NUMERICAL INVESTIGATION OF SHOCK WAVE FLOW INITIATED BY IMPULSIVE IRRADIATION IN A METAL

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Impulsive irradiation of a metal by short electromagnetic waves, particularly a laser pulse, or by powerful electron beams with low pulse duration (10^{-9}-10^{-8} sec) and energies insufficient for evaporation or fusion of the metal, results in practically instantaneous heating of a certain layer of substance. Under such heating, the layer of solid does not succeed in being expanded and the increase in thermal energy is accompanied by the appearance of a compressive stress. The problem of dissociation of the discontinuity that initiates a shock wave in the unperturbed layer and an unloading wave in the perturbed (heated) layer, analogous to the problem of discontinuity dissociation in gases [1], occurs on the boundary of the hot and cold layers. Moreover, an unloading wave occurs on the free surface of the hot layer. Interaction of these two unloading waves results in the formation of a tension pulse near the leading free surface, which passes over the whole specimen after the compression pulse. The presence of such a tension pulse passing through a whole specimen is an essential singularity of shock wave flow originating because of the instantanteous heating of a certain layer of substance. The maximal value of the tensile stresses, and therefore the possible fracture zone, can be located at both the leading and trailing surfaces of the plate [2].

The process of compressive and tensile stress formation in metals under the action of a laser pulse and the qualitative analysis of the damping of these stresses are presented in [3]. A theoretical study of the different aspects of the propagation of stress waves caused by the action of a thermal pulse has been made in a number of papers. An analytical solution is obtained in [4] for the problem of stress wave propagation in an elastic half-space. A numerical solution of this same problem with destruction of the heated layer taken into account is given in [5]. A numerical investigation of the destruction of an aluminum plate under impulsive thermal heating is performed in [6] in an elastic-plastic approximation. The authors showed that although energy absorption occurs mainly near the surface of irradiation, the destruction is localized around the opposite (rear) surface of the plate. As a result of a numerical analysis of thermal viscoelastic-plastic waves, it is obtained in [7] that the maximal value of the compressive and tensile stress is reached in the heating zone; consequently, destruction occurs near the leading edge of the specimen. Dependences of the maximal compressive and tensile stresses on the intensity of exposure are obtained in [8] on the basis of a numerical solution of the equations of heat conduction and of elastic wave propagation.

Within the framework of a model of an elastic-plastic solid a numerical analysis is performed in this paper for the processes of compression and tension wave propagation and interaction upon their formation during instantaneous heating of a certain layer from a metal specimen. The influece of the exposure intensity and the depth of the heated zone on the maximal value of the tensile stresses and its localization is investigated.

FORMULATION OF THE PROBLEM

A metallic specimen of length L is subjected to a powerful irradiation pulse (less than 100 nsec exposure time) that is absorbed in a layer of thickness ℓ adjoining the left surface of the specimen. The left (exposed) surface of the specimen will be called the forward, and the right the rear surface. The thickness ℓ of the layer absorbing the radiation depends on the material properties and mode of exposure. It can be considered that the energy is absorbed. uniformly over the depth [2]. An energy q_0 is absorbed per unit mass of substance in the layer of thickness ℓ, which characterizes the exposure intensity. Since the exposure time is small, the substance does not succeed in being expanded and all the absorbed energy goes into an increase in the thermal energy of this layer, determined by the kinetic energy of the atoms.

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If the material equation of state is taken in the Mie–Grunheisen form [9, 10],

$$e(\rho, T) = e_p(\rho) + e_T(\rho, T), \quad p(\rho, T) = p_p(\rho) + p_T(\rho, T), \tag{1}$$

where $p_p(\rho) = Ax^{2/3}\exp b(1 - x^{-1/3}) - Kx^{4/3}$; $x = \rho/\rho_0$, $e_p(\rho) = 3Ab^{-1}\rho_0^{-1} \times \exp b(1 - x^{-1/3}) - 3K\rho_0^{-1}x^{1/3}$; ρ_0 is the initial density, A, b, K are material constants), then $q_0 = \Delta e = \Delta e_T = c_V\Delta T = c_V(T_* - T_0)$ (T_0 is room temperature). The pressure realized here is $p_* = \Delta p_T = \gamma_T(\rho)\rho\Delta e_T$ ($\gamma_T(\rho)$ is the Grunheisen factor).

An elementary estimate shows that the process of heated layer expansion can be considered adiabatic. Indeed, for a $L = 10^{-2}$ m specimen length and $v_y \approx 5 \cdot 10^3$ m/sec compression wave propagation velocity in iron, the characteristic time of the problem is $t = L/v_y = 2 \cdot 10^{-6}$ sec. The temperature change during this time because of heat conduction is felt at the distance [11] $x_T = \sqrt{\tau D}$, which is $0.65 \cdot 10^{-2}$ mm ($D = 2.1 \cdot 10^{-5}$ m²/sec is the thermal diffusivity coefficient of iron); consequently, the heat conduction phenomenon can be neglected. An analogous conclusion is obtained in [7] as a result of a numerical investigation of the contribution of heat conduction to the damping of compression and tension pulses.

The problem was solved in a one-dimensional formulation. The mass, momentum, and energy conservation equations in the plane one-dimensional case have the following form in the Lagrange coordinates (r, t):

$$\frac{\rho_0}{\rho}\frac{\partial \rho}{\partial t} = -\rho\frac{\partial v}{\partial r}, \quad \rho_0\frac{\partial v}{\partial t} = \frac{\partial \sigma^1}{\partial r}, \quad \rho_0\frac{\partial e}{\partial t} = \sigma^1\frac{\partial v}{\partial r} \tag{2}$$

(v is the particle mass velocity and σ^1 is the principal component of the stress tensor). The medium was considered elastic-plastic; consequently, $\sigma^1 = -p(\rho, T) + \tau^1$; τ^1 is the stress deviator that is subject to Hooke's law in the elastic domain and is later conserved at the yield point

$$\frac{\partial \tau^1}{\partial t} = \frac{4}{3}\mu\frac{\rho_0}{\rho}\frac{\partial v}{\partial r}, \quad \tau^1 \leqslant \frac{2}{3}\tau^*. \tag{3}$$

Here μ is the elastic modulus, and τ^* is the material yield point that depends on the pressure, i.e., the capacity of the material to resist plastic deformation grows as the pressure rises; this circumstance can be taken into account if $\tau^* = \alpha p + \beta$ is taken (α and β are material constants).

For the given equations of state (1) the system of differential equations (2) and (3) is closed. Mathematically this problem is formulated as follows: find the functions ρ, v, T, τ^1, p satisfying (1)-(3), the initial conditions $\rho(r, 0) = \rho_0$, $v(r, 0) = 0$, $\tau^1(r, 0) = 0$, $T(r, 0) = T_*$, $p(r, 0) = p_*$ for $0 \leqslant r \leqslant l$, $T(r, 0) = T_0$, $p(r, 0) = 0$ for $l < r \leqslant L$ and the boundary conditions $\sigma^1(0, t) = \sigma^1(L, t) = 0$ in the domain $0 \le r \le L$.

ANALYSIS OF THE NUMERICAL RESULTS

Within the framework of the model elucidated above, numerical investigaions were performed by the method of lines by using the pseudoviscosity of the wave process in iron and aluminum plates of thickness L = 10 mm subjected to impulsive exposure of different intensity q_0 during fractions of a microsecond. The thickness of the heated layer was 0.7 mm in iron and 2 mm in the aluminum. The computations for both the aluminum and the iron were performed for three values of q_0 that are presented in the table together with the appropriate values of the temperature T_* and the pressure p_*. The first two values of q_0 were taken identical for the aluminum and the iron, the third was chosen in such a manner that the heating temperature in this case was close to the melting point. Such a choice permits modeling both weak compression and rarefaction pulses and the greatest possible as well. According to the data in [12], when the internal energy reaches the threshold value after which evaporation starts, the tensile pulse diminishes since the vapors being formed exert pressure on the surface of the solid and do not let it unload.

The charcteristic details of the compression and tension wave formation, propagation and interaction process can be observed in the diagrams of the stress σ^1 in iron and aluminum.

Stress diagrams in iron are presented in Fig. 1 for the first experiment at different times (the time is given in microseconds). As a result of discontinuity dissociation on the boundary of the hot and cold layer in the unperturbed layer there is a compression wave of

TABLE 1

Experiment Number	$q_0 \cdot 10^3$, J/kg	T_*, K	p_*, GPa	Experiment Number	$q_0 \cdot 10^3$, J/kg	T_*, K	p_*, GPa
	Iron ($l = 0.7$ mm)				Aluminum ($l = 2.0$ mm)		
1	170	665	2,2	1	170	490	1,0
2	420	1210	5,3	2	420	775	2,5
3	690	1800	8,8	3	530	900	3,0

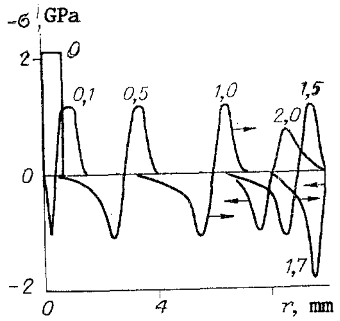

Fig. 1

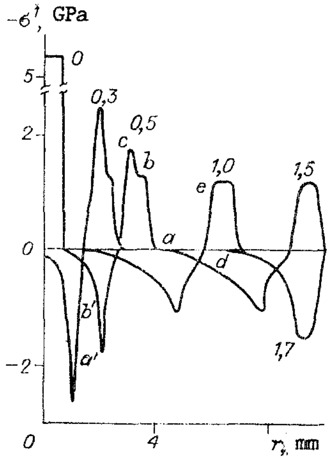

Fig. 2

intensity approximately $\frac{1}{2}p_*$ and an unloading wave in the perturbed layer. Its interaction with the unloading wave being propagated from the forward free surface results in the formation of tensile stresses with amplitude 1 GPa near this surface, which is also approximately $\frac{1}{2}p_*$ (time 0.1 μsec). The unloading wave going from the forward free surface determines the width of the compression pulse while the unloading wave going to the right from the unperturbed material is reflected by compression on reaching the free surface and determines the width of the tension pulse. Later a stable configuration consisting of compression and tension pulses moves over the specimen.

The stresses originating here lie in the elastic domain, and the compression and rarefaction pulses are propagated practically undamped. Near the rear free surface, the tensile stresses grow to 1.75 GPa because the compression pulse going ahead is reflected, upon emerging on it, by the unloading wave whose interaction with the impinging tensile pulse magnifies it (the wave propagation directions are shown by arrows).

The stress diagrams in iron are presented in Fig. 2 for high-exposure intensities (for the second experiment). The elastic-plastic behavior of the material turns out to be essential here. The elastic compression wave ab with intensity 1.2 GPa is isolated and moves undamped at a higher velocity than the plastic wave bc. The elastic wave ed that rapidly "eats away" the plastic compression wave bc is also isolated in the unloading and the same compression pulse as in the preceding case approaches the free surface. The significant tension pulse at the beginning (its intensity is $\approx\frac{1}{2}p_*$) also damps out rapidly because of the elastic compression wave a'b' proceeding in the stretched medium. An already insignificant tension pulse (~1 GPa), which is newly increased upon interaction with the compression pulse reflected from the rear free surface, approaches the rear specimen surface. The tension being formed at the rear surface is ~1.75 GPa (exactly the same as in Fig. 1 but less than at the forward free surface).

The curve of the maximal tensile stresses in iron has two local maximums in iron, at the forward and rear surfaces of the specimen, under sufficiently large exposure intensities, i.e, when the compression and rarefaction pulses being formed lie in the plastic domain. The tensile stresses being formed at the specimen rear surface are practically independent of the exposure intensity (for a sufficient specimen length) and equal 1.75 GPa.

The maximum of the tensile stresses at the forward free surface depends on the exposure intensity and can be substantially greater than the maximum of the tensile stresses near the

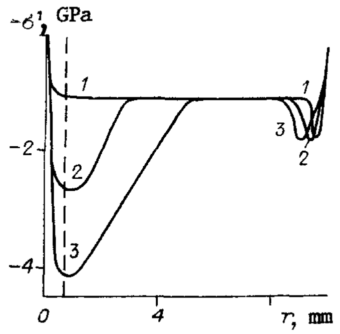

Fig. 3

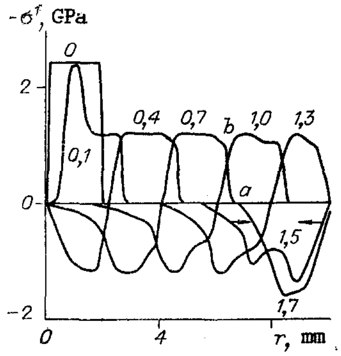

Fig. 4

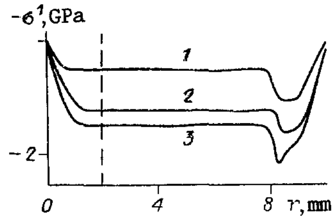

Fig. 5

specimen rear surface. Curves of the maximal tensile stresses in iron are presented in Fig. 3, where the digits indicate the number of the appropriate experiment. The tensile stresses at the forward surface are 4.2 GPa for the exposure intensity when the heating temperature is close to the melting point (curve 3); in practice this is the greatest possible value of the tensile stress in iron under pulse exposure.

Evolution of the compression and rarefaction pulses in aluminum is shown in Fig. 4 in an example from the second experiment. Although the exposure intensity here is the same as in the iron in Fig. 2, the heating temperature and therefore the stress being formed is almost halved since the specific heat of aluminum is almost twice the specific heat of iron. The flow here is also two-wave in nature: elastic and plastic waves are separated out in the loading and unloading. But, since the width of the pulse is large, both the compressive and the rarefactive plastic waves do not succeed in being damped. Compression and rarefaction pulses, equal to the initial pulse in amplitude, reach the rear free surface. The tensile stresses at the rear free surface grow because of interaction with the reflected compression pulse. The tension pulse depends on the compression and rarefaction wave amplitudes that are determined by the radiation intensity. Consequently, the curves of the maximal tensile stresses in aluminum, presented in Fig. 5, differ from the corresponding curves in iron. They all remain constant, depending on the exposure intensity (the numbers in Fig. 5 indicate the number of the appropriate experiments) and have a local maximum only at the rear surface. The greatest possible value of the tensile stresses in aluminum, governed by the melting point, is 2.1 GPa for a given specimen length.

Thus, shock wave flow being formed during pulse exposure of a metal is characterized by the fact that a tension pulse passes behind the compression pulse through the whole specimen and can result in destruction of the specimen for a sufficient exposure energy. The envelopes of the maximal tensile stresses can differ substantially for different metals at sufficiently large exposure intensities, and have one maximum at the rear free surface or two local maximums, at the forward free surface and at the rear surface. The most probable destruction zone associated with the site of the greatest tensile stresses can, depending on the material, the thickness of the heated layer, and the exposure intensity, be at both the specimen forward and rear surfaces. The algorithm proposed permits the determination of the possible destruction zone for given exposure parameters.

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RELAXATION MODEL FOR DESCRIBING THE STRAIN OF POROUS MATERIALS

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Plastic volume deformation characterizes the strain of porous media. Various models involving, in particular, the porosity concept, are used for its description. A survey of these models is given in [1]. Maxwell's nonlinear model [2] has been found useful for plastic shearing strain in the case of rapidly occurring processes. We propose that plastic volume deformation also be considered within the framework of the relaxation model. Relaxation equations of elastoplastic strain with plastic volume and shearing strain are derived. An example illustrating the determination of interpolation expressions for the equation of state and the volumetric relaxation time is given. The proposed model describes qualitatively the anomalous increase in the amplitude of the reflected wave, which has been detected experimentally (see, for instance, [3]).

Assume that the medium under consideration does not experience shearing strain and that the stress tensor in this medium is reduced to pressure. In this case, the strain values in the medium are determined only by changes in the density ρ, which, for the assigned field of velocities u_i, is found from the continuity equation

$$\partial\rho/\partial t + u_\alpha \partial\rho/\partial x_\alpha + \rho\partial u_\alpha/\partial x_\alpha = 0. \quad (1)$$

As is known [4], in the absence of shearing strain, the density is related to the principal values of the Hencky tensor of logarithmic strain h_i by the relationship $\rho = \rho_0 \exp(-h_1 - h_2 - h_3)$ (ρ_0 is the initial density of the medium). If there is only volume strain in the medium, then $h_1 = h_2 = h_3$ and $\ln(\rho/\rho_0)$, the compression logarithm, constitutes the measure of deformation.

Assume that the volume strain rate can be divided effectively into its elastic and plastic parts:

$$\frac{d}{dt}\sum_{i=1}^{3} h_i = \frac{\partial u_j}{\partial x_j} = \frac{d}{dt}\sum_{i=1}^{3} h_i^e + \frac{d}{dt}\sum_{i=1}^{3} h_i^p.$$

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