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Performance Optimization of Ti-6Al-4V in Electrical Discharge Machining Using Graphene-Modified Dielectric Medium

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Abstract

Electrical discharge machining (EDM), one of the most commonly used unconventional machining techniques, assumes significance in the production of complex products having high strength and wear-resistance capabilities. Ti-6Al-4V titanium alloys are still widely used in biomedical, aerospace, and defense sectors due to their superior strength, resistance to corrosion, and low-fatigue properties. Conversely, conventional EDM of Ti-6Al-4V titanium alloys faces limitations due to problems such as excessive TWR, spark instability, low MRR, and compromise on surface integrity.

In order to solve the mentioned problems, the current study proposes an investigation of the feasibility of applying an environmentally friendly method of modifying the EDM process by adding graphene NPs into the dielectric medium during the machining process, with an aluminum tool used as the workpiece. Machining performance parameters, MRR and TWR, have been evaluated. The parameters' optimization has been conducted by specifying the Design of Experiments in a structured manner according to the Taguchi method with L16 orthogonal array layout. The significance of the results has been confirmed by the analysis of variance.

The findings have clearly mentioned the importance of the graphene-based dielectric in enhancing the stability of the spark, improving the MRR rate, reducing the TWR rate, and providing a better surface integrity. It was also proven from the surface morphology analysis of the SEM that the overall performance was enhanced with the use of the graphene-based nanofluid and the aluminium electrode in the EDM process for machining the titanium alloy Ti-6Al-4V.

Keywords— MRR, TWR, DOE, EDM, Graphene, EDM, ANOVA

I. INTRODUCTION

Nonconventional machining, also known as unconventional machining process, is a machine tool, which does not use a traditional tool to cut material in a subtractive manner. All types of

conductive material and semiconductors are machinable by the nontraditional, very efficient machining process of micro-EDMing. As EDM is a contactless process involving very low mechanical stresses, it can be utilized to machine soft materials. EDM is an electro-thermal process, which employs controlled sparks generated between a workpiece and a minute electrode. A single high-frequency pulse is used to remove the unit during micromachining, and the relative positions of electrode and workpiece are controlled. An arc discharge causes material to be locally heated and vaporised at the arc point (fig. 1). When it comes to bulk materials, the traditional method of performing µEDM occurs in dielectric fluid such as de-ionized water. However, the study will evaluate the use of a graphene solution in EDM of Ti6Al4V in comparison with the conventional processes. This shows that there is 50% improvement in material removal rate, 2.5 times betterment in surface hardness, and 40% decrease in electrode wear rate. Ti6Al4V EDM processes can be largely enhanced using graphene in an efficient way, as seen from the results [1]. It states that the machining of Ti-6Al-4V through EDM can be made more effective by using graphene-coated aluminium electrodes that make material removal rate (MRR) higher and also lower the rate of tool wear (TWR). The higher electrical conductivity and concentration of spark energy in graphene makes the machining process more efficient [2]. On the other hand, it states that when graphite powder is added to kerosene dielectric, surface cleanliness and MRR become significantly better for machining performance of Ti-6Al-4V alloy. This means that graphene can be considered in a similar manner [3]. In this paper, the application of graphene nanoparticles dispersed within the dielectric used in the process of electric discharge machining (EDM) of titanium alloy Ti-6Al-4V is investigated as a means of increasing machining accuracy. The paper explains that the dispersion of sparks may lead to geometrical inaccuracy despite the contribution of graphene towards increased cutting speed. It reveals that through the use of optimum parameters such as negative tool polarity and aluminium electrodes, it is possible to minimize axial and radial dimensional errors [4]. In this study, the application of nano-graphene based dielectric in electric discharge machining (EDM) of Ti6Al4V is analyzed and the effectiveness of the technique compared to kerosene. Graphene plays an important role in machining by increasing the discharge energy and decreasing surface roughness. From experimental results, the paper reveals optimal parameters to attain 61.4% reduction of roughness, showing the potential of graphene in EDM processes [5]. It focuses on the advantage of the bulk resistance of silicon in making multi-channel discharges for improved surface finish and minimization of heat-affected zones [6]. It is concerned with sustaining material removal rates and improving surface quality by applying semiconductor electrodes in EDM. Though graphene and PSO methods are not mentioned, the findings highlight the advantages of semiconductor electrodes in comparison to traditional copper electrodes [7]. It demonstrates how well graphene-based dielectrics work to improve Ti-6Al-4V machining, with a maximum material removal rate (MRR) of 7.602 mm^3/min, which is 64.5% better than kerosene. Additionally, research shows that graphene exhibits a much reduced tool wear rate (TWR) of 0.17

mg/min, suggesting that it could be used in environmentally friendly EDM applications [8]. This paper explores the utilization of nano-graphene powder-mixed dielectrics in Ti-6Al-4V µED milling of micro-electric discharge, which exhibits significant increases in crater size reduction and material removal rate (MRR). A highest MRR improvement of 575% under low discharge energy is realized when graphene is added, enhancing erosion efficiency, particularly in medium discharge energy regimes [9]. It emphasizes increasing temperature, cutting forces, and tool life while turning Ti-6Al-4V alloy using a variety of lubrication techniques, such as graphene-rich nanofluids [10]. Tool wear, surface roughness, and material removal rate are particularly improved when silicon carbide powder is added to the dielectric solution during EDM of titanium alloys. As a result, the strategic use of graphene in this situation is not taken into account in the study [11]. It investigates the effects of silicon powder distributed in kerosene as a dielectric by optimizing parameters such as peak current, pulse on time, and pulse off time. In comparison to conventional EDM, PMEDM has been seen to enhance surface roughness (Ra) and material removal rate (MRR) by a huge margin [12]. In this research, the optimal parameters of Ti-6Al-4V alloy through signal-to-noise ratio and grey relationship analysis have been determined based on performance measures like electrode wear ratio, MRR, and surface roughness. The proposed strategy would be able to optimize the process of EDM and make it easy to tune multiple performance factors [13]. In order to optimize the process of powder mixed electrical discharge machining (PMEDM), response surface methodology (RSM) and particle swarm optimization (PSO) have been implemented. In this process, improvement of characteristics like material removal rate (MRR), Ra, and tool wear rate (TWR) has been considered. To prove the efficiency of PSO in optimizing EDM parameters, a copper electrode was used to mill the AlSiCp12% metal matrix composite. It has been proven that the test results were consistent with expectations [14]. The paper considers a fuzzy based TOPSIS method for analyzing the impacts of various process parameters on surface roughness, wear rate, and material removal rate. In addition to being multi-objective optimization techniques, the research pays more attention to the significant influences of conductive particle concentration and current on the performance of the EDM process with AISI 1040, EN31, and HCHCr steel materials [15]. This paper is interested in enhancing the MRR and surface roughness of Inconel 718 through the optimization of some parameters using the techniques of fuzzy logic and RSM. Using the below process parameters, MRR and surface roughness values of 16.623 mm^3/min and 3.71 µm respectively were obtained: Pulse on time, gap voltage, powder concentration, pulse off time, and pulse current [16].

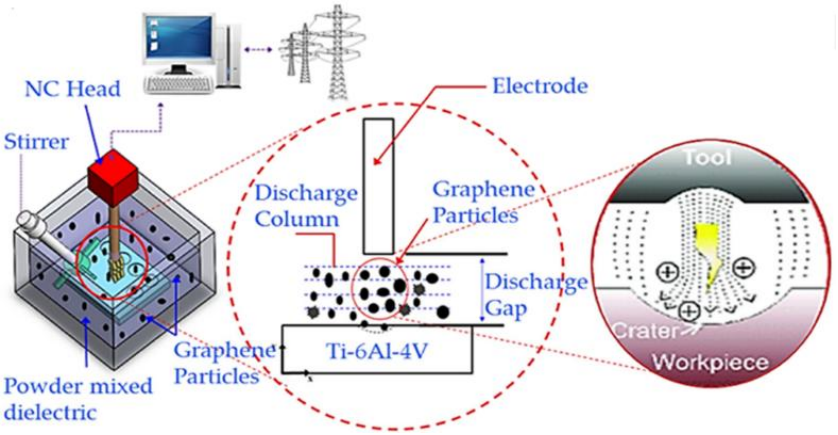


Figure1: Schematic diagram of the EDM system [4].

1.1 Procedure to Prepare Graphene using Chemical Oxidation Method

Material Required to Prepare Graphene

1. Graphite: Graphite granules should be of Mesh Size 300 to 400
2. Phosphoric Acid (H3PO4): Approx. 40 ml of Phosphoric Acid is used as a Catalyst in the process.
3. Sulphuric Acid (H2SO4): Approx. 1 liter
4. 4. Potassium Permagnet (KMnO4): 18 gm KMnO4 is required per Batch. The total required is Approx. 500 gm
5. 5. Hydrogen Peroxide: Approx. 1 liter

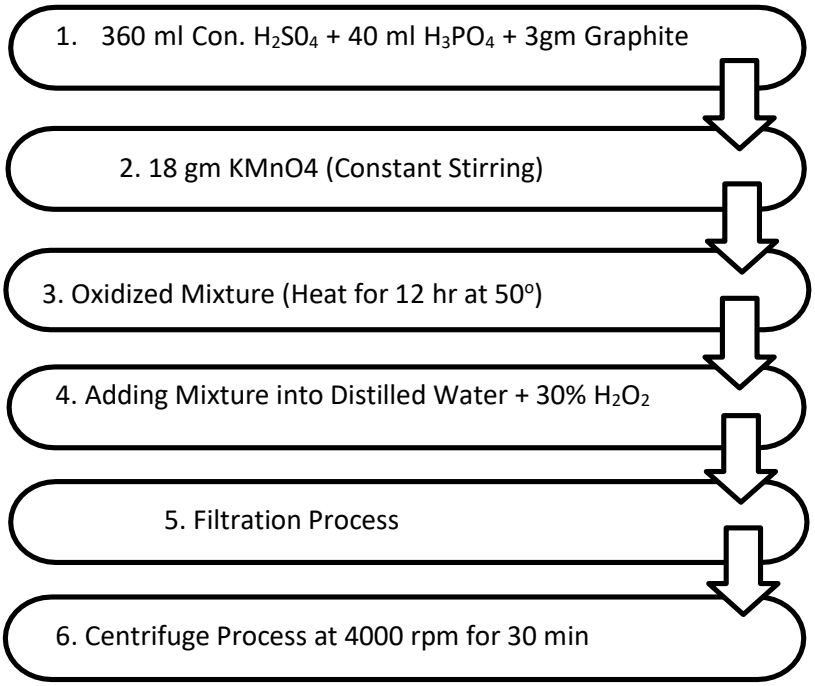


Figure 2: Procedure of Graphene Synthesis

The remarkable physical, mechanical, thermal, and electrical properties of graphene, a two-dimensional allotrope of carbon, have attracted unmatched attention in recent years [17]. Composed of a single sheet of hexagonal-carbon atoms, graphene is the thinnest but one of the strongest materials known. Due to its wonderful combination of ultra-high thermal conductivity (in excess of 5000 W/mK), superior electrical conductivity, superior mechanical strength (around 200 times that of steel), and excellent lubricating property, graphene is an extremely versatile material for advanced engineering and manufacturing operations [18-19]. The high-rate heat dissipation and efficient charge transfer enabled by graphene's special structure can significantly impact the behavior of electrical discharges in processes such as Electrical Discharge Machining (EDM). Graphene nanocrystals suspended in dielectric fluids improve the fluid's electrical breakdown strength and thermal conductivity, enabling more consistent sparking creation and stable discharge conditions in the machining gap [19–20]. Furthermore, graphene's low weight and large surface area facilitate its absorption of heat and energy, avoiding residual thermal stresses on the machined surface as well as localised overheating and microcrack formation [20]. Surface finish, material removal rates, tool wear rates, and process stability are all improved in Graphene can be incorporated in the EDM by incorporating graphene nanocrystals into the dielectric fluid. Acting as bridging agents between the tool and the workpiece, the graphene nanoparticles help in achieving sparking discharges and dielectric breakdown easily [21-22]. Also, due to the graphene particles suspended in the fluid, the debris removal is easy, thereby preventing any unnecessary short-circuited sparks [22]. This is why graphene nanoparticles have come to be known as one of the best additions to nanofluid-based EDM machining because of its excellent properties. The ability of graphene to improve the electrical and thermal properties of the dielectric fluid makes this possible [21].

The influence of input variables on the MRR and TWR of the ECD process of grey cast iron is studied in this research. Gap voltage and pulse-on time have more effect on the MRR and TWR than other parameters, as per the results of the RSM approach. The ideal combination to obtain minimum TWR and maximum MRR using the TOPSIS [23] technique is determined. The aim of this research is to improve the tribological properties of Ti6Al4V alloy, which is often used as a base material for aerospace machining parts, through TiN coating and plasma nitrodeposition heat treatment. Both roughness and hardness values were determined prior to and after coating, while wear behavior of Ti6Al4V alloys under dry sliding conditions and certain loads was investigated. As a result of the analysis, the TiN coated specimens have better wear resistance when sliding at a constant velocity compared to uncoated ones based on the value of friction coefficient.

II. Methodology

2.1 Workpiece Material Selection

The titanium alloy Ti6Al4V is the work material utilised in this project. Below is a discussion of how these materials were chosen. The well-balanced properties of titanium alloys (Ti6Al4V) include strength, ductility, fracture toughness, high-temperature strength, creep characteristics, weldability, machinability, and thermal workability. It is very resistant to erosion, has a high strength-to-weight ratio, and performs well with composite structures. The chemical composition and physical properties of Ti-6Al-4V are shown in Tables 1 and 2, respectively.

TABLE 1 SHOWS THE CHEMICAL COMPOSITION OF TI-6AL-4V.

Contents	Ti	Al	V	Fe	O	C	N	H
Percent %	89.86	5.89	3.93	0.165	0.128	0.017	0.005	0.002

TABLE 2 PHYSICAL PROPERTIES OF TI-6AL-4V

Hardness (HRC)	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)
34	952	1062

2.2 Aluminium Electrode with Ti-6Al-4V Workpiece -

An aluminum electrode and the workpiece material, Ti-6Al-4V, are used in the experiment. Process factors including gap voltage, pulse-on time, and current are changed to observe their effects on MRR and TWR.

2.3 Experimental Details

Details regarding electrode materials and workpiece materials for experimental investigations are provided below table 3. A final experiment was performed using an Aluminium electrode. All experiments were performed at a constant feed rate.

2.4 Workpiece material: Ti-6Al-4V (Titanium Grade 5)

1.Tool: Aluminium Electrode

The following settings were altered in order to conduct the experiments:

The current (A) values are 15, 25, 35, 45

The voltage gaps (V) are 40, 45, 50, and 55.

Pulse On Time (µs): 100, 200, 300, 400

2.5 Experimental L9 Orthogonal Array for Final Experiments

With orthogonal L16 arrays for an aluminium electrode and Ti-6Al-4V as the workpiece material, Tables 3 and 4 display an orthogonal array of the final trials at four current, voltage, and pulse on time levels.

TABLE 3 PROCESS PARAMETERS AND LEVELS FOR FINAL EXPERIMENTS

Parameters	Symbol	Levels	Unit	1	2	3	4
Peak Current	I	15, 25, 35, 45	A	15	25	35	45
Gap Voltage	Vg	40, 45, 50, 55	V	40	45	50	55
Pulse-ON Time	TON	100, 200, 300, 400	µs	100	200	300	400

TABLE 4 EXPERIMENTAL L16 ORTHOGONAL ARRAY FOR FINAL EXPERIMENTS

Exp. No.	Current (A)	Voltage Gap (V)	Pulse on time (µs)
1	15	40	100
2	15	45	200
3	15	50	300
4	15	55	400
5	25	40	200
6	25	45	100
7	25	50	400
8	25	55	300
9	35	40	300
10	35	45	400
11	35	50	100
12	35	55	200

13	45	40	400
14	45	45	300
15	45	50	200
16	45	55	100

III. Result and Discussions

TABLE 5 EXPERIMENTAL RESULTS

Expt. No.	Current (A)	Gap Voltage (V)	Pulse On (µs)	Tool Weight Before (g)	Tool Weight After (g)	Depth (mm)	TWR (g/min)	MRR (mm^3/min)
1	15	40	100	21.58	21.525	1.1	0.0055	11
2	15	45	200	21.525	21.466	1.86	0.0059	18.6
3	15	50	300	21.898	21.838	1.91	0.006	19.1
4	15	55	400	21.838	21.779	2.055	0.0059	20.55
5	25	40	200	21.585	21.431	2.44	0.0154	24.4
6	25	45	100	21.431	21.372	1.985	0.0059	19.85
7	25	50	400	21.248	21.139	3.655	0.0109	36.55
8	25	55	300	21.139	21.065	2.825	0.0074	28.25
9	35	40	300	21.425	21.348	2.94	0.0077	29.4
10	35	45	400	21.348	21.24	3.99	0.0108	39.9
11	35	50	100	21.544	21.498	1.52	0.0046	15.2
12	35	55	200	21.498	21.43	3.1	0.0068	31
13	45	40	400	21.287	21.166	4.24	0.0121	42.4
14	45	45	300	21.166	21.11	2.44	0.0056	24.4
15	45	50	200	21.094	21.032	2.25	0.0062	22.5
16	45	55	100	21.032	20.997	1.31	0.0035	13.1

3.1 ANOVA for TWR

The ANOVA table evaluates the effect of pulse on time, voltage, and current on tool wear rate (TWR). Of the three components, pulse on time makes up the largest portion of TWR (0.38%), followed by voltage (0.27%) and current (0.24%). All three factors are demonstrated to significantly affect TWR with relatively low p-values and notable F-ratios. The model fits the data well, as evidenced by the modest error contribution (0.1%). Overall, the study demonstrates that adjusting pulse on time is the most crucial aspect in lowering TWR, even though voltage and current are equally critical but somewhat less relevant in the Ti-6Al-4V EDM process.

TABLE 6 ANALYSIS OF VARIANCE FOR TWR WITH ALUMINIUM CARBIDE ELECTRODE

Source	**DF**	**SS**	**MS**	**F ratio**	**P value**	**Contribution (%)**
Current	3	0.000036	0.000012	4.85	4.85	0.24
Voltage	3	0.000041	0.000014	5.53	5.53	0.27
Pulse on Time	3	0.000058	0.000019	7.88	7.88	0.38
Error	6	0.000015	0.000002			0.1
Total	15	0.000150				



Figure 3: TWR Main Effects Plot

Figure 3 illustrates how current, voltage, and pulse timing affect the mean TWR. A response endures in contrast to current, where the TWR increases proportionately at 15A to 25A, reaches its maximum value, and then decreases as current increases. This indicates that tool wear has an effect on the mean at moderate current levels but stabilises or slightly declines at high current levels. The TWR for voltage peaks at 40V and decreases at higher voltages; higher voltages may result in controlled discharges because they alter the tool's wear. This TWR starts at 100 µs, increases at 200 µs, and then slightly lowers at 300 µs before increasing at 400 µs, when the pulse is truly on time. The tool may experience greater thermal stress as a result of longer pulse duration, leading to an increase in wear in this nonlinear pattern. Current and pulse on time have non-linear effects, but voltage and TWR often have a definite inverse connection. This suggests that the ideal values of these parameters are crucial for reducing tool wear in Ti-6Al-4V EDM.

Regression Equation

$$TWR = 0.007512 - 0.001688\ \text{C_15} + 0.002388\ \text{C_25} - 0.000038\ \text{C_35} - 0.000662\ \text{C_45} + 0.002663\ \text{V_40} - 0.000463\ \text{V_45} - 0.000587\ \text{V_50} - 0.001613\ \text{V_55} - 0.002637\ \text{Pon_100} + 0.001063\ \text{Pon_200} - 0.000837\ \text{Pon_300} + 0.002412\ \text{Pon_400}$$

3.2 Analysis of variance for MRR

From the table above, it can be concluded that the most influential predictor is pulse on time, with its influence being 63%, and its p-value is 0.005 and F-ratio of 13.13, which means it is statistically significant. Current is another influential predictor, with an influence of 24%, and its p-value is 0.042, making it statistically significant. Voltage, on the other hand, has very little influence, with its influence being 2.9% and has no statistical significance (p=0.632). The error level is very low at 9.6%.

Table 7: ANOVA for TWR with Aluminium Carbide Electrode

Source	**DF**	**SS**	**MS**	**F ratio**	**P value**	**Contribution (%)**
Current	3	317.47	105.82	5.16	0.042	0.24
Voltage	3	37.61	12.54	0.61	0.632	0.029
Pulse on Time	3	807.76	269.25	13.13	0.005	0.63
Error	6	123.07	20.51			0.096
Total	15	1285.91				



Figure 4: MRR Main Effects Plot

Current, voltage, and pulse on time are three factors that greatly influence the machining operation in EDM based on the Material Removal Rate (MRR) main effects plot (Fig. 4). From Fig. 4, it can be seen that the optimum value of current in which maximum MRR is achieved lies within the range of 35 A, since the MRR rises sharply from 15 A to 35 A, peaks at 35 A, and starts decreasing again as it goes to 45 A. For voltage, its optimum value is within 40 V since MRR decreases steadily from 30 V to 70 V, reaching its peak at 40 V, thus, implying that the lower the voltage used, the better. The biggest factor influencing MRR among these three is the Pulse On Time, which starts off at 100 µs and reaches its peak at 400 µs, where its MRR is the highest.

Regression Equation

$$MRR = 24.76 - 7.45\,\text{C_15} + 2.50\,\text{C_25} + 4.11\,\text{C_35} + 0.84\,\text{C_45}\ 200 + 2.04\,\text{V_40} + 0.92\,\text{V_45} - 1.42\,\text{V_50} - 1.54\,\text{V_55} - 9.97\,\text{Pon_100} - 0.64\,\text{Pon_200} + 0.53\,\text{Pon_300} + 10.09\,\text{Pon_400}$$

IV. SEM Images of Machined Surface of Ti-6Al-4V

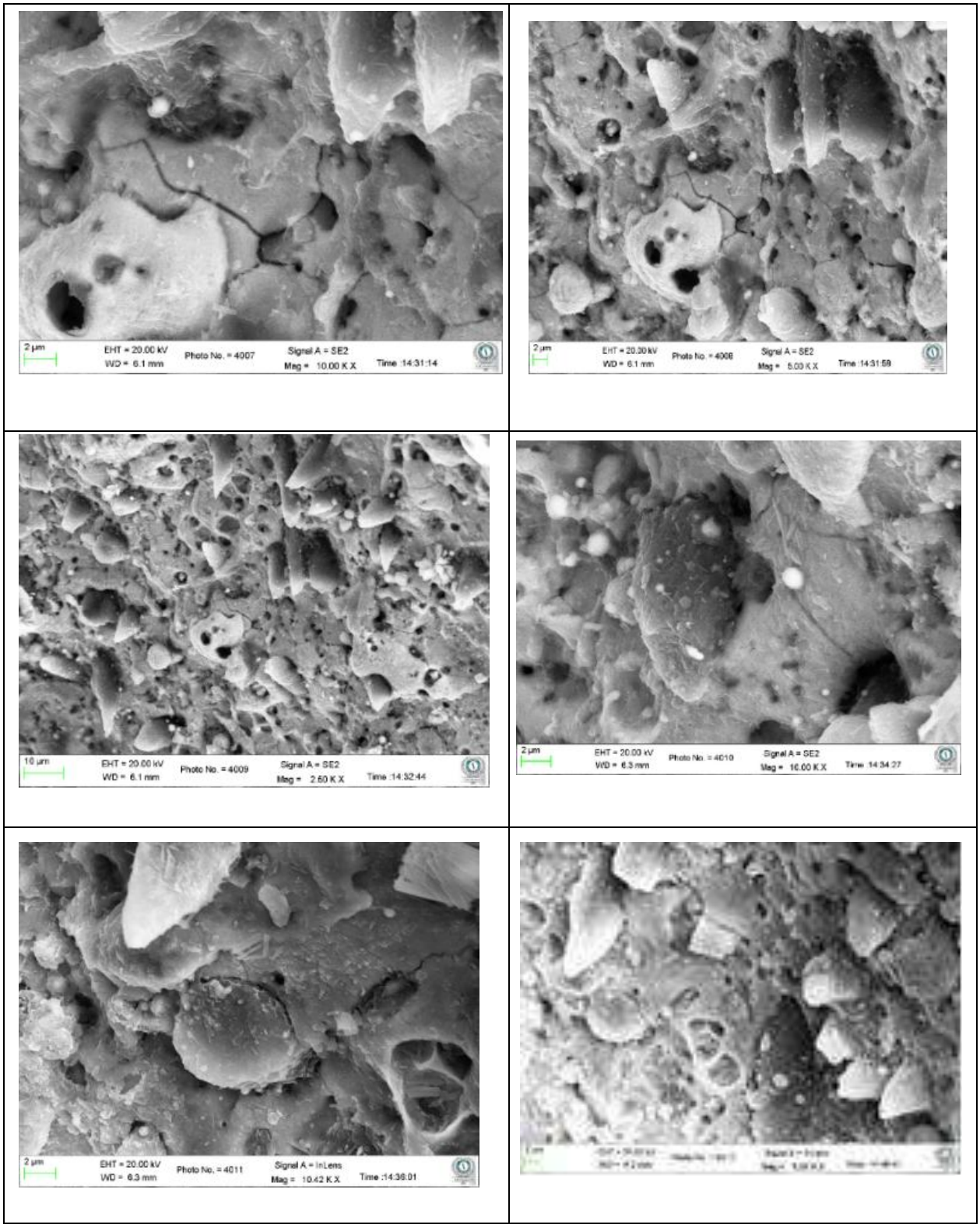


Figure 5: SEM pictures of a surface machined with an Al electrode for Ti-6Al-4V

The surface that was machined using a Ti-6Al-4V work piece in an EDM with an aluminum tool electrode and graphene powder mixed with dielectric fluid is shown in Figure 5's SEM images. The dielectric's graphene helps to better stabilise and disperse the sparks' energy, resulting in a more even removal of workpiece material. Compared to the traditional EDM, the surface in these images has less microcracks and craters. The micrographs specifically show cleaner textures and smaller recast layers, as well as improved debris flushing and less heat damage due to the graphene powder. The excellent thermal conductivity of graphene may have caused a reduced heat-affected zone and quick cooling of the molten residue during graphene formation. A steady and effective spark erosion process is further supported by the decrease in spherical globules and shallow craters. Additionally, the presence of graphene influences the surface energy properties by encouraging steady spark generation and wetting. The aluminium electrode generally improves the surface finish quality, reduces the impact of tool wear, and supports the stabilised microstructure of the machined Ti-6Al-4V alloy with graphene-mixed dielectric, according to the SEM investigation.

V. Conclusion

From the results of the current investigation, it is confirmed that the EDM process performance is enhanced in a sustainable manner with the inclusion of graphene nanoparticles by applying the process of modification with the help of an aluminum tool electrode and reinforced dielectric fluid. The results indicate that the addition of graphene nanoparticles into the EDM process has enhanced the stability of the spark, refined the surface, reduced tool wear rate, and increased the material removal rate.

In addition, the evaluation of the machining efficiency through the Taguchi L16 orthogonal array and ANOVA analysis proves the dominant and nonlinear effect of the significant parameters, namely discharge current, gap voltage, and pulse-on time. Indeed, the optimized combination of the parameters for the highest MRR was found at higher current levels (35A), lower voltage (40V), and longer pulse-on duration (400μs).

The use of SEM for surface morphology analysis again provides further validation for the role of graphene nanoparticles, as a thinner recast layer, crater uniformity, and reduced microcrack formation can be achieved, attributable to better thermal conductivity properties, as well as uniform spark energy distribution.

Furthermore, the specific machining performance, which could be attained by using the aluminium electrode in practice, is greatly encouraged by its low melting point and higher thermal conductivity in comparison with other electrodes. As a result, a significant enhancement in machining performance can be achieved by using the combined effect of the aluminium electrode in conjunction with the graphene-based mixed dielectric fluid.

Overall, graphene-based modification of the dielectric may offer a better route toward sustainable and high-quality EDM of Ti-6Al-4V. This is quite an essential alloy for the aerospace, biomedical, and defense industries. However, future research should attempt to apply environmentally benign dielectric media, vegetable oil, in order to really make this process more compatible with global SDGs.

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Author contributions
Conceptualization, S.S. and P.B.G.; methodology, P.B.G.; investigation, P.B.G.; resources, V.S.G.; data curation, S.S. and V.S.G.; writing—original draft preparation, P.B.G.; writing—review and editing, S.S., V.S.G.; visualization, S.S., P.B.G., and V.S.G.; supervision, S.S. and P.B.G.

Competing interests not applicable.

Ethics approval not applicable.

Consent to participate not applicable.

Consent to publish not applicable.

Data availability
The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding authors.

Conflicts of Interest: The authors declare no conflicts of interest.

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