Effect of the position of the sample surface relative to the focal plane of the optical system on the efficiency of the ZnS nanoparticle yield during laser ablation

© A.V. Kharkova, D.A. Kochuev, A.A. Voznesenskaya, K.S. Khorkov

Vladimir State University,
600024 Vladimir, Russia

E-mail: alenaenergie@gmail.com

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The process of synthesis of zinc sulfide nanoparticles at different positions of the treated surface relative to the focal plane of the optical system is investigating. The dependence of the ablation treatment performance is obtaining depending on the position of the focal plane of the optical system relative to the treated surface. The most effective ablation mode is observing in the case of the position of the focal plane below the treated surface of the sample, at which the mass of the removed material is 100 mg within 75 minutes, which is at least 2 times more effective than processing at the focus.

Keywords: ablation synthesis of nanoparticles, control of nanoparticle dispersion.

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1. Introduction

The use of subpicosecond laser pulses to produce nanoparticles is an effective tool. Fine-tuning of the laser ablation parameters makes it possible to effectively influence the properties of the resulting nanoparticles. The main factors influencing the properties of the obtained nanoparticles during laser ablation are the processing medium and the power density of the laser beam [1–3]. The purpose of the study is to study the synthesis of nanoparticles at different positions of the treated surface relative to the focal plane of the optical system.

2. Samples and study method

A subpicosecond laser system with a wavelength of 1030 nm, a pulse duration of 280 fs, and a pulse repetition rate of 10 kHz was used to conduct a series of experiments. CVD-ZnS was used as a sample. The experiments were carried out in an inert argon gas environment. The treatment area was 16 by 16 mm, the raster on the treated surface was formed by lines 50 mm wide, the density of the lines was 100 lines/mm, the speed of the beam was 1000 mm/s. The cycle of obtaining one sample was 75 m, which corresponds to the time to obtain a minimum sufficient amount of powder material for its study in the shortest time period. Nanoparticles were collected using an electrofilter, and deposition took place on electrodes. The study of the yield efficiency of the material was carried out by weighing the sample before and after ablation on an OHAUS ADVENTUR CRAR scale, the error did not exceed 1 %. In the process of obtaining nanoparticles, the energy in the pulse was 50 μJ, the error in changing the laser radiation power during the ablation process did not exceed 0.5 %.

The irradiation of the zinc sulfide surface with a change in position relative to the focal plane of the laser beam is schematically shown in S1, S2 and S3. The position of the surface of the irradiated sample relative to the focal plane of the lens. Figure 1 shows a diagram of femtosecond laser ablation processes, where *1* is the cloud of ablated nanoparticles, *2* is the area of laser beam exposure, *3* is the treated sample of polycrystalline zinc sulfide, *4* is the laser erosion torch and plasma channel during optical breakdown of argon, *5* is the plasma channel formed as a result of breakdown of argon and ablated nanoparticles entering it; the following designations are accepted: d is the spot diameter, E is the pulse energy. The gray rectangles indicate processes that are not characteristic of the considered state of the system, the green ones indicate the processes occurring during the treatment of the zinc sulfide surface with ultrashort laser pulses according to the treatment zones S1-S3. The position of the planes (S1, S2 and S3) differs in the position of the sample surface relative to the focal plane of the lens along the axis z. The plane S1 implies the location of the surface of the processed ZnS sample by 20 mm above the caustic area. The laser beam propagates through argon without causing plasma formation and filamentation at energies not exceeding the radiation resistance of the medium [4]. Upon reaching the ZnS surface, the laser radiation power density exceeds the ablation threshold of the material, and nanoparticles are released without optical breakdown of the medium and intense plasma formation, which eliminates significant beam shielding and the effects of the laser erosion flare on ablation products.

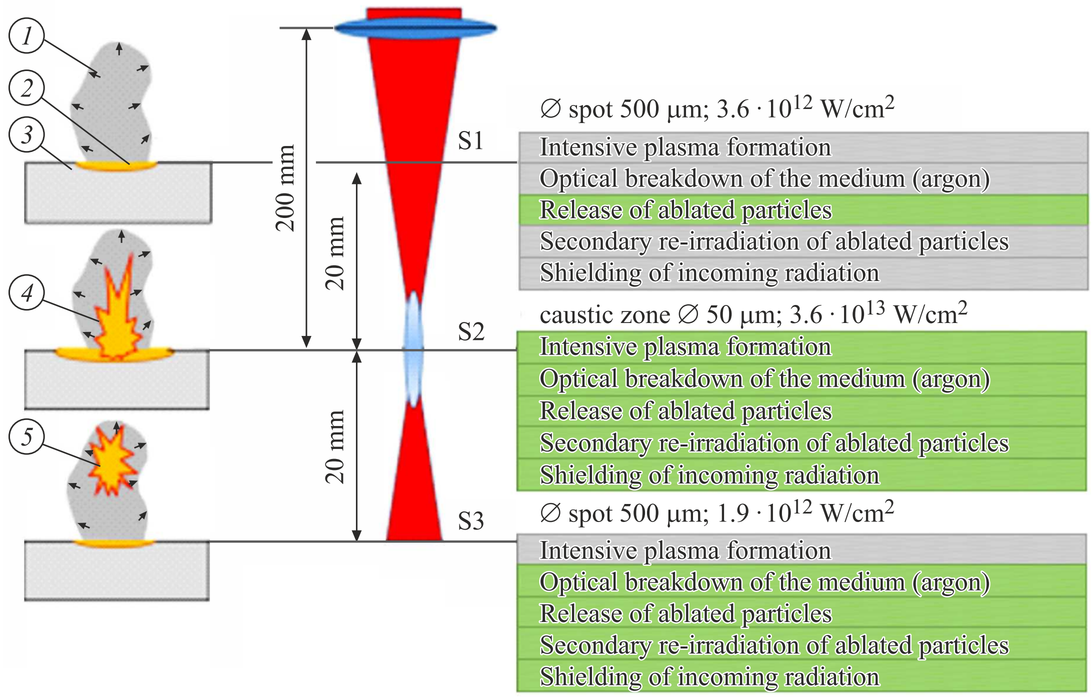

Figure 1. Diagram of the location of the surface of the irradiated sample relative to the caustics of the laser beam.

Processing in the S2 plane comprises focusing on the sample surface directly in the area of beam tightening, at this point the greatest amount of energy is concentrated, $\sim 3.4\,\mathrm{J/cm^2}$. In this position, the formation of an optical breakdown and a pronounced erosive flare are observed in the area of laser radiation exposure, which together leads to shielding of the laser beam and reduces the effectiveness of ablation. In the S3 plane, the constriction region is located above the sample surface, while optical breakdown/plasma formation takes place above the sample surface. A negative effect is a decrease in the power of laser radiation reaching the sample surface through the optical breakdown region, and pronounced overexposure occurs when ablated nanoparticles enter the caustic region. Thus, the processing conditions in the S1 region are the most suitable for increasing the efficiency of the ablation process, since they avoid radiation shielding due to plasma formation, repeated overexposure of nanoparticles, and thermal exposure to plasma. The main processes can be divided into 4 stages. The first stage corresponds to the time of photon energy transfer to the electronic subsystem, and the process of multiphoton absorption takes place [5–7]. The second stage includes the process of transferring electron energy to ions, with characteristic time scales up to 10^{-12} s [6,8]. The formation of a vapor-gas cloud and its expansion is accompanied by a phase explosion, the average stage lasts up to 10^{-10} s [5,9]. The process of condensation of molecules from a vapor-gas cloud is associated with the formation of initial particles — nuclei, which form up to 10^{-9} s. The spread of ablation products is characterized by the interaction of particles with buffer gas (collisions with subsequent loss of energy) [6,9], including when maintaining a sufficient surface temperature, aggregation of nanoparticles is possible.

Thus, depending on the position of the focus, not only the energy density values will change, but also the physical processes occurring during exposure.

3. Results and discussion

Based on the data obtained, the dependence of the amount of material removed on the focus position of the laser beam was obtained (Figure 2). The graph shown in Figure 2 was based on the data on the deleted material. Figure 2 shows a nonlinear relationship, the red dotted line marks the area corresponding to the focus position. The green triangles corresponded to the results of the first experiment, and additional series of experiments were selectively conducted to assess the reliability of the results (marked with blue diamonds and red circles). Given their overlap with each other with minimal error, it is possible to talk about the reproducibility of the experiment. The most effective ablation mode is observed when the focus of the laser radiation is in the depth of the sample. This fact can be explained as follows. When the focus is positioned above the surface of the sample, an optical breakdown of the medium occurs, a plasma flare occurs, while the energy is sufficient to start the ablation process of the material. The particles that fly off the surface actively interact with the plasma. The plasma torch shields part of the incident

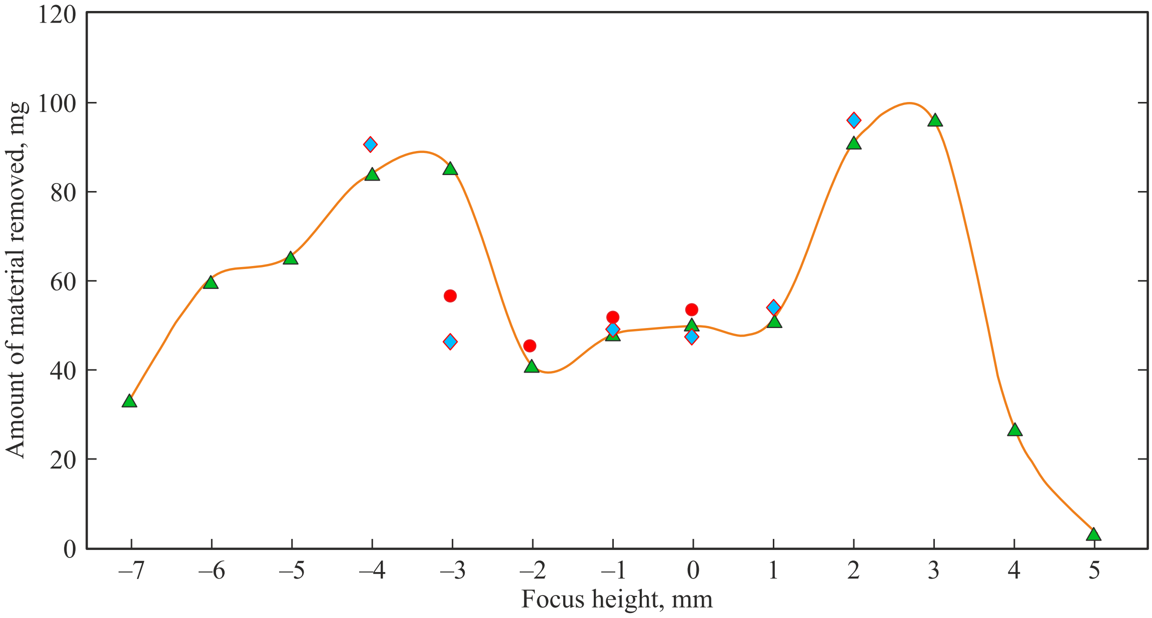

Figure 2. The dependence of the mass removed on the focus position of the laser beam during ablation of zinc sulfide.

laser radiation, which reduces the efficiency of the ablation process. The formation of a plasma flare is not observed in case of focusing in the depth of the sample, which is due to insufficient energy for the breakdown of the medium, at the same time there is enough energy for the ablation process of the material, the ejected particles freely leave the treatment area without interfering with the newly incoming laser pulse, which allows maintaining high ablation efficiency during the full treatment cycle.

The experimental results are consistent with the scientific results described in the article [3], where the authors report that the maximum ablation parameters are achieved when the sample is placed out of focus. At the same time [2], the interaction between the plasma torch and the spatial distribution of laser energy depends on the distances from the focal point to the sample surface. This distance has an important effect on the dynamics of the expansion and optical radiation of the plasma flare, which is the next stage of research in the framework of the experimental work.

4. Conclusion

Processing with power density parameters exceeding the ablation threshold and not exceeding the plasma formation threshold makes it possible to efficiently synthesize nanoparticles. In addition to eliminating the effects associated with plasma formation, an effective release of particles is carried out during the ablation process. This conclusion is confirmed by the conducted studies and is clearly presented in the form of the resulting dependence. The most effective mode is to focus the beam deep into the sample, and the mass of the material to be removed is 100 mg for 75 minutes, which is at least 2 times more efficient than in-focus processing.

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Conflict of interest

The authors declare that they have no conflict of interest.

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