Study of the strata formation during the explosion of foils in vacuum

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Abstract. The formation of the strata during fast explosion of metal foils at current densities of 0.1 GA/cm² has been studied experimentally. To observe the strata, the soft x-ray radiation generated by an X-pinch was used. The study of the process of stratification during the foil explosion was carried out with a setup consisting of three generators. One of the generators (WEG-2), was operated to initiate the explosion of the foils, while the others (XPG radiographs) were used for diagnostics. The generator WEG-2 has the capacitance of 250 nF, the charge voltage of 20 kV, and the current rate of 16 A/ns. The radiographs XPG have the capacitance of 1 µF, the charge voltage of 43 kV, the current of 300 kA, and the current rise time of 180 ns. X-pinch produced by four Mo wires was a load for the radiographs. The delay between the operation of the WEG-2 and XPG generators was set using a DPG trigger pulse generator. We performed the experiments with the Al and Cu foils. The length of foil was 2 cm, the foil width was 1 mm, and the foil thickness was 6 µm. It has been revealed that strata were formed early in the explosion, i.e. at the stage when the metal melted. Analysis of the experimental results suggests that the most probable reason for the stratification is the thermal instability developing because of the increase in resistivity of the foil metal with temperature.

1. Introduction
In recent years, a number of studies have been published on the electrical explosion of conductors. Interest to this problem is caused by the wide use of exploding conductors in engineering applications (see, e.g., [1–3]). On the other hand, observations of the processes occurring during the explosion of conductors give information on thermodynamic properties and phase transitions of metals [4–9].

The explosion of conductors is accompanied, as a rule, by the formation of strata—alternating layers of material of increased and decreased density. The phenomenon of stratification during a wire explosion (WE) was studied by many researchers, and the wire diameters at which strata were detected ranged from tens of micrometers [10, 11] to several millimeters [12, 13]. A brief review of the studies on the stratification during WE can be found elsewhere [14, 15]. The publications devoted to the stratification during a foil explosion (FE) are few in number. This seems to be due to that the FE process as a whole has been studied inadequately, notwithstanding that the problem of the failure of metal coatings in metalized capacitors (self-healing capacitors)
is rather urgent [16,17]. Nevertheless, strata were detected for exploded thin (20 nm) aluminum films at a specific input energy of about 4 kJ/g [18].

In this paper, we present the results of radiographic examinations of the dynamics of formation of strata for Al and Cu foils at current densities of $\sim 10^8$ A/cm$^2$. The stratification dynamics was recorded throughout the current pulse with a two-frame x-ray backlighting system. The paper is organized as follows. Section 2 describes the experimental setup; the experimental results are given in section 3. Comparison of the experimental results with the estimates obtained with the help of the electro-thermal instability model [14, 19–22] also is performed in section 3, which is followed by Conclusion.

2. Experimental setup

2.1. The electric circuit

The electric circuit diagram is given in figure 1a. The experiment on studying the process of stratification during FE was carried out on a setup consisting of three current generators. One of the generators (WEG-2) was operated to initiate FE and the other two (XPG radiographs) were used for diagnostics. The use of two diagnostic generators, each producing an x-ray flash with the help of an X-pinch [23], makes it possible to take two sequential pictures during an explosion of one foil.

The WEG-2 generator has a capacitance $C_0 = 250$ nF and a charge voltage $V_0 = 20$ kV, and provides a current rise rate $dI/dt = 16$ A/ns. Each of the XPG radiograph [24, 25] has a capacitance of 1 $\mu$F and a charge voltage of 43 kV, and provides a current rise rate of 1.7 kA/ns.
The generator current $I_{\text{XPG}}$ to the X-pinch load (four Mo wires 25 $\mu$m in diameter) was 110 kA. The delay between the operations of the WEG-2 and XPG generators was set by a trigger pulse generator. The delay time $\Delta t_1$ between the operations of the WEG-2 and XPG-1 generators was varied in the range from 0 to 1.2 $\mu$s; the delay time $\Delta t_2$ between the operations of the XPG-1 and XPG-2 generators was varied in the range from 0.015 to 0.12 $\mu$s. The vacuum x-ray diodes detected the X-pinch radiation. A resistive voltage divider was used for voltage measurements, and the current through the exploding foil was measured with a B-dot probe. The resistive voltage divider measured only the voltage across the circuit section where the foil was connected. The inductance of this section was 270 nH. In constructing voltage waveforms, the inductive component was subtracted from the readings of the divider. The B-dot probe, placed near the grounded electrode, was calibrated in reference to the readings of a calibrated shunt. The parameters of the WEG-2 generator are close to those of the WEG-1 generator [21]: the inductance $L_1 = 1163$ nH and the resistance $r_g = 0.36$ $\Omega$. The test foil was fastened in a special holder with its contacts to the electrodes soldered [21, 26]. The chamber was evacuated to a pressure below $6 \times 10^{-5}$ Torr with a turbomolecular pump.

2.2. The backlighting system

It is well known [23, 25] that the radiation source in an X-pinch is a hot spot several micrometers in size arising at the crosspoint of the pinch conductors. In the backlighting system shown in figure 1b, the straight line connecting the wire crosspoints in X-pinch 1 and X-pinch 2 coincided with the optical axis of the system. The surface of the x-rayed foil was arranged normal to the system optical axis. X-pinches 1 and 2 were placed at a distance $A = 16$ cm to the left and to the right of the foil, respectively. After passing the radiation produced by X-pinch 1 through the exploded foil, the conductor image was recorded with camera 1. Similarly, the image of the foil after the passage of the radiation produced by X-pinch 2 was recorded with camera 2. Cameras 1 and 2 were placed at a distance $B = 173$ cm to the right and to the left of the foil, respectively. Thus, the magnification factor of the backlighting system, $K = B/A$, was 10.8; the space resolution was dictated by the size of the plasma blob in the X-pinch [25], and it was 2–3 $\mu$m. For recording x-ray radiation, Mikrat film was used in cameras 1 and 2 which was disposed behind an aluminized Kimfoil filter transmitting radiation of energy $h\nu > 0.8$ keV. To prevent the radiation of X-pinches 1 and 2 from hitting cameras 1 and 2, respectively, the backlighting system was furnished with screening rods. The rods, each 2 mm in diameter, were placed 2 cm away from the centers of the X-pinches.

3. Experimental results

The experiment was performed with Al and Cu foils of length 20 mm, width 1 mm, and thickness 6 $\mu$m. Figure 2 presents the typical current and inductively corrected voltage waveforms recorded during an explosion of a foil in vacuum. Herein, the signals from the X-pinch sources are also shown.

All the recorded $V(t)$ waveforms, irrespective of the foil material, show a peak in the range 300–350 ns from the onset of current flow through the foil. In papers [21, 22, 26–29], the peak voltage recorded across a conductor exploding in vacuum is termed the collapse voltage, $V_{\text{coll}}$. By the time $t = t_{\text{coll}}$ at which $V(t) = V_{\text{coll}}$, a low-density corona consisting of the gas desorbed from the metal surface is formed around the conductor [21, 26, 30]. The velocity of expansion of the corona is 2–10 cm/µs [28, 30]. Soon after the formation of the corona, the temperature in it reaches several electron-volts [29], resulting in an increase in conductivity. The increase in corona conductivity and volume has the result that the voltage across the circuit section containing the foil sharply decreases (figure 2) After $t = t_{\text{coll}}$, the current carried by the foil gradually decreases, and the foil is shunted by the corona plasma. It seems that the foil current becomes completely shunted within 30–50 ns after $t_{\text{coll}}$. The energy deposition into the foil material stops. In our
Figure 2. Waveforms of voltage $V(t)$ and current $I(t)$ recorded for a Cu foil at $V_0 = 10$ kV and the accompanying XRD signals.

Table 1. The foil explosion parameters.

| Foil material | $j_{\text{melt}}$, MA/cm$^2$ | $\varepsilon_{\text{dep}}$, kJ/g | $\varepsilon_{\text{melt}}$, kJ/g | $t_{\text{melt}}$, ns | $\lambda_{\text{melt}}$, µm | $\lambda_{\text{min}}$, µm |
|---------------|-------------------------------|----------------------------------|-------------------------------|---------------------|------------------|------------------|
| Al (20 kV)    | 67 ± 10                       | 5.2 ± 1.0                        | 0.4                           | 115                 | 26 ± 2           | 31               |
| Cu (10 kV)    | 70 ± 7                        | 2.4 ± 0.5                        | 0.2046                        | 165                 | 22 ± 5           | 37.5             |

experiments with exploding foils, $t_{\text{coll}}$ averaged over seven shots was 170 ns for Al foil and 285 ns for Cu foil.

On the other hand, according to theoretical predictions [20, 21], when the foil is melted and electric current flows through the liquid metal, striations can arise due to thermal instabilities. The time dependence of the energy deposited in the foil found from experimental data allows us to determine the time $t_{\text{melt}}$ at which the specific input energy becomes equal to the melting energy $\varepsilon_{\text{melt}}$. It turned out that $t_{\text{melt}}$ was substantially less than $t_{\text{coll}}$; namely, $t_{\text{melt}}$ was 115 and 165 ns for Al and Cu foil, respectively. Consequently, in our experimental conditions, the time of current flow through the liquid metal could be sufficient for thermal instabilities to develop.

The average FE parameters for different foil materials are presented in table 1. The data were averaged over seven shots. The melting time and current density are denoted, respectively, by $\varepsilon_{\text{melt}}$ and $j_{\text{melt}}$. The energy $\varepsilon_{\text{dep}}$ denotes the total deposited energy that was determined by integration of the electric power. The integration was terminated when the anode-cathode resistance dropped to one tenth of its peak value. It is possible to see that $\varepsilon_{\text{dep}} \gg \varepsilon_{\text{melt}}$.

The maximum current density was estimated by the formula

$$j_{\text{melt}} = \frac{I_{\text{melt}}}{A},$$

where $I_{\text{melt}}$ is the current at the point in time $t = t_{\text{melt}}$ and A is the foil area.

Figure 3 present a fragment of an x–ray shadowgraph taken for an explosion of Al foil within 296 ns after the onset of current flow through the foil (Sh. 07). For this shot, we had $t_{\text{melt}} = 110$ ns and $t_{\text{coll}} = 141$ ns. The picture clearly shows striations, namely, alternating fringes corresponding to molten metal strips transparent and nontransparent to x rays. The small irregularities seen in the shadowgraph, which are transparent to x rays, are associated with effervescence of the metal.

Based on the shadowgraphs, we plotted the striation wavelength $\lambda$ as a function of the time $t$ from the onset of current flow through the foil, assuming the fringe spacing equal to $\lambda$. The results for exploded Cu and Al foils are presented in figure 4. Herein, a linear approximation of
Figure 3. X-ray image of an Al foil obtained within 296 ns after the start of the WEG-2 current pulse. The foil was backlighted by a flash produced X-pinch 2. In the upper and lower right corners, the shadows of the Mo wires of X-pinch 1 are seen.

Figure 4. The average striation wavelength versus time for Al and Cu foils explosion.

the experimental data, $\lambda_{av}(t)$, is given. As mentioned, we suppose that striations arise nearly at $t_{melt}$. Using the $\lambda_{av}(t)$ plot given in figure 4, we can evaluate the initial striation wavelength, $\lambda_{melt}$. The value of $\lambda_{melt}$ corresponding to the melting time was $26 \pm 1.5 \mu m$ and $22 \pm 5 \mu m$ for the Al and the Cu foil, respectively. Figure 4 presents the evolution of the average striation wavelength for Al and Cu foils.

Otherwise, according to the thermal instabilities theory [20, 21], the minimal wave length $\lambda_{min}$ can be determined by the formula

$$\lambda_{min} = \frac{2\pi}{j} \sqrt{k_B \left(\frac{\partial T}{\partial \delta}\right)},$$

(2)

where $j = j_{melt}$, $\delta$ is the material resistivity, $k_B$ is the Boltzmann constant. From expression 2, it follows that $\lambda_{min}$ is determined by the current density. The value of $\lambda_{min}$ obtained by formula was $31 \mu m$ and $37.5 \mu m$ for the Al and the Cu foil, respectively. The value of $\lambda_{min}$ has been entered in table 1.

4. Conclusion
The results of experimental studying the formation of strata during the explosion of aluminum and copper foils of micrometer thickness have been described and analyzed. The shots were
performed at the fast FE mode with an approximately constant current density 0.1 GA/cm². It has been revealed that strata were formed early in the explosion, i.e. at the stage when the metal melted. Analysis of the experimental results suggests that the most probable reason for the stratification is the thermal instability developing because of the increase in resistivity of the foil metal with temperature.

Acknowledgments

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References

[1] Mazarakis M G, Cuneo M E, Stygar W A, Harjes H C, Sinars D B, Jones B M, Deeney C, Waisman E M, Nash T J, Struve K W and McDaniel D H 2009 Phys. Rev. E 79 016412
[2] Grabovskii E V, Levashov P R, Oleinik G M, Olson C L, Sasorov P V, Smirnov V P, Tkachenko S I and Khishchenko K V 2006 Plasma Phys. Rep. 32 718–728
[3] Kotov Y A 2003 J. Nanopart. Res. 5 539–550
[4] Lebedev S V and Savvatimskii A I 1984 Sov. Phys. Usp. 27 749–771
[5] Tkachenko S I, Khishchenko K V, Vorob’ev V S, Levashov P R, Lomonosov I V and Fortov V E 2001 High Temp. 39 674–687
[6] Khishchenko K V, Tkachenko S I, Levashov P R, Lomonosov I V and Vorob’ev V S 2002 Int. J. Thermophys. 23 1359–1367
[7] Khishchenko K V, Tkachenko S I and Levashov P R 2006 Tech. Phys. Lett. 32 126–128
[8] Tkachenko S I, Levashov P R and Khishchenko K V 2006 J. Phys. A: Math. Gen. 39 7597–7603
[9] Korobenko V O and Emel’yanov O A 2005 Tech. Phys. Lett. 32 861–864
[10] Oreshkin V I, Baikov A V, Zhigalin A and Rousskikh A G 2008 Phys. Plasmas 15 027206
[11] Rousskikh A G, Oreshkin V I, Chaikovsky S A, Labetskaya N A, Shishlov A V, Beilis I I and Baksht R B 2008 Phys. Plasmas 15 102706
[12] Oreshkin V I, Rousskikh A G, Chaikovsky S A and Oreshkin E V 2010 Phys. Plasmas 17 072703
[13] Knapp P F, Greenly J B, Gourdain P A, Hoyt C L, Pikuz S A, Shkolovskaya T A and Hammer D A 2010 Rev. Sci. Instrum. 81 10E501
[14] Rousskikh A G, Oreshkin V I, Zhigalin A, Beilis I I and Baksht R B 2008 Phys. Plasmas 15 027206
[15] Rousskikh A G, Oreshkin V I, Chaikovsky S A and Oreshkin E V 2010 Phys. Plasmas 17 072703
[16] Knapp P F, Greenly J B, Gourdain P A, Hoyt C L, Pikuz S A, Shkolovskaya T A and Hammer D A 2010 Rev. Sci. Instrum. 81 10E501
[17] Oreshkin V I, Rousskikh A G, Chaikovsky S A and Oreshkin E V 2010 Phys. Plasmas 17 033505
[18] Rousskikh A G, Oreshkin V I, Zhigalin A, Beilis I I and Baksht R B 2010 Phys. Plasmas 17 033505