EXPERIMENTAL INVESTIGATION OF THE INTERACTION OF LASER RADIATION WITH COMPOSITE MATERIALS

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Experimental data on the determination of mass entrainment, crater displacement velocity, coke layer thickness, and effective heat of ablation for two types of lasers are given.

The mechanism of the interaction of laser radiation with composite materials differs substantially from its interaction with metals, crystals, etc. in the values of the mass entrainment, crater displacement velocity, and other parameters.

In our investigation of the interaction of laser radiation with composite materials, we used two industrial continuous lasers operating on YAG ($\lambda = 1.06$ μm) and on a CO_2—Ne—He gas mixture ($\lambda = 10.6$ μm). The radiation flux density was between $0.5 \cdot 10^5$ and $1.2 \cdot 10^5$ W/cm². The experimental apparatus was essentially the same as the type generally used, which has been described, among other things, in [1]. The only difference was the method of focusing the laser radiation. In the case of the CO_2 laser the focusing was done by means of a spherical mirror (F = 50 mm); in the case of the laser operating on YAG the radiation was focused by means of a glass lens (F = 110 mm). In focusing the laser radiation on the target, it is not possible to determine the value of the diameter of the focusing spot experimentally, and therefore we calculated the geometric dimensions of the optical schemes for the two types of laser [2]. Taking account of the modal structure of the laser radiation, we determined the diameter of the focusing spot, and after that we determined the incident radiant power density, so that we could compare the mass entrainment, the crater displacement velocity, the thickness of the coke layer, and the effective heat of ablation for the above-mentioned types of laser. For the YAG laser we had to solve the "inverse" problem, i.e., find the distance from the lens plane to the focus and then find the diameter of the lens. The reason for this approach is that the geometry of the YAG laser resonator makes it unstable ($r_1 = r_2 = \infty$), in addition to which the focus of this laser depends on the output power. The comparison with respect to the above-mentioned parameters was carried out at a power density of $I = 52$ kW/cm² and $I = 112$ kW/cm² for two composite materials: material No. 1 was asbestos plastic, and material No. 2 was asbestos capron. Unlike the methodology of [1, 3], the flare formed by the interaction of the laser radiation with the material was not blown away by a stream of gas directed perpendicular to the target.

In Figs. 1 and 2 all the dimensionless quantities shown are related to the dimensional formula $a = a_r/a_m$, where a is the quantity that has been made dimensionless, a_r is the running variable, and a_m is the maximum value obtained in the experiment.

The energy absorbed by the material may be expended on two types of mass removal: 1) the "fast" form of mass removal from the surface of the irradiated material, which consists in pyrolysis of the resin contained in the plastic and vaporization of the matrix of the plastic; 2) the "secondary flow" form, which causes mass removal due to the deep absorption of the energy flux as a consequence of the thermal conductivity of the reinforcing matrix of the composite material.

The depth of absorption for polymer resins is comparable to the wavelength of the radiation of the laser operating in the 10.6-μm range. The secondary flow consists of pyrolysis products blown into the flare through the layer of coke that is formed. The clogging of the micropores in the coke layer, which is caused by the deposition of atomic carbon in them, and the subsequent breakoff of the pores bring about a macroentrainment of coke into the region of the flare. Furthermore, the combustion wave front is stabilized after some time

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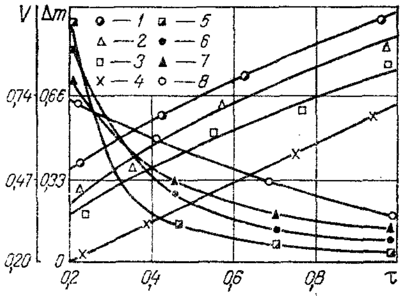

Fig. 1. Variation of mass entrainment for material No. 1 at I = 112 kW/cm^2 (1, λ = 10.6 μm; 2, λ = 1.06 μm) and I = 52 kW/cm^2 (3, λ = 10.6 μm; 4, λ = 1.06 μm) and of crater displacement velocity for materials No. 1 (5, λ = 10.6 μm; 6, λ = 1.06 μm) and No. 2 (7, λ = 10.5 μm; 8, λ = 1.06 μm) as functions of time of experiment.

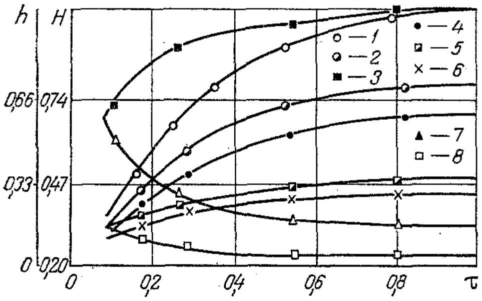

Fig. 2. Variation of coke layer thickness for materials No. 1 (2, λ = 1.06 μm; 4, λ = 10.6 μm) and No. 2 (1, λ = 1.06 μm; 3, λ = 10.6 μm) and of the effective heat of ablation for materials No. 1 (5, λ = 1.06 μm; 7, λ = 10.6 μm) and No. 2 (6, λ = 1.06 μm; 8, λ = 10.6 μm) as functions of time of experiment at I = 52 kW/cm^2.

in the flare formed by the laser radiation.

When the surface is at high temperature, if it is acted upon by the laser radiation for a prolonged period, the molten layer becomes fluid, and this leads to a further loss of mass. However, the results of [1, 4] indicate that the fundamental mechanism of mass removal is vaporization and the formation of a "coke layer." The formation of this coke layer, in turn, causes obscuration of the incident laser radiation.

Moreover, it must be noted that the mass entrainment, the crater displacement velocity, the effective heat of ablation, and the coke layer thickness are affected by the fact that the ablation products attenuate the laser radiation.

Thus, the interaction of laser radiation with composite materials is a complex physicochemical process whose individual stages are closely interconnected.

For material No. 2, unlike material No. 1, the variation of mass entrainment with time of experiment was found to be the same, but its rate of variation was greater for the same experimental conditions.

In investigating how the variation of the coke layer thickness along the axis of propagation of the laser beam depended on time of experiment for materials No. 1 and No. 2, at I = 112 kW/cm^2 we found that the rate of increase was greater and the variation itself was more clearly pronounced than at I = 52 kW/cm^2 (Fig. 2).

As the power density increases from I = 52 kW/cm^2 to I = 112 kW/cm^2, for materials No. 1 and No. 2, the effective heat of ablation decreases for the same experimental conditions.

On the basis of the results obtained, we can draw the following conclusions:

1) Material No. 2 is less resistant to disintegration than material No. 1. At high power values and prolonged times of experiment the variation of the mass entrainment is nonlinear, whereas for small power values it is linear.

2) The maximum mass entrainment is observed for a laser radiation wavelength of λ = 10.6 µm, which is evidently related to the depth of absorption of laser radiation for polymer resins, comparable at this wavelength and minimal coke layer thickness.

3) The crater displacement velocity is maximum during the initial period; this is due to the minimal thickness of the coke layer at that time.

4) As the time of experiment is increased, the thickness of the coke layer increases, while the crater displacement velocity decreases exponentially; the maximum crater displacement velocity corresponds to a wavelength of λ = 1.06 µm.

5) The maximum coke layer thickness corresponds to a wavelength of λ = 1.06 µm, owing to the maximum absorption for the upper layer of coke, whose degree of blackness is close to that of an absolutely black body (the surface temperature of the coke layer in a stationary regime, determined with an optical pyrometer, was $T_{\text{crater}} \approx 200°\text{C}$).

6) The maximum velocity of displacement of the crater formed by the laser radiation and the maximum coke layer thickness are associated with material No. 2.

7) The variation of the effective heat of ablation for materials No. 1 and No. 2 as a function of time of experiment is exponential, with the curve for material No. 1 increasing and the curve for material No. 2 decreasing as the time of experiment is increased; for both materials the maximum heat of ablation is observed for λ = 1.06 µm.

8) In the mechanism of mass removal we can distinguish three stages: sublimation, formation of the coke layer, and attenuation of the laser radiation by the ablation products, and therefore we do not observe a single-valued relation between the mass entrainment and the crater displacement velocity. Thus, for radiation with λ = 10.6 µm the mass entrainment is greater than for λ = 1.06 µm, but the thickness of the coke layer is less, while the crater displacement velocity for λ = 1.06 µm is higher than for λ = 10.6 µm, since the average attenuation coefficient is higher for λ = 10.6 µm than for λ = 1.06 µm [5].

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