Spin regimes of sublimation of solids under the action of laser radiation

S. I. Anisimov, S. M. Gol'berg, and M. I. Tribel'skiĭ

L. D. Landau Institute of Theoretical Physics, USSR Academy of Sciences
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It is shown that when a condensed body is evaporated by a laser (electron) beam there are realized, under certain conditions, regimes of phase-transition front propagation, similar to spin combustion in a gasless system. The evaporation front is not isothermal and its motion into the interior of the solid phase is accompanied by rotation around a symmetry axis. The characteristics of the spin sublimation regime are determined by solving the problem numerically.

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A theoretical analysis of the phase-transition, ionization, and chemical-transformation waves produced by laser radiation is limited in most cases to consideration of plane waves propagating with constant velocity (see Refs. 1 and 2). This analysis is insufficient for the investigation of laser sublimation of solids since, as established in Ref. 3, a plane sublimation front is unstable in a certain range of parameters to small perturbations. The present article is devoted to the study of the nonlinear evolution of an unstable plane evaporation front. It is shown that under certain conditions the stability development can lead to the onset of a specific nonstationary evaporation regime, with a non-isothermal front. The trajectories of the points of the front are helical lines, and the overall picture of the front propagation is similar to the spin combustion discovered and investigated in recent years.[4-6] We emphasize that the existence of spin evaporation regimes is not connected with any asymmetry of the laser beam or with singularities in the properties of the evaporated substance. It is due entirely to instability of the surface-evaporation process.

The analysis that follows is based on the known[2,3] formation of the problem of evaporation of a condensed body in vacuum under the influence of an energy flux incident on its surface. The temperature field in the solid is described by the heat-conduction equation with the following boundary condition and the evaporation front (the position and shape of which are not known beforehand are determined in the course of solving the problem):

$$\varkappa \frac{\partial T}{\partial n} = \rho L_{eff} c_0 \exp\left(-\frac{U_{eff}}{T}\right), \tag{1}$$

where c_0 is a constant of the order of the speed of sound in the condensed phase, $\varkappa$ is the thermal conductivity, ρ is the density of the condensed phase, L_{eff} and U_{eff} are the effective specific and atomic heats of evaporation, which depend on the local value of the curvature of the evaporated surface; the derivative is calculated along the normal to the evaporation front.

It has been established in Ref. 3 that at radiation intensities q exceeding a certain critical q_c a plane evaporation front becomes unstable. The dependence of the instability growth rate on the wave number is shown in Fig. 1 [in the considered problem, $\mathrm{Im}\,\gamma(k) \equiv 0$ for the unstable branch of the perturbation spectrum].

The most effective for the investigation of the nonlinear behavior of the solutions in the unstable region are numerical methods. The results reported below pertain to the case of a two-dimensional temperature field. While retaining all the qualitative features of the general three-dimensional case, it calls for a much smaller volume of numerical calculations. An analysis of the results of the numerical solution shows that at small excesses above threshold the initial condition, which is the sum of a large number of modes with approximately equal amplitudes, develops into a quasi-stationary evaporation wave with a non-plane front. The fundamental period of the produced structure corresponds to the maximum of the linear growth rate, $\lambda_m = 2\pi/k_m$. If the intensity q of the laser radiation greatly exceeds the threshold, the region where the increment is positive can become so wide that multiple harmonics of the monochromatic initial perturbation will land in it. This calls for satisfaction of the obvious condition $q > \tilde{q}$, where $\tilde{q}$ is determined from the equation $2k_1(\tilde{q}) = k_2(\tilde{q})$ [k_1 and k_2 are respectively the lower and upper limits of the instability interval $\gamma(k) \geqslant 0$, see Fig. 1]. Calculations show that in this case an important role is played by generation of harmonics, which leads to nonstationary regimes of sublimation-wave propagation. Actually the stationarity is violated even earlier, at q somewhat smaller than $\tilde{q}$, since the coupling between the modes can compensate for the small damping of the second harmonic. Understandably, at q close to $\tilde{q}$ one can expect the appearance of nontrivial nonstationary regimes. To a certain degree, a similar situation arises in the theory of nonstationary combustion.[5,6] As the supercriticality increases, individual vibrational and spin modes are first excited, after which the temperature field becomes stochastic in the region of "strong nonstationarity."[7]

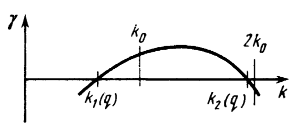

FIG. 1. Growth rate of instability as a function of the wave number.

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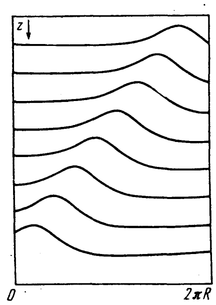

FIG. 2. Successive positions of the sublimation front (development of cylindrical surface, $R=1.6/\mu$). Intervals $\Delta t=11/\mu^2\chi$. The radiation is incident from above along the z axis.

The temperature field corresponding to spin modes is in the general case three-dimensional. To reduce the problem to two-dimensional we shall consider the evaporation of a thin-wall hollow cylinder irradiated along its axis (the z axis). In this case one can neglect the radial component of the temperature gradient. Results of calculations of a typical variant are shown in Fig. 2. A small perturbation of the evaporation front, in the form of a sum of harmonics with wavelengths $2\pi R$ and πR (R is the cylinder radius) was specified at the initial instant. The time-invariant radiation intensity was chosen such that the short-wave components of the initial perturbation (with wave number $2k_0=2/R$, see Fig. 1) was in the region of weak damping. After a certain transient process, an asymptotic regime of sublimation-wave propagation was established. Figure 2 shows the development of the lateral surface of the cylinder and several successive positions of the sublimation front. It is easily seen that the front is uniformly displaced along the cylinder axis (the vertical direction in the figure) and rotates simultaneously around the axis. The initial conditions determine here only the character of the transient process and the direction of the wave rotation. On the other hand, the structure of the steady-state spin-evaporation wave, at fixed values of the radiation intensity, of the cylinder radius, and of the thermal-physical constants of the material, is universal and does not depend on the initial conditions. In the presented calculation variant the linear rotation velocity is smaller by approximately one order of magnitude than the translational velocity of the front; the characteristic "wavelength" of the perturbation is $\lambda_0 \equiv 2\pi/k_0 \approx 10/\mu$, where μ is the coefficient of absorption of radiation by the target material; the displacement of the front along the z axis is decreased in the figure by a factor of 10 relative to the amplitude. The time interval between successive positions of the front is $\Delta t = 11/\mu^2\chi$, where χ is the thermal diffusivity of the target.

It follows thus from the presented calculations that there can exist nonstationary surface-evaporation regimes similar to spin combustion. A direct experimental indication of the existence of such regimes is contained in Ref. 8, where evaporation of quartz under the influence of radiation from a CO_2 laser was investigated. A motion picture of the development of the crater shows that the point of maximum displacement of the evaporation front traces a helical line in the course of time. This interesting observation has not been convincingly explained to this day.

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