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HEATING OF METALLIZED PARTICLES BY HIGH-INTENSITY LASER RADIATION

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Regularities of heating of metallized particles having a polyethylene core and an aluminum shell by high-intensity radiation at $\lambda = 10.6$ μm to the onset of core melting are discussed. It is shown that the particle size, shell thickness, and radiation intensity affect the degree of heating nonuniformity and the time for attaining the melting point of polyethylene.

Two-layer spherical particles, including those with metallic coatings, are formed and used in various technologies [1, 2]. The specific features of absorption and internal optical fields in metallized particles are discussed in [3]. Heating of such particles by high-intensity laser radiation (HILR) has not been investigated yet. Since this problem is of great significance for development of new technologies of laser deposition of various coatings, we have investigated the heating of metallized particles exposed to HILR with a wavelength of 10.6 μm.

For definiteness, we have assumed that the particles have an aluminum shell and their core consists of polyethylene. Since the melting point of aluminum, $T_{mel} = 933$ K, is much higher than that of polyethylene, $T_{mel} = 411$ K, in the first stage we worked with the temperature range $293 < T < 411$ K. The radii of the irradiated particles have been varied from 1 to 15 μm.

The radiation absorbed by polyethylene particles coated with an aluminum shell may be described by the model of a two-layer spherical particle with a concentric core. The energy distribution inside these particles is calculated using the theory of diffraction of electromagnetic radiation on a multilayer sphere with the algorithms given in [4, 5]. The distribution of the absorbed energy Q in a particle volume is characterized by the relation

$$Q/I = 4\pi n\kappa B/\lambda\,, \tag{1}$$

where $B = (E \cdot E^*)/|E_0|^2$. We have used the following refractive indices at room temperature: $m = 1.52 - i0$ for polyethylene [6], $m = 30.6 - i64.8$ for aluminum [7].

It should be noted that the energy distribution inside a spherical particle possesses cylindrical symmetry relative to the diameter coinciding with the direction of propagation of incident radiation (this diameter is called the principal one). Therefore it is sufficient to consider the energy distribution only within the angle range $0 \le \theta \le 180^\circ$. At $180 \le \theta \le 360^\circ$ the distribution is symmetric. We have calculated the heat release only for the shell of a two-layer particle since the particle core does not absorb radiation of the specified wavelength. Heat release in the two-layer particle shell is highly nonuniform. The maximum nonuniformity in the propagation of the absorbed energy is observed in the direction of the propagation of the incident radiation ($\theta = 0 - 180^\circ$) (Fig. 1). The highest peak of the absorbed energy is located on the illuminated surface of the particle in a small region near the direction $\theta = 0^\circ$. At a distance from the particle surface toward the center the amount of the absorbed energy decreases sharply in both the shadow and illuminated parts of the shell.

The value of the heat release in the aluminum shell depends on its thickness $\Delta R = R_2 - R_1$. With a decrease in ΔR, starting from some value, the amount of the absorbed energy in the shell increases. The shell thickness depends on the radius of the particle. In the case of $R_2 = 1$ μm, $\Delta R = 0.03$ μm, and at $R_2 = 5$ μm, $\Delta R = 0.05$ μm. For particles with $R_2 = 5$ μm, with a decrease in the shell thickness from $\Delta R = 0.05 \mu m$ to $\Delta R = 0.02$ μm the maximum value of the absorbed energy increases by a factor of 2.3. This is due to the fact that most of the energy

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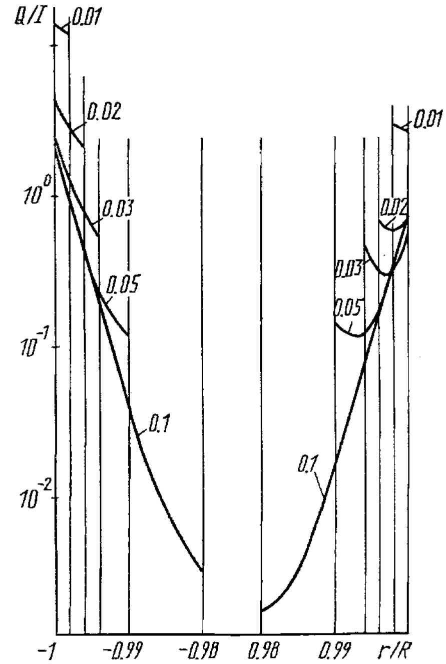

Fig. 1. Distribution of absorbed energy along the principal diameter inside shells of metallized particles for $R_2 = 5$ μm; figures at the curves, shell thicknesses mm); vertical lines, boundaries between cores and shells. Q/I, cm^{-1}.

is absorbed by a thin layer near the shell surface. When the shell thickness decreases, the energy begins to penetrate into the core, thus increasing absorption in the shell due to multiple passage of radiation through it.

We consider the model problem on a two-layer spherical particle heated by monochromatic unpolarized radiation, taking into account that the thermophysical and optical characteristics of the core and the shell depend on the temperature.

In the general case, the temperature distribution in the core and the shell of two-layer particles is described by a system of equations with the corresponding boundary and initial conditions:

$$c_1 \rho_1 \frac{\partial T_1}{\partial t} = \frac{1}{r^2} \frac{\partial}{\partial r} \left(\lambda_1 r^2 \frac{\partial T_1}{\partial r} \right) + \frac{1}{r^2 \sin\theta} \frac{\partial}{\partial \theta} \left(\lambda_1 \sin\theta \frac{\partial T_1}{\partial \theta} \right) + Q_1 (r, \theta, T_1, n_1, \kappa_1); \quad (2)$$

$$c_2 \rho_2 \frac{\partial T_2}{\partial t} = \frac{1}{r^2} \frac{\partial}{\partial r} \left(\lambda_2 r^2 \frac{\partial T_2}{\partial r} \right) + \frac{1}{r^2 \sin\theta} \frac{\partial}{\partial \theta} \left(\lambda_2 \sin\theta \frac{\partial T_2}{\partial \theta} \right) + Q_2 (r, \theta, T_2, n_2, \kappa_2); \quad (3)$$

$$| T_1 (0, \theta, t) | < \infty ; \quad (4)$$

$$T_1 (R_1, \theta, t) = T_2 (R_1, \theta, t); \quad (5)$$

$$\lambda_1 (T_1) \frac{\partial T_1 (R_1, \theta, t)}{\partial r} = \lambda_2 (T_2) \frac{\partial T_2 (R_1, \theta, t)}{\partial r}; \quad (6)$$

$$-\lambda_2 (T_2) \frac{\partial T_2 (R_2, \theta, t)}{\partial r} = \alpha \left[T_2 (R_2, \theta, t) - T_m \right]; \quad (7)$$

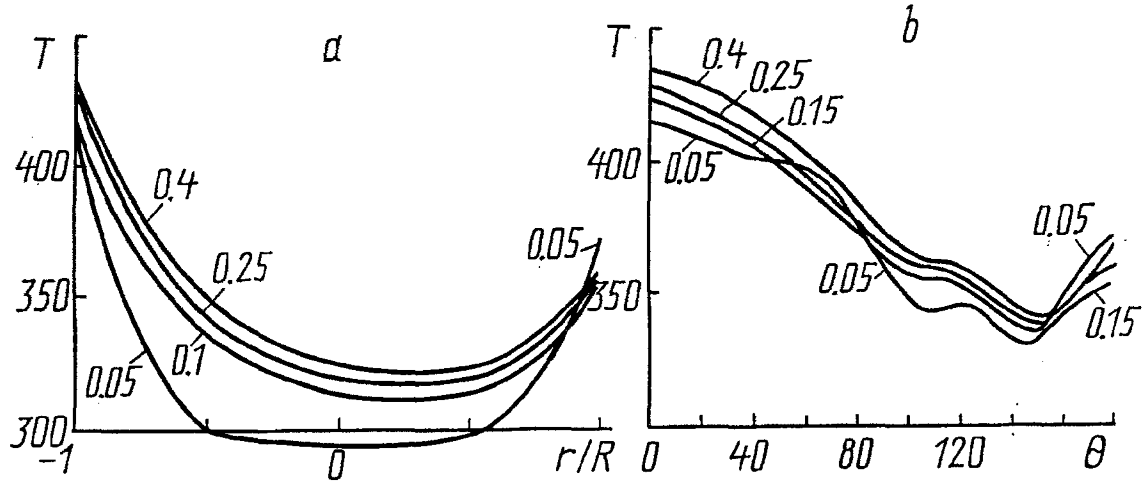

Fig. 2. Temperature distribution inside two-layer particles at the moment of core melting for different shell thicknesses in the direction of propagation of incident radiation propagation ($\theta = 0-180^0$) (a) and over a particle surface (b); $R_2 = 5\ \mu$m, $I = 5\cdot 10^7$ W/cm^2, figures at the curves are shell thicknesses (μm), T, K; θ, deg.

$$\left.\frac{\partial T_1}{\partial \theta}\right|_{\theta=0} = \left.\frac{\partial T_1}{\partial \theta}\right|_{\theta=\pi} = 0\,, \quad \left.\frac{\partial T_2}{\partial \theta}\right|_{\theta=0} = \left.\frac{\partial T_2}{\partial \theta}\right|_{\theta=\pi} = 0\,; \tag{8}$$

$$T_1\,(r\,,\,\theta\,,\,0) = T_{10}\,; \quad T_2\,(r\,,\,\theta\,,\,0) = T_{20}\,. \tag{9}$$

The index 1 indicates quantities pertaining to the core ($0 \le r \le R_1$), and the index 2 indicates the shell ($R_1 \le r \le R_2$).

Nonlinear system of equations (2), (3) with conditions (4)-(9) may be solved only by numerical methods. We constructed an absolutely stable locally one-dimensional implicit scheme on a nonuniform space-time grid, which is solved by an iterative technique [8]. The iteration cycle continues until the sought solution acquires the prescribed accuracy. In each iteration process the system is solved by the elimination method.

In the present problem, the temperature range inside a particle is not great (from 293 to 411 K) but allowing for a strong temperature effect we introduced the current values of thermal conductivity $\lambda_1(T_1)$ and $\lambda_2(T_2)$, heat capacity $c_1(T_1)$ and $c_2(T_2)$, and density $\rho_1(T_1)$ and $\rho_2(T_2)$ of aluminum and polyethylene in correspondence with the temperature values at each node of the grid for each time step using approximation formulas constructed from data of [9, 10]. The function of heat sources $Q_2(r, \theta, T, n_2, \kappa_2)$ was recalculated with account for the dependences of the real n_2 and imaginary κ_2 parts of the refractive index of aluminum on the temperature averaged over the shell volume. For aluminum, the temperature dependences of the refractive and absorptive indices were obtained from data of [7]: $n = 1.5\cdot 10^5 T^{-1.5}$, $\kappa = 3.9\cdot 10^4 T^{-1.125}$. In the present problem Q_1 was equal to zero. Temperature values at the nodes were printed out when the melting point of polyethylene was $T_{\rm mel} = 411$ K at one or more nodes of the grid of the two-layer particle core. But in the shell, the temperature could be higher.

For the considered range of sizes of the particles their heating depends strongly on the particle radius, thickness of its shell, and intensity of incident radiation. As one might expect, the heating nonuniformity is maximum in the direction $\theta = 0-180^0$ of propagation of the incident radiation. The maximum-heating region lies in the illuminated hemisphere of the particle within $0 \le \theta \le 20^o$ (Fig. 2). As the distance from the particle surface toward its center increases, the heating temperature decreases, and then it increases again as the hemisphere inshadow is approached (the region of angles $\theta > 170^0$). The minimum-heating region lies at the center of the particle. When fine particles ($R_2 < 2\ \mu m$) are heated, the nonuniformity of heating decreases strongly with increase in the thickness of the two-layer particle shell. For instance, for $R_2 = 1\ \mu$m with $\Delta R = 0.01\ \mu$m the maximum temperature difference is $\Delta T = T_{\max} - T_{\min} = 105$ K, and with $\Delta R = 0.1\ \mu$m, $\Delta T = 30$ K. For coarse particles (R_2

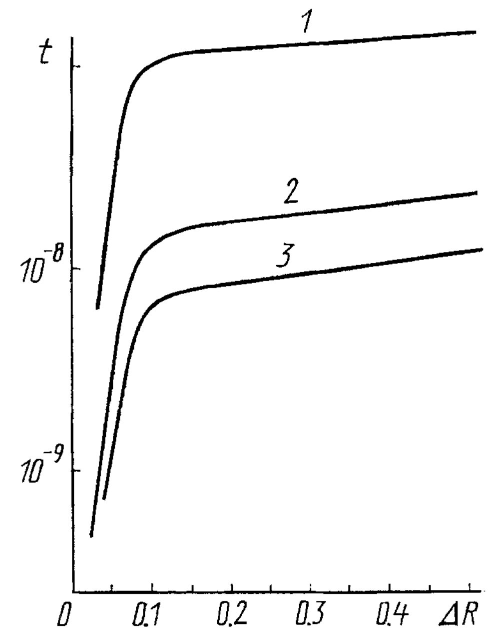

Fig.3. Heating time for metallized particles to the onset of core melting versus thickness of aluminum shells with $R_2 = 5\ \mu$m: 1, $I = 10^7$ W/cm^2; 2, $5 \cdot 10^7$; 3, 10^8. t, sec; ΔR, μm.

$= 5\ \mu$m, Fig. 2), the heating nonuniformity depends weakly on the shell thickness and is approximately 110–125 K for different ΔR. On passing to a region of even higher values of R_2 ($R_2 \geq 10\ \mu$m) ΔT increases with the thickness of the two-layer particle shell due to the insignificant change in the heating temperature at the center and its substantial increase on the particle surface with an increase in ΔR. When the shell thickness increases, the temperature, as a rule, increases at almost all points inside the particle. The increase in the absorbed energy with a decrease in the shell thickness (Fig. 1) results in more rapid heating of the particle core up to the melting point (Fig. 3).

It can be inferred from the curves in Fig. 3 that in the shell thickness range considered the heating time at first increases sharply up to thicknesses starting from which the heat release in the shell is weakly dependent on its thickness. Then the heating time increases insignificantly. A tenfold increase in the incident radiation, i.e., from $I = 10^7$ W/cm^2 to $I = 10^8$ W/cm^2, results in a decrease in the heating time of a two-layer particle by a factor of more than 10. Similar dependences t (ΔR) are observed for other particle sizes.

The conducted studies of heating of metallized particles having a strongly absorbing aluminum shell and a nonabsorbing polyethylene core to the temperature of the onset of polyethylene melting have revealed that this process depends strongly on particle size and shell thickness. In the case of fine particles and thick shells, the heating becomes uniform, and the temperature drop decreases, unlike thin shells, where heating remains nonuniform. For large metallized particles the heating is strongly nonuniform for all the shell thicknesses considered.

NOTATION

λ, I, wavelength and intensity of the radiation incident on the particles; Q, amount of heat released per unit time per unit volume of the substance in the vicinity of a point inside the particle with the spherical coordinates r, θ, φ; $m_1 = n_1 - i\kappa_1$, complex refractive index for the core substance of a two-layer particle; $m_2 = n_2 - i\kappa_2$, the same for the shell substance; ρ_i, c_i, λ_i ($i = 1, 2$), specific density, heat capacity, and thermal conductivity of the substances forming the particle; T, temperature; α, heat transfer coefficient between the shell substance of the particle and the medium surrounding it; T_{mel}, temperature of the medium surrounding the particle; t, time.

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