Ablative Laser Processing of Metals and Dielectrics in an Electrostatic Field

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Abstract. The work considers the task of synthesis of highly dispersed spherical powder granules by laser ablation method. To improve the geometry of synthesized particles and increase the process productivity, an electrostatic system for collecting ablation products was used, which allows the formed particles to leave the area of laser irradiation without being subjected to excessive exposure to a heat source. Using an external field makes particle motion predetermined, ensuring their adhesion to the electrodes. The paper shows the experimental results on the removal of ablated particles, as well as an assessment of the effectiveness of electrostatic field for accelerating particle motion.

1. Introduction
The synthesis of fine powders by the method of fem to second laser ablation of material provides high-purity spherical particles with a controlled dispersion of sizes [1–3]. During laser ablation treatment, the resulting ablation products can make a significant contribution to the process. Ablated particles can repeatedly fall under the next laser pulse, thereby causing reflection, scattering, and absorption of a significant part of the radiation [4–6]. Laser ablation products, in addition to direct interaction with laser radiation, significantly increase the lifetime and temperature of a laser-induced plasma plume [7–9], which decrease the energy entering processing area.

As the most relevant way to solve the described problem is to use an electrostatic field to remove ablated particles. Using an electrostatic field allows ablation products to be removed from the laser radiation propagation region without deteriorating surface quality and causing dispersion of synthesized micro- and nanoparticles [10–14].

2. The study of electrostatic field influence on the mass of ablated material
The experiment was carried out in accordance with the scheme shown in figure 1, under the following conditions: the processed materials are titanium VT1-0, and aluminum oxide, pulse repetition rate – 10000 Hz, full pulse duration – 300 fs, energy of each pulse – 55–145 μJ, lens focal length – 200 mm, processing area – 8x1 mm, scanning density – 30 lines / mm, scanning speed – 10 mm / s, number of pulses – 1.2 · 10⁷ pulses, electrostatic field strength – 30 kV. The processing took place under normal conditions, argon was used as the working medium.

To study the efficiency of using the electrostatic field, a series of experiments was carried out with different energies in a laser pulse. The experiments revealed a positive effect of electrostatic field on the overall laser ablation dynamics. As can be seen from the graphs presented in figure 2, with a sequential increase in the average radiation power to 950 mW, an increase in fraction of removed material is
observed both when using an electrostatic field and without it. Further, however, for a treatment mode without an electrostatic field, a significant decrease in function is observed. In turn, for ablation in an electrostatic field at a power of 1450 mW for titanium, the efficiency increase is about 85%, for alumina 70%.

![Figure 1. Experimental setup of laser ablation processing.](image)

![Figure 2. Dependence of removed material mass on laser radiation average power in conditions of an electrostatic field (red lines) and without it (green lines). A – for alumina, B – for titanium.](image)

3. Evaluation of the effectiveness of using the electrostatic field for the removal of ablation products

When using an electrostatic field of high intensity, the mechanics of the expansion of ablated particles becomes predetermined. Ablation products, acquiring a charge, are deposited on high-voltage electrodes [15–17]. To confirm the assumption of increasing the efficiency of laser ablation, we estimate the rate of particle removal from the laser radiation propagation region. To assess, first of all, it is necessary to determine a number of conditions: the distance that a particle must travel to exit the probable region of laser radiation propagation is taken to be 0.5 mm; the time for which a particle must leave a given region...
is 100 μs (the time interval between pulses based on the laser repetition rate). Particles characteristic diameter synthesized as a result of ablation by ultrashort pulses ranges from 5 nm to 1 μm and depends on the material and the mode of exposure (figures 3, 4) [18–20].

Figure 3. The obtained nanopowder of oxide ceramics based on Al₂O₃: A – histogram of nanoparticle sizes distribution, B – SEM image of obtained nanoparticles.

Figure 4. Titanium nanopowder obtained in argon medium (granule dispersion 10-40 nm): A – histogram of nanoparticle sizes distribution, B – SEM image of obtained nanoparticles.

To determine the force necessary for a particle to overcome the region of propagation of laser radiation in the interpulse time interval, we write the following relation:

\[ F_{el} - F_{st} = m \cdot a, \]

where \( F_{el} \) – electrostatic field strength, \( F_{st} \) – Stokes drag force for spherical particles, \( m \) – particle mass, \( a \) – acceleration.

\[ F_{el} = q \cdot E \]

where \( q \) – particle charge, \( E \) – field strength.

Particle charge is determined from the relation \( q = e \cdot \varphi \), \( e \) – particle capacity, \( \varphi \) – electric potential. Particle capacity is defined as \( 4 \pi \varepsilon \varepsilon_{0} R \), \( \varepsilon \) – dielectric constant of argon (taken equal to one), \( \varepsilon_{0} = 8.85 \times 10^{-12} \text{ F/m} \) (electric constant), \( R \) – radius of a spherical particle. The potential is determined from the relation \( \varphi = U/2 \) the field strength at the interelectrode gap is 30 kV, ablated particles are located in the center of interelectrode gap, thus the voltage is 15 kV.
\[ F_{st} = 3\pi \cdot \mu \cdot D \cdot v, \]  

where \( \mu \) – dynamic viscosity coefficient, \( D \) – particle diameter, \( v \) – particle velocity.

\[ q \cdot E - 3\pi \cdot \mu \cdot D \cdot v = \frac{mdv}{dt}, \]  

\[ \frac{dv}{dt} + 3\pi \cdot \mu \cdot D \cdot \frac{v}{m} = \frac{qE}{m}. \]  

Define the constants:

\[ k_1 = \frac{3\pi \eta D}{m}, \]  

\[ k_2 = \frac{qe}{m}. \]  

Consider a first-order differential equation with respect to the function \( v(t) \) with the initial condition:

\[ \frac{dv}{dt} + k_1 v = k_2, \quad v(0) = 0. \]  

A particular solution to the problem has the following form:

\[ v(t) = \frac{k_2}{k_1} (1 - e^{-k_1 t}), \]  

\[ v(t) = \frac{qe}{3\pi \eta D} \left( 1 - \exp\left( -\frac{3\pi \eta D}{m} t \right) \right). \]

The obtained velocity distribution for spherical titanium particles depending on the size, presented in graphical form, is shown in figure 5. Similar results are obtained for alumina powders. The estimation method shows the acquisition by ablated particles of considerable speed as a result of exposure to an electrostatic field.

![Figure 5](image-url)  

*Figure 5.* Dependence of movement speed of spherical titanium particles in an electrostatic field of 30 kV on diameter.
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