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ORIGINAL ARTICLE

Characteristics of plasma channel in powder-mixed EDM based on monopulse discharge

Xiaolong Wang [1] · **Yonghong Liu** [1] · **Yanzhen Zhang** [1] · **Qiang Sun** [1] · **Zhen Li** [1] · **Yang Shen** [1]

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Abstract Electrical discharge machining (EDM) was developed over 70 years ago, but the knowledge of plasma channels that form during this process remain understudied. Therefore, this study systematically investigated the breakdown process and impedance characteristics of plasma channels through singe-pulse discharge experiments. The influence of discharge current and gap distance on the breakdown process and impedance characteristics of plasma channels was also analyzed. The results of this work can contribute to the existing body of knowledge of the physical nature of EDM.

Keywords Impedance · Discharge · Powder-mixed · Plasma channel

1 Introduction

As a non-traditional machining technology, electrical discharge machining (EDM) has been indispensable in advanced manufacturing, as well as in the areas of machine manufacturing, astronautic aviation, electronics, instrumentation, automobile, molding, light industry, etc. EDM performs a critical function in the manufacture of high-strength, hard materials and complex parts with high sharpness. However, the basic theories involved in EDM, including the formation of plasma channels, are still far from perfect even with the development of EDM 70 years ago [1–5]. The existing research gap in the area of EDM and its mechanisms has restricted the further development of this machining process. Thus, studying the fundamental theory of EDM is of great technological significance.

EDM research is also made complex by the short discharge duration and relatively narrow discharge space in relevant experiments. Existing studies mainly focus on spectroscopic measurements [6–11], simulation analysis of discharge plasma [12–15], and reverse deduction according to discharge pit morphology [16, 17]. Kojima et al. [11] studied the expansion process of and temperature distribution in plasma channels by using spectroscopic and high-speed video technology and reported that plasma channels can expand completely in just a few microseconds. Kapoor et al. [6] and Ramkumar et al. [6–8] investigated the temperature distribution and electron density in plasma channels by spectroscopic technology. Mujumdar et al. [14] conducted a simulation to determine the composition, temperature of electrons and other ions, radius, and inner pressure of plasma channels; a model of a microdischarge channel in deionized water was developed after deriving assumptions and solving mass and energy conservation equations. Zhang et al. [17] indirectly studied the expansion process of plasma channels by measuring the geometry of a discharge pit, including the recast area; they found that the radius of plasma channels changes over time. Furutani et al. [18] described the influence of discharge current and pulse duration on the titanium carbide deposition process by EDM with oil. Hui et al. [19] created a monopulse discharge system to study the discharge characteristics of cool electrodes.

In the 1990s, Mohri et al. discovered that EDM working liquid with fine metal powder can significantly improve surface roughness. Afterward, scholars from many countries began investigating the mechanism of powder-mixed EDM. Prihandana et al. [20] investigated the influence of

✉ Yonghong Liu
liuyh@hdpu.edu.cn

[1] College of Mechanical and Electronic Engineering, China University of Petroleum, Qingdao 266580, China

molybdenum disulfide powder suspended in dielectric fluid on the micro-EDM of Inconel 718. Pecas et al. [21] used a powder-mixed dielectric to improve the polishing performance of conventional EDM. Tzeng et al. [22] investigated the effects of various powder characteristics on the efficiency of the EDM of SKD11; they found an increase in the spark gap with the addition of an appropriate amount of powder to the dielectric fluid. Bhattacharya et al. [23] investigated the performance of the powder-mixed EDM of high-carbon high-chromium die steel materials. Jahan et al. [24] used graphite nanopowder-mixed dielectric to die and mold materials. Meng et al. [16] studied the discharge crater morphology of powder-mixed EDM and concluded that plasma channels form a bell shape during positive machining. Chow et al. [25] described the formation and corruption of the discharge channel and electric bridge.

The body of knowledge of EDM and its mechanisms remains inadequate despite the many studies in the area of plasma channels. The discharge process involves electromagnetic phenomena, fluid mechanics, heat transfer theory, electrochemistry, colloid chemistry, and so on [2]. Hence, the process is so complex that its ion motion, electromagnetic, and impedance characteristics are still poorly understood.

In the present study, the impedance characteristics of a plasma column were investigated systematically and thoroughly by using a self-building experimental platform. The breakdown process and impedance characteristics of the plasma channel in EDM and powder-mixed EDM were also comparatively studied.

The findings of this work can contribute to the existing knowledge of the physical characteristics of EDM.

2 Experimental procedure

2.1 Experimental setup

The following materials were used for the experiment: aluminum powder (100 nm), kerosene oil, and copper bar (3 mm in diameter).

A simple direct current (DC) pulse circuit was built to eliminate the influence of electronic components (Fig. 1a). Then, 220-V alternating current (AC) was converted into DC after changing the voltage and rectifier filter. A 10,000-μF filter capacitor was used to maintain a constant voltage during the discharge process. The pulse voltage was set to 360 V. An insulated gate bipolar transistor (IGBT) was used to generate pulses; the pulse width was adjusted by a single-chip microcomputer. A non-inductive resistor was also used to eliminate the influence of parasitic capacitance.

A Plexiglas container was utilized as the experimental platform (Fig. 1b). Two copper bars were inserted into the container and fixed by two screws. In sampling the discharge waveform, a feeler was used to adjust the distance between the copper bars and the oscilloscope. The parasitic capacitance and inductance in this circuit were accurately measured by an inductance capacitance resistance (LCR) digital bridge.

The impedance characteristics of the plasma column in pure kerosene were first investigated and then compared with those in powder-mixed kerosene to determine the mechanism of the breakdown process. During the discharge process, a multichannel oscilloscope was used to detect the voltage across the plasma channel (Up) and the voltage across the whole circuit (*U*), as shown in Fig. 1a.

2.2 Calculation

As mentioned previously, a non-inductive resistor was used in the experiment to eliminate the influence of parasitic capacitance. However, the cross-sectional area of the copper bars was extremely small that parasitic capacitance could be ignored. Therefore, the inductive reactance and capacitive reactance of the whole circuit were found negligible. The LCR digital bridge also confirmed the small value of the inductive reactance and capacitive reactance in the discharge circuit.

$$U_P = U - U_R \tag{1}$$

$$I = U_R / R \tag{2}$$

The resistance of the plasma channel can be written as follows:

$$R_P = U_P / I = \frac{U_P R}{U - U_P} \tag{3}$$

3 Experimental results and discussion

In traditional EDM, the dielectric is pure kerosene and the breakdown distance is small. In the present work, the gap distance was 0.02 mm when pure kerosene was used as the dielectric. When powder-mixed kerosene was used as the dielectric, the breakdown distance increased up to approximately 0.5 mm because of the large amount of aluminum powder between the copper bars. Therefore, the breakdown process in the case of powder-mixed EDM was studied under a different gap distance.

Figure 2a shows the discharge voltage versus the elapsed time given gap widths ranging from 0.02 to 0.4 mm. Despite the gap distance of 0.02 mm, the formation time of the plasma channel in pure kerosene oil was slightly shorter than that in powder-mixed kerosene oil. When powder-mixed kerosene was used as the dielectric, a large gap distance equated to a slow formation of the plasma channel. The critical breakdown voltage also increased with increasing gap distance because of the dependency of the breakdown process on the field strength

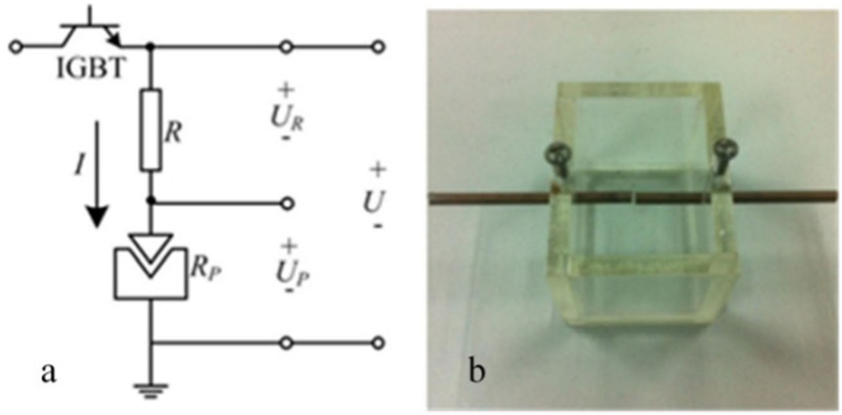

Fig. 1 **a** Experimental circuit; **b** experimental device

between the copper bars. In addition, the discharge voltage (U_P) depended on the gap width after the formation of the plasma channel; that is, the discharge voltage (U_P) increased with the increase of the gap width.

Figure 2b shows the discharge current versus the elapsed time at different distances. The discharge current of the plasma channel in pure kerosene showed the fastest increase. However, when powder-mixed kerosene was used as the dielectric, the discharge current was slow to reach its peak value as the gap distance increased. When the discharge process was stable, the discharge current decreased as the gap distance increased. At a gap distance of 0.4 mm, the discharge current reached its peak after at least 10 μs.

Figure 2c shows the impedance versus the elapsed time given gap widths ranging from 0.02 to 0.4 mm. As in the breakdown process, the impedance of the plasma channel increased with increasing gap distance. The impedance showed the smallest value when the gap distance was 0.02 mm regardless of whether pure kerosene oil or powder-mixed kerosene oil was used as the dielectric. Theoretically, the impedance of a plasma channel carries a large value before the breakdown process. In the present study, the impedance decreased quickly during the breakdown process and the velocity at which it decreased depended on the gap distance; that is, a short gap distance equated to a fast decrease in impedance. As shown in Fig. 2c, the value of the impedance increased with increasing gap distance when the discharge process was stable.

The breakdown process in EDM is traditionally completed in a short time; hence, it is easily overlooked when analyzing discharge waveforms [2, 3]. However, in the present work, the duration of the breakdown process increased as the gap distance increased. When the gap distance was 0.4 mm, the entire breakdown process was completed in 6 μs; it reached its stable state after approximately 10 μs. The short duration of the breakdown process does not affect the rough machining process because of the adoption of a long pulse duration. However, such factor should be considered in the finishing machining process because it is comparative to pulse duration.

The formation of a plasma channel is very complicated. According to traditional theory [2, 3], field electron emission occurs when the electric field strength is higher than the energy required in electron emission. In this process, electrons accelerate from the cathode to the anode under an electric field. When an electron collides with an atom, a new electron and an ion appear and move toward the electrodes. The avalanche ionization contributes to the formation of a plasma channel because the density of the electron and ion reaches a critical value. On the basis of this theory, we used Newton's laws to explain the differences in breakdown duration at different gap distances.

The acceleration velocity of one electron in the electric field is

$$a = \frac{eU_p}{dm} \tag{4}$$

where e is the elementary charge, d is the gap distance, and m is the mass of the electron.

If we ignore the energy lost in the electron collision, the time spent for the electron to move from the cathode to the anode can be calculated by

$$\mathrm{t} = \sqrt{2d/a} = d\sqrt{\frac{2m}{eU_P}} \tag{5}$$

The equation above shows that the duration of the movement of an electron (ion) from a cathode (anode) to an anode (cathode) is proportional to gap distance.

After discussing the breakdown process of EDM, we now look into the impedance characteristics of the plasma channel. The value of the discharge voltage and discharge current and that of the impedance were all measured after the formation of a stable plasma channel.

Figure 3 shows the impedance of the plasma channel versus the current-limiting resistance given gap widths ranging from 2 to 30 Ω. The impedance increased linearly with increasing current-limiting resistance regardless of whether pure kerosene oil or powder-mixed kerosene oil was used as the

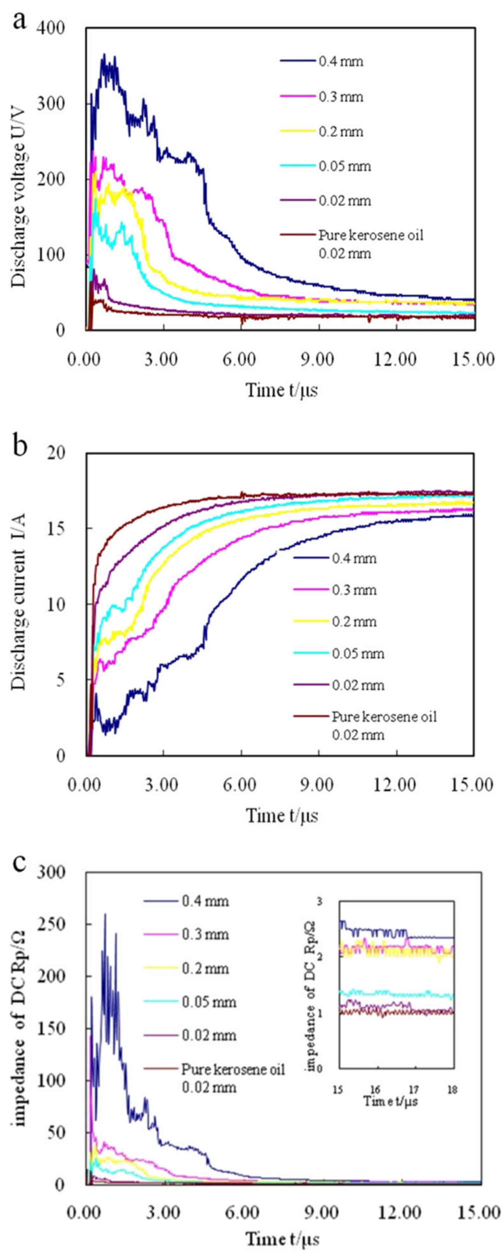

Fig. 2 Change of **a** discharge voltage, **b** discharge current, and **c** impedance in the breakdown process

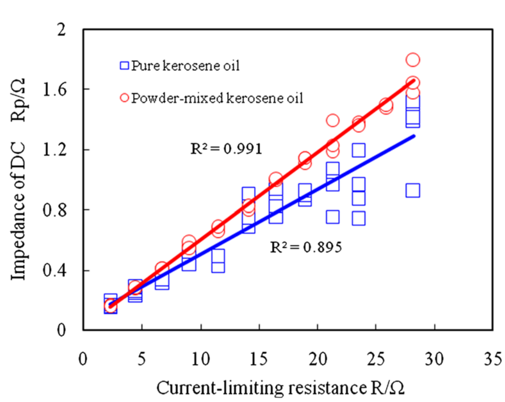

Fig. 3 Impedance versus current-limiting resistance

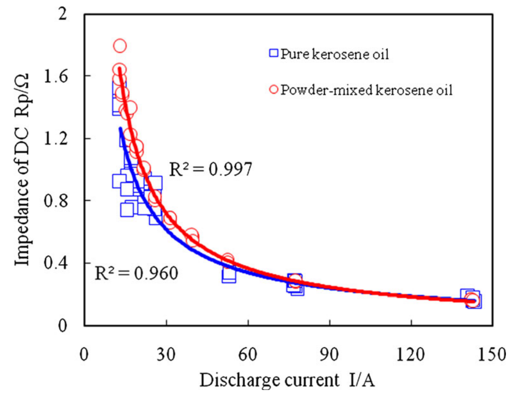

Fig. 4 Discharge current versus impedance

dielectric. The linear correlation coefficients were 0.893 and 0.991 for the pure kerosene oil and powder-mixed kerosene oil, respectively.

Note that the dispersion degree of the impedance increased as the current-limiting resistance increased. This phenomenon was due to the decrease in the stability of the plasma channel as the current-limiting resistance increased. This fact can be explained by the variation in the diameter of the plasma channel. Increasing the current-limiting resistance *R* decreases the discharge current, plasma channel diameter, and anti-jamming ability of the plasma channel.

The dispersion degree of the impedance in the case of pure kerosene oil as the dielectric was larger than that in the case of powder-mixed kerosene oil as the dielectric. Therefore, the plasma channel that formed in the powder-mixed kerosene oil was more stable than that in the pure kerosene oil.

Figure 4 shows the impedance of the plasma channel versus the discharge current given gap widths ranging from 0 to 150 A. The impedance exponentially decreased as the discharge current increased; that is, the impedance decreased quickly as the discharge current increased from less than 30 A. However, its decrease slowed down when the discharge current exceeded 30 A. Figure 4 indicates the minimum impedance of the plasma channel at approximately 0.2 Ω.

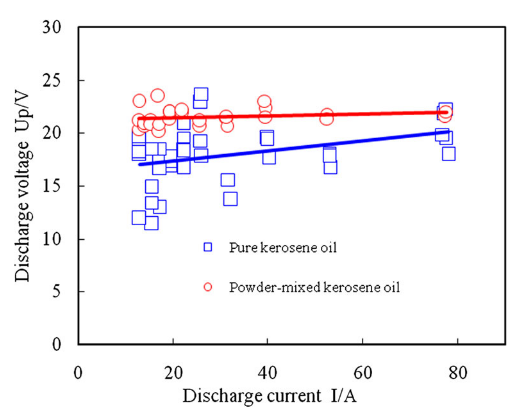

Fig. 5 Discharge voltage versus discharge current

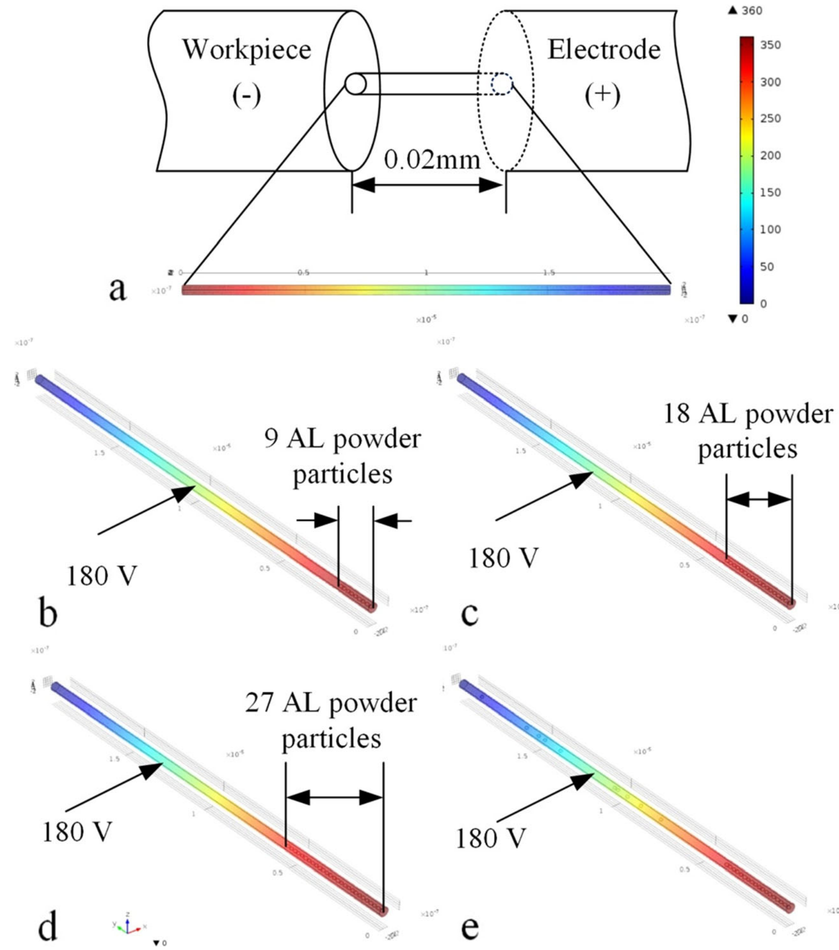

Fig. 6 Effect of electric bridge formed by suspended Al powder particles in the discharge channel: **a** schematic of the simulated discharge channel and the discharge channel without powder particles; **b–d** discharge channel with electric bridge formed by 9, 18, and 27 Al powder particles, respectively; **e** normal discharge channel with electric bridge and suspended Al powder particles

Figure 5 shows the discharge voltage (U_P) of the traditional EDM and powder-mixed EDM. The discharge voltages (U_P) differed in the cases involving the two dielectric media even at the same discharge current. The dispersion degree of the discharge voltage (U_P) in the case in which pure kerosene oil served as the dielectric was larger than that under the case in which powder-mixed kerosene oil served as the dielectric. The two lines in the figure, which were determined through least square curve fitting, indicate that the discharge voltage (U_P) was not significantly affected by the discharge current.

Notably, the dispersion degree of the discharge voltage (U_P) decreased as the discharge current increased. The dispersion degree ranged from 12 to 25 V when the

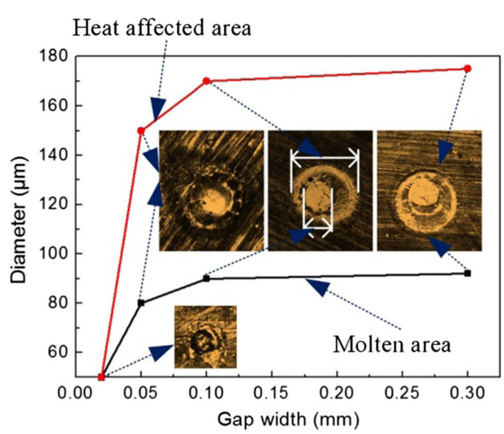

Fig. 7 Crater diameters of molten and heat-affected areas on titanium cathode when copper and titanium alloy were used as anode and cathode, respectively

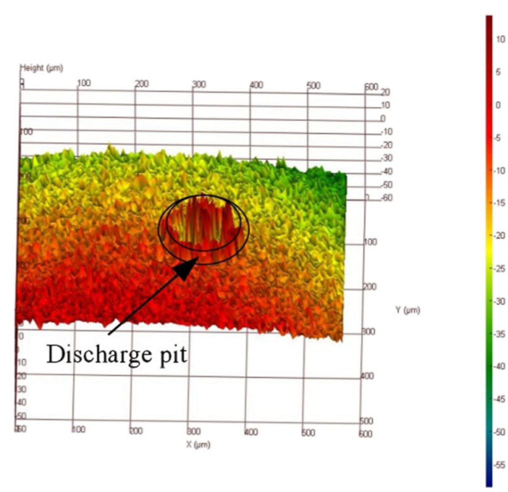

Fig. 8 Surface appearance of discharge pit

discharge current was less than 25 A. The range was even smaller when the discharge current exceeded 40 A than when the discharge current was below 40 A.

Next, changes in the plasma channel were simulated using COMSOL Multiphysics. The discharge gap between the electrode and workpiece was set to 0.02 mm, and the radius of the aluminum powder was 100 nm. Figure 6 shows that the electric field strength was affected by the presence of the aluminum powder. A narrow plasma channel without any powder was thus selected. Figure 6b–e displays the results of using powder particles at a gap voltage of 360 V. After the addition of a single input pulse, a transient electric bridge formed near the positive electrode. In Fig. 6a, a 180-V position was observed at the middle of the discharge gap. When aluminum powder particles were added into the kerosene, the 180-V position changed, moving toward the negative electrode (Fig. 6b–d). This change was due to the varied lengths of the electric bridge. Figure 6e shows a normal discharge channel with an electric bridge and suspended Al powder particles. In this figure, the 180-V position is the same as that in Fig. 6c because the electric bridges in both figures were of the same length. The electric bridge compressed the discharge channel significantly, resulting in a narrow and concentrated discharge column. The stability of the electric bridge improved as the discharge current increased. These results indicate that the plasma channel in the powder-mixed kerosene oil was more stable than that in the pure kerosene oil dielectric.

Titanium alloy (Ti-6Al-4V) is a typical representation of a material that is “difficult to machine”; it is widely used in the fields of biomedicine, aerospace, and engine turbine and vehicle manufacturing because of its high strength-to-weight ratio, high yield stress and toughness, excellent resistance to corrosion, and good biocompatibility (Shokrani et al. 2012 [26]). Hence, this material was used in this study. Figure 7 shows the change in the crater diameters of the molten and heat-affected areas that formed on the titanium cathode as the gap width increased under the following reference conditions: discharge current of 15 A, discharge voltage of 360 V, and Al powder concentration of 1 g/L. The molten area represents the region where the electrode material melted, whereas the heat-affected area indicates the region where the color of the electrode surface was affected by heat. The crater diameters of the molten and heat-affected areas that formed on the titanium cathode both increased with increasing gap width. Figure 8 shows the 3D surface appearance of the titanium cathode at a gap width of 0.025 mm. The diameter and depth of the crater were both only 50 μm.

These results can be used in the further study of micro-EDM in monopulse discharge systems.

4 Conclusions

The use of electric circuits can be controlled in a very precise way by an IGBT in analyzing the impedance characteristics of a plasma channel in which EDM was proposed. By analyzing and contrasting the formation of a plasma channel in both pure kerosene oil and powder-mixed kerosene oil, the following points were found:

1. The formation of the plasma channel in pure kerosene oil took less than 1 μs because of the extremely small gap distance. However, for the plasma channel in the powder-mixed kerosene oil dielectric, the breakdown process increased with increasing gap distance. Avalanche ionization theory was used to explain this result.
2. The impedance of the plasma channel exponentially decreased with increasing discharge current according to the power series law. In addition, the impedance increased linearly with increasing current-limiting resistance.
3. The plasma channel in the powder-mixed kerosene oil was more stable than that in the pure kerosene oil. Its stability increased with increasing discharge current. The simulation result showed that the discharge channel was compressed by the electric bridge formed by Al powder particles. Therefore, the discharge column was narrow and the plasma channel became stable.
4. The single-discharge craters on the titanium alloy used in this study were investigated in a monopulse discharge system at different gap widths. The 3D surface appearance revealed a small discharge crater.

   The physical characteristics of EDM require further research.

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