cessing grain fusion and rapid recrystallization of the melt are realized in the surface region of the high temperature superconductor material without change in phase composition, leading to a large increase in the number of contacts between ceramic grains, with resulting formation of a current-carrying surface layer having high critical current density values ($\sim 10^4$ A/cm^2) at nitrogen temperatures.

NOTATION

λ, wavelength; T_c, transition temperature to superconductive state; I_{cr}, critical current; n, number of turns in primary winding; J_{cr}, critical current density; t, superconductive ring thickness; d, superconductive ring width.

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METAL FUSION BY LASER RADIATION ACTION IN AN OXIDIZING MEDIUM

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Results are presented from a calculation of fusion of a massive zirconium plate under the action of laser radiation with consideration of simultaneous surface oxidation.

Interaction of concentrated heat fluxes with metals is found in various scientific and technological applications [1-3]. In [4, 5] the process of laser heating of a massive copper target in an oxidizing atmosphere was considered. In this situation an oxide film was formed on the irradiated metal surface, which leads to an intense change in the absorption capability of the target. In the models considered the temperatures were limited to values below the fusion point of copper [1-5]. In the present study the investigation of laser radiation interaction with a two layer oxide–metal system will be extended in temperature through the point of target fusion to the point of commencement of fusion of the zirconium dioxide layer using the example of zirconium.

The process studied can be described briefly as follows. Radiation from a CO_2-laser with wavelength λ = 10.6 μm and constant energy density falls on the surface of a massive metal target made of zirconium and is partially absorbed at a depth of the order of the skin layer. Since in metals the latter is much less than the laser radiation wavelength and the depth

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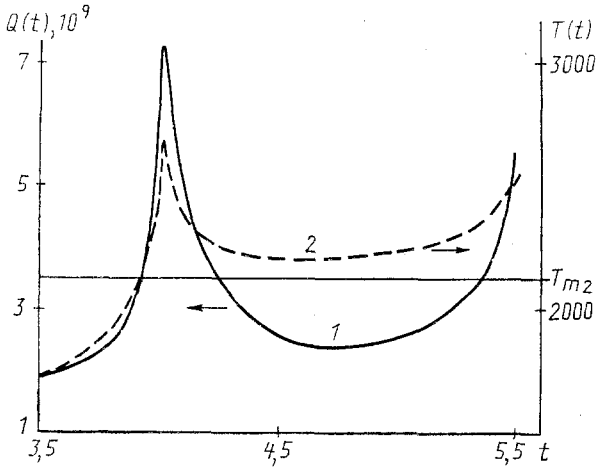

Fig. 1. Energy flux density absorbed by target Q(t), W/m² (curve 1), and temperature of oxide–metal boundary T(t), K (curve 2), vs laser radiation action time t, msec.

affected by the thermal source thus developed, the absorption can be considered a surface phenomenon. Heating of the metal surface activates oxidation of zirconium to the dioxide. The kinetics of oxide film growth on the target surface can be described by a parabolic law [6]:

$$\frac{d\xi(t)}{dt} = \frac{\beta}{\xi}\exp\left[-\frac{T_\beta}{T_1(z=0,\ t)}\right],\ \xi(t=0)=0.$$

The oxide film then grows from the metal surface toward the laser radiation. After formation of an oxide layer the absorbing capability of the two-layer system formed changes intensely as the target oxidizes because of interference between laser radiation reflected from the free surface of the oxide and the oxide–metal boundary. The absorption capability depends on oxide film thickness in the following manner [7]:

$$A(\xi) = 1 - |r|^2,\ r = \frac{r_{01}\exp(-2i\psi) + r_{12}}{\exp(-2i\psi) + r_{01}r_{12}},\ r_{12} = \frac{r_{01} - r_{02}}{r_{01}r_{02} - 1},$$

$$r_{01} = \frac{1-\sqrt{\varepsilon_1}}{1+\sqrt{\varepsilon_1}},\ r_{02} = \frac{1-\sqrt{\varepsilon_2}}{1+\sqrt{\varepsilon_2}},\ \sqrt{\varepsilon_1} = n_1 + i\varkappa_1,$$

$$\sqrt{\varepsilon_2} = n_2 + i\varkappa_2,\ \psi = \frac{2\pi\sqrt{\varepsilon_1}}{\lambda}\xi.$$

A characteristic feature of the absorption capability $A(\xi)$ is that with growth in film thickness ξ it first passes through a maximum, then decreases, goes through a minimum, and continues to oscillate with decreased amplitude, tending to some limit. The $A(\xi)$ extrema are located at distances close to oxide film thickness which are multiples of a quarter wavelength of the laser radiation in the oxide $\lambda/4\sqrt{n_1}$. The time dependence of $\xi(t)$ and $Q = qA(\xi)$ are shown in Figs. 1 and 2.

The laser radiation is absorbed within the oxide layer in a volume process. However, the calculations performed show that over the course of the entire period considered the thickness of the oxide layer is much less than the depth affected by the heat source produced. Therefore, with an error of the order of 5% we can assume that all the laser energy is absorbed directly on the free oxide surface. In the thermal part of the problem we consider development of the two-layer oxide–metallic substrate film with differing layer thermophysical characteristics and the presence of heat loss from the free oxide surface due to convection and radiation. Calculations showed that consideration of the latter leads to a 10% time delay in development of the entire process. The dependence of metal and oxide thermophysical characteristics on temperature was neglected. In the stage of target heating the mathematical formulation of the problem appears as follows:

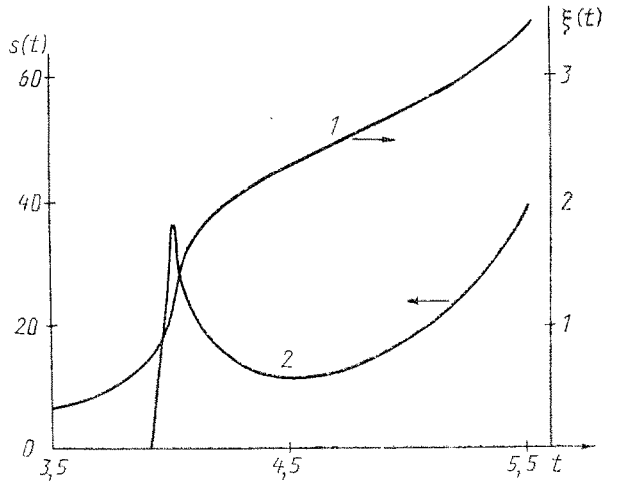

Fig. 2. Oxide film thickness ξ(t), μm (curve 1) and depth of metal substrate fusion s(t), μm (curve 2) vs laser action time t, msec.

$$a_1\frac{\partial^2 T_1}{\partial z^2}=\frac{\partial T_1}{\partial t},\quad -\xi(t)\leqslant z\leqslant 0,\quad a_2\frac{\partial^2 T_2}{\partial z^2}=\frac{\partial T_2}{\partial t},\quad z\geqslant 0,$$

$$-\lambda_1\frac{\partial T_1}{\partial z}\Big|_{z=-\xi}=qA(\xi)-p[T_1(-\xi,\ t)],\quad -\lambda_1\frac{\partial T_1}{\partial z}\Big|_{z=0}=$$

$$=-\lambda_2\frac{\partial T_2}{\partial z}\Big|_{z=0},\quad T_1(0,\ t)=T_2(0,\ t),\quad p(T)=\alpha(T-T_0)+\sigma\sigma_0(T^4-T_0^4),$$

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

The fusion point of zirconium is less than that of its dioxide, and the temperature change across the layer is so small that even before the first maximum in absorption is reached the metal substrate begins to melt. As a result, there develops between the oxide and the solid metal a metallic melt layer, the boundary of which with the oxide remains fixed, while the boundary with the metal moves. In the calculations the physical characteristics of the metal and its melt were taken identical. The mathematical formulation of the thermal problem in the stage of fusion of the metal substrate takes on the form:

$$a_1\frac{\partial^2 T_1}{\partial z^2}=\frac{\partial T_1}{\partial t},\quad -\xi(t)\leqslant z\leqslant 0,\quad a_2\frac{\partial^2 T_3}{\partial z^2}=\frac{\partial T_3}{\partial t},\quad 0\leqslant z\leqslant s(t),$$

$$a_2\frac{\partial^2 T_2}{\partial z^2}=\frac{\partial T_2}{\partial t},\quad z\geqslant s(t),\quad -\lambda_1\frac{\partial T_1}{\partial z}\Big|_{z=-\xi}=qA(\xi)-p[T_1(-\xi,\ t)],$$

$$\lambda_1\frac{\partial T_1}{\partial z}\Big|_{z=0}=\lambda_2\frac{\partial T_3}{\partial z}\Big|_{z=0},\quad T_1(0,\ t)=T_3(0,\ t),\quad -\lambda_2\frac{\partial T_3}{\partial z}\Big|_{z=s}=$$

$$=-\lambda_2\frac{\partial T_2}{\partial z}\Big|_{z=s}+\rho_2 L_2\frac{ds}{dt},\quad T_3(s,\ t)=T_2(s,\ t)=T_{m2},\quad T_2(z=\infty,\ t)=T_0.$$

The equations described were solved numerically on a computer by a finite difference method [8]. After each time step the coordinate grids in all three layers were extended uniformly or compressed to the new thicknesses. The various figures show time dependences of some of the physical quantities involved. It is evident that after the absorption passes through its first maximum the temperature of the oxide–metal boundary begins to decrease because of intense heat liberation into the depths of the target. As a result the boundary of the melt with the solid phase of the metallic substrate which has moved inward turns in the opposite direction and partial crystallization of the melt occurs. The melt does not recrystallize completely, since the absorption capability of the target, and thus, the temperature fields, reach their minimum and begin to grow again. Metal fusion recommences, although shortly thereafter the metal oxide reaches its fusion point at the free surface and calculation was terminated.

In the final outcome we may make the following conclusions.

1) The time dependences of absorbed laser radiation energy, the temperature fields in the target, and the depth to which the metal substrate fuses oscillate in the process considered;

2) the thickness of the oxide film always increases monotonically, although at a varying rate.

NOTATION

t, time of laser radiation action; z, spatial coordinate measured into depths of metal substrate from fixed oxide–metal boundary; $\xi(t)$, oxide film thickness; β, constant of parabolic oxidation law; T_β, oxidation activation energy, deg; $A(\xi)$, absorption capability of target; λ, laser wavelength; ε_1, ε_2, dielectric permittivities; n_1, n_2, refraction coefficients; $\varkappa_1$, $\varkappa_2$, extinction coefficients; q, incident thermal flux density of laser radiation; α, heat convection coefficient from oxide surface; σ, oxide greyness coefficient; σ_0, Stefan–Boltzmann constant; T_0, initial target temperature; λ_1, λ_2, thermal field coefficients; a_1, a_2, thermal diffusivity coefficients; T_1, T_2, T_3, temperature fields; T_{m2}, metal fusion temperature; ρ_2, metal density; L_2, latent heat of metal fusion; s(t), depth to which metal substrate fuses. Subscripts: 1, oxide; 2, metal; 3, metal melt.

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