Light-induced motion of particles in suspension

G.V. Grigoryan, S.D. Zakharov, M.A. Kazaryan, N.P. Korotkov, S.E. Skipetrov, and A.G. Tamanyan

P.N. Lebedev Physical Institute, Russian Academy of Sciences, Moscow

Received February 21, 2000

We consider a simplified geometry of experiments on acceleration of microparticles by laser radiation. It is shown that the effects of light-induced motion of particles should be taken into account in calculations of the processes of multiple scattering of light in random media.

Introduction

The feasibility of light-induced acceleration of charged and polarizable particles was mentioned for the first time in Ref. 1. With the advent of new high-power lasers operating in cw or pulsed modes, the spectrum of possible methods of acceleration was significantly expanded.[2,3] The calculations performed for mean power of more than 1 W in the visible spectral region and diffraction-limited laser beams showed that acceleration of microparticles at the beam focus due to light pressure can exceed the acceleration of free-fall by a factor of tens of thousands.

Far higher acceleration can be achieved as laser radiation interacts with absorbing microparticles.[4] With the development of lasers having high peak and mean power (repetitively pulsed lasers), new particle acceleration mechanisms caused by microexplosions of adjacent regions and accompanied by generation of powerful acoustic shock waves were considered.[5] In combination with the intracavity processing of materials in active optical systems,[6] repetitively pulsed acceleration of microparticles allowed a new technology − decorative processing of materials using accelerated microparticles − to be developed.

Method of intracavity processing of materials in active optical system

Figure 1 shows possible geometry of an experimental setup.

Let us describe briefly the intracavity processing of materials by a laser beam, at which a cell with particle suspension contains the object of processing. This method is currently used for processing materials by laser beams of almost any configuration. As is seen from the figure, this system operates as follows: an amplified spontaneous radiation emitted by the laser active medium *6* passes through the optical system *4* and illuminates the material to be processed (object) *2*. The light scattered and reflected by the object is collected by the optical system *4* into a beam, which bears the information about the object, and then this beam is amplified in the active medium *6*. As the beam leaves the amplifier, a part of it is reflected by the beam-splitter *7* and reflector *13*. This part creates a magnified image of the object *2* on the screen *14*. The other part of the beam passes through the beam-splitter *7*, optical gate *9*, and mask *10* and is reflected from the feedback mirror *11*. After amplification in the active medium *6*, this creates the amplified, in brightness, distribution of the light flux corresponding to the mask configuration on the object surface. The beam power is determined by measuring the power of the beam portion reflected from the beam-splitter *5* toward the wattmeter 15. In such geometry, the object 2 and the mirror 11 comprise a self-matched cavity. Rays from different points of the object and the mask are mixed in the active medium, and their interaction provides for efficient conversion of the mean power into the radiation reflected from open areas of the mirror *11* (Refs. 7 and 8). The specific power on the object more than M^2 times exceeds the power on the open areas (M is the magnification factor of the optical system), and this can cause melting, evaporation, and structure transformations of the illuminated part of the object *2*. At the same time, the opaque parts of the mask are almost free of load. Consequently, diaphragms made of black paper, fabric, etc. can be used in experiments, and they are not deformed or destroyed in the process.

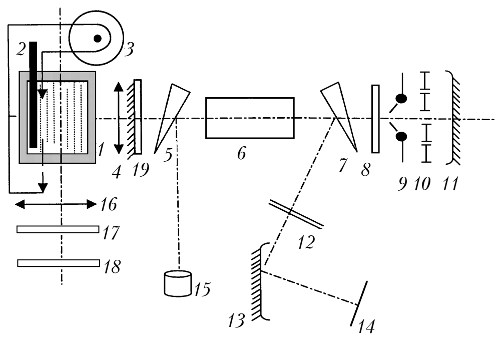

Fig. 1. Modernized experimental setup for processing materials by microparticles accelerated by laser radiation: cell with suspension *1*, processed material *2*, suspension flow-through *3*, optical focusing system *4*, beam-splitters *5* and *7*, laser active medium *6*, spectral filters *8*, *12*, and *17*, optical gate *9*, mask *10*, concave reflecting mirrors *11* and *13*, screen for visual observation *14* and *18*, wattmeter *15*, projection objective *16*, partially reflecting mirror of the cavity *19*.

0235-6880/00/05 456-03 $02.00

In these experiments, the dimensions of the obtained zones from 0.3 to 5 μm, which are comparable with the minimum permissible dimensions of the used optics, were calculated by the Rayleigh criterion. This method is of significance in recording bulky information at the laser pulse repetition rate of 10^4 Hz and pulse duration of 10^{-8} s.

Collective motion of particles in suspension

If a cell with suspension *1* is used as an object in the setup shown in Fig. 1, it could be expected that particles of the suspension affect the formation of the light field and radiation, in its turn, will cause motion of the particles. In Ref. 9 it was shown that erythrocytes (diameter of ~ 5 μm, mass of 10^{-10} g) chaotically distributed about the center of the suspension, which was initially at rest, migrated into the region of the central light spot after the turn-on of the cavity. Cells at the center broke down and form conglomerates with the size five to ten times exceeding the size of individual cells. Motion of all the particles in the illuminated area proved to be light-induced within 20 s after the formation of conglomerates. The motion was strictly ordered and had a cyclic character. Under certain conditions, conglomerates accumulated near the surface of the object *2* and colliding particles could not leave the central region. Conglomerates grew up to the size of the illuminated surface. The speed of erythrocytes was estimated as 1 cm/s.

When a suspension with transparent particles was used, the following process was observed. Particles distributed around the center migrated into the region of the central light spot and were trapped there due to light pressure. The character of this specific light-dynamic effect apparently differs from a simple capture of particles into a light-induced trap,[10] which was theoretically described in Refs. 11 and 12.

Laser acceleration of light-absorbing particles

There exist several mechanisms responsible for acceleration of microparticles: heating and motion of a medium (convective motion), heating of the surface of an absorbing particle (radiometric motion), pressure at particle evaporation (reaction pressure).

If the absorption coefficient is high, all these mechanisms can be far more significant than the light pressure. For example, according to Ref. 4, the reactive pressure can be estimated as

$$p_r \sim M v_f \sim I v / [\lambda + (l/2)\, v^2] \approx$$

$$\approx (p_l\, c v)\, [\lambda + (l/2)\, v^2],$$

where λ is the specific heat of evaporation; v_f is the material outflow rate;

$$p_r / p_l \approx cv\, [\lambda + (l/2)\, v^2] \sim cv/\lambda \sim 10^4.$$

This pressure can be used, in particular, to accelerate microparticles[4,13] up to 10^6–10^8 cm/s to provide modeling of artificial fast moving particles like micrometeorites, which would provide for high local concentrations of energy in the processes of particle collisions with the surface and with each other.

The setup shown in Fig. 1 employs the so-called shock-wave acceleration in the field of laser radiation.[5] Particles with the size from 1 to 10 μm at the concentration of 10^5 mm^{-3} were used as strongly absorbing particles. At the power density $I \sim 10^9$ W/cm^2, intense motion of particles along the beam was observed on the screen *18*. The particles colliding with the quartz plate (object *2*) destroyed its surface layer and some of them penetrated at the depth of 8–10 μm. The configuration of the processed area corresponded to the shape of the mask on the mirror. Given the penetration depth d, we can calculate the initial speed

$$v \approx \sqrt{\pi d^3 H \varepsilon \rho / 6m}\ ,$$

where ε is the specific heat of evaporation; ρ is the density; m is the mass; $H \approx 4$–5 is the constant factor. Thus, the speed was estimated as $v_0 \sim 10^6$ cm/s.

The behavior of particles in dense random media was studied in Refs. 14–16 in the case that the light-induced flow of accelerated particles moved inside a cylindrical area. The technique of measurement of the flow speed was based on the use of the autocorrelation function of the scattered light.

Multiple scattering of light

Multiple scattering of light is a subject of numerous studies for many years. Our recent studies showed the importance of consideration of the light interaction with a matter in calculations of statistical properties of multiple scattering. In particular, acceleration of microparticles at multiple scattering under the exposure to radiation was considered, which affects the temporal correlation function of the scattered radiation.

Our calculations demonstrated that the described phenomenon must have two important consequences: (a) under some specific conditions the ponderomotive action should be taken into account when interpreting experimental results and (b) statistical analysis of multiple scattering could serve a tool for studying the phenomenon of laser acceleration of particles in high-concentration suspensions. The developed theoretical model is based on the diffusion approximation and can be successfully used for the cases (a) and (b). Our results indicate that the considered technique can be useful in practice, for example, when studying propagation of high-power laser pulses through atmospheric clouds and water media with microinclusions, in solution of the problem of laser processing of materials, and in medical applications of lasers.

References

1. G.A. Askaryan, Zh. Eksp. Teor. Fiz. **42**, No. 6, 1567–1570 (1962).
2. A. Ashkin, Phys. Rev. Lett. **24**, 156 (1970).
3. A. Ashkin, Phys. Rev. Lett. **25**, 1321 (1970).
4. G.A. Askaryan and E.M. Moroz, Zh. Eksp. Teor. Fiz. **43**, 2319 (1962); **45**, 258 (1967).
5. S.D. Zakharov, M.A. Kazaryan, and N.P. Korotkov, JETP Lett. **60**, No. 5, 317–319 (1994).
6. K.L. Zemskov, M.A. Kazaryan, G.G. Petrash, and A.S. Skropchenko, in: *Brief Communications on Physics* (Physical Institute of the Academy of Sciences, 1988), No. 5, p. 30.
7. K.L. Zemskov, M.A. Kazaryan, V.M. Matveev, G.G. Petrash, and A.S. Skipchenko, Kvant. Elektron. **10**, 336 (1983).
8. M.A. Kazaryan, V.M. Matveev, and G.G. Petrash, Kvant. Elektron. **11**, 932 (1984).
9. R.V. Ambartsumyan, S.D. Zakharov, K.I. Zemskov, M.A. Kazaryan, N.P. Korotkov, and G.G. Petrash, in: *Brief Communications on Physics* (Physical Institute of the Academy of Sciences, 1988), No. 8, p. 35.
10. A. Ashkin, J.M. Dziedzic, and T. Yamane, Nature **330**, 769 (1987).
11. G.A. Askaryan, Usp. Fiz. Nauk **110**, No. 1, 115–116 (1973).
12. A. Ashkin et al., Opt. Lett. **11**, 288 (1986).
13. G.A. Askarian, M.S. Rabinovich, M.M. Savehenko, V.K. Stepanov, and V.B. Studenov, JETP Lett. **5**, 258 (1967).
14. S.E. Skipetrov, S.S. Chesnokov, S.D. Zakharov, M.A. Kazaryan, N.P. Korotkov, et al., Kvant. Elektron. **25**, No. 5, 434–438 (1998).
15. S.E. Skipetrov, S.S. Chesnokov, S.D. Zakharov, M.A. Kazaryan, and V.A. Shcheglov, JETP Lett. **67**, No. 9, 635–639 (1998).
16. S.E. Skipetrov, S.D. Zakharov, M.A. Kazaryan, and N.P. Korotkov, J. of Moscow Physical Society **7**, 411–421 (1997).