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MODELING A COMBUSTION WAVE USING LASER RADIATION

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A description of an experimental installation for studying the process of heating of metal targets by radiation from a CO_2-laser operating in the regime of continuous generation is given. The dynamics of the change in the temperature, heating rate, and factor of absorption of aluminium particles is shown. Data on the values of the optical constants of aluminium oxide and thermodiffusion constants obtained on the basis of temperature changes and the electrodynamic relations describing absorption of radiation by stratified media are given.

We consider the possibilities of using a laser for investigating the processes of ignition and combustion of metal particles. Figure 1 shows the schematic diagram of the installation. Radiation of CO_2-laser 1 (the power is 80 W, the outer diameter of the radiation spot is ~40 mm) reflecting from mirror 2 is focused by lens 3 on specimen 4. The diameter of the radiation spot focused on the specimen is 0.8-1.5 mm. A portion of radiation (~5%) is removed by the semitransparent mirror 5 and is focused by lens 6 on calorimeter 7 of the IMO-2 power meter 8. The time of exposure to radiation incident on the particle vertically downward is controlled by mechanical bolts 9, i.e., by a forebolt, and a shutter with a time of operation of 3 msec. Spherical particles of aluminium 0.8-1.2 mm in diameter serve as targets. The particle size is determined on a measuring microscope with an error of 40 μm. Temperature measurements are performed using VR 5/20 thermocouples 50 μm in diameter; the thermocouples are rolled to a thickness of 18-20 μm. The signal from the thermocouple is applied to F 1510 amplifier 10 and to U7 amplifier 12 through *RC*-network 11 with a time constant of ~0.01 sec. The amplified signals are recorded by the N 117 mirror-galvanometer oscillograph 13.

The procedure imposes certain limits on the size of a particle: it must be thermally thin, i.e., the relation $R_0 \sim \sqrt{a\tau}$ must be satisfied, where R_0 is the particle radius, τ is the characteristic time of the process, and a is the thermal diffusivity.

The temperature signal is calibrated by the standard calibration characteristic of the VR 5/20 thermocouple [1]. One of the reasons for the significant error of measuring the temperature is the dependence of the thermocouple readings on the temperature distribution along the thermoelectrodes. This error may be eliminated by calibrating the thermocouple in the same temperature field in which its operation is assumed. In this connection the thermocouples are calibrated by reference lines, for which purpose we take the solidification points of zinc, aluminum, silver, copper, nickel, and platinum. The experimental points are in good agreement with the standard curve; a small discrepancy is observed in the high-temperature region ($T > 1800$ K).

The signal dT/dt is calibrated by the sections of a linear change in the temperature, as a rule, on the initial sections of heating (to $T = 900$ K).

Figure 2 shows typical experimental dependences of the temperature T and the temperature derivative dT/dt on time.

We discuss the procedure for determining the optical constants. When heating a metal target in the oxidizing medium on the metal surface an oxide film forms, one of the properties of which is considerable molecular absorption. As the oxide film grows, a variation in the absorptivity and the rate of heating occurs. In a stratified

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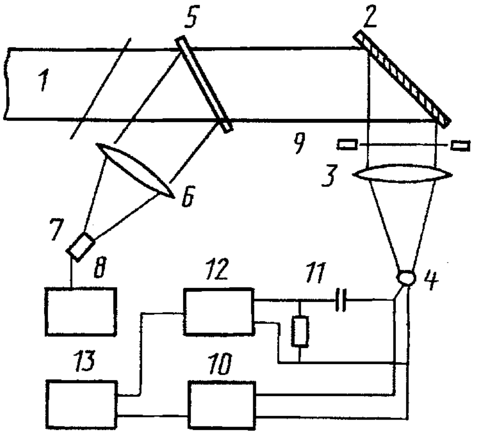

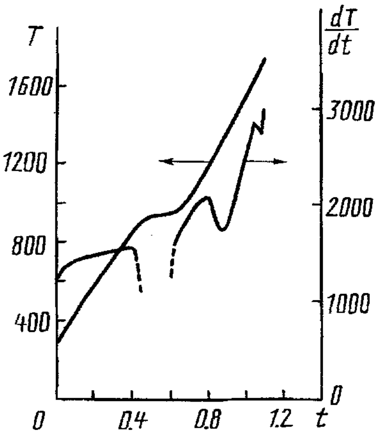

Fig. 1. Schematic diagram of the experimental installation.

Fig. 2. Experimental dependences of the temperature T (K) and the temperature derivative dT/dt (K·sec^{-1}) on the time t (sec).

oxide-metal system we observe interference phenomena whose dynamics is sensitive to a change in temperature, which enables us to determine the optical constants on the basis of temperature change [2].

The heating of a thermally thin target by radiation can be approximately described by the relation

$$mc\frac{dT}{dt} = WA(T) - P_{\text{loss}},$$

where m is the target mass; c is the specific heat of the metal; W is the power of the incident radiation; P_{loss} is the total power of the heat losses; $A(T)$ is the absorptivity of the target.

The cooling of the target once the action of radiation has ceased is described by the dependence

$$mc\frac{dT}{dt} = -P_{\text{loss}}.$$

Subtracting the latter relation from the former one with the same value of temperature on the sections of heating and cooling we obtain

$$A(T) = \frac{mc}{W}\left[\left(\frac{dT}{dt}\right)_{\text{heat}} - \left(\frac{dT}{dt}\right)_{\text{cool}}\right].$$

In deriving this equation we take no account of the heat release of the chemical reaction of oxidation, but since the reaction takes place both in heating of the target and in its cooling the error after subtraction of the equations is bound to be insignificant.

The absorptivity of the stratified system is expressed in terms of the optical characteristics of the metal and the oxide. For the case of normal incidence of radiation we have [3, 4]

$$A(x) = 1 - |r|^2, \quad r = \frac{r_{12}\exp(-2i\psi) + r_{23}}{\exp(-2i\psi) + r_{12}r_{13}},$$

$$r_{12} = \frac{1-\sqrt{\varepsilon}}{1+\sqrt{\varepsilon}}, \quad r_{13} = \frac{1-\sqrt{\varepsilon_0}}{1+\sqrt{\varepsilon_0}}, \quad r_{23} = \frac{r_{12}-r_{13}}{r_{12}r_{13}-1},$$

$$\sqrt{\varepsilon} = n + i\kappa, \quad \sqrt{\varepsilon_0} = n_0 + i\kappa_0, \quad \psi = \frac{2\pi x}{\lambda}\sqrt{\varepsilon}. \tag{1}$$

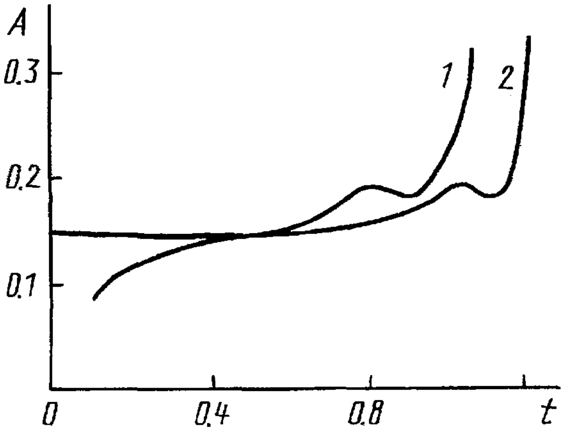

Fig. 3. Experimental (1) and theoretical (2) dependences of the absorptivity of a particle heated by radiation on time.

Here ε, ε_0 are the dielectric constants of the oxide and the metal; n and n_0 are the refractive indexes of the oxide and the metal; κ and κ_0 are the absorption coefficients of the oxide and the metal; λ is the wavelength of the incident radiation; x is the oxide layer thickness; r_{12} and r_{13} are the amplitude coefficients of reflection from the oxide and the metal, respectively.

As a rule, at the frequency of CO_2-laser radiation the following conditions are satisfied: $1 - |r_{12}|^2 >> 1$, $\chi << 1$, $n > 1$ ($A_0 = 1 - |r_{13}|^2$ is the absorptivity of the pure metal). Taking this into account with small values of the optical thickness $\alpha x << 1$ ($\alpha = 4\pi\kappa/\lambda$ is the absorption coefficient of the oxide) we can write the approximate expression

$$A(x) = \frac{n^2 A_0 + 2\kappa(\beta x - \sin\beta x)}{n^2 + (1 - n^2)\sin^2(\beta x/2)}, \quad \beta = \frac{4\pi n}{\lambda}. \tag{2}$$

The location of the extrema is determined from the condition $dA/dx = 0$. Determining the location of the extremals on the curve $A(T)$ experimentally, it is possible, by using relation (2), to calculate the values of the optical constants for the metal oxide. For example, for aluminum oxide we obtained $n = 1.28 \pm 0.04$, $\kappa = (2.27 \pm 0.52)\cdot 10^{-2}$.

We will describe oxide film growth on the basis of the relation

$$\frac{dx}{dt} = \frac{d}{x}\exp(-E/RT),$$

which is valid at the initial stage of heating under conditions where the rate of the exothermic reaction is controlled by ion diffusion in the oxide layer (d and E are constants, R is the universal gas constant). Neglecting heat losses into the ambient medium, we can obtain

$$\int_{T_0}^{T} \exp(-E/RT)\,dT = \frac{W}{mcd}\int_{x_0}^{x} xA(x)\,dx,$$

where T_0 and x_0 are the ambient temperature and the initial value of the oxide layer thickness. Determining the temperatures T_1 and T_2 corresponding to the same minimum point of $A(T)$ with different radiation power densities, from the latter relation with the aid of expansion of the exponent by the Frank-Kamenetskii method we can find the values of the thermokinetic constants. For aluminum oxidation in the air it is found that: $d = 1.61\cdot 10^{-7}$ m$^2\cdot$sec^{-1}, $E/R = 1200$ K. Experimentally determined values of the optical constants and the thermodiffusion constants are used in constructing a mathematical model of the pre-ignition period of laser thermochemical oxidation of aluminum [5]. The model includes the equation of balance of the target energy (taking into account the energy contribution of oxidation as well as radiation and convective heat losses), the parabolic law of oxidation, and the relation for determining the absorption factor. On the basis of numerical calculations we studied the behavior of a series of characteristics of the heating process (the target temperature, the rate of heating, the absorptivity, and the time dependence of the oxide film thickness). Figure 3 gives experimental and theoretical dependences of the absorption factor for a particle 0.97 mm in diameter heated by constant radiation with a power of 12.5 W.

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