Investigation of Wire EDM Process Parameters for Machining of Mild Steel Specimen using TAGUCHI Methods

Nishant Saxena[1], Promise Mittal[2], Pavan Agrawal[3]

[1]*M.Tech Scholar, Mechanical Engg Department, VITM, Gwalior, India*
[2]*Asistant Professor, Mechanical Engg Department, VITM, Gwalior, India*
[3]*Associate Professor, Mechanical Engg Department, VITM, Gwalior, India*

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Abstract: *Wire EDM is an emerging technology in the field of non-conventional machining to fabricate very complex products with very high degree of precision. Wire EDM is a very complex process involving the different process parameters. In the present investigation an optimization of wire EDM will be perform using Taguchi optimization method. The parameters involved are pulse-on time, pulse-off time, peak current and servo voltage. Cutting rate, Surface Roughness, Dimensional Deviation and Wire Wear Ratio are taken as the responses. Experimental investigation will be performing on Wire-EDM machine. Wire electrical discharge machining process is a highly complex, time varying & stochastic process. The major applications of this process are in the fields of dies, moulds, precision manufacturing and contour cutting etc. Any complex shape can be generated with high grade of accuracy and surface finish using CNC WEDM. The output of the process is affected by large no of input variables. Hence a suitable selection of input variables for the wire electrical discharge machining (WEDM) process depends heavily on the operator's technology & experience. WEDM is extensively used in machining of conductive materials when precision is of prime importance. Rough cutting operation in wire EDM is very challenging one because improvement of more than one performance measures viz. Metal removal rate (MRR), surface finish are quite challenging task. The study demonstrates that the WEDM process parameters can be adjusted so as to achieve better metal removal rate, surface finish, electrode wear rate and dimensional deviation.*

Keywords:

Wire EDM, Taguchi Design of Experiments, ANOVA, Cutting Rate, Cutting Speed.

1. Introduction

The ultimate goal of the WEDM process is to achieve an accurate and efficient machining operation without compromising the machining performance. This is mainly carried out by understanding the interrelationship between the various factors affecting the process and identifying the optimal machining condition from the infinite number of combinations. The authors believe that the WEDM process due to its ability to efficiently machine parts with difficult-to machine materials and geometries has its own application area unmatched by other manufacturing processes. Electrical discharge wire cutting, most commonly known as wire electrical discharge machining (WEDM), involves physical process like heating and cooling. WEDM has grown in the large scale because of its advantages of infecting material hardness, no cutting force, high accuracy and ability to machine complex shapes and profiles especially in tool and die making industries. Material is removed from the work piece by a series of rapidly recurring current discharges between two electrodes, separated by a dielectric liquid and subject to an electric voltage. The most important performance characteristics for a WEDM process include material removal rate (MRR)/cutting speed, surface finish and kerf width. Discharge current, pulse time, pulse frequency, wire speed, wire tension, servo voltage and flushing pressure of dielectric fluid are the parameters which influence the performance of the process. Material removal rate, surface roughness and cutting width (kerf) were considered as a performance measures considered in this study. The WEDM process makes use of electrical energy generating a channel of plasma between the cathode and anode, and turns it into thermal energy at a temperature in the range of 8000 – 12,000 ºC. Taguchi suggested the use of Orthogonal Arrays (OAs) for the designing of experiments. He has also developed the concept of linear response graph which simplifies the design of OA experiments. This technique creates a standard orthogonal array to accommodate the effect of several factors on the target value and defines the plan of experiments. The Grey theory can provide a solution for a system in which the model is unsure or the information is incomplete. Besides, it provides an efficient solution to the uncertainty, multi-input and discrete data problem. The main advantage of these designs lies in their simplicity, easy adaptability to more complex experiments involving number of factors with different number of levels.

A. Introduction of WEDM:

Recent developments in the manufacturing industry have fuelled the demand for materials having higher strength, hardness and toughness. These materials pose a problem while machining with conventional machines available. The new materials available are lightweight combined with greater hardness and toughness. Sometimes their properties may create major challenges during their machining. Hence, non-conventional machining methods including electrochemical machining (ECM), ultrasonic machining (USM), electrical discharging machine (EDM) and the newly developed hybrid machining etc. are applied to machine such difficult to machine materials.

The most generalized machine tool to machine these materials is WEDM. Wire Electric Discharge Machining (WEDM) is a process by which a conductive material is cut by means of a thin wire electrode (generally brass) which follows a CNC controlled path. WEDM leaves a totally random pattern on the surface as compared to tooling marks left by milling cutters and grinding wheels. Since its inception in 1960's by the contributions from Lazarenko Brothers, it has revolutionaries the tool and dies making industry to a much wider extent. WEDM has evolved over time from being just used for manufacturing tools and dies to the machine of exotic space age alloys including Hastelloy, Inconel, titanium, Carbide, Polycrystalline diamond compacts and Conductive ceramics. Figure 1.1 shows the schematic of WEDM. It can machine anything regardless of its hardness, the only condition being the material should be electrically conductive.

It is probably the most exciting and diversified machine tool developed by the manufacturing industry in the last fifty years and has numerous advantages to offer.

Machining on WEDM is initiated by drilling a hole on the workpiece or starting from the edge. Here, the electrical energy is transformed into thermal energy by a series of discrete sparks being generated by spark generator. Sparks are formed through a sequence of rapid electrical pulses generated by the machine's power supply and these are thousands of times per second. Each spark forms an ionization channel under extremely high heat and pressure, in which particles flow between the wire electrode and the workpiece, resulting in vaporization of localized sections.

WEDM is a special adoption of EDM process for removal of material from the workpiece surface. The only difference between WEDM and EDM process is the type of tool being employed. The shape of the tool in EDM is the replica of the product to be obtained while in WEDM it is a continuously moving thin brass wire (generally diameter 0.25mm). The wire is fed through a pair of tensioning rollers. Both the workpiece and the tool are immersed in a continuously flowing pressurized dielectric fluid (deionised water). The dielectric fluid serves two purposes:

a) It acts as an insulator till a threshold voltage is reached.

b) It acts as a cooling agent.

It also flushes away the debris from the machining zone. Since there is no contact between the tool and workpiece, the process is free from any forces. This significantly reduces the need for special fixtures to support the workpiece as required in conventional processes. The process leaves no residual burrs, thus eliminating the need for any finishing process.

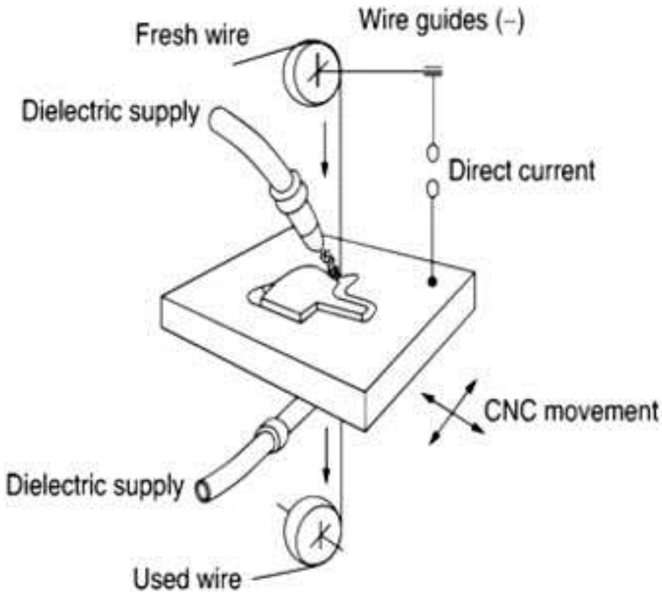

Fig. 1 Schematic diagram of WEDM

2. Experimental Set up and Process Parameter Selection

A. Machine Tool:

The experiments were carried out on a wire-cut EDM machine (Electronica ELPULS55 (enova 1S)) of Electronica Machine Tools Ltd. installed at CIPET: Centre for Skilling and Technical Support (CSTS) – Gwalior, M.P.

The WEDM machine tool (Figure 3.1) specifications are given in the following table.

Technical Specifications (CNC Wire cut EDM)

Machine Name	Unit	CNC Wire cut EDM
Main Axis Transverse (X,Y)	Mm	400 x 300
Aux Axis Transverse (u,v)	Mm	100 x 100
Work Table size	Mm	680 x 500
Max. taper angle	Mm	35°/50
Max. work piece height	Mm	300
Max. work piece weight	Kg	500
Max. machine current	Ampire	25
Resolution	mm	0.0005 mm
Max. wire spool capacity	8 kg (16-45 kg optional with de collar)	
Wire electrode diameter	0.25 mm (standard) 0.1, 0.15, 0.2, 0.3 (optional)	
Wire spool size	DIN 125, DIN 160, P-3-R, P—R	
Connected Load	13 KVA	
Dielectric fluid	De-ionized water	
Dielectric capacity	Liters	850

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Fig. 2 Pictorial View of WEDM Machine Tool

A. Work piece Material:

Mild Steel with size 30cm X 30cm X 50cm was used as a work piece material. Tables 2 and 3 give the limiting chemical composition and physical constants respectively of Mild Steel.

Mild steel is a type of carbon steel with a low amount of carbon – it is actually also known as "low carbon steel." Although ranges vary depending on the source, the amount of carbon typically found in mild steel is 0.05% to 0.25% by weight, whereas higher carbon steels are typically described as having a carbon content from 0.30% to 2.0%. Less carbon means that mild steel is typically more ductile, machinable, and weldable than high carbon and other steels, however, it also means it is nearly impossible to harden and strengthen through heating and quenching. The low carbon content also means it has very little carbon and other alloying elements to block dislocations in its crystal structure, generally resulting in less tensile strength than high carbon and alloy steels. Mild steel also has a high amount iron and ferrite, making it magnetic.

Mild steel is made similar to how other carbon steels are made. A common way this is done involves a combination of iron ore and coal. Once the coal and iron ore are extracted from the earth, they are melted together in a blast furnace. Once melted, the mixture is moved to another furnace to burn off any impurities that they may have, as well as to make any other adjustments to the mild steel's chemical composition. Following that, the steel is allowed to solidify into a rectangular shape. This slab of mild steel is then usually brought down to the desired size using processes called hot rolling or cold drawing, although there are other methods that can also be used.

1) 1. Chemical Composition of Mild Steel:

Carbon	0.16-0.18%
Silicon	0.40% max
Manganese	0.70-0.90%
Sulphur	0.040% Max
Phosphorus	0.040% Max

2) 2. Physical and Mechanical Constants of Mild Steel

Hardness, Brinell	126
Tensile Strength, Ultimate	440 MPa
Tensile Strength, Yield	370 MPa
Elongation at Break (In 50 mm)	15.0 %
Reduction of Area	40.0 %
Modulus of Elasticity (Typical for steel)	205 GPa
Bulk Modulus (Typical for steel)	140 GPa
Poissons Ratio (Typical For Steel)	0.290
Machinability (Based on AISI 1212 steel. as 100% machinability)	70 %
Shear Modulus (Typical for steel)	80.0 GPa

B. Preparation of Specimen:

A designed shape was cut from the sample work piece with using zinc coated brass wire

Fig. 3 Samples before WEDM Machining

Fig. 4 Sample after finishing on WEDM Machine

C. Process Parameters:

1. Pulse on time (TON)

2. Pulse off time (TOFF)

3. Peak Current (IP)

4. Servo voltage (SV)

5. Duty Cycle

6. Wire Tension

7. Wire Feed

8. Flushing Pressure of Dielectric

3. Experimental Results and Analysis

A. Introduction:

The present chapter gives the application of the Taguchi experimental design method. The scheme of carrying out experiments was selected and the experiments were conducted to investigate the effect of process parameters on the output parameters e.g. cutting rate, Gap Voltage and cutting time. The experimental results are discussed subsequently in the following sections.

B. Selection of Orthogonal Array and Parameter Assignment:

For the present experimental work four process parameters each at four levels have been decided. It is desirable to have minimum three levels of process parameters to reflect the true behavior of output parameters under study. The process parameters are renamed as factors and they are given in the adjacent column. The levels of the individual process parameters/factors are given in Table 5.1.

Process Parameters and their Levels

Factors	Parameters	Units	Lavel 1	Lavel 2	Lavel 3
A	T ON	μs	113	118	120
B	T OFF	μs	50	48	44
C	IP	A	100	130	160
D	SV	V	40	55	70

As per Taguchi experimental design philosophy a set of four levels assigned to each process parameter has three degrees of freedom (DOF). This gives a total of 12 DOF for four process parameters selected in this work. The nearest three level orthogonal array available satisfying the criterion of selecting the OA is L9 for each trial in the L9 array, the levels of the process parameters are indicated in Table 5.2.

Taguchi's L9 Standard Orthogonal Array

Trial	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

C. Experimental Results:

The WEDM experiments were conducted to study the effect of process parameters over the output response characteristics with the process parameters assigned to columns as given in Table 5.2. The experimental results for cutting rate and Cutting time are given in Table 5.3 and Table 5.4. 09 experiments were conducted using Taguchi experimental design methodology for obtaining S/N values. In the present study all the designs, plots and analysis have been carried out using Minitab 17 statistical software.

Experimental Results of Cutting Rate

Trial	Ton	Toff	Ip	SV	Cutting Rate	S/N Ratio	MEAN
1	113	50	130	55	1.38	2.797581728	1.38
2	113	48	100	40	1.39	2.860296005	1.39
3	113	44	160	70	1.42	3.045766888	1.42
4	118	50	100	70	1.46	3.287057116	1.46
5	118	48	160	55	1.48	3.405234308	1.48
6	118	44	130	40	1.38	2.797581728	1.38
7	120	50	160	40	1.86	5.390258884	1.86
8	120	48	130	70	1.92	5.666024574	1.92
9	120	44	100	55	2.02	6.107027389	2.02

Experimental Results of Cutting Time:

Trial	Ton	Toff	Ip	SV	Cutting Rate	S/N Ratio	MEAN
1	113	50	130	55	61	-35.7066	61
2	113	48	100	40	59	-35.4170	59
3	113	44	160	70	58	-35.2686	58
4	118	50	100	70	50	-33.9794	50
5	118	48	160	55	52	-34.3201	52
6	118	44	130	40	48	-33.6248	48
7	120	50	160	40	47	-33.4420	47
8	120	48	130	70	46	-33.2552	46
9	120	44	100	55	48	-33.6248	48

D. Analysis and Discussion of Results

The WEDM experiments were conducted by using the parametric approach of the Taguchi's method. The effects of individual WEDM process parameters, on the selected quality characteristics - cutting rate and cutting speed have been discussed in this section. The average value and S/N ratio of the response characteristics for each variable at different levels were calculated from experimental data. The main effects of process variables both for raw data and S/N data were plotted. The response curves (main effects) are used for examining the parametric effects on the response characteristics. The analysis of variance (ANOVA) of raw data and S/N data is carried out to identify the significant variables and to quantify their effects on the response characteristics. The most favourable values (optimal settings) of process variables in terms of mean response characteristics are established by analyzing the response curves and the ANOVA tables.

1. Effect on Cutting Rate and Cutting Time

Figures 5.1 show the main effect plot for cutting rate (Raw Data) and Cutting Time. It is quite evident from the graph that the cutting rate increases with increase in pulse on time while it continuously decreases with increase in pulse off time; cutting rate continuously shows mixed values with increase of peak current and increase in servo voltage and at the same time cutting time decreases with increase in pulse on time and it increases with increase of pulse on Time, while it continuously increases with increase in pulse off time. Cutting time continuously shows mixed values with increase of peak current and increase in servo voltage.

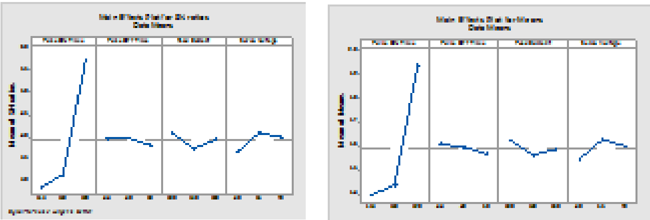

Fig 5. Main Effect Plot for cutting Rate:

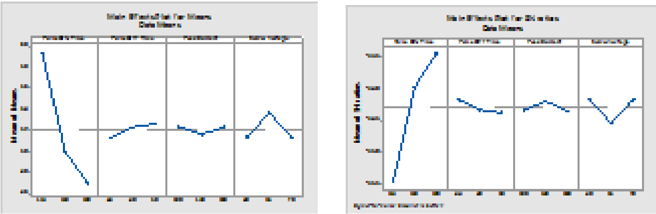

Fig 6. Main Effect Plot for cutting time:

Response Table for Signal to Noise Ratios:

Larger is better

Level	Pulse ON Time	Pulse OFF Time	Peak Current	Servo Voltage
1	2.901	3.983	4.085	3.683
2	3.163	3.977	3.754	4.103
3	5.721	3.825	3.947	4.000
Delta	2.820	0.158	0.331	0.421

Response Table for Means:

Level	Pulse ON Time	Pulse OFF Time	Peak Current	Servo Voltage
1	1.397	1.607	1.623	1.543
2	1.440	1.597	1.560	1.627
3	1.933	1.567	1.587	1.600
Delta	0.537	0.040	0.063	0.083
Rank	1	4	3	2

2. Selection of optimal levels for cutting Rate

In order to study the significance of the process variables towards cutting rate, analysis of variance (ANOVA) was performed. From table, it is clear that pulse on time, pulse off time, peak current, servo voltage significantly affect the mean value of cutting rate. The pulse on time has the greatest effect on cutting rate with about 90.78% of total contribution and is followed by pulse off time , peak current and servo voltage in that order.

As cutting rate is the "Larger is better" type quality characteristic, it can be seen from Figure 5 that the third level of pulse on time(A3), first level of pulse off time(Bl), first level of peak current (C1), and first level of servo voltage (Dl) provide maximum value of cutting rate. The S/N data analysis Figure 5 suggests Third level of pulse on time (A3), first level of pulse off time (Bl), first level of peak current (C1), and second level of servo voltage (D2) as the best levels for maximum CR in WEDM process.

Response Table for Signal to Noise Ratios:

Smaller is better

Level	Pulse ON Time	Pulse OFF Time	Peak Current	Servo Voltage
1	-35.46	-34.17	-34.34	-34.16
2	-33.97	-34.33	-34.20	-34.55
3	-33.44	-34.38	-34.34	-34.17
Delta	2.02	0.20	0.15	0.39

Response Table for Means:

Level	Pulse ON Time	Pulse OFF Time	Peak Current	Servo Voltage
1	59.33	51.33	52.33	51.33
2	50.00	52.33	51.67	53.67
3	47.00	52.67	52.33	51.33
Delta	12.33	1.33	0.67	2.33
Rank	1	3	4	2

3. Selection of optimal levels for Cutting Time

In order to study the significance of the process variables towards cutting rate, analysis of variance (ANOVA) was performed. From table, it is clear that pulse on time, pulse off time, peak current, servo voltage significantly affect the mean value of cutting time. The pulse on time has the greatest effect on cutting time with about 94.42% of total contribution and is followed by pulse off time , peak current and servo voltage in that order.

As cutting time is the "Smaller is better" type quality characteristic, it can be seen from Figure 6 that the First level of pulse on time(A1), Third level of pulse off time (B3), First level of peak current (C1), and Second level of servo voltage (D2) provide maximum value of cutting time with the best levels for minimum cutting time in WEDM process.

4. Estimation of Optimum response characteristics

A. Cutting Rate

The optimum value of cutting rate is predicted at the optimal level of significant variables which have already been selected as the third level of pulse on time(A3), first level of pulse off time(Bl), first level of peak current (C1), and first level of servo voltage (Dl)

$$\mu = \bar{T} + (\overline{A_3} - \bar{T}) + (\overline{B_1} - \bar{T}) + (\overline{C_1} - \bar{T}) + (\overline{D_1} - \bar{T})$$

Where:

$\bar{T}$ = overall mean cutting rate = 1.59 mm/min

$\overline{A_3}$ = average cutting rate at Third level of pulse on time = 1.93 mm/min

$\overline{B_1}$ = average cutting rate at First level of pulse off time = 1.40 mm/min

$\overline{C_1}$ = average cutting rate at First level of peak current = 1.40 mm/min

$\overline{D_1}$ = average cutting rate at first level of servo voltage = 1.40 mm/min

Substituting the values of various terms in above equation

μ = 1.93 + 1.40 + 1.40 + 1.40 – (3 X 1.59)

μ = 1.36 mm/min

B. Cutting Time:

The optimum value of cutting time is predicted at the optimal level of significant variables which have already been selected as the Second level of pulse on time(A2), Second level of pulse off time(B2), Second level of peak current (C2), and first level of servo voltage (Dl)

$$\mu = \bar{T} + (\overline{A_1} - \bar{T}) + (\overline{B_3} - \bar{T}) + (\overline{C_1} - \bar{T}) + (\overline{D_2} - \bar{T})$$

Where:

$\bar{T}$ = overall mean cutting time = 52.11 min

$\overline{A_1}$ = average cutting time at first level of pulse on time = 59.33 min

$\overline{B_3}$ = average cutting time at Third level of pulse off time = 47 min

$\overline{C_1}$ = average cutting time at First level of peak current = 59.33 min

$\overline{D_2}$ = average cutting time at Second level of servo voltage = 50 min

Substituting the values of various terms in above equation

μ = 59.33 + 47 + 59.33 + 50 – (3 X 52.11)

μ = 56.33 min

5. Conclusions

A. The effects of process parameters viz. pulse on time, pulse off time, peak current and servo voltage on response characteristics viz. cutting rate and cutting time were studied.

B. The optimal set of parameters was obtained for various performance measures using Taguchi's design of experiment methodology.

C. All the process parameters pulse on time, pulse off time, peak current and servo voltage are significant.

D. For cutting rate pulse on time (90.78), and for cutting time pulse on time (94.42) are the most significant factors.

E. Optimal set of parameters for cutting rate is A_3-B_1-C_1-D_1, and for cutting time A_2-B_2-C_2- D_1.

Machining Characteristics	**Optimal Settings of parameters**	**Value obtained by Taguchi method**
Cutting Rate	A_3-B_1-C_1-D_1	1.336 mm/min
Cutting Time	A_2-B_2-C_2-D_1.	52.67 min

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