Production of the micron powders by the electric explosion of metallic fibers

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Abstract. The paper presents the results of experimental studies of the powder production by an electric explosion of titanium fibers in argon media. The main features of energy input in the fibers and its phase transformation were established. It was found that spherical titanium particles (with a diameter of 80-170 μm) were produced at energy consumptions varied from 1.15 to 1.25 J/mg. The characteristic times of the energy input were about 60-100 μs. Reached particle purity was 97.32-99.63 % and determined only by a purity of raw fibers. This method can be useful for the production of metallic powders with low oxygen concentration for addictive manufacturing or high temperature synthesis.

1. Introduction
An electrical explosion of thin (with characteristic thickness δ≈20…50 μm) metal fiber (EEF) obtained, for example, by the method [1], is a complicated process [2]. There are different modes of electrical explosions differing by energy input into a conductor and, as a consequence, the dynamics of conductor destruction. In the mode of “slow” energy input (during the time τd) appearing magnetohydrodynamic (MHD) instabilities [3, 4] exert a great influence on the explosion dynamics. Characteristic time of MHD instabilities formation is τMHD. Those instabilities cause formation of periodic knots divided by pinches along the melting conductor. Grinding of the conductor with production of spherical melt drops (characteristic diameter dp≈100…200 μm) happens because of overheating in the pinches. That is exactly the mode of EEF that could be practically interested for producing of metal powders (for example, titanium) with a preset purity.

Energy estimations for heating, melting and full evaporation of metal fibers show that energy consumption can be of h0≈10…12 J/mg for the particles production. However the real consumptions QR could be less than h0 because of the evaporation is solely in the pinches. Thus the EEF method of production of metal particles is more prospective than the procedure of the full fiber evaporation with the next condensation.

The condition of the “slow” energy input from a charged capacity C0 into the fiber with an effective electrical resistance Req is

\[ \tau_d >> \tau_{MHD} \] (1)

Here τd ≈ Req·C0 is the time constant of the circuit. The characteristic time of the MHD instabilities in a square fiber is \( \tau_{MHD} \approx \frac{\delta^2}{2 \cdot c_A} \), where \( c_A \) is the Alfvén velocity. Then it’s possible to obtain \( \tau_{MHD} \approx \frac{\delta^2}{I_c} \cdot \rho \cdot \mu_0^{0.5} \), where \( I_c \) is a characteristic current, \( \rho \) is a density of fiber melt, and \( \mu_0 \) is magnetic constant. Estimation evidences that for titanium fibers (with \( \delta \approx 20…50 \mu m \)) at \( I_c=0.1…1.0 \) kA the
values of $\tau_{MHD}$ don’t exceed $\tau_{MHD} \approx 0.2\ldots1.4$ μs. Analytical estimation of $\tau_d$ is difficult because of a significant uncertainty in the values of $R_{eff}$. That is related to the process of the fiber destruction by the electrical explosion when there are some phase transformations, including melting, metal evaporation and vapor ionization. Accurate estimation of $\tau_d$ is possible only by experiments. Therefore the purpose of this study is to receive data about the main processes of transformation metal fibers into fine and selection of the most suitable process parameters.

2. Experimental set
The research facilities cluster “Beam-M” [5–9] was used for the explosion diagnostic. The experimental set for studying of the titanium particle production by the electric explosion of the fibers is shown in Figure 1. The studies were carried out for titanium fibers (1) with a characteristic thickness $\delta \approx 20\ldots50$ μm and a resistance $R_0 \approx 10\ldots35$ Ω. For gathering of the explosion products the fiber (1) was fastened inside a quartz tube (2). Experiments were performed in a chamber (3) in an inert argon atmosphere with pressure of 740…770 Torr.

The circuit included a capacitor $C_0 = 0.6$ μF (4) which was charged up to $U_0 = 2.5\ldots5.0$ kV by Spellman 825-5P charger (5) through an electrical ballast $R_b = 10$ kΩ (6). Circuit switching was carried out by high performance thyratron (7) (PulseTech, Ltd.) with a synchronizing signal from BNC 575 pulse generator (8).

The current $I(t)$ and voltage $U(t)$ dynamics were measured by a Rogovsky belt (9) and a voltage divider (10). The current and the voltage dependence were displayed on Tektronix TDS2024B oscilloscope (11). Features of the fiber explosion were visualized by VS-285C high-speed camera (12) connected with PC by USB interface. The exposure time was 100 ms. Quartz window (13) served for observing the radiation from exploding fibers.

![Figure 1. Experimental set: 1 – metal fiber; 2 – quartz tube; 3 – vacuum chamber; 4 – capacitor; 5 – charger; 6 – electrical ballast; 7 – thyratron; 8 – pulse generator; 9 – Rogovsky belt; 10 – voltage dividers; 11 – oscilloscope; 12 – camera; 13 – window; 14 – PC.](image-url)
The explosion products collected inside a quartz tube were characterized by SEM (Zeiss Ultra plus electron microscope), EDX (INCA Energy 350 XT) and optical microscopy.

3. Results and discussions
The studies allowed to establish the main features of the temporal dynamics of current $I(t)$, capacitor voltage $U_C(t)$ and fiber voltage $U_R(t)$, and conductor resistance $R(t)$ at different modes of energy input (see Figures 2 and 3). The dependence of these values on $Q_R$ is shown in Figures 2 and 3 too. Here $Q_R=(m_R)^{-1} \int I(t) \cdot U_R(t)dt$ is a specific energy input into titanium fiber with mass $m_R$. It was established that the features of electrical explosion of a fiber depend essentially on a voltage $U_0$. The conclusions about phase transitions in the fiber were made by a comparison between $Q_R$ and enthalpies of phase changes $h$.

The electrical explosion with the formation of micron particles occurred when the capacitor voltage was relatively small ($U_0<4$ kV). This mode (see Figure 2) was characterized by sharp (during $\tau_{max} \approx 1.2...3.0 \mu s$) increasing of $I(t)$ and $U_R(t)$ up to $I_{max} \approx 100...120$ A and $U_{R_{max}} \approx 3.2...3.5$ kV. Further monotonic decreasing of $I(t)$ and $U_R(t)$ was detected. The $R(t)$ dynamics evidenced that its first peak was related to the thyatron commutation. Further $R(t)$ was approximately constant (at the level of $R/R_0=2...4$) during $\approx 40...50 \mu s$. Thereafter, the circuit breaking and $R(t)$ increasing were detected. The $Q_R$ values were close to $h \approx 1.15...1.25$ J/mg that corresponded to the heating and partial melting of the fibers. MHD instabilities led to forming of pinches. Temperature in the pinches increased sharply that caused local evaporation and the fiber destruction with the particles forming (see Figure 4).

![Figure 2](image-url)
Figure 3. Dynamics of the main features of the electrical explosion at $R_0=19.5$ Ω and $U_0=5$ kV: 1 – $I(t)$, 2 – $U_C(t)$, 3 – $U_0(t)$, and 4 – $R(t)$.

Otherwise, the electric explosion with significant splashing and evaporation of titanium were detected when the capacitor voltage was relatively high ($U_0>4$ kV). The features of that mode are presented in Figure 3. The main difference was in the presence of the second current maximum $I_{\text{max}} \approx 50…190$ A. This fact was explained by the ignition of arc discharge. Wherein $R(t)$ decreasing up to $R/R_0 \approx 0.10…0.57$ was detected. Further the circuit breaking was occurred because of vapor leaking from the arc. This behavior of the main parameters was caused by high energy input ($Q_R \approx 2.8…3.6$ J/mg) that, in its turn, led to effective evaporation of the fiber and ionization of titanium vapors.

Figure 4. Image of the exploding fiber: 1 – overheating zone and 2 – dispersed part of fiber.
Microscopy confirmed the fact of obtaining of shiny micron metallic particles. The pieces of non-evaporated fibers with periodical solidified knots and pinches were found too (see Figure 5).

**Figure 5.** Optical image of products: titanium particles and non-evaporated pieces (indicated by arrows A) of fibers with solidified knots.

**Figure 6.** SEM images of some titanium particles.

**Table 1.** Chemical compound of the particles.

| Spectrum   | Chemical compounds, % |
|------------|------------------------|
|            | Al   | Ti     | Fe   | Total |
| Spectrum 1 | 1.67 | 98.33  | -    | 100   |
| Spectrum 2 | 1.32 | 98.68  | -    | 100   |
| Spectrum 3 | 1.63 | 97.32  | 1.05 | 100   |
| Spectrum 4 | 1.03 | 98.97  | -    | 100   |
SEM image of the some particles produced at \( U_0 = 3.5 \) kV is presented in Figure 6. The particle had spherical form with an average diameter \( d_p \) of 80...170 \( \mu \)m. Based on EDS data (some of them see in Table 1), it was shown that a purity of the particles was varied from 97.32 to 98.97 % as for the raw fibers. Aluminium and iron also were registered in the particles. Oxygen, nitrogen or the other gases were not detected.

4. Conclusion
The considered mode of the electrical explosion of metallic (including titanium) fibers is recommended for the micron \( (d_p = 80...170 \mu \text{m}) \) particles production at \( U_0 = 3.0...3.5 \) kV and \( R_0 = 10...20 \) \( \Omega \). The titanium particles purity was 97.32 to 99.63 %. The using of these titanium particles are under consideration for different applications, such as a catalyst, additive manufacturing etc.

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