Maximum Values of Energy Deposition during Resistive Stage and Overvoltage at Current Driven Nanosecond Wire Explosion[1]

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Abstract – The copper and tungsten wires of the diameter of *d*=25 μm were exploded in vacuum, air and water by current pulse with the rate increase of ~ 50 A/ns. Energy deposited into the wires at different stages of explosion in the media and maximum voltage reached during wire explosion was estimated from the experiments. We investigated in a wide range of initial conditions the stage of conductivity loss and processes accompanying it upon electrical explosion of single wires in nanosecond regimes.

1. Introduction

Electrical explosion of wires (EEW) in a medium is widely used in investigation of thermodynamic processes when energy is rapidly introduced into matter [1] and also in high-current pulse engineering, where electrically explosive devices operate as simple and effective current switches [2], [3]. Nevertheless, in spite of the large number of publications on this subject, many elements of the processes accompanying EEW remain unexplained. In particular, the processes influencing the sharp decrease in conductivity of products of wire explosion have not been investigated in detail. No model exists by means of which the overvoltage magnitude on duration of the current pause could be forecast. In papers [2]-[4], there are presented semiempirical formulas obtained on the basis of similitude theory when processing a large amount of experimental data on wire explosion in the milli- and microsecond ranges. Applying these formulas for explosions of copper wire in the nanosecond range, for example, yields results significantly (sometimes several times in magnitude) different from experimental data.

The present paper reports on a series of experiments on electrical explosion of Ni, Cu, W, Al and Mo wires of $d = 25$ μm with current density $j \sim 10^{12}$ A/m^2 and rate of rise $(\mathrm{d}I/\mathrm{d}t) \sim 50$ A/ns. Choice of this rate-of-rise is driven by its relevance to wire-array experiments occurring worldwide that have similar rates of rise. For example, 300-wire tungsten array on Sandia Z-machine facility typically have a ~ 50 ns linearly-rising prepulse that reaches a maximum of about 1.5 MA for the entire array, for a rate-of-rise of about 100 A/ns [5]. Similar numbers occur at Russian's Angara-5 facility [6].

2. Experimental results

The scheme of the experiment, details of the electrical measurements and calibrations are described in paper [7]. The measurements were conducted with various charged voltages on the condenser. Also varied were the length and radius of the wires, consisting of various metals, which were exploded in vacuum, air and water. The experiments were conducted on an installation having the following parameters: $C = 0.1$ μF, $U_{max} = 35$ kV and $L = 340$ nH. The interelectrode gap was varied: $l = 12$, 18 and 22 mm.

Electrical parameters of the discharge were measured using the resistive voltage monitor and the wide band coaxial shunt. Independently measured derivative of the current gave us the possibility to eliminate a contribution of inductance component of the load voltage. All the monitors were carefully calibrated and had the time resolution not worse than 1 ns. The resistance of wires, $R(t)$, and energy deposition, $w(t)$, versus time were calculated according to the following equations

$$R(t) = U_r(t)/I(t), \qquad w(t) = m^{-1}\int_0^t U_r I d\tau, \qquad (1)$$

where $U_r(t) = U(t) - L\,dI(t)/dt$ is the resistive part of the voltage.

In all known experiments on electrical explosion of wires in media (see for example [3]), one observes characteristic stages whose presence weakly depend on the material of the exploded wire and medium. The first stage or the stage of resistive heating of the wire begins at the instant of engaging discharge current. Then follows the stage of sharp increase in resistance (sometimes by an order of magnitude and more) accompanied by a current drop and the appearance of an overvoltage peak (the voltage on the wire exceeds the magnitude of the initial voltage U_0). In a number of cases, this is followed by a stage of current break (pause), when the magnitude of the

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[1] The work was supported by the RFBR 04-02-17292 and 05-02-17533

current drops to tens of amperes and the voltage is comparable to the charged. Then (with sufficient magnitude of residue voltage), shunting breakdown of the interelectrode gap occurs.

In the resistive stage, one can consider that due to the large difference in conductance of medium and metal all the energy deposits to the wire, the loss in radiation, heat exchange with the external medium, etc. being insignificant. Wire conductivity loss occurs in the process of phase explosion (see for example [8]), as a consequence of which the liquid wire core disperses (turns into mixture of drops and vapor). Therefore, compactness of the conducting condensed matter is lost, resulting in a sharp increase in wire radius and resistance of the interelectrode gap and a drop in voltage there. Experimental data on explosion of two parallel gold wires in vacuum are given in [9]. Wire explosion products pass freely through each other without interacting, which is an indication that they are of the nature of drops.

From the beginning of phase explosion, it is no longer possible on the basis of current and voltage measurement data to say unambiguously what portion of energy is deposited on heating wire matter. Current distribution at this instant becomes nonhomogeneous in thickness of core and plasma corona and energy is expended on increasing the kinetic energy of diverging explosion products, formation of shock waves in the medium and radiation in various spectral ranges.

Let us consider in more detail the stage of phase explosion, which is clearly seen on voltage and resistance time-dependences, for example in explosion of copper and nickel wire (Fig. 1). In the explosion of copper wires, the drop in voltage on the gap is twice the initial voltage on the condenser and in the explosion of nickel wires one and a half times. In the case of copper wire explosion, the melting stage and the liquid-wire heating stage are not distinguishable on the oscillograms because the increase in voltage occurs monotonically until maximum voltage is reached. The instant when the interelectrode gap begins to lose conductivity can be shown on the time dependence of current (current begins to drop sharply). In the explosion of nickel wire (Fig. 1), this instant coincides with the instant when the voltage begins to increase sharply. In the case of copper wire explosion, the beginning of a drop in current can be taken as the beginning of time reading for the stage of phase explosion and overvoltage pulse. In the investigated regimes, the resistance could increase ten times in 10–15 nanoseconds (see Table 1).

3. Overvoltage modeling

A simple model of a discharge circuit in the form of an oscillatory circuit with variable resistance was used for quantitative analysis of overvoltage pulses. To obtain rather simple relations we have not strived to find solutions of equations from the instant current is engaged and restricted ourselves to the analysis of only the discharge stage where overvoltage peak occurs. Time dependence of resistance was given by the equation: $R(t) = R_1 \exp((t-t_1)/\tau)$. The exponential dependence of resistance on time agrees quite well with obtained experimental data. For circuit parameters, corresponding to the experimental installation, the relation $R_1 C >> L/R_1$ is satisfied. Therefore, the voltage on the condenser changed quite slowly in the time characteristic for overvoltage pulse duration, so to a first approximation it may be considered constant. In this case, the differential equation $L\mathrm{d}I/\mathrm{d}t + IR(t) = U_1$ with initial conditions $R(t_1) = R_1$, $I(t_1) = I_1$ was considered and the solution obtained has the following form:

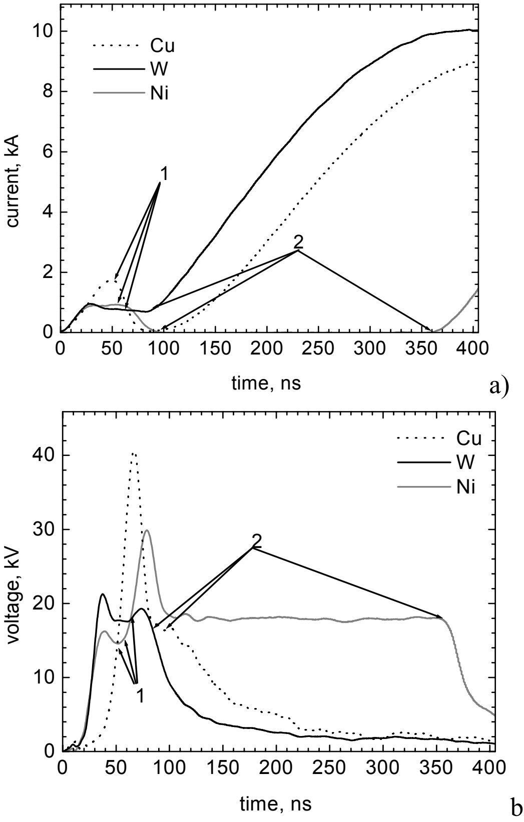

Fig. 1. Time dependence of (a) current and (b) voltage when Exploding 25-micron Copper, Nickel and Tungsten Wires ($U_0 = 20$ kV). Arrows “1” and “2” indicate the beginning of phase explosion and shunting breakdown, respectively

$$I(\xi) = \exp(\xi)\{E_0(\xi)k_2 + I_1 \exp(k_1)\}, \qquad (2)$$

here, E_0 is an integral exponential function; $\xi = -k_1 \exp((t-t_1)/\tau)$; $k_1 = R_1 \tau/L$; $k_2 = U_1 \tau/L$. For large values of overvoltage, to a first approximation one can let $U_1 = 0$. In this case, expressing voltage through current and voltage, $U(t) = R(t)\, I(t)$, one can find the maximum of this function, which is reached when $t_{max} = \tau \ln(L/\tau R_1) + t_1 = \tau_m + t_1$. The maximum value of voltage can be written in a rather simple form:

$$U_{ov} = U_1 \frac{L}{R_1 \tau} \exp\left(\frac{R_1 \tau}{L} - 1 \right), \qquad (3)$$

or excluding $\tau R_1/L$

$$\frac{U_{ov}}{U_1} = \exp(\tau_m/\tau) \exp[\exp(-\tau_m/\tau) - 1]. \qquad (4)$$

For a numerical solution of equation of an oscillatory circuit, the initial conditions were given at a certain instant of time t_1 in the following form: $R(t_1) = R_1$, $I(t_1) = I_1$ and $(dI/dt)_{t=t1}=0$. The last of these conditions is due to the fact that with the beginning of increasing resistance current begins to decrease, so that before this it has reached a local maximum.

Table 1. Typical parameters registered at the electric explosion of 25 μm wires at $U_0 = 20$ kV±10%

wire material	Cu			W		
w_s, kJ g^{-1}	5.4			4.6		
R_0, Ω	0.4			1.2		
R_m, Ω	4.4			26.9		
medium	vacuum	air	water	vacuum	air	water
w_{ph}/w_s	1.2	1.4	1.4	-	1.2	1.2
w_{ov}/w_s	1.2	2.4	2.6	0.3	1.5	1.9
w_d/w_s	1.2	3.6	3.9	0.3	1.5	2.8
U_{ov}, kV	20	44	40	23	23	22
τ_{ov}, ns	5	15	20	-	15	40
R_{max}, Ω	10	250	300	30	30	150

The designations used in Table are as follows: w_s is the sublimation energy; R_0, R_m are the wire resistance under normal conditions and at the melting temperature in liquid state; w_{ph}, w_{ov} and w_d are the energy deposited into the wire to the moment of phase explosion, maximum voltage and breakdown; U_{ov} is the voltage drop at the interelectrode gap at the moment of maximum voltage; τ_{ov} is the time of sharp rising of voltage to maximum; R_{max} is the maximum resistance of the interelectrode gap.

In Fig. 2 the results of numerical calculations are presented for time dependences of (a) voltage, and (b) resistance for various rates of resistance rise as compared with experimental data in the case of 25 μm copper wire and $U_0 = 20$ kV. The best agreement with experiment was obtained when $\tau = 8$ ns. Curves obtained for formula (3) are also shown in this figure. It can be seen that the assumption $U_1 = 0$ is quite acceptable at the initial stage of resistance growth but then introduces certain errors: a smaller voltage is reached at maximum and its drop occurs somewhat faster.

Figs 3 show the results of modeling overvoltage pulses with the data in [10]; for $\tau_m \sim 15$ ns, it was obtained that the overvoltage value presented in the paper is reached at $\tau = 11$ ns.

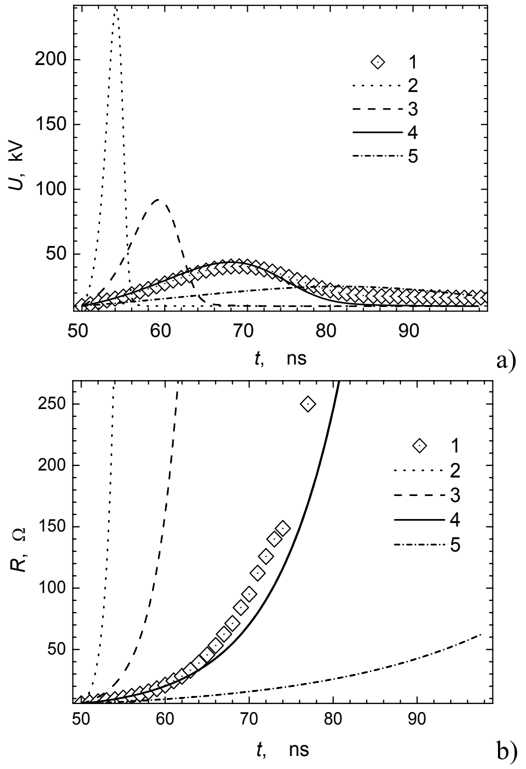

Fig. 2. Comparison of the calculated dependence of the overvoltage pulse (a) and resistance (b) at different rates of the circuit resistance growth with the experimental data: 1 – experimental data; 2-5 - $\tau = 1$, 3, 8 and 20 ns correspondingly

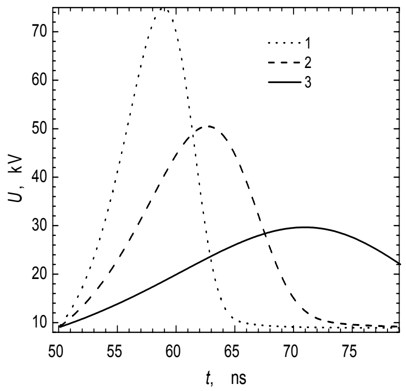

Fig. 3. Modeling of the overvoltage pulse at different rates of circuit resistance growth and inductance $L = 520$ nH for the data of [10]: 1–3 $\tau = 3$, 5 and 11 ns correspondingly. Peak voltage ~ 30 kV with 15 ns risetime was measured in [10]

It is of interest to use the obtained results to analyze data presented in [11], where it is stated that it is possible to achieve a 12-fold increase in overvoltage when exploding a 12 μm tungsten wire, 20-mm long and corresponding energy deposition of 180 eV per atom. The time to reach maximum voltage was $\tau_m = 20$ ns for $U_0 = 60$ kV and $C = 7$ nF. Since the inductance of the circuit was not given in the indicated paper, in accordance with the current rise rate the possible interval of its values was evaluated.

Time dependences of overvoltage for circuit parameters corresponding to experiment [11] are shown in Fig. 4. It can be seen that a 12-fold increase in overvoltage can be attained in characteristic time $\tau_m < 1$ ns for $L = 0.5$ μH and in 4 ns for $L = 3$ μH (initial data for current is $I_1 = 400$ A and resistance $R_1 = 250\ \Omega$, taken in accordance with the experiment in [11].

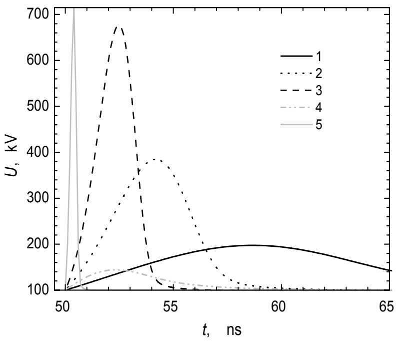

Fig. 4. Modeling of the overvoltage pulse at different rates of circuit resistance growth and its inductance for the data of [11]: 1-3 - $\tau = 7$, 2 and 0.9 ns at $L = 3$ μH; 4 and 5 - $\tau = 3$ and 0.14 ns at $L = 0.5$ μH. Peak voltage ~ 700 kV with 20 ns risetime was presented in [11]

The minimal time of circuit ruptures due to wire explosion can be evaluated by assuming that the loss of conductivity is due to the divergence of dispersed products of wire explosion. The divergence time cannot be less than a certain characteristic hydrodynamic time τ_h i.e. the time required for the passage of sound wave of wire radius at the beginning of phase explosion; and for the wire parameters used in [11], $\tau_h \sim 5$ ns. If this is so, the indicated values of overvoltage cannot be reached even theoretically. In view of this, also unattainable will be the value of energy deposited in the wire at the resistance stage, exceeding the energy of sublimation 20 times. If we use as initial data the experimental value of ~ 20 ns for time of reaching the maximum value of voltage the overvoltage value will not exceed two. Therefore, when explaining this experiment it would seem to be more reasonable to suppose some experimental errors, for example, breakdown of measurement detector.

We can conclude that according of our model there is an inconsistency between pulse width and overvoltage peak for the circuit parameters from [11]. The discharge circuit in [11] includes the transmission line between the capacitor and the load (the complete experimental setup is presented in [12]). Including of the transmission line segment into the circuit does not increase the overvoltage value. Actually, decreasing of the τ leads to decrease of the inductance of the transmission line involved into the process and the energy transmitted to the load. Therefore the overvoltage value obtained for the oscillatory circuit was overestimated compare with the overvoltage in the circuit with the transmission line segment.

More energy can indeed be deposited in a tungsten wire with polyimede-coated dielectric than in a bare conductor when exploding in vacuum, as was done in [10]. However, its magnitude did not exceed that required for complete vaporization of all of the conductor mass, to be more exact $w_d/w_s \sim 0.42$ (here, w_d is the energy deposited in the wire before shunting breakdown and w_s the sublimation energy). Moreover, in explosions in media too, we were unable to deposit in a tungsten wire more energy than $3\,w_s$ even up to shunting breakdown (see Table 1).

3. Conclusions

The experiments show that any surrounding media or dielectric coating of the wires significantly increased energy deposited to the wires in comparison with exploding of the wires in vacuum.. Numerical calculations and theoretical investigations have demonstrated that exist the unique rate of conductivity loss τ with which it is possible to get the overvoltage peak value and its timing τ_m correspond to the experimental data.

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