

that the peaks of the curves emerge into a certain steady level. Thus, from the results of a numerical experiment it follows that the temperature field in the chamber wall after five to six material treatment cycles almost emerges into a steady periodic regime. A periodic thermal regime for the chamber walls is most critical, and therefore it is necessary to use this regime in evaluating thermoelastic stresses in the chamber walls. In addition, the maximum temperature of the internal chamber wall should not exceed the ignition temperature of the gas mixture for deburring.

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NUMERICAL CALCULATION OF THERMOELASTIC STRESSES IN CHAMBERS FOR DETONATING A GAS MIXTURE

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With detonation of a gas mixture in a chamber as a result of induced detonation product convection, caused by a shock wave, the thermal flow towards the walls of the chamber is described by a rapidly decreasing time function so that the maximum temperature at the internal surface of a chamber with a size of the order of ~ 0.4 m is reached in a time $\sim 10^{-2}$ sec. This time in order of value is the same as the typical time for the decrease in thermal flow or shock-wave attenuation [1]. In time $\tau_0 \approx 10^{-2}$ sec a layer of metal with thickness $\delta = \sqrt{4a\tau_0} \approx 10^{-3} - 3 \cdot 10^{-3}$ m (a is thermal diffusivity) is heated [2], and the thickness of the chamber wall is normally several centimeters. Simple estimates of circumferential stresses in the internal surface of a steel chamber according to data in [2] with detonation of a propane-oxygen mixture $C_3H_8 + 10O_2$ with initial pressure $P_0 = 0.8$ MPa are as follows: thermal stresses $\sigma_t = E_1 \alpha_1 \Delta T \approx 1330$ MPa, elastic static stresses as a result of gas pressure with instantaneous combustion $\sigma_y = (Pr_0)/H \approx 40$ MPa (P is pressure at the internal surface), dynamic stresses taking account of the reflection of detonation waves $\sigma_d \approx 10\sigma_y = 400$ MPa. Here it assumed that $E_1 = 21 \cdot 10^4$ MPa, $\alpha_1 = 12.1 \cdot 10^{-6}$ deg $^{-1}$, $\Delta T = 524$ deg, $r_0 = 0.16$ m, $H = 0.04$ m (E_1 is elasticity modulus, α_1 is linear expansion coefficient, ΔT is the increase in temperature over the initial temperature, r_0 is chamber internal radius, H is thickness). These estimates show that in chambers for treating materials by gas detonation thermal stresses σ_t in the surface layer are the main factor in failure. For this reason there is specific interest in accurate calculation of the thermal stress fields in the walls of a chamber using the distribution of temperature fields obtained in [3].

The aim of the present work is numerical calculation of the thermoelastic stress fields in the chamber walls and then on the basis of the calculation, recommendation of some simple approximate approach for estimating the maximum thermal stresses. In the last case the periodicity of thermal flow at the internal surface is considered.

1. Pressure at the Internal Surface Required in Order to Calculate Thermal Stresses.

The pressure of gas mixture detonation products within the chamber in relation to time may be found by proceeding from an equation of state for an ideal gas

$$P(\tau) = (\rho RT(\tau))/\mu \quad (1.1)$$

(P , ρ , R , μ , T are pressure, gas density, gas constant, molecular weight, and gas temperature). The change in gas temperature with time in the chamber is determined from the first rule of thermodynamics

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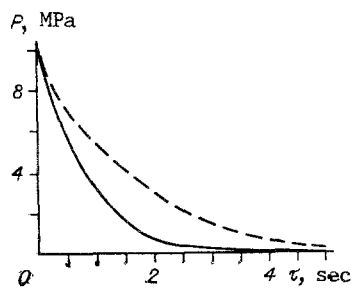


Fig. 1

$$dU = c_V(T)dT \quad (1.2)$$

(U is internal energy, c_V is heat capacity of the gas with constant volume). On the other hand, a change in the total internal energy for the gas in a unit of time may be presented as

$$dU = Q(\tau)Sd\tau, \quad (1.3)$$

where S is total internal surface of the chamber; τ is current time; thermal flow [2] $Q(\tau) = Q_1 \exp(-k\sqrt{\tau}) + Q_2 \exp(-\beta\tau)$; Q_1 , Q_2 , β , k are some constants depending on the geometric dimensions of the chamber and the gas mixture composition and initial pressure.

Relationships $c_V = c_V(T)$ found approximately are provided in [4]. By solving set of Eqs. (1.2) and (1.3) it is possible to determine the relationship $T = T(\tau)$ and then from (1.1) to determine $P = P(\tau)$. With a sufficient degree of accuracy for our purposes the relationship $c_V = c_V(T)$ from [4] is approximated by a cubic parabola

$$c_V(T) = \gamma T^3 + c_{V0} \quad (1.4)$$

(γ is some constant, c_{V0} is gas heat capacity with 'instantaneous' combustion which is found for each gas mixture independently). We obtain constant γ from an additional approximate equality which expresses conservation of energy: $U \approx mQ_C$ (m is mass, Q_C is specific heat of combustion of the gas mixture). As a result of approximation (1.4) the procedure is considerably simplified for determining the relationship $c_V = c_V(T)$. Shown in Fig. 1 is the dependence of pressure $P(\tau)$ on time. The broken line corresponds to approximation (1.4), and the solid line corresponds to the relationship $c_V = c_V(T)$ from [4]. In numerical calculations the following values of constants are taken: $Q_1 = 3.65 \cdot 10^7$ W/m², $Q_2 = 3.66 \cdot 10^7$ W/m², $k = 3.36$ sec^{-0.5}, $\beta = 41.4$ sec⁻¹, $\rho = 11.16$ kg/m³, $R = 8.314$ J/(kg·deg), $\mu = 0.034$ kg/mole, $m = 0.343$ kg, $Q_C = 1.1 \cdot 10^7$ J/kg, $c_{V0} = 147.5$ J/deg.

2. Numerical Calculation of Thermoelastic Stresses in the Chamber Walls. In numerical calculation the chamber is considered as a finite two-layer cylinder with presence of thermal protection (thin internal layer of a material with high thermal conductivity) or a single layer cylinder with absence of it. It is assumed that pressure at the internal surface is uniform over the chamber length. The external surface of the cylinder is assumed to be free from loads, and the ends are restrained. Calculation of the stress-strain state (SSS) of a finite two-layer cylinder is performed within the scope of linear two-dimensional unconnected axisymmetrical thermoelasticity theory by the finite element method using a computation program [5] modified for calculating thermoelastic stresses. As the temperature field in the problem use is made of that obtained in [3] and which relates to heating of the chamber walls with the first initiation of gas detonation. Parameters for copper and steel are taken as those for parameters of the internal and external layers of the cylinder in the calculation, respectively. Here the following constants are taken: $E_1 = 13.4 \cdot 10^4$ MPa, $E_2 = 21 \cdot 10^4$ MPa, $\nu_1 = 0.368$, $\nu_2 = 0.27$, $\alpha_1 = 1.66 \cdot 10^{-5}$ deg⁻¹, $\alpha_2 = 1.13 \cdot 10^{-5}$ deg⁻¹, $r_0 = 0.16$ m, $R_1 = 0.164$ m, $R_2 = 0.2$ m, $L = 0.48$ m.

Thus, the following equations of motion are integrated numerically:

$$\begin{aligned} \mu_i(\Delta u_i - u_i/r^2) + (\lambda_i + \mu_i)(\partial e_i/\partial r) &= \beta_i \partial t/\partial r, \\ \mu_i \Delta w_i + (\lambda_i + \mu_i)(\partial e_i/\partial r) &= \beta_i \partial t/\partial r, \quad i = 1, 2 \end{aligned}$$

with boundary conditions

$$\begin{aligned} r = r_0: (\sigma_{rz})_1 &= \mu_1(\partial u_1/\partial z + \partial w_1/\partial r) = 0, \\ (\sigma_r)_1 &= \lambda_1 e_1 + 2\mu_1 \partial w_1/\partial r - \beta_1 t(r_0, \tau) = P(\tau), \\ r = R_2: (\sigma_{rz})_2 &= \mu_2(\partial u_2/\partial z + \partial w_2/\partial r) = 0, \\ (\sigma_r)_2 &= \lambda_2 e_2 + 2\mu_2 \partial w_2/\partial r - \beta_2 T_0 = 0 \end{aligned}$$

and conditions at the layer interface

$$\begin{aligned} r = R_1: (\sigma_r)_1 &= (\sigma_r)_2, (\sigma_{rz})_1 = (\sigma_{rz})_2, \\ u_1 &= u_2, w_1 = w_2. \end{aligned}$$

Restraint conditions are fulfilled at the chamber ends

$$\begin{aligned} z = 0: u_i(r, 0) &= w_i(r, 0) = 0, \\ z = L: u_i(r, L) &= w_i(r, L) = 0. \end{aligned}$$

Here $(\sigma_r)_i$, $(\sigma_{rz})_i$ are radial and tangential stresses; λ_i , μ_i , α_i are Lamé parameters and linear thermal expansion coefficients; $\beta_i = (3\lambda_i + 2\mu_i)\alpha_i$; $e_i = \partial u_i/\partial r + u_i/r + \partial w_i/\partial z$; u_i , w_i are radial and axial displacements; T_0 is initial temperature; L is chamber length; $\Delta = \partial^2/\partial r^2 + (1/r)(\partial/\partial r) + \partial/\partial z$; r_0 , R_2 are internal and external chamber radii; R_1 is layer interface radius.

In view of symmetry for the problem half of the cylinder is considered ($0 \leq z \leq L/2$, $r_0 \leq r \leq R_2$). This region is approximated by 200 eight-node isoparametric axisymmetrical finite elements (there are ten elements through the thickness, five elements in the internal layer, and twenty elements over the cylinder length). The grid selected appeared to be the optimum in the sense that computation experiments for a finer grid did not give a marked change in the SSS picture.

In the computation program [5] stresses were determined at nodes of Gaussian integration located at certain distances from the boundary of an element in relation to the order of integration adopted. In this work stresses through the chamber thickness were derived as four different points (two points in each layer) closest to the contact and outer surfaces. Therefore, in the future we shall use the term 'close to the surface' meaning in fact these nodes. Stresses were derived in two sections over the chamber length: close to the end and at the center. Calculation was also carried out for the case of a single-layer chamber (absence of thermal protection).

As might be expected, in the center of the chamber ($z = L/2$) the thermoelastic stress field is almost indistinguishable from the corresponding stress fields in an infinite cylinder. Thermoelastic stress fields in an infinite two-layer cylinder may be obtained comparatively easily, for example, by using the generalized functions method [6, 7]. Presented in Figs. 2 and 3 are the distributions of circumferential stresses σ_θ through the thickness in the center of single- and two-layer chambers at different instants of time. Curves 1-3 relate to $\tau = 0.25$; 0.6; 0.95 sec. In a single-layer chamber made of steel in the first instants of time in the internal surface layer there is a very high stress gradient. For a two-layer chamber this value is comparatively small, and circumferential stresses experience a jump at the contact boundary.

Shown in Fig. 4 is the dependence of thermoelastic stresses σ_θ on time at the internal surface of the chamber. The time interval in question is 1 sec. Curves 1 and 3 relate to single-layer chambers made of copper and steel, 2 relates to a two-layer chamber, and 4 and 5 relate to approximate determination of stresses (see below). As can be seen from Fig. 4, with presence of thermal protection there is a marked reduction in maximum values of thermoelastic stresses. However, the ratio of circumferential thermoelastic stresses σ_θ at the internal surface to the corresponding yield strengths σ_* (for steel and copper $\sigma_* = 430$ and 68.5 MPa) for steel single- and two-layer chambers they appeared to be $\sigma_\theta/\sigma_* = 10-12$, $\sigma_\theta/\sigma_* = 4-5$. Therefore, the function of the thermal protection consists as follows from our calculations and estimates in a reduction of thermoelastic stresses in the steel layer at the boundary with the copper (cracks which arise in the copper as a result of plastic flow do not penetrate into the steel with heating and cooling of the layer). These stresses in a steel

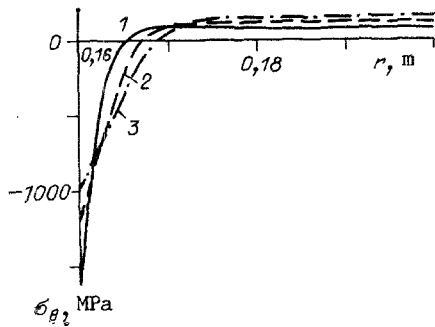


Fig. 2

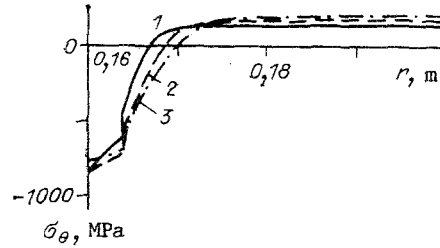


Fig. 3

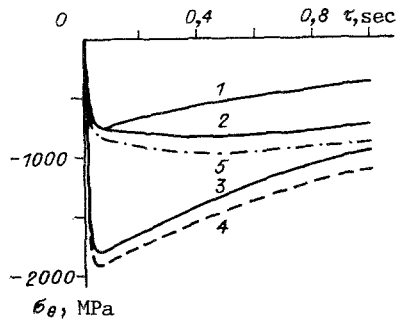


Fig. 4

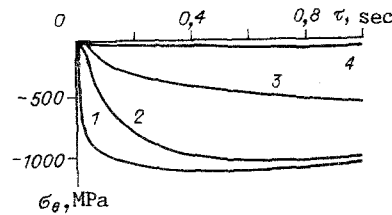


Fig. 5

layer are reduced by approximately a factor of three (see Figs. 2 and 3) compared with thermoelastic stresses at the surface of a single-layer chamber and the ratio σ_θ/σ_* appears to be 1-1.5; it is apparent that an increase in the thickness of thermal protection may reduce it to a value lower than one.

Close to the chamber ends the maximum circumferential stresses exceed in absolute value axial stresses in the center of the chamber. Shown in Fig. 5 are curves for circumferential thermoelastic stresses close to the ends of a two-layer chamber in relation to time at the four points through the thickness described above. Curve 1 relates to circumferential stresses close to the internal surface, 2 close to the contact surface from the direction of the internal layer, 3 from the direction of the external layer, and 4 close to the external surface. It is noted that for a two-layer chamber compared with a single-layer chamber there is a marked increase in the time for which stress reaches the maximum value. Maximum values of circumferential thermoelastic stresses close to the ends as a result of the edge effect exceed similar stress values in the center of the chamber by about a factor of 1.5.

In view of the linearity of the problem thermoelastic stresses may be presented as superposition of elastic and thermal stresses. It emerges from the numerical calculations provided that thermal stresses make a specific contribution to the chamber wall SSS. For circumferential elastic stresses in the center of a single-layer chamber the following equation is valid $\sigma_\theta(r) = P(\tau)((R^2 + r^2)r_0^2)/((R^2 - r_0^2)r^2)$. The maximum pressure at the internal surface determined in part 1 is ~ 10 MPa (see Fig. 1). The circumferential elastic stresses at the internal surface $\sigma_\theta(r_0) = 45.5$ MPa. It can be seen from comparison with the maximum values of thermoelastic stresses which are ~ 1000 MPa that the contribution of elastic stresses to the SSS is very small.

3. Approximate Equations for Thermal Stresses. From the point of view of practice it is very important to evaluate the maximum thermal stresses in the chamber wall. At the center of the chamber the stress field is almost indistinguishable from the corresponding stress fields in an infinite cylinder. This situation makes it possible to evaluate the maximum stresses in terms of an expression for stresses in an infinite cylinder.

For a uniform cylinder approximate expressions for circumferential thermal stresses used with relatively short times may be obtained by following [8]. Omitting the computations, the final expressions for stresses at the internal surface are written in the form

$$\sigma_{\theta}(r_0, \tau) = \frac{\alpha_1 E_1}{1 - \nu_1} \left\{ -t(r_0, \tau) + \frac{a}{\lambda_1} \frac{2r_0}{R_2^2 - r_0^2} \left[Q_1 \frac{2}{k^2} (1 - \exp(-k\sqrt{\tau})(1 + k\sqrt{\tau})) + Q_2 \frac{2}{\beta} (1 - \exp(-\beta\tau)) \right] \right\}, \quad (3.1)$$

where λ_1 , ν_1 are thermal conductivity coefficient and Poisson's ratio; $t(r_0, \tau)$ is temperature at the internal surface. With short times by ignoring the second term we obtain

$$\sigma_{\theta}(r_0, \tau) = -\alpha_1 E_1 t(r_0, \tau) / (1 - \nu_1). \quad (3.2)$$

It is evident that for quite thick-walled cylinders the second term in (3.1) cannot be ignored. Results of calculation by (3.1) are in very good agreement with the accurate solution for a single-layer cylinder up to $\tau_0 \approx 30$ sec, and in Fig. 4 the corresponding curve is almost indistinguishable from curve 3. Curve 4 in Fig. 4 relates to circumferential stresses in the internal surface of a steel single-layer cylinder found with calculation by (3.2). Apparently by means of this equation it is possible to evaluate circumferential stresses in the internal surface of a two-layer cylinder (line 5 in Fig. 4). In both cases use of (3.2) gives a relative error compared with the numerical solution of not more than 10-15%. Estimate (3.2) for maximum thermal stresses is only valid however for the first cycle of initiating detonation. As was obtained in [3], after five to six material treatment cycles with gas detonation a periodic temperature field is established in the chamber wall. Thermal stresses, as for the temperature field in the approximate procedure suggested in [3], are represented in the form of static and dynamic components. The static term in this case is the static distribution of thermal stresses in a long cylinder when the temperature field in a single-layer cylinder is

$$t_0(r) = T_1 \ln(R_2/r) / \ln(R_2/r_0) + T_0, \quad (3.3)$$

and in a two-layer cylinder it is

$$t_0(r) = T_1 (\ln(R_2 R_1) + k_{\lambda} \ln(R_1 r) + (1 - k_{\lambda}) \ln(R_1/r) S_-(r - R_1)) / D + T_0. \quad (3.4)$$

Here $k_{\lambda} = \lambda_2 / \lambda_1$; $D = \ln(R_2/R_1) + k_{\lambda} \ln(R_1/r_0)$; λ_2 is thermal conductivity coefficient of the external layer; T_1 is the increase in internal surface temperature of the chamber wall over the initial temperature for a steady-state temperature regime (the value of T_1 is easily determined according to [3]); $S_-(x)$ is an asymmetric unit function [7]. By substituting (3.3) and (3.4) in the corresponding equations for thermal stresses we obtain the static term for the thermal stresses field in the chamber wall. For circumferential and axial stresses

$$\sigma_{\theta}^0(r) = \frac{\alpha_1 E_1 T_1}{2(1 - \nu_1)} \left[1 - \ln \frac{R_2}{r} - \frac{r_0^2}{R_2^2 - r_0^2} \left(1 + \frac{R_2^2}{r^2} \right) \ln \frac{R_2}{r_0} \right],$$

$$\sigma_z^0(r) = \frac{\alpha_1 E_1 T_1}{2(1 - \nu_1)} \left[1 - 2 \ln \frac{R_2}{r} - \frac{2r_0^2}{R_2^2 - r_0^2} \ln \frac{R_2}{r_0} \right].$$

For a two-layer cylinder the expressions for thermal stresses in the case when the temperature at the external surface is prescribed are given in [6]. In view of their cumbersome nature they are not given here.

An estimate of the dynamic component of the stress field is expression (3.2), where $t(r, \tau)$ is temperature field with action of thermal flow Q_S [3]. For a two-layer chamber $Q_S(\tau) = Q(\tau) - T_1 / (h_1/\lambda_1 + h_2/\lambda_2)$ (h_2 is external layer thickness).

Thus, in order to evaluate the thermal stress field with a steady-state temperature regime a simple approximate approach is suggested. For example, in order to evaluate circumferential thermal stresses in the internal surface of a single-layer chamber we have

$$\sigma_{\theta}(r_0, \tau) = \sigma_{\theta}^0(r) - \alpha_1 E_1 t(r_0, \tau) / (1 - \nu_1).$$

Thus, the effect of thermal protection on thermoelastic stresses in the chamber wall is calculated numerically. With restrained ends the maximum circumferential stresses are in the

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 $\sim 1-10$ μ sec 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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