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Metastable States of Liquid Tungsten under Subsecond Wire Explosion[1]

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A numerical simulation of the initial stage of tungsten wire self-heating by a high-power microsecond current pulse was carried out. A wide-range semi-empirical equation of state to account for the effects of melting and evaporation of tungsten at high temperatures was used. The metastable states were included in the process model, and the results of the simulation are in good agreement with experimental data.

KEY WORDS: equation of state; homogeneity; metastable states; phase track; thermophysical properties; tungsten; wire explosion.

1. INTRODUCTION

Subsecond self-heating of metals by a powerful current pulse is an accepted technique for experimental studies of the numerous physical phenomena occurring in matter at high energy densities [1–6]. Therefore, theoretical investigations of electrical explosion of wires are of significant interest [7–10].

In pulse-heating experiments the surface temperature of a specimen in the solid and liquid state is usually measured by optical techniques. A quantitative analysis of experimental data is based on the assumption of specimen homogeneity. However, the phase transitions (melting and evaporation) occur in the temperature range of interest. The impact of these transitions on the specimen homogeneity is the main subject of this study.

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We carried out a numerical simulation of the initial stage of tungsten wire self-heating by a high-power microsecond current pulse. We implemented a semi-empirical equation-of-state model [11–13], which describes the thermodynamic properties of tungsten, accounts for melting and evaporation, and covers the entire range from normal conditions to very high temperatures and pressures, as in Ref. 10.

An alternation of expansion and compression waves is typical for subsecond regimes of energy deposition [10]. During the self-heating experiment the metallic wires reach the thermodynamic states described by the liquid-vapor coexistence curve. Under certain conditions the liquid phase is known to exist for a while in metastable states [14]. Thus a model describing the heated wire has to allow for the existence of these metastable states.

2. MODELING

A one-dimensional cylindrical-wire explosion has been modeled. We used the following set of magnetic-hydrodynamic (MHD) equations for the Lagrangian description,

$$dm/dt = 0, \tag{1}$$

$$\rho\, dv/dt = -\partial P/\partial r - (2\mu r^2)^{-1}\, \partial(r^2 B_\varphi^2)/\partial r, \tag{2}$$

$$\rho\, d\varepsilon/dt = -P\, \partial(rv)/\partial r + r^{-1}\, \partial(\kappa r\, \partial T/\partial r)/\partial r + j^2/\sigma_w + k(r)E_w, \tag{3}$$

$$d(\mu B_\varphi)/dt = \partial[(\sigma_w r)^{-1}\, \partial(rB_\varphi)/\partial r]/\partial r, \tag{4}$$

where v, m, ρ, and T are the velocity and the specimen mass, density, and temperature, respectively; $\varepsilon = \varepsilon(\rho, T)$ and $P = P(\rho, T)$ are the specific internal energy and pressure given by the tungsten equation of state [10]; B_φ and μ are the magnetic induction and the absolute magnetic permeability; $\sigma_w(\rho, T)$ and $\kappa = \kappa(\rho, T)$ are the electrical and thermal conductivities; $j = (\mu r)^{-1}\, \partial(rB_\varphi)/\partial r$ is the current density; E_w is the specific energy loss due to heat radiation from the surface; and $k(a) = 1$ and $k(r) = 0$ at $r \neq a$, where a is the wire radius.

The heating current $I = I(t)$ is determined by the equation describing the electrical circuit

$$d^2(LI)/dt^2 + d(R_l I)/dt + I/C = 0, \tag{5}$$

where L is the inductance, C is the capacitance of the capacitor, and R_l is the resistance of the specimen. The value of R_l is calculated from the equation

$$R_l(t) = l\left[2\pi \int_0^a \sigma_w r\, dr\right]^{-1} \tag{6}$$

where l is the wire length.

Initial and boundary conditions are as follows:

$$\rho(r, t_0) = \rho_0, \quad T(r, t_0) = T_0, \quad v(r, t_0) = 0, \quad B_\varphi(r, t_0) = 0, \tag{7}$$

$$v(a, t) = da/dt, \quad v(0, t) = 0, \quad B_\varphi(a, t) = \mu I(t)/(2\pi a), \quad B_\varphi(0, t) = 0, \tag{8}$$

$$I(t_0) = 0, \quad (dI/dt)|_{t=t_0} = U_0/L, \tag{9}$$

$$(\partial T/\partial r)|_{r=0} = 0, \quad \kappa(\partial T/\partial r)|_{r=a} = \rho v_b(\Lambda - a_k R T_a), \quad P(a, t) = P_a, \tag{10}$$

where ρ_0, T_0, and U_0 are the initial density, temperature and capacitor voltage, v_b is the velocity of the evaporation wave, Λ is the specific heat of vaporization, R is the gas constant, T_a is the temperature of the wire surface, P_a is the ambient pressure, and a_k is a constant determined by the ambient pressure, such that $a_k = 0.77$ for evaporating to vacuum and $a_k = 0.5$ for the case of high pressure surroundings [15].

The electrical conductivity is defined by the semiempirical formula

$$\sigma_w(\rho, T) = \sigma_0 \frac{(\rho/\rho_0)^\delta}{1 + \beta(T - T_0)}, \tag{11}$$

where σ_0, ρ_0, T_0, β, and δ are the constants for solid and liquid states [5]. The electrical conductivity of two-phase states in the melting region is determined by

$$\sigma_{ef} = \nu\sigma_s + (1 - \nu)\,\sigma_l, \tag{12}$$

where σ_s and σ_l are the electrical conductivities of the solid and liquid phases, respectively and ν is the relative amount of the solid phase.

The thermal conductivity is calculated according to the Wiedemann–Franz law,

$$\kappa(\rho, T) = k_{\mathrm{WF}} T \sigma_w(\rho, T), \tag{13}$$

where k_{WF} is the Wiedemann–Franz constant.

Two numerical simulations of electrical explosion were carried out for the parameters of tungsten wire and electrical circuit from Ref. 5:

$a_0 = 0.175$ mm, $l = 8.7$ cm, $L = 4.5$ μH, $C = 6$ μF, and $U_0 = 20$ kV. The wide-range multiphase equation of state for tungsten [10] was used in both these simulations. The metastable (superheated or superexpanded) states of liquid tungsten were accounted for in the first one (EOS1), whereas in the second simulation, we assumed the equilibrium phase transition of liquid to vapor (EOS2). The ambient pressure P_a was defined as $P_a = \max[0.1\ \text{GPa}, P_b]$, where P_b is the pressure of saturated vapor at temperature $T = T_a$, in the case of EOS1; $P_a = 0.1$ GPa in the EOS2 simulation.

3. RESULTS

The calculated radial distribution functions of density and pressure as a function of heating time are shown in Figs. 1 and 2. It can be seen that expansion and compression waves alternate with each other and propagate along the wire radius. These acoustic waves are generated in the region of phase transition due to the inhomogeneous distribution of pressure in the wire at the beginning of the melting transition.

The phase tracks of some wire layers in the density-temperature and pressure-temperature planes for the case of EOS1 are shown in Figs. 3 and 4. A perturbation originates in the melting region and propagates from the outer boundary to the axis of the wire. After that, the perturbation is reflected off the axis and propagates to the outer boundary, where it reverses direction again. The relative temperature and density variations increase to 5 and 1.5%, respectively, when melting starts, decrease when melting is

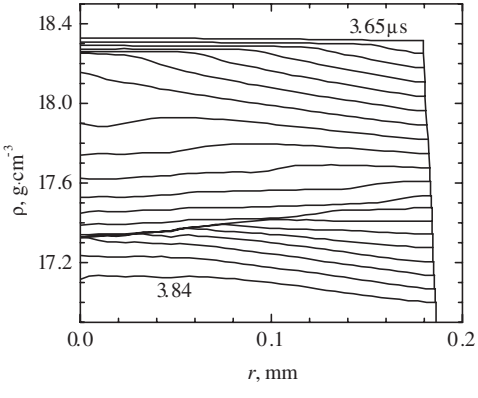

Fig. 1. Density of the heated wire as a function of radial position and time, from $t = 3.65$ (upper curve) to 3.84 μs (lower curve). The time interval between neighboring curves is 0.01 μs.

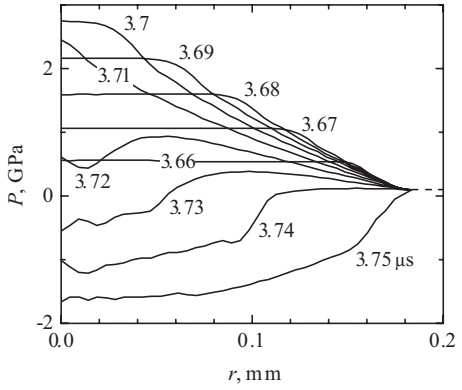

Fig. 2. Pressure of the heated wire as a function of radial position and time, from $t = 3.66$ to 3.75 μs. The dashed line denotes the ambient pressure P_a.

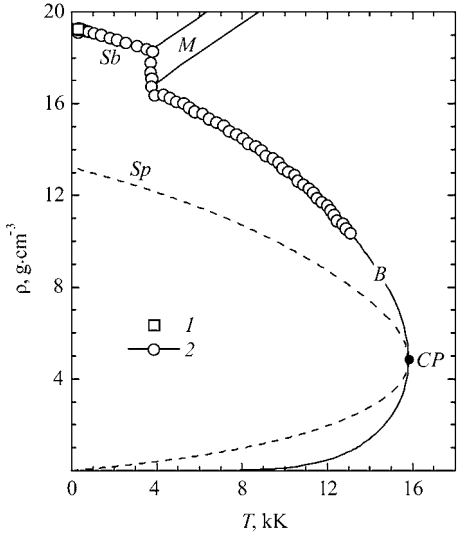

Fig. 3. Track of the wire layer with $r/a = 0.1$ in the ρ–T-plane. M is the melting region, Sb and B are the binodals of the solid-vapor and liquid-vapor transitions, Sp is the spinodal, and CP is the critical point according to the multiphase equation of state of tungsten from Ref. 10; 1, the initial state; 2, the calculated track.

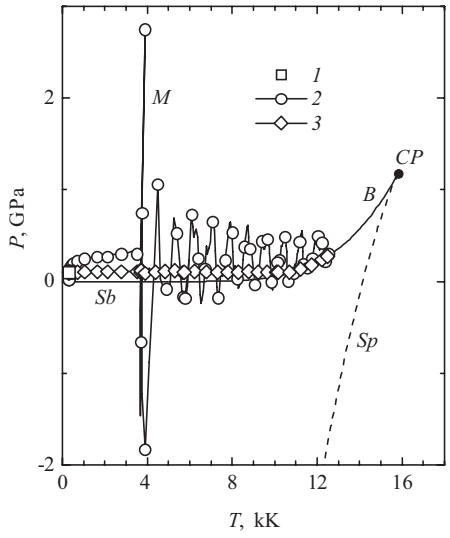

Fig. 4. Tracks of the wire layers with $r/a = 0.10$ (2) and 0.98 (3) in the P–T-plane. M, Sb, and B are the melting, sublimation, and evaporation curves, Sp is the spinodal of the liquid phase, and CP is the critical point of tungsten from Ref. 10; 1, the initial state.

completed, and increase again after the initiation of intense surface boiling. These variations are not significant and the ρ–T phase tracks of the different wire layers almost coincide with the liquid binodal curve, see Fig. 3. At the same time, the pressure varies by an order of magnitude along the wire radius, see Fig. 4. Such behavior is typical for condensed matter.

The total duration of the metastable states varies with the wire radius and the maximal total duration $\tau \sim 20$ ns corresponds to the innermost layer of the wire. According to the theory of homogeneous nucleation [14], the time of nuclei formation in the absence of external fields is $\tau_n \sim 10$ ns. In the presence of a magnetic field the nuclei formation is inhibited and τ_n increases significantly [16]. This is the reason why we have to account for the metastable states when modeling the wire heating.

The typical time of MHD-instability growth for the modeled regime of wire heating is about $\tau_{\mathrm{MHD}} \sim 2$ μs [17]. The melting transition is completed at $t \simeq 3.8$ μs. Consequently the growth of the MHD-instability and an abrupt increase of the nucleation rate are expected shortly after $t \sim 5.6$–5.8 μs. The current model is not sufficient for the simulation of later stages of these processes. Therefore, the simulation was terminated at $t \simeq 5.8$ μs.

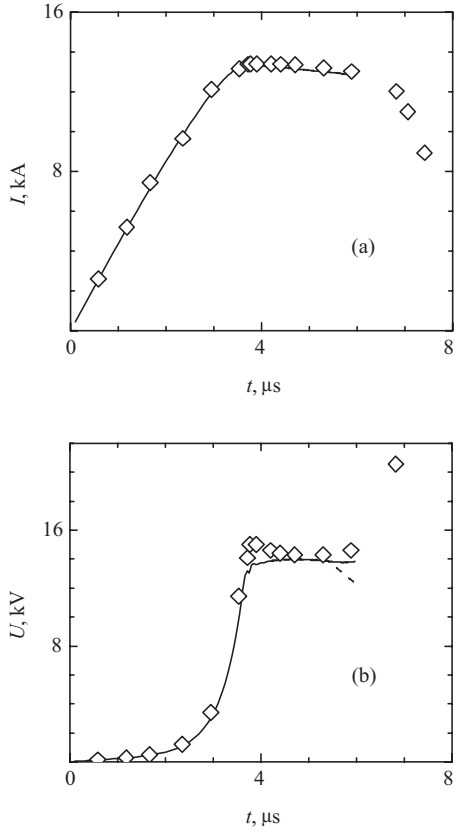

Fig. 5. Heating current (a) and voltage drop (b) across the wire as a function of time. Solid and dashed lines denote the results of the numerical calculations for the cases of EOS1 and EOS2 respectively; the open rhombs represent experimental data from Ref. 5.

The results of the simulations (for the two cases of EOS1 and EOS2) and the experimental results [5] are compared in Fig. 5. A sharp increase in the experimental voltage and the wire radius was observed in Ref. 5 after $t \simeq 6$ μs. According to the above analysis, these effects seem to be caused by the growth of MHD-instability and abrupt nuclei formation.

In the EOS1 simulation some wire layers stay in metastable states for only a short time $\tau < \tau_n$. As a result the values of the heating current and the voltage drop are almost the same in the EOS1 and EOS2 simulations until $t \simeq 5.36$ μs. After this point the saturation pressure is comparable

with the ambient pressure and here EOS2 deviates considerably from both EOS1 and the experimental results. The wire layers, starting from the outermost, enter into the two-phase liquid-vapor region. The voltage drop decreases, in disagreement with the experimental results [5].

However, the principal difference between the two simulations is exhibited by the radial pressure distribution. In contrast to EOS2, the simulation allowing for the metastable states (EOS1) yields a smooth dependence of pressure on radial position.

4. CONCLUSIONS

The melting process discussed here gives rise to alternating expansion and compression waves. These waves propagate from the outer surface to the wire axis and in the reverse direction. The density and temperature are only slightly perturbed by these waves, but the pressure varies by an order of magnitude.

Metastable states of liquid metal exist behind the front of the expansion wave. The duration of the metastable states is less than the relaxation time of matter decay into the liquid and gaseous phases, and their occurrence is an essential feature of wire self-heating. Neglecting this phenomenon seriously affects the modeling results.

In the modeled regime of wire self-heating the radial distribution functions of thermophysical parameters stay weakly inhomogeneous until the start of the intense evaporation of metal from the wire surface. Thus, the heating regime proposed in Ref. 5 and used in the current simulation is applicable for investigations of the thermophysical properties of liquid tungsten.

The simulation results appear to imply that the linear stage of MHD-instability growth and the intense nuclei formation constitute the mechanism of wire break-up during the electrical explosion.

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