



# Optimization Of Process Parameters of Die Sinking EDM Process on Aluminum MMC

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## Abstract:

Aluminum-Boron Metal Matrix Composites (MMCs) offer superior specific strength and wear resistance suitable for aerospace applications but pose significant challenges for conventional machining. This study investigates the Electric Discharge Machining (EDM) of Al-Boron MMC using a Copper-Tungsten electrode to optimize machining quality. A Taguchi L9 Orthogonal Array experimental design was employed to analyze the effects of Pulse-on Time (100-500  $\mu\text{sec}$ ), Pulse-off Time (200-900  $\mu\text{sec}$ ), and Peak Current (7-22 Amp). The influence of these parameters was evaluated using Minitab 19 software to determine optimal process settings for enhanced machinability like material removal rate and surface roughness.

**Keywords:** Metal Matrix Composites(MMCs), Electric Discharge Machining(EDM), Material Removal Rate, Surface Roughness, Pulse time on,Pulse time off, peak current.

## Introduction:

### Metal Matrix Composites (MMCs)

Metal Matrix Composites (MMCs) represent a significant advancement in materials engineering, designed to combine the ductility and toughness of metal matrices with the high modulus and hardness of ceramic reinforcements. By embedding ceramic particles, fibers, or whiskers into a metal substrate, MMCs achieve superior mechanical properties that conventional metals cannot match. These properties include enhanced stiffness, lower density, improved wear resistance, and high thermal stability. Aluminum Matrix Composites (AMCs) are among the most widely utilized class of MMCs due to aluminum's excellent strength-to-weight ratio and castability. These composites are increasingly critical in industries such as automotive and aerospace, where they are used for high-performance components like drive shafts, brake rotors, cylinder liners, and piston heads. The continuous demand for lighter, stronger materials in aircraft manufacturing drives ongoing research into improving the tribological behavior and functional lifespan of these composites.

### Aluminum Alloy 7075 (Al-7075)

In this study, the specific matrix material selected is Aluminum Alloy 7075 (Al-7075). Belonging to the 7xxx series of aluminum alloys, Al-7075 is characterized by Zinc as its primary alloying element, typically comprising 5.6–6.1% of the composition, along with significant additions of Magnesium and Copper. This alloy is renowned for possessing one of the highest strength-to-weight ratios of any aluminum alloy, with tensile strength comparable to many steels. Its exceptional fatigue strength and machinability make it a standard material in the aerospace industry for highly stressed structural parts, such as wing structures, fuselages, and helicopter gears. However, pure Al-7075 has average wear resistance; therefore, reinforcing it to create an Al-7075 composite significantly enhances its surface hardness and tribological performance, making it suitable for even more rigorous friction environments.

### Boron Carbide Reinforcement

The reinforcement material used in this composite is **Boron Carbide (B<sub>4</sub>C)**, an extremely hard boron-carbon ceramic. Often referred to as "Black Diamond," it is the third hardest substance known to man, ranking behind only diamond and cubic boron nitride. Structurally, it consists of a complex lattice of boron and carbon atoms (typically B<sub>12</sub> C<sub>3</sub> units), which provides exceptional covalent bond strength. Unlike silicon carbide, boron carbide is distinct for its low density (2.52 g/cm<sup>3</sup>) and high neutron absorption cross-section. It is produced by the reduction of boron oxide with carbon at high temperatures. In the context of MMCs, adding Boron Carbide particles to the Al-7075 matrix drastically improves the composite's wear resistance and hardness, although these same properties make the material difficult to machine using conventional cutting tools.

### Processing: Die-Sinking EDM

To effectively machine these hard-to-cut Aluminum-Boron Carbide composites, **Die-Sinking Electric Discharge Machining (EDM)** is employed. This non-conventional subtractive manufacturing process utilizes thermal energy to remove material without direct physical contact. The setup involves two electrodes submerged in a dielectric fluid (such as kerosene or transformer oil): the tool electrode (shaped to the desired cavity) and the workpiece. A high-voltage potential difference is applied between them, generating a series of controlled, high-frequency electrical sparks. Each spark generates intense heat that melts and vaporizes microscopic amounts of the workpiece material. The dielectric fluid serves a dual purpose: it acts as an insulator to prevent premature arcing and as a coolant that flushes away the eroded debris (swarf). By precisely controlling parameters such as pulse duration ( $T_{on}$ ), current intensity, and pulse-off time, complex geometries can be machined into the hard AMC workpiece with high precision and minimal mechanical stress. The performance and precision of Electric Discharge Machining (EDM) are governed by several critical process parameters that control the erosion of the workpiece. Foremost among these is the **Discharge Current ( $I_p$ )**, measured in amperes, which serves as the primary factor determining the Material Removal Rate (MRR) by providing the thermal energy necessary to melt and vaporize the material. This energy is delivered during the **Pulse-on Time ( $T_{on}$ )**, a specific duration in microseconds where the peak current is active, facilitating the transfer of spark energy from the electrode to the workpiece. Following this discharge is the **Pulse-off Time ( $T_{off}$ )**, the interval between consecutive pulses; this non-active period is essential for allowing the dielectric fluid to flush away eroded debris and prevent arcing. Physically, the stability of this process relies on the **Arc Gap**, the maintained distance between the electrode and the workpiece, which must be precisely controlled to ensure efficient spark generation and dimensional accuracy. Finally, the relationship between these timing parameters is expressed as the **Duty Cycle**, which represents the percentage of the total cycle time that the pulse is active, calculated as the ratio of on-time to the sum of on-time and off-time.

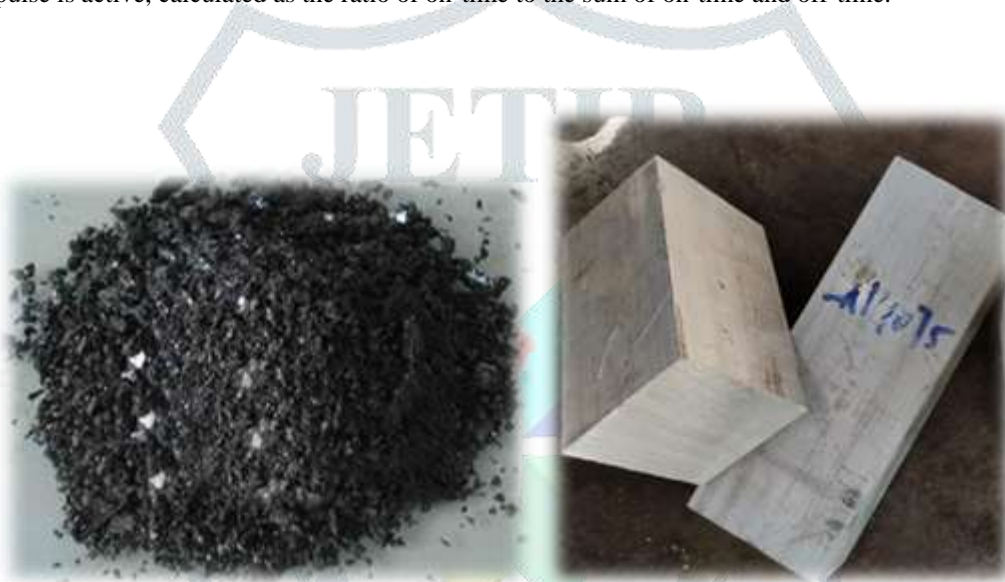


Figure 1.1: Boron Carbides as Reinforcement      Figure 1.2: Raw Material of Aluminum 7075

### Literature Review

**Et Sohani. Al. [1]** this study examined how tool geometries—circular, triangular, square, and rectangular—affect Material Removal Rate (MRR) and Tool Wear Rate (TWR) in Electrical Discharge Machining. Results identified the circular geometry as the most efficient for maximizing MRR while minimizing TWR. Beyond shape, discharge current and pulse-on time emerged as the most critical parameters influencing performance, while pulse-off time and tool dimensions showed moderate effects. The model's reliability was statistically confirmed through ANOVA and Fisher's F-test at a 95% confidence level. Ultimately, the findings establish a clear hierarchy for tool selection to optimize EDM efficiency.

**Puri et. Al. [2]** "This study used numerical modeling and Response Surface Methodology (RSM) to analyze White Layer Depth (WLD) in WEDM of M2 die steel. Investigating a rough cut followed by a trim cut, the authors found that WLD rises with increased pulse-on time in the rough cut. Conversely, increasing the pulse-on time in the trim cut reduces WLD. The study also observed that increasing machining speed during the trim cut causes WLD to first decrease and then subsequently rise."

**Taweel T. A. El- [3]** "This study evaluates the performance of a novel Al-Cu-Si-based composite electrode, fabricated via powder metallurgy, in the Electrical Discharge Machining (EDM) of CK-45 steel. The investigation focused on the effects of three key process parameters—specifically peak current, dielectric flushing pressure, and pulse-on time—on performance metrics such as Material Removal Rate (MRR) and Tool Wear Rate (TWR). The experimental design and analysis were conducted using Response Surface Methodology (RSM). The results identified peak current as the most influential factor affecting both MRR and TWR, while dielectric flushing pressure also demonstrated a significant impact. notably, the Al-Cu-Si composite electrode exhibited higher sensitivity to peak current and pulse-on time compared to conventional tools."

**Asif Iqbalet. Al.[4]** The study examine the effects of different cutting parameters on the machinability of hardened steel Austenitic chromium-nickel stainless steel using copper anode in electrochemical machining. The machining parameters considered the voltage,

spindle speed of tool and feed rate on the responses material removal rate, EWR and surface roughness. The RSM was used to analyze the parametric and relationships connections among the three regulator factors on the material removal rate, EWR and surface roughness. The advanced models indicate the voltage and spindle speed of tool are the most important machining factors affecting MRR, EWR and SR.

**Et Nanimina. Al. [5]** The researcher examined the effects of Al6061-30%A12 O3 MMC through EDM. They used peak current, pulse on time and pulse time off as the machining parameters and material removal rate and tool wear rate as the responses. They found that high current and pulse time on rise the material removal rate. They also observed more tool wear at low peak current and pulse on time.

**Et Anish. Al. [6]** The author established quadratic replicas for the cutting rate, SR and kerf deviation to match the critical cutting limitations: pulse time off, pulse time on, peak current, wire feed, spark gap voltage and tightness in wire EDM procedure for pure Ti. We used a trial design of the Case Behnken based on RSM to conduct the experimental and errors work and found that the main parameters affecting the response factors are pulse time on, pulse time off, Ip and spark break energy. We also verified that the machining rate, SR and kerf deviations matched with investigated results with 95% self-assurance level.

**Raj. Mohan et. Al. [7]** The study examined how cycle limitations and their communications, such as voltage, pulse on, pulse off, current. affected the (MRR) in austenitic chromium-nickel stainless steel as anode. (S/N)ratio and examination of variance (ANOVA) were applied to evaluate the influence of the limits on MRR and the Taguchi technique was used to optimize machining limitations. The results showed that the two most important factors that affect the MRR are peak current and pulse time on.

**Herpreet. Singh et. Al. [8]** This describes the effects of different constraints, such as pulse time on and pulse time off, on the EDM process using metal as workpiece and copper electrodes with or without cryogenic treatment. The cryogenic handling is applied to enhance the MRR and reduce the TWR. The results show that the TWR declines with increasing pulse time on for both cryogenically treated and untreated copper electrodes. The tool wear rate rises with rising pulse time off. The material removal rate reduces with rising pulse time on from 50µs to 100µs and increases with increasing pulse time off from 15µs to 20µs.

**Bhosle et. Al. [9]** This study utilized the Taguchi technique and an L18 orthogonal array to identify the optimal boundary conditions for micro-EDM drilling of Inconel 600 alloy using a tungsten carbide (WC) tool. By varying voltage, capacitance, feed rate, and pulse timings, the researchers evaluated performance based on material removal rate (MRR), taper angle, overcut, and diametral deviation. ANOVA was subsequently employed to determine the significance and relative contribution of each process constraint. The results established that a configuration of 175V, 1000 pF, 20 µm/s feed rate, 15 µs pulse-on, and 50 µs pulse-off yields the highest MRR with minimal geometric inaccuracies. Ultimately, these findings provide a precise benchmark for maximizing efficiency and precision in micro-hole fabrication.

**Chandramoulli et. Al. [10]** The study shows effect of EDM process constraints on machining of 17-4 PH steel was investigated in this study. The parameters selected were peak current, pulse time on, pulse time off and tool lift time and the output responses were material removal rate (MRR) and surface finish (SR). Taguchi technique was used to plan L27 orthogonal array with CuW tool. ANOVA technique was done using MINITAB 17 software to analyze the influence of input procedure constraints on output responses. The consequence of ANOVA discloses that pulse time on has high ratio influence for MRR (58.3%) and for SR (76.7%)

### Experimentation

#### MMC Preparation:

The fabrication of Aluminum Metal Matrix Composites (AMCs) was conducted using the cost-effective stir casting technique to ensure homogenous particle distribution. The Al-7075 matrix alloy was melted in a graphite crucible at a temperature exceeding 850°C. To enhance wettability and interfacial bonding, Boron Carbide (B<sub>4</sub>C) reinforcement particles were preheated to the same temperature prior to mixing. This experimental investigation focused on three distinct composite compositions, varying the B<sub>4</sub>C reinforcement ratios at **6%, 8%, and 10%** respectively. The preheated particulates were manually stirred into the molten slurry to prevent agglomeration and ensure uniform dispersion before being poured into preheated sand molds.

#### Mechanical Properties: Results and Discussion

The mechanical characterization of the Al-7075 metal matrix composites reinforced with Boron Carbide (B<sub>4</sub>C) revealed distinct trends in hardness, tensile strength, and ductility across the three varying reinforcement percentages. In terms of hardness, the experimental data indicates a inverse relationship between reinforcement concentration and Brinell Hardness Number (BHN); the sample with 6 % reinforcement exhibited the highest hardness at 68.40 BHN, followed by a decrease to 66.17 BHN at 8 %, and a further significant drop to 57.13 BHN at 10 %. Conversely, the Ultimate Tensile Strength (UTS) demonstrated a non-linear trend, peaking at the intermediate reinforcement level. The 8 % sample achieved the maximum tensile strength of 102.656 N/mm<sup>2</sup>, outperforming the 6 % sample (99.548 N/mm<sup>2</sup>) and the 10 % sample, which dropped to 95.183 N/mm<sup>2</sup>. Ductility, measured by percentage elongation, was highest in the 6 % sample at 3.6%, with a notable reduction observed in the 8 % sample (3.12%) before slightly recovering to 3.2% in the 10 % sample. These results suggest that while lower reinforcement levels favor hardness and ductility, the 8 % composition offers the optimal balance for maximizing tensile strength in this specific fabrication setup.

**Design of experiments**

To ensure experimental accuracy and efficiency, the data collection was structured using the Design of Experiments (DoE) technique, specifically employing the Taguchi method with an L9 Orthogonal Array. Three governing process parameters were selected for investigation: Pulse-on Time ,Pulse-off Time , and Peak Current.

Prior to machining, the workpiece and electrode were cut to precise dimensions, and the initial weight of the workpiece was recorded to facilitate subsequent material removal calculations. The components were then securely mounted in the Die-Sinking EDM setup, with the servo mechanism calibrated to maintain a stable spark gap. For each experimental run, the specific parameter levels defined by the orthogonal array were input into the machine controller to perform a hole-cutting operation. Upon the automatic completion of each cycle, the machine halted, and the procedure was replicated for all subsequent samples. Finally, the collected data was processed and analyzed using Minitab 19 software to determine optimal machining conditions.

↓	C1	C2	C3
	TIME ON	TIME OFF	PEAK CURRENT
1	100	200	7
2	100	500	15
3	100	900	22
4	200	200	15
5	200	500	22
6	200	900	7
7	500	200	22
8	500	500	7
9	500	900	15

Figure 2.1: DOE Worksheet



Figure 2.2: Workpieces

**Results:**The experimental outcomes for the Electric Discharge Machining (EDM) of the Al-MMC were analyzed based on the Taguchi L9 Orthogonal Array, focusing on Material Removal Rate (MRR) and Surface Roughness . The Material Removal Rate showed significant variation across the trials, ranging from a minimum of 3.214 to a maximum of 12.500. The highest MRR was achieved in Trial 9  $T_{on}=500$ ,  $T_{off}=900$ ,  $I_p=15$ , indicating that an optimal combination of pulse timing and current is essential for efficient erosion. Conversely, the Surface Roughness values ranged between 4.08  $\mu m$  and 6.43  $\mu m$ , highlighting the direct impact of discharge energy on surface quality. The smoothest surface finish  $Ra = 4.08$  was observed in Trial 6, which utilized a low Peak Current of 7 A, whereas the roughest surface  $Ra = 6.43$  occurred in Trial 5, where the Peak Current was increased to 22 A.

Table 1.1 Table Represent The Result of Surface Roughness and Material Removal Rate.

S No	Sample ID	SR ( $\mu m$ )	(MRR) in ( $mm^3/min$ )
01	1	4.19	4.64
02	2	4.81	6.42
03	3	5.37	5.71
04	4	5.10	8.92
05	5	6.43	9.285
06	6	4.08	4.64
07	7	5.81	3.928
08	8	6.09	3.214
09	9	4.45	12.5

Table 1.2 Response table for signal to noise ratios-surface roughness:

Level	Pulse time on	Pulse time off	Peak current
1	-13.56	-13.96	-13.45
2	-14.18	-15.17	-13.59

3	-14.65	-13.26	-15.35
Delta	1.09	1.91	1.90
Rank	3	2	1

The peak current and pulse time off are the most significant machining parameter for surface roughness followed by pulse time on in EDM for machining Al MMC material with copper tungsten electrode.

**Table 1.3 Response table for signal to noise ratios-MRR:**

Level	Time on	Time off	Peak current
1	14.87	14.73	12.26
2	17.23	15.21	19.03
3	14.64	16.88	15.45
Delta	2.58	2.07	6.77

The peak current and pulse time on are the most significant machining parameter for MRR followed by pulse time off in EDM for machining Al MMC material with copper tungsten electrode.

#### Confirmation test results:

The test results show that the experimental values outperform the predicted values. This demonstrates that the Taguchi technique is an effective method to provide better solutions for single objective optimization problems.

**Table 1.4 Optimal Machining Process Parameter Of EDM Machining**

Response	Optimal machining parameters			Predicted	Experimental
	Pulse time on ( $\mu\text{sec}$ )	Pulse time off ( $\mu\text{sec}$ )	Peak current (amp)		
Ra( $\mu\text{m}$ )	200	900	7	4.32	4.08
MRR ( $\text{mm}^3/\text{min}$ )	500	900	15	10.27	12.5

**Conclusion:** This study successfully investigated the impact of Electric Discharge Machining (EDM) process parameters—specifically Pulse-on Time, Pulse-off Time, and Peak Current—on the machinability of Aluminum Metal Matrix Composites (Al-MMC). Utilizing the Taguchi technique with an L9 Orthogonal Array and Minitab 19 for optimization, the experiments identified distinct optimal settings for differing objectives. The analysis determined that the optimal conditions for minimizing Surface Roughness were a Pulse-on Time of 200  $\mu\text{sec}$ , Pulse-off Time of 900  $\mu\text{sec}$  and Peak Current of 7 A. Conversely, maximizing the Material Removal Rate (MRR) required a higher energy setting: Pulse-on Time of 500  $\mu\text{sec}$  Pulse-off Time of 900  $\mu\text{sec}$  and Peak Current of 15 A. Signal-to-Noise (S/N) ratio analysis revealed that Peak Current is the most significant factor influencing both responses. Validation through confirmation tests demonstrated a strong correlation between experimental and predicted values, confirming the efficacy of the Taguchi method for optimizing single-objective machining problems.

**Acknowledgment:** The author (1) would like to express my deep sense of gratitude and indebtedness to internal guide dr. T. Krishnaiah Author (2), assistant professor, Anurag university.

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