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# DESTRUCTION OF THIN FILMS AND FOILS BY CONTINUOUS SPECTRUM RADIATION

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UDC 535.21

An explosive source was used in [1] to study the effect of high power UV radiation on aluminum foils. It was shown that failure thresholds of the specimens studied significantly exceeded the sublimation energy because radiation was screened by the vapor evolved. Much data is also available [2] on the action of laser radiation on metal films, according to which, depending on irradiation conditions and the quality of the film preparation, the energy expended in destroying the film can vary from the heat of fusion to the sublimation energy. The goal of the present study is to experimentally determine energy thresholds for destruction of foils and thin films of aluminum and bismuth under the action of continuous spectrum radiation of relatively low power. A high power (up to 200 kA) electrical discharge was used as the radiation source. The experiments were performed in argon and air at normal density. The maximum radiation flux density on the specimen surface comprised ~100 kW/cm$^2$ with duration up to 100 μsec.

The films used were produced by thermal deposition of metal on glass substrates in a vacuum. The film thickness was determined to an accuracy of 5% by weighing the specimens before and after deposition.

The dynamics of discharge channel growth and the process of specimen destruction were recorded by an SFR-2M high speed camera; uncertainty in velocity and distance measurements was approximately 5%.

The discharge was initiated by electrical explosion of a planar aluminum foil 90 × 70 mm in area and 8 μ thick, located on a dielectric surface. A capacitor bank with net capacitance

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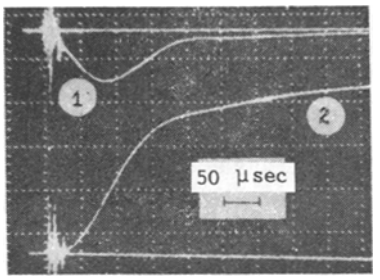


Fig. 1

of 3.2 μF charged to 4.8 kV was used as the energy storage device. The duration of the first half-cycle of the current pulse, over the course of which practically all the energy was liberated in the discharge, was ~160 μsec. The specimens and discharge gap were located in a single chamber 0.2 $m^3$ in volume. Before filling with argon the chamber was first evacuated to a residual pressure of ~1 Pa. The maximum brightness temperatures of the discharge channel measured by a photodiode in the spectral interval $\lambda = 0.43 \pm 0.05$ μ were 14 and 18 kK in argon and air, respectively.

The specimens to be irradiated were located at a distance of 100-120 mm from the plane of the foil discharge initiator. This distance was chosen such that the value of the energy incident on the specimen surface over the irradiation time (limited by the duration of the motion of the discharge-generated shock wave to the specimen surface) was maximized.

A two-section pyrodetector [3] was used to record the flux density $q_d(t)$ and the radiant energy $E_d(t) = \int_0^t q_d(t)\,dt$ in a plane 470 mm from the plane of the initiator along the perpendicular constructed from the center of the latter. Oscillograms of $q_d(t)$ and $E_d(t)$ (1 and 2) for a discharge in air are shown in Fig. 1. Detector location in the plane of the specimen was not possible since it would be damaged by the radiation incident on its absorbing surface. The uncertainty in measuring power amplitude was 15%.

The radiant flux density q(t) incident on the specimen surface was determined by recalculating $q_d(t)$ in the following manner. It was established by the high speed cine camera that over the course of ~100 μsec after the beginning of radiation the discharge channel retained a rectangular form in plan, then transformed to an oval, with the leading edge of the channel remaining planar. The radiant flux density created by an emitting rectangle with sides 2a and 2b, radiating by the Lambert law, at a distance h from its surface, depends on the source geometry [4]:

$$q \sim q_0\left[\frac{a}{(a^2+h^2)^{1/2}}\operatorname{arctg}\frac{b}{(a^2+h^2)^{1/2}} + \frac{b}{(b^2+h^2)^{1/2}}\operatorname{arctg}\frac{a}{(b^2+h^2)^{1/2}}\right].$$

Here $q_0$ is the flux density from the surface. Hence with known time dependences of the discharge channel geometric dimensions and the position of its leading edge relative to the specimen we can reconstruct the relationship between radiant power at the position of the detector $q_d$ and the specimen q. We note that if we consider the radiator to be a disk of the same area, the recalculation results will differ by no more than 1.5%.

The characteristic time for propagation of the thermal conductivity wave through the thickness $\delta$ of the specimen $\tau \sim \delta^2/\chi$ (where $\chi$ is the thermal diffusivity coefficient) did not exceed 2 μsec in any case.

Together with a diagram of the experimental configuration, Fig. 2 shows the flow produced by irradiation of a bismuth specimen in argon. As in the other experiments the photographs were made in two directions: parallel to the specimen plane and from a mirror installed at an angle below the specimen. The specimen consisted of a glass plate 1 with deposited film 2 in the form of eight fields, the dimensions of each being 7 × 4 mm. The film thickness varied from 0.5 to 3.5 μ.

Some time after the beginning of the irradiation, shock waves 3 appear at the film surface, caused by the escape of evaporating material. The propagation rates of these waves are approximately equal and close to the speed of sound in the surrounding gas. The forward "evaporation products" – gas boundary 4, moving at a velocity of 50 m/sec, corresponds to evaporation of the thinner film. The film then "clarifies" (radiation appears from the back

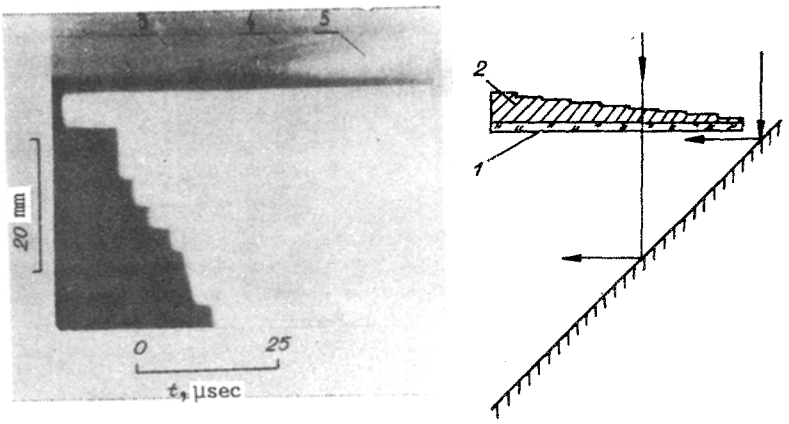


Fig. 2

side of the specimen, recorded by the inclined mirror), which can naturally be related to destruction due to escape of material in the form of vapor and liquid metal droplets. We will now call the quantity $E_* = \int_0^{t_*} q dt$ the specimen destruction energy (where $t_*$ is the time between the beginning of specimen irradiation and its "clarification"). After destruction of the film the velocity of the forward vapor boundary increases to 150 m/sec, a scintillating region 5 is formed near the surface, which expands at a rate of ~100 m/sec, apparently because of absorption of shortwave radiation in the evaporated material. The velocity of the vapor boundary is probably affected by lateral expansion. A similar pattern is observed in radiation action on aluminum films 0.5-3.3 μ thick.

Figure 3 shows photographs illustrating the appearance and development of inhomogeneities in the process of destruction of an 8 μ aluminum foil with area 30 × 30 mm, located on the surface of a glass plate in an argon atmosphere. The vertical line shows the glass plate surface, to its right is the parallel surface of the specimen, while to the left is the view through the mirror with field of view 28 mm. The digits at the top denote time from the beginning of irradiation in μsec. The film edges were folded under to avoid inhomogeneities related to roughness on the film edges.

Material begins to escape from the specimen surface in the form of individual jets 1, the distance between which is about 1 mm on average, then a boundary 2 becomes visible, apparently corresponding to the maximum density gradient. The boundary velocity is about 100 m/sec while the jets move approximately twice as fast. Material escape is accompanied by formation of an acoustical disturbance 3.

The measurement results indicate that commencement of material escape and partial evaporation correspond to a radiant energy (without consideration of losses) applied to a unit area of foil of $E_i$ = 1.4 J/cm$^2$ or, recalculated to unit mass, 0.65 kJ/g, which is less than the enthalpy of fused aluminum $\Delta H(\ell, T_f)$ = 1.1 kJ/g [5]. Upon reaching an energy level $E_*$ = 6.4 J/cm$^2$ (or 3 kJ/g) the expanding metal layer "clarifies."

During this "clarification" process, which occurs over a relatively short time interval (5-10 μsec) compared to the total destruction time, there first appear glowing points 0.1 mm in diameter, located quite regularly over the specimen surface with a density of about 100 cm$^{-2}$. These are apparently centers of more intense metal fusion and evaporation. Development and radial expansion of local failure in these centers leads to formation on the surface of a structure in the form of tangent spots up to 1.5 mm in diameter. At the moment of "clarification" the volume of the expanding metal layer is hundreds of times the initial foil volume.

When a 1.4 μ thick aluminum foil is irradiated in air material begins to escape at an energy of $E_i$ = 2.7 kJ/g, close to the liquid metal enthalpy at the boiling point $\Delta H(\ell, T_B)$ = 3.3 kJ/g [5], which is markedly higher than the value recorded in the experiment with the foil. The general form and dimensions of the inhomogeneities which develop upon irradiation of the film are also different: it fails in individuals spots up to 0.5 mm in diameter, the number of which increases up to 200 cm$^{-2}$ during the "clarification" process. In contrast to the foil experiments, the forward boundary of the vapor remains smooth, without individual jets or disturbances. The evaporated material did not scintillate in air.

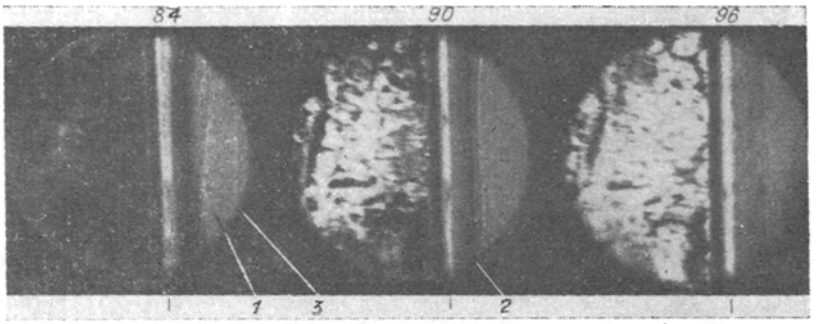


Fig. 3

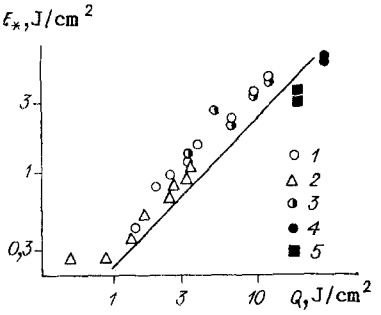


Fig. 4

The experimental results were used to construct the dependence (Fig. 4) of destruction energy $E_*$ on the energy $Q = \rho\delta Q_0$, required for evaporation of a metal specimen of given thickness (for aluminum $Q_0 = 14.1$ kJ/g [5], for bismuth $Q_0 = 1.0$ kJ/g [6]): 1, 2, aluminum and bismuth films in argon; 3, aluminum film in air; 4, aluminum foil in argon. Also shown are data obtained previously [7] for irradiation of lead foil ($\delta = 15$ μ) in air (points 5). The straight line corresponds to the condition $E_* = \Delta H(\ell, T_B)$ (for the metals studied $\Delta H(\ell, T_B) \approx 0.23Q_0$ [5, 6]). It is evident that the destruction energy measurement results for the various metals and experimental conditions agree well with each other and correspond approximately to $\Delta H(\ell, T_B)$. In particular, expansion of the incident radiation spectrum into the shortwave region in argon as compared to air (because of the higher ionization potential of the former) does not have an effect on $E_*/Q$. The maximum fraction of vapor in the destruction "products" does not exceed 20%. Slightly higher values of $E_*$ (and $E_i$) for films as compared to foils (for aluminum) may be caused by the different reflective properties of the specimens, the state of the metal–substrate surface (in the case of foil an air gap is more probable), as well as the mechanical properties of the films and foils.

The quantity $E_*$ is an effective energy value which does not consider losses to reflection from the specimen surface, heat removal into the depths of the substrate, etc. Estimates analogous to those of [2] indicate that the energy transmitted to the substrate up to the time of destruction increases with decrease in specimen thickness and for the thinnest films used may reach 0.85 of the incident energy. The integral reflection over the spectrum has been estimated to be ~0.5 [8]. Thus specimen destruction apparently occurs with absorption of energy significantly less than that required for heating the metal to the boiling point.

The causes of this low-threshold destruction are unclear. The dimensions of the inhomogeneities observed in the irradiation process ($\gtrsim 10^2\ \delta$) scarcely permit an explanation of specimen destruction by any kind of surface effects, for example, rolling of the liquid metal into drops [2]. Most probable is the following pattern of processes in the specimen. When the metal absorbs a corresponding amount of energy it fuses. In the liquid metal a small quantity of vapor is formed on various kinds of inhomogeneities – heterogeneous or homogeneous [9]. As a result of such local "boiling" the liquid volume increases significantly and at some threshold energy value the liquid loses continuity and divides into fine droplets, not resolvable by the experimental apparatus used.

In the process of foil destruction an important role is also played by stresses which develop in the foil material due to rapid heating, which can lead to loss of stability and

produce large deformations which destroy the material [10]. High local stresses can also appear at inhomogeneities in the material upon heating [11].

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# CHARACTER OF FRACTURE AND FILTRATION PROPERTIES OF A FLUID-SATURATED POROUS MEDIUM IN AN UNDERGROUND EXPLOSION

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It is well known that the mechanical action of an explosion in low-porosity media (such as granite) leads to an improvement in the filtration properties of the medium throughout the region affected by the explosion. In high-porosity media saturated with gas, however, explosions lead to a sharp deterioration in the medium's filtration properties [1]. An explosion in a high-porosity cemented medium saturated with a liquid is accompanied by a nonmonotonic change in its filtration parameters near the explosion. Here, while a locally deteriorated zone is formed, permeability overall is improved compared to the original value [2]. The size of the zone in which the filtration characteristics of the medium change turns out to be greater than in the case of the action of an explosion of the same power in a monolithic medium such as granite.

In the present study, we discuss the results of experimental and theoretical investigations of features of the mechanical effect of an underground explosion on porous liquid-saturated media. We examine the reasons for the qualitative difference between the radial dependences of the permeability corresponding to an underground explosion in media having different porosities and levels of saturation.

1. Experimental Method. Tests were conducted under laboratory conditions with spherical explosive charges of TÉN weighing from 1 to 2 g. The charges were exploded in artificially

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