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EDM of Ti6Al4V under nano graphene mixed dielectric: A detailed roughness analysis

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Abstract

Surface finish has an essential role in superior performance of machined products which becomes crucial for sophisticated applications like invasive biomedical implants and aerospace components. Ti6Al4V is popular in these applications due to its exceptional characteristics of weight-to-strength ratio. However, Ti6Al4V is a difficult-to-cut material, therefore, non-traditional cutting techniques especially, Electric Discharge Machining (EDM) are widely adopted for Ti6Al4V cutting. The engagement of nano powders are used to upsurge the cutting rate and surface quality. Among the different powders a novel nano-powder additive i.e. graphene has not been tested in EDM of Ti6Al4V. Therefore, the potential of nano-graphene is comprehensively investigated herein for roughness perspective in EDM of Ti-alloy. The experimental design is based on Taguchi L18 orthogonal framework which includes six EDM parameters. The experimental findings are thoroughly discussed with statistical tests and physical evidence. The surface quality achieved with an aluminum electrode was found best amongst its competitors. Whereas, the worst surface asperities were noticed when brass electrode was used under graphene mixed dielectric. Moreover, it is conceived that the positive tool polarity provides lower roughness for all types of electrodes. Furthermore, optimal settings have been developed that warrant a reduction of 61.4% in the machined specimen's roughness compared to the average roughness value recorded during the experimentation.

Keywords: EDM; Nanoparticles; Graphene; Roughness; ANOVA; Titanium; Polarity; Aluminium; Brass

1. Introduction

In the advanced era of material & technology, new engineering materials have been developed that possess high strength, making them difficult-to-machine with traditional machining processes. Ti6Al4V, which has attained global attention for many industrial applications, belongs to the said materials' category. Its key characteristics, such as high durability, low thermal conductivity, less reactivity, as well as high elastic modulus, are the sources that provoke its cutting difficulty [1]. In that perspective, researchers have diverted their focus from traditional to non-conventional technologies to cut the said alloy. Among different cutting alternatives Electric Discharge Machining (EDM) has secured an important place due to its cutting versatility specifically for electrically conductive material regardless of their mechanical characteristics [2, 3]. This process was introduced by B. R. Lazarenko et al. [4] about six decades ago, who used repetitive sparks produced between the tool and workpiece to machine cavities in the substrate. Later on, the importance of EDM was emphasized, and it has been deployed in making dies & molds, biomedical parts, aerospace components, automobile, and military applications [5–7].

EDM, a Spark Erosion process, operates on the thermoelectric energy principle [5, 8]. It uses thermal and electrical energy to generate a series of electric sparks by discharging the dielectric fluid present in the inter-electrode space. This produces an intense pulse discharge and forms a plasma channel that leads to material erosion from the workpiece/specimen. The discrete repetitive sparking generally raised the temperature up to 12,000ºC, which is enough for the melting & vaporization of the specimen. The eroded particles (chips) over the surface of the workpiece are flushed away with the help of dielectric liquid pumped into the machining zone [9, 10].

Considering the supremacy of EDM, it is employed herein for the cutting of Ti6Al4V, which is renowned for its strength, wear resistance, toughness, and good surface protection against corrosion even at high temperatures [11]. The aforementioned significance promotes the use of Ti-alloy in biomedical, aerospace, petrochemical, and many other superior technologies [12]. Although the EDM can match the requirements of the stated applications of the selected material. However, it works based on a slow-cutting mechanism. The powder base additives are commonly used to enhance the cutting rate and to improve surface finish of the cut specimen. It is vital to observe that surface quality has a direct bearing in deciding the functional characteristics of the product like abrasion, wear resistance, fatigue, and light reflection [13]. Moreover, in biomedical applications, surface roughness (SR) plays a pivotal role in amplifying the biochemical characteristics and furnishing adequate stress distribution. It also assists in the clinical site to stimulate and promote osseo-integration and bone interlocking, respectively. The previous literature has confirmed that a suitable SR value (Average Surface Roughness – R_a) should be around 1 μm to 1.5 μm to develop a perfect fixation of the biomedical implant [14]. Therefore, the achievement of a suitable magnitude of SR for Ti6Al4V is crucial as far as its applications are concerned.

Multiple researchers have been found on SR perspective with different kinds of electrode materials, i.e., copper, aluminium, brass, graphite, tungsten, steel, and other materials under powder-based dielectrics [15]. For instance, Tiwary et al. [16] probed the impact of various combinations of dielectric during micro-EDM of Ti6Al4V. It was concluded that deionized water with Cu-powder can provide smaller craters that eventually translate into lower SR. Rafal and Dorota [17] examined the cutting potential of reduced graphene oxide (RGO) mixed dielectric during EDM of heat-treated steel (55NiCrMoV7) employing Cu electrode. It was claimed that discharges during a single pulse got multiplied under RGO flakes mixed dielectric. Eventually, SR magnitude got compromised. Al-Amin et al. [18] claimed that powder mixed EDM (PM-EDM) increases surface texture and enhances the mechanical characteristics of biomaterials such as Ti-alloys and also improves the surface integrity of machined specimens. The potential of graphene-based dielectric while EDM of Inconel 718 using Cu-tool was studied in another research. It was cited that the immensity of surface integrity is lower at a current of 2 A and a pulse on-time of 10 μsec, respectively [19].

Khan et al. [20] inspected the role of Al_2O_3 (alumina) based dielectric on SR magnitude using Cu electrode while machining of AISI 304 steel. They employed a 0.3 mg/L concentration of alumina in a dielectric medium and proposed a statistical model. They suggested that the value of SR reduces as alumina powder is mixed in the dielectric liquid. Sugunakar et al. [21] deliberated the performance of PM-EDM on surface integrity of a Nickel alloy (RENE 80). They considered pulse on-time/off-time and current as design variables by varying powder types such as aluminium (Al), graphite (Gr), and a mixture of Al-Gr. They proposed that a rise in Al powder concentration from 0g/L to 9g/L in the dielectric considerably improves the surface integrity of the said alloy along with the greater reduction in recast layer over the specimen's surface. Ayanesh and Anand [22] summarized a review on PM-EDM. They presented that EDM under powder mixed dielectric widely improved the SR and raised the MRR, which are generally the more outstanding issues of EDM under fundamental dielectric conditions. They concluded that PM-EDM enhances machining performance and assists in attaining a mirror-like surface finish. Similarly, Mohd et al. [23] also made a comprehensive discussion about PM-EDM. They said that adding powder in dielectric leads to amplifying the response parameters of EDM like MRR, EWR, with a lower value of SR. Lamichhane et al. [24] have modified the surface of 316L stainless steel (SS) (a good biocompatible material for bone's implants) in PM-EDM by employing hydroxyapatite nano-powder (HNP) in the cutting regime. They described that surface of SS 316L is decreased when the dielectric has been practiced the HNP. It is well known that mixing of nanopowders in the dielectric liquid not only improves the surface finish but the machining efficiency is also greatly improved as evidenced by aforementioned studies. Beside these, literature also demonstrated that addition of powder improves the process efficiency rather than increasing the surface roughness. Such as Ayanesh and Anand [22] stated in their review article that mixing of SiC powder in the dielectric medium raises the MRR, TWR, and SR. In this article, they also studied the effect of various powders on the machining efficiency. And they come up with a conclusion that PM-EDM plays a crucial role for upsurging the said responses.

A careful review of available literature depicts that graphene-based dielectric contributes positively to improving the cutting rate in EDM [25, 26]. However, the improvement in cutting rate also demands to have a fine machined surface quality to justify its use in electric discharge cutting of Ti6Al4V. The addition of nanoparticles is likely to be the source of discharge energy drop because of their inclusion between the electrode and workpiece gap. The inadequate check on discharging can result in confined sparking between tool and specimen that leads to poor surface finish. As mentioned earlier, the significance of surface quality can never be neglected in EDM. More specifically, the materials that have their uses in critical applications like in biomedical and aerospace, high surface finish is essential for accurate part functionality. The authors have already evaluated the effect of graphene nano-particles on the material removal rate (MRR) and tool wear rate (TWR) during EDM of Ti6Al4V. The investigation successfully claimed that graphene nano-particles notably raised the MRR magnitude and lessened the TWR [5]. However, the aspect of the performance of graphene mixed dielectric in terms of surface roughness has yet to be comprehensively studied which is a crucial requirement to justify the suitability of machined parts in its intended application. Therefore, the focus of this research is to investigate the cutting potential of nano-graphene mixed dielectric in terms of surface quality while performing EDM of Ti6Al4V. Furthermore, the selection of the best electrode in graphene mixed dielectric for surface finish perspective has also been performed herein. In this context three electrodes namely, brass, aluminium, and copper have been engaged in this study. Experimentation was conducted under Taguchi's L18 design using nano-graphene mixed dielectric. The experimental outcomes were thoroughly analyzed employing optical and scanning electron microscopic evidence. An optimal parametric setting for improved surface quality has also been proposed and authenticated.

2. Materials & Methods

The recent study practices Ti-alloy (Ti6Al4V) as a working specimen. The composition of Ti-alloy (Ti6Al4V) has been verified through atomic emission spectrometry and tabulated in Table 1. The salient traits of the work part are illustrated in Table 2 [27, 28]. The dimension of the work part, such as length, breadth, and thickness, has been taken as 90 mm, 80 mm, and 15 mm, respectively. The experimentation has been completed on a die sinker EDM (model: RJ-230) against three electrodes having the same diameter of 9 mm and distinct tool materials viz aluminium (Al), brass (Br), and copper (Cu). The schematic of machining arrangement for the processing of Ti-alloy is portrayed in Fig. 1.

The current experimental framework comprises a stirrer for making a homogeneous blend of graphene nano-platelets (GNPs) in the dielectric regime. The micro impressions of 0.2 mm depth were machined in the work part under a dielectric mixture of kerosene oil with graphene (0.5 g/l). The use of graphene powder is attributed to the fact that it has extensive mechanical and electrical properties, which allows it to examine in different application areas such as sensor devices, capacitors, and micro-organism repellency [29]. The prime attributes of graphene nanoparticles are demonstrated in Table 3. However, the dissemination of sparking may

compromise the quality of the machined profile. Therefore, in this research the surface quality aspect of Ti-alloy has been analyzed in terms of SR against six essential input variables, i.e., tool polarity (TP), electrode material (E), discharge current (DC), pulse time ratio (PTR), spark voltage (SV), and flushing time (FT). The choice of the aforementioned design parameters was based on two key considerations, i.e., (1) impact of a particular variable is not previously explored on the output response, (2) or output response is strongly affected by the input parameters [5]. The other control factors were adjusted as constant in this work. To define the parametric levels, preliminary trials were accomplished before the actual experimentation. All electrode types were considered during initial trials. The defined levels of each parameter are expressed in Table 4. All decided parametric levels were repeated to get a complete machining impression in actual experimentation. Because it was witnessed in Fig. 2 that intense burn marks and unusual impressions were generated on the workpart due to excessive tool heating. So, after preliminary trials, those levels have been defined for the input variables which ensure the availability of complete machining impression. Besides the selected input parameters, discharge energy (E_d) is also a chief parameter of EDM and depends on three factors such as discharge voltage (U_e), discharge current (I_e), and pulse duration (t_i), as shown in equation 1 [30]. Since, the aforenamed three independent variables were not fixed in this study, therefore, value of discharge energy was also varying accordingly from level 1 (450 µJ) then level 2 (1600 µJ) to level 3 (3750 µJ). The actual machining has been performed under Taguchi L18 orthogonal design of experiments, which has been validated as a promising design strategy in literature [31]. ANOVA (Analysis of Variance) is also done to evaluate the most contributing variables, which greatly impact surface quality.

$$E_d \ (\mu J) = U_e \ (Volts) \times I_e \ (Amperes) \times t_i \ (\mu sec) \tag{1}$$

It is pertinent to notice that SR has several features of surface asperities, such as R_a, R_t, and R_z. However, this work is entirely focused on R_a magnitude which is simply defined as the average value of calculated surface's peaks and valleys. After completion of experiments, the magnitudes of SR in terms of R_a were obtained with the help of the surface roughness meter (Model: Surtronic S128) by Taylor Hobbson. Evaluation length was set at 4 mm during measurement whereas cutoff was set at 0.8 mm. 3D surface plots were also made with the help of optical profilometer (Contour GT-K) manufactured by Bruker. For each of the 3D surface plot, an area of 2.2 mm × 1.7 mm was scanned and an average value was reported. For analyzing the outcomes comprehensively, the impact of input parameters on SR has been examined statistically by developing parametric plots of mean values. The R_a values were evaluated against all parametric levels of the selected design variables. In order to have a detailed insight of the process variables impact on the SR, optical and scanning electron microscopic (SEM) analyses were performed. For SEM analysis scanning electron microscope (Model: VEGA3) manufactured by TESCAN was used. Finally, an optimal setting was suggested and validated for minimum roughness during EDM of selected workpart.

3.   Results & Discussion

The experimental trials were completed under Taguchi L18 design, and the roughness value is measured for each machined sample. Five roughness measurements were recorded and then the average is reported. The magnitude of design parameters and the respective outcomes are expressed in Table 5.

Afterwards, ANOVA was employed to segregate the remarkable control factors for SR. The analysis was done at a confidence level of 95%. The ANOVA findings are mentioned in Table 6. The collected outcomes from the ANOVA table revealed that there are mainly two significant factors, namely, electrode type & spark voltage having p-magnitude equal to 0.004 and 0.047, respectively. After getting results from experiments, main effect plots were made to foresee the trend of selected variables on the output response (R_a), as shown in Fig. 3.

The parametric shift of polarity illustrated in Fig. 3 depicts that a lower magnitude of roughness is obtained at positive tool polarity. The positive polarity of the EDM designates that the tool is positively charged, and the workpiece carries an opposite charge while vice versa is valid for negative tool polarity. It has been inferred from Fig. 3 that there is not a large difference between roughness values achieved with the two modes of polarities. This detection is in accordance with the ANOVA results shown in Table 6, where it has been demonstrated that polarity bears an insignificant contribution to determining the roughness of the machined cavity. Basically, when Ti6Al4V is machined under powder (nanoparticles graphene) mixed EDM at negative polarity, more energy is liberated with the ionization of nanoparticles in the discharging gap. Thus, a large number of positive ions strike the workpiece forcibly and as a result, SR is compromised. This increment in SR is attributed to the formation of the large-sized craters that are also manifest in the optical micrographs (Fig. 4) taken for the machined cavities at negative electrode polarity. Contrarily, the positive polarity exemplifies that the usage of graphene generates a better surface because erosion takes place in a stable manner until the entire machining operation is finished. It is pertinent to note that positive polarity of electrode not only enhanced the surface finish but the tool wear rate (TWR) is also gets smaller. This aspect of TWR has been already examined and published by authors for the graphene mixed EDM of Ti6Al4V [5]. They claimed that positive tool polarity assists in spark stabilization due to excessive heat dissipation in the surface of workpart after pulse duration. As a result, TWR is reduced. For the purpose of comparison between SR and TWR of the current and published study, respectively, against positive tool polarity, it can be concluded that positive electrode polarity has competence to decrease both SR and TWR when graphene nanopowders are added in kerosene dielectric while cutting of Ti6Al4V through EDM. In a nut shell, to get a better surface finish with smooth asperities in EDM of Ti6Al4V, positive polarity under emulsion of graphene nano-powder is recommended.

The impact of electrode material can never be neglected in EDM. The significant role of the said control variable has also been witnessed herein, as can be seen in the ANOVA results presented in Table 6. Electrode material turns out to be highly influential variable for determining the SR in EDM of the Ti6Al4V under the nano-graphene mixed dielectric. Three distinct electrodes viz Al, Brass, and Cu were selected to carry out the EDM of Ti-alloy (Ti6Al4V) by utilizing the

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graphene nanoparticles in the kerosene oil. The effect of the aforementioned electrodes on the magnitude of SR is illustrated in Fig. 3. It has been ascertained that the aluminium is performing better than brass and copper tool materials in terms of better surface quality in electric discharge cutting of the selected alloy. The reason for this shift corresponds to the low melting point of Al (933.45 K) followed by Br (1203.15 K) and Cu (1357.77 K) materials. This low melting temperature of Al-tool cause more severe burn on the electrode surface irrespective of workpart material. Therefore, large amount of material chipped out from the electrode and imparted less deep craters on the specimen's surface as furnished in Fig. 5(a). Contrarily, Br is giving poor surface finish owing to its low thermal conductivity (1.09 W/cm-^{o}C) as compared to Al (2.05 W/cm-^{o}C) and Cu (4.13 W/cm-^{o}C) electrode. The low value of thermal conductivity in the presence of graphene nanoparticles promote the heat energy in the plasma channel. This helps to disperse the sparking over the machined surface causing rough impressions with intense craters on the operated surface as demonstrated by micrographs presented in Fig. 5(b). Whereas, the copper tool again provides lower SR but not as good as Al-electrode does. The trend behind this change is due to adherence of a large number of carbon particles with the tool surface which tend to decrease the SR as well as leaving fewer wide craters on the workpiece as portrayed in Fig. 5(c). The adherence of carbon particles is evidenced in case of Cu owing to its sticky nature. Therefore, the surface quality of Ti-alloy is upgraded. The overall comparison between the selected electrodes in terms of producing different sizes of craters is evident in SEM images, as shown in Fig. 6. The machined surface obtained with Al electrode is observed to be the better one in comparison to rest of the electrodes where shallow craters are noticed as portrayed in Fig. 6(a). The surface is crowded with deep craters when brass electrode is engaged as depicted in Fig. 6(b). The surface asperities achieved with the Cu electrode are better as compared to that obtained with brass as highlighted in Fig. 6(c). It has been claimed that SR is improved when Al-electrode is utilized during EDM of Ti-alloy under graphene-kerosene dielectric emulsion.

The second significant factor after the electrode material is SV, as indicated by ANOVA in Table 6. The effect of SV on SR magnitude is highlighted in Fig. 3. It comprises three levels, i.e., 3V, 4V, and 5V. The SR value upsurges as SV rose from 3V to 4V and afterwards no significant rise is observed in the magnitude of SR as SV promotes from 4V to 5V. The primary reason for the first alteration in SR is linked with the empowerment of spark energy which creates ionization of the nano-powder. Subsequently, a powerful explosion yields a large amount of discharge energy which gives rise to the creation of large size craters on the specimen's surface, as presented in Fig. 7. A similar finding has also been reported in another study conducted in EDM of Nitinol [32]. Therefore, 1st level of SV is most preferable for getting a good surface finish in EDM of Ti6Al4V.

The effect of DC has also been investigated on SR during EDM of Ti-alloy under graphene mixed dielectric, as presented in Fig. 3. In this investigation, R_a is assessed against three levels of DC such as 6 amps, 8 amps, and 10 amps. It has been inferred that with an increase in the value of DC from 6 – 8 amps, the SR magnitude decreases as portrayed in Fig. 3. The reduction in SR

with an increase in DC has also been witnessed in another study carried out on the same substrate [33]. The reduction of SR from 6 – 8 amps is accredited to the availability of the necessary discharge strength in the cutting regime owing to the presence of nano graphene in the dielectric. The existence of high energy discharges provides a valuable heat input that efficiently removes the work material. Moreover, this heat energy keeps the melt pool in place for a bit longer time, which helps to flush the melted debris. Thus, the chances of the re-deposition of the melted droplets reduce, which leads to the achievement of low SR. The reduction in re-deposition is also witnessed in optical micrographs shown in Fig. 8(a). Moreover, it also generates fewer peaks to valleys impressions as characterized in a graph presented in Fig. 8(b). Therefore, the magnitude of SR got reduced. Whereas, further increase in the current up to 10 amps improves the SR due to higher discharge energy. It is important to mention that the existence of nano-graphene particles also provokes the discharge energy to a further extent. The combined effect of high DC along with the graphene results in a powerful explosion at the machined area. Consequently, the localized heat input to the target surface forms deep craters on the machined profile which gives rise to the SR. Hence, 2nd level of DC is more suitable for getting good surface quality.

It is well-established fact in EDM that it works on the melting and vaporization of the work part. However, the phenomenon of melting and flushing are continued through a spark cycle. Melting occurs in the on-time part of the pulse, whereas flushing occurs during the off-time period. A proper match between the two is essential to avoid the re-deposition of the melted debris. Especially, the role becomes more crucial if certain nanoparticles are mixed in it like graphene in this case. Therefore, this parameter got investigated herein and its trend is demonstrated in Fig. 3. Based on the results depicted in Fig. 3, it is concluded that 1st level (0.5) of PTR is more beneficial in terms of good surface quality followed by 3rd (1.5) and then 2nd level (1.0). The reason for the increasing trend of SR with PTR from 0.5 to 1.0 is mainly due to a rise in the value of Ton as PTR is a fraction of on-time by off-time. As Ton progressed the more energy is focused on the work part because of longer pulse duration resulting in deep and wide craters. Moreover, this also upsurges the chance of melt re-deposit if not flushed properly. Hence, the size of the melt-redeposit is significantly raised, which lowers the surface quality, as evidenced in SEM image portrayed in Fig. 9. The melt re-deposits noticed on the machined surface at PTR of 1 is notably larger in contrast to that found at PTR of 0.5 as demonstrated in SEM micrographs shown in Fig. 9(a) and Fig. 9(b) respectively. Moreover, prolong sparking over the workpiece surface yields in-depth heat-affected zone, which ultimately results in poor surface finish. Accordingly, the Ra value increased. Conversely, the quality of surface improved with the further increase in PTR to 1.5 due to ionization of nanoparticles. The ionization of the graphene particles above a certain threshold is not suitable for SR whereas below that threshold its ionization helps to reduce SR as is the case herein. The ionization of graphene particles makes a protective layer onto the cutting area and assist the sparking phenomenon to produce stable erosion of material that results in reduction of SR. Hence, it is necessary to engage the minimum level of PTR in EDM of Ti6Al4V when graphene particles are used in the dielectric medium.

Flushing is referred to the removal of chips (small debris) from the work-electrode gap by utilizing the flushing liquid which is usually kerosene oil. In the EDM process, the flushing liquid removes the debris and ionized gas particles during the operational situation and sustain the minimum temperature between the workpiece and tool. Thereof, the effect of FT on SR in the graphene mixed EDM of Ti6Al4V is evaluated and its trend is demonstrated in Fig. 3. It also consists of three levels; 4 μsec, 6 μsec, and 8 μsec. The highest value of FT, i.e., 8 μsec yields a good surface finish when machining has been done in graphene associated dielectric. Since FT is accountable for bringing out a large quantity of material from the work part, so its large value, such as 8 μsec warrants the flushing of a huge amount of debris, which lessens the chance of debris redeposition. Eventually, a better surface finish is the outcome. However, at 4 μsec debris are stacked over the workpiece instead of being efficiently removed due to the less discharge energy as compared to 6 μsec, which causes hindrance in the charging process and generates a recast layer as depicted in Fig. 10. Therefore, it is recommended to operate at a higher value of FT, as in this case 8 μsec for electric discharge cutting of Ti6Al4V.

After a detailed discussion of the parametric plots for SR against each control variable, the optimal setting was suggested using signal-to-noise ratio analysis. The required setting for getting the minimum value of SR during EDM of the selected specimen is tabulated in Table 7. The proposed setting confirmed the significant reduction in R_a magnitude, which translated into a good surface finish under graphene based dielectric as described in Table 8. If the roughness results achieved at optimal combination are compared with the parametric setting (Exp. No. 6 of actual experimentation) that provides a roughness value near to the average, 51.1% improvement is noticed, as depicted in Table 8. The reduction in SR is also evident in 3D surface plots taken for the two aforementioned conditions, as illustrated in Fig. 11.

A comparison of SR has also been developed between the graphene mixed dielectric and conventional EDM oil as witnessed in Fig. 12. For that purpose, minimum, average, and maximum values of SR were taken from the experimental design. It can be noticed that surface finish is notably compromised when kerosene oil is only utilized as dielectric medium for the cutting of Ti6Al4V through EDM. As per the literature, when electric field (or high voltages) is applied under powder mixed EDM then it produces energized ions which get accelerated and start moving in zig zag style. As an effect, electric sparks disperse due to reduction in the breakdown voltages which tends to wider the work-electrode gap. This wider gap creates bridging effect because of interlocking phenomenon in the direction of current flow. Thus, more stable discharging occurs that corresponds to get a fine finish over a machined cavity, as portrayed in Fig. 13 [22, 34]. Hence, kerosene oil yielded poor surface finish. In addition to ionization of powder particles, breakdown of kerosene oil is also takes place because of high spark energy in the cutting zone that yields carbon particles which re-deposited over the machind cavity and leaves a residual layer of carbon, as claimed by different researchers in their investigations [5, 35, 36]. Fig. 14 illustrates a one more comparison among the two aforesaid alternatives that has been made by implementing optimized parameteric setting (provided in

Table 7) for the proposed EDM setup. Both the above graphs successfully revealed that addition of nanopowder (graphene) in the conventional EDM oil is proved to be efficient in terms of giving appreciable surface finish.

For the machining efficiency point of view, the results of previous publication based on the investigation of material removal rate and tool wear rate under graphene mixed EDM of Ti6Al4V, are also presented herein (see Table 9).

Conclusion

The current research comprehensively investigates the impact of graphene-based dielectric liquid on the SR magnitude while EDM of Ti6Al4V by taking six important parameters into account. The ANOVA was done to evaluate the prime variables which are greatly changing the quality of the specimen's surface. Furthermore, optical and SEM analyses were accomplished to explain the findings insightfully. The following conclusions are drawn based on experimental findings:

i. The performance of graphene mixed dielectric is rated superior to that of simple kerosene. The addition of nano graphene in kerosene reduces the surface roughness to 70.8% in contrast to simple kerosene.The graphene nanoparticles disperse the discharge energy, reduce the break down voltage, increase the gap between workpiece and electrode, and consequently bridging effect is created through these nanoparticles. As a result, more stable sparking occurred over the machined surface and surface roughness is decreased notably.

ii. The positive polarity of the tool provides better surface quality in EDM of Ti6Al4V under graphene-based dielectric irrespective of the tool material. Since positive polarity produced more stable sparking than that of negative polarity under graphene based dielectric, therefore surface quality is improved.

iii. Electrode material has found to be the most significant factor (having a percentage contribution of 55.37%) governing the the SR value under graphene mixed kerosene dielectric. The electrode of Al is observed to be best suited in comparison to the rest of the tool materials for getting lower SR. A primary reason for getting noble surface quality is the low melting temperature of Al as compared to brass and copper electrodes. SEM analysis also witness that the surface asperities notably reduces when Al electrode was engaged under graphene mixed dielectric.

iv. Amongst the six parameters, spark voltage is the second most influential parameter (with percentage contribution of 19.3%) for controlling the surface finish when nano-graphene is employed in EDM of the selected Ti-alloy. The lower magnitude of roughness is achieved when SV is set at its lower level of 3V.

v. The required parametric setting assisting the EDM process for achieving the minimum value of SR are; polarity = positive, electrode type = Al, SV = 3V, DC = 8 amps, PTR = 0.5, and FT = 8 μsec, also validated through confirmatory trials. Furthermore, the developed optimal settings warrant a reduction of 61.4% in the roughness of the machined specimen as compared to the average roughness value recorded during the whole experimentation.

Statements & Declarations

Competing Interests: The authors have no relevant financial or non-financial interests to disclose.

Data availability: The paper has no associated data. All data gathered regarding this publication is presented.

Code availability: Not Applicable

Ethics approval: Not Applicable

Consent to participate: All participants cosent to participate in this research.

Consent for publication: All authors have consented the submission of this article to the journal.

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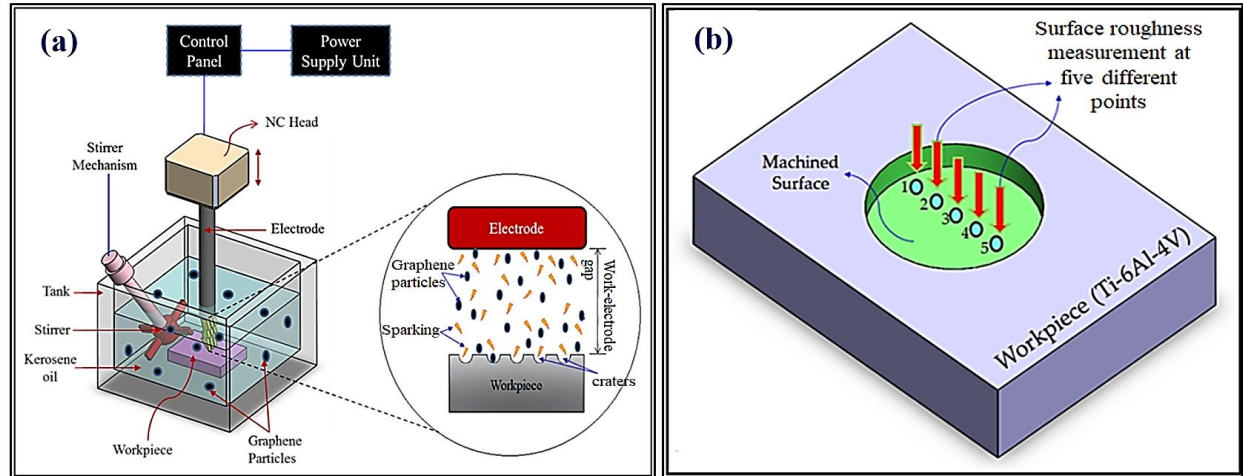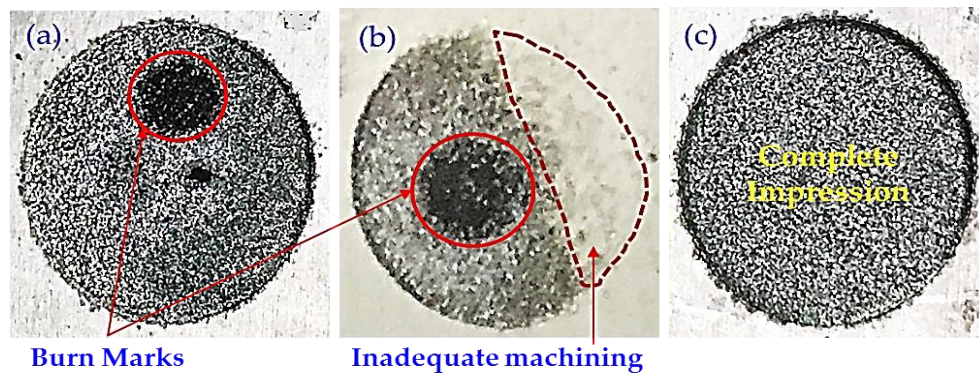
Figure 1 Experimental arrangement of EDM; (a) Schematic and basic principle of EDM, (b) Schematic for the measurement of SR magnitude at various points

Figure 2 Preliminary trials' images of machined specimen indicating; (a) burn marks, (b) burn mark with an incomplete machined surface, (c) complete impression
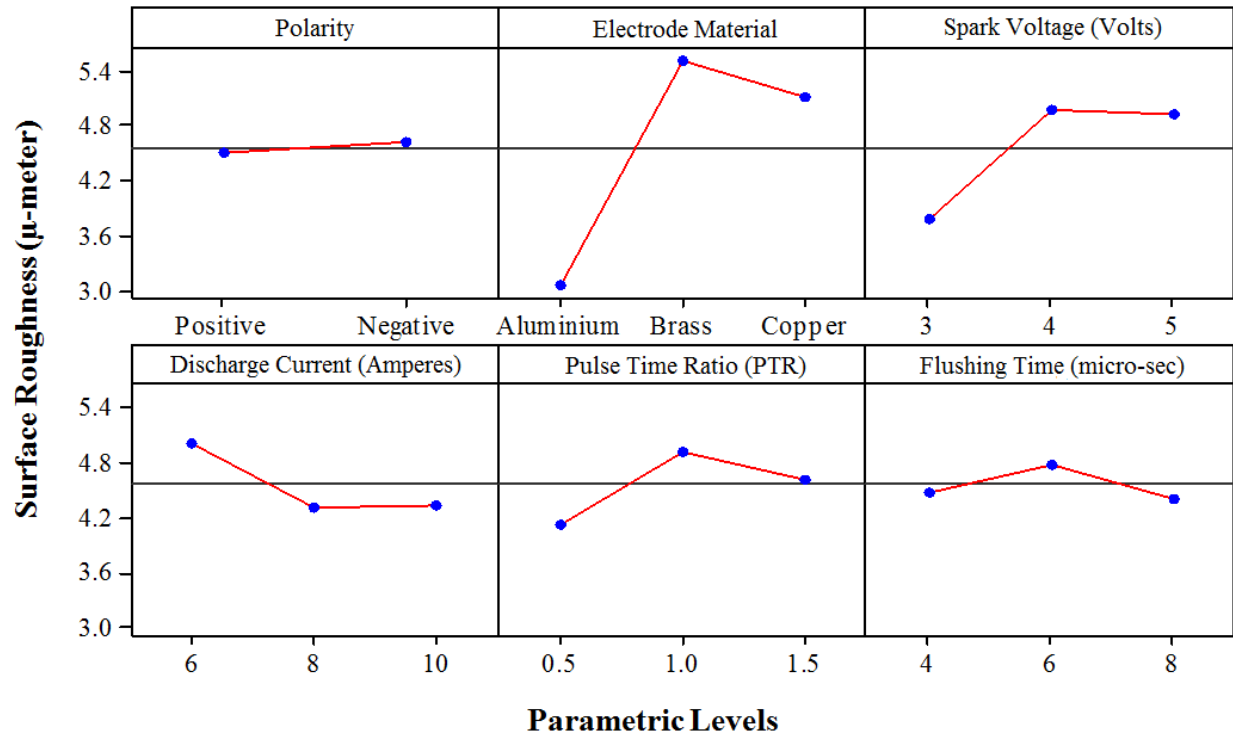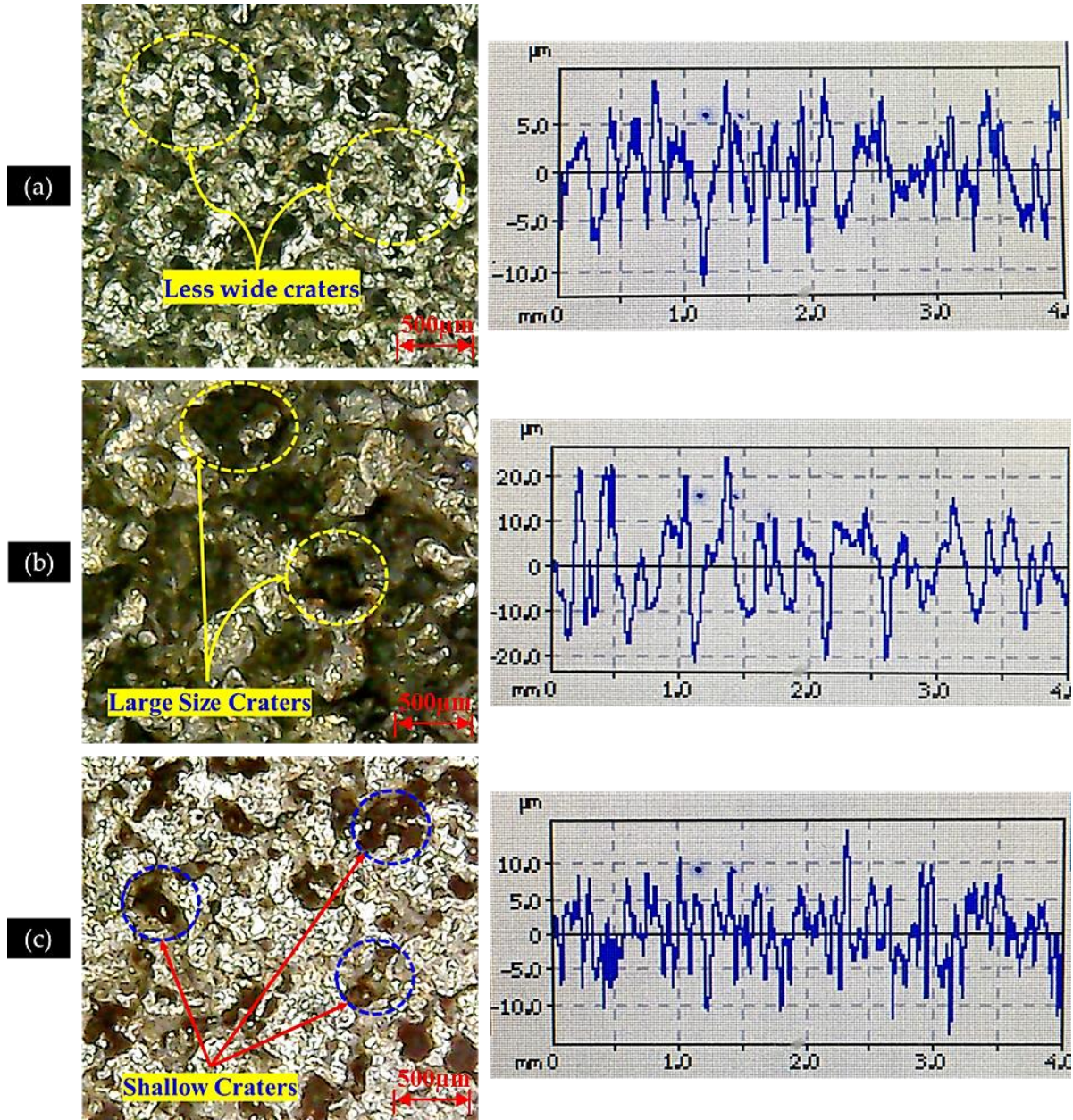
Figure 3 Parametric Plots against each control variables using graphene nanoparticles in the dielectric medium
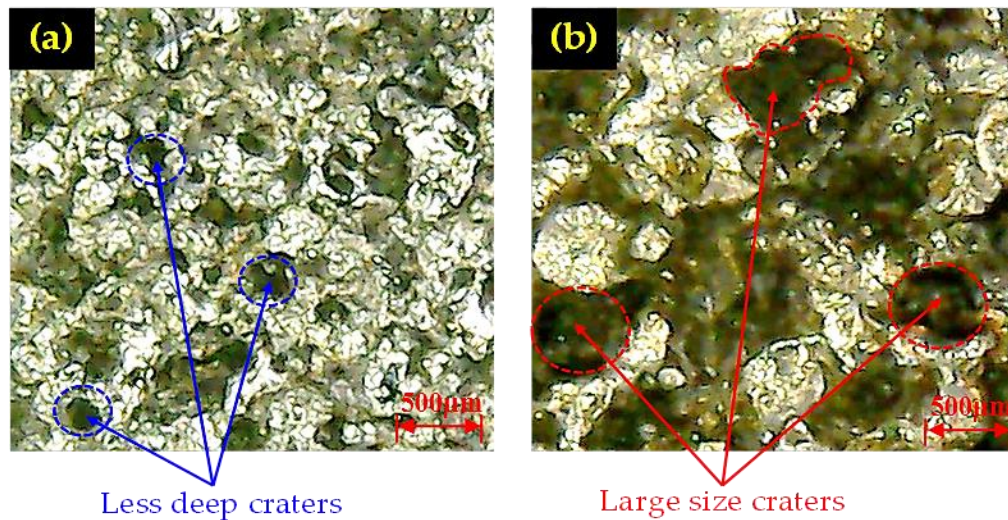

Figure 4 Micrographs at two different polarities; (a) positive polarity with small size craters, (b) negative polarity with large and deep creators

Figure 5 Micrograph's comparison of electrodes with their graphical demonstration; (a) Al is giving less wide craters with low peak-to-valley distance, (b) Br is showing poor surface finish with large size craters and high peak-to-valley distance, (c) and Cu is illustrating the shallow craters with intermediate peaks and valleys
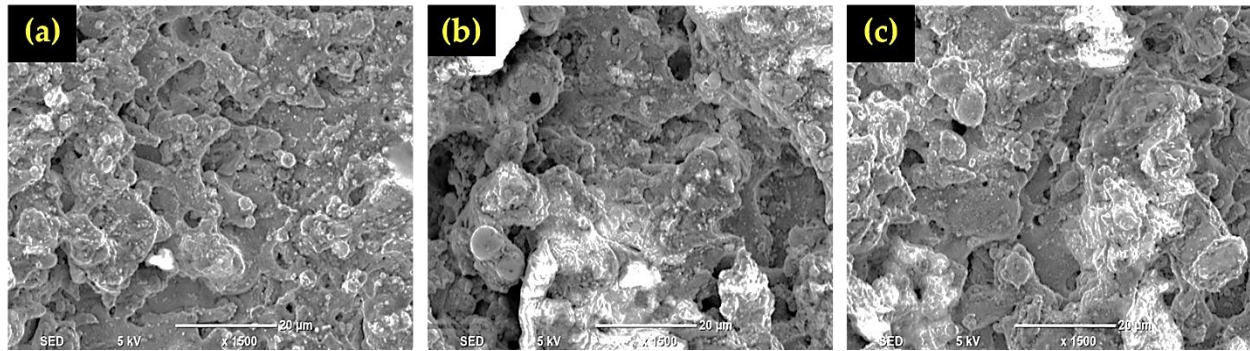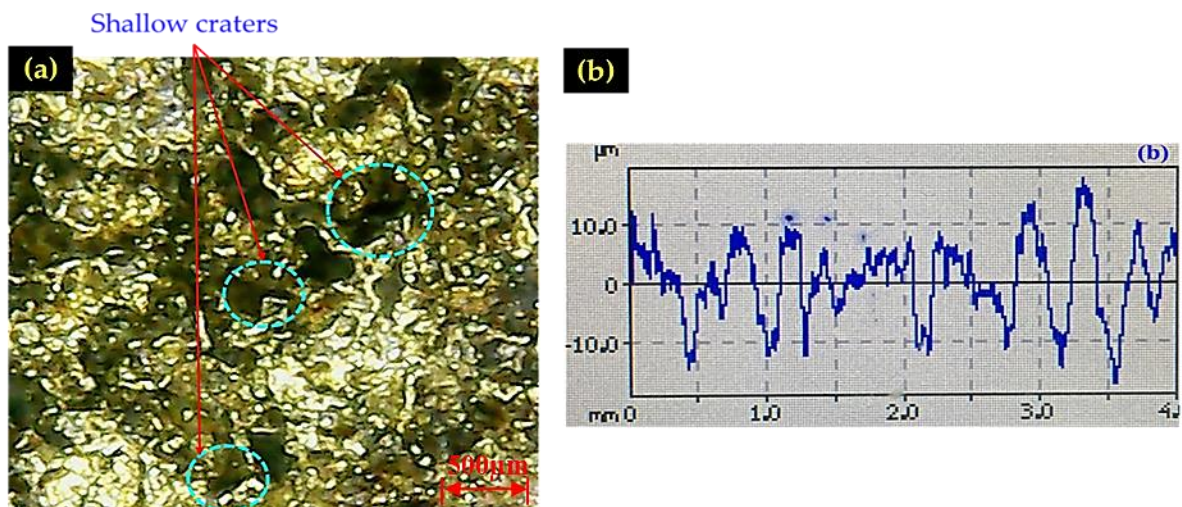
Figure 6 SEM images of machined surface using electrode of ; (a) Al, (b) Brass, and (c) Cu
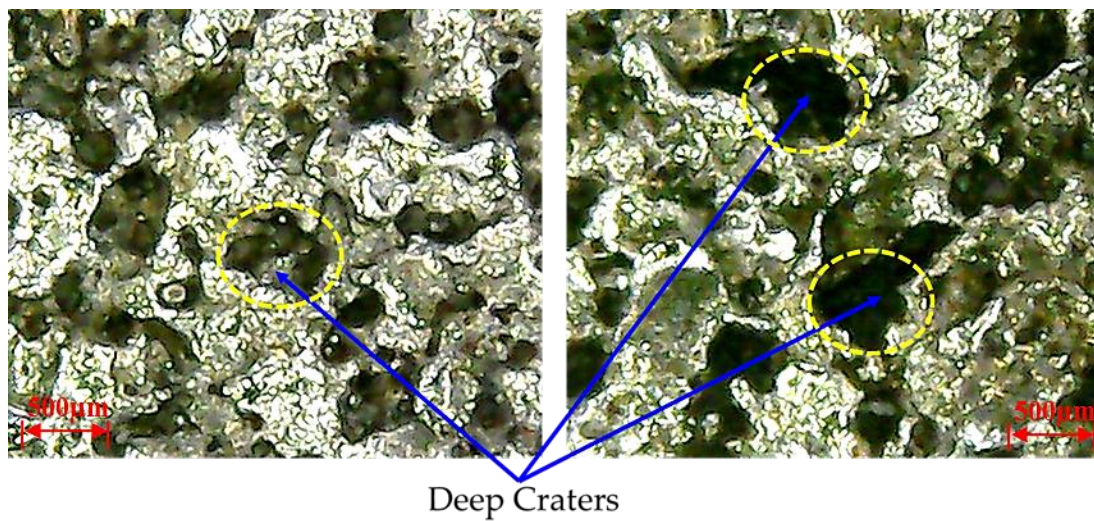
Deep Craters

Figure 7 Optical Micro-image is portraying deep craters at SV equal to 4V and 5V

Figure 8 Effect of DC at 8 amps; (a) Micrographs appearing shallow craters on the workpart surface, (b) Variation in R_a values representing considerable peaks and valleys
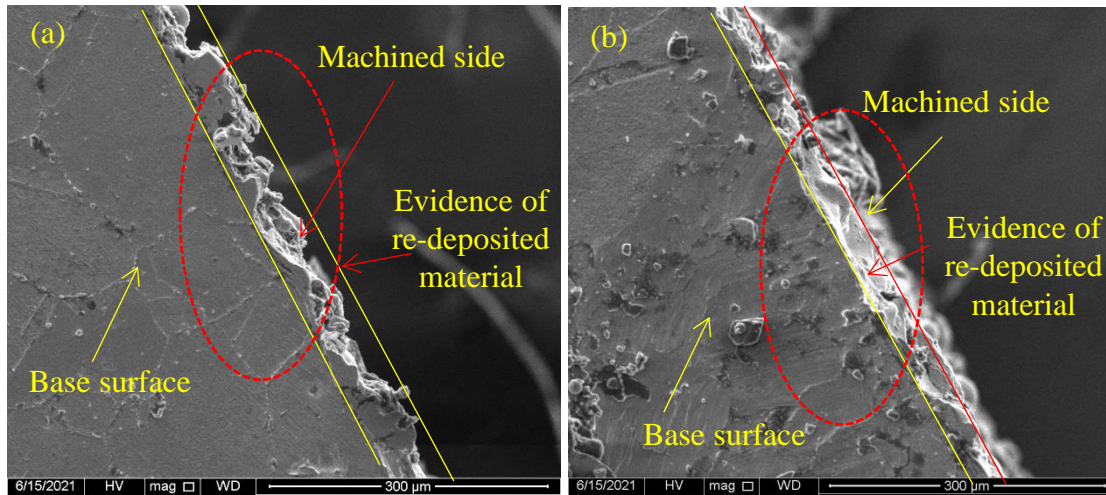
Figure 9 SEM image of machined surface at; (a) PTR = 1.0, (b) PTR = 0.5
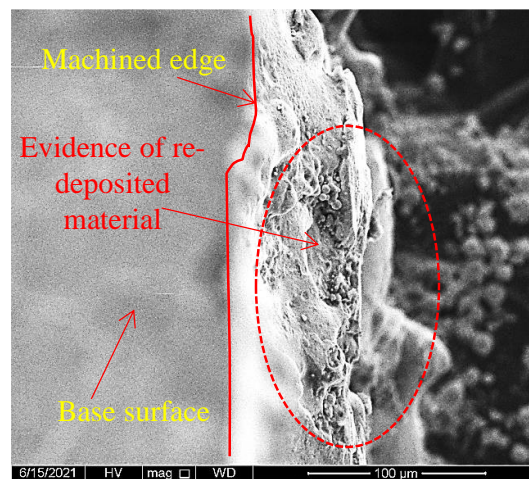
Figure 10 SEM image showing re-deposited layer on specimen's surface
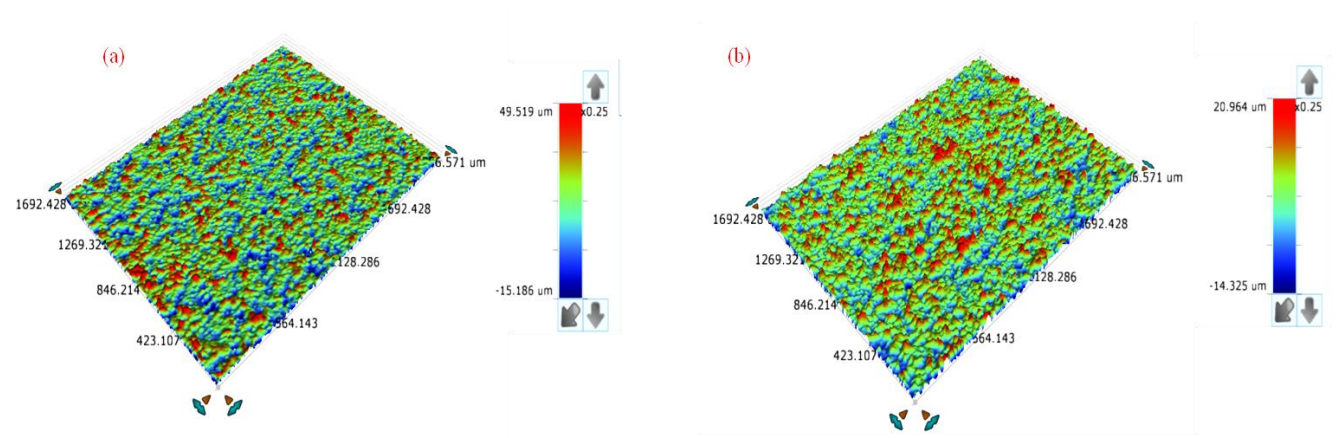
Figure 11 3D roughness profiles at; (a) optimal settings, (b) non-optimal settings
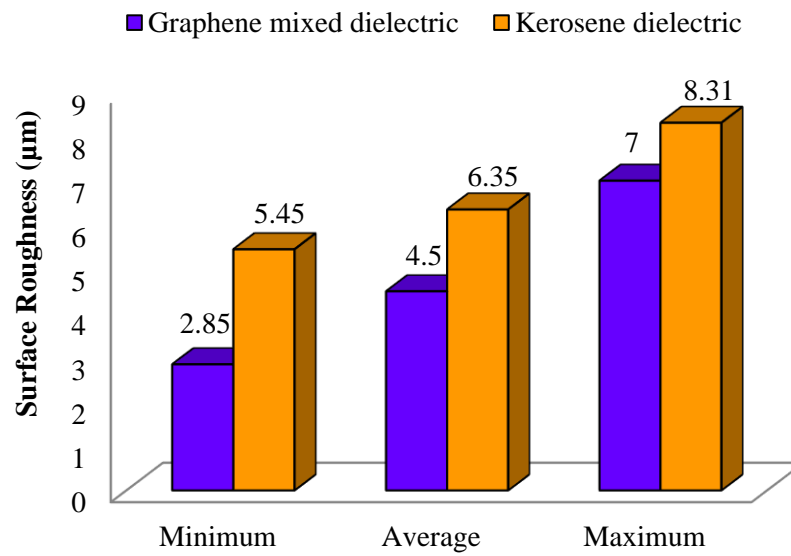
Figure 12 A comparison of SR between graphene mixed and kerosene dielectrics
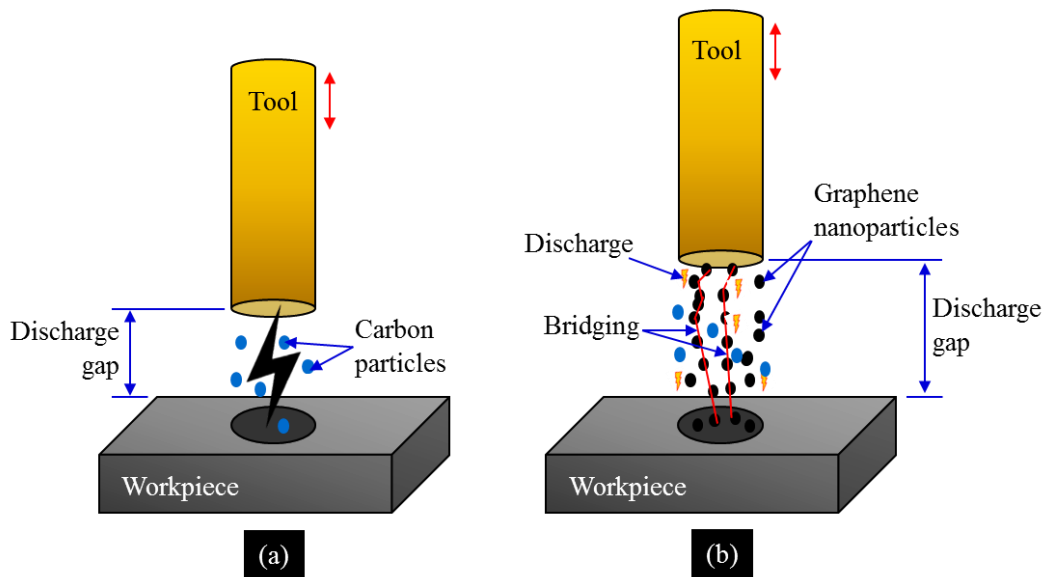
Figure 13 Schematic illustrates the role of nanopowder in EDM dielectric; (a) Kerosene based EDM, (b) Graphene nanoparticles mixed EDM

Figure 14 Comparative analysis of SR under graphene and kerosene based dielectrics

Tables 1-4 pertain to the materials and methods section

Tables 5-9 pertain to Results and Discussion section

Table 1 Composition of specimen

Elements	Al	V	C	N	O	H	Fe	Y
Wt. %	6.50	4.0	0.085	0.05	0.2	0.015	0.25	0.005

Table 2 Salient features of specimen [27, 28]

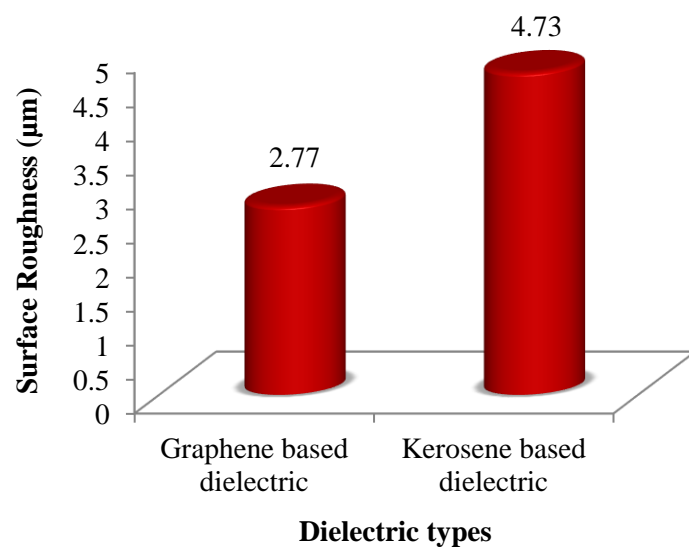| Characteristics (Units)	Values
Hardness (HRC)	36
Yield Strength (MPa)	828
Electrical Resistivity (ohm–meter)	1.724×10^{-6}
Elastic Modulus (MPa)	44×10^{3}
Tensile Strength (MPa)	895
Thermal Conductivity (W/cm-^{o}C)	67×10^{-3}
Poisson's Ratio	0.31

Table 3 Prime features of graphene particles

Properties (Units)	Magnitude
Density (g/L)	60-90
Thickness (meter)	$(2-10) \times 10^{-9}$
Diameter (meter)	$(2-10) \times 10^{-6}$
Color	Grey / black powder
Carbon content (%)	>99
Electrical conductivity (S/m)	80×10^{3}
Surface area (m^{2}/g)	20-40
Additional impurities (wt. %)	<1
Percentage of water (wt. %)	<2

Table 4 Design Parameters & their defined levels

Input variables (Units)	1st Level	2nd Level	3rd Level
Polarity	Positive	Negative	-
Electrode type	Al	Brass	Cu
Spark Voltage (Volts)	3	4	5
Discharge Current (Amperes)	6	8	10
Pulse time ratio	0.5	1.0	1.5
Flushing time (μsec)	4	6	8

Table 5 Control Variables and roughness parameters under graphene mixed dielectric

Exp. No.	Control Variables						Output Response (SR) - μm							
	P	E	SV	DC	PTR	FT	Ra_1	Ra_2	Ra_3	Ra_4	Ra_5	R_a	R_t	R_z
1	1	Al	3	6	0.5	4	2.90	2.91	2.89	2.88	2.92	2.90	20.00	16.00
2	1	Al	4	8	1.0	6	3.52	3.61	3.60	3.68	3.59	3.60	24.75	18.00
3	1	Al	5	10	1.5	8	3.41	3.49	3.45	3.44	3.46	3.45	29.25	19.75
4	1	Brass	3	6	1.0	6	5.15	5.10	5.13	5.09	5.28	5.15	39.00	26.00
5	1	Brass	4	8	1.5	8	5.30	5.41	5.35	5.35	5.34	5.35	38.50	28.50
6	1	Brass	5	10	0.5	4	4.05	4.01	4.06	4.08	4.05	4.05	33.00	23.00
7	1	Cu	3	8	0.5	8	3.05	3.10	3.15	3.09	3.11	3.10	31.25	22.25
8	1	Cu	4	10	1.0	4	5.95	6.05	6.00	5.99	6.01	6.00	54.00	35.00
9	1	Cu	5	6	1.5	6	6.19	6.19	6.18	6.23	6.21	6.20	45.25	35.75
10	2	Al	3	10	1.5	6	2.85	2.90	2.82	2.88	2.80	2.85	20.50	14.50
11	2	Al	4	6	0.5	8	2.90	2.93	2.96	2.91	2.85	2.91	21.25	16.50
12	2	Al	5	8	1.0	4	3.19	3.21	3.20	3.18	3.22	3.20	24.75	17.75
13	2	Brass	3	8	1.5	4	4.49	4.50	4.51	4.52	4.48	4.50	35.00	27.00
14	2	Brass	4	10	0.5	6	6.12	6.14	6.15	6.18	6.16	6.15	47.00	34.25
15	2	Brass	5	6	1.0	8	6.95	6.98	6.99	7.00	7.08	7.00	54.00	39.25
16	2	Cu	3	10	1.0	8	3.79	3.81	3.80	3.78	3.82	3.80	37.25	23.50
17	2	Cu	4	6	1.5	4	5.51	5.53	5.58	5.55	5.58	5.55	36.75	31.00
18	2	Cu	5	8	0.5	6	5.24	5.25	5.23	5.26	5.27	5.25	42.00	29.00

1 = Positive polarity, 2 = Negative polarity

Table 6 ANOVA for SR

Variables	DOF	Seq SS	Adj SS	Adj MS	F value	P value
P	1	0.0450	0.0450	0.0450	0.08	0.793
E	2	18.2211	18.2211	9.1106	15.22	0.004
SV	2	6.3469	6.3469	3.1735	5.30	0.047
DC	2	2.1078	2.1078	1.0539	1.76	0.250
PTR	2	1.6936	1.6936	0.8468	1.42	0.314
FT	2	0.9011	0.9011	0.4506	0.75	0.511
Error	6	3.5906	3.5906	0.5984		
Total	17	32.9061				

Table 7 Optimal combination for achieving minimum R_a

Sr. No.	Control variables	Optimal value
1	Polarity	Positive
2	Electrode material	Al
3	Spark voltage	3 V
4	Discharge current	8 amps
5	Pulse time ratio	0.5
6	Flushing time	8 μsec

Table 8 Confirmatory experimental outcomes

Variables' settings	Surface Roughness (R_a) - μm		Difference (in %)
	Predicted value	**Actual value**	
Optimal; P1, E1, SV1, DC2, PTR1, FT3	2.77	2.68	3.4%
Non-optimal; (Exp. No. 6) P1, E2, SV3, DC3, PTR1, FT1	4.28	4.05	5.6 %
Improvement %		51.1	

Table 9 Results of MRR and TWR during EDM of Ti6Al4V under graphene mixed dielectric [5]

Responses (Units)	Maximum Value	Minimum Value
MRR (mm^3/min)	7.602	0.136
TWR (mg/min)	63.91	0.170