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Investigating the Mechanical Properties and EDM Performance of the Composite Made of Al6063 and Nanoparticle TiO_2

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Abstract: In manufacturing, material machining plays a vital role in fabricating a wide variety of components and structures. Metal matrix composites (MMCs) exhibit unique behavior during the machining process compared to conventional metals and alloys because of their multiphase composition with distinct physical and mechanical properties. This research investigates the machining behavior of Al6063-TiO_2 composites on the non-conventional machine, which is known as E-D-M machine, and assesses the influence of E-D-M machine process performance factors on this behavior. Using the stir casting technique, Al6063-TiO_2 composites with different TiO_2 concentrations, ranging from 1% to 5% by weight, were synthesized. The resulting composites were characterized, revealing that the composite with 5% TiO_2 concentration showed the highest hardness. The study aimed to identify the optimal EDM machining parameters for these composites by conducting a series of experiments. The EDM machining based experiments involved four factors at four levels: current (4-10 A), POT (pulse on time) (ton, 60-120 μs), POFFT (pulse off time) (toff, 20-26 μs), and pressure (0.6-1.2 atm). This study investigates the impact of introducing TiO_2 nanoparticles ranging in size from 55 nm to 100 nm into Al6063, with the majority falling within the range of 55 nm to 70 nm. The findings show that, when the percentage of TiO_2 nanoparticles grew up to 5 percent, the composite's strength increased proportionally. The largest improvement seen was almost 20% stronger than the base metal Al6063. Besides the increase in strength, a rise in the composite's corrosion resistance was also seen, with the composite exhibiting the best resistance at a 5 percent TiO_2 concentration. A similar tendency was also observed in the composites' wear resistance. However, the volumetric wear rate increased significantly when subjected to a 3 kg weight. This study emphasizes the significance of TiO_2 nanoparticle concentration in regulating the mechanical and electrochemical properties of Al6063-TiO_2 composites. These findings provide valuable data that could guide future efforts to enhance these parameters for a variety of industrial applications. Delta values ordered current, pulse-on time, pressure, and pulse-off time in order of relevance. This ranking helps optimize Al6063-TiO_2 composite EDM process parameters for better machining. This extensive investigation shows that TiO_2 nanoparticles significantly affect the machining behavior of Al6063-TiO_2 composites when EDM is applied. The findings clarify the relationship between EDM performance characteristics and Al6063-TiO_2 composite machining behavior, providing vital data for industrial applications. The findings also open the door to studying the machining features of comparable metal matrix composites and improving their mechanical and electrochemical properties.

Keywords: Al6063, Nanoparticle, TiO_2, Composite, MMC, EDM machining, Machining Optimization

1. Introduction

As the need for high-performance materials with unique features continues to increase, continuing research focuses on the development of such materials that can enhance the endurance and performance of components. The creation of composite materials, which includes mixing at least two chemically and physically different components with distinguishable interfaces, is one method utilized by researchers. Lightweight, strong, and inexpensive, aluminum metal matrix composites stand out among the many varieties of composite materials. Several industries, including the automotive, aerospace, defense, and electrical sectors, have already adopted these composites, and their potential uses continue to expand as research into their properties and production processes continues[1,2)].

Composite materials seen as a wide ranges industrial materials based on the matrix material used in their construction. The three primary categories of composite materials are ceramic matrix composites (CMCs), metal matrix composites (MMCs), and polymer matrix composites (PMCs). CMCs are composed of ceramic elements in the matrix phase, making them highly resistant to corrosion, have a high melting point, and possess strong compressive strength. PMCs, on the other hand, incorporate polymers as the matrix phase, making them easy to fabricate, chemically inert, and corrosion-resistant, while also being able to impart color to the composite. MMCs, which use metals as their matrix phase, offer a promising future for materials due to their high strength-to-weight ratio, creep resistance, and temperature operability[3,4,40,41)].

Metal matrix composites (MMCs) are advanced class of materials with a vast array of possible uses in a variety of sectors. MMCs are increasingly used in components such as cylinder liners, connecting rods, and engine blocks in aircraft building, sports equipment, and electronic applications. Their high thermal conductivity makes them suitable for portable electronics such as laptops and smartphones, as well as aerospace structures including antennas, engines, and airplanes. There are numerous methods for generating MMCs, such as solid-solid reaction processes, such as mechanical alloying and isothermal heat treatment, and solid-liquid reaction processes, such as quick solidification processing and direct melt/metal oxidation. Reinforced particles play a greater significance in the manufacture of composite materials with superior qualities than matrix materials [5,6)].

The 6XXX family of aluminum alloys are often used in structural applications due to their strong strength to weight ratio. To ensure the safe use of these alloys in construction, they must undergo heat treatment. AL6063, which comprises 0.6% magnesium and 0.4% silicon, synergistically interacts to form Mg_2Si, thereby facilitating the process of heat treatment[7,8)]. AL6063 is a precipitation-hardened alloy with low processing costs and excellent properties such as high strength, formability, weldability, and corrosion resistance [9,10)].

The ultimate yield strength of Al6063 initially increases with annealing, achieves its maximum value, and then declines with additional annealing during the heat treatment process. This alloy, when heat-treated, displays a high level of corrosion resistance, and these types of metals exhibit crack resistance in their heat-treated alloy states. Al6063 is appropriate for usage in structural, maritime, and automotive applications due to its superior extrudability, reduced corrosiveness due to heat treatment, and longer annealing time [11,12)].

The novelty of present research lies in the incorporation of TiO_2 nanoparticles into the Al6063 matrix to create a metal matrix composite with enhanced properties. To the best of researchers knowledge, this is one of the few studies that systematically investigates the effects of varying TiO_2 concentrations on the mechanical and electrochemical properties of the resulting Al6063-TiO_2 composites. Furthermore, the study provides a comprehensive analysis of the machining behavior of these composites using electrical discharge machining (EDM), highlighting the impact of TiO_2 concentration on EDM performance factors. This innovative approach offers valuable insights into the processing and machining of Al6063-TiO_2 composites, paving the way for their potential applications in various industries.

The overarching aim of this research revolves around delving deep into the potential implications of integrating TiO2 nanoparticles into Al6063, particularly in reference to their mechanical, wear properties, and suitability in EDM machining. The study ventures to comprehend if and how the presence of these nanoparticles can be influential in enhancing or modifying the intrinsic properties of Al6063. The systematic objectives set to encapsulate this general aim include:

a. Composite Synthesis: Engage in the formulation of Al6063-TiO2 composites employing the stir casting method. The focus here will be on creating variations by adjusting TiO2 concentrations, specifically between 1% and 5% by weight, to discern the concentration effect.

b. Mechanical Property Analysis: Undertake a rigorous assessment of the mechanical properties, prominently strength and hardness, of the resultant Al6063-TiO2 composites. The intent will be to juxtapose these findings against the baseline metrics recorded for pure Al6063 to decipher the impact of TiO2 nanoparticle integration.

c. Corrosion and Wear Resistance Evaluation: Probe into the anti-corrosion capabilities and wear resistance attributes of the Al6063-TiO2 composites. By pitting them against the foundational properties of Al6063, the objective is to deduce if the inclusion of nanoparticles offers any distinctive advantage.

d. EDM Machining Behaviour Study: Investigate the machining dynamics of the Al6063-TiO2 composites when subjected to electrical discharge machining (EDM). Of particular interest will be understanding how varying TiO2 concentrations might play a role in reshaping EDM performance characteristics.

e. Potential Applications & Enhancement Areas: Based on the amalgamated insights from the above objectives, the study aims to outline potential practical applications for the Al6063-TiO2 composites. Simultaneously, it will also spotlight areas that might require further enhancements, particularly grounded in the observed shifts in mechanical and electrochemical properties.

2. Literature Review

Nanoparticle addition to aluminum alloys is an attractive field of research that has the potential to greatly improve the material's mechanical properties. These tiny particles, typically less than 100 nanometers in size, can act as reinforcement to boost the alloy's strength and stiffness by impeding the migration of dislocations inside the material's crystal structure, hence enhancing its fatigue and corrosion resistance. It has been demonstrated that the use of nanoparticles in aluminum alloys is particularly promising for applications requiring high strength-to-weight ratios, such as in the aerospace and automotive industries. Ongoing research efforts in this area are focused on optimizing the nanoparticle size, distribution, and orientation within the alloy matrix to maximize the benefits of this approach and revolutionize the design and production of high-performance, lightweight materials[13,14,15]. Most commonly reinforcement materials used for the AMC fabrication was shown in table 1. Diverse researchers concentrated on the optimal stirring techniques[16,17,18,23] for producing a composite using particles and base components. It was a crucial step in producing a superior Al6063 composite. After studied various published literature[19,20,21,22] stir speed should vary among 400 to 600 RPM and melting temperature for base metal Al6063 vary among 550 C to 800 C.

Table 1 Most commonly used reinforcement materials used for AMC making

Base Material	**Reinforcement materials**	**Important Properties**	**Application**	**References**
A356, Al6061	Al2O3	Hardness improvement, High Strength	Coating and heat related applications	[Mazahery et al], [Sadeghi et al]
Al3003, Al6063	TiO_2	Tensile, impact and hardness improvement	Automotive applications	[Kumar KA et al], [Srivastava, A. K.]
Al6061	ZrO2	Wear properties improvement	Ceramic, Thermal coatings	[Parveen A et al], [Ramachandra M et al]
Al2024	TiB2	Wear Resistance improvement	Structural applications	[He N, Zhang J et al]
Al6061, Al5052	ZrB2	Thermal stability	Structural applications	[Dinaharan I et al] [Mohan A et al]
Al6061	SiC	High hardness, stiffness, good thermal properties and refractoriness	Connecting rod, piston, shaft, rotors, brake disc, and rubber tyres, etc.	[Kamrani S et al] [Prasad SV et al]
Al-MMC	Graphite	Low density, high thermal conductivity, and good mechanical strength	Heat sinks, brake disc, and piston	[Omrani E et al]
Al6082	Red Mud	Tensile strength, hardness and economical	Drive shaft, bicycle industry, brakes, and fitting	[Samal P et al]
Al6063	Al2O3	Mechanical and microstructural properties analysis with machining capability analysis	General manufacturing products	[Borisade et al]
Al6063	Al2O3	SEM based analysis to find the micro structural properties of the MMC	Machining products	[Folorunso et al]

In the present study, the wear behavior of an Al6063-based composite was explored, and several major research articles[24,25,26,27,28,29] were chosen for a thorough examination of the tribological data.

Shuvho et al (2020)[30] studied in their research work for wear analysis using the input parameters of normal loading increment and sliding velocity variation, the Al base MMC was used for the present study. In this study, filler particles were also used to make the MMC more robust then its alloy form. The findings of the study show that it is possible to control the friction and wear rate of

MMCs based on aluminum, and the MMCs contribute to an increase in the friction coefficient and wear resistance. The results also show that the MMCs have improved mechanical and tribological capabilities, making them highly valuable in several industries, such as aerospace and vehicle manufacture. Using advanced techniques such as scanning electron microscopy and energy-dispersive X-ray spectroscopy enabled the researchers to investigate the morphology and chemical properties of the MMCs in-depth. The study's findings can help predict the tribological properties of Al-6063 MMCs, making them useful in engineering applications.

According to Shuvho et al (2020)[31)], the potential for aluminum-based metal matrix composites (AMMCs) to replace traditional monolithic materials in a variety of industries, including aerospace and automotive, due to their superior mechanical properties. The research shows that AMMCs based on Al 6063 and reinforced with Al2O3, SiC, and TiO_2 possess better hardness, tensile strength, and yield strength in comparison to pure Al 6063. Additionally, the researchers utilized various techniques, such as energy dispersive x-ray spectroscopy (EDS), X-ray diffraction (XRD), and Fourier Transform Infrared Spectroscopy (FTIR), to analyze the microstructure, surface morphology, elemental composition, and chemical functional groups of the AMMCs. These findings show the potential for AMMCs to be used in high-performance applications that require improved strength-to-weight ratios, fatigue resistance, creep resistance, and high-temperature retention.

Lokesh et al (2018)[32)] discusses a study that aimed to improve the mechanical properties of Al 6063 alloy, which has low strength and intermediate hardness, for use in truck wheels and railroad cars. The researchers added refractory reinforcement to improve the material's hardness, tensile strength, and high-temperature characteristics. They used varying ratios of Cu and TiO_2 particles as reinforcement in Al6063 matrix to create metal matrix composites via stir casting. The study evaluated the effect of the amount of copper particles on the composite's microstructure, tensile, impact, and hardness measurements, and the specimens were prepared according to ASTM standards. The main conclusion of the study was that the addition of Cu particles as filler material improves the strength of the metallic composite, with higher copper content leading to increased hardness, tensile strength, and impact strength. The findings have implications for improving the design and performance of materials used in transportation applications.

Sharma et al.[33)] employed an electromagnetic stir casting machine to fabricate Metal Matrix Composites (MMCs) comprising of Al 6063 alloy and TiO_2 and B4C particles. The weight percentages of these reinforcements varied between 2% and 12%, specifically, the contribution of B4C fluctuated from 1% to 6%, and that of TiO_2 oscillated from 1% to 6%. A comprehensive evaluation of the mechanical properties of the composite was performed to ascertain the influence of these reinforcements. The pivotal findings and results elucidated that the incorporation of nanoparticles within the matrix material considerably boosted the tensile strength of the MMC, leaping from 110 MPa to a striking 190.8 MPa. Likewise, an escalation in hardness was observed, moving from 60BHN to 83BHN. Conversely, a slight drawback was noted in the form of a reduction in impact strength, falling from 20 Joules to 12 Joules. Despite this, the overall results signify that MMCs, consisting of an aluminum alloy reinforced with TiO_2 and B4C, could potentially be deployed across a multitude of applications, particularly those necessitating high strength and hardness such as in the aerospace and automotive industries.

In a study by Podder et al (2021)[34)], a new hybrid composite was made by using Al alloy and CU particle as filler materials and made by using stir casting machine. In present study nano particle TiO_2 was also mixed with the matrix material. In present study various process parameters were investigated to find their role for MMC strength properties, including percentage of reinforcement, particle size, percentage of copper, cooling time, percentage of binder, and stirring time. After analyzing the data, a response surface model was created to predict and estimate the factors that influence the composite's impact property. Experiments were performed to verify the model's predictions, and various techniques were employed to investigate the composite's microstructural properties. The study revealed that the particles were evenly dispersed throughout the composite, leading to improvements in both its impact and microstructural qualities.

Using clay soil and sand mold, a new technique for producing Al6063-Cu composites with reinforcements was devised. This composite was blended with hybrid abrasive particles utilizing a stirrer mechanism, and Taguchi L18 orthogonal arrays were implemented to reduce the number of experiments. To measure the composite's elastic modulus, ductility, and density, it was examined with varying concentrations of hybrid abrasive (5 percent, 7.5%, and 10 percent). These qualities improved by 31.42 percent, 40 percent, and 19.81 percent, respectively, according to the findings. This composite can be used to manufacture a variety of devices, including bearings, valves, and aircraft electronics. A RSM model was utilized to forecast these attributes and determine the influence of each attribute[35)].

In this study[36)] a hybrid composite using Al 6063 matrix material with ceramic particles was manufactured from Mg silicate and Al. The major rationale for including ceramic into the matrix material was because to its naturally low density and high strength in MMC. The MMC was inexpensive and had a low density, with particles and matrix material spread uniformly throughout the microstructure. Adding 5 percent by weight of reinforced particles decreased the composite's density by roughly 20 percent and increased its porosity by 16 percent. The composite performed significantly better in the Izod impact test than the pure Al6063 alloy, absorbing twice as much energy. The experiment findings of the manufactured MMC for Stress and Strain relations demonstrate the compressive nature of the present MMC, and these plots aid in determining the energy absorption applications for various industries. As per the results, at 50MPa stress level the energy absorption of the MMC made with ceramic and Al Alloy was 22.5 MJ/m3.

This study37) analyzed the impact of process factors such as compaction time and pressure on the samples' hardness and wear behavior. The findings revealed that the hardness of the material increased up to 6 volume percent of nano Alumina, but then decreased after that point. The wear rate was lowest for samples generated at a compaction length of 60 minutes, while it was highest for samples produced at 90 minutes. The study also showed that the hardness and wear resistance of the samples significantly improved with the aging process. These results could be useful in optimizing the powder metallurgy process for the fabrication of MMCs with enhanced mechanical properties. All these review papers help to find the main research gap required for the present study and it was found that only fabrication of the MMC was not the full research but also the machining capability of the fabricated MMC was required for its industrial application specially where strength and quality properties were more crucial parameters.

Borisade et al,202345) investigates the effects of using alumina-rich waste material, called valoxy, as an alternative to alumina in the development of aluminum matrix composites. The study fabricates composites with varying amounts of valoxy and alumina using a double stir casting approach. The results show that valoxy contains a high percentage of Al2O3, making it a potential sustainable alternative to traditional alumina. The composites containing valoxy exhibit improved properties compared to the base alloy and composites containing pure alumina. Specifically, composites with 7.5 wt% valoxy show better hardness, tensile strength, and fracture toughness. Additionally, the density of the composites decreases with an increase in valoxy content. The study also observes that composites with valoxy show improved wear behavior. Overall, the results indicate that valoxy has the potential to be a cost-effective and sustainable reinforcement material for aluminum matrix composites.

Folorunso et al 202346) evaluates the effects of age-hardening on the mechanical behavior of an aluminum (6063) alloy reinforced with alumina particles. The researchers fabricated aluminum (6063)/Al2O3 composites with varying weight percentages of Al2O3 particles and subjected them to age-hardening treatment. The microstructures were examined using scanning electron microscopy (SEM) and the mechanical properties were evaluated using tensile tests and fracture toughness measurements. The results showed that age-hardened composites exhibited significant improvements in tensile strength and fracture toughness compared to the as-cast composites. The highest strength and fracture toughness were observed in composites aged for 180 minutes. The authors attribute these improvements to the formation of coherent precipitates of Mg2Si in the age-hardened composites. Overall, the study demonstrates the beneficial effects of age-hardening on the mechanical behavior of aluminum alloy composites reinforced with alumina particles.

Danappa et al 202048) discusses the dry sliding wear behavior of Al7075 metal matrix composites (MMCs) with varying amounts of graphite (Gr) particles and nano titanium dioxide (TiO2) particles. The composites were fabricated using the stir casting technique, and the influence of wear parameters and the wt. % of TiO2 particles on the wear rate was examined. The study used response surface methodology (RSM) to design experiments and found that the wear rate was lowest at 3-5 wt% TiO2 particles in the MMC. The results showed that the wear rate decreased under lower load conditions with different sliding speed and distance conditions. The addition of TiO2 particles reduced the wear rate, while increasing load and sliding speed led to higher wear rates. Overall, the study provides insights into the wear behaviour of Al7075/Gr/nano TiO2 MMCs and their potential applications in engineering fields. In present study the stirring process was most important part for better quality of MMC fabrication, so the stir process was kept for the whole research work on the basis of these reference studies47, 48, 49).

3. Method and Materials

The research approach in this study involved the use of a novel heat treatment method to create Al and MMC composites. This was based on a matrix filled with nanoparticle TiO_2, which aimed to improve the mechanical and wear properties. The process involved mechanical stirring and cleaning in preparing the composites using Al6063 and nanoparticle TiO_2 with or without curing. A specially formulated styrene-free MMC with the appropriate viscosity was used to distribute the alloy during intense mixing. The resulting composites had significantly improved properties compared to previous ones.

The composite produced in this study was utilised to evaluate the mechanical and wear parameters of MMCs with varying compositions. In addition, the morphology of the cracked surfaces was examined to identify the characteristics that lowered stress concentration, such as interactions and agglomerations, pull-outs, and voids. The study flowchart is depicted in Figure 1.

Using aluminium Al6063 rods procured from Jaipur, the composite was fabricated. A powdered version of TiO_2, a nanoparticle used in the production of AMC, was acquired locally in Jaipur. TiO_2 is a refractory material distinguished by its high hardness, low density, and resistance to thermal shock and abrasion.

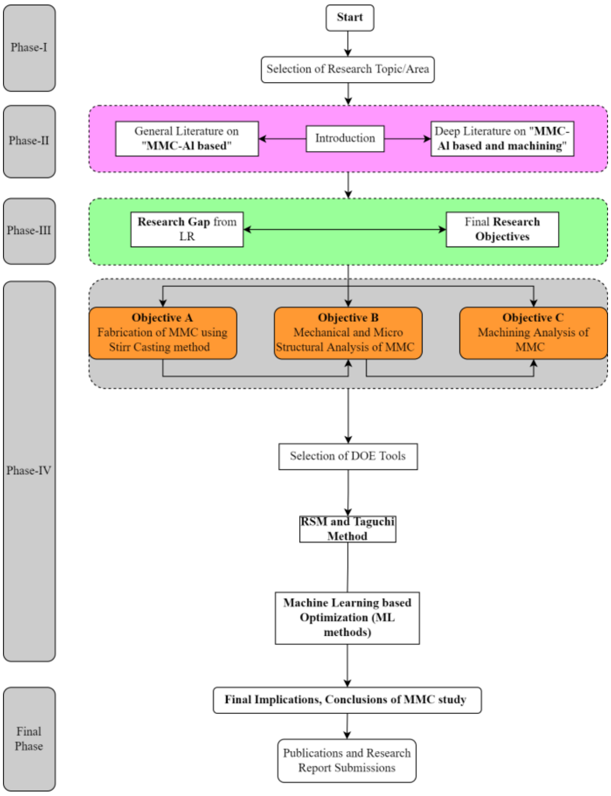


Fig. 1: Research Flow Diagram of the present investigation

The raw Al6063 rods were melted in a college laboratory to remove impurities before undergoing stir casting. Figures 2 and 3 show the cutting and melting process of the rods respectively.

Fig. 2: Cutting of Al6063 rods for melting

Figure 3 shows the initial melting process served to purify the base material by removing impurities on the surface of Al6063 material. Subsequently, a simple sand-casting method was used to produce the rods required for the stir casting process.

Fig. 3: Melting of Al6063 rods to remove the impurities

Aluminum alloy 6063 is a medium strength alloy that is often used in the construction industry for architectural applications. It has a remarkable corrosion resistance along with the surface finish. The alloy has a lower strength as compared to other alloys in the 6000 series, but it has better formability and machinability characteristic. It can be heat treated to increase its strength, but it does not have as high a strength-to-weight ratio as other alloys. The alloy has good weldability and can be anodized to improve its corrosion resistance and surface finish. Its mechanical properties can be enhanced by the addition of elements such as magnesium and silicon. Overall, aluminum alloy 6063 is a useful alloy with a combination of good formability, machinability, and corrosion resistance. The composition and mechanical properties of the base Al6063 material is shown in table 2 and table 3 respectively.

Figure 4 illustrates the frequency distribution of nanoparticle sizes within the Al6063 matrix. The x-axis represents nanoparticle size, which ranges from 50 nm to 100 nm, while the y-axis indicates frequency distribution. The plot indicates that the nanoparticle size is predominantly concentrated around [55 nm to 70 nm], suggesting the consistency of our nanoparticle incorporation method. This uniform distribution is a critical factor in enhancing the composite's mechanical properties and wear resistance, as indicated by our results. SEM/Dynamics light Scattering was used to find the particle distribution in present study and by using the ImageJ software

Table 2 chemical composition of the Al6063 [38)]

Si	Fe	Cu	Mn	Ni	Zn	Ti	Sn	Mg	Al
%	%	%	%	%	%	%	%	%	%
0.466	0.343	0.002	0.0015	0.006	0.007	0.001	0.001	0.49	balance

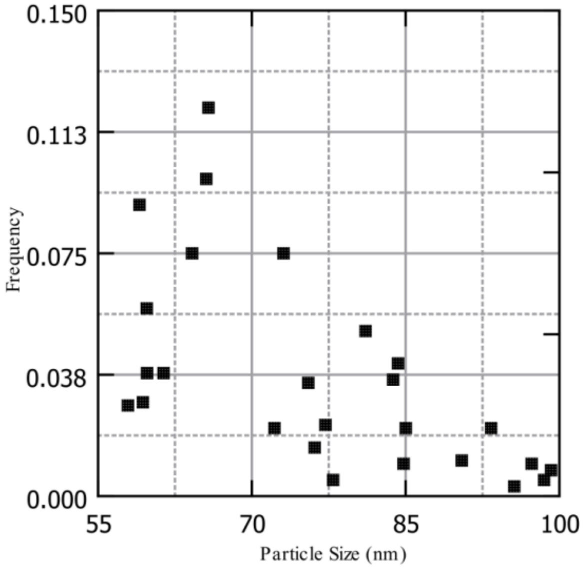


Fig. 4: Particle Distribution of TiO_2 nanoparticle

The microstructure of TiO_2 nanoparticles was investigated utilizing a working distance of 3 millimeters and an accelerating voltage of 10 kilovolts. The contrast and brightness of the photos were increased so that the particles could be distinguished from the backdrop. Using the ImageJ software, calibration was performed for length scales between 10 nm and 100 nm, and picture magnification ranged from 1000 to 50,000 times[39]. Over 150 particles were analyzed using this software, developed by the NIH, to determine the mean area-equivalent diameter and shape descriptors. The threshold image of the TiO_2 nanoparticles is shown in Figure 5, which illustrates the distribution of the particles.

Table 3 mechanical properties of the Al6063 [34,35,38]

Material	Density (kg/m3)	Micro hardness (BHN)	UTM (GPa)	TS (MPa)
Al-6063	2700	75	215	197
TiO_2	4230	89	230	680

EM: Elastic Modulus; TS: Tensile Strength

The particle distribution of the TiO_2 nanoparticles was determined through TEM analysis, and the results are presented in Figure 4.

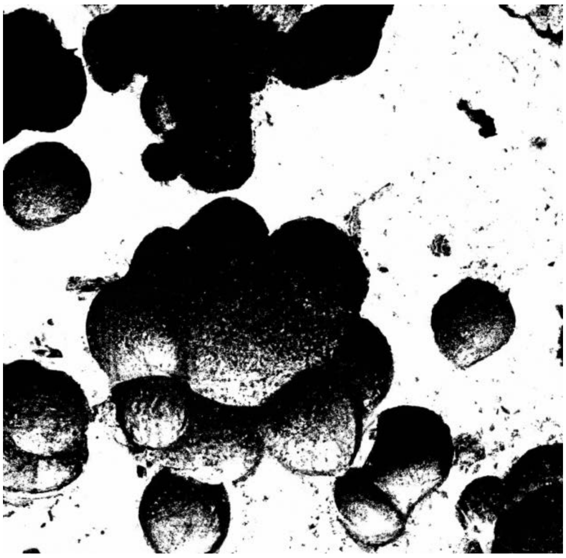


Fig. 5: Particle Distribution of TiO_2 nanoparticle using ImageJ software[39]

4. Fabrication Steps

To create the composite materials, impurity-free Al6063 aluminum was melted in a graphite crucible using an electrical resistance furnace. This was done to prevent oxidation of the aluminum during the casting process, and the temperature of the molten aluminum was maintained at 750^{o}C. Stir casting machine was used to fabricate the MMC made by Al 6063 and Nano particle TiO_2 having different compositions. The machine setup is shown in figure 6. The required amount of TiO_2 nanoparticles was accurately weighed and then added to the Al6063 in proportions of 1, 3, and 5 by weight percent. To ensure stable and fine TiO_2 nanoparticles, the TiO_2 was heated to 500 degrees Celsius to remove any moisture before being carefully added to the molten aluminum at 750 degrees Celsius. Drossing and fluxing methods were adopted to free the molten metal from impurities present in Al6063. The mixture was stirred using a motor-controlled stirrer for three to five minutes to thoroughly combine the ingredients. The composite was then heated to 750 degrees Celsius and stirred again with a mechanical stirrer to disperse the TiO_2 nanoparticles throughout the molten Al6063. The liquid Al6063-TiO_2 mixture was poured into cast iron molds and allowed to cool and solidify. Once removed from the molds, the Al6063-TiO_2 composites were machined to the desired dimensions and shapes. This process was repeated to produce composites with different weight percentages of reinforcement. During making of MMC, the first step is to stir the molten metal with TiO2 particles for 300~350 sec at the rate of 200 RPM[45] for making the homogenization of the mixture, then heating the mixture to super-heated temperature of 780±10 C, and then again making the mechanical stirring for 650 sec for 400~450 RPM[45,46,47,48,49], after that the proper mixed mixture pour into the molds prepared by sand casting process.

Fig. 6: Stir casting machine used for making the composite

After completing the stir casting process, the composite liquid metal was used to create a product through the sand-casting method. The samples were prepared according to ASTM standards and project requirements. Figures 7 and Figure 8 show the sand-casting method used in the study.

The stir casting method was employed to produce the Al6063-TiO_2 composites. The Al6063 alloy was melted in a furnace, and once a stable molten state was achieved, the TiO_2 nanoparticles were introduced. The mixture was mechanically stirred at a speed of [500 RPM][43] to ensure a homogeneous dispersion of the TiO_2 nanoparticles throughout the Al6063 matrix.

Fig. 7: Send casting process for making the object from composite melting

Fig. 8: Mold filled with composite liquid material

5. EDM machining

Electrical Discharge Machining (EDM) is a method that removes material from a workpiece using electrical sparks. It is primarily used to manufacture complicated shapes or to remove materials that are difficult to machine using conventional techniques, such as hardened steel or titanium. In electrical discharge machining (EDM), an electrode is used to generate sparks that remove material from the workpiece. The electrode is manufactured from a conductor, such as copper or graphite, and is fashioned to resemble the final product. Typically, the workpiece is composed of a conductive substance and is placed in a tank containing dielectric fluid, which functions as an insulator.

The EDM process begins by applying a voltage between the electrode and the workpiece. The applied voltage in an Electrical Discharge Machining (EDM) process plays a crucial role in affecting the characteristics of the dielectric fluid, which has a substantial effect on the spark generating process. When a voltage is supplied between the electrodes of an EDM machine, an electric field is created within the dielectric fluid in between. As the voltage is increased, the strength of the electric field increases, which might result in the ionization of the dielectric fluid. Ionization is essentially the removal of electrons from the atoms of a fluid, which results in the production of charged particles. This procedure forms a 'plasma channel' or a ‘spark channel,' so facilitating the transition from insulator to conductor. Once the dielectric fluid has been ionized and the plasma channel has been formed, a spark can be started. The spark then discharges over the gap, resulting in material removal from the workpiece. The strength and frequency of these sparks are directly proportional to the applied voltage; a greater voltage results in more energetic and frequent sparks, which results in more aggressive material removal.

This causes a spark to jump between the two, which removes a small amount of material from the workpiece. The process is repeated in various times, with the electrode moving in a precise pattern to create the desired shape. EDM is a very accurate and precise machining method, and it is often used to produce parts with tight tolerances. It is also very useful for producing complex shapes that would be difficult to machine using traditional methods. However, it can be slow and expensive, and it is not well-suited for machining large volumes of material.

In this study, machining was conducted on Al6063-TiO_2 composite specimens using an EDM machine with a circular electrode. The spark gap was kept at 3 millimeters and distilled water served as the dielectric fluid. The surface roughness was measured with a Mitutoyo softest SJ-301 roughness checker, and the EDM machine is shown in Figure 9. On an Electrical Discharge Machining (EDM) device, machining trials were conducted using the Taguchi experimental design approach. Prior to completing these experiments, a comprehensive literature analysis and a localized survey concentrating on EDM machining techniques were conducted. This preparation phase allowed for the selection of suitable Pulse Off Time (TOFF), Pulse On Time (TON), CURRENT, and VOLTAGE parameters.

Fig. 9: EDM machine used for present study

6. Taguchi Method

The Taguchi approach is a method of optimizing manufacturing processes through the use of statistical analysis. It involves several stages, including determining the process input parameters to be investigated, selecting levels for those parameters, and choosing an appropriate orthogonal array to use as an experiment table. After running experiments using the orthogonal array, the next step is to analyze the response parameters measured in previous stages the S/N ratio which is known as Signal to Noise Ratio. This technique is used to evaluate the quality of the response output and can be divided into three categories: high, medium, and low. In the present examination, the Taguchi method was employed to conduct the experiments, and a total of 16 experiments were necessary. Table 5 displays the final orthogonal array L16 chosen for the inquiry.

6.1 Factor and Levels

This research investigates the use of non-conventional machining, specifically electrical discharge machining (EDM), to create holes in a work-piece fabricated using Matrix material of aluminum (Al6063) and titanium dioxide (TiO_2) as Nano particle. The scope of the study was to improve the strength of the aluminum base material through the use of the MMC.

The findings of the tests done on the EDM machine are described in this chapter, and Table 4 contains the final list of study criteria. This study aimed to give a more comprehensive understanding of the machining process and its influence on the MMC's strength.

Table 4 factor and levels

Factor/Levels	I	II	III	IV	Unit
current	4	6	8	10	A
ton	60	80	100	120	micro sec
toff	20	22	24	26	micro sec
Pressure	0.6	0.8	1	1.2	Atm

The current investigation used the Taguchi Method, a design-of-experiment technique, to examine the impacts of four process factors on the machining process: current, tone, toff, and pressure. These parameters are presented in Table 4, and the Taguchi Method-generated experiment table is shown in Table 5. This strategy was chosen in order to study the correlations between process factors and machining outcomes more efficiently.

Table 5 Experiment results for cutting time and Surface roughness

Sr No	Current	Ton	Toff	Pressure	CT
1	4	60	20	0.6	3.38
2	4	80	22	0.8	3.86
3	4	100	24	1	3.94
4	4	120	26	1.2	3.72
5	6	60	22	1	3.95
6	6	80	20	1.2	5.91
7	6	100	26	0.6	5.52
8	6	120	24	0.8	4.99
9	8	60	24	1.2	8.00
10	8	80	26	1	6.45
11	8	100	20	0.8	8.85
12	8	120	22	0.6	7.55
13	10	60	26	0.8	6.47
14	10	80	24	0.6	5.53
15	10	100	22	1.2	6.92
16	10	120	20	1	6.82

7. Result and Discussion

7.1 Tensile Strength Analysis

In the present study, the experimental stress and strain curves were discussed for all compositions fabricated for the present study. The UTM was used to determine the tensile strength of the machined component. The workpiece was positioned within the UTM, and a load was gradually increased until the workpiece failed. For the calculation of tensile strength, the force exerted and the workpiece's elongation were recorded. All tests was conducted department laboratory at Nirwan University, Jaipur.

The tensile properties like tensile stress, yield stress, and percentage of elongation were calculated using the stress train diagram shown in Figure 10. The limit of proportionality, which is the point at which the material deforms permanently, is larger for Al6063-TiO_2 composites than for pure Al6063.

This indicates that the Al6063-TiO_2 composites have a higher load bearing capacity and greater durability than pure Al6063. The stress-strain curve for Al6063-TiO_2 composites in Figure 10 shows a linear profile from the point of yield stress until the test specimen breaks.

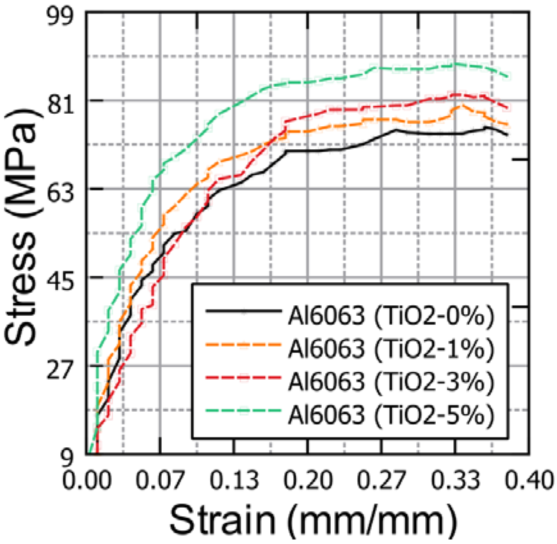


Fig. 10: Experimental Stress Strain results for Composite

As exhibited in Figure 10, the yield behavior of the composite was detected at extremely low strain levels, after which the stress increased according to the increase in stain. The results profile in Figure 10 was then compared to previously published research[44]. After strain rate of 0.2 the stress was also showing the approx. constant behavior of the profile.

7.2 Corrosive nature of composite

The corrosion rate of composites of varying composition fabricated for the present study was evaluated through an accelerated corrosion test in which the samples were placed in a solution containing 3.5% weight of NaCl at room temperature. It was observed that an oxide layer forms on metal surfaces over time. This oxide layer, made up of Al(OH)3, is produced as a result of the precipitation of a white, gelatinous gel or flakes in the corrosion pits. However, as the applied voltage increases, the corrosive Cl ions can erode the oxide layer until it is no longer present. Weight loss due to corrosion nature of the composite was shown in figure 11.

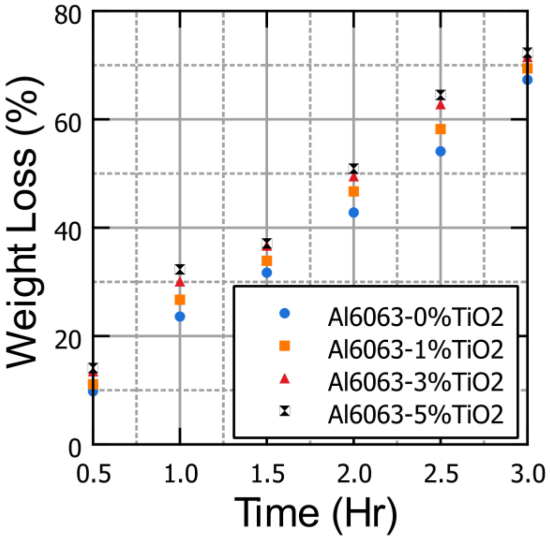


Fig. 11: Corrosive study for Composite Al6063 and TiO_2 nanoparticle

7.3 Wear Rate Analysis

An important part of comprehending the performance and durability of composite materials is the analysis of wear. By examining the material's performance under various circumstances of wear and tear, wear analysis assists in determining its acceptability for certain applications. Through wear analysis, we may acquire a deeper knowledge of the Al6063 and TiO_2 composite's wear behavior, including its resistance to wear, wear mechanisms, and wear rate. This information is crucial for optimizing the performance and longevity of the composite in a variety of applications. Figure 12 depicts the SEM image of a composite of TiO_2 (5% wt) and Al6063 cracks.

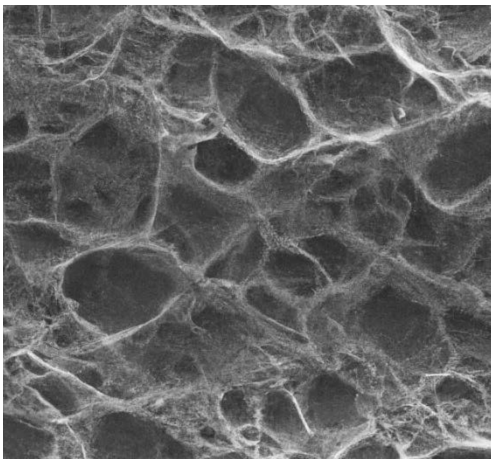


Fig. 12: SEM image (75 micro m) for fractured composite at 5% TiO_2 wt percentage in Al6063

The volumetric wear loss was measured and plotted against dry sliding distance for three different loads: 1.0, 1.5, 2.0 and 2.5 kg. The graphs in Fig. 13-16 show the volumetric loss under these different loads at various sliding ranges. It was found that the volumetric wear decreases as the sliding range increases. This is because the increase in sliding range leads to a shift in frictional force, which causes the MMCs to heat up. As the temperature increases, the composite becomes softer, leading to an increase in volumetric wear loss.

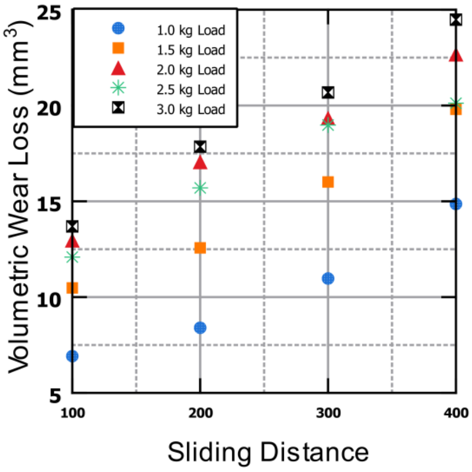


Fig. 13: Volumetric wear loss at different load conditions for Al6063

Figure 13 illustrates that as the load and sliding distance for wear testing increase, the loss of the work piece made of Al6063 also increases. It was noted in figure 13 that when the load on an object increased, the volumetric loss of the object also increased, but it increased more rapidly after the 2 kg load condition. The same profiles were shown for composite materials made of TiO_2 (1% to 5%).

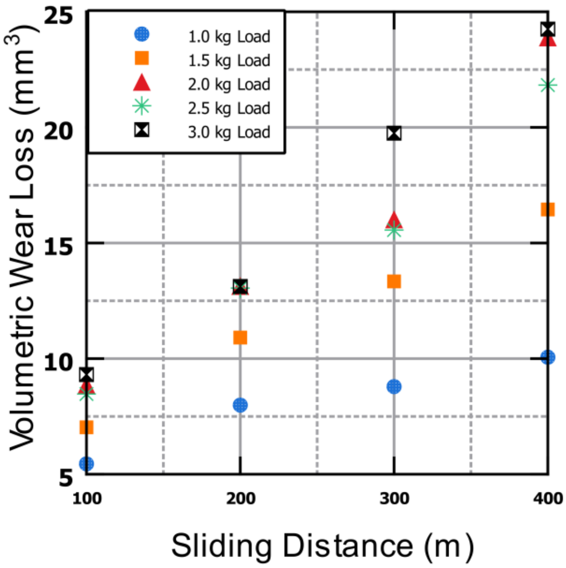


Fig. 14: Volumetric wear loss at different load conditions for Al6063+1%wt of TiO_2

Figure 14 demonstrates that as the sliding distance increases from 100 m to 400 m, the volumetric wear also increases for all load conditions ranging from 1 kg to 3 kg. This can be observed by the upward trend in the graph as the sliding distance increases. It is important to note that the volumetric wear is affected by both the load and the sliding distance. As the load increases, the wear on the work piece also increases. Similarly, as the sliding distance increases, the wear on the work piece also increases. This can be seen in the steeper slope of the graph as the sliding distance increases. It is also worth noting that the effect of the sliding distance on the volumetric wear is more pronounced than the effect of the load.

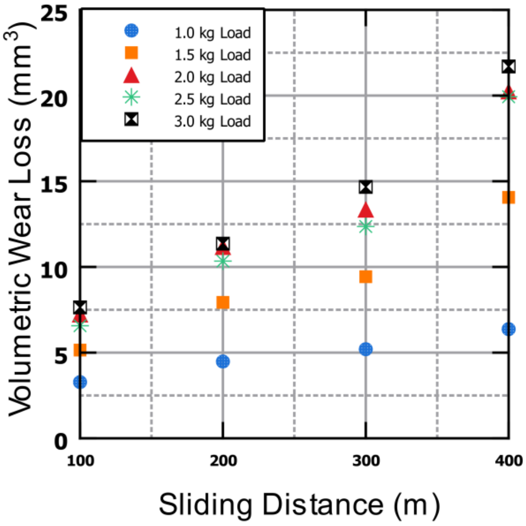


Fig. 15: Volumetric wear loss at different load conditions for Al6063+3%wt of TiO_2

This can be seen by the relatively smaller differences in the volumetric wear between the different load conditions compared to the differences in the volumetric wear between the different sliding distance conditions. Overall, these results suggest that both the load and sliding distance play a significant role in determining the volumetric wear of the work piece made of Al6063.

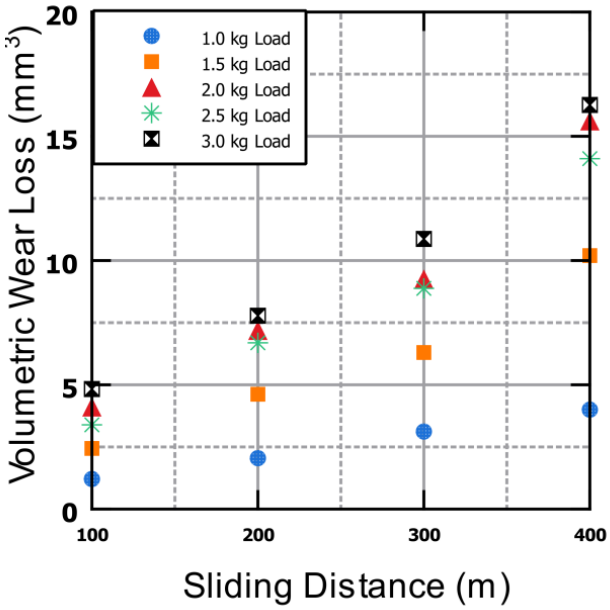


Fig. 16: Volumetric wear loss at different load conditions for Al6063+5%wt of TiO_2

In figure 15 and figure 16, the impact of sliding distance and normal load at 3% wt and 5% wt TiO_2 nanoparticle were present respectively.

7.4 EDM machining analysis for Cutting Time

To determine the cutting time (CT), researcher used a stopwatch to measure the duration of the experiment conducted on the EDM machine. Researchers repeatedly measured the cutting time to assess the quality of the machine's cutting performance. The results of the experiments, including any reductions in time, are presented in this section. To analyze the signal-to-noise ratio, researchers used the cutting time data from both runs of each experiment. The S/N ratio for individual cutting time was present in table 6. The EDM machining was performed for composite made of Al6063 and 5% wt of TiO_2 Nanoparticle, because this composite show the maximum strength properties then other composites.

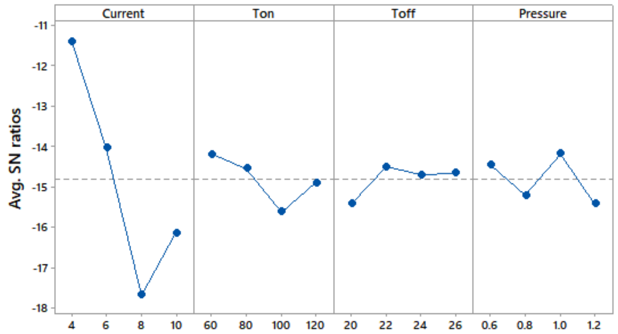
Table 5 Experiment results for cutting time (min)-S/N ratio

Sr No	Current	Ton	Toff	Pressure	CT	S/N
1	4	60	20	0.6	3.38	
2	4	80	22	0.8	3.86	
3	4	100	24	1	3.94	
4	4	120	26	1.2	3.72	
5	6	60	22	1	3.95	
6	6	80	20	1.2	5.91	
7	6	100	26	0.6	5.52	
8	6	120	24	0.8	4.99	
9	8	60	24	1.2	8.00	
10	8	80	26	1	6.45	
11	8	100	20	0.8	8.85	
12	8	120	22	0.6	7.55	
13	10	60	26	0.8	6.47	
14	10	80	24	0.6	5.53	
15	10	100	22	1.2	6.92	
16	10	120	20	1	6.82	

The signal-to-noise ratio analysis for cutting time analysis was present in figure 17 and in table 6. To minimize the cutting time for the composite (Al6063+5% TiO_2), the option "smaller is better" was selected for the present investigation.

Table 6 Rank Identification for CT parameter of composite (5%TiO_2)

Level	**Current**	**Ton**	**Toff**	**Pressure**
1	-11.41	-14.2	-15.41	-14.46
2	-14.04	-14.55	-14.51	-15.21
3	-17.69	-15.62	-14.7	-14.18
4	-16.14	-14.9	-14.66	-15.43
Delta	6.28	1.42	0.9	1.25
Rank	**1**	**2**	**4**	**3**



Signal-to-noise: Smaller is better

Fig. 17: S/N ratio analysis for CT response parameter of composite (5% TiO_2)

In this study on cutting composite materials, four factors were analyzed to determine their impact on the cutting time of the object. These factors were peak current, pulse on time, peak pressure of the tool, and pulse off time. The outcome of the S/N ratio was that the most crucial factor for the present investigation was Current and second crucial factor was TON and then Pressure and

TOFF was least important factors for the current study. This was showed in both table 6 and figure 17. Peak current has the greatest influence on the cutting time of the composite object (Al6063+5%TiO_2), while pulse off time has the least impact.

8. Conclusion

Using the stir casting method, we manufactured Al6063-TiO_2 composites with different amounts of TiO_2 ranging from 1% to 5% by weight in this study. Characterization of the resulting composites revealed that the composite containing 5 percent TiO_2 exhibited superior hardness, showing the promising potential of TiO_2 additions. To determine the ideal Electrical Discharge Machining (EDM) settings for these composites, we conducted a series of experiments involving four variables at four unique levels. We observed a significant increase in the variability of EDM parameters while working with Al6063-TiO_2 composites as compared to the base material, and this impact was amplified as the TiO_2 concentration increased.

Based on comprehensive research, we ordered these factors according to their delta values. This importance hierarchy - current, pulse-on time, pressure, and pulse-off time - gives essential insights for optimising the EDM process parameters for Al6063-TiO_2 composites and improving machining performance. In conclusion, our extensive investigation confirms that the addition of TiO_2 nanoparticles has a substantial effect on the machining behaviour of Al6063-TiO_2 composites. This knowledge is crucial when applying EDM for machining processes and has significant value in industrial applications. Our findings lay the groundwork for future research into the machining features of similar metal matrix composites, as well as the possibility of enhancing their mechanical and electrochemical properties.

This study examines the effects of adding TiO_2 nanoparticles from 55 to 100 nm to Al6063, primarily 55–70. 5% TiO_2 nanoparticles increased composite strength proportionately. Al6063 strengthened 20%. 5 percent TiO_2 strengthened and corrosion-resistant the composite. Composites wore identically. 3 kg volumetric wear rose considerably. This work reveals TiO_2 nanoparticle concentration controls Al6063-TiO_2 composite mechanical and electrochemical performance. These findings may improve industrial parameters. Delta values prioritized current, pulse-on, pressure, and pulse-off. This ranking improves Al6063-TiO_2 composite EDM characteristics. TiO_2 nanoparticles greatly affect Al6063-TiO_2 composite EDM machining. EDM and Al6063-TiO_2 composite machining data help industry. The discoveries enable comparable metal matrix composites with optimized mechanical and electrochemical characteristics.

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