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Influence of Process Parameters on Performance Characteristics during EDM of Aluminum Alloy 6082

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***Abstract* - The present work aims to investigate the influence of process parameters such as peak current, Pulse-on-time and pulse off time on performance characteristics namely, Material removal rate(MRR), Tool wear rate(TWR) and Surface roughness(SR) during Electrical Discharge Machining of Aluminum alloy 6082. Experiments have been carried out by Taguchi design of experiments (DOE) methodology. The level of influence of process parameters on performance characteristics has also been identified with help of Analysis of Variance (ANOVA). Optimal combination of process parameters was obtained using Taguchi method considering each performance characteristic separately. Results reveal that all the chosen responses namely MRR, TWR, and SR are increased with increase in peak current and pulse on time and are decreased with increase in pulse off time. Further peak current and pulse on time have significant affect on MRR, TWR and SR, whereas pulse off time has no significant affect. Confirmation experiments were conducted at optimal parametric setting to validate predicted responses values.**

Key words: Electrical Discharge Machining, Taguchi method, peak current; Pulse on time; pulse off time; Material Removal Rate; Tool Wear Rate and Surface Roughness.

I. INTRODUCTION

The material removal in EDM process is basically through the conversion of electrical energy into thermal energy. The succession of electrical discharges occurring repeatedly between electrodes. The two electrodes are immersed in a dielectric medium that are separated by small gap. The removal of material from the work piece takes place as a result of localized melting and even vaporization of material through high temperature spark. As there is no physical contact between the tool and work piece that eliminate mechanical stresses, chatter and vibration problems during machining that enable EDM.

The rotary motion of work piece improves the dielectric circulation through the discharge gap results increasing in MRR [1]. The surface characteristics and machining damage caused during EDM of AISI D2 tool steel were studied in terms of machining parameters [2]. The variations of geometrical tool wear characteristics and machining performance outputs such as MRR, TWR and SR for various peak currents, dielectric flushing methods and pulse on times were studied [3]. The usefulness of electrodes made through powder metallurgy method in comparison with copper electrode during EDM was correlated. Taguchi methodology was used to identify the effect of process input factors (viz. current, duty cycle and flushing pressure) on the output factors (viz. MRR and SR) [4]. The machining characteristics of EN8 steel with disc type rotating copper electrode during rotary EDM have been studied [5]. The effect of peak current, pulse on time and gap voltage on the responses that are MRR and SR with different tool electrodes namely copper, brass and graphite was studied [6]. The optimization of parameters of EDM process for machining of Ti – 6A1 – 4V alloy considering multiple performance characteristics using Taguchi method and grey relational analysis have been reported [7]. The effect of machining parameters such as pulse current and pulse on time on EDM characteristics namely, material removal rate, tool wear ratio, surface roughness, white layer thickness and depth of heat affected zone during machining of AISIH13 steel was presented [8]. Improvement in MRR was observed considering tool rotation and various intensities of external magnetic field as input variables [9]. The EDM characteristics of silicon carbide (SiC) single crystal material were investigated. EDM machining performances of SiC have experimentally studied and compared to that of steel [10]. The individual effect of process parameters such as peak current, pulse duration and pulse off time on performance characteristics namely MRR, TWR and SR during EDM of PH17-4 stainless steel as work material and electrolyte copper as electrode were reported [11]. However Aluminum alloy 6082 (AA6082) material is used for milk churns, trusses,

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cranes, ore skips, beer barrels, bridges, highly stressed applications and transport applications makes more attention of researchers to study machinability of this material. However, AA6082 material is difficult to machining with conventional machining processes due to its high hardness. Hence it is important to investigate the machinability characteristics of AA6082 material during EDM. From the literature survey it was found that less work has been reported on electrical discharge machining of AA6082 material. Hence AA 6082 material has been chosen as work material in the present work for experimentation.

II. EXPERIMENTAL SETUP, PROCEDURE AND EQUIPMENT

The AA6082 was chosen as work material and specimens were prepared with the dimensions of 100 × 50 × 13 mm^3 for conducting all the experiments. The chemical composition of AA6082 material is shown in Table 1 and Table 2 presents the physical and mechanical properties of AA6082 material.

TABLE 1: CHEMICAL COMPOSITION OF AA6082 MATERIAL

Element	Percentage (%)
Manganese (Mn)	0.40 - 1.00
Iron (Fe)	0.0 - 0.50
Magnesium (Mg)	0.60 - 1.20
Silicon (Si)	0.70 - 1.30
Copper (Cu)	0.0 - 0.10
Zinc (Zn)	0.0 - 0.20
Titanium (Ti)	0.0 - 0.10
Chromium (Cr)	0.0 - 0.25
Aluminum (Al)	Balance

TABLE 2: PHYSICAL AND MECHANICAL PROPERTIES OF AA6082 MATERIAL

Density	2.70 Kg/m3
Specific capacity	400 (J/kg °k)
Thermal conductivity	180 W/m.K
Electrical resistivity	0.038×10^{-6} Ω m
Modulus of elasticity	70 GPa
Melting Point	555 °C
Hardness Vickers	100 HV
Proof Stress	310 MPa
Tensile Strength	340 MPa
Elongation	11%
Shear Strength	210 MPa

The electrolytic copper of diameter 14mm and length 60 mm was used as tool material for machining AA6082 material and its physical properties are presented in the Table 3.

TABLE 3: PHYSICAL PROPERTIES OF ELECTROLYTE COPPER

Density	8.95 (g/cm^3)
Specific capacity	383 (J/kg °C)
Thermal conductivity	394 (W/m °C)
Electrical resistivity	1.673×10^{-8} Ω m
Melting point	1083°C

TABLE 4: WORKING RANGE OF THE PROCESS PARAMETERS AND THEIR LEVELS

Parameter	Unit	Level1	Level2	Level3
Peak current, I	Amps	8	16	24
Pulse on time, T_{on}	μs	50	100	150
Pulse off time, T_{off}	μs	35	65	95

TABLE 5: EXPERIMENTAL CONDITIONS

Working conditions	Description
Work piece	AA6082 (100mm×50mm×13mm)
Electrode	Electrolyte copper Ø 14mm and length 60 mm
Dielectric	Commercial EDM Oil grade SAE 240
Flushing	Side flushing with pressure 0.5MPa
Polarity	Positive
Supply voltage	240 V
Machining time	5 minutes

TABLE 6: EXPERIMENTAL LAYOUT USING AN $L_9(3^4)$ OA

Sr.No	A	B	C
	Peak current	Pulse on time	Pulse off time
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

All the experiments were carried out on EDM machine model MOLD MASTERS605 with commercial EDM oil grade SAE240 as a dielectric fluid through side flushing. Taguchi L_9 (3^4) OA was considered for the present study and experiments were conducted as per the OA shown in Table 6. Each experiment was repeated three times to minimize the experimental errors. The experimental conditions were presented in Table 5. Three process parameters with three levels were considered in present study and their working range and levels were chosen based on trend of MRR and SR obtained from trial experiments. The working range of the process parameters and their levels are presented in Table 4. Further material removal rate (MRR), tool wear rate TWR), and surface roughness (SR) were chosen to evaluate machining performance. A digital weighing balance (citizen) having capacity up to 300 grams with a resolution of 0.1gms was used for weighing the work pieces and electrodes before machining and after machining. Then the material removal rate (MRR) and tool wear rate are calculated with weight loss method and is as follows.

$$MRR\left(mm^3/_{min}\right) = \frac{\Delta W}{\rho_w \times t} \dots\dots\dots (1)$$

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$$TWR\left(mm^3/_{min}\right) = \frac{\Delta T}{\rho_t \times t} \dots\dots\dots (2)$$

Where ΔW is the weight difference of work piece before and after machining (g), ρ_w is density of work material (g/mm³), ΔT is the weight difference of electrode before and after machining (g), ρ_t is density of electrode material (g/mm³) and t is machining time in minutes. Surface roughness of the machined work pieces were measured using Talysurf surface roughness tester. Roughness measurements were carried out in the transverse direction on machined surface with sampling length of 0.8 mm.

Taguchi method was used to determine optimal combination of process parameters to maximize MRR, and minimize TWR and SR. Taguchi method uses the S/N ratio to measure the quality characteristic deviating from the desired value. The experimental values of MRR, TWR, and SR are transformed into their signal-to-noise ratios (S/N ratio). The MRR is chosen as "higher-the-better" characteristic whereas TWR and SR were selected as "lower-the-better" characteristics. After calculation of S/N ratio, the effect of each machining parameter at different levels was separated. The mean S/N ratio for each process parameter at each level was calculated by averaging the S/N ratios for the experiments at the same level for that particular parameter. Mean of means response tables and mean of means graphs for MRR, TWR, and SR were prepared. The analysis of variance (ANOVA) was used to determine the significant affect of process parameters on the performance measures.

III. RESULTS AND DISCUSSIONS

A. Effect of Process Parameters on MRR

The average values of MRR, TWR, and SR for each experimental run and their respective S/N ratio values are presented in Table 7.

TABLE 7: AVERAGE EXPERIMENTAL RESULTS AND S/N RATIOS OF MRR, TWR, AND SR

Exp No.	Process parameters			MRR		TWR		SR	
	I (A)	T_{on} (µs)	T_{off} (µs)	Mean (mm³/min)	S/N Ratio	Mean (mm³/min)	S/N Ratio	Mean (µm)	S/N Ratio
1	8	50	35	5.4259	14.6894	0.1122	19.0001	3.8583	-11.7278
2	8	100	65	6.6666	16.4781	0.2244	12.9795	4.3570	-12.7838
3	8	150	95	7.9740	18.0335	0.2632	11.5943	4.7640	-13.5594
4	16	50	65	15.5555	23.8377	0.3600	8.8739	6.4798	-16.2312
5	16	100	95	19.7400	25.9069	0.4200	7.5350	8.3302	-18.4132
6	16	150	35	24.9629	27.9459	0.4130	7.6810	9.2785	-19.3496
7	24	50	95	38.5185	31.7134	0.4432	7.0680	8.7040	-18.7944
8	24	100	35	45.8880	33.2340	0.5210	5.6632	10.8468	-20.7060
9	24	150	65	47.9258	33.6114	0.5611	5.0192	11.9325	-21.5346

From Figure 1 it was observed that MRR increases with increasing in peak current. The increase in peak current increases spark energy that causes increased current density. This rapidly over heats the work piece resulting increase in MRR with peak current. As current increases, discharge strikes the work surface intensively which creates an impact force on the molten material in the molten puddle. This causes more material ejection of out of the crater. Another observation from the present experiment is that the MRR increases with increase in pulse on time. The discharge energy in the plasma channel and the period of transferring this energy in to the electrodes increases with increase in pulse on time. This phenomenon leads to formation of bigger molten material crater on the work which results in increase in MRR (V.V Reddy et al, 2014). However MRR decreases with increase in pulse off time.

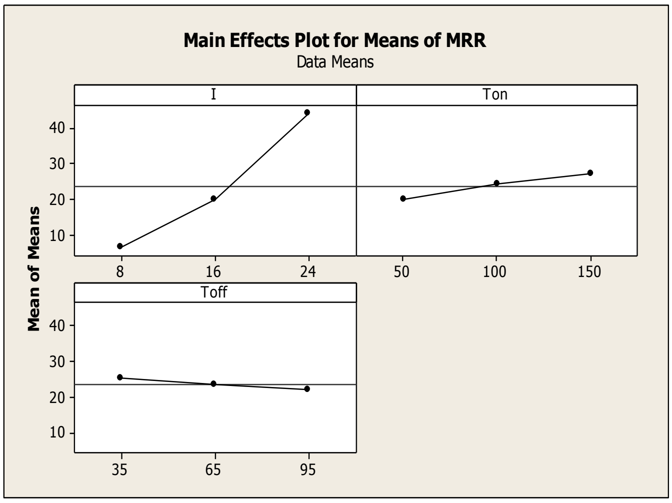

Figure 1: Effect of process parameters on mean data of MRR

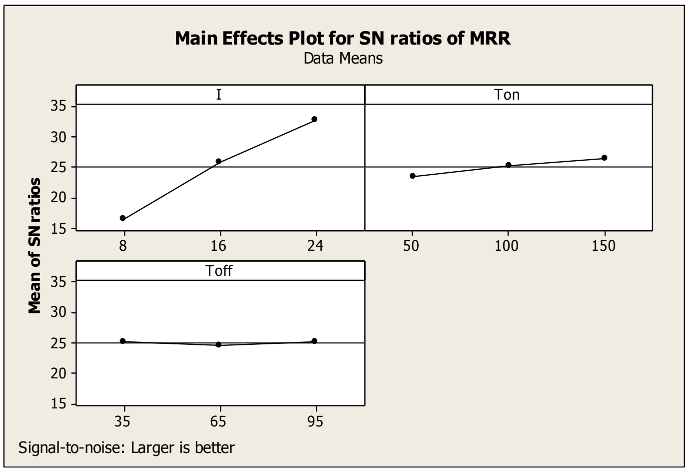

Figure 2: Effect of process parameters on S/N Ratios of MRR

Since it is always desirable to maximize the MRR larger the better option is selected. Figure 2 suggested that when peak current is at 24A (level 3), pulse on time is at 150μs (level 3) and pulse off time is at 35μs (level 1), provide maximum MRR.

Table 8: ANOVA for MRR (mm³/min), using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
I(A)	2	2157.07	2157.07	1078.54	855.27	0.001
T_{on}(μs)	2	77.05	77.05	38.53	30.55	0.032
T_{off}(μs)	2	17.09	17.09	8.54	6.77	0.129
Error	2	2.52	2.52	1.26		
Total	8	2253.73				

S = 1.12296 R-Sq = 99.89% R-Sq (adj) = 99.55%

Table 8 presents the ANOVA for MRR at 95% confidence level. The data presented in the ANOVA reveals the significance of input parameters on MRR which is as follows. The peak current, pulse on time and pulse off time are significant factors affecting the MRR since respective F values are higher than F_{cr}. Further optimum value of MRR is calculated as 49.2334 (mm³/min) and corresponding S/N ratio is 34.5729 at the optimal parameter setting.

B. Effect of Process Parameters on TWR

The average values of TWR for each trial and their respective S/N ratio values are presented in Table 7. Figure 3 presents main effects plot for means of TWR. Figure 4 shows main effects plot for S/N ratios of TWR. It is observed from Figure 3 and Figure 4 that the increase in tool wear rate with increase in peak current as well as pulse on time. This can be explained as increase in peak current causes increase in spark energy resulting in increase in TWR.

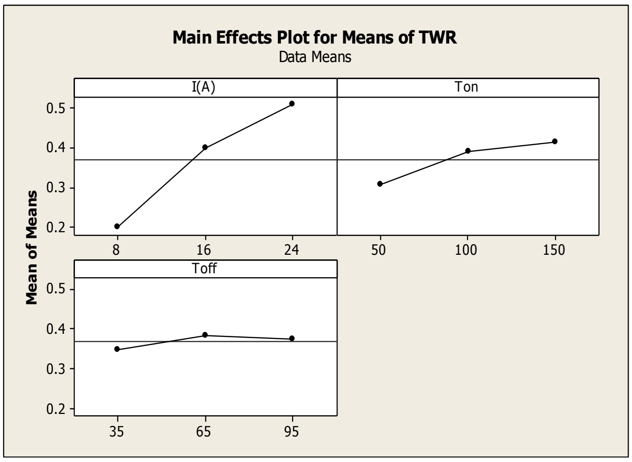

Figure 3: Effect of process parameters on mean data of TWR

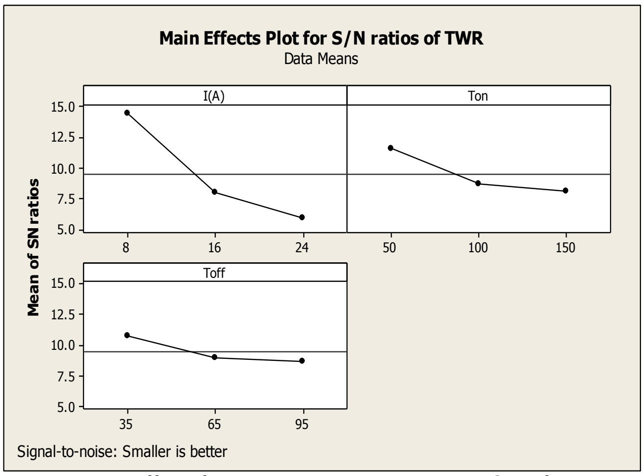

Figure .4: Effect of process parameters on S/N ratio data of TWR

Further spark energy and the period to transfer this energy in to the electrodes increases with increase in pulse on time which results in increase in TWR. However slight increase in TWR is noticed with increase in pulse off time. Since it is always desirable to minimize the TWR smaller the better option is selected. From the Figure 4 it is observed that minimum TWR value was achieved when peak current was at 8A (level 1), pulse on time at 50 μs (level1) and pulse of time at 35μs (Level1).

TABLE 9: ANOVA FOR TWR (MM^3/MIN), USING ADJUSTED SS FOR TESTS

Source	DF	Seq SS	Adj SS	Adj MS	F	P
I(A)	2	0.146540	0.146540	0.073270	194.03	0.005
T_{on}(μs)	2	0.019032	0.019032	0.009516	25.20	0.038
T_{off}(μs)	2	0.001851	0.001851	0.000925	2.45	0.290
Error	2	0.000755	0.001851	0.000378		
Total	8	0.168178	0.000755			

S = 0.0194323 R-Sq = 99.55% R-Sq (adj) = 98.20%

Table 9 presents the ANOVA for TWR at 95% confidence level. The data presented in the ANOVA reveals the significance of input parameters on TWR which is as follows. The peak current, and pulse on time are significant factors affecting the TWR since respective F values are higher than the F_{cr} .Where as pulse off time has not significant effect on TWR. Optimum TWR value was calculated as 0..1164mm³/min and corresponding S/N ratio is 17.9725.

C. Effect of Process Parameters on SR

The average values of SR for each trial and their respective S/N ratio values are presented in Table 7. Figure 5 presents main effects plot for means of SR. Figure 6 shows main effects plot for S/N ratios of SR. Further it is observed from the Figures 5 and Figure 6 that there is increase in surface roughness with increase in peak current. This can be attributed to the fact that increase in peak current causes increase in spark energy resulting in the formation of deeper and larger craters result into increase in surface roughness. It is also noticed that surface roughness increases with the increase in pulse on time. The spark energy and time of transferring energy in to the work piece increases with increase in pulse on time. This phenomenon leads to increase in formation of molten pool resulting in deeper and larger craters which again results in increase in SR. However decrease in surface roughness value is observed with increasing in pulse off time. This may be due to proper removal of debris from the discharge channel.

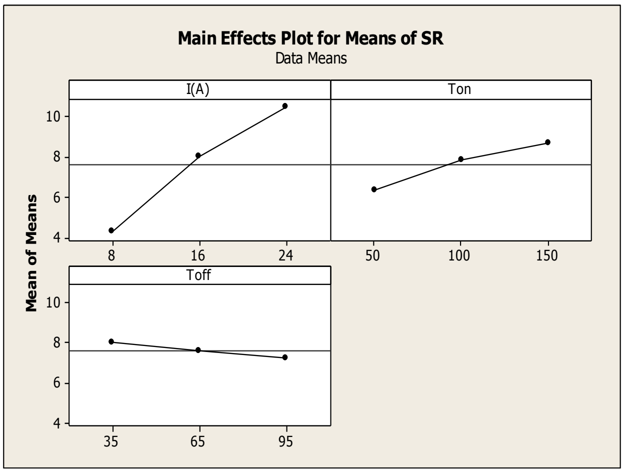

Figure 5: Effect of process parameters on mean data of SR

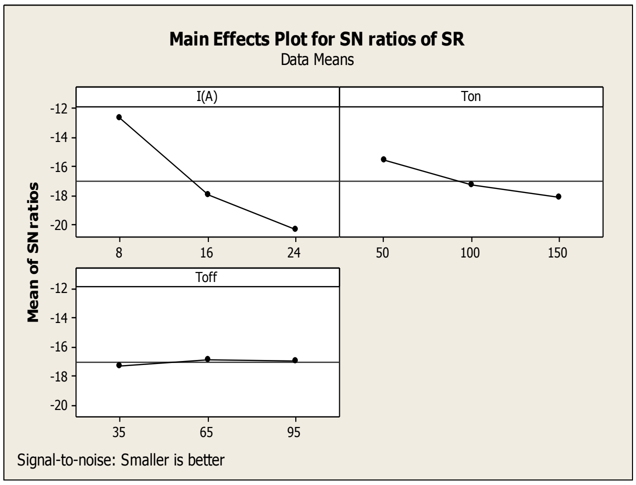

Figure 6: Effect of process parameters on S/N ratio data of SR

Since it is always desirable to minimize the SR smaller the better option is selected. From Figure 6 noticed that minimum SR value is attained when peak current at 8 A (level 1), pulse on time at 50μs (level 1) and pulse off time at 65μs (Level 2).

TABLE 10: ANOVA FOR SR, USING ADJUSTED SS FOR TESTS

source	DF	Seq SS	Adj SS	Adj MS	F	P
I(A)	2	57.833	57.833	28.916	70.73	0.014
Ton	2	8.245	8.245	4.122	10.08	0.090
Toff	2	0.799	0.799	0.400	0.98	0.506
Error	2	0.818	0.818	0.409		
Total	8	67.694				

S = 0.639387 R-Sq = 98.79% R-Sq (adj) = 95.17%

Table 10 represents the ANOVA for SR at 95% confidence level. The data presented in the ANOVA reveals the significance of input parameters on SR which is as follows. The pulse on time, peak current, and pulse off time are significant factors affecting the SR since respective F values are higher than theF_{cr} . Optimum surface roughness value is calculated as 3.0299μm and corresponding S/N ratio is -11.1025.

IV CONFIRMATION EXPERIMENTS:

To verify the predicted optimal values of responses such as MRR, TWR, and SR three confirmation experiments were conducted at their optimal parametric settings .The data from the confirmation experiments and their comparisons with respective predicted values and the deviation of predicted results from experimental results were calculated as percentage error and are presented in Table 11.

$$\%\text{error} = \frac{\text{experimentalvalue} - \text{predictedvalue}}{\text{experimentalvalue}} \times 100 \ldots\ldots\ldots (4.1)$$

TABLE 11: CONFIRMATION OF EXPERIMENTS AT OPTIMAL CONDITIONS

S.No.	Optimum parameters			Response	Experimental value	Predicted value	%error
	I (A)	T_{on} (µs)	T_{off} (µs)				
1	24	150	35	Max.MRR (mm³/min)	50.10	49.2334	1.72
2	8	50	65	Min.SR (µm)	3.0700	3.0299	1.30
3	8	50	35	Min.TWR (mm³/min)	0.112	0.116	-3.57

V. CONCLUSIONS

The conclusions derived from the work were as follows:

1. Responses namely MRR, TWR, and SR are increased with increase in peak current and pulse on time. However MRR TWR and SR decrease with increase in pulse off time.
2. Optimal combination of process parameters (I=24A, T_{on} =150µs and T_{off} = 35 µs) µs yield maximum MRR (49.2334mm³/min). Whereas process parameters (I=8A, T_{on} =50µs and T_{off} = 35 µs) setting yield minimum TWR (0.116mm³/min). However minimum SR (3.0299µm can be obtained at process parameters (I = 8A, T_{on} = 50µs and T_{off} = 65µs).setting.
3. Peak current and pulse on time are significant parameters affecting MRR, TWR and SR. While pulse off time has no significant affect.

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