FINITE ELEMENT STUDY OF THE INITIAL STAGES OF EXPLOSION OF SINGLE WIRE Z-PINCH VALIDATED BY EXPERIMENTS

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

[1]Centre for Plasma Physics and Lasers
Technological Educational Institute of Crete - TEI of Crete
Chania, GR-73133, Greece
Rethymnon, GR-74100, Greece
web page: http://www.cppl.teicrete.gr, e-mail: v.kaselouris@chania.teicrete.gr

[2]School of Applied Sciences – TEI of Crete
Rethymnon, Chania, GR -74100 -73133, Greece

[3]School of Production Engineering & Management
Technical University of Crete
Chania, GR-73100, Greece

Keywords: Finite Element Method – FEM, magneto-hydrodynamics, Z-pinch, Johnson-Cook material model, Gruneisen equation of state.

Abstract. *The Z-pinch plasma device is a type of plasma confinement system that uses electrical current to generate a magnetic field that compresses a current-carrying wire. In this study, a coupled transient multiphysics three dimensional (3D) finite element (FE) model is developed in order to simulate the initial stages of an exploding single metallic wire. The thermal, mechanical and electromagnetic properties of the 3D - FE model are temperature dependent and correspond to the experimental, obtained from a modified Fraunhofer diffraction laser probe technique. The Z-pinch pulsed powered device used in the experiments is capable of producing a peak current of 30 kA with a rise time (10%-90%) of 60 ns. In order to simulate the metallic material's response, a strength material model (Johnson-Cook) along with an equation of state (Gruneisen), are used. An equation of state is necessary in order to describe the hydrodynamic (HD) response of the material, while the strength material model describes the deviatoric behavior. The model validation is achieved by the comparison of the expansion rates of the exploded material of the numerical vs the experimental obtained results. The current research study aims to contribute towards the understanding of the solid-to-plasma phase change problem.*

1 INTRODUCTION

The Z-pinch plasma device is a type of plasma confinement system that uses electrical current to generate a magnetic field that compresses a current-carrying wire. The physical processes that take place at the initial stages of electrical exploding wire play an important role in plasma formation in pulsed-power Z-Pinch experiments [1, 2]. The early time dynamics of the processes involved in the explosion of the wire has been proven to be important for the development of Magneto-Hydrodynamic (MHD) instabilities of the Z-pinch plasma [1,3]. Improvements in the technology of fast pulsed electrical power have re-opened interest in the field of fast, dynamic z-pinches as x-ray sources for indirect-drive Inertial Confinement Fusion applications [4].

In order to investigate the initial stages of the matter's change from thermoelastic to melting and plasma regimes thick metallic copper wires have been used in this study. For such wires, electrical charges flow through the skin depth which plays an important role for the exploding dynamics. A transient electromagnetic-thermal-structural computational model, based on the Finite Element Method (FEM), is developed in order to provide valuable insights for important quantitative parameters such as temperature, density and expansion rate of the exploded material. Moreover, laser probing diagnostics such as schlieren, interferometric and diffraction imaging techniques have been used for the measurement of the wire dynamics at the initial stages of the explosion. The multiphysics FEM simulations validated by laser probing diagnostics constitute a valuable tool for understanding the initial stages of plasma formation in the wire.

2 FINITE ELEMENT SIMULATION

A 3D multiphysics magneto-hydrodynamic simulation based on FEM is developed using a commercial code [5].The electromagnetic fields are computed by solving the Maxwell equations in the eddy-current approximation. The Maxwell equations are solved using a finite element method (FEM) for the conductors coupled with a boundary element method (BEM) for the surrounding vacuum. The elements used are based on discrete differential forms (Nedelec-Like elements) for improved accuracy for both methods. Furthermore, the skin depth effect which is the tendency of the fast-changing current to gradually diffuse through the thickness of the conductor, resulting in current density being highest near the surface of the conductor is also taken into account. When the electromagnetic fields have been computed, the Lorentz force F=**j**x**B**, where **j** is the current density and **B** the magnetic field, is evaluated at the nodes and added to the mechanical solver, which computes the deformation of the wire. The new geometry is used to compute the evolution of the EM fields in a Lagrangian way. Moreover, the Joule heating power term (j^2/σ, where σ the electrical conductivity) is added to the thermal solver in order to update the temperature [5].

The hydrodynamic and deviatoric behavior of the metal is taken into account simultaneously by using an equation of state combined with a strength material model. Analytical Gruneisen equation of state [6] coupled with Johnson-Cook [7] strength material model are used for this purpose. Furthermore, electrical conductivity versus temperature and density is computed using Burgess equation of state (temperature-dependent conductivity with phase change from solid to liquid condition) [8]. Temperature dependent properties of thermal expansion, thermal conductivity and specific heat, as well as the latent heat of melting of copper are also taken into account.

The Johnson-Cook material model takes into account the effect of plastic strain, strain rate and temperature rise. The flow stress is expressed by:

$$\sigma_y = (A + B\varepsilon_{pl}^n)(1 + C\ln\dot{\varepsilon}_{pl})(1 - \frac{T - T_r}{T_m - T_r})^m \tag{1}$$

where ε_{pl} is the equivalent plastic strain, $\dot{\varepsilon}_{pl}$ is the plastic strain rate, A yield stress, B is hardening constant, C is strain rate sensitivity, n is hardening exponent, m thermal softening exponent, T_m melting temperature and T_r room temperature. For this study the analytical Gruneisen equation of state with cubic shock velocity-particle velocity (D-U_p) defines pressure for compressed materials as

$$P = \frac{\rho_0 C_0^2 \mu[1 + (1 - \frac{\gamma_0}{2})\mu - \frac{\alpha}{2}\mu^2]}{[1 - (S_1 - 1)\mu]^2} + (\gamma_0 + \alpha\mu)\mathrm{E} \tag{2}$$

where $\mu = (\rho/\rho_0)-1$ is the standard volumetric strain, C_0 is the intercept of the D-U_p curve, γ_0 is the gamma gruneisen coefficient, while α is the first-order volume correction to γ_0 and S_1 a unitless coefficient of the slope of the v_s-v_p curve. For expanded materials it has the formula

$$P = \rho_0 C_0^2 \mu + (\gamma_0 + \alpha\mu)\mathrm{E} \tag{3}$$

Regarding the boundary conditions, the ends of the wire are fixed at environmental temperature, at 27 ^{o}C. An important aspect of the developed simulation is that the Lagrangian mesh is adaptively refined in order to accurately simulate the dynamic phase changes of matter in the region of the skin depth. The loading source term is the alternating current as measured and recorded during the real experiments.

3 EXPERIMENTAL SET-UP

Experiments are carried out using a Z-pinch pulsed powered device implemented in a mode of producing a peak current of 30 kA with a rise time (10%-90%) of 60 ns. The Z-pinch device consists of a Marx bank with energy capacity of 600J, a water-filled pulse forming line (PFL) and a self-breaking SF6 switch. A wire of copper, with 300 μm diameter and 15.2 mm length, is placed in a vacuum chamber evacuated at 10^{-4} mbar. The wire is fixed by being soldered to 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 diffraction imaging, schlieren and interferometric laser probing techniques. This gives the ability of ns time resolved tracing of the explosion stages. The imaging of the Fraunhofer diffraction at the focus of a lens is employed as a method to determine the expansion of the wire at times before plasma formation [9].

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 coronal plasma is revealed from the bright light appeared at the same side of the wire as that the knife is placed. A Mach-Zehnder interferometer in finite-fringe mode is also developed and used for plasma density measurements.

4 RESULTS

The explosion of the initially solid metal wire and its intermediate phases are investigated, up to the plasma formation, in this study. In order to investigate the wire diameter dynamics before plasma formation, a modified Fraunhofer diffraction method is implemented with high accuracy in measuring the width. In Fig. 1 are depicted experimental and numerical results concerning the expansion of the wire's diameter for up to 140 ns after the current start. Satisfactory agreement is recorded. At 140 ns after initiation of the current flow the wire's maximum temperature on the outer region is 2400 ^{0}C below the copper's boiling point (2562 ^{0}C) according to FEM simulation.

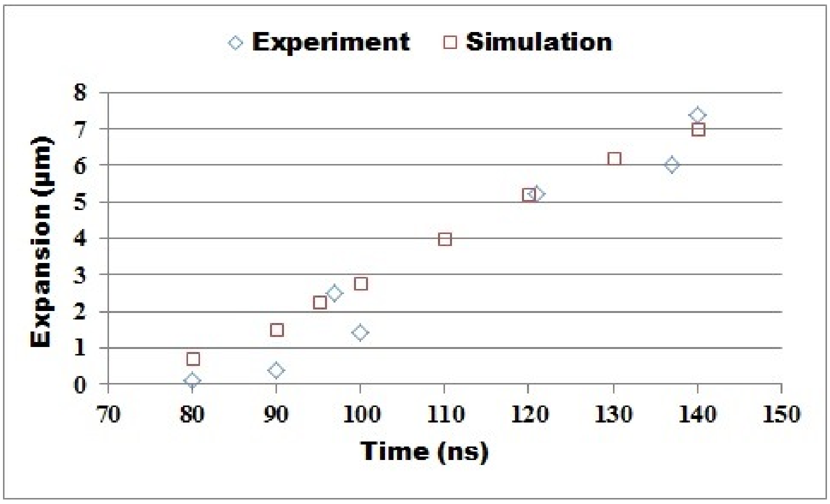

Figure 1. Comparison of diffraction imaging experimental vs FEM numerical results of wire's expansion

At about 220 ns from the current start corona plasma formation has been extended along the wire. Fig. 2 presents an interferometric and a schlieren laser probe image at 220 ns after the current start.

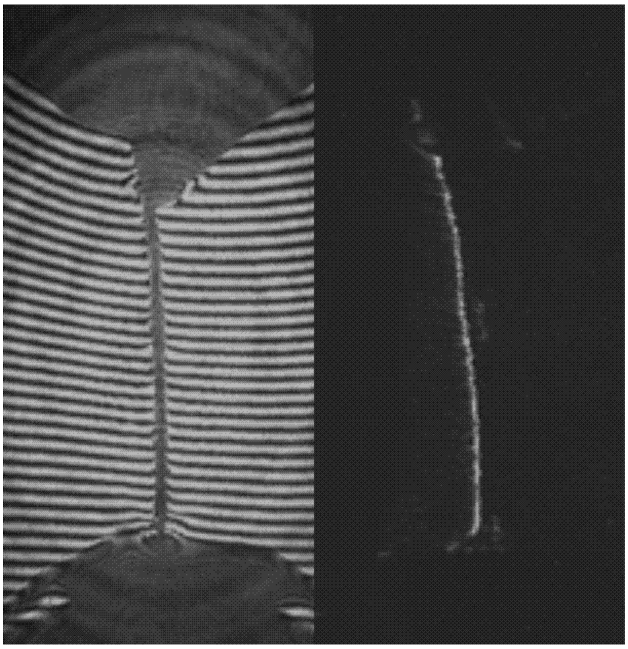

Figure 2. Interferogram (left) and schlieren image (right) at 220ns after current start.

In Fig. 3, the numerical results of the temperature and density of a cross-section of the wire for the same time-step, are presented.

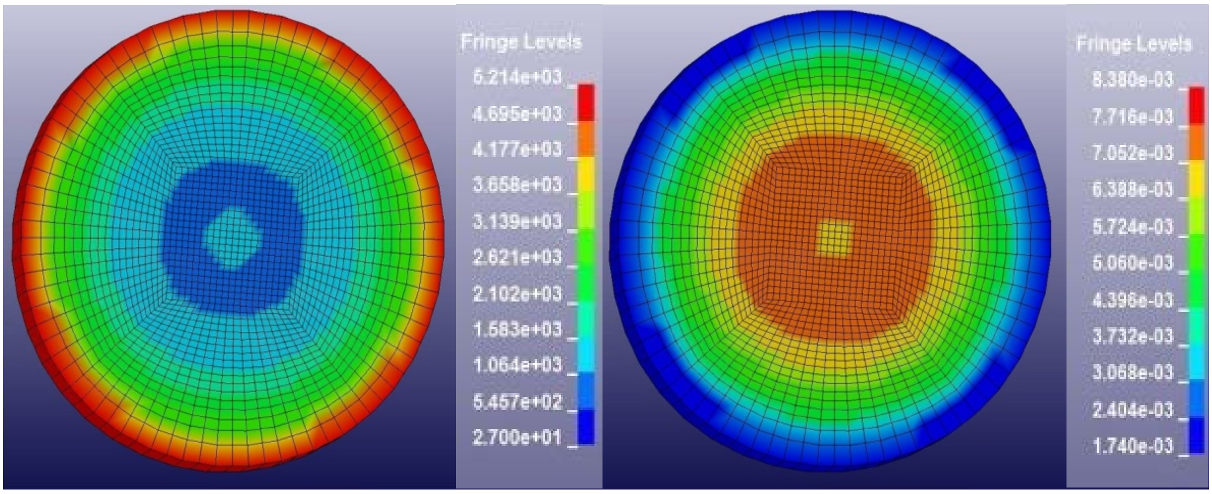

Figure 3. Finite element numerical results for temperature (left, ^{0}C) and density (right, g/cm^3) from a cross section of the wire at 220 ns from current start.

The maximum temperature of the outer part of the wire is 5200 ^{0}C, (well above copper's boiling point) and has a density of 1.7 g/cm^3 (while copper's solid density is 8.96 g/cm^3). The value of 1.7 g/cm^3 is in the range of experimental measured values for strongly coupled dense copper plasma density found in the literature [10]. Therefore, simulation indicates that coronal plasma has probably already been formed. Moreover, in the following Figs. 4 and 5, the temperature and density results in relation to time from current start respectively, are presented.

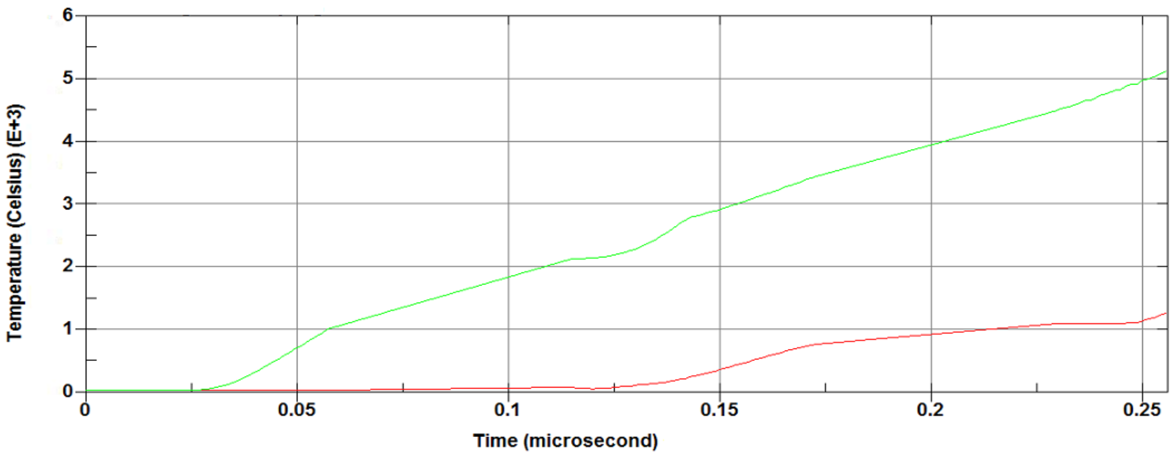

Figure 4. Finite element numerical results of temperature in relation to time for 150 μm away from the wire's center (outer region of the wire, green curve) and for 5 μm far from the centre (core region of the wire, red curve)

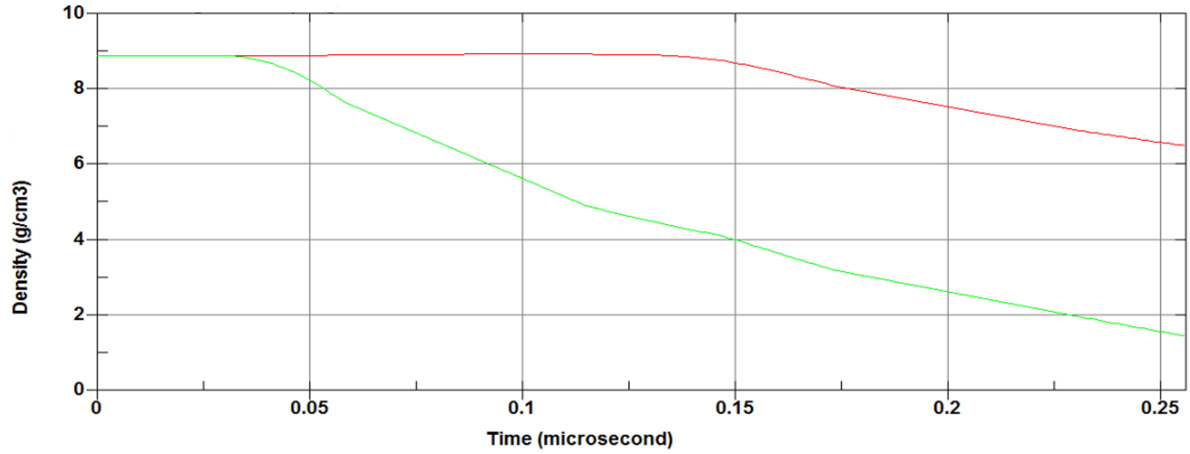

Figure 5. Finite element numerical results of density in relation to time for 150 μm away from the wire's center (outer region of the wire, green curve) and for 5 μm far from the centre (core region of the wire, red curve)

5 CONCLUSIONS

The combination of the multiphysics FEM model and the experimental method is capable to describe the wire expansion dynamics for temperatures below the boiling point. A good agreement of experimental vs FEM results is also observed concerning the initial times of coronal plasma formation. Further coupled-field numerical simulations that use a multiphase equation of state instead of the analytical Gruneisen along with new experiments are currently under development.

ACKNOWLEDGMENTS

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").

REFERENCES

[1] Haines, M.G. (2011), *"A review of the dense Z-pinch, Plasma"*, Phys. Control. Fusion Vol. 53, pp. 093001.
[2] Tatarakis, M. et al., (1998), *"Optical probing of fiber z -pinch plasmas"*, Phys. Plasmas Vol. 5, pp. 682.
[3] Oreshkin, V.I. et al., (2004), *"Wire explosion in vacuum: Simulation of a striation appearance"*, Phys. Plasmas vol. 11, pp. 4771-76.
[4] Matzen, K.M. et al., (1999), *"Fast z-pinches as dense plasma, intense x-ray sources for plasma physics and fusion applications"*, Plasma Phys. Control. Fusion, Vol. 41, pp. A175-184.
[5] Le Blanc, G. et al., (2008), *"Ramp wave compression in a copper strip line: comparison between MHD numerical simulations (LS-DYNA) and experimental results (GEPI device)", 10th International LS-DYNA Conference*, Dearborn, Michigan, 8-10 June 2008.
[6] Nagayama, K., (2011), "*Introduction to the Gruneisen Equation of State and Shock Thermodynamics"*, Kindle Edition.
[7] Johnson, G.R and Cook, W.H., (1985) *"Fracture characteristics of three metals subjected to various strains, strain rates, temperatures and pressures"*, Eng. Fract. Mech Vol. 21, pp. 31-48.
[8] Burgess, T., *"Electrical resistivity model of metals", 4th International Conference on Megagauss Magnetic-field generation and related topics*, Santa Fe, NM, 14-17 July 1986.
[9] Khodier, S.A., (2004), *"Measurement of wire diameter by optical diffraction"*, Opt. & Laser Technol. Vol. 36, pp. 63-67.
[10] Desilva, A.W. and Kunze, H.J., (1994), *"Experimental study of the electrical conductivity of strongly coupled copper plasmas"*, Phys. Rev. E Vol. 49, pp. 4448.