Optimization in Electric Discharge Machining of D2 Steel with Multiple Surface Rough nesses Characteristics with the Help of Tool Produced By Rapid Prototyping by Hybrid Taguchi Method

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Abstract:

The present study highlights a multi-objective optimization problem by applying utility concept 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. As traditional Taguchi method cannot solve a multi-objective optimization problem; Taguchi's Lower-the-Better (LB) criteria; individual response characteristics has been transformed into corresponding utility values. Individual utility values have been added finally to compute overall utility degree which serves as representative objective function for optimizing using Taguchi method. The study combined utility theory 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; utility concept; Taguchi method; Electric Discharge Machining, Direct Metal Laser Sintering.*

I. INTRODUCTION AND PRIOR STATE OF ART

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. Direct Metal Laser Sintering is the most advanced Rapid Prototyping Technology.
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 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. 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 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

costs..Rapid Prototyping Technology 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

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 usingscopper, 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,

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 utility concept 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 utility concept has been coupled with Taguchi method in the present investigation. By using utility theory, 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.

1) Utility Concept

According to the utility theory [Kumar et al. (2000), Walia et al. (2006)], if X_i is the measure of effectiveness of an attribute (or quality characteristics) i and there are n attributes evaluating the outcome space, then the joint utility function can be expressed as:

$$U(X_1, X_2, ..., X_n) = f(U_1(X_1).U_2(X_2).................U_n(X_n)) \quad (1)$$

Here $U_i(X_i)$ is the utility of the i_{th} attribute.

The overall utility function is the sum of individual utilities if the attributes are independent, and is given as follows:

$$U(X_1, X_2, ..., X_n) = \sum_{i=1}^{n} U_i(X_i) \quad (2)$$

The attributes may be assigned weights depending upon the relative importance or priorities of the characteristics. The overall utility function after assigning weights to the attributes can be expressed as:

$$U(X_1, X_2, ..., X_n) = \sum_{i=1}^{n} W_i.U_i(X_i) \quad (3)$$

Here W_i is the weight assigned to the attribute i.

A preference scale for each quality characteristic is constructed for determining its utility value. Two arbitrary numerical values (preference number) 0 and 9 are assigned to the just acceptable and the best value of the quality characteristic respectively. The preference number P_i can be expressed on a logarithmic scale as follows:

$$P_i = A \times \log\left(\frac{X_i}{X_i^{'}}\right) \quad (4)$$

Here X_i is the value of any quality characteristic or attribute i, $X_i^{'}$ is just acceptable value of quality characteristic or attribute i and A is a constant. The value A can be found by the condition that if $X_i = X^*$ (where X^* is the optimal or best value), then $P_i = 9$.

Therefore,

$$A = \frac{9}{\log \frac{X^*}{X_i^{'}}} \quad (5)$$

The overall utility can be expressed as follows:

$$U = \sum_{i=1}^{n} W_i . P_i \quad (6)$$

Here W_i is the weight assigned to the attribute i .

Among various quality characteristics types, viz. Lower-the-Better, Higher-the-Better, and Nominal-the-Best suggested by Taguchi, the utility function would be Higher-the-Better type. Therefore, if the quality function is maximized, the quality characteristics considered for its evaluation will automatically be optimized (maximized or minimized as the case may be). In the proposed method utility values of individual responses are accumulated to calculate overall utility index which serves as the single objective function for optimization.

2) 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)

$$\text{S/N ratio} = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \quad (7)$$

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)

$$\text{S/N ratio} = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \quad (8)$$

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)

$$\text{S/Nratio} = -10\log_{10}\left(\frac{\mu^2}{\sigma^2}\right) \quad (9)$$

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

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.

3) Experimentation

3.1 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.

3.2 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 describethe 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).

3.3 Work piece material used:

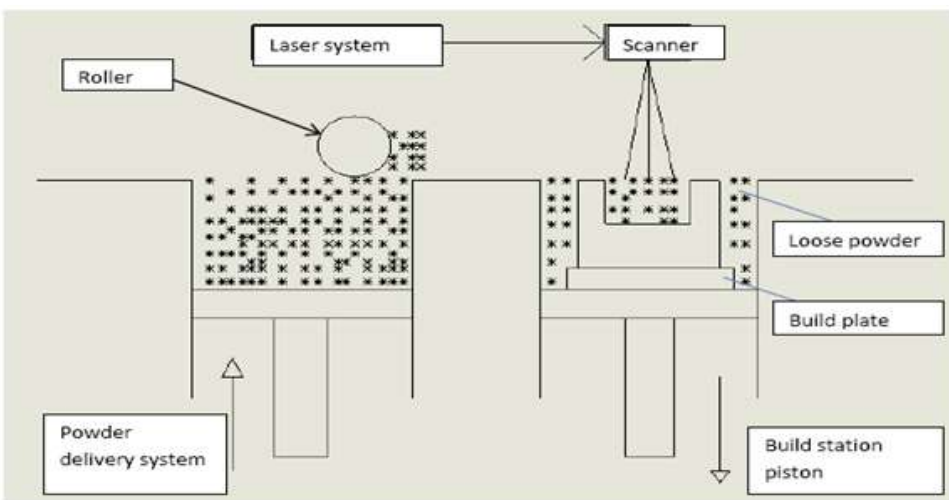
The present study was carried out with D2 Steel Workpiece.

3.4 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.

3.41 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.

3.5 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 current (*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 3. 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

3.6 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

4) Data Analysis

Experimental corresponding to L_9 Orthogonal Array (OA) design of experiment (Table 2) have been explored to calculate utility values of individual quality attributes by using equations (4-5). For all the roughness parameters Ra, Rz, Rq, Rku and Rt lower the better criteria has been used. The maximum of entries for each roughness parameter from Table 4 have been considered as just acceptable value; whereas minimum observed value has been treated as the best (desired) value. Individual utility measures of the responses have been furnished in Table 3.

The overall utility index has been computed using equation (6); tabulated in Table 4 with their corresponding (signal-to-noise) S/N ratio. In this computation it has been assumed that all quality features are equally important (same priority weight age). Figure 1 reflect S/N ratio plot for overall utility index; S/N ratio being computed using equation (10).

The overall utility index is then optimized (maximized) using Taguchi method.Taguchi's HB (Higher-the-Better) criterion has been explored to maximize the overall utility index (Equation 8).

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

Here t is the number of measurements, and y_i the measured ith characteristic value i.e. ith quality indicator. Optimal parameter setting has been found from Figure 1. The optimal setting should confirm highest utility index (HB criterion). **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.

In table 3 utility values of individual responses for each setting is calculated using equation

Table 3Utility Values for Individual Responses

Sl. No.	Utility Value for Ra	Utility Value for Rz	Utility Value for Rq	Utility Value for Rku	Utility Value for Rt
1	5.9947	6.3872	5.9008	2.3473	6.1328
2	2.9596	3.5517	2.9287	6.2156	7.2245
3	9	8.5215	9	1.9167	9
4	1.2665	0.3255	0.7779	0	0
5	0	3.346	0.0956	9	1.8263
6	4.6727	6.165	4.6806	2.6212	3.2931
7	7.4519	9	7.1746	1.5909	7.2245
8	0.1793	0	0	5.6734	3.1967
9	2.1155	2.5896	1.5054	2.2868	1.8512

The overall utility index is calculated by using equation 6 (Assigning equal weightage to all the responses). Signal to Noise Ratio (with Higher the Better criteria) for the overall utility index for each settings were calculated using Minitab software.

Table 4: Overall Utility Degree and the corresponding SN Ratio

Sl. No.	Overall Utility Index	Corresponding S/N Ratio
1	26.7628	28.5506
2	22.8801	27.1892
3	37.4382	31.4663
4	2.3699	7.4946
5	14.2679	23.0872
6	21.4326	26.6215
7	32.4419	30.2221
8	9.0494	19.1324
9	10.3485	20.2975

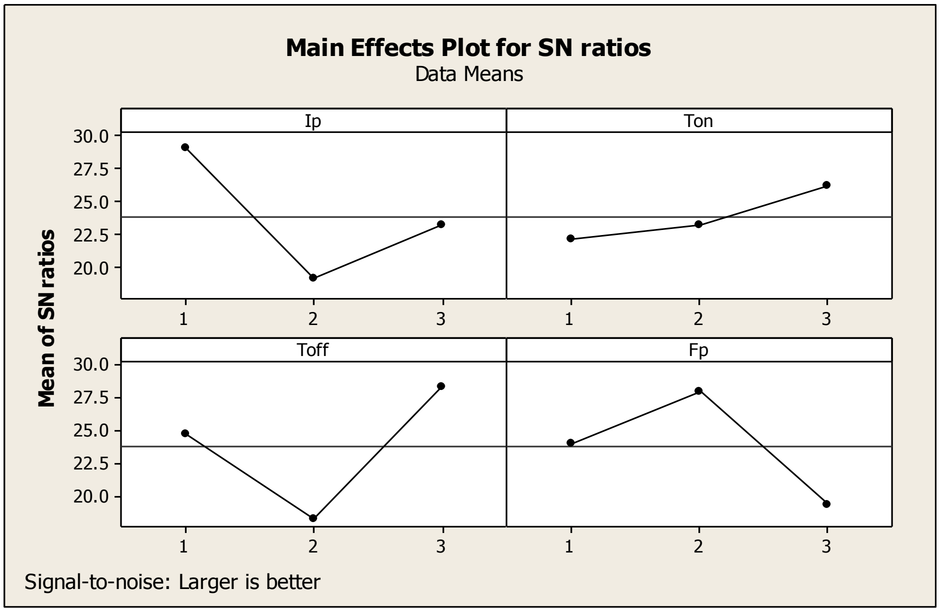


Figure 1: Evaluation of optimal setting

Table 5: Response Table for Analysis of Means (ANOM)

Level	Ip	Ton	Toff	Fp
1	29.03	20.52	19.08	17.13
2	12.69	15.50	11.87	25.58
3	17.28	23.07	28.05	16.29
Delta	16.34	7.67	16.18	9.30
Rank	1	4	2	3

5) 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) Utility based Taguchi method has been found fruitful for evaluating the optimum parameter setting to solve a multi-response optimization problem.
2) Confirmatory test has validated the parametric setting determined by utility based Taguchi Approach.
3) The said approach can be recommended for continuous quality improvement and off-line quality control of a process/product.

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