Experimental and numerical investigation of the early time dynamics of single wire plasma explosions

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ABSTRACT

The aim of this work is to investigate the initial stages of the Z-pinch explosion as the phase changes from solid to plasma. Experiments of single wire explosion were carried out using a Z-pinch device implementing a current pulse of 35 kA peak with rise time of 60 ns (10%-90%). Experimental results concerning the expansion dynamics of the exploded material were obtained from a modified Fraunhofer diffraction pattern method and also shadowgraphic and interferometric techniques utilizing a 150 ps pulsed laser. Furthermore, a coupled transient electromagnetic-thermal-structural multiphysics computational FEA (Finite Element Analysis) using a single material ALE (Arbitrary Lagrangian-Eulerian) element is carried out. In order to simulate the matter's response, a strength material model along with an equation of state for pressure and an equation of state for electrical conductivity are used. Temperature-dependent material properties are also taken into account. The comparison of experimental and numerical results aims to contribute towards the comprehension of transition from solid to plasma phase of the wire.

The Z-pinch plasma device is a topic with continues interest due to the important emerging applications and the fascinating fundamental physics involved [1]. The physical processes at the initial stages of the plasma formation along the wire, flowing by high current pulse, are very important for the plasma evolution on Z-pinch devices. [2] The early time dynamics have been proven to be important for the development of the MHD instabilities in plasma. [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 through experiments and simulations in this work.

For the experimental investigation of the initial times of wire explosion a Z-pinch pulsed power device is used, powered from a Marx-bank of 600 Joule energy capacity after passing through a water-filled pulse forming line (PFL) and a self-breaking SF6 switch. A copper wire of 300 um diameter and 15.2 mm length is fixed by soldering at the conical shaped electrodes inside a vacuum chamber of 10^{-4} mbar. A V-dot probe measure the derivative of the voltage at the PFL and a Rogowski groove measure the derivative of the current passing through the wire. For the optical probing of the fast phenomena during the wire explosion a SBS-compressed Nd:YAG Q-switch laser (EKSPLA, SL312) with 150 ps pulse duration and 532 nm wavelength is utilized. Shadowgraphy, schlieren and interferometric imaging techniques are implemented to record the early times of the plasma formation. The schlieren stop is a knife-edge oriented parallel to the wire which enable the distinguish of the light deviation caused by plasma from that caused by neutral Cu vapors.[4] The imaging of the Fraunhofer diffraction pattern at the focus of a lens is employed as a method to measure the expansion of the wire at times before the plasma formation.[5]

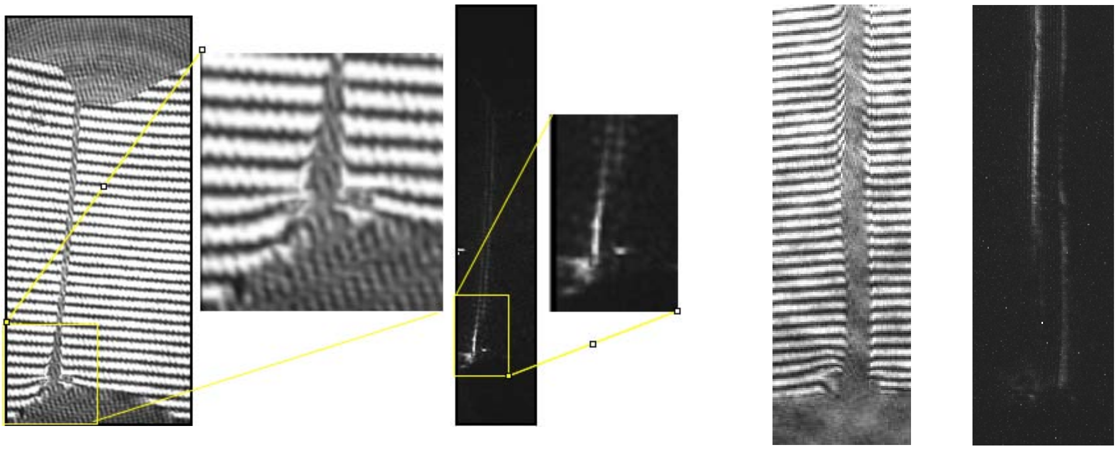
A coupled 3D transient electromagnetic-thermal-structural multiphysics computational FEA analysis using a single material ALE (Arbitrary Lagrangian Eulerian) element is carried out. Electromagnetic fields are computed by solving the Maxwell equations in the eddy-current approximation. When the electromagnetic fields have been computed, the Lorentz force term $F=\mathbf{j}\times\mathbf{B}$, where **j** is the current density and **B** the magnetic field, is evaluated and added to the mechanical solver, which computes the deformation of the wire. Moreover, the Joule heating term (j^2/σ, where σ the electrical conductivity) is added to the thermal solver in order to update temperature. Furthermore, the skin depth effect of the conducting wire is also taken into account.[6]

The ALE algorithm consists of a classical Lagrangian step in which the mesh moves along with the modeled material, a rezone step in which the mesh is modified to preserve good quality through the computation of the Eulerian time step and a remapping step in which the solution is conservatively transferred from the old mesh to the new rezoned one.

The hydrodynamic and deviatoric behavior of the metal is taken into account by using an equation of state combined with a strength material model. Analytical Gruneisen equation of state [7] coupled with Johnson-Cook [8] strength material model are used for this purpose. Furthermore, electrical conductivity versus temperature and density is computed using

Burgess equation of state [9]. Regarding the boundary conditions, the ends of the wire are fixed at environmental temperature, at 27 °C. An important feature of the developed simulation is that the ALE mesh is adaptively refined in order to accurately simulate the dynamic phase changes of matter. The loading source term is the alternating current as measured and recorded during the real experiments.

A series of interferometric and schlieren images, taken at different times after the current start, showing that the plasma formation time is about 150 ns ± 10 ns, it doesn't occur simultaneously along the wire and the transition from neutral vapors to plasma is very fast. At later time the corona plasma occupies all the wire length. Figure 1 shows two instances from the initiation of the coronal plasma. The upwards/downwards fringe shifts at the interferograms, as well as the left/right lighten at the schlieren images, is attributed respectively to the plasma/ vapors domination on the refractive index near the wire.



(a) (b)

Figure 1. Interferograms and schlieren images from the initiation of coronal plasma forming at a) 150 ns and b) 162 ns (different shot) after the current start.

For the measurements of the wire expansion (solid or melted) before the plasma formation the Fraunhofer diffraction pattern of the laser pulse at the focus of a lens is recorded and the wire diameter is calculated from the fitting of $(\mathrm{sinc}(x))^2$ function at the line out plot along the fringes axis (Figure 2). An average radial expansion rate of 65 m/s results from the experimental measurements, while a radial expansion rate of 60 m/s is computed from the simulations.

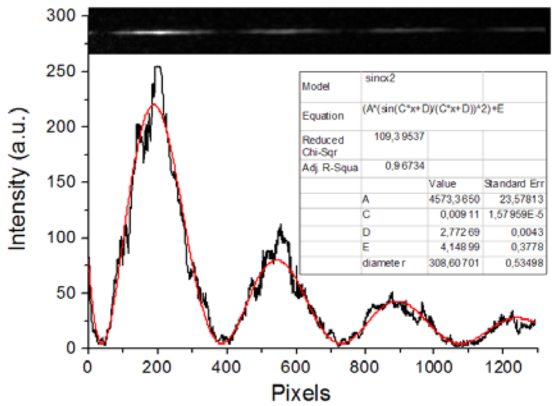


Figure 2. Line out of the diffraction pattern (top image) and calculation of the wire's diameter.

In Figure 3 the temperature and density simulation results in relation to the time after the current start are presented. The vaporization of the copper at a time of 160 ns is in consistence with the indication of vapors in the experimental images at these times.

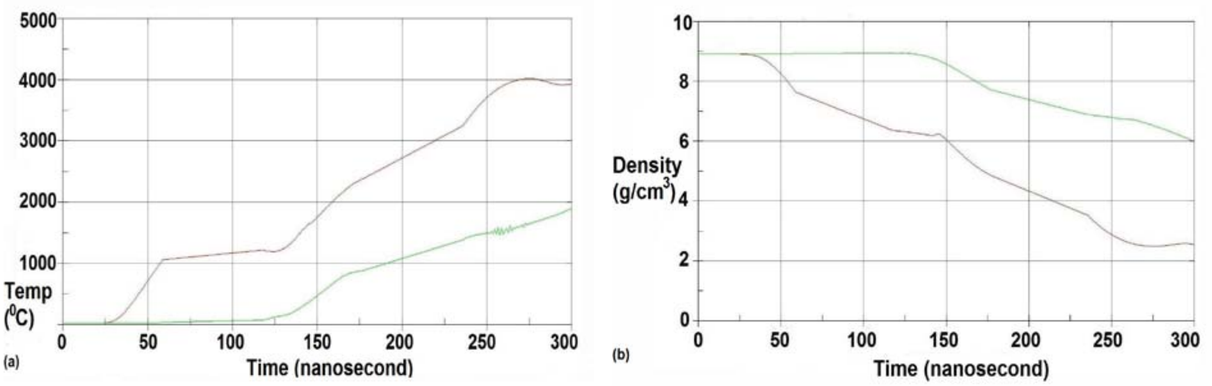


Figure 3. Finite element numerical results of a) temperature and b) density in relation to time, for elements 150 μm away from the wire's axis (outer region, red curve) and 5 μm far from the axis (core region, green curve).

The combination of the multiphysics FEM model and the experimental method is capable to describe the wire expansion dynamics. Further numerical simulations that use a multiphase equation of state instead of the analytical Gruneisen along with new experiments are still under development in order to monitor the conditions for coronal plasma formation.

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