Study of thin metallic film explosion in vacuum

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Abstract. An experiment with Al, Cu and Ni exploding foils was carried out at a current density of $(0.5-1) \times 10^8$ A/cm^2 through the 6-μm foil with a current density rate of about $(0.5-1) \times 10^8$ A/cm^2·s. To record the metal foil effervescence during the foil explosions, a two-frame radiographic system was used. It was shown that the duration of the explosion resistive phase was considerably lower than the metal boiling time. The foil energy deposition is equal to 30-70% of the sublimation energy.

1. Introduction

In recent years, the wire explosion in vacuum has been the subject of quite many studies [1-5] due to the wide application of wire arrays for the production of high-density hot plasmas. The foil explosion in vacuum still remains the least understood phenomenon. However, the electrical explosion of thin beryllium foils is a key point in the MagLIF (Magnetized Liner Inertial Fusion) project [6] aimed at producing high-density, high-temperature plasmas by compressing a magnetic field with a light metal liner. In this connection, it is of interest to study the main features of thin metal foil explosions in vacuum, such as the energy deposition in the exploding foil material and the material boiling. This paper presents the results of an experiment on the explosion of thin metal (Al, Cu, and Ni) foils at a current density of $(0.5-1) \times 10^8$ A/cm^2 in the foil and a current density rise rate of $(0.3-0.8) \times 10^{15}$ A/cm^2·s. Measurement of the standard characteristics of the exploding foils was performed simultaneously with their x-ray imaging. The paper is organized as follows. Section 2 describes the experimental setup and procedures. The experimental results are presented in Section 3 and discussed in Section 4, which is followed by Conclusion.
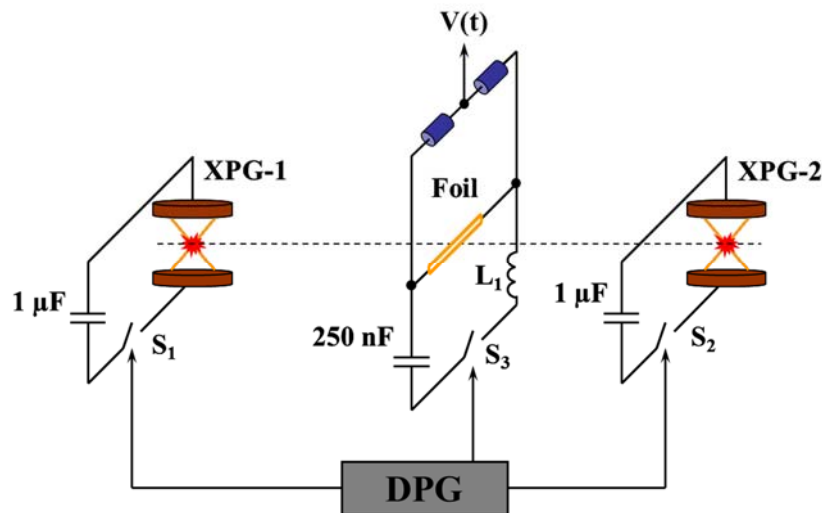
2. Experimental setup

The foil explosion experiment was carried out using a setup comprising three current generators. The WEG-1 generator [7] was operated as a driver to initiate foil explosions, the XPG-1 and XPG-2 generators (radiographs) [8] were used for diagnostics. The spatial image of the exploding wire was taken using 2-ns x-ray flashes generated in the load unit of the XPG-1 and XPG-2 generators. The three generators were started from an external power supply by means of switches S1, S2, and S3, respectively. The delays between the operations of the XPG-1, XPG-2, and WEG-1 generators were

set with the help of a DPG trigger pulse generator; the operation jitter was 50 ns for each of the three generators.

A resistive voltage divider was used for voltage measurements, and the current through the exploding foil was measured with a B-dot probe. The voltage divider measured only the voltage across the circuit section where the foil was connected.

Figure 1. Schematic of the electric circuit of the experimental setup.

Constructing the voltage waveforms, we subtracted the inductive component from the readings of the divider. The B-dot probe was placed near the ground electrode. The probe was calibrated in reference to the readings of a calibrated shunt. The parameters of the entire circuit of the WEG-1 generator were determined from the current and voltage waveforms obtained in the short-circuit mode. The test foil was fastened in a special holder with its contacts soldered to the electrodes [3]. The chamber was evacuated to a pressure less than $6 \cdot 10^{-5}$ Torr with an oil-vapor pump. Bare x-ray diodes were used to detect the x-ray flashes that were generated by the XPG generators. The backlighting system for x-ray imaging of the exploding foils is described in detail elsewhere [9].

3. Experimental results

The experiment was performed with Al, Ni, and Cu foils of 20mm length, 1mm width, and 6 μm thickness. For exploding Al and Ni foils, the charge voltage of the WEG-2 generator capacitor was 20 kV, providing a current rise rate of $\sim 0.7 \times 10^{15}$ A/cm$^2 \cdot$s. The authors of Ref.2 demonstrated for a W wire explosion that the increase of the current rise rate results in the energy input increase. To estimate the effect of the current rise rate on the deposited energy for exploding Cu foils, the WEG-2 generator capacitor was charged to 20 and 10 kV, at which the current rise rate was $\sim 0.3 \times 10^{15}$ and $\sim 0.7 \times 10^{15}$ A/cm$^2 \cdot$s, respectively.

3.1. Electrophysical measurements

Figure 2 presents the typical current and inductively corrected voltage ($V_{corr} = V - LdI/dt$) waveforms recorded during a foil explosion in vacuum. Herein, the energy $\varepsilon(t)$ deposited in the discharge is also shown.

The energy $\varepsilon(t)$ was determined as

$$\varepsilon(t) = \int_0^t I \left(V - L \frac{dI}{dt} \right) dt .$$

As it follows from the waveforms shown in Fig. 2, $V_{corr} = V - LdI/dt$ reaches a maximum within 200-300 ns after the onset of current passage through the foil, which is followed by its sharp decrease.

This voltage behavior is quite similar to that featured by wire explosions. Following a usual nomenclature [1, 3], we treat the time, at which V_{corr} reaches a maximum, as the collapse time t_{coll}. At $t = t_{coll}$, the foil resistance also reaches its maximum value $R_{foilmax}$; for the shot presented in Fig. 2, we have $R_{foilmax} = 0.87\ \Omega$. Assume that the energy deposited in the foil material, ε_{dep}, is equal to the energy deposited in the discharge during the period from $t = 0$ to $t = t_{res}$ at which $R_{foil} = 0.1 R_{foilmax}$. According to the nomenclature of Ref. [1], the time t_{res} corresponds to the period of the resistive (Joule) heating. The energy deposited in the discharge increases further after $t = t_{res}$.
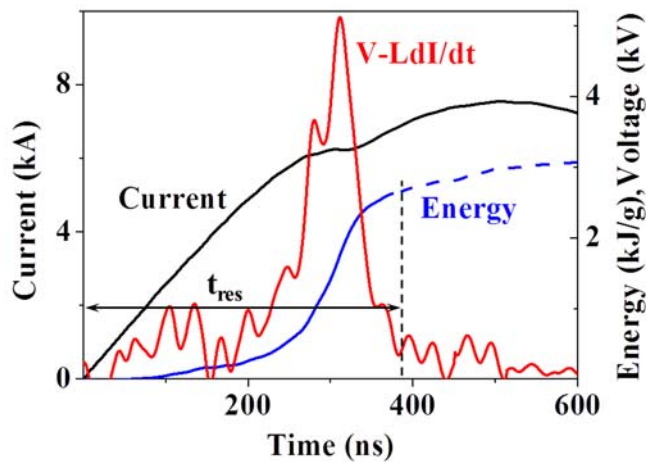
Figure 2. Waveforms of inductively corrected voltage $V_{corr} = V - LdI/dt$ and current I(t), and the time behavior of the energy $\varepsilon(t)$ deposited in the discharge for a Cu foil exploded at $V_0 = 10$ kV (0.3×10^{15} A/cm$^2 \cdot$s). The time t_{res} corresponds to the period of Joule heating of the foil material.

In Fig. 2, the portion of the curve $\varepsilon(t)$ at $t > t_{res}$ is indicated by a dashed line. Note that a similar behavior of $\varepsilon(t)$ at $t > t_{res}$ was observed for Ag wires of 2-3 cm lengths (see Fig. 8 in Ref. 1). It seems that at $t > t_{res}$, the energy is deposited in the plasma corona that shunts the foil core. Table I summarizes the deposited energy averaged over seven shots. The data were derived from the voltage and current measurements for all tested foils.

Table 1. The measured specific deposited energy averaged over seven shots. As discussed above, the energy is deposited in a foil during the initial resistive heating stage.

Foil material	Current density rise rate $dj/dt \times 10^{15}$, A/cm^{2}s	Deposited energy ε_{dep}, kJ/g	Melting energy ε_{melt}, kJ/g	Evaporation energy ε_{evap}, kJ/g	Percent of evaporation energy deposited in foil, %
Al	0.7 ± 0.1	5.3 ± 0.5	0.4	10.85	49
Ni	0.6 ± 0.1	1.3 ± 0.1	0.3	6.3	21
Cu	0.71 ± 0.1	3.3 ± 0.3	0.205	4.75	69
Cu	0.33 ± 0.06	2.4 ± 0.2	0.205	4.75	50

The tabulated data show that, similar to exploding wires, the energy deposited in a foil exploding in vacuum is significantly greater than the melting energy, making 20% for materials with high boiling point (Ni) and 50-70% for materials with low boiling point (Al, Cu). These data almost coincide with those given in Ref. 1. Thus, according to our experimental data, the material of an exploding foil turns into a liquid not later than 100 ns after the onset of current passage through the foil. Based on these data, we may suppose that, as with exploding wires, during a foil explosion, a shunting discharge starts developing over the surface of the molten metal at $t = t_{coll}$. Note, that the Cu foil data present the

experimental proof of an increase of energy deposition into a foil core with the current rate for exploding foils in a vacuum just it has been shown before in Ref.2 for wire explosion.

3.2. X-ray backlighting

When backlighted at $t < t_{res}$, a foil is opaque to x rays, and during this period, the magnetic field of the current flowing through the foil hinders its expansion. The x-ray patterns taken at a time after $t = t_{res}$ show small irregularities (bubbles) transparent to x rays. Figure 3a shows the x-ray pattern of an Al foil taken 365 ns after the onset of current passage through the foil; for this shot, the time t_{res} was 190 ns. In the magnified x-ray fragment, the bubbles of a characteristic size of several micrometers are clearly seen. Once bubbles have occurred, they rapidly grow in number. The time dependence of the number of bubbles per 1 mm^2 obtained for foils of various materials, $N_{bubble}(t)$, is shown in Figure 3b. We denote the time corresponding to the onset of a sharp rise of the function $N_{bubble}(t)$ as t_{boil}, the time at which the foil material starts boiling.
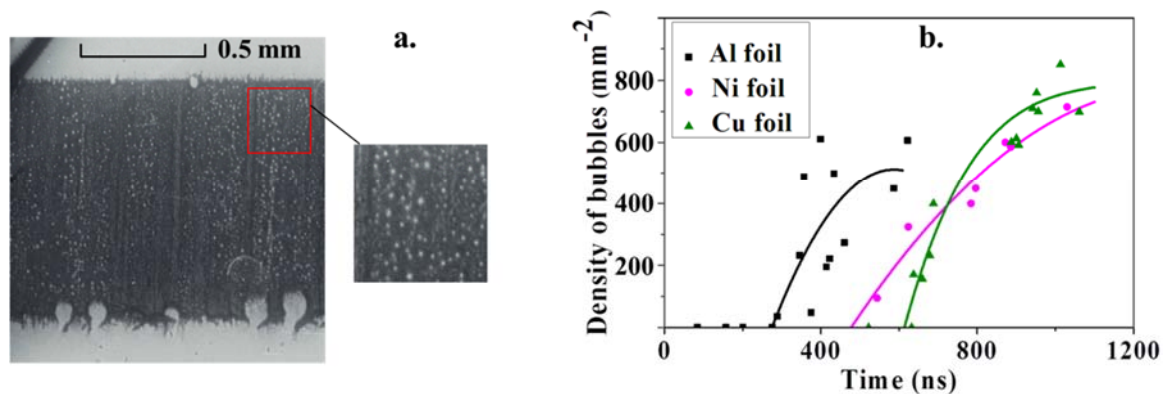
Figure 3. X-ray pattern of an Al foil taken 365 ns after the onset of current passage through the foil; the time t_{res} for this shot was 190 ns (*a*); the number of bubbles per 1 mm^2 versus time for exploded Al, Ni, and Cu foils (*b*).

Table 2. The resistive heating time and the boiling time for different foil materials.

Foil material	Current density rise rate dj/dt ×10^{15}, A/cm^{2}s	Resistive heating phase duration t_{res}, ns	Time of the foil boiling t_{boil}, ns
Al	0.7 ± 0.1	175 ± 5	275 ± 20
Ni	0.6 ± 0.1	104 ± 5	483 ± 20
Cu	0.71 ± 0.1	209 ± 5	n/a
Cu	0.33 ± 0.06	286 ± 5	600 ± 20

As it follows from the data presented in Table 2, the period between $t = t_{res}$ and the onset of boiling (t_{boil}) is some hundreds of nanoseconds, being significantly greater than the statistical measurement error. The observed delay between the onset of boiling of the liquid foil material and the cessation of its heating can be accounted for by metastable states arising in the liquid metal of the exploded foil. The decay of the metastable states in our experimental conditions is described in detail elsewhere [10].

4. Discussion

The occurrence of a shunting corona during an electrical explosion of wires is well known for a long time [1-3, 11], but the medium in which the corona develops remains the subject of discussion. In principle, the medium in which the shunting occurs may be the low-density plasma resulting from the expansion of the conductor material [2, 12, 13], or the shunting is a consequence of the breakdown

developing in the cloud of the gas desorbed by the hot metal surface [4, 10, 11]. In our foil explosion experiments, the delay of the metal boiling relative to t_{res} on its own may indicate that the shunting discharge develops in the desorbed gas. Below, we shall discuss how the "desorption model" aids to interpret our experimental data.

The shunting of conductors electrically exploding in vacuum is discussed in detail elsewhere [4]. The scenario of the shunting of an exploding foil can be described in brief as follows. The molten surface of the foil intensely desorbs gas; the gas expansion velocity is determined by the foil temperature. Until the gaseous shell is broken down, the pressure of the magnetic field induced by the current flowing through the foil hinders the expansion of the foil material, the foil temperature increases and can reach T_{foil} = 0.2-0.6 eV [10]. For hydrogen, which is the main component of the gas absorbed on the metal surface, the gaseous shell expansion velocity (implying $T_{gas} \approx T_{foil}$) is in the range $(0.6-1.1) \times 10^6$ cm/s. As the gaseous shell expands further, the gas density decreases, and so does the electric strength of the shell. Simultaneously, the resistance of the foil increases with temperature. Thus, we have two factors that determine the collapse time:

  i.   the increase of the voltage across the electrode gap due to the increase of the foil resistance,
  ii.   the decrease of the breakdown field strength of the gaseous shell, E_{gas}, due to the decrease of the gas density that it is correct for the left part of the Paschen's curve.

As a result, the gaseous shell is broken down at t = t_{coll}, and a high-conductivity corona is formed during the period between t_{coll} and t_{res}. According to the above reasoning, E_{gas} should not depend on the foil material. Actually, at dj/dt = 0.71×10^{15} A/cm^{2}s, according to our data, E_{gas} is equal to 4-6 kV/cm and does not depend on the foil material.
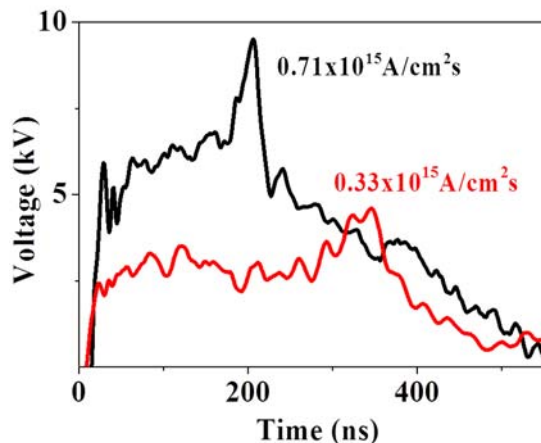
Figure 4. Waveforms of the voltage across an exploding Cu foil for the rise rate of the current through the foil $d\mathbf{j}/d\mathbf{t}$ = 0.71×10^{15} and 0.33×10^{15} A/ cm^{2}s.

The doubling of $d\mathbf{j}/d\mathbf{t}$ resulted in a 30-40% increase of the deposited energy (see Table 1) mainly due to the increase of the foil flashover voltage. It follows from the plots showing the time behaviour of the voltage across the electrode gap, $\mathbf{V}(t) = R_{foil}I + LdI/dt$ (Fig. 4), that were obtained for exploding Cu foils at different $d\mathbf{j}/d\mathbf{t}$. The waveforms clearly indicate that the increase of the hold-off voltage and the energy deposited in the foil material is accompanied by the decrease of pulse duration of the voltage across the gap.

5. Conclusion

The experimental study of the electrical explosion of Al, Cu, and Ni foils in vacuum has shown that the specific energy deposited in the foil material, ε_{dep}, makes several tens of percents of the evaporation energy ε_{evap}. The obtained $\varepsilon_{dep}/\varepsilon_{evap}$ ratio is close to that measured previously for exploding wires [1, 4]. It has also been revealed that the foil material starts boiling 300-600 ns after the cessation of Joule heating. Based on the experimental observations, it has been concluded that the shunting of a

foil exploding in vacuum is due to the discharge developing in the cloud of gas desorbed from the foil surface.

Acknowledgements

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