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Enhancing Electrical Discharge Machining Performance for AA6061-WC Composites Fabricated by Powder Metallurgy

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Abstract

In this study, the effects of Electrical Discharge Machining (EDM) on an aluminum (AA6061) Metal Matrix Composite (MMC) reinforced with tungsten carbide are examined. Poor surface roughness (SR) and a slower metal removal rate (MRR) are experienced during conventional machining of an MMC. Therefore, EDM is the best alternative method for cutting complex shapes in MMC. In this experiment, aluminum (AA6061) with WC added in three different concentrations was used (i.e., 3%, 6% and 9%). While maintaining a constant dielectric cleaning pressure, applied voltage, and electrode feed rate, machining procedures are accomplished by modulating the pulse on time (A), pulse off time (B), and peak current (C). Taguchi methods are used to optimize the parameters. It has been determined that using a 3% WC reinforcement increases MRR while decreasing SR. It is also found that the A and C parameters have a more significant effect on the MRR and SR.

Keywords

Metal matrix composite, Electrical discharge machining, Taguchi method, Surface roughness, Metal removal rate, Tungsten carbide

Introduction

For crucial applications like those in the automotive and aerospace industries, where features like lower weight and increased wear resistance are essential, the market's standard monolithic materials fall short [1]. MMC is a novel material made by combining the benefits of many methods, such as stir casting, powder metallurgy, etc. However, the abrasive character of the AA6061 base material and the random emergence of reinforcing in the MMC make the material extremely difficult to produce. Traditional tools also suffer from a high rate of wear [2, 3].

EDM is a nontraditional machining technology that may efficiently remove metal from tougher surfaces. Because the tool and the work material never make physical contact during EDM, mechanical stress at the machined surface is never created [4]. Steel has been the most common material for EDM operations, while Cu rod in cylindrical form has been the most common tool material, evaluation, and future scope essay. Many studies [5, 6] have looked at MRR, TWR, and SR, however the most common affecting factors are pulse on/off time and current.

EDM research on vortex method and pressure die cast aluminum-silicon carbide composites has been conducted [7]. The results show that the current and the reinforcement percentage have significant effects on the MRR and the SR. Researchers [8, 9] found that optimizing the EDM's processing variables including pulse on time, discharge current, and flushing pressure reduced tool wear during the machining of hard AMC with 5% WC produced via the liquid casting method.

Parameter values for EDM machining of various hard materials are optimised using a variety of approaches, including Taguchi, DOE, Analysis of Variance (ANOVA), and RSM [10]. Results show that pulse on time, current, and voltage affect the response parameters MRR and SR value. Different studies find different values for the most crucial elements influencing EDM performance. Most studies have suggested that Peak current influences EDM performance [11, 12].

Based on these findings, the parametric optimization of powder metallurgy-prepared AA6065-WC composites requires serious consideration. To succeed in precision machining nowadays, it is necessary to evaluate machining parameters for non-traditional machining processes like EDM. As a result, the effects of electric discharge machining on AA6061 that has been strengthened with powder metallurgically-prepared WC particles in a range of weight percentages is evaluated here. The machinability features of Al with WC MMC are analyzed in relation to factors such as Pulse on time, Pulse off time and Peak current. The percentage of reinforcement in the specimen has no bearing on the testing procedure (3%, 6%, or 9% WC).

Experimentation and Materials

Materials

In this study, the MMC is formed from aluminum and WC. Each component is counted according to its weight share. Three different types of MMC specimens are prepared using WC with a 44 nm particle size and aluminum (Grade AA6061) with a 72 nm particle size and three different proportions of WC, namely 3%, 6%, and 9% by weight.

Fabrication of MMC

In this research, the powder metallurgy method was applied to create MMC. Experiments are performed using manufactured cylindrical specimens with a 25 mm diameter and a 25 mm length. To obtain a homogenous mixture, aluminum powder and WC powder are combined well and stored in Ball mill unit for 4 h. The material is first shaped in a press using pressure, and then sintered in an electric furnace at 425 °C.

Mechanism of EDM

By generating a spark between an electrode (Tool) and the work piece, the EDM Procedure removes the MRR. Spark generation results in increased pressure and temperature at the connection. This causes melting and evaporation to occur in specific areas.

Machining of MMC

Axes of electronika 4 experiments were conducted using a CNC-controlled EDM machine. The electrode was a copper rod that was 12 mm in diameter. Throughout the machining process, we maintained a stable dielectric fluid pressure, applied voltage, and electrode feed rate. Parameters that were malleable in this study included A, B, and C. Figure 1 shows the EDM configuration.

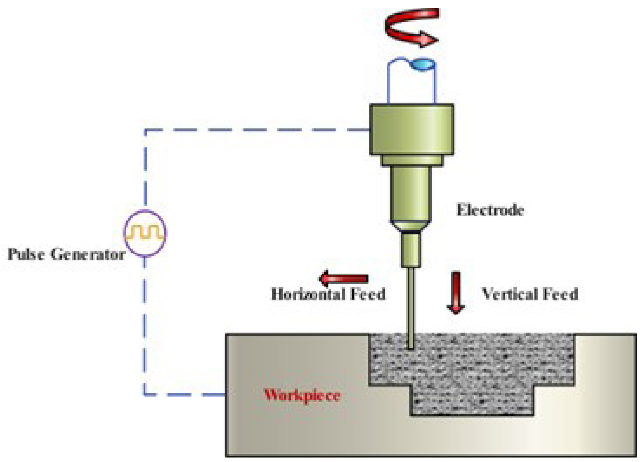

Figure 1: EDM method experimental set up.

By continuously feeding the electrode into the MMC cylinder via the fixture (Work holding system) installed above the machine table, a hole can be formed in the circle. Each hole's machine time was tracked. The MRR can be calculated [13, 14].

$$MRR = \frac{W1-W2}{T}\ \mathrm{g \cdot min^{-1}} \quad (1)$$

where W_1 and W_2 (g) represents the starting and final weight of the sample after machining and T represents machine time in minutes.

The SR of the machined MMC was measured using a Mitutoyo brand SR tester, and the results were recorded. Table 1 lists the ranges and values for each process parameter.

Experimental analysis

Response values like MRR and SR were analysed by altering the input factors (A, B, and C) that influence the process of machining.

For MRR, the larger the better concept is recommended, which means that the output value must be higher so that the necessary material may be removed in a shorter amount of time. Similarly, a smoother surface will increase the component's durability and visual appeal. Therefore, a smaller

Table 1: Processing factor values and its levels.

S. No	Symbol	Factors	Unit	Levels		
1	A	Pulse on time	µs	50	70	90
2	B	Pulse off time	µs	3	6	9
3	C	Peak current	A	14	18	22
4	D	Dielectric fluid	-	Kerosene		
5	E	Flush rate	Kgf/cm^2	6		
6	F	Gap voltage	V	45		

the better concept is best suited for a reduced SR value, i.e., a lower output value is required.

Taguchi's concept of orthogonal arrays was employed to create the experimental setup. ANOVA is a statistical approach for ranking the significance of many variables within a predetermined confidence range. The signal-to-noise ratio quantifies the extent to which actual performance characteristics deviate from ideal values.

Experimental detail

Three input parameters were given values to create an L9 orthogonal array. Separate studies were run for each possible combination of 9 factors for each type of fruit. This experimental setup required the machining of a total of 27 parts. The equation 1 allows for the determination of MRR. The average SR value is determined by moving the stylus of the SR tester along the machined surface. Table 2, table 3, and table 4 display the collected data.

Results and Discussion

Table 2: Experimental design for aluminum (AA6061) with WC 3%.

Run	A	B	C	MRR (g min^{-1})	SR (μm)
1	50	3	14	0.1738	14.73
2	50	6	18	0.2610	17.56
3	50	9	22	0.2789	18.41
4	70	3	18	0.2654	17.60
5	70	6	22	0.2927	18.46
6	70	9	14	0.2090	16.46
7	90	3	22	0.3081	19.63
8	90	6	14	0.2463	17.15
9	90	9	18	0.2775	17.79

Table 3: Experimental design for aluminum (AA6061) with WC 6%.

Run	A	B	C	MRR (g min^{-1})	SR (μm)
1	50	3	14	0.1572	15.68
2	50	6	18	0.2121	18.64
3	50	9	22	0.2372	21.45
4	70	3	18	0.2176	19.05
5	70	6	22	0.2489	21.68
6	70	9	14	0.1591	16.99
7	90	3	22	0.2525	22.31
8	90	6	14	0.1604	18.22
9	90	9	18	0.2345	20.48

Table 4: Experimental design for aluminum (AA6061) with WC 9%.

Run	A	B	C	MRR (g min^{-1})	SR (μm)
1	50	3	14	0.1954	16.27
2	50	6	18	0.2132	17.20
3	50	9	22	0.2816	18.40
4	70	3	18	0.2490	17.77
5	70	6	22	0.2904	18.62
6	70	9	14	0.2012	16.50
7	90	3	22	0.3005	19.88
8	90	6	14	0.2067	16.98
9	90	9	18	0.2637	17.83

A greater MRR is the single most important condition for improving production economics in each industry. The property's exquisite surface finish is essential to meeting the next consumer expectation, which is improved aesthetics and durability. The MRR will initially be the focus of our efforts. The S/N ratio and MRR for the DOE are calculated using Minitab 20 [15, 16]. The response table of MRR values for 3% WC, 6% WC, and 9% WC were calculated and are provided in table 5 based on the experimental results.

Spark energy (discharge energy) (Em) refers to the amount of electrical energy available for MRR [17].

Table 5: Response table of MRR for 3% WC, 6% WC and 9% WC.

3% WC			
Level	**A**	**B**	**C**
1	-12.65	-12.32	-13.66
2	-11.93	-11.50	-11.44
3	-11.18	-11.94	-10.66
Delta	1.48	0.81	2.99
Rank	2	3	1
6% WC			
1	-14.01	-13.76	-15.98
2	-13.76	-13.81	-13.10
3	-13.48	-13.69	-12.18
Delta	0.53	0.13	3.80
Rank	2	3	1
9% WC			
1	-12.87	-12.23	-13.93
2	-12.25	-12.62	-12.36
3	-11.90	-12.17	-10.73
Delta	0.97	0.45	3.20
Rank	2	3	1

$$Em = Ton \times Vg \times Id \quad (2)$$

It is evident from equation 2 that pulse on time, peak current, and applied voltage are the primary determinants of spark energy [18]. Increases in peak current result in a greater number of anions being thrown against the surface of the work piece. As a result, the temperature at the spark's origin is raised because of the greater concentration of higher spark energy. The higher spark energy causes the work piece to heat up, melting a larger portion of the work piece, resulting in a greater MRR. The larger MRR can be attributed to the increased spark energy, which increases the work piece's melting point and melts more material [19, 20]. Signal to noise ratio of MRR vs pulse on, pulse off time, and peak current are shown as main impacts in figure 2a, 2b, and 2c, respectively.

The average S/N of the response (MRR) is plotted against the level of each process parameter (X axis) in the plot.

Figure 2a demonstrates a linear relationship between peak current and MRR up to a maximum value. After then, there is a minor drop in MRR. This occurs because the anions responsible for melting the work piece are produced in greater quantity when the current applied is steadily increased. If the current is increased over a certain point, the generated anions will have to penetrate further to melt the material underneath the fused material. This causes a mild decrease in the later stages. In both (b) and (c) figure 2 shows the same thing. Pulse on time fluctuation has a small impact on MRR, as depicted in figures 2a, 2b, and 2c. The breadth of the plasma stream could be increased by extending the pulse on time. Work temperature is raised by the broader plasma, but not as quickly as by the peak current. Figures 2a, 2b, and 2c show that increasing the pulse off time does not improve MRR. This is because more time passes in between sparks when the pulse off time is increased.

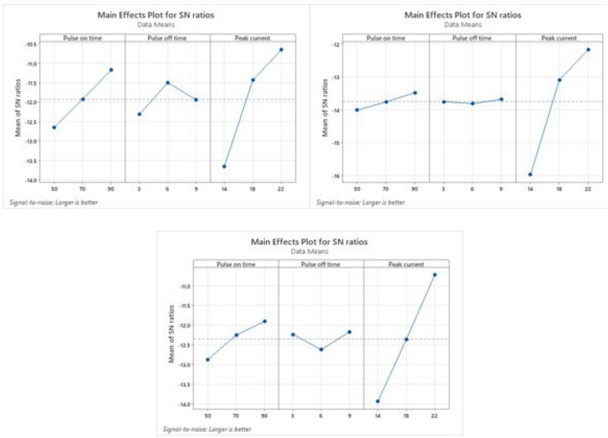

Figure 2: Main effects plot: **(a)** 3% WC; **(b)** 6% WC; and **(c)** 9% WC.

Analysis on MRR

The F-test is the most trustworthy method for determining the importance of parameters on response values. The final value of the response is more sensitive to changes in any parameters having a higher F value.

Table 6 shows that the two most influential variables in MRR are peak current and pulse on time. The effect of pulse off time on MRR is minimal.

For the 3% WC variation, the peak current F value is 28.39, the pulse off time is 1.23 and the pulse on time is 6.02. This indicates that peak current has a much larger effect than pulse on time and is therefore the key contributor. Both the 6% WC and the 9% WC variations follow the same general trend. If the p value for a process parameter in an ANOVA is less than 0.05, it is statistically significant.

As can be seen from the foregoing, the pulse off time is not a particularly important characteristic, but the peak current is of paramount importance.

Table 7 displays the optimum process factor combinations as determined by inspection of the major effect plot for MRR and the mean response table. Level 3's peak current setting (20 A), PON's 90 s, and POFF's 3 s are optimal.

Contour graphs of the variation in MRR vs A and C are shown in Figure 3a, 3b and 3c. The lowest MRR value is seen in figure 3a between a pulse on time of 70 μs and a peak current value of 14 A to 12.6 A. When the A is higher than or equal to 55 μs and peak current is greater than 16 A, the MRR is achieved. More material can be melted in less time if the A and C are both increased, because larger sparks may be generated at higher levels.

More MRR is possible for the WC 6% and WC 9% within the same A and C parameters. The highest possible MRR is 19.80 for the 3% WC variety, 19.04 for the 6% WC type, and 14.24 for the 9% WC variant under ideal conditions. As the ratio of WC particles increases in the composite materials, the MRR value inevitably drops [21, 22].

Table 7: Optimal combination of process factors for MRR.

S. No	Factor	3% WC		6% WC		9% WC	
		Level	Value	Level	Value	Level	Value
1	A (μs)	3	90	3	90	3	90
2	B (μs)	1	3	1	3	1	3
3	C (A)	3	22	3	22	3	22

Table 6: ANOVA for MRR.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F value	P-value
Aluminum (AA6061) with WC 3 %							
A	2	0.002336	16.43%	0.002336	0.001168	6.02	0.142
B	2	0.000478	3.36%	0.000478	0.000239	1.23	0.448
C	2	0.011011	77.47%	0.011011	0.005506	28.39	0.034
Error	2	0.000388	2.73%	0.000388	0.000194	-	-
Total	8	0.014213	100.00%	-	-	-	-
Aluminum (AA6061) with WC 6 %							
A	2	0.000279	2.23%	0.000279	0.000140	2.51	0.285
B	2	0.000015	0.12%	0.000015	0.000008	0.14	0.881
C	2	0.012143	96.77%	0.012143	0.006071	58.99	0.009
Error	2	0.000111	0.89%	0.000111	0.000056	-	-
Total	8	0.012548	100.00%	-	-	-	-
Aluminum (AA6061) with WC 9 %							
A	2	0.001108	8.09%	0.001108	0.000554	5.40	0.156
B	2	0.000279	2.04%	0.000279	0.000139	1.36	0.424
C	2	0.012110	88.38%	0.012110	0.006055	108.95	0.017
Error	2	0.000205	1.50%	0.000205	0.000103	-	-
Total	8	0.013702	100.00%	-	-	-	-

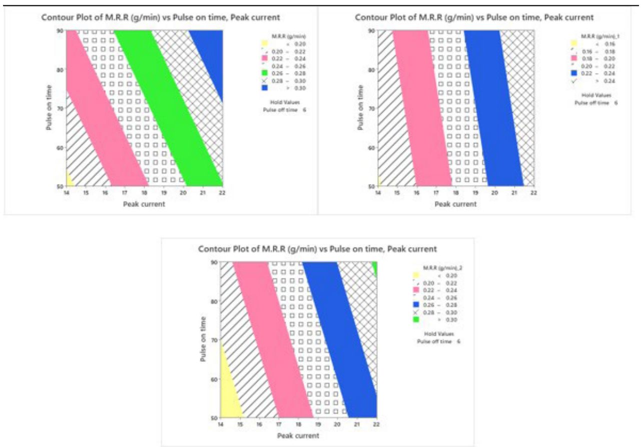

Figure 3: Contour plot on MRR: **(a)** 3% WC; **(b)** 6% WC; and **(c)** 9% WC.

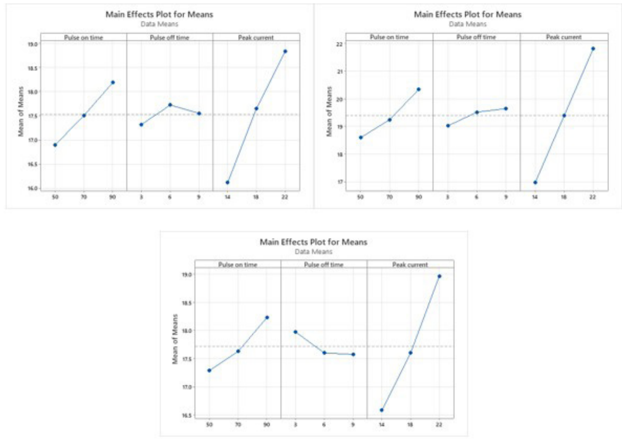

Figure 4: Data mean plots for main effects: **(a)** 3% WC; **(b)** 6% WC; and **(c)** 9% WC.

Next to MRR, the most anticipated criterion is the quality of the surface. Smaller pits formed during EDM result in a poorer surface polish value. Reducing the temperature during the spark helps regulate the melting-induced pit formation. Minitab 20 is used to measure the signal-to-noise ratio and the central tendency of the experimental design. Table 8 displays the response table of SR value for 3, 6, and 9% WC, based on the experimental results. Mean results demonstrate the primary influence in figure 4 and figure 5a, 5b and 5c. Which demonstrates the correlation between the A, B and C and the SR Value.

The effects of changing the A, B and C are depicted in figure 4a, 4b, and 4c, respectively. As peak current rises, so does the surface's roughness. Increasing the current to 18 is shown clearly in the graph. The SR value similarly climbs gradually, although it begins to drop off slightly above a certain threshold. Therefore, a low pulse on time is preferable for achieving a low value of SR. The peak current is much larger than the rise in Ra value caused by increasing the pulse on time.

Table 8: Response table of SR for 3% WC, 6% WC and 9% WC.

	3% WC		
Level	**Pulse on time**	**Pulse off time**	**Peak current**
1	-24.52	-24.71	-24.13
2	-24.85	-24.97	-24.93
3	-25.18	-24.88	-25.49
Delta	0.66	0.26	1.37
Rank	2	3	1
	6% WC		
1	-25.31	-25.49	-24.57
2	-25.64	-25.78	-25.74
3	-26.14	-25.82	-26.77
Delta	0.82	0.33	2.20
Rank	2	3	1
	9% WC		
1	-24.74	-25.06	-24.39
2	-24.91	-24.90	-24.91
3	-25.20	-24.89	-25.55
Delta	0.45	0.17	1.16
Rank	2	3	1

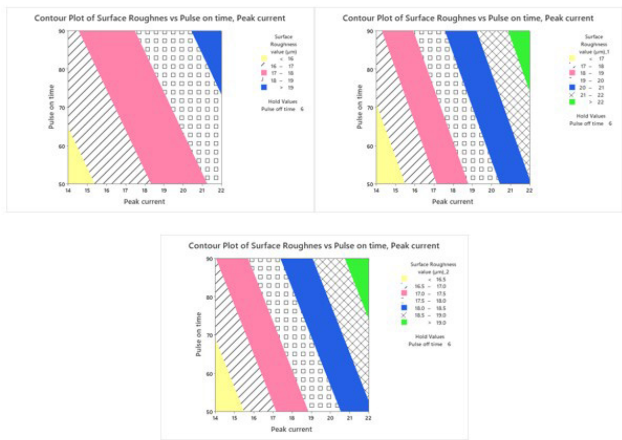

Figure 5: Contour plot on SR: **(a)** 3% WC; **(b)** 6% WC; and **(c)** 9% WC.

Extending the pulse off time, as shown in figure 4a, 4b, and 4c, has no influence on the SR value. The SR value barely shifts as the pulse off time is raised because the active impact of anions is less.

Analysis on SR

Parameters' impact on response values and their significance. The F test is the most reliable method. Table 9 displays the results of an ANOVA for the SR of three different WC concentrations: 3%, 6%, and 9%. The 6% WC type's peak current, on time, and off time all have F values of 68.77, 10.95, and 2.42, respectively. This indicates that C is more important than A.

Both the 9% WC and the 3% WC variations follow the same general trend. Table 10 displays the optimum process parameters for SR Fine surface finish can be achieved with the following parameters set to their optimal values: A (1, 50 µs), B (1, 3 µs) and C (1, 14 A).

Figure 5a demonstrates that the minimum SR value occurs for peak current values between 14 A and 11 A and pulse on times smaller than 45 µs. The WC 6% and WC 9% both show the same pattern of findings over the same range of A and C. Minimal SR values for the ideal values of the

Table 9: ANOVA of SR for 3% WC.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F value	P-value
Aluminum (AA6061) with WC 3%							
A	2	2.4991	16.39%	2.4991	1.2495	1.86	0.350
B	2	0.2460	1.61%	0.2460	0.1230	0.18	0.846
C	2	11.1600	73.17%	11.1600	5.5800	8.29	0.108
Error	2	1.3468	8.83%	1.3468	0.6734	-	-
Total	8	15.2520	100.00%	-	-	-	-
Aluminum (AA6061) with WC 6%							
A	2	4.6760	11.47%	4.6760	2.3380	30.22	0.032
B	2	0.6588	1.62%	0.6588	0.3294	4.26	0.190
C	2	35.2838	86.54%	35.2838	17.6419	228.00	0.004
Error	2	0.1548	0.38%	0.1548	0.0774	-	-
Total	8	40.7733	100.00%	-	-	-	-
Aluminum (AA6061) with WC 6%							
A	2	1.3592	13.12%	1.3592	0.67960	11.03	0.083
B	2	0.2973	2.87%	0.2973	0.14863	2.41	0.293
C	2	8.5817	82.82%	8.5817	4.29083	69.62	0.014
Error	2	0.1233	1.19%	0.1233	0.06163	-	-
Total	8	10.3614	100.00%	-	-	-	-

Table 10: Optimal combination of processing factors for SR.

S. No	Factor	3% WC		6% WC		9% WC	
		Level	Value	Level	Value	Level	Value
1	A	1	50	1	50	1	50
2	B	1	3	1	3	2	6
3	C	1	14	1	14	1	14

processing parameters are 12.43μ for the 3% WC variation, 13.38μ for the 6% WC variety, and 13.97μ for the 9% WC variation. SR is proportional to the amount of WC particles present. A higher SR value can be deduced from an increase in the proportion of WC particles.

Conclusions

Results from the experiments were analysed, and it was found that:

- The rate at which metal is removed improves with increases in both A and C, but changes to the value of POFF have little to no effect.
- As the WC content increases, the MRR drops. This is because the presence of tougher WC particles in the material slows down the process. As a result, raising the reinforcement material's WC content reduces the MRR.
- Increasing the duration of the C will result in a greater rate of material removal.
- Reduced A and C produce a superior SR. This is because there is enough time to remove debris and cool the melted area, resulting in fewer pits and less heat generated at the spark.
- Pits around WC particles are caused by the concentration of WC in the material. That is, a higher proportion of WC results in a worse surface quality (a higher SR value) due to an increase in pitting.

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None.

Conflict of Interest

None.

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