chamber ends and they exceed similar stresses in the center by about a factor of 1.5. In chambers for detonating a gas mixture the main contribution to the SSS is thermal stresses. Simple approximate equations are suggested in order to evaluate the maximum thermal stresses in the chamber walls.

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THERMOCOUPLE MEASUREMENT OF METAL TEMPERATURE UNDER PULSED DEFORMATION CONDITIONS

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An increase in temperature with pulsed deformation of a metal is a parameter which is very sensitive to loading conditions. In fact, this situation includes the possibility of using local temperature sensors. In using a local sensor it is necessary to disturb the continuity of a test specimen. As a rule, the presence within the volume of a specimen subjected to pulsed deformation of any cavities, notches, nonconductors, etc., even if it has a weak effect on such parameters as pressure, density, or flow rate, distorts in an uncontrolled way the temperature field. With characteristic times for test processes of ~1-10 μsec a local sensor of reasonable dimensions as a result of thermal conductivity does not manage to reach thermal equilibrium with a loaded specimen, and its temperature may differ markedly from the specimen temperature. Therefore, under conditions of pulsed deformation the temperature sensor should be the specimen itself. With a thermocouple method of measurement this sensor-specimen may be obtained by joining two metals to each other which have similar mechanical but different thermoelectric characteristics so that the separation boundary for the metals does not introduce distortions in the temperature field. As a result of the thermoelectric effect an increase in specimen temperature caused by deformation of it leads to development within the metal of electric currents, an electric and magnetic field, and consequently to occurrence of a difference in electric potential between different points of the external surface of the specimen. The distribution of the potential over the external surface of the specimen contains information about temperature distribution over the interface of the metals. It is not difficult to measure by experiment the difference in potentials between two fixed points on this surface. If the temperature is constant along the whole metal interface and if values of thermoelectric coefficients are known, then the temperature of the interface is determined from measuring the potential difference in a straight-

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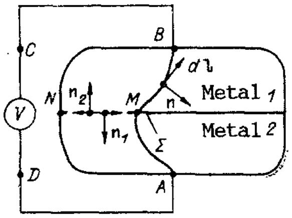

Fig. 1

forward way. However, in principal it is a fact that with pulsed deformation of the metal interface there are always areas with a different temperature. (For example, even in the case when the interface is a plane, and loading is carried out by a plane shock wave (SW) with a front parallel to this plane, the natural unloading wave which always arises leads to nonuniform metal heating along the interface.) Therefore, with the thermocouple method of temperature measurement under conditions of pulsed deformation the following problem arises. Let us say that the temperature at a certain point in the metal interface is of interest to us. Question: under what conditions is it possible to determine the temperature at this point of the difference in potentials is measured between some two points at the outer specimen surface? We consider the problem applied to measuring temperature behind a plane SW front, but as will be seen from that given below, a number of the results obtained have a more general character.

Let there by a cylindrical symmetrical specimen consisting of two metals 1 and 2 (Fig. 1) joined along plane Σ: $z = 0$ (a cylindrical coordinate system (r, φ, z) is considered). We connect to points A and B on the axis of symmetry an instrument which measures electric voltage (in the future we shall nominally call it a voltmeter). Let a section of the measuring lead BC be made of metal 1, and section DA be made of metal 2, and the voltmeter is connected to points C and D by a lead made of metal 1. We assume that at a certain instant of time an SW passes through the specimen causing at each point of the metal (r, φ, z) an increase in temperature $\Delta T(r, z) = T(r, z) - T_0$ (T_0 is initial specimen temperature equal to the temperature of the surroundings), and the temperature at points C and D is maintained equal to T_0 all the time. Let us be interested in the temperature behind the SW front. In this case it is necessary to explain whether it is possible from the voltmeter readings to determine the temperature at those points of boundary Σ where the lateral unloading wave has not yet arrived (here we assume that the metals are joined so that relative sliding of them is impossible and the temperature of the boundary equals the temperature of the metal). For this in order to explain the voltage dependence in the voltmeter we divide a closed loop L lying in some plane $\varphi = \text{const}$ and passing through the voltmeter through the measuring lead from B to A, and from A to B through the specimen intersecting Σ at some point M. The integral of the electric field intensity $\mathbf{E}$ along L is connected with the voltage in the voltmeter V as follows:

$$\oint\limits_L \mathbf{E}\,d\mathbf{l} = V + \int\limits_D^A \mathbf{E}\,d\mathbf{l} + \int\limits_A^M \mathbf{E}\,d\mathbf{l} + \int\limits_M^B \mathbf{E}\,d\mathbf{l} + \int\limits_B^C \mathbf{E}\,d\mathbf{l}, \tag{1}$$

where $d\mathbf{l}$ is an element of length along L. On the other hand,

$$\oint\limits_L \mathbf{E}\,d\mathbf{l} = -\frac{d\Phi}{dt} \tag{2}$$

(Φ is magnetic field flux through L). From (1) and (2) we obtain

$$V = -\frac{d\Phi}{dt} - \int\limits_D^A \mathbf{E}\,d\mathbf{l} - \int\limits_A^M \mathbf{E}\,d\mathbf{l} - \int\limits_M^B \mathbf{E}\,d\mathbf{l} - \int\limits_B^C \mathbf{E}\,d\mathbf{l}. \tag{3}$$

By using Ohm's law connecting the electric field in the metal with temperature:

$$\mathbf{E} = -\frac{1}{e}\nabla\mu + \frac{1}{\sigma_i}\mathbf{j} + s_i\nabla T, \quad i = 1,\ 2. \tag{4}$$

Here e is electron charge; μ is chemical potential; σ_i, s_i are conductivity and absolute thermoelectric coefficient of the metal i; $\mathbf{j}$ is current density. In the future we assume that σ_i are constant and s_i only depend on temperature.

Since the resistance of the voltmeter is much greater than that of the specimen, then it is possible to assume that current does not flow along the measuring lead. Then by substituting $\mathbf{E}$ from (4) in (3) we have

$$V = -\frac{d\Phi}{dt} + \int_D^C \frac{1}{e} \nabla\mu \, d\mathbf{l} - \int_A^M \frac{1}{\sigma_2} \mathbf{j} \, d\mathbf{l} - \int_M^B \frac{1}{\sigma_1} \mathbf{j} \, d\mathbf{l} + \int_{T_0}^{T_M} (s_1 - s_2) \, dT \tag{5}$$

(T_M is temperature at point M).

It is noted that the second term in this expression equals zero. In fact, the integral of $\nabla\mu$ with respect to the closed loop equals zero, and in the section from C to D including the voltmeter $\nabla\mu = 0$ since this section consists of one metal which is at constant temperature.

In order to calculate Φ we separate two loops: L_1 and L_2 lying in the same plane as L. We obtain the first by passing from the place of emergence of Σ at the external surface of the specimen (point N) to M along Σ from M to B along L, and from B to N along the specimen external surface. We form the second by passing from M to N along Σ, from N to A along the external surface, and from A to M along L. Since on the outside of the specimen there is no magnetic field, then Φ equals the sum of the fluxes through L_1 and L_2, and therefore taking account of (4),

$$\frac{d\Phi}{dt} = -\oint_{L_1} \mathbf{E} \, d\mathbf{l} - \oint_{L_2} \mathbf{E} \, d\mathbf{l} = -\oint_{L_1} \frac{1}{\sigma_1} \mathbf{j} \, d\mathbf{l} - \oint_{L_2} \frac{1}{\sigma_2} \mathbf{j} \, d\mathbf{l}. \tag{6}$$

In a cylindrically symmetrical case the magnetic field only has a φ-component $\mathbf{H} = \mathbf{e}_\varphi H$. Then from the equation $\mathbf{j} = \operatorname{rot} \mathbf{H}$ it follows that at the metal interface and at the external surface of the specimen

$$\mathbf{j} \, d\mathbf{l} = -\frac{\partial H}{\partial n} \, dl \tag{7}$$

(n is unit vector of the external normal to $d\ell$). Taking account of (6) and (7), from (5) we obtain

$$V = \int_{T_0}^{T_M} (s_1 - s_2) \, dT - \int_B^N \frac{1}{\sigma_1} \frac{\partial H}{\partial n_1} \, dl - \int_N^A \frac{1}{\sigma_2} \frac{\partial H}{\partial n_2} \, dl - \int_N^M \left(\frac{1}{\sigma_1} \frac{\partial H}{\partial n_1} + \frac{1}{\sigma_2} \frac{\partial H}{\partial n_2} \right) dl. \tag{8}$$

Whence it can be seen that voltage in the voltmeter markedly depends on magnetic field behavior around the specimen boundary. The magnetic field itself in each of the metals satisfies an equation of the diffusion type

$$\Delta \mathbf{H} = \mu_0 \sigma_i \partial \mathbf{H} / \partial t, \quad i = 1, 2, \tag{9}$$

μ_0 is a magnetic constant.

From continuity of the tangential components of $\mathbf{E}$ in Σ and (4) and (7) it follows that the source of the magnetic field for Eq. (9) is in Σ in the place where there is a temperature gradient along Σ in the radial direction. The amount of magnetic flux dJ generated in a unit of time in a section of length dr,

$$dJ = \left(\frac{1}{\sigma_1} \frac{\partial H}{\partial n_1} + \frac{1}{\sigma_2} \frac{\partial H}{\partial n_2} \right) dr = -(s_1 - s_2) \frac{\partial T}{\partial r} \, dr. \tag{10}$$

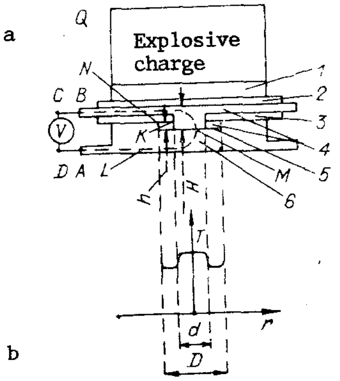

Fig. 2

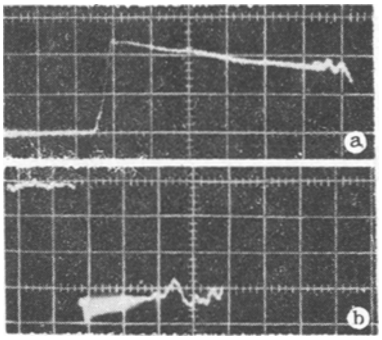

Fig. 3

From this point of view all of the terms in (8) have a clear physical meaning. The first is the result of the direct effect of the temperature gradient along the integration path. The second and third are the amount of magnetic flux emerging at the external surface of the specimen for 1 sec. The fourth is the amount of magnetic flux generated in section Σ from N to M for 1 sec.

We consider what will determine voltage in the voltmeter at different instants of time t is with t = 0 instantaneous specimen heating occurred. The magnetic field which is generated where there is a temperature gradient along the metal interface diffuses through the metal along the direction towards the external surface in which all of the time the condition H = 0 is fulfilled. Characteristic times for which the magnetic field reaches the external surface for each of the metals is correspondingly $\tau_1 \sim \mu_0\sigma_1\delta_1^2$ and $\tau_2 \sim \mu_0\sigma_2\delta_2^2$ (δ_1 and δ_2 are distances from the place of finding a temperature gradient in Σ to the external surface). For definiteness we assume that $\tau_1 < \tau_2$. By using (10) we present (8) in the form

$$V = \int_{T_0}^{T_N} (s_1 - s_2)\,dT - \int_{B}^{N} \frac{1}{\sigma_1}\frac{\partial H}{\partial n_1}\,dl - \int_{N}^{A} \frac{1}{\sigma_2}\frac{\partial H}{\partial n_2}\,dl \tag{11}$$

(T_N is temperature at point N).

At instants of time $t \ll \tau_1$ the magnetic field does not manage to diffuse to the external surface and the last two terms in (11) are close to zero. Consequently, with $t \ll \tau_1$ voltage in the voltmeter is determined by the temperature in the area of emergence of the metal interface at the external specimen surface T_N and it depends weakly on temperature within T_M. Therefore with $t \ll \tau_1$ an unusual effect arises of screening of the central region by the specimen edge zone. Screening is a special case of the common phenomenon of an electromagnetic field skin. Only in this case the field increases from within the specimen to the outside in contrast with a normal skin considered with penetration of a field from the outside into the depth of the metal. In fact, screening of the central region of the thermocouple will always arise and not only in the special case of cylindrical geometry considered here.

Thus, if the aim of the experiment is to measure temperature behind the SW front, i.e., the temperature in that region of the specimen when the unloading wave has not yet arrived and where the metal only undergoes single-stage compression, then the specimen should be such that the minimum τ_1 is much less than the characteristic time for the test process. This limitation shows that the most natural specimen configuration represented by a bimetallic cylinder with characteristic dimensions in several millimeters is unsuitable. In fact, even for metals with quite poor conductivity of the constantan type $\sigma \approx 2\cdot10^6\ \Omega^{-1}\cdot\mathrm{m}^{-1}$ (not speaking about copper for which $\sigma \approx 6\cdot10^7\ \Omega^{-1}\cdot\mathrm{m}^{-1}$) the diffusion time with these dimensions is ~100 μsec whereas the characteristic time for shock-wave processes is ≈1 μsec. In addition, with specimen dimensions in several millimeters it does not generally make sense to record voltage for a time greater than ≈1 μsec since in this time either the unloading wave manages to reach the center of the specimen or voltage of a reverse sign develops caused by emergence of the SW into the second electrode of the thermocouple. With this experimental arrangement the effect of screening leads to the situation that the voltage recorded will not be determined by the temperature behind the SW front which it is proposed to measure, but the temperature at the edge of the specimen in the region of plastic deformation in the unloading wave.

As a result of this voltmeter readings will in fact depend only on how the edge of the thermocouple is made.

With $t \gg \tau_1, \tau_2$ established the stationary distribution of flexes through the volume of the specimen. The problem of voltage in the thermocouple in this case was determined in [1] where it was shown that voltage in the voltmeter depends in a quite complicated way on temperature distribution over the whole metal interface. At intermediate instants of time ($t \sim \tau_1, \tau_2$) voltmeter readings determine both the change in magnetic flux and the temperature distribution over the metal interface. Voltage in the thermocouple will depend strongly on specimen geometry. The possibility of recovering the temperature in the central region from voltage measured with $t \sim \tau_1, \tau_2$, requires particular consideration in each specific case.

The following thermocouple construction for measuring temperature behind the front of a stationary plane SW in copper was used in the present work. The axial cross section of the experimental assembly is given in Fig. 2a. In order to exclude the possibility of the metals sliding in relation to each other at the instant of loading, the blanks for the thermocouple were prepared by explosive welding of constantan and copper sheets. Then a cylindrically symmetrical specimen was prepared. The SW was introduced through a copper screen 1 and insulator 2. Constantan thickness in the central region H = 5 mm, and beneath the insulator 3h = 100 µm. The insulator was prepared from Teflon 60 µm thick. The diameter of the central region d = 10 mm, and the diameter of the interface 5 of constantan 4 and copper 6 was D = 20 mm. The diameter of the whole assembly was 75 mm. Loading was carried out by a plane SW with pressure behind the front of 15, 20, 30, 39 GPa. Pressure was measured by a manganin transducer. Given in Fig. 3 are typical pressure (a) and temperature (b) oscillograms. The sweep was 0.5 µsec/square, and along the vertical it was 1 mV/square. Pressure at the maximum was 15 GPa.

Temperature gradients along the metal interface in this thermocouple were located in two areas: with $r = d/2$ and $r = D/2$. The radial dimension of the region where the temperature varied was of the order of the thickness of the constantan coating h. Until the lateral unloading wave reached the metal interface temperature distribution T(r) in the boundary had the form shown qualitatively in Fig. 2b. Since shock adiabats for copper and constantan are quite similar [2], and thermal conductivity of copper is greater by a factor of twenty than that of constantan, the temperature in the central region of the metal interface differed by 1-2% in all from the temperature behind the stationary SW front in copper.

In order to explain how temperature governs the voltage in this thermocouple we turn to (9). Since $h \ll d$, the terms $(1/r)(\partial H/\partial r)$ and H/r^2 in ΔH may be ignored compared with $\partial^2 H/\partial r^2$ and $\partial^2 H/\partial z^2$, then (9) is presented as

$$\partial^2 H/\partial r^2 + \partial^2 H/\partial z^2 = \mu_0 \sigma_i \partial H/\partial t, \qquad (12)$$

i.e., close to the position of the temperature gradient H a plane diffusion equation is satisfied without discharge of the magnetic field into the volume of the metal [the term $-H\cdot r^2$ in (9)]. Therefore the problem of finding the magnetic field is conveniently reformulated into a problem of diffusion of certain particles. In fact, these problems coincide entirely if the concentration of particles is H, they are generated at the interface, they diffuse through the metal according to Eq. (12), and by emerging at the external surface they disappear (according to the condition H = 0). Here the diffusion coefficient in metal i equals $1/\mu_0\sigma_i$, and the number of particles generated in 1 sec in a unit length of Σ in the radial direction is $\mu_0^{-1}(s_1 - s_2)\partial T/\partial r$. Then the last term in (8) is proportional to the number of particles generated for 1 sec at the boundary:

$$N_0 = -\int_N^M \frac{1}{\mu_0}(s_1 - s_2)\frac{\partial T}{\partial r}\,dr,$$

and the second and third terms are the number of particles emerging for 1 sec at the external surface:

$$N(t) = -\int_B^N \frac{1}{\mu_0\sigma_1}\frac{\partial H}{\partial n_1}\,dl - \int_N^A \frac{1}{\mu_0\sigma_2}\frac{\partial H}{\partial n_2}\,dl.$$

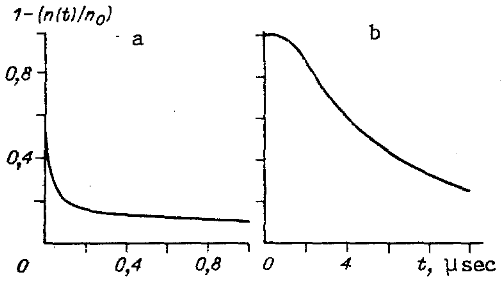

Fig. 4

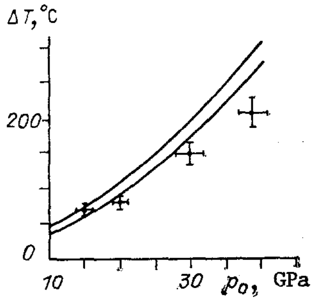

Fig. 5

therefore (8) may be presented in the form

$$V = \int_{T_0}^{T_M} (s_1 - s_2)\, dT - \mu_0 N_0 + \mu_0 N(t). \tag{13}$$

First we consider the subsidiary problem. Let at instant t = 0 in the area where a temperature gradient in Σ is found n_0 particles be generated instantaneously, and at instant t at the external surface n(t) particles emerge from them. If in this area of Σ there operates a constant source generating for 1 sec N_0 particles, then at instant t of the number of particles generated for the time from τ to $\tau + d\tau$ at the external surface emerges that fraction of particles as with instantaneous generation of n_0 particles an instant t = 0: $n(t - \tau)/n_0$. Then if a source of constant power started to operate with t = 0, then at instant t at the external surface emerges $\int_0^t \frac{n(t-\tau)}{n_0} N_0 d\tau$ particles. On the other hand, this number of particles equals $\int_0^t N(t)\, dt$. By equating these expressions and differentiating with respect to t we write

$$N(t) = \frac{n(t)}{n_0} N_0,$$

i.e., in order to determine voltage in the thermocouple it is sufficient to find n(t), and from (13) we have

$$V = \int_{T_0}^{T_M} (s_1 - s_2)\, dT - \left(1 - \frac{n(t)}{n_0}\right) \int_{T_N}^{T_M} (s_1 - s_2)\, dT. \tag{14}$$

The relationship $1 - n(t)/n_0$ obtained by the numerical Monte Carlo method for the thermocouple used by us is given in Fig. 4a. It can be seen that after 100 nsec from the volume of the metal 80% of the particles have departed. Since T_N in this case cannot be less than the temperature with adiabatic compression T_S, with pressures in the SW of $p \leq 50$ GPa the integral in the second term in (14) is at least half the first integral. For example, according to calculation by the procedure in [3] with p = 40 GPa, $T_M - T_0 \simeq 250$-280°C, and $T_S - T_0 \simeq 120$°C. Therefore, after 100 nsec the addition to the voltage due to screening [second term in (14)] in this case does not exceed 10%. Since all the same $T_N > T_S$, then it is clear that this is known to be a high estimate. Thus, it is possible to say that the time resolution of this thermocouple is not worse than 100 nsec, i.e., a thermocouple of the suggested construction after 100 nsec after passage of the SW front through the metal interface measures the temperature in the central part in spite of the fact that $t \ll \tau_2$ and the diffusion process for the magnetic field is still not yet established. This is due to the fact that the conductivity of copper is greater by a factor of thirty than that of constantan, as a result of which almost all of the magnetic field which is generated at the interface diffuses through the constantan and emerges into the gap filled with insulator 3 (see Fig. 2). Only a small part of the magnetic flux emerges into the copper, and with $t \sim \tau_1$ an almost steady distribution of fluxes and fields is established in the constantan.

Given in Fig. 4b for comparison is the relationship $1 - n(t)/n_0$ for a thermocouple composed of constantan and copper disks each 25 mm in diameter and 2.5 mm thick. Even after 1 μsec in this metal geometry about 1% of the particles emerge in all, screening is very strong, and voltage in the thermocouple in fact is independent of the temperature in the central region T_M. In fact, with $n(t) \ll n_0$ from (14) it follows that

$$V = \int_{T_0}^{T_N} (s_1 - s_2)\, dT.$$

The dependence of the increase in temperature $\Delta T(p)$ behind the SW front on pressure obtained from experimental measurement of voltage in a thermocouple of the construction suggested is given in Fig. 5. Temperature was determined by the procedure developed in [4]. The temperature range obtained from calculation by the procedure in [3] is bounded by solid lines in Fig. 5.

Thus, in the present work the effect is studied of nonstationary electromagnetic effects on the possibility and reliability of measuring temperature by a thermocouple method under pulsed deformation conditions; a screening effect is established for the central region of the thermocouple by the edge zone; the temperature in copper with pressures from 15 to 39 GPa is measured.

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