EDM PROCESS OPTIMIZATION USING GRAPHENE-BASED NANO-FLUIDS: SURFACE, MICROSTRUCTURAL, AND PERFORMANCE EVALUATION OF ALUMINUM 7075

Resham Naz[1], Shahid Mehmood*[2], Ali Haider[3], Sultan Mehmood[4], Umair hameed[5]

[1,2,5] *University of Engineering and Technology, Taxila*
[4] *Kohat Cement Factory KPK*
[3] *Heavy Industry Taxila HIT*
[1]resham.naz@students.uettaxila.edu.pk, [*2]shahid.mehmood@uettaxila.edu.pk, [3]alihaider.17804@gmail.com, [4]sultan.mehmood@kohatcement.com, [5]umairhameed661@gmail.com

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Corresponding Author: *
Resham Naz

Abstract
The given research is devoted to measuring the surface conditions and machining quality of the aerospace-grade alloys machined with the help of Electrical Discharge Machining (EDM) in a dielectric medium supplemented with graphene. EDM is an unconventional, popular machining technique, which is particularly appropriate in machining intricate-to-machine titanium or nickel-based super-alloys, which are common in the aerospace sector. The introduction of graphene nanoparticles into the dielectric fluid will enhance efficiency in machining as the thermal and electrical conductivity of the medium will be changed [1].
The objective of the work is the influence on the main output variables of graphene concentration on such parameters as the surface roughness, micro-hardness, recast layer development, and the alteration of the microstructure in the machined zone. In addition, the influence on the process performance indicators, including the tool wear rate (TWR) and material removal rate (MRR), is addressed adequately. The test results show that in the event that dielectric is mixed with graphene, it considerably improves the surface quality and MRR, and reduces micro-cracks and erosion of tools when compared to plain conversions which are registered using conventional EDM methods [1]. The obtained results are then used to conclude that graphene-aided EDM may be a practical way of improving the machinability and surface finish of aerospace alloys and consequently, development of more efficient, accurate and reliable components employed to the aerospace industry will be achieved [1].

Background

The analysis of the effect of electrode dielectric pairs on the surface attributes of EDM has been carried out in many studies. The use of a copper electrode with a kerosene dielectric usually produces stable sparking because copper is an excellent electrical and thermal conductor, hence leading to moderate surface roughness and less wear tool. In experiments With the tool steels and nickel alloys, it is reported that the pulse parameters where the mean current and pulse-on time are moderate, give smoother surfaces (Ra ~10 µm). Nonetheless, kerosene tends to form a carbon-rich recast (white) layer through decomposition of the hydrocarbons, and this layer is susceptible to micro- and nano-cracks that, in turn, decrease fatigue strength and corrosion resistance. Although copper-kerosene-based EDM can give a fair MRR and surface integrity, issues of white-layer build-up are also present, which makes it ideal to even attempt to use pure flushing, pulse shaping, or have nano-powder additives to reduce the build-up of carbon [2].

Replacing the ionized water dielectric with copper electrodes is also found to give much smoother EDMed surfaces due to superior flushing and cooling. Surface roughness experienced has been reported to be at ~2.2 m in optimized cases with thinner and cleaner recast layers as opposed to oil-based fluids. In the case of aluminum-7075-T6, EDM with water will be used to create finer textures and a lesser contamination of the carbon component, with an accuracy of 0.8 to 1 micron when strictly monitoring electric parameters. However, to avoid fast quenching-induced cracks or rough finishes, as in the case of the machining process using kerosene, good flushing and pulse stability are crucial [3].

Kerosene Graphite Electrodes are often linked to an increase in MRR since Graphite tends to start melting at high temperatures and sublimates; this is at the cost of surface finish. In Al7075-T6, the values of Ra normally fall within 4-8 μm, because the transfer of carbon can be observed both to the electrode and the dielectric, thereby increasing white-layer thickness, and creating surface carbon networks of cracks. Although desirable in speed of material removal, the cruder, fissured surfaces need more precise tuning of parameters, should they be required in a high-precision environment [3].

INTRODUCTION

Electronic discharge Machining (EDM) is another common non-traditional machining process and it is also massively utilized in modern advanced manufacturing of highly complex and strong parts. In contrast to conventional machining processes that use mechanical forces of cutting, material is machined away by a sequence of carefully controlled electrical discharges (sparks), issued between the tool electrode and the workpiece, both of which should be electrically conductive. These are discharged in a dielectric fluid, usually hydrocarbon oil or deionized water, whose purpose is not only to insulate the electrodes until the breakdown voltage is achieved but also to aid in the cooling of the system and flushing the debris within the spark gap [1]. EMV can cut a great amount of hard materials, brittle or intricate shapes, which are tough or cannot be machined at all by their traditional counterparts, like milling or turning. This is because no direct contact between the workpiece and tool is made.

Aluminum 7075-T6 is one of the most commonly used in aerospace applications since it is a superior, high-performance aluminum alloy with great mechanical properties. It has good tensile and fatigue strengths, also, good corrosion resistance, and a good strength-to-weight ratio, which makes it a perfect material to use in aerospace and defense [3]. Nevertheless, it has rather low thermal conductivity, High strength, and it's very challenging to work on with conventional cutting tools. Such obstacles are an extreme wear of the tool, an unfavorable surface finish, and a lack of dimensional accuracy owing to the production of heat and adherence of chips [4]. Consequently, EDM is found as one of the highly qualified options in machining Aluminum 7075-T6, offering an excellent control of the material cutting pathway with minimal loading of the mechanical stresses on the mechanical piece. Over the past few years, the attention of the researchers has been on enhancing the performance of EDM through alteration in the properties of the dielectric fluid. An advantageous method is the suspension of nanoparticles on the dielectric medium, which is called nanoparticle-assisted EDM.

This study will make an effort of carrying out systematic investigation of how the addition of cost effective graphene nanoparticles in the dielectric fluid that serves the Aluminum 7075-T6 is affected in relation to its machining with the EDM. Specifically, the paper addresses the impact of graphene addition on such key performance indicators as the surface integrity, microstructural alterations, material removal rate (MRR), and the machining efficiency in a broad sense. The knowledge of the effects will lead to better adjustment of EDM parameters in increased productivity and the quality of the surface, especially when aerospace and high-precision industries are involved [3].

EDM Types

EDM has two basic types, i.e., Die Sinker EDM or Ram type, and Wire Cut EDM [8].

Die-Sinking EDM: Die-sinking EDM operates in a vertical setup where the electrode and workpiece are submerged in a dielectric fluid. Also known as Sinker EDM is a cavity-type EDM or volume EDM [8] in which both the electrode and workpiece are submerged in a dielectric fluid like kerosene, de-ionized water, or oil etc, which are connected to a power supply. An electrical potential is created between the tool and work workpiece with the help of a power supply. When the electrode reaches near to workpiece, breakdown of the dielectric occurs, thus a plasma channel is formed, also resulting in spark jumps. At random locations between tool and work workpiece gap, these sparks occur in large numbers, usually several hundred thousand sparks per second due to which workpiece material erodes and the gap increases. To continue the machining process, the electrode is automatically lowered by the machine.

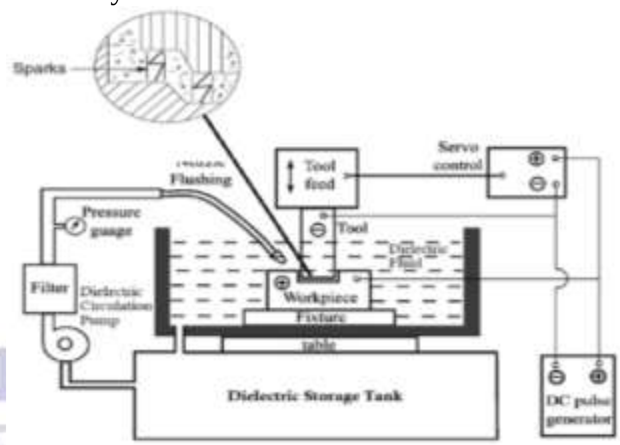


Figure 1Schematic diagram of Die Sinking EDM

Wire-Cut EDM: Wire-cut EDM, also known as the wire EDM, uses a thin and continuously reciprocating wire as the electrode. Mostly, the workpiece is cut through by the wire, which is normally made of brass, producing sparks as it moves. It is suited when accurate 2D profiles and intricate shapes are to be made out of hard materials. As well, it is commonly used in the manufacture of tools and dies (punches and dies, as well as precision parts). The whole process of machining occurs within a bath of dielectric fluid, which is usually deionized water [2].

Both types of EDM are CNC machines in which there is no direct contact between workpiece and electrode (in case of die-sinker) or wire (in case of wire-cut), due to which thermal stresses are generated with no production of vibrations, mechanical stresses, or pressed [9, 10]. However, because of rapid heating and cooling, thermal stresses are generated [11].

Materials and Methods

The determination of this study was the selection of proper materials to be used to bring out the experimental results precisely of the effects of EDM parameters on surface integrity. The materials offered are Workpiece Material - Aluminum 7075 Alloy. The choice of workpiece material was aluminum 7075 alloy, as it is a strong alloy with a high strength-to-weight ratio and good fatigue properties, widely used throughout the aerospace and automotive industries. Zinc is the primary alloying element in the alloy and is characterized by difficulties in machining using conventional methods, which makes it suitable for EDM analysis. Aluminum 7075: chemical makeup is as follows **[3].**

Table 1: Chemical composition of Aluminum Alloy 7075

Element	Percentage (%)
Zinc	6.64
Magnesium	2.47
Copper	1.67
Chromium	0.196
Aluminum	88.5

Table 2: Comparison of physical properties with the ASTM standard

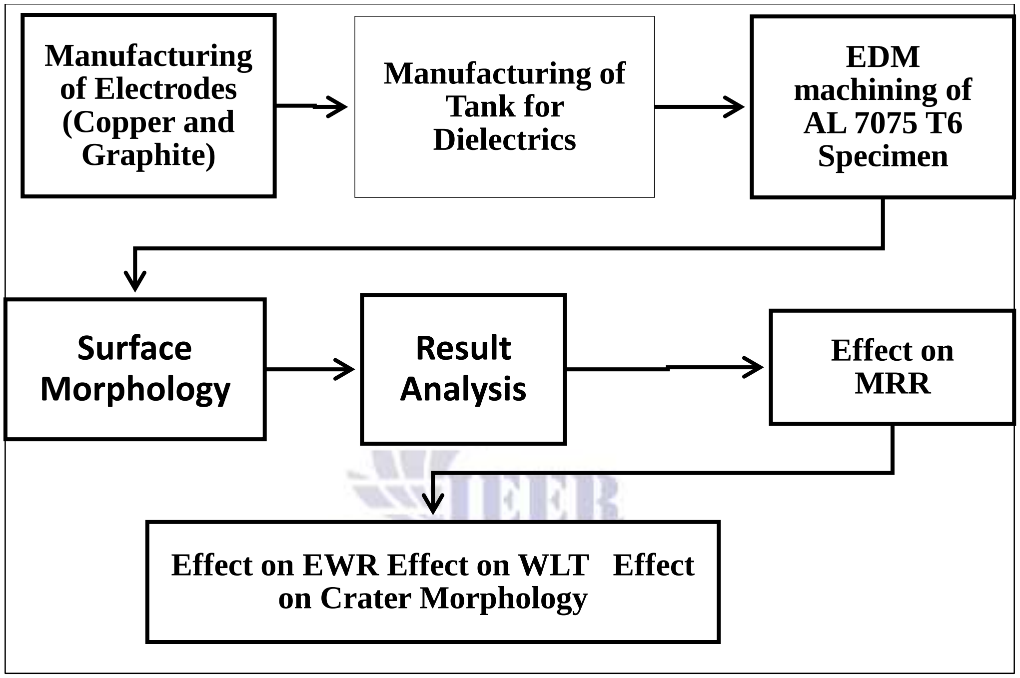
Property	Measured/ Literature Value	ASTM Standard Range	Remarks
Density	2.81 g/cm^3	2.80 g/cm^3	Matches
Ultimate tensile strength	570 MPa	540-572 MPa	Matches
Yield strength	503 MPa	480-505 MPa	Matches
Elongation	11-12 %	11%	Matches
Vickers Harndness	175-180 HV	175 HV	Matches
Impact Energy (Charpy)	85 J	80-120 J (ductile zone)	Ductile
Thermal Conductivity	130 W/m.K	130-150W/m.K	Acceptable

Such a baseline comparison guarantees compliance with the standards of ASTM B209 and the validity of experimental findings.

Methodology

In the present study, it was done to determine the influence of the addition of graphene to dielectric fluid on the EDM performance of Aluminum 7075-T6 alloy when using copper and graphite as electrodes was determined. The methodology consisted of systematic preparation of electrodes and workpieces, choice of dielectric fluids (kerosene, deionized water, and graphene-enriched kerosene), and controlled EDM experiments with the parameters optimized. Material Removal Rate (MRR), Tool Wear Ratio (TWR), surface morphology, micro-hardness, and the white layer thickness were measured using precision weighing, Vickers hardness test, and Scanning Electron Microscopy (SEM). The overall process was made to be reproducible, reliable, and meaningfully comparable to standard material properties. Given below is the flow chart of the Methodology [3].

Flow chart of Methodology



Results and Discussion

Here are the results of EDM experimentation of the Aluminum 7075-T6 alloy in the presence of copper and graphite electrode and varying dielectric: pure kerosene, deionized water, and graphene-mixed kerosene. Material Removal Rate (MRR), Tool Wear Ratio (TWR), surface morphology, micro-hardness, and white layer thickness were used to evaluate performance, with statistical analysis (ANOVA) and qualitative SEM observations [3].

The performance of the machining process (in terms of machining rate and tool life) in relation to the machining tool's geometry and its characteristics, such as tip life, material, and machinability. The nature of the electrode and the dielectric fluid played a great role in the machining performance. When the electrodes were made of copper, the discharges of sparks were stable, and moderate values of MRR were obtained among all the dielectrics. Graphite electrodes had better MRR because of their greater thermal resistance and reduced density. The dielectric fluids where graphene was mixed with kerosene always had the highest MRR, and copper and graphite had a 15-20 and 20-25 such improvement over pure kerosene, respectively [1].

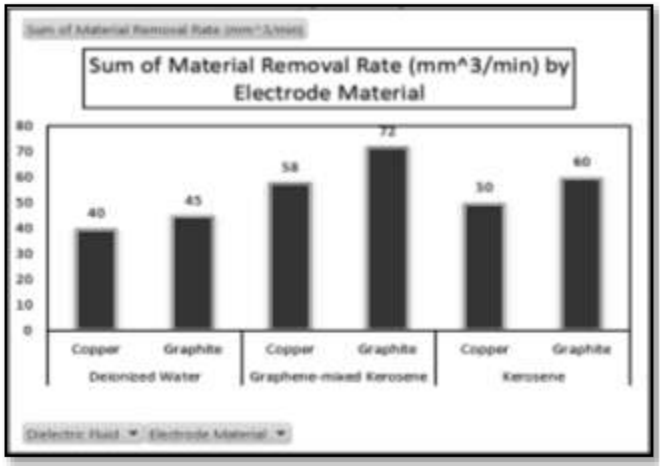


Fig: 2 Material Removal Rate

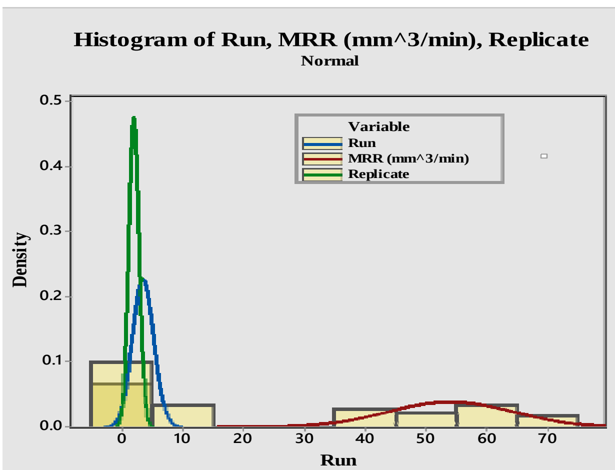


Figure 03 Histogram of Run, MRR, Replicate (normal Probability Plot)

The histogram affirms the conclusion in writing that graphene-enhanced kerosene recorded the highest and consistent MRR. The fact that this setup consistently produced better machining performance is confirmed by the green peak which indicates that the MRR range (which is narrow and high) is a sign of good performance. Conversely, in deionized water a low and dispersed MRR value was derived, because it has a high cooling rate, and lacks carbon based byproducts as elucidated. The factor by which viscosity and spark energy transfer influence MRR is

In this graph, the Material Removal Rate (MRR) was compared in terms of a series of runs with various electrodes and Dielectric fluid combinations. The y coordinate of the point is the MRR in mm³/min, and the x coordinate of the point is the number of runs (1 to 16). Every line is a different setup (Uncoated or graphene-coated Al electrode with various dielectrics). We observed MRR values tend to be larger with graphene-coated electrodes, particularly towards the final runs, and this shows better machinability.

also mentioned in the analysis which is visually discussed by the achieved performances of various setups in the histogram. Among the dielectric fluids, graphene-mixed kerosene resulted in the highest MRR regardless of electrode type. The suspended graphene nanoparticles in the kerosene enhanced the dielectric's conductivity, leading to improved spark bridging and reduced dielectric breakdown voltage. This modification facilitated faster discharges and better flushing of molten material, particularly when paired with graphite electrodes. For instance, MRR improved by approximately 15–20% with graphene-mixed kerosene compared to conventional kerosene under the same current and pulse-on time settings.

In contrast, deionized water, although environmentally cleaner, led to the lowest MRR values due to its high cooling rate and lack of carbonaceous byproducts, which limits crater depth and spark penetration. Additionally, the lower viscosity of water may cause premature spark quenching, reducing the thermal energy transferred to the workpiece.

In conclusion, the highest MRR was obtained using the graphite electrode in graphene-enhanced kerosene dielectric, proving to be the most effective setup for achieving faster machining without significantly compromising electrode wear or surface quality. [4][5]

Table 3: ANOVA of the Experiments [12].

Source	Sum of squares	Mean squares	F value	R^2 value	R^2 (pred)
EDM with an Al electrode					
Peak current	4.9832	2.4916	471.55	98.18%	96.43%
Gap voltage	0.0951	0.0476	11.30	—	—
Pulse on time	0.4452	0.2226	33.12	—	—
Total	5.5235	—	—	—	—
EDM with a graphene-coated Al electrode	**Sum of squares**	**Mean squares**	**F value**	**R^2 value**	**R^2 (pred)**
Current	6.9811	3.4906	539.34	97.84%	95.77%
Gap voltage	0.1543	0.0772	14.41	—	—
Pulse on time.	0.2886	0.1443	25.02	—	—
Total	7.4240	—	—	—	—

TWR analysis revealed that graphite electrodes had a lower wear rate than copper, and graphene-modified dielectric had a lower wear rate still, since it stabilized the energy of sparks and reduced arcing. The results of ANOVA (Table 3) proved that peak current exerted the greatest impact on both MRR and TWR, whereas the secondary influence was detected on the gap voltage and pulse-on time. The dominant factor affecting the Tool Wear Rate (TWR) in uncoated aluminum electrodes was peak current SEM analysis: The morphology of surfaces is examined using surface profilers. Surface (contributing to ~98 percent of the variation), and in graphene-coated electrodes was peak current (contributing to ~93 percent of the variation). Pulse-on time and gap voltage had small impacts, but with large contribution factors. A good model fit was confirmed by a high R 2 (96-98) value. In general, graphene-coated electrodes showed more resistance to thermal erosion, minimizing TWR, and providing an improved tool protection during long-term machining [1].

Morphology (SEM Analysis) The surface morphology is measured with surface profilers [17].

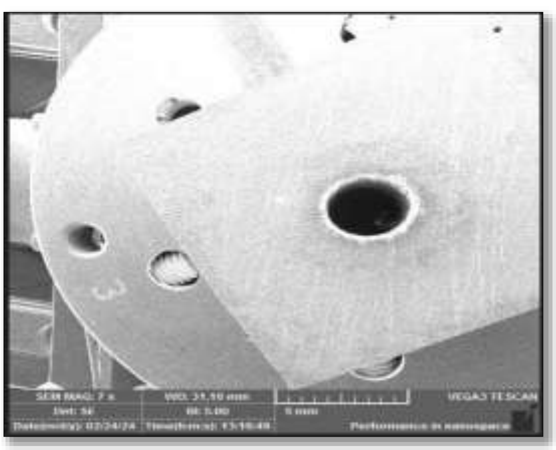


Fig 5: Sample Image in SEM

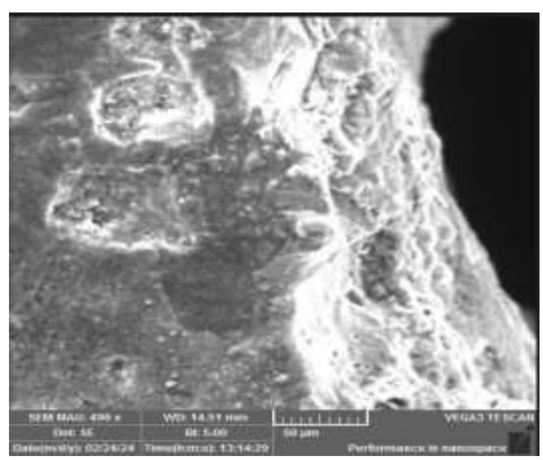


Fig: 6 Deep SEM Analysis WLT With SEM

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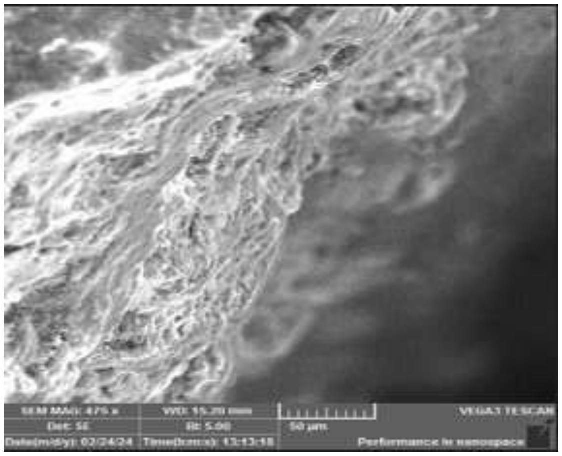

Fig 7: SEM Analysis (Doped with graphene

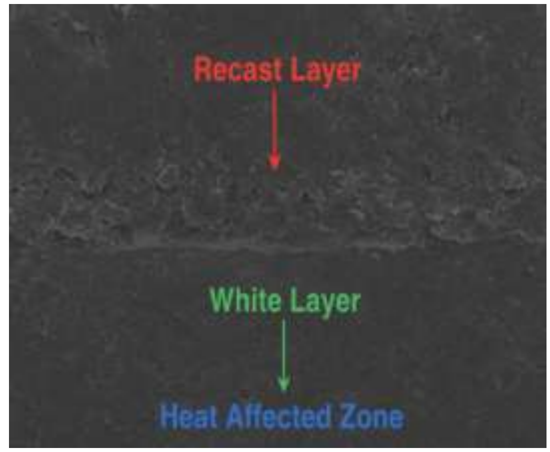

Fig 8: WLT and Heat Affected Zone

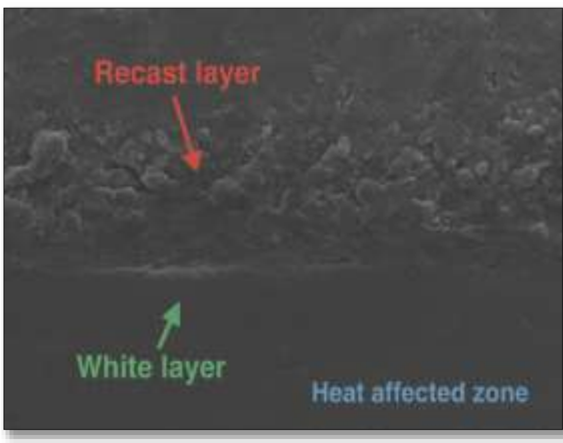

Fig 9: SEM Analysis (Doped with Graphene)

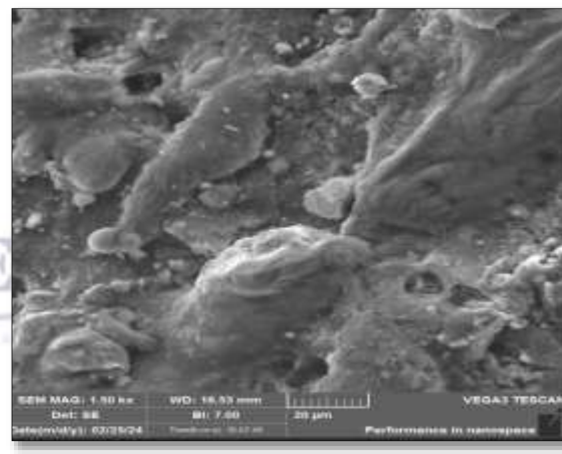

Fig 10: WLT with Graphene nanoparticles

This is attributed to the higher energy density and deeper craters produced by graphite, which result in more intense melting and slower cooling near the center of each spark site. On the other hand, specimens machined using graphene nanoparticle–mixed kerosene demonstrated a marked reduction in white layer thickness, with average values ranging between 7–12 µm. This thinning effect is believed to be the result of more stable and distributed spark discharges, as well as improved heat dissipation facilitated by the presence of graphene. The nanoparticles help regulate the plasma channel and enable faster removal of molten material, thereby limiting the extent of re-solidification on the surface.

Copper electrodes, while producing lower overall energy per spark, resulted in thinner white layers than graphite when used in both kerosene and graphene-mixed dielectric. However, the layers were often more irregular and less uniform, especially in standard kerosene, due to uneven spark intensity caused by higher electrode wear. Specimens machined in deionized water

showed a unique behavior: although the white layer was relatively thin due to rapid quenching, micro-cracks were more common. SEM analysis

of the EDM-machined surface at 1.50 kx (20 µm scale) and 500x (100 µm scale) shows that the surface has morphological characteristics that are

attributable to the electrical discharge machining process. But in the high-magnification image (1.50 kx) the surface is coarse and disorganized, containing molten and solidified globular structures which imply the presence of a recast or white layer. They are 10 to 25 mm structures which are shaped as a solid as the molten material solidifies without complete flushing out by the dielectric fluid. The material appears dense and with small cracks and irregular nodules that signify thermal forces that were used in the process. A bigger view of the machined surface at lower magnification (500x) would show that there are numerous micro-craters and depressions of different magnification
40 to 80 mm in diameter) dispersing all over the surface. Under the recast layer, it is possible to identify a heat-affected zone (HAZ), where the recast is partially melted and heated without full fusion. Localized heating leads to variations in the microstructure and hardness in this region. The macroscopic surface morphology reveals quick melting and solidification typical of EDM, leading to inhomogeneous recast formation and different depths of craters because of the variability of discharge energy and pulse duration. All of these characteristics influence the surface integrity, hardness, and tribology of the machined material, which makes the post-processing process essential in order to eliminate the recast layer and stabilize the microstructure. This was likely due to the thermal shock from the water's higher cooling rate, which can lead to internal stress accumulation. In conclusion, the use of graphene-enhanced kerosene, especially with graphite electrodes, resulted in not only reduced but also more uniform white layer thickness, which contributes to
improved fatigue life, better adhesion in coating applications, and enhanced surface integrity [1].

Conclusion

This study investigated the surface properties of Aluminum 7075 alloy machined using Electrical Discharge Machining (EDM) with a focus on the influence of graphene nanoparticle doping in the dielectric fluid. It has been demonstrated by the experimental results that the machining performance and surface integrity can be improved significantly by means of a careful choice of the electrode material and dielectric composition. The graphite electrode mixed with the graphene-mixed kerosene oil showed the highest results in terms of material removal rate (MRR), surface morphology, micro-hardness and control of white layer. The improved dielectric conductivity of graphene nanoparticles stabilized the mechanism of discharge and made the material flushing easier, as well as minimized thermal damage. Due to it, the machined surfaces were smoother with less micro-cracks and finer craters and more homogeneous white layers. Although copper electrodes were found to be efficient in material removal, they were less efficient in spark stability and were characterized by increased electrode wear. Although deionized water is environmentally friendly, it led to thermal shock and micro-cracking because of the aggressive cooling property of this water. Compared to this, however, graphene-enhanced kerosene provided a good compromise between spark energy, flushing efficiency and thermal control. The addition of graphene nanoparticles resulted in the growth of micro-hardness by up to 25%, which proves the possibility of surface strengthening. SEM and optical microscopic results established that EDM process when optimized in nanofluids could give high-quality surface and subsurface quality to Aluminum 7075 in the application of advanced engineering [3].

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