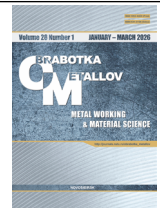




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Sustainability evaluation using an eco-index for Inconel 718 EDM with a hybrid Al_2O_3 -graphene nano-dielectric fluid

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ABSTRACT

Introduction. Environmentally sustainable machining is crucial to improve the manufacturing sector's cost-effectiveness and resource efficiency while mitigating its negative environmental impact. The "eco-index" is a multi-criteria metric that assesses the sustainability of the electrical discharge machining (EDM) of *Inconel 718* by quantifying its total environmental and economic impact using a normalized and weighted approach. **The purpose of this work** is to describe the eco-index for *Inconel 718* EDM, which assesses sustainability through environmental indicators such as energy and material consumption, waste generation, emissions, and toxicity, as well as economic indicators including operating and disposal costs along with productivity metrics. However, there are limited studies on sustainability evaluation using the eco-index for *Inconel 718* EDM processed with a hybrid nano-dielectric fluid. **The methods of investigation.** This study investigates the machining performance and environmental sustainability of the EDM process of *Inconel 718* using a hybrid nanoparticle-mixed dielectric fluid. A hybrid nano-dielectric fluid was prepared by dispersing Al_2O_3 and graphene nanoparticles in an equal proportion (total concentration of 0.1%) in EDM oil using a two-step method involving SDS as a surfactant, magnetic stirring, and ultrasonication to ensure a stable suspension. Experiments were conducted on an EDM machine with a copper electrode by varying the pulse on-time (50–150 μ s), peak current (3–10 A), and discharge voltage (40–50 V). Key performance responses, including material removal rate (MRR), surface roughness (R_a), tool wear rate (TW), hole cylindricity (ρ), energy consumption (E), and a weighted eco-index (EI), were evaluated to quantify the combined productivity, quality, and sustainability performance. **Results and Discussion.** The results demonstrate that the hybrid nano-dielectric fluid improves overall EDM efficiency compared to conventional EDM oil by promoting stable discharge behaviour, enhanced heat transfer, and efficient debris flushing, which increases MRR, improves surface finish, reduces tool wear, enhances the cylindricity of the machined hole, and lowers energy consumption, leading to a higher eco-index across most machining conditions. Surface integrity analysis using SEM revealed a substantial reduction in recast layer thickness, which decreased from 17.05 μ m (base oil) to 3.91 μ m (hybrid nano-dielectric fluid), indicating reduced thermal damage and resolidification. EDX further confirmed nanoparticle involvement through carbon enrichment (graphene deposition) and Al-O signatures (alumina contribution), supporting the proposed mechanisms for improved plasma stability and reduced metallic redeposition. Overall, the hybrid Al_2O_3 -graphene nano-dielectric fluid provides an effective and sustainable approach for the EDM of *Inconel 718* by balancing precision, productivity, and environmental efficiency.

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Introduction

Superalloys, such as *Inconel 718*, are widely used in chemical processing, aerospace, and marine engineering due to their exceptional strength, creep resistance, and corrosion durability at elevated temperatures. However, machining these alloys using conventional methods is challenging due to their

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low thermal conductivity and high hardness, leading to excessive tool wear, poor surface finish, and low material removal rates. The integrity of the machined surface is critical for *Inconel 718* components, as flaws introduced during machining can initiate fatigue cracks in service [1].

Electrical discharge machining (*EDM*) is a widely used non-traditional process for producing precision and complex features in difficult-to-cut materials. Recent studies indicate that adding graphene powder to deionized water used as the *EDM* dielectric can significantly improve the machinability of titanium alloys. The presence of graphene promotes bubble formation, which modifies discharge characteristics, thereby facilitating material removal, improving surface finish, and reducing electrode wear [2]. Beyond fine precision work, *EDM* is increasingly applied for substantial material removal, particularly for superalloys that are difficult to machine conventionally. For instance, *EDM* of *Inconel 825* with dielectric fluids containing multi-walled carbon nanotubes (*MWCNTs*), graphene, or their blends was found to enhance performance. These nano-additives improve material removal rate, surface finish, and produce a thinner recast layer with fewer defects, owing to graphene's excellent dispersion and high thermal conductivity [3].

The addition of graphene oxide (*GO*) to a conventional dielectric fluid has been shown to improve the *EDM* performance of *Nimonic* alloys. Employing this nanoparticle-enhanced dielectric with a copper electrode significantly increases the material removal rate (*MRR*), reduces tool wear (*TW*), and improves surface finish, indicating enhanced machining efficiency and process stability [4]. Similarly, using a graphene-based nanofluid as the dielectric for *EDM* of *Inconel 718* resulted in improvements in material removal rate, reduced electrode wear, and superior surface finish, attributed to graphene's high thermal conductivity and stable sparking characteristics. *SEM* analysis revealed fewer microcracks and smoother surfaces compared to those obtained with conventional dielectric fluid [5].

Graphene nanopowder addition also proved beneficial in micro-*EDM* milling of *Hastelloy C276*, producing a more uniform surface, accelerating debris removal, and extending tool life. The dielectric enriched with graphene also contributed to increased surface hardness and enhanced overall stability [6].

Near-dry *EDM* of nickel-based superalloys using carbon nanotube (*CNT*)-enhanced dielectrics exhibits similar trends, yielding higher material removal, lower tool wear, and improved surface quality [7]. For micro-*EDM* milling of *Ti-6Al-4V*, nano-powder dielectrics with *CNTs* or *SiC* facilitated material removal, reduced electrode wear, and produced cleaner surfaces. *CNTs* outperformed *SiC*, resulting in fewer microcracks and the best surface quality [8]. Furthermore, a hybrid *Al₂O₃-SiO₂* nanofluid in deionized water enhanced *EDM* performance on *Ti-6Al-4V*. Optimal concentration of this hybrid nanofluid led to increased material removal, reduced tool wear, fewer cracks, and a thinner recast layer, thereby improving surface quality due to the synergistic effect of *Al₂O₃* and *SiO₂* [9].

During micro-*EDM* milling of *Inconel 718*, the addition of 50 nm *MoS₂* powder at a concentration of 5 g/L to the dielectric improved material removal and enhanced surface finish. The powder suppressed stray arcing and short-circuiting, resulting in cleaner and more circular micro-holes. Overall, powder-mixed dielectrics significantly enhance the viability of micro-*EDM* milling for hard nickel-based alloys [10].

Employing powder-mixed dielectrics in the *EDM* of *Inconel 718* under optimal conditions (4 g/L powder concentration, 40 A current, 200 μ s pulse duration) has been shown to increase the material removal rate by nearly 50%. Tool wear was also significantly reduced, improving overall machining performance and surface finish [11].

Similarly, incorporating 0.4 wt.% graphene into the dielectric for *EDM* of *Inconel 625* led to a substantial increase in material removal rate, with optimal results observed at 12 A current and a 50 μ s pulse duration. The close agreement between experimental and predicted values demonstrates that graphene-assisted powder-mixed electrical discharge machining (*PMEDM*) is an efficient and reliable method for machining nickel-based alloys [12].

Electrical discharge machining (*EDM*) generates extremely high localized temperatures, typically between 8,000 and 12,000 °C. Researchers mitigate this thermal load through careful process parameter optimization, appropriate electrode material selection, or hybrid machining strategies. The intense sparking can alter the microstructure and mechanical properties of the machined surface by modifying the surface and subsurface layers [13].

Nanoparticle-based cutting fluids, particularly hybrid Al_2O_3 and $MWCNT$ nanofluids, have been shown to enhance lubrication and heat dissipation during the machining of *Inconel 718*. These fluids extend tool life, improve surface finish, and reduce cutting forces, making them beneficial for the precision turning of difficult-to-machine materials [14].

Further investigations demonstrated that using $Cu-MWCNT$ composite electrodes in the *EDM* of mild steel increased surface hardness by 163% and reduced micro-crack formation, highlighting the potential of nanoparticle-assisted *EDM* to modify surface properties [15]. It is concluded that the addition of conductive particles to the dielectric medium stabilizes spark generation, enhances the material removal rate and surface finish, thereby improving the overall sustainability of the *EDM* process [16].

Based on response surface methodology (*RSM*) and fuzzy logic models, the application of titanium powder-mixed *EDM* to *Inconel 718* resulted in improved material removal and surface quality, with the prediction models demonstrating high accuracy. This confirms the effectiveness of titanium particles in enhancing *EDM* performance [17].

Research on the *EDM* of *Inconel 800* using a dielectric fluid mixed with tungsten carbide or boron carbide powders showed significant improvements in material removal rate and surface quality. The study highlighted the predominant influence of powder additives and proper tool material selection on machining outcomes [18].

Pellegrini and *Ravasio* [19] proposed a sustainability index to evaluate energy and dielectric consumption, electrode wear, and environmental impact. This approach can improve both the efficiency and environmental sustainability of *EDM* for nickel alloys when employing nanoparticle-based dielectric fluids. For example, a dielectric fluid composed of deionized water mixed with $SiC-PEF$ powder outperformed traditional oil-based dielectrics, providing a more eco-friendly solution with a reduced environmental footprint [20].

A recent review highlighted concerns regarding harmful emissions and byproducts from machining processes, emphasizing the critical need to enhance the environmental sustainability of *EDM* by reducing energy and dielectric consumption [21]. Bio-oils, such as jatropha oil, demonstrate effective material removal and improved surface finish while generating less pollution than conventional kerosene, positioning them as a promising long-term sustainable alternative [22].

The addition of ceramic powders such as SiC and B_4C enhances material removal rate and surface finish, whereas metal-based powders like molybdenum and chromium increase surface hardness. Carbon nanotubes and graphene promote more stable sparking and higher material removal rates; however, they can lead to particle agglomeration, which may induce minor surface defects [23, 24].

An assessment of sustainability in micro-*EDM* milling revealed that dielectric fluid consumption and electrode degradation are significant environmental factors. Brass electrodes combined with water-based dielectrics were identified as the most environmentally favorable option among those studied [25].

To mitigate environmental impact, while minimizing energy consumption and tool wear, the application of a sustainability index is crucial. An *Eco-Index* can be used to evaluate machining performance by integrating productivity, energy efficiency, and surface quality into a single metric. The results of such studies underscore the need for normalization techniques to enable fair comparisons among different parameters in the final sustainability score [26].

The remote sensing ecological index (*RSEI*) serves as a reliable environmental indicator for monitoring ecological recovery in rare-earth mining areas, assessing environmental changes, and promoting sustainable management practices [27]. Furthermore, the use of a weighted aggregation method provides a comprehensive performance overview by consolidating multiple economic, environmental, and social sustainability metrics into a single composite index, as demonstrated in studies on the steel industry [28].

The combination of surfactants and conductive powders in *EDM* has been shown to stabilize spark generation. For instance, machining hard materials like *AISI D2* steel with a dielectric containing chromium powder and *SPAN-20* surfactant facilitates material removal and improves surface finish [29]. While cryogenic treatment combined with *PMEDM* shows promise for more environmentally friendly performance, this hybrid approach requires further refinement [30]. Cutting force modeling indicates that hybrid nanofluids enhance the machinability of *Inconel 718* [31]. To achieve superior surface finish, extended tool life, and

higher material removal rates, the dielectric is often mixed with micro- or nano-sized powders, which enable controlled surface modification [32].

Nanoparticles with a size smaller than 10 nm exhibit superior thermal properties, leading to more effective sparking in micro-EDM milling [33]. The EDM of nickel alloys is enhanced by dielectric fluids containing Al_2O_3 , graphene, or SiC nanoparticles, which improve spark stability, cooling, and debris removal, thereby reducing tool wear and improving surface quality. However, non-uniform particle dispersion can destabilize PMEDM, compromising machining reliability. This issue is addressed by continuous stirring of the nanofluid, which maintains uniform particle suspension and enhances thermal conductivity. A hybrid Al_2O_3 –graphene nanodielectric fluid is selected for this study due to its excellent dispersion stability and thermal transfer capabilities.

Despite the machining advantages, very limited research has been conducted on evaluating the eco-index for the EDM of *Inconel 718* using hybrid nano-dielectric fluids. Therefore, this work focuses on enhancing the machinability of *Inconel 718* by achieving stable and uniform nanoparticle dispersion in the dielectric, aiming to improve EDM efficiency, process stability, and overall performance. The study involves machining with a dielectric fluid based on Al_2O_3 and graphene nanoparticles and investigates key EDM outcomes: material removal rate (MRR), surface roughness (Ra), tool wear (TW), geometric form error such as cylindricity (ρ), and energy consumption (E). The resulting improvements in process efficiency contribute to enhanced environmental sustainability, which is evaluated through an eco-index calculation as illustrated in Fig. 1.

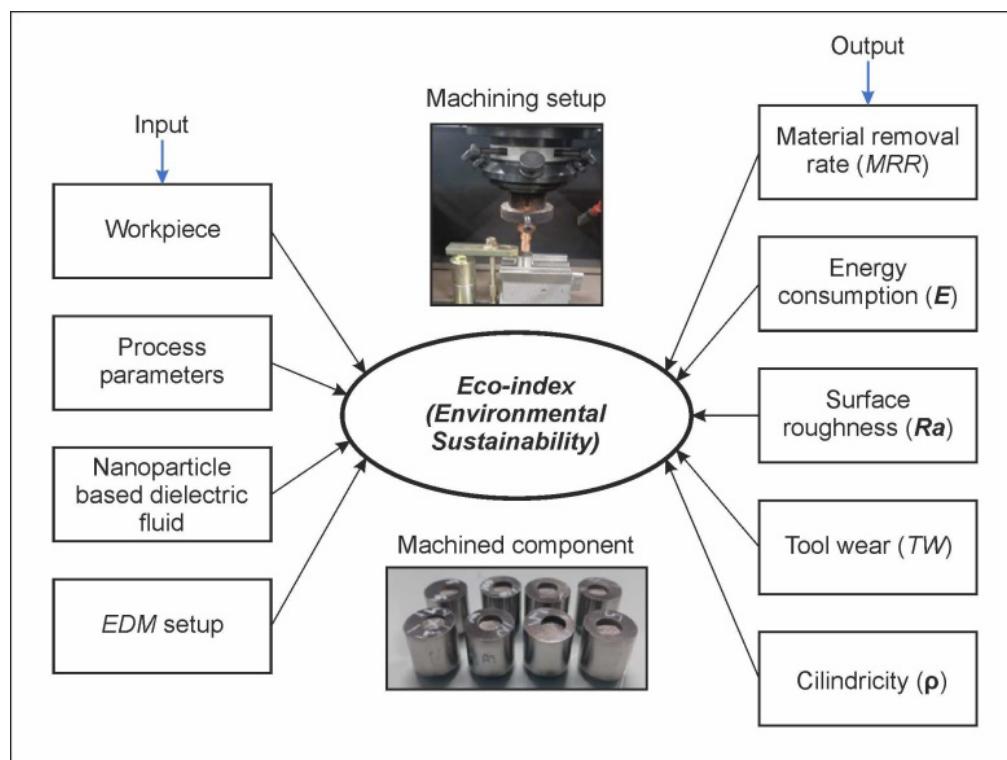


Fig. 1. Framework for environmental sustainability assessment

Methods

All machining experiments were conducted on an *Eltech D300 ZNC EDM* machine equipped with a 40 A ZNZ generator, featuring travel dimensions of $X=300$ mm, $Y=200$ mm, and $Z=250$ mm. The Z -axis is driven by an AC servo motor. For this study, the standard setup was modified to accommodate nanofluids as the dielectric medium. The modified system included a dedicated dielectric circulation system comprising a work tank and a drain tank (250 mm × 150 mm × 75 mm), connected by a 24 W submersible pump to ensure continuous fluid flow. A magnetic filter was installed to effectively remove machining debris, and a mechanical stirrer was added to maintain homogeneous dispersion of nanoparticles in the EDM oil.

The workpiece material was *Inconel 718* rods with dimensions of 20 mm in length and 25 mm in diameter. Table 1 presents the elemental composition of *Inconel 718*. A 13 mm diameter electrolytic copper electrode was used as the tool to machine holes to a depth of 3 mm. Preliminary trials were performed prior to the main experiments to finalize the operating conditions. Based on insights from the literature, preliminary tests, and the capabilities of the *ZNC-series EDM* machine, the selected process parameters for this investigation are summarized in Table 2. The overall experimental methodology is depicted in Fig. 2.

Table 1

Chemical composition of *Inconel 718* alloy (wt%)

<i>C</i>	<i>Cr</i>	<i>Al</i>	<i>Ti</i>	<i>Si</i>	<i>Ni</i>	<i>Mo</i>	<i>Mn</i>	<i>Nb+Ta</i>	<i>Cu</i>	<i>Fe</i>
0.026	17.42	0.48	0.84	0.35	54.06	2.88	0.32	5.10	0.23	Balance

Table 2

Experimental parameters for EDM

Polarity	Normal positive
Dielectric fluid	<i>EDM</i> oil, nanoparticle-enhanced <i>EDM</i> oil
Flushing pressure	0.1 kg/cm ²
Gap voltage (V)	40 and 50
<i>T_{on}</i> (μs)	50 and 150
<i>I_p</i> (A)	3 and 10
Drill depth	3 mm (constant)
Retract distance (<i>R_d</i>)	2 mm (constant)

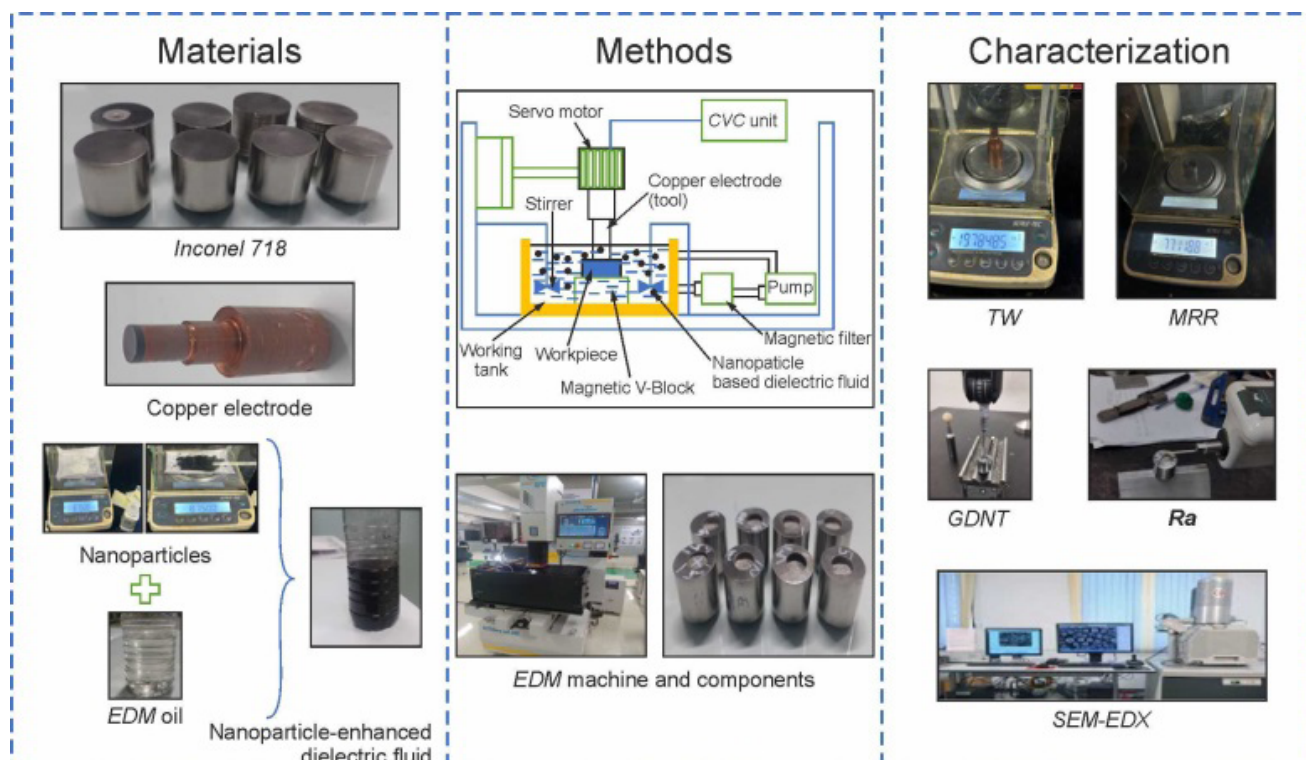


Fig. 2. Research methodology chart

In this study, nanofluids were formulated by blending aluminum oxide (Al_2O_3) and graphene (Gr) nanoparticles with a standard synthetic hydrocarbon-based EDM oil. The nanoparticle concentration was selected to balance dispersion stability and tribological performance. A two-step preparation method was employed to ensure uniform nanoparticle dispersion in the base fluid, as illustrated in Fig. 3. The total nanoparticle concentration was maintained at 0.1% by weight, with an equal mass ratio (50:50) of Al_2O_3 and graphene used to prepare the hybrid nano-dielectric fluid.

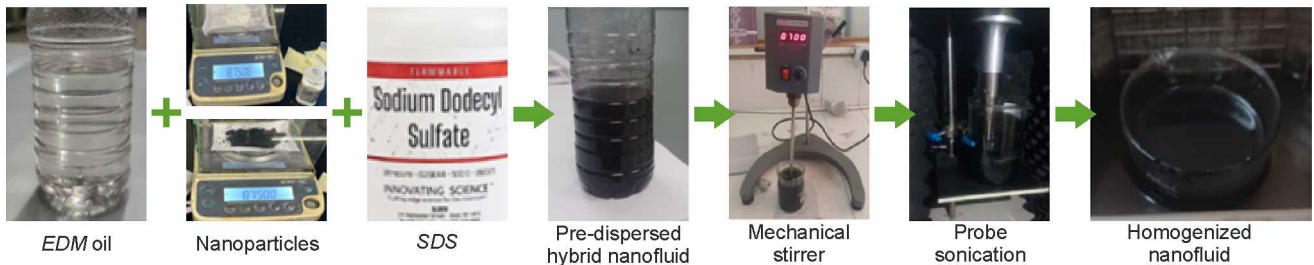


Fig. 3. Two-step method for nanofluid preparation

To enhance nanofluid stability, sodium dodecyl sulfate (SDS) surfactant was added at a weight ratio of 1:10 relative to the total nanoparticle mass [3]. The mixture was first stirred magnetically for 30 minutes and then subjected to ultrasonication for 20 minutes at approximately 30 °C to achieve uniform dispersion. Ultrasonication was performed using a *PKS 500F* probe sonicator. The properties of the nanoparticles used are provided in Table 3.

Table 3

Attributes of nanoparticles

Property	Al_2O_3	Graphene
Purity (%)	99.9	99
Average particle size (nm)	20–50	5–10
Bulk density (g/cm^3)	0.5	0.1
Morphology	Spherical	Spherical
Color	White	Black

The material removal rate (MRR) was determined by measuring the weight loss of the workpiece using a precision *SCALE-TEC* balance. The MRR was calculated by dividing the mass difference (initial minus final) by the product of machining time and the material's density.

$$MRR = \Delta m_w / (\rho_w \cdot t),$$

where Δm_w is the mass loss of the workpiece; ρ_w is the workpiece material density; t the machining time.

Surface roughness (R_a) was measured using a stylus-type profilometer (Model: *MarSurf M300*, *Mahr*, Germany). Measurements were performed with a cut-off length of 0.25 mm and a traverse length of 1.75 mm, in accordance with *ISO* standards. The reported R_a value is the average of five readings taken at three different locations on the machined surface.

Tool wear (TW) was also quantified by weight loss, measured on the same balance. It was calculated by dividing the difference between the initial and final tool weights by the product of the tool material's density and the machining time.

$$TW = \Delta m_t / (\rho_{Cu} \cdot t),$$

where Δm_t is the mass loss of the tool; ρ_{Cu} is the density of the copper electrode; t is the machining time.

The cylindricity (ρ) of the machined holes was measured using a coordinate measuring machine (CMM). Energy consumption (E) was evaluated as the product of average voltage (V), average current (I_p), and machining time.

$$E = V_{avg} \cdot I_{p,avg} \cdot t,$$

where V_{avg} is the average discharge voltage; $I_{p,avg}$ is the average discharge current; t is the total machining time.

Assessment of the recast layer (RL) is critical for evaluating the surface integrity of EDM components, as it provides insight into thermal effects and potential defects. To prepare specimens for RL analysis, the machined sample was sectioned using wire- EDM with a water-cooled dielectric to minimize thermal alterations, ensuring accurate characterization.

Results and Discussion

This section presents an analysis of the sustainability of EDM through *Eco-Index* evaluations for components machined under various conditions using two different dielectric fluids. The experimental conditions are summarized in Table 4. All other machining parameters, including retract distance (R_d), duty cycle (τ), and arc sensitivity (A_{sen}), were held constant throughout the study.

Table 4

Experimental test matrix (full factorial design)

Run No.	T_{on} (μs)	I_p (A)	Gap voltage (V)
1	150	10	50
2	50	3	50
3	50	10	50
4	150	3	40
5	150	10	40
6	50	10	40
7	150	3	50
8	50	3	40

The *Eco-Index* serves as a critical indicator of the sustainability of the EDM process, reflecting environmental impact, economic factors, and machining performance to assess overall process efficiency. It is derived from multiple factors, such as material removal rate, tool wear, surface finish, energy consumption, and dimensional accuracy.

MRR and surface roughness (R_a)

A high material removal rate (MRR) enhances productivity, while a low surface roughness (R_a) is crucial for desired surface integrity. Therefore, achieving a balance between these two responses is necessary and indicative of overall process performance [34, 35]. Fig. 4 presents the MRR and R_a trends for the two dielectric conditions: conventional dielectric fluid and nanoparticle-based dielectric fluid.

Fig. 4 shows a clear increase in MRR and a significant reduction in R_a when using the nanoparticle-based dielectric fluid. This improvement stems from the enhanced thermophysical properties imparted by the nanoparticles. In this study, a hybrid dielectric containing Al_2O_3 and graphene was employed, which exhibits a strong synergistic effect. Al_2O_3 particles increase the spark gap distance, promoting multiple discharges over a larger effective area. Graphene provides conductive pathways within the dielectric,

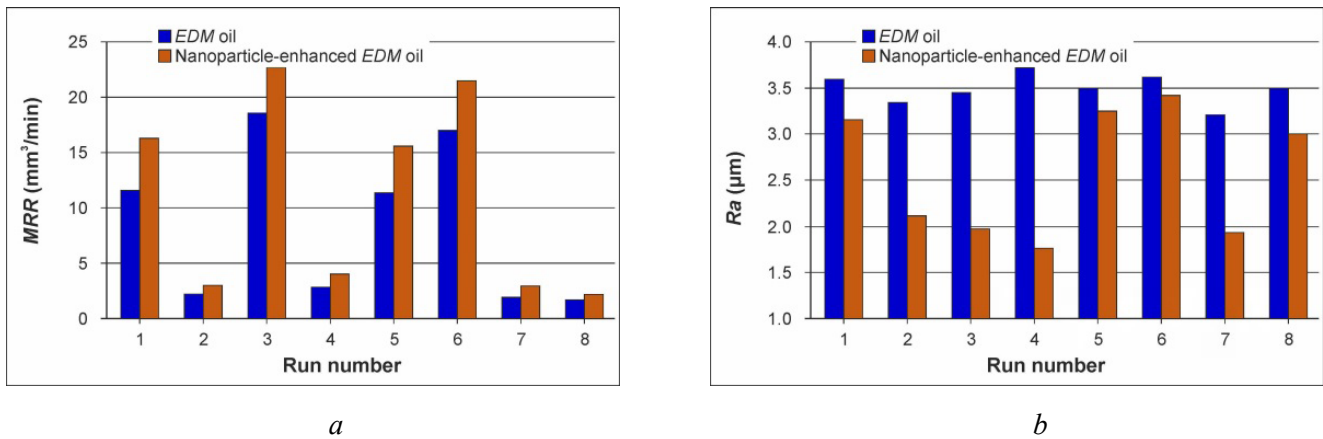


Fig. 4. Variation of (a) material removal rate (MRR) and (b) surface roughness (Ra) with experimental run number for conventional EDM oil and nanoparticle-enhanced dielectric fluid

facilitating dielectric breakdown at lower voltages and enabling more uniform discharges, ultimately improving MRR [36].

Furthermore, graphene's high thermal conductivity allows heat to be rapidly transferred from the spark zone, promoting efficient localized melting and material removal. This characteristic helps regulate temperature fluctuations in the discharge zone and prevents excessive heating, thereby reducing thermal damage and microstructural alterations. The improved heat dissipation also mitigates residual stresses, contributing to a more uniform surface finish [37].

In summary, graphene's excellent dispersion and high thermal and electrical conductivity establish a consistent conductive network, ensuring efficient sparking and enhanced machining performance. The addition of Al_2O_3 further increases the spark gap distance, promoting multiple discharges over an enlarged effective area.

Tool wear (TW), cylindricity (ρ), and energy consumption (E)

Nanoparticle-mixed dielectrics significantly enhance EDM performance by improving heat transfer and stabilizing the discharge process. Their use reduces tool wear, improves dimensional accuracy, and lowers energy consumption through more efficient spark distribution and effective debris removal [38]. In previous work, optimization of nanoparticle concentration was shown to improve key EDM responses such as MRR , Ra , and TW . For example, in the EDM of *Hastelloy C-276*, a lower concentration of nano-graphene yielded optimal machining results, demonstrating that even minimal additions can significantly enhance performance [39].

Fig. 5 shows that tool wear, cylindricity deviation, and energy consumption are all lower when using a nanoparticle-based dielectric compared to a conventional dielectric without nanoparticles. This is attributed to the nanoparticles' role in enhancing discharge stability and improving heat dissipation. The more stable sparking reduces taper and eccentricity, leading to improved cylindricity. Furthermore, the higher effective conductivity and more efficient energy transfer under these conditions minimize electrode erosion, thereby reducing tool wear. Additionally, a protective layer formed between the tool and the plasma by the nanoparticles shields the electrode from direct exposure to high temperatures, further decreasing tool wear. The combined effect of stabilized sparking and enhanced cooling also reduces specific energy consumption, promoting process sustainability.

Research on graphene-mixed dielectric EDM of *Inconel 718* supports these findings. The results showed a 13.88% improvement in MRR and a 25.76% improvement in cylindricity compared to a pure dielectric [40]. The nanoparticles alter the dielectric's breakdown characteristics, generating more consistent and uniform discharges. This helps prevent random arcing and irregular melting, which reduces taper and eccentricity in the machined holes [5].

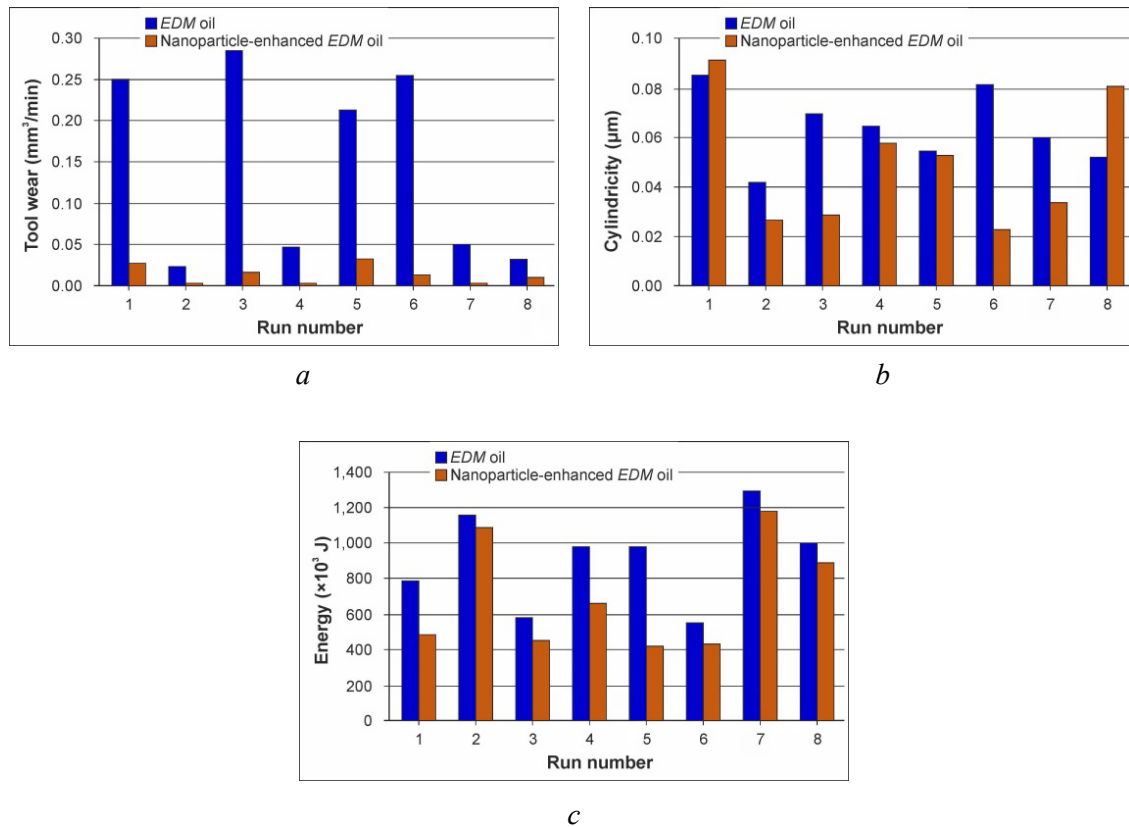


Fig. 5. Variation of (a) tool wear rate (*TWR*), (b) hole cylindricity (ρ), and (c) energy consumption (*E*) with experimental run number for conventional *EDM* oil and nanoparticle-enhanced dielectric fluid

Eco-Index

The *Eco-Index* is a critical metric for assessing the sustainability of *EDM*, providing a broader perspective than traditional machining performance metrics alone. It integrates environmental impact, energy consumption, and process capability into a single comprehensive score. This section highlights the contribution of the *Eco-Index* to evaluating both the environmental and operational performance of *EDM*. A higher *Eco-Index* score indicates more sustainable and efficient machining, serving as a valuable guide for selecting process parameters that minimize environmental impact [25].

This investigation incorporated several *EDM* parameters that influence both environmental and machining performance. Key factors such as energy consumption (*E*), tool wear (*TW*), material removal rate (*MRR*), cylindricity (ρ), and surface roughness (R_a) were consolidated into a single numerical value. Weighting factors were assigned to each factor based on its importance in determining overall process sustainability, as shown in Table 5.

After assigning the weights, the normalized scores for each parameter were calculated for all experimental runs by scaling the data between their maximum and minimum observed values. This min-max normalization transforms each parameter to a value between 0 and 1, ensuring a consistent evaluation scale. Normalization was performed using Eq. (1) for beneficial criteria (higher is better) and Eq. (2) for non-beneficial criteria (lower is better) [41].

Table 5

Weighting factors (w_i) for *Eco-Index* calculation

Material removal rate, <i>MRR</i> (mm ³ /min)	Energy consumption, <i>E</i> (J)	Surface roughness, R_a (μm)	Hole cylindricity, ρ (μm)	Tool wear rate, <i>TWR</i> (mm ³ /min)
0.40	0.20	0.20	0.10	0.10

$$\text{Normalization (higher is better)} = \frac{x - x_{\min}}{x_{\max} - x_{\min}}, \quad (1)$$

$$\text{Normalization (lower is better)} = \frac{x_{\max} - x}{x_{\max} - x_{\min}}, \quad (2)$$

where x denotes the measured value of a specific factor; x_{\max} and x_{\min} represent its maximum and minimum values observed across the eight experimental runs.

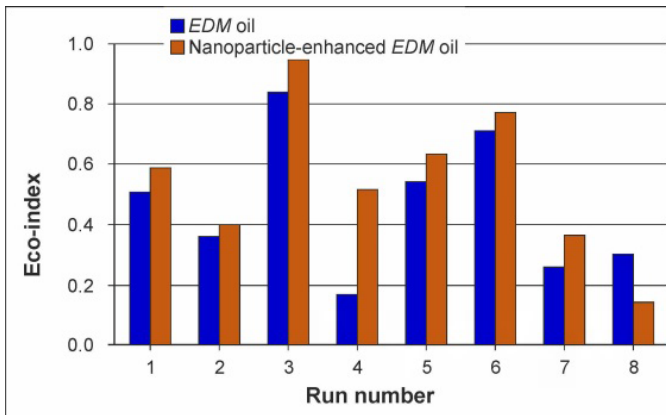


Fig. 6. Comparison of the overall eco-index for conventional EDM oil and nanoparticle-enhanced dielectric fluid across experimental runs

In this investigation, a hybrid dielectric medium (50:50 Al_2O_3 and graphene) significantly reduced recast layer formation. Comparisons were made between specimens machined with a conventional EDM oil and an EDM oil containing 0.1% nanoparticles.

For analysis, the EDM-machined specimens were sectioned into 5 mm × 5 mm × 5 mm cubes using wire-EDM. They were then cold-mounted to prevent thermal damage, followed by diamond polishing and acid etching. RLT was measured using a scanning electron microscope (FEI Nova NanoSEM 450) and the ImageJ software to determine the average thickness from measurements at five different locations.

Fig. 7 presents SEM micrographs and the average RLT for components machined with the base EDM oil and the hybrid nano-dielectric. The results show that components machined with the hybrid nano-dielectric fluid have a significantly lower average RLT of 3.91 μm, compared to 17.05 μm for those machined with

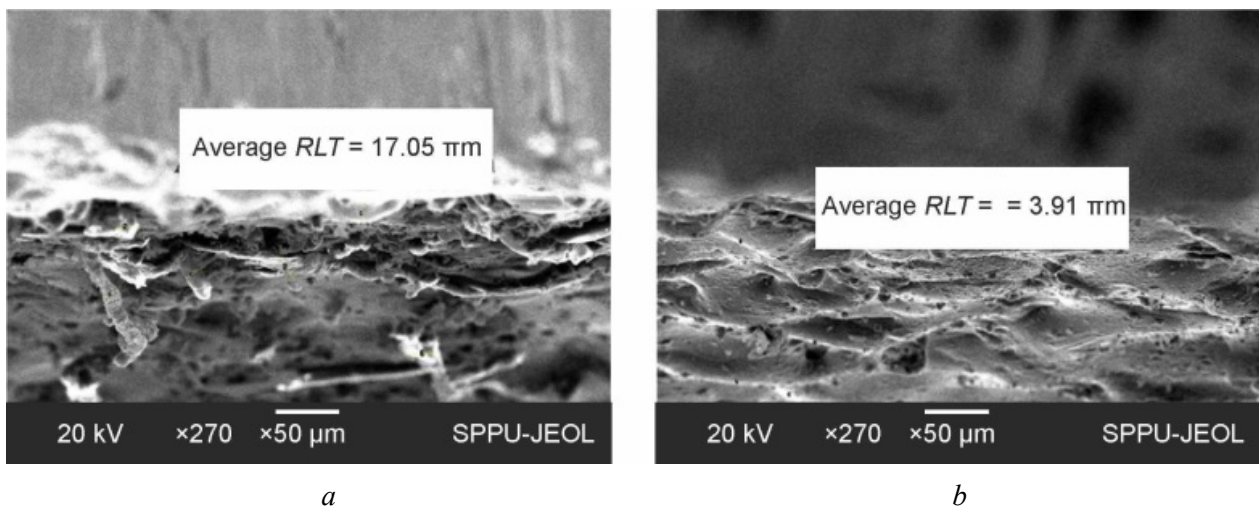


Fig. 7. Recast layer thickness (RLT) on ED-machined surfaces using (a) base dielectric fluid and (b) hybrid nano-dielectric fluid

the base oil. This reduction is attributed to the fact that conventional *EDM* oil promotes high localized spark energy, poor heat dissipation, and ineffective debris flushing. In contrast, the nanoparticle-based dielectric mitigates these issues.

Specifically, the hybrid nano-dielectric fluid reduces *RLT* because Al_2O_3 has high melting point and thermal stability, promoting more uniform discharge energy distribution and lower peak spark temperatures by acting as a micro-insulating barrier.

Furthermore, graphene was well-dispersed, forming a conductive network within the base fluid. Its single-layer structure of sp^2 -hybridized carbon atoms in a hexagonal lattice provides a large surface area, facilitating rapid and uniform heat transfer [42]. Additionally, graphene's high electrical conductivity and surface area enable efficient heat evacuation from the machining zone, preventing excessive heat penetration and enhancing plasma channel stability. This reduces thermal damage and the heat-affected zone, thereby further minimizing the recast layer. The synergistic effect between Al_2O_3 and graphene enhances plasma stability, improves debris flushing, and suppresses excessive re-solidification of molten material, as is evident from Fig. 7.

EDS analysis

Energy-dispersive X-ray spectroscopy (*EDS*) was used for elemental analysis of the *EDM*-machined surfaces. Figs. 8 and 9 present the *EDS* spectra for components machined with the hybrid nano-dielectric and the base *EDM* oil, respectively. The analysis shows a significantly higher carbon deposition on the surface machined with the base oil compared to the hybrid nano-dielectric. The quantified carbon content was 20.9% for the nanoparticle-based oil and 31.09% for the base oil.

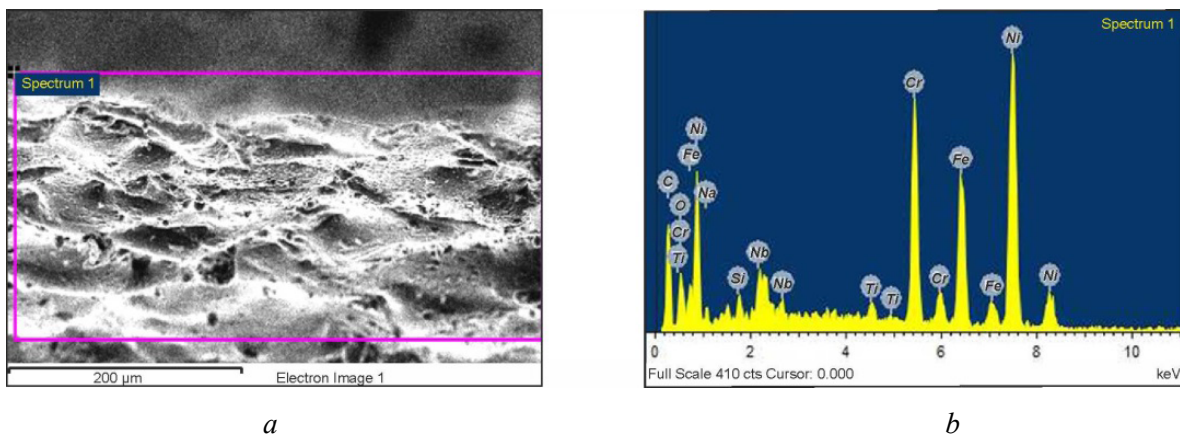


Fig. 8. *EDX* spectrum and corresponding electron image of the *ED*-machined surface machined with the hybrid Al_2O_3 -graphene nano-dielectric fluid

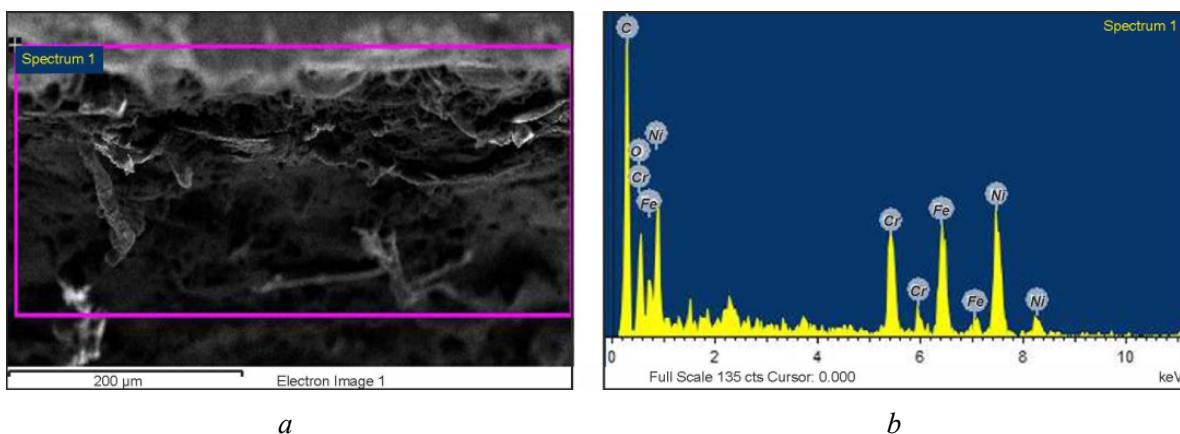


Fig. 9. *EDX* spectrum and corresponding electron image of the *ED*-machined surface machined with base *EDM* oil

The uniform dispersion of nanoparticles in the graphene-based nanofluid prevents localized overheating, reduces thermal damage, and minimizes surface irregularities [43]. *EDX* analysis further reveals that the hybrid nano-dielectric fluid significantly alters the surface chemistry of the machined components. The detection of aluminum and oxygen confirms the participation of alumina, while increased carbon indicates graphene deposition. These nanoparticles collectively stabilize the plasma channel, enhance heat dissipation, and reduce metallic re-deposition, resulting in a thinner and more chemically uniform recast layer.

In contrast, with conventional *EDM* oil, the *EDS* spectra are dominated by peaks from the workpiece material, reflecting uncontrolled melting and re-solidification. This corroborates the observed increase in recast layer thickness and surface defects.

Conclusion

This study investigated the electric discharge machining (*EDM*) of *Inconel 718* using a nanoparticle-mixed dielectric fluid. The machining outcomes were compared with those obtained using a conventional *EDM* dielectric to evaluate improvements in machinability and the overall *Eco-Index*.

The following conclusions were drawn:

- hybrid nano-dielectric fluid (0.1 wt.% of a 50:50 mixture of Al_2O_3 and graphene in *EDM* oil, stabilized with *SDS* via mechanical stirring and ultrasonication) was successfully employed on a *ZNC-EDM* machine to conduct stable machining trials on *Inconel 718* with a copper electrode across pulse-on time (50–150 μ s), peak current (3–10 A), and voltage (40–50 V) ranges.

- Compared to conventional *EDM* oil, the hybrid nano-dielectric fluid significantly enhanced machining performance and sustainability, exhibiting a higher material removal rate (*MRR*), improved surface finish (lower R_a), reduced tool wear, superior hole geometry (improved cylindricity), and lower energy consumption. These improvements collectively resulted in a higher overall *Eco-Index*.

- These enhancements are attributed to the synergistic effect of the nanoparticles. Al_2O_3 contributes by distributing discharge energy and moderating peak temperatures due to its thermal stability, while graphene facilitates conductive bridging, promotes stable dielectric breakdown, and enables rapid heat transfer owing to its high electrical and thermal conductivity. Together, they ensure stable sparking, efficient energy transfer, and improved debris flushing.

- Surface integrity analysis confirmed that machining with the hybrid nano-dielectric fluid produces a significantly thinner recast layer. The average recast layer thickness (*RLT*) was reduced from 17.05 μ m (base oil) to 3.91 μ m, indicating reduced thermal damage and less re-solidified material.

- *EDX/EDS* results corroborated the surface modification mechanism: surfaces machined with the hybrid nano-dielectric exhibited carbon enrichment (from graphene deposition) and the presence of aluminum and oxygen (from alumina). This is consistent with enhanced plasma stability and reduced uncontrolled melting and material re-deposition.

- The *Eco-Index* evaluation, which integrated productivity, energy consumption, tool wear, surface finish, and geometrical accuracy, demonstrated that most parameter combinations yielded higher index values with the hybrid nano-dielectric fluid. This confirms that nanoparticle-assisted *EDM* can achieve a superior balance between precision, productivity, and environmental sustainability.

- In summary, this study validates hybrid Al_2O_3 –graphene nano-dielectrics as a viable and sustainable approach for the *EDM* of *Inconel 718*, particularly in applications where surface integrity (specifically recast layer control), energy efficiency, and extended tool life are critical requirements.

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Conflicts of Interest

The authors declare no conflict of interest.

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