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EXPERIMENTAL ANALYSIS OF DRY WEDM USING DESIGN OF EXPERIMENTS

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***Abstract*— Dry electric discharge machining (EDM) is an environment-friendly modification of the oil EDM process in which liquid dielectric is replaced by a gaseous medium. In the current work, parametric analysis of the process has been performed with tubular copper tool electrode and Tungsten Carbide work-piece. Experiments have been conducted using air as the dielectric medium to study in the first part the effect of gap voltage, peak current, pulse on time, pulse off time and wire feed on material removal rate (MRR) and in the second part the effect of wire tension and wire velocity on amplitude of lateral vibration in wire to improve the surface finish (Ra). First of all input parameters which contribute in obtaining desired material removal rate (MRR) and surface finish (Ra) are finalized by referring previous literature. Then baseline data is collected for current process parameters, which gives response in terms of material removal rate and surface finish. Further experimental analysis is carried out for optimizing the input parameters like gap voltage, peak current, pulse on time, pulse off time, wire feed, wire tension and wire velocity for getting desired output, which is material removal rate (MRR) and surface finish (Ra). Experimental analysis is accomplished by using Design of Experiments (Taguchi design). For the design, performance and analysis of DOE statistical software (MINITAB 17) is utilized.**

***Keywords*— Design of experiment, Wire vibration, EDM, MRR, Parameter optimization, Taguchi design.**

I. INTRODUCTION

Electric discharge machining (EDM) is one of the most popular non-traditional machining processes being used today. Use of mineral oil-based dielectric liquids is the major cause of environmental concerns associated with the EDM process. Dry EDM is an environment-friendly modification of the oil EDM process in which the liquid dielectric is replaced by a gaseous medium. Dielectric wastes generated during the oil EDM process are very toxic and cannot be recycled. Also, toxic fumes are generated during machining due to high temperature chemical breakdown of mineral oils. The use of oil as the dielectric fluid also makes it necessary to take extra precaution to prevent fire hazards. Replacing liquid dielectric by gases is an emerging field in the environment-friendly EDM technology. High velocity gas flowing through the tool electrode into the inter-electrode gap substitutes the liquid dielectric. The flow of high velocity gas into the gap facilitates removal of debris and prevents excessive heating of the tool and work-piece at the discharge spots [13].

In the scope of this project already established theory about impact of input process parameters in WEDM on material removal rate & surface finish is included. This theory will be revalidated using experimental analysis. Current theory about various process parameters is given below:

Gap Voltage – It is the voltage applied between the tool and the work piece. The applied voltage determines the total energy of the spark. If the voltage is high, erosion rate increases and the higher machining rate is achieved. But at the same time, higher voltage will also contribute to poor surface finish. In order to achieve higher machining rate, higher voltage should be used, which results in higher tool wear. Therefore for WEDM, a very moderate value of voltage needs to be used [11] [13].

Peak Current - This is another very important parameter that determines almost all the machining characteristics such as machining rate, surface finish. The term ‘peak current’ often used to indicate the highest current during machining. The higher the peak current setting is, the larger is the discharge energy. From experimental evidences of previous research work, it seems that sensitivity of peak current setting on the cutting performance is stronger than that of pulse on time. When the peak current is too high, it may lead to higher tool wear as well. Peak current is known as the amount of power used in discharge machining which this parameter is measured in amperage and above all this is the most important parameter in EDM machining. Using higher currents will definitely improve the material removal rate but it will deteriorate the tool wear and surface finish [9] [13].

Pulse on time – This is the duration of the time the current is allowed to flow per cycle. Material removal rate is directly proportional to the amount of energy applied during this pulse on time. This energy is controlled by the peak current and the length of the pulse on time. The main EDM operation is effectively done during this pulse on time. With longer period of spark duration, the resulting cater will be broader and deeper, therefore the surface finish will be rougher. Shorter spark duration on the other hand helps to improve surface finish [11] [13].

Pulse off time – This is the duration of time between two successive sparks when the discharge is turned off. Pulse off time is the duration of the rest or pause required for the re-ionization of the dielectric. This time allows the molten material to solidify and to be washed out of the spark gap. If the pulse off time is too short, it will cause spark to be unstable and then more short circuiting will occur. Although larger pulse off time slows down the process, it can provide stability required to successfully EDM a given application. When the pulse off time is insufficient as compared to on time, it will cause erratic cycling and retraction of the advancing servomotors, slowing down the operation [11] [13].

Wire feed – Wire feed is another important parameter in WEDM that shows the speed of the wire. As the wire feed increases the wire consumption and in result the cost of machining will increase. While low wire feed can cause to wire breakage in high cutting speed [12].

Wire tension (T_f) – As shown in the fig.1 wire tension strengthens the wire and ensures that it will not sag down during operation.

Wire velocity (V_w) –It is the velocity of the wire electrode in axial direction.

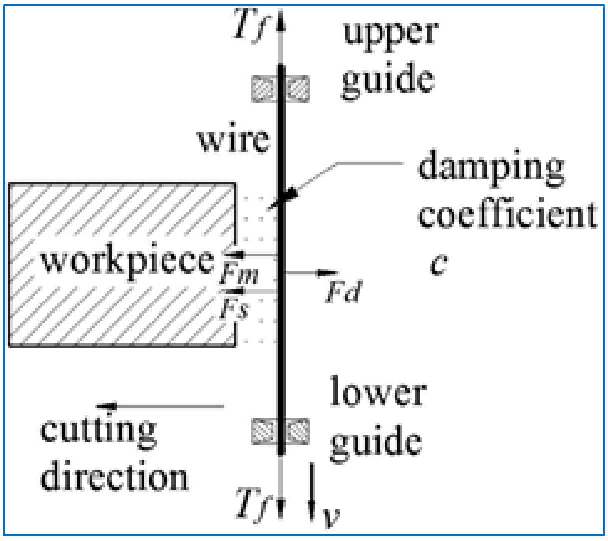

Fig.1 Force analysis diagram of wire electrode

In the previous study about wire movement in WEDM, many researches employed the classical string vibration equation (a) to analyse deflection and vibration.

$$EI_0\frac{\partial^4 y}{\partial z^4} - T_f\frac{\partial^2 y}{\partial z^2} + \rho S\frac{\partial^2 y}{\partial t^2} + c\frac{\partial y}{\partial t} = F_{(z,t)} \quad \ldots(a)$$

Where, F(z,t) is the displacement of wire, E is Young's modulus, I_0 is the second moment of area, T_f is the wire tension, ρ is the wire mass density, S is the cross-section area, c is the coefficient of damping because of dielectric fluid viscosity [15].

To develop more high-precision model of wire vibration, there are three points needed to be improved based on Eq. (a):

1) Wire vibration is spatial movement characteristics including cutting directional and lateral vibration, while only the theoretical solution of cutting directional vibration can be obtained in Fig. 19. However, the lateral vibration has a greater impact on workpiece geometric accuracy in WEDM, and this impact mainly includes corner-error and kerf width [15].

2) In the actual machining process, wire is not static but trans-porting between two guides [15].

3) The wire vibration is a complicated behavior, and it cannot be explained by mechanics of materials. In addition, the non-uniform temperature distribution and electromagnetic force are significant factors which cannot be ignored [15].

II. Problem Statement

Pictorial view and schematic diagram of dry WEDM process are shown in fig.2 and fig.3 respectively [2] [4].


Fig.2 WEDM Process Set-up

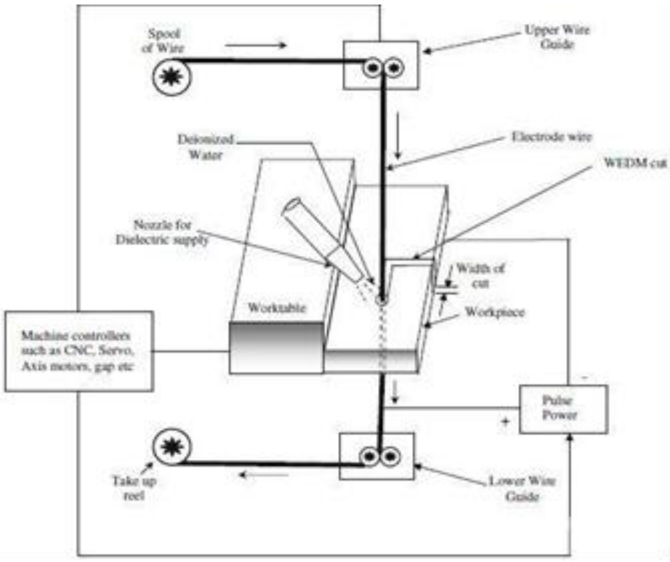

Fig.3 Schematic diagram of WEDM

In current situation desired material removal rate (MRR) and surface finish (Ra) is not obtaining. Current process parameters and obtained response is given in table 1.

TABLE I

Before Process Parameters And Process Performance

Before - As is condition						
Process Parameters						
Gap Voltage	Peak Current	Pulse on time	Pulse off time	Wire feed	Wire Tension	Wire Velocity
V_g (V)	I_p (A)	T_{on} (µs)	T_{off} (µm)	W_f (m/min)	T_f (N)	Vw (m/s)
90	100	600	1500	4	18	0.5
Response						
Material Removal Rate					Surface Finish	
MRR (mm^3/min)					Ra (µm)	
1.74					1.60	

So as it is visible from the Table I obtained material removal rate is 1.74 mm^3/min and surface finish is 1.60 µm. whereas, desired values are 3.0 mm3/min and 1.2 µm respectively. So the present response is very much deviated from the desired values.

III. Research Methodology

A. Identification of input process parameters:

From the previous research work, for getting the best result for the performance of the WEDM process following parameters needs to be optimized [3].

- Gap Voltage
- Peak Current
- Pulse on time
- Pulse off time
- Wire feed
- Wire Tension
- Wire Velocity

B. Base Line Data Collection:

For any random setting, data regarding WEDM performance i.e. Material Removal Rate (MRR) and Surface Finish (Ra) is collected. This forms the baseline for further experimentation.

- MRR = Volumetric material removal / Process time (mm3/min)
- Ra = Surface finish (µm)

C. Designing or Formulating Design Of Experiments :

Defining levels or range of setting parameters, Selecting the DOE type (i.e. Taguchi / Factorial), and Generating orthogonal matrix containing different sets of setting parameters.

D. Experimentation :

- Gathering data of WEDM performance i.e. Material Removal Rate (MRR) and Surface Finish (Ra) for each set of parameters mentioned in matrix.
- Completing the matrix by consolidating results.

E. DOE Analysis :

- Generating Interaction plot for all parameters and finding out S/N ratio (Larger is Better) for Material removal rate and (Smaller is Better) for Surface finish.
- $S/N = -10 \log ((1/n) (\sum (1/y^2))$ ….. for Larger is Better. Where, y is value of response variables and n is number of observations in the experiments [14]. $S/N = -10 \log (\Sigma (Y2)/n))$ ….. for Smaller is Better. Where, y is value of response variables and n is number of observations in the experiments [14].
- Calculating the contribution of each parameter on the required response.
- Generating the Optimization plot.
- Finalizing the setting parameters.

F. Confirmation Run:

- Putting up the finalized parameters on machine and taking confirmation regarding the performance.
- Standardizing the parameters and compiling the results:
- Standardizing the optimized parameters and compiling the results. Then in the end concluding the experimentation and preparing the report.

IV. Experimental Set-up

Fig.4 Experimental Set-up

Fig.5Work-piece mounted on EUROCUT MARK II machine

The experiment was carried out on EUROCUT MARK II machine (Fig.3). The electrode wire material was brass-copper (90:10). Diameter of wire was 0.25 mm. Dielectric fluid used was compressed air. Electrode can be used once only because of dimensional deviation, so wire was continuously feed through the feeding mechanism. Work-piece was a block of K96 KENNAMETAL Grade Tungsten Carbide with Dimension 50×50×10 (all in mm). From the work-piece of above given dimensions, small pieces were cut and Volumetric material removal amount is measured while keeping process time constant as 30 sec. From Volumetric material removal and process time Material Removal Rate (MRR) is calculated. After taking cut surface finish of the cut is measured using portable surface finish tester manufactured by Mitutoyo Surftest SJ-210 series [1] [4].

Experimentation parameters and their specifications are given in following table [4].

TABLE II

EXPERIMENTATION SPECIFICATION TABLE

Sr. No.	Parameter	Specification
1	Workpiece Material	K96 KENNAMETAL Grade Tungsten Carbide
2	Workpiece Dimension	50X50X10 (all in mm)
3	EDM used	EURO CUT MARK II
4	Tool Material	Brass-Copper alloy
5	Die Electric Fluid	Compressed air at 4.0 Bar
6	Instrument for measuring vibration amplitude	Piezo-electric vlocity pick-up
7	Measuring Instrument for Volumetric Material Removal	Digital Weighing scale is used to measure weight difference, then density of Tungsten Carbide is taken as 15630 Kg/m^3. To calculate the Volumetric material removal.
8	Measuring Instrument for Surface Finish	Portable surface finish tester manufactured by Mitutoyo Surftest SJ-210 series
9	Process Parameter Setting	Set on Human Machine Interface Mistubishi GOT 1000 series

V. EXPERIMENTATION

For first experimentation following parameters are taken

- Gap Voltage
- Peak Current
- Pulse on time
- Pulse off time
- Wire feed

Values of above parameters are taken at 3 different levels. Then available design of Taguchi Design Of Experiment is checked in MINITAB 17 software. From available DOE designs L27 design is chosen, i.e. in order to complete the experimentation 27 Nos of DOE runs need to be taken, each DOE run consists of specific combination of above input process parameters. Purpose of this experimentation is to obtain the Material Removal Rate (MRR) at different combinations of above input parameters. This is performed to understand the contribution and impact of input parameters on desired output from WEDM process. So that in the end optimized values of input process parameters are obtained [6] [7].

Table IIIindicates the chosen DOE design, which is having 27 experimentation runs. Input process parameters given in each run are put on the machine using Human Machine Interface and response in terms of Material Removal Rate (MRR) is calculated [6] [7].

TABLE III

L27 STRUCTURE OF TAGUCHI DOE DESIGN

DOE Taguchi Design					
DOE Run No.	Gap Voltage	Peak Current	Pulse on time	Pulse off time	Wire feed
	V_g (V)	I_p (A)	T_{on} (µs)	T_{off} (µm)	W_f (m/min)
1	50	50	200	500	4
2	50	50	200	500	6
3	50	50	200	500	8
4	50	80	500	1500	4
5	50	80	500	1500	6
6	50	80	500	1500	8
7	50	110	800	2500	4
8	50	110	800	2500	6
9	50	110	800	2500	8
10	80	50	500	2500	4
11	80	50	500	2500	6
12	80	50	500	2500	8
13	80	80	800	500	4
14	80	80	800	500	6
15	80	80	800	500	8
16	80	110	200	1500	4
17	80	110	200	1500	6
18	80	110	200	1500	8
19	110	50	800	1500	4
20	110	50	800	1500	6
21	110	50	800	1500	8
22	110	80	200	2500	4
23	110	80	200	2500	6
24	110	80	200	2500	8
25	110	110	500	500	4
26	110	110	500	500	6
27	110	110	500	500	8

Table IVShows the obtained response for each DOE run performed under this experimentation. Where first of all volumetric material removal is calculated using following formula.

VMR = Mass difference (Before cut – After cut) / Density of material under test…… (mm^3)

Where,

Density of Tungsten Carbide = 15630 Kg/m^3.

Mass difference is evaluated using weighing scale.

Then Material Removal Rate (MRR) is calculated using following formula.

MRR = VMR / Process Time (Tp)…… (mm^3/min).

TABLE IV

RESPONSE OBTAINED FOR EACH DOE RUN

DOE Run No.	**Response**		
	Volumetric Material Removal	**Process Time**	**Material Removal Rate**
	Vol (mm^3)	**T_p (min)**	**MRR (mm^3/min)**
1	0.54	0.50	1.08
2	0.60	0.50	1.20
3	0.53	0.50	1.06
4	0.58	0.50	1.16
5	0.62	0.50	1.24
6	0.69	0.50	1.38
7	1.10	0.50	2.20
8	0.93	0.50	1.86
9	0.88	0.50	1.76
10	0.76	0.50	1.52
11	0.79	0.50	1.58
12	0.77	0.50	1.54
13	1.11	0.50	2.22
14	1.03	0.50	2.06
15	1.08	0.50	2.16
16	1.48	0.50	2.96
17	1.55	0.50	3.10
18	1.53	0.50	3.06
19	1.15	0.50	2.30
20	1.16	0.50	2.32
21	1.24	0.50	2.48
22	1.52	0.50	3.04
23	1.44	0.50	2.88
24	1.46	0.50	2.92
25	1.89	0.50	3.78
26	1.96	0.50	3.92
27	1.93	0.50	3.86

For second experimentation following parameters are taken

- Wire Tension
- Wire Velocity

Values of above parameters are taken at 4 different levels. Then available design of Taguchi Design Of Experiment is checked in MINITAB 17 software. From available DOE designs L16 design is chosen, i.e. in order to complete the experimentation 16 Nos of DOE runs need to be taken, each DOE run consists of specific combination of above input process parameters. Purpose of this experimentation is to obtain the Surface Finish (Ra) at different combinations of above input parameters. This is performed to understand the contribution and impact of input parameters on desired output from WEDM process. So that in the end optimized values of input process parameters are obtained [6] [7].

Table V indicates the chosen DOE design, which is having 16 experimentation runs. Input process parameters given in each run are put on the machine using Human Machine Interface and response in terms of Surface Finish (Ra) is recorded [6] [7].

TABLE V

RESPONSE OBTAINED FOR EACH DOE RUN

DOE Taguchi Design			**Response**
DOE Run No.	**Wire Tension**	**Wire Velocity**	**Surface Finish**
	T_f (N)	**V (m/s)**	**Ra (µm)**
1	10.00	0.10	0.90
2	10.00	0.30	0.86
3	10.00	0.50	1.95
4	10.00	0.70	1.80
5	20.00	0.10	1.52
6	20.00	0.30	2.20
7	20.00	0.50	2.60
8	20.00	0.70	0.94
9	30.00	0.10	0.88
10	30.00	0.30	1.86
11	30.00	0.50	0.86
12	30.00	0.70	2.26
13	40.00	0.10	2.10
14	40.00	0.30	0.68
15	40.00	0.50	1.20
16	40.00	0.70	1.32

VI. ANALYSIS OF DESIGN OF EXPERIMENT

Based on the response of each DOE run performed in first set of experiments, SN ration (larger is better) is obtained for Material Removal Rate (MRR). SN ratio is calculated for individual parameter using MINITAB 17 software. as shown in Fig.6 following values are optimized values for getting larger Material Removal Rate (MRR) [14] [6] [7].

- Gap Voltage = 110 V
- Peak Current = 110 A
- Pulse on time = 200 µsec
- Pulse off time = 500 µsec
- Wire feed = 4 m/min.

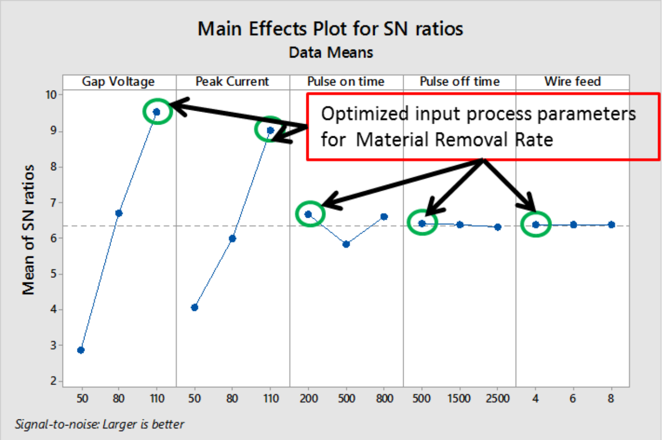

Fig.6Optimized Parameters for MRR

Ranking of contributing factors are obtained by generating response table. Following is the ranking order of influencing parameters starting from most to least [14].

- Gap Voltage
- Peak Current
- Pulse on time
- Pulse off time
- Wire feed

TABLE VI

RESPONSE TABLE FOR S/N RATION FOR MRR

Response Table for Signal to Noise Ratios
Larger is better

Level	Gap Voltage	Peak Current	Pulse on time	Pulse off time	Wire feed
1	2.874	4.061	6.653	6.422	6.360
2	6.691	6.000	5.829	6.373	6.365
3	9.526	9.029	6.608	6.296	6.366
Delta	6.652	4.968	0.824	0.126	0.007
Rank	1	2	3	4	5

Based on the response of each DOE run performed in second set of experiments, SN ration(smaller is better) for Surface Finish (Ra). SN ratio is calculated for individual parameter using MINITAB 17 software. as shown in Fig.7 following values are optimized values for getting smaller value of Surface Finish (Ra) [14] [6] [7].

- Wire Tension = 40 N
- Wire Velocity = 0.3 m/s

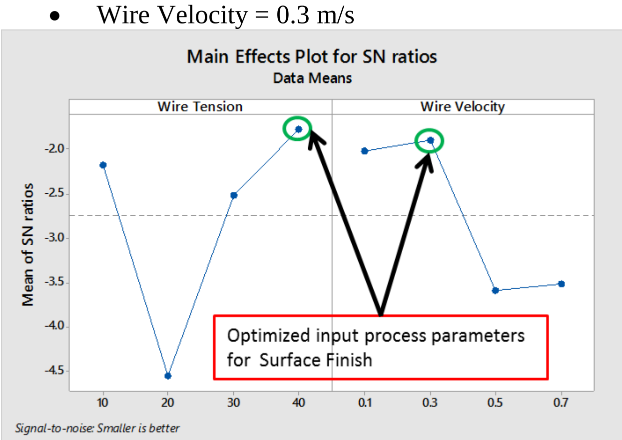

Fig.7 Optimized Parameters for Surface Finish

Ranking of contributing factors are obtained by generating response table. Following is the ranking order of influencing parameters starting from most to least [14].

- Wire Tension
- Wire Velocity

TABLE VII

RESPONSE TABLE FOR S/N RATION FOR MRR

Response Table for Signal to Noise Ratios
Smaller is better

Level	Wire Tension	Wire Velocity
1	-2.170	-2.014
2	-4.562	-1.895
3	-2.513	-3.593
4	-1.772	-3.515
Delta	2.789	1.699
Rank	1	2

VII. RESULTS

After analysing the main effect plot and response table, values of optimized parameters are obtained; same are given in Table VII. Values of optimized parameters are quite different from the values of normal process parameters.

TABLE VII

OPTIMIZED PROCESS PARAMETERS

After - Optimized Parameters						
Process Parameters						
Gap Voltage	Peak Current	Pulse on time	Pulse off time	Wire feed	Wire Tension	Wire Velocity
V_g (V)	I_p (A)	T_{on} (µs)	T_{off} (µm)	W_f (m/min)	T_f (N)	Vw (m/s)
110	110	200	500	4	40	0.3
Response						
Material Removal Rate					Surface Finish	
MRR (mm^3/min)					Ra (µm)	
3.08					0.80	

Optimized parameters were put on WEDM machine and output response is recorded in terms of MRR and Ra, their values are also given in Table VII.In fig.8 comparison is made for before input parameter optimization and after input process parameter optimization condition of WEDM process performance.

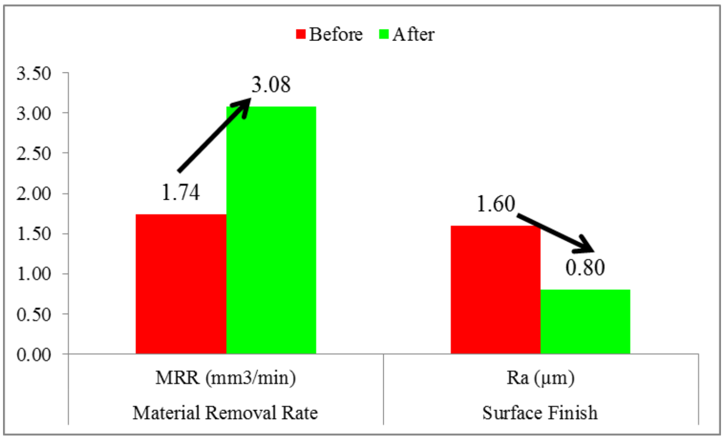

Fig.8WEDM process performance comparison before v/s after

VIII. CONCLUSIONS

This paper describes the experimental analysis Dry WEDM process for optimizing the input process parameters in order to obtain the desired values Material Removal Rate (MRR) and Surface Finish (Ra) on Tungsten Carbide work-piece. It also gives insight about process parameter optimization using Taguchi DOE.

First experimental analysis has been carried out using Taguchi design with 27runs. Following are the finalized value of process parameters,

- Gap Voltage = 110 V
- Peak Current = 110 A
- Pulse on time = 200 µsec
- Pulse off time = 500 µsec
- Wire feed = 4 m/min.

Second experimental analysis has been carried out using Taguchi design with 16 runs to reduce the vibration in the wire and in turn improve the surface finish. Following are the finalized value of process parameters,

- Wire Tension = 40 N
- Wire Velocity = 0.3 m/s

By putting the above values of input process parameters obtained WEDM process performance is as follows,

- Material Removal Rate (MRR) = 3.08 mm^3/min.
- Surface Finish (Ra) = 0.8 µm.

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