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MODELING THERMAL PROCESSES IN THE SHOCK LOADING OF POROUS MATERIALS

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Shock loading of porous materials within the pressure range 1.5-3 GPa makes it possible to obtain monolithic products [1-3]. Higher loading pressures (30-100 GPa) are used to study the equations of state of different substances under critical conditions [4]. It was shown in [5] that shock loading is characterized by highly nonequilibrium thermal processes. This high level of disequilibrium is due both to the sudden compression of the substance behind the shock wave (SW) and to the effect of powerful heat flows on the surface of particles of the substance. At the low pressures characteristic of powder compaction methods, thermal nonequilibrium is manifest in fusion of the particle surface [2, 3].

An increase in pressure or porosity in the pressing operation leads to an increase in the proportion of the substance that is converted to the liquid state and to a further intensification of heat release at the boundaries of particles. In this case, it is necessary to recognize the existence of a region of the substance in which the temperature exceeds the boiling point at normal pressure. Two layers can in turn be discerned within this region. In the first layer, internal energy is greater than the energy of vaporization, while in the second layer the former is less than the latter. When pressure is relieved, the molten layer – in which the acquired internal heat energy exceeds the energy necessary for vaporization – changes to the vapor state. Bulk boiling should be expected to occur in the second layer. The state of the substance behind the shock front actually depends on the ratio t^*/τ (where t^* is the time of arrival of the unloading wave, $\tau = R^2/a$ is the characteristic time of establishment of thermal equilibrium in an individual particle of radius R, and a is the diffusivity of the particle). At $t^*/\tau \ll 1$, there is not sufficient time for the particle to be heated uniformly, and vaporization and boiling may take place in the superheated material after the arrival of the unloading wave. When $t^*/\tau \gg 1$, an equilibrium temperature is established in the particle. Here, the state of the substance after arrival of the unloading wave is determined by the p-v diagram.

When the energy of the SW is low, the substance remains in the solid state. If the adiabatic curve corresponding to unloading passes through a two-phase region, then the substance is dispersed. When the curve passes above the critical point, the material vaporizes.

Thus, by varying the energy expended in shock compression and the parameter t^*/τ, it is possible to use the shock loading of porous materials to obtain different final states: monolithic solids, finely dispersed powders with a developed porous surface, ultradispersed particles, or a dense plasma.

We will examine the dynamic loading of powdered metal by a plane shock wave. The internal energy of the substance ε behind the front of the SW can be determined from the Hugoniot curve $\varepsilon = (p + p_0)(1/\rho_{00} - 1/\rho)/2$ and represented in the form of the sum: $\varepsilon = \varepsilon_g + \varepsilon_d + \varepsilon_t$. Here, ρ_{00} and ρ are the initial and final densities ahead of and behind the shock front; p is pressure; ε_g, ε_d, and ε_t are the fractions of energy expended by the SW on

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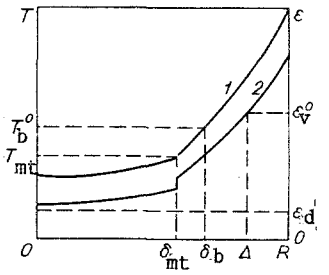

Fig. 1

compression of the gas in the pores, on bulk deformation of the particles, and on the liberation of heat at the boundaries of the particles, respectively.

Estimates show, for example, that $\varepsilon/\varepsilon_g \simeq 10^3$ for powdered aluminum with $\rho_0/\rho_{00} \simeq 3$ compressed by a pressure of 10 GPa. Similar estimates back up the analysis made in [1], where it was shown that the presence of gas in porous media has almost no effect on dynamic compaction processes. In connection with this, we can ignore the energy expended on compression of the gas and assume that $\varepsilon = \varepsilon_d + \varepsilon_t$.

It is evident from the experimental results in [6, 7] that the bulk strain energy ε_d is ≈70% of the total energy of the shock wave. However, it is not presently possible to reliably estimate the thickness δ of the thermal layer of the substance in which energy is liberated.

We will examine two limiting cases: $\delta = 0$ and $\delta = R$. At $\delta = 0$, all of the energy of the SW ε is given off in the form of heat and, during the time Δt, is uniformly distributed over the surface of the particles. We will adopt the analogy in [2], in which a powder is regarded as consisting of spherical particles of the same radius R. The interval Δt characterizes the time of passage of the SW over the distance ~2R [1]. Then during the time $\Delta t = 2R/D$ a unit surface of a particle is acted upon by the heat flux $q = \varepsilon M_0/(\Delta t S) = \varepsilon\rho_0 D/6$ (S, M_0 are the surface area and the mass of one particle and D is the velocity of the SW). For copper particles with $\rho_{00} = 3.0$ g/cm^3 and R = 100 μm loaded by an SW with p = 7.5 GPa, $q \simeq 2\cdot 10^8$ W/cm^2. Similar heat flows generated by lasers under normal conditions lead to heating of the surface of supercritical temperatures [8] and its gasdynamic disintegration. To describe processes occurring during the compression of powders with allowance for melting, we adopt Stefan's mathematical model in its enthalpy formulation [9]:

$$\frac{\partial H}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\lambda}{c\rho}\frac{\partial H}{\partial r}\right),\ 0<r<R,\ t>0; \tag{1}$$

$$\frac{dR_{mt}(t)}{dt} = \frac{\lambda}{\rho L_{mt}}\left(\frac{\partial T}{\partial r}\Big|_{r=R_{mt}(t)-0} - \frac{\partial T}{\partial r}\Big|_{r=R_{mt}(t)+0}\right),\ T|_{r=R_{mt}(t)} = T_{mt}; \tag{2}$$

$$-\lambda\frac{\partial T}{\partial r}\Big|_{r=R} = \begin{cases} q, & t\leqslant\Delta t, \\ 0, & t>\Delta t; \end{cases} \tag{3}$$

$$\frac{\partial T}{\partial r}\Big|_{r=0} = 0,\ t>0; \tag{4}$$

$$H|_{t=0} = H_0,\ 0\leqslant r\leqslant R,\ R_{mt}|_{t=0} = R; \tag{5}$$

$$H = \begin{cases} cT, & T<T_{mt}, \\ cT + L_{mt}, & T>T_{mt}. \end{cases} \tag{6}$$

Here, (1) is the heat-conduction equation; (2)-(4) are the conditions at the fusion front, on the particle surface, and at the point r = 0; (5) are the initial conditions; (6) connects enthalpy with temperature; $R_{mt}(t)$, R are the position of the fusion front and the radius of the particle; L_{mt} is the heat of fusion; c, ρ, and λ are the heat capacity, den

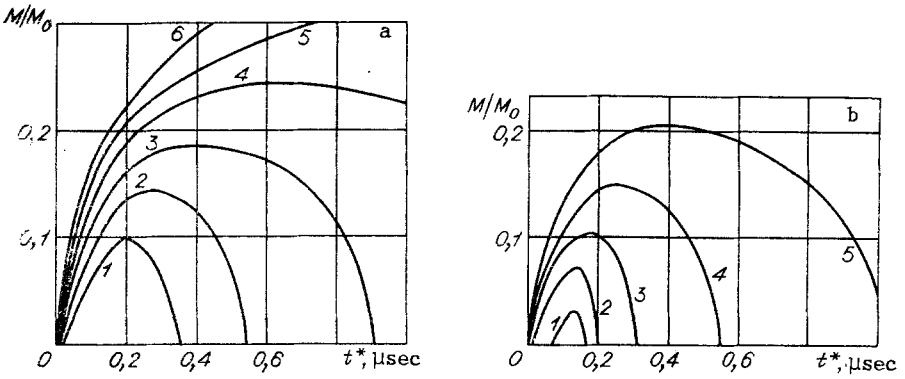

Fig. 2

sity, and thermal conductivity of the particle material. System (1)-(6) was solved numeri cally by the enthalpy method [9].

Figure 1 shows characteristic distributions of the temperature and internal energy (curves 1, 2) of a single particle. Of the greatest interest are the zones in which the temperature is higher than the boiling point under normal conditions T_b^0. These superheated zones are formed by heating under high pressure. We point out three of them, delineated by the boundaries δ_{mt}, δ_b, and Δ. The boundary with the coordinate $r = \delta_{mt}$ determines the position of the isotherm $T = T_{mt}$ (fusion front - solid). The coordinate $r = \delta_b$ gives the conditional boundary where temperature is equal to the boiling point at normal pressure ($T = T_b^0$), while the boundary $r = \Delta$ denotes the level of the energy of vaporization of the particle material ε_v^0 with instantaneous unloading. When pressure is relieved at the moment of arrival of the unloading wave, the layer of material at $\Delta \leq r < R$, with a thermal energy exceeding ε_v^0, is transformed to the vapor state. In the same region of material (with $\delta_b \leq r < \Delta$), we should expect boiling when $T > T_b^0$ but $\varepsilon < \varepsilon_v^0$. In this case, a porous structure forms on the surface.

It is evident from an analysis of the dynamics of the temperature fields in a particle that the position of the boundaries δ_{mt} and δ_b, Δ (which in turn determine the relative amounts liquid and vapor present) depends to a considerable extent on the intensity of the shock wave, the dimensions of the particles, and the time at which unloading of pressure begins t^*. The latter determines the time pressure is sustained on a certain section from the moment of passage of the SW to the moment of arrival of the unloading wave.

Figures 2 and 3 generalize calculations of the shock-wave loading of copper powder with an initial porosity $\rho_0/\rho_{00} \simeq 3$ and $R = 100$ μm for different loading conditions. Figure 2 illustrates the dependence of the relative amount of the substance (M/M_0) at $T > T_b^0$ on the intensity of shock loading p and the time that the pressure is sustained t^*. The calculations shown in Fig. 2a with p = 2.7; 3.7; 4.4; 6.1; 7.5; 9.1 GPa (lines 1-6) correspond to models describing the surface release of SW energy ($\delta = 0$) and can probably serve as upper bounds for the phase states of the substance. The results in Fig. 2b (lines 1-5 for p = 3.7; 4.8; 6.1; 7.5; 9.1 GPa) give the lower bounds for phase composition and constitute the model in which bulk heat release occurs ($\delta = R$). In essence, the curves determine the amount of vapor in the powder after arrival of the unloading wave. For example, at an SW pressure of 6 GPa, the maximum value of M/M_0 lies within the interval 10-25%. At $t^* \simeq 0.2$ μsec, we should expect that 10-20% of the powdered material (upper and lower bounds) will have the thermal conditions for boiling.

The difference between the upper and lower bounds at $t^*/\tau \lesssim 1$ is 10-30%. This is acceptable for practical use. At large t^*, when $t^*/\tau \gg 1$, the difference in the estimates increases. However, it is too approximate to adopt the model of bulk heat release after the shock front for this case.

Figure 3 shows similar results connected with estimation of the fraction of molten material in the powder (the notation in Fig. 3a corresponds to that in Fig. 2a; for Fig. 2b, p = 2.7; 3.7; 4.8; 6.1). It should be noted that bulk compression may result in complete melting of the particles at the given values of SW pressure. For example, thermal

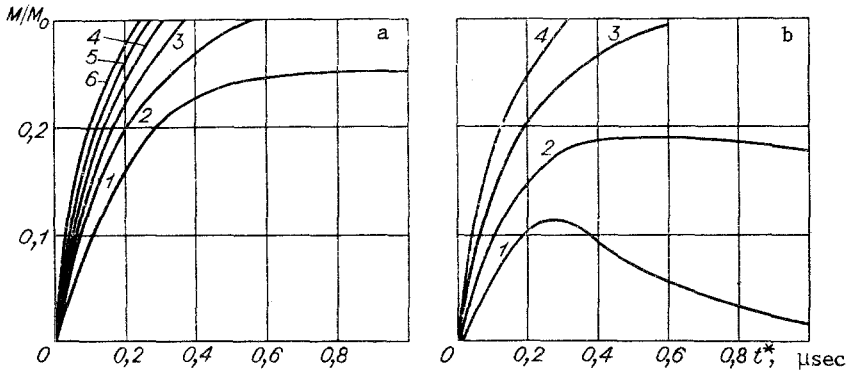

Fig. 3

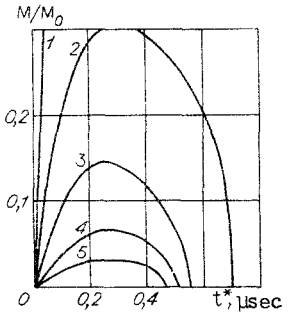

Fig. 4

nonequilibrium can be ignored at SW pressures above 10 GPa for particles whose thermophys ical parameters are close to those of copper.

To analyze the effect of the dimensions of the particles on the phase composition of powdered copper, we performed calculations for shock loading with p = 7.5 GPa. Figure 4 (R = 10, 50, 100, 200, and 500 μm - lines 1-5) illustrates the fraction of boiled material in particles of different diameters. The calculations show that the fraction of material that boils increases with a decrease in particle size. Copper powder with $R \lesssim 10$ μm is completely transformed to the vapor state.

Thus, the relations of the above-described model of thermal nonequilbrium for powdered media subjected to shock loading make it possible to predict the realization of different final states in the substance - from monolithic solids to dense plasmas. By varying the energy of shock compression and the time for which pressure is sustained, it is possible to obtain particles of specified dimensions, as well as particles with developed surface porosity.

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NUMERICAL MODELING OF THE THERMAL REMOVAL OF BURRS BY CONCENTRATED ENERGY FLOW

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Thermal conditioning is one of the most promising methods of removing burrs from metal products [1]. Such conditioning is done inside a chamber via the combustion of a gas-oxygen mixture. The combustion heats the burrs locally to their melting or combustion point. Another thermal conditioning technique is based on the use of concentrated energy flows – especially laser radiation. This approach results in melting and vaporization of the burrs [2]. The treatment regimes for machine parts are usually determined experimentally [3].

The goal of the present investigation is to numerically study the removal of burrs from the surface of a wall through fusion and vaporization occurring under the influence of concentrated energy flows. Determining the laws governing the burr-removal process as different parameters are varied makes it possible to devise a method of selecting heat-treatment regimes and optimizing existing technologies.

It is now possible to thermally load substances with a short-lived heat flow by using lasers, explosive plasma sources, high-enthalpy gas jets, and other means. The main factors determining the thermal regime in the material in such processes is the acting heat flux, its duration, and the form of the surface. The material undergoes thermal decomposition as a result of melting and vaporization (the combustion of thin burrs will not be examined here). In cases where convection is also a factor, it is also necessary to consider the spreading of molten material on the surface and its flow from the surface. In connection with this, it is important to study the dynamics of melting and vaporization and the laws governing the motion of the phase boundaries, as well as to evaluate the heating of the product near burrs.

We will examine the action of a heat flux $\mathbf{Q}$ on the surface of a semifinished product with burrs on it (Fig. 1). The heat flow is uniform with respect to both time and space. For the sake of definiteness, we choose the geometric form of the burrs to be isosceles triangles. Since burrs are generally much smaller than the product on which they are found, it is sufficient to examine a finite region $\Omega(t)$. The size of this region changes over time due to possible motion of the external boundary ω during melting and vaporization.

The temperature field in the region $\Omega(t)$ can be evaluated on the basis of Stefan's mathematical model in the two-dimensional formulation, with allowance for features of the phase transformations on the surface of the wall:

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