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Acceleration of metallic flyers at the Angara-5-1 installation

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Abstract. Loading of the sample by magnetic field allows studying the dynamic characteristics of substances at sub-microsecond processes. At the Angara-5-1 installation, megabar pressures are generated by the magnetic field produced by the current with linear density of 5 MA/cm. Velocity to 10 km/s was obtained during previous experimental studies with a duralumin flyer of 1 mm thick. The present report contains the results of the experiment on acceleration of flyers made from other metals, such as copper and titanium. The numerical simulation was carried out to estimate the parameters of the flyer made from these metals under the action by the current with a linear density of ≈ 4.5 MA/cm. The time dependencies of the velocity for different layers of flyers, their displacement from the initial position, and the distribution of the temperature, density, pressure and current density in different time over its thickness were obtained. A comparison of the simulation results and experimental data is presented.

1. Introduction

The aim of the present work is to create high-pressure states of solid matter by a magnetic field of the current flowing through a sample. Loading the sample by magnetic field allows us to study the dynamic characteristics of substances at sub-microsecond processes [1, 2]. Precision measurement of the parameters of these samples will make it possible to specify the equation of state of matter in extreme states [3–7]. To create high-pressure at the Angara-5-1 installation the electrode system was modernized, which allowed reducing the inductance and increasing the current through the load. It was obtained that, in the output unit, the current reached up to 5 MA, and the linear current density at the flyer was 5 MA/cm [1].

2. Experimental setup

The experiments were carried out at the Angara-5-1 installation [8]. To reduce the inductance of the output unit, the gap between the anode and the cathode was reduced to 3 mm. The scheme of the central part of the facility is shown in figure 1. The anode (made of different materials) has an internal anode chamber with a diameter of 44 mm. The anode and the cathode (made of



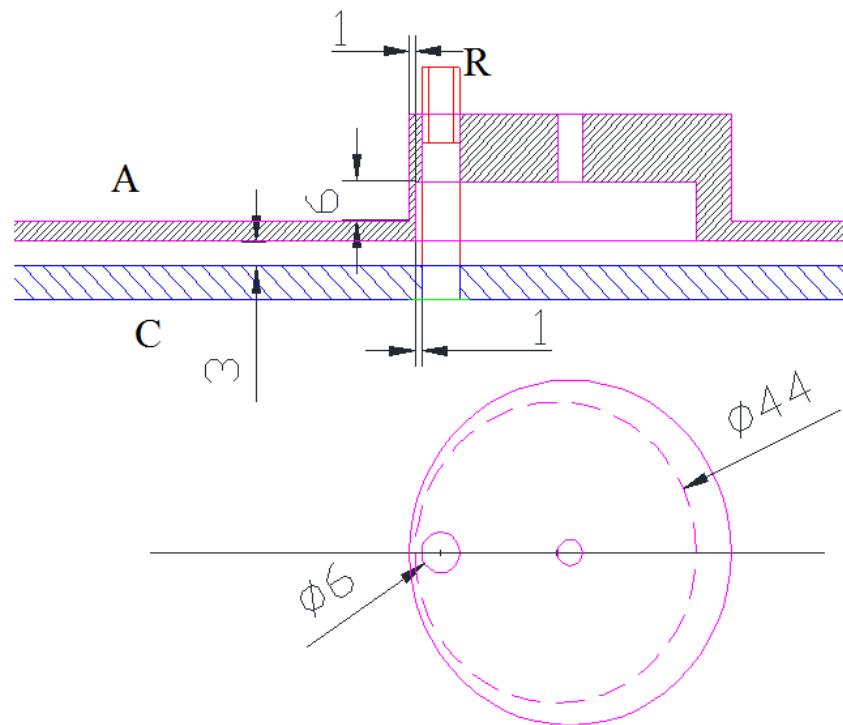


Figure 1. Design of the flyer mounting: A is the anode; C is the cathode; R is the rod.

stainless steel) are connected by the rod (of stainless steel) with the diameter of 6 mm. Due to asymmetric arrangement of the anode rod inside the internal cylindrical chamber, the current is concentrated near the rod; inside the gap of 1 mm between the rod and the anode, a strong magnetic field of 6 MG is created [1]. Under the influence of this field, this anode section is accelerated outward of the anode cavity (into the left in figure 1). So the part of the anode shown in figure 1 with the size of 6 mm is the flyer; the thickness of flyer is 1 mm.

The total current was measured by magnetic probes system at the different radius [1]. The miniature magnetic probe was placed in the anode cavity through the hole (figure 1).

The movement of the flyer was determined using the laser shadow imaging. Laser SL-233 ($\lambda = 532$ nm is the wavelength, $\tau = 0.1$ ns is the pulse duration) was used to obtain 2 or 3 shadow images of flyer in different times [1]. This information allowed us to have 2 or 3 points on the flyer trajectory. Extra continuously working laser beam was used in some shots to illuminate the external surface of the flyer. The instant of a change of the reflected light intensity showed the beginning of the flyer movement. The total information from two lasers allowed us to obtain 3 or 4 points about the flyer position during the same shot.

3. The results of the experiment

In the most experiments, the current in the anode cavity reached 5 MA. A typical oscillogram of the current, which was fixed by the miniature magnetic probe near the flyer, is presented in figure 2.

3.1. Destructions of the anode and the cathode

Under the action of strong magnetic pressure generated by the current, the flyer begins to move from the anode. During such strong dynamic influence, both the anode and the cathode are destroyed. Figures 3 and 4 show anodes and cathodes, which are destroyed after the experiment.

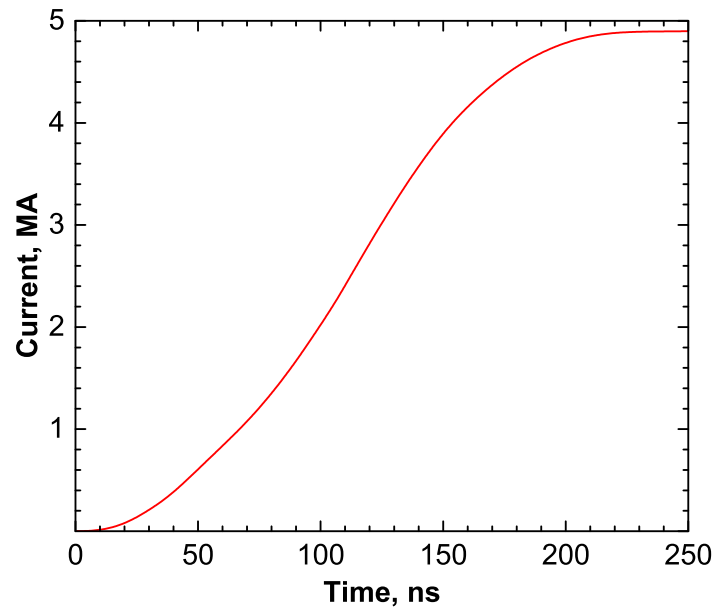


Figure 2. The time dependence of the current obtained by the miniature probe near the flyer.



Figure 3. Destroyed anodes of copper (from the left-hand side) and duralumin (from the right-hand side) after shots are in the foreground; the duralumin anode before a shot is behind. The arrows show to the flyer position.

3.2. The displacement of the flyers

In this paper, the results for flyers made of titanium, copper and duralumin are presented. With the use of laser probing, the flyer position was recorded at 2 or 3 moments (figures 5–7); time is counted off from the beginning of the current. Using these data, one can estimate the differential velocity of the external boundary of the flyer; using set of the positions obtained during different shots, one can track the average trajectory of the flyer and estimate its average velocity [1].



Figure 4. The rear view of the cathode, which is destroyed after a shot, is from the left-hand side; the cathode forepart (next to the anode) is displayed from the right-hand side. The cathode with the rod before a shot is in the center.

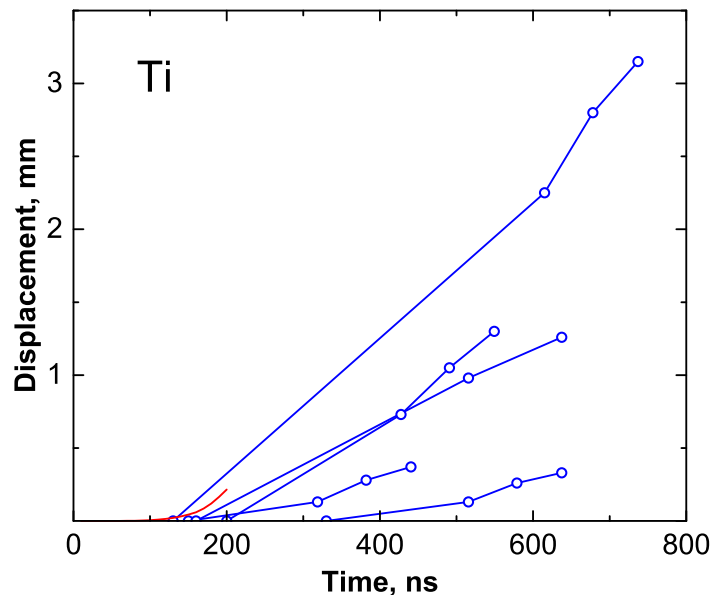


Figure 5. The time dependence of the displacement of the back surface of the titanium flyer. The points obtained in the same shot are connected by blue solid lines; the simulation results are represented by red solid curve.

Figure 5 shows the experimental data and simulation results obtained during the study of the displacement of the titanium flyer. During these experiments the current amplitude was about 4 MA. It is noteworthy that the differential velocity was comparable to the calculated one.

Figure 6 shows the experimental and simulated results from the study of the displacement of the copper flyer. The current amplitude during shot 5935 was 5.5 MA; during shots 5936 and 6049—5 MA.

Some results of laser probing of a flyer made of duralumin were partially presented earlier in paper [1]. Figure 7 shows more experimental data in comparison with simulated results from the study with the duralumin flyer. The current amplitude in these shots is changed in the range of 4.5–5 MA. Noteworthy is the fact that, in a number of shots, the differential velocities

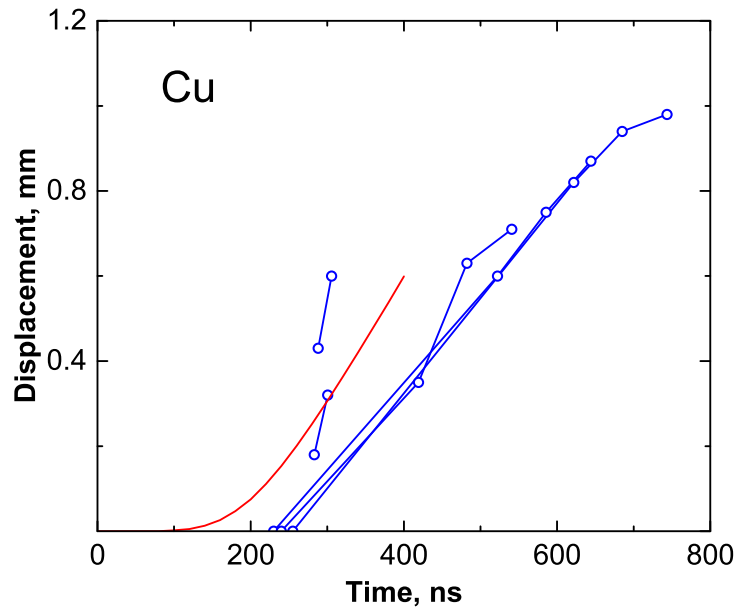


Figure 6. The time dependence of the displacement of the back surface of the copper flyer. Notations are the same as in figure 5.

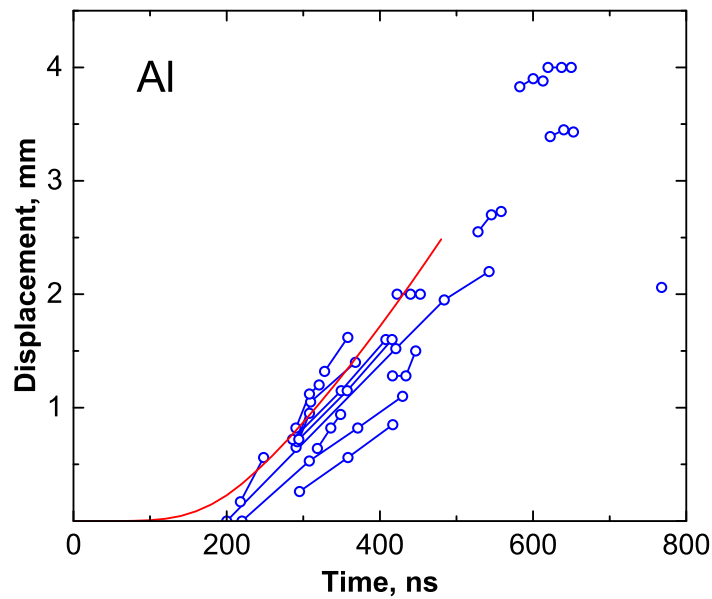


Figure 7. The time dependence of the displacement of the back surface of the duralumin flyer. Notations are the same as in figure 5.

are small, zero or even negative but, in the same time, the average velocity always is of about 10 km/s. This can be explained by the fact that, when displacements are greater than 1 mm, the external boundary of the flyer starts to distort, to blur and ceases to be flat. Furthermore, since the probing beams pass near the flyer at slightly different angles, it can give misleading information about the position of the flyer external boundary. We can state that, in the case of duralumin flyer, the differential and average velocities reach 10 km/s.

4. Numerical modeling

Numerical modeling of the evolution of the flyer parameters was conducted in the framework of the one-dimensional magnetohydrodynamic model [9,10]. To describe thermodynamic properties of matter in a wide ranges of volumes and temperatures, we used equation of state [11] taking into account phase transitions (melting and evaporation) and possibility of realizing metastable state, which should be important at the fast processes [12]. To determine transport properties of matter, we used the conductivity models from papers [13–15]. The time dependence of current was determined as follows: $I(t) = 0.5I_0[1 - \cos(\pi t/\tau_0)]$, when $t < \tau_0$, and $I(t) = I_0[1 - t/t_1]$, when $t \geq \tau_0$. Here, I_0 is the current amplitude; $\tau_0 = 180$ ns; $t_1 = 200$ ns. The thickness of the flyer was $h_0 = 0.9$ mm; and the linear current density was $I_l = I_0/s = 4.5$ MA/cm, where s is the width of the flyer.

5. Conclusion

The output node of the Angara-5-1 installation has been modified for reducing the inductance and hence for increasing the current; it has allowed increasing the current up to 5 MA. In such conditions, the flyer with thickness of 1 mm made of duralumin reaches the velocity of 10 km/s. For copper and titanium flyers the velocity is less than for duralumin and equals 5–6 km/s. The experimental data are in a good agreement with the numerical results.

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