

STRAIN RATE, TEMPERATURE AND STRUCTURE EFFECTS ON THE FLOW STRESS OF METALS AND ALLOYS UNDER SHOCK-WAVE LOADING

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Summary Results of measurements of dynamic yield stress and spall strength of metals are presented. Rate and temperature dependences of the flow stress and the resistance to fracture are obtained for the strain rate range of 10^3 to 10^9 s⁻¹. The results are discussed in terms of requirements to constitutive relationships.

It is well known that the flow stress of crystalline solids increases with an increase in the strain rate. For many metals, this dependence sharply increases, when the rate of deformation exceeds $\sim 10^3$ – 10^4 s⁻¹, which is interpreted as the consequence of the change in a mechanism of dislocations motion. For small strain rates, dislocation overcomes obstacles due to the joint action of the applied stress and thermal fluctuations. Because of this, the increase of temperature is accompanied by the decrease in the yield strength of materials. For sufficiently high strain rates, the dominant drag mechanism becomes the phonon viscosity. Because the phonon viscosity is proportional to the temperature, for very high strain rates one can expect an increase in the flow stress with an increase in temperature.

Investigations of temperature-rate relations of the resistance to deformation and fracture of metals and alloys at shock-wave loading are motivated by the need in a basis for developing the models and constitutive relationships which would be workable over wide range of strain rates, stresses and temperatures, search for new information about basic mechanisms and governing factors of these processes, and by necessity to provide experimental basis for atomistic simulations of the deformation and fracture processes. Main methods of studying elastic-plastic and strength properties of shocked solids are well developed. There are two direct (without computer simulations) ways to get information about relationships between the plastic strain rate and the flow stress: measurements of the decay of the elastic precursor wave [1, 2] and measurements of the rise time of plastic shock wave [3, 4]. The time range available for shock-wave measurements has been recently expanded to picoseconds and approaching the ultimate shear strength values becomes real.

In the presentation, some new and obtained earlier [5-9] experimental data on the elastic precursor decay and rise times of plastic shock waves in several metals and alloys at normal and elevated temperatures are systematized. The data on precursor decay include last measurements at micron and submicron distances where realized shear stresses are comparable with their ultimate (“ideal”) values (Fig. 1). Results of measurements have been transformed into dependences of plastic strain rate on the shear stress (Fig. 2).

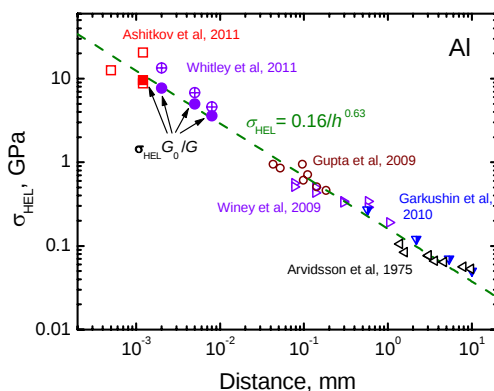


Figure 1. Decay of the elastic shock wave in aluminum.

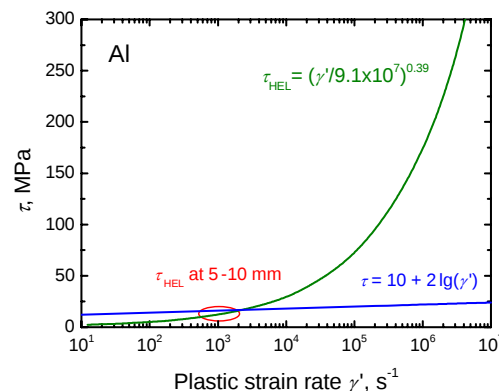


Figure 2. Rate sensitivity of the flow stress in aluminum.

It has been found the precursor decay may occur in several regimes which are characterized by different decay rates. Anomalous growth of the Hugoniot elastic limit with heating (Fig. 3) correlates with a fast decay regime and is not observed when the decay is relatively slow. In hard metals, the stress needed to overcome obstacles far exceeds the forces of phonon drag, which are, therefore, unable to make a significant contribution into the resistance of the alloys to plastic flow (Fig. 4). Hardening of a material shifts the transition in drag controlling mechanism towards higher strain rates.

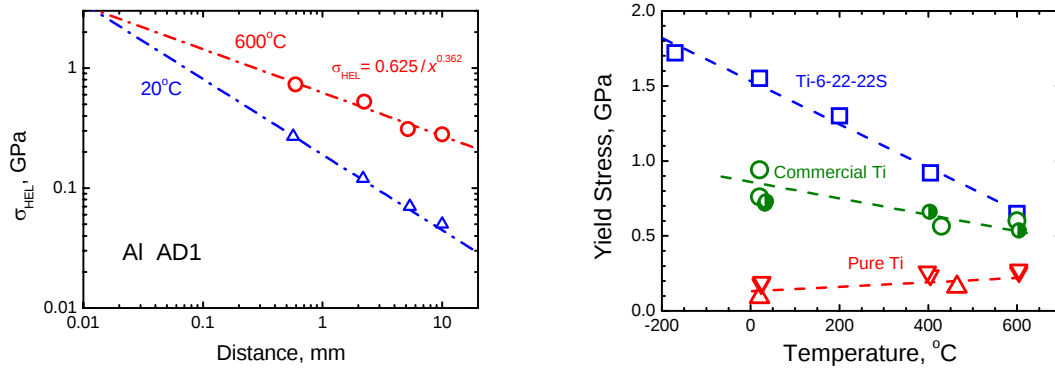


Figure 3. Decay of elastic precursor wave in AD1 aluminum at normal and elevated temperatures.
Figure 4. Temperature dependences of dynamic yield stress of titanium and its alloy.

An analysis of the rise times of plastic shock waves shows by order of magnitude faster plastic strain rates at corresponding shear stresses than that at the Hugoniot elastic limit (HEL). Hardening of a material by decreasing grain size or by other method may appear or not appear in increase of the HEL value depending on the branch of the flow stress dependence upon the plastic strain rate which is realized for chosen sample thickness. Moreover, it was observed that harder ultra-fine-grained tantalum may demonstrate even lower HEL value than less hard coarse-grained one (Figs. 5). Probably it is explained by faster decay in the ultra-fine-grained material where grain boundaries may be the dislocation sources. Requirements to constitutive models for high-rate plastic deformation are formulated on the base of experimental observations.

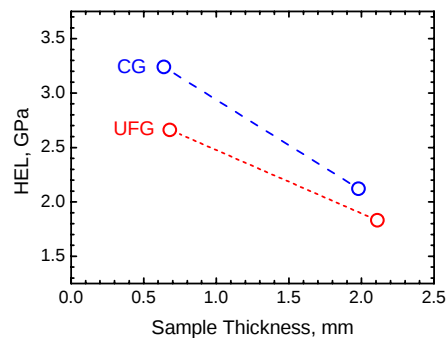


Figure 5. Decay of elastic precursor wave in coarse-grain (CG) and ultra-fine-grained tantalum

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