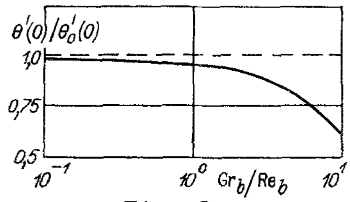

Fig. 3

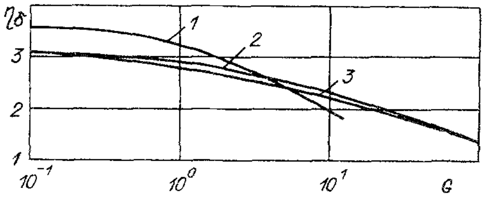

Fig. 4

Gr_b/Re_b^2. In the case where the contributions of the linear and quadratic terms in Eq. (1) are comparable, the control parameter is Gr_b/Re_b. It should also be noted that for granular beds, the numerical values of Gr/Re (the control parameter for a linear filtration law, $Gr = g\beta\Delta T\Pi x/\nu^2$, $Re = u\sqrt{\Pi}/\nu$) and Gr_b/Re_b (with a deviation from the linear law) are identically equal. As noted above, this makes it possible to use the asymptote for free convection, which is analogous to the asymptote for mixed convection under conditions of linear filtration.

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MELTING OF LEAD IN SHOCK COMPRESSION

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The transition of a solid in shock-wave compression to the liquid phase (as in any phase transition during shock compression) occurs within a certain pressure range associated with a section on the Hugoniot curve corresponding to a mixture of two phases. Schemes for the formation of the accompanying flows were examined, for example, in [1, 2] for a phase transformation involving a reduction in volume and in [3] for fusion. It was noted in [3] that the fusion of a substance in a shock wave (SW) cannot be recorded by presently known empirical methods based on the measurement of wave and mass velocities because the change in the parameters of the substance during melting is very small. In well-known experiments, conclusions on the occurrence of melting in an SW were made on the basis of changes in the viscosity of metals behind the shock front [4] and impulsive x-ray diffraction study of the character of motion of the free surface of a specimen during impact [3].

Here, we present experimental results on the fusion of lead in an SW obtained by two independent methods: study of the dependence of the dynamic yield point Y_d on the amplitude of the stress σ_x in unidimensional shock-wave compression; study of microstructural changes in specimens after shock-wave loading.

We used manganin wire stress gauges located in two mutually perpendicular sections of the test specimen to directly measure the longitudinal σ_x and transverse σ_y components of

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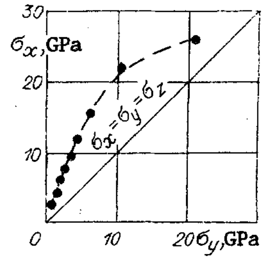

Fig. 1

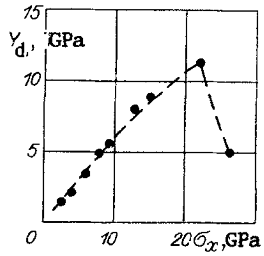

Fig. 2

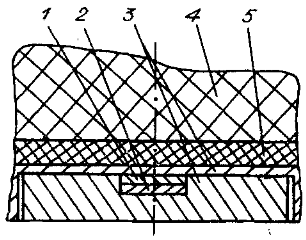

Fig. 3

the stress associated with shock compression in the range 2.0-26 GPa. Under conditions of unidimensional deformation, the difference in these stresses determines the dynamic yield point ($Y_d = \sigma_x - \sigma_y$). When this point is reached behind the front of a plane SW, the material undergoes a transition from the elastic to the plastic state. An increase in the stress associated with shock compression σ_x is accompanied by an increase in the temperature of the substance behind the shock front. The effect of these two factors (stress and temperature) on Y_d — which characterizes the resistance of the material to deformation in shock-wave compression — is directly proportional.

It is evident that in the range of σ_x in which melting occurs, the value of Y_d should decrease and should approach zero with the complete transformation of the substance to the liquid phase. The method used in our experiments was described in detail in [5]. To create plane stationary SW's of different amplitudes in the specimens of lead S4, we used explosive devices which created a wave with a table-shaped profile of 1-3 μsec duration in copper and aluminum shields (see [6], for example). The results of the experiments, presented in Figs. 1 and 2 in the coordinates $\sigma_x - \sigma_y$, $Y_d - \sigma_x$, respectively, show that the stress state of lead behind the front of the plane SW differs from the state of cubic hydrostatic compression: the ratio of the mean stress $\sigma_0 = (\sigma_x + 2\sigma_y)/3$ to the stress associated with shock compression σ_x is about 0.6 and is nearly constant in the range 2.0-20 GPa.

The dynamic yield point increases linearly in the range of stresses σ_x from about 22 GPa. There is then a sharp reduction (from 12 GPa at σ_x = 22 GPa to 5 GPa at σ_x = 26 GPa) (Fig. 2). Linear extrapolation of the initial branch of the relation $Y_d(\sigma_x)$ to $Y_d = 0$ gives $\sigma_x \approx 30$ GPa. It follows from the experimental data in Figs. 1 and 2 that the complete transition of lead to the liquid phase — for which $Y_d \approx 0$ — occurs at stresses greater than 30 GPa. It can be suggested that the sharp reduction in Y_d at $\sigma_x > 22$ GPa is connected with the beginning of fusion of lead behind the shock front.

To establish the fact of melting of the metal in shock-wave compression, we loaded a compound specimen consisting of the test metal and a lower-melting metal. The latter served as a fusion indicator and was capable of forming solid solutions or intermetallic compounds with the test metal [7]. If the metal melts during loading, then the liquid phase, moving with the lower-melting indicator metal, forms a melt which, upon removal of the load, crystallizes into one of the intermediate intermetallic phases on a solid solution. Detection of such compounds, obtained by dynamic loading, through microstructural methods (metallographic, x-ray diffraction, electron microscopic), unambiguously indicates the fact of melting of the test metal. The scheme used to perform the experiment is shown in Fig. 3. The specimen, consisting of disks pressed tightly together (the test metal 1 and the indicator metal 2), was enclosed in a special storage ampule 3 and loaded by a plane SW of a specified intensity. The SW was generated by the rupture of a damping gasket 4 by an explosive charge 5. The stress associated with the shock wave was varied by changing the thickness of the charge and the gasket.

In a series of tests, we successively increased the stress σ_x from one test to the next in increments of 1-2 GPa in the range 18.5-22 GPa. Bismuth was used as the indicator metal. After each loading, the intact specimen was subjected to microstructural analysis under steady-state conditions. The results of study of microstructural changes unambiguously showed that, beginning at a stress of 20.5 GPa (with an initial specimen temperature of about 10°C), a solid solution of bismuth and lead is formed. The crystalline lattice of the compound is close-packed hexagonal, with the parameters $a = 3.5 \cdot 10^{-10}$ m and $c = 5.79 \cdot 10^{-10}$ m.

The solid solution, with its corresponding crystalline lattice, was termed the ε-phase in [8]. For comparison: a lead cubic face-centered lattice with $a = 4.939 \cdot 10^{-10}$ m, a bismuth rhombic lattice with $a = 4.736 \cdot 10^{-10}$ m, $\alpha = 57°14'$. The formation of the solid solution of lead and bismuth as a result of shock-wave loading is evidence of the melting of lead behind the shock front.

The results obtained here by two independent methods confirm and augment each other. Thus, the coincidence of the shock-compression stresses σ_x at the SW front, at which there is an abrupt change in the relation $Y_d = Y_d(\sigma_x)$ and structural changes indicating the fusion of lead, proves the hypotheses that the maximum of $Y_d(\sigma_x)$ corresponds to the melting point, and that melting of the lead occurs in the SW rather than during its unloading.

The results obtained here agree well with the data in [3], where it was noted that the melting of lead in an SW occurs at stresses of 23-25 GPa. According to the results in [9], fusion of lead takes place in the stress range 27-33 GPa. It was shown in [10] that lead behind a shock front is already molten at stresses of 40 GPa, which supports the theoretical estimates made in [11].

Thus, it can be stated that the range of shock-compression stresses in which lead melts in the shock wave is 20-30 GPa.

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