Experimental study of slow electrical explosion of thin titanium wires

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Abstract. The paper presents results of experimental studies of a slow (during 50÷100 μs) electric explosion of thin titanium wires in argon and air media. In that explosion wire destruction and its fragmentation are complex processes associated with thermo-mechanical stresses and electromagnetic forces. The explosion was characterized by oscillography and photography. Schlieren photos of the explosion allowed to visualize features of the wire dispersion. It was demonstrated that the nature of wire defragmentation was determined by a specific energy input $Q_R$. At $Q_R \approx 1.2÷1.5$ J/mg wire fragmentation occurred with the formation of micron particles (with a diameter of 50÷150 μm). At $Q_R \approx 2.5÷2.8$ J/mg forming of not only micron particles but also titanium nano powders due to electric arc ignition and extreme wire evaporation with the following non-equilibrium condensation. In the mode of high specific energy inputs generation of shock waves took place. The measured wave velocities reached of 700÷750 m/s. The manufactured titanium particles had purity of 96.65÷99.01 % as for raw wires.

1. Introduction
An electric explosion of thin (with a characteristic diameter $\delta \approx 20÷50$ μm) metal wires (EEW) [1] is a sharp change of conductor state in a result of an intensive energy input. The conductor overheating leads to lattice destruction, phase transitions, generation of shock waves and electromagnetic radiation. The end-products of the explosion are metal vapors and powders. A capacitor $C_0$ with auxiliary systems is used a power supply.

Slow, fast and ultrafast modes of the explosion are known [2, 3]. Those modes are differed by the characteristic time scales. The main time scales are MHD instabilities time $\tau_{MHD}$, sublimation energy input time $\tau_{\Lambda}$ and ohmic energy input from a source $\tau_{W}$. For slow mode $\tau_{MHD} \approx \delta/c_A$, where $c_A$ is the Alfven velocity and the condition of the slow explosion is

$$\tau_{MHD} < \tau_{\Lambda} < \tau_{W}$$  \hspace{1cm} (1)

For the sublimation energy input time $\tau_{\Lambda}$ it is possible to presume $\tau_{\Lambda} \approx \rho c_s^2 \sigma/j^2$, where $\rho$ is a density, $c_s$ is a sound velocity, $\sigma$ is an electrical conductivity and $j$ is a current density. For maximum current density $j \approx I_{max}/\delta^2$, where $I_{max}$ is a current amplitude. For $I_{max} = 10^2$ A and the above $\delta \tau_{MHD} \approx 0.75÷4.67$ μs and $\tau_{\Lambda} \approx 5.3÷8.3$ μs. Successful fulfillment of the condition (1) is linked with...
ohmic energy input during $\tau_W$. To estimate $\tau_W$ it is possible to write $\tau_W \approx R_{EEW} C_0$. But it is difficult to define an effective electrical resistance $R_{EEW}$ because of non-linear processes of wire transformation. An accurate estimation for $\tau_W$ it is possible with experimental data about current $I(t)$ and voltage $U(t)$ waveforms.

One of the main processes of EEW is wire fragmentation. It is a complicated process [4] linked with generation of not only electromagnetic forces [5] but also stress waves [6] in the wire. The fragmentation leads to micron particles formation [7]. On the other hand generation of plasma beads and an electric arc could lead to extreme metal evaporation and finer powder formation. Control of these processes is a way for the wire conversion to the products with a specified dispersion (e.g. to the micro- or nanopowders).

2. Experimental set
The experimental studies were carried out with the set (see figure 1).

**Figure 1.** Experimental set: 1 – exploding wire, 2 – vacuum chamber, 3 – explosion products, 4 – container, 5 – pump, 6 – capacitor, 7 – charger, 8 – electrical ballast, 9 – thyatron module, 10 – current monitor, 11 – voltage divider, 12 – oscilloscope, 13 – laser beam, 14 – Nd-YAG laser, 15 – lens, 16 – pinhole, 17 – screen, 18 – camera, 19 – interference filter, 20 – synchronizing unit, 21 – tumbler switch.
A titanium wire (1) was clutched by current leads and installed in a vacuum chamber (2). Accumulation of the products (3) occurred in a quartz tube container (4). Pumping out of the chamber was carried out by a vacuum pump (5). The studies were performed in inert argon or air atmosphere with the pressure of ≈ 1 bar. A power circuit included a pulsed capacitor \(C_0 = 0.6 \ \mu\text{F}\) (6) charged up to \(U_0 = 2.5\pm 5.0\) kV by Spellman 825–5P charger (7) through an electrical ballast \(R_b = 10\ \text{k}\Omega\) (8). The circuit commutation was fulfilled with a quick-acting thyratron module (9) (PulseTech, Ltd.). A tumbler switch (21) was used for breaking of the charge circuit until the thyratron commutation. Pearson 110 current monitor (10) and voltage dividers (11) were used for measuring of current \(I(t)\) and voltage \(U(t)\) waveforms. Tektronix TDS2024B oscilloscope (12) served for registration. The system of synchronizing of laser (14), thyratron (9) and camera (18).

The titanium wires (1) were manufactured with the procedure [8]. The initial wire resistance \(R_0\) varied from 7 to 50 Ω. Raw titanium wires and the products were characterized by SEM (Zeiss Ultra plus 55), optical microscopy and EDX (INCA Energy 350 XT). It was demonstrated that the raw wire purity is 96.65±99.01 %.

3. Results and discussions

The studies allowed to establish the main features of the temporal dynamics of current \(I(t)\), capacitor \(U_C(t)\) and wire voltage \(U_b(t)\), and conductor resistance \(R(t)\) at different modes of energy input (see figures 2 and 3). These modes were different, above all, by behavior of \(R(t)\) and \(I(t)\) and were numerically characterized by a specific energy input \(Q_r = \frac{m_0}{R} \int I(t)U_b(t)\text{d}t\). Here \(m_0\) is initial wire mass. An initial resistance \(R_0\) determined \(Q_r\) magnitude and a process of wire destruction.

The electrical explosion with the formation of micron particles occurred at \(R_0 < 20\ \text{Ω}\) and \(E_0 < 3.7\ \text{J}\). Corresponding characteristic waveforms are on figure 2. This mode was characterized by sharp (during \(\tau_{\text{max}} = 1.2\pm 3.0\ \mu\text{s}\)) increasing of \(I(t)\) and \(U_b(t)\) up to \(I_{\text{max}} \approx 100\pm 120\ \text{A}\) and \(U_{b\text{max}} \approx 2.5\pm 3.6\ \text{kV}\). Further monotonic decreasing of \(I(t)\) and \(U_b(t)\) was detected. That mode was characterized by the specific energy input of \(Q_r \approx 1.2\pm 1.5\ \text{J/mg}\).

The other mode (see figure 3) of electrical explosion with an extreme wire overheating, its evaporation and splashing was detected for \(R_0 > 20\ \text{Ω}\) and \(E_0 > 3.7\ \text{J}\). The main difference of that mode was due to non-monotonically behavior of \(R(t)\) and \(I(t)\). The presence of the second current maximum \((I_{\text{max}} \approx 40\pm 190\ \text{A})\) and the resistance minimum \((R_{\text{min}} \approx 3\pm 5\ \Omega)\) was detected. This fact was explained by the arc ignition in the vapours. The estimated specific energy input was of \(Q_r \approx 2.5\pm 2.8\ \text{J/mg}\).

Schlieren photos of electrical explosions were received for different moments of time \(t\) (see figures 4 and 6). No significant difference was found for explosions in air and argon. But the influence of the specific energy input was detected. For the mode with \(Q_r \approx 1.2\pm 1.5\ \text{J/mg}\) the wire (1) destruction (during 20±30 µs) occurred (see figure 4) with formation of the extended (with a length of 5…15 mm) wire fragments (2) and the finer fragments with the micron particles (3). The fragmentation was caused by local overheating and thermal stresses. Figure 5 presents long-exposure photography of the wire explosion. No electric arcs and shock waves were visualized.
Figure 2. Waveforms of the main features of the electrical explosion in argon at $R_0=18 \, \Omega$ and $E_0=3.7 \, J$: 1 – $I(t)$, 2 – $U_C(t)$, 3 – $U_R(t)$, and 4 – $R(t)$.

Figure 3. Waveforms of the main features of the electrical explosion in argon at $R_0=47.6 \, \Omega$ and $E_0=3.7 \, J$: 1 – $I(t)$, 2 – $U_C(t)$, 3 – $U_R(t)$, and 4 – $R(t)$. 
Figure 4. Schlieren photos of the initial wire (a) and electrical explosion process (b) at $t = 20 \mu s$ and $Q_R \approx 1.2$ J/mg: 1 – wire, 2 – wire fragments and 3 – fine fragments and particles.

Figure 5. Long-exposure photography of the wire explosion at delay time of 50 $\mu s$: 1 – wire fragments 2 – particle tracks.

For the mode with the two current maxima (at $Q_R \approx 2.5\div2.8$ J/mg) schlieren photos are presented in figure 6. It was shown that during 20–30 $\mu s$ an initial wire (1) was still visualized. That wire was a source of explosion products (2) contained titanium vapors and fine powders which overexposed the photo. The expanded products generated a shock wave (with a velocity of 700–750 m/s), which front was visualized (3).

A difficult shape of the interface between the explosion products and the compressed gas was caused by an irregularity of the wire diameter. Overheating and vaporizing of the wire took place precisely in those shape defects. At times about 50 $\mu s$ the initial wire was completely transformed into explosion products. The presence of overheated vapors in the products (2) led to the arc ignition (see figure 7) and extreme evaporation of the wire. At the latest stages (>185 $\mu s$) the shock wave already left visualization area. Explosion products gradually cooled down (4) under thermal gravity convection and turbulence effects. Metal particles condensed, scattered and settled down on the vacuum chamber elements.
Figure 6. Schlieren photos of electrical explosion process at the different times and $Q_R \approx 2.7$ J/mg: 1 – wire, 2 – explosion products, 3 – shock wave front and 4 – cooling products.

Figure 7. Long-exposure photography of the wire explosion at delay time of 50 μs: 1 – electric arc and 2 – particle tracks

SEM images of the particles produced at the different modes are shown in figure 8. For $Q_R \approx 1.2$ J/mg the products included particles with an average diameter $d_p$ is 50÷150 μm and the wire fragments. For higher $Q_R$ products included micro- and nano particles ($d_p \approx 10÷100$ nm). The presence of the nano particles was caused with non-equilibrium vapor condensation on the micro particles. EDX demonstrated that its purity is as for raw wires (96.65÷99.01 %). The energy costs are 2÷3 J/mg. It should be noted that they are significantly lower than for titanium particle manufacturing by full wire evaporation with the next condensation (=12 J/mg).
Conclusion
EEW is a complicated process associated with wire destruction, shock wave generation, radiation etc.
In the mode of a slow energy input (during 50…100 μs) wire fragmentation led to micro particles (at $Q_R \approx 1.2 \div 1.5$ J/mg) or micro particles surrounded by nano powders (at $Q_R \approx 2.5 \div 2.8$ J/mg). The energy cost is 4÷6 times less than for the available technologies. So EEW is prospective for the wire transformation into the metal powders with a specified dispersion.

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