SAND2011-7133C

Cavitation and Hollow Foam-like Structure Formation in the Dense Core of Exploded Wire

Sergey A. Pikuz[a,d], Vasiliy V. Zhakhovsky[b], Tatiana A. Shelkovenko[a,d], Patrick F. Knapp[a], Cad L. Hoyt[a], Jonathan D. Douglass[a], Charles E. Seyler[a], Daniel B. Sinars[c], Michael P. Desjarlais[c], Svetlana I. Tkachenko[e], Vera M. Romanova[d], Alexey E. Ter-Oganesyan[d], Albert R. Mingaleev[d], Sergey N. Mishin[d], Taliat A. Hattatov[e], Pavel V. Sasorov[f] and David A. Hammer[a]

[a]*Cornell University, Ithaca, NY 14853, USA*
[b]*University of South Florida, Tampa, FL 33620, USA*
[c]*Sandia National Laboratories, Albuquerque, NM 87185, USA*
[d]*P. N. Lebedev Physical Institute RAS, Moscow 199991, Russia*
[e]*Moscow Institute of Physics and Technology, Moscow Region 141700, Russia*
[f]*Institute for Theoretical and Experimental Physics, Moscow 117218, Russia*

Abstract. Complex hollow structures have been observed in the cores of single exploded wires and multiwire arrays using high resolution X-ray radiography. The radiographs show features suggesting that the core is a foam-like liquid-vapor mixture. Similar structures were observed in images of wire explosions in air using high resolution laser probing. Large-scale molecular-dynamics (MD) simulations of 50-200 nm radius aluminum and nickel wires show that fast bulk heating by electric current results in melting and radial expansion of the wires and propagation of strong radial rarefaction waves that converge at the center. When the pressure in this converging wave reaches the dynamic tensile strength of the melt, cavitation starts inside the wire. This leads to formation of a low-density foam-like material in the central part of the wire surrounded by a dense liquid cylindrical shell, in good qualitative agreement with the experimental X-ray radiographs.

Keywords: exploded wire, dense core, cavitation, molecular dynamics, x-ray radiography.
PACS: 79.20.Eb, 62.50.Ef, 02.70.Ns

Dense cores surrounded by conducting plasma in experiments with single wires exploded in microsecond discharges were observed long ago [1,2]. It was shown that the dense cores have a complicated inhomogeneous multiphase structure, but experimental methods at that time were incapable of of elucidating the many processes occurring in a wire explosion and, therefore, did not enable creation of an adequate explanation. Long lived wire cores were also observed in multiwire loads many years ago using laser probing [3]. These experiments showed the existence in the discharge channel of some structures that were stable and probably much more dense than the plasma visible on laser and pinhole images. The first direct experimental confirmation of the existence of a dense core with sharp well-defined and relatively stable boundary was demonstrated in Ref. [4]. In this work the X-ray radiation from an X pinch [5] was used for imaging of exploded Al wires. Further development of point projection radiography using the X pinch as a source of probing radiation [6,7] and monochromatic imaging using bent crystals [8,9], enabled observation of dense cores in many experiments connected with wire explosion. So the existence of long-lived cores within lower density coronal plasmas during nanosecond explosions of single wires or multiwire arrays is now well established.

However, the physical state of the core material and the processes occurring there are still a matter of conjecture. Using the technique of high resolution X-ray point-projection radiography [10], a complex small-scale structure has been observed in the exploding wire cores of both single-wire [11-14] and multiwire loads [15-16]. The radiographs show features implying that the core has become a foam-like, liquid-vapor mixture [11-12] that is a result of rapid phase transitions in the wire matter after initial energy deposition. In all wire explosion experiments the initial energy deposition in the wire occurs during resistive heating that lasts a short time relatively to the total discharge time [13]. During the stage after wire surface breakdown, voltage collapse occurs and the current redistributes from the wire core to the surrounding coronal plasma [1,13,17]. At this moment the magnetic pressure compressing the dense wire material decreases greatly and the wire core starts to expand. Liquid core expansion causes the development of different multiphase core structures, the details of which are very dependent on experimental conditions. Even if this general sequence of processes is reasonably well-known, the real mechanism of development of core structures is not clear. Here we describe the first attempts to take advantage of direct simulation of dense core dynamics by the method of molecular dynamics (MD).

One of the most important requirements for realistic MD simulations is the availability of accurate interatomic potentials suitable for simulation of a metal under extreme conditions. To this end, we employed an EAM potential for aluminum (Al) that has been recently developed specifically to simulate the metal response to a wide range of compressive and tensile stresses [18]. In our MD simulation, the cylindrical sample representing a wire in vacuum is a perfect ***fcc*** crystal of Al with radius R=100 nm and thickness of $\boldsymbol{l_z}$ = 40.2 nm, where the crystal is subject to periodic boundary conditions in the $\boldsymbol{l_z}$ direction. The sample contains 75,592,044 Al atoms, and has an initial temperature of 300 K and zero external pressure.

To heat up the wire to a temperature T_o a Langevin thermostat is used for entire sample. The Langevin forces given by $F_i = \varepsilon_I - \beta v_i$ are applied to each i-atom. The friction coefficient, β, of the atom velocity, v_i, and Gaussian random force, ε_I, must be carefully chosen in order to heat the material up to T_o during the prescribed time. In particular, these parameters should satisfy the conditions $\{\varepsilon_I^2\} = 2\beta T_o/h$ and $m/\beta = \tau$, where h is the MD integration time step and τ is characteristic time of heating. The last condition leads to time evolution of the temperature as $T(t)=T_o[1-\exp(-t/\tau)]$. In order to avoid non-physical deceleration of material expanding in the radial direction, the Langevin forces are applied only to to the ϕ and z components of the atomic velocity in cylindrical coordinates. For example, the fast heating of a wire up to a temperature T_o = 4kK in 5ps with a characteristic time τ = 1 ps requires an energy deposition of about 1.04 eV/atom. Such heating leads to the build-up of pressure to 17.3 GPa, since the thermal expansion of the sample does not have enough time to relax the growing internal pressure. The wire undergoes relatively little expansion during heating because the acoustic time $\tau_s = R/c_s \approx 20$ ps, where $c_s \approx 5$km/s is the sound speed in Al, is notably longer than the heating time. At the free surface of the wire, where the pressure is always zero, a cylindrical rarefaction/tensile wave is formed and propagates toward the center of sample. The pressure in the converging rarefaction wave becomes negative at some moment. The tensile stress (negative pressure) in such a wave increases in amplitude as it approaches the center until it reaches the tensile strength of the material, σ_c, at some critical radius R_c. After that bubble nucleation occurs and a cavitation wave associated with the critical tensile stress begins to propagate toward the center. It should be noted that close to the moment of convergence of the rarefaction wave and its reflection from the center, the tensile stress very quickly exceeds σ_c everywhere within the central part of cylinder, which leads to almost simultaneous bulk cavitation of material. The results of MD modeling for different T_o are shown on Fig.1. Modeling of Ni wire explosion gives the similar result.

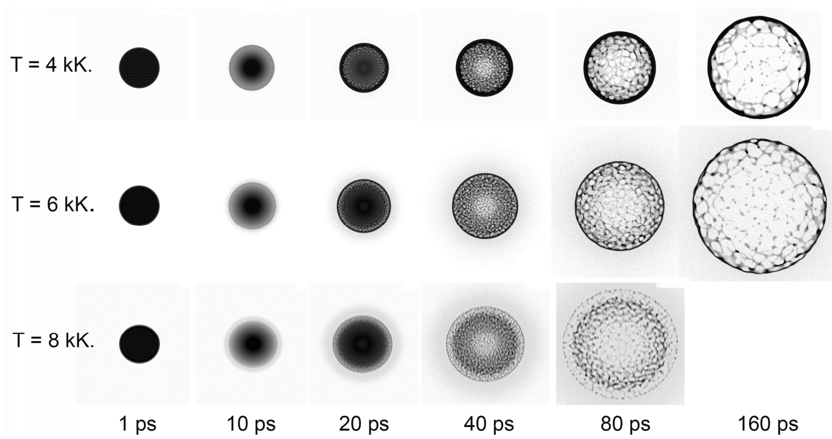

FIGURE 1. Density maps of the dense cores in explosion of Al wire with 200 nm intial diameter simulated using MD model under different initial temperature in the case of "inertial confinement".

The results obtained in MD modeling correspond unexpectedly well to experimental results reported earlier in Refs. [11-16], in which absorption profiles of the dense cores indeed look like hollow structures. In nanosecond wire explosion experiments, the acoustic time τ_s is longer than heating time and a regime of "inertial confinement" as described above cannot be realized unless external magnetic pressure is taken into account. The pressure reaches the multi-GPa level in the initial phase of wire explosion when the discharge current is flowing through the bulk wire material. After wire surface breakdown the discharge current transfers to surrounding wire corona and magnetic field on the wire surface drops to relatively low value. To calculate the process of Al wire explosion from a "cold start," we used an advanced 1D MHD model taking into account solid-liquid and liquid-vapor phase transitions as well as the possibility of metastable states of condensed matter [19]. The discharge parameters corresponded to experiments [20] (I_{max} = 5 kA, first quarter-period time 350 ns, 25 μm Al wire). After that, a MD simulation of an Al wire preheated to the conditions taken from the MHD simulation at time 5.35 ns was performed, with initial density of melt 1.8 g/cc, temperature 6 kK, pressure 2.6 GPa. Simulations were done for different radii of wire: 50, 100, and 200 nm. The latter was done with 2048 CPUs. Simulation of a wire with larger radius ***R*** requires ~500*(*R*/100nm)2 CPUs. However, our results show good similarity of expansion flows in wires with different radii. Therefore, it is possible that MD results can be extrapolated to micron-sized wires. Density maps of an exploded 400 nm Al wire in the case of "magnetic confinement " are shown on Fig. 2a.

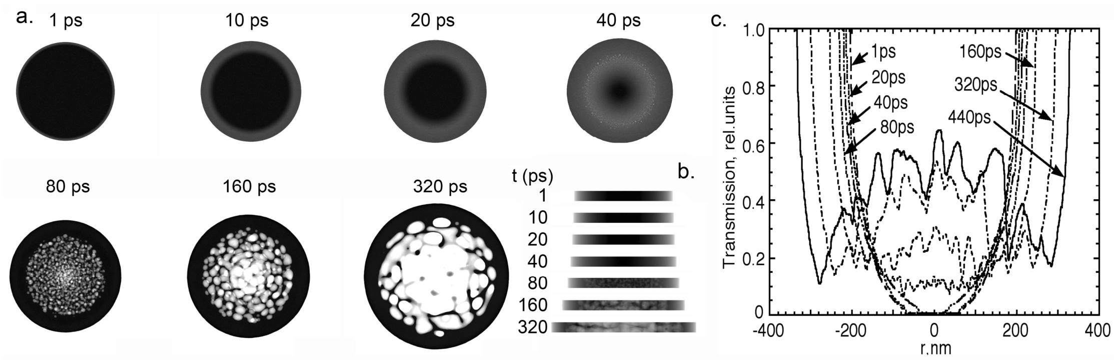

FIGURE 2. (a) Density maps of the dense cores in explosion of Al wire with 400 nm initial diameter simulated using MD model in the case of "magnetic confinement"; (b) Synthetic radiographs of the cores in radial direction; (c) – transmission profiles of synthetic radiographs.

Analysis of previous results of x-ray point-projection radiography of exploded wires obtained in different experiments indicates that structures similar to those shown in Figs. 1 and 2 were observed for many materials (see for examples images in papers [6,10-15]). Here in Figures 3a-c we present radiograph images of exploded Al wires only. These images were obtained in completely different experimental conditions.

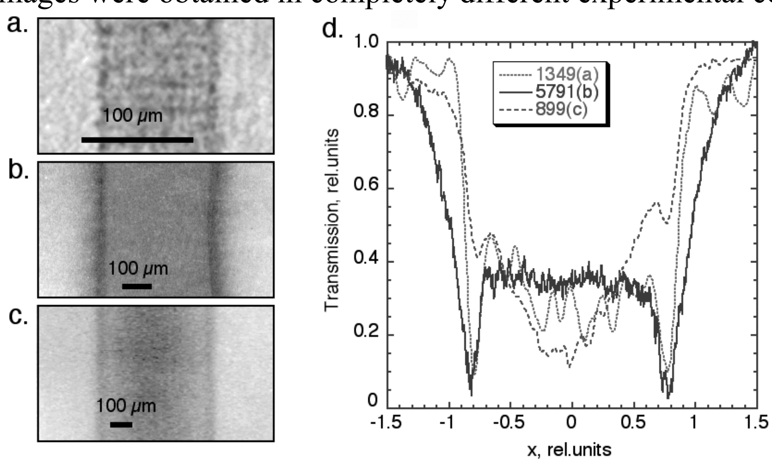

FIGURE 3. Radiographs of the cores of exploded Al wires obtained in different experiments: (a) – diameter 12.7 μm wire, I_{max}=1.5 kA, $\tau_{1/4per}$ = 350 ns, (b) - diameter 25 μm, I_{max}=25 kA, τ_{rise} = 40 ns, (c) - diameter 30 μm, I_{max}=75 kA, τ_{rise} = 100 ns, (d) – normalized transmission profiles of the cores.

In Figure 3a the radiograph image was obtained in experiments with discharge current through a wire load of about 5 kA with a first quarter-period time of 350 ns [13]. The initial energy deposition in the wire material occurred during the first 50 - 70ns followed by rapid development of the coronal plasma and expansion of the dense core. The image in Fig. 3a was one of three parallel 12.7 μm Al wires in the load when the current had switched mostly to the plasma in between the wires. The image in Fig.3, like the experiments in Ref. [14], involved two parallel 25 μm Al wires in the return current circuit on the XP pulser with a 50 kA, 40 ns risetime current pulse through them. Figure 3c was obtained in an experiment with a 16 Al wire array (wire diameter 30 µm, array diameter 16 mm) on the COBRA pulser (load current 1.2 MA, risetime 100 ns). The radiography setup is presented in Ref. [21]. All three transmission curves of the images were normalized to the dense core widths and the minimum an maximum transmission and are presented in Fig. 3d. The experimental profiles are generally very similar to the profiles of the synthetic radiographs from MD simulations (See Fig. 2b) shown in Fig. 3e. The presence of the tube-like wire cores in wire arrays could explain the experimentally observed rapid disappearance of portions of the dense core just before implosion of an array due to the core wall material being consumed in a short time (Fig. 4).

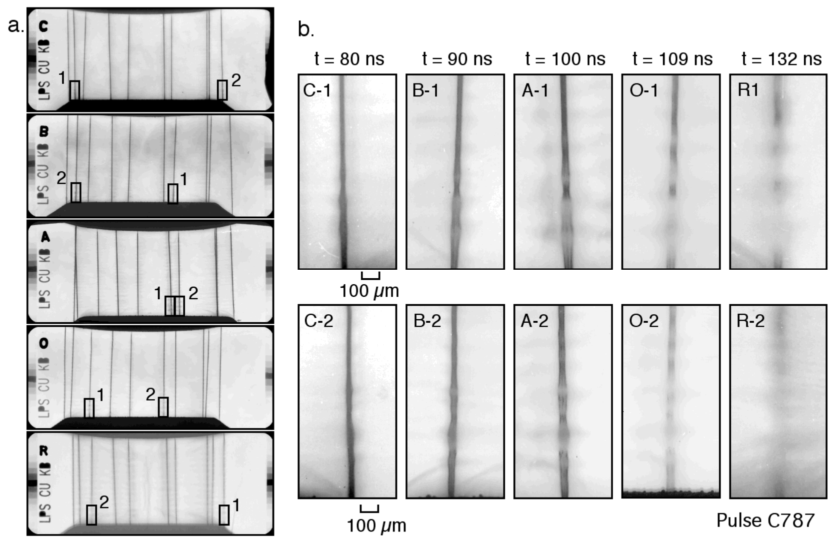

FIGURE 4. Radiograph images of wire array obtained using the COBRA STAR diagnostic [21] (10 W wires 12.7 µm, 12 mm array diameter).

Tube-like structures were also observed in the experiments with wire explosions in air (Fig. 5). These images were obtained in tests in which the discharge current was interrupted just after the resistive heating phase [20].

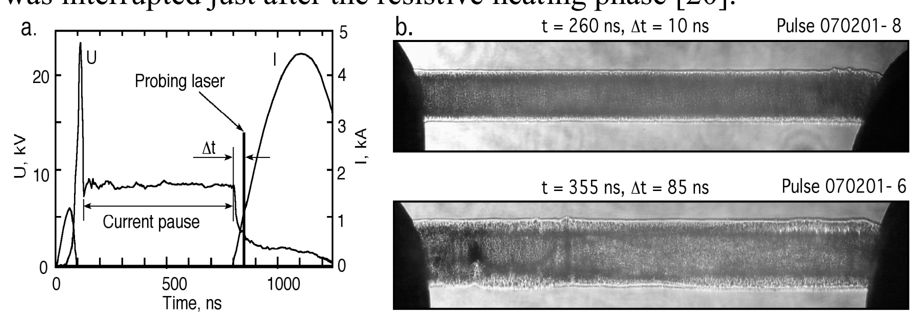

FIGURE 5. (a) Current and voltage scope traces in experiment with Al wire explosions in air in the regime with current pause; (b) Laser Schlieren images.

In summary, we emphasize that the cavitation process in tensile-stressed material with the subsequent formation of a dense shell is common for materials heated in a short enough time. For example, the fast laser heating of metals also leads to cavitation of the subsurface layer and formation of dense liquid shells [18, 22].

ACKNOWLEDGMENTS

Thanks to S. I. Blinnikov for fruitful discussion.

This work was partially supported by the SSAA program of the NNSA under DOE Cooperative Agreement No. DE-FC03-02NA00057 and programs of Russian Ministry of Science and Education under Program Nos. GK 02.740.11.0447 and 2.1.1/5470 and the Russian Foundation for Basic Research (projects Nos. 11-08-00624-a and 11-02-01210-a). MD simulations were performed using NSF TeraGrid facilities.

REFERENCES

1. E. D. Edelson, T. Korneff, in *Exploding wires*, edited by W. G. Chace and H. K. Moore, New York: Plenum Press, 1964, pp. 267-284.
2. K. S. Fansler, D. D. Shear, in *Exploding wires*, edited by W.G. Chace and H.K. Moore, New York, Plenum Press, 1968. pp. 185-193.
3. S. M. Zakharov, G. V. Ivavnenkov, A. A. Kolomenskii, S. A. Pikuz, A. I. Samokhin, *Sov. J. of Plasma Physics* **13**, 115-136 (1987).
4. D. H. Kalatar, D. A. Hammer, *Phys. Rev. Lett.* **71**, 3806-3809, (1993).
5. S. M. Zakharov, G. V. Ivanenkov, A. A. Kolomenskii, S. A. Pikuz, A. I. Samokhin, and I. Ulshmid, *Sov. Tech. Phys. Lett*. **8**, 456-458 (1982).
6. T. A. Shelkovenko, S. A. Pikuz, D. A. Hammer, Y. S. Dimant, A. R. Mingaleev, *Phys. Plasmas* **6**, 2840-2846 (1999).
7. S. V. Lebedev, F. N. Beg, S. N. Bland, J. P. Chittenden, A. E. Dangor, M. G. Haines, S. A. Pikuz, T. A. Skelkovenko, *Phys. Rev.Lett.* **85**, 98-101 (2000).
8. S. A. Pikuz, T. A. Shelkovenko, V. M. Romanova, D. A. Hammer, A. Ya. Faenov, V. A. Dyakin, T. A. Pikuz, *Rev., Sci., Instrum*. **68**, 740-744 (1997).
9. D. B. Sinars, G. R. Bennett, D. F. Wenger, M. E. Cuneo, D. L. Hanson, J. L. Porter, R. G. Adams, P. K. Rambo, D. C. Rovang, and I. C. Smith, *Rev., Sci. Instrum.* **75**, 3672-3675 (2004).
10. T. A. Shelkovenko, D. B. Sinars, S. A. Pikuz, K. M. Chandler, D. A. Hammer, S. A. Pikuz, *Rev. Sci. Instrum.* **72**, 667-670 (2001).
11. S. A. Pikuz, T. A. Shelkovenko, D. B. Sinars, J. B. Greenly, Y. S. Dimant, D. A. Hammer, Phys. Rev. Lett. **83**, 4313-4316, (1999).
12. S. A. Pikuz, G. V. Ivanenkov, T. A. Shelkovenko, D. A. Hammer, *JETP Letters* **69**, 377-382 (1999).
13. D. B. Sinars, Min Hu, K. M. Chandler, T. A. Shelkovenko, S. A. Pikuz, J. B. Greenly, D. A. Hammer, B. R. Kusse, *Phys. Plasmas* **8**, 216-230 (2001).
14. S. A. Pikuz, G. V. Ivanenkov, T. A. Shelkovenko, D. A. Hammer, *JETP Letters* **69**, 377-382 (1999).
15. G. V. Ivanenkov, A. R. Mingaleev, S. A. Pikuz, D. A. Hammer, T. A. Shelkovenko, *Plasma Physics* Reports **25,** 851-862 (1999).
16. S. V. Lebedev, F. N. Beg, S. N. Bland, J. P. Chittenden, A. E. Dangor, M. G. Haines, M. Zakaullah, S. A. Pikuz, T. A. Skelkovenko, D. A. Hammer, *Rev. Sci. Instrum*. **72**, 671-673 (2001).
17. S. I. Tkachenko, V. M. Romanova, A. R. Mingaleev, A. E. Ter-Oganesyan, T. A. Shelkovenko, S. A. Pikuz, *Eur. Phys. J.* **D 54**, 335-341 (2009).
18. V. Zhakhovskii et al., *Appl. Surf. Sci.* **255**, 9592-9596 (2009).
19. V. E. Fortov, K. V. Khishchenko, P. R. Levashov, and I. V. Lomonosov, *Nucl. Instr. Meth. Phys. Res. A* **415,** 604-610 (1998).
20. S. I. Tkachenko, A. R. Mingalev, V. M. Romanova, A. E. Ter-Oganesyan, T. A. Shelkovenko, S. A. Pikuz, *Plasma Physics Reports* **35**, (2009).
21. J. D. Douglass, D. A. Hammer, *Rev. Sci. Instrum* **79**, 033503 (2008).
22. B. J. Demaske, V. V. Zhakhovsky, N. A. Inogamov, I. I. Oleynik, *Phys. Rev. B* **82**, 064113 (2010).