SOME LAWS GOVERNING THE BREAKDOWN OF SOLIDS BY LASER RADIATION

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A macroscopic model of the breakdown of opaque solids, including metals, by laser radiation is presented. Implicit general relationships (model functions) are obtained for the depth and diameter of the developing fissure. These relations characterize the similarity of the breakdown processes and are susceptible of experimental verification. They become explicit and coincide with the analytic solutions of the corresponding problems for two limiting cases of interaction: short single pulses and relatively small radiation fluxes. The development of the fissure depth can be determined for an arbitrary pulse from model functions, a family of which exhibits a parametric dependence on the ratio of the specific activation energies of melting and vaporization of the material. The time evolution of the ejection of the material from the fissure is described by an exponential function that can be used to compute the ejected mass in terms of a thermophysical parameter n. The results of computing the breakdown mass for the case of pure metals agree with experimental data. In the case of brittle materials the breakdown mechanism under consideration is further complicated by cracking and splintering. In that case the "brittle" breakdown can assume the major role and can completely determine the kinetics and the end result of the interaction between the radiation and the solid.

1. INTRODUCTION

THE currently available lasers furnish light beams powerful enough to cause the breakdown of various materials. The laser-induced breakdown of materials has been the subject of a large number of experimental studies but few theoretical papers.

The variety of physical processes responsible for the breakdown of matter by radiation and the diversity of their dependence upon the parameters of the light flux and material preclude at present a rigorous theoretical analysis of the general case of interaction. The experimental studies of the breakdown of various materials revealed a qualitative picture of the phenomenon and a number of important quantitative relationships of the interaction process. At the same time, no special breakdown features due to the coherence and monochromaticity of the radiation were observed. Consequently, the methods of investigating the interaction mechanism and the results obtained can be extended to any radiation of sufficient power, at least in the visible and near infrared regions.

Among the studies of theoretical nature, one should note the solution of the thermal conductivity problems associated with surface heating by laser radiation in which part of the material is vaporized [1-3], or studies to determine welding parameters [4-7]. The recently published paper by Anisimov and others [8] develops a quasi-stationary theory of a one-dimensional vaporization of metals by laser radiation obtained in the free-running mode. A direct experimental determination of the basic quanitative breakdown characteristics of a number of metals and a photographic study of the interaction kinetics yields values of the same order of magnitude as the pure vaporization theory. However the experimentally observed evaluation of the breakdown region (fissures) is essentially not one-dimensional and is accompanied by formation of vapor and molten matter. At the same time, the mass of the liquid metal can exceed the vaporized mass, as is pointed out by the authors of [8] themselves.

Along with thermal processes, estimates were made of the recoil momentum [9] and of the ponderomotive forces [10] associated with the interaction of light with matter. The breakdown of dielectrics is attributed either to the occurrence of thermal stresses [11] or to stimulated Mandel'shtam-Brillouin scattering; mention should be made of the detailed work of Ashkinadze et al.[12], for example.

The physical models proposed for the interaction between laser radiation and matter have been developed only for the individual stages of the interaction; they are therefore incomplete and ap-

plicable only within fairly limited ranges of light flux density and material properties.

Another basic defect of almost all the studies is the assumption of a two-phase breakdown scheme, i.e., a solid-vapor scheme, without taking the melting of the material into account.

An analysis of the process and the available experimental data allow us to postulate a qualitative picture of the development of the laser-induced breakdown of solids. The absorbed energy of radiation is expended in heating the material and causes its breakdown; the latter consists of a combination of vaporization on the one hand and melting-flushing of the material from the breakdown region (fissure) on the other. The role of each process and the mass of the breakdown material ejected in molten and vaporized form vary during the pulse from pure vaporization in the beginning to predominantly melting-flushing at the end of the radiation pulse.

The vaporized material produces in the cavern a definite pressure that flushes a layer of molten material off the walls of the cavern and ejects it to the outside. A portion of the absorbed energy is thus transformed into the kinetic energy of vapor and liquid drops; however, the contribution to the kinetic energy is small compared to the thermal losses when the radiation pulse is relatively long. In the case of a short powerful pulse the share of kinetic energy in the energy balance of the breakdown increases sharply and may become dominant. Since the free-running laser radiation has a spiked structure as a rule, i.e., it consists of a large number of successive random pulses, the vaporized material is ejected in separate batches resembling a series of successive micro-explosions. The flushing of the melt is more inertial in nature and proceeds continuously if the fissure is well developed. When the energy flux is insufficient to melt and vaporize the material, the thermal conductivity mechanism is the principal factor responsible for energy transfer from the irradiated area (volume). The limit of the breakdown onset was estimated by Ready [3] and by Rykalin and Uglov [7].

Material breakdown by partial vaporization and melting-flushing is characteristic of metals and some dielectrics. In certain dielectrics, mainly semi-transparent and heterogeneous materials, the above mechanism is made more complex by brittle breakdown such as microcracks and splintering. In a number of cases the mass (or volume) of the material destroyed by thermally induced phase transitions is much smaller than that due to the brittle breakdown mechanism. In this case, the latter determines the overall nature of the breakdown. In this paper we consider the interaction of light radiation with metals and opaque dielectrics whose breakdown is due to the vaporization and melting-flushing mechanism and is not significantly affected by other mechanisms.

2. SELECTION OF KEY PARAMETERS AND BASIC EQUATIONS

The problem is formulated in the following manner. A powerful radiation flux falls on the surface of a semi-infinite solid. The flux density at the irradiated area should exceed a certain critical value (characteristic of each substance); the breakdown begins above that value and proceeds according to the vaporization and melting-flushing mechanism. We use the following limitations:

1. All the radiation energy is absorbed in the material; consequently we neglect the reflection of light from the surface and from the plasma. The reflection is significant only at the very beginning of the interaction and practically all the energy should be absorbed by a thin layer of the material as the process develops. This is true of the overwhelming majority of materials (an exception is magnesium oxide, for example). There is little absorption and scattering in the gaseous jet outside the breakdown region, since the vapor density inside the fissure is much higher than in the jet.

2. We neglect the ejection of solid material, as it is very rarely observed in the experiments and the mass of the solid particles is small.

3. The energy scattered by mechanical waves in the material and by thermal conductivity is not taken into account. According to estimates based on experimental results, light pulses ~ 1 msec long result in wave-dissipated energy that is 3—5 orders lower than the radiation energy. Heat-conduction losses under these conditions do not exceed 5% of the total energy. The lower limit of flux values for which thermal conductivity "fails" to dissipate the absorbed energy, and material breakdown ensues, is determined by an equilibrium between energy absorption and heat dissipation.

4. The radiation wavelength is not significant since we consider the combination of thermal and mechanical processes. Consequently, the results will be valid within the range of wavelengths that does not contain the lines of the molecular bonds. For the sake of simplicity we confine ourselves to the visible and near-infrared regions.

5. According to estimates, losses to external reradiation, chemical reactions, and ionization can be neglected.

6. We also neglect atmospheric pressure, gravitational forces, and other factors that are insignificant in the interaction process.

In view of the above, the sought breakdown parameters, such as the running values of the depth $l(\tau)$ and diameter $d(\tau)$ of the developing fissure and the mass of the ejected material $m(\tau)$ are determined by the following basic parameters: time τ reckoned from the onset of breakdown, energy $E(\tau)$ emitted by the source (such as a laser) from the onset of the breakdown to a given time instant

$$E(\tau)=\int_0^\tau W(\tau)\,d\tau,$$

where $W(\tau)$ is the radiation power, specific (per unit mass) energy of conversion of the material into liquid (q) and vapor (Q), material density ρ, and coefficient of light absorption μ.

If the radiation is focused, we also consider quantities defining the focusing conditions: relative lens aperture $\alpha = D_0/F$, and depth of focus h, i.e., the distance between the real focus and the surface of the medium.

Consequently the sought quantities l, d, and m will depend only on the system of key parameters:

$$l(\tau)=f(\tau, E(\tau), \rho, q, Q, \mu, \alpha, h);$$

$d(\tau)$ and $m(\tau)$ are written in a similar manner. We select τ, E and Q as the independent-dimension parameters and, in accord with the π-theorem of dimensional analysis, we reduce expressions for l, d and m to relationships between dimensionless complexes (see [13] for example):

$$\frac{l(\tau)}{\tau Q^{1/2}}=f_1\left(\alpha,\ \frac{q}{Q},\ \frac{h}{\tau Q^{1/2}},\ \frac{\rho\tau^3Q^{5/2}}{E(\tau)},\ \mu\tau Q^{1/2}\right),$$
$$\frac{d(\tau)}{\tau Q^{1/2}}=f_2\left(\alpha,\ \frac{q}{Q}\ \frac{h}{\tau Q^{1/2}},\ \frac{\rho\tau^3Q^{5/2}}{E(\tau)},\ \mu\tau Q^{1/2}\right),$$
$$\frac{Qm(\tau)}{E(\tau)}=f_3\left(\alpha,\ \frac{q}{Q},\ \frac{h}{\tau Q^{1/2}},\ \frac{\rho\tau^3Q^{5/2}}{E(\tau)},\ \mu\tau Q^{1/2}\right). \quad (1)$$

Equations (1) contain an implicit description of the breakdown process under consideration. If all the dimensionless function arguments are constant, the left-hand side of the equations should also remain constant. Consequently, the equations in (1) characterize the similarity of (1) the process and allow us to verify the quantities experimentally. Strictly speaking, the values of $E(\tau)$, τ, and Q should not become equal to 0 or ∞ over the entire working range, a circumstance always realized under actual conditions.

Let us examine a narrower class of processes characterized by constant focusing of the radiation and pertaining to the breakdown of materials with a large absorption coefficient μ. As we know from the optics of metals, the majority of metals have large and approximately equal values of μ at a wavelength $\sim 1\ \mu$. This also includes many dielectrics with effective depth of transparency less than 10^{-3} mm, since the dependence of the breakdown parameters on μ is fairly weak. Consequently, the characteristic α will be a constant in the functions, and the dimensionless combinations with h and μ drop out of (1).

In the special case of the breakdown of materials having the same ratio of specific energy of conversion of solid to liquid and vapor, q/Q = const, these relationships are greatly simplified:

$$l(\tau)=\tau Q^{1/2} f_4\left(\frac{\rho\tau^3Q^{5/2}}{E(\tau)}\right),\quad d(\tau)=\tau Q^{1/2} f_5\left(\frac{\rho\tau^3Q^{5/2}}{E(\tau)}\right),$$
$$m(\tau)=\frac{E(\tau)}{Q} f_6\left(\frac{\rho\tau^3Q^{5/2}}{E(\tau)}\right). \quad (2)$$

If l, d, or m is a power-law function of one of the key parameters or is approximated by such a function (which can always be accomplished with a given degree of accuracy), its dependence on the remaining parameters will also be given approximated by a power-law function. This follows from the fact that the argument of the function is limited to a single dimensionless combination of parameters. Therefore (2) can be written as follows, omitting for brevity the arguments of l, d, m, and E:

$$l=\text{const}\cdot\tau Q^{1/2}\left(\frac{\rho\tau^3Q^{5/2}}{E}\right)^k=\text{const}\left(\frac{\rho}{E}\right)^k\tau^{1+3k}\,Q^{(5k+1)/2},$$
$$d=\text{const}\cdot\tau Q^{1/2}\left(\frac{\rho\tau^3Q^{5/2}}{E}\right)^b=\text{const}\cdot\left(\frac{\rho}{E}\right)^b\tau^{1+3b}\,Q^{(5b+1)/2},$$
$$m=\text{const}\cdot\frac{E}{Q}\left(\frac{\rho\tau^3Q^{5/2}}{E}\right)^n=\text{const}\cdot\rho^nE^{1-n}\tau^{3n}Q^{5n/2-1}. \quad (3)$$

3. LIMITING CASES OF INTERACTION

Simple physical considerations and experimentally established facts lead to the conclusion that $l(\tau)$ and $m(\tau)$ do not decrease with increasing τ and E and do not increase with increasing Q. By an analysis of (3) we get from the above conditions a system of inequalities for the variation range of the exponents of ρ, E, τ, and

Q, i.e., for the limits within which each of these parameters affects l and m:

$$\begin{gathered} -1/5 \geqslant k \geqslant -1/3, \quad 2/5 \geqslant n \geqslant 0, \\ 1/3 \geqslant -k \geqslant 1/5, \quad 1 \geqslant 1-n \geqslant 3/5, \\ 2/5 \geqslant 1+3k \geqslant 0, \quad 6/5 \geqslant 3n \geqslant 0, \\ 0 \geqslant \frac{5k+1}{2} \geqslant -\frac{1}{3}, \quad 0 \geqslant \frac{5n}{2}-1 \geqslant -1. \end{gathered} \tag{4}$$

The range limits of the exponent b and thus of the powers that determine the diameter d of the parameters can be found in terms of the depth and the ejected mass. At any instant of time, the mass of the broken-down matter is

$$m(\tau) = \frac{\pi}{4}\rho \int_0^l d^2(l)\,dl,$$

where $l = l(\tau)$. If a certain typical fissue shape remains approximately the same during the development process, $d \approx \text{const} \cdot l$, then we obtain from (3)

$$d \approx \text{const} \cdot \left(\frac{m}{\rho l}\right)^{1/2}$$

$$= \text{const} \cdot \left(\frac{\rho}{E}\right)^{(n-k-1)/2} \tau^{[3(n-k)-1]/2}\, Q^{[5(n-k)-3]/4}.$$

The range limits of k and n in (4) yield the variation limits of the exponents of the parameters determining $d(\tau)$ in (3); the limiting values of the corresponding exponents for $d(\tau)$ and $l(\tau)$ coincide. Consequently the limiting breakdown processes have a spherical symmetry.

An inspection of (4) leads directly to certain conclusions concerning the role of individual factors in the breakdown process. For example, the radiation energy strongly affects the quantity of mass ejected from the fissure and exerts a much weaker effect on the depth of the fissure. The depth is also weakly dependent on the specific energy of conversion to vapor (Q), which confirms the significant role of the ejection of material in liquid phase. The breakdown parameters (l, d, and m) depend explicitly on the time, i.e., the interaction process is in general nonstationary. The effect of the density of the material on the depth and mass indicates energy losses to mechanical work expended in ejecting the material.

The specific breakdown work determined experimentally from the final values of the mass m_0 and the energy $E_0 = E(\tau_e)$ is not the same for all materials, but depends on the radiation energy:

$$\gamma_0 = E_0/m_0 = \text{const} \cdot E_0^n \qquad (0.4 \geqslant n \geqslant 0).$$

Consequently, a rigorous comparison of the strength of materials based on this characteristic is valid only for equal radiation energy per pulse.

Let us consider the limiting cases in the process of material breakdown by high-power radiation.

a. At the upper limit of the range of exponents in (4), ($k = -1/5$ and $n = 2/5$) Eqs. (3) assume the form

$$l = \text{const} \cdot (E/\rho)^{1/5} \tau^{2/5}, \qquad m = \text{const} \cdot \rho^{2/5} E^{3/5} \tau^{6/5}. \tag{5}$$

The process described by these expressions is independent of the specific energy of conversion to vapor and is determined only by the quantities ρ, E, and τ. It is easy to show that the expression for the diameter is similar to that for l.

The resulting relationships coincide with Sedov's solution of the problem of a powerful point explosion in an ideal incompressible liquid [14], and describe the development of the spherical-fissure radius and the mass ejected from it. We can also regard (5) as the law of motion of a spherical shock wave preceding the material breakdown, since the self-similar motion of an incompressible liquid is a limiting case of adiabatic flows with infinite c_p/c_v in the case of point explosions. Therefore the constants in expressions (5) for l and m are $(2\pi)^{-1/5}$ and $1/3(2\pi)^{2/5}$ respectively.

In physical terms this case corresponds to material breakdown by a very short single radiation pulse, such as that obtained from a Q-switched laser. The energy of the single pulse absorbed by a very small volume vaporizes this volume, whose magnitude can be neglected compared with the size of the breakdown region. The resulting gas (plasma) with a very high energy density expands at a high speed as from a point source and causes a purely mechanical breakdown of the neighboring layers of material. The expansion has an explosive character and proceeds practically without vaporization of the ejected mass.

b. The lower limit of the exponential range corresponds to $k = -1/3$ and $n = 0$. From (3) we obtain

$$l = \text{const} \cdot (E(\tau)/\rho Q)^{1/3} \quad \text{(the same for d)}, \qquad m = \text{const} \cdot E(\tau)/Q.$$

The resulting equations describe the process of pure vaporization of the material and expansion of a fissure that remains similar to its initial shape ($d \sim l$). The depth and mass vary in time only with $E(\tau)$, i.e., they "follow" the course of the radiation energy. As expected for the case of pure vaporization, the vaporized mass does not depend on density of the material. The specific work of breakdown γ_0 is constant in this case and equal to the specific energy of conversion of a unit

mass to vapor. Therefore the constant in the expression for m can be set equal to unity, and the value of the constant for l, for a point source of heat, amounts to $(\frac{3}{2}\pi)^{1/3}$. The process of breakdown by vaporization is quasistationary.

The real breakdown of a solid by radiation lies generally between the above limiting mechanisms of interaction, and proceeds with simultaneous vaporization and melting-ejection of the material. The process is described by the implicit equations in (1), or for a more limited class of problems by (2), where the breakdown parameters depend only on a single dimensionless complex. As we have seen, in limiting cases these equations become explicit and coincide with the solutions obtained by analytical means for corresponding problems.

4. BREAKDOWN KINETICS AND EXPERIMENTAL CHECK ON THE OBTAINED RELATIONSHIPS

A typical radiation permitting an experimental observation of the breakdown of solids consists of free-running laser pulses with a total duration ~1 msec. Such a pulse consists of a series of individual spikes ~1 μsec long with randomly changing amplitudes and intervals between the spikes; the latter are an order of magnitude longer than the spike itself.

The breakdown is produced by the pure vaporization mechanism in the course of the first few (or several dozen) spikes of such a pulse incident on a solid surface. Since the fissure has not yet developed during that period, the expansion of the vaporization products approaches spherical symmetry, i.e., the vapor pressure drops like $\sim 1/R^3$ and the absorption of the following radiation by the vapor proceeds approximately like $\sim 1/R^2$. The breakdown products thus provide negligible shielding and the vaporization process itself is quasistationary. The fissure depth increases very slowly and only during the action of the spikes, so that the breakdown is of an intermittent nature.

As the fissure increases the expansion of vapor (plasma) increasingly departs from the spherical symmetry, resulting in a rising absorption by plasma. The flow of escaping vapor heats and melts the walls of the fissure, ejecting drops of molten matter together with the vapor. Both processes intensify as the fissure develops and the proportion of the ejected liquid becomes larger. This disrupts the quasi-stationary nature of the breakdown and changes the intermittent process (accompanying the spike structure of radiation) to a quasi-continuous action due to the inertial flushing of the molten material. The depth of the fissure cavity and the ejected mass become explicitly dependent on the time.

Towards the end of the radiation pulse, vaporization play a diminished role in the breakdown and the melting-flushing process becomes dominant. The radiation absorbed by the plasma within the fissure is not useless, however, and contributes to the melting-flushing breakdown process by increasing the vapor temperature and pressure. Absorption in the jet outside the fissure is considerably lower and can be observed experimentally only at the end of the process, when the breakdown material is deposited on protective glass or on the focusing lens itself, where it screens the radiation. The material becomes ionized apparently in the gaseous phase by absorption of the incident radiation.

Experimental verification of (2) consists in determining the form of the model functions from the experimental functions $l(\tau)$, $E(\tau)$, and $m(\tau)$:

$$\frac{l(t)}{tQ^{1/2}} = f_4\left(\frac{\rho t^3 Q^{5/2}}{E(t+\tau_G)}\right), \tag{2a}$$

$$\frac{Qm(t)}{E(t+\tau_G)} = f_6\left(\frac{\rho t^3 Q^{5/2}}{E(t+\tau_G)}\right). \tag{2b}$$

The functions f_4 and f_6 are parametrically dependent on the ratio q/Q, and the time t is reckoned from the onset τ_b of intense development of the fissure. Figure 1 shows plots of the function f_4 for tin and aluminum (q/Q is 0.033 and 0.08 respectively) in logarithmic coordinates. The slope of the tangent at any point on the plot characterizes the value of the power k of the power-law approximation of function f_4. The plots show that an approximation in the form of a power-law function is not acceptable in this case.

Consequently, generalized model functions plotted for every value of the parameter q/Q can be used to predict the course of the function $l(t)$ and the final value of fissure depth for any function $E(t)$, i.e., for any radiation pulse. We should take into account here the different starting points of the functions $E(t)$ and $l(t)$. For example, the computed value of the final depth in aluminum for an energy of 150 J is 6.3 mm, while the experimental value for duraluminum is about 6.5 mm according to Anisimov et al.[8]. The coalescence of the model curves (Fig. 1) for various materials at a point corresponding to the onset of breakdown indicates that during the initial period the interaction is indeed a pure vaporization process.

The model function for the ejection of the broken-down mass is obtained in the same manner

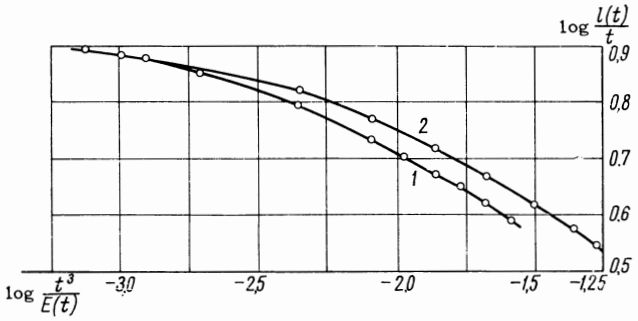

FIG. 1. Model functions of fissure depth for tin (1) and aluminum (2).

as in the case of the fissure depth. Since the course of the function m(t) is adequately approximated by the power-law expression (3), the model plots become straight lines in logarithmic coordinates:

$$\log \frac{m(t)}{E(t)} = B + n \log \frac{t^3}{E(t)}.$$

B is determined by the values of q and Q of the material and also by the initial focusing conditions. An example of a function modeling the mass ejection for tin is shown in Fig. 2 for a pulse energy E_0 = 188 J. The slope of the straight line gives the value of the exponent n, which is 0.24 for tin. Let us note that this value is approximately halfway between the limiting values 0 and 0.4 in (4), indicating that vaporization and melting-flushing have an approximately equal effect.

Since (2b) is strictly valid only when q/Q is constant, the parameter n in the power-law approximation of mass m is different for different materials and is determined by the value of this ratio. The constant factor in the last equation of (3) defines the focusing conditions and depends on the angular dimension α of the radiation flux.

Thus it is possible to obtain a general equation for the ejection of mass in the breakdown of various practically opaque materials by powerful radiation flux:

$$m(t) = A(\alpha)\rho^n Q^{5n/2-1} t^{3n} E^{1-n}(t + \tau_b). \qquad (6)$$

If the depth of focusing remains constant, the factor $A(\alpha)$ depends on the relative aperture of the focusing lens $\alpha = D_0/F$. The quantity τ_b is the

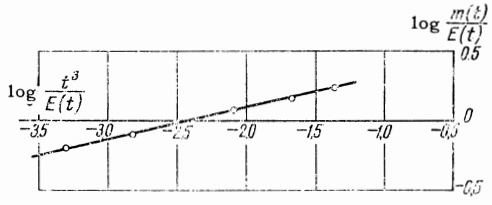

FIG. 2. Model function of ejected mass for tin (E_0 = 188 j) for use in determining the parameter n.

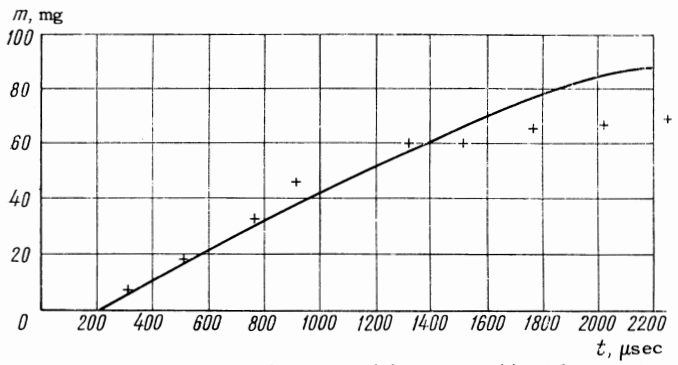

FIG. 3. Comparison of computed function m(t) with experimental data (+ designates tin, E_0 = 72 J).

time elapsed from the arrival of the light front at the surface of the material to the onset of the breakdown.

The above equation was used to compute the time dependence of the material ejection for a pulse energy of E_0 = 72 J in the case of tin. Figure 3 shows a comparison of the computed function with the approximate experimental values of m(t). The computed and experimental values are in satisfactory agreement; the divergence towards the end of the pulse is due to screening of radiation by the deposition of vapor on the protective glass, as pointed out above.

The total mass ejected per pulse as computed according to (6) for the case of pure metals agrees within 20% with the experimental data of Anisimov et al.[8] The computed results differ significantly from the tabulated values of the heat of sublimation; in some cases (tin) the difference may exceed a factor of 2.5.

The parameter n in (6) determines the mass as a function of the specific energy Q of conversion to vapor, and also the explicit time dependence of mass due to the inertial nature of the liquid-phase ejection. In other words, n characterizes the relationship between the concurrent processes of vaporization and melting-flushing in the material breakdown at various radiation energies, and thus depends on the ratio of specific energies of activation q/Q of these processes: n = n(q/Q).

The parameter n can be determined by two methods for every material. The functions m(t) and E(t) obtained in the same experiment are used to compute the value of n corresponding to the limiting ratio q/Q, as shown in the case of tin. The resulting value of n is then used in computations based on (6) for any form of the radiation pulse E(t) for the same material (q/Q = const), or for any other material having approximately the same value of q/Q.

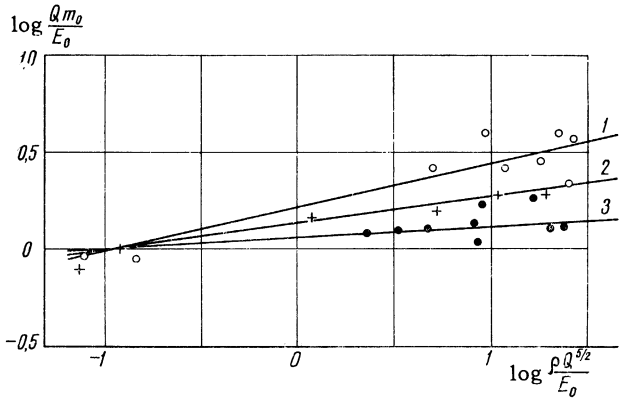

FIG. 4. Parameter n obtained from final results. 1–for q/Q = 0.05 - 0.08; 2–for q/Q = 0.096 - 0.1; 3–for q/Q = 0.13 - 0.156.

The other method consist in determining the parameter n from the end results of the interaction at a constant pulse length. If we substitute the energy of the entire light pulse E_0 and the total ejected mass m_0 into (6) and take logarithms, we arrive at the following expression

$$\lg \frac{Qm_0}{E_0} = A_m + n \lg \frac{\rho Q^{5/2}}{E_0}.$$

Individual points plotted from the experimental values of m_0 and E_0 readily fall on the linear plots for groups of metals having close values of the q/Q ratio (Fig. 4). It must be noted here that the considerable scatter of the experimental points is due to certain differences in the divergence of the light beam at different energies, to small systematic deviations of the focus from the surface, and to errors in computing the values of q and Q. Moreover, every averaged straight line was derived for several metals within an interval of values for q/Q.

The slope of each straight line defines a sought value of n in the table. Of interest is the fact that all straight lines intersect at a common point, the origin of coordinates. This point corresponds to the relation $E_0 = Qm_0$, i.e., to energy losses to vaporization of the total mass only, and permits us to find the constant A_m associated with the focusing. The table shows that n increases with decreasing q/Q. Consequently, at low values of q/Q when the material is much easier to melt than to vaporize, the parameter n grows larger, i.e., the ejected mass increases. This once more emphasizes the major role of melting-flushing in radiation-induced breakdown of material.

An exact form of the function n(q/Q) requires an analysis of the kinetics of two-dimensional breakdown and expansion of material with all its three phase states taken into account. This will make it possible to compute the ejection of the breakdown mass without having to use experimentally determined parameters.

Range of q/Q	Metals	n average
0.13—0.156	Iron, nickel, titanium	0.085
0.096—0.1	Copper, cadmium	0.15
0.05—0.08	Magnesium, lead, bismuth, aluminum	0.22
0.033	Tin	0.24*

*The value of n for tin was determined from the time-dependent function m(t) in one experiment.

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