickness. .A SLS/RAP-I system was used by NUAA, China, to fabricate direct RT electrodes. A multi component powder system which consisted of steel, polyester and phosphate was used. Laser sintering was used to fabricate the green part. Then post-treatment was applied in three steps. Firstly, low temperature sintering was applied (260-300^{0}C) to decompose the polyester. Secondly, high temperature sintering was applied (760-1,040^{0}C) and a rigid inorganic compound was produced from the phosphate-steel reaction. Finally, copper infiltration was applied at 1,120^{0}C to improve quality. After fabrication of three electrodes with different component proportions of sintered material, they conducted experiments to study the influence of the process parameters on electrode performance and to optimize the process. They concluded that these electrodes were suitable for finishing cuts in EDM.

Use of DMLS and metallization process for manufacture of direct or indirect tooling of complex shaped electrodes for EDM is rarely observed in Indian manufacturing and research organization due to heavy investment in acquiring RP machine and coating set up. However, limited facilities are available at Indian Institute of Technology Kharagpur, Indian Institute of Information Technology, Design and Manufacture Jabalpur, and Indian Institute of Technology Chennai. Well-developed coating facilities are available at Bhaba Atomic Research Centre Mumbai. Full scale industrial application of the process has not explored in Indian manufacturing firms although it has been realized potential application exists in automobile and sheet metal industries for die making. However, limited research on optimization of EDM machining parameters using DMLS electrode has been carried out at Central Mechanical Engineering Research Institute Durgapur. Similarly, works on electro-less alloy/composite coatings has been extensively carried out at Metallurgical and Materials Engineering Department, Indian Institute of Technology Roorkee. However, an integrated approach for successful manufacture of electrodes for EDM operations in industries is missing in Indian research and practices.

In the present research, the optimization of EDM machining parameters using electrode produced by direct metal laser sintering electrode has been dealt for multiple Surface Roughness characteristics using Principal Component Analysis coupled with Taguchi method based design of experiment to improve its productivity. In view of the fact that traditional Taguchi approach fails to solve a multi-response optimization problem; to overcome this shortcoming Principal Component Analysis has been coupled with Taguchi method in the present investigation. By using Principal Component Analysis, 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 aforesaid optimization technique has been highlighted in the paper.

2. Weighted Principal Component Analysis (WPCA)

In the application of PCA method, the main processes of dealing with the multi-response problem are (1) to compute the quality loss of each response, (2) to normalize the quality loss of each response, (3) to transform these normalized quality loss into a multi-response index or a named multi-response performance statistic, (4) to obtain the best combination of factors/levels, and (5) to perform a confirmation experiment. Above all, process (3) is the spirit of PCA method in solving the multi-response problem. Process (3) is based on Pearson and Hotelling to explain structure of variance-covariance by the way of linear combinations of the normalized value of each response. Let Y_i be the normalized value of the i^{th} response, for $i = 1,......., p.$ To compute PCA, $k(k \leq p)$ components will be obtained to explain the variance in the p responses. Principal components are independent (uncorrelated) of each other. Simultaneously, the explained variance of each principal component for the total variance of responses is also gained. The formed j principal component is a linear combination $Z_j = \sum_{i=1}^{p} a_{ji} Y_i$, for $j = 1,.........,k$ subjecting to $\sum_{i=1}^{p} a_{ji}^2 = 1$; also, the coefficient a_{ji} is called Eigen vector.

Now, this paper explores the WPC method to overcome the shortcomings of multi-response problem in the PCA method [19]. To achieve the object, first, all principal components are to be used in this WPC method; thus, the explained variance can be completely explained in all responses. Second, because 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 (MPI) is $\mathrm{MPI} = \sum_{j=1}^{k} \mathrm{W_j Z_j}$, where $\mathrm{W_j}$ is the weight of the $\mathrm{j^{th}}$ principal components. The larger the MPI is, the higher the quality.

3. Taguchi Method

Taguchi Method was proposed by Dr. 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, [Antony and Antony (2001)]. It is the ratio of the mean (Signal) to the standard deviation (Noise). The ratio depends on the quality characteristics of the product/process to be optimized. The standard S/N ratios generally used are as follows (Equations 1-3): - Higher the Better (HB), Lower the Better (LB) and Nominal is Best (NB). The optimal setting is the parameter combination, which has the highest S/N ratio.

Higher-the-better (HB)

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

Where n = 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.

Lower-the-better (LB)

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

This is applied for problems where minimization of the performance characteristics is intended. This is termed as smaller-the-better type problem.

Nominal-the-best (NB)

S/N Ratio= $-10\log_{10}\left(\frac{\mu^2}{\sigma^2}\right)$ (3)

Here, $\mu =$ mean and $\sigma =$ Standard deviations

Based on the signal-to-noise (S/N) analysis, the signal-to-noise (S/N) ratio 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. Finally, a confirmatory experiment is conducted to verify the optimal processing parameters obtained from the parameter design.

4. Experimentation

4.1 Selection of EDM process parameters:

The selected process parameters for current research include peak curreent (*Ip, A*), pulse on time (*Ton*, µs) and pulse off time (*Toff,* µs) , flushing pressure (Fp, Kgf/cm²) while other parameters have been assumed to be constant over the experimental domain.

4.2 Selection of response variables:

From literature review it is found that, all the studies, whether experimental or analytical, mostly concentrate on the average roughness value for surface quality. But consideration of only average roughness is not sufficient to describe the surface quality of a machined surface. The present study thus aims at consideration of the following five roughness parameters as the response variables: average roughness (*Ra*); average maximum height of the profile (Rz), root mean squared roughness (*Rq*); kurtosis (*Rku*) and total height of the profile (Rt)..

4.3 Work piece material used:

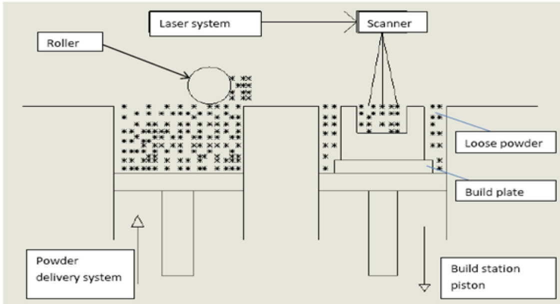
The present study was carried out with D2 Steel Workpiece.

4.4 Tool Electrodes used:

In the experiment a direct metal laser sintered (DMLS) part (cylindrical in shape with 20mm length & 20mm diameter) using DirectMetal20 is used as EDM electrode.

4.41 DMLS Tool (Special Tool) Preparation

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 250 extended machine which consists of a laser unit, a control computer, a build chamber, a powder dispenser, a wiper blade and a build cylinder. 3D CAD model of the cylindrical specimen (20mm diameter & 20 mm length) was modelled using "Magic RP software". CAD model in STL format was sliced using "EOS RP Tools". The layer thickness was maintained constant at 40µm. 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 degree Celsius. Laser power, layer thickness, hatch width and hatch spacing and Laser scan speed were maintained constant at 228W, 40µm, 5mm, and 0.2 mm respectively.



(Direct Metal Laser Sintering Process)

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.

4.5 Design of Experiment (DOE)

The design of experiments technique permits us to carry out the modeling and analysis of the influence of process variables (design factors) on the response variables. In the present study peak curreent (*Ip, A*), pulse on time (*Ton*, µs) and pulse off time (*Toff,* µs) & flushing pressure (Fp, Kgf/cm²) have been selected as design factors while other parameters have been assumed to be constant over the experimental domain.

The process variables (design factors) with their values on different levels are listed in Table 1. The selection of the values of the variables is limited by the capacity of the machine used in the experimentation as well as the recommended specifications for different work piece and tool material combinations. Three levels, having equaled spacing, within the operating range of the parameters have been selected for each of the factors. In the present investigation, L_9 Orthogonal Array (OA) design has been considered for experimentation. Interaction effect of process parameters has been assumed negligible.

Table 1: Process parameters and domain of experiments

Levels	DMLS Electrode			
	Ip (Ampere)	Ton (µsec)	Toff (µsec)	Fp (Kgf/cm²)
1	8	100	10	0.3
2	10	150	20	0.6
3	12	200	30	0.9

4.6 Equipment used

The equipment's used are (1) CNC EDM Machine (ECOWIN M/C, Taiwan Make, and MIC 432CS Model) for EDM operation and (2) Surface Roughness Tester Talysurf (Taylor Hobson, Surtronic 25) for surface roughness measurement.

Table 2: Experimental results along with design matrix

Sl. No.	L_9 OA				Measured Responses				
	Ip	Ton	Toff	Fp	Ra	Rz	Rq	Rku	Rt
1	1	1	1	1	3.7	19.967	4.55	2.667	27.4
2	1	2	2	2	4.367	21.733	5.297	2.31	25.3333
3	1	3	3	3	3.14	18.733	3.883	2.71	22.3

4	2	1	2	3	4.79	23.933	5.913	2.91	42.5667
5	2	2	3	1	5.133	21.867	6.123	2.083	37.3333
6	2	3	1	2	3.977	20.1	4.843	2.64	33.6
7	3	1	3	2	3.417	18.467	4.263	2.743	25.3333
8	3	2	1	3	5.083	24.167	6.153	2.357	33.8333
9	3	3	2	1	4.573	22.367	5.697	2.673	37.2667

5. Data Analysis Results and Discussions

Experimental data has been normalized first. Normalized response data are shown in Table 3. For all surface roughness parameters (Lower-the-Better) LB criteria has been selected. Data has been normalized using the equations shown below.

Corresponding to LB (Lower-the-Better) criteria:

$$X_i^*(k) = \frac{\min X_i(k)}{X_i(k)} \qquad (4)$$

Here, $i = 1, 2, ..., m;$
$k = 1, 2, ..., n$

Assuming, the number of experimental runs in Taguchi's OA design is m , and the number of quality characteristics is n .

$X_i^*(k)$ is the normalized data of the $k\,th$ element in the $i\,th$ sequence.

$X_{0b}(k)$ is the desired value of the $k\,th$ quality characteristic. After data normalization, the value of $X_i^*(k)$ will be between 0 and 1. The series $X_i^*, i = 1, 2, 3, ..., m.$ can be viewed as the comparative sequence used in the present case.

After data normalization a check has to be made whether responses are correlated or not. Table 4 represents Pearson's correlation coefficient between the responses. In all cases non-zero value of correlation coefficient indicates that all response features are correlated to each other. In order to eliminate response correlation Principal Component Analysis has been applied. Table 5 represents results of PCA (Eigen value, Eigen vector, accountability proportion and cumulative accountability proportion).

Next, correlated responses have been converted into uncorrelated quality indices called principal components (Z1, Z2, Z3). These individual principal components have been furnished in Table 8 and Z4 and Z5 are left out on account of negligible accountability proportion. Accountability proportion of individual principal components has been treated as individual priority weights. Finally, multi-response performance index (MPI) has been computed using the following equation (Table 7).
MPI=Z1×0.746+Z2×0.21+Z3×0.035
(5)

The MPI has been taken as a single response and is optimized (maximized) using Taguchi method. HB (Higher-the-Better) criterion has been explored to maximize the multi-response performance index.

$$SN\,(Higher - the - better) = -10\log\left[\frac{1}{t}\sum_{i=1}^{t}\frac{1}{y_i^2}\right]$$

The predicted optimal setting becomes $Ip_1Ton_3Toff_3Fp_2$. (Superscript represents optimal level of corresponding factors). After evaluating the optimal parameter settings, the optimal result was verified using the confirmatory test. So quality is improved.

Table 3.Normalized Data

Sl. No.	Ra	Rz	Rq	Rku	Rt
Ideal	1.0000	1.0000	1.0000	1.0000	1.0000
1	0.8486	0.9249	0.8534	0.781	0.8139
2	0.719	0.8497	0.7331	0.9017	0.8803
3	1	0.9858	1	0.7686	1
4	0.6555	0.7716	0.6567	0.7158	0.5239
5	0.6117	0.8445	0.6342	1	0.5973
6	0.7895	0.9188	0.8018	0.789	0.6637
7	0.9189	1	0.9109	0.7594	0.8803
8	0.6177	0.7641	0.6311	0.8838	0.6591
9	0.6866	0.8256	0.6816	0.7793	0.5984

Table 4: Check for correlation

Sl. No.	Correlation between responses	Pearson correlation coefficient	Comment
Ra and Rz	0.940		Both are correlated
Ra and Rq	0.998		Both are correlated
Ra and Rku	-0.093		Both are correlated
Ra and Rt	0.871		Both are correlated
Rz and Rq	0.946		Both are correlated
Rz and Rku	0.020		Both are correlated
Rz and Rt	0.814		Both are correlated
Rq and Rku	-0.058		Both are correlated
Rq and Rt	0.882		Both are correlated
Rku and Rt	0.183		Both are correlated

Table 5: Results of Principal Component Analysis (PCA)

	ψ_1	ψ_2	ψ_3
Eigen Value	3.7288	1.0511	0.1726
Eigen Vector	0.511	-0.110	-0.068
	0.497	-0.006	-0.599
	0.513	-0.076	-0.073
	0.007	0.972	-0.170
	0.478	0.191	0.776
AP	0.746	0.210	0.035
CAP	0.746	0.956	0.991

N.B.: AP: Accountability Proportion; CAP: Cumulative Accountability Proportion

Table 6.Individual Principal Components

Sl. No.	Individual Principal Components		
	Z1	Z2	Z3
Ideal	2.0060	0.9710	-0.1340
1	1.7256	0.7508	-0.1752
2	1.5929	1.5929	-0.0816
3	1.9973	0.7462	-0.0862
4	1.3108	0.6692	-0.2698
5	1.3501	0.9655	-0.3002
6	1.5942	0.7404	-0.2817
7	1.8599	0.7300	-0.1740
8	1.3404	0.8644	-0.1846
9	1.4023	0.7395	-0.2591

Table 7.MPI and corresponding SN Ratio

Sl. No.	MPI	S/N Ratio of CQL
1	1.4388	3.16001
2	1.5200	3.63687
3	1.6437	4.31645
4	1.1089	0.89785
5	1.1994	1.57928
6	1.3349	2.50897
7	1.5347	3.72047
8	1.1750	1.40076
9	1.1923	1.52771

Table 8: Response Table for Analysis of Means (ANOM)

Level	Ip	Ton	Toff	Fp
1	1.486	1.361	1.316	1.277
2	1.214	1.250	1.226	1.415
3	1.301	1.390	1.459	1.309
Delta	0.272	0.140	0.234	0.138s
Rank	1	3	2	4

6. Conclusions

The following conclusions may be drawn from the results of the experiments and analysis of the experimental data in connection with multi-response optimization in Electric Discharge Machining operation.

1) Application of PCA has been recommended to eliminate response correlation by converting correlated responses into uncorrelated quality indices called principal components which have been as treated as independent response variables for optimization.
2) Based on accountability proportion (AP); treated as individual response weights, WPCA can combine individual principal components into a single multi-response performance index MPI to be taken under consideration for optimization. This is really helpful in situations where large number of responses have to be optimized simultaneously.
3) The said approach can be recommended for continuous quality improvement and off-line quality control of a process/product.

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