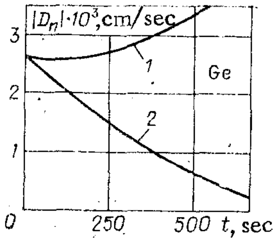

Fig. 3

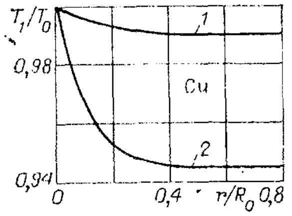

Fig. 4

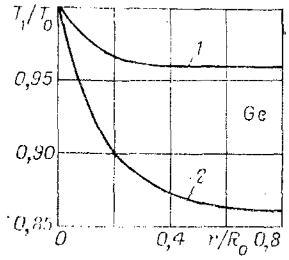

Fig. 5

Numerical results obtained for the materials studied are shown in Tables 1-3 (crystallization time is in seconds; the difference between the initial and final temperatures on the external boundary is in °C; the pressure in the liquid phase is in dyn/cm^2. These three quantities are shown in the respective tables).

Figures 2 and 3 show the dependence of crystallization rate on time, while Figs. 4 and 5 show the radial temperature distribution. Lines 1 and 2 in Figs. 2-5 correspond to the classical problem and the problem with allowance for stresses.

In conclusion, we thank V. V. Pukhnachev, B. D. Annin, and A. N. Cherepanov for their active support and valuable advice.

LITERATURE CITED

1. V. S. Zemskov, I. N. Belorukova, et al., "Solidification of copper and silver in near-zero-g experiments," Acta Astron., 9, No. 10 (1982).
2. A. M. Vainberg, "An important refinement of the classical formulation of the Stefan problem," Transactions of the Second Conference "Differential Equations and Applications," Russe, Bulgaria (1982).
3. I. K. Kikoin, Tables of Physical Quantities [in Russian], Atomizdat, Moscow (1976).
4. M. P. Shaskol'skii (ed.), Acoustic Crystals [in Russian], Nauka, Moscow (1976).
5. E. V. Galaktionov and É. A. Tropp, "Asymptotic method of calculating thermoelastic stresses in a thin rod," Izv. Akad. Nauk SSSR, Fiz., 40, No. 7 (1976).
6. A. D. Kovalenko, Thermoelasticity [in Russian], Vishcha Shkola, Kiev (1975).
7. L. V. Ovsyannikov, Introduction to Continuum Mechanics [in Russian], Novosib. Gos. Univ., Novosibirsk (1976).
8. A. Nadai, Plastic Strain and Fracture of Solids [Russian translation], Vol. 2, Mir, Moscow (1969).

NUMERICAL STUDY OF THE ACTION OF GAS-EXPLOSIVE TUBE ON THE SURFACE OF A STEEL WALL

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UDC 535.211:536.4

An experimental study was made in [1] of the feasibility of the heat treatment of the inside surface of a steel channel with a gas-explosive discharge. The surface layer of the specimen subjected to such action usually consists of a zone of solidified melt of about 20 μm and a heat-affected zone of about 30 μm, where α–γ–α' structural transformations have taken place. The explosive action of the discharge is accompanied by the removal of a substantial amount of material from the surface of the channel. The depth of the layer removed may reach 100 μm. Such values as these for the depths of the fusion and heat-affected zones and the removed layer are difficult to explain by the thermal effect on the wall of the bunch of shock-compressed gas formed in front of the gas-explosive jet of explosion products (JEP). The convective action of the JEP which follows the shock-compressed gas should be taken as the basis of the removal mechanism, as well as of the appearance of the fusion and heat-affected zones. In fact, the heat flow to the wall of the channel from the plasma bunch and

Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 5, pp. 122-125, September-October, 1985. Original article submitted July 9, 1984.

0021-8944/85/2605-0713$09.50

the JEP can be calculated from the formula [2] $q = St\rho u(h + u^2/2)$, which agrees satisfactorily with empirical data [3]. The parameters of the plasma and the explosive jet can be evaluated by examining an approximate model of gasdynamic flow in gas-explosive charges [4]. In accordance with the Hugoniot curve of air at a mass velocity $u = 10.5$ km/sec, the pressure $p = 1600 \cdot 10^5$ N/m^2, while the density and enthalpy in the shock-compressed gas $\rho_1 = 1.4 \cdot 10^{-2}$ g/cm^3 and $h_1 = 66$ kJ/g and in the JEP $\rho_2 = 0.54$ g/cm^3 and $h_2 = 0.58$ kJ/g. The Reynolds number for the plasma (with an air viscosity $\nu_1 = 2 \cdot 10^{-3}$ g/(cm·sec) [5]) has a value $Re_1 = 8 \cdot 10^6$, while in accordance with the chosen model $Re_2 = 10^8$ for the JEP [with $\nu_2 = 10^{-3}$ g/(cm·sec)]. The heat-transfer criterion St (Stanton number) for the resulting turbulent boundary layer is calculated from the formula [3] $St = 0.0288\ Re^{-1/5}\ Pr^{-2/3}$. The Reynolds number Re and Prandtl number Pr were determined from the physical properties of the boundary layer with the characteristic temperature

$$T = T_g + 0{,}5(T_g - T_w) + 0{,}22(T_0 - T_g),$$

where T_g and T_w are the temperatures of the core of the gas flow and the wall, respectively; T_0 is the stagnation temperature:

$$T_0 = T_g\left(1 + \frac{\gamma - 1}{2} M^2\right);$$

γ is the adiabatic exponent; M is the Mach number. Given the above assumptions, the heat flow to the channel wall from the shock-compressed gas $q_1 = 5.7 \cdot 10^6$ W/cm^2, while the heat flow from the detonation products $q_2 = 10^8$ W/cm^2. The larger value of q_2 is due mainly to the greater value of density ρ_2. These estimates show the dominant effect of the explosive jet of detonation products on heat exchange with the channel.

Two mechanisms of removal of material from the channel surface are possible. The first ascribes the removal to melting of the surface and continuous entrainment of the melt by the gas flow as a result of high shear stresses on the explosion products—metal boundary. The second mechanism provides for attainment of the boiling point by the wall surface and intensive diffusive vaporization through the laminar sublayer of the flow, with subsequent mixing of the vaporized atoms in the turbulent core of the flow.

In this case too we can evaluate the depth of the removed layer from an approximate relation. The relation follows from the thermal balance on the gas—metal boundary [6]:

$$\delta = q_2\tau/(\rho L_{1,2} + \rho c T^*_{1,2}),$$

where τ is the time of action of the JEP gas flow on the wall, equal to 10^{-5} sec; c and ρ are the specific heat and density of the wall; $L_{1,2}$ are the heats of vaporization and fusion; $T^*_{1,2}$ are the melting and boiling points. Using the value of the heat flow from the JEP $q_2 = 10^8$ W/cm^2, we find that the depth of the removed layer is about 10^{-1} cm with the first mechanism and about 10^{-2} cm with the second mechanism. These findings are of the same order of magnitude as the experimental data. Thus, material removal may be affected by both mechanisms. Here we will examine the mechanism of removal by vaporization.

Intensive vaporization of the wall may alter the structure of the boundary layer of the flow and correspondingly reduce heat flow to the wall. This occurs if the gas-kinetic pressure of the vapor exceeds the pressure in the jet p. The gas-kinetic pressure of the metal vapor at the wall $\sim nkT^*_2 \sim 5 \cdot 10^7$ N/m^2 (n is the density of the saturated vapor), which is one-third the pressure in the jet. This finding indicates that vaporization cannot significantly alter the structure of the boundary layer. Here, the change in heat flux to the wall as a result of the kinetic energy of the vaporized substance is

$$\Delta q \sim \frac{3}{2}\frac{RT^*_2}{\mu}\frac{d\delta}{dt}\rho,$$

where $d\delta/dt$ is the velocity of the vapor—metal phase boundary; R is the universal gas constant; μ and ρ are the molecular weight and density of the vaporized substance. The quantity $\Delta q \sim 10^5$ W/cm^2 under the given conditions for the steel channel, with $\Delta q \ll q_2$.

To perform numerical modeling, the thermal problem on the wall of the channel is formulated as follows (Fig. 1a). A plasma bunch of the length $s_1 = (y + l)/\beta$ (β is the degree of compression, l is the charge length) and an explosive jet of detonation products of the length $s_2 = l(u/V - 1)$ [4] (V is the rate of detonation of the explosive) move along a certain section of the channel wall. Ignoring the slight instability of the contact boundary between the plasma and the combustion products [7] and the slight expansion of the detonation products

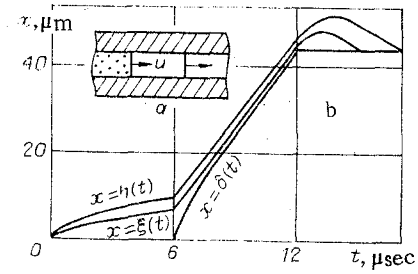

Fig. 1

as a result of the rarefaction wave, we can assume that a flow $q_1 = St\,\rho_1 u(h_1 + u^2/2 - h_w)$ acts on the surface of the wall over the time $\tau_2 = s_2/u$ and a flow $q_2 = St\,\rho_2 u(h_2 + u^2/2 - h_w)$ (h_w is the enthalpy of the wall) acts on the surface over the subsequent period of time $\tau_2 = s_2/u$. Here, the subscript 1 pertains to parameters of the plasma, while 2 pertains to parameters of the detonation products. Three phase fronts may develop in the surface of the steel wall: fronts associated with the α–γ structural transformation, fusion, and vaporization. A mathematical model of the resulting multifront Stefan problem and a method of solving it were examined in [8]. If the surface of the wall is heated to the boiling point, then the following conditions hold due to the entrainment of vaporized metal by the gas flow

$$q = L\rho \frac{d\delta}{dt} - \lambda \frac{\partial T}{\partial x}\Big|_{x=\delta(t)}, \quad T(t, \delta(t)) = T_2^*,$$

where L and δ are the heat of vaporization and the coordinate of the vaporization boundary; λ is the thermal conductivity of the wall; T_2^* is the boiling point, calculated from the Clausius–Clapeyron relation

$$T_2^* = T_0^* \Big/ \left(1 - R\frac{T_0^*}{L}\ln\frac{p_0}{p}\right)$$

(p_0 and T_0^* are the atmospheric pressure and the boiling point at atmospheric pressure).

Figure 1b shows the dynamics of motion of the phase fronts associated with vaporization $x = \delta(t)$, function $x = \xi(t)$ and the α–γ structural transformation $x = \eta(t)$ on a section located 55 cm from the beginning of the channel with the following parameters of the explosive charge: detonation rate V = 7.5 km/sec, charge length l = 15 cm, inside diameter 1.5 cm. During the time of action of the plasma bunch $0 < t \leqslant \tau_1$ ($\tau_1 = 6\cdot10^{-6}$ sec), two fronts move into the depth of the wall: the α–γ transformation front and the fusion front. Subsequent action of the detonation products ($\tau_1 < t \leqslant \tau_1 + \tau_2$, $\tau_2 = 6\cdot10^{-6}$ sec) is accompanied by formation of the vaporization front, with the velocity of the vaporization boundary exceeding the velocity of the fusion boundary. This means that the melt formed by the plasma bunch is partially or completely vaporized in the detonation products. The subsequent path of the curves ($t > \tau_1 + \tau_2$) reflects the stage of cooling of the heated layer.

Figure 2a shows the dependence of the quantity of entrained material from the surface on the distance along the channel. The resulting values of δ allow us to suggest that removal of the material may be significantly influenced by vaporization of the wall during passage of the explosive jet of detonation products.

Metallographic analysis of specimens cut from tubes treated with a gas-explosive discharge shows [1] that there are zones of cooled melt and heat-affected zones in certain specimens. The formation of these zones is connected with the action of the expanded detonation products in the rarefaction wave. The dependence of the heat flow to the wall on the time

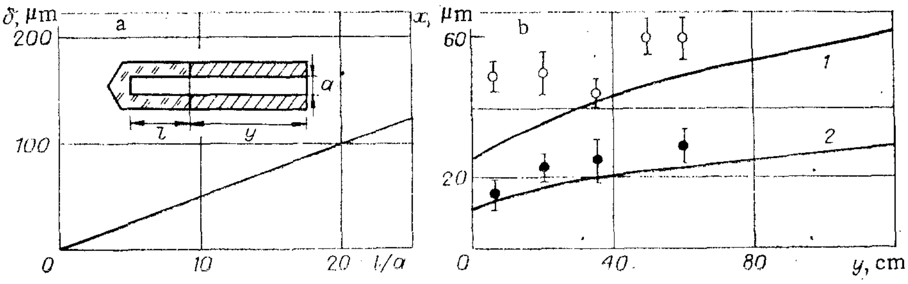

Fig. 2

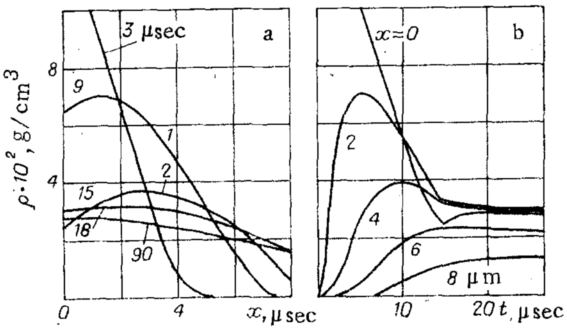

Fig. 3

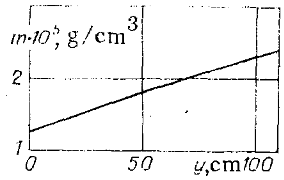

Fig. 4

in this part of the gasdynamic jet flow can be approximately represented in the form $q_3 = q_2(1 - t/\tau_3)$, where τ_3 is the time of action of the rarefaction wave.

Figure 2b compares calculated depths of fusion (curve 2) and thermal quenching (curve 1) with values obtained experimentally [1] along a steel tube (with a charge length l = 28 cm). The increase in the thickness of these zones toward the end of the channel is due to an increase in the size of the unloading wave and a corresponding increase in the time of action τ_3.

The process of heat treatment of the wall may be accompanied by diffusive saturation of the melt with components of the explosion products. Such saturation occurs mainly with the action of the expanding explosion products (EP). Diffusion of elements from the plasma and from the main flow of the EP jet can be ignored in view of the above analysis of the thermal effect. The large temperature gradients in the melt, reinforced by the high boiling point (6000-8000°K), facilitate the process of diffusion due to the appreciable dependence of the diffusion coefficient D on temperature. In the Einstein–Stokes approximation, D can be determined from the formula

$$D = kT/6\pi\nu r, \tag{1}$$

where k is the Boltzmann constant; ν is the viscosity of the melt; r is the radius of a diffusing particle. Ignoring diffusion in the solid phase and assuming a mass-transfer condition on the surface in conformity with Newton's law, we have

$$-D\partial\rho_i/\partial x_{x=\delta} = \alpha(\rho_i - \rho_w) \equiv q_d,$$

where ρ_i is the concentration of the i-th component of the EP; ρ_w is the concentration on the surface of the wall; α is the mass-transfer coefficient; q_d is the diffusion current. It can be assumed that the diffusion process satisfies the classical transport boundary-value problem [9]. If we ignore the effect of the impurity on the thermal regime in the wall, then at the phase boundary we can take the condition $\partial\rho_i/\partial x|_{x=\xi(t)} = 0$.

Analysis of the composition of the final detonation products [10] shows that the dominant component of the EP is atomic nitrogen. Assuming complete dissociation of N_2 molecules on the surface, the diffusion current of nitrogen can be evaluated on the basis of the Reynolds analogy [2]: $q_d \simeq q\rho/(h + u^2/2)$. This estimate gives $q_d \approx 300$ g/(cm²·sec) for a diffusion current of nitrogen from EP.

Figure 3a shows characteristic distributions of nitrogen concentration through the depth of the melt at different moments of time. Boundary condition (1), determined for a rarefaction wave in EP, leads to a situation whereby the concentration maximum is reached in the depth of the wall rather than on its surface (curves 1 and 2). The dynamics of the change in concentration at different points through the depth of the wall is shown in Fig. 3b. The concentration maximum subsequently shifts toward the surface, and the final distribution of the impurity in the wall is smoothed out.

Figure 4 shows the calculated dependence of the mass of nitrogen in the wall on the distance along the channel. The mass of nitrogen m at a distance of 1 m from the beginning of the channel is $2.4 \cdot 10^{-5}$ g/cm², while the nitrogen concentration on the surface is 0.4% by wt. with a characteristic diffusion-zone depth of 15 μm.

LITERATURE CITED

1. V. I. Kirko, G. A. Shvetsov, and V. P. Chistyakov, "Strengthening the inside surfaces of steel tubes with a plasma generated by an explosion," Izv. Sib. Otd. Akad. Nauk SSSR, Ser. Tekh. Nauk, No. 2 (1982).

2. Yu. V. Lapin, Turbulent Boundary Layer in Supersonic Gas Flows [in Russian], Nauka, Moscow (1982).
3. S. N. Ishutkin, V. I. Kirko, and V. A. Simonov, "Study of the thermal effect of shock-compressed gas on the surface of colliding plates," Fiz. Goreniya Vzryva, 16, No. 6 (1980).
4. M. A. Tsikulin and E. G. Popov, Radiative Properties of Shock Waves in Gases [in Russian], Nauka, Moscow (1977).
5. S. L. Polak (ed.), Principles of the Physics and Chemistry of Low-Temperature Plasmas [in Russian], Nauka, Moscow (1971).
6. H. S. Carslaw and J. C. Jaeger, Conduction of Heat in Solids, 2nd ed., Oxford Univ. Press (1959).
7. A. M. Davydov, E. F. Lebedev, et al., "Rayleigh—Taylor instability on a plasma—explosion-products boundary," Teplofiz. Vys. Temp., No. 2 (1983).
8. N. I. Pak, "Numerical method of solving a multifront Stefan problem with the use of movable grids," Inzh. Fiz. Zh., 45, No. 3 (1983).
9. A. V. Lykov, Heat and Mass Transfer (Handbook) [in Russian], Énergiya, Moscow (1978).
10. K. P. Stanyukovich (ed.), Physics of Explosions [in Russian], Nauka, Moscow (1975).

REFLECTION OF A PLANE LONGITUDINAL SHOCK WAVE OF CONSTANT INTENSITY FROM A PLANE RIGID BOUNDARY WITH A NONLINEAR ELASTIC MEDIUM

A. A. Burenin and V. V. Lapygin

UDC 539.3

A consequence of the second law of thermodynamics in gasdynamics is the well-known theorem of Cemplen on the existence of only compressional shock waves. Ths system of differential equations of gasdynamics has the property that they lead to solutions consistent with this theorem. With certain additional conditions, a similar situations occurs for quasi-longitudinal (bulk) shock waves in an elastic medium. In particular, in the formulation of self-modeling problems in the nonlinear dynamical theory of elasticity [1], one can often prove a priori that the leading front of bulk deformations propagating in the elastic medium is either a shock wave or a centralized wave depending on whether the introduced perturbations lead to compression or expansion of the medium. Another case is that of quasitransverse (shear) shock waves. We note that [2] a purely transverse shock wave, leading only to shear without a change in volume, can exist in a nonlinear elastic medium only for a particular deformed state in front of the surface of discontinuity. This means that a shear shock wave will always simultaneously be a compressional wave. It was shown in [2] that in this case- the bulk deformations are of second order in comparison with shear deformations and for real materials they lead to an expansion of the medium. On the other hand, in [3] the self-modeling problem on the pure shear of an elastic half-space was considered, and it was shown that a centralizer shear wave also leads to expansion, for the same properties of the elastic medium. Therefore, one can obtain two solutions of the same self-modeling problem of the nonlinear dynamical theory of elasticity depending on the formulation of the problem. Self-modeling dynamical problems of the nonlinear theory of elasticity were considered in [1, 3-5] and shock waves in an elastic medium in [2, 6, 7].

In the present paper we formulate and present the numerical results of the self-modeling problem of the nonlinear dynamical theory of elasticity for the reflection of a plane longitudinal shock wave of constant intensity from a plane rigid boundary with an elastic medium. It is shown that for angles of incidence of the original shock wave which are less than a certain critical value (which depends on the wave intensity) two solutions of the problem are possible: a reflected quasitransverse shock wave or a centralized shear wave. For angles of incidence exceeding the critical value, the solution exists only for the reflected shock wave. The leading front of the bulk deformations is caused by the reflection of the shock wave from the rigid barrier and is a quasitransverse shock wave.

1. The system of equations describing the dynamical deformation of an elastic medium in a rectangular coordinate system in terms of the Euler variables has the form [8, 9]

Voronezh. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 5, pp. 125-129, September-October, 1985. Original article submitted June 15, 1984.

0021-8944/85/2605-0717$09.50