EDM Drilling of Inconel 718, SS304, and EN24 Materials under Plain and Hybrid Nanoparticle-mixed Dielectric Conditions

Paresh Kulkarni
Professor
School of Engineering Management and Research, D Y Patil International University (DYPIU), Akurdi, Pune, Maharashtra
India

Satish Chinchanikar
Department of Mechanical Engineering
Vishwakarma Institute of Technology, Pune
Maharashtra
India

In electric discharge machining (EDM), conductive nanoparticle-mixed dielectrics showed better machining performance, although their impact on eco-performance indices for different engineering materials using hybrid nanoparticle-mixed dielectrics remains less explored. With this view, this study investigates EDM drilling of Inconel 718, SS304, and EN24 materials by varying pulse-on time, discharge current, and gap voltage, utilizing both plain and hybrid nanoparticle mixtures of graphene and aluminium oxide in the dielectric. Discharge current and pulse-on time notably influenced EDM performance, particularly with Inconel 718 and SS304 in plain dielectric conditions. Compared to conventional dielectrics, nanodielectrics demonstrated a 34.97% improvement in material removal rate, a 25.92% reduction in surface roughness, a 77.15% decrease in tool wear rate, and a 22.01% lower roundness error. Additionally, energy consumption was reduced by 18.11%, contributing to an 18.6% increase in overall eco-index. Reduced recast layer formation further confirmed enhanced thermo-physical interactions with nanodielectric, suggesting improved eco-performance for EDM.

Keywords: *Electrical Discharge Machining, Nanodielectric, Material Removal Rate, Tool Wear Rate, Surface Roughness, Roundness, Eco-Index Sustainability.*

1. INTRODUCTION

Electrical discharge machining (EDM) is usually used to machine Inconel 718 and stainless steels, which are hard to cut by conventional machining. In EDM, controlled discharges of electron energies in a dielectric medium are used for the removal of material. In EDM, the machining discharges (plasma formation and energy), process accuracy and control, and dielectric modification are extremely critical.

Electrical Discharge Machining (EDM) effectively addresses the limitations of traditional techniques like turning and milling, which struggle with hard materials due to tool wear and difficulty in achieving complex shapes with fine finishes [1]. The EDM process using powder mixed dielectric influences material removal rate and surface finish by modifying spark characteristics, but it presents challenges such as powder dispersion, dielectric dispersion, and debris control. This is directed towards understanding the behaviour of the process, optimizing parameters, and enhancing the applicability of the process in industrial machining. It facilitates further investigations of parameter optimization of higher performance [2,3].

The studies reported the bubble flushing process in micro-EDM and its capability in the process of removing dielectrics and the debris. It also discussed the interaction between the debris and the bubble, which helps in understanding and comprehending the optimization of machining mechanism [4]. The bubble formation plays a significant role in controlling the efficiency of EDM and has been extensively investigated in many aspects throughout the years. High speed imaging combined with signal analysis of the discharge signals provides a method to measure the behaviour of the bubbles which is a significant controlling parameter in the efficiency of EDM. The results have to do with depth-wise bubble dynamics to machining performance and process mechanism [5-6].

The hybrid Taguchi-based Grey Relational Analysis (T-GRA), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and Artificial Neural Network (ANN) approach effectively optimized eductor-based powder-mixed EDM (PMEDM) of Inconel 718, providing reliable multi-response optimization with strong predictive accuracy [7]. Machining hard to-cut materials in EDM remains challenging due to unavoidable tool wear and difficulty in maintaining dimensional accuracy, despite optimization and electrode enhancements [8]. The near-dry EDM of Inconel 718 has still challenges in balancing between high material removal and surface, controlling overcut and thermal effects and balancing high material removal and surface dimensional accuracy and integrity [9]. The exploration of the different dielectric materials in EDM has been already researched sufficiently well over the years to cover a variety of traditional and high fluidized systems to determine its effect on the performance of machining.

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Correspondence to: Dr. Paresh Kulkarni, School of Engineering Management and Research, D Y Patil International University, Pune, 411044, India.
E-mail: paresh.kulkarni@dypiu.ac.in
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Near-dry EDM studies reported enhanced metal removal rate, lower tool wear rate, and surface roughness with air–deionized water [10].

The process parameters and the properties of the electrode–dielectric system mainly determine various aspects of the EDM process, such as dimensional and geometrical accuracy, surface integrity, and mechanisms of the material removal. However, few studies have systematically reviewed micro-EDM, considering its variants, process parameters, and their interactive effect on the performance of micro-scale machining [11,12]. The literature review reveals the potential for improvement of the EDM performance, especially by modifying the dielectric properties, which is an important aspect in improving the efficiency of the EDM machining process and also green and sustainable manufacturing. Effect of dielectric oil viscosity on wire EDM process indicates that with increase in viscosity of the dielectric oil, the removal rate increases but the surface roughness and corner accuracy decrease due to poor flushing of debris out of the spark gap. It also helps to reduce the vibration of wires, which slightly improves the straightness and waviness of the wires [13].

One of the factors that affect the machining efficiency in EDM is the removal of debris. Studies reported that by using the highly carbonated high-viscosity dielectric, discharge energy and metal removal rate were significantly improved which eliminated the need for external flushing. But the thicker the recast layers, the higher the micro-crack density, and the worse the surface integrity of the recasted layer will be, which will result in an inefficient debris removal process [14]. Al_2O_3 powder addition to the dielectric fluids plays a vital role in improving the EDM operation by imparting stability to the sparks, increasing MRR and surface finishing. Transformer oil proved to have the best machining properties with respect to MRR, surface quality and general performance out of all the tested media [15]. The hybrid Al_2O_3–graphene nano-dielectric is used to improve the MRR for Inconel 718, surface quality, energy efficiency, and minimize tool wear in the EDM process and achieved a higher eco-index. It also reduces thermal damage of the product, which reduces the formation of recast layers, hence can be seen as effective in sustainable and precise machining [16].

Nanoparticles possess unique properties that enhance machining efficiency across various processes, and EDM is no exception. The recent research highlights the influence of different dielectric media on EDM performance, particularly in material removal, surface finish, and process stability, while indicating scope for further optimization [17]. The EDM parameters were optimized for metal removal rate and tool wear while machining AISI M2 steel using Taguchi, ANOVA, and fuzzy logic. Results showed that the copper electrode with optimal settings delivered superior performance [18]. Recent research indicates that incorporating graphene powder into deionized water utilized as the EDM dielectric can effectively enhance the machining ability of titanium alloys. When graphene is present, bubbles form in it modifies discharge efficiency which improves material removal, makes surfaces smoother, and puts less stress on the electrodes [19]. In micro-EDM milling of Inconel 718, adding 50 nm MoS_2 powder (5 g/L) to the dielectric made it softer to remove material and made the surface smoother. The powder kept stray arcing and short circuits from generating, which made the micro holes clean and circular. In general, powder-mixed dielectrics made micro-EDM of hard nickel-based alloys much desired [20].

Adding 0.4 wt.% graphene to the dielectric for EDM of Inconel 625 also made the material removal rate move up substantially. At 12 A and a 50 μs pulse duration, the best results were observed. The close match between the experimental and projected results showed that graphene-assisted PMEDM is an efficient and reliable method to machine nickel-based alloys [21]. The literature review indicates that the incorporation of nanoparticles contributes to enhanced machining efficiency irrespective being type of machining operations [22]. The thermo-electrical properties of the workpiece significantly affect the machinability of PMEDM, influencing both material removal rate and tool wear [23]. Despite advances in research, several gaps persist in understanding nanoparticle-assisted EDM drilling. Studies reported rarely reported the coupled effects of discharge conditions and nanoparticle behavior on EDM drilling performance and surface integrity. This study aims to systematically assess EDM drilling conditions and their influence on machining characteristics and surface quality, offering an integrated examination of EDM drilling using plain and nanodielectric to enhance understanding of process-response dynamics.

The present study investigates machining performance, geometric accuracy, and subsurface integrity during EDM of Inconel 718, EN24, and SS304 using plain and hybrid aluminium oxide (Al_2O_3) and graphene nanoparticle-mixed dielectrics. Metal removal rate (MRR), tool wear rate (TWR), surface roughness (Ra), energy consumption (E), and EDM-machined hole characteristics, such as hole roundness (Rou) and its edge quality microscopic analysis with overall eco-index (EI), were investigated. Recast layer evolution is examined to assess thermal damage. Energy consumption is analysed to establish a link between process efficiency and sustainability, providing a comprehensive assessment from all materials and application perspectives for eventually achieving precision and green manufacturing of the EDM process.

2. MATERIALS AND METHODS

2.1 Details of machine and materials

All machining trials were carried out on an Eltech D300 ZNC EDM machine fitted with a 40 A generator, offering travel dimensions of X-300, Y-200, and Z-250 mm. The Z-axis movement is driven by an AC servo motor. The standard setup was modified for EDM drilling under plain and hybrid nanoparticle-mixed dielectric conditions. The updated arrangement included a separate dielectric circulation system with a work tank and a drain tank, linked by a 24 W submersible pump for continuous fluid flow. Additionally, a magnetic filter was incorporated to efficiently remove machining debris and mechanical stirrer was included in view of keeping

nanoparticles well mixed in EDM oil. The same setup is shown in Fig. 1.

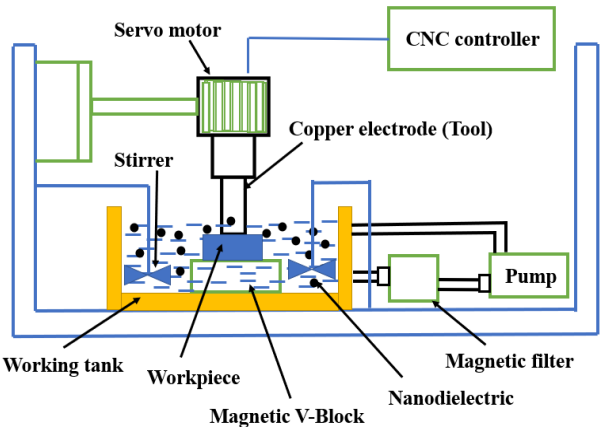


Figure 1. EDM drilling setup

Inconel 718, EN 24 and SS304 rods with dimensions of 20 mm in length and 25 mm in diameter were used as the workpiece material. To ensure appropriate material selection and to establish the relevance of material composition in EDM machining, compositional analysis was carried out. The chemical composition of Inconel 718, EN24, and SS304 was determined using optical emission spectroscopy in accordance with the applicable standards and presented in Table 1.

Table 1. Chemical compositions of materials

Inconel 718		EN 24		SS 304	
Element	Wt%	Element	Wt%	Element	Wt%
Ni	54.06	C	0.41	C	0.062
Cr	17.42	Mn	0.52	Mn	1.49
Nb+Ta	5.10	Si	0.27	Si	0.51
Mo	2.88	S	0.018	S	0.017
Si	0.35	P	0.027	P	0.033
Ti	0.84	Cr	1.00	Cr	18.23
Cu	0.23	Mo	0.22	Ni	8.09
Al	0.48	Ni	1.31		
Mn	0.32				
C	0.026				

Copper electrode was used to obtain a hole of 12 mm diameter for 3 mm depth. Based on insights from literature, pilot studies, and the EDM machine capabi–lities, the process parameters selected are summarized in Table 2.

Table 2. Experimental parameters for EDM experiments

Polarity	Normal positive
Dielectric fluid	EDM oil, and Nanoparticle-based EDM oil
Flushing pressure	0.1 kg/cm^2
Gap voltage (V)	40 and 50
T_{ON} (µsec)	50 and 150
I (A)	3 and10
Drill depth (mm)	3 (constant)
Retract distance (mm)	2 (constant)

Although the pulse generator's maximum cur–rent capacity is 40 A, experiments were conducted at 3 A and 10 A to explore low-to-moderate discharge ener–gy under stable conditions. The selected current levels do not reflect the generator's maximum capabilities but are meant for specific operational stability in the study. Higher discharge currents were excluded from the study due to their significant impact on crater formation, deb–ris generation, and nanoparticle behavior. Investigating these effects was outside the scope of the current expe–riment, but their influence on machining perfor–mance is noted as an important area for future research.

2.2 Details of nanoparticles and nanodielectric

The present study considers the aluminium oxide (Al_2O_3) and graphene (Gr) nanoparticles owing to its desirable characteristics such as graphene has excep–tionally high electrical conductivity and thermal con–ductivity which significantly enhance spark initiation and plasma channel stability in EDM by forming tran–sient conductive bridges within the inter-electrode gap. Graphene has two-dimensional morphology which furt–her increases the probability of particle interaction, lea–ding to improved discharge frequency and energy distribution. Whereas Al_2O_3 nanoparticles, being elec–trically insulating with high thermal stability and hardness, act as discharge regulators by increasing inter-particle spacing and preventing continuous arcing.

The presence of Al_2O_3 promotes uniform spark dispersion and controlled energy release, resulting in finer crater formation and improved surface integrity. Considering these respective advantages of each nano–particle we have considered hybrid nano-dielectric. The hybrid combination of Al_2O_3 and graphene thus estab–lishes a synergistic mechanism, where conductive path–ways are effectively moderated by insulating particles, enabling stable plasma channel formation. The details of nanoparticles are as shown in Table 3.

Table 3. Specifications of nanoparticles

Characteristics	Nanoparticles	
	Al_2O_3	Gr
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

Methodology adopted to form the nanodielectric is shown in Fig. 2. The nanoparticle concentration in the dielectric oil was maintained at 0.5 g/L, with a 50:50 proportion of each nanoparticle, to formulate the hybrid nanodielectric [24]. After adding the nanoparticles to the base dielectric fluid (EDM oil), the mixture was subjected to 20 minutes of mechanical stirring followed by 20 minutes of probe ultrasonication to ensure proper dispersion and homogeneity. To enhance the stability of the nanofluid and to improve the zeta potential of nanodielectric, sodium dodecyl sulphate was incorpo–rated as a surfactant at a proportion equal to 0.1 wt.% of the total nanoparticle [25].

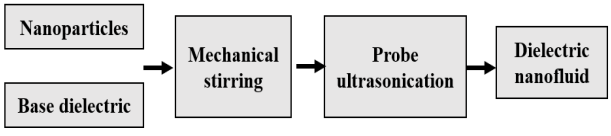


Figure 2. Nanodielectric preparation steps

2.3 Characterization of nanodielectric

The dynamic light scattering (DLS) analysis was done for evaluating dispersion quality of nanoparticles in dielectric fluid to get desired result in machining and results are as shown in Figs. 3-4. The particle size analysis using DLS revealed a Z-average diameter of 33.89 nm and 35.21 nm with a polydispersity index of 0.561 and 0.563, indicating a moderately broad size intensity distribution exhibited a dominant peak at approximately 44.65 nm and 45.17 nm, along with a secondary peak at 6.49 nm and 6.57 nm for Al_2O_3 and graphene, respectively, as shown in Figs. 3-4 suggesting a bimodal dispersion of nanoparticles. The nanoscale size range is favourable for enhancing spark initiation and plasma channel formation in EDM. The relatively high Polydispersity Index (PDI) indicates partial agglomeration, which may influence discharge stability. Therefore, to avoid the adverse effects of agglomeration, the study incorporated a continuous stirrer in the machining setup.

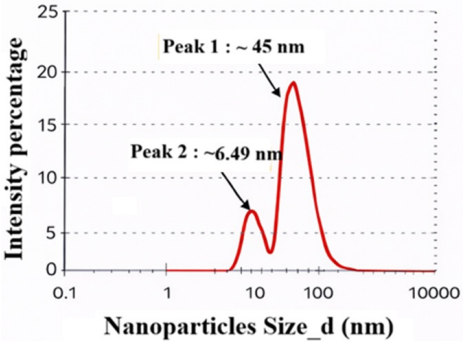


Figure 3. DLS analysis of Al_2O_3 nanodielectric

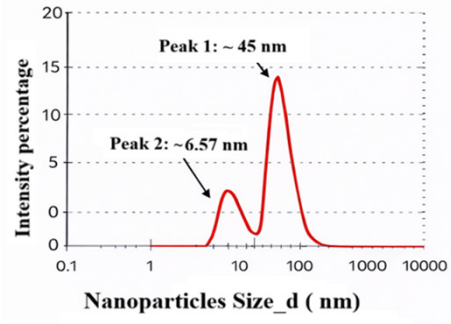


Figure 4. DLS analysis of Graphene nanodielectric

The X-ray diffraction (XRD) analysis of the Al_2O_3 and graphene nanoparticles as shown in Figs. 5-6. The Fig 5 revealed distinct and sharp diffraction peaks, confirming their crystalline nature. The prominent peaks observed in the 2θ range of 20°-70° correspond to characteristic planes of aluminium oxide, indicating phase purity and structural stability. The absence of any additional peaks suggests that no secondary phases or impurities were present. The high crystallinity of the nanoparticles is advantageous for EDM applications, as it ensures thermal stability under high discharge distribution for Al_2O_3 and graphene, respectively. The temperatures and consistent behaviour within the inter-electrode gap. XRD analysis of graphene in Fig. 6 shows a sharp peak at ~26° (002 plane), confirming the layered hexagonal structure of graphene with an inter–layer spacing of ~0.34 nm. Minor peaks near ~43° and ~54° correspond to the (100) and (004) planes. The narrow, intense (002) peak indicates good crystallinity and multilayer graphene. The DLS and XRD analyses of both Al_2O_3 and graphene confirm their suitability for EDM application and their potential to enhance machi–ning performance.

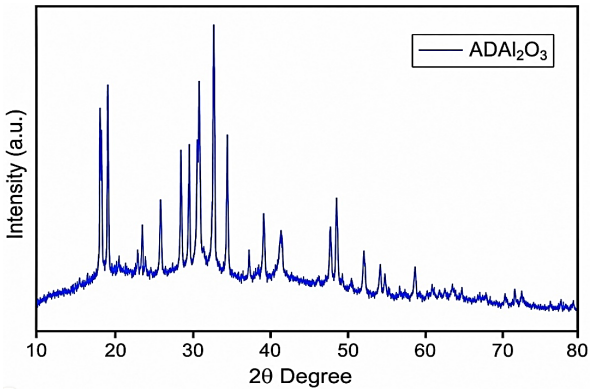


Figure 5. XRD analysis of Al_2O_3 nanoparticles

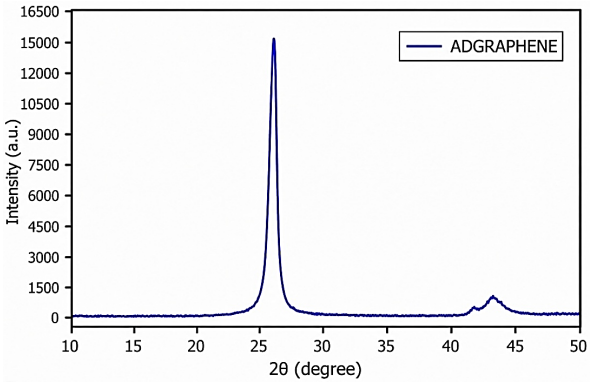


Figure 6. XRD analysis of Graphene nanoparticles

The output responses considered in this study inc–lude material removal rate (MRR), tool wear rate (TWR), roundness (Rou), surface roughness (Ra), ener–gy consumption (E) and overall eco-index (EI). The corresponding characterization methods and instruments employed for their evaluation are described below. The MRR of the EDM processed samples was measured using a weighing machine. It was determined by taking the difference between the initial and after weights of the workpiece (ΔW_w) and dividing it by the product of machining time (t) and work material density (ρ_w) as shown at (1):

$$\mathrm{MRR} = \frac{\Delta W_w}{t\rho_w}. \tag{1}$$

The surface roughness (Ra) of the EDM-machined specimens was measured using a stylus-type instrument. The measurements were carried out with a cut-off len–gth of 0.25 mm and a traverse length of 1.75 mm in accordance with ISO standards. For each sample, rea–dings were taken at three different locations, and the reported Ra value represents the average of three mea–surements. Tool wear rate (TWR) was determined using the same SCALE-TEC setup by calculating the diffe–rence between the tool weight before and after mac–hining (ΔW_T), divided by the product of tool material density (ρ_T) and machining time (t) as shown in (2):

$$\mathrm{TWR} = \frac{\Delta W_T}{t \rho_T}. \quad (2)$$

Roundness (Rou) of the machined features was eva–luated using a coordinate measuring machine. Energy consumption (E) was estimated from the product of discharge voltage (V), current (I) and machining time (t) as shown in (3).

$$\mathrm{E} = \mathrm{V}\, I\, t \quad (3)$$

The drilled hole edge accuracy, was examined using a MAZ-3020 video measuring machine. Analysis of the recast layer provides information on the thermal effects of EDM and the defects generated during the machining process which was measured using scanning electron microscope (SEM).

3. RESULTS AND DISCUSSION

This section presents the mechanisms of performance outcomes of EDM machining using plain dielectric and nanodielectric mediums. The different materials such as Inconel 718, EN24 and SS304 were analysed and effect of different parameters of EDM process together gives the sustainable, green and accurate and precise manufacturing, which ultimately contributes to the overall eco-index. Three different materials were taken in to consideration to investigate the uniformity of mechanism and outcomes of the study. The study examines the effect of conventional dielectric and nano-enhanced dielectric fluids on the cutting mechanisms of materials. The experimental cutting conditions were kept constant for all three materials, are displayed as shown in Table 4, with and without nanoparticles for all three materials. Experimental setup adopted in the study is shown in Fig. 7.

Table 4. Experimental conditions

Run	T_{on} (µs)	I (A)	Gap voltage (V)
1	50	10	40
2	150	10	40
3	50	10	50
4	150	10	50
5	50	3	40
6	150	3	40
7	50	3	50
8	150	3	50

3.1 Metal removal rate (MRR)

The MRR is an important parameter in the EDM pro–cess, which indicates the volume of material removed per unit time. It is primarily controlled by discharge energy, pulse duration, peak current, and thermo-physical properties of the work material. Materials are typically used in application where Inconel 718 is much stronger and more thermally resistant are used, and these will be found with lower MRR comparison with EN24 and SS304 with similar machining condition. Optimizing MRR is essential to optimize the product rate with surface integrity and the overall process sus–tainability [26,27].

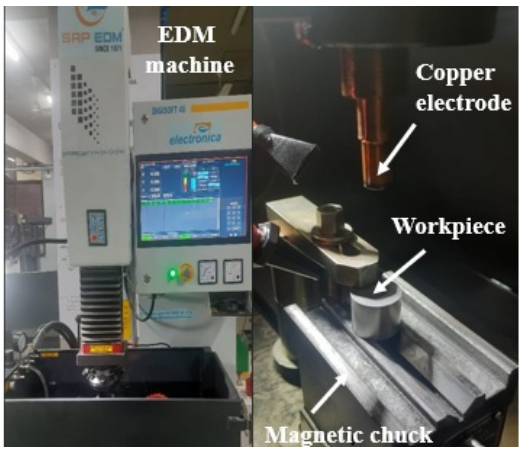


Figure 7. Experimental setup

The study examined that EDM performance, mainly MRR is largely determined by the discharge energy parameters and material properties, there are inherent trade-offs and balancing between productivity, tool wear, and surface integrity [28]. MRR is one of the key parameters that affects the energy efficiency and green manufacturing. This study was focused on all three materials under conventional and nano-dielectric fluids. The results show that nano-dielectric fluids have a posi–tive effect on MRR, as they promote an effective discharge under specified pulse energies. As shown in Fig. 8, enhancement was achieved by achieving impro–ved debris flushing, formation of conductive bridges, more stable initiation and growth of sparks leads to greater thermal erosion. Changes in alloying elements are related to electrical and thermal properties, that are related to the distribution of the spark energy and MRR. This enables correlation studies were conducted on the effect of nanoparticles on the relationship of material composition and machining efficiency in EDM [29].

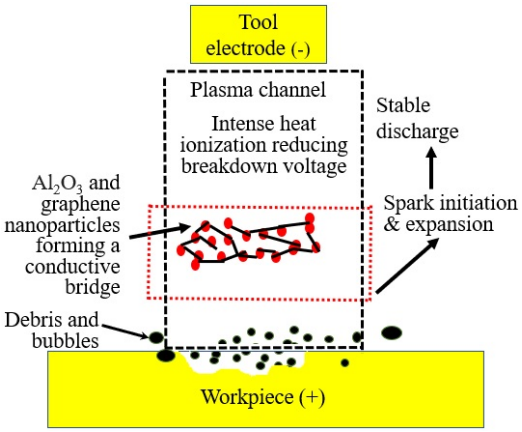


Figure 8. Material erosion in nanodielectric EDM

The highest MRR for the material EN24, followed by SS304 and the lowest for Inconel 718 as it can be seen from Fig. 9. It can be seen that MRR get sig–nificantly affected by the current followed by the pulse-on-time. However, this effect can be seen as more prominent for Inconel 718 and SS 304 as compared to EN 24. This effect is mainly controlled by the variation of thermo-physical and electrical properties of the materials. The MRR trend (EN24 > SS304 > Inconel 718) is due to the material properties. In the case of properties, the

increased thermal and electrical conduc–tivity of EN24 enables it to be used in spark efficient generation and heat dissipation, while Inconel 718, which has low thermal conductivity, high melting tem–perature, high corrosion resistance and high strength which yields the lower MRR. The enhancement in additional MRR is achieved by further adding Al_2O_3 and graphene nanoparticles, which help to improve the discharge behaviour. Graphene imp–roves electrical conductivity and sparks, and Al_2O_3 stabilizes the discharge and gives even energy distribution. These two combined contribute to the enhancement of plasma energy tran–sfer, debris removal and channel formation, resulting in a relatively high MRR.

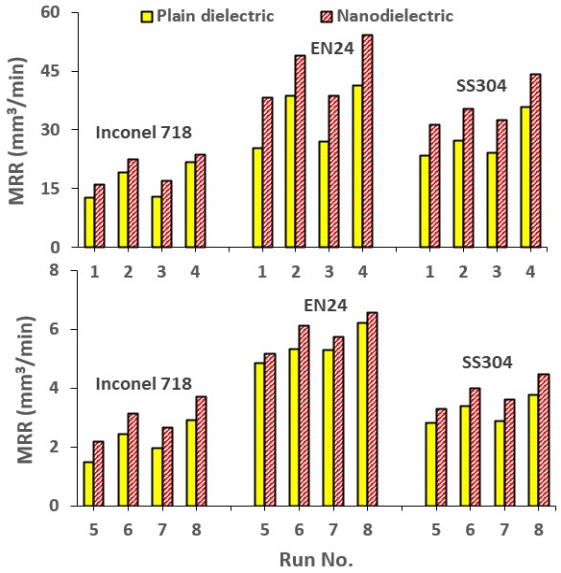


Figure 9. MRR varying with cutting conditions for different materials

3.2 Tool wear rate and surface roughness

The properties of the work material have a significant effect on tool wear rate (TWR), especially thermal conductivity and melting point. Inconel 718 has the highest tool wear among the materials studied as alloy has the lowest heat dissipation coefficient due to its complex alloy chemistry, while EN24 shows the lowest as it possesses the higher thermal conductivity amongst. The presence of nanoparticles in the dielectric has a significant effect on reducing the tool wear by stabilizing the discharge, enhancing the transfer of heat, and lower intensity of sparks. The hybrid nanodielectric demonstrates a clear synergistic advantage, making it an effective approach for enhancing tool life in EDM of difficult-to-machine materials [30-31]. With its relati–vely low thermal conductivity, Inconel 718 is a signi–ficant constraint in the field of EDM.

As shown in Fig. 10, the workpiece cannot extract heat fast enough, so discharge energy remains in the plasma region and is reflected back to the electrode. This high thermal load has a great effect on the erosion of the tool. In addition, hard intermetallic phases and recast layer thickness are obtained due to Nb, Mo and Ti con–tent. Such phenomena formations disrupt discharge stabi–lity, possible secondary sparking and localized arcing, causing further damage to the tool electrode. Fig.11 shows the similar results obtained for all three materials.

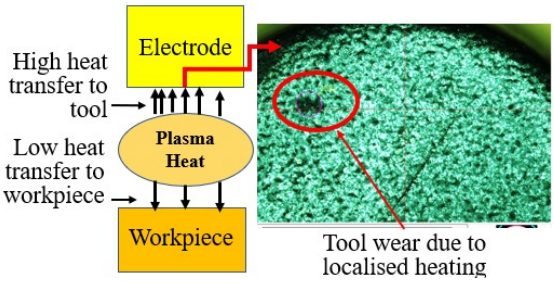


Figure 10. Tool wear due to localised heating

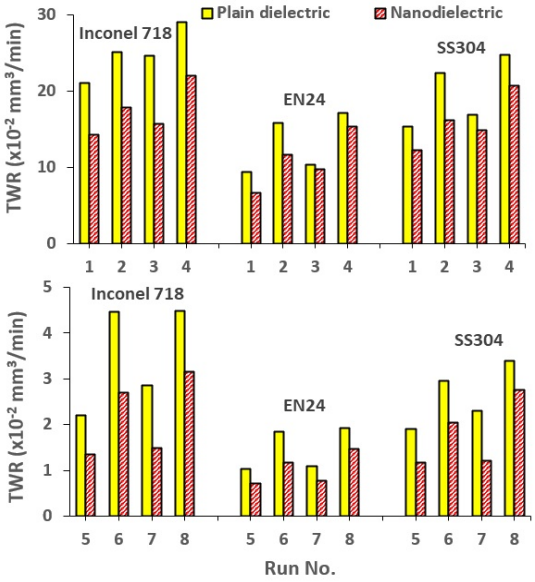


Figure 11. Tool wear rate varying with cutting conditions for different materials

The thermo-physical properties of the work material are known to have a significant effect on the surface roughness in EDM. Because EN24 material has a higher thermal conductivity, it is suitable for efficient cooling and uniform crater formation, making it the better finish to the workpiece. The surface quality of SS304 is moderate, whereas the surface quality of Inconel 718 is poor because there is heat accumulation and deeper surface discharge craters formation [32-34]. Nanodi–electric is used to improve the surface quality by stabi–lizing the spark and removing debris. The nanoparticles help to create a more even plasma channel which mini–mises erratic plasma discharges and improves the formation of smaller, evenly distributed craters in the machined surface. From Fig. 12, it is clearly seen observed phenomena.

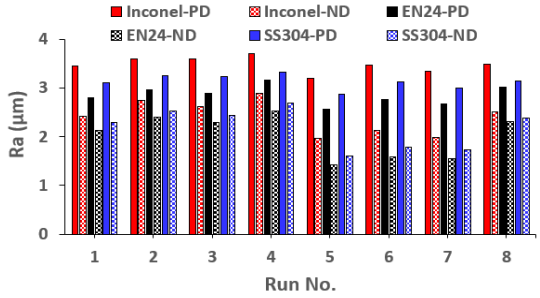


Figure 12. Surface roughness varying with cutting conditions for different materials

3.3 Roundness, edge integrity and recast layer

The thermal and electrical characteristics of the material to be drilled affect the roundness and edge quality of EDM drilling [35-36]. EN24 has a higher thermal conductivity and provides more uniform heat dissipation and stable spark erosion, leading to superior geometrical accuracy and cleaner hole edges. In SS304, the performance is moderate and there are slight deviations in shape and edge integrity. As can be observed in Fig. 13, the localized heat concentration, recast layer formation and irregular material removal gives highest rise to larger roundness errors and poor edge quality with Inconel 718.

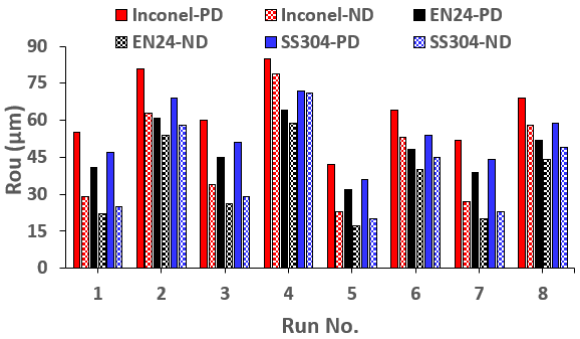


Figure 13. Roundness error varying with cutting conditions for different materials

To investigate the effect of discharge current and pulse-on time on roundness, polar plots were created for all three materials at higher discharge current and pulse-on time. Measurement was carried with average 500 data points measured around circumference with Low-pass Gauss type filtration method and cut off frequency was kept up to 50 UPR (Undulations per revolution) and Figs. 14-16 reveals that the nanodielectric gives a more uniform and circular profile of hole in comparison to the conventional dielectric oil across all three materials.

In case of nanodielectric, the radial variation has reduced and lobed discharge was not observed, indicating more stable discharge characteristics and a more uniform distribution of sparks. Experimental results revealed that the incorporation of nanodielectric enhanced geometrical accuracy during EDM machining. A substantial improvement in roundness was observed for Inconel 718 (56.99%), SS304 (44.44%), and EN24 (64.48%), yielding an average enhancement of 55.30% over machining without nanoparticle assistance. This enhancement is associated with a better debris removal and a more uniform plasma channel due to the introduction of nanoparticles [37].

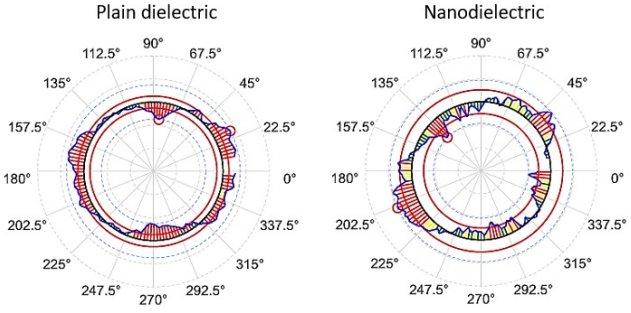


Figure 14. Polar plots for roundness: Inconel 718

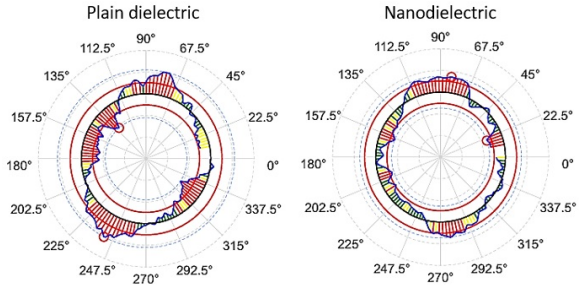


Figure 15. Polar plots for roundness: SS304

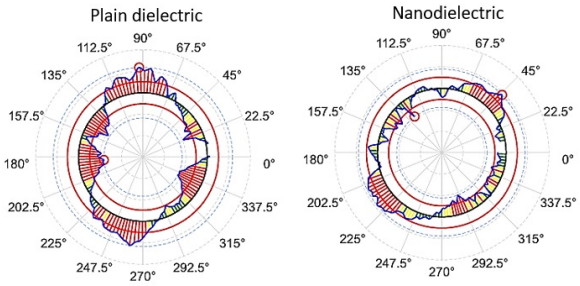


Figure 16. Polar plots for roundness: EN24

Materials with a high thermal conductivity will have smoother edges, and alloys such as Inconel 718 will create irregular edges and thicker recast layers. Nano–particle-based dielectric not only stabilizes discharges, but also increases the effectiveness of debris removal, which leads to higher and more even edge quality [38]. The materials in the present study and their edge quality for different machining parameters are illustrate in Fig. 17. To analyze the effect, the run with the highest cur–rent and pulse-on time (Ton) under both plain and nanodielectric conditions has been considered. Fig.17 clearly indicat that nanodielectric condition exhibited cleaner hole edges than plain dielectric conditions across materials.

During EDM machining, the intense local heat pro–duces melting and vaporisation of both the part material and the electrode material. The recast layer is formed when a portion of the molten material does not get comp–letely removed from the machine surface by the dielectric fluid, and resolidifies on the machine surface at a very fast rate. This layer then disturb the integrity of machined components mainly surface finish and other material properties. Thickness and properties of this layer will vary with discharge energy, pulse duration, flu–shing conditions and dielectric properties of the material.

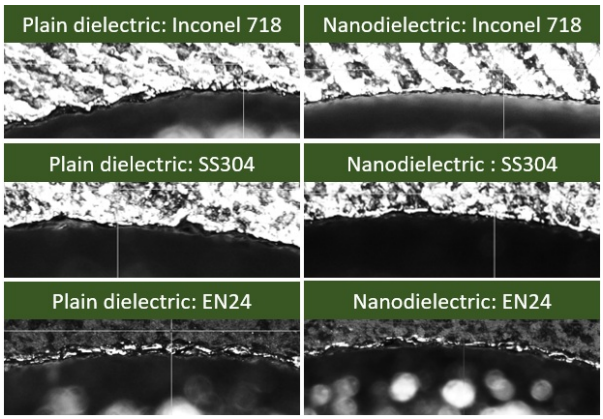


Figure 17. Drilled hole edge quality for different materials with plain and nanodielectrics

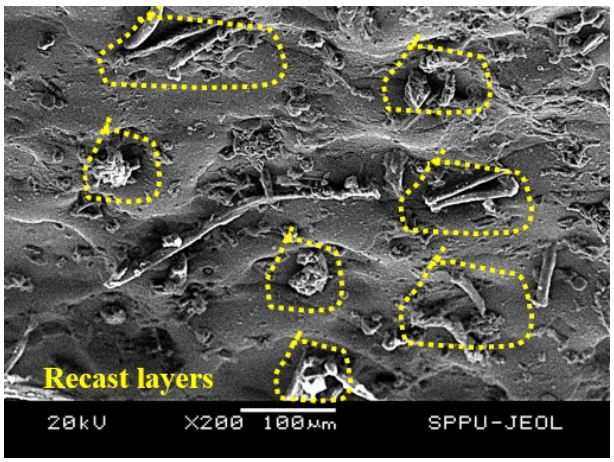


Figure 18. Recast layer formation with plain dielectric

For the nanoparticle-mixed dielectric EDM, the morphology and uniformity of recast layer can be en–hanced by the spark distribution and effective debris removal. To understand the effect on recast layer for–mation, one machining condition with higher parame–ters and for Inconel 718 among the three materials considered in the study, was selected for detailed analysis under both plain dielectric and nanodielectric conditions. Nanodielectric cutting conditions outper–forming the plain dielectric cutting conditions in terms of recast layer formations which can be predominantly seen from Figs. 18 and 19.

3.4 Energy consumptions and carbon footprint

Apart from the machining performance measu–rement like MRR and tool wear, surface rough–ness and cylindricity, energy consumption is one of the important indicators to assess the sustainability of the EDM process. This parameter not only allows an evaluation of the efficiency of the process but also its environmental impact especially in comparison with the conventional dielectric process. From Fig. 20, it is clearly seen that under nanodielectric condition energy consumption is substantially reduced in all the materials.

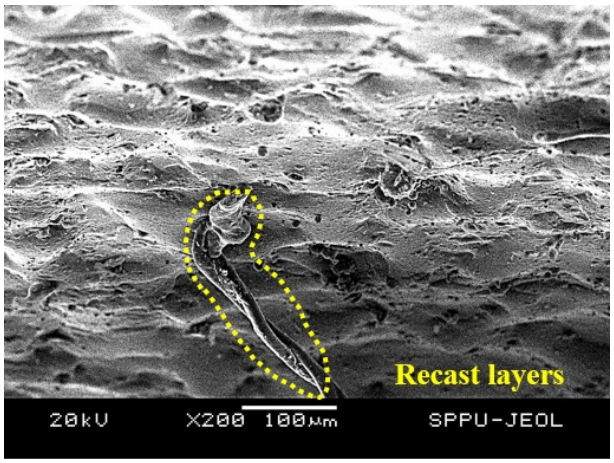


Figure 19. Recast layer formation with nanodielectric

Wherein Inconel 718 has the highest energy con–sumption, EN24 has the lowest and SS304 has moderate energy consumption. This is a major increase in the electricity consumption which leads to higher carbon emissions particularly in the context of fossil fuel-based energy supply. The overall carbon footprint is further increased due to the use of auxiliary systems such as dielectric circulation, cooling, and machine tool uses.

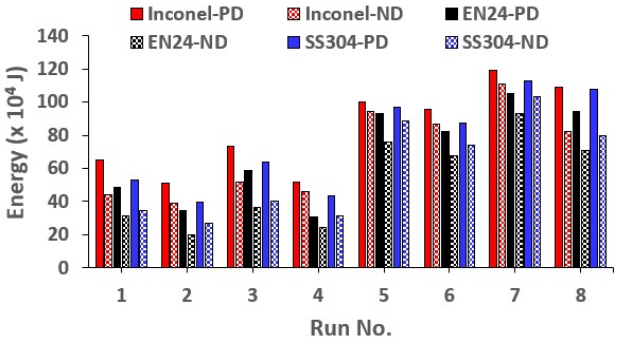


Figure 20. Energy consumption varying with cutting conditions for different materials

As electrical energy generation is closely associated with the carbon footprint of the EDM process, reduction in energy consumption directly contributes to the reduction of carbon footprints of the EDM process [39]. Using nanodielectric can enhance the efficiency of the machining process and minimize the amount of time required for the process, thus lowering the total energy consumption. Because of this energy savings, the number of emissions per tonne of material processed is also reduced, making the process more environmentally sustainable. Therefore, energy efficient operation of EDM is a key aspect for obtaining the green manufa–cturing. The study found that machining plays a critical role in the sustainability and carbon footprint generation [40]. The combination of multi-energy fields, high-per–formance lubricants and nanostructured technologies significantly optimises the performance of the machine and the quality of the surface of the material being processed, even in difficult-to-cut materials. These stra–tegies are important for high efficiency, low carbon and sustainable production. The overall contribution of carbon footprint from manufacturing sector at global level was 37.4 (Gt) in 2023 [41].

3.5 Eco-Index evaluation

The Eco-Index is a crucial index to evaluate the overall sustainability of EDM process since it gives a more holistic evaluation than the traditional performance measures of EDM. It represents the overall environ–mental, energy and machining performance. This helps to determine the effectiveness of EDM in both the environment and operation. The Eco-Index value depi–cts the machining efficiency and sustainability, which are helpful for determining process conditions that mi–nimize environmental impact [42]. In this study, some of the parameters of EDM that influence the sustai–nability and machining quality were taken into consi–deration. Numerical index was introduced, which merges the parameters of interest such as energy con–sumption (E), tool wear rate (TWR), material removal rate (MRR), roundness error (ρ) and surface roughness (R□). The parameters were assigned equal weightage that were based on process parameter significance for

overall process sustainability. Table 5 shows the individual responses, their optimization criterion, and their corresponding weighting factors.

Table 5. Specifications of nanoparticles

Responses	Optimization criterion	Weighting factor
Material removal rate (MRR)	Higher is better	0.2
Tool wear rate (TWR)	Lower is better	0.2
Surface roughness (R□)	Lower is better	0.2
Roundness error (ρ)	Lower is better	0.2
Energy consumption (E)	Lower is better	0.2
Total		1.0

All the experimental responses were then normalized with the maximum and minimum values of the experiments after the weights were assigned. All the parameters were normalized using the min-max normalization method, which transformed each parameter into the range 0 to 1 to make comparisons among different responses possible. Each response was first normalized to a dimensionless scale between 0 and 1 to eliminate differences in units and magnitude. For beneficial responses (where higher values are desired), (4) was used, and for non-beneficial responses (where lower values are desired), (5) was used for the normalization procedure [43]. The normalized objective parameters were subsequently combined using their respective weighting factors to obtain the overall Eco-Index.

$$x_{norm}\ \text{(Higher is better)} = \frac{x - x_{\min}}{x_{\max} - x_{\min}} \qquad (4)$$

$$x_{norm}\ \text{(Lower is better)} = \frac{x_{\max} - x}{x_{\max} - x_{\min}} \qquad (5)$$

The incorporation of nanodielectric resulted in a noticeable enhancement in eco-index for all investigated materials compared to plain dielectric EDM. The eco-index improved by approximately 17.63% for Inconel 718, 28.37% for EN24, and 9.79% for SS304, demonstrating the positive contribution of nanoparticle-assisted dielectric towards sustainable machining performance as shown in Fig. 21.

Further investigations are needed to broaden experimental ranges by incorporating different discharge-current regimes, pulse characteristics, nanoparticle properties, and flushing strategies to improve the understanding of nanoparticle-assisted discharge behavior. Attention is needed on higher discharge energy effects regarding nanoparticle transport, dispersion, agglomeration, and material removal mechanisms. The creation of larger experimental databases integrated with machine learning and real-time monitoring could lead to predictive machining systems.

The study emphasizes the useful applications of nanoparticle-assisted EDM in precise machining of difficult engineering materials, particularly for the die-and-mold, advanced manufacturing, automotive, biomedical, and aerospace industries. This method is beneficial for creating complex geometries and precision components, wherein traditional machining faces limitations such as high tool wear and suboptimal surface quality.

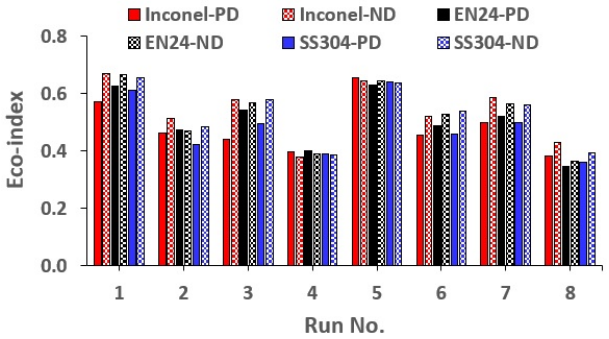


Figure 21. Eco-index varying with cutting conditions for different materials

From an industrial viewpoint, the process encompasses precision machining and surface modification of high-value components. The identified parameters can guide suitable operating conditions for desired machining performance and support the development of predictive models and multi-objective optimization frameworks. Nonetheless, large-scale implementation necessitates additional investigation.

4. CONCLUSION

The following conclusions could be drawn from the present study:

- The study shows that the addition of nanoparticles to dielectrics (Al_2O_3+graphene) significantly improves the performance of EDM under the studied conditions for all three materials; Inconel 718, EN24 and SS304, by providing better plasma channel stability and spark uniformity.
- The increase in material removal rate (MRR) was about 21.62% for Inconel 718, 43.98% for EN24, and 39.31% for SS304, with an average increase of 34.97 % with the use of nanodielectric compared to plain dielectric.
- The use of nanodielectric significantly reduced the tool wear rate (TWR) about 81.74% for Inconel 718, 87.67% for EN24, and 77.15% for SS304.
- The nanodielectric decreased the surface roughness of the drilled hole by around 25.91% for all the investigated materials compared to EDM drilling with plain dielectric. This shows enhanced machining stability and superior surface quality, due to a controlled distribution of the discharge energy and better heat transfer inside the machining zone with the use of nanodielectric.
- Substantial improvement in roundness was observed for Inconel 718 (56.99%), SS304 (44.44%), and EN24 (64.48%), yielding an average enhancement of 22.01% over machining without nanoparticle assistance. Polar plots showed a lower radial deviation and had minimal localized deviation (lobing) with nanodielectric.
- The improved edge integrity and smaller recast layer thickness with nanodielectric confirm stable material removal with lower thermal damage. The use of nanoparticles resulted in better debris evacu–

ation and uniform crater formation which led to better machining of a EDM drilled hole.

- The energy use was reduced under nanodielectric conditions that led to reduction in carbon footprint. The eco-index was improved by 17.63% for Inconel 718, 28.37% for EN24, and 9.79% for SS304 and the average improvement was 18.60%.
- Discharge current and pulse-on time notably influenced EDM performance, particularly with Inconel 718 and SS304. However, this effect was more prominent for plain dielectric conditions.
- Al_2O_3–graphene nanodielectric provided better EDM drilling performance against plain dielectric for Inconel 718, EN24, and SS304 confirms its suitability as a better nanodielectric for EDM of engineering materials.
- Further investigations are needed to broaden experimental ranges by incorporating different discharge-current regimes, pulse characteristics, nanoparticle properties, and flushing strategies to improve the understanding of nanoparticle-assisted discharge behavior. Attention is needed on higher discharge energy effects regarding nanoparticle transport, dispersion, agglomeration, and material removal mechanisms

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NOMENCLATURE

Al_2O_3	Aluminium oxide
ANN	Artificial Neural Network
DLS	Dynamic Light Scattering

EDM	Electrical Discharge Machining
EI	Eco-Index
Gr	Graphene
MRR	Material Removal Rate (mm^3/min)
PMEDM	Powder-mixed Electrical Discharge Machining
PDI	Polydispersity Index
SEM	Scanning Electron Microscope
T-GRA	Taguchi-based Grey Relational Analysis
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TWR	Tool Wear Rate (mm^3/min)
UPR	Undulations per Revolution
XRD	X-ray Diffraction

Symbols

ρ_w	Work material density (g/cm^3)
ρ_t	Tool material density (g/cm^3)
E	Energy consumption (J)
I	Discharge Current (A)
V	Discharge Voltage (V)
t	Machining time (S)
T_{on}	Pulse-on Time (μS)
R_a	Surface roughness (μm)
R_{ou}	Roundness (μm)
ΔWw	Difference between the initial and after weights of the workpiece (g)
ΔW_T	Difference between the tool weight before and after machining (g)

ЕЛЕКТРОЕРОЗИЈСКО БУШЕЊЕ МАТЕРИЈАЛА INCONEL 718, SS304 И EN24 У УСЛОВИМА ОБИЧНОГ И ХИБРИДНОГ ДИЕЛЕКТРИКА СА МЕШАВИНОМ НАНОЧЕСТИЦА

П. Кулкарни, С. Чинчаникар

У електроерозијској обради (EDM), проводни диелектрици са мешавином наночестица показали су боље перформансе обраде, иако је њихов утицај на индексе еколошких перформанси за различите инжењерске материјале коришћењем хибридних диелектрика са мешавином наночестица још увек мање истражен. Са овим циљем, ова студија истражује електрично ерозијско бушење материјала Inconel 718, SS304 и EN24 варирањем времена импулса, струје пражњења и напона размака, користећи и обичне и хибридне мешавине наночестица графена и алуминијум оксида у диелектрику. Струја пражњења и време импулса значајно су утицали на перформансе електричне обраде, посебно са Inconel 718 и SS304 у условима обичног диелектрика. У поређењу са конвенционалним диелектрицима, нанодиелектрици су показали побољшање брзине уклањања материјала за 34,97%, смањење храпавости површине за 25,92%, смањење брзине хабања алата за 77,15% и мању грешку округлости за 22,01%. Поред тога, потрошња енергије је смањена за 18,11%, што је допринело повећању укупног еко-индекса од 18,6%. Смањено формирање рециклираног слоја додатно је потврдило побољшане термофизичке интеракције са нанодиелектриком, што указује на побољшане еколошке перформансе за електричну обраду.