Hindawi
Advances in Materials Science and Engineering
Volume 2019, Article ID 5625360, 11 pages
https://doi.org/10.1155/2019/5625360

Research Article

Comparison of Micro-EDM Characteristics of Inconel 706 between EDM Oil and an Al Powder-Mixed Dielectric

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Received 4 November 2018; Accepted 5 March 2019; Published 1 April 2019

Academic Editor: Hongtao Zhu

Inconel 706 is a newly developed aeronautical material that has corrosion resistance along with high mechanical strength. Conventional machining of Inconel 706 results in a poor surface finish and a low-dimensional accuracy. Hence, micro-EDM (electrical discharge machining) is utilized to machine Inconel 706. This work proposes a comparison of micro-EDM characteristics of Inconel 706 between EDM oil and an Al powder mixture. The effects of input parameters on the surface roughness, material removal rate, tool removal rate, and microstructures of the machined surfaces between EDM oil and EDM oil mixed with Al were investigated. It was clarified that micro-EDM with a certain amount of Al powder added to the EDM oil can attain a high MRR and better surface integrity. However, the TWR discharge gap was larger than that in the EDM oil. Furthermore, it was observed that more attachment of the workpiece was adhered to the top surface of the electrode in the EDM oil due to its unstable machining. It was explained that the MRR increases with an increase in the Al concentration and then tends to decline.

1. Introduction

Nickel-based superalloys have become a promising material in aircraft turbines, nuclear reactors, petrochemical plants, food processing equipment, etc. [1]. However, the high-temperature strength, hardness, and chemical wear resistance of Inconel alloys pose a challenge for machining tools. The common methods for cutting Inconel alloys, such as ramping or taper turning and rotary machining, will eliminate the predominant notching of the cutting tools. However, it may cause a catastrophic fracture of the entire cutting edge when machining Inconel alloys. Furthermore, the traditional machining of micro- and complex shape components for aerospace applications using Inconel alloys is extremely difficult [2]. Consequently, EDM (electrical discharge machining) has become an effective way to machine Inconel alloys. With the greatly increased demand for fabricating advanced materials, EDM has been found to be a superior processing method compared with traditional machining [3–5]. Additionally, EDM plays an important role in the modern manufacturing industry, especially in the areas of defense, aerospace, and special materials applications, and has been developed as an alternative to machining Inconel alloys [6]. Compared to the poor machinability of Inconel alloys using conventional mechanical cutting methods, EDM shows a superior processing reliability due to not having an external force between the tool electrode and workpiece, as well as its electrocorrosion principle [7]. Research on machining Inconel alloys mainly focuses on WEDM (wire electrical discharge machining). Garg et al. proposed the effect of wire materials on the cutting performance of WEDM for machining an Inconel superalloy. It was determined that a zinc-coated brass wire is most suitable for Inconel 718 [8, 9]. An investigation of the machining time and surface roughness in a wire-EDM for Inconel 800 was conducted by Majumder et al. It was observed that a better surface finish can be machined by a smaller pulse-on time and pulse current [10]. In the known literature, the SR (surface roughness) and MRR of Inconel alloys mainly depends on the input parameters. The diameter of the wire in WEDM was investigated by Sharma et al., who concluded that a smaller diameter wire is advantageous over a larger diameter wire, since it improves productivity and the surface quality of the machined components [11]. All of the above have to do with WEDM, which cannot meet the requirements for machining small holes and special shapes in components of Inconel alloy. Therefore, it is necessary to study sinker EDM of Inconel alloy. The sinker EDM is a comprehensive machining technology. The study of Inconel alloys using EDM is critical for meeting ideal industrial requirements. There are a few studies on PMEDM (powder-mixed electrical discharge machining) of Inconel alloys. PMEDM is one of the most crucial technologies for advancing EDM. The influence of adding powder to the dielectric fluid on a machined surface has been studied by Fong and Chen [12]. They found that it generates fewer cracks on the surface and decreases the thickness of the recast by adding a certain size of particles (70–80 nm) to the dielectric fluid. Sung-Long et al. conducted micro-EDM experiments and used deionized water mixed with titanium powder as a dielectric for modifying the surface of pure titanium. They found that it displayed a negative correlation between the content of Ti powder and thickness of the recast layer [13]. Tiwary et al. were involved in an investigation on the effect of dielectrics during microelectro discharge machining of Ti-6Al-4 V [14]. They determined that the machined profile and topography of the microhole obtained with Cu powder mixed with deionized water were found to be superior compared to those machined with EDM oil or pure deionized water.

In addition to PMEDM, many researchers have begun to explore the influence of different kinds of dielectrics in electrical discharge machining. It was reported by Sadagopan and Mouliprasanth that biodiesel as a dielectric has a better performance in terms of the MRR, TWR, and surface finish compared to kerosene and transformer oil [15]. Nguyen et al. discovered deionized water as a dielectric fluid in micro-EDM demonstrated a higher material removal rate and a lower tool wear than hydrocarbon oil. Additionally, it is a relatively economic and environmental work fluid. The machined surface was found to suffer less from material migration due to less debris forming in the micro-EDM [16]. Nonetheless, EDM oil is widely used in factories due to its low viscosity, good insulation, and high melting point. In general commercial electric spark machines, EDM oil is chosen as the working fluid, since it is easy to produce and has a low cost.

It has also been observed that very few studies are available describing the EDM machining of Inconel 706. The study of EDM machining of Inconel 706 mainly focused on WEDM, and machining Inconel 706 in EDM mixed with Al powder has rarely been studied. Therefore, this work was conducted to investigate the EDM characteristics in different dielectric fluids. Indeed, comparative experiments were conducted for machining Inconel 706 between EDM oil and EDM oil-mixed microaluminum (Al) powder. The reasons for the differences in the surface integrity, MRR (material removal rate), TWR (electrode wear rate), and SR (surface roughness) are discussed. Additionally, a performance evaluation of an Al powder-mixed dielectric for machining Inconel 706 is proposed in the study.

2. Experimental Work

2.1. Experimental Setup. Die-sinking (DOPHEN) EDM manufactured by Shenzhen Du Feng Engineering Co., Ltd. was used in the experiments. To meet the desired requirements and experimental design, a new EDM setup was developed by the authors. Figure 1 describes a photographic view of the developed experimental machine.

The lateral jet-flushing method was used in the experiment to enable flushing from the workpiece area. A commercial high-pressure pump was used to maintain constant pressure at 0.1 kgf/cm^2 during the entire machining process. The control display of the die-sinking EDM provides the manual input machining parameters, including the pulse-on time, the pulse-off time, and the theoretical processing depth. A stereomicroscope (type: VHX-1000), manufactured by the Japan KEYENCE company, was used to observe the profile of the machined blind hole. The surface roughness of the hole was measured by using a laser scanning confocal microscope (type: VK-X200K) manufactured by the Japan KEYENCE company. A scanning electron microscope (model: S-3400N), manufactured by the company Hitachi in Japan, was used to observe the surface morphology of the machined surface. The schematic diagram (Figure 2) consists of three parts: the workpiece clamp, working fluid circulation system, and tool holder. We developed the workpiece clamp taking boosting stability and precision during the electrical discharge machining process into account. Hence, the two ends of the Inconel 706 sheet are clamped tightly by using the vertical retaining block to prevent vibration of the workpiece during EDM process.

2.2. Fabrication of the Tool, Preparation of Workpieces, and Different Concentrations of Al Powder-Mixed Dielectric. Due to its high thermal conductivity and high conduction temperature coefficient, Inconel 706 was selected as the target workpiece material for EDM. The chemical composition of Inconel 706 is shown in Table 1.

A specimen 50 mm × 10 mm × 5 mm in size was cut from the plate by using the medium-speed wire cutting machine (model: H-CUT32F, manufactured by China Liao Gao company). We chose a copper rod 700 μm in diameter as the tool electrode. Considering the effect of the electrode section roughness on processing, the end face of each electrode was polished with 1500# sandpaper. The aluminum particle concentration in the working fluids had tremendous influence on the EDM. To obtain the optimal particle concentration, the experiment utilized EDM oil with different Al powder concentrations to machine microholes by EDM. As shown in Figure 3, weigh a certain amount of aluminum

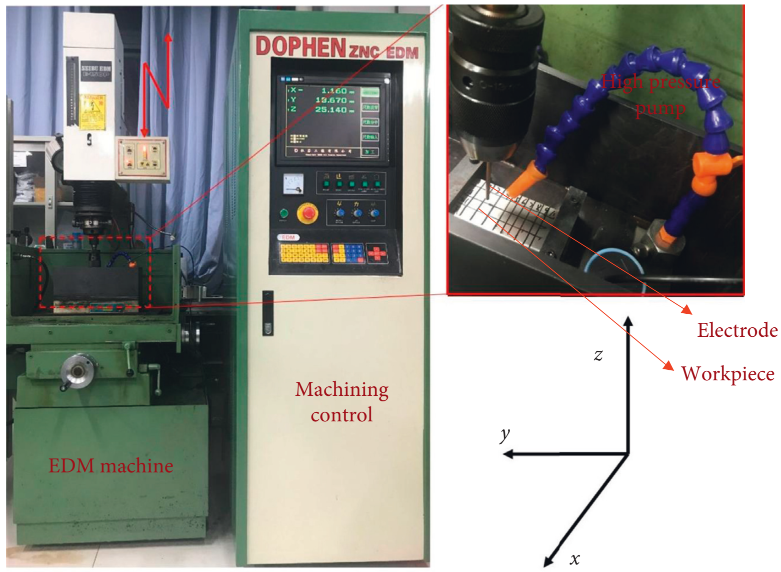


Figure 1: Photograph of the experimental setup.

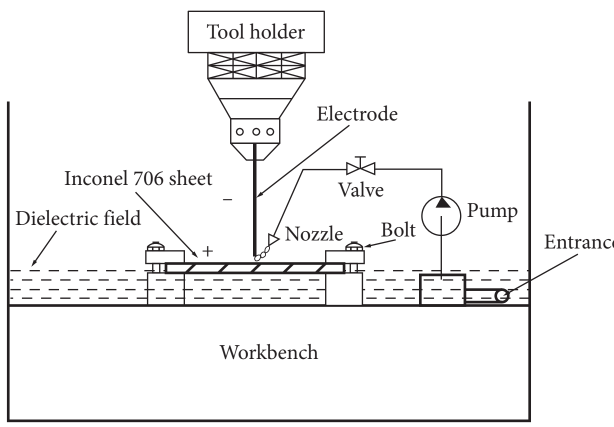


Figure 2: Diagram of EDM.

Table 1: Nominal chemical composition of the as-received Inconel 706 [17].

Alloy (%)	Ni + Co	Cr	Fe	Ni + Ta	Ti	Co	C	Mn	Si	S	Cu	Al	P	
Inconel 706	Min	39	14.5	Bal	2.5	1.5								
	Max	44	17.5		3.3	2	1	0.06	0.35	0.35	0.02	0.3	0.4	0.02

powder with high-precision electrons, and then use a flat bottom beaker to make a certain volume of EDM oil. Finally, mix the aluminum powder into the EDM oil, and stir it evenly with a glass rod.

3. Results and Discussion

3.1. Microstructure Properties of the As-Received Inconel 706. Inconel 706 was chosen as the target material since it is widely applied due to its outstanding properties, such as its high toughness and ductility, good surface stability, and oxidation [18]. As shown in Figure 4, the elemental composition of Inconel 706 was detected by an EDX (energy dispersive X-ray) spectroscopy analysis. It was observed that there are many tiny pits on the surface of the alloy. However, the integral surface of the alloy is relatively smooth, which is visualized by an observation of the machined blind holes.

3.2. Differences in Machining Performances. The Cu electrode was set to negative because the energy distribution into the anode is larger than that into cathode [19]. All the experiments were performed under the experimental conditions shown in Table 2. All the other machining parameters that are not listed in Table 2 were kept the same in the experiments.

The materials removal rate (MRR) and tool wear rate (TWR) of EDM are key response parameters assessing the

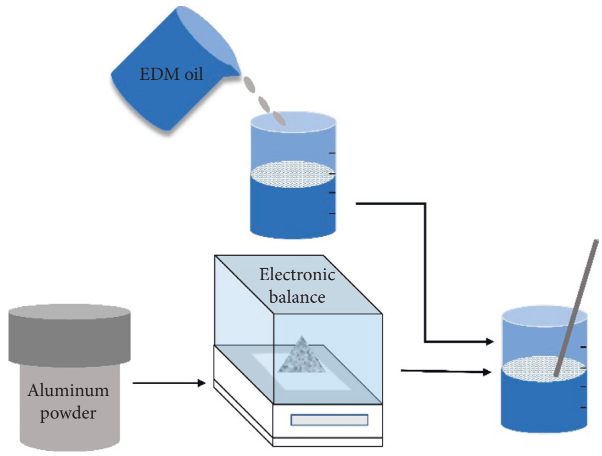


Figure 3: Preparation of different EDM oil with Al powder.

machining efficiency and machining stability. The volume of removal was observed by using a laser scanning confocal microscope.

MRR in cubic millimeter per minute is calculated by the following equation [20]:

$$\mathrm{MRR} = \frac{V}{t}\left(\mathrm{mm}^3/\mathrm{min}\right), \quad (1)$$

where V is the volume of the workpiece material removed and t is the machining time.

Since the electrodes used in each experiment are rod electrodes of equal sections, the relative wear is used to represent the electrode wear for convenient measuring. The TWR is calculated using the following equation [21]:

$$\mathrm{TWR} = \frac{\Delta \mathrm{LE}}{h} \times 100\%. \quad (2)$$

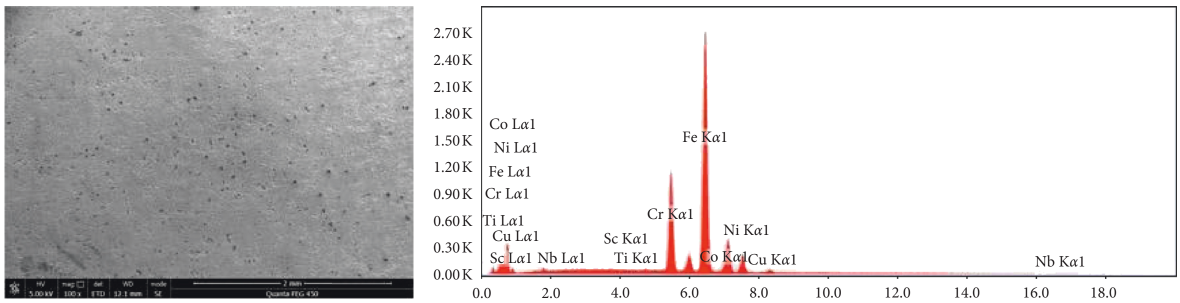
As shown in Figure 5, ΔL_{E} is the electrode loss length and h is the machining depth.

From Figure 6(a), it can be determined that the MRR increases with an increase in the pulse-on time, demonstrating similar trends in the two different dielectric liquids. This occurs because the pulse-on time T_{on} is responsible for the heat energy generated in the gap for melting and vaporization [22]. The increase in the crater depth and diameter is due to the increment of the pulse-on time, which can be explained by the following equation [23]:

$$W_0 = \int_0^{ti} u(t)i(t)dt, \quad (3)$$

where W_0 is the energy of a single pulse, u is the gap discharge voltage, and i and ti are the discharge current and pulse width, respectively. As shown in the formula, the single pulse energy is proportional to the discharge, which hence leads to an increase in the MRR as the pulse-on time increases. On the contrary, the MRR was always higher in EDM oil mixed with Al than in EDM under an all preset pulse-on time. Moreover, the MRR is increased significantly by 64% in EDM oil mixed with Al compared with MRR in EDM oil under a pulse-on time of 6 μs. It may be primarily due to more removal at a high pulse-on time and MRR changes slightly in a low pulse-on time. Secondly, during the formation of each discharge channel, Al particles are suspended in the working area, which makes the dielectric fluid more conductive. Figure 6(b) depicts that the TWR decreased significantly when the pulse-on time increased from 1 μs to 3 μs in two different working fluids. However, the TWR increased as the pulse-on time increased from 3 μs to 6 μs. According to Figure 6(b), the tool wear rate in EDM mixed with Al is slightly higher than in EDM oil. This phenomenon may be attributed to the carbon-based elements contained in the EDM oil being deposited on the electrode surface, and the aluminum powder suspended in the working fluid weakens the effect of the carbon nuclides attached to the electrode surface after machining. Additionally, the suspended aluminum powder washes the surface of the electrode at a high speed as the working fluid circulation, which causes destruction of the carbon black layer formed on the surface of electrode. Figure 7 depicted the influence of the peak current on the machining performance in different dielectric liquids. It is observed from Figure 7(a) that the MRR increases with an increase in the peak current of the two dielectrics. As mentioned earlier, the peak current is similar to the effect of the pulse-on time to the MRR. Since an increase in the peak current gives a rise to the single spark intensity, the more the heat energy transmitted into the workpiece, the more the material melted and vaporized from workpiece [24]. As shown in Figure 7(a), the MRR in EDM oil mixed with Al is higher than that in EDM oil. The aluminum powder produced the higher MRR due to the low electrical resistivity, which allows the sparking to take place from a large distance compared to EDM oil, leading to a rise in the sparking frequency. Different from the effect of pulse-on time on the electrode loss, Figure 7(b) demonstrated that the TWR increases as the current increases. The discharge energy increases with the peak current, which is responsible for melting and vaporizing the material from the electrode, leading to more TWR. The TWR in the EDM oil with mixed Al is higher than that in just EDM oil due to the conductivity of the suspended Al powder, which increases the secondary discharge. The secondary discharge causes additional machining around the edge of the electrode, which happens to be comparatively weak in EDM oil [25].

The narrow and uniform spark gap leads to the difficulty in removing discharge debris from the working area which causes frequent occurrence of abnormal discharges such as short circuit in the machining of microhole by micro-EDM [26]. The unilateral discharge gaps, which were calculated by dividing the difference in the hole diameter (D) and electrode diameter (d) by 2, are plotted in Figure 8. Figure 9 shows pulse-on time dependencies of unilateral discharge gap between EDM oil and EDM oil mixed with 10 g/L Al powder. It is clearly evident that the discharge gap is enhanced with an increase in the pulse-on time. Furthermore, the EDM oil requires a smaller discharge gap due to its lower conductivity; hence, the larger discharge gap was obtained by adding Al powder in the EDM oil. The conductivity of Al strengthens the extension of the gap distance, which well



(a) (b)

Element	Weight %	Atomic %	Net int.	Error %	K ratio	Z	A
ScL	0.43	0.54	0.84	18.92	0.0028	1.0254	0.6379
CuL	4.51	4.00	26.19	22.03	0.0076	0.9753	0.1724
TiK	0.48	0.56	52.09	13.88	0.0048	1.0083	0.9213
CrK	19.28	20.85	1868.98	2.30	0.2018	1.0035	0.9660
FeK	64.91	65.36	4827.10	2.08	0.6079	1.0036	0.9202
CoK	0.64	0.61	42.80	20.85	0.0058	0.9837	0.9206
NiK	6.18	5.92	350.55	5.99	0.0514	1.0204	0.8067
NbK	3.57	2.16	15.68	58.28	0.0374	0.8815	0.9871

Figure 4: Microstructure (a) and the EDX analysis (b) of Inconel 706.

Table 2: Process parameters used during the EDM process.

Machining parameters	Value
Working liquid	EDM oil and EDM oil mixed with Al powder size of 1 μm (5 g/L, 10 g/L, 15 g/L, 20 g/L, 40 g/L)
Preset peak current (I)	3, 5, 7 (A)
Voltage (V)	190 V
Pulse-on time (T_{on})	1, 3, 6 (μs)
Pulse-off time (T_{off})	20 (μs)
Feeding depth (mm)	1 mm
Jumping height (mm)	0.8 mm

contributes to the flow of dielectric and the movement of discharge debris in microhole machining; however, increased spark gap also causes a lower profile accuracy.

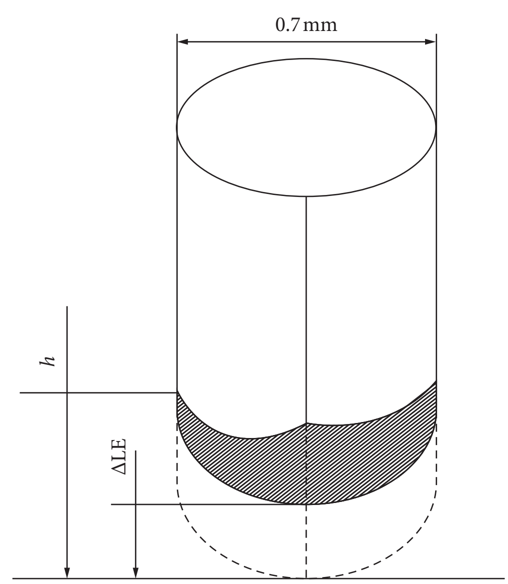


Figure 5: Calculation diagram of the tool wear rate.

3.3. Difference in Surface Integrity. The values of SR (surface roughness) are shown in Figure 10. The SR increases with the increase in the pulse-on time or peak current between the two working fluids.

As seen from Figure 10, there was a significant difference in the SR between EDM oil and EDM oil with added Al. The SR value was larger in EDM oil than with the added aluminum. With preset parameters of $T_{on} = 1\,\mu$s and peak current = 3 A, the SR is decreased significantly by 41.9% in EDM oil mixed with 10 g/L Al compared to the SR in EDM oil. Figure 10 illustrates that the improvement of the surface smoothness can be obtained by adding Al powder in the EDM oil. The EDM's surface of Inconel 706 in EDM oil presented many flake pits under both pulse-on time and peak current, whereas the machined surface in EDM oil mixed with Al powder presented less irregular deposition of debris, microholes, and crater marks. This was due to the extension of the gap during the machining process. In EDM, the debris was easily removed from the discharge gap, and the spark energy was dispersed by the suspended Al powder. By observing the surface morphology after machining, it was determined that many black ablation parts appeared in the bottom surface of the machined workpiece in EDM oil, which is because the energy is too concentrated to quickly eliminate ionization. Mixing the aluminum powder in the EDM oil decreases the electrical

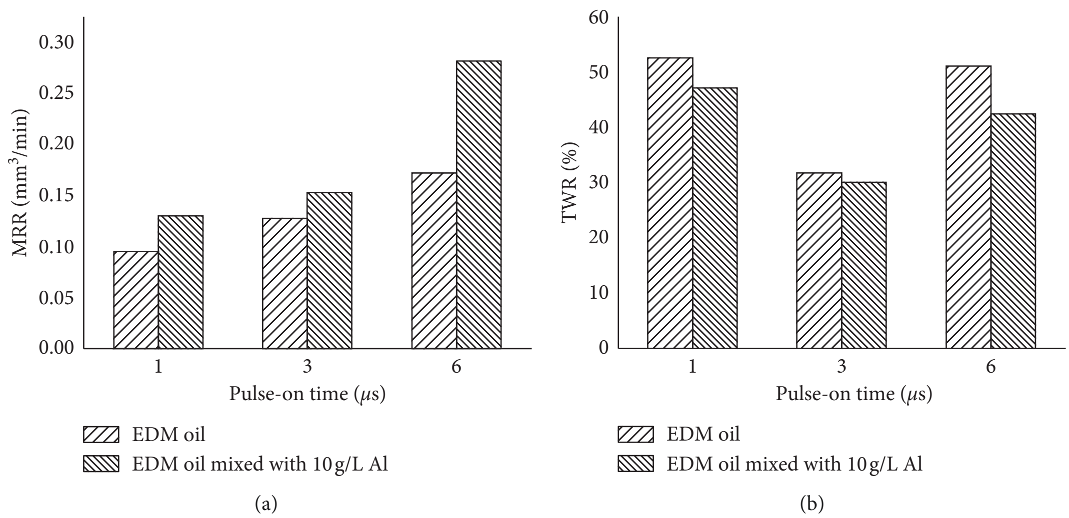


Figure 6: Influence of pulse-on time on the machining performance in different dielectric liquids.

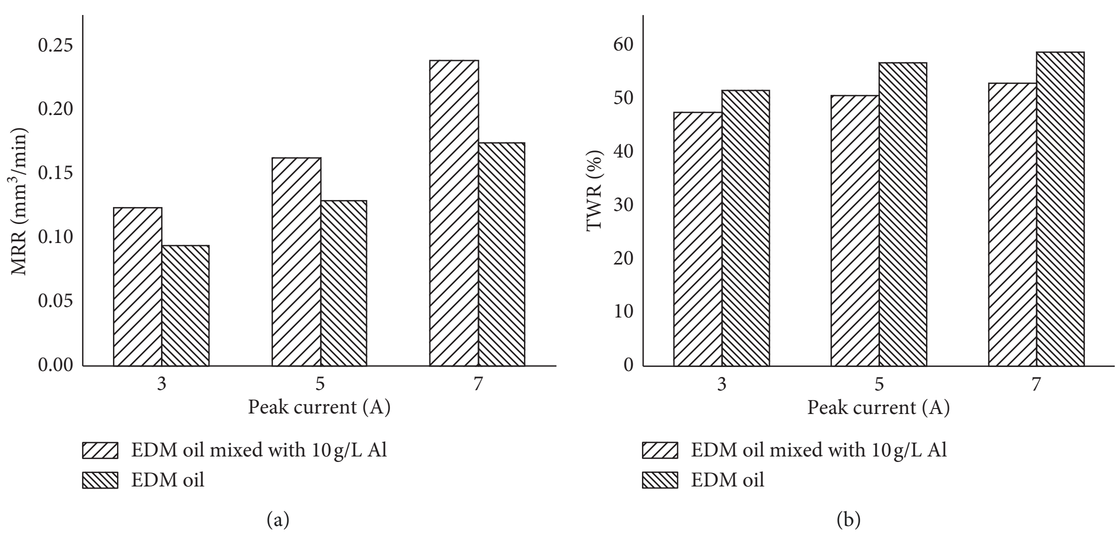


Figure 7: Influence of the peak current on the machining performance in different dielectric liquids.

resistivity of the working fluids which obviously reduces the capacitance distributed in the fluids. Meanwhile, the dispersed pulse energy resulted in a smaller discharge mark. Therefore, a significant improvement in the surface topography of the machined surface was achieved by adding Al powder to EDM oil. Figure 11 shows an elemental analysis of the EDM surface of Inconel 706 in EDM oil mixed with Al powder. Elements of Cr, Fe, Ni, Al, Cu, and Sc are found on the machined surface of Inconel 706 after EDM in EDM oil mixed with 10 g/L Al. It is considered that the increase in Cu is due to the transportation of elemental Cu from the electrode material to the Inconel 706 workpiece during EDM. Elemental Al is considered to be from the aluminum powder added to the working fluid adhering to the surface of the workpiece. Except for the appearance of Al, the same analysis result was obtained in the analysis of the EDM'd surface in EDM oil [27]. Additionally, the majority of the electrode material was transferred to the recast surface, whose tensile residual stresses may be induced due to rapid heating and cooling in EDM.

3.4. Discussion on the Influence of Particle Concentration. Figure 12 shows the effect of the Al powder concentration on the MRR. It illustrates that the MRR increases when the concentration of Al is increased from 0 g/L (EDM oil) to 15 g/L at a pulse-on time of 1 μs and a peak current of 3 A. However, the MRR is on a downward trend after a concentration of 15 g/L Al. This is because the discharge energy was dispersed in a very less amount into an area to melt and vaporize the workpiece materials via Al powder. Excessive particles that cannot be suspended are deposited near the electrodes, which may cause a poor removal of debris and less removal of workpiece materials.

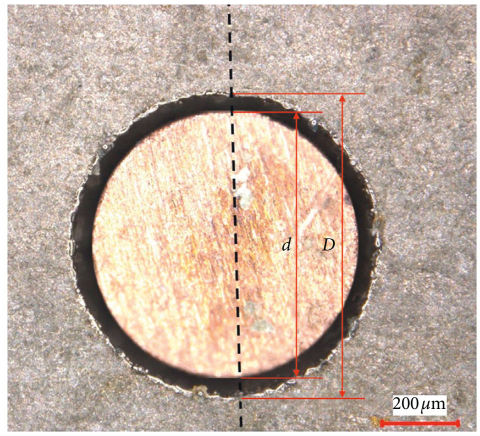


Figure 8: Main discharge working area with a pulse-on time of 1 μs and a pulse-off time of 20 μs and peak current of 3 A.

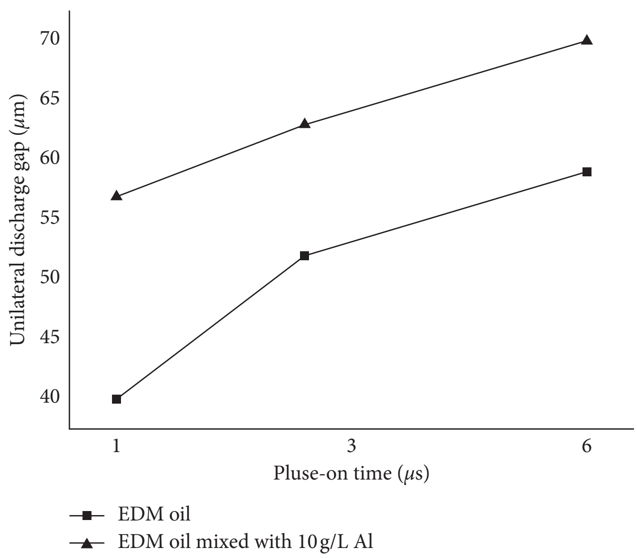


Figure 9: Pulse-on time dependencies of unilateral discharge gap between EDM oil and EDM oil mixed with 10 g/L Al powder.

It is apparent from Figure 13 that a better surface integrity was obtained from the case of EDM oil with 15 g/L Al powder. Depicted in Figure 13, it is distinctly visible that the microcracks and many microglobules exist in the machined surface in the EDM oil. It is evident that microvoids and microglobules are not more prominent in EDM oil mixed with Al. The addition of aluminum powder makes the distortion of the gap electric field more intense, and the Tandem discharge is easily formed between the powders, which causes the parasitic capacitance between the poles to decrease, and the discharge gap increases to form a uniformly distributed discharge pit. Also, the conductive aluminum powder disperses the discharge pulse and thus leads to a decrease in the infiltration depth of the microcracks. Therefore, the amount of microvoids and microglobules are significantly reduced with a dielectric mixed with a certain amount of Al powder.

An EDAX analysis of the machined surface of the electrode is shown in Figure 14. It is determined that the elements of Cr and Fe presented in Figure 14(a) are more significant than those shown in Figure 14(b). In other words, there are more elements of Inconel 706 that exist at the end of the electrode with the working fluid of the EDM oil. This is because there is more intensive sparking in the machining zone, which causes a local energy concentration in the EDM oil. Hence, a thicker melting and solidifying layer that consists of significant workpiece reattachment is formed on the surface of the electrode. Additionally, compared to the EDM oil-mixed Al powder, more unstable machining appeared in the EDM oil, which leads to an arcing, and the discharge point is too concentrated to remove the workpiece materials efficiently.

4. Conclusion

In the study, the micro-EDM characteristics of Inconel 706 with a Cu electrode in EDM oil and EDM oil with added Al powder were investigated. Here, are the main findings:

(1) The developed EDM machine setup is capable of successful machining microholes in Inconel 706 by improving the flush fluid system and clam.

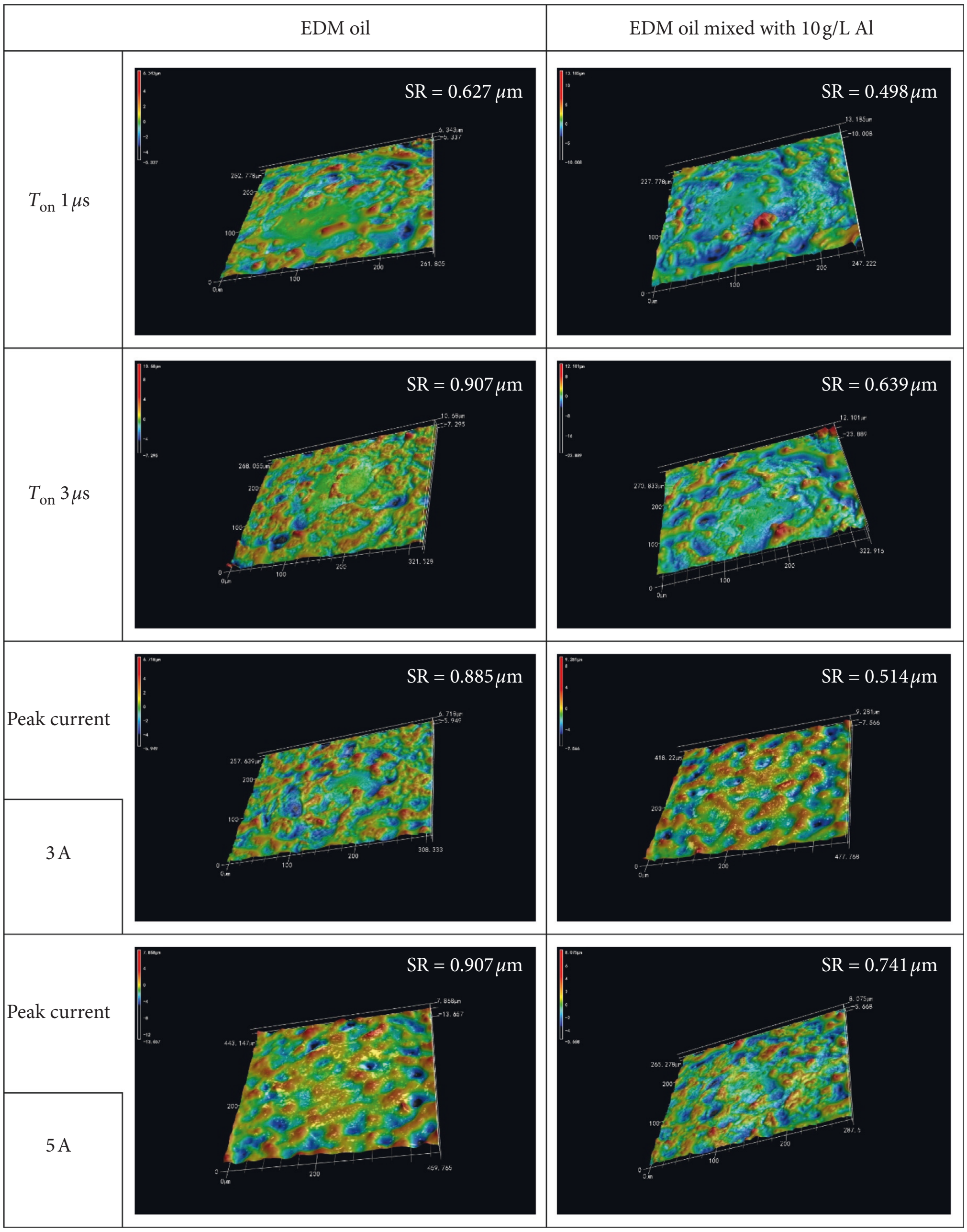


Figure 10: Surface topography plot of machined Inconel 706 between two dielectric fluids.

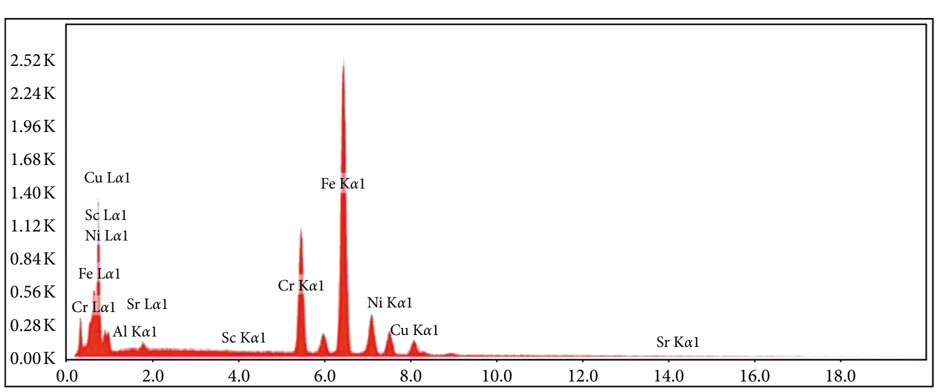


Figure 11: Elemental analysis of the EDM surface of Inconel 706 in EDM oil mixed with Al powder.

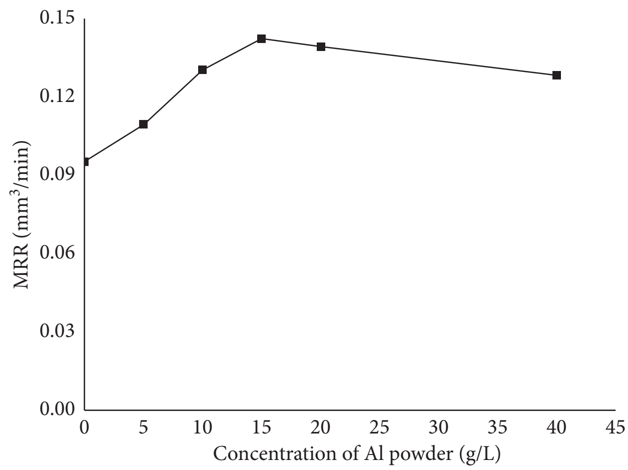


Figure 12: Material removal rate versus the concentration of Al powder.

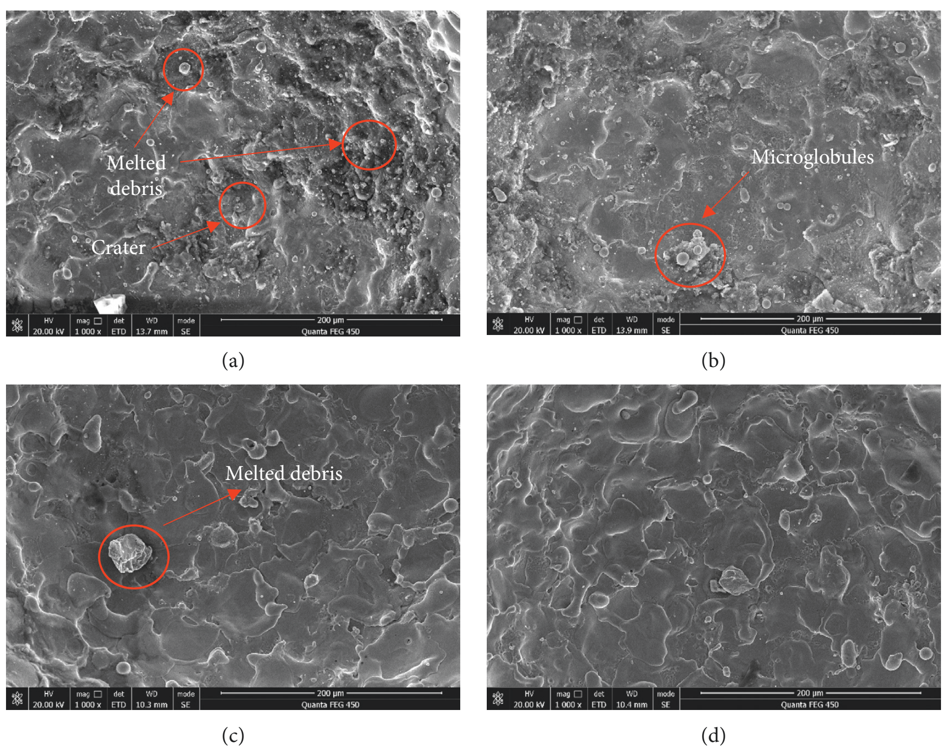
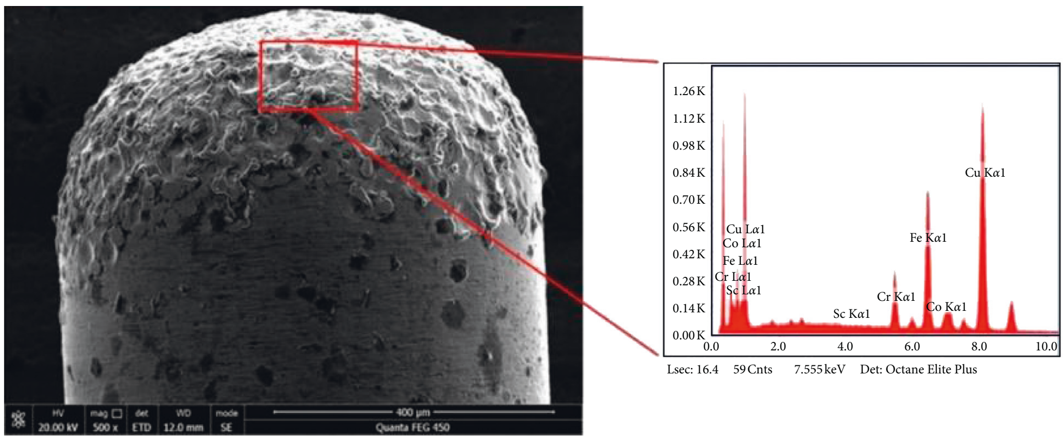


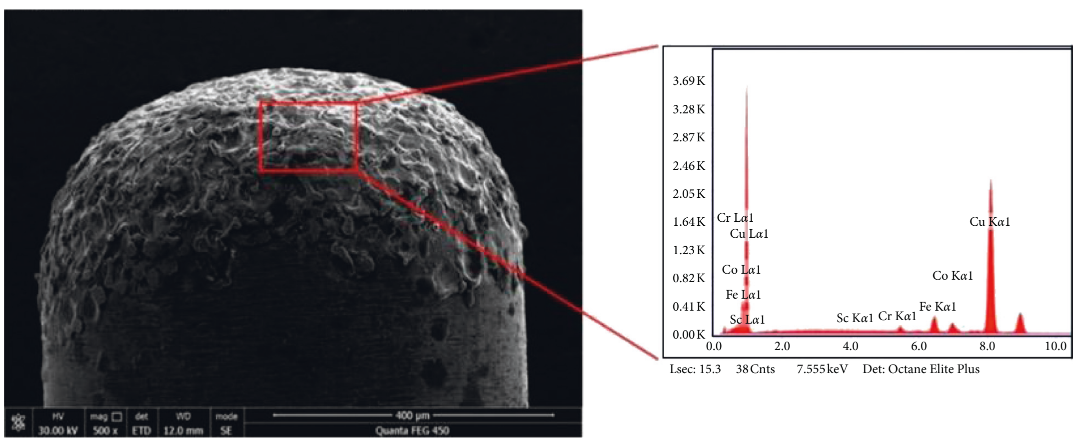
Figure 13: SEM graph of EDM machined surface at: (a) EDM oil; (b) EDM oil mixed with 5 g/L Al; (c) EDM oil mixed with 10 g/L Al; (d) EDM oil mixed with 15 g/L Al.

(2) In EDM oil mixed with 10 g/L Al, the MRR of Inconel 706 increases from 0.135 (mm^3/min) to 0.283 (mm^3/min) between the pulse-on time of 1 μs and 6 μs. Also, it increases by 95% with increase in peak current from 3 A to 7 A. An increase in the pulse-on time and peak current strengthens the spark intensity in the two dielectric fluids. However, the TWR in the EDM oil-mixed Al is higher than that in the EDM oil due to the conductivity of the suspended Al powder, which increases the secondary discharge. Moreover, the TWR increases slightly by 6.25% and 13.7% in EDM oil and EDM oil mixed with 10 g/L Al, respectively, with increase in peak current from 3 A to 7 A due to the coverage effect of the electrode surface and increased amount of electric corrosion deposited onto the electrode.

(3) A significant increment of 25.9% in SR has been found at 7 A peak current and pulse-on time of 1 μs in EDM oil compared to EDM oil mixed with 10 g/L. Adding a certain concentration of Al powder to EDM oil is found to decrease the SR of Inconel 706 in EDM.



(a)



(b)

FIGURE 14: EDX analysis of the top surface of the electrode: (a) EDM oil; (b) EDM oil mixed with 10 g/L Al powder.

(4) A 3 μs pulse-on time, 3 A peak current, and concentration of Al powder of 10 g/L are found more appropriate to get better surface integrity.

(5) EDX observations of the machined surface of the electrode showed that less workpiece materials existed on the top surface of the electrode in the EDM oil mixed with Al powder due to more stable machining in the EDM oil mixed with Al powder.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The authors would like to thank the Houling Wang and Key Laboratory of Advanced Manufacturing Technology for Mold and Die, Shenzhen University, PR of China, for their support to this work.

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