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MECHANISMS OF SHOCK WAVE GENERATION AND DIFFERENT SCENARIOS OF SECOND BREAKDOWN DEVELOPMENT UPON ELECTRICAL EXPLOSION OF WIRES

V.M. Romanova[1], S.I. Tkachenko[2], D.V. Barishpoltsev[1], G.V. Ivanenkov[1], A.E. Ter-Oganesyan[1], A.R. Mingaleev[1], T.A. Shelkovenko[1] and S.A. Pikuz[1]

[1]*P.N.Lebedev Physical Institute, Moscow, Russia*

[2]*Joint Institute for High Temperatures, Russian Academy of Sciences, Moscow, Russia*

The structure of the discharge channel upon nanosecond wire explosion has been studied using laser Schlieren probing. Wires of 25 μm diameter and 12 mm length were exploded in air and vacuum by 10 kA current pulse having a 50 A/ns rise time. The development of shock waves in the air was observed. The propagation of shock waves was analyzed using a simple model of flat piston. It became possible to draw conclusions the dislocation of the flow of the main part of the current in the volume of the discharge channel. This permitted to distinguish two scenarios of development of secondary breakdown of the interelectrode gap. The scenario (shunting or internal) in accordance with which secondary breakdown develops in each concrete case depends to a large extent on the properties of the exploding conductor.

In experiments on electrical explosion of wire, it is not possible to investigate the distribution of current by direct means. Therefore, as a rule, it is implicitly assumed that until the instant of secondary breakdown current flow in the wire. Then, it is shunted along the boundary between the wire and the medium or plasma formed by matter polluting the wire surface. In wire explosions in vacuum as well as in media, after secondary breakdown the resistive deposit of energy in the dense layers of wire explosion products practically ceases. We would show that such scenario not always is valid.

Experiments were performed on a set-up having the following parameters: capacitance $C = 100$ nF, maximum charged voltage $U_0 = 20$ kV and circuit inductance $L = 340$ nH with length of interelectrode gap $l = 12$ mm and initial wire diameter $d = 25$ μm. This set of parameters secures an EEW with an initial pre-breakdown stage (resistive heating of wire and phase explosion) without development of MHD-instability. The analysis considered mainly data for explosion of tungsten and copper wire because it is known that the characteristic appearance of the discharge channel for these materials cardinally differs. A reduction of varying parameters permits to reveal the main regularities for the selected EEW conditions.

Data on the localization of the channel of current flow will help when constructing a model of secondary breakdown for EEW.

Fig. 1 shows examples of optical images when exploding 25-micron copper and tungsten wires in air. The images have been selected to demonstrate that discharge channels of exploding copper wires greatly differ from those of tungsten wires. The most noticeable difference is that when exploding a copper wire the region of dense products of explosion occupies practically all of the disturbed volume, i.e., their outer boundary, denoted by arrow 4, do not greatly lag from the position of the shock wave, denoted by arrow 1. On the other hand, when exploding a tungsten wire in air the region of dense products of explosion (arrow 2) occupies barely a third of the radius of the region disturbed by the shock wave. We analyzed the data at our disposal to show possible causes for such a significant difference.

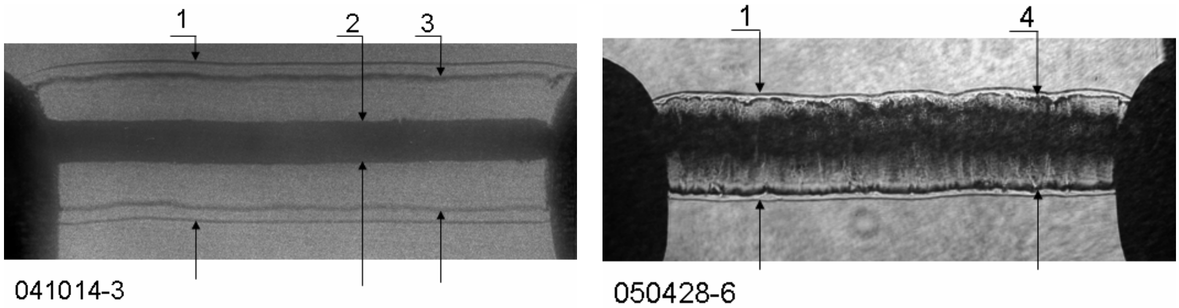

Fig. 1. Optical images of the discharge channel upon exploding a) tungsten ($t = 590$ ns) and b) copper ($t = 415$ ns) wires in air ($U_0 = 20$ kV, $l = 12$ mm, $d = 25$ μm).

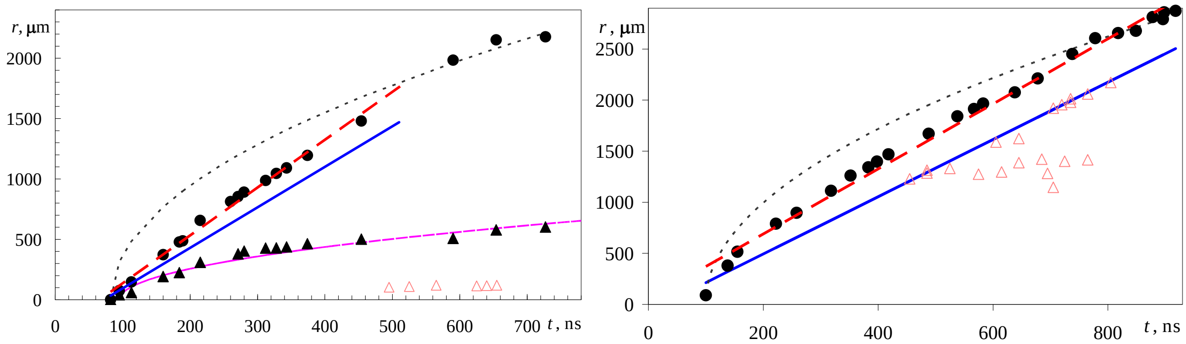

Fig. 2. Positions of the shock wave front and boundaries of the region of explosion products upon electrical explosion of wires of (a) tungsten and (b) copper. Solid circles show experimental data for positions of the SW front; solid triangles - experimental data for positions of the dense region upon electrical explosion of W wire in air; open triangles - experimental data for positions of the dense region upon electrical explosion of W and Cu wires in vacuum; solid lines denote the positions of the piston; dashed lines – linear approximations of the experimental data from the positions of the SW front; dashed-dotted lines – the parabolic time dependence for the positions of dense products; dotted lines – the parabolic time dependencies for the SW position according to the model of a powerful cylindrical explosion.

According to Fig. 2, the front velocities, D, of shock waves generating upon exploding wires in air for a long time are practically constant and significantly exceed the velocity of sound in air c_{s0}, i.e., Mach number $M = D/c_{s0} >> 1$. Thus, for an electrical explosion in air of a 25-μm tungsten wire $D = 4 \cdot 10^3$ m/s ($M \sim 11$) and for a copper wire $D = 3.2 \cdot 10^3$ m/s ($M \sim 9$).

To analyze the processes accompanying generation and propagation of SW with constant velocity, we used a well known model in which a mechanical impermeable piston moves uniformly with velocity u, generating a shock wave moving with constant front velocity D in a motionless ideal gas (non-viscous, non-conducting of heat). Without taking into account relaxation processes, the temperature behind the SW front will be $T_1 = 7.5$ and 4.8 kK, pressures $P_1 = 160$ and 102 atm and piston velocities $u_1 = 3.3$ and 2.7 km/s in our case of explosion of tungsten and copper wires, respectively. The density in both cases will be the same and if the density of a motionless medium corresponds to the density of air under normal conditions ($\rho_0 = 1.2$ kg/m^3), then $\rho_1 = 7.2$ kg/m^3.

According to interpolation of data from [1] when one takes into account all the relaxation processes (chemical reactions, dissociation, ionization and excitation of vibrations) for shock waves, the intensity of which correspond to our investigations, the width of the relaxation layer will be $\delta \sim 30$ and 120 μm upon the explosion of tungsten and copper wires, respectively. Behind the front of the wave propagating in air, as a result of all the relaxation processes requiring the expenditure of energy, there occurs an additional drop in temperature. According to interpolation of data from [1] the following values of average temperatures are obtained: $T \approx 4.9$ and 3.4 kK.

In the case of a flat piston, the parameters obtained above describe the state of the medium in the entire region between the front of the shock wave and the piston generating it. In the case of cylindrical or spherical symmetry, these parameters describe the state of the medium only immediately behind the density jump, and there is adiabatic compression of gas between the cylindrical or spherical piston and the shock wave. Let us determine the value of the piston velocity corresponding to cylindrical symmetry. One can determine the velocity of a spherical piston (u_3) as a function of SW velocity using the data given in [2]. According to these data and our experimental data for the velocities of SW front, the velocities of spherical pistons corresponding to electrical explosion of tungsten and copper wires are $u_3 = 3.7 \cdot 10^3$ and $u_3 = 3 \cdot 10^3$ m/s, respectively. Since $|u_1 - u_3| << u_1$, the value of a cylindrical piston u_2 can be determined as the average arithmetic velocity of a flat u_1 and spherical u_3 piston. Thus, the sought velocities will be $u_2 \approx 3.5 \cdot 10^3$ m/s and $2.9 \cdot 10^3$ m/s upon exploding tungsten and copper wires, respectively. In Figs. 2a and b, the positions of the pistons determined in accordance with the calculated velocities are plotted on the thick solid lines.

The image of the discharge channel presented in Fig. 2a was obtained at the instant $t \sim 590$ ns for electrical explosion of tungsten wire. In accordance with evaluations of piston velocity and the velocity of SW front known from experiment, the distance between the piston position and wave front turns out to be ~ 350 μm. Since the distance between the SW front and the boundary of the region denoted by arrow 3 corresponds to the indicated value, one can assert that in Fig. 1a there can be seen a region that plays the role of piston when generating and maintaining constant velocity of the shock wave. Therefore, in this region intense release of energy occurs. A region with such intense release of energy can be only a current-conducting region.

The image of the discharge channel for electrical explosion of copper wire presented in Fig. 1b was obtained at the instant 415 ns the size of the region between arrows 1 and 4, δ_{Cuex} ~ 200 μm, is of the order of the distance between the piston and wave front. Thus, one can conclude that, in the case of explosion of copper, its explosion products constitute the piston the displacement of which maintains constant velocity of the SW front.

Moreover, in accordance with our data, it can be stated that upon electrical explosion in vacuum the development of the secondary breakdown proceeds by analogous two scenarios. For example, in Fig. 2 there are also presented data (denoted by open triangles) about position of boundaries of the region occupied by dense products upon electrical explosion of tungsten and copper wires in vacuum. It can be seen that the distance to which the explosion products diverge in the case of EEW of copper wire in vacuum is of the same order as in air (open triangles are not far from a position of the flat piston).

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