Study of foil explosion using the soft x-ray radiography

A S Zhigalin¹, V I Oreshkin¹, ², A G Rousskikh¹ and R B Baksht¹

¹ Institute of High Current Electronics of the Siberian Branch of the Russian Academy of Sciences, Akademichesky Avenue 2/3, Tomsk 634055, Russia
² National Research Tomsk Polytechnical University, Lenin Avenue 30, Tomsk 634050, Russia
E-mail: zhigalin@ovpe2.hcei.tsc.ru

Abstract. The experiments were carried out upon a research facility comprising three current generators. One of them was used to initiate the explosion of a foil and the other two, X-pinch backlighting sources were used for diagnostics. In the experiments, an upper limit has been determined for the decay time of the metastable state of a superheated metal. For aluminum, at a foil thickness of 6 µm and a deposited energy of 5.3 ± 0.5 kJ/g, the metastable state decay time was about 90 ns; for copper, at the same foil thickness and a deposited energy of 2.1 ± 0.3 kJ/g, it was about 250 ns; for nickel at the same foil thickness and a deposited energy of 1.3 ± 0.4 kJ/g, it was about 390 ns.

1. Introduction

Studying the processes involved in a conductor explosion (CE) provides important information about extreme states of materials, as the thermodynamic parameters that are inherent in a CE cannot be achieved in any other laboratory experiments. The increased focus on the CE studies is related, in particular, with the efforts toward the implementation of controlled fusion in a Z-pinch geometry both in wire array implosion experiments [1, 2] and using the MagLIF approach [3, 4]. Essential to an electrical explosion of conductors is the presence of electric and magnetic fields that govern the modes of both the explosion per se and the change in the phase state of the metal during its heating and a possible transition to a metastable state. The metastable states resulting from phase changes must be taken into account in simulating wire explosions (WEs) [5–7] to describe adequately the WE and achieve a reasonable agreement between the simulation predictions and relevant experimental data.

The decay of the metastable state in a superheated liquid is accompanied by the appearance of bubbles. The detection of bubbles and the monitoring of their evolution make it possible to infer the mechanism of occurrence and decay of the metastable state [8, 9]. The CE modes are highly diversified and may be different in a great number of parameters (the medium in which the explosion occurs, the original geometry of the conductor, the current rate, etc). It seems that among all the CE modes, the foil explosion (FE) in vacuum is best suited to study the decay of the metastable state of a superheated liquid metal.
2. Experimental setup and procedure

The experiment upon studying the phase decay of the metastable liquid in an FE was carried out on a setup consisting of three current generators (figure 1). A wire explosion generator (WEG-3, 14 kA, 450 ns) was used to initiate FEs and two X-pinch backlighting sources (XPG generators, 250 kA, 200 ns) were used for diagnostics [10]. The use of two diagnostic generators, each producing an x-ray flash with the help of an X-pinch, makes it possible to take two sequential pictures of a single exploding foil.

The current of the WEG-3 could be varied in amplitude from 7 to 14 kA by varying the charge voltage of the generator capacitive energy store, $V_0$, from 10 to 20 kV. Varying $V_0$ allowed us to pick out the WEG-3 current rate that would provide the same current density at the explosion time for all the foils.

Each of the XPGs produced a damped sinusoidal current pulse of amplitude 180–250 kA and quarter period rise time 180–200 ns. In the load unit of each of the generators (XPG-1 and XPG-2), an X-pinch assembly (four molybdenum wires of diameter 25 µm) was mounted which produced probe radiation pulses. At the time of occurrence of an x-ray flash, the XPG current rate was 1.7 kA/ns.

The foil was soldered to the electrodes of a special holder and inserted, together with the holder, into a vacuum chamber to which the WEG-3 electrodes were connected. On operation of the WEG-3, an electric current started flowing through the foil. Thereafter, the XPG-1 was started, with a preset delay, with the use of a delay pulse generator (DPG). The delay between the operations of the WEG-3 and XPG-1 was varied in the range from 70 to 1200 ns. The XPG-2 was started after the operation of the XPG-1. The delay between the operations of the XPG-1 and XPG-2 was varied in the range from 15 to 120 ns. A resistive voltage divider was used for measuring the voltage across the foil load $V_{\text{load}}$. The time derivative $dI/dt$ of the current flowing in the exploding foil was measured with a B-dot probe. The current was estimated by numerically integrating the B-dot probe data. The resistive voltage divider measured only the
voltage across the circuit section where the foil was connected (see figure 1). The inductance of this section, \( L_1 \), was 270 nH. In constructing voltage waveforms, the inductive component was subtracted from the readings of the divider.

On operation of the XPG-1 and the XPG-2, short x-ray flashes occurred at the cross point of the X-pinch conductors [11]. The radiation produced by the two X-pinches passed through the chamber containing the exploding foil and then transmitted to photographic cameras. To image the exploding foil at photon energies \( h\nu > 0.8 \) keV, a piece of Mikrat-300 film was used which was placed behind an aluminized Kimfoil filter (4-\( \mu \)m-thick Kimfoil with a deposited 0.4-\( \mu \)m-thick aluminum layer). A detailed description of the geometry and procedure of soft x-ray backlighting systems is given in [12, 13].

To detect the time of occurrence of x-ray flashes (the time at which an image of the exploded foil was taken, \( t_{\text{image}} \), vacuum x-ray diodes (XRDs) were used. They were placed behind composite filters which consisted of a 0.4-\( \mu \)m-thick aluminum layer, a 4-\( \mu \)m-thick Kimfoil layer, and a piece of 6-\( \mu \)m-thick polypropylene film. Detectors of this type are sensitive to photons of energies \( h\nu > 750 \) eV. The duration (FWHM—full width at half maximum) of the soft x-ray flash was 1–2 ns. The space resolution was dictated by the size of the hot plasma that radiated at \( h\nu > 750 \) eV, and it was 8–10 \( \mu \)m.

3. Experimental results

The CE experiments were performed with Al, Ni and Cu foils of length 20 mm, width 1 mm, and thickness 6 \( \mu \)m. Figure 2(a, b) presents typical current and voltage waveforms obtained for exploded Al and Cu foils, respectively. The hatched area in figure 2(a, b) corresponds to the interval between the times \( t_1 \) and \( t_2 \) in which bubbles were detected in x-ray images taken for the foil of given material. For \( t < t_1 \) there were no bubbles in the image; for \( t > t_2 \) bubbles could not be imaged, as their boundaries were blurred.

The FE process, like a WE in vacuum, is accompanied by the formation of a dense vapor-liquid core and a high-conductivity low-density corona. As a result, the energy deposition to the foil material due to its resistive heating ceases. According to the nomenclature proposed in [14, 15], the resistive energy deposition time \( t_{\text{res}} \) (figure 2) corresponds to the time interval between the onset time of current flow through the foil and the time at which the conductor resistance decreases to a value making 10% of its maximum resistance during the explosion. Table 1 presents the range of \( t_{\text{res}} \) measured in the experiment. The tabulated data indicate that the maximum current density \( j_{\text{max}} \) attained at a maximum current was nearly the same for all exploded foils, equal to about \( 10^8 \) A/cm\(^2\). In estimating the current density we used the initial cross-sectional area of the foil:

\[
  j(t) = \frac{I(t)}{\Delta w},
\]

where \( I(t) \) is the current through the foil, \( \Delta \) is the foil thickness (\( \Delta = 6 \) \( \mu \)m), and \( w \) is the foil width (\( w = 1 \) mm). Note that to obtain the same value of \( j_{\text{max}} \) for all explosions, we had to vary the charge voltage \( V_0 \) of the energy store of the WEG-3. The values of the energy deposited in the foil material by the end of the resistive phase, \( \varepsilon_{\text{dep}} \), presented in table 1 were estimated by taking into account of only the inductively corrected voltage \( V_{\text{foil}} \):

\[
  V_{\text{foil}} = V_{\text{load}} - L_1 \frac{dI}{dt}.
\]

The spread in values of \( \varepsilon_{\text{dep}} \) was determined as a root-mean-square deviation. We see that the experimental values of \( \varepsilon_{\text{dep}} \) are an order of magnitude greater than the values of the energy required to melt the metal, melt.

Once the resistive phase comes to an end (\( t \approx t_{\text{res}} \)), the entire discharge current starts flowing through the corona, the magnetic pressure no longer acts on the core material, and the material
Figure 2. Typical current and voltage waveforms obtained in explosions of Al (a), Cu (b) and Ni foils (c). The hatched area corresponds to the interval between the times $t_1$ and $t_2$ in which bubbles were detected in x-ray images of the foils.

Table 1. Experimental data: $V_0$ is the charge voltage; $j_{\text{max}}$ is the maximum current density; $t_{\text{res}}$ is the resistive phase duration; $\varepsilon_{\text{dep}}$ is the deposited energy; $\varepsilon_{\text{melt}}$ is the melting energy; $\varepsilon_{\text{evap}}$ is the evaporation energy.

| Metal | $V_0$ (kV) | $j_{\text{max}}$ ($10^8$ A/cm$^2$) | $t_{\text{res}}$ (ns) | $\varepsilon_{\text{dep}}$ (kJ/g) | $\varepsilon_{\text{melt}}$ (kJ/g) | $\varepsilon_{\text{evap}}$ (kJ/g) |
|-------|------------|---------------------------------|----------------|-------------------------------|-----------------------------|------------------------------|
| Al    | 20         | $1.1 \pm 0.1$                   | 155–215        | 5.3 $\pm$ 0.5                | 0.4                         | 10.85                        |
| Cu    | 10         | $1.0 \pm 0.1$                   | 335–370        | 2.1 $\pm$ 0.3                | 0.205                       | 4.75                         |
| Ni    | 20         | $0.8 \pm 0.1$                   | 104–130        | 1.3 $\pm$ 0.4                | 0.3                         | 6.3                          |

goes to the metastable state of stretched superheated liquid. As this state is not stable, the liquid starts boiling, which shows up as x-ray-transparent bubbles in x-ray images. For all foils, we could detect bubbles only in a certain time after the end of the resistive phase. The x-ray images taken at $t < t_{\text{res}}$ showed no bubbles.

A snapshot of the boiling process is shown in figure 3 containing a fragment of an x-ray image of a Cu foil taken at $t_{\text{image}} = 1140$ ns (980 ns after the end of the resistive phase).

Note that the space resolution of x-ray backlighting did not allow the determination of a bubble size.
Figure 3. X-ray image of an exploded Cu foil taken in 980 ns after $t_{\text{res}}$ with a 1-ns exposure time (FWHM of the x-ray pulse) (a) and a doubly enlarged fragment of the image (b).

Figure 4. X-ray image of an exploded Al foil taken in 389 (a) and 446 ns (b) after $t_{\text{res}}$ with a 1-ns exposure time (FWHM of the x-ray pulse).

Similar patterns were observed for the exploded Al foils. Figure 4 presents two sequential x-ray images of an exploded Al foil. The image in figure 4(a) was taken using the XPG-1 (389 ns after $t_{\text{res}}$); the image in figure 4(b) was taken using the XPG-2 (446 ns after $t_{\text{res}}$). Different contrast of the images is connected with the different magnitude of the x-ray radiation of the XPG-1 and XPG-2 backlighting sources. We did not observed the bubble separation during the x-ray backlighting study. Meanwhile we recorded the appearance of the new x-ray transparent bubbles in the sequential x-ray images and, therefore, the rise of the bubble surface density $N_{\text{bubble}}$. For example, according to the data in figure 4, $N_{\text{bubble}}$ was increasing from 200 mm$^{-2}$
Figure 5. Deposited energy $\varepsilon_{\text{dep}}$ (blue line) and $N_{\text{bubble}}$ (red squares) versus time after the onset of current flow for Al (a), Cu (b) and Ni foils (c); the dashed blue line corresponds to the end of the resistive phase ($t_{\text{res}}$) and the dashed red line corresponds to the onset of boiling ($t_{\text{boil}}$); $\Delta t = t_{\text{boil}} - t_{\text{res}}$.

at 389 ns up to 280 mm$^{-2}$ at 446 ns. To evaluate $N_{\text{bubble}}$ for an x-ray image taken at a given $t_{\text{image}}$, a square of area 0.2 $\times$ 0.2 mm$^2$ was chosen at the center of the image and the number of bubbles counted in this area was normalized to 1 mm$^2$ [figure 3(b)].

Figure 4 indicates that the magnetohydrodynamic (MHD) flute instability was developed at the exploded foil edge (the instability was most pronounced for the experiment with Al). Instabilities of this type grow under the action of the magnetic field pressure, which is proportional to the squared magnetic induction. In the geometry under consideration, the magnetic pressure at the edge of the foil was approximately twice the value at its center. The size of the boundary region, where the MHD instabilities were developed, was determined by the characteristic size of the magnetic field irregularities. In addition, the magnetic field topology was such that the magnetic field induction near the foil center did not change at distances of the order of the foil width, whereas near the foil edge, it decreased inversely with distance from the edge. This also enhanced MHD instabilities at the edge of the foil. At the foil center, no instability occurred, and the bulk boiling was due to the phase decay of the metastable superheated metal.

To estimate the decay time of the metastable state, the function $N_{\text{bubble}}(t)$ was constructed. Here, $N_{\text{bubble}}$ is the density of bubbles and $t$ is the time interval between the onset time of current flow through the foil and the time at which an x-ray image of the foil was taken, $t_{\text{image}}$.

The values of $N_{\text{bubble}}$ thus obtained are presented versus $t$ in figure 5 for Al, Cu and Ni foils. The x-ray images taken at times shorter than or close to $t_{\text{res}}$ showed no bubbles, that is we had $N_{\text{bubble}} = 0$ [see figure 5(a, b)]. The first x-ray images of Al, Cu and Ni foils on which bubbles
were detected were taken, respectively, in 290 and 640 ns ($t_{\text{image\ min}}$) after the onset of current flow through a given foil. We take the time $t_{\text{image\ min}}$ as the start time of the boiling metastable fluid, $t_{\text{boil}}$.

The plots of $\varepsilon_{\text{dep}}(t)$ in figure 5 roughly correspond (in magnitude and time) to an “average” of 10–15 shots. It can be seen that the time $t_{\text{boil}}$ does not coincide with $t_{\text{res}}$. The time delay $\Delta t$ between the end of the resistive phase and the onset of boiling was estimated for the shots with the shortest imaging times as $\Delta t = t_{\text{boil}} - t_{\text{res}}$. We obtained $\Delta t \approx 90$ ns for Al, $\Delta t \approx 250$ ns for Cu, and $\Delta t \approx 390$ ns for Ni.

4. Conclusion
Thus, it has been shown that in experiments on the explosion of foils with the energy deposited in the foil equal to about a half of the vaporization energy, the volume boiling occurs which is caused by the bubble appearance of the superheated metastable metal. The delay time of the phase decay of a superheated metastable metal has been estimated. For aluminum it is about 90 ns at a deposited energy of $5.3 \pm 0.5$ kJ/g and a foil thickness of 6 $\mu$m. For copper, at the same foil thickness and a deposited energy of $2.1 \pm 0.3$ kJ/g, it is about 250 ns. For nickel at the same foil thickness and a deposited energy of $1.3 \pm 0.4$ kJ/g, it was about 390 ns.

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