formed in the coating owing to evaporation; V_{roll}, rate at which the melt rolls up into a bead; σ, surface tension; ρ, density. Indices: cr — critical; f — flame; roll — rolling up; h — heating; m — melt; 1 — coating; 2 — substrate.

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CALCULATING KINETICS OF OXIDE FILM GROWTH DURING LASER HEATING

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UDC 536.2

The process of oxide film growth on the surface of a copper target in air under the action of CO_2-laser radiation is considered.

The processes of metal oxidation under the action of concentrated thermal fluxes are met with in various scientific and technical applications [1-3]. A wide range of studies has been dedicated to such problems, and overviews of the literature have been presented in [1, 3]. Upon heating of metal by radiation at wavelength $\lambda = 10.6$ μm in an oxidizing atmosphere the oxide film which forms upon the metal surface significantly increases absorption by the target. In a number of problems knowledge of temperature distributions and temperature gradients in the oxide film and metallic substrate is needed. Comparison of temperature values on the free oxide surface and the metal—oxide boundary is also of interest. In the model used in [2] it was proposed that the oxide film is thermally thin, while the laser radiation was in the form of periodic pulses, with the duration of the individual pulses being much shorter than the time intervals between pulses. This assumption permits replacing the time dependence of radiant flux density with the sum of delta-function pulses and assuming that the oxide film grows in the periods between individual pulses. In [4] the development of dissipative structures during metal oxidation was studied and an asymptotic law was defined for development of one-dimensional compressible structures. The oxidation process was considered only to oxide film thicknesses so small that no oscillations in the laser radiation absorption coefficient were observed.

In the present study we will consider the process of oxidation of a massive copper target by CO_2-laser radiation with consideration of thermal losses from the free surface of the oxide film due to convection and thermal radiation. The thermophysical parameters of the body will be considered temperature-independent. In the thermal balance condition on the oxide—air boundary the smallness of the oxide film in comparison to the depth of the thermal effect of the surface heat source was taken into account:

$$\xi(t) < \left| 2dt \exp\left(-\frac{T_d}{T_m}\right)\right|^{1/2} \ll \sqrt{a_1 t}.$$

The absorptivity of the two-layer oxide—metal system $A(\xi)$ was calculated with the well known model of [5]:

$$A(\xi) = 1 - |r|^2,\ r = \frac{r_{01}\exp(-2i\psi) + r_{12}}{\exp(-2i\psi) + r_{01}r_{12}},$$

$$r_{12} = \frac{r_{01} - r_{02}}{r_{01}r_{02} - 1},\ r_{01} = \frac{1 - \sqrt{\varepsilon}}{1 + \sqrt{\varepsilon}},\ r_{02} = \frac{1 - \sqrt{\varepsilon_0}}{1 + \sqrt{\varepsilon_0}}, \quad (1)$$

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$$\sqrt{\varepsilon} = n + i\varkappa,\ \sqrt{\varepsilon_0} = n_0 + i\varkappa_0,\ \psi = \frac{2\pi}{\lambda}\sqrt{\varepsilon}\,\xi.$$

Calculations show that maxima in the absorption of the oxide—metal system are reached at oxide film thicknesses of approximately $\xi = \lambda/4n$. Physically this model corresponds to heating of a copper target in air. In the general case a three-layer structure $CuO/Cu_2O/Cu$ develops [6]. However the presence of a cupric oxide layer does not have a significant effect on target absorption or heating [7], which allows us to use the two-layer model in the geometric optics approximation. The oxide film grows toward the laser, the growth kinetics following a parabolic law [6]

$$\frac{d\xi(t)}{dt} = \frac{d}{\xi}\exp\left[-\frac{T_d}{T_1(0,\ t)}\right],\ \xi(0) = \xi_0. \tag{2}$$

Calculations were continued to the melting points of the oxide and metal. The mathematical formulation of the problem has the form

$$a_1\frac{\partial^2 T_1}{\partial z^2} = \frac{\partial T_1}{\partial t},\ t \geqslant 0,\ 0 \leqslant z \leqslant \xi(t),$$

$$a_2\frac{\partial^2 T_2}{\partial z^2} = \frac{\partial T_2}{\partial t},\ t \geqslant 0,\ z \leqslant 0,$$

$$\lambda_1\frac{\partial T_1}{\partial z}\bigg|_{z=\xi(t)} = qA(\xi) - p(T_1(\xi,\ t)), \tag{3}$$

$$\lambda_1\frac{\partial T_1}{\partial z}\bigg|_{z=0} = \lambda_2\frac{\partial T_2}{\partial z}\bigg|_{z=0},\ T_1(0,\ t) = T_2(0,\ t),$$

$$T_2(\infty,\ t) = T_1(z,\ 0) = T_2(z,\ 0) = T_0,$$

$$p(T) = \alpha(T - T_0) + \sigma\sigma_0(T^4 - T_0^4).$$

System (3) was solved simultaneously with Eqs. (1) and (2) by a finite difference method using the following scheme:

$$T_j^{i+1}(N) = T_j^i(N) + \frac{\tau a_j}{(h_j^i)^2}[T_j^i(N-1) - 2T_j^i(N) + T_j^i(N+1)],\ j = 1,\ 2,$$

$$T_1^{i+1}(1) = T_1^{i+1}(2) + (\Delta\xi^{i+1} + h_1^i)[qA(\xi^{i+1}) - p^{i+1}],$$

$$T_2^{i+1}(N1) = T_1^{i+1}(N1),$$

$$T_1^{i+1}(N1) = \left[\frac{\lambda_1 T_1^{i+1}(N1-1)}{h_1^i} + \frac{\lambda_2 T_2^{i+1}(N1+1)}{h_2^i}\right]\left(\frac{\lambda_2}{h_2^i} + \frac{\lambda_1}{h_1^i}\right)^{-1},$$

$$T_2^{i+1}(N_2) = T_1^1(N) = T_2^1(N) = T_0,\quad N = \begin{cases} 1,\ \ldots,\ N1,\ j = 1, \\ N1,\ \ldots,\ N2,\ j = 2, \end{cases}$$

$$T_1^{i+1}(N) = T_1^{i+1}[z^{i+1}(N)],$$

$$p^{i+1} = \alpha[T_1^{i+1}(1) - T_0] + \sigma\sigma_0\{[T_1^{i+1}(1)]^4 - T_0^4\},$$

$$z^{i+1}(N) = \xi^{i+1}\frac{N1 - N}{N1 - 1},\ N = 1,\ \ldots,\ N1 - 1,$$

$$\xi^{i+1} = \left\{(\xi^i)^2 + 2d\tau\exp\left[-\frac{T_d}{T_2^i(N1)}\right]\right\}^{1/2},$$

$$h_1^{i+1} = \frac{\xi^{i+1}}{N1 - 1},\ \Delta\xi^{i+1} = \xi^{i+1} - \xi^i,\ \xi^1 = \xi_0.$$

After each step in time the coordinate grid in the oxide layer was changed by a uniform extension to the new oxide film thickness. In particular, calculations show that up to the temperature of cupric oxide fusion (1506 K) the thermal losses due to convection and thermal radiation in the formulation of Eq. (3) are low in comparison to the amount of laser power absorbed. The time dependences of absorptivity, oxide film thickness, oxide free surface temperature, oxide—metal boundary temperature, and the difference of the latter two were obtained (Figs. 1, 2). It was shown that as a result of oscillation in the absorptivity of the oxide—metal system the temperatures of the free oxide surface and the oxide—metal boundary, as well as their difference, undergo oscillations, lagging the former oscillations in time and

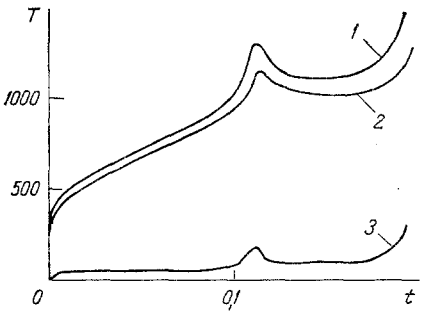

Fig. 1

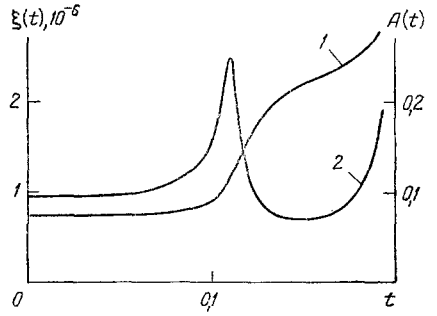

Fig. 2

Fig. 1. Oxide free surface temperature (K) (curve 1), oxide—metal boundary temperature (curve 2) and their difference (curve 3) vs time (sec) for $q = 6 \cdot 10^8$ W/m^2.

Fig. 2. Oxide film thickness (m) (curve 1) and oxide—metal system absorptivity (curve 2) vs time (sec) for $q = 6 \cdot 10^8$ W/m^2.

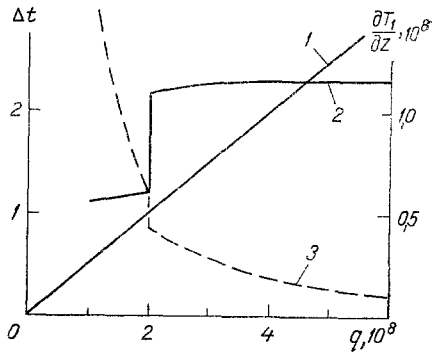

Fig. 3. Temperature gradient (K/m) in oxide film at first absorptivity maximum (curve 1), at time free oxide surface attains cuprous oxide fusion temperature (curve 2) and time (sec) at which free oxide surface reaches that temperature (curve 3) vs laser radiation flux density (W/m^2).

having lower amplitudes. In the initial stage of oxidation, where the oxide film growth rate is small and the absorptivity changes only weakly, the temperature of the oxide free surface and the oxide—metal boundary are proportional to $\sqrt{t}$. With increase in temperature the frequency of the oscillations in A(t), $T_1(\xi, t)$ and $T_2(0, t)$ increases, due to increase in the oxide growth rate. The time dependence of the oxide film thickness (Fig. 2, curve 1) is a monotonically increasing function, the rate of increase of which, as is evident from the corresponding equation, oscillates together with the temperature of the oxide—metal phase boundary. The absorptivity of the two-layer oxide—metal system, calculated with Eq. (1), is shown by curve 2 of Fig. 2. Calculations of temperature fields in the oxide layer (Fig. 3) showed the presence of significant temperature gradients (up to $1.5 \cdot 10^8$ K/m for $q = 6 \cdot 10^8$ W/m^2).

An important characteristic of the oxidation process is the time $\Delta t(q)$ at which the free surface of the oxide reaches the melting point of cuprous oxide (Fig. 3). With increase in energy flux density this time decreases monotonically. For $q = 2 \cdot 10^8$ W/m^2 Δt drops discontinuously. This effect was first described qualitatively in [8]. The discontinuity is produced by the fact that at that flux intensity the fusion point is reached simultaneously at the second and third maxima of the oxide free surface temperature. The value of the temperature gradient in the oxide layer undergoes a similar discontinuity at the moment the cuprous oxide fusion point is reached at $q = 2 \cdot 10^8$ W/m^2. The temperature gradient at the point of the first absorptivity maximum is directly proportional to the incident radiant flux density. Nonuniformity in heating of the oxide film at high incident radiation intensities and significant temperature gradients in the oxide layer are capable of producing cracking of the oxide coating and peeling from the metal surface,

which may in turn degrade heat removal from the oxide film into the metal substrate. This process creates conditions for superheating of the oxide film and its further destruction.

NOTATION

t, pulse action time; $\xi(t)$, oxide film thickness; $A(t)$, $A(\xi)$, absorptivity of oxide—metal system; r_{01}, r_{02}, r_{12}, amplitude reflection coefficients at air—oxide, air—metal, oxide—metal boundaries; ε, ε_0, dielectric permittivities of oxide and metal; λ, wavelength of CO_2 laser radiation; d, constant in parabolic oxidation law; T_a, copper oxidation activation temperature; $T_j(z, t)$, temperature field; λ_j, a_j, thermal conductivity and diffusivity coefficients; q, incident energy flux density; z, spatial coordinate; α, coefficient of heat convection from oxide surface; σ, oxide grayness coefficient; σ_0, Stefan—Boltzmann constant; T_0, initial system temperature; ξ_0, initial oxide film thickness; τ, time step; h_j, coordinate step; $\Delta t(q)$, time at which cuprous oxide fusion temperature is reached; T_m, copper fusion temperature. Subscripts: 0, air; 1, oxide; 2, metal; j = 1, 2.

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