MECHANISM FOR THE FLASH UNDER THE EFFECT OF MONOCHROMATIC RADIATION ON METAL SURFACES

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A flash is due to the piston effect during the spraying and subsequent evaporation of a melt drop layer in a medium with initial pressures and temperatures equal to the temperature and pressure of the vapors which have been formed earlier above the metal surface, but at a diminished flow velocity.

The comparison between experimental and theoretical results [1-6] shows that for radiation fluxes $q \simeq 10^7$ W/cm^2 at the wavelength $\lambda \simeq 1.1$ μm, a sharp discrepancy exists on an aluminum surface between the large computed and the small experimental flash times (the beginning of the avalanchelike temperature rise and the optical absorption of the vapors) τ_{fl}. Thus, for average fluxes $\sim 1.5 \cdot 10^7$ W/cm^2, according to [5, 6], the experimental heating and flash development time on aluminum is $\geqslant 0.5$ μsec. The results apparently depend weakly on the surrounding gas (air, helium, argon, vacuum). The computed time is on the order of 10^2 μsec. This discrepancy is conserved even when taking account of separation of the electron and gas temperature $T_e > T$ and the ionization nonequilibrium which result in an increase in the electron concentration and the coefficient of optical absorption of the vapors.

Theoretically, according to [3, 5], for a flash to develop with $q \sim (10^7 - 10^8)$ W/cm^2 it is necessary that the optical thickness be >0.01, which corresponds to a temperature of >5000°K at pressures of tens of atmospheres (the initial warming of the vapors to these or lower parameters could be achieved by heating the surface and by the piston effect on the target).

It is difficult to explain the discrepancy between theory and experiment by contaminating impurities. Thus, the spectral width of the neodymium laser radiation used in the experiment is much greater than the width of the atomic spectral lines with the absorption coefficient $k(\nu) \gg 1$, although in other cases there is theoretically the possibility (with a very low probability) of incidence of the narrow (gas) laser line on a line contained in negligible quantities (<0.1%) of impurities. Easily ionized admixtures can specify a multiple increase in the electron concentration n_e and the absorption coefficient $k(\nu)$ sufficient for a flash (corresponding to a change in n_e for $T = 4000 \to 5000$°K) only for an impurity content >0.1%. The strong dependence, noted in [4], of the flash time on the state of the surface can be explained by the strong dependence of the surface heating time to the boiling point $\tau_{heat} \infty 1/q^2 (1 - \alpha)^2$ on the coefficient of reflection α.

Let us show that a flash cannot be explained by nonequilibrium since the latter is small. The separation of the temperatures T_e, T is diminished substantially upon taking account of the energy exchange during inelastic collisions, which were not considered in [1-3].

For the characteristic values $T_e \simeq T \simeq 4000$°K; $p = 15$ atm; $q \simeq 10^7$ W/cm^2, we have from the Saha formula $n_e = 1.2 \cdot 10^{16}$ cm^{-3}; the atom concentration is $N = 2.8 \cdot 10^{19}$ cm^{-3}, the molar fraction of electrons is $x_e = n_e/N = 4.3 \cdot 10^{-4}$ (Al vapors). The free – free part of the coefficient of absorption by electrons in a field of neutral atoms was calculated according to [7] and equals $k_0 = 1.4 \cdot 10^{-3}$ cm^{-3} for a radius $r_{Al} = 2.5$ Å. The free – free and free – bound parts of the coefficient of absorption in an ion field equals $k_+ = 2.1 \cdot 10^{-3}$ cm^{-1} according to the Kramers formula with $Z_{ef} = 1$.

According to a simple estimate [8], the electron distribution function is Maxwellian for these conditions; hence the excitation section of a resonance level $\varepsilon_p = 3.14$ eV by electron impact was used, which was computed as a function of the energy from the data in [9].

For the influx velocity and the energy loss per unit volume during elastic electron – ion collisions and inelastic collisions between electrons and atoms, we have

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$$\frac{d\varepsilon}{dt} = qk(\nu) \ll \left|\frac{q\varepsilon_{ei}}{dt}\right| \ll \left|\frac{d\varepsilon_{ea}}{dt}\right|.$$

The inequalities are strengthened for T>4000°K.

In the long run, the role of the inelastic losses is determined by a "narrow place": the velocity of deactivation of the excited state Al* during collisions with Al atoms with the passage of the excitation energy into translation energy.

The deactivation (quenching) section is unknown for Al; it can apparently be determined by a process analogous to dissociative recombination with a probability strongly dependent on the mutual location of the potential curves of the stable and unstable states of the Al_2 molecule [10]. Taking into account the presence of a stable molecular state of Al_2, it is natural to expect that the probability of this process can turn out to be quite large. Thus, for the value $r_{Al} \simeq 2.5$ Å we obtain for the rate of loss during deactivation $-d\varepsilon_{aa}/dt \gg |d\varepsilon_{aa}/dt|$, and corresponding to this, the rapid equilibration of the separation between T and T_e.

The significant emission of electrons, apparently because of thermoemission by microinhomogeneities during the action of laser radiation with an ~1μm wavelength $\tau \sim 1$ msec duration, and energy density ε up to 1 J/cm^2 on an aluminum plate in a vacuum, has been detected experimentally in [17]. With the growth of ε during the simultaneous diminution in τ, i.e., with the rise in temperature, the growth of the thermoemission by many orders of magnitude is possible [12]. In the presence of a thermodynamic vapor — liquid equilibrium, the electron concentrations cannot exceed the thermodynamic concentrations being determined by the ionization equilibrium (the Saha formula) in the vapor, correspondingly the flash cannot be explained by thermoemission because of overheating by target microinhomogeneities.

One of the equally likely mechanisms for a flash at moderate q is local overheating of the vapor during evaporation of the drops being formed during fractionation of the liquid melt because of the combined effect of the inhomogeneity of the laser radiation, surface tension, pressure, and inertia forces.

The following model for the step-by-step origination of a flash is proposed below: evaporation of the target surface resulting in the formation of a vapor with a temperature of ~4000°K and a pressure of ~10-20 atm (direct heating from the target and partially the piston effect); drift of the contact boundary to a comparatively long distance from the surface, formation of melt drops flying slowly relative to the cold and hot evaporating drops; optical shielding of the target surface by a layer of drops and attenuating or cutting off its evaporation; drop in the vapor velocity at the surface with the conservation of the same pressure and temperature; heating of the drops and their evaporation into this medium; a new rise in the vapor pressure and temperature above the layer of evaporating drops because of the piston effect (but during the evaporation of the layer of drops).

Assuming the formation and fractionation of the melt drops to be determined by the pressure gradients because of the laser radiation inhomogeneities near the surface, we take the surface tension $\sigma \leq 914$ dyn/cm [12]* and the pressure gradient as governing parameters, which we represent as

$$S_l = \frac{\partial(p + \rho v^2)}{\partial x} \simeq \zeta \frac{p + \rho v^2}{d},$$

where d is the characteristic size of the light spot; v is the mean velocity of atoms flying off from the melt, ζ is an empirical coefficient close to one according to [14].

Since $\rho v \infty q/q_{ev}$, and for a semi-Maxwellian distribution

$$v \simeq \sqrt{2kT_{sur}/\pi m_{Al}} \simeq 0.9 \text{ km/sec} \simeq \text{const},$$

where T_{sur} is the surface temperature ~4000°K; q_{ev} is the heat of evaporation 11.8 kJ/g [15], m_{Al} is the mass of an aluminum atom, ρ is the density of the vapor at the surface, then

$$p - p_0 \simeq p \simeq \rho v^2 \simeq \frac{\beta}{2} \frac{vq(1-\alpha)}{q_{ev}}, \tag{1}$$

where β is a semiempirical factor close to 0.8 under the conditions in [5] (see the experimental pressures behind the shock front in [5]; low values of β are apparently due to significant losses by heat conduction in the target), and $p_0 \ll p$ is the initial air pressure above the target.

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*Since the critical temperature for Al is $T_{cr} \simeq 8400$°K [13], the drop in σ with temperature should be slower than that computed according to the theoretical dependence proposed in [12]. Let us note that the heat-conduction coefficient of liquid Al varies negligibly to T ~6500°K [13].

From dimensionality relationships, the upper value of the characteristic drop diameter and the fractionation layer thickness, corresponding to the static equilibration of the pressure drop and the surface tension forces, is for $d \simeq 5$ mm

$$D_{\max} \sim \left[\frac{\sigma q_{\text{ev}} d}{\beta \zeta v q (1-\alpha)} \right]^{1/2} \simeq 40 \ \mu\text{m}.$$

However, there exists a mechanism resulting in a sharp increase in the total pressure gradients after the beginning of evaporation and corresponding to the substantial diminution in the drop size.

Neglecting the heat of fusion (0.4 kJ/g) in comparison with the heat for heating to ~3000°K, we obtain the melt thickness to the beginning of boiling from the heat-conduction equation (for a coefficient of liquid heat conduction $\varkappa \simeq 0.6$ W/cm · deg):

$$\Delta x \sim \varkappa \Delta T / q (1-\alpha) \simeq 3.6 \ \mu\text{m};$$

the melting time

$$\Delta t \sim (\Delta x)^2 c_p \rho_l / \varkappa \simeq 0.3 \ \mu\text{sec}$$

($\rho_l \simeq 2.7$ g/cm^3 is the density of Al).

The thin liquid film is itself unstable. The self-accelerating mechanism of drop formation is that a certain amplification of the laser radiation on one of the sections and a corresponding rise in the local pressure result in the occurrence of a flow of melt and the displacement of fluid from the lower layers into the adjacent sections with the latter becoming cool because of fluid mixing and the drop in the intensity of evaporation and head ρv^2. Growth of the drop $(p+\rho v^2)$ hence contributes to a still greater acceleration of the overflow and a further rise in the gradient $\partial(p+\rho v^2)/dl$.

Under the combined effect of the head

$$\Delta p \sim C_f \rho v^2 \frac{\pi R^2}{2\pi R^2},$$

where the coefficient is $C_f \simeq 1$ [16] for the existing Reynolds number ~50, and the surface tension $2\sigma/R$, the drop diameter during fractionation of the melt layer is

$$D \simeq \frac{8\sigma}{\rho v^2} = \frac{16 \sigma q_{\text{ev}}}{\beta v q (1-\alpha)}. \tag{2}$$

The quantity of the liquid phase being sprayed is hence apparently limited only by the condition of self-consistency: the optical thickness in a layer of drops being determined by the ratio between the total area of the opaque sections πR^2 of the drops and the area of the acting spot $\pi d^2/4$ should be on the order of 0.5-1. It follows from the closeness of the drop diameter and the thickness of the melt layer (for any q) that the spacings between the drops are also on the order of their size at the time of layer formation (the whole liquid phase is "skimmed").*

The time of drop acceleration by the stream to the velocity v of the head ρv^2 is

$$\tau_{\text{acc}} \sim \frac{Mv}{\pi R^2 \rho v^2} = \frac{64 \rho_l \sigma q_{\text{ev}}^2}{3 v q^2 (1-\alpha)^2 \beta^2}.$$

The time to form the absorbing layer (the time for the drops to traverse the spacing ~D) is

$$\tau_{\text{layer}} \sim \sqrt{\frac{2MD}{\pi R^2 \rho v^2}} \simeq \left[\frac{683 \sigma^2 \rho_l q_{\text{ev}}^3}{\beta^3 v^3 q^3 (1-\alpha)^3} \right]^{1/2}. \tag{3}$$

The time to heat the drops to the boiling point is

$$\tau^{(\text{K})}_{\text{heat}} \sim \frac{c_p M \Delta T}{q (1-\alpha) \pi R^2} \simeq \frac{32 \rho_l c_p \Delta T \sigma q_{\text{ev}}}{3 \beta q^2 (1-\alpha)^2 v}. \tag{4}$$

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* The formation of the drops and their heating are accelerated by vapor condensation on their surfaces. Thus, for a vapor density of $\rho \cong 10^{-3}$ g/cm^3 and spherical condensation at the speed of sound, the lower boundary of the time to heat a 5 μm diameter drop by $\Delta T = 2500$°K is >0.3 μsec.

The initial temperature drop ΔT, governing the temperature gradient of the melt on the evaporating surface is found from the heat-conduction equation for a thickness $\Delta x \sim D$:

$$T_{\text{boil}} - T_{\text{d}} \equiv \Delta T \sim \frac{1}{2}\,\frac{q(1-\alpha)}{\varkappa}\,\frac{8\sigma}{\rho v^2} \simeq \frac{8\sigma q_{\text{ev}}}{\beta\varkappa v}$$

or, if ΔT exceeds $(T_{\text{boil}} - T_{\text{m}})/2$, takes the latter value, where T_{d} is the initial temperature of the drop being formed; $T_{\text{boil}} \simeq T_{\text{sur}} \simeq 4000$°K; T_{m} is the melting point $\simeq 1000$°K.

The evaporation time is

$$\tau_{\text{ev}}^{(\text{K})} \sim \frac{q_{\text{ev}} M}{q(1-\alpha)\pi R^2} = \frac{32}{3\beta}\,\frac{q_{\text{ev}}^2 \sigma \rho_l}{v q^2 (1-\alpha)^2}.$$

During $\tau_{\text{sat}}^{(\text{K})}$ a drop traverses the path

$$s^{(\text{K})} \simeq \frac{8}{3}\,\frac{\rho_l c_p^2 (\Delta T)^2 \sigma}{q^2(1-\alpha)^2} \tag{5}$$

with acceleration.

Substituting the numerical values for $\varkappa \simeq 0.6$ W/cm · deg, $c_p \simeq 1$ J/g·deg, we obtain $D \simeq 4.8$ μm; $M \simeq 1.6 \cdot 10^{-10}$ g; $\tau_{\text{acc}} \simeq 5.1$ μsec; $\Delta T \simeq (T_{\text{boil}} - T_{\text{m}})/2 \simeq 1500$°K; $\tau_{\text{sat}}^{(\text{K})} \simeq 0.26$ μsec; $\tau_{\text{ev}}^{(\text{K})} \simeq 2.0$ μsec; $s^{(\text{K})} \simeq 6$ μm; $\tau_{\text{layer}} \simeq 0.23$ μsec.

Similar results are obtained for copper, e.g., despite the significant differences in the thermophysical parameters [12, 15]. From the energy balance

$$\frac{\rho_{\text{sat}}(T)}{2}\, v(T)\, q_{\text{ev}} \simeq \frac{\beta}{2}\, q(1-\alpha), \tag{6}$$

where $\rho_{\text{sat}}(T)$ is the density of the saturated vapors, and from (1)-(5), we find $T_{\text{sur}} \simeq 4300$°K; $\rho v^2 \simeq 25$ atm; $D \simeq 4.4$ μm; $\tau_{\text{layer}} \simeq 0.3$ μsec; $\tau_{\text{sur}}^{(\text{K})} \simeq 0.35$ μsec; $s^{(\text{K})} \simeq 6.2$ μm; $v \simeq 0.6$ km/sec.

The drops of the melt do not themselves cause the flash although they increase the absorption coefficient (in addition, the absorbed energy is expended in the evaporation of drops and the effect is equivalent to the transfer of sections of the evaporating surface a distance $s^{(\text{k})}$; however, a growth of 1.5-2 times is possible for the absorption in the vapor because of the increase in the optical path of the radiation due to multiple reflection and scattering by the drops).

Therefore, the role of the drops is determined by the local overheating of the vapor during the motion and evaporation in the stream, which play the part of seed centers of absorption because of the sharp temperature dependence of $k(\nu)$.

A natural limit on the model being developed is the condition $s^{(\text{k})} \gtrsim D$, which reduces for aluminum to

$$q \lesssim \rho_l c_p^2 \beta v (\Delta T)^2 / 6(1-\alpha) q_{\text{ev}} \simeq 1.2 \cdot 10^7 \text{ W/cm}^2$$

(for copper $1.4 \cdot 10^7$ W/cm²). At the same time, e.g., for $q \simeq 10^6$ W/cm² we would obtain $\tau_{\text{fl}} \geq \tau_{\text{sat}}^{(\text{k})} \simeq 26$ μsec for the minimal flash time (if it were generally possible).

For the evaporation of drops in a medium with the pressure p_0 (in the case under consideration $p_0 = 15$ atm), under the assumption of a significant drop in the velocity of the vapor because of the "shadow effect" (both the diminution in evaporation because of shielding of the radiation by the drops and the formation of a "dead zone" of the stream on the reverse side of the drop layer), the total static pressure P would equal the sum of the external p_0 and the excess pressure needed to produce the head $\rho v^2 = S_{\text{M}}/\rho$, where S_{M} is the mass flow rate of the vapor.

Using (1) and the Clapeyron equation, we find

$$P \simeq p_0 + \frac{S_{\text{M}}^2 kT}{P m_{\text{Al}}} \simeq p_0 + \frac{kT}{P m_{\text{Al}}}\left[\frac{\beta q(1-\alpha)}{2 q_{\text{ev}}}\right]^2$$

from the relationship

$$P = p_0\, \frac{1 + \sqrt{1 + \dfrac{4}{p_0^2}\,\dfrac{kT}{m_{\text{Al}}}\left[\dfrac{\beta}{2}\,\dfrac{q(1-\alpha)}{q_{\text{ev}}}\right]^2}}{2} \simeq 3.64\, p_0, \tag{7}$$

where $\beta \simeq 2$ (because of the preliminary almost total heating of the drop and its small size, the losses by heat conduction in the drop and heating of the vapor being formed can be neglected). In conformity with the phase dependence

$$P \sim \exp\left(-\frac{m_{\mathrm{Al}}\, q_{\mathrm{ev}}}{kT}\right)$$

the temperature of the drop should be raised by

$$\Delta T \sim \frac{kT^2}{m_{\mathrm{Al}}\, q_{\mathrm{ev}}} \ln 3.64 \simeq 350^\circ\mathrm{K} \tag{8}$$

For $T = 4350^\circ$K we have $\rho \simeq m_{\mathrm{Al}} P/kT \simeq 4.1 \cdot 10^{-3}$ g/cm^3; $\nu = S_M/\rho \simeq 1.0 \cdot 10^5$ cm/sec; $\rho v^2 \simeq 43$ atm.

A temperature rise to*

$$\frac{T_2}{T_1} \sim \left(\frac{P_T}{p_0}\right)^{\frac{\gamma-1}{\gamma}} \simeq (6.5)^{0,333} = 1.9 \text{ times (for } \gamma \simeq 1.5) \tag{9}$$

is possible at the stagnation point of such a jet in a uniform flow (plane layer of drops) at the stagnation pressure $P_T = P + \rho v^2$.

Therefore, for this extreme case we obtain a maximum gas temperature to 8200°K for a total pressure of $P_T \sim 100$ atm at distances of many diameters from the evaporating layer of drops depending on the thickness of the vapor layer within whose limits the initial velocities (up to the beginning of drop evaporation) are small. Corresponding to these parameters are: $N = 8.9 \cdot 10^{19}$ cm^{-3}; $n_e = 3.2 \cdot 10^{18}$ cm^{-3}; $x_e = 3.4 \cdot 10^{-2}$, the coefficient of absorption is $k(\nu) = k_0 + k_+ = 1.8 + 14 = 16$ cm^{-1}.

The time to heat the vapor to 1000°K (which can be taken approximately as the beginning of the flash) for this absorption coefficient is

$$\tau \sim \frac{c_p \rho \Delta T}{k(\nu) q} \simeq 2.6 \cdot 10^{-2}\ \mu\text{sec},$$

which corresponds to the absorbing vapor having traversed the distance $\tau v \sim 26\ \mu$m $\sim 5D$.

Estimates using the excitation section of the level $\varepsilon_p = 3.14$ eV [9] (the possible narrow place for stepwise ionization) show that the time to build up ionization equilibrium is $\ll \tau$.

A practical formulation for an approximate estimate of the flash time according to (4) (taking (3) into account) follows from the analysis made.

The possibility of flash development for weaker fluxes is determined (for the numerical solution of gasdynamic equations, for example) by giving $v \simeq 0$ as the initial condition at this time while conserving the distributions of T, p, and ρ existing at this time and the results of the subsequent solution of the gasdynamic problem.

NOTATION

q, flux density of the monochromatic radiation; λ, radiation wavelength; τ_{ev}, time corresponding to the beginning of the flash; T, T_e, gas and electron temperatures; $k(\nu)$, spectral coefficient of absorption (per unit length) for the wave number ν; p, gas pressure; n_e, electron concentration; N, atom concentration; x_e, molar fraction of electrons; r_{Al}, radius of aluminum during interaction with electrons; k_0, k_+, parts of the absorption coefficient corresponding to the free—free and free—bound electron transitions in a field of neutral atoms (k_0) and ions (k_+); Z_{ef}, effective charge on the nucleus in the Kramers formula; σ, surface tension of the melt; S_l, total pressure gradient; ρ, density; v, gas velocity at the evaporating surface; d, effective diameter of the light spot; β, ξ, dimensionless empirical coefficients; q_{ev}, head of evaporation (per unit mass); T_{sur}, temperature of the evaporating surface; α, coefficient of reflection; $T_{\mathrm{boil}} \simeq T_{\mathrm{sur}}$, boiling point during development of evaporation in a medium with a steady pressure rise; D, effective diameter; R, radius of the liquid drop; $\varkappa$, heat-conductivity coefficient of the liquid or solid phase; ρ_l, density of the melt; c_p, specific heat of the melt or vapor; Cf, gasdynamic drag coefficient of the drop in the vapor stream; M, mass of the drop; τ_{acc}, time to accelerate the drop to the velocity v by the head ρv^2; τ_{layer}, characteristic time for formation of the drop layer; $\tau^{(k)}_{\mathrm{heat}}$, time

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* For Mach numbers ~1-2 the results of a temperature computation by means of the Poisson adiabat and by the usual adiabat differ slightly.

to heat the drops of melt to the boiling point; $\tau_{ev}^{(k)}$, time for drop evaporation; $S^{(k)}$, spacing traversed with acceleration of drops of the melt during the time $\tau_{heat}^{(k)}$; $\rho_{sat(T)}$, density corresponding to the saturated vapor with the temperature T; S_M, mass rate of flow of vapor; p_0, vapor pressure before the beginning of evaporation of melt drops; P, static vapor pressure at which drop evaporation occurs; γ, adiabatic index; T_1, T_2, initial and final temperatures under adiabatic compression; P_T, stagnation pressure.

LITERATURE CITED

1. I. V. Nemchinov and S. P. Popov, Pis'ma Zh. Eksp. Teor. Fiz., 11, 495 (1970)
2. I. V. Nemchinov and S. P. Popov, Prikl. Mekh. Tekh. Fiz., No. 5 (1971).
3. V. I. Bergel'son et al., Kvantovaya Elektron., No. 4 (16) (1973).
4. A. I. Barchukov et al., Zh. Eksp. Teor. Fiz., 66, No. 3 (1974).
5. N. N. Kozlova, A. I. Petrukhin, and V. A. Sulyaev, Kvantovaya Elektron., 2, No. 7 (1975).
6. N. N. Kozlova et al., Kvantovaya Elektron., 2, No. 9 (1975).
7. V. A. Kamenshchikov, Yu. A. Plastinin, et al., Radiation Properties of Gases at High Temperatures [in Russian], Mashinostroenie, Moscow (1971).
8. V. N. Soshnikov and E. S. Trekhov, Zh. Tekh. Fiz., 37, No. 8 (1967).
9. L. A. Vainshtein, I. I. Sobel'man, and E. A. Yukov, Excitation Sections of Atoms and Ions by Electrons [in Russian], Nauka, Moscow (1973).
10. D. R. Bates (editor), Atomic and Molecular Processes, Academic Press (1962); V. N. Soshnikov, Elementary Processes in a Low-Temperature Plasma [in Russian], Moscow Engineering Physics Institute (1969).
11. L. V. Gurvich et al., Thermodynamic Properties of Individual Substances [in Russian], Vol. 1 (1962).
12. I. A. Kikoin (editor), Table of Physical Quantities [in Russian], Vol. 1 (1962).
13. A. Grosse, Rev. Int. Hautes Temp. Refract., 3, No. 2 (1966).
14. J. F. Ready, Effects of High-Power Laser Radiation, Academic Press (1971).
15. V. S. Chirkin, Thermophysical Properties of Nuclear Engineering Materials [in Russian], Atomizdat, Moscow (1968).
16. L. I. Sedov, Similarity Methods and Dimensional Analysis in Mechanics [in Russian], Nauka, Moscow (1965).
17. G. A. Pelepelina and B. T. Fedyushin, Prib. Tekh. Eksp., No. 6 (1975).