

# Effect of hydroxyapatite and yttria-stabilized zirconia nano-powders on surface integrity of Ti-6Al-4V in powder-mixed electrical discharge machining with multi-response optimization

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## ABSTRACT

This study investigated the influence of nano-powder type on the surface integrity of Ti-6Al-4V titanium alloy during powder-mixed electrical discharge machining (PMEDM). Three nano-powder conditions, namely hydroxyapatite (HA), yttria-stabilized zirconia (YSZ), and a mixed powder (50 wt.% HA + 50 wt.% YSZ), were dispersed in deionized water at a constant concentration of 1 g/L. The powder concentration was selected based on preliminary experiments, while continuous ultrasonic dispersion and mechanical stirring were employed to ensure homogeneous particle distribution throughout the machining process. A three-factor, three-level full factorial design comprising 27 experimental runs was conducted to evaluate the effects of peak current (18–30 A), pulse-on time (100–200  $\mu$ s), and powder type on two key surface integrity responses: surface roughness (Ra) and recast layer thickness (RLT). The experimental results showed that both peak current and pulse-on time significantly affected the surface characteristics. Increasing the discharge energy generally increased the amount of material melted and re-solidified, resulting in higher surface roughness and thicker recast layers. The powder type also played a crucial role in determining machining performance, demonstrating its influence on discharge stability and surface quality. Grey relational analysis (GRA) was employed for multi-response optimization by simultaneously considering surface roughness and recast layer thickness. Among the 27 experimental runs, Experiment 14 achieved the highest (GRG = 0.855), indicating the best overall machining performance by providing the most favorable combination of low surface roughness and minimum recast layer thickness. Overall, the findings confirm that nano-powder mixed EDM is an effective approach for improving the surface integrity of Ti-6Al-4V alloy. The study further demonstrates that appropriate selection of machining parameters and ceramic nano-powders can significantly enhance the surface characteristics of titanium alloys, highlighting the potential of PMEDM for advanced bio-medical implant applications.

**Keywords:** Ti-6Al-4V, powder-mixed electrical discharge machining, surface integrity, surface roughness, recast layer thickness, hydroxyapatite, yttria-stabilized zirconia, grey relational analysis.

## INTRODUCTION

Metallic biomaterials, particularly stainless steels, cobalt–chromium alloys, commercially pure titanium, and titanium alloys, are extensively used in biomedical applications because of their excellent mechanical properties, corrosion resistance, and biocompatibility. Among these materials, Ti-6Al-4V is the most widely utilized titanium alloy for load-bearing

implants owing to its high specific strength, superior corrosion resistance, and favorable biological performance [1,2].

Despite these advantages, Ti-6Al-4V remains difficult to machine by conventional methods because of its low thermal conductivity, high chemical reactivity, and poor machinability, often resulting in excessive tool wear, dimensional inaccuracies, and inadequate surface integrity [3,4]. Consequently, electrical

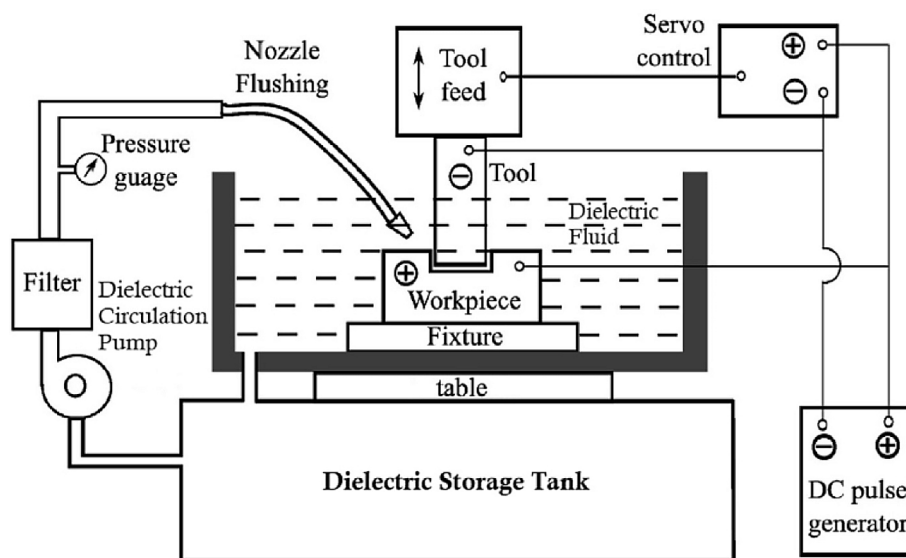
discharge machining (EDM) has become an attractive alternative for machining Ti-6Al-4V because it removes electrically conductive materials irrespective of their hardness without generating mechanical cutting forces [5]. Although numerous studies have investigated EDM and PMEDM of Ti-6Al-4V, most have primarily focused on machining performance indicators such as material removal rate, tool wear, and dimensional accuracy, whereas comparatively limited attention has been devoted to surface integrity, particularly the combined influence of different nano-powder types on both surface roughness and recast layer thickness. In this context, the present study aims to compare hydroxyapatite (HA), yttria-stabilized zirconia (YSZ), and their mixture under identical PMEDM conditions to clarify their role in controlling surface integrity and to identify the optimum machining condition using Grey Relational Analysis.

Electrical Discharge Machining is a non-conventional thermo-electric machining process in which material is removed from the workpiece by a series of controlled electrical discharges between the tool electrode and the workpiece. Since EDM is a non-contact process, it can be used to machine hard, brittle, and difficult-to-cut materials without generating conventional cutting forces. This makes EDM highly suitable for manufacturing dies, molds, punches, aerospace parts, automotive components, and surgical devices [6]. Figure 1 illustrates the basic working principle of EDM [7].

### Powder mixed EDM

Powder mixed EDM (PMEDM) is an advanced variant of conventional Electrical discharge machining (EDM) in which fine electrically conductive or semi-conductive powder particles are suspended in the dielectric fluid to improve machining performance and surface integrity. The suspended particles modify the electric field between the tool electrode and the workpiece, increase the inter-electrode gap, reduce the dielectric breakdown strength, and promote the formation of a more stable discharge channel. Consequently, PMEDM improves spark distribution, enhances debris flushing, and increases machining stability, resulting in superior surface quality compared with conventional EDM [2,9].

Early PMEDM studies primarily employed micron-sized powders, such as graphite, silicon carbide (SiC), aluminum (Al), and aluminum oxide ( $Al_2O_3$ ). These powders enhanced machining performance by increasing the discharge gap and improving debris removal. Moreover, micropowders remain attractive for many industrial PMEDM applications because of their relatively low cost, wide availability, and proven capability to improve machining performance. However, their relatively large particle size limited suspension stability and reduced their ability to effectively control plasma channel characteristics. Recent advances in nanotechnology have shifted research toward nano-powders because of their high specific surface area, improved



**Figure 1.** Schematic of electrical discharge machining showing the working principle of the process [8]

suspension stability, and superior dispersion within the dielectric medium [8,10]. Figure 2 illustrates the fundamental mechanism of the PMEDM process [11].

Nano-powders have demonstrated significant potential for improving EDM performance by promoting a more uniform spark distribution and homogeneous thermal energy transfer. Their presence in the dielectric fluid contributes to plasma channel stabilization, reduces localized heat concentration, enhances debris flushing, and suppresses excessive recast layer formation and surface cracking. These characteristics make nano-powder-assisted PMEDM particularly suitable for machining titanium alloys intended for biomedical applications, where superior surface integrity is essential [6,10].

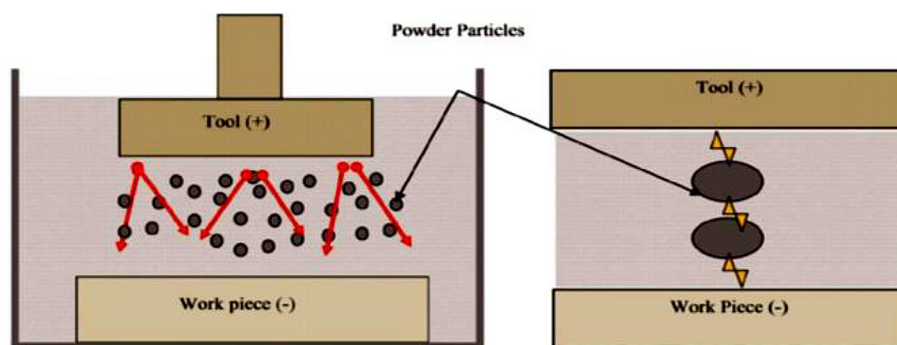
The performance of PMEDM is governed not only by the electrical machining parameters but also by the characteristics of the added powder, including particle size, concentration, morphology, electrical conductivity, thermal conductivity, and chemical composition. Appropriate selection of these parameters directly influences discharge stability, spark energy distribution, material removal mechanisms, and the resulting surface characteristics. Consequently, optimizing powder properties has become an important research direction for improving both machining efficiency and functional surface performance [12,13].

Recent investigations have further demonstrated that PMEDM should be regarded not only as an advanced machining process but also as an effective surface engineering technique capable of modifying the metallurgical characteristics of machined surfaces. Besides improving machining performance, powder-assisted discharges significantly influence surface morphology, phase transformation, chemical

composition, recast layer formation, and overall surface integrity. Therefore, recent PMEDM studies have increasingly focused on functional surface modification in addition to machining efficiency [14].

Among the ceramic powders investigated for biomedical PMEDM applications, hydroxyapatite (HA) and yttria-stabilized zirconia (YSZ) have attracted considerable attention because of their favorable biological and mechanical properties. Hydroxyapatite exhibits a chemical composition similar to that of natural bone mineral, providing excellent bioactivity and promoting osseointegration. In contrast, YSZ possesses high hardness, fracture toughness, thermal stability, and wear resistance. Previous studies have demonstrated that both powders improve the surface integrity of titanium alloys while simultaneously enhancing their functional characteristics for biomedical applications [12,15].

Although PMEDM has evolved into an advanced surface engineering process and significant progress has been achieved in improving machining performance and surface metallurgical characteristics, most previous investigations have focused on engineering steels rather than biomedical titanium alloys. Consequently, comparatively limited attention has been devoted to systematically evaluating the influence of different bioceramic nano-powders, particularly HA, yttria-stabilized zirconia (YSZ), and their mixed-powder combination, on the surface integrity of Ti-6Al-4V alloy under identical PMEDM conditions. Therefore, the present study addresses this research gap by systematically comparing these three powder conditions and identifying the optimum machining parameters using Grey relational analysis (GRA). Table 1 summarizes recent PMEDM studies and highlights the research gap addressed in the present work.



**Figure 2.** Schematic representation of the mechanism of the PMEDM process [11]

**Table 1.** Summary of recent studies on powder-mixed electrical discharge machining (PMEDM) and the research gap addressed in the present study

| No. | Authors                                                | Workpiece material     | Powder type                                    | Optimization method                           | Main findings                                                                                                                                                           | Research gap / Limitation                                                                                                                                           |
|-----|--------------------------------------------------------|------------------------|------------------------------------------------|-----------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1   | Gul and Abdul-Rani (2023) [10]                         | Review study           | Various conductive and ceramic powders         | Literature review                             | Reviewed PMEDM mechanisms, process parameters, applications, and future research directions.                                                                            | Limited discussion on bioceramic nano-powders (HA and YSZ) for biomedical titanium alloys.                                                                          |
| 2   | Chaudhari et al. (2023) [2]                            | Ti-6Al-4V              | Al <sub>2</sub> O <sub>3</sub> + Nano-graphene | ANOVA                                         | Improved spark distribution, reduced surface roughness, and enhanced overall machining performance.                                                                     | Bioceramic nano-powders were not investigated.                                                                                                                      |
| 3   | Farooq et al. (2023) [12]                              | Ti-6Al-4V ELI          | SiC                                            | ANFIS                                         | Improved surface quality and machining efficiency through PMEDM using different tool electrode materials.                                                               | Mixed ceramic nano-powders were not evaluated.                                                                                                                      |
| 4   | Nguyen VT, Dinh VT, Phan DP, Vu DB, Vu NP. (2025) [16] | 90CrSi tool steel      | SiC                                            | Multi-criteria decision-making (MCDM) methods | Optimized PMEDM parameters to improve MRR while reducing Ra and EWR using MCDM.                                                                                         | Limited to 90CrSi with SiC powder; did not investigate Ti-6Al-4V, hybrid nanopowders, RLT, or ANN-based prediction.                                                 |
| 5   | Le et al. (2025) [17]                                  | X40CrMoV5-1 tool steel | Powder-Mixed EDM                               | Experimental investigation                    | Demonstrated that PMEDM improved discharge stability and enhanced the metallurgical characteristics of the machined surface.                                            | Study focused on tool steel rather than biomedical titanium alloys.                                                                                                 |
| 6   | Srivastava et al. (2023) [18]                          | Review study           | Various PMEDM powders                          | Literature review                             | Reviewed recent advances in PMEDM, including powder characteristics, process optimization, and emerging research trends.                                                | Lack of comparative studies on HA, YSZ, and mixed bioceramic powders for Ti-6Al-4V.                                                                                 |
| 7   | Present study                                          | Ti-6Al-4V grade 5      | HA, YSZ, and 50 wt.% HA +50 wt.% YSZ           | Grey relational analysis (GRA)                | Systematically compared three bioceramic nano-powder conditions and identified the optimum PMEDM parameters for minimizing surface roughness and recast layer thickness | Addresses the identified research gap by providing a systematic comparison of bioceramic nano-powders under identical PMEDM conditions for biomedical applications. |

## EXPERIMENTAL WORK

### Workpiece material

Grade 5 Ti-6Al-4V titanium alloy was used as the workpiece material in the present study because of its widespread application in biomedical implants and high-performance engineering components, where high specific strength, excellent corrosion resistance, and superior biocompatibility are essential. The alloy was supplied as plates with nominal dimensions of 200 × 200 × 5 mm and was subsequently sectioned

into specimens measuring 30 × 30 mm using a water-jet cutting process prior to the EDM experiments. Representative photographs of the Ti-6Al-4V specimens are presented in Figure 3, while the chemical composition of the alloy is summarized in Table 2.

### Tool electrode material

A copper electrode with a diameter of 10 mm and a length of 50 mm was employed as the tool electrode throughout all machining experiments. Copper was selected because of its high electrical

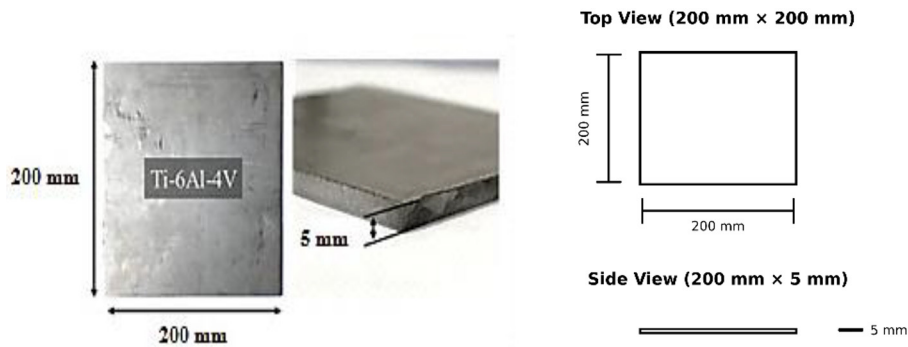


Figure 3. Workpiece material specimens

Table 2. Chemical composition of the Ti-6Al-4V alloy

| Element | Ti   | Al   | V    | Cr     | Cu      | Fe    | Mn     | Mo     | Sn    | Ni     | Si     | C      |
|---------|------|------|------|--------|---------|-------|--------|--------|-------|--------|--------|--------|
| wt. %   | 89.1 | 6.36 | 4.08 | 0.0064 | <0.0020 | 0.147 | 0.0073 | 0.0078 | 0.259 | 0.0024 | 0.0136 | 0.0069 |

conductivity, excellent thermal conductivity, and stable discharge characteristics, which ensure efficient energy transfer, reduced electrode wear, and consistent machining performance during die-sinking EDM. the chemical composition of the electrode material is summarized in Table 3, while Representative photographs of the copper electrode are presented in Figure 4.

### Dielectric medium and nano-powder additives

The machining experiments were carried out using deionized water as the dielectric medium. To investigate the influence of suspended ceramic nanoparticles on the surface integrity of Ti-6Al-4V alloy, the dielectric fluid was modified by adding different nano-powders. Three powder conditions were investigated: HA, YSZ, and a mixed-powder condition consisting of 50 wt.% HA and 50 wt.% YSZ. The total powder concentration was maintained at 1 g/L for all experiments. This concentration was selected based on preliminary experiments in which three concentrations (0.5, 1.0, and 2.0 g/L) were evaluated. Among these, the concentration of 1 g/L provided the most favorable combination of surface roughness and recast layer thickness. Therefore, it was selected as the optimum concentration and maintained

constant throughout the study to isolate the effect of powder type.

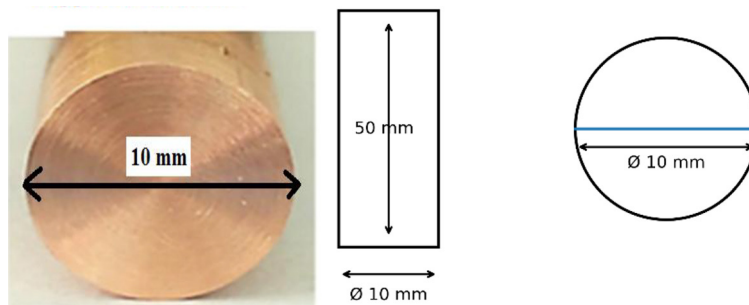
Before each machining experiment, the required amount of nano-powder was dispersed in the deionized water using an ultrasonic probe homogenizer (sonicator), as shown in Figure 5. The ultrasonic treatment was applied to break up nanoparticle agglomerates and achieve a uniform dispersion of the ceramic nanoparticles within the dielectric fluid. During the machining process, continuous magnetic stirring was employed to maintain a homogeneous suspension and minimize particle sedimentation throughout the experiments. Both HA and YSZ powders had a nominal particle size of 60 nm.

### EDM equipment and machining parameters

All machining experiments were performed using a die-sinking electrical discharge machining (EDM) machine (CHMER, Model CM323C). The experimental design was developed to investigate the effects of three primary machining parameters on the surface integrity of Ti-6Al-4V alloy, namely peak current, pulse-on time, and powder type. Peak current was investigated at three levels (18, 24, and 30 A), pulse-on time at three levels (100, 150, and 200  $\mu$ s), and three powder conditions were considered, namely HA, yttria-stabilized

Table 3. Chemical composition of the copper alloy used as the tool electrode

| Element | Cu   | Zn      | Pb     | Sn    | Mn     | Fe     | Si     | Al    | Ag     | Ti     |
|---------|------|---------|--------|-------|--------|--------|--------|-------|--------|--------|
| wt. %   | 99.4 | <0.0005 | 0.0422 | 0.159 | 0.0138 | 0.0356 | 0.0326 | 0.164 | 0.0026 | 0.0005 |



**Figure 4.** Copper electrode used in the PMEDM experiments



**Figure 5.** Ultrasonic probe homogenizer (sonicator) used for dispersing ceramic nano-powders in the dielectric fluid prior to the PMEDM experiments

zirconia (YSZ), and a mixed powder consisting of 50 wt.% HA and 50 wt.% YSZ. To ensure a systematic evaluation of these variables, all other machining parameters were maintained constant throughout the experiments. These included a pulse-off time of 75  $\mu$ s, an open-circuit voltage of 240 V, positive workpiece polarity and negative tool polarity, a powder concentration of 1 g/L, and a machining depth of 1 mm.

The selected machining parameters and their corresponding levels are summarized in Table 4, while the EDM machine and the dielectric circulation system are presented in Figures 6 and 7, respectively.

## Design of experiments

Design of experiments (DOE) is a statistical methodology used to systematically plan, conduct, and analyze experimental investigations in order to evaluate the effects of multiple input variables

on selected response characteristics. By allowing several factors to be examined simultaneously, DOE minimizes the number of required experiments while providing reliable information on the individual and interactive effects of process parameters. In advanced manufacturing processes such as powder-mixed electrical discharge machining (PMEDM), machining performance is influenced by multiple variables operating simultaneously. Therefore, DOE provides an efficient framework for evaluating the relationships between process parameters and machining responses.

In the present study, a three-factor, three-level full factorial design ( $3^3$ ) was employed to investigate the effects of machining parameters on the surface integrity of Ti-6Al-4V alloy during PMEDM. The selected input factors were peak current (18, 24, and 30 A), pulse-on time (100, 150, and 200  $\mu$ s), and powder type (HA, YSZ, and a mixed powder consisting of 50 wt.% HA and 50 wt.% YSZ), resulting in a total of 27 experimental runs. The experimental design matrix was generated using Minitab® software to ensure a systematic, balanced, and statistically reliable arrangement of the experiments.

The response variables considered in this investigation were Ra and RLT, which are widely recognized as key indicators of surface integrity in EDM. Ra was used to evaluate the quality of the machined surface, whereas RLT was used to quantify the thickness of the re-solidified layer formed as a result of melting and rapid solidification during the discharge process.

The adoption of a full factorial design comprising 27 experimental runs provided a balanced compromise between experimental cost and statistical reliability while ensuring adequate data for evaluating the effects of the selected machining parameters and identifying the optimum machining conditions. The complete experimental design matrix is presented in Table 5.

**Table 4.** EDM process parameters and their levels

| Parameter                  | Level 1       | Level 2  | Level 3      |
|----------------------------|---------------|----------|--------------|
| Peak current (A)           | 18            | 24       | 30           |
| Pulse-on time ( $\mu$ s)   | 100           | 150      | 200          |
| Powder type                | HA            | YSZ      | Mixed powder |
| Pulse-off time ( $\mu$ s)  | 75            | –        | –            |
| Voltage (V)                | 240           | –        | –            |
| Polarity                   | Workpiece (+) | Tool (–) | –            |
| Powder concentration (g/L) | 1             | –        | –            |
| Machining depth (mm)       | 1             | –        | –            |

### Surface roughness measurement

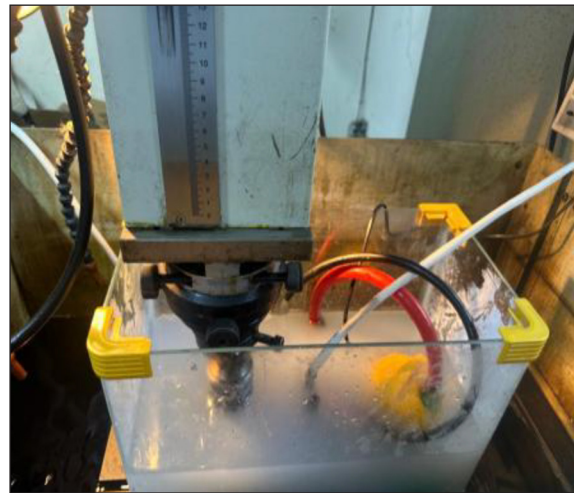
After machining, each specimen was sectioned into two halves using a wire electrical discharge machining (Wire-EDM) machine to facilitate surface roughness measurement and subsequent surface characterization. Prior to measurement, the machined surfaces were thoroughly cleaned to remove any residual dielectric fluid and loose debris. Surface roughness was evaluated in terms of the arithmetic average roughness ( $R_a$ ), which represents the average deviation of the surface profile from the mean line. The measurements were carried out using a portable stylus-type surface roughness tester (Pocket Surf, Mahr Federal, Germany) equipped with a diamond stylus. A cut-off length of 0.8 mm and an evaluation length of 4.0 mm were employed in accordance with ISO 4287 and ISO 4288 standards. To improve measurement reliability and minimize the influence of local surface irregularities, three measurements were taken at different locations on each machined specimen, and the average value was recorded as the final surface roughness ( $R_a$ ) for each experimental condition. This measurement methodology is consistent with those adopted in previous EDM and powder-mixed EDM (PMEDM) studies [19–25]. The prepared specimens used for surface roughness measurement are presented in Figure 8.

### Recast layer thickness evaluation

After the EDM process, the machined specimens were sectioned longitudinally through the center of the machined cavity using a wire electrical discharge machining (Wire-EDM) machine to expose the cross-section required for recast



**Figure 6.** EDM machine used in the PMEDM experiments



**Figure 7.** Dielectric fluid tank for the PMEDM system

layer thickness (RLT) evaluation while minimizing mechanical damage to the machined surface, as shown in Figure 9. The sectioned specimens were mounted in acrylic resin to facilitate metallographic preparation, followed by sequential grinding using silicon carbide (SiC) abrasive papers with grit sizes of 180, 220, 320, 400, 600, 800, 1000, and 2500. The specimens were subsequently polished using an alumina suspension to obtain a mirror-like surface suitable for microscopic examination. Thereafter, the polished specimens were chemically etched using Kroll's reagent, consisting of 2% HF, 6% HNO<sub>3</sub>, and 92% distilled water, to reveal the microstructure and clearly distinguish the recast layer from the unaffected base material. The complete metallographic preparation procedure, including mounting,

**Table 5.** Design of experiments (DOE) matrix for the 27 experimental runs

| Pt Type | Blocks | Current | Pulse - on | Powder type | Ra    | RLT   |
|---------|--------|---------|------------|-------------|-------|-------|
| 1       | 1      | 18      | 200        | YSZ         | 2.251 | 12.14 |
| 1       | 1      | 18      | 200        | HA          | 4.652 | 22.12 |
| 1       | 1      | 18      | 100        | YSZ         | 2.8   | 17.03 |
| 1       | 1      | 18      | 150        | HA          | 4.615 | 9.24  |
| 1       | 1      | 18      | 100        | HA          | 4.317 | 14.82 |
| 1       | 1      | 18      | 100        | Mixed       | 3.248 | 16.19 |
| 1       | 1      | 24      | 150        | Mixed       | 3.772 | 26.71 |
| 1       | 1      | 18      | 200        | Mixed       | 2.55  | 13.28 |
| 1       | 1      | 24      | 200        | HA          | 4.004 | 18.59 |
| 1       | 1      | 30      | 100        | YSZ         | 2.925 | 23.16 |
| 1       | 1      | 30      | 150        | Mixed       | 4.334 | 23.91 |
| 1       | 1      | 24      | 100        | Mixed       | 2.796 | 10.97 |
| 1       | 1      | 30      | 150        | HA          | 3.14  | 19.44 |
| 1       | 1      | 30      | 100        | HA          | 2.923 | 7.58  |
| 1       | 1      | 30      | 100        | Mixed       | 4.412 | 16.27 |
| 1       | 1      | 24      | 200        | YSZ         | 2.85  | 15.34 |
| 1       | 1      | 30      | 200        | Mixed       | 4.996 | 12.45 |
| 1       | 1      | 24      | 200        | Mixed       | 4.932 | 14.09 |
| 1       | 1      | 30      | 200        | YSZ         | 3.089 | 17.47 |
| 1       | 1      | 24      | 100        | HA          | 2.653 | 17.35 |
| 1       | 1      | 30      | 150        | YSZ         | 3.254 | 13.22 |
| 1       | 1      | 18      | 150        | YSZ         | 2.885 | 15.19 |
| 1       | 1      | 30      | 200        | HA          | 3.834 | 17.21 |
| 1       | 1      | 24      | 150        | HA          | 4.79  | 13.13 |
| 1       | 1      | 24      | 150        | YSZ         | 2.352 | 13.97 |
| 1       | 1      | 24      | 100        | YSZ         | 3.582 | 10.78 |
| 1       | 1      | 18      | 150        | Mixed       | 5.547 | 12.99 |



**Figure 8.** Surface profilometer used for surface roughness (Ra) measurement

grinding, polishing, and chemical etching, is illustrated in Figure 10. The etched cross-sections were then examined using an optical microscope for recast layer thickness evaluation, as shown in Figure 11. The recast layer thickness was measured as the perpendicular distance from the outer

machined surface to the interface between the recast layer and the unaffected base material. To improve measurement accuracy and account for local variations in the recast layer, thirty measurements were taken at uniformly distributed locations along the machined surface of each specimen, and the average value was reported as the final recast layer thickness (RLT) for each experimental condition. This measurement procedure followed the methodology commonly adopted in previous PMEDM studies [21].

### Data reliability and experimental consistency

The measured values of Ra and RLT obtained from the 27 experimental runs were used to evaluate the influence of the selected machining parameters on the surface integrity of Ti-6Al-4V



**Figure 9.** Sectioning of EDM specimens using wire electrical discharge machining (Wire-EDM)



**Figure 10.** Metallographic preparation of Ti-6Al-4V specimens for recast layer thickness measurement

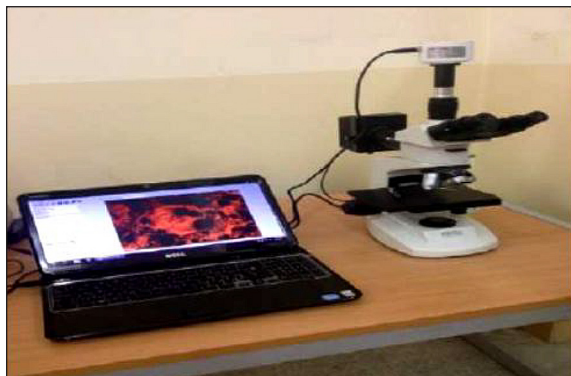
alloy. To ensure the reliability and consistency of the experimental results, all machining trials were performed under identical operating conditions, with only the selected input variables, namely peak current, pulse-on time, and powder type, being systematically varied according to the experimental design. All remaining machining parameters were maintained constant throughout the study. Surface roughness measurements were obtained by averaging three readings taken at different locations on each specimen, while recast layer thickness was determined from the average of thirty measurements acquired from optical microscope images. This experimental procedure minimized measurement variability and improved the repeatability and reliability of the reported results.

## RESULTS

### Surface roughness and recast layer analysis

The main effects plots were used to evaluate the influence of peak current, pulse-on time, and powder type on the Ra and RLT of Ti-6Al-4V alloy. As illustrated in Figures 12 and 13, increasing discharge current and pulse-on time generally increased both Ra and RLT owing to the higher thermal energy generated during the EDM process, which promoted greater material melting and subsequent re-solidification. Among the investigated nano-powders, YSZ generally produced lower values of both Ra and RLT than HA and the mixed powder, indicating improved discharge stability, more uniform

spark distribution, and enhanced debris removal from the machining gap. These observations provide the basis for the subsequent multi-response optimization using GRA.

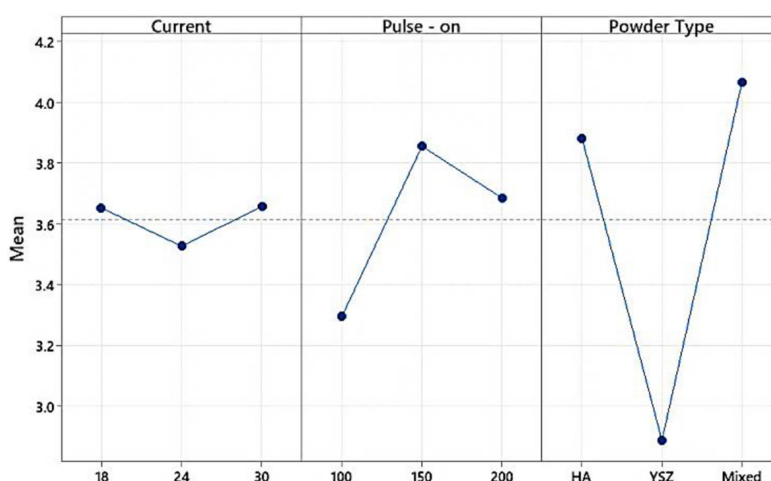


**Figure 11.** Optical microscope used for recast layer thickness (RLT) measurement

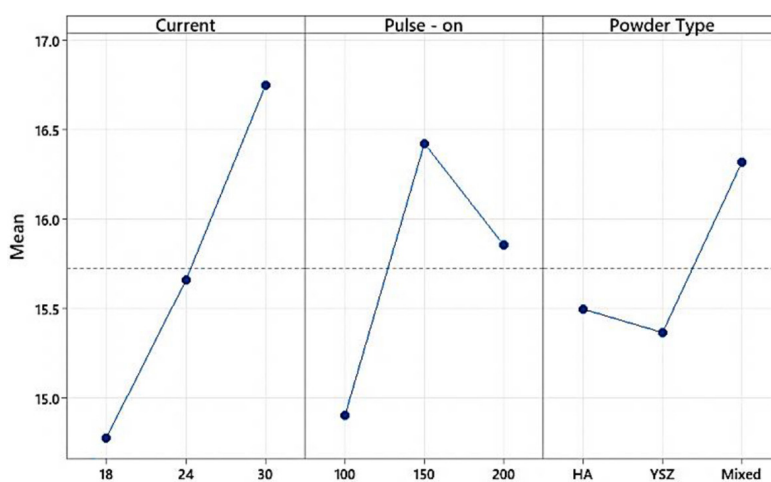
### Multi-response optimization using grey relational analysis

Since surface integrity depends simultaneously on minimizing both surface roughness and recast layer thickness, GRA was employed to determine the overall optimum machining performance. The experimental data were first normalized using the smaller-the-better criterion, followed by the calculation of the GRC using a distinguishing coefficient of 0.5. Finally, the GRG was obtained as the arithmetic mean of the individual GRC values for Ra and RLT. The normalization results, deviation sequences, GRC values, and Grey relational grade (GRG) rankings are presented in Tables 6–7.

The calculated GRG values clearly demonstrated that machining performance varied considerably with the selected process parameters.



**Figure 12.** Main effects plot showing the influence of machining parameters on surface roughness (Ra)



**Figure 13.** Main effects plot showing the influence of machining parameters on recast layer thickness (RLT)

This variation indicates that peak current, pulse-on time, and powder type collectively influence the thermal behavior of the discharge process and, consequently, the resulting surface integrity.

Among the twenty-seven experimental runs, Experiment 14 achieved the highest (GRG = 0.855), indicating the best overall machining performance by simultaneously minimizing surface roughness and recast layer thickness. The corresponding machining conditions were 30 A peak current, 100  $\mu$ s pulse-on time, and HA nano-powder.

The second and third highest GRG values were obtained in Experiments 1 and 25, with GRG values of 0.839 and 0.771, respectively. Overall, the five highest-ranked experiments were Experiments 14, 1, 25, 12, and 8, confirming that different combinations of machining parameters can provide competitive surface integrity. However, Experiment 14 produced the most favorable compromise between the two quality characteristics considered in this study.

The superior performance observed in Experiment 14 may be attributed to the combined influence of the selected machining parameters and powder type, which likely promoted more stable discharge conditions and a more uniform distribution of discharge energy within the machining gap. Consequently, improved surface integrity was achieved, as reflected by lower surface roughness and a thinner recast layer compared with the remaining experimental conditions.

### **Correlation between surface roughness and recast layer thickness**

A positive correlation was observed between Ra and RLT throughout the experimental investigation. In general, machining conditions associated with higher discharge energy produced both higher surface roughness and thicker recast layers. This behavior is attributed to the greater amount of thermal energy generated during the discharge process, which promotes extensive melting of the workpiece material followed by rapid re-solidification. Consequently, larger discharge craters and thicker re-solidified layers are formed, leading to deterioration in surface integrity.

Optical microscopy observations further supported these findings. The cross-sectional micrographs corresponding to the five highest-ranked experiments identified by Grey relational analysis (Experiments 14, 1, 25, 12, and 8) exhibited

noticeable differences in recast layer thickness, consistent with the GRG rankings. In particular, Experiment 14, which achieved the highest GRG = 0.855, exhibited the thinnest recast layer among the top-ranked experiments, confirming its superior overall surface integrity. These observations demonstrate the effectiveness of Grey relational analysis as a multi-response optimization tool for identifying machining conditions that simultaneously minimize surface roughness and recast layer thickness.

## **GREY RELATIONAL ANALYSIS**

Grey system theory has been widely applied in manufacturing engineering, process optimization, decision-making, and multi-criteria evaluation owing to its capability to analyze systems characterized by limited or uncertain information. Among its techniques, GRA is one of the most effective multi-response optimization methods, as it enables the simultaneous evaluation of multiple performance characteristics by converting them into a single GRG.

In the present study, GRA was employed to determine the optimum machining conditions for the PMEDM process by simultaneously considering two critical surface integrity responses: Ra and RLT. Since lower values of both responses are desirable for biomedical implant applications, optimizing only one response may not accurately represent the overall machining performance. Therefore, GRA was adopted to identify the machining parameter combination that provides the best overall surface quality.

The GRA procedure consisted of four sequential steps. First, the experimental data were normalized using the smaller-the-better criterion to eliminate the influence of different units and measurement scales. Consequently, the normalized values ranged from 0 to 1, where values closer to 1 indicate superior machining performance. Subsequently, the GRC was calculated to evaluate the relationship between each experimental result and the ideal reference sequence. A distinguishing coefficient ( $\zeta$ ) of 0.5 was adopted, as it is the most commonly recommended value for providing a balanced discrimination among the performance responses. Finally, the GRG was determined by averaging the GRC values of the selected responses. The experimental runs were then ranked according to

their GRG values, where a higher GRG indicates better overall machining performance [22,23]. The detailed steps of the grey relational analysis are presented in Tables 6–7.

The GRG was calculated as the arithmetic mean of the GRC for Ra and RLT, assigning equal weights (0.5) to both responses.

The GRA results revealed noticeable variations in the GRG values among the twenty-seven experimental runs, reflecting the significant influence of discharge current, pulse-on time, and powder type on the overall surface integrity of the machined specimens. Since the GRG simultaneously considers both Ra and recast layer thickness, the obtained values provide a comprehensive evaluation of the combined machining performance under different PMEDM conditions.

Among all experimental runs, Experiment 14 achieved the highest GRG = 0.855, indicating

the optimum machining condition for simultaneously minimizing surface roughness and recast layer thickness. The superior performance of this experiment can be attributed to the appropriate combination of machining parameters and powder type, which promoted more stable discharge conditions and a more uniform distribution of discharge energy within the machining gap. As a result, improved surface integrity was achieved, characterized by lower surface roughness and a thinner recast layer compared with the other experimental conditions.

Based on the calculated GRG values, the experimental runs were ranked in descending order of overall performance. The five highest-ranked experiments were Experiments 14, 1, 25, 12, and 8, with Experiment 14 exhibiting the best overall machining performance. These results demonstrate the effectiveness of Grey relational

**Table 6.** Normalized response values for grey relational analysis

| Exp | Ra    | RLT   | Norm-Ra  | Norm-RLT |
|-----|-------|-------|----------|----------|
| 1   | 2.251 | 12.14 | 1        | 0.761631 |
| 2   | 4.652 | 22.12 | 0.271541 | 0.239937 |
| 3   | 2.8   | 17.03 | 0.833434 | 0.506012 |
| 4   | 4.615 | 9.24  | 0.282767 | 0.913225 |
| 5   | 4.317 | 14.82 | 0.37318  | 0.621537 |
| 6   | 3.248 | 16.19 | 0.697512 | 0.549922 |
| 7   | 3.772 | 26.71 | 0.538532 | 0        |
| 8   | 2.55  | 13.28 | 0.909284 | 0.702039 |
| 9   | 4.004 | 18.59 | 0.468143 | 0.424464 |
| 10  | 2.925 | 23.16 | 0.79551  | 0.185572 |
| 11  | 4.334 | 23.91 | 0.368022 | 0.146367 |
| 12  | 2.796 | 10.97 | 0.834648 | 0.822791 |
| 13  | 3.14  | 19.44 | 0.730279 | 0.380031 |
| 14  | 2.923 | 7.58  | 0.796117 | 1        |
| 15  | 4.412 | 16.27 | 0.344357 | 0.54574  |
| 16  | 2.85  | 15.34 | 0.818265 | 0.594354 |
| 17  | 4.996 | 12.45 | 0.167172 | 0.745426 |
| 18  | 4.932 | 14.09 | 0.18659  | 0.659697 |
| 19  | 3.089 | 17.47 | 0.745752 | 0.483011 |
| 20  | 2.653 | 17.35 | 0.878034 | 0.489284 |
| 21  | 3.254 | 13.22 | 0.695692 | 0.705175 |
| 22  | 2.885 | 15.19 | 0.807646 | 0.602196 |
| 23  | 3.834 | 17.21 | 0.519721 | 0.496602 |
| 24  | 4.79  | 13.13 | 0.229672 | 0.70988  |
| 25  | 2.352 | 13.97 | 0.969357 | 0.66597  |
| 26  | 3.582 | 10.78 | 0.596177 | 0.832723 |
| 27  | 5.547 | 12.99 | 0        | 0.717198 |

**Table 7.** Grey relational coefficients (GRC), grey relational grade (GRG), and ranking

| Run | GRC-Ra   | GRC-RLT  | GRG      | Rank |
|-----|----------|----------|----------|------|
| 1   | 1.000000 | 0.677168 | 0.838584 | 2    |
| 2   | 0.407014 | 0.396806 | 0.401910 | 27   |
| 3   | 0.750114 | 0.503024 | 0.626569 | 11   |
| 4   | 0.410768 | 0.852116 | 0.631442 | 10   |
| 5   | 0.443726 | 0.569176 | 0.506451 | 19   |
| 6   | 0.623062 | 0.526272 | 0.574667 | 14   |
| 7   | 0.520038 | 0.333333 | 0.426686 | 25   |
| 8   | 0.846430 | 0.626597 | 0.736514 | 5    |
| 9   | 0.484563 | 0.464885 | 0.474724 | 24   |
| 10  | 0.709733 | 0.380394 | 0.545063 | 16   |
| 11  | 0.441705 | 0.369376 | 0.405540 | 26   |
| 12  | 0.751482 | 0.738325 | 0.744903 | 4    |
| 13  | 0.649586 | 0.446441 | 0.548014 | 15   |
| 14  | 0.710345 | 1.000000 | 0.855172 | 1    |
| 15  | 0.432659 | 0.523966 | 0.478313 | 23   |
| 16  | 0.733422 | 0.552092 | 0.642757 | 8    |
| 17  | 0.375142 | 0.662626 | 0.518884 | 17   |
| 18  | 0.380688 | 0.595023 | 0.487856 | 21   |
| 19  | 0.662912 | 0.491647 | 0.577280 | 13   |
| 20  | 0.803902 | 0.494699 | 0.649301 | 7    |
| 21  | 0.621652 | 0.629069 | 0.625361 | 12   |
| 22  | 0.722174 | 0.556914 | 0.639544 | 9    |
| 23  | 0.510059 | 0.498307 | 0.504183 | 20   |
| 24  | 0.393599 | 0.632815 | 0.513207 | 18   |
| 25  | 0.942253 | 0.599499 | 0.770876 | 3    |
| 26  | 0.553206 | 0.749315 | 0.651260 | 6    |
| 27  | 0.333333 | 0.638731 | 0.486032 | 22   |

analysis as a multi-response optimization technique for identifying the optimum PMEDM parameters to enhance the surface integrity of titanium alloy (Table 8–9).

Therefore Experiment 14 is the optimal experiment because it has the highest grey relational grade.

These five experiments consistently exhibited lower values of both surface roughness and recast layer thickness, indicating their superior overall machining performance according to grey relational analysis.

## CORRELATION BETWEEN SURFACE ROUGHNESS AND RECAST LAYER

A clear positive correlation was observed between Ra and RLT throughout the PMEDM

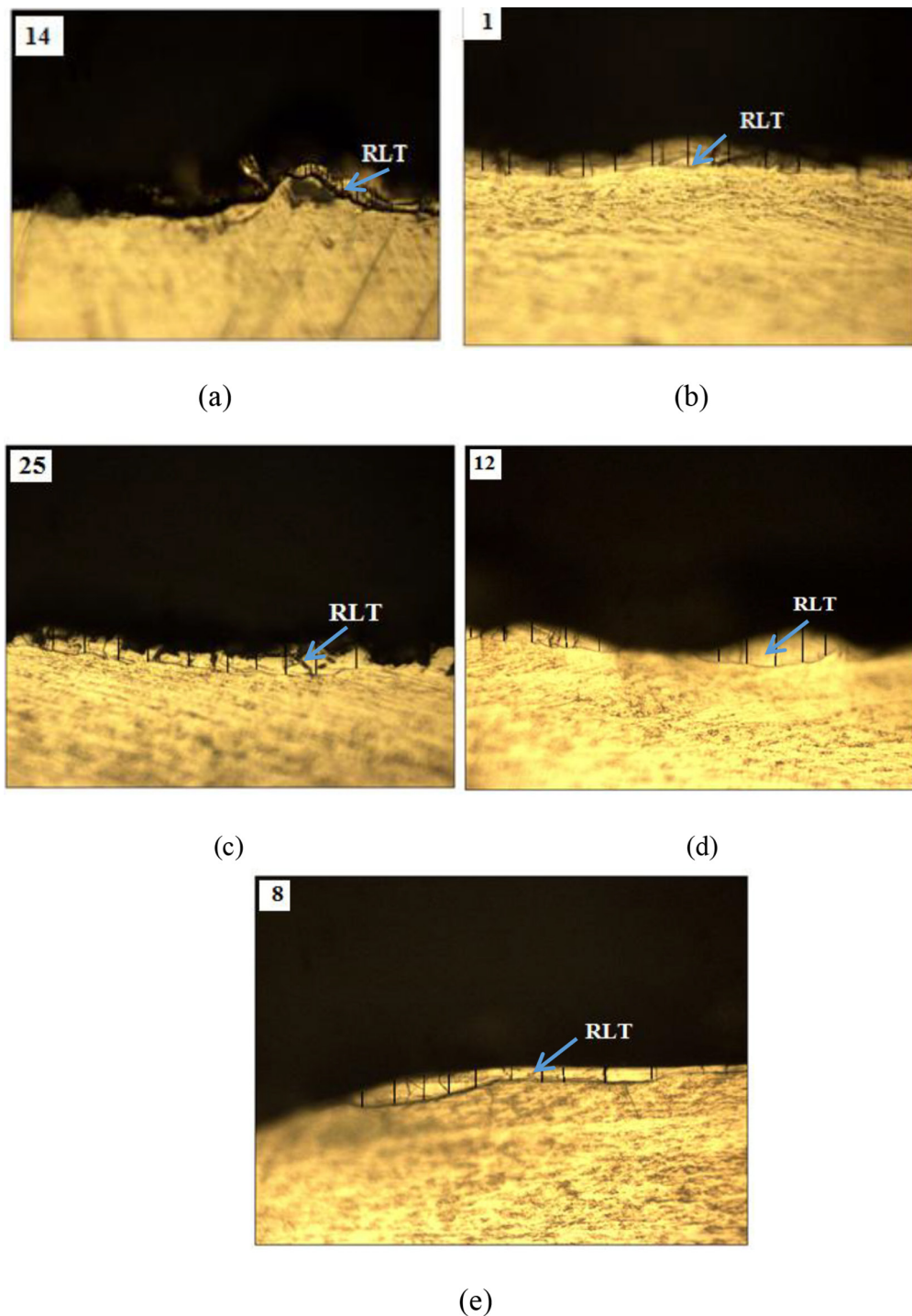
experiments. In general, machining conditions associated with higher discharge energy produced both higher surface roughness and thicker recast layers. This behavior is attributed to the

**Table 8.** Optimal experiment highest GRG value

| Exp | Ra    | RLT  | GRG   |
|-----|-------|------|-------|
| 14  | 2.923 | 7.58 | 0.855 |

**Table 9.** Top 5 experiments according to GRG

| Rank | Exp | GRG   |
|------|-----|-------|
| 1    | 14  | 0.855 |
| 2    | 1   | 0.839 |
| 3    | 25  | 0.771 |
| 4    | 12  | 0.745 |
| 5    | 8   | 0.737 |



**Figure 14.** Optical micrographs showing the recast layer thickness of the five highest-ranked experiments (Experiments 14, 1, 25, 12, and 8) based on Grey relational analysis: (a) Exp. 14, (b) Exp. 1, (c) Exp. 25, (d) Exp. 12, and (e) Exp. 8.

greater amount of thermal energy generated during the discharge process, which promotes extensive melting of the workpiece material followed by rapid re-solidification. Consequently, larger discharge craters and a thicker re-solidified layer are formed, leading to deterioration in surface integrity.

The addition of ceramic nano-powders to the dielectric fluid effectively reduced both surface roughness and recast layer thickness by improving discharge stability, promoting a more uniform distribution of spark energy, and enhancing debris removal from the machining gap. Among the investigated powder conditions, YSZ exhibited

the best overall performance, producing the lowest values of both Ra and RLT.

The recast layer thickness was measured using an optical microscope after metallographic preparation of the specimens. Representative optical micrographs corresponding to the five highest-ranked experiments based on Grey relational analysis (Experiments 14, 1, 25, 12, and 8) are presented in Figure 14(a–e). These micrographs clearly demonstrate the variation in recast layer thickness under different machining conditions and confirm the effectiveness of the optimized PMEDM parameters in improving the surface integrity of Ti-6Al-4V alloy.

## CONCLUSIONS

This study investigated the influence of nano-powder type on the surface integrity of Ti-6Al-4V alloy during PMEDM. HA, YSZ, and their mixed powder (50 wt.% HA + 50 wt.% YSZ) were evaluated under different combinations of peak current and pulse-on time. Based on the experimental investigation and multi-response optimization using GRA, the following conclusions can be drawn:

1. The surface integrity of Ti-6Al-4V was strongly influenced by peak current, pulse-on time, and nano-powder type. Increasing the discharge energy generally increased both surface roughness and recast layer thickness owing to greater material melting and rapid re-solidification.
2. The experimental results demonstrated that the addition of ceramic nano-powders to the dielectric significantly improved machining performance by modifying the discharge behavior and enhancing surface integrity compared with conventional EDM.
3. Grey relational analysis successfully integrated surface roughness and recast layer thickness into a single performance index, providing an effective approach for multi-response optimization of the PMEDM process.
4. Among the twenty-seven experimental runs, Experiment 14 achieved the highest GRG = 0.855, indicating the best overall machining performance by simultaneously minimizing surface roughness and recast layer thickness.

The findings demonstrate that nano-powder mixed EDM is a promising surface modification technique for Ti-6Al-4V alloys and has

considerable potential for improving the surface quality of biomedical components and other high-performance engineering applications.

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