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Effect of Electrical Discharge Machining Parameters and Cryogenic Treatment on Surface Roughness of Aluminum Metal Matrix Composite (Al6061/SiC/Graphite)

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Abstract**: This study examines how process parameters -Current (Amp), Pulse on time (T_{on}), Duty cycle, and voltage (v) affects the surface finish of the hybrid aluminum composite (Al6061/SiC/Graphite), comparing the effectiveness of cryogenic treatment on the EDM tool with a non-treated tool. One factor at a time (OFAT) approach shows that increasing current from 4 A to 12 A raises surface roughness from 0.2 µm to 2.5 µm. However, using silicon carbide, cryogenically treated electrodes, and longer pulse-on times can reduce roughness, though debris removal may be needed. Higher voltages above 120 V also increase roughness, which can be lessened by better flushing and cryogenic treatment. Lower duty cycles (0.36 to 0.48) yield smoother surfaces, while medium duty cycles (0.6 to 0.72) increase roughness, which can also be mitigated by cryogenic treatment.**

Index Terms —Aluminum metal matrix composite, EDM, Surface roughness, Silicon Carbide, Graphite

I. INTRODUCTION

The Hybrid aluminum Metal Matrix Composites (AlMMCs) has prominent research inclination due to their exceptional various properties. These composites are lightweight, electrically distinctive, heat-resistant also exhibit excellent resistance to fatigue, wear, and creep, making them ideal for various engineering and manufacturing applications [1][2][3]. Composite materials combine two or more distinct phases, offering superior properties compared to the individual components. The matrix phase, which is continuous and malleable, provides essential support and distributes the load with the dispersed phase [4][5][6].

In prior research, aluminum and titanium have been used for crafting metal matrix composites [7][8][9].The reinforcement is embedded discontinuously within the matrix. Reinforcing agents like SiC, SiO_2, Al_2O_3, AlN, B_4C, and BN enhance the strength of the metal or alloy matrix and allow for the customization of specific properties [10].Silicon carbide (SiC) significantly improves the mechanical properties of AlMMCs, making it useful for automotive industry and other engineering applications. Dhanasekaran et al. (2015) studied SiC as a reinforcement material, noting that it affects dislocation density, precipitation reinforcement, and grain size. Their findings showed that adding 20% SiC by weight to the composite increased tensile strength by 16% and yield strength by 50% over to the base alloy [11].Maurya et al. (2016) studied the impact of silicon carbide (SiC) particles in Al alloy (Al6061) using electromagnetic stir casting. They created composites with varying SiC percentages and used Scanning Electron Microscopy (SEM) to observe the SiC particles. The results showed even diffusion of SiC within the alloy matrix, increasing its density since SiC is heavier than Al 6061. Additionally, hardness and tensile strength improved in composites with up to 8 wt% of SiC [12].

Selvakumar et al. (2019) focused on the impact of SiC on the surface roughness of aluminum 6061 composite. They found that SiC reinforcement has improve the tensile strength of such composites, seed strength, and stiffness. Additionally, surface roughness decreased in samples with 10 wt% SiC due to the higher SiC content [13].The current trend is to replace conventional liquid lubricants with solid lubricants in composites. Solid lubricants like graphite and molybdenum disulfide (MoS2) effectively reduce wear and friction, eliminating the need for fluid lubrication. This approach can enhance tribological performance in various mechanical systems [14].In 2021; Madhan Kumar et al. highlighted the use of graphite to enrich the properties of these composites. The team chose to use stir casting process since it was simple and affordable. They established that by adding graphite, the mechanical strength, wear resistance and electrical conductivity of composites were greatly enhanced through extensive tests like tensile, hardness, impact, wear, optical microscopy and electrical conductivity testing. Through careful control of stirring conditions they were able to Achieve an even dispersion of reinforcement throughout the matrix [15][16].

Prior research investigations have proven that stir casting is a most easy to use and affordable technique of fabricating Aluminium metal matrix composites (AMMCs) with better mechanical properties [17]. Polytechnic et al. (2017) showcased the cost-effectiveness and simplicity of stir casting for AMC production. In a similar vein, Kumar et al. (2021) focused on enhancing the mechanical properties of Al7075 matrix with SiC particles. Both studies underscore the promising capability of stir casting in AMC fabrication and the potential to bolster mechanical strength through strategic reinforcement selection. [18, 19, 20]. Conventional manufacturing techniques often fall short in terms of efficiency and productivity, as outlined in the source. Yet, unconventional methods like Electrical Discharge Machining (EDM) stand out for their ability to achieve precise engineering, particularly in shaping intricate forms. EDM's advantage lies in its cost-effectiveness, especially with challenging materials, as it doesn't entail direct tool-to-workpiece contact. This feature minimizes wear and allows for increased cutting speeds. Consequently, EDM presents a viable solution for processing materials that are conventionally hard to handle, leading to cost savings and enhanced efficiency. [21][22][23]. In a 2021 study, Mumtaz et al. explored the influence of operational variables on the tool wear rate in EDM. They utilized analysis of variance (ANOVA) and Taguchi's method for experimental design to assess the effectiveness of their experiments. This comprehensive study offers valuable insights into the influence of operational parameters on EDM machining of Al+B_4C+-Graphite metal matrix composite [24].

In 2019, Gurdev Singh Grewal explored the effectiveness of cryogenic treatment of copper electrodes in EDM compared to traditional ones when working with EN24 steel[25]. Using Taguchi method optimization, they fine-tuned electrode rotation, current, and gap voltage. Their study measured tool wear rate , surface finish , and overcut (OC) as key output metrics. Additionally, the research highlighted the significance of graphite and silicon carbide (SiC) in strengthening aluminum metal matrix composites. It also suggested that cryogenic treatment might enhance the EDM process. However, further research is needed to fully understand how cryogenic treatment influences the performance of EDM tools [26][27][28][29]. This work examines how critical process parameters and EDM tool performance are affected by cryogenic treatment when self-lubricating SiC and graphite reinforced aluminum MMCs are machined. The research attempts to evaluate the advantages of using cryogenic treatment in EDM operations by comparing Surface Roughness of composites after machining over machining with untreated tools, as well as by closely examining of SEM images for deep understanding. OFAT methodology will be employed in the study to thoroughly investigate the effect on tool wear.

II. MATERIALS AND METHODS

A. Materials

Alloys, especially those in the 6000 family, are increasingly favored for making Metal Matrix Composites (MMCs) due to their favorable ductility, weldability, and corrosion resistance compared to other alloy series. Alloy 6061, a key member of the 6000 series, is particularly valued for its balanced blend of silicon, magnesium, and titanium. This combination enhances corrosion resistance, controls recrystallization, and refines the grain structure. When combined with silicon carbide and graphite, Alloy 6061 produces a novel hybrid MMC. This unique blend improves wear resistance, thermal stability, and mechanical strength by leveraging graphite's solid lubricating properties and Sic's mechanical durability. Such composites hold great promise for high-performance engineering applications [30, 31, 32].

B. Stir Casting of Composite

Stir casting is a commonly employed method for manufacturing metal matrix composites (MMCs), particularly those with aluminum matrices [12][13]. In this process, reinforcing particles like silicon carbide (SiC) and graphite are dispersed throughout the molten aluminum alloy via mechanical stirring. This agitation ensures satisfactory reinforcement distribution within the matrix material. The matrix material of aluminium alloy was first preheated to 300°C and then melted at 750°C in a furnace or crucible. Reinforcing particles, consisting of 15% SiC and 5% graphite by weight, were accurately weighed and preheated to 300°C for 60 minutes to remove impurities and moisture, reducing the final composite's porosity. To prevent settling, the furnace's melting temperature was adjusted to 650°C temperatire. The already preheated SiC and graphite particles were gradually added to the molten aluminum matrix while stirring at 650 rpm for 10 min for proper distribution. The composite in molten form poured into a already preheated and coated mold, left to solidify, resulting in the final composite casting, depicted as a round bar.

Fig 1 (A) STIR Casting Setup

Fig 1 (B) AMMC

C. Cryogenic Treatment of EDM Tool

During the deep cryogenical treatment (DCT) of the EDM copper electrode (Fig-2), a precise protocol was followed. The electrode's temperature was methodically lowered to -194°C at a controlled rate of 10°C per minute. It remained stable at this temperature for 2 hours before gradually returning to room temperature at the same controlled rate. After this initial treatment, additional cryogenic cycles(as illustrated in Fig-3) were conducted to alleviate induced stresses, raising the temp to 150°C at the rising rate of 10°C per minute for two hours before returning to room temperature. These treatments aimed to enhance various properties of the electrode, including thermal conductivity, hardness, wear resistance, dimensional and thermal stability, and fatigue resistance, aligning with research recommendations [33, 34, 35, 36]. Cryogenic treatment thus improves cutting tool performance and longevity by boosting thermal conductivity and heat dissipation capacity

FIG 2 EDM Electrode

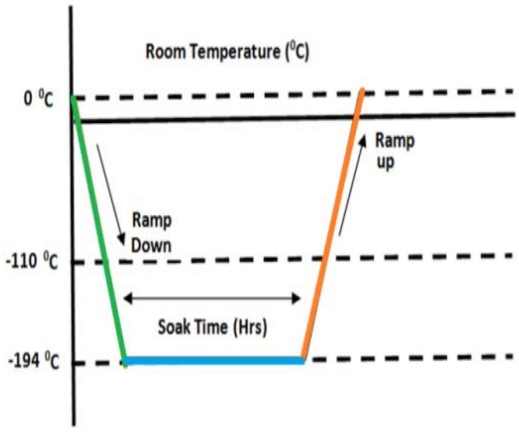

Fig 3: Cryogenic Treatment Cycle

D. Electric Discharge Machining

Electric Discharge Machining (EDM) employs controlled electrical discharges in a dielectric fluid to remove material from a work piece. A voltage difference between the work piece and electrode generates high-intensity electric fields, leading to rapid electrical discharges (sparks) that melt and vaporize material. The dielectric fluid aids in conductivity, cools, and flushes away eroded particles [37, 38].In Fig-4, machining operations were conducted using an EDM machine (Oscar Max Die-Sinking), which is a product of Oscar Max and manufactured in Taiwan. Throughout the EDM process, commercial EDM oil with a density of 0.75 *kg/m³* as the dielectric fluid medium. Copper (Cu) electrodes, each with a diameter of 10.0 *mm (Ø)*, were employed as the machine electrodes. The direct electrode polarity configuration was consistently applied in all experimental endeavors. The EDM process parameters -Current (Amp), Duty cycle, voltage (v) and pulse-on time (T_{on}). The selection of these parameters was based on insights from previous research and recommendations derived from our own earlier investigation. Each machining operation lasted for 5-minute duration, resulting in a machining mark on the composite work piece, illustrated in Fig-5.

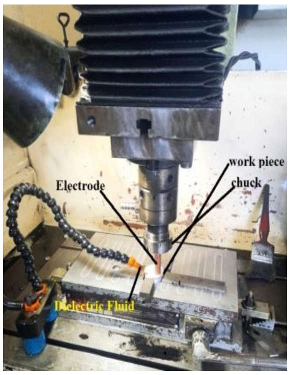

Fig 4 Electrical Discharge Machining

Fig-5 Machined AlMMC

III. METHODOLOGY

A. One-factor-at-a-time (OFAT) strategy

The OFAT method is widely used in scientific and engineering investigations to assess the impact of individual variables on a system or process. It involves adjusting one variable while keeping others constant, allowing researchers to observe changes in the system's behavior[39][40]. Our study employs this method by systematically altering one process parameter at one time while keeping the rest constant.We conduct hole drilling operations on both deep cryogenic-treated copper tools and untreated tools, recording machining times. The data collected are utilized to create graphs for detailed analysis as specified in Table 1.

Table 1: Experimentation EDM Parameters their setting values

Exp no	**Edm Tool**		**Current (Amp**	**Pulse-on-Time (T_{on})**	**Gap Voltage (G_V)**	**Duty cycle (DC)**
1 to 5	DCT	NTT	4*A*,6*A*, 8*A*, 10*A*, 12*A*	Constant 250 *μs*	Constant: 150*V*	Constant :0.96
6 to 10	DCT	NTT	Constant :12A	50 *μs*, 100 *μs*, 150 *μs*, 200 *μs*, 250 *μs*	Constant: 150*V*	Constant :0.96
11 to 15	DCT	NTT	Constant :12A	Constant 250 *μs*	30 *V*, 60 *V*, 90 *V*, 120 *V*, 150 *V*	Constant :0.96
16 to 20	DCT	NTT	Constant :12A	Constant 250 *μs*	Constant: 150*V*	0.36,0.48, 0.60, 0.72, 0.96

*Deep Cryogenic Treated Tool (DCT) Non Treated Tool (NNT)

IV. MEASUREMENTS

Surface roughness is crucial in evaluating machined surfaces, indicating their smoothness or roughness. Industry standards typically employ specialized testers to precisely measure surface roughness, using Equation (1) to calculate the average roughness, Ra. In this study, the TR110Plus, a high-precision surface roughness tester, was employed. It traversed a 5 mm length and measured roughness within the range of 0.1 µm to 10.0 µm.

$$Ra = 1/L \int_0^L |y(x)|\, dx \qquad (1)$$

Where, Ra is the average roughness, L is the measurement length, and y(x) is the height deviations within that length.

V. RESULTS AND DISCUSSIONS

A. Effect of Current on Surface Roughness SR)

Fig-6 illustrates the noticeable effect of machining current on surface roughness (Ra) in Aluminum Metal Matrix Composites (AMMCs). As the current rises from 4A to 12A, Ra increases significantly from 1.2 µm to 2.5 µm. This increase is attributed to the heightened heat generation at higher currents, which can alter the material's microstructure and surface finish. Additionally, it can escalate material removal, resulting in rougher surfaces with larger craters and irregularities. However, the presence of Silicon Carbide (SiC) helps counteract this effect by efficiently dissipating heat due to its excellent thermal conductivity. Similarly, graphite, another proficient thermal conductor found in some MMCs, aids in maintaining stable machining temperatures, resulting in smoother surface finishes with lower Ra values. Cryogenic treatment of copper electrodes offers another avenue to enhance surface roughness. Studies [41,42] indicate that this treatment improves thermal conductivity, reduces tool wear, and enhances heat dissipation, resulting in less wear on cryogenically treated electrodes and smoother machined surfaces. However, research by Liu et al. (2018) and Lal et al. (2001) suggests that this advantage diminishes at higher currents due to increased thermal and electrical stresses overpowering the benefits of cryogenically treated tools (DCT) [43,44].

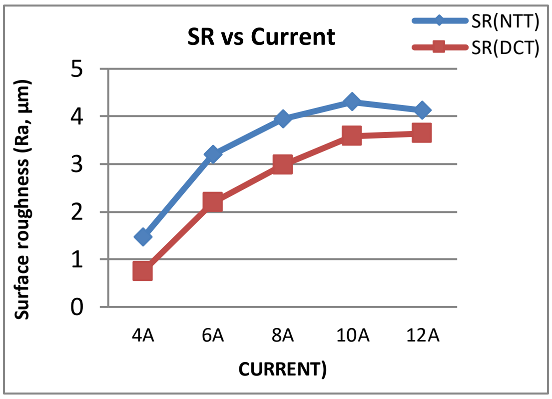

Fig-6 Effect of Current on Surface Roughness

B. Effect of Pulse on Time on Surface Roughness (SR)

As shown in Fig -7, the surface roughness of composite is affected by pulse on time period . Longer pulse-on times result in more energy transferred to the workpiece, creating more craters and a thicker recast layer, thus increasing surface roughness. However, after 200 µs, The roughness of surface decreases regardless of tool treatment (NTT or DCT), attributed to machining debris particularly aluminum and silicon particles in the dielectric fluid medium. These particles alter the shape of plasma pathway during electrical discharge, leading to a smoother surface finish due to a more controlled material removal process. Additionally, improved tool properties from DCT may maintain tool integrity, reduce wear, and consequently enhance surface quality [45] .

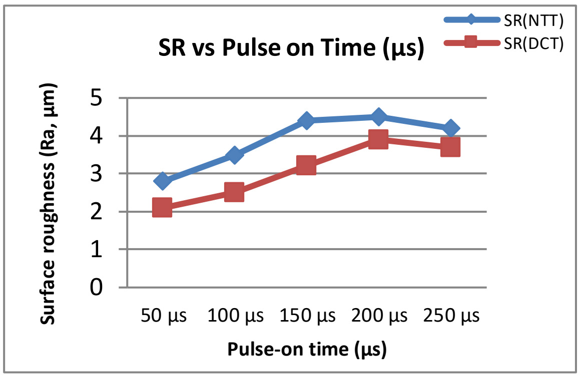

Fig-7 Effect of Pulse on Time on Surface Roughness

C. Effect of Voltage on Surface Roughness (SR)

Fig-8 illustrates that raising the voltage from 30 V to 120V can result in heightened surface roughness. Increased voltage generates more discharge energy, leading to large and more deep craters formation on the work surface. However, at high voltages (120 V and above), both treated and non-treated tools show a slight decrease in surface roughness values. This is attributed to improve flushing of the dielectric fluid at higher voltages, aiding in debris removal from the working gap, hence a downward trend is observed beyond 120 V. Cryogenically treated EDM tools exhibit superior surface finish at lower voltages, while non-treated tools tend to display slightly higher roughness values due to their susceptibility to wear [46]. At medium voltages (60-120 V), cryogenically treated tools consistently exhibit increasing surface roughness values, albeit slightly lower than non-treated tools, which experience wear and produce a moderately rougher finish

D. Effect of Duty Cycle on Surface Roughness (SR)

A lower duty cycle (0.36-0.48) typically produces smoother surfaces due to brief, concentrated heat exposure and smaller material removal inconsistencies. Conversely, a medium duty cycle (0.6-0.72) may increase surface roughness, characterized by larger irregularities and craters, as a result of prolonged heat exposure. Even at a high duty cycle (0.96), where the pulse-on time (Ton) duration might expand the plasma, the average surface roughness (Ra, µm) does not exhibit significant reduction (refer to Fig-9). Silicon carbide (SiC) and hexagonal boron nitride (hBN), renowned for their thermal conductivity, can effectively dissipate heat. With increasing duty cycles, these materials assist in managing heat, potentially preventing excessive thermal effects that could lead to rougher surfaces. Employing a cryogenically treated tool improves surface finish by reducing tool wear. This treatment enhances tool hardness and wear resistance, thereby enhancing surface quality[42]. Conversely, an untreated tool results in only moderate surface finish. Cryogenic treatment sustains tool performance and material integration, leading to a decreased occurrence of surface irregularities on machined surfaces.

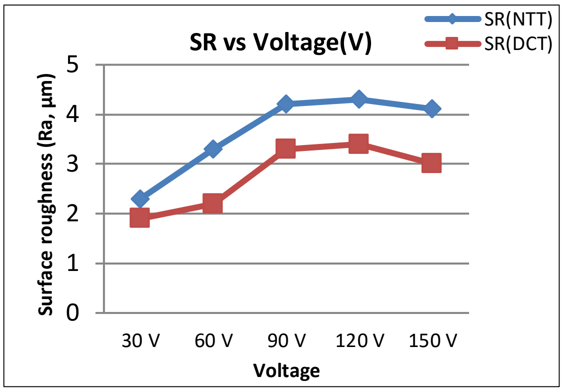

Fig-8 Effect of Voltage on Surface Roughness

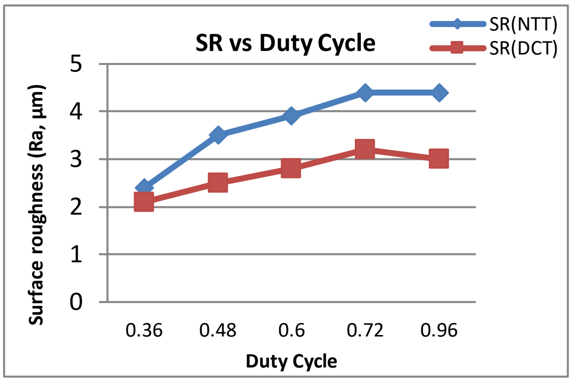

Fig-9 Effect of Duty Cycle on Surface Roughness

VI. CONCLUSIONS

i. Boosting peak current and employing cryogenically treated copper electrodes can notably influence surface roughness during EDM.

ii. Surface roughness is impacted by pulse-on time, initially rising before declining due to machining debris altering the plasma channel.

iii. Elevated voltage typically results in rougher surfaces, yet cryogenically treated tools can offset this effect, particularly at lower voltages.

iv. Lower duty cycles and cryogenically treated tools facilitate smoother surfaces, while higher duty cycles may induce heightened surface roughness.

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