Analyzing micromachining errors in EDM of Inconel 600 using various biodegradable dielectrics

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Abstract Inconel 600 is a Ni-based superalloy having exclusive properties like high strength and stability in harsh conditions. However, its accurate machining is challenging via conventional cutting methodologies. As a result, the use of electric discharge machining is common in cutting Inconel 600 precisely. But the intrinsic issue of overcut associated with traditional EDM limits its appreciation in cutting Ni-based alloy. Moreover, conventional dielectric oil used in EDM releases hazardous fumes and gases that put the operator's health at risk. Therefore, in this study, six different biodegradable dielectrics have been investigated for their potential in controlling the dimensional overcut, which have yet to be evaluated thoroughly. The performance of biodegradable dielectrics (canola, amla, olive, sunflower, coconut, and mustard oil) against four types of electrode materials has been evaluated using full factorial design in the EDM of Inconel 600. Experimental findings are analyzed with statistical tests and optical/scanning electron microscopic evidence. The experimental results indicated that canola dielectric yield the smallest dimensional overcut. However, combination of sunflower oil and copper electrode proved as second premier case to reduce the overcut. Compared to the conventionally used kerosene oil, the biodegradable dielectrics (canola and sunflower) display a 63% and 1.2-folds reduction in overcut.

Keywords: EDM; Overcut; Dimensional; Accuracy; Biodegradable; Dielectrics; Inconel; Canola; Amla; Olive; Sunflower; Coconut; Mustard

1. Introduction

Ni-based Superalloys, especially Inconel 600, have captured acceptance in numerous applications pertaining to their superb strength, good weldability, non-magnetic nature, excellent resistance to corrosion, and high stability at an elevated pressure. However, the greater strength of said alloy complicates its cutting with conventional cutting techniques [1]. Thereof, commonly non-conventional machining processes are engaged. Electric Discharge Machining (EDM) is one of the appreciated options considering the non-conventional cutting techniques due to its flexibility to machine difficult-to-cut materials regardless of their mechanical characteristics [2–4].

EDM is a material removal process in which high thermal energy is generated via repetitive sparking, which ionizes the dielectric fluid available in the tool-workpiece gap [5–7]. Eventually, discharge intensity produces a plasma channel which acts as an intense heat source. The localized heating occurs because of the developed plasma channel which tends to melt and vaporize the particles from the substrate [8]. The melting and vaporization of the eroded materials are accomplished by the aid of a series of electric sparking, which generally enhances the temperature up to 12,000ºC. The debris over the specimen is then flushed away with the assistance of dielectric liquid which is directed on the cutting zone [9–11]. In this study, EDM has been employed for the cutting of Inconel 600 which has unique characteristics as described earlier [12]. The associated characteristics allow the Inconel 600 to be used in widespread applications including airframe, aeronautical, furnace body, muffles, and retorts [13, 14]. Considering the characteristics and applications of the selected material, the use EDM is well justified. However, conventionally Kerosene oil is employed as a dielectric in EDM, which emits toxic fumes/gases during the cutting process. This is a serious concern with regard to the operator's health and the environment [15, 16]. Therefore, different biodegradable oils such that canola, amla, coconut, mustard, sunflower, neem, and olive oils have been engaged to maintain the sustainability aspect of the EDM process [17, 18]. However, it is considered difficult to have a control over the randomly occurring sparking phenomenon during the machining process. Correspondingly, it becomes challenging to achieve the cutting dimensions precisely in all the machining orientations. It is worthy to state that geometric accuracy plays a vital duty in ensuring the accurate functionality of the machined specimen [19]. It has already been reported that the use of traditional dielectric(s) yield significant dimensional variations during EDM [20]. Therefore, vegetable oils, as mentioned before, have been practiced instead of kerosene oil to produce components with tight tolerances. In this context the demand of minimum overcut is well justified considering that the machined part has to be assembled to give an end product. In the case of microcavities, the variation in micron has a pronounced impact on the cut dimensions, making it even more critical to meet the requirement. Therefore, in the present investigation, the geometric accuracy in terms of overcut for Inconel 600 has been thoroughly examined during vegetable oil based EDM for producing 200 µm deep cavities.

Numerous studies have been found discussing the influence of process parameters on dimensional overcuts while EDM of a variety of materials. For instance, Bhosle and Sharma [21] optimized the parameters by using grey relational analysis (GRA) during micro-EDM of Inconel 600 under EDM oil as dielectric. They considered five machine factors including capacitance, voltage, pulse on and off time (T_{on} and T_{off}), and feed rate. It was revealed that capacitance was the most driving factor for determining the overcut magnitude. Optimized parametric combination was also proposed using GRA approach. Cyril et al. [22] performed micro electro discharge drilling on stainless steel 316L, considering the varying amount of different additives viz., Al, graphite, and silicon carbide (SiC) into the dielectric liquid i.e. DCO 1000i EDM oil. The researchers have reported that overcut (OC) was increased by adding more additives due to the significant discharging. They also claimed that OC can be reduced in the absence of powder/additives available in the dielectric medium. Naveed et al. [23] probed the dimensional errors in both radial and axial orientation during EDM of Ti6Al4V by employing four distinct electrode materials (aluminium-Al, brass-Br, copper-Cu, and graphite-Gr) under kerosene dielectric. They have considered three input factors, i.e., tool polarity, discharge current, and pulse time ratio. It was estimated that the selection of negative polarity and Cu electrode decrease the geometric errors significantly.

Prasanna and Rajamanickam [24] compared the performance of different electrode materials such as Cu and Alumina-Titanium oxide coated Cu under conventional EDM oil considering overcut as a response attribute. It was cited that coating on Cu electrode helps to reduce overcut by 62.5%. In another study reported on EDM of die steel, the impact of manganese powder was examined in the context of dimensional deviation. They have engaged two types of dielectric liquids during their investigation: (i) EDM oil, (ii) Kerosene oil. It was claimed that a greater amount of powder addition in the aforesaid dielectrics improve the material removal rate (MRR) however, overcut value got compromised. The large dispersion of arcing between the work surface and electrode was cited to be the cause of the higher value of overcut [25]. The influence of modified electrode geometry was also tried to lower the magnitude of dimensional errors in EDM using kerosene as dielectric. The electrode having a certain relief angle was employed in the context. It was reported that the OC value was reduced when the relief angled tool was engaged in EDM [26]. Zainal et al. [27] comprehensively presented the variation of OC on the EDM of Ti6Al4V using copper-tungsten (Cu-W) as a tool material and conventional EDM oil as dielectric liquid. A full factorial experimental design was employed to scrutinize the impact of T_{on}, T_{off}, servo voltage, and peak current on the dimensional accuracy. The results elaborated that OC is greatly reduced after setting the above parameters at optimum values predicted from a mathematical model.

In addition to these studies, different researchers have performed experimentation under biodegradable dielectrics while EDM of various alloys including steel, nickel and titanium [28–32]. For example, Singaravel et al. [33] inspected the influence of sunflower oil on MRR, tool wear rate (TWR), and surface roughness (SR) while EDM of Inconel 800. They showed that presence of biodegradable oil as dielectric liquid, instead of kerosene, upsurges the MRR. Moreover, the results of TWR and SR were also considerably improved with sunflower oil as compared to the kerosene dielectric due to small number of carbon particles available in the sparking zone. They further claimed that biodegradable oil is a good alternate of hydrocarbon-based dielectrics owing to similar and upgraded dielectric properties. In another study, Singaravel et al. [34] analyzed the impact of biodegradable oils (Canola, Sunflower, and Jatropha) during machining of Ti6Al4V through EDM process. Three electrodes (Cu, Br, and Cu-W) were engaged to inspect the surface quality against the defined factors. After comparing the outcomes with the traditional dielectric (Kerosene oil), the researchers revealed that surface integrity is appreciably raised under the application of vegetable oils. Mali et al. [35] have explained the feasibility of waste vegetable oil (Pongamia

Pinnata) in the context of sustainable EDM of Inconel 718. The three responses including MRR, TWR, and SR were evaluated against the defined set of input parameters. They concluded that the aforementioned vegetable oil can replace the conventional dielectric of EDM because of delivering admirable results during machining. Dastagiri et al. [36] also investigated the potential of Pongamia Pinnata (PP) oil as dielectric while cutting of EN 31 steel material via EDM process. Three input factors namely T_{on}, T_{off}, and current were chosen to measure their consequence on MRR, TWR, SR, electrode wear rate (EWR). They determined that use of PP oil in the kerosene dielectric improved the responses as previously mentioned. They summarized that PP oil has unique features than the conventional EDM oil such that high flash point, excellent dielectric strength, less carbon contents, and good biodegradability.

After a careful review of the literature published in the field of EDM, it has been discerned that no momentous work has been reported on EDM of Inconel 600 for producing dimensionally accurate micro-impressions under biodegradable dielectric(s). The geometrical accuracy aspect of the said Ni-alloy in different biodegradable dielectrics is not examined in much detail so far. Therefore, this study is primarily aimed to examine the potentiality of biodegradable dielectrics during EDM Inconel 600 to achieve dimensionally consistent machined parts. A full factorial design of the experiment was used employing six biodegradable dielectrics and four electrode materials namely; aluminium (Al), brass (Br), copper (Cu), and graphite (Gr). For an insightful examination of the finding scanning electron microscopy (SEM), optical microscopy, and Energy Dispersive X-rays (EDX) spectroscopy were performed. Finally, an optimal setting to have a minimum overcut was also developed and validated.

2. Materials and Methods

The present study has used Inconel 600 due to its extensive applications in processing industry, structural sectors, and atomic chambers. The Ni-based Superalloy (Inconel 600) allows its use in aforementioned areas because of outstanding features as discussed in the former section [12, 37]. As Inconel 600 has been nominated as a difficult-to-cut material thus, commonly non-traditional cutting techniques are engaged wherein EDM holds a prominent place for machining of the said alloy. The schematic of working principle of EDM and overcut are presented in Figs. 1 (a and c) whereas Fig 1(b) is representing the measurement of machined cavity's dimensions on coordinate measuring machine (CMM).

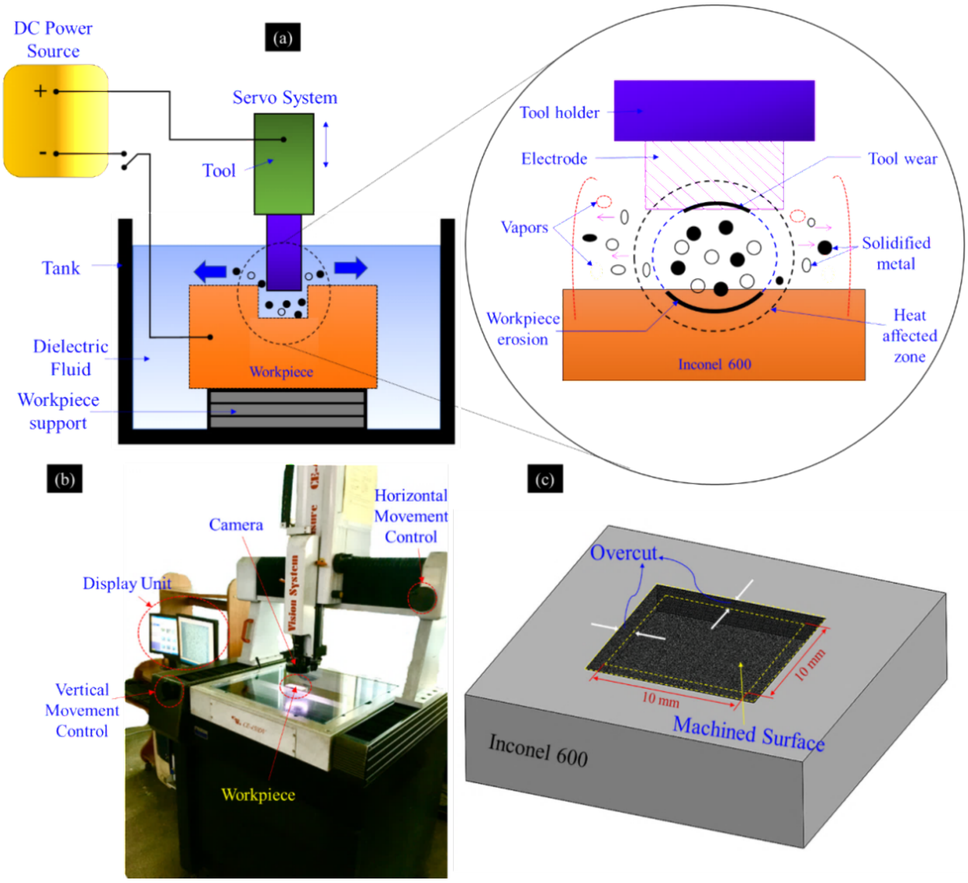


Figure 1. Experimental arrangement: (a) EDM Schematic, (b) Setup of coordinate measuring machine (CMM), (c) Overcut on a workpiece schematic.

The literature has witnessed that the EDM process under kerosene oil can generate hazardous fumes, which has serious health and environmental implications [38–40]. For that purpose, six different biodegradable dielectrics, i.e., Olive, Sunflower, Canola, Mustered, Amla, and Coconut oils have been engaged during EDM of Inconel 600. The aspect of overcut in terms of dimensional variation has been thoroughly explored in this work. The salient properties of all the oils are elaborated in Table 1 [41–44]. It is admissible to note that the significance of the tool materials could not be ignored during EDM. The choice of the premier electrode in the aforesaid oils is also an essential question in this study that is still to be responded. Thus, four electrodes namely aluminium (Al), brass (Br), copper (Cu), and graphite (Gr) were used in this research to find out the right tool for each of the oils. Furthermore, the optimal parametric combination was also developed and authenticated. The selection of these tool materials depends on their excellent machinability in terms of the defined response.

Table 1. Important traits of different vegetable oils.[41–44]

Biodegradable Oils	**Dielectric strength (KV)**	**Viscosity (Pa-sec)**	**Densit y (g/mL)**	**Flash Point (ºC)**
Canola Oil	54-61	44.71	0.910	315

Olive Oil	26-41	43.60	0.912	177
Sunflower Oil	38-45	41.40	0.890	274
Mustard Oil	28	63.40	0.967	110
Amla Oil	50	102.8	0.966	210
Coconut Oil	60	27.90	0.915	266

A workpiece of dimensions 50 mm x 50 mm x 50 mm (length x width x thickness) was employed for the experimentation. The elemental composition of Inconel 600, which was verified via Energy Dispersive X-rays (EDX) analysis, is shown in Fig. 2. However, the important properties of Inconel 600 are illustrated in Table 2 [28]. The constant and variable parameters used in the EDM of Ni-alloy are enlisted in Table 3. Initial trial experiments were conducted before conducting the actual experimentation. The benefit of initial trials was to select that setting of EDM where there is a minimal/no chance of any burn mark or inadequate impression. Afterward, experimentation was performed under full factorial design of experiment (DOE) technique. Depth of cut was fixed at 2 µm during each experimental run. After successful completion of experiments, the magnitude of overcut is found by means of Coordinate Measuring Machine (CMM). The lengths of the machined cavity have been found at three points and then average is reported. The difference of the set machined dimensions and those achieved after machining was calculated, which is termed as dimensional error in this research. The error value achieved is thus referred as overcut. The schematic of measurement along with CMM setup are shown in Fig. 1. Afterwards, data analysis has been performed employing line graphs and bar charts. In order to get a detailed insight of the results as well as understand the chemistry of process, SEM was used. The pictorial evidence was also collected through optical microscopy. At the end, optimal setting was provided and confirmed.

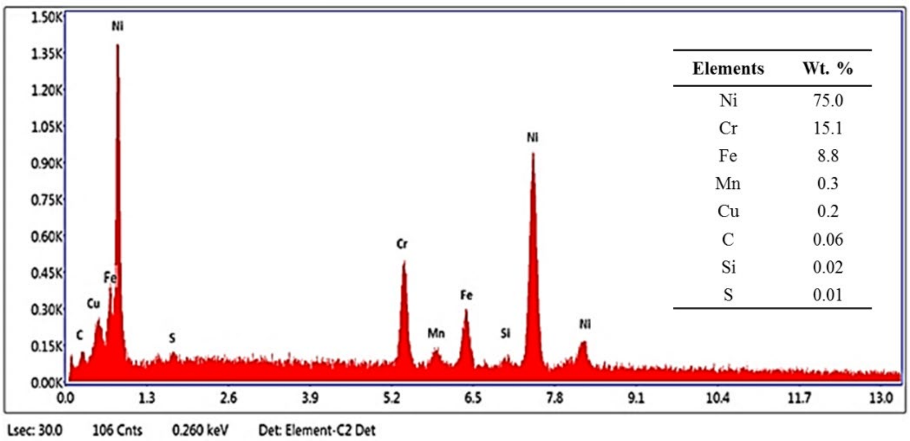


Figure 2. EDX analysis presenting the chemical composition of Inconel 600.

Table 2. Salient features of the work part.[28]

Characteristics	**Density**	**Melting point**	**Coefficient of Expansion**	**Modulus of Elasticity**	**Hardness**	**Thermal conductivity**
Units	Kg/m^3	K	µm/m-^{o}C	kN/mm^2	HRC	W/m K
Values	8470	1686.1	13.3	206	135	15

	5

Table 3. Machine input parameters.

Too Materials	Aluminium	Brass	Copper	Graphite		
Dielectric Fluids	Canola oil	Sunflower oil	Olive oil	Mustard oil	Amla oil	Coconut oil

3. Results and Discussion

The current research was used full factorial DOE to investigate the geometric accuracy of Inconel 600 in terms of overcut under different combination of dielectrics. Four tool materials, as mentioned earlier, were engaged as electrodes. After completion of experiments, the results have been summarized as depicted in Table 4. Then a comprehensive detail has been reported on the above motive to highlight the important facts regarding the dimensional accuracy of the Inconel 600 during its cutting on EDM. Ultimately a single optimized setting was suggested and validated.

Table 4. Experimentation outcomes.

Experiment Number	Electrode Type	Biodegradable oils	Overcut (mm)	Experiment Number	Biodegradable oils	Overcut (mm)
1	Aluminium	Olive oil	0.0895	13	Mustard oil	0.2205
2	Brass		0.0425	14		0.0425
3	Copper		0.0980	15		0.0670
4	Graphite		0.3900	16		0.2710
5	Aluminium	Sunflower oil	0.0770	17	Amla oil	0.0865
6	Brass		0.0425	18		0.0725
7	Copper		0.0380	19		0.2725
8	Graphite		0.1820	20		0.1960
9	Aluminium	Canola oil	0.1615	21	Coconut oil	0.0495
10	Brass		0.0165	22		0.0535
11	Copper		0.1315	23		0.1545
12	Graphite		0.2400	24		0.2545

The geometrical accuracy of Inconel 600 has been summarized in terms of overcut versus four-electrode materials viz Al, Br, Cu, and Gr. The actual minimum dimensional overcut errors against each said electrode are presented in Fig. 3. The graphical demonstration of the effect of various vegetable oils on the OC against the aforesaid tools is displayed in Fig. 4. It has been noticed that the graphite electrode has proved to be the worst in terms of geometrical accuracy in contest to the rest of the tool materials when olive oil is the selected dielectric. The value of overcut attained in this case is 0.39 mm. The machined surface achieved via said combination is observed to have irregular pattern as witnessed in the SEM images shown in Fig. 5. This is due to its higher thermal conductivity (1950.0 $Wm^{-1}K^{-1}$) of graphite in contrast to the other electrodes. The high conductance of heat causes the severe melting and vaporization of the workpart. Since, significant wear of material occurs from the workpart owing to significant concentration of the heat input on the target surface thereof machined impression also enlarged in all dimensions. Thus, overcut is raised. Another aspect that also contributes in overcutting is the porous structure of graphite because of which it cannot maintain a coherent focus of the electric discharges at the cutting zone especially from the edges. Consequently, materials also got removed beyond the defined periphery of the desired cavity, which is translated to an increase in OC. It has also been revealed the melting of excessive material from the substrate also provokes the chances of melt re-deposition during the pulse off-time. This adherence of the melted droplets has been witnessed in this work while cutting the Inconel 600 by EDM using graphite electrode and olive oil dielectric as shown in Fig. 6. In olive oil, geometric accuracy is significantly improved when a brass electrode is employed as illustrated in Fig. 7. The OC value (0.0485 mm) obtained with brass electrode is approximately 8 times less than the 0.39 mm found with graphite electrode. The values of OC achieved with Al and Cu are closely spaced as highlighted in Fig. 4. The difference in OC values found with both of these electrodes is just 0.0085 mm. In terms of comparison the performance of Al is rated better as Al yield low magnitude of OC (0.0895 mm). Keeping an eye on outcomes, it has been noticed that the performance of the olive dielectric seems to be the best in terms of OC if brass is engaged as electrode in EDM of Inconel 600. Conversely, a sudden shift with the trend of said electrode was noticed from olive oil to sunflower oil dielectric.

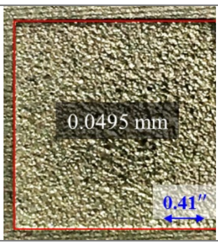
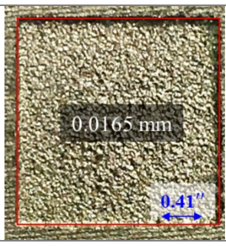
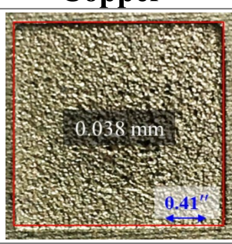
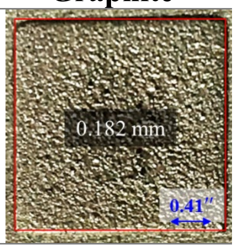
Dimensional Errors	**Electrode Materials**			
	Aluminium	**Brass**	**Copper**	**Graphite**
Minimum Overcut				

Figure 3. Results of minimum dimensional error against the selected electrodes.

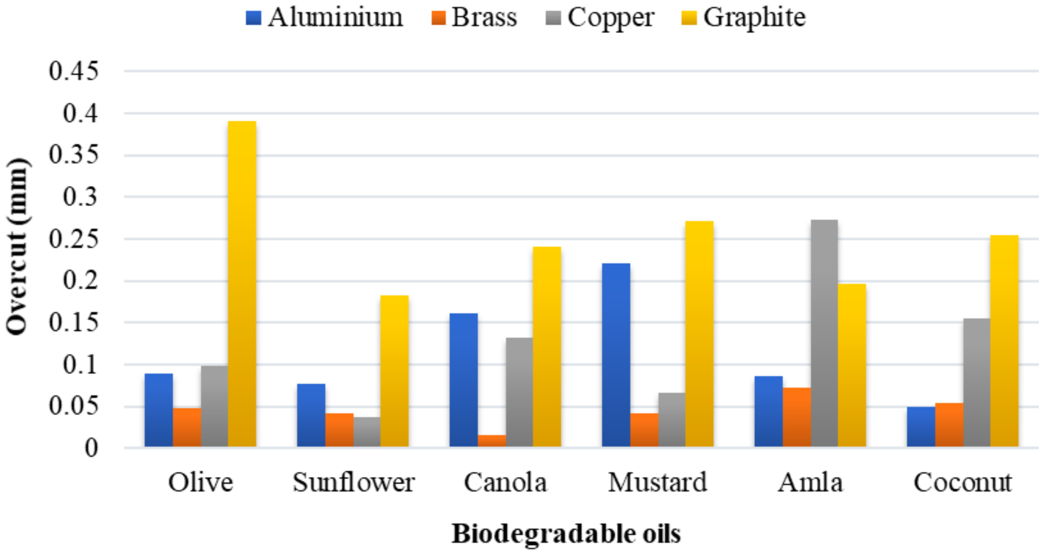


Figure 4. Evaluation of overcut versus different vegetable oils.

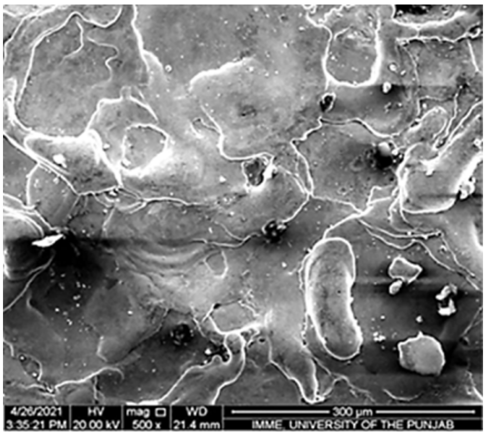


Figure 5. Surface morphology of Inconel 600 under olive oil against graphite tool.

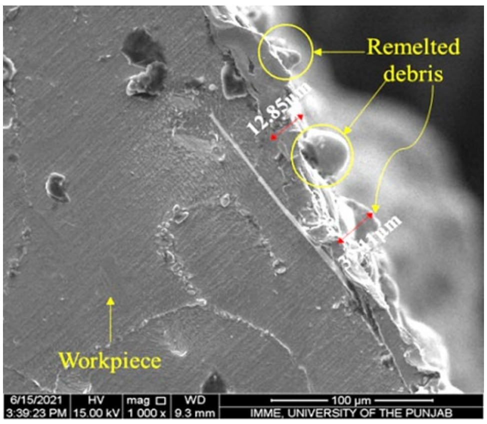


Figure 6. SEM image representing melted and re-deposition of the material when combination of graphite electrode with olive oil dielectric is employed.

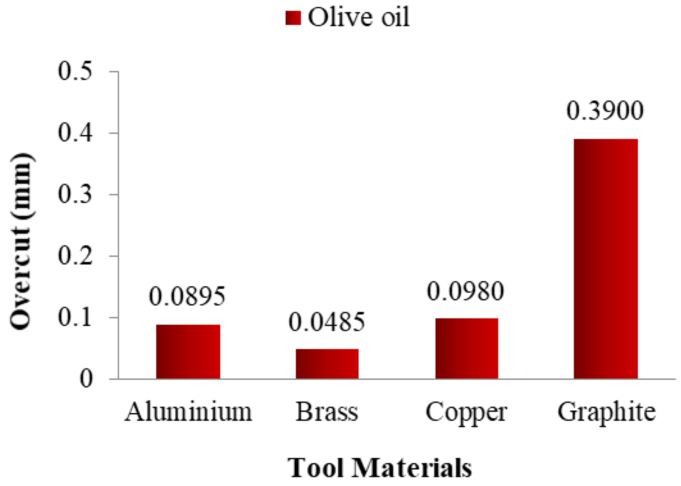


Figure 7. Mutual comparison of overcut among electrode materials under olive oil dielectric.

The sunflower oil-based EDM has delivered relatively satisfying results with Cu electrode. The comparative assessment of OC against four types of electrodes depicts that highest OC i.e. 0.182 mm is found with graphite tool whereas lowest (0.038 mm) was noticed for Cu under sunflower dielectric as shown in Fig. 8. The minimum value is 3.78% lower than that of highest one when sunflower oil dielectric is engaged. However, the minimum value of OC attained via sunflower dielectric with Cu electrode is 27.6% less than that found with brass electrode in olive oil dielectric. The maximum OC is received against graphite electrode if sunflower oil is used. The rest of the electrodes i.e., brass and Al provides intermediate values of OC wherein the OC for Al is greater in magnitude. Although the performance of Al is inferior to that of brass but the value of OC is reduced as sunflower oil is used instead of olive. Whereas, in case of, brass OC is improved when olive oil is taken as dielectric instead of sunflower oil. Though the performance of Cu is ranked inferior in olive oil, but Cu becomes the best choice for getting the lesser OC if sunflower oil is the selected dielectric as evident in Fig. 8. For both canola and mustard oils, the brass electrode has claimed better geometric precision as depicted in Fig. 4. The better performance of brass is due its lower electrical conductivity (16×10^6 S/m) as compared to Al (35×10^6 S/m) and Cu (59.6×10^6 S/m). The lower conductivity offers lesser amount of current/electrical energy in the machining regime where electro-erosion is required to be happen. As the magnitude of input energy is reduced thereof relatively small materials got removed from the target surface as a result of electro-erosion. Considering that the erosion reduces in all the cutting orientations so, it can be inferred that plasma channel width is comparatively confined which improves the sparking focus on the target. Hence, the OC value got reduced while using the brass tool in EDM of the selected Ni-based alloy using the aforesaid dielectrics. Though the brass provides lower value of OC for both the oils however, the value realized with canola oil is more appreciated as it is 1.57% lesser in comparison to that achieved with mustard oil. In case of canola oil the worst performance was observed in case of graphite electrode where an OC of 0.24 mm has been noted. This might happen due to the low density of graphite (1770 kg/m^3) and high dielectric strength of canola dielectric. The high dielectric strength requires extensive discharge energy in the machining region for initiating the machining action. Thus, a powerful sparking is developed in the cutting regime which penetrates in the work surface. Consequently, grater amount of material is removed for the machined impression in all the cutting dimensions. So, OC is raised. Moreover, the lower density of graphite tool is more susceptible to widen the plasma channels' width. The compromise in the coherence of the sparking focus also contributes in up-surging the OC value. Another, drawback associated with the high material removal is the high probability of thicker recast layer formation if melted debris is not efficiently evacuated. The formation of recast has also been observed when EDM of Inconel is carried out under canola oil using graphite tool as highlighted in Fig. 9. The comparison of four electrodes in terms of OC values is performed as well under the said oil as illustrated in Fig. 10. It is pivotal to state that the performance of graphite further deteriorates in case of mustard oil.

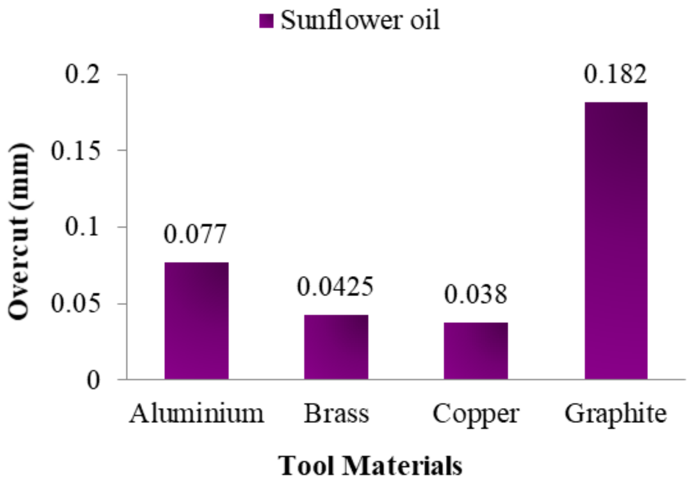


Figure 8. Overcut values against different electrodes under sunflower dielectric.

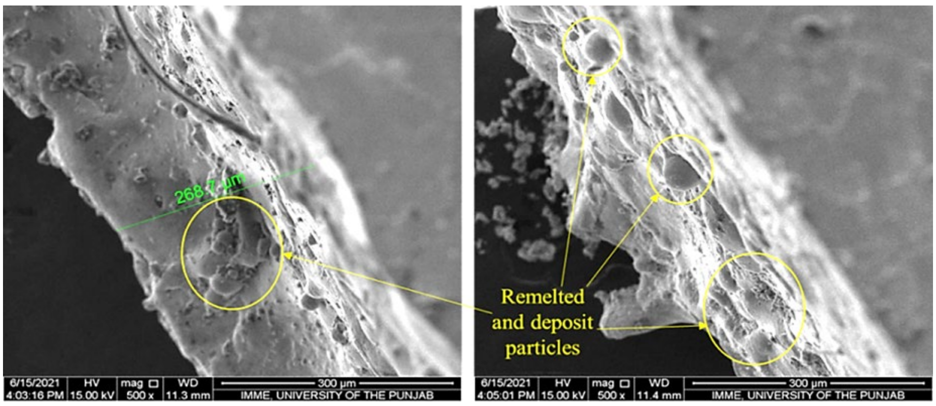


Figure 9. SEM images indicating recast layer onto surface of Inconel 600 with brass electrode under canola oil.

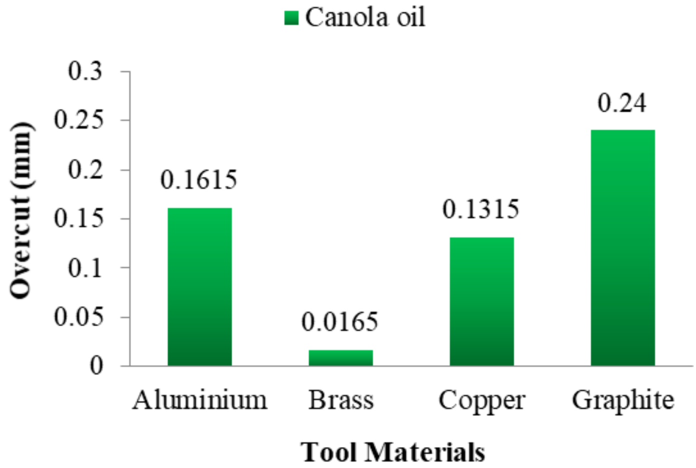


Figure 10. Comparison of overcut against tool materials under canola dielectric.

Contrary to the previous case where sunflower oil is engaged, the performance of Cu is compromised in the canola dielectric where an increase of 3.46 times is realized in OC during EDM of Inconel 600. Though the performance of Cu is inferior in Canola however, it provides lower value of OC if mustard oil is used as dielectric. There exists more than 90% lowering of OC as far as the Cu electrode is concerned. The lower dielectric strength of mustard oil (28 KV) is responsible for this effect. The low dielectric strength is a depiction that the thermal breakdown of dielectric molecules will occur at relatively smaller discharge energy. Thereof, the electric explosion takes place is weak as it is the outcome of low discharge energy. As a result, a reduced heat input is experienced by the workpiece material leading to lower material erosion. Correspondingly, OC is decreased by employing mustard oil as shown in Fig. 11. It is also worthy to mention that Al produces high OC values in both Canola and Mustard oils. However, dimensional error is more pronounced in case of Mustard oil as far as Al electrode is concerned. The compromised performance of Al in terms of OC is attributed to its lower melting point. Actually, the surface of the Al electrode is more prone to erosion during the electric erosion process owing to its lower melting temperature (660 ºC) as compared to that of workpiece material (1413 ºC). The efficacy of the eroded tool surface is deemed less effective for maintain the coherence of the spark on the work surface owing to its random nature. Subsequently, OC is enhanced.

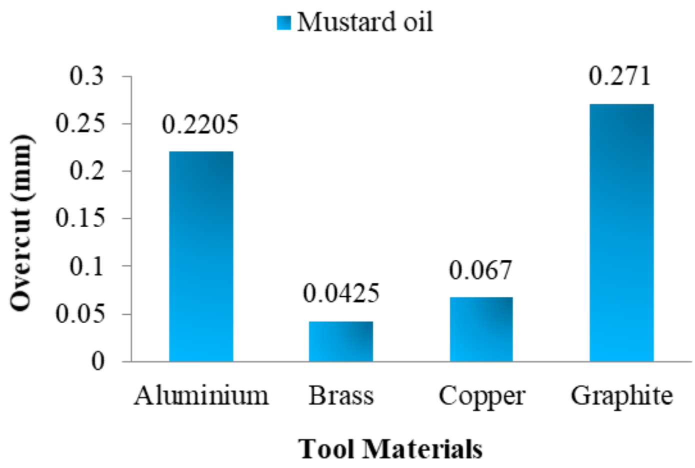


Figure 11. Overcut magnitudes obtained with each electrode in mustard oil dielectric.

Contrarily, an opposite trend is revealed for the electrode of Al if the dielectric is amla oil as presented in Fig. 4. The OC value which was 0.2205 mm in case of Mustard oil reduces to 0.0865 mm under Amla oil. This is due to the high dielectric strength of amla oil (50 KV) as compared with the mustard oil (28 KV). The high magnitude of dielectric strength limits the excessive sparking/arcing which result in better heat utilization in the machined zone. Eventually, OC value improved in case of Al electrode. The comparative assessment of OC values realized against the four electrodes using amla oil is presented in Fig. 12. The behavior of Cu electrode also got inversed in the amla oil in contrast to that observed with the mustard oil i.e., OC significantly increased. It is pertinent to mention that the highest value of OC (0.2725 mm) has been found with the copper tool and amla oil dielectric. The poor dimensional control in the aforesaid case is because of the fact that availability of large number of ionized particles in the amla oil after discharging at high energy. Actually, the viscosity of amla oil (102.8 NS/m^2) is highest amongst all the nominated dielectrics and dielectric viscosity plays a fundamental role during the formation of plasma channel. High viscosity requires high thermal breakdown voltages which results in penetrating heat flux. This phenomenon upsurges the OC value. Therefore, magnitude of OC is amplified. The brass tool material is claimed to be the impressive option for lowering OC using the amla oil during EDM of Inconel 600. Though, the lowest value (0.0725 mm) is noticed with brass tool in amla oil however, this value is 1.7 times greater as compared to the minimum value obtained using mustard oil with the same electrode. The better performance of brass is linked with its higher density (8.73×10^{-3} g/mm^3) and melting temperature i.e., 940 ºC as compared to its counterpart Al. Both the said attributes lower the wear of the tool which in terms helps to achieve better dimensional control.

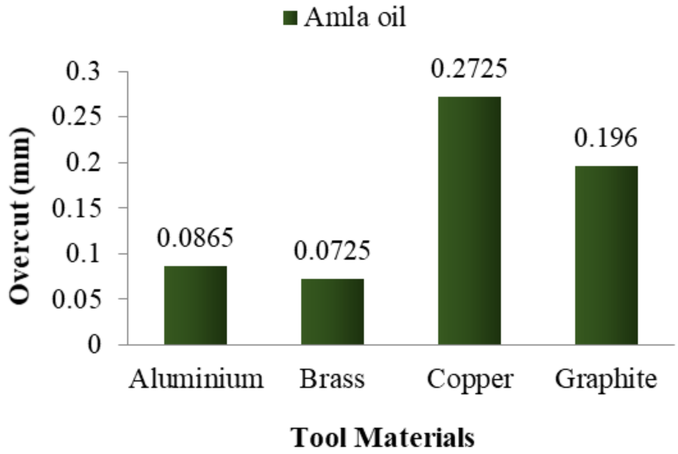


Figure 12. Overcut values for four electrodes under amla oil.

Interestingly, the value of OC decreases for all the electrodes instead of graphite tool when coconut oil is taken as dielectric as depicted in Fig. 4. However, the highest reduction is found in case of Cu where the OC lowers by 76% in contrast to the previous case. The minimum lowering in OC was noticed in case of graphite where 29.8% lowering of OC is realized. The inferior performance of the graphite in contest to the other tools is attributed to its porous structure. This structure offers a challenge over the controlled sparking. The poor controlled sparking causes the work material to be eroded in an unstable manner that likely to provoke the sideways sparking. Eventually, material got removed from the cut periphery beyond the defined limit. Thus, overcut formation is seriously compromised. The best output in terms of dimensional accuracy has been noticed in case of Al electrode if coconut oil is engaged in EDM of Inconel 600 followed by brass and Cu as indicated in Fig. 13. The appreciable performance of Al electrode in coconut oil is because of the high dielectric strength (60 KV) of the aforementioned dielectric. As previously discussed, that higher strength of dielectric bound the excessive sparking in the cutting zone. Subsequently, lower heat input is realized by the target surface followed by a confined material removal form the target. This translates in lower OC value. If the lowest value acquired with the application of coconut oil is compared with that attained with the mustard oil, it has been revealed that there exists an improvement of 46%.

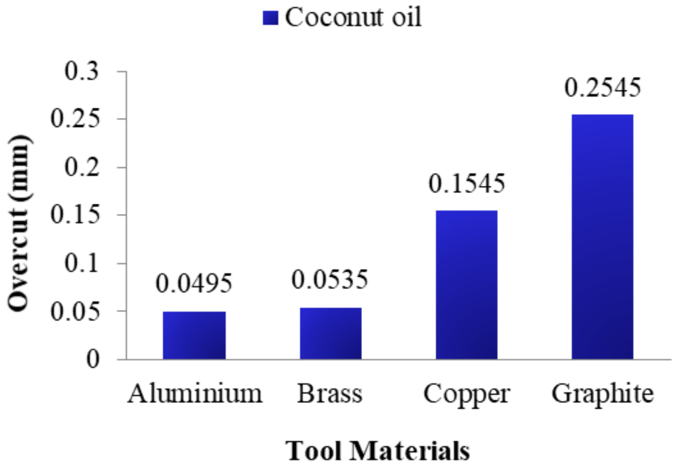


Figure 13. Overcut values for four electrodes under coconut dielectric.

It has been revealed after comparing the minimum values of OC realized with all electrodes under the selected six bio-degradable dielectrics that Canola oil with brass electrode is the best choice for dimensionally consistent machined profile. In terms of other dielectrics, sunflower oil with Cu tool is proved to be the second-best choice considering the dimensional accuracy perspective. Although the brass electrode under the Canola oil has proved to the impressive alternative in the context of OC, but for the sake of differentiation between kerosene and said vegetable oil in the said perspective, an additional trial was performed with the kerosene oil. Rest of the parameters has remained same and just the difference is of the dielectric type. It is noticed that brass electrode under canola oil performed better than kerosene dielectric. The low viscosity of kerosene oil also acts as a stimulus for the raising the value of overcut. The low viscosity means that lesser discharge energy is required for initiating the spark in the cutting zone. Thus, more material erosion is noticed in the cutting zone. The greater material erosion amplifies the magnitude of overcut in the machined cavity. The value of OC obtained with brass tool in the kerosene dielectric is 63% more as compared to that achieved under Canola oil employing the same electrode as demonstrated in Fig. 14. Summarizing the discussion of overcut, it is suggested that the best optimal setting for achieving noble geometric accuracy while EDM of Inconel 600 is the electrode of brass under Canola oil dielectric. After a detailed examination and discussion of the outcomes, the optimal setting against the set response has been reported and summarized in Table 5. It is mentioned that brass is the most appreciated electrode in terms of providing minimum magnitude of overcut.

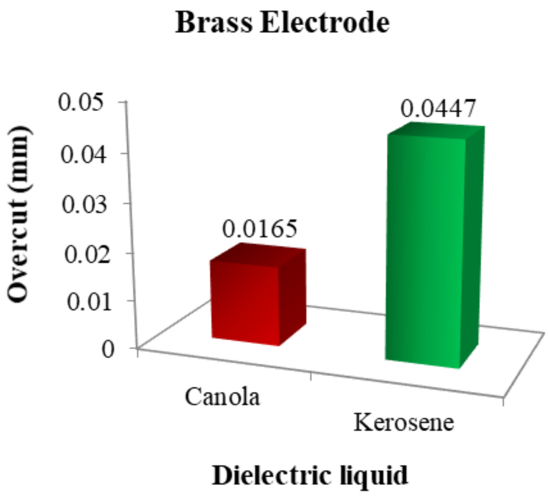


Figure 14. Comparative analysis of OC between Canola and kerosene oil dielectrics against brass electrode

Table 5. Optimal setting for the cutting of Inconel 600 via EDM process.

Best alternatives	Response	Dielectric	Electrode	Value (Units)
1st best option	Overcut	Canola	Brass	0.0165 (mm)
2nd best option		Sunflower	Copper	0.0380 (mm)

Conclusion

The current research focuses on the investigation of geometric accuracy of the Inconel 600 during the EDM process. To ensure the sustainable machining, six biodegradable oils were utilized because of their friendliness with the health and environment. Keeping all parameters constant except electrode type and dielectric, the results were inspected statistically along with the collection of evidences through EDX and SEM. The following conclusion can be extracted based on the above discussion:

1. The supremacy of biodegradable dielectrics has also been verified for dimensional accuracy perspective. The dielectric namely canola yields the smallest value of dimensional error i.e., 0.0165 mm. However, the second best dielectric is sunflower oil comprising a value of overcut equal to 0.0380 mm. These aforementioned overcut values when compared with that found with kerosene, a significant reduction of 63% and 1.2 times is revealed with the said biodegradable dielectrics respectively.
2. Results revealed that the electrode of graphite provides the worst dimensional consistency under bio-degradable dielectrics. However, the maximum dimensional error (0.39 mm) was noticed when EDM is performed under Olive oil using graphite electrode.
3. In overall terms the electrode of brass has proved to be the best choice for producing dimensionally accurate micro-impression of 0.2 mm depth in Inconel 600. The electrode of Cu has found to be the second-best choice. In

order to achieve better dimensional accuracy with coconut oil, the electrode of Al has noted to be the best selection.

4. Though the minimum overcut is found with Canola oil dielectric however, the overcut values are closely spaced when Sunflower oil is engaged as dielectric medium.
5. The optimal combination that can provide the dimensionally consistent machined cavity in EDM of Inconel 600 is to use brass as an electrode material and Canola oil as dielectric.

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Disclosure statement

The authors report there are no competing interests to declare

Data availability statement

All the data associated with this work is presented in the manuscript.

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