One hundred kilojoules of energy storage in water wire electric explosion deposition energy study

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Abstract. In this experiment, the electro-explosive deposition energy in water of aluminum-magnesium welding wire model ER5356 at 100 kJ capacitive storage energy was investigated. The loop current and the load discharge voltage during the wire electrical explosion were measured using a self-integrating Roche coil and a capacitive voltage divider, respectively. The physical process of electrical explosion and the energy deposition process were delineated by the measured loop currents and load voltages. The current waveform and load voltage of the electric explosion in water of 1.2 mm-3.0 mm diameter Al-Mg wire at 100 kJ stored energy were measured; the changes of load resistance value, load power and deposition energy of the wire loaded with electric explosion were calculated. The results show that the peak circuit current and peak time point decrease and then increase with increasing diameter, and the minimum value is achieved at 1.6 mm wire diameter; the load voltage and load resistance values gradually decrease with increasing diameter; the load power and total deposited energy of discharge achieve the maximum value at 2.0 mm diameter. At 100 kJ energy storage, there is an optimal range between 1.6 mm and 2.4 mm wire diameter.

1. Introduction
Electrical explosion of wires (EEW) is a phenomenon in which a pulsed high current released by a capacitor passes through a metal wire, and the wire undergoes a phase change and expands rapidly due to the instantaneous deposition of large amounts of energy in the wire by the ohmic heating mechanism, accompanied by luminescence and explosive sound. After years of research, wire electro-explosion has been used in the preparation of nanopowder [1][2], concrete crushing[3], coal mining[4]and fossil energy development[5][6], etc. have been widely used. Researchers have also made some research results in the phase transition and breakdown mechanism of wire electrical explosions[7], integral spectra, and shock waves[8]. At present, there is a lack of research on the electric explosion of metal wires in water under larger capacitance energy storage. Although the thinner wire phase change consumes less energy, the load voltage and phase change resistance value is higher, which is conducive to energy deposition, but its vaporization completion time is too early and the formation of low resistance value of the plasma, resulting in insufficient deposition time, affecting the energy deposition effect; thicker wire phase change consumes more energy, energy deposition time
is longer, the current value is larger, but the load voltage and phase change resistance value is too low, also affecting the energy deposition effect. The diameter of the wire is the best match for the energy deposition effect, thus there is an optimal diameter matching value. The process of the associated electrical explosion and the optimal matching of the wire parameters under large energy storage are not well defined. In this paper, we investigate the circuit current and load voltage values of the wire electroburst in ER5356 Al-Mg wire in water at 100 kJ capacitive energy storage to investigate the relevant processes of electroburst and the optimal diameter point for energy deposition.

2. Experimental design and discharge process division

2.1. Experimental design

The experimental setup is designed as in Figure 1. In Figure 1, the laboratory 380 V AC power is converted to 660 V AC power by a transformer, rectified by a 30 kV high-voltage DC power supply, and then charged to a 35 kV high-voltage pulse capacitor C (434 μF) through a current limiting resistor R_c. At the same time, an air pump inflates the inside of the gas spark switch (air pressure 0.4–0.6 MPa) to raise the breakdown voltage between the electrodes. When the specified voltage is reached, the switch is deflated and the electrodes achieve self-breakdown and discharge the wire in the load transducer through the high-voltage coaxial cable to achieve an electrical explosion. In this experimental loop, the inherent inductance of the loop is L_0, L_0 includes the capacitor, switch, loop connection and coaxial high-voltage cable inductance; the inherent resistance of the loop is R_0, L_0 is the inductance from the voltage measurement point to the upper end of the wire, and L_d is the inductance of the return structure at the lower end of the wire. The experimental loop current measurement is performed using a Pearson 4418 model Roche coil, which has a sensitivity of 1 kA/V, a rising edge of 200 ns, a bandwidth of 0.7 Hz to 2 MHz, and a maximum measurement pulse current amplitude of 200 kA. The experimental load voltage measurement uses a homemade voltage divider with a voltage division ratio of 5892.3:1, and the measurement recording instrument for this experiment uses a Tektronix MDO. The experiment was performed on ER5356 Al-Mg wire with a diameter of 1.2 mm to 3.0 mm and a length of 80 mm under 100 kJ capacitive energy storage.

In order to measure the circuit intrinsic inductance L_0 and intrinsic resistance R_0, this experiment is conducted a 60 kJ capacitive storage circuit short-circuit discharge experiment, at this time, let the load ends without any wire, directly by adjusting the distance of direct contact to achieve a short circuit, the circuit will be in the undamped oscillation state, the circuit current and capacitance voltage changes as shown in Figure 2.
After calculation, the loop intrinsic inductance $L_0$ is 8.51 μH, the loop intrinsic resistance $R_0$ is 28.732 mΩ, and the critical damping $R$ is 280.059 mΩ.

The load power and deposition energy of the metal wire are calculated as follows:

$$P = U_R \times I$$ (1)

$$E = \int U_R \times Idt$$ (2)

2.2. discharge process division

In the case of sufficient capacitive energy storage, the wire in water electric explosion will undergo a series of phase change processes, these processes can be distinguished by the changes in loop current, load voltage and wire resistance to some extent, this paper gives a simple division of the process to analyze the wire electric explosion.

To give a diameter of 1.2 mm, length of 100 mm, 80 kJ capacitive energy storage in water wire electric explosion of the physical process of the roughly divided, as shown in Figure 3.

The process of wire electric explosion can be roughly divided into the following six parts. 0~t1: solid state heating stage; t1~t2: melting stage; t2~t3: liquid state heating stage; t3~t4: vaporization stage; t4~t5: breakdown stage; t5~t6: plasma expansion stage.

Among them, 0~t1 stage is difficult to find accurately on the graph due to the inconspicuous change of wire resistance and voltage, so it can be unified as the pre-vaporization stage.

In terms of deposition energy calculation, the same can be divided into four stages.

![Fig.3 Wire electric explosion in water deposition energy division](image)

Where: 0~t1: pre-vaporization stage deposition energy $E_1$; t1~t2: vaporization stage deposition energy $E_2$; t2~t3: breakdown stage deposition energy $E_3$; t3~t4: plasma stage deposition energy $E_4$; 0~t6: total deposition energy $E_{all}$ ($E_a$) before the first sink current over the zero point; the deposition energy of the entire discharge is called the total deposition energy $E_{All}$ ($E_A$).

3. Results&Discussion

3.1. The effect of wire diameter on the physical process of electrical explosion

The loop electrical parameters are shown in Figure 4 and Figure 5.
Fig. 4 Waveforms of electrical parameters of different diameter wire electrical explosions

(a) Loop Current
(b) Load Voltage
(c) Load resistance
(d) Load power

(a) Current forward peak
(b) Current peak time point
From Figs. 4(a) and 5(a), it can be seen that the peak circuit current shows an overall increasing trend with increasing wire diameter at 100 kJ energy storage, but the peak current of the wire with 1.6 mm diameter is instead smaller than that of the wire with 1.2 mm diameter; Fig. 6(b) shows that the peak current of the wire with 1.6 mm diameter has the shortest arrival time, which is due to the 1.6 mm wire shows a change in the discharge pattern at larger energy storage. At lower storage energies, the vaporization time completion point of the 1.6 mm diameter wire is at the first falling edge of the current, while the vaporization completion time point gradually moves forward to the first rising edge of the current when the storage energy is increased. At 100 kJ energy storage, the vaporization completion point of 1.6 mm wire is near the junction of the rising and falling edges of the current, and there is a less obvious "current double peak" phenomenon, so the current peak arrives earlier; above 100 kJ energy storage, we can see that the 1.2 mm wire has an initial peak at the rising edge of the current. This position is the completion point of wire vaporization time. The 1.2 mm diameter wire completes vaporization before the 1.6 mm diameter wire, and although the initial peak of current is lower, the plasma state with lower resistance is formed first, while the 1.6 mm diameter wire is still in the state of high resistance at this time, resulting in a decrease in the peak of current, so its peak of current is higher than the latter. From Fig. 5(c), we can see that as the diameter of the wire increases, the current rise rate also gradually decreases, which is due to the increase in the energy consumed by the wire and leads to a longer phase transition time, and at the same time, we can see that with the further increase in diameter, the current rise rate gradually decreases to a stable level, which can be considered as entering a "short circuit" state. "The energy consumed by the phase transition of the wire will exceed the capacitive energy storage of the circuit.
From Fig. 4(b) and Fig. 5(d)(e), it is obvious that as the diameter of the wire increases, the voltage on the load gradually decreases, and its peak voltage arrival time $T_b$ is gradually delayed, and its load voltage peak/voltage peak time point and diameter change basically conform to a linear relationship. At the same time, it can be seen that the maximum value of the load voltage are no longer able to exceed the voltage value corresponding to the capacitor energy storage (21.5 kV), i.e., there is no overvoltage phenomenon, presumably because the load resistance failed to exceed the critical damping value of the circuit's inherent parameters.

It should be noted that after the wire completes the vaporization breakdown to form the plasma and after the current passes the first zero point, the load voltage does not gradually return to zero, but gradually in the subsequent current oscillation, still has a certain non-negligible load voltage value, so its deposition energy is not negligible, so the deposition energy calculated in this paper should be divided into two parts, the former is the deposition energy before the current passes the first zero point $E_a$ and the latter is the total energy $E_A$ deposited during the whole circuit discharge process.

From Fig. 4(c), it can be seen that as the diameter of the wire increases, the number of carriers also gradually increases, and the peak resistance of the load shows a continuous decreasing trend, and the decline gradually slows down. At the same time, it can be seen that, due to the late completion of the vaporization breakdown of the coarse wire, it is already close to the time when the current first crosses zero, at which time the resistance voltage is no longer accurate and loses its meaning by $U/I$; at the same time, it can be seen that the peak value of the phase change resistance of the wire does not exceed the critical damping value of 280.059 mΩ for this experimental circuit, which is not good for the energy deposition of the wire phase change resistive load and needs to be considered and solved.

From Fig. 4(d) and Fig. 5(f), it can be seen that the load power shows a trend of increasing and then decreasing with the increase of diameter. The maximum point of load power is 2.0 mm at 100 kJ. The values of the above parameters are shown in Table 1.

Table 1 Parameters of electrical properties related to the electrical explosion of different diameters of metal wires

| Energy | D/mm | $I_{\text{max}}$/kA | $T_a$/μs | $I_{\text{av}}$/($kA \cdot \mu s^{-1}$) | $U_{\text{max}}$/kV | $T_b$/μs | $P_{\text{max}}$/GW | R/mΩ |
|--------|------|----------------|--------|-------------------------------|----------------|--------|----------------|------|
| 100 kJ | 1.2 mm | 101.19 | 78.24 | 2.16 | 14.58 | 22.48 | 1.12 | 189.59 |
|        | 1.6 mm | 100.84 | 48.48 | 2.08 | 11.21 | 37.68 | 1.13 | 111.31 |
|        | 2.0 mm | 116.68 | 62.64 | 1.86 | 10.62 | 56.96 | 1.20 | 94.60 |
|        | 2.4 mm | 120.36 | 66.40 | 1.81 | 6.81 | 81.84 | 0.65 | 72.67 |
|        | 3.0 mm | 121.31 | 69.28 | 1.75 | |

The duration of each phase its at different diameters is shown in Figure 6.
As can be seen in the above figure, the time consumed for pre-vaporization, vaporization and breakdown generally shows a significant upward trend with increasing diameter; the time consumed for the plasma expansion phase at the moment $t_5~t_6$ gradually decreases. It should be noted that the above time periods only consider the case before the current crosses a zero point, and the decrease in the plasma expansion phase time may not mean that the wire consumes more energy for deposition in the previous three phases, and its needs to be further explored on the deposition energy related curve. The specific values of the duration of each stage are shown in Table 2.

### Table 2 Statistics of the phase transition time of electric explosion of different diameters of metal wires

| Energy (kJ) | Diameter (mm) | $0\sim t_3/\mu s$ | $t_3\sim t_4/\mu s$ | $t_4\sim t_5/\mu s$ | $t_5\sim t_6/\mu s$ |
|------------|---------------|------------------|------------------|------------------|------------------|
| 100        | 1.2           | 17.92            | 4.56             | 5.36             | 125.92           |
| 100        | 1.6           | 31.52            | 6.16             | 9.12             | 101.84           |
| 100        | 2.0           | 44.64            | 12.32            | 9.52             | 76.56            |
| 100        | 2.4           | 64.32            | 17.52            | 17.12            | 39.12            |

### 3.2. Effect of wire diameter on deposition energy characteristics

Figure 7 shows the deposition energy $E_a$, the total deposition energy $E_A$ of the discharge process before the loop current passes a zero point.
From Fig. 7(a)(b), it can be seen that, at 100 kJ storage energy, the maximum value of either the deposition energy before the current passes the first zero point or the total deposition energy of the discharge process is always obtained between diameters 1.6 mm or 2.0 mm. On the one hand, it can be shown that the deposition energy after the current passes the zero point cannot be neglected, and on the other hand, it can be reasonably speculated that, with the circuit parameters of this experiment, an optimal diameter exists between 1.6 mm and 2.4 mm in diameter for the circuit parameters of this experiment.

Figures 7(c)-(f) show the deposition energy at each stage before the current passes the first zero point for different diameters. It can be seen that the deposition energy before vaporization is generally low for different diameters of the wire; after the storage energy is further increased, there is room for further increase in the vapor deposition energy with increasing diameter; for the breakdown deposition energy, its maximum value is achieved around 2.0 mm diameter, and for the plasma expansion stage energy, the deposition energy gradually decreases with increasing diameter. Because the stage division is unknown for the time being, the deposition energy performance after the first crossing of the zero point of the current is not considered in this part for the time being. The specific energy values for each stage are shown in Table 3.
Table 3 Values of deposition energy for each stage at different diameters

| Energy | D/mm | E₁/kJ | E₂/kJ | E₃/kJ | E₄/kJ | E₅/kJ | E₆/kJ |
|--------|------|-------|-------|-------|-------|-------|-------|
| 100 kJ | 1.2 mm | 1.49  | 2.72  | 4.49  | 12.39 | 21.10 | 39.72 |
|        | 1.6 mm | 2.46  | 4.16  | 7.58  | 13.16 | 27.35 | 41.36 |
|        | 2.0 mm | 3.05  | 6.68  | 7.74  | 9.41  | 26.88 | 45.21 |
|        | 2.4 mm | 3.46  | 7.58  | 6.98  | 2.74  | 20.76 | 42.21 |

4. Conclusion
In this paper, experiments were conducted on ER5356 Al-Mg welding wires with diameters ranging from 1.2 mm to 3.0 mm under the condition of 100 kJ capacitive energy storage and wire length of 80 mm, and the relevant findings are as follows.

(1) Subject to the influence of wire thickness on the time point of vaporization completion, the peak current of the wire will show a trend of decreasing and then increasing with the change of diameter in a larger diameter range.

(2) As the diameter increases, the load voltage and resistance of the wire are gradually reduced; the load voltage and the full process deposition energy achieve a maximum at a diameter of 2.0 mm, and the optimal diameter of the wire electric explosion is between 1.6 mm and 2.4 mm for a given circuit energy storage, wire length and intrinsic parameters.

(3) With the increase in diameter, except for the plasma expansion phase, the duration of all phases of wire electroburst gradually increase with the increase in diameter; wire electroburst deposition energy before vaporization and vaporization deposition energy are increased with the increase in diameter.

Since the experiments made in this paper ER5356 aluminum and magnesium welding wire in the market without further subdivision of the diameter options, can be in the follow-up experiments, can be supplemented with more experiments near 100 kJ storage energy, while changing the length, to explore the larger deposition energy and calculate its deposition efficiency, and then find the best matching parameters.

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