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ORDER, DISORDER, AND PHASE TRANSITION IN CONDENSED SYSTEM

Effect of Small Preliminary Deformation on the Evolution of Elastoplastic Waves of Shock Compression in Annealed VT1-0 Titanium

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Abstract—The evolution of an elastoplastic waves of shock compression in VT1-0 titanium in the as-annealed state and after preliminary compression is measured. A preliminary strain of 0.6% and the related increase in the dislocation density are found to change the deformation kinetics radically and to decrease the Hugoniot elastic limit. An increase in the preliminary strain from 0.6% to 5.2% only weakly changes the Hugoniot elastic limit and the compression rate in the plastic shock wave. The measurement results are used to plot the strain rate versus the stress at the initial stage of high-rate deformation, and the experimental results are interpreted in terms of dislocation dynamics.

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1. INTRODUCTION

The study of the temperature–rate dependences of the deformation and fracture resistance of metals and alloys in the submicrosecond mechanical loading range makes it possible to investigate the main laws of deformation-induced defect motion and to create a basis for developing wide-range models and constitutive relationships to calculate high-rate deformation and fracture under various, including technological, conditions. Studies in this field are performed using the methods of the physics and mechanics of shock waves in condensed matter and are based on measuring and analyzing the structure of elastoplastic waves of shock compression and their evolution during the propagation in materials [1–6]. In particular, in recent years we carried out an extensive series of experiments to study the temperature–rate dependences of the deformation resistance of metals and alloys with various crystal structures and found that the behavior of solids at high strain rates can differ qualitatively from that under normal conditions [4, 7]. In particular, we revealed an anomalous increase in the plastic flow stress with temperature at a high strain rate. We determined the set of materials in which this phenomenon can occur depending on the relation between the contributions of phonon viscosity and "barrier" forces, including the forces created by Peierls–Nabarro barriers and hardening inclusions.

In investigations, we arrived at the conclusion that the detected high initial strain rates can be explained on the assumption about intense dislocation multiplication at the very early stages of deformation in an elastic precursor. To check this assumption, we decided to measure the evolution of an elastoplastic wave of shock compression in a metal at various initial dislocation densities and to determine the relation between the strain rate and the stress as a function of the state of material. As an object of inquiry, we chose commercial-purity VT1-0 titanium, since it was comprehensively studied in our works [8, 9]. VT1-0 titanium contains about 99.3% Ti, belongs to α alloys, and has high resistance to plastic deformation and brittle and fatigue fracture. The elastoplastic and strength properties of commercial titanium under shock compression conditions were studied in [10–13], which revealed a significant contribution of twinning to inelastic deformation mechanisms under these conditions [10], a strong Bauschinger effect (which manifests itself during repeated shock-wave loading) [12], and a weak temperature dependence of Hugoniot elastic limit [11, 13].

2. EXPERIMENTAL

Samples were cut from a rod 40 mm in diameter. Before cutting the workpieces were vacuum annealed at a temperature of 700°C, which was reached in 70 min. After holding for 1 h, the workpieces were fur-

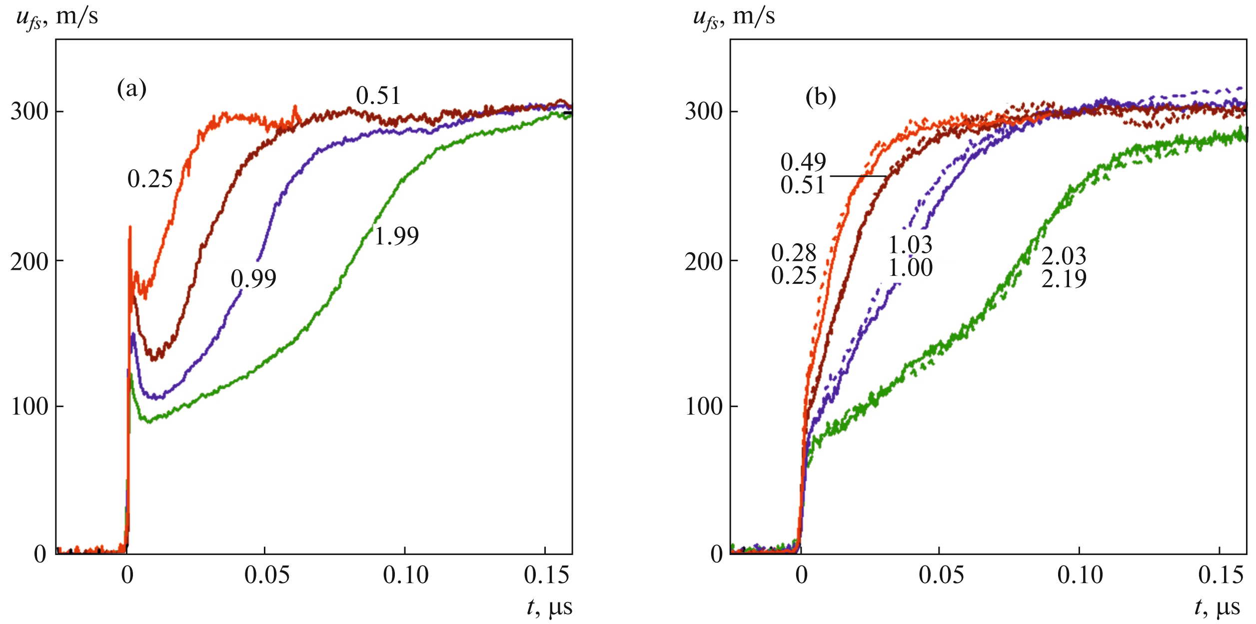

Fig. 1. (Color online) Free surface velocity histories of titanium samples (a) in the as-annealed state and (b) after preliminary strain of (solid curves) 0.6% and (dashed curves) 5.2%. The numerals at the curves indicate the sample thickness in mm.

nace cooled. One workpiece was spark-cut to form plane disklike samples 0.3–2 mm thick, and two others were upset in a press to a residual strain of 0.6 and 5.2% and were then cut into samples. The Rockwell hardness of the samples after annealing was 99.6 HRF, upsetting to 0.6% increased the hardness by 1%, and upsetting to 5.2% increased the hardness to 102.6 HRF. Before measurements, the sample surfaces were ground, polished, and etched to remove surface defects and to achieve the required reflectivity.

Shock-wave experiments were performed on a gas gun, which was used to launch aluminum flyer plates at a speed of about 390 m/s. In experiments, we monitored the velocity of the free back sample surface as a function of time (free surface velocity histories $u_{fs}(t)$) when a compression wave approached it. For detection, we used a VISAR laser Doppler velocimeter at a time resolution of 1.5–2.0 ns [14].

3. RESULTS

Figure 1 shows the results of measuring free surface velocity histories. A stress peak is formed in the as-annealed material against the background of an elastic precursor, which points to accelerated plastic deformation. This acceleration is most likely to be caused by dislocation multiplication during deformation. During propagation, this peak decays partly due to the action of an unloading zone and partly due to stress relaxation as a result of plastic deformation. The stress in the minimum between elastic and plastic waves also decreases when the shock wave propagates. At this stage, the decay is only caused by plastic deformation [15]. A preliminary plastic deformation of 0.6% radically changes the deformation kinetics and decreases the Hugoniot elastic limit. An increase in the preliminary deformation from 0.6 to 5.2% weakly changes the Hugoniot elastic limit and the compression rate in the plastic shock wave. We can speak about the saturation of the plastic-deformation carrier (dislocations, twins) density after a strain of 0.6%.

Figure 2 shows the compression stress decay in the elastic precursor (Hugoniot elastic limit σ_{HEL}) when it propagates in annealed titanium and titanium deformed by 0.6%. For annealed samples, the stresses at the points of the minimum between the elastic and plastic waves and the maximum of the frontal peak are presented. Since the parameters of the short stress peak are measured at a significant error, the data "at the peak" obtained in new measurements were supplemented with the values obtained in [8].

All three groups of data on precursor decay in Fig. 2 can be described at an acceptable accuracy by the power relations

$$\sigma_{HEL} = S(h/h_0)^{-\alpha}, \qquad (1)$$

where h_0 = 1 mm and parameters S and α for three experimental series are S = 1.55 GPa and α = 0.341 for the annealed material at the points of minimum, S = 1.96 GPa and α = 0.393 for the states at the precursor peak in annealed titanium, and S = 1.05 GPa and α = 0.262 for the deformed material.

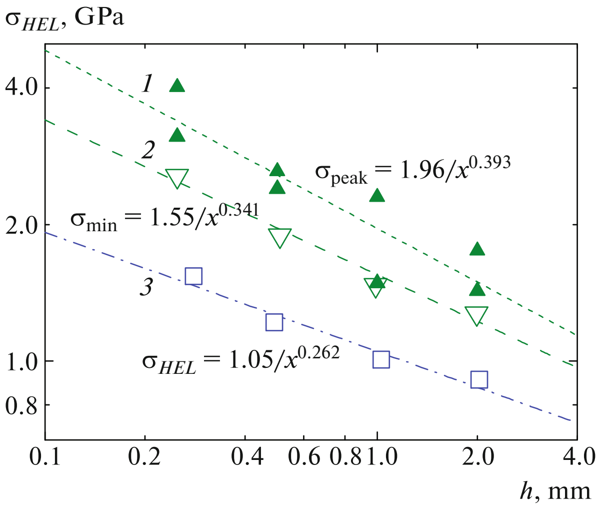

Fig. 2. (Color online) Decay of the elastic precursor when a compression wave propagates in (*1*, *2*) as-annealed VT1-0 titanium and (*3*) titanium subjected to plastic deformation by 0.6% after annealing. The stresses (open triangles) at the minimum between the elastic and plastic waves and (solid triangles) at the maximum of the frontal peak are indicated for the annealed samples. The data “at the peak” obtained in new measurements were supplemented with the values obtained in [8]. The stresses at the elastic precursor front are given for the deformed material.

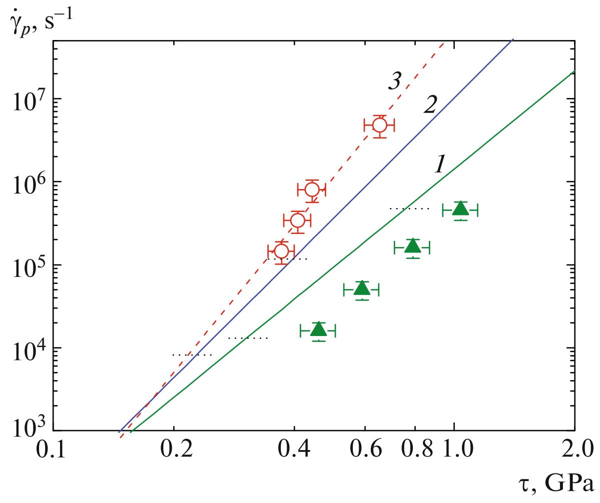

Fig. 3. (Color online) Strain rate vs. the shear stress in the elastic precursor for (*1*) as-annealed VT1-0 titanium and (*2*) VT1-0 titanium deformed by 0.6%. Triangles show the parameters at the precursor peak for as-annealed titanium, solid line *1* shows parameters at the minimum for the annealed material and (*2*) at the elastic precursor front in deformed titanium. Circles and dashed line *3* show states in the plastic shock wave according to [9]. Horizontal dotted lines indicate measured parameter ranges.

4. DISCUSSION

In the acoustic approximation, the decay of an elastic precursor is caused by the development of plastic deformation and stress relaxation and is related to plastic strain rate $\dot{\gamma}_p = (\dot{\varepsilon}_x^p - \dot{\varepsilon}_y^p)/2$ behind the front by the expression [5]

$$\left.\frac{d\sigma_x}{dh}\right|_{HEL} = -\frac{4}{3}\frac{G\dot{\gamma}_p}{c_l}, \tag{2}$$

where $G = (3/4)\rho_0(c_l^2 - c_b^2)$ is the shear modulus; c_l and c_b are the longitudinal and bulk sound velocities, respectively; ρ_0 is the material density; σ_x is the compression stress in the wave propagation direction; h is the distance traveled by the wave; and $\dot{\varepsilon}_x^p$ and $\dot{\varepsilon}_y^p$ are the plastic strain rates along and across the wave propagation direction, respectively. Equation (2) is valid for the parameters at the precursor front provided their gradients behind the front are small and at the point of minimum between the elastic and plastic waves. After substituting empirical Eq. (1) into Eq. (2), we eventually obtain

$$\dot{\gamma}_p = \frac{3}{4}\left(\frac{\tau E'}{SG}\right)^{(\alpha+1)/\alpha}\frac{S\alpha c_l}{h_0 G}, \tag{3}$$

where τ is the shear stress. Finally, the dependences of the strain rate behind the precursor front on the maximum shear stress shown in Fig. 3 take the form

$$\dot{\gamma}_p = \dot{\gamma}_0\left(\frac{\tau}{\tau_0}\right)^{(\alpha+1)/\alpha}, \tag{4}$$

where $\tau_0 = 1$ GPa and $\dot{\gamma}_0 = 1.4 \times 10^6$ s^{-1} for the minima between the elastic and plastic waves in the annealed material and $\dot{\gamma}_0 = 1.0 \times 10^7$ s^{-1} at the precursor front in the deformed material.

The strain rate at the precursor peak was estimated with allowance for the hydrodynamic component of the precursor decay [15, 16],

$$F = -\frac{2a^2}{U_S}\frac{d\sigma_x}{dh} - \left(1 - \frac{a^2}{U_S^2}\right)\frac{\partial\sigma_x}{\partial t}, \tag{5}$$

where $F = 2G\dot{\varepsilon}_x^p = (8/3)G\dot{\gamma}$ is the relaxation function, U_S is the elastic shock wave velocity, and a is the velocity of sound at the precursor peak in the Lagrangian coordinates. U_S and a were estimated on the assumption that the Poisson ratio is constant and the quasi-acoustical approximation is valid for the shock wave velocity [2, 4], which gives

$$U_S = c_l + bu_p, \quad a = c_l + 2bu_p, \quad u_p = u_{fs}/2. \tag{6}$$

Here, coefficient b for the Hugoniot of elastic compression coincides with the analogous coefficient of the equilibrium Hugoniot. The compression stress drop rate at the precursor peak was estimated as

$$\frac{\partial\sigma_x}{\partial t} = 0.5\rho_0 c_l\frac{\partial u_{fs}}{\partial t}.$$

We took $\partial\sigma_x/\partial t \approx \text{const} = 133 \times 10^6$ GPa/s for the calculations because of a large error at the measurement resolution limit. This assumption should not cause a large error, since the second term in Eq. (5) contains a small difference between the squared velocity of sound and the squared shock wave velocity. Figure 3 shows the estimates. The error of the data obtained for the stress peak is small: in principle, they can be satisfactorily described by Eq. (4) at $\dot{\gamma}_0 = 3.75 \times 10^5\ \text{s}^{-1}$ and the same exponent ($\alpha = 0.34$) as in the state at the minimum between the elastic and plastic waves. In Fig. 3, the boundaries of the measured parameter ranges are indicated by horizontal dashed lines in the dependences of the strain rate on the shear stress in the elastic precursor, at the minimum for the annealed material, and at the elastic precursor front for deformed titanium. A comparison of these parameter ranges with the states at the peak demonstrates that stress relaxation in going from the peak to the minimum occurs at almost the same strain rate. Therefore, the estimated strain in this process is 0.27% at the upper boundary, which corresponds to 0.25 mm traveled by the wave, and decreases to 0.01% at the lower boundary, which corresponds to a distance of 2 mm. As is seen in the wave profiles shown in Fig. 1, stress relaxation at the peak takes 6–10 ns.

As is seen from Fig. 3, a strain of 0.6% increases the initial strain rate by more than an order of magnitude at the same shear stress in the parameter range under study. As noted above, an increase in the preliminary strain to 5.2% weakly affects the strain rate in the elastic precursor. However, the strain rate in the plastic shock wave turns out to be high. The shear strain at the middle of the shock wave is estimated at $\gamma_m = 1.7\%$ for a maximum shock-compression stress of 10.7 GPa (upper point in the curve) and at 0.6% for a shock wave with a maximum shock compression of 3.9 GPa (lower point). These estimates were made using the relationship

$$\gamma_m = \frac{1}{2}\left(\varepsilon_m - \frac{\tau_m - \tau_{HEL}}{G}\right). \qquad (7)$$

where ε_m and τ_m are the total strain in the compression direction and the shear stress at the middle of the shock wave (where the shear stress is maximal), respectively, and G is the shear modulus.

According to the well-known Orowan relation, the strain rate is proportional to the dislocation density at a fixed stress, and an increase in the strain rate by an order of magnitude means an increase in the density of mobile dislocations by an order of magnitude. Our results demonstrate that even small initial strains are accompanied by intense dislocation multiplication. The relative position of the dependences of the strain rate on the shear stress in the elastic precursor, at the minimum of the annealed material, and at the elastic precursor front for deformed titanium is consistent and can be interpreted as a monotonic increase in the density of mobile dislocations with the strain irrespective of its rate (see Fig. 3). On the other hand, the higher strain rates in the plastic shock wave indicate that the density of mobile dislocations is saturated at higher strains under these conditions.

5. CONCLUSIONS

To test the assumption about intense dislocation multiplication at the initial stage of shock-wave compression of metals, we measured the evolution of an elastoplastic waves of shock compression in VT1-0 titanium in the as-annealed state and after preliminary compression. It was found that a preliminary strain of 0.6% and the related increase in the dislocation density radically changed the deformation kinetics and decreased the Hugoniot elastic limit. An increase in the preliminary strain from 0.6 to 5.2% weakly changes the Hugoniot elastic limit and the compression rate in the plastic shock wave. Using the measurement results, we plotted the strain rate versus the stress at the initial stage of high-rate deformation. A preliminary strain of 0.6% was shown to increase the initial strain rate by more than an order of magnitude at the same shear stress. The results of analyzing the evolution of wave profiles indicate a monotonic increase in the density of mobile dislocations with the strain at the initial stage irrespective of the operating stress. On the other hand, the density of mobile dislocations in the plastic shock wave is saturated at higher strains. Our results can be used to develop models and relationships for high-rate deformation of metals.

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