Experimental research of the fine foil explosion dynamics

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Abstract. The work is devoted to studying of substances properties at high specific deposit energy using double-frame pulsed backlighting system. The high specific deposit energy was reached at electrical conductor explosion (ECE). Fast mode of ECE was investigated. Fine foils of aluminum, cooper, titanium and nickel were used as conductors. Experiments were carried out on the experimental complex consisting of three current generators. The first generator WEG-1 was used for explosion of the fine conductors. This generator represents fast capacitor with capacity 250 nF, which was charged to voltage 10 to 30 kV. The investigated conductor was mounted in special holder and the foil contacts with the electrodes were soldered. Two other generators - radiographs XPG-1 and G2 with x-pinch load were used two frame X-ray backlighting imaging. The generators current pulses had amplitude 300 kA and rising time 180 ns with a low inductance load. Four crossed molybdenum wires with diameter of 25 µm were used to form an x-pinch. Using of the x-pinchs soft x-ray radiation the images of exploded foil were registered with temporal resolution of 2 ns. The images were detected by a photo film located behind the filter. The x-ray imaging, together with the measurements of the current flowing through a conductor and voltage on the exploded conductor had allowed inferring of the energy deposited into the conductor, delay time of the bubbles formation relative to the moment of current-cutoff and the time dependence of the vapor bubbles quantity.

1. Introduction

Formation and disintegration of the metastable states are great of interest for fundamental and applied science. Metastable state of a substance occurs when the material is rapidly heated to temperatures higher than those of phase transition in conditions of suppression of nuclei of a new phase [1]. At a high level of metastability, phase separation occurs as nucleus or spinodal disintegration [2-5] whose properties still remain insufficiently studied at high density of energy generated or accumulated in the material. The phase separation mechanism is determined by kinetics of spontaneous structurization of material with a wide spectrum of applications in physics, astronomy, biology, material science and various technologies. This effect occurs in a wide class of problems of high energy density physics, mechanics, and power engineering, and is important for advance in technologies of nanopowder...
production by electrical metal wire explosion, methods for suppression of steam explosion as a critical
stage of severe accident at nuclear power plants, critical and transient phenomena in multiphase flows,
etc.

Disintegration of superheated metastable liquids is sufficiently studied for liquids with a
temperature of boiling under normal conditions comparable with room temperature [1]. Such data are
very scant for liquid metals whose boiling temperature is several thousand degrees. At the same time,
they are important for studying such processes as explosive emission [6], where metal can stretch
during explosion of explosion of micropoints under the action of electric forces [7], in production of
nanopowders [8] during electrical wire explosion (EWE) [9,10], etc.

Formation of the metastable states could be investigated at the fine foil electrical explosion with the
energy deposition comparable with sublimation energy. This paper describes the experimental results
obtained at the electrical explosion of the aluminum, nickel, copper and titanium foils. The
experimental purpose was to find out a relation between the energy deposition into the foil and the
dynamics of the vapor bubble rising at the foil boiling. In order to get the relation a diagnostics set was
developed that included precise current and voltage measurements combined with two frame soft x-
ray imaging based on the x-pinch.

2. Experimental setup

The experiments had been performed using three synchronized generators. The generator WEG-2 [11]
was used for foil electrical explosion. The generator consists of fast capacitor with capacity of 250 nF
with a controlled high pressure gas switch. The charging voltage was varied in the range of 10-30 kV
in order to match various foils parameters. The typical generator WEG-2 current pulse had a peak 8-15
kA with a rising time of 400 ns. Two frame soft x-ray backlighting system was based on two pulsed
generators G-1 (XPG-1 [11-13]) and G-2 that could provide the current peak up to 300 kA with a
rising time of 180 ns. Each generator had an x-pinch load that produced soft x-ray pulse. The
generators’ operating was approximately the same as described in [14]. Significant modification in the
triggering scheme was performed. The primary trigatron type switches were replaced by thyratrons.
As result the jitter between the generators current pulses and low voltage synchronization pulses (300
V, 100 ns) was reduced to ± 15 ns. The generators WEG-2, G-1, G-2 were synchronized by
programmable three channel pulser DPG with independent controlled delays between the channels.
The DPG provides pulses (300 V, 100 ns) with adjustable delays (0 – 1000 μs) with the time step of 25
ns.

The x-ray backlighting system arrangement is shown in Figure 1. X-pinchess and the exploding foil
were placed in line.

The x-rays from the x-pinch 1 passed through the foil and formed the backlighting image on the
film 2. The x-rays from x-pinch 2 passed the foil from the opposite side forming the image on the film
1. In order to avoid film 1 exposure by x-pinch 1 a metal rods with diameter of 2 mm were placed
between the x-pinchess and the films. The rods were placed at the distance of 2 cm from the x-pinchess
that provided the rod shadow size on the film higher than the film size. Hence, the film 1 was not
directly exposed by x-pinch 1 x-rays. The film 2 was protected from radiation of the x-pinch 2 in the
same manner. The rod 2 shadow produced by x-pinch 1 on the film 2 (see Figure 1) had significantly
lower size (10 mm) due to higher distance from x-ray source to the rod. That allowed enough wide foil
region to be imaged (see Figure 2). The same is correct for the film 1. The magnification of the
projection scheme was 10.8 that made it possible to get quality images. In order to exclude the
interference between the x-pinches and the exploding foil additional polypropylene filters with thickness of 6 microns were mounted (filters 2 and 3 in Figure 1).

**Figure 2.** X-ray backlighting image of the exploded aluminum foil on the film 2. Clearly visible are the rod 2 and wires of the x-pinch 2. The bubbles formation on the edge of the foil is evident.

The metal foils under investigations had a length of 20 mm, thickness of 5 microns and width of 1 mm. The foils were soldered to the electrodes of the special holder. The last one was inserted into the dielectric vacuum chamber where the holder electrodes were connected to the WEG-2 power feeder. The charging voltage of the WEG-2 was 20 kV for Al, Ti and Ni foils, while for copper foils it was 10 kV. In order to measure energy deposition to the foil both the current through the foil and the voltage on the foil were measured. An active voltage divider and a B-dot loop were used for measurements. After the WEG-2 current pulse started the generator G-2 was triggered with required delay. The delay between the WEG-2 and G-2 current pulses was varied in the range 300-1200 ns. The G-1 generator was triggered later then G-2 generator with adjustable delay which was varied from 15 to 120 ns.
When a current pulse is applied to a x-pinch a very short soft x-ray pulse could be produced [11-13]. The soft x-rays produced by x-pinches driven by G-1 and G-2 generators were used for the foil explosion backlighting imaging. The x-rays images were recorded in the spectral range higher 0.8 keV using MICRAT-300 film and thin filter. The filter consisted of Kimfol film with thickness of 4 microns with aluminum coating with thickness of 0.4 microns.

The timing of the x-ray pulses was detected by two filtered x-ray diodes (XRD) with aluminum cathodes. The filters were composed from of Kimfol film with thickness of 4 microns with aluminum coating with thickness of 0.4 microns and polypropylene film with thickness of 6 microns. Such combination allowed to have high XRD response in the spectral region higher 0/75 keV. The current, voltage and XRDs traces were registered by TDS-3054C oscilloscope (Tektronix, Inc., Oregon, USA ) with bandwidth of 500 MHz.

The energy deposition into the exploding foil was estimated using experimental traces of the current derivative \( dI(t)/dt \) and voltage \( U(t) \). The energy deposition could be expressed as:

\[
W(t) = \int I(t) \cdot (U(t) - U_L(t)) \cdot dt
\]

(1)

The current \( I(t) \) was inferred by integrating of the current derivative trace. The B-dot loop was calibrated using a current shunt with well defined resistance. It is known that a voltage trace \( U(t) \) has an active and inductive terms. In order to eliminate the inductive term \( U_L(t) \) it was measured by replacing of the foil by copper rod with diameter of 1 mm which had approximately the same inductance. The energy deposition was inferred by integrating of expression (1) till the voltage drop caused by foil shunting due to discharge in the low density corona.

The backlighting images registered at different times in course of the explosion were used for counting of the bubbles number. The bubbles appeared as a result of the foil boiling. The total bubbles number was normalized on the 1 mm\(^2\). The bubbles temporal behavior (time dependence of the bubble diameter) was determined using two x-ray images with different time delay.

3. Experimental results

Figure 3 presents time dependencies of the current and voltage, energy deposition and number of the bubbles per mm\(^2\) for different materials of the foil. The shunt discharge time could be evidently noted by the voltage trace dropping and the current trace knee. The energy deposition was measured to reach 5 – 5.8 kJ/g (46-54% sublimation energy) for aluminum, 1.3 – 1.8 kJ/g (21-29 % sublimation energy) for nickel; 0.9 – 1 kJ/g (10-11 % sublimation energy) for titanium and 2-2.5 kJ/g (42-53 % sublimation energy) for copper.

The figure 3 shows that boiling start does not correspond to the shunt discharge appearance (voltage drop). This delay could be interpreted as upper limit of the metastable state disintegration. This delay was measured to be 110, 350 and 315 ns for aluminum, nickel and copper foils, correspondingly. No boiling of the titanium foil was observed.

From analysis of the consequent frames it was obtained that maximum diameter of the bubbles does not exceed 12 microns that is doubled width of the foil. The duration of the bubble formation was measured to be not over 40 ns. The bubbles diameter increases faster at the beginning of the bubbles rising. Then the velocity of bubbles rising drops. In general the bubble diameter time dependence could be described by expression:

\[
\frac{dD_b}{dt} = 0.19 - 0.019 \cdot D_b \ [\mu m /ns], \quad D_b \leq 10 \mu m
\]

(2)

Thus, the x-ray imaging, together with the measurements of the current flowing through a conductor and voltage on the exploded conductor had allowed inferring of the energy deposited into the conductor, delay time of the bubbles formation relative to the moment of current-cutoff and the time dependence of the vapor bubbles quantity.
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