OPTIMISATION OF PROCESS PARAMETERS FOR MINIMISING THE SURFACE ROUGHNESS DURING WIRE-ELECTRICAL DISCHARGE MACHINING (WEDM) OF SILICON PARTICLE REINFORCED AL6061 COMPOSITE

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ABSTRACT

In the recent era, the advanced machining methods are popularly used for machining of simple to complex profiles in engineering materials. In this work, the machinability of 8 % silicon particle reinforced Al6061 composite is investigated by WEDM. The effect of control parameters namely current (I_c), pulse-off time (T_{off}), wire-speed (W_s), pulse-on time (T_{on}) and voltage (V) on surface roughness is investigated. Taguchi L_{16} orthogonal array is used in the experimental design and the results are analysed using statistical methods. Study showed that, the T_{on} is the highly significant parameter which contributed maximum (38.27%) to variation of surface roughness followed by voltage (31.02 %), wire speed (17.11 %), current (7.11%) and pulse-off time (5.39 %). The optimum settings which produced the minimum surface roughness (expected R_a - 3.302 μm) are current: level 3 (4A), T_{on} : level 1 (20 μs), T_{off} : 10 μs (level 1), W_s - level 4 (1400 rpm) and voltage - 80 V (level 1). The regression model is developed for predicting the surface roughness with R^2 value of 87.30%. The model predicting accuracy of the model is verified for the experimental results.

KEYWORDS: Wire-EDM, Material Removal Rate, Aluminium Composite, Pulse-off Time, Wire Speed & Pulse-on Time

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1. INTRODUCTION

The Aluminium is the most popular metal used after iron and its world's annual production is 58.3 million tonnes. According to United States geological survey, the sector wise use of aluminium alloys is as follows, the transportation industry - 36 %, building and construction – 26 %, packaging industries -17%, engineering industries 14 % and others 7 %. In general, these metals possess low density, good malleability, corrosion resistance and electricity conductivity. The properties of aluminium can be further improved by alloying with other materials such as SiC, Al_2O_3 , MgO, WC, SiO_2 and B_4C , etc [1]. The aluminium is designated from 1XXX to 8XXX series [2] based on the material composition. Due to low density, the aluminium alloys are popularly used in transport applications (automobiles, aeroplanes and ships) for reducing fuel consumption and hence carbon emission. Aluminium 6000 series contains 95.8 % - 98.6 % Al, 0.8% - 1.2 % Mg and 0.4 - 0.8 % Si and other alloying elements. This material shows excellent mechanical properties and weldability, hence, it finds applications in aircraft fittings, electrical fittings and connectors, camera lens mounts, marine fittings and hardware, couplings, hinge pins, magneto parts, decorative hardware, brake and hydraulic pistons, valve parts and bike frames, etc. SiC particles are used as reinforcement particles in composites because of its high strength to weight ratio, thermal stability, resistance to wear [3, 4]. The microstructural and mechanical properties of Al 6061 with SiC nanoparticles (500 nm) showed improved Young's modulus and toughness [5]. Cao Fenghong et al [6] studied the effects of Si

and tungsten carbide reinforcement in aluminium composites. The strong interfacial bond created in the matrix and the reinforced particles in these composites were found to transfer and distribute the load onto the reinforcement from the matrix. This resulted in enhancement of the elastic modulus and the strength of composite. Nair et al. [7] made a review of metallurgy of Al-SiC composites in which the elastic stiffening effects of the SiC whiskers are detailed through continuum mechanics models. The type of reinforcement, its size, shape and quantity were found to significantly influence the mechanical properties [8] of the developed composite.

Although, pure aluminium possess good machinability, the machining of silicon reinforced aluminium is challenging. The abrasive nature the alloying element lead to rapid tool wear which affects the surface quality and production rate. The term machinability indicates the ease of machining. This is determined parameters like tool wear rate, machined surface quality, chip evacuation, Material Removal Rate (MRR) and power consumption [9], etc. ThambuSornakumar et al. [10] studied the effect of milling (tool: M2 high speed steel, diameter: 5 mm) of silicon carbide reinforced aluminium alloy. The increase of cutting speed (10-30 m/min) resulted in improving the machining and burnishing effect on the milled surface which led to decrease of surface roughness. But, increase in feed (0.1-0.5 m/min) rate increased the surface roughness due to reduced contact time of tool with the work piece. The machining also resulted in the pull-out and fracture of particles from the matrix. This led to formation of voids and cavities on the machined surface, hence resulted in poor surface quality in the SiC reinforced composites. But, the ceramic reinforcement in aluminium showed better wear resistance [11]. Shoba et al. [12] investigated the cutting forces (feed force $-F_f$, cutting force $-F_c$, radial force $-F_d$) developed on 0 - 8 wt. % SiC and rice husk ash reinforced composite. The cutting force components F_f , F_c , and F_d were lower in the reinforced specimens compared to unreinforced specimens. Also, the F_f , F_c , and F_d were found to decrease with the increase in SiC content in the matrix. This is due to a change in deformation behaviour matrix by the addition of reinforcement. The increase in proportion of reinforcement also increased the material hardness, which resulted in formation of the machined chip by large plastic shear [13] and thus decreased the cutting force with the increase in reinforcement proportion. Ravi Sekhar et al. [14] made a detailed review of particle fracture and its pull-out from the matrix, dislocation phenomena, wear modes, cutting forces as-well-as chip formation mechanism involved in machining of metal matrix composites with particle reinforcement.

M. S. Said et al [15] optimised the machining parameters while drilling Al-Si composites using uncoated carbide, TiCN and TiN coated drill bit. The cutting tool initially showed abrasive wear due to presence of hard reinforcements. This exposed the fresh tool surface, which begun to adhesion with the matrix material and resulted in adhesion wear. The lower cutting speeds resulted in formation of built-up edges. The tool life was considerably improved by coating different materials, use of higher cutting speed and coolants during machining. PalaniSivaprakasam et al. [16] determined the machinability of A413-9% composite using zinc coated copper wire in wire-EDM. The operating parameters such as I_v , capacitance and tool feed-rate showed significant interaction effect on kerf-width and surface roughness. The MRR was increased due to higher current and pulse-on time duration while machining of SiC/Al composite [17-20]. When composition of SiC particle is increased upto 15% in the matrix phase, the MRR was decreased and the further increase in SiC content showed the reverse trend. Agrawal and Yadava [21] investigated the surface roughness and MRR of AA6025 composite (SiC:10wt.% and Al_2O_3 :10wt. %). The studies showed that, the machining performance was improved with use of conductive powder in the dielectric fluid. Basically, the conductive particles reduced the strength of dielectric fluid and increased the spark gap. This phenomenon assisted in ignition process due to generation of a stable and high discharge in the spark gap [22]. Sarabjeet singh sidhu et al. [23] studied the EDM surface properties of 6 % SiC/A356.2, 10 % SiC-5 %

quartz/Al, and 30 %SiC/A359 composite. The surface hardness was found to be increased with an increase in the particle density. While machining, it was also observed that higher metal transfer occur through the copper tool compared to graphite electrode tool material. Dey et al. [24] optimized the process parameters for machining of Al6061/cenosphere composite. The increase in pulse I_c and T_{on} produced the bigger crater and high surface waviness on the machined surface and resulted in poor surface quality and increased electrode wear rate in Al (6351)–SiC–B₄C composite [25]. Literature study indicated silicon particle reinforcement for aluminium materials show excellent properties in the composite. The use of this material for different applications is restricted by the quality of the cut surface and tool wear rate. The conventional machining methods results in high tool wear-rate, formation of pits, voids, micro-cracks and fractured reinforcements on the cut surface. To address these challenges, various non-conventional machining methods are attempted by different researcher groups. This article optimise the process parameters for obtaining low surface roughness while machining of 8 % silicon particle reinforced Al-6061 composite by wire-EDM and develop the regression model to predict the surface roughness.

2. MATERIALS AND METHODS

2.1 Experimental set up and Specimen Details

Figure1 shows the details of experimental test rig. In the present work, experimental work is carried out using a 2-axis (X-320 mm, Y-400 mm) computer numerically controlled wire-EDM made by Concord wire-EDM, India (Model: DK7732). Molybdenum wire (diameter: 0.16 mm) is used tool electrode during the experiments. Mixture of soft water and gel is used as dielectric fluid. The resolution of the controller is 0.001 mm.

Figure 1: Experimental Setup.

The SiC particles (size: 170 μ m) reinforced Al-6061 test specimen is prepared by mechanical stirring. The matrix material is melted at a temperature 850°C in a crucible and the pre-heated (650°C) reinforcing particles (4 % and 8 % by weight) are added to molten matrix and uniformly distributed in the matrix by stir casting. The metal mould is pre-heated to 200°C for pouring molten metal and then allowed for cooled to room temperature.

2.2 Design of Experiments

The process parameters such as I_c , $T_{on-time}$, $T_{off-time}$, W_s and I_v are chosen to study its effect on rate of material removal (MRR). The voltage is varied at two different levels and I_c , $T_{on-time}$, $T_{off-time}$, W_s are varied at four different levels. The level set for process parameters is shown in Table 1 and these levels are chosen based on machine specification and the results

of trial experiments. The minimum number of experiments to study the influence of chosen process parameters at chosen level is 13 (degree of freedom) and hence nearest orthogonal array available of designing the experiment is L16 ($4^5 \times 1^2$) Taguchi array. Hence, the same is adopted for this study. Table 2 shows the complete experimental design. The experiments were replicated for two trials in each experimental condition. Thickness of specimens (10 mm) and the supply pressure of dielectric fluid were kept constant during experiments.

Table 1: Wire-EDM Process Parameters and its Setting

Parameters	Unit	Code	Level 1	Level 2	Level 3	Level 4
current	A	A	3	4	5	6
Pulse-on time	μs	B	20	30	40	50
Pulse-off time	μs	C	10	15	20	25
wire speed	RPM	D	175	350	700	1400
voltage	V	E	80	90	-	-

Table 2: The Experimental Design and Corresponding Response Data

Trial no	Settings of the Process Parameters					Surface Roughness		
	Current	T _{on-time}	T _{off-time}	Wire-speed	Voltage			
1	3	20	10	175	80	4.96	5.26	5.66
2	3	30	15	700	80	6.60	5.64	6.16
3	3	40	20	350	90	7.00	7.02	7.96
4	3	50	25	1400	90	7.14	6.28	8.30
5	4	20	15	350	90	5.58	5.54	5.94
6	4	30	10	1400	90	4.82	5.80	5.42
7	4	40	25	175	80	7.12	6.04	6.96
8	4	50	20	700	80	7.32	6.38	7.04
9	5	20	20	1400	80	4.24	4.92	4.82
10	5	30	25	350	80	6.72	5.96	7.52
11	5	40	10	700	90	7.16	7.64	5.68
12	5	50	15	175	90	10.42	10.18	9.24
13	6	20	25	700	90	6.32	7.14	6.74
14	6	30	20	175	90	7.40	8.08	8.26
15	6	40	15	1400	80	6.08	5.17	7.42
16	6	50	10	350	80	5.76	8.14	7.70

2.3 Measurement of Response Data

The prepared specimens are cut for a length of 20 mm using WEDM. In each experiment, the settings for process parameters are varied as shown in the table 2. Further, the machined specimen is split completely after measuring its kerf-width. Using Taylor surtronic instrument the surface roughness (R_a) was measured across the cut surface for a sampling length of 10 mm. The average R_a value obtained in each trial is shown in table2 as response data. Figure 2 shows the cut surfaces of test samples machined at different test condition.

Figure 2: Cut Surface of the Machined Samples.

2.4 Analyses of Response Data by using Signal to Noise (S/N)

The response data, i.e., the surface roughness at different experimental condition is analysed using Signal to Noise (S/N) ratio for robustness of the experimental analysis. As the objective of the investigation is to obtain the lower surface roughness on the machined work-piece “smaller-the-better” (equation 1) criteria is adopted for the analysis. The term signal means the required response value and noise signifies the possible error from different sources.

$$S / N = -10 \log \left[\left(\frac{1}{n} \right) \sum_{i=1}^k y_i^2 \right] \quad (1)$$

Where, y_i - R_a value at i^{th} trial and n is 2.

3. RESULTS AND DISCUSSIONS

3.1 The Effect of I_c , $T_{on-time}$, $T_{off-time}$, W_s and I_v on Surface Roughness

Figure 3 show the main effect plot of S/N ratio of surface roughness at different experimental conditions. It is observed from figure 3 (a) that at current settings of 3 A to 4 A, a lower R_a values were obtained. Current beyond 4A upto 6A showed increase in average R_a values the machined surface from 6.163 μm to 7.018 μm . This is mainly due to higher intensity of the spark energy with increase in input current and results removing greater volume of material from the work-piece. Figure 3 (b) shows that effect of T_{on} on R_a values. The increase in T_{on} from 20 μs to 50 μs resulted in increasing the average surface roughness from 5.593 μm to 7.825 μm . The intensity of the spark energy increase with an increase in T_{on} duration and results reducing the spark frequency. This leads formation of recast layer and the energy of the preceding sparks re-melts the recast layer as well as the parent metal. This results in uneven machined surface and increase the surface roughness at higher T_{on} duration. Figure 3 (c) shows that effect of T_{off} on R_a values. The shorter T_{off} of 10 μs resulted in lower R_a values. Increase in T_{on} further upto 15 μs resulted in a steady increase in R_a and then it almost remained constant for other setting of T_{off} duration upto 25 μs . It shows that a very short duration of T_{off} is sufficient to flush-out the debris of machining before the beginning of next spark. Beyond the optimum duration of T_{off} -10 μs , the machining results in the formation of the recast layer due to reduced spark frequencies and non-machining time.

Figure 3: The Main Effect Plot of S/N ratio of Surface Roughness.

At T_{off} of 10 μs the machining resulted in lowest average R_a values of 6.167 μm is observed. Further, it is observed in figure 3 (d) that, the R_a decreased with an increase in the W_s of electrode-wire. At High drum rotation speed of 175 RMP, the highest R_a values of 7.465 μm is observed values. The R_a values were steadily decreased due to increase in drum-speed from 175 RPM to 750 RPM. This is due to the fact that the debris of machining is effectively removed by increasing the electrode wire-speed. The effective removal of debris prevented its recasting on the machined surface and hence reduced the surface roughness. At 1400 RPM a very lowest R_a value of 5.867 μm is obtained. Figure 3 (e) shows the effect of I_v on R_a value. It is seen that average R_a is increased from 6.233 μm to 7.128 μm for change in voltage from 80 V to 90 V. This is because of the higher amount of energy discharged in each spark during the machining.

3.2 Analysis of Variance (ANOVA) of R_a

The results of ANOVA for S/N ratio of R_a values are shown in table 3. The significance of the effect of I_c , $T_{on-time}$, $T_{off-time}$, W_s and I_v on surface roughness is determined through F-test on ANOVA data at confidence level of 95 %. From the standard table, the critical values of F for 16 number error degree of freedom 2 are 3.63. From the table 3, it is seen that the F values of all chosen parameters namely of I_c , $T_{on-time}$, $T_{off-time}$, W_s and I_v are higher than the critical F value of 3.63 and hence the influence of all these parameters on R_a is significant. It means changes in settings of any of these parameters will significantly affect the R_a . Further, the contribution(%) of each process parameter is calculated to find the relative effect of these parameters on the response data. The T_{on} is the most influencing parameter which contributed highest (38.27%) to variation of surface roughness followed by voltage (31.02 %), wire speed (17.11 %), current (7.11%) and T_{off} (5.39 %). The error contribution on the response is 1.12 %.

Table 3: ANOVA for S/N Ratio

Parameter	Degree of Freedom	Seqsum of Square	Adjmean Square	F
Current	3	3.2517	1.0839	6.37
Pulse-on time	3	17.5123	5.8374	34.33
Pulse-off time	3	2.4645	0.8215	4.83
wire speed	3	7.8311	2.6104	15.35
voltage	1	4.7313	4.7313	27.82
Residual Error	2	0.3401	0.1701	
Total	15	36.1310		

The optimum settings to the parameters namely I_c , $T_{on-time}$, $T_{off-time}$, W_s and I_v is determined to yield the lowest R_a values on Al6061-SiC_p composite while machining by wire-EDM. Experimental design for optimisation is made using Taguchi method. The average R_a obtained at levels of I_c , $T_{on-time}$, $T_{off-time}$, W_s and I_v is shown in Table 4. The corresponding S/N ratio of the response data is shown in Table 5. The lowest surface roughness is achieved at the settings, A₂B₁C₁D₄E₁ i.e., I_c : level 2 (4A), T_{on} : level 1 (20 μ s), $T_{off-time}$: 10 μ s (level 1), drum/wire speed - level 4 (1400rpm) and voltage - 80 V (level 1). The maximum change (delta) in surface roughness due to change in settings of different parameters at different levels is also shown in the same table. Based on the delta values, the process parameters are ranked in the order of their influence as pulse-on time: I, wire-speed: II, voltage: III, current: IV and pulse-off time: V. At the optimum settings the expected R_a is predicted using equation (2) as 3.302 μ m. The confirmation experiments at settings A₂B₁C₁D₄E₁ show good agreement with the prediction (maximum deviation of 7.63 %).

$$R_a = A_2 + B_1 + C_1 + D_4 + E_1 - 4 \times \text{Average } R_a \quad (2)$$

Table 4: The Average Surface Roughness

Level	Current	Pon	Poff	Wire-Speed	Voltage
1	6.498	5.593	6.167	7.465	6.233
2	6.163	6.532	6.997	6.652	7.128
3	7.042	6.771	6.703	6.737	
4	7.018	7.825	6.853	5.867	
Delta	0.878	2.232	0.831	1.598	0.895
Rank	4	1	5	2	3

3.4 Regression Modelling of MRR

A regression model is developed to establish relationship between wire-EDM parameters (x_1 : Current, x_2 : Pulse-on time, x_3 : Pulse-off time, x_4 : wire-speed, x_5 : voltage) and the response MRR. The generalised form of regression model is given by equation (3) and the developed model is given by equation (4). The coefficients of determination (R^2) of the equation is 87.30%. The distribution of residuals for the developed model is shown in figure 4 (a-b) which shows that the residuals are distributed around the line of fit linearly and hence confirms the adequacy test model linearity. Figure 4 (b) show the surface roughness predicted by developed mathematical model and the experimental results. The predicting accuracy of this model is tested within the experimental range, $3 \geq x_1 \geq 6$; $20 \geq x_2 \geq 50$; $10 \geq x_3 \geq 25$; $375 \geq x_4 \geq 1400$; $80 \geq x_5 \geq 90$, the maximum average prediction error is 8.39 %.

$$y = c + k_1 \times x_1 + k_2 \times x_2 + \dots + k_n \times x_n \quad (3)$$

Where, y – dependent parameter

c – model constant

$x_1, \dots, x_n$ – control parameter

$k_1, \dots, k_n$ – coefficients of control parameters

$$R_a = -4.358 + 0.2436 \times x_1 + 0.0694 \times x_2 + 0.03532 \times x_3 - 0.4707 \times x_4 + 0.0895 \times x_5 \quad (4)$$

Figure 4: (a) Normal Probability Chart.

(b) Distribution of Residuals.

Figure 5: Comparison of Surface Roughness Predicted by Model with Experimental Results.

4. CONCLUSIONS

Based on the wire-EDM of 4wt. % to 8 wt. % SiC particle reinforced Al6061 alloy, the following conclusions are drawn. The wire-EDM parameters such as current, T_{on} , $T_{off-time}$, W_s , I_v showed significant influence on surface roughness. The R_a value is increased significantly with shorter pulse on-time duration, low current and higher wire-speed with contribution of 38.27%, 31.02 % and 17.11 % respectively. The optimum settings which produced the minimum surface roughness are current: level 2 (4A), pulse-on time: level 1 (20 μ s), pulse-off time: 10 μ s (level 1), drum/wire speed - level 4 (1400 rpm) and voltage - 80 V (level 1). The expected surface roughness (R_a) at this setting is 3.302 μ m. To predict the surface roughness within the operating range ($3 A \geq x_1 \leq 6 A$; $20\mu s \geq x_2 \leq 50\mu s$; $10\mu s \geq x_3 \leq 25\mu s$; $375 \text{ rpm} \geq x_4 \leq 1400 \text{ rpm}$; $80 V \geq x_5 \leq 90 V$) The regression model is developed with average R^2 -87.30 %. The average model prediction error is found to 8.39 %.

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