Observation of Early Stage of Underwater Electrical Wire Explosion by Shadowgraph

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ABSTRACT Early stage of underwater electrical wire explosion was observed by shadowgraph. By decreasing initial energy, the early stage of wire explosion was slowed down and possible to capture shadow photos during phase transitions. The vaporization process of wire is usually axially non-uniform due to random local micro explosions along the wire. The degree of non-uniform will be significantly decreased when increasing the initial energy. During explosion of the wire, more than one shock waves were generated not only from phase transition, but also from different pulses of deposition power. A modified piston model was introduced to explain the phenomenon.

INDEX TERMS Underwater electrical wire explosion, shadowgraph.

I. INTRODUCTION

The shock wave (SW) generated by underwater electrical wire explosion (UEWE) have increasingly attracted attention due to a growing number of applications, such as increasing the production and enhancing the recovery in oil wells [1], target ignition for the inertial confinement fusion [2], electro-hydraulic forming [3], non-thermal food processing [4] and warm dense matter [5].

When pulsed high current flow through a metallic wire immersed in water, the wire experiences fast Joule heating and a series of phase transitions [6]. The mechanism for the generation of SW is usually attributed to the rapid volume expansion during phase transitions. Some phase transitions happen concurrently with pulse discharge. They were defined as “early stage” of UEWE in this paper.

Much effort had been made to investigate the shock waves generated by UEWE. Streak camera was often used to take time-resolved picture of UEWE. Two wave fronts around the exploding wire were usually observed on the photo, they were identified with the melting SW and vaporization SW. Several microseconds later, the melting SW was overtaken by vaporization SW [7], [8]. Shadowgraph and Schlieren photography were also used to observe the exploding wire and the shock wave. By comparing the experimental interferograms with the calculated interferograms, the parameters of the highly compressed water were obtained and then fed into numerical simulation of the shock wave generation [9], [10]. On the condition of underheat UEWE, in which the deposition energy is lower than that required to fully vaporize the wire, Li first recorded the waveform of the melting SW [11]. He also found that the maximum pressure of the shock wave was determined by the vaporized mass [12]. By using a short-circuit switch, Han compared the vaporization SW with the shock wave generated by the plasma formation process. He found that the vaporization plays a significant role in the generation of the shock waves in UEWE [13]. Nevertheless, shape of exploding wire hasn’t been observed directly.

In this paper, early stage of exploding wire was captured by slowing down deposition rate of energy. By comparing deposition energy with shadow photos of exploding wire taken at the same time, the understanding of physics process of exploding wire could be deepened. Random local micro explosions along the wire were directly observed during early stage of wire explosion. It was found that the local micro explosions came mainly from the vaporization process of UEWE. Multi shock waves generated by different circuit periods were also observed. A modified piston model was introduced to explain the phenomenon. It revealed that power deposited into wire continuously struggled with pressure from surrounding water.

II. EXPERIMENTAL SETUP

Fig. 1 shows the experiment setup consisting of electrical system (red frame) and optical system (blue frame). Through a field distortion switch and a high voltage cable,
the energy-storage capacitor (0.5 µF) is discharged to the copper wire (0.2 mm in diameter, 20 mm in length) immersed in the water chamber. The waveforms of discharge current \(i(t)\) and wire voltage \(u(t)\) were measured directly with Rogowski coil (Pearson 101, bandwidth 4 MHz) and voltage divider (Tektronix P6015A, bandwidth 75 MHz). All waveforms were captured by an oscilloscope (Tektronix DPO2024).

In optical system, a pulse laser (532 nm, 80 mJ, 750 ps) was used for backlighting. By using beam splitter and PIN photodiode, intensity profiles of laser were recorded by oscilloscope so that the exact time of laser emission could be confirmed. An attenuator (1000:1) and filter (532 nm) were placed before CCD (Nikon D3300) to avoid damage by strong pulse laser and self-emission of discharge channel.

The operation of electrical system and optical system were synchronized by time delay unit. In each experiment, the laser was triggered several microseconds after the rise of the current. The delay time varies from 0 to 20 µs with step size of 0.1 µs. During the experiments, the light in the laboratory was closed, and the CCD keeps long exposure with minimum sensitivity.

In all experiments described in this paper, the circuit load is a single copper wire of 20 mm in length and 0.2 mm in diameter, and the energy required to start melting, to complete melting, to start vaporization, and to complete vaporization are 2.6 J, 3.8 J, 8.1 J, and 34.5 J, respectively.

III. RESULTS AND DISCUSSIONS

A. OVERALL PROCESS OF EXPLODING WIRE

In the first series of experiments, the capacitor was charged to 17 kV so that the wire was exactly fully vaporized. Fig. 2(a) shows the measured current and resistive voltage of wire. The deposition energy was calculated to be 34.5 J using the formula below where \(u_R\), \(i\) and \(u_W\) were resistive voltage, measured current and measured voltage; \(L_W\) was the wire inductance obtained by calculation.

\[
E_d(t) = \int_0^t u_R(t) \cdot i(t) \cdot dt \\
= \int_0^t [u_W(t) - L_W \frac{di(t)}{dt}] \cdot i(t) \cdot dt \tag{1}
\]

The deposition power and deposition energy are shown in Fig. 2(b). Besides electrical waveforms, there are 6 vertical line labeled (a)∼(f) represents different exposure time of each experiment.

Fig. 3 shows six shadow photos of exploding wire with different exposure time listed in Fig. 2.
In Fig. 3(a), the deposition energy was 7.4 J, which indicated the wire was fully melt and ready to start vaporizing. In the center of the picture there existed a black vertical line of liquid wire for which the density was so high that the laser could not pass through it. On each side of the central liquid wire, there was one vertical line, it was identified with the front of the shock wave from melting. The volume of wire did not change much in the photo, that might be the reason why the melting SW(I) was too weak to be distinguished.

In Fig. 3(b), the deposition energy grew up to 9.1 J, a little bit higher than the energy of 8.1 J required for starting vaporization, which implied that the wire was fully melt and partially vaporized. A new obvious SW(I) was observed propagating for less than 1 mm, and the initial weak melting SW(I) was about 1 mm ahead of it. Considering its short propagation distance and time, the latter stronger SW(I) was supposed to be generated at the time vaporization started.

In Fig. 3(c), as deposition energy grew from 9.1 J to 14.7 J, no new shock wave was observed. The melting SW(I) wasn’t observed then, it might be attenuated while propagating in water, or be overtaken by SW(I).

In Fig. 3(d), the deposition energy rose to 24.7 J but was still lower than the energy of 34.5 J required for fully vaporization. As a result of more energy deposited into the liquid wire, more mass of the liquid wire was vaporized. In the center of the picture, the vertical black line was now replaced by a vertical black column, which implied that the dense mixture of the liquid and vapor expanded. Some parts along wire exploded ahead of others, indicating they had a faster phase transition process. Besides exploding parts, the third obvious SW(I) was observed.

In Fig. 3(e), the discharge channel turned to be a bamboo-like shape when deposition energy was close to vaporization enthalpy of 34.5 J.

In Fig. 3(f), the energy stopped depositing at the level of fully vaporization. Outside the discharge channel, the forth obvious SW(I) was formed due to much faster expansion of discharge channel.

From six shadow photos of exploding wire, we had a preliminary view of overall process of exploding wire. However, there were still two question needed to figure out.

One question was, why the discharge channel was bamboo-like in Fig. 3(e). The another one was, why there were four shock waves observed in the overall process of UEWE.

To figure out the two questions, three more series of experiments were designed and carried out.

**B. LOCAL MICRO EXPLOSIONS IN UNDERHEAT UEWE**

In this part, we aimed to have a clearer insight of early vaporization process of wire explosion. In order to further limit deposition rate, the initial voltage was reduced to 15 kV. The deposition energy injected into wire was calculated to be 24 J, which was much less than vaporization enthalpy of 34.5 J and the deposition rate was also slow enough to take clear shadow photos during the process of vaporization.

**C. MULTI SHOCK WAVES FROM DIFFERENT CIRCUIT PERIODS**

In Fig. 3(f), we found that four shock waves were observed in one shadow photo. Other than the first SW(I) was generated...
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FIGURE 5. Shadow photos of exploding wire at different exposure time and deposition energy in 20 kV.

FIGURE 6. Shadow photos of exploding wire at different exposure time and deposition energy in 25 kV.

from melting, the latter three SWs were all generated during vaporization. They might come from pauses of deposition power. As shown in Fig. 2(b), the deposition power fall to zero three times because of circuit period of about 2 µs. Every time deposition power re-rose from zero, a brand new SW was formed and observed in Fig. 3(b), Fig. 3(d) and Fig. 3(f).

To confirm the relationship between shock waves and deposition power, two more series of experiments were carried out by increasing the initial voltage to 20 kV and 25 kV. The shadow photos generated by initial voltage of 20 kV and 25 kV are shown in Fig. 5 and Fig. 6.

The wire exploded in 20 kV had a much quicker deposition rate shown in Fig. 5. The deposition energy reached to vaporization enthalpy in 3 µs. SW(I) was generated from process of vaporization and overtook the melting SW quickly. The SW(I) generated by rapid expansion of discharge channel was also observed 1 µs later.

When the initial voltage increased to 25 kV, the wire quickly melted and vaporized in 1.5 µs. Fig. 6(a) shows that the shock wave could not be distinguished from discharge channel. In Fig. 6(b), only one obvious SW was formed. From Fig. 6(b) to Fig. 6(c), more than 20 J of energy was deposited into discharge channel in another deposition power peak, while there was no new SW generated.

In Fig. 7 the deposition power of 17kV, 20kV and 25kV were shown together in different color. Before the main and highest peak shown in frame of corresponding color, there are 3, 2 and 1 peaks. Accordingly, 3, 2 and 1 shock waves were observed in corresponding shadow photos.

In order to understand why the number of shock waves is so closely related to the deposition power, we need to know how the shock wave is generated. The generation of shock wave is usually explained with piston model [14] in which a fast expanding body such as the exploding wire is considered as a piston. The movement of piston compresses the surrounding water, forming a wave. The velocity and amplitude of the wave are determined only by the movement speed of the piston. If the piston is in a process of accelerated movement, the latter wave will have faster velocity and higher amplitude. As a result, the latter stronger wave will continuously catch up the former wave, forming a discontinuity surface of pressure, which is named shock wave.

In order for the exploding wire to generate shock wave, the volume expansion of the exploding wire should be accelerated even when it faces to the increasing the resistance from the continuously compressed water, which means that the energy deposited into the exploding wire should be faster and faster. For a pulse of the deposition power, the volume expansion of the exploding wire is accelerated and the shock wave is generated at the rising edge. In contrast, the volume expansion is slowed down or even the volume contraction occurs at the falling edge. That is why one pulse of the deposition power generates one shock wave.

Fast volume expansion of the exploding wire in water as a result of fast energy deposition is responsible for the generation of the shock wave. For this reason, there may be multi shock waves even in a single phase transition of vaporization if multi pulses of the deposition power are needed to deposit the energy for fully vaporize the wire.

IV. CONCLUSIONS

By using shadowgraph method and slowing down energy deposition rate, we directly captured the images of early stage of exploding wire. The vaporization process of wire exploding is usually axially non-uniform due to random local micro explosions. The degree of non-uniform could
be significantly decreased when increasing initial energy. During explosion of the wire, more than one shock wave might be generated not only from phase transition, but also from different circuit periods. A modified piston model was introduced to explain the phenomenon. It revealed that power deposited into wire continuously struggled with pressure from surrounding water.

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