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INVESTIGATION OF PHYSICAL PROCESSES IN THE CENTRIFUGAL DISPERSION OF MATERIALS WITH HIGH VAPOR AND GAS RELEASE

A. N. Ponomarev

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We have analyzed the physical processes in a vacuum chamber in the centrifugal dispersion of blanks of D16 and AMg6 aluminum blanks rotating at a rate of 10–80 m/sec with local melting under the action of a stationary electron beam of power density $\sim 10^9$ *W/*m^2*. A method for approximate calculations of melting under flash heating, diffusion, and vapor and gas release into vacuum is proposed.*

In the course of experiments on vacuum impact-drop compaction of specimens, it was revealed that the evacuation system of an ad hoc water-cooled vacuum chamber of volume about 1300 liters provides an abnormally high evacuation rate of hot (T = 1000 K) products of vapor and gas release of alloys exceeding many times its rated value for the vacuum pumps used [1]. The reason for this should be sought in the so-called "getter," gas-absorbing, effect. The mechanisms of action of various getters are complex and differ from pure physical absorption — along with absorption, chemical and electrical processes proceed in them to a different degree.

1. Features of Experiments on Impact-Drop Compaction. Figure 1 schematically represents the centrifugal dispersion. An aluminum alloy blank in the form of a disk of height 70–100 mm and perimeter about 1 m on the narrow heating band of its cylindrical surface, rotating at a controlled rate, was exposed to an electron beam with an energy of about 20 keV (focal diameter of ~3–4 mm). For the calculations, we took a square with a side of 3.6 mm.

Below we present the results of the calculations and experiments for the most studied "main" dispersion conditions at a rotation frequency f = 20 Hz (circular rotation of 20 m/sec, centrifugal acceleration of 2500 m/sec^2). After ~1 min of irradiation, a narrow beam of drops began to separate steadily from the blank with a frequency of about ν = 6400 Hz and a mass flow G_m = 1.5 g/sec, which in the first 1.5–2 min of dispersion could be considered to be monodisperse with a diameter in the solid state d_{sol} = 0.55 m (d_{liq} = 0.575 mm), and the beam proper — a train (series). In this time interval, the mass ablation band of the blank remains approximately cylindrical, and the change in the blank radius on the heating band is about 7 μm per rotation. Subsequently, there appears a gradually growing dagger-like cut space with a sharp top, with its finite size at the base exceeding the heating spot diameter and reaching 8–10 mm (Fig. 2). These features are described in more detail in [2].

The ranges of contents of standard doping components and possible impurities of D16 and AMg6 alloys are specified by their corresponding State Standards and are as follows (in mass %): D16: 4.3 Cu, 0.6 Mn, 1.5 Mg (the range of the Mg content is 1.2–1.8), the Zn impurity is up to 0.3; AMg6: (5.8–6.8) Mg, (0.5–0.8) Mn, (0.02–0.1) Ti, and (0.0002–0.005) Be.

Since the values of the partial pressure of magnesium vapors over these alloys, even with allowance (according to the Raoult law) for the small values of its molar fractions, exceed by 3–5 orders of magnitude, depending on the temperature, the total pressure of the basis metal (aluminum) and all the other standard components, in our problem these alloys can be treated, in calculating the vapor release, as binary solutions with a practically nonvaporizable basis. For liquid solutions, the diffusion coefficient of magnesium in aluminum, equal to $D = 7.54 \cdot 10^{-9}$ m^2/sec (in the required range of T and C), is known [3]. The influence of the possible volatile zinc impurity is not considered here because of the indefiniteness of its actual content in alloys, but the proposed computational procedure is suitable for it as well.

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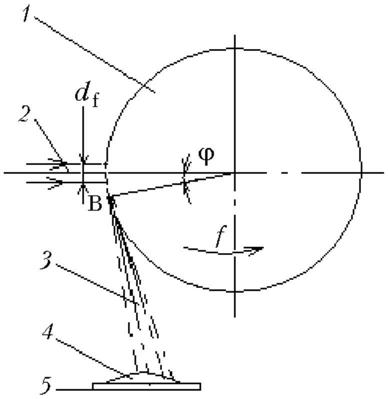

Fig. 1. Scheme of the centrifugal dispersion: 1) blank disk (πd_b = 1 m); 2) electron beam; 3) flow of drops with separation at point B (angle $\varphi \approx 11^o$); 4) impact-drop compact; 5) thermostated substrate reciprocating transversely to the figure plane.

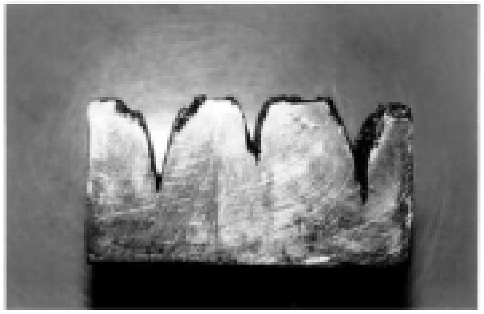

Fig. 2. View of the cross-section of the blank ablation cavity (M 1:1.5).

The situation with input data for determining the gas release is much more difficult. The experimental data of [4, 5] and other studies point to the presence in aluminum alloys of hydrogen, oxygen, nitrogen, methane, and other hydrocarbons, with hydrogen forming the largest volume. As for hydrogen, it is known that for aluminum with a normally oxidized surface the phenomenon of physical sorption of moisture is not a reversible process, and heating at any temperatures leads to a release of hydrogen (along with an insignificant release of water vapors depending on conditions). This holds true not only for the outer surfaces of specimens, but also for the inner intercrystalline surfaces of the alloy structure. The decomposition rate of such forms of moisture "condensed" on the surface in contact with aluminum sharply increases when the temperature is increased from 550 to 650°C [5], i.e., in the "solidus–liquidus" range of these alloys. Since the solubility of hydrogen upon crystallization falls off practically to zero, it may be considered in estimating the gas release that in the process of impact crystallization of melt drops under the conditions of thin-layer spreading of drops in the experiments performed hydrogen is completely released into vacuum, which leads for drops to a certain value of the ratio of the number of Mg vapor atoms per H_2 molecule. The value of this ratio is also used in estimating the quantity of hydrogen released from a dispersed blank.

2. Calculation Model of Thermal Conditions Taking into Account the Melting and the Mass Flows of Vapor. Estimations of thermal conditions of the heating band with allowance for melting are based on the results of the solution of the problem simplified (in the one-dimensional formulation) by neglecting the heat leaks from the melt pool into the blank and assuming that at the initial instant of time the blank is already at a temperature T_{cr} close to the "crystallization point." Such an assumption can be considered acceptable, since the temperature of the cold (20°C) surface of the blank at the end of the focal heating spot reaches the melting temperature already 10–12 μsec after the beam is switched on. At $q_0 \sim 10^9$ W/m^2, by the time of the formation, at the 50–60th second from the beginning of irradiation, of stable separation of drops from the blank, conductive and other leaks become comparatively small.

We consider identical operation cyclograms for all points on the heating band of the blank surface (the perimeter πd_b = 1 m, the heating band width is 3.6 mm) rotating with a frequency f = 20 Hz (v = 20 m/sec) under the action of a stationary electron beam with conditional dimensions of the irradiation spot of 3.6 × 6 mm^2.

Under the beam, a point of any considered section on the heating band runs first a distance of 3.6 mm in the time $\tau_0 = 0.18 \cdot 10^{-3}$ sec under the action of the heat flux pulse $q_0 = 10^9$ W/m^2 or, assuming then for the calculations a single time scale $\tau_0 = 0.18 \cdot 10^{-3}$ sec, we consider the dimensionless time interval of the first stage to be $0 \le \bar{\tau} = \tau/\tau_0 \le 1$. Then at $1 \le \bar{\tau} \le 10$ the second, also transitory stage of melting and deepening of the melt pool due to the heat accumulated in the liquid melt superheated to a temperature above the crystallization temperature T_{cr}, is realized. By the end of a time interval of such duration, as will be shown below, the depth of the melt pool practically reaches its maximum value $x_{\max}$ (in dimensionless parameters $\bar{x} = x/x_{\max} \approx 1$). If the melt density $\rho = 2.35 \cdot 10^3$ kg/m^3 and the melting heat $r = 0.36 \cdot 10^6$ J/kg, then

$$x_{\max} = \frac{q_0 \tau_0}{\rho r} = 0.213 \cdot 10^{-3} \text{ m} . \tag{1}$$

During the remaining part of the long time interval from the total value of the rotation period $\tau_{\mathrm{rot}} = \pi d_b / v = 50 \cdot 10^{-3}$ sec or $\bar{\tau}_{\mathrm{rot}} = 278$ for estimating the value of heat release a fortiori "with a deficit," we assume that in the interval of $10 \le \bar{\tau} \le 278$ the band surface is at T_{cr} = 870 K (conditional value of the crystallization temperature, since the "solidus–liquidus" interval is neglected here). In the calculations, we used the following dimensionless quantities of the melt parameters:

$$a = \frac{\lambda T_{\mathrm{cr}} \rho r}{q_0^2 \tau_0} = 0.253 , \qquad b = \frac{2r}{c T_{\mathrm{cr}}} = 0.9404 , \tag{2}$$

where λ = 60 W/(m·K) and c = 880 J/(kg·K) are the heat conduction and heat capacity of the melt.

In the proposed refined procedure of integral calculations of the surface temperature T_s and the melting dynamics of bodies on the basis of thermal balances, we use the conventional [6, 7] (for such calculations) approximate prerequisities and assumptions, the main ones of which are stationarity of the processes in a solid body and linearity of the temperature profiles in the melt layer. The refinement, as compared to [6, 7], consists of the direct more complete account of the heat capacity of the melt with the introduction into the thermal balance, besides the melting expenditure $\left(\int_0^\tau q_r d\tau \right)$, also of a part of the total energy input $q_0 \tau_0$ in the form $\left(\int_0^\tau q_c d\tau \right)$ of the melt superheating in a pool with current depth x. In view of this, the thermal balance equation can be written as

$$q_0 \tau = \int_0^\tau q_r d\tau + \int_0^\tau q_c d\tau = \rho r x + \rho c x \frac{T_s - T_{\mathrm{cr}}}{2} . \tag{3}$$

This relation, which is applicable to $\bar{\tau} \le 1$, is written in dimensionless form as

$$\bar{\tau} = \bar{x} + \frac{\bar{x} (\bar{T}_s - 1)}{b} , \tag{4}$$

where $\bar{T}_s = T_s / T_{\mathrm{cr}}$.

At time $\bar{\tau} = 1$ the energy input into the melt pool terminates and at $\bar{\tau} \ge 1$ the heat content $q_0 \tau_0$ in it under the assumed conditions of heat losses remains unaltered, i.e.,

$$1 = \bar{x} + \frac{\bar{x} (\bar{T} - 1)}{b} . \tag{5}$$

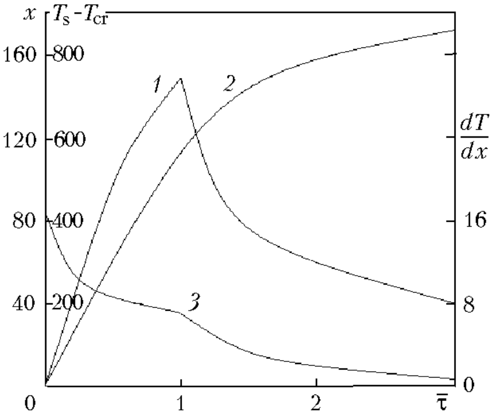

Fig. 3. Change in the heat transfer parameters in the heating pulse $(0 \le \bar{\tau} \le 1)$ and in the aftereffect interval $(\bar{\tau} \ge 1)$: 1) temperature difference between the melt pool surface and bottom; 2) depth of the melt pool; 3) temperature gradient for the melt pool deep. $T_s - T_{cr}$, K; x, μm; $\frac{dT}{dx}\,10^{-6}$, K/m.

The other balance equation needed for solving the problem stated is the same for both time intervals $\bar{\tau} \le 1$. It defines the relation between the quantities of heat supplied to the melting front (bottom of the melt pool) and the rate $dx/d\tau$ of its deepening:

$$\frac{\lambda\,(T_s - T_{cr})}{x} = \frac{\rho r dx}{d\tau}$$

or in the dimensionless form

$$\bar{T}_s - 1 = \frac{\bar{x}}{a}\frac{dx}{d\bar{\tau}}\,. \tag{6}$$

Eliminating from (4) and (6) the dimensionless temperature, we obtain an ordinary first-order differential equation for determining the dynamics of change in the melt pool depth, which belongs to Abel equations of the second kind:

$$\frac{\bar{x}^2}{ab}\frac{d\bar{x}}{d\bar{\tau}} = \bar{\tau} - \bar{x}\,, \tag{7}$$

which was solved with the aid of the odesolve function of the Mathead 2001 package for Windows. Then we determined from (4) the dimensionless quantities of superheating $\bar{T}_s - 1 = (T_s - T_{cr})/T_{cr}$ of the pool surface with respect to the melting front temperature T_{cr}. The curves $(T_s - T_{cr}) = f(\tau)$ and $x = f(\tau)$ are given in Fig. 3. The same figure also gives the values of the temperature gradients $dT/dx = (T_s - T_{cr})/x$ in the melt, which in the considered range $0 \le \bar{\tau} \le 1$ have values from $16 \cdot 10^6$ K/m at $\bar{\tau} = 0$ to $6.6 \cdot 10^6$ K/m at $\bar{\tau} = 1$. The dependence on $\bar{\tau}$ of the absolute values of melt surface temperatures needed for calculating the evaporation in the $0 \le \bar{\tau} \le 1$ range has been interpolated approximately by the following formula:

$$T_s\,(\bar{\tau}) = 763.11 \cdot \bar{\tau}^{0.54467} + 858.72\,. \tag{8}$$

For $\bar{\tau} \ge 1$, having eliminated from (5) and (6) the dimensionless temperature, we obtain the following differential equation with separated variables:

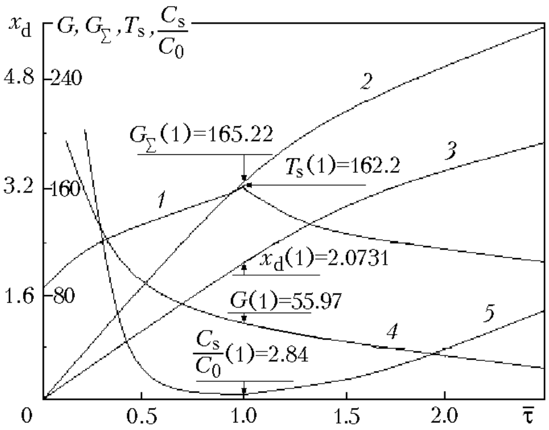

Fig. 4. Change in the mass transfer parameters in the heating pulse ($0 \le \bar{\tau} \le 1$) and in the aftereffect interval ($\bar{\tau} \ge 1$): 1) surface temperature of the melt pool; 2) total rate of flow of the Mg mass; 3) diffusion layer thickness; 4) instantaneous flow rate of Mg vapor; 5) ratio between Mg concentrations on the melt pool surface and bottom. $T_s \cdot 10^{-1}$, K; $G_\Sigma \cdot 10^6$, kg/m^2; x_d, μm; $G \cdot 10^2$, kg/(m^2·sec); $\frac{C_s}{C_0} \cdot 10^3$, rel. units.

$$ab\,d\bar{\tau} = \bar{x}^2 \frac{d\bar{x}}{1-\bar{x}} . \tag{9}$$

Integrating (9) with the initial condition following from the solution of Eq. (7) $\bar{x}|_{\bar{\tau}=1} = 0.525$, we have

$$ab\bar{\tau} = 2\,(1-\bar{x}) - \ln\,(1-\bar{x}) - (1-\bar{x}^2) - 1.5816 . \tag{10}$$

At $\bar{\tau} \ge 1$ the relation between the dimensionless quantities of superheating of the melt pool surface ($\bar{T} - 1$) and the quantities of current distance to the melt front $\bar{x}$ determined by (10) is established by formula (5):

$$\bar{T}_s - 1 = b\frac{1}{\bar{x} - 1} . \tag{11}$$

The change in the dimensional parameters determined for the considered conditions of constancy of the specific heat content in the melt $q_0\tau_0$ with dimensionless time $\bar{\tau}$ (for $\bar{\tau} \ge 1$) is also shown in Fig. 3.

The absolute values of the melt surface temperature T_s in the $1 \le \bar{\tau} \le 10$ range have been approximately interpolated by the formula

$$T_s\,(\bar{\tau}) = 718.69\bar{\tau}^{-1.3351} + 883.36 . \tag{12}$$

3. Computational Procedure and Analysis of Results of Calculation of the Mass Vapor Release. The computational procedure includes approximate methods of determining the dynamics of the diffusion mass flow of the volatile component to the surface of the melt pool from its volume and its equal free-molecular convective flow of vapor from the surface into the ambient vacuum. In the general case, for the binary mixture the expression for the diffusion flow is of the form [8]

$$G = -\,\rho D \,\mathrm{grad}\, C + \rho\,\frac{D_{\mathrm{therm}}}{T}\,\mathrm{grad}\, T . \tag{13}$$

Here the first term stands for the volatile component mass transfer by the concentration diffusion according to Fick's law in the direction counter to the concentration gradient, and the second one — the transfer of a lighter volatile component in the direction of the gradient T, i.e., also to the melt surface. Because of the lack of data on D_{therm} the thermal diffusion is neglected below despite the presence (see Fig. 3) of very high temperature gradients in the melt.

The aim of the calculations performed in this section is to determine the numerical value (quantity) of the mass flow of magnesium vapors in order to find subsequently, by estimating of the mass release of hydrogen, the total volume vapor and gas release into the vacuum chamber.

With the above prerequisities and restrictions, we have developed an integral method of approximate calculation of evaporation of melts under dynamically changing conditions with the use of a precalculated temperature curve of the melt pool surface by relations (8) and (12) and under other conditions. The important feature — the possibility of performing an independent precalculation of thermal regimes — is a consequence of the small thickness x_{d} (Fig. 4) compared to the values of x (see Fig. 3), as well as of comparatively small heat losses due to the evaporation and thermal emission from the melt pool surface, whose influence can be neglected.

The salient points of the method are as follows:

1) the profiles of change in concentrations from the initial value C_0 to $C_{\text{s}}(\tau)$ on the surface in a layer of hitherto unknown thickness $x_{\text{d}}(\tau)$ are linear;

2) at any instant of time τ the mass deficit of the volatile component in a diffusion layer of thickness x_{d} is strictly equal to the value of the total expenditure of vapors $G_\Sigma(\tau) = \int_0^\tau G(\tau)d\tau$ that has been attained by this instant at the considered point.

Then the value of the mass deficit can be calculated as

$$G_\Sigma(\tau) = \frac{\rho}{2}(C_0 - C_{\text{s}})\, x_{\text{d}}\,, \tag{14}$$

and the instantaneous specific rate of flow — by the formula

$$G(\tau) = \frac{d}{d\tau} G_\Sigma(\tau)\,. \tag{15}$$

The value of $G(\tau)$ can be written in two ways. In the first one — in terms of the diffusion flow in the melt with a diffusion coefficient in the liquid $D = 7.54\cdot10^{-9}$ m^2/sec) [3]:

$$G(\tau) = \rho D \frac{(C_0 - C_{\text{s}})}{x_{\text{d}}}\,. \tag{16}$$

Using (14) and (16), the unknown time variable G in Eq. (15) can be expressed in terms of G_Σ by transforming (15) to the form

$$\frac{x_{\text{d}}^2}{2D}\frac{dG_\Sigma}{d\tau} = G_\Sigma\,. \tag{17}$$

In the second way, the instantaneous rate of the diffusion flow $G(\tau)$ can be given in terms of its equal free-molecular specific rate of flow of vapor from the body surface into the ambient vacuum at a pressure of saturated vapors for magnesium $p_{\text{sat}}(\tau) = 9.6817\cdot10^9\cdot\exp\left(\frac{-15{,}825}{T_{\text{s}}(\tau)}\right)$. In the SI system, the equation of the above rate of flow has the form

$$G(\tau) = \left(0.0438 \sqrt{\frac{A_{\text{v.c}}}{T_{\text{s}}(\tau)}}\, P_{\text{sat}}(\tau) \frac{A_{\text{v.c}}}{A_{\text{nons}}} \right) C_{\text{s}}(\tau)\,. \tag{18}$$

Depending on (18), we denote the complex between brackets as $\beta(\tau)$ and call it the coefficient of convective mass transfer between the surface and the ambient vacuum at a concentration of the volatile component in it at infinite distance from the body $C_\infty = 0$. Then (18) acquires the form of a "Newton" relation similarly to the expression for the convective thermal flow $q = \alpha(T_{\text{s}} - 0)$:

$$G = \beta\,(C_{\text{s}} - 0) = \beta C_{\text{s}}\,. \tag{19}$$

Here the quantity β is equal numerically to the flow G of the vapor mass of pure ($G_{\text{s}} = 1$) magnesium from the melt surface into vacuum. From the equality of the flow rates (16) and (19) follows

$$C_0 - C_{\text{s}} = \frac{C_{\text{s}} B x_{\text{d}}}{1 + B x_{\text{d}}} \quad \text{or} \quad \frac{C_{\text{s}}}{C_0} = \frac{1}{1 + B x_{\text{d}}}\,, \quad B = \frac{\beta}{\rho D}\,. \tag{20}$$

Note that the product written in the form $B x_{\text{d}} = \dfrac{x_{\text{d}}}{\rho D} : \dfrac{1}{\beta}$ is an analog of the Biot criterion $\text{Bi} = \dfrac{x}{\lambda} : \dfrac{1}{\alpha}$ for heat transfer processes. Both parameters have the physical meaning of the ratios between the resistance to the mass or heat transfer from the bulk of the body onto its surface and the resistance to their convective transfer from the surface into the environment.

Eliminating $C_0 - C_{\text{s}}$ from (14) by means of (20), we obtain the relation between x_{d} and G_Σ in the form of the algebraic equation $(B x_{\text{d}})^2 - 2yBx_{\text{d}} - 2y = 0$ with solutions

$$B x_{\text{d}} = y + \sqrt{(y+1)^2 - 1} \quad \text{or} \quad \frac{B^2 x_{\text{d}}^2}{2} = y \left(y + 1 + \sqrt{(y+1)^2 - 1} \right), \tag{21}$$

where $y = \dfrac{G_\Sigma B}{\rho C_0}$. Substituting $x_{\text{d}}^2/2$ from (21) into (17), we obtain the basic differential equation for determining the dependence $G_\Sigma(\bar{\tau})$:

$$y + 1 + \sqrt{(y+1)^2 - 1}\, \frac{B}{\rho C_0}\, dG_\Sigma = L d\bar{\tau}\,, \tag{22}$$

where $L = B^2 D\tau = (B x_{\text{d}})^2 \dfrac{D\tau}{x_{\text{d}}^2}$ is a dimensionless mass transfer analog of the x-independent criterion $L_{\text{h}}(\tau) = \text{Bi}^2\ \text{Fo}$ in heat transfer theory [6].

In the general case, at a time-variable temperature of the body or $B = B(\tau)$ (see (20)) relation (22) cannot be integrated analytically. In the case where $T_{\text{s}} = \text{const}$ and, accordingly, $B = \text{const}$, the solution of (22) is of the form

$$\left[(y+1)^2 + (y+1)\sqrt{(y+1)^2 - 1} - \ln\left(y + 1 + \sqrt{(y+1)^2 - 1} \right) \right] \Bigg|_{y_1}^{y} = 2B^2 D\tau_0\, (\bar{\tau} - \bar{\tau}_1) \tag{23}$$

or, if the function on the left-hand side of (23) is denoted as $F(y)$, then

$$F(y) = 2B^2 D\tau_0\, (\bar{\tau} - \bar{\tau}_1) + F(y_1) = 2\,[L(\bar{\tau}) - L(\bar{\tau}_1)] + F(y_1)\,. \tag{24}$$

Errors of the proposed approximate method of calculations can be estimated by comparing their results at $T_{\text{s}} = \text{const}$ to the results of exact calculations. Because of lack of necessary data on direct calculations of the mass transfer, comparison to the calculations on convective heat transfer [6] can be made since these processes are analogous. Numerical equality of the sought variables (here dimensionless transfer potentials $\theta_h = T_s/T_0$ and $\theta = C_s/C_0$) in these processes will take place when all the three similarity conditions are fulfilled: for the same geometry of the bodies (here semi-infinite bodies) and one and the same kind of boundary conditions (BC) (here BC of the third kind), the same forms of writing the initial and infinity conditions (at $\bar{\tau} = 0$, the initial temperature T_0 in one problem and the initial concentration C_0 in the other and at zero values of these parameters at infinity), and at numerical equality in the general case of two corresponding determining criteria for heat transfer and mass transfer — Fourier or Biot numbers or only one of them, $L = L_h$, in determining the parameters on the surface of the body.

Here, for comparison, the results of the solution of problem 4 in [6] on convective cooling of a semi-infinite body in a medium with a zero temperature are acceptable. In calculating the dynamics of change in the dimensionless surface temperature $\theta_h = T_s/T_0$ (i.e., at $x = 0$) the solution of problem 4 depends not on two criteria, but on one, the x-independent combined criterion $L_h = \mathrm{Bi}^2\ \mathrm{Fo}$:

$$\theta_h = T_s/T_0 = 1 - \mathrm{erfc}\,(\sqrt{L_h})\,\exp\,(L_h)\,, \tag{25}$$

where $\mathrm{erfc}(u) = \frac{2}{\pi}\int \exp\,(-u^2)du$ is an additional probability integral. The corresponding determining complex for the mass transfer $L = \mathrm{Bi}_{x,\mathrm{d}}^2\ \mathrm{Fo}_{x,\mathrm{d}}$ upon reduction by x_d takes on the form $L = B^2D\tau_0\bar{\tau}$ (see the right-hand side of formulas (22)–(24)).

To lower errors of comparison at T_s = const to the exact solution, it is expedient to obtain the dependence for direct determination of the mass transfer potential $\theta = C_s(T)/C_0$ without additional recalculations. To this end, let us write expression (15) in view of (20) in the form

$$\beta C_s = \frac{\rho}{2B\tau_0}\,\frac{d\,[(C_0 - C_s)\,Bx_\mathrm{d}]}{d\bar{\tau}}$$

or

$$2B^2D\tau_0 d\bar{\tau} = \frac{1}{C_s}\,d\left[\frac{(C_0 - C_s)^2}{C_s}\right] = \frac{1}{\theta}\,d\left[\frac{(1-\theta)^2}{\theta}\right],$$

so that upon integration we have

$$\left(\frac{1}{2\theta^2} + \ln\theta\right)\Bigg|_{\theta_1}^{\theta} = 2\,(B^2D\tau_0\bar{\tau})\Big|_{\bar{\tau}_1}^{\bar{\tau}} = 2\,(L - L_1)\,. \tag{26}$$

We will make comparison of the computational procedures for the conditions of flight of a melt drop in vacuum at T_s = const = 1000 K and $\theta_1|_{\bar{\tau}_1=0} = \frac{T_s}{T_0} = 1.0$ of duration $\bar{\tau} = \frac{0.01}{0.18\cdot10^{-3}} = 55$. In so doing, $B(1000) = 0.55532\cdot10^6$ 1/m, $L = 23.019$, $L_1 = 0$. To such conditions by (26) there corresponds the approximate value of $\theta = \frac{C_s(55)}{C_0} = 0.10119$, and the exact value by (24) at $L_h = 2.3019$ will be equal to $\theta_h = 0.11513$, which gives an acceptable ("with a deficit") value of the relative error of the approximate method of calculations $\delta = \frac{0.11513 - 0.10119}{0.11513}\cdot$ $\cdot100\% = 12\%$.

4. Vapor and Gas Release of AMg6 (Mg — vapor, H_2 — gas) Melt Drops. With the help of the above value of the mass transfer potential $\theta = C_s/C_0 = 0.1012$ we can calculate the absolute value of the mass flow of vapors $\dot{m}_v$ at $\nu = 6400$ drops/sec for drops of diameter 0.575 mm (the surface area $S_1 = 1.042\cdot10^{-6}$ m^2) at a constant temperature T = 1000 K (B = 0.5553·10^{6} 1/m). By (20) and (14) at the end of the flight ($\bar{\tau}$ = 55) the diffusion layer thickness x_{d} = 16.0·10^{-6} m, $G_{\Sigma}(55)$ = 1.149·10^{-3} kg/m^{2}, $\dot{m}_1 = \dot{m}_{\mathrm{v}} = G_{\Sigma} S_1 \nu$ = 7.66·10^{-6} kg/sec or

$$\dot{n}_{\mathrm{v}} = \left(\frac{\dot{m}}{A}\right)_{\mathrm{v}} = 0.315 \cdot 10^{-6} \text{ kmole/sec} . \tag{27}$$

For hydrogen, let us assume the maximum content: 1 cm^{3} under normal conditions (p = 10^{5} Pa, T = 273 K) per 1 cm^{3} of the melt in the solid state [4]. Then, at a flow rate of drops G_{m} = 1.5·10^{-3} kg/sec or 0.56 cm^{3}/sec under normal conditions Q_{gas} = 0.56 cm^{3}/sec. Proceeding from the value of the molar volume of ideal gas 22.41 m^{3}/kmole, the flow rate of 0.56 cm^{3}/sec corresponds to

$$\dot{n}_{\mathrm{gas,1}} = \frac{0.56 \cdot 10^{-6}}{22.41} = 0.025 \cdot 10^{-6} \text{ kmole/sec}$$

or

$$\dot{m}_{\mathrm{gas,1}} = (\dot{n}M)_{\mathrm{gas}} = 0.05 \cdot 10^{-6} \text{ kg/sec} . \tag{28}$$

The ratio between the masses and the number of magnesium atoms per hydrogen atom is

$$\frac{\dot{m}_{\mathrm{v}}}{\dot{m}_{\mathrm{gas}}} = \frac{7.66 \cdot 10^{-6}}{0.05 \cdot 10^{-6}} = 153 , \quad \frac{\dot{n}_{\mathrm{v}}}{2\dot{n}_{\mathrm{gas}}} = \frac{0.315 \cdot 10^{-6}}{2 \cdot 0.025 \cdot 10^{-6}} = 6.3 . \tag{29}$$

The molar mass M and the gaseous mixture density under the conditions of the experimental chamber (T = 1000 K and p = 0.2 Pa) are as follows:

$$M = \left(\frac{\dot{m}_{\mathrm{v}}}{\dot{m}_{\mathrm{v}} + \dot{m}_{\mathrm{gas}}} \frac{1}{A_{\mathrm{v}}} + \frac{\dot{m}_{\mathrm{gas}}}{\dot{m}_{\mathrm{v}} + \dot{m}_{\mathrm{gas}}} \frac{1}{M_{\mathrm{gas}}}\right)^{-1} = 22.66 , \quad \rho_{\mathrm{mix}} = 0.545 \cdot 10^{-6} \text{ kg/m}^{3} .$$

5. Vapor and Gas Release of the Dispersing Body (AMg6 Alloy). The results of the calculations by Eq. (22) of the vapor release from a permanently existing melt pool of length 36 mm ($\bar{\tau}$ = 10) at a value of the diffusion coefficient of magnesium D = 7.54·10^{-9} m^{2}/sec in a liquid alloy with the use of the above Mathcad program product for the range of $\bar{\tau}$ = 0–2.5 are presented in Fig. 4. At $\bar{\tau}$ = 10 the quantity G_{Σ} reaches the value

$$G_{\Sigma} = \int_{0}^{10} G \tau_0 d\bar{\tau} = 0.4377 \cdot 10^{-3} \text{ kg/m}^{2} .$$

The value of the mean intensity of vapor release in the time $\tau = \tau_0 \bar{\tau}$ = 1.8·10^{-3} sec $G_{\mathrm{mean}}(0\text{–}10) = G_{\Sigma}/t$ = 0.243 kg/(sec·m^{2}). The absolute vapor release from a pool area S_2 = 36·3.6·10^{-6} m^{2} is $\dot{m}_2 = G_{\mathrm{mean}} S_2$ = 31.61·10^{-6} kg/sec.

Taking into account the high value of the diffusion coefficient in the melt and the large quantity of fresh melt entering the pool as its depth x increases in the course of melting (see Fig. 3), as well as the high mass flow from it G_{m} = 1.5·10^{-3} kg/sec in the form of separating drops, it may be presumed that the value of $\dot{m}_2$ = 31.61·10^{-6} kg/sec remains unchanged for 240 sec — the time of the dispersion session, assuming thereby that a relative quantity of H_2 mass equal to that for drops is released from the melt pool (see (27)):

$$\dot{m}_{\mathrm{gas,2}} = \frac{31.61}{7.66} \cdot 0.05 \cdot 10^{-6} = 0.21 \cdot 10^{-6} \text{ kg/sec} .$$

The whole of the dispersing blank (except for the melt pool) is a solid body, for which the diffusion coefficient of magnesium D = 7.16·10^{-14} m^{2}/sec at T = 870 K [3] is five orders of magnitude smaller than the coefficient

D for the melt. Therefore, on the solid part of the blank surface, because of the large diffusion resistance to the mass transfer, continuous magnesium de-enrichment of the surface and a weakening of the vapor flows in the course of the experiment should occur.

Since the calculations are performed on the assumption that the temperature of the considered part of the blank surface is constant and equal to 870 K, the vapor release can be calculated by formulas (23) and (24). In so doing, the strong increase (by five orders of magnitude) in the values of $B = \frac{\beta}{\rho D}$ and $y = \frac{G_\Sigma B}{\rho C_0}$ determines the value of $y \gg 1$, which permits neglecting unity compared to the value of y, as well as the logarithmic term of formula (23), and makes it possible to solve approximately (with an error less than 0.1% already at $y > 100$) (23) in the explicit form:

$$G_\Sigma(\tau) = \rho C_0 \sqrt{D\tau + \frac{G_\Sigma^2(0)}{\rho^2 C_0^2}} \quad \text{and} \quad G = \frac{dG_\Sigma}{d\tau} = 0.5\rho C_0 D \left(\sqrt{D\tau + \frac{G_{1\Sigma}^2(0)}{\rho^2 C_0^2}} \right)^{-1}$$

or at $G_{1\Sigma}(0) = 0$

$$G = 0.5\rho C_0 \sqrt{D/\tau} \,.$$

For the considered blank surface of area $S_3 = 68\cdot 10^{-3}$ m^2 in the time interval of the experiment from $\tau = 0$ sec to $\tau = 240$ sec, the absolute vapor release from the blank surface $\dot{m}(\tau) = G$ under the conditions used at different instants of time (τ = 0. 1, 60, 120, and 240 sec) $\dot{m}_3(0) = 4.6\cdot 10^{-3}$ kg/sec, $\dot{m}_3(1) = 1.6\cdot 10^{-6}$ kg/sec, $\dot{m}_3(60) = 0.21\cdot 10^{-6}$ kg/sec, $\dot{m}_3(120) = 0.15\cdot 10^{-6}$ kg/sec, $\dot{m}_3(240) = 0.104\cdot 10^{-6}$ kg/sec.

Proceeding from the results of the calculations in Subsections 4 and 5, by the minimum value of the mass quantity of vapor release $\dot{m} = \dot{m}_1 + \dot{m}_2 + \dot{m}_3(240) + \dot{m}_{\text{gas},2} = (7.66 + 31.61 + 0.104 + 0.26)\cdot 10^{-6}$ kg/sec, one can determine the volume vapor release:

$$Q = \frac{m}{\rho_{\text{mix}}} = \frac{39.6\cdot 10^{-6}}{0.545\cdot 10^{-6}} = 73 \text{ m}^3/\text{sec} \,.$$

Note that such a value of Q is the lowest estimate, since the calculations were "minimum" and several factors able to increase the obtained value were neglected. The main factor is the thermal diffusion in the presence of extremely high temperature gradients (see, e.g., Fig. (3) (melt pool)).

6. Results of Calculations and Discussion. The obtained large value of the volumetric rate of flow (~73 m^3/sec) of the magnesium-hydrogen mixture should be compared to the real possibilities of the system of evacuation of the operating chamber of the facility with water cooling of the walls for vapor condensations. The main danger to the operation of the available evacuation system (a jet oil-vapor vacuum pump plus cold walls of the chamber) was presented by the formation on the wall of a "diffusion shutter" from noncondensable gases, which could practically reduce to zero the condensation of metal vapors on them.

The calculated capacity of the AVP-5 vacuum unit under the conditions of the experiments performed cannot be higher than $Q_{\text{calc}} = 0.2$ m^3/sec because of the high temperature of the medium being pumped out and the presence of hydrogen in it [9]. From this it follows that even without taking into account the volumes of other noncondensable gases released, an evacuation rate considerably higher (by more than two orders of magnitude) than the possible real capacity of the vacuum unit is attained in the experiments. The qualitative reasons explaining the phenomenon of "superfast evacuation" that appeared in the experiments performed were found in numerous investigations on getters (gas absorbers) for vacuum electronic devices made more than half a century ago [1].

The mechanisms of action of different getters are complex and differ from pure physical adsorption — besides adsorption, chemical and electrical phenomena participate in them to a different extent. There are several types of effective mechanisms that especially suit the conditions of the experimental facility, e.g., when there occurs "disperse gettering at which absorption occurs at the time when a getter is dispersed or sublimated in the presence of the absorbed gas" [1, p. 518]. Exactly such conditions for successful absorption of gases were observed in the experiments performed: the hot vapor of the getter — magnesium — interacted with the gases. Another suitable type of intensive absorption mechanism is observed when an electron flow interacts with the gases and the gas dissociates or, as a result of collisions with electrons, excited molecules or ions are formed, "as, for example, in the case of hydrogen" [1, p. 518]. Moreover, in the case of arc-induced evaporation of a metal, "titanium and magnesium intensively absorb gases" [1, p. 519]. Additionally, in the experimental chamber, there were intense X-rays generated in the zone of blank and aluminum alloy irradiation by an electron beam with an energy of 20–25 keV.

Thus, it may be suggested that hydrogen, when still inside the chamber, before entering the vacuum pump and approaching the walls, is absorbed by a part of the magnesium vapors, providing the possibility for the remaining part to condense on the walls. It enters into a chemical bond with magnesium, since, when heated, magnesium reacts with hydrogen to form MgH_m hydrides, where m = 1, 2, 3, 4 [10, p. 308]. The main hydride is MgH_2. Thus, in the hydrides one hydrogen atom can be chemically bound by magnesium atoms in a quantity from 1 to 25. In our case, there is a large store of magnesium: 6.3 atoms per hydrogen atom (see (29)).

The considered getter mechanism of "ultrafast evacuation" of a mixture of hot magnesium vapors and the fundamental gas component (hydrogen) under the physical conditions of the experiments performed can, consequently, function.

An additional indirect confirmation of the validity of the getter mechanism of mutual combining at the atomic level of a mixture of a part of hot magnesium vapors and gases is provided by visual observation (through an X-ray absorbing port-hole) of the processes proceeding in the working chamber. As soon as an electron beam is entered into the evacuated chamber, the blank melting process develops and escape of drops begins. During the time interval from a few (2–4 sec) seconds (beginning) to 40–50 sec (end) the character of glow of the medium in the chamber rapidly changes and then remains visually unaltered. Initially, it was not glowing and completely transparent; only a relatively low-luminosity sharply defined electron beam of orange color was observed. Then the medium became foggy, of bright bluish-green color, and the objects in the chamber became invisible or visible (only near the chamber part-hole) indistinctly. The glow of the electron beam at the beginning of the time interval under consideration sharply changes, it increases practically abruptly, becomes dazzlingly bright, and also bluish-green in color, and then it merges with the brightly glowing background. The foggy blurriness of the objects in the chamber and the diffuse glow of the medium should obviously be related here to the appearance in it of condensed dust-like particles (in the given case, particles of magnesium hydrides), whose evaluated (by the features of the light scattering) size is of the order of a tenth fraction of a micrometer, and the glow color — to the started interaction of magnesium vapors with electrons, including electrons scattered by the target.

Thus, account of the getter effect gives a satisfactory physical explanation of the experimental results obtained under vacuum dispersion of molten aluminum alloys, which consists of the phenomenon of "ultrafast evacuation" of a water-cooled vacuum chamber.

NOTATION

A, atomic mass; Bi, Biot criterion; c, heat capacity, J/(kg·K); C, relative concentration, kg/kg; d, diameter, m; D, diffusion coefficient, m^2/sec; f, rotation frequency, Hz; Fo, Fourier criterion; G, specific value of the mass flow, kg/sec^2; m, mass, kg; M, molecular mass; n, number of moles; p, pressure, Pa; q, specific heat flow, W/m^2; Q, volume flow, m^3/sec; r, melting heat, J/kg; S, area, m^2; T, temperature, ^{o}C; v, velocity, m/sec; x, distance from the surface, m; α and β, heat and mass transfer coefficients; θ, dimensional mass or heat transfer potential; λ, heat conductivity coefficient, W/(m·K); ν, separation frequency of drops, drops/sec; ρ, density, kg/m^3; τ, time, sec; δ, relative error of a quantity, %. Subscripts: rot, rotation; gas, noncondensable gas; d, diffusion parameter; liq, liquid state; b, blank disc; cr, crystallization; v.c, volatile component; m, metal; sat, saturation; 0, initial state; s, surface; v, vapor of volatile component; nons, nonvaporizable solvent; calc, calculated value; r, melting expenditure; c, heat-accumulation expenditure; mix, gas-vapor mixture; mean, mean value; h, heat transfer; therm, thermal diffusion; sol, solid state; f, focal spot of the beam; bar, relative value; dot, time derivative; 1, 2, 3, drop surface, melt pool, blank; ∞, value of a quantity at infinite distance from the body; Σ, total quantity; max, maximum.

REFERENCES

1. S. Dushman, *Scientific Foundations of Vacuum Technology* [Russian translation], IL, Moscow (1950).
2. A. V. Desyatov and A. N. Ponomarev, Physical specific features of the processes of formation of directed flows of drops in a vacuum under electron-beam dispersion of a rapidly rotating body, *Engineering Physics*, No. 4, 39–43 (2005).
3. I. S. Grigor'ev (Ed.), *Physical Quantities: Handbook* [in Russian], Énergoatomizdat, Moscow (1991).
4. M. B. Al'tman, A. A. Lebedev, and V. M. Chukhrov, *Smelting and Casting of Light Alloys* [in Russian], Metallurgiya, Moscow (1969).
5. S. V. Sergeev, *Physicochemical Properties of Liquid Metals* [in Russian], Oborongiz, Moscow (1952).
6. A. V. Luikov, *Theory of Heat Conduction* [in Russian], Vysshaya Shkola, Moscow (1967).
7. A. I. Pekhovich and V. M. Zhidkikh, *Calculations of the Thermal Regime of Solids* [in Russian], Énergiya, Leningrad (1976).
8. D. V. Sivukhin, *General Course in Physics* [in Russian], in 5 vols., Nauka, Moscow (1990); *Thermodynamics and Molecular Physics*, Vol. 2.
9. L. N. Rozanov, *Vacuum Technology* [in Russian], Vysshaya Shkola, Moscow (1982).
10. *Chemical Encyclopaedic Dictionary* [in Russian], Sovetskaya Éntsiklopediya, Moscow (1983).