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Nanoparticle Incorporation to Enhance Titanium Alloy Electric Discharge Machining Capabilities

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Abstract

The primary objective of this study was to examine the effects of the Powder-blended Micro Electric Discharge Machining (PMEDM) technique on micromachining applications, specifically when sea water is employed as the dielectric medium. Tiny apertures with a width of 200µm were punctured over Ti-6Al-4V plates. In the initial round of experimentation, the machining performance was evaluated by subjecting sea water to various process variables without the inclusion of any other ingredients. The effects of input variables, including electrode material, hole voltage, current, Pulse-on-time, and Duty factor, on the Material Removal Rate (MRR), Tool Wear Rate (TWR), Overcut (OC), Circularity Error (CE), and Taper Ratio (TR) were analysed by conducting tests in accordance with Taguchi's L18 plan design. The method employed to ascertain the optimal parametric configuration for multi-objective enhancement involved utilising the strategy of soliciting inclination based on similarity to an ideal arrangement. The present study aimed to investigate the effects of foreign materials on the dielectric-based miniature electrical discharge machining (EDM) process in sea water. This was achieved by utilising powders with varying weight concentrations and molecule sizes, including non-conductive (Al2O3), semi-conductive (SiC), and conductive (Al) powders. The experimental setup ensured that the variable boundaries were maintained at their ideal settings. The results indicate that the choice of tool has a notable influence on the functioning of micro EDM when sea water is employed as the dielectric, without the inclusion of extraneous particles. The performance metric of multi-objective execution in PMEDM is influenced by the conductivity of supplementary compounds. An 83.18 percent increase in Material Removal Rate (MRR) was observed when SiC added compounds were utilised in Powder Mixed Electrical Discharge Machining (PMEDM). Conversely, there was a drop in Tool Wear Rate (TWR) by 36.42 percent, Open Circuit voltage (OC) by 21.48 percent, Current Efficiency (CE) by 45.15 percent, and Tool Roughness (TR) by 22.87 percent.

Keywords – PMEDM, RoC, Nano particles, Titanium, EDM

Introduction

Because of its excellent physical and mechanical properties, parts constructed of Ti-6Al-4V are becoming increasingly used in microsystems [1]. It is critical to achieve higher efficiency with delicate mathematical characteristics while micro machining Ti-6Al-4V for making miniature components and frameworks [2]. One of the most recent machining processes is micro EDM. Machining action on a wide range of electrically conductive materials of any hardness is profoundly ideal for precisely fabricating simple to sophisticated mathematical pieces. The role of dielectric liquid in EDM is quite important and serves some crucial needs. When the applied voltage exceeds the dielectric strength, the protective medium creates a plasma channel between the instrument and the workpiece. By dissolving and vapourizing, the plasma channel aids the machining movement. The dielectric medium aids in the removal of flotsam and jetsam from the flash hole formed for each electric emission. It also serves as a coolant and a perfect encasing, allowing release at various points on the workpiece for progressive electric heartbeats. As a result, the dielectric concept in EDM is an incredibly essential boundary that has an unexpected impact on the material evacuation process and the character of the machined surface.

Hydrocarbon oils are frequently employed as dielectric fluids in the electrical discharge machining (EDM) process. Nevertheless, the utilisation of hydrocarbon oil as a dielectric introduces several complexities, such as the emission of noxious gases, predominantly carbon monoxide (CO) and methane (CH_4), significant health concerns, and the degradation of undesirable materials. Subsequently, various dielectric liquids, including as deionized water and regular water, are carefully optimised to achieve environmentally sustainable and cost-effective production [3]. In order to attain environmentally sustainable assembly practises, specialists have recommended the use of dry, near-dry, and water-based electrical discharge machining (EDM) as viable alternatives to the conventional oil-based EDM [4]. According to the findings of Kou and Hun [5], the utilisation of water-based dielectric liquids during rapid machining on Ti-6Al-4V resulted in a significant fivefold increase in the rate of material expulsion compared to the conventional oil-based EDM method. In a study conducted by Tang and Duo (6), it was demonstrated that the use of tap water as a dielectric in Ti-6Al-4V EDM is feasible when employing a red copper pole with a diameter of 10 mm. It has been established that electric discharge machines (EDMs) utilising tap water as a dielectric fluid exhibit commendable material removal rates (MRR) while maintaining minimal operational expenses, and do not provide any discernible risks to management or the environment. The study article indicates that the highest Mean Reciprocal Rank (MRR) was attained when employing regular water as a dielectric medium. Additionally, there have been reports indicating that the inclusion of electrically conductive additives diminishes the protective capabilities of the dielectric material at the flash hole. Consequently, this leads to an increase in the width of the gap between the cathode hole, resulting in increased material removal rate (MRR) and improved surface finish [7].

The study utilised non-conductive Al2O3 particles as additives in oil-dielectric and copper devices with a 12 mm cross-section for the purpose of machining AlSiCp12 percent metal lattice composite (MMC) using EDM. The researchers made a significant finding that the expansion of Al2O3 powders has a positive effect on the breakdown characteristics, resulting in an improvement in the machining rate and a decrease in surface roughness [8]. The researchers incorporated alumina powders with a particle size of 45 nm into a deionized water-dielectric solution during the process of electrical discharge machining (EDM) on Inconel, in conjunction with a copper device measuring 5 mm x 15 mm [9]. It was shown that the incidence of arcing was higher in conventional electrical discharge machining (EDM) compared to pulsed magnetic electrical discharge machining (PMEDM). Additionally, it was noted that the enlargement of alumina powders during the machining process led to the extension of the flash hole, hence facilitating the removal of debris and ensuring a consistent machining performance. In their study, Chow et al. [10] examined the impact of silicon carbide (SiC) and aluminium additions, characterised by molecule sizes of 1m, on the dielectric properties of lamp oil. This investigation was conducted during the process of tiny cut electrical discharge machining (EDM) on titanium amalgam. The results of their study indicated that SiC powders exert a more pronounced influence on material removal rate (MRR) compared to aluminium. In their study, Kibria et al. (2011) provided evidence that the use of a B4C-blended deionized water dielectric in the micro EDM process of titanium compound led to a reduced range of diameteral difference at the section and the formation of holes at higher release energy. This effect was observed to be more pronounced compared to the use of unadulterated deionized water. In their study, Pecas and Henriques (2012) incorporated silicon particles as additives into Castrol-liquid dielectric during the process of electrical discharge machining (EDM) on AISI H13 hot work tool steel. The experiments were conducted using a copper apparatus with varying surface areas, ranging from 1 to 64 cm2. The typical size of the introduced drug molecule was measured to be 10 metres, while the concentration of the supplementary material was determined to be 2 grammes per litre. The authors of the study employed logical reasoning to conclude that the expansion of the dielectric in semi-conductive silicon powders effectively mitigates the anomalous emissions, hence facilitating the achievement of a machined surface exhibiting a pristine reflectivity. In their study, Tzeng and Lee (2013) employed copper as the material for the device, with a width of 8 mm, and lamp oil as the dielectric medium, in order to conduct Pulse Modulated Electrical Discharge Machining (PMEDM) on SKD11 shape steel. The authors analyse the effects of aluminium, chromium, copper, and silicon carbide particles on the process of expulsion. The findings from their exploratory study revealed that the mean removal rate (MRR) exhibited an increase when the volumetric powder concentration was set at 0.5 cm3/L, and the particle sizes ranged from 10-15 µm. The utilisation of chromium powder resulted in the highest material removal rate (MRR) compared to other materials. The inclusion of copper as an additive did not result in any significant impact on the mean removal rate (MRR), perhaps due to its increased density.

The study conducted by Nguyen et al. (2014) examined the impact of titanium particles present in oil-dielectric on the electrical discharge machining (EDM) process of SKD device steel. In their experimental investigation, the researchers selected certain materials (copper and graphite) for the devices, determined the parameters for the apparatus (such as extremity), measured the duration of beat on and beat off times, controlled the current, and adjusted the powder focus. The researchers' findings indicated that the main limiting factor was the process of powder fixing. The increase in titanium powder expansion leads to a lengthening of the material evacuation cycle, while concurrently reducing surface irritation. The study conducted by Prihandana et al. [15] examined the impact of incorporating molybdenum disulphide compounds into a miniature electrical discharge machining (EDM) system that utilises lamp fuel as the dielectric medium. Utilising Cu, Cu-W, and Ag-W devices, the researchers successfully fabricated miniature apertures with a depth of 25μm and a length of 1000 m on workpiece materials composed of Cu, metal, and Cu-W. In their experimental procedure, the researchers utilised MoS_2 additives with a molecular size of 2 m and a centralization ranging from 2 to 5 g/L. The results of their study demonstrated that the incorporation of semi-conductive MoS_2 additives resulted in the production of machined apertures that were dark and free of spots, hence enhancing the material removal rate (MRR). The concept was described in the study conducted by S. Rajamanickam et al, where tap water was utilised as the dielectric medium. However, in this study, our emphasis was on employing sea water as the dielectric medium [16].

Based on the findings presented in the PMEDM, it has been observed that different types of supplementary substances, varying levels of concentration, and differences in molecule size exhibit unique and discernible impacts on the performance of machining processes, specifically in terms of material removal rate (MRR), tool wear rate (TWR), and surface finish quality. The assessment of the writing also highlighted the limited amount of study conducted in the area of PMEDM utilising normal water dielectric. Consequently, the objectives that were set for this current study have been established. Firstly, it is important to acknowledge the impact of cycle boundaries in the context of Ti-6Al-4V micro-electrical discharge machining (EDM) utilising sea water as the dielectric medium. Furthermore, this study aims to examine the effects of electrically non-conductive, semi-conductive, and conductive powders, namely Al_2O_3, SiC, and Al, when used as dielectric additives in the process of Powder Mixed Electrical Discharge Machining (PMEDM). The investigation focuses on evaluating the impact of these substances on two key performance metrics: machining speed and layered precision. The evaluation is conducted based on several parameters, including Material Removal Rate (MRR), Tool Wear Rate (TWR), Overcut (OC), Circularity Error (CE), and Taper Ratio (TR).

Materials and methods

The experimental work was conducted using the ELTECH D300 machine gadget manufactured by Electronica Hightech. A distinctive tank was designed and produced, incorporating a syphon, a legal filtration system, and a blending mechanism to facilitate the circulation of sea water dielectric liquid mixed with additives. The technique of side flushing was implemented at the flash hole, and the pressure was consistently maintained at 0.5 kg/cm2. In the process of Powder Mixed Electrical Discharge Machining (PMEDM), three distinct types of powder were employed, namely electrically non-conductive aluminium oxide (Al_2O_3), semi-conductive silicon carbide (SiC), and conductive aluminium (Al). These powders were selected based on their varying molecule sizes and weight concentrations. The cost-effective EDM tube instruments, specifically copper tubes, with an outside diameter of 300 μm and an inner diameter of 120 μm, were employed as small tools for machining purposes. The specimens utilised in this study were titanium combination Ti-6Al-4V plates with a thickness of 550 μm. The machining process was conducted by configuring the device as an anode. Considering the potential wear on the instrument, the machining depth at the Z-hub was established at 1 mm. The MRR was calculated by utilising the ratio of weight reduction of the workpiece to the machining time. The measurement of the workpiece was accurately completed by employing a microbalance with a resolution of 0.01 mg. The identification of TWR was achieved through the examination of the Z-hub length during the machining process. The machined opening's profile at both the entry and exit sides was examined using a metallurgical microscope with a magnification of X100.The most extreme distinction between the width of the machined opening and the instrument was utilized to decide the overcut. The roundness mistake of the machined opening was proposed as far as circularity, which is a spiral distance between the base delineating circle and the greatest writing circle. The distinction in measurement of the entry and passage openings was checked by tracking down the TR [17].

After engaging in the process of drafting a review and doing initial analysis, the boundaries and operational scope of the cycle were identified. The selected parameters for interaction boundaries included the material of the apparatus, the voltage across the hole, the current flowing through the top, the duration of the beat on-time, and the duty factor. The trial configuration proposed by Taguchi was successfully implemented to conduct exploratory analysis in tiny EDM, utilising a reduced number of experiments, hence reducing costs and time requirements. Therefore, it was employed to strategize the experimental design for the present research endeavour. The study examined Taguchi's L18 symmetrical cluster in light of the number and degree of cycle boundaries. The utilisation of this approach was to standardise and convert multiple performance indicators (MRR, TWR, OC, CE, and TR) with varying units into a single performance characteristic. It aids in determining the optimal parametric configuration that exhibits the highest degree of relative proximity, as measured by the Closeness Coefficient (CC), to the optimal solution. A weightage of 0.2 was assigned to the variables MRR, TWR, OC, CE, and TR when calculating the worth of the CC. Finally, an analysis of variance (ANOVA) was conducted on the cycle characteristics to examine the significance and impact of cycle borders on the multi-objective performance attribute.

The scientists were enthusiastic about revealing the impact of electrically conductive additives on the performance of particulate matter in electric discharge machining (PMEDM) while analysing the influence of additives on tap water EDM. Following that, non-conductive aluminium oxide (Al2O3), semi-conductive silicon carbide (SiC), and conductive aluminium (Al) particles were employed as additives in the dielectric of tap water. In order to maintain the machine at the optimal multi-objective setting, an additional series of L18 testing was conducted. These tests involved varying levels of control factors in the powder mixed electrical discharge machining (PMEDM) process, specifically focusing on the type of powders used, the concentration of weight, and the average particle size of the additives. The effects of additional drugs on the overall performance of PMEDM in terms of multiple objectives were investigated. Finally, a comparison was conducted between the performance of the standard water tiny electrical discharge machine (EDM) with and without the inclusion of other substances.

RESULTS AND DISCUSSION

Impact of input variables on MRR of sea water dielectric based micro EDM

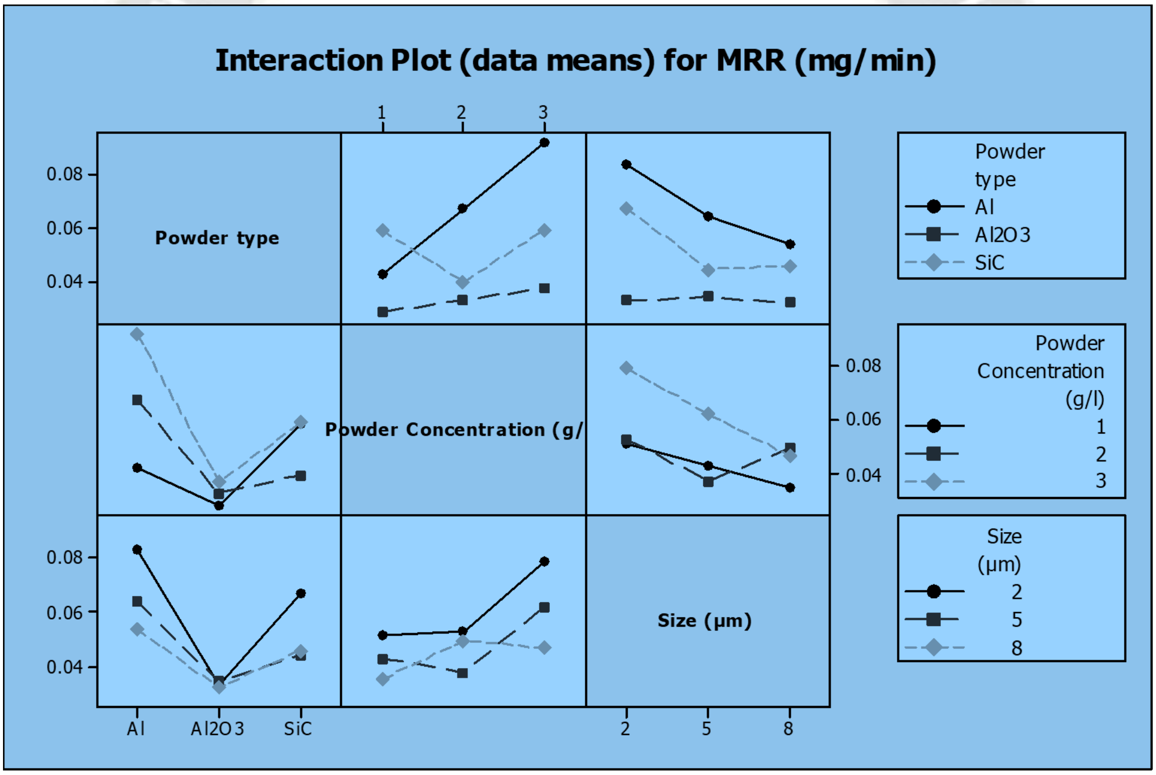

Figure 1 – Interaction impact of distinct variables on MRR of titanium alloy

The findings of the experiment using pure sea water as a dielectric fluid are depicted in Figure 1, which displays the crucial effects plot for the multi-objective performance characteristic method, together with the analysis of variance (ANOVA) outcomes. The device material has emerged as the predominant interface for interaction. In the context of miniature electrical discharge machining (EDM), the flow of electric current occurs within a small-scale device. This device necessitates a high level of thermal conductivity in order to effectively dissipate the substantial amount of energy generated after each discharge event. Moreover, the utilisation of a proficient electrically conductive apparatus facilitates the establishment of a reliable plasma channel, hence enabling the attainment of stable machining operations. Copper, known for its enhanced electrical and thermal

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conductivity compared to other metals, exerts a notably substantial influence on the multi-objective execution brand.

The data presented in Figure 2 clearly demonstrates a positive correlation between the duration of on time and the corresponding increase in Material Removal Rate (MRR). The primary rationale behind this phenomenon is because as the heart rate increases, the duration of time during which current flows in a circuit also increases. The increase in energy release ultimately leads to an increase in Material Removal Rate (MRR). As the duration of the pulse off-time in a circuit increases, the interval during which the current is turned off also increases. Consequently, the dissipated energy decreases, resulting in a reduced material removal rate (MRR) curve. A little adjustment in the angle of curvature of the Minimum Radius of Return (MRR) is made in order to achieve a seamless tension alignment. This phenomenon can be attributed to the positive correlation between increased flushing pressure and the rate of trash removal, resulting in an increase in Material Removal Rate (MRR). Similar consequences of disintegration occur in the case of hardware. When the material removal rate (MRR) of a workpiece increases, the rate at which the hardware disintegrates also increases due to an increase in the release energy between the tool and the workpiece. The time-weighted rate (TWR) increases as the duration of the heartbeat on-time expands, and decreases as the duration of the pulse off-time expands.

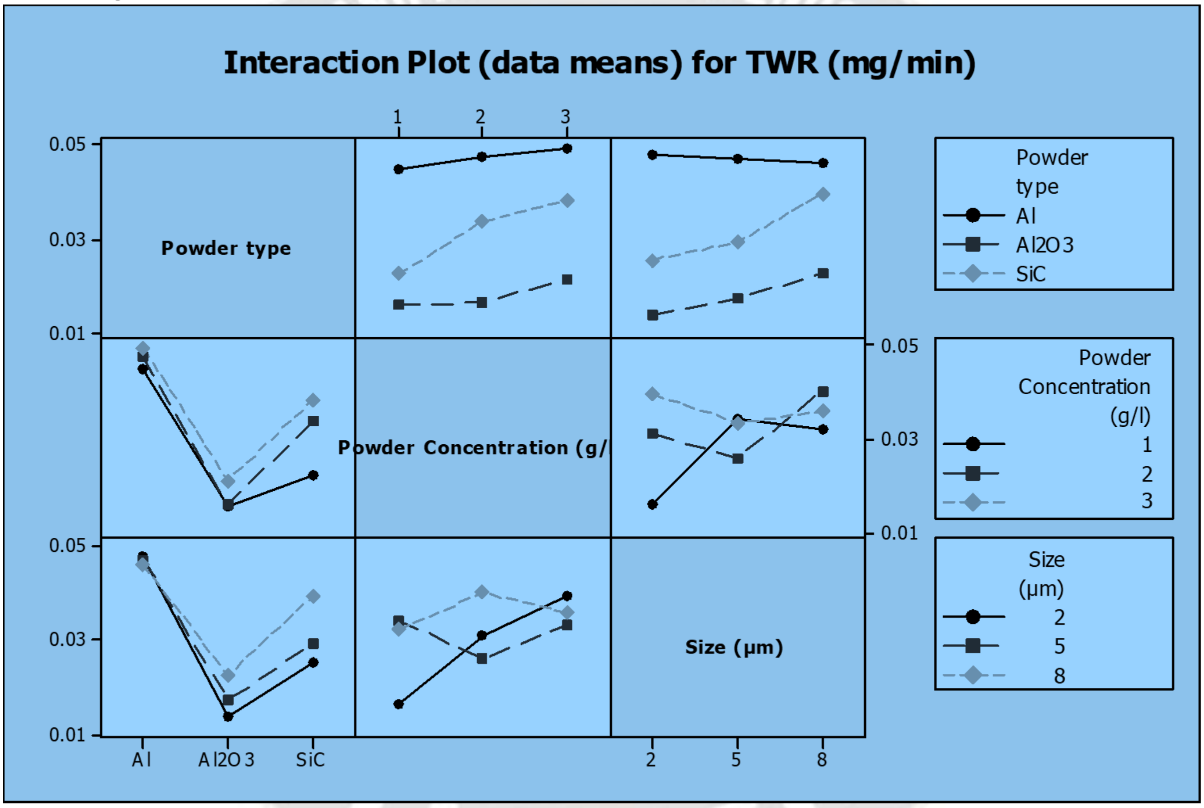

Figure 2 – Interaction impact of distinct variables on TWR of titanium alloy

Moreover, it has been observed that augmenting the flash energy can expedite the electrolytic reaction occurring at the flash hole when utilising regular water as a dielectric, leading to unpredictable machining outcomes [18]. Considering the influence of the obligation component, the increase in its value negatively affects machining performance. There is an inverse relationship between the level of responsibility and the duration of rest periods within a given cycle. Consequently, in the absence of a suitable interval for the heartbeat to cease, the dielectric material is unable to fully restore its protective properties prior to the subsequent discharge. The occurrence of arcing, rather than electrical discharge machining (EDM), at the flash hole is responsible for the initiation of unstable machining. This might be interpreted as a reduced energy release and an ample amount of downtime that contributes to the stable machining at the flash hole. According to the study [19], optimal machine settings were determined to have lower levels of hole voltage, top current, pulse on-time, and obligation factor.

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Impact of input variables on RoC of sea water dielectric based micro EDM

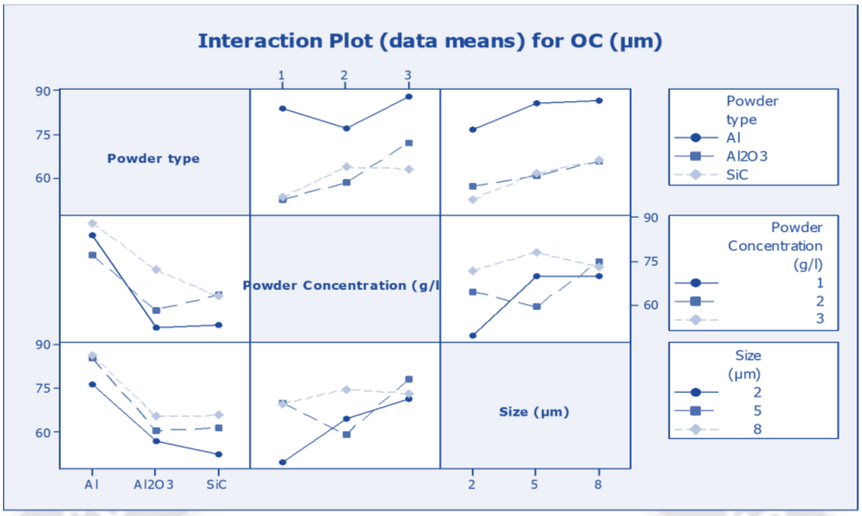

Figure 3 – Interaction impact of distinct variables on OC of titanium alloy

This study examines the influence of interaction boundaries in PMµEDM on the phenomenon of overcut. The influence of extremities on the overcut is minimal, as depicted in Figure 3. The expansion in release energy is attributed to voltage and capacitance, which in turn leads to an increase in the overcut [20]. Consequently, whenever there is a significant increase in the release of energy, there is a substantial excess of material removed. The rotational velocity of the shaft is directly proportional to the electromagnetic force exerted on the dielectric fluid situated between the machinery and the workpiece, which encompasses both particulate contaminants and fine powders. As a result, when the rotational speed of the shaft increases, a significant excess material is removed.

At lower feed rates, there is a higher occurrence of release, as indicated by previous research [21]. This higher release frequency results in a greater overcut compared to higher feed rates, which are associated with lower release frequencies. When powder particles are introduced into the dielectric liquid, the particles in close proximity to the workpiece generate discharges, leading to an increase in overcut. An increase in the degree of centralization of powder particles results in a corresponding increase in the extent of overcutting. The occurrence of little overcut is observed in cases when there is an absence of particle integration within the dielectric liquid.

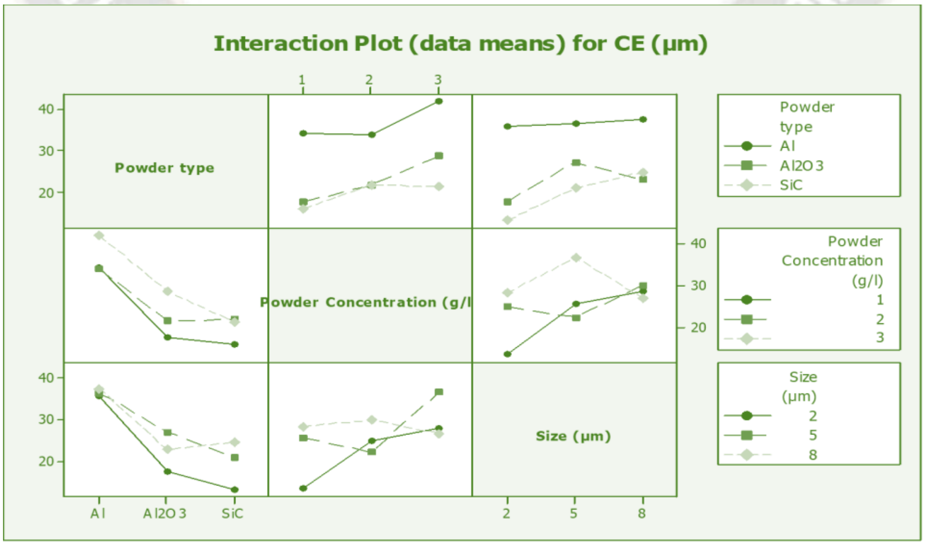

Figure 4 – Interaction impact of distinct variables on CE of titanium alloy

The process of oxidation described in the text would result in the release of excess energy, leading to unintended machining in the dielectric of the tap water. This state is considered undesirable for achieving steady micro EDM, as depicted in Figure 4. The electrical resistivity at the flash hole is increased when Al2O3-based PMEDM is expanded in ordinary water dielectric [22,23]. While the inclusion of protected Al2O3 particles and other conductive and semi-conductive additives may not effectively interact with the scaffolding arrangement, it does serve to reduce the combustion of regular water dielectric. This reduction occurs particularly when operating at higher discharge energy levels, such as larger hole voltage, top current, beat on-time, and duty factor machine settings [24]. Additionally, it facilitates the removal of different scaffolds (releases), hence enabling reliable machining. Consequently, the dielectric expansion exhibited by ordinary water when employed as a dielectric liquid in PMEDM is advantageous [25].

The efficacy of flushing is limited in the context of a cylindrical cathode tube, as it primarily performs the cutting operation at the periphery of the aperture. Furthermore, the excavation process at greater depths is accompanied by the presence of a minimal amount of powder and debris particles that also contribute to the filling of the underground terminal cavity. Insufficient flushing can compromise the interaction between PM-EDD, perhaps leading to numerous restarts of the cycle. The influence of control variables on the thrust-to-weight ratio (TWR) is depicted in Figure 8, specifically for two different configurations: (a) a strong tapering device terminal and (b) an empty tube shaped apparatus cathode. The presence of empty cylindrical instrument terminals led to a significant correlation between the particles and the waste, so establishing a connection with silicon. The expansion of this association could potentially enhance the TWR's ability to achieve higher levels of performance.

Relative investigation of the miniature EDM and PMEDM

The optimal configuration of interaction boundaries was determined based on the primary impacts plot for the method of multi-objective execution in miniature EDM without additives. The configuration includes a copper electrode, a hole voltage of 40 V, a top current of 5 A, a pulse on-season of 100μs, and a duty factor of 0.55. In this study, the optimal control factors for the added substances in the PMEDM multi-objective performance were determined based on the mean diagram. Specifically, the identified control variables were SiC added substances, with a concentration of 1 g/L and an average particle size of 2μm. The exploratory results of the optimal cycle parametric setup for micro EDM without the use of extra chemicals include a Material Removal Rate (MRR) of 0.0423 mg/min, a Tool Wear Rate (TWR) of 0.0287 mm/min, an Overcut (OC) of 39.6μm, a Crater Exit (CE) of 245μm, and a Tool Roughness (TR) of 0.0132. In contrast, the Particle Mass Emission Detection Method (PMEDM) exhibits a Mean Removal Rate (MRR) of 0.0432 milligrammes per minute, a Total Weight Removal (TWR) of 0.0214 millimetres per minute, an Overall Concentration (OC) of 47.6 micrometres, a Concentration Efficiency (CE) of 11.5 micrometres, and a Total Removal (TR) of 0.0136. According to the referenced study [26], it is recommended to observe an 84.38 percent increase in MRR, a 53 percent drop in TWR, a 20.13 percent decrease in OC, a 54.90 percent decrease in CE, and a 10.86 percent decrease in TR. Consequently, the utilisation of particles in conventional water-based Electrical Discharge Machining (EDM) exhibits significant enhancement in machining performance.

Conclusions

This article examines the influence of sea water dielectric on micro EDM, both with and without the use of additives. The PMEDM process was enhanced by the addition of electrically non-conductive Al2O3, semi-conductive SiC, and conductive Al particles. The aforementioned findings have been derived.

The choice of apparatus material and the establishment of electrical cycle boundaries were found to have a notable influence on the multi-objective performance of micro EDM in the absence of extra substances. The hierarchy of significance has undergone a transition, with a shift from the material of the apparatus to factors such as beat on-time, peak current, hole voltage, and obligation factor. A modest enhancement was noticed when comparing the use of a dielectric medium combined with tap water.

The results obtained from the copper tube apparatus were superior in comparison to those obtained from the metal cylinder instrument. The recommended parameters for achieving the most efficient electrical cycle boundary settings in micro EDM, without the use of additional substances, are as follows: a hole voltage of 30 V, a top flow of 0.5 A, a beat on-season of 100μs, and an obligation component of 0.55. In the context of PMEDM, the SiC powder, known for its semi-conductive properties, demonstrated the highest impact on the multi-objective execution characteristic. It was succeeded by the Al2O3 and Al powders.

The presence of conductive additives, specifically aluminium (Al), has been found to result in arcing and short-circuiting during the machining process. This phenomenon adversely affects the precision of layering, particularly when compared to the use of silicon carbide (SiC) and aluminium oxide

(Al2O3) additives. The addition of SiC substances has been identified as the most effective factor in PMEDM when considering additional compounds. These SiC substances are typically used at a weight concentration of 1 g/L and possess a molecular size of 2µm.

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