Study of the Exploding Aluminum Wire Stratification[1]

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Abstract – The report presents experimental and simulation results related to the study of the exploding aluminum wire stratification. X-pinch was used as an x-ray backlightning. A tabletop XPG-1 generator was a current source for the X-pinch. A burst of x-rays in the 0.6÷3 keV energy range produced the radiographs at different time delays after the exploding wire current onset. The size of the x-ray point source is less than 5 μm, and the duration of the x-ray burst is 1÷2 ns. The XPG-1 generator has the following parameters: the capacitor bank capacitance is 1 μF; the circuit inductance is 30 nH; the charge voltage is 43 kV.

Experiments on the wire explosion in vacuum were carried out on the WEG-1 pulser. The WEG-1 pulser consists of a low inductance (70 nF) capacitor typically charged to 10–30 kV and a triggered gas switch. The pulser inductance is 1100 nH. We used aluminum wires of diameter 50, 35, and 20 μm. The cutoff discharge method was applied to the discharge time control. This method permits to analyze the stratification dynamics at a varies specific energy input to the exploding wires. The simulation predictions were compared with the experimental data.

1. Introduction

The electrical wire explosion (EWE) has long been of interest for researchers [1] due to its appeal for fundamental research (the thermodynamic parameters of an exploded wire reaches extreme values) and wide engineering applications.

Experiments show [1÷3] that an EWE is accompanied by stratification – the formation of alternate high- and low-density strata. The phenomenon of stratification during an EWE has been known since the late 1950s [1], but there is still no consensus about the mechanism by which the process occurs. The authors of [4] suggest that strata result from the evolution of magnetohydrodynamic (MHD) instabilities of the sausage-type with a mode $m = 0$. However, in a fast EWE (at current densities $j \geq 10^8$ A/cm^2 [5]), this mechanism is inoperative, because the characteristics times of energy deposition in a wire are shorter than the time it takes for this type MHD instabilities to develop. Another explanation for the stratification is the development of thermal MHD instabilities [6, 7]. If the specific resistance of matter increases with increasing the temperature, as is with metals in the liquid and condensed states, thermal instabilities become responsible for stratification.

The paper reports on experimental studies of the stratification during a fast electrical explosion of Al wires at current densities of $1 \cdot 10^8$–$1.4 \cdot 10^8$ A/cm^2. The formed strata were investigated using soft x-rays produced at a hot X-pinch point.

2. Experimental procedure

The experiments were performed on an experimental complex consisting of two current generators: a WEG-1 generator [8, 9] used for EWE initiation and an XPG-1 generator [10] used for diagnostics.

2.1. Explosion of Al wires on the WEG-1 current generator

The Al wires to be tested were of 20, 35, and 50 μm in diameter and 20 ± 0.5 mm in length. The high-voltage electrode was an anode at a capacitor charge voltage U_0 = 10, 20, and 30 kV.

The test wire was mounted in a special holder, with the wire contacts soldered on the electrodes. The chamber was pumped down to a pressure lower than $6 \cdot 10^{-5}$ torr by an oil-vapor pump.

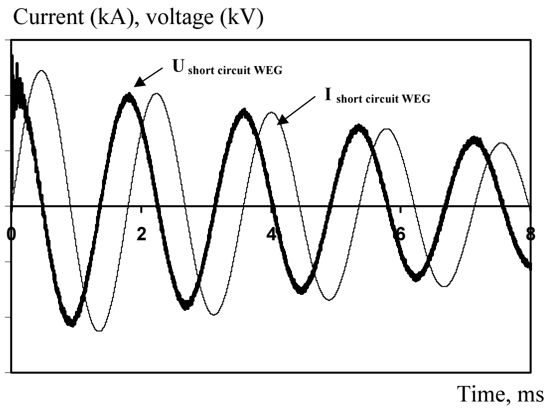

Fig. 1. Oscillograms of the voltage and current in the short-circuit mode of the WEG-1 current generator

In the WEG-1 current generator, a high-resistance divider and an inductive loop were used for electro-

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physical diagnostics. The high-resistance divider measured the voltage across that part of the circuit where the exploded wire was located. The inductance of this circuit section L_1 = 270 nH. The loop was calibrated using readings from a calibrated shunt. The parameters of the entire WEG-1 generator circuit were determined from oscillograms of the current and voltage taken in the short-circuit mode (Fig. 1). Taking into account the oscillation period and damping rate of the current amplitude, the circuit inductance L_k = 1163 nH and the circuit resistance r_k = 0.36 Ω.

2.2. XPG-1 X-pinch x-ray generator

The XPG-1 x-ray generator [10] is based on a current generator consisting of four capacitor-switch assemblies, each with a 0.25 μF capacitance. The charge voltage is 43 kV. The X-pinch load was four ∅13 μm tungsten wires. The generator current load XPG to the X-pinch load was 215 kA. Oscillograms of the current for the short-circuited load and for the X-pinch load (four ∅13 μm W wires) are shown in Fig. 2.

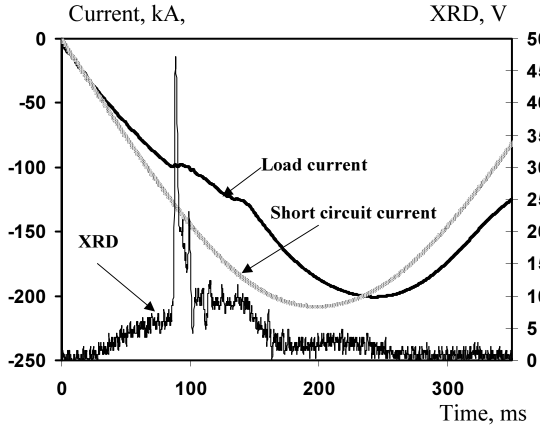

Fig. 2. Oscillograms of the load current I_{load} XPG, current I_{short} circuit XPG in the short-circuit mode and XRD signal

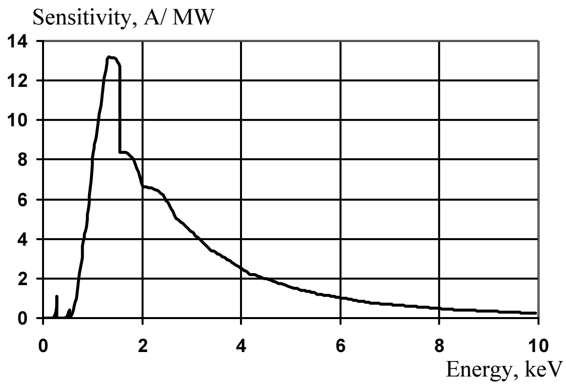

Fig. 3. Spectral sensitivity of the vacuum X-ray diode

The pulsed x-ray source features micron dimensions and an x-ray flash of about 1÷2 ns. The radiation energy range of the source is up to 5 keV and between 20 and 100 keV. The source allows spatial resolution of the fine structure of rapidly time-varying small objects. In our study, the x-ray flash was used for radiography of exploded wires.

In the XPG-1 pulse generator, a high-resistance divider, an inductive loop, and a vacuum X-ray diode with a copper photocathode were used for electrophysical diagnostics. The photocathode was located downstream of a filter which was 0.2 μm aluminum applied on 2 μm kimfoil. The spectral sensitivity of the vacuum x-ray diode is shown in Fig. 3.

2.3. Joint operation of the WEG-1 and XPG-1 generators

The experimental arrangement illustrating the joint operation of the WEG-1 and XPG-1 generators is shown schematically in Fig. 4. The WEG-1 generator was used for exploding the wire under study and the XPG-1 current generator was used for x-ray examination of the exploded wire at different points in time. The two generators were synchronized using a GI-1 trigger pulse generator. The time spread of the operation of the XPG-1 and WEG-1 generators was 50 ns. Images of the exploded wire were taken using a Mikrat-500 film.

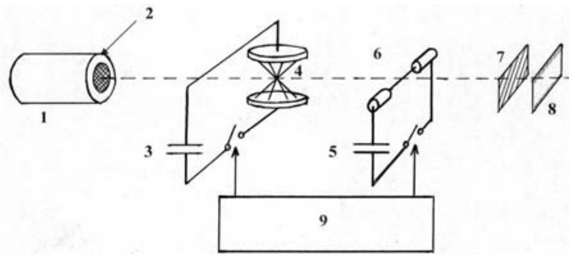

Fig. 4. Experimental arrangement: 1 – XRD; 2 – filter; 3 – C = 1 μF; 4 – X-pinch; 5 – C = 70 nF; 6 – exploding wire; 7 – filter; 8 – film; 9 – trigger pulse generator

3. Discussion of the results

It is seen from the oscillograms shown in Fig. 2 that with the X-pinch load made of four ∅13 μm wires, the radiation detected by the vacuum x-ray diode has one peak of FWHM 2 ns. With the illumination, it is possible to take images of the exploded wire at different points in time. A typical image of the exploded Al wire is shown in Fig. 5. For dimension calibration of the exploded wire, a test object of given dimensions was located in the immediate vicinity of the test wire. On the images presented, the test object was an Al wire. For determination of the radiation energy range, some experiments were performed using two Mikrat-500 film layers arranged in series. The first film can transmit radiation of energy greater than 1.7 keV. Experiment shows that no image is present on the second film. Because upstream of the radiographic film there was a filter made of 0.4 μm aluminum and 4 μm kimfoil, the radiation energy cannot be less than 0.7 keV. These data suggest that all images were taken in the energy range 0.7÷2 keV.

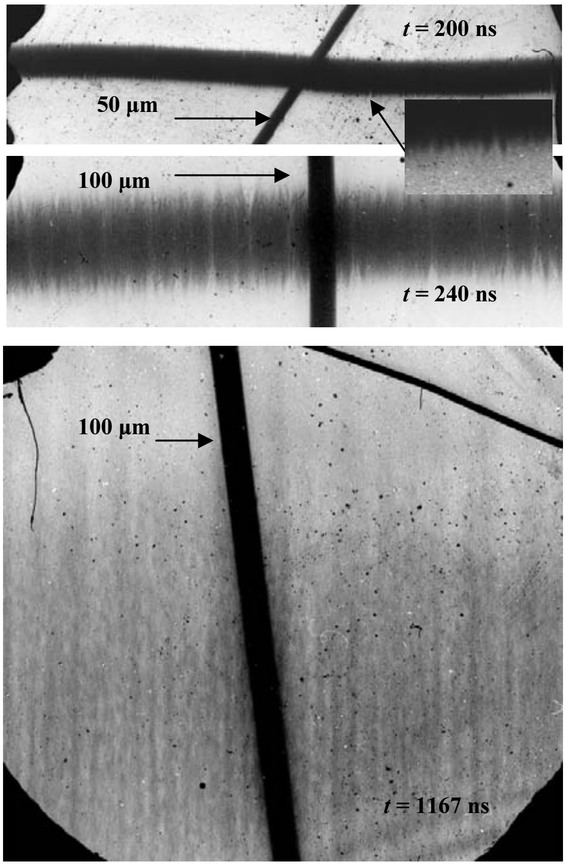

Fig. 5. Typical images of an exploded Al wire of 50 µm in diameter. The charge voltage of the WEG-1 generator is 20 kV. Exposition time is 2 ns

Figures 6 and 7 show the time dependence of the visual diameters of exploded Al wires of initial diameter 50 µm and of the average stratification wavelength. The dependences were obtained in a series of experiments with initial conditions similar to those in which observations were made at different points in time. The diameter of the expanded wires was measured along the outer boundary of the image visible on the film and the average stratification wavelength was determined by averaging over 10 strata of the stratified structure. The number of strata was estimated on the outside of the exploded wire.

In this series of experiments, part of the shots was made with the current through the exploded wire switched off. The objective of experiments with switched-off current was to determine the energy deposition required for stratification. The experiments show that in this mode, stratification starts to develop at an energy deposited in the wire of about 4÷4.5 kJ/g. The average stratification wavelength was unaffected. Analysis of available experimental data allows the conclusion that in the mode without switching off the current, after the shunting discharge ignition over the wire surface, the current flows outside the visible boundary of expansion of the exploded wire. Figures 6 and 7 shows linear approximations of the experimental values. Using the linear approximations, we can determine the expansion rate of the exploded wire, the rate of increase of the stratification wavelength, and the onset of the processes. Moreover, the approximation curve shown in Fig. 7 indicates that for this explosion mode, the initial stratification wavelength is 5÷10 µm.

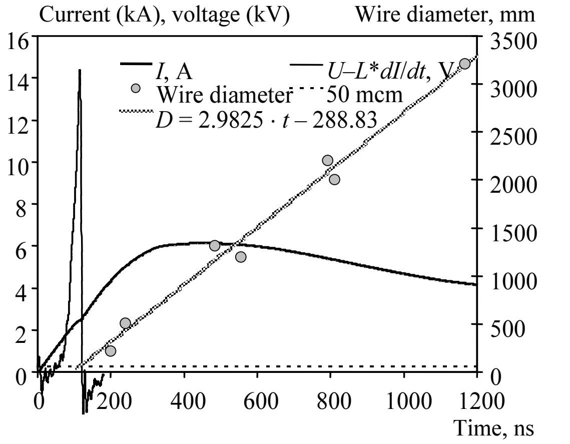

Fig. 6. Time dependence of the voltage, current, experimental exploded Al wire diameter and linear approximation ($D = 2.98 \cdot t - 288.8$)

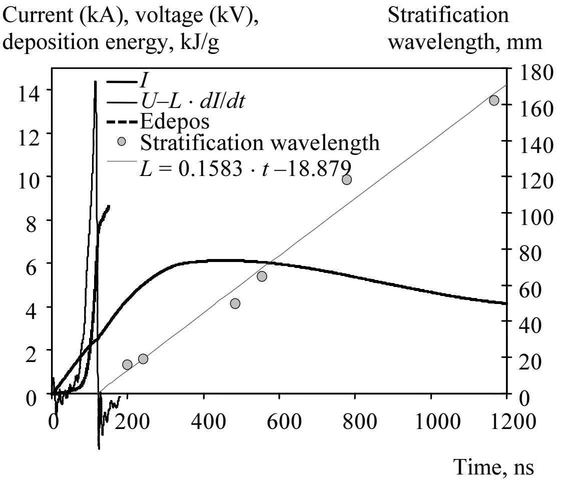

Fig. 7. Time dependence of the voltage, current, time of breakdown, energy deposition, experimental stratification wavelength of the exploded Al wire, and linear approximation ($\lambda = 0.1583 \cdot t - 18.879$)

4. Conclusion

The results of experiments on the electrical explosion of Al wires show that stratification occurs early in the explosion, i.e., at the stage of metal heating. At the initial point in time, the average stratification wavelength is 5÷10 µm. After the ignition of the shunting discharge over the wire surface, the average strata wavelength increases with time. For an Al wire of 50 µm in diameter, the rate of increase of the average stratification wavelength is $d\lambda/dt \sim 1.6 \cdot 10^4$ cm/s and the expansion rate of the wire is $(1.4 \div 1.6)\ 10^5$ cm/s.

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