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POWDER MIXED ELECTRO DISCHARGE MACHINING OF EN19 STEEL

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Abstract
The paper systematically categories the literature on EDM and presents a systematic review of literature methodically. The literature on classification of EDM has so far been very limited. The paper presents an overview of EDM and also highlights the contributions of EDM initiatives towards improving manufacturing performance. The paper reveals the important issues in EDM ranging from maintenance techniques.
Keywords: EDM , PMEDM

With the advancement of technology in the industrial field and also with the growth in the field of material science, the hard materials which are difficult to machine by conventional methods of machining, which find different applications in the field of aerospace, nuclear, power and other industries, can be easily machined by the modern machining methods which are popularly known as unconventional machining methods. Also the latest trends in this field provide a concern to the industry and it becomes first choice rather than an alternative to conventional methods from the technical point of view. These machining methods show wide range of applications and they are very successful for machining materials which have high strength, heat resistance and wear resistance. In conventional machining method, it uses the cutting tool ability to stress the material beyond the yield point to start the machining, for this purpose, material of cutting tool should be harder than the work piece material. In conventional machining method, the tool get eroded after the successive machining operations while in unconventional machining, there is no direct contact between tool and work-piece so it notices very little erosion of tool. With the increase in the need of hard materials which are nowadays mostly used in various industries. This machining method is time consuming as it is difficult to machine hard materials since the material removal rate reduces with the increase in hardness of work piece material. These machining processes are not introduced to industrial field to replace the conventional machining processes but to supplement them.

Powder mixed EDM (PMEDM)

The mechanism of PMEDM is quite different from the conventional EDM process. In this process, abrasive powder is mixed in the dielectric fluid and it is circulated in the fluid with the help of pump at a certain velocity. When a voltage of ranges between 80-320 is applied between the tool electrode and workpiece, the spark gap is filled up with additive particles. The distance setup between the tool and workpiece is increased from 25-50 to 50-150mm. These charged particles are accelerated by the electric field and they act as conductors. The powder particles arrange themselves under the sparking area and gather in clusters. The chain formation helps in bridging the gap between the tool and the work piece.

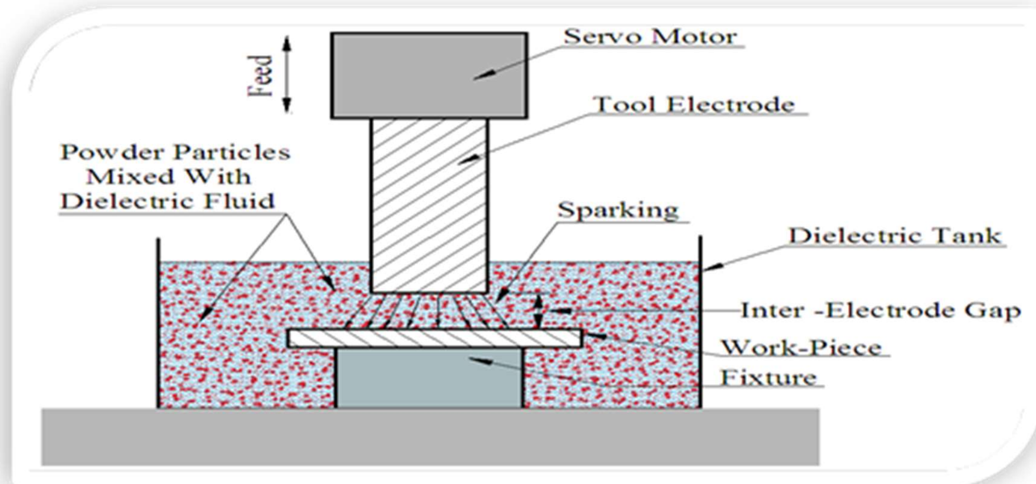

Figure 1.1 PMEDM Mechanism

The floating particles impede the ignition process by providing a higher discharge probability and also lowering the breakdown strength of the dielectric fluid. As a result of which material removal rate (MRR) is increased, tool wear rate is lowered and sparking efficiency is improved. Some of the commonly used abrasive powders are chromium, titanium, copper, aluminium, nickel, cobalt, iron, graphite, molybdenum, silicon and silicon carbide with quoted grain sizes between 1 µm and 100 µm.

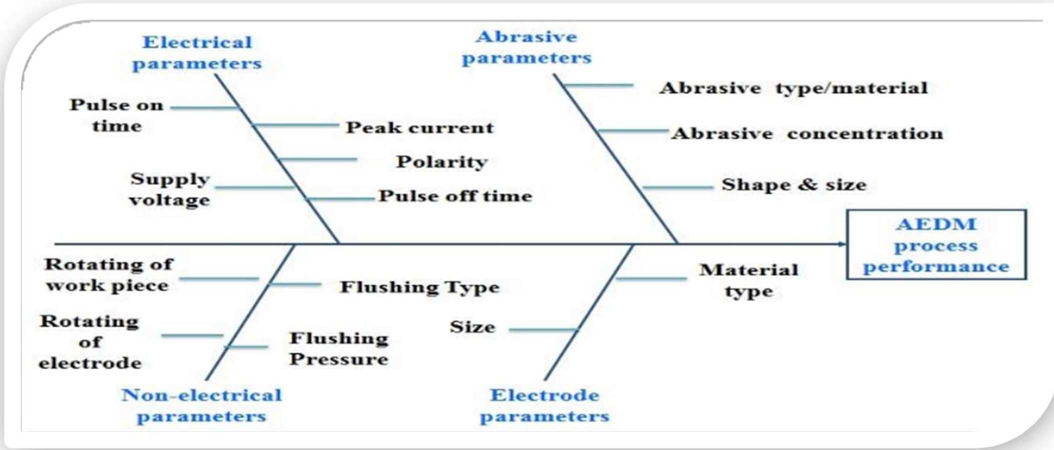

Figure 1.2 Factors affecting PMEDM process

PROBLEM FORMULATION

Gap in reviewed literature

Electrical discharge machining is one of the most popular non-traditional machining processes used for creating complex shapes within the parts and assemblies in the manufacturing industry. Its unique feature of using thermal energy to machine electrically conductive parts regardless of hardness has been its distinctive advantage. It erodes metal through the action of electrical discharges of short duration and high current intensity between the tool electrode and the work- piece. This process can machine any material, which is electrical conductive, irrespective of its hardness, shape and strength that are extremely difficult to machine when using conventional processes. Even highly delicate sections and weak materials can be machined without any fear of distortion because there is no direct contact between the tool and the work-piece. Although EDM machining technology is widely used in mechanical components manufacturing, it suffers from few limitations such as low machining efficiency and poor surface finish which are the key problems in its development. To overcome the limitations of EDM, a relatively new advancement in the direction of process capabilities is the addition of powder in the dielectric fluid of EDM. This new technique is called abrasive EDM (AEDM). AEDM employs abrasive particles which are mixed in the dielectric fluid and it has a different machining mechanism when compared to conventional EDM machining. It has been proved that the AEDM can distinctly improve the surface finish and surface quality to obtain near mirror like surfaces at relatively high machining rate. From the literature reviewed, it is observed that considerable research work has been done on various aspects of electrical discharge machining and abrasive mixed EDM of low carbon steels, carbides and a few die steels but no work has been carry out to

study EDM of EN19 steel. A comprehensive study on the effect of machining conditions on EN19 steel using AEDM process was not reported so far even though EN19 is widely used in various engineering applications. As a result the economical machining of EN19 still possesses difficulty to manufacturers. There is a need to investigate the machining of this material with conventional copper electrodes by varying different machining parameters such as electrode polarity, current intensity, pulse on time, pulse off time, discharge voltage, and concentration

of additives in kerosene oil. All these parameters are important for an effective study of the EDM process as a production operation. Material removal rate justifies the economy of the process and its selection in comparison to the conventional methods of machining. It also affects the surface finish and dimensional accuracy of the cavity produced. The rate of material removal depends upon various factors such as amount of energy in each discharge, duty cycle, frequency of discharge, electrode material, electrode size, work-piece material, polarity and dielectric flushing condition. Similarly, proper knowledge of WR is essential for determining the electrode material, size and number of electrodes. This also governs the economics of the EDM process. Hence the study of this factor becomes important. Surface finish produced on the machined surface plays an important role in production. It becomes more desirable when hardened materials are machined which require no subsequent polishing or grinding. The surface generated by EDM is actually a multitude of spherical craters produced by the energy contained in the sparks and this again depends upon the amperage, frequency, flushing pressure, material of electrode, polarity and finish on the electrode. These craters help in retaining lubrication during press working and are desirable in such applications. Dimensional accuracy is always essential from any machining process. New machining data obtained on AEDM of EN19 steel have a great importance and could be further used as base for applications of EN19 steels in engineering elements.
This Research work is undertaken to study the effect of machining characteristics of EN19 steel using conventional copper electrode in blind hole making operation of AEDM process. The chemical composition of EN19 steel is given table 3.1.

Table 3.1 Chemical composition of EN19 steel

Element	Value
C	0.35 - 0.45
Mn	0.50 - 0.80
Si	0.10 - 0.35
S	0.04
P	0.04
Cr	0.90 - 1.40
Mo	0.20 - 0.40

Planning of Research Work

Proper planning of experimental procedure is essential to obtain good results of research work. A brief description of selected parameters/variables and other equipment (machine tool, measuring equipments etc.) used in present study is given in the following text.

Research Design Variables

The design variables are described into two main groups:

1. Output response parameters i.e material removal rate (MRR), tool wear rate (TWR), wear ratio (WR), and surface roughness (SR).

2. Input machining parameters as shown in table 3.2.

Table 3.2 Input machining parameters

Variable	Units	Set-up
Work-piece	---	EN19
Block size of work-piece	mm	80 x 45 x 4
Tool electrode material	---	Copper
Tool electrode diameter	mm	9
Abrasive material	---	Chromium
Grain size of abrasive	µm	100
Abrasive concentration	g/l	0, 5, 10
Polarity	---	Positive and negative
Gap voltage	volt	30 - 50
Peak current	amp	4 - 12
Pulse on time	µs	90 - 200
Pulse off time	---	30 - 60
Dielectric Fluid	---	Kerosene

EN19 steel is chosen as work material in the present research work and copper is used as an electrode material. The diameter of the electrode was taken as 9 mm. Chromium fine powder with grain size 100 µm was chosen to mix in the dielectric fluid. The specifications of electrode material are given in table 3.3.

Table 3.3 Specifications of Electrode Material

Specification	Value
Density (g/cm^3)	8.96
Specific heat capacity (J/g-K)	0.385
Coefficient of thermal expansion (/ºC)	17×10^{-6}
Electrical conductivity (S/m)	59.6×10^{6}
Tensile strength (MPa)	90
Melting point (ºC)	1084
Thermal conductivity (W/m/K)	394
Electrical resistivity at 20ºC (Ω m)	1.673×10^{-8}
Specific heat at 293 K (kJ/kg/K)	0.383
Boiling point (ºC)	2595

Machine and Equipment

The following equipments were used in this experimental work:

1. EDM machine tool (Figure 3.1) Brand: OSCARMAX, Taiwan Model: EDMS645

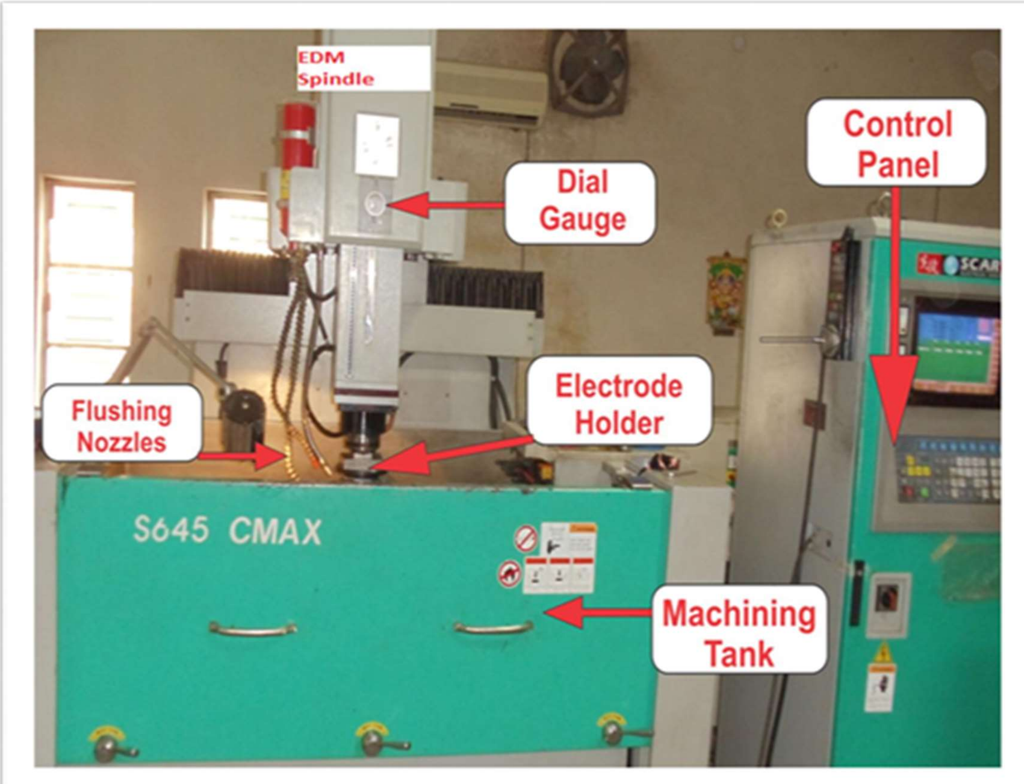

Figure 3.1 Machine tool

2. Surface roughness tester (Figure 3.2) Brand: Mitutoyo
Model: Surftest SJ-201P

Figure 3.2 Mitutoyo surface roughness tester

3. Balance (Figure 3.3) Brand: SHINKO-Japan Model: SER14628549

Figure 3.3 Precision Balance

Precision balance was used to measure the weight of the work-piece and electrode before and after the machining process.

Response parameters Evaluation

In this section, evaluation methods of response parameters under consideration are discussed.

MRR Measurement

The material removal rate (material erosion rate) may be expressed as material eroded from work-piece per unit time. In the present research work MRR of the work-piece was measured by dividing the difference of weight of work-piece (measured before and after machining with the help of weight balance) against the machining time elapsed during machining.

TWR Measurement

The TWR may be expressed as material eroded from tool electrode per unit time. In this study TWR of the electrode was measured by dividing the difference of weight of electrode (measured before and after machining with the help of weight balance) against the machining time elapsed during machining.

WR measurement

The WR may be expressed as ratio of wear rate of tool and work-piece. It is expressed and calculated with the help of following equation:

WR = Tool wear rate

Material removal rate

SR Measurement

The surface roughness of the work-piece can be expressed in many ways like arithmetic average (Ra), average peak to valley height (Rz) etc. The arithmetic surface roughness value (Ra) was used in this study. Ra is the arithmetic average roughness of the deviations of the roughness profile from the central line along the measurement. It can be represented as:

L

$Ra = 1/L \int |h(x)\, dx|\ 0$

Where, h(x): value of roughness profile L: evaluation length

EXPERIMENTATION

Introduction

Before starting the experiment work, first step was to design the experiments. Taguchi method is used as an efficient approach to determine the optimal machining parameters in the electrical discharge machining process. In this section, the use of the Taguchi method to determine the machining parameters with optimal machining performance in the EDM process is illustrated.

Design of Experiments

DOE (Design of Experiments) provides a powerful means to achieve breakthrough improvements in product quality and process efficiency. In 1980s Taguchi devised special method which uses a special design of orthogonal array to study the entire parameter space with only a small number of experiments. This method developed rules to carry out experiments, which further simplified and standardized the design of the experiment, along with minimizing the number of factor combinations that would be required to test for the factor effects.

Taguchi method

The Taguchi method can optimize performance characteristics through the settings of process parameters and reduce the sensitivity of the system performance to sources of variation. The steps involved in Taguchi method are:

1. Identification of response functions and machining parameters to be evaluated.
2. Determine the number of levels for the process parameters and possible interaction between them.
3. Select the appropriate orthogonal array.
4. Assign the process parameters to the orthogonal array and conduct the experiments accordingly.
5. Analyze the experimental results and select the optimum level of process parameters.

In the present research work, selected input machining parameters with their designation are listed in table 4.1. Table 4.2 and table 4.3 enlists levels of machining parameters and assigned values of machining parameters at these levels for experimental work.

Table 4.1 Input machining parameters with their designation

Machining Parameter	Electrode Polarity	Discharge Current (amp)	Pulse on time (µs)	Pulse off time (µs)	Voltage (volt)	Concentration of abrasives (g/l)
Symbol	Ep	Id	Ton	Toff	Vd	Ca

Table 4.2 Levels of input machining parameters

Designation	**Machining Parameter**	**Levels of machining parameters**		
Ep	Electrode Polarity	1	2	---
Id	Discharge Current	1	2	---
Ton	Pulse on time	1	2	3
Toff	Pulse off time	1	2	3
Vd	Discharge Voltage	1	2	3
Ca	Concentration of abrasives	1	2	3

Table 4.3 Assigned values of input machining parameters at different levels

Designation	**Input Machining Parameter**	**Levels and corresponding values of machining parameters**		
		Level 1	**Level 2**	**Level 3**
Ep	Electrode Polarity	Positive	Negative	---
Id	Discharge Current	4A	8A	12A
Ton	Pulse on time	90 µs	150 µs	200 µs
Toff	Pulse off time	30 µs	45 µs	60 µs
Vd	Discharge Voltage	30 volt	40 volt	50 volt
Ca	Concentrationof abrasives	0 g/l	5 g/l	10 g/l

Table 4.4 Experimental combinations of the machining parameters using L18 orthogonal array

Exp. No.	Electrode Polarity Ep	Discharge current Id	Pulse on time Ton	Pulse off time Toff	Discharge voltage Vd	Concentration of abrasives Ca
1	1	1	1	1	1	1
2	1	1	2	2	2	2
3	1	1	3	3	3	3
4	1	2	1	1	2	2
5	1	2	2	2	3	3
6	1	2	3	3	1	1
7	1	3	1	2	1	3

8	1	3	2	3	2	1
9	1	3	3	1	3	2
10	2	1	1	3	3	2
11	2	1	2	1	1	3
12	2	1	3	2	2	1
13	2	2	1	2	3	1
14	2	2	2	3	1	2
15	2	2	3	1	2	3
16	2	3	1	3	2	3
17	2	3	2	1	3	1
18	2	3	3	2	1	2

L18 orthogonal array is selected. This orthogonal array has 6 columns and 18 rows. One machining parameter is assigned to each column. Total 18 rows give the parametric combination (in terms of levels) for each experiment.

Signal-to-Noise (S/N) ratio

The S/N ratio for the ith performance characteristic in the jth experiment can be expressed as:

• Smaller the better (for making the system response as small as possible) Used for

TWR, WR and SR (to be minimized):

$$(S/N)_{ij} = -10^{*}\text{Log}_{10}\left\{\frac{1}{n}\sum_{k=1}^{n} y_{ijk}^{2}\right\} \quad (4.1)$$

• Larger the better (for making the system response as large as possible) Used for MRR (to be maximized):

$$(S/N)_{ij} = -10^{*}\text{Log}_{10}\left\{\frac{1}{n}\sum_{k=1}^{n} \frac{1}{y_{ijk}^{2}}\right\} \quad (4.2)$$

Where:

n = the number of tests

yijk = experimental value of ith performance characteristic in the jth experiment at the kth test.

A commonly applied statistical treatment - The Analysis of Variance (ANOVA) - is used to analyze the results of the OA experiment in product design, and to determine how much variation each quality-influencing factor has contributed. ANOVA is a statistical technique that identifies factors significantly affecting the experimental results. The procedural steps of ANOVA can be accomplished by constructing an ANOVA tables.

Experimental Procedure

EN19 work-piece of rectangular shape was properly cleaned to remove any unwanted particles. It was then weighed. Copper electrode was machined of 9 mm diameter. Electrode was also weighed on weighing machine to get the initial weight of the electrode before machining. Experiments were conducted on OSCAMAX EDM-S645 machine. The existing circulation system of machine is not used during experimentation. There was a need to develop a new abrasive-mixed dielectric circulation system for the experimentation. A new experimental setup for AEDM was developed in the workshop. The new AEDM system was designed for 9 liters of Kerosene oil. The system consists of a sheet metal container, called the machining tank. To hold the work piece, a new work piece fixture assembly is developed in workshop. This fixture is placed in the machining tank and the work-piece is fixed in the fixture for machining. Required quantity of dielectric fluid is filled in the machining tank. Tool electrode is tightened in the tool holder of the machine. A distance 10mm is maintained between nozzle outlet of the machine and the tool electrode for each experiment. The input values of machining parameters were set by using the hand held keyboard for each experiment. These values were taken as per the design of experiment conditions obtained from L18 orthogonal array chosen. During experimentation, the mains supply switched “ON”. Then the erosion was switched “ON”, and also the stop watch to note down the starting time of cut. After blind hole making operation, the machine tool and stop watch stops instantly to note down the time elapsed during cutting operation. The electrode was machined every time after each experiment to remove distortions and to obtain a flat surface. Initial and final weight of electrode and work-piece are measured and noted down every time an experiment is performed as per the design. To conduct abrasive mixed dielectric experiments, required quantity of chromium abrasive powder mixed in the kerosene oil. A small dielectric circulation pump is installed for proper circulation of the abrasive-mixed dielectric fluid into the discharge gap. The pump and the stirrer are placed in the same tank in which machining is performed to ensure proper circulation of chromium abrasive. All the six experiments in which 5 g/l concentration of abrasive is used were performed. Next six experiments were performed in the same way by keeping the concentration of 10g/l. Results of AEDM of EN19 at concentrations of 0g/l, 5g/l and 10g/l in terms of initial and final readings of work-piece weight, electrode weight, time elapsed in cutting operation are listed in Appendix A.I.

RESULTS AND DISCUSSION

Pure Kerosene oil dielectric, 05 gram/liter chromium additives suspended kerosene oil and 10 gram/liter chromium additives suspended kerosene oil (using as dielectric) electro discharge sinking experiments (as already elaborated in previous discussions) were conducted to make no thorough holes of 9 mm diameter in EN 19 steel work-piece. A cylindrical copper solid rod electrode was made another pole of EDM cycle on OSCARMAX-CNC S645 EDM machine. Experimentation trials of AEDM of EN19 steel involved six machining variables i.e. electrode polarity, current intensity, pulse on time, pulse off time, discharge voltage, and concentration of additives in kerosene oil. They are labelled as Ep, Id, Ton, Toff, Vd, Ca respectively. Out of these six variables, one variable i.e. polarity varies at level 1 and level 2. Other five variables i.e. current intensity, pulse on time, pulse off time, discharge voltage and concentration of additives varies at level 1, level 2 and level 3. Four machining responses i.e. MRR, TWR, WR and SR (bottom) weare taken to measure output of process. The experimental plans for AEDM process were based on Taguchi method and the performance of AEDM of EN19 steel is described using MINITAB 17 package. In subsequent sections, obtained results are elaborated in detail.

5.1 Presentation and Discussion of results for MRR

Experimentally obtained MRR results along with calculated S/N ratios and Means for all the 18 runs (presented in form of level values) are shown in table 5.1

Table 5.1 Experimental results (MRR, S/N ratios and Means) in EDM of EN19 steel

Exp. No.	Ep	Id	Ton	Toff	Vd	Ca	Material removal rate (g/min)	S/N Ratios	Means Value
1	1	1	1	1	1	1	0.020000	-33.9794	0.02
2	1	1	2	2	2	2	0.014345	-36.8659	0.014345
3	1	1	3	3	3	3	0.008950	-40.9637	0.00895
4	1	2	1	1	2	2	0.112088	-19.0088	0.112088
5	1	2	2	2	3	3	0.083459	-21.5706	0.083459
6	1	2	3	3	1	1	0.084706	-21.4417	0.084706
7	1	3	1	2	1	3	0.227848	-12.8471	0.227848
8	1	3	2	3	2	1	0.170732	-15.3537	0.170732
9	1	3	3	1	3	2	0.198000	-14.0667	0.198
10	2	1	1	3	3	2	0.002397	-52.4084	0.002397
11	2	1	2	1	1	3	0.002229	-53.0395	0.002229
12	2	1	3	2	2	1	0.001467	-56.6686	0.001467
13	2	2	1	2	3	1	0.005686	-44.9035	0.005686
14	2	2	2	3	1	2	0.006459	-43.7968	0.006459
15	2	2	3	1	2	3	0.006282	-44.0387	0.006282
16	2	3	1	3	2	3	0.002974	-50.532	0.002974
17	2	3	2	1	3	1	0.005643	-44.9691	0.005643

18	2	3	3	2	1	2	0.009074	-40.8443	0.009074

Results from the table 5.1 were used in MINITAB 17 software for ANOVA and F-test statistical calculations for drawing conclusions about MRR. Taguchi method is used to analyze the results of MRR and S/N ratio and concerned statistical figures. Table 5.2 reports ANOVA and F-test data corresponding to S/N ratios for material removal rate.

Table 5.2 F-test data and ANOVA statistical values for S/N ratios of MRR

Source	DF	Seq SS	Adj SS	Adj MS	F-value	F -critical*	P	% age contr.
Ep	1	2570.53	2570.53	2570.53	85.28	5.99	0.000	69.70
Id	2	867.35	867.35	433.68	14.39	5.14	0.005	23.52
Ton	2	1.58	1.58	0.79	0.03	5.14	0.974	0.04
Toff	2	20.82	20.82	10.41	0.35	5.14	0.721	0.57
Vd	2	25.17	25.17	12.58	0.42	5.14	0.676	0.68
Ca	2	21.94	21.94	10.97	0.36	5.14	0.709	0.60
Residual error	6	180.86	180.86	30.14				
Total	17	3688.24						

Figure 5.1 depicts % age contribution of input variables for MRR.

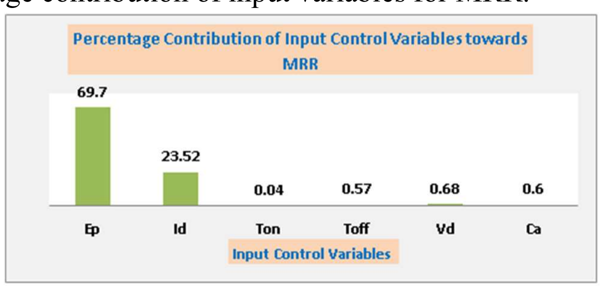

Figure 5.1 % age contribution of input variables (for output MRR)

Statistical results (by using MINITAB 17 package) of ANOVA and F-test are presented in table

5.2. Comparing calculated F-values (from ANOVA table) with same referred from "table for statisticians" it is noted that Ep and Id has the significant effect on MRR. F-value of Ep is larger than other control variables, which presented that Ep has highest contribution (69.70%) followed by Id (23.52%) towards MRR. Significant effect of Ep and Id is also observed from calculated P-

value corresponding to these variables which is less than 0.05 at 95% confidence level. Other involved control variables i.e. Ton, Toff, Vd and Ca are affecting MRR with only a contribution of 0.04%, 0.57%, 0.68% and 0.6% respectively. Calculated F-value of all these four variables (Ton, Toff, Vd and Ca) is less than their table of statisticians' F-value; which shows that their involvement is non-significant. At the same time, their P-value (more than 0.05) further reveals that their involvement/contribution is non-significant. Above results are drawn at 95% confidence level ($\alpha = 0.05$).

Table 5.3 Response table (for S/N data) for MRR

Level	Ep	Id	Ton	Toff	Vd	Ca	Mean (Ep+Id+Ton+Toff+Vd+Ca)/6
1	-24.01	-45.65	-35.61	-34.85	-34.32	-36.22	-35.11
2	-47.91	-32.46	-35.93	-35.62	-37.08	-34.50	-37.25
3		-29.77	-36.34	-37.42	-36.48	-37.17	-35.44
Delta	23.90	15.89	0.72	2.57	2.75	2.67	
Rank	1	2	6	5	3	4	

Following G.Taguchi approach guidelines, S/N ratios (for every experimental run) are computed to note average S/N ratio corresponding to every variable and level. Every variable and concerned levels have biggest and least values of S/N ratios. These values are used to compute delta statistic in response table 5.3. This delta statistic evaluates the relative extent of variable effects. More is the delta statistic more the effect of concerned variable on output response. Highest 'delta' statistic of Ep is categorizing it as the most prominent input variable whereas lowest 'delta' for Ton is categorizing it as least prominent input variable. Taguchi's larger the better option is taken to draw main effects plot for MRR. Figure 5.2 and Figure 5.3 represents main effects plots (mean data and S/N ratios data) of MRR respectively.

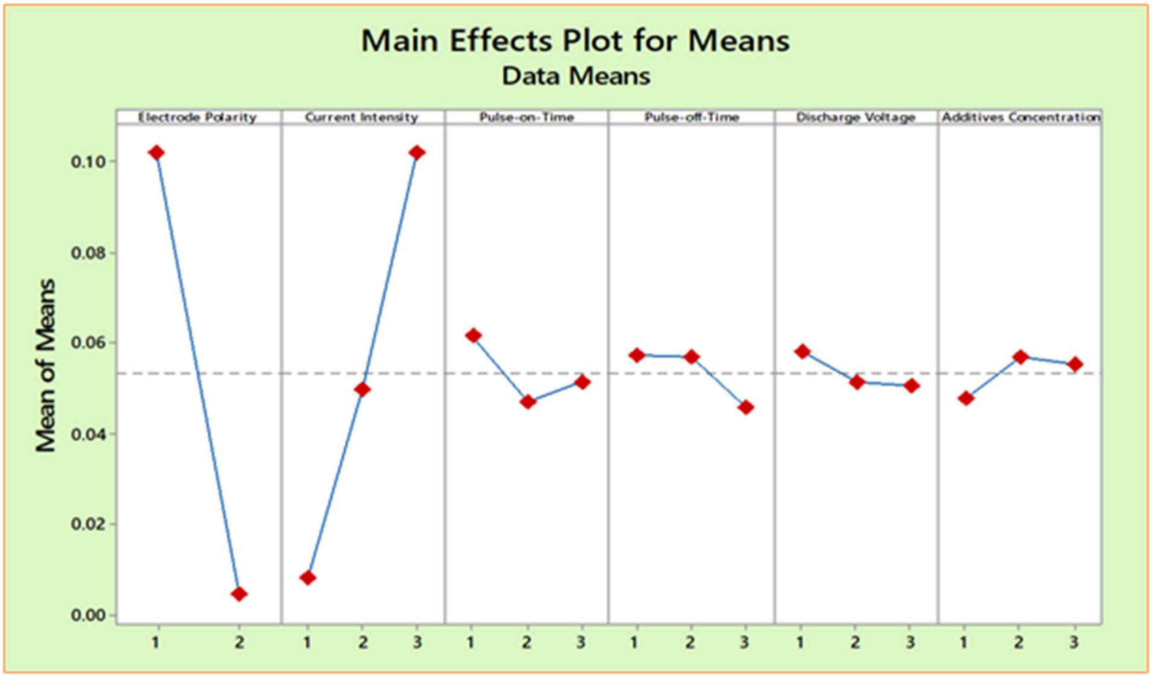

Figure 5.2 Main effects plot (for means value MRR output)

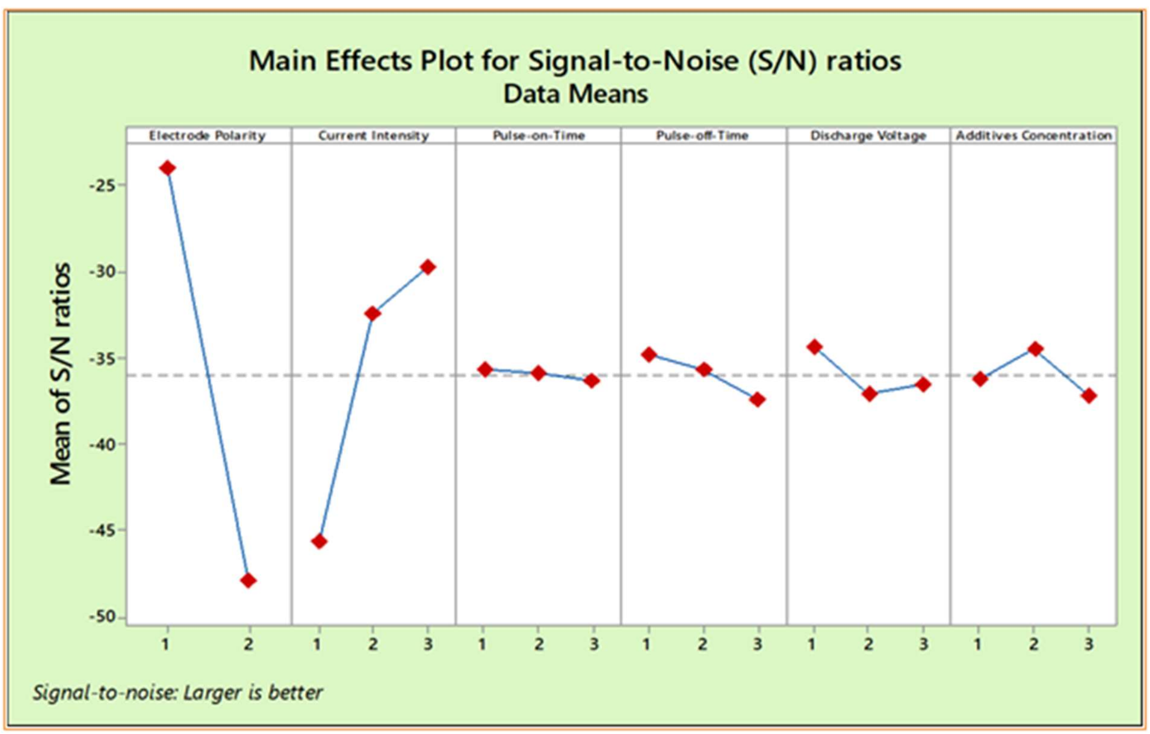

Figure 5.3 Main effects plot (for S/N value MRR output)

Larger the better option for MRR is satisfied by input machining variables as per their levels and actual values shown in table 5.4

Table 5.4 Actual values and levels of input variables satisfying desired option for MRR

Variable Symbol	Ep	Id	Ton	Toff	Vd	Ca
Variable level	1	3	1	1	1	2
Variable actual value	+ve	12 ampere	90 µs	30 µs	30 volt	5 g/litre

Main effects plot in figure 5.2 shows more MRR at 1st electrode polarity level when compared to 2nd electrode polarity level. In 1st electrode polarity level, tiny mass electrons moving at high velocity thump the work-piece with intense thrust and with high energy which cause net more erosion. But in the 2nd electrode polarity level, massive ions speeds towards the work-piece and hit it with reduced momentum which melts less EN19 material from plate and hence lesser MRR. More powerful and strong sparking producing higher temperature, causing more to EN 19 steel plate melting and eroding occrs when the current is increased from 1st level to 3rd level. It is obvious that that the thermal energy increases with Ton. Increase in Ton from 1st to 2nd level swell the plasma channel in the interelectrode space. Due to this, thermal energy density diminishs in the spark space and results in less removal of EN19 material. But Ton changing from 2nd level to 3rd level, effect of increased energy pronounced and more MRR obtained. Increament in Toff from level 1st to 3rd reduces MRR because more the time spark remains off at 3rd level of Toff. Any change in Vd does not significantly affects the MRR. With the suspension of Cr (at 2nd level) abrasives into the kerosene oil during EDM of EN19, MRR starts its increasing trend. Presence of Cr abrasives in kerosene oil, enlargement and wideness of spark gap size is responsible for increased MRR. Due to this, quickly discharging occurs and removes more EN19 steel. But more more suspension is again not desired.

5.1 Presentation and Discussion of results for TWR

Experimentally obtained TWR results along with calculated S/N ratios and Means for all the eighteen runs (presented in form of level values) are shown in table 5.5

Table 5.5 Experimental results (TWR, S/N ratios and Means) in EDM of EN19 steel

Exp. No.	Ep	Id	Ton	Toff	Vd	Ca	Tool Wear rate (g/min)	S/N Ratios	Means Value
1	1	1	1	1	1	1	0.000606	64.34968	0.000606
2	1	1	2	2	2	2	0.000624	64.10048	0.000624
3	1	1	3	3	3	3	0.000358	68.92246	0.000358
4	1	2	1	1	2	2	0.003297	49.6384	0.003297
5	1	2	2	2	3	3	0.002256	52.93461	0.002256
6	1	2	3	3	1	1	0.002353	52.56778	0.002353
7	1	3	1	2	1	3	0.007595	42.38952	0.007595
8	1	3	2	3	2	1	0.004878	46.23508	0.004878

9	1	3	3	1	3	2	0.006000	44.43697	0.006
10	2	1	1	3	3	2	0.000545	65.27745	0.000545
11	2	1	2	1	1	3	0.000514	65.77591	0.000514
12	2	1	3	2	2	1	0.000783	62.12863	0.000783
13	2	2	1	2	3	1	0.001264	57.9678	0.001264
14	2	2	2	3	1	2	0.001700	55.39247	0.0017
15	2	2	3	1	2	3	0.001629	55.76404	0.001629
16	2	3	1	3	2	3	0.000826	61.6581	0.000826
17	2	3	2	1	3	1	0.001283	57.83818	0.001283
18	2	3	3	2	1	2	0.002647	51.54655	0.002647

Results from the table 5.5 were used in MINITAB 17 software for ANOVA and F-test statistics calculations for drawing conclusions about TWR. Taguchi method is used to analyze the results of TWR and S/N ratio and concerned statistical figures. Table 5.6 reports ANOVA and F-test data corresponding to S/N ratios for tool wear rate.

Table 5.6 F-test data and ANOVA statistical values for S/N ratios of TWR

Source	DF	Seq SS	Adj SS	Adj MS	F-value	F-critical	P-value	% age contr.
Ep	1	126.80	126.798	126.798	4.70	5.99	0.073	12.07
Id	2	681.91	681.911	340.955	12.65	5.14	0.007	64.92
Ton	2	4.65	4.651	2.326	0.09	5.14	0.918	0.44
Toff	2	30.88	30.883	15.441	0.57	5.14	0.592	2.94
Vd	2	19.65	19.653	9.826	0.36	5.14	0.709	1.87
Ca	2	24.75	24.754	12.377	0.46	5.14	0.652	2.36
Residual error	6	161.72	161.717	26.953				
Total	17	1050.37						

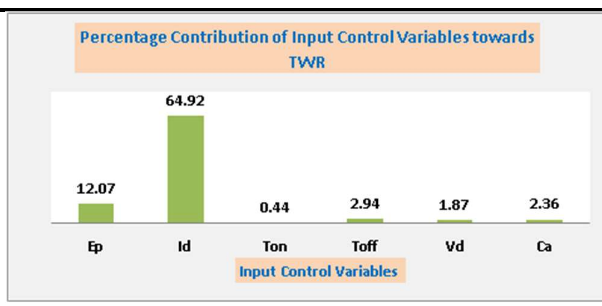

Figure 5.4 depicts % age contribution of input variables for TWR.

Figure 5.4 % age contribution of input variables for TWR

Statistical results (by using MINITAB 17 package) of ANOVA and F-test are presented in table

5.6. Comparing calculated F-values (from ANOVA table) with same referred from "table for statisticians" it is noted that only Id has the significant effect on TWR. F-value of Id is larger than other control variables, which presented that Id has highest contribution (64.92%) followed by Ep (12.07%) towards TWR. Significant effect of Id is also observed from calculated P-value corresponding to this variable which is less than 0.05 at 95% confidence level. Other involved control variables i.e. Ton, Toff, Vd and Ca are affecting TWR with only a contribution of 0.44%, 2.94%, 1.87% and 2.36% respectively. Calculated F-value of all these five variables (Ep, Ton, Toff, Vd and Ca) is less than their table of statisticians' F-value; which shows that their involvement is non-significant. At the same time, their P-value (more than 0.05) further reveals that their involvement/contribution is non-significant. Above results are drawn at 95% confidence level ($\alpha = 0.05$).

Table 5.7 Response table (for S/N data) for TWR

Level	Ep	Id	Ton	Toff	Vd	Ca	Mean (Ep+Id+Ton+Toff+Vd+Ca) /6
1	53.95	65.09	56.88	56.30	55.34	56.85	57.40
2	59.26	54.04	57.05	55.18	56.59	55.07	56.20
3		50.68	55.89	58.34	57.90	57.91	56.14
Delta	5.31	14.41	1.15	3.16	2.56	2.84	
Rank	2	1	6	3	5	4	

Following G. Taguchi approach guidelines, S/N ratios (for every experimental run) are computed to note average S/N ratio corresponding to every variable and level. Every variable and concerned level has biggest and least values of S/N ratios. These values are used to compute delta statistic in response table 5.7. This delta statistic evaluates the relative extent of variable

effects. More is the delta statistic more the effect of concerned variable on output response. Highest 'delta' statistic of Id is categorizing it as the most prominent input variable whereas lowest 'delta' for Ton is categorizing it as least prominent input variable. Taguchi's smaller the better option is taken to draw main effects plot for TWR. Figure 5.5 and Figure 5.6 represents main effects plots (mean data and S/N ratios data) of TWR respectively.

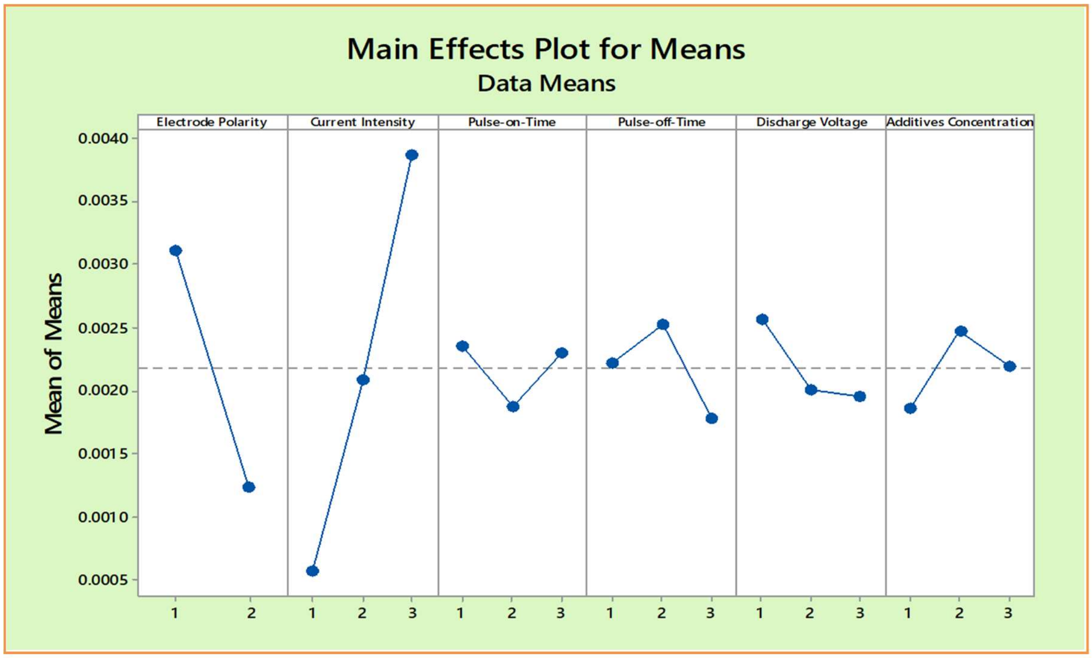

Figure 5.5 Main effects plot (for means value TWR output)

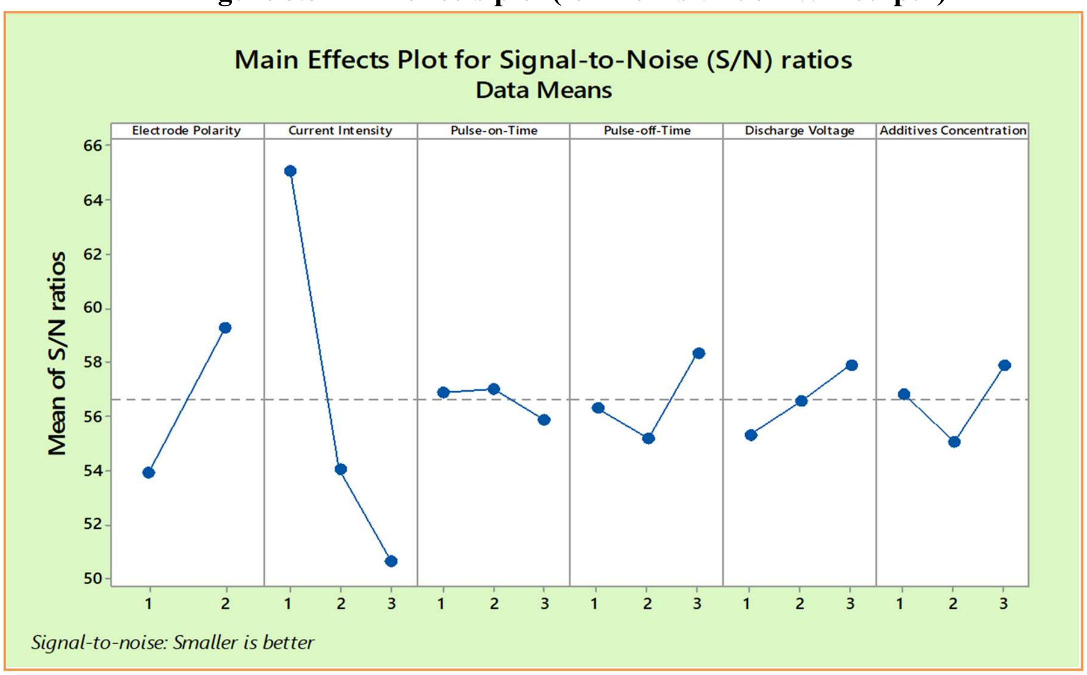

Figure 5.6 Main effects plot (for S/N value TWR output)

Smaller the better option for TWR is satisfied by input machining variables as per their levels and actual values shown in table 5.8

Table 5.8 Actual values and levels of input variables satisfying desired option for TWR

Variable Symbol	Ep	Id	Ton	Toff	Vd	Ca

Variable level	2	1	2	3	3	1
Variable actual value	-ve	04 ampere	150 µs	60 µs	50 volt	Pure Kerosene oil

Main effects plot in figure 5.5 shows less TWR is less when performing the run at Ep 2nd level as compared with TWR at Ep 1st level. TWR enhances when Id changes from level 1st to level 3rd. It is because increases in Id leads to enhances the pulse energy and causing more heat energy

in interelectrode space, leads to performs more melting and evaporation of the Cu electrode. TWR decreases with increase in Ton between 1st level to 2nd level. The plasma channel swell at high Ton and energy density of discharge decrease which do not melt the Cu material electrode and hence TWR lowers down. But changing Ton from level 2nd to level 3rd increases the TWR again. TWR firstly small increases and then quickly fallens as the Toff changes in the range. TWR decreases as the Vd value increases from level 1st to level 3rd. TWR firstly sll increases and the quickly fallen as the suspension of Cr abrasives increases in Kerosene oil.

5.1 Presentation and Discussion of results for WR

Experimentally obtained WR results along with calculated S/N ratios and means for all the eighteen runs (presented in form of level values) are shown in table 5.9

Table 5.9 Experimental results (WR, S/N ratios and Means) in EDM of EN19 steel

Exp. No.	Ep	Id	Ton	Toff	Vd	Ca	Wear ratio	S/N Ratios	Means Value
1	1	1	1	1	1	1	0.030303	30.37028	0.030303
2	1	1	2	2	2	2	0.043478	27.23456	0.043478
3	1	1	3	3	3	3	0.040000	27.9588	0.04
4	1	2	1	1	2	2	0.029412	30.62958	0.029412
5	1	2	2	2	3	3	0.027027	31.36403	0.027027
6	1	2	3	3	1	1	0.027778	31.12605	0.027778
7	1	3	1	2	1	3	0.033333	29.54243	0.033333
8	1	3	2	3	2	1	0.028571	30.88136	0.028571
9	1	3	3	1	3	2	0.030303	30.37028	0.030303
10	2	1	1	3	3	2	0.227273	12.86905	0.227273
11	2	1	2	1	1	3	0.230769	12.73644	0.230769
12	2	1	3	2	2	1	0.533333	5.460025	0.533333
13	2	2	1	2	3	1	0.222222	13.06425	0.222222

14	2	2	2	3	1	2	0.263158	11.59567	0.263158	
15	2	2	3	1	2	3	0.259259	11.72531	0.259259	
16	2	3	1	3	2	3	0.277778	11.12605	0.277778	
17	2	3	2	1	3	1	0.227273	12.86905	0.227273	
18	2	3	3	2	1	2	0.291667	10.70226	0.291667	

Results from the table 5.9 were used in MINITAB 17 software for ANOVA and F-test statistics calculations for drawing conclusions about WR. Taguchi method is used to analyze the results of WR and S/N ratio and concerned statistical figures. Table 5.10 reports ANOVA and F-test data corresponding to S/N ratios for wear ratio.

Table 5.10 F-test data and ANOVA statistical values for S/N ratios of WR

Source	DF	Seq SS	Adj SS	Adj MS	F-value	F-critical	P	% age contr.
Ep	1	1555.50	1555.50	1555.50	741.69	5.99	0.000	96.20
Id	2	14.47	14.47	7.23	3.45	5.14	0.101	0.90
Ton	2	10.74	10.74	5.37	2.56	5.14	0.157	0.66
Toff	2	11.41	11.41	5.71	2.72	5.14	0.144	0.71
Vd	2	12.11	12.11	6.06	2.89	5.14	0.132	0.75
Ca	2	0.09	0.09	0.05	0.02	5.14	0.978	0.01
Residual Error	6	12.58	12.58	2.10				
Total	17	1616.91						

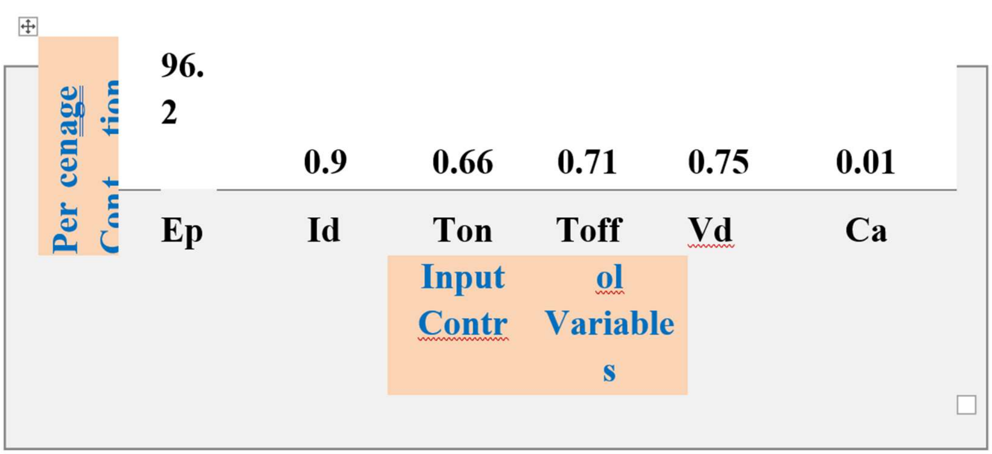

Figure 5.7 % age contribution of input variables for WR

Statistical results (by using MINITAB 17 package) of ANOVA and F-test are presented in table

5.10. Comparing calculated F-values (from ANOVA table) with same referred from "table for statisticians" it is noted that Ep has the significant effect on WR. F-value of Ep is larger than other control variables, which presented that Ep has highest contribution (96.20%) followed by Id (0.90%) towards WR. Significant effect of Ep is also observed from calculated P-value corresponding to this variable which is less than 0.05 at 95% confidence level. Other involved control variables i.e. Ton, Toff, Vd and Ca are affecting WR with only a contribution of 0.66%, 0.71%, 0.75% and 0.01% respectively. Calculated F-value of all these five variables (Ep, Ton, Toff, Vd and Ca) is less than their table of statisticians' F-value; which shows that their involvement is non-significant. At the same time, their P-value (more than 0.05) further reveals that their involvement/contribution is non-significant. Above results are drawn at 95% confidence level (α = 0.05).

Table 5.11 Response table (for S/N data) for WR

Level	Ep	Id	Ton	Toff	Vd	Ca	Mean (Ep+Id+Ton+Toff+Vd+Ca) /6
1	29.94	19.44	21.27	21.45	21.01	20.63	22.29
2	11.35	21.58	21.11	19.56	19.51	20.57	18.95
3		20.92	19.56	20.93	21.42	20.74	20.71
Delta	18.59	2.15	1.71	1.89	1.91	0.18	
Rank	1	2	5	4	3	6	

Following G.Taguchi approach guidelines, S/N ratios (for every experimental run) are computed to note average S/N ratio corresponding to every variable and level. Every variable and concerned level has biggest and least values of S/N ratios. These values are used to compute delta statistic in response table 5.11. This delta statistic evaluates the relative extent of variable effects. More is the delta statistic more the effect of concerned variable on output response. Highest 'delta' statistic of Ep is categorizing it as the most prominent input variable whereas lowest 'delta' for Ca is categorizing it as least prominent input variable. Taguchi's smaller the better option is taken to draw main effects plot for WR. Figure 5.8 and Figure 5.9 represents main effects plots (mean data and S/N ratios data) of WR respectively.

Figure 5.8 Main effects plot (for means value WR output)

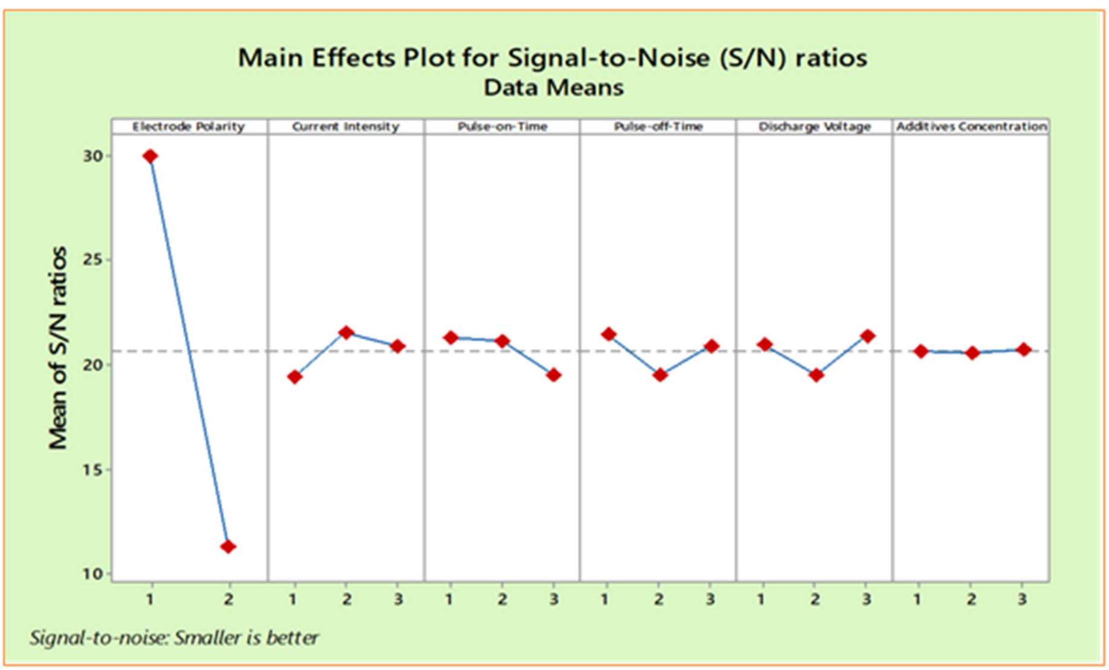

Figure 5.9 Main effects plot (for S/N value WR output)

Smaller the better option for WR is satisfied by input machining variables as per their levels and actual values shown in table 5.12.

Table 5.12 Actual values and levels of input variables satisfying desired option for WR

Variable Symbol	Ep	Id	Ton	Toff	Vd	Ca

Variable level	1	2	1	1	3	3
Variable actual value	+ve	08 ampere	90 µs	30 µs	50 volt	10 g/litre

Main effects plot in figure 5.8 shows more WR at positive Ep and less WR at negative Ep. It is due to the fact that greater MRR is yields at positive Ep and lesser at the negative Ep. With stare to Id, the variation of curve signify that WR insignificantly affected by change in Id. Definite

movement of WR curve for change in Ton and Toff and for Vd and Ca depend upon the values of MRR and TWR curves corresponding curves with respect to these control parameters.

5.1 Presentation and Discussion of results for SR

Experimentally obtained SR results along with calculated S/N ratios and means for all the eighteen runs (presented in form of level values) are shown in table 5.13

Table 5.13 Experimental results (SR, S/N ratios and Means) in EDM of EN19 steel

Exp. No.	Ep	Id	Ton	Toff	Vd	Ca	Surface Roughness	S/N Ratios	Means Value
1	1	1	1	1	1	1	3.73	-11.4342	3.73
2	1	1	2	2	2	2	4.3	-12.6694	4.3
3	1	1	3	3	3	3	3.58	-11.0777	3.58
4	1	2	1	1	2	2	6.36	-16.0691	6.36
5	1	2	2	2	3	3	5.82	-15.2985	5.82
6	1	2	3	3	1	1	5.44	-14.712	5.44
7	1	3	1	2	1	3	7.79	-17.8307	7.79
8	1	3	2	3	2	1	7.37	-17.3493	7.37
9	1	3	3	1	3	2	6.72	-16.5474	6.72
10	2	1	1	3	3	2	3.51	-10.9061	3.51
11	2	1	2	1	1	3	3.8	-11.5957	3.8
12	2	1	3	2	2	1	3.11	-9.85521	3.11
13	2	2	1	2	3	1	4.58	-13.2173	4.58
14	2	2	2	3	1	2	3.13	-9.91089	3.13
15	2	2	3	1	2	3	2.88	-9.18785	2.88
16	2	3	1	3	2	3	4.16	-12.3819	4.16
17	2	3	2	1	3	1	4.49	-13.0449	4.49

18	2	3	3	2	1	2	4.25	-12.5678	4.25

Results from the table 5.13 were used in MINITAB 17 software for ANOVA and F-test statistics calculations for drawing conclusions about SR. Taguchi method is used to analyze the results of SR and S/N ratio and concerned statistical figures. Table 5.14 reports ANOVA and F-test data corresponding to S/N ratios for surface roughness.

Table 5.14 F-test data and ANOVA statistical values for S/N ratios of SR

Source	DF	Seq SS	Adj SS	Adj MS	F-value	F-critical	P-value	% age contr.
Ep	1	51.074	51.0745	51.0745	16.58	5.99	0.007	42.74
Id	2	41.016	41.0163	20.5081	6.66	5.14	0.030	34.32
Ton	2	5.623	5.6231	2.8116	0.91	5.14	0.451	4.71
Toff	2	2.282	2.2815	1.1408	0.37	5.14	0.705	1.91
Vd	2	0.617	0.6170	0.3085	0.10	5.14	0.906	0.52
Ca	2	0.422	0.4219	0.2110	0.07	5.14	0.935	0.36
Residual Error	6	18.480	18.4796	3.0799				
Total	17	119.514						

Figure 5.10 depicts % age contribution of input variables for SR.

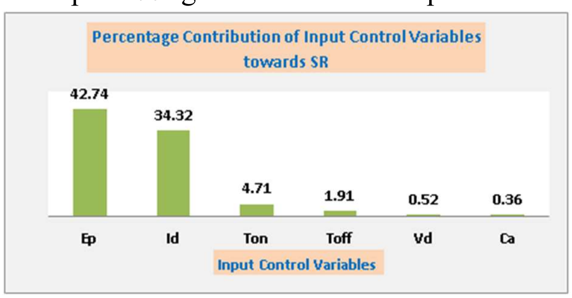

Figure 5.10 % age contribution of input variables for SR

Statistical results (by using MINITAB 17 package) of ANOVA and F-test are presented in table

5.14. Comparing calculated F-values (from ANOVA table) with same referred from "table for statisticians" it is noted that Ep and Id has the significant effect on SR. F-value of Ep is larger than other control variables, which presented that Ep has highest contribution (42.74%) followed by Id (34.32%) towards SR. Significant effect of Ep and Id is also observed from calculated P-value corresponding to these variables which is less than 0.05 at 95% confidence level. Other involved control variables i.e. Ton, Toff, Vd and Ca are affecting SR with only a contribution of 4.71%, 1.91%, 0.52% and 0.36% respectively. Calculated F-value of all these

four variables (Ton, Toff, Vd and Ca) is less than their table of statisticians' F-value; which shows that their involvement is non-significant. At the same time, their P-value (more than 0.05) further reveals that their involvement/contribution is non-significant. Above results are drawn at 95% confidence level (α
= 0.05).

Table 5.15 Response table (for S/N data) for SR

Level	Ep	Id	Ton	Toff	Vd	Ca	Mean (Ep+Id+Ton+Toff+Vd+Ca) /6
1	-14.78	-11.26	-13.64	-12.98	-13.01	-13.27	13.16
2	-11.41	-13.07	-13.31	-13.57	-12.92	-13.11	12.90
3		-14.95	-12.32	-12.72	-13.35	-12.90	13.25
Delta	3.37	3.70	1.32	0.85	0.43	0.37	
Rank	2	1	3	4	5	6	

Following G.Taguchi approach guidelines, S/N ratios (for every experimental run) are computed to note average S/N ratio corresponding to every variable and level. Every variable and concerned level has biggest and least values of S/N ratios. These values are used to compute delta statistic in response table 5.15. This delta statistic evaluates the relative extent of variable

effects. More is the delta statistic more the effect of concerned variable on output response. Highest 'delta' statistic of Id is categorizing it as the most prominent input variable whereas lowest 'delta' for Ca is categorizing it as least prominent input variable. Taguchi's smaller the better option is taken to draw main effects plot for SR. Figure 5.11 and Figure 5.12 represents main effects plots (mean data and S/N ratios data) of SR respectively.

Figure 5.11 Main effects plot (for means value SR output)

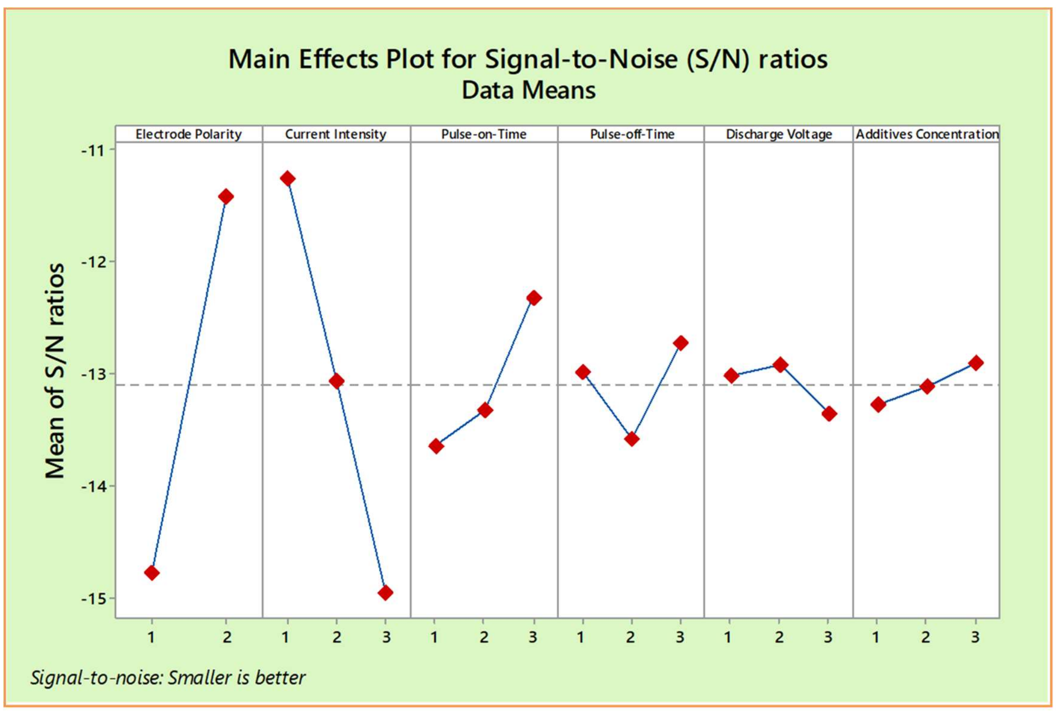

Figure 5.12 Main effects plot (for S/N value SR output)

Smaller the better option for SR is satisfied by input machining variables as per their levels and actual values shown in table 5.16

Table 5.16 Actual values and levels of input variables satisfying desired option for SR

Variable Symbol	Ep	Id	Ton	Toff	Vd	Ca
Variable level	2	1	3	3	1	3
Variable actual value	-ve	04 ampere	200 µs	60 µs	30 volt	10 g/litre

Main effects plot in figure 5.11 shows less in 2nd Ep level condition when compared to 1st Ep level condition. In 1st Ep level, chromium abrasives flow with small mass electrons at rapid speed. When hits the EN19 surface, produces more deep and wide areas on EN19 surface.

Reverse is the case at other Ep level. At this condition, +ve charge ions which are heavy in mass, they carry the chromium abrasive particles with lesser speed. So they strikes the EN 19 surface with small pressure momentum and hence produce less wider and less deeper cavities on EN19 steel. SR increase with increase in Id because more powerful sparking at higher Id has more thermal cum pressure energy to hit/strike on EN19 surface to produce deep cavities on EN19 piece. SR decreases with increase in Ton upto 3rd level whereas it slightly increases and then decreases with Toff. Increase in Vd, increases the SR because sparks at increased potential are full of thermal and pressure energy, produces more rough and deep cavities on EN19 piece. A little reduction in SR observed at more concentrated kerosene dielectric.

Optimum AEDM machining variables

Larger MRR, lowest TWR, Lowest WR and Lowest SR are taken as desired conditions to optimize AEDM of EN19 steel in this work. Optimum values of input variables and thir levels are represented in table 5.17

Table 5.17 Desired conditions for responses & experimentally noted optimum input variables

Output	Desired Condition	Ep	Id	Ton	Toff	Vd	Ca
MRR (g/min)	Larger	+ve	12 ampere	90 µs	30 µs	30 volt	5 g/litre
TWR (g/min)	Lowest	-ve	04 ampere	150 µs	60 µs	50 volt	Pure kerosene oil
WR	Lowest	+ve	08 ampere	90 µs	30 µs	50 volt	10 g/litre
SR (µm)	Lowest	-ve	04 ampere	200 µs	60 µs	30 volt	10 g/litre

Validation of results

Validation experiments were conducted keeping the input variables as per table 5.14 for MRR, TWR, WR and SR. Table 5.18 shows the results of the validation runs and their comparisons with theoretical values given by Minitab 17 software.

Table 5.18 Validation test results

Output	Predicted value	Actual value	Error
MRR (g/min)	0.229899	0.207139	9.9 %
TWR (g/min)	0.000267	0.000287	7.8%
WR	0.026083	0.027934	7.1%
SR (μm)	2.51	2.71	8.3%

Error in predicted value of each output and experimental value for that output is small (within 10%). This confirms that the experimental results are valid.

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