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Analysis of WEDM of Aluminium 6063 Using Taguchi and Analysis of Variance Methods

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E-mail: [1]pntpn7@gmail.com, [2]tilakraj64@gmail.comAbstract

Abstract—*Wire Electric Discharge Machining (WEDM) process is used to cut conductive materials of any hardness. The process is specialized in cutting complex geometries that would be difficult to be produced using conventional machining process. The objective of the present research work is to study the effect of different process parameters viz. pulse on time, pulse off time, servo voltage and wire feed rate on the response parameters viz. material removal rate, surface roughness and wire wear ratio using 0.25 mm diameter zinc coated brass wire and de-ionized water as dielectric fluid. Al (Aluminium) 6063 is used as work piece material. Taguchi design methodology has been chosen for design of experiment and L9 orthogonal array (OA) has been selected for present study. Analysis of variance (ANOVA) and main effect plots have been used to find the significant process parameters and their effect on the response parameters and to optimize the WEDM process.*

1. INTRODUCTION

In 1969, the SWISS FIRM AGIE produced the world's first wire electric discharge machine, the process was fairly simple, not complicated and wire choices were limited to copper and brass only [1]. *Wire Electric Discharge Machining (WEDM)* has greatly improved in terms of accuracy, quality, productivity and precision, thus immensely helped the tooling and manufacturing industry. WEDM operated in industry today are equipped with Computer Numerical Control (CNC) which helps in improving efficiency and accuracy [2]. WEDM is considered as a unique adoption of the conventional EDM process which uses a continuously moving wire as electrode. The degree of accuracy of work piece dimensions obtainable and the fine surface finishes make WEDM particularly valuable for applications involving manufacture of stamping dies, extrusion dies and prototype parts [3]. WEDM is a process which erodes and removes material by the electric sparks generated in the small gap between the wire electrode and the work piece at a pulsating direct current supply of 20 to 30 kHz. De-ionized water is used as the dielectric fluid which stabilizes the sparks and flushes out the eroded metal. As there is no direct contact between the work piece and the wire, the mechanical stresses are absent during machining [4]. *Material removal rate (MRR)*, *surface roughness (SR)* of the machined surface by wire EDM and the *wire wear ratio (WWR)* will depend on different machining parameters such as pulse on time, pulse off time, servo voltage and wire feed rate etc.

2. EXPERIMENTATION AND METHODOLOGY

2.1. Experimentation

The experiments were carried out on the ELEKTRA SPRINTCUT 734 WEDM machine of Electronica Machine Tools Ltd. installed at CNC Lab in Department of Mechanical Engineering, YMCAUST, Faridabad, Haryana, India. The WEDM machine tool (Fig. 1) has the following specifications:

Features	Values
Design	Fixed column, moving table
Table size	440 x 650 mm
Max. work piece height	200 mm
Max. work piece weight	500 kg
Table size	300, 400 mm
Auxiliary table traverse (u, v)	80, 80 mm
Wire electrode diameter	0.25 mm (Standard)
Generator	ELPULS-40 A DLX
Controlled axes	X Y, U, V simultaneous / independent
Interpolation	Linear & Circular
Least input increment	0.0001mm
Least command input (X, Y, u, v)	0.0005mm
Input Power supply	3 phase, AC 415 V, 50 Hz
Connected load	10 KVA
Average power consumption	6 to 7 KVA

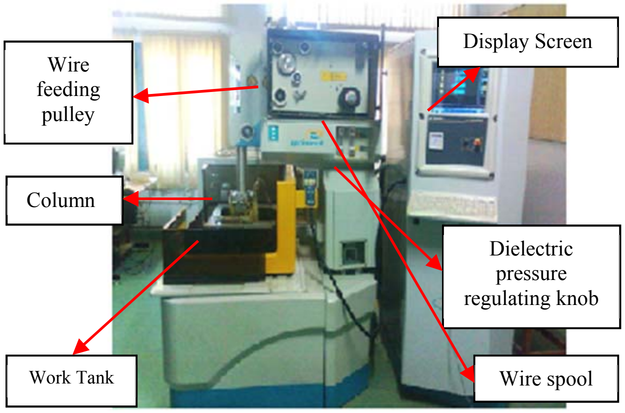

Fig. 1: CNC WEDM ELEKTRA SPRINTCUT 734

Aluminium 6063 (Al 6063) was chosen as work piece material which is an Aluminium alloy with magnesium and silicon as the alloying elements and is a medium strength alloy commonly used for architectural fabrication, stair rails, window and door frames, pipe and tubing, and Aluminium furniture. The chemical composition and some physical properties of the Aluminium 6063 are shown in Table 1 and Table 2 respectively.

Table 1: Composition of Al 6063 [5]

Element	Weight %	Element	Weight %
Mg	0.45-0.9	Cr	max. 0.1
Si	0.2-0.6	Cu	max. 0.1
Fe	max. 0.35	Zn	max. 0.1
Mn	max. 0.1	Others	max. 0.15
Ti	max. 0.1	Al	Balance

In WEDM the electrode is a continuously moving wire which is feed at a constant desired rate. Here the wire used was **Zinc coated brass wire of diameter 0.25 mm.** The properties of the wire as given by the manufacturer are listed in the Table 3.

Four parameters viz. pulse off time, pulse on time, servo voltage and wire feed rate were selected as process parameters. Three levels for each factor had been selected during experimental work. Selected levels for the above stated four input parameters and the fixed parameters are shown in Table 4.

Table 2. Physical Properties of Al 6063 [6]

Property	Value	Property	Value
Yield strength	214 MPa	Ultimate strength	241 MPa
E	68.9 GPa	Machinability	50 %
Brinell hardness	73	Elongation	12%
Electrical resistivity	3.32×10^{-6} ohm-cm	Density	2700 g/mm^3

Table 3. Wire Composition [Source: Manufacturer manual]

Wire type	Diameter (mm)	Core Composition	Coating Composition	Tensile Strength (kgf/mm^2)	Color
JET CUT ATS	0.25	CuZn37	Zinc	60 – 65	Silver grey

The purpose of the pilot experiments is to study the variations of the WEDM process parameters on performance measures such as MRR, SR, and WRR. Various input parameters varied during the experimentation were *pulse on time (T_{ON}), pulse off time (T_{OFF}), servo voltage (SV)* and *wire feed rate (WF)* while others factors were kept constant.

The procedure followed during machining operation on WEDM machine tool included following steps viz. a) The wire was made vertical with the help of verticality block; b) The work piece was mounted and clamped on the work table; c) A reference point on the work piece was set for setting work co-ordinate system (WCS). The programming was done with the reference to the WCS. The reference point was defined by the ground edges of the work piece; d) A gap of 8 mm between upper and lower nozzles cum wire guides was maintained during all the experimental trials; e) The program was made for cutting operation on the work piece and a U shaped cut of size 5 mm × 5 mm was obtained on each of the eighteen work pieces of both Brass and Aluminium.

The Aluminium work piece after machining is shown in Fig. 2.

Table 4. Process Parameters and their Levels

Input Parameters	Symbol	Units	Levels		
			1	2	3
Pulse on Time	T_{ON}	µs	100	120	130
Pulse off Time	T_{OFF}	µs	50	40	30
Servo Voltage	SV	Volt	80	70	60
Wire Feed Rate	WF	m/min	3	2	1

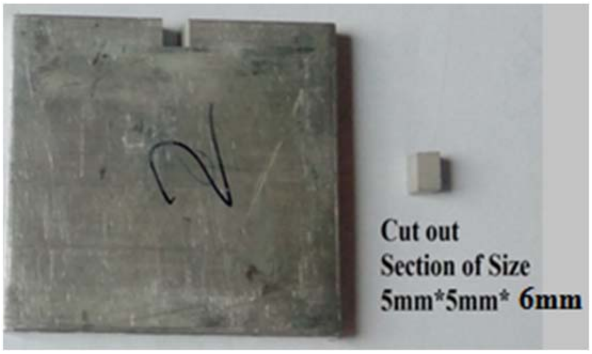

Fig. 2. Aluminium work piece after machining

2.2. Methodology

Robust design of an experiment is very necessary to reach at accurate result. The author has used "*The Taguchi Method"* as *design of experiment (DOE)* technique. The methodology involves identification of controllable and uncontrollable parameters and the establishment of a series of experiments to find out the optimum combination of the parameters which has greatest influence on the performance and the least variation from the target of the design [7]. *Orthogonal array (OA)* plays a critical part in achieving the high efficiency of the Taguchi method. Taguchi's orthogonal arrays are experimental designs that usually require only a fraction of the full factorial combinations [7]. **L_9** OA for four parameters with three levels of each was used for Taguchi's approach to DOE.

The *analysis of variance (ANOVA)* is the statistical treatment most commonly applied to the results of the experiments in determining the percent contribution of each parameter against a stated level of confidence .

Taguchi DOE, L_9 OA, *Signal to Noise (S/N) ratios* calculations for response parameters, S/N ratio main effect plots and ANOVA were performed on *MINITAB17* software. The parameters that influence the output can be categorized into two classes, namely controllable (or design) factors and uncontrollable (or noise) factors. Controllable factors are those factors whose values can be set and easily adjusted by the designer. Uncontrollable factors are the sources of variation often associated with operational environment.

Table 5. L_9 Orthogonal Array

Experiment No.	Input Parameters			
	T_{ON}	T_{OFF}	SV	WF
1	100	50	80	3
2	100	40	70	2
3	100	30	60	1
4	120	50	70	1
5	120	40	60	3
6	120	30	80	2
7	130	50	60	2
8	130	40	80	1
9	130	30	70	3

The S/N ratio depends on the quality characteristics of the process to be optimized. In the present work three response parameters were chosen viz. *material removal rate (MRR), surface roughness (SR)* and *wire wear ratio (WWR)*.The quality characteristics of these responses are shown in Table 6.

Table 6. Quality characteristics of response parameters

Response Name	Response Type
MRR	Larger The Better
SR	Smaller The Better
WRR	Smaller The Better

I. Larger the Better

This S/N ratio is usually the chosen for desirable characteristics.

S/N = -10 Log_{10} [mean of sum of squares of reciprocal of measured data]

II. Smaller the Better

This S/N ratio is usually the chosen for all undesirable characteristics.

S/N = -10 Log_{10} [mean of sum of squares of measured data]

MRR is measured in mm^3/min. Weight of the work piece has been measured before and after each machining operation and time for each machining operation has been noted from the digital display of the machine. Micro balance with "Least Count" of 0.0001 gram kept in Metrology Lab in IIT Delhi was used to measure the weight of work pieces.

Mathematical formula used for measuring MRR is given below:

$$MRR = (Wi - Wf)/(\rho \times t) \quad (1)$$

Where

W_i = Initial weight of work piece material in grams

W_f = Final weight of work piece material in grams

ρ = Density of work piece material in g/mm^3

t = Time period of each trials in minutes

SR was measured by digital micro surface meter "Form Talysurf Intra" installed in Metrology Lab in IIT Delhi. Surface roughness was measured over a distance of 2mm.

WWR is the ratio of the weight loss during machining of the wire to the initial weight of the wire. Weight of wire was measured on the same micro balance as used for the measurement of weights of work pieces.

Mathematically, WWR can be denoted as

$$WWR\ in\,\% = (Iw - Fw) \times 100/\,Iw \quad (2)$$

Where,

I_W = Initial weight of the wire before machining

F_W = Final weight of the wire after machining

3. RESULTS AND DISCUSSIONS

3.1. Results for MRR

The S/N ratios had been calculated to identify the major contributing factors towards MRR variation. The main effects plots for S/N Ratios for MRR gives the graphical variation of material removal rate with respect to input parameters viz. pulse on time, pulse off time, servo voltage and wire feed rate. The S/N ratios, main effects plots, response table for S/N ratios for MRR and ANOVA table for MRR are shown in Table 7, Fig. 3, Table 8 and Table 9 respectively.

Table 7: S/N ratios for MRR

T_{ON}	T_{OFF}	SV	WF	MRR	S/N Ratio
100	50	80	3	0.84	-1.5144
100	40	70	2	1.88	5.48316
100	30	60	1	6.16	15.7916
120	50	70	1	12.35	21.8333
120	40	60	3	18.75	25.46
120	30	80	2	8.82	18.9094
130	50	60	2	33.29	30.4463
130	40	80	1	31.81	30.0513
130	30	70	3	54.2	34.68

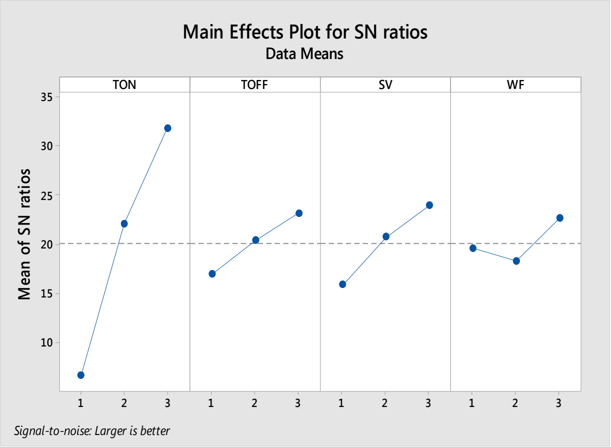

Fig. 3. Main effects plots for S/N ratios for MRR

Table 8. Response table for S/N ratios for MRR

Level	T_{ON}	T_{OFF}	SV	WF
1	6.587	16.922	15.815	19.542
2	22.068	20.331	20.665	18.28
3	31.726	23.127	23.899	22.559
Delta	25.139	6.205	8.084	4.279
Rank	1	3	2	4

Table 9. ANOVA for MRR

Source	DF	Adj SS	Adj MS	F-Value	P-Value
T_{ON}	2	2161.29	1080.96	17.06	0.003
T_{OFF}	2	9234	46.17	0.11	0.895
SV	2	123.5	61.74	0.15	0.861
WF	2	164.3	82.16	0.21	0.818
Error	24	7626.25	1271.04		
Total	32	10168.29			
DF - Degrees of Freedom, SS - Sum of Squares, MS - Mean Squares (Variance), F-ratio of variance of a source to variance of error, $P < 0.05$ determines significance of a factor at 95% confidence level.					

The results of Table 7 and Fig. 3 reveal that MRR is increasing with increase in pulse on time, decrease in pulse off time and decrease in servo voltage. The largest S/N ratio value gives the optimum value for the material removal rate. It is noticed from the response table for MRR i.e. from Table 9 that change in wire feed and pulse off time rate has little effect on MRR value. Analysis of variance for material removal rate as shown in Table 9 indicates that the most significant factor and the most contributing factor is pulse on time; pulse off time and wire feed rate are the least significant factors.

3.2. Results for SR

The S/N ratios had been calculated to identify the major contributing factors towards SR variation. The main effects plots for S/N Ratios for SR gives the graphical variation of surface roughness with respect to input parameters viz. pulse on time, pulse off time, servo voltage and wire feed rate. The S/N ratios, main effects plots, response table for S/N ratios for SR and ANOVA table for SR are shown in Table 10, Fig. 4, Table 11 and Table 12 respectively.

Table 10. S/N ratios for SR

T_{ON}	T_{OFF}	SV	WF	SR	S/N Ratio
100	50	80	3	0.7092	2.98463
100	40	70	2	0.5617	5.00991
100	30	60	1	0.9415	0.52359
120	50	70	1	1.3306	-2.481
120	40	60	3	1.3754	-2.7686
120	30	80	2	1.2078	-1.6399
130	50	60	2	1.0778	-0.6508
130	40	80	1	2.6202	-8.3667
130	30	70	3	1.4911	-3.4701

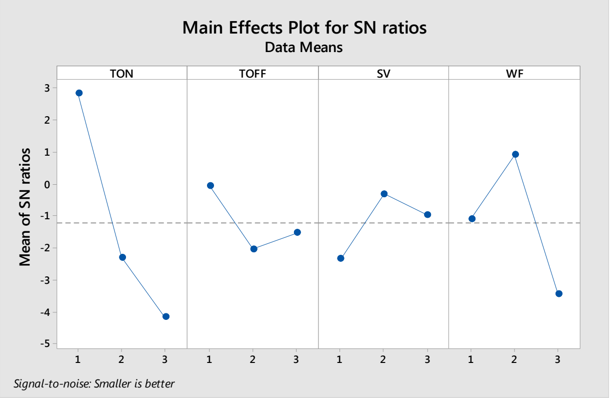

Fig. 4. Main effects plots for S/N ratios for MRR

Main effects plots (Fig. 4) give information about the effects of the individual input parameter on the SR. It is evident from the graph that an increase in pulse on time and decrease in pulse off time results in increase in surface roughness. The increasing voltage improves surface finish of the machined surface. The largest S/N ratio value gives the optimum value for the surface roughness.

Table 11. Response table for SR

Level	T_{ON}	T_{OFF}	SV	WF
1	2.83938	-0.04903	-2.34065	-1.08470
2	-2.29648	-2.04179	-0.31372	0.90642
3	-4.16253	-1.52881	-0.96525	-3.44135
Delta	7.00191	1.99276	2.02693	4.34776
Rank	1	4	3	2

Table 12. ANOVA for SR

Source	DF	Adj SS	Adj MS	F-Value	P-Value
T_{ON}	2	1.487	0.7434	3.27	0.109
T_{OFF}	2	0.3541	0.177	0.43	0.672
SV	2	0.293	0.4262	0.34	0.722
WF	2	0.7162	0.3581	1.01	0.42
Error	24	8.5502	1.4251		
Total	32	11.4006			

DF - Degrees of Freedom, SS - Sum of Squares, MS - Mean Squares (Variance), F-ratio of variance of a source to variance of error, $P < 0.05$ determines significance of a factor at 95% confidence level.

From table 11, it is observed that pulse on time is the most contributing factor and pulse off time is the least contributing factor. Also from table 12, it is noticed that pulse on time is the most significant factor and servo voltage is the least significant factor.

3.3. Results for WWR

The SN ratios have been calculated to identify the major contributing factors and the interactions between input parameters variation and the WWR values. The S/N ratios, main effects plots, response table for S/N ratios for WWR and ANOVA table for WWR are shown in Table 13, Fig. 5, Table 14 and Table 15 respectively.

Table 13. S/N ratios for WWR

T_{ON}	T_{OFF}	SV	WF	WWR	S/N Ratio
100	50	80	3	0.165	15.65032
100	40	70	2	1.156	-1.25916
100	30	60	1	3.312	-10.4018
120	50	70	1	0.454	6.858883
120	40	60	3	0.0825	21.67092
120	30	80	2	1.098	-0.81205
130	50	60	2	1.784	-5.0279
130	40	80	1	3.023	-9.60876
130	30	70	3	0.454	6.858883

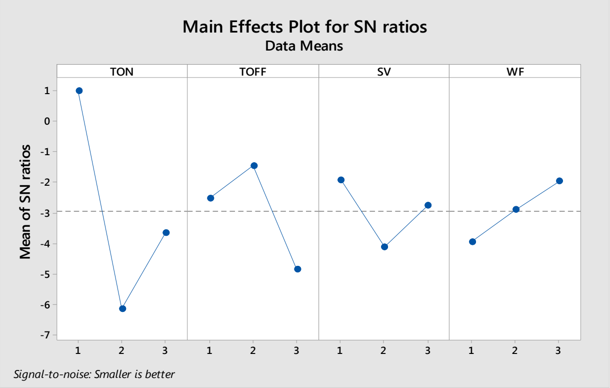

Fig. 5. Main effects plots for S/N ratios for WWR

It is evident from the Fig. 5 that increase in pulse on time, decrease in pulse off time and decrease in wire feed rate increases the wire wear ratio i.e. increased wire wear. Variation in servo voltage has less effect on WWR. The largest S/N ratio value gives the optimum value for the wire wear ratio. Analyzing the table 14, it is found that wire feed rate and pulse on time are the most contributing factors towards WWR and it is evident from the table 15 that .wire feed rate is the most significant factor and pulse off time is the insignificant factor.

Table 14: Response table for WWR

Level	T_{ON}	T_{OFF}	SV	WF
1	0.9805	-2.5288	-1.9339	-3.9430
2	-6.1454	-1.4610	-4.1185	-2.9076
3	-3.6618	-4.8369	-2.7743	-1.9761
Delta	7.1259	3.3760	2.1846	1.9670
Rank	1	2	3	4

Table 15. ANOVA for WWR

Source	DF	Adj SS	Adj MS	F-Value	P-Value
TON	2	2.504	1.252	0.83	0.479
TOFF	2	1.091	0.5485	0.32	0.74
SV	2	1.715	0.8574	0.53	0.616
WF	2	6.195	3.0977	3.5	0.098
Error	24	34.533	5.7554		
Total	32	46.044			

DF - Degrees of Freedom, SS - Sum of Squares, MS - Mean Squares (Variance), F-ratio of variance of a source to variance of error, $P < 0.05$ determines significance of a factor at 95% confidence level.

4. CONCLUSIONS

The effects of the selected process parameters on the response parameters viz. material removal rate (MRR), surface roughness (SR) and wire wear ratio (WWR) of the wire electric discharge machining (WEDM) for Aluminium 6063 have been discussed. The other factors like peak current, wire tension, type of dielectric fluid, wire material, wire diameter and dielectric fluid pressure. An optimal set of process variables that yields the optimum values for response parameters of the WEDM process has also been obtained.

The author has reached at following conclusions from the present study:

- With the increase in pulse on time, decrease in wire feed rate and decrease in pulse off time MRR increases. From the ANOVA of MRR it is observed that pulse on time is the most significant factor. The optimal value 42.35 mm^3/min of MRR was obtained at T_{ON} = 130μs, T_{OFF} = 30 μs, SV = 70volts, WF = 3m/min.
- With the increase in pulse on time and wire feed rate; decrease in servo voltage and pulse off time SR increases. From the ANOVA of SR it is observed that pulse on time is the most significant factor. The optimal value 0.6051μm of MRR was obtained at T_{ON} = 100μs, T_{OFF} = 30 μs, SV = 60volts, WF = 1m/min.
- With the increase in pulse on time, decrease in wire feed rate and decrease in pulse off time WWR increases. From the ANOVA of WWR it is observed that wire feed rate is the most significant factor. The optimal value 0.0825 % of WWR was obtained at T_{ON} = 100μs, T_{OFF} = 50 μs, SV = 80volts, WF = 3m/min.

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