LOCALIZED SHEAR IN METALS UNDER IMPACT LOADING

G. V. Stepanov and V. A. Fedorchuk

The results of studies on localized shear strain in high-strength steel, a titanium alloy, and mild sheet steel under impact loading are given. The analysis of experimental results, microstructural changes, and numerical simulation demonstrates that adiabatic shear bands formed at high-rate deformation are influenced by strain hardening and heating in plastic flow and phase transformations in a material. The distribution of temperatures in the regions of strain localization is responsible for the development of microstructural changes. Nonuniform deformation without intense strain localization develops at lower shear rates and small strain increments per loading cycle, eliminating considerable heating of a material.

Introduction. As is known, intense dynamic loads give rise to a specific nonuniform stress state of structural elements made of metals. This state is the result of propagation of elastic and elastoplastic (longitudinal, shear, flexural) waves and their interaction with the waves reflected from the free boundaries and/or interfaces separating layers with different properties. Intense loads in the regions of higher stresses cause localized plastic flow. Localized shear (shear strain in a narrow band whose width at high strain rates is reduced down to 10 μm) is a special case of intense plastic deformation [1, 2]. The specific features of localized shear at low impact velocities and the effect of strain rates and conditions, the stress-strain state in particular, are still not clearly understood. This paper presents the results of shear strain localization studies and their analysis, including microstructural changes induced by localized shear under impact loading.

Experimental investigations were performed on high-strength steel, titanium alloy, and mild sheet steel specimens. Plane specimens were tested under repeated impact loading, simulating the isothermal process of deformation, and the tests of disk-shaped ones were performed under single impact loading, which caused the development of adiabatic shear bands.

1. Scheme of Plane-Specimen Testing. Shear tests of high-strength steel and a titanium alloy under impact loading were performed on identical specimens cut from 5–7-mm-thick rolled sheets as-received (without any heat treatment) with 40 HRC (steel) and 42 HRC (titanium alloy) hardnesses (Fig. 1a). The specimens were produced with two thinned portions where strain is localized. The thickness of a layer removed by finishing from the thinned portions was about 0.05 mm.

The loading scheme (Fig. 1b) is a modification of the scheme used earlier [3], which differs in that the elongated ends of a specimen are rigidly fixed in the frame to eliminate their possible rotation. Specimen 1 inserted in the II-groove of frame 2 is pressed down with cover plate 3. The midportion of the specimen (between thinned portions) is loaded with the impact of rigid body 4 at a preset velocity along load-transmitting rod 5 having the II-groove to envelop the specimen. The load-transmitting rod is centered by the cylindrical hole surface in the frame. The displacement of the midportion per loading cycle is determined by the gap between the lower end of the rod and plate 6 in the frame. A plate of smaller thickness is mounted after each impact cycle to ensure a preset strain increment.

In low-velocity tests (5 m/s), the rod was loaded with the impact of a free-falling body (M = 10 kg). The impact velocity was calculated from the height of the body fall \( H_M = V_M^2 / 2g \), and the displacement rate of the midportion of a specimen was taken equal to the impact velocity.

In high-velocity tests (up to 50 m/s), the rod was affected by the impact of a steel disk (60 mm in diameter, 10 mm thick) mounted in a foam plastic cylinder (sabot). This sabot with the disk was accelerated by gas pressure along a 64-mm barrel of a pneumatic machine up to a preset velocity. The impact velocity was calculated from...
the time interval $t_b$ between the moments of closure of two electrical contact gauges mounted near the end of the barrel: $V_M = b_b / t_b$ ($b_b$ is the distance between the gauges). The time $t_b$ was registered with an electronic chronometer. The displacement rate of the midportion of a specimen $v$ was determined from the condition of inelastic interaction between the loading body of the mass $M$ and the transmitting rod of the mass $m$:

$$v = V_M \frac{m}{M + m}.$$  

(1)

**Adiabatic Temperature Increase.** Repeated impact loading leads to an increment of shear strains under conditions close to isothermal ones. The calculated temperature increase due to plastic flow with the strain intensity per cycle $\delta\varepsilon_i$ or the shear strain $\gamma$ under adiabatic conditions is determined by the equations

$$\Delta T = \frac{\sigma_i \delta e_i}{(\rho c_v)},$$

$$\Delta T = \frac{\tau \delta \gamma}{(\rho c_v)}.$$

(2)

If the displacement of the midportion of a specimen per cycle $\delta u < 0.2$ mm and the width of its thinned portion $a = 2$ mm (used in the experiment), an increase in strain $\delta \gamma = \delta u / a = 0.1$. If the mean shear stress $\tau = 0.7$ GPa and $\rho c_v = 3.2$ MJ/(m$^2$·K), then the maximum increase in temperature $\Delta T < 50$, and its effect on the strength of a material can be neglected.

The duration of an impact $t_c$ is approximately equal to $\delta u / V$. At $\delta u = 0.2$ mm and $V = 5$ m/s, $t_c > 40 \cdot 10^{-6}$ s. Thus, the stress state within thinned portions might be reckoned as quasistatic at this velocity. At a velocity above 5 m/s, the distribution of stresses can deviate from the quasistatic one, and with such a model only approximate results are obtained.

**Determination of Strains in Plastic Shear.** We assume that in the plastic regions (thinned portions), with the exception of the areas adjacent to the contour of a specimen, the stress state is close to pure shear. The strain in plastic shear $\gamma$ after several loading cycles with the displacement $\delta u$ is determined by summing the increments of shear strain per cycle $\delta \gamma = \delta u / a$:

$$\gamma = \Delta u / a = \tan \beta, \quad \Delta u = \Sigma \delta u$$

(3)

(such an evaluation of shear strain is also applicable to large strains arising in the plastic region).