Optimization in EDM of D2 Steel with Multiple Surface Roughness Characteristics Using Hybrid Taguchi Method

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Abstract - The present study presents a multi-response optimization problem by applying Principal Component Analysis (PCA) combined with Taguchi method. The aim of the study is to evaluate the best process environment which could simultaneously fulfill multiple Surface Roughness characteristics. As traditional Taguchi method cannot solve a multi-objective optimization problem; to overcome this limitation, Principal component analysis has been coupled with Taguchi method. 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.

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 non-traditional machining process which can efficiently machine electrically conductive metals irrespective of their geometry and hardness by use of thermal energy. It is e to manufacture number of automotive and aerospace components, dies and moulds. In absence of any physical contact between the tool electrode and the work electrode during machining, mechanical stresses are eliminated. EDM is done with a 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 a desired shape. The power supply by producing a series of electrical spark discharges between the tool electrode and the work electrode removes material from the work electrode by thermal erosion. In EDM soft metal tool electrode can machine very hard material.Number of industries does use EDM for high precession machining. Die Sinking EDM is the major EDM variant. The most common measures for surface roughness is centerline average roughness R_a measured in μm. But considering the centerline average roughness alone may not give exact picture of surface roughness. So other important roughness parameters like R_z , R_q , R_{ku} and R_t should also be considered. Optimization of the process parameters is required, in order to achieve the desirable surface performance characteristics. Complexity of eroded cavity increases the cost of EDM machining. So for reducing cost of EDM Tool as well as product development time rapid prototyping (RP) technology has been developed. This includes a set of methods, in which addition of material on layer-by- layer basis creates the shape of the desired component. RT techniques can be broadly classified into direct, indirect and patterns of casting [Rosochowski and Matuszak, (2000)]. The direct methods employ 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 required components. The most common of RP techniques is Stereolithography (SL), which creates plastic parts using photo-curable resins. Laser Sintering (LS) provides 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 SL and LS manufacturing processes. It is observed that SL offers greater dimensional accuracy (±0.15 mm) and surface finish (from 1 to 5 μm) compared to LS while LS offers greater mechanical strength of prototypes compared to SL [kurth (1991); (Liu and Jiang, 2003)] specifically when it uses metal powders. Apart from the above two other well-known RP techniques are Laminated Object Manufacturing (LOM), Fused Deposition Modeling (FDM), 3D Printing, Thermo Jet Printing (THJ), etc. While these methods are concerned with RP, many researchers [(Greul, Pintat and Greulich, 1995); (Ippolito, Iuliano and Gatto, 1996); (Booking, Rennie and Bennett, 2000)] attempted to produceelectrodes, too. In EDM mechanism both the work and tool electrodes are eroded simultaneously. It is observed thatPulse on time (T_{on}), Pulse off Time (T_{off}) and Discharge Current (I) are the factors which have maximum influence on EDM performance. The dimensional accuracy of the produced part relies on the surface texture and dimensional accuracy of the tool electrode. Electrodes manufactured using RP techniques should have very good dimensional accuracy and acceptable surface roughness.

It is seen that the EDM cycle for mould and dies production takes from one fourth to two fifth of the total lead time and half of the production cost [Semon (1975)]. The production of electrode itself consumes half of the total cost in EDM. Majority of the dies and moulds to be produced need more than one cavities and each needs a different electrode of specific shape. An effective additive technology to create single piece electrodes would considerably reduce lead-time and tooling cost. RP is a unique method for quick formation of physical models directly from Computer Aided Design (CAD) models. RT usually, is connected with fast tooling manufacturing with the help of prototypes made by RP. Researchers are now paying their attention to minimize lead-times and development costs. Greul, Pintat and Greulich, (1995), Ippolito, Iuliano and Gatto, (1996), Dickens et al., (1997) made efforts to develop methods for RP-EDM tooling by the use of stereo lithography (SL) models. It was observed that the thin-coated stereo lithography electrodes present wear and failure mechanisms.

Durr, Pilz and Eleser (1999) developed simple cylindrical metal electrodes by direct metal laser sintering (DMLS) using Ni, bronze and copper phoshite as metal powders. First Copper phoshite intermingled with bronze as low melting material which was followed by second thermal 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 $mm^3/\min$ and it resulted in greater TWR than conventional electrodes and not acceptable roughness quality in the workpiece. Finally, it was suggested that the performance of the electrodes need to improve significantly for practical application. Tay and Haider (2001) also made an attempt to fabricate metal electrodes by DMLS by using the powder metal containing of copper, tin, nickel and phosphorus. The University of Bournemouth [Dimla, Hopkinson and Rothe, (2004)] concentrated on the shell thickness of copper shell electroplated DLMS 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 DLMS electrodes were not suitable for industrial use due to the unevenness in copper shell thickness. A SLS/RAP-I system was used by NUAA, China [Zhao et al. (2003)], to manufacture direct RT electrodes. The powders used for the purpose were steel, polyester and phosphate. To fabricate the green part laser sintering was done which was followed by treatment in three phases. Sintering was done at low temperature (between 260-300 ^{o}C) to decompose the polyester in the first phase. Then sintering was done at high temperature (between760-1,040 ^{o}C) and a rigid inorganic compound was formed due to phosphate-steel reaction. In the last phase to improve quality copper infiltration was done at 1,120 ^{o}C. It was observed that electrodes manufactured by the above method were suitable for finishing operations in EDM. Meena and Nagahanumaiah, (2006) applied Taguchi fractional factorial design of experiments in order to investigate the effects of EDM parameters on the DMLS electrode performance employing EOSINT M 250 machine and an EOS Direct Metal 50 metal powder system. It was found that, as with conventional electrodes, the current is the main parameter. 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. Czyzewski et al., (2009) described a method of rapid prototyping of electrically conductive components based on 3D printing technology. The prototyped model is made of plasterbased powder bound 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 nanofibers (CNF) in epoxy resin. Amorim et al., (2013) 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 combination of copper and bronze nickel powder. Pawar et al. 2016 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 the responses.

In the present research, the optimizations of EDM machining parameters using different type of electrodes like brass, copper and DMLS Electrode using Direct Metal 20 has been carried out for optimization of multiple surface roughness characteristics performance characteristics using Principal component analysis (PCA) 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 PCA has been coupled 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 [Datta, Bandopadhyaya and Pal, (2008)], desirability function based Taguchi [Datta, Bandopadhyaya and Pal, (2006)], and utility concept based Taguchi methods [Kumar, Barua, and Gaindhar, (2000); Walia, Shan and Kumar (2006)] employed for multi-objective optimization problems in different manufacturing processes which neglect response correlation may lead to inaccurate results. To overcome this constraint, the study suggests application of WPCA to remove response correlation and to convert correlated responses into uncorrelated quality indices called principal components. These principal components have been combined further to determine the composite principal component called multi-response performance index (MPI) (Mohanty et al. 2009). In this way the multi-objective optimization problem has been transformed into an equivalent single objective optimization problem which has been solved by Taguchi method.

2. WEIGHTED PRINCIPAL COMPONENT ANALYSIS (WPCA)

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

a) To measure each response for each setting,

b) To normalize each response for each setting between 0 to 1

c) To convert these normalized responses into a multi-response index

d) To get the best combination of factors/levels, and

e) To carry out a confirmation experiment.

Data normalization for smaller-the-better criterion is done using the following equation.

i. SB (Smaller-the-Better)

$$Y_i(k) = \frac{\min X_i(k)}{X_i(k)} \tag{2.1}$$

Here, i = 1,2,........,m; k = 1,2,........., n and $Y_i(k)$ is the normalized value, where the number of experimental runs in Taguchi's orthogonal array (OA) design as m and the number of quality characteristics as n , $Y_i(k)$ represents the normalized data of the k^{th} element in the i^{th} sequence.

To compute PCA, $k\left(k \le p\right)$ components will be obtained to explain the variance in the p responses. The j^{th} principal component obtained is a linear combination

$$Z_j = \sum a_{ji} Y_i \tag{2.2}$$

for $j = 1, ..., k$ subjecting to $\sum_{i=1}^{p} a_{ji}^2 = 1$; where the coefficient a_{ji} is called eigenvector.

As 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

$$MPI = \sum_{j=1}^{k} W_j Z_j \tag{2.3}$$

where W_j is the weight of the j^{th} principal components. The larger MPI indicates better 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 ratio for smaller the better criterion is given as follows:

Smaller-the-Better (SB)

$$S/N\ ratio = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \tag{3.1}$$

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

The optimal setting is the parameter combination, which has the highest S/N ratio.

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 current (I_p, *A*), pulse on time (T_{on}, μs) and pulse off time $(T_{off}, \mu s)$, flushing pressure ($F_p, kN/m^2$) and tool electrode 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, not much research work is carried out considering the different surface roughness characteristics. So in this case five important roughness parameters R_a, R_z, R_q, R_{ku} and R_t are chosen as response variables.

where R_a is the arithmetic mean surface roughness of all the profile values,

R_z is the surface roughness depth which is the average absolute value of five highest peaks & five lowest valleys over the evaluation length,

R_q is the root mean square roughness which is the root mean square average of the roughness profile ordinates,

R_{ku} is the skewness which is the symmetry of the profile about the mean line and

R_t is the total height of the roughness profile which is the maximum peak to valley height of the profile in the evaluation length.

4.3 Work Piece Material

The present study was carried out with D2 Steel Workpiece. The chemical composition of the work piece materials are shown in Table 1.

Table 1
Composition (wt. %) of work piece material (D2 steel)

C	Si	Cr	Mo	V	Fe
1.50%	0.30%	12.00%	0.80%	0.90%	84.50%

5. TOOL ELECTRODES

In the experiment 3 tools, brass, copper & direct metal laser sintered (DMLS) part using Direct Metal20 are used as EDM electrodes. All the three electrodes are cylindrical in shape with 20mm in each in diameter and length. The chemical composition test was done for the three tools with the help of XRF Analyzer (Epsilon-1, PANalytical) and compositions are shown in Table 2.

Table 2
Chemical composition of tool electrodes (wt. %)

Electrode Used		
Copper	Brass	DMLS (Using DirectMetal 20)
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%		

DMLS tool preparation

DMLS is a liquid phase sintering method, which builds 3D geometries layer by layer. EOSINT 250 extended machine (which has a laser unit, a control computer, a powder dispenser, a build chamber and a wiper blade) is employed to build the part using DirectMetal 20. 3D CAD model of the cylindrical specimen (20 mm diameter and 20 mm length) was modelled using “Magic RP software”. CAD model in STL format was sliced using “EOS RP Tools”. The layer thickness has been maintained at 40 µm. The sliced data was transferred to the process computer of DMLS machine where laser path was generated with PSW software. A steel base plate has been mounted on building platform. The building platform is heated to a temperature of 80^oC. Laser power, layer thickness, hatch width and hatch spacing and Laser scan speed were maintained constant at 228 W, 40 µm, 5 mm, and 0.2 mm respectively. The Schematic diagram of Direct Metal Laser Sintering Process has been presented in Fig. 1. Sintering was carried out in nitrogen atmosphere (oxygen level <1.5%).

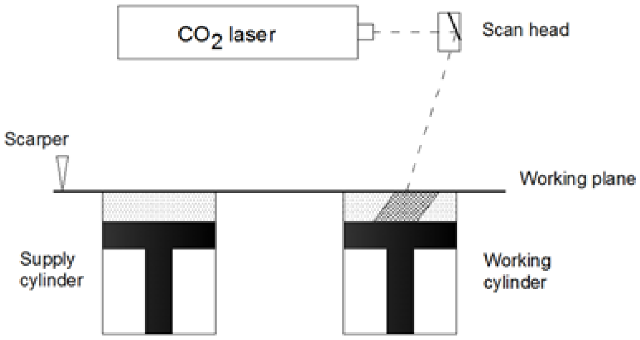

Fig. 1 Schematic arrangement of DMLS machine

5.1 Design of Experiments (DOE)

In the present study discharge current (I, A), pulse on time $(T_{on}, \mu s)$, pulse off time $(T_{off}, \mu s)$ and flushing pressure $(F_p, kN/m^2)$ and Tool Electrode (TE) have been selected as process parameters 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 3.

Table 3
Process parameters and domain of experiments

Levels	I (Amp)	T_{on} (µs)	T_{off} (µs)	F_p (kN/m²)	Tool Electrode (TE)
1	8	100	10	29.43	Brass
2	10	150	20	58.86	Copper
3	12	200	30	88.29	DMLS

The measured parameters along with designed matrix have been shown in Table 4.

Table 4
Experimental results along with design matrix

Sl. No.	L_{27} OA					Measured responses				
	I	T_{on}	T_{off}	F_p	TE	R_a	R_z	R_q	R_{ku}	R_t
1	1	1	1	1	1	2.11	11.3	2.63	3.16	19.3
2	1	1	1	1	2	2.94	14.333	3.527	2.447	21.733
3	1	1	1	1	3	3.7	19.967	4.55	2.667	27.4
4	1	2	2	2	1	1.927	11.2	2.463	3.17	17.4
5	1	2	2	2	2	3.03	16.1	3.693	2.523	22.333

6	1	2	2	2	3	4.367	21.733	5.297	2.31	25.333
7	1	3	3	3	1	1.9	10.967	2.407	3.09	17.033
8	1	3	3	3	2	2.667	14.1	3.293	2.63	20.333
9	1	3	3	3	3	3.14	18.733	3.883	2.71	22.3
10	2	1	2	3	1	2.283	12.2	2.84	3.067	19.733
11	2	1	2	3	2	3.573	18.8	4.417	2.653	26.233
12	2	1	2	3	3	4.79	23.933	5.913	2.91	42.567
13	2	2	3	1	1	2.347	12.433	2.907	2.91	19.233
14	2	2	3	1	2	3.347	16.533	4.043	2.433	26.367
15	2	2	3	1	3	5.133	21.867	6.123	2.083	37.333
16	2	3	1	2	1	2.31	12.433	2.873	3.083	20.033
17	2	3	1	2	2	3.53	19.4	4.753	2.527	27.167
18	2	3	1	2	3	3.977	20.1	4.843	2.64	33.6
19	3	1	3	2	1	2.31	12.433	2.873	3.083	20.033
20	3	1	3	2	23	3.457	18.533	4.287	2.85	28.967
21	3	1	3	2	3	5.257	24.2	6.397	2.333	36.7
22	3	2	1	3	1	2.783	14.267	3.41	2.643	21.767
23	3	2	1	3	2	3.9	19.8	4.803	2.74	27.567
24	3	2	1	3	3	5.083	24.167	6.153	2.357	33.833
25	3	3	2	1	1	2.647	14.2	3.3	2.72	22.133
26	3	3	2	1	2	3.933	20	4.907	2.77	32.233
27	3	3	2	1	3	4.573	22.367	5.697	2.673	37.267

6. DATA ANALYSIS

Experimental data from Table 4 (responses) has been normalized using Eq. 2.1 and are presented in Table 5. For all the roughness parameters considered smaller the better (SB) criteria are selected.

Table 5
Normalized experimental data for PCA

Sl. No.	For R_a	For R_z	For R_q	For R_{ku}	For R_t
1	0.9	0.991	0.937	0.731	0.883
2	0.646	0.781	0.698	0.944	0.784
3	0.514	0.561	0.541	0.866	0.622
4	0.986	1	1	0.729	0.979
5	0.627	0.696	0.667	0.916	0.763
6	0.435	0.515	0.465	1	0.672
7	1	1.021	1.023	0.748	1
8	0.712	0.794	0.748	0.878	0.838
9	0.605	0.598	0.634	0.852	0.764
10	0.832	0.918	0.867	0.753	0.863
11	0.532	0.596	0.558	0.871	0.649
12	0.397	0.468	0.417	0.794	0.4
13	0.81	0.901	0.847	0.794	0.886
14	0.568	0.677	0.609	0.949	0.646
15	0.37	0.512	0.402	1.109	0.456
16	0.823	0.901	0.857	0.749	0.85
17	0.538	0.577	0.518	0.914	0.627
18	0.478	0.557	0.509	0.875	0.507
19	0.823	0.901	0.857	0.749	0.85

20	0.55	0.604	0.575	0.811	0.588
21	0.361	0.463	0.385	0.99	0.464
22	0.683	0.785	0.722	0.874	0.783
23	0.487	0.566	0.513	0.843	0.618
24	0.374	0.463	0.4	0.98	0.503
25	0.718	0.789	0.746	0.849	0.77
26	0.483	0.56	0.502	0.834	0.528
27	0.415	0.501	0.432	0.864	0.457

Table 6
Results of PCA for the quality indicators

Principal Components	Z_1	Z_3	Z_3	Z_4	Z_5
Eigen value	4.4483	0.4827	0.0601	0.0074	0.0014
Eigenvector	$\begin{vmatrix} 0.472 \\ 0.465 \\ 0.472 \\ -0.368 \\ 0.450 \end{vmatrix}$	$\begin{vmatrix} -0.079 \\ -0.177 \\ -0.110 \\ -0.906 \\ -0.360 \end{vmatrix}$	$\begin{vmatrix} -0.135 \\ -0.572 \\ -0.168 \\ -0.164 \\ 0.775 \end{vmatrix}$	$\begin{vmatrix} 0.670 \\ -0.623 \\ 0.287 \\ 0.129 \\ -0.254 \end{vmatrix}$	$\begin{vmatrix} 0.551 \\ 0.193 \\ -0.809 \\ -0.012 \\ 0.061 \end{vmatrix}$
AP	0.890	0.097	0.0.012	0.001	0.000
CAP	0.890	0.996	0.998	1.000	1.000

Principal component analysis is a data reduction technique. Usually if the first few principal components explain close to 90% of the variability other principal components are ignored. .Out up 5 principal components only the first principal component (Z_1) has been considered (from Table 6) as the first principal component itself accounts for 89% of variation compared to 11% by the remaining 4 (Z_2, Z_3, Z_4 and Z_5) put together. Due to this Z_2, Z_3, Z_4 and Z_5 have not been calculated. So Z_1 represents the entire data without much loss of information. The calculated values of Z_1 are presented in Table 7.

The relation between principal component Z_1 and responses is given by;

Z_1 = 0.472 × R_a (Normalized) + 0.465 × R_z (Normalized) + 0.472 × R_q (Normalized) – 0.368 × R_{ku} (Normalized) + 0.450 × R_t (Normalized)

Table 7
Calculated first principal components

Sl. No.	Z_1	Sl. No.	Z_1	Sl. No.	Z_1
1	1.4562	10	1.34	19	1.3188
2	1.0029	11	0.7631	20	0.778
3	0.72	12	0.4896	21	0.4119
4	1.5747	13	1.3076	22	1.0589
5	0.9407	14	0.8118	23	0.7031
6	0.5987	15	0.3996	24	0.4463
7	1.6044	16	1.3188	25	1.092
8	1.1123	17	0.7125	26	0.656
9	0.8931	18	0.631	27	0.5204

Accountability proportion of the each principal component is treated as its individual priority weight. In this case as only the first principal component has been considered, the multi-response performance index (MPI) is given as:

$$MPI = 0.890 \times Z_1$$

Table 7
MPI and SN ratio

Sl. No.	MPI	SN Ratio	Sl. No.	MPI	SN Ratio	Sl. No.	MPI	SN Ratio
1	1.2960	2.25210	10	1.1926	1.52990	19	1.1737	1.39114
2	0.8926	-0.98686	11	0.6792	-3.36005	20	0.6924	-3.19286
3	0.6408	-3.86555	12	0.4357	-7.21625	21	0.3666	-8.71615
4	1.4015	2.93186	13	1.1638	1.31757	22	0.9424	-0.51529
5	0.8372	-1.54342	14	0.7225	-2.82324	23	0.6258	-4.07129
6	0.5328	-5.46872	15	0.3556	-8.98076	24	0.3972	-8.01982
7	1.4279	3.09396	16	1.1737	1.39114	25	0.9719	-0.24757
8	0.9899	-0.08817	17	0.6341	-3.95684	26	0.5838	-4.67472
9	0.7949	-1.99375	18	0.5616	-5.01146	27	0.4632	-6.68463

Values of MPI and the corresponding SN ratio for all experimental runs are listed in Table 7. Main effects plot for SN ratio has been represented by Fig. 2. The predicted best parametric combination becomes $I_1 T_{on3} T_{off3} F_{p3} TE_1$ (Subscript represents optimal level of corresponding factors) as obtained from Fig. 2.The process model for MPI obtained through regression analysis is given below as;

$$MPI = 1.66203 - 0.144256\ I + 0.0128556\ T_{on} + 0.0290611\ T_{off} + 0.0219667\ F_p - 0.344172\ TE$$

After evaluating the best parametric combination, the result was verified using the confirmatory test. So quality is improved.

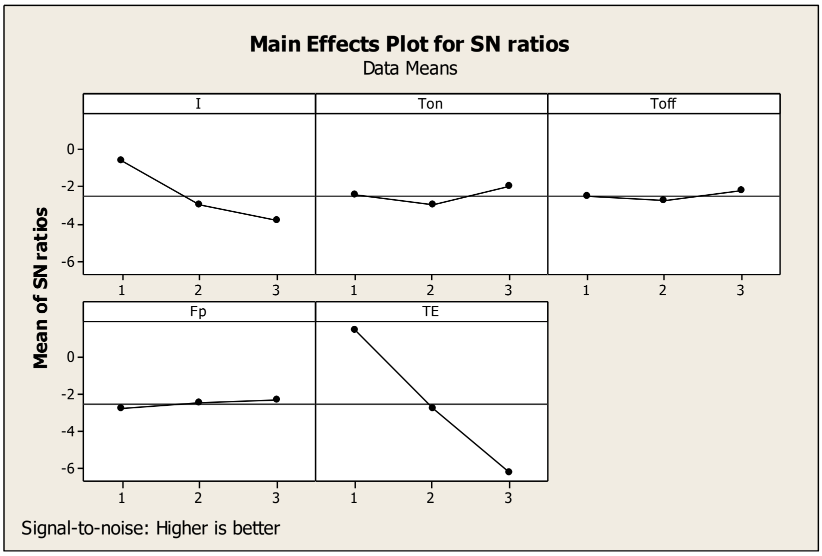

Fig. 2 Main effects plot for SN ratio for MPI

Table 8
ANOVA for MPI

Source	DF	Seq SS	Adj SS	Adj SS	F	P	% Contribution	Significance of factors
I	2	0.40093	0.40093	0.20047	38.44	0.000	14.615	Significant
T_{on}	2	0.02198	0.02198	0.01099	2.11	0.154	0.801	Insignificant
T_{off}	2	0.02316	0.02316	0.01158	2.22	0.141	0.844	Insignificant
F_p	2	0.00923	0.00923	0.00461	0.88	0.432	0.336	Insignificant
TE	2	2.20445	2.20445	1.10228	211.35	0.000	80.358	Significant
Error	16	0.08345	0.08345	0.00522			3.042	
Total	26	2.74330						

S = 0.0722184   R-Sq = 96.96%   R-Sq(adj) = 95.06%

From ANOVA (shown in Table 8) TE and I are found to be the significant factors. MPI is gradually decreasing with increase in the value of I . MPI is highest for Brass electrode followed by copper electrode followed by DMLS electrode.

7. CONCLUSIONS

The following conclusions may be drawn from the results of the experiments and study of the experimental data in the connection with optimization of multiple surface roughness characteristics with (1) discharge current, (2) pulse on time, (3) pulse-off time, (4) flushing pressure and (5) tool electrode as process parameters in EDM 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 parameter setting obtained by the cited method.
3) Tool electrode and discharge current have been found to be the most significant factors affecting the responses from ANOVA.

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