Shock acceleration of particles in a laser beam

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A motion of strongly absorbing particles suspended in a liquid caused by a periodic-pulse laser beam has been studied theoretically and experimentally. A mechanism of shock acceleration of particles is proposed. It differs from the mechanism of convective entrainment. This new method makes it possible to perform patterned microscopic treatment of a target surface during bombardment by a light-controlled flux of particles with velocities $\sim 10^6$ cm/s.
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Research on the interaction of light beams with neutral microscopic particles is a comparatively new field, which grew particularly rapidly after the invention of laser oscillators and amplifiers. Various possible mechanisms for the acceleration of particles in laser beams were proposed and studied in an early work[1] and a later one.[2] Conditions for optical acceleration of particles were arranged in Ref. 3, and the particle velocities measured. The velocities turned out to be extremely high ($\sim 10^6$ cm/s for particles of micron size). However, the mechanisms which have been discussed generally describe the behavior of particles in low-density media. We believe that it is possible to realize a different mechanism, in which a laser beam causes a motion of microscopic particles suspended in a liquid which absorbs the light only poorly.

In the present study we have shown that it is possible to use periodic-pulse light to drive strongly absorbing solid particles suspended in a liquid into high-velocity motion. We have shown that the particle velocities achieved experimentally agree with velocities calculated on the basis of the mechanism proposed here. In addition, we have used this scheme to process the surface of a target with a flux of solid particles accelerated in a laser beam.

The experiments were carried out in the layout of a laser projection microscope with feedback,[4] in which the light source is a copper-vapor active medium. The light was focused by an objective onto an object and reflected. After a second passage through the objective and after amplification in the active medium, the light was reflected by a feedback mirror and reamplified in the active medium. The object was a quartz cell with a particle suspension. A wedge inserted in the resonator and the projection mirror constructed an image of the object on a screen near the focal plane of the objective. This image was enlarged and intensified. The light scattered from the suspension was collected by a separate lens for observation of the behavior of the particles on a special screen. The pulse repetition frequency of the light was 10 kHz, and the pulse length was 10–20 ns. The strongly absorbing particles were powder grains of boron carbide (B_4C) and iron carbonyl. The size of the particles was 1–10 μm, and their concentration was $\sim 10^5$ mm^{-3}. The cell was 0.1 mm thick. A mask which formed a specified distribution of the

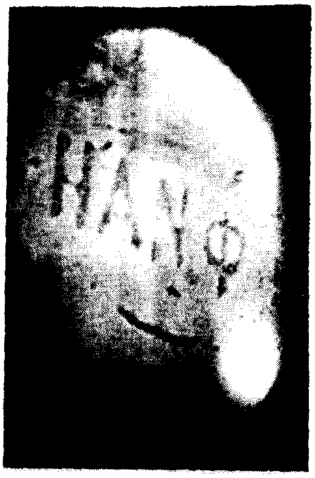

FIG. 1.

intensity of the applied beam was deposited on the feedback mirror. At a peak power density $I \sim 10^9$ W/cm^2, an intense motion of the particles along the beam, directed toward the back wall of the cell, was observed on the screen. The light was then focused onto this back wall. The particles striking the quartz wall destroyed the surface layer, and some of them were implanted in the glass at a depth up to 8–10 μm. The configuration of the treated region of the glass corresponded precisely to the mask at the mirror. Figure 1 is a photograph of the treated region of the glass (the thickness of the lines forming the letters is ~ 10 μm). Examination of the damaged regions of the glass under a microscope revealed that the track left by an individual particle was a crater with the shape characteristic of the crater resulting from the interaction of a meteorite with the surface of a planet. Knowing the depth to which a particle penetrates, d, we can then estimate the initial velocity of the particle:[5]

$$v_0 \simeq \sqrt{\frac{\pi d^3 H \epsilon \rho}{6m}},$$

where ϵ is the specific heat of vaporization of the target material, ρ is the density of the target material, m is the mass of the incident particle, and $H \simeq 4-5$ is a numerical factor. We find $v_0 \sim 10^6$ cm/s.

Let us examine the interaction of a focused beam with a particle (Fe) with a radius ≤ 2 μm. Beginning at $I \sim 5 \times 10^8$ W/cm^2, the heated material (Fe) undergoes direct sublimation in water.[6] The heating zone, which forms initially at the surface of the particle, moves off into the water as the vapor expands. Over a pulse length $\tau_p \sim 10^{-8}$ s, an energy $E \sim 8 \times 10^{-6}$ J is released near the particle. This energy is sufficient to vaporize water with a volume $V \sim 10^{-9}$ cm^3. Actually, this energy is released in a volume $V_0 \sim a^2 l$, where a is the particle radius, and l is a characteristic thickness of the heating by conduction: $l \sim \sqrt{\chi t}$, where χ is the thermal conductivity of water. We find $V_0 \lesssim 10^{-11}$ cm$^3 \ll V$. The temperature of the zone is[6] $T \sim 10^4$ K. As a result, there is an explosion in the adjacent region, and a shock wave forms. We can estimate the radius of the shock wave from the solution of the point-explosion problem:[7]

$$R \simeq \left(\frac{E}{\rho_{H_2O}}\right)^{1/5} t^{2/5} \simeq 2\times10^{-3}\ \text{cm},$$

for a time $t=10^{-7.5}$ s and a wave velocity

$$\frac{dR}{dt}\sim\frac{2}{5}\left(\frac{E}{\rho_{H_2O}}\right)^{1/2} R^{-3/2}\sim10^{5}\ \text{cm/s}.$$

Assuming that vapor forms behind the shock front and that the boundary of the displaced water moves at the same velocity, we find the mass of this water and the momentum transferred to the object:

$$P\sim m\,\frac{dR}{dt}.$$

We can find the velocity of the particle at the end of the pulse from the equation of motion, in which we write the drag as in the case of a sphere which is undergoing vibrational–translational motion at a high frequency $\omega\sim1/\tau_p$ in a liquid (Ref. 8):

$$v_{\max}\sim\frac{F_{ex}}{3\pi a^2\sqrt{2\eta\rho_{H_2O}\omega}}\left(1-e^{-\tau_p/\tau}\right),\quad \text{where}\quad \tau\sim\frac{2a(2\rho_{Fe}+\rho_{H_2O})}{9\sqrt{2\eta\rho_{H_2O}\omega}}.$$

Here $F_{ex}=P/\tau_p$ is the external force acting on the particle, and η and ρ_{H_2O} are respectively the viscosity and density of water. We thus estimate the velocity to be $v_{\max}\sim10^6$cm/s under our conditions. This figure agrees in order of magnitude with the velocities found experimentally.

The mechanism proposed here differs from the mechanism of convective entrainment, which involves simple heating and motion of the medium, which is heated from the surface of the absorbing particle. The mechanism proposed here makes it possible not only to process various materials but also to separate mixtures of different particles in a liquid, e.g., as a suspension of these particles is pumped through gaps.

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