Second Discharge Characteristics of Aluminum Wire Electrical Explosion Under Various Argon Pressures

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Abstract Electrical wire explosion is a promising method for the preparation of metal nanopowder, but the properties of metal nanopowder are affected by the second discharge process of electrical wire explosion. The second discharge characteristics of aluminum wire electrical explosion under variant argon pressures were studied in a RLC discharge circuit. The results show that the curve of the second discharge voltages versus the pressure presents a U-shape. To clarify the roles of aluminum vapor and argon in the process of the second discharge, a spectrograph and a high speed framing camera were used to study the radiation spectrum and spatial distribution of the electrical explosion plasma. It is observed that argon participates in the second discharge process under low pressure. A discharge channel develops along the surface of the aluminum vapor. Under higher pressure, a second discharge takes place in the aluminum vapor and the discharge channel is inside the aluminum vapor.

Keywords: electrical explosion, nanopowder, second discharge, pressure, spectra, framing pictures

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(Some figures may appear in colour only in the online journal)

1 Introduction

Electrical wire explosion (EEW), a sharp phase-changing process driven by a high-density current pulse is a promising way for the preparation of metal nanopowder [1-6]; it has already drawn the attention of researchers over many years [7-15]. The second discharge of EEW refers to the process of plasma formed by metal vapor discharge. The research of Beilis, Kalantar, and Tkachenko, et al. [7] showed that the second discharge channel performs a “core-corona” structure and the shunt effect of the plasma layer limits energy deposition, temperature and the degree of gasification of the wire. Tkachenko, Cho, and Kotov, et al. [12] found that the deposition energy obviously affects the size of nanopowder produced by EEW. Improving the deposition energy of wire during the resistive phase could significantly increase the specific surface area of metal nanopowder and reduce the number of the sub-micron scale particles. Therefore, the second discharge characteristics of EEW, which affects the deposition energy, have an important influence on nanopowder performance. The study of Liu Longchen [16] showed that particle shape, size, and distribution of aluminum nanopowder could be affected by the argon pressure. Under higher argon pressure, the aluminum nanopowder produced has a better spherical particle shape, a larger count mean diameter, and a broader range of aluminum nanopowder size distribution. Studies of nanopowder preparation mainly aim at the influence of experimental conditions on the nanopowder characteristics. Studies also focus on the mechanism of the second discharge in the vacuum environment, lacking experimental data in different gases and under different gas pressures. Researches on the effect of gas pressure on the second discharge characteristics will help clarify the physical mechanism of EEW in ambient gas and optimize the circuit parameters for nanopowder preparation.

In this paper, the second discharge characteristics of the aluminum wire electrical explosion have been investigated at various argon pressures. Also, the radiation spectrum and spatial distribution of electrical explosion plasma have been measured to explain the role of argon in the second discharge process using the spectrograph and high speed framing camera.

2 Experimental setup

Experiments were conducted in a capacitor discharge circuit, as shown in Fig. 1. A 200 nF capacitor, with a charging voltage of 20 kV and an energy of 40 J, provided the electrical pulse to drive the wire explosion.
through a gas spark switch. The current rising rate was about 40 A/ns during the resistive heating stage. The circuit inductance was about 370 nH. The circuit resistance was about 0.27 Ω. The explosion device was settled in a metal sealing chamber with an inner conductor diameter of 30 mm. In order to reduce the inductance of the discharge circuit, the wire and holding electrodes constituted a coaxial structure with eight 14 mm-diam external backflow poles, which were symmetrically arranged on the edge of a 260 mm-diam disc. Aluminum wire, 20 mm-long, 40-µm-diam, was fixed to the axis of the coaxial structure, far less than the skin depth of aluminum wire ($\delta = \sqrt{2/(\omega \mu_0 \sigma)} \approx 78$ µm, where $\omega$ is the angular frequency of the current pulse, $\mu_0$ is the vacuum magnetic permeability, $\sigma$ is the aluminum electric conductivity). Thus the deposition energy of the aluminum wire was uniform. The aluminum wire melting energy $E_l$ is about 0.027 J; the vaporization energy $E_g$ is about 0.74 J; and the atomization energy $E_a$ is about 0.81 J [17].

The diagram of the experimental setup is presented in Fig. 2. In the experiments, the chamber was first vacuumized to about 5 Pa, and then filled with argon to the required pressure. If the required pressure was low, the process was repeated several times to ensure the purity of the argon in the chamber. Optical diagnosis of the electrical explosion process was taken by a high speed framing camera and spectrograph, whose optic axis was at the same height as that of the wire midpoint. A convex lens was placed between the spectrograph and the observation window, through which the wire was imaged on the narrow slit of the spectrograph, which is parallel to the wire.

The current through the wire was measured via a Rogowski coil (Pearson110A). The voltage across the wire was measured by a high voltage probe (Tektronix p6015a). The waveforms were recorded by an oscilloscope (Tektronix DPO 4104). The exposure times of the high speed framing camera (Pco-HSFC- Pro) and spectrograph (PI acton 2300I) were both set to 3 ns. The measuring range of the spectrograph was from 350 nm to 480 nm with a 300 g/mm grating. The high speed framing camera and spectrograph were triggered by the synchronous signal generator DG535 as soon as the DG535 received the trigger signal from the oscilloscope.

3 Result and discussion

3.1 The electrical characteristics of aluminum wire electrical explosion

The electrical characteristics of the aluminum wire electrical explosion were investigated under different argon pressures. The typical current and voltage waveforms at different argon pressures with $P = 10$ Pa, 200 Pa, 50 kPa, and 160 kPa are shown in Figs. 3 and 4, respectively, in which $t=0$ is the discharge-starting point.

Before the phase explosion, the current and voltage waveforms under different pressures are almost coincident respectively. It is indicated that the electrical characteristics of EEW are hardly influenced by the argon pressure in the resistive-heating stage. At $t \approx 17$ ns, the voltage rising rate decreased while the current rising rate remained the same. It means that the wire equivalent resistance decreases. At this time, wire deposition energy $E$ was about 0.083 J, equaling to $3E_l$ and $0.11E_g$. The wire was melted, but not vaporized.
When a phase explosion took place, the wire heated by the pulse current instantly turned into dense aluminum vapor, the current rate decreased (see Fig. 3) and the resistance increased immediately. The voltage of the wire increased sharply (see Fig. 4). The voltage of the wire includes both resistive and inductive parts, expressed as

\[ U = iR + L \frac{di}{dt}, \]

where \( U \) is the voltage; \( i \) is the current through the wire; \( R \) is the resistance of the aluminum wire; \( L \) is the inductance of aluminum wire, about 32.3 nH. The rapid increase of wire resistance resulted in rapid voltage rising. Under the effect of the sharply increasing electric field, the second discharge of the aluminum vapor took place to form a well-conductive plasma discharge channel, then the voltage fell, and the electric current increased. The peak value of voltage is defined as the second discharge voltage.

Fig. 5 shows the curves of the second discharge voltage, i.e. the peak value of voltage, versus the pressure of argon. It is interesting to note that the second discharge voltages versus the pressure show a U-shaped curve. The lowest second discharge voltage occurs at the pressure of about 200 Pa. When argon pressure decreases from 200 Pa to 10 Pa, the second discharge voltage increases because the gas density and particle collision frequency decrease. Gas density increases and the mean free path decreases when pressure increases from 200 Pa to 160 kPa, which results in the decrease of ionization probability. Therefore, the second discharge voltage increases subsequently.

Fig. 6 illustrates a linear relationship between the deposition energy before voltage breakdown and the second discharge voltage. The deposition energy is very low at the bottom section of the U-shaped curve of second discharge voltages. Enhancing the second discharge voltage is an effective method to improve the deposition energy.

Fig. 7 illustrates a linear relationship between the deposition energy before voltage breakdown and the second discharge voltage. The deposition energy is very low at the bottom section of the U-shaped curve of second discharge voltages. Enhancing the second discharge voltage is an effective method to improve the deposition energy.

3.2 The radiation spectrum and spatial distribution of the electrical explosion plasma

In order to clarify the effect of metallic vapor and argon on the second discharge process, the characteristics of the radiation spectrum and the spatial distribution of the second discharge plasma were measured at different argon pressures.
The plasma radiation spectrum and spatial distribution images at $t=10$ ns under $P=10$ Pa and 100 kPa are presented in Figs. 8 and 9, respectively. When $P=10$ Pa, the strongest spectral line is Ar II (see Fig. 8(a)), and the aluminum wire is surrounded by a wide light layer (see Fig. 9(a)). Combined with Figs. 3 and 4, it is indicated that the argon around the wire is ionized by a small amount of hot electrons emitted from liquid aluminum, forming a better conductive corona around the wire. When $P=100$ kPa, Al I lines are stronger (see Fig. 8(b)), and the bright area is very fine (see Fig. 9(b)). The reason is that a large number of low excitation energy aluminum atoms are excited, while argon is hardly ionized under the high pressure.

Fig. 8 Spectra at $t=10$ ns under (a) $P=10$ Pa and (b) $P=100$ kPa

Fig. 9 The plasma space distribution at $t=500$ ns under (a) $P=10$ Pa and (b) $P=100$ Pa

Fig. 10 Spectra at $t=500$ ns under (a) $P=10$ Pa, 200 Pa and (b) $P=20$ kPa, 50 kPa, 100 kPa and 160 kPa

of the continuous spectrum because of the interaction between hot high-pressure aluminum vapor and argon. Spectra are mainly Al I and Al II, which shows that aluminum ionizes primarily while argon is hard to ionize under high pressure. When $P=160$ kPa, the spectral lines are very weak, and the second discharge voltage is higher, which means that high pressure would greatly suppress the ionization.
Plasma spatial distribution at \( t = 500 \) ns under different pressures is shown in Fig. 11. It is obviously seen that Argon pressure has a significant influence on the spatial distribution of EEW plasma. When \( P = 10 \) Pa (see Fig. 11(a)), the distribution of plasma is diffused, and the edge is brighter. In this situation, aluminum vapor spreads outward easily, leading to a low density and large electron mean free path at the edge. When aluminum vapor and argon are both involved in the ionization, then surface discharge takes place. In the bottom section of the U-shaped curve of the second discharge voltage (see Fig. 11(b) and (c)), ionization takes place in argon, the second discharge voltage is low and the deposition energy is little. In this condition, the areas near the electrodes where the electric field is stronger are brighter than others. Because of electrons emitted from the cathode surface, argon ionization is more intense, resulting in the occurrence of a larger bright area near the cathode, which is especially apparent when \( P = 2 \) kPa. As the pressure increases, on one hand argon becomes difficult to be ionized; on the other hand, argon hinders the outward diffusion of aluminum vapor, making the gas density increase and the electron mean free path reduce. It is difficult to accumulate enough energy, resulting in the rise of a second discharge voltage. Therefore, the discharge often takes place within the aluminum vapor and the discharge channel becomes brighter and thinner. When \( P = 160 \) kPa (see Fig. 11(f)), the second discharge plasma channel is at the axis position of the wire, distributed evenly along the lengthwise and radial direction.

4 Conclusions

In this paper, the second discharge characteristics of an aluminum wire electrical explosion were investigated under different argon pressures. It is found that the second discharge voltage changes with the pressure in the form of a U-shaped curve. Optical diagnostic images show that after the occurrence of an aluminum wire phase explosion, the argon pressure can significantly affect the second discharge process of an aluminum wire electrical explosion. Under lower pressure, argon is ionized, taking part in the discharge process, resulting in the occurrence of aluminum vapor creeping discharge. Under higher pressure, aluminum vapor is the main ionized species, leading to discharge within the vapor. As the discharge pressure increases, the discharge channel tapers and brightens.

References

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