Experimental and numerical study of the initial stages of explosion of thick single wire z-pinch

E. Kaselouris[1,2], V. Dimitriou[1,3], A. Skoulakis[1,4], I. Fitilis[1,4], Y. Orphanos[1], I.K. Nikolos[2], E. Bakarezos[1,5], N.A. Papadogiannis[1,5] and M. Tatarakis[1,4,a]

[1]*Centre for Plasma Physics & Lasers, Technological Educational Institute of Crete (TEI), Chania & Rethymnon, Greece*

[2]*School of Production Engineering & Management, Technical University of Crete, Chania, Greece*

[3] *Department of Natural Resources & Environmental Engineering, Technological Educational Institute of Crete (TEI), Chania, Greece*

[4] *Department of Electronic Engineering, Technological Educational Institute of Crete (TEI), Chania, Greece*

[5]*Department of Music Technology& Acoustics Engineering, Technological Educational Institute of Crete (TEI), Rethymnon, Greece*

a) Author to whom correspondence should be addressed. Electronic mail: m.tatarakis@chania.teicrete.gr

Abstract

This study focuses on the understanding of the dynamics of the initial phases of an exploding single metallic wire using a Z-pinch plasma device aiming to contribute towards the investigation of the solid-to-plasma phase change problem by taking into account the intermediate transition phases. The Z-pinch device is capable of producing a peak current of 70 kA with a rise time (10% - 90%) of 60 ns. Experimental results of the expansion dynamics of the exploded wire were obtained using laser probing diagnostics such as shadowgraphy, interferometry and diffraction imaging. A coupled transient multiphysics three dimensional computational model based on the Finite Element Method, with material temperature-dependent properties, is developed in order to simulate with high accuracy the spatiotemporal dynamics in the thermoelastic, melting and ablation regimes where phase changes take place. Important parameters such as temperature and current density distributions, as well as the expansion rate of the exploded material are investigated and compared with the experimental results.

Pulsed power exploding wire plasmas such as Z-pinches, is a research topic with continuous interest not only due to the important emerging applications which cover a wide range of disciplines, but also due to the fascinating fundamental physics involved [1 and papers there in]. Furthermore, the unstable character of the Z-pinch plasma, due to the onset of MHD instabilities [2, 3 and papers there in] makes it particularly attractive for research. Especially, the early time dynamics of a Z-pinch plasma have been proven to be important for the development of the MHD instabilities [2, 3]. So as to study such dynamics including the crucial study of the phase change conditions from the thermoelastic to the melting and plasma regimes, thick metallic wires have been investigated and presented in this work. For such wires, the current flows through the skin depth which plays an important role for the exploding dynamics [4]. Laser probing diagnostics such as shadowgraphy, interferometric and diffraction imaging have been used for the measurement of the wire dynamics in the thermoelastic, melting and plasma regimes. An advanced Finite Element Method (FEM) simulation is developed with the aim to fully describe the spatiotemporal dynamics and predict with high accuracy the thermo-mechanical phenomena in the thermoelastic melting and ablation regimes where phase changes occur. Here, we focus on the very initial stages of the current-wire interaction aiming to understand the phase transition from the thermoelastic to the melting regime.

The Z-pinch pulsed power device consists of a Marx bank of 600J energy capacity, a water-filled pulse forming line (PFL) and a self-breaking SF6 switch. The copper wire of 300μm diameter and 15.2 mm length is placed in a vacuum chamber evacuated at 10^{-4} mbar. The wire is fixed by soldering it to the conical shaped copper electrodes. A V-dot probe and a Rogowski groove are used to measure the derivatives of the voltage at the PFL and of the current passing through the wire respectively. The second harmonic of a SBS-compressed Nd:YAG, Q-switch laser (EKSPLA, SL312) with 150 ps pulse duration is used for the laser probing diagnostics. Shadowgraphy, schlieren, interferometric and diffraction imaging laser probing techniques are implemented in this study. For the schlieren imaging a knife-edge oriented parallel to the wire is used at the focal length of the imaging lens and the formation of plasma is revealed only at the blocked side of the wire [5]. A Mach-Zender interferometer is also developed and used. The imaging of the Fraunhofer diffraction at the focus of the lens is employed as a method to determine the expansion of the wire before plasma formation [6].

A 3-D coupled mechanical/thermal FEM (Finite Element Method) simulation is developed using the ANSYS finite element software. The model conveys a simultaneous analysis of the thermal and structural parameters as defined by the solution of the heat conduction and mechanical motion equations [7]. The mechanical equation determines the displacements of the wire imposed by the pulsed current while the heat conduction equation predicts the temperature distribution. Convective heat transfer as well as radiative transfer in the wire are neglected. A small element size is essential in order to accurately simulate the dynamic phase changes of matter in the region of the skin depth. An important aspect of the developed simulation is that the Lagrangian mesh is adaptive depending on the simulation needs. Concerning the boundary conditions, the ends of the wire are fixed at environmental temperature (27 ^oC). The source term of the heat generation rate (W/m^3) is the Joule heating term j^2/σ, where j is the current density and σ the electrical conductivity. The analytical equation of j that takes into the diffusion of the current is:

$$j = \frac{I_{\exp}}{2\pi\delta(r_0 + (e^{\frac{-r_0}{\delta}} - 1)\delta)} e^{\frac{-(r-r_0)}{\delta}}$$

where I_{exp} is the experimentally measured pulsed current, δ the skin depth, $r_0$the radius of the cross section of the wire and r the varied radius. The temperature dependent material properties are taken into account in this study. In particular, the quantities of electrical conductivity [8], thermal expansion, young modulus, thermal conductivity and specific heat of copper are considered temperature dependent until the melting point (1085 ^oC). Furthermore, at the end of each solution step, if the temperature of an element is higher than the melting temperature, phase change occurs, by considering the latent heat of melting in the model.

In this study the initial stages (mainly in the thermoelastic and melting regimes) of the exploded wire are under investigation. A series of interferometric and schlieren images show that the coronal plasma formation is initiated at about 150 ns after the current start. Indicatively, Figure 1a presents an interferometric and a schlieren laser probe image at 150 ns after the current start. It shows that coronal plasma formation has just started near the cathode. At later times the plasma formation is extended along the wire and the anode. Before this time, the wire, due to the Joule heating, experiences thermal expansion as well as melting and

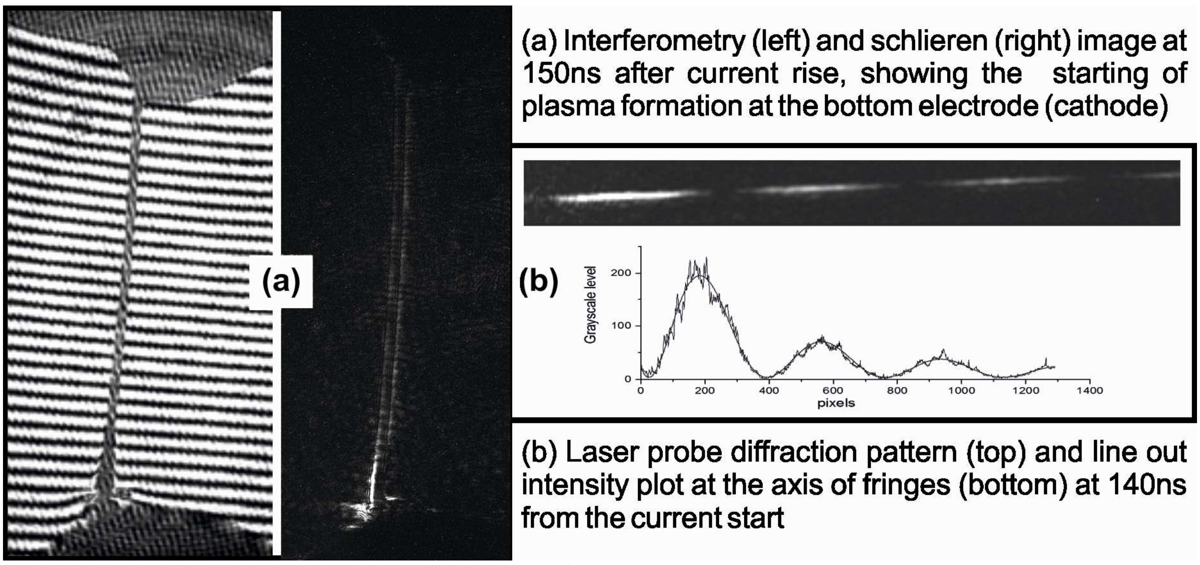

Figure 1

vaporization. In order to investigate the wire diameter dynamics just before plasma formation, a modified Fraunhofer diffraction laser probe diagnostic with high special resolution (~1μm) is implemented. Figure 1b illustrates preliminary experimental results at 110ns from the current start predicting wire expansion of ~ 4μm.

Figure 2a illustrates typical numerical simulations for the 300μm diameter wire and length 15.2 mm which demonstrate that the wire begins to melt at 86 ns from the current start. The expansion of the wire at this time is 1.1 μm. The temperature distribution predicted by the 3-D FEM model is also shown in Figure 2b.

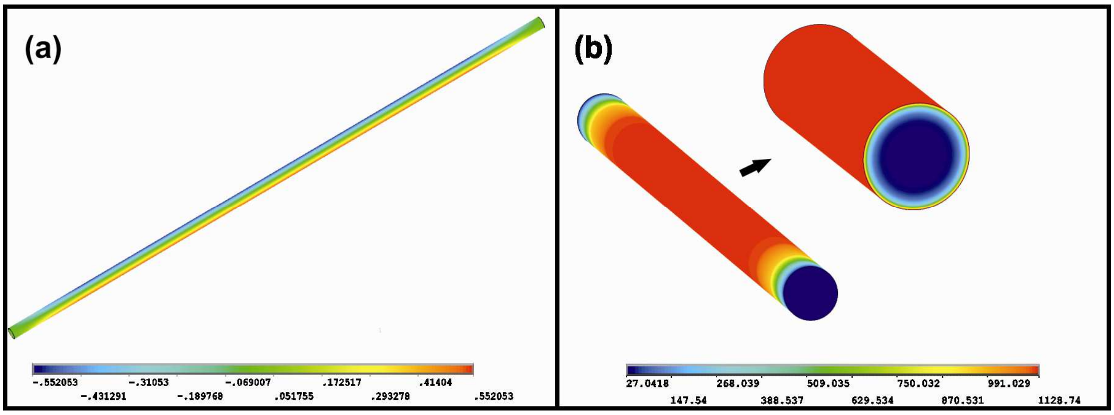

Figure 2. 3-D FEM numerical simulations for the 300μm diameter wire at 86ns from the current start (thermoelastic regime), a) An expansion of 1.1 μm is demonstrated, b) The predicted temperature distribution at the same time (at the right is the enlarged crossection of the wire)

Further coupled-field numerical simulations that will also take into account the influence of the magnetic field by solving the Maxwell equations in the Eddy-current approximation along with new experiments are under development. An adequate equation of state will also be used in order to study the hydrodynamic behavior of the metallic wire. The aim of these future studies would be to determine the role of the joule heating and the magnetic force in thick and thin wires before and after plasma formation.

References

[1] M.G. Haines, Plasma Phys. Control. Fusion **53**, 093001 (2011)

[2] M. Tatarakis et al., Physics of Plasmas **5**, 682 (1998)

[3] J. P. Chittenden et al., Physics of Plasmas **4**, 4309 (1997)

[4] D.P. Wall et al., J. of Applied Physics **98**, 023304 (2005)

[5] S. I. Tkachenko et al., Plasma Phys Rep. **35**, 734-753 (2009).

[6] S.A. Khodier, Optics & Laser Technology **36,** 63-67 (2004)

[7] V. Dimitriou et. al, Appl. Phys. Lett. **103**, 114104 (2013)

[8] R. A. Matula, J. Phys. Chem. Ref. Data **8**, 1147 (1979).

The authors acknowledge financial support through the Action "National Research Infrastructure for HiPER" MIS 376841 (co-funded by the European Union and Hellenic National funds within the Operational Programme "Competitiveness and Entrepreneurship").