International Journal of Plasticity 25 (2009) 671–694

Contents lists available at ScienceDirect

International Journal of Plasticity

journal homepage: www.elsevier.com/locate/ijplas

High-pressure strength of aluminum under quasi-isentropic loading

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ARTICLE INFO

Article history:
Received 9 December 2008
Available online 14 December 2008

Keywords:
Stress waves
Constitutive behavior
High-pressure loading

ABSTRACT

Under shock loading, metals typically increase in strength with shock pressure initially but at higher stresses will eventually soften due to thermal effects. Under isentropic loading, thermal effects are minimized, so strength should rise to much higher levels. To date, though, study of strength under isentropic loading has been minimal. Here, we report new experimental results for magnetic ramp loading and impact by layered impactors in which the strength of 6061-T6 aluminum is measured under quasi-isentropic loading to stresses as high as 55 GPa. Strength is inferred from measured velocity histories using Lagrangian analysis of the loading and unloading responses; strength is related to the difference of these two responses. A simplified method to infer strength directly from a single velocity history is also presented. Measured strengths are consistent with shock loading and instability growth results to about 30 GPa but are somewhat higher than shock data for higher stresses. The current results also agree reasonably well with the Steinberg–Guinan strength model. Significant relaxation is observed as the peak stress is reached due to rate dependence and perhaps other mechanisms; accounting for this rate dependence is necessary for a valid comparison with other results.

1. Introduction

The strength (deviatoric) behavior of a solid is what distinguishes it from a fluid and is an essential part of describing and modeling a solid's behavior. In particular, the strength of materials under

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0749-6419/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijplas.2008.12.003

conditions of high-pressure is important for ballistics and armor applications, planetary physics, diamond anvil cells, fusion capsule implosions, and a variety of other impact phenomena.

While there is a reasonably good understanding of the mechanisms controlling material strength (e.g., dislocation formation and motion, twinning, etc.) under quasi-static conditions, this is clearly not the case for the highly dynamic conditions of impact events or laboratory shock experiments. In fact, it seems unlikely that it will be possible to experimentally resolve dynamic deformation mechanisms in the foreseeable future, though progress is possible through molecular dynamics modeling (Kubota et al., 2006). Nevertheless, it is clear that the most important effects from a phenomenological view are pressure hardening, work hardening, strain rate sensitivity, thermal softening, and phase transformations. Except for phase transformations, most of these effects are included in the models currently available for the high-pressure strength of metals (e.g., Preston et al., 2003; Steinberg et al., 1980; Steinberg and Lund, 1989). What are often lacking for these models, though, are measured model parameters for materials of interest.

As recently reviewed by Vogler and Chhabildas (2006), several experimental techniques have been used to measure or infer strength at high pressures including lateral stress gauges, pressure-shear loading, comparison with hydrostat, measurement of non-hydrostatic stresses in a diamond anvil cell (DAC), monitoring the rate of instability growth, and the so-called self-consistent method involving unloading and reloading. Each of these techniques has advantages and disadvantages such as its precision, pressure range over which it can be used, assumptions necessary in its use, etc. Except for the use of the DAC, all of the techniques mentioned above involve dynamic material behavior at high pressures. The relationship between static DAC strength measurements and strengths measured in dynamic experiments has not been fully established.

The bulk of the dynamic strength data in the literature involves shock-loaded materials. However, strength can be much more important under isentropic loading than under shock loading because heating under isentropic loading is significantly less. For example, an equation of state (EOS) by Kerley (1987) for aluminum gives melting along the principal Hugoniot at approximately 120 GPa and 4500 K. Once a material has fully melted, of course, it has no strength. In contrast, the isentrope has a temperature of less that 800 K at a pressure of 200 GPa, and the material is expected to remain solid to extremely high pressures. The lower temperature along the isentrope reduces thermal softening of the material, so that strength should be significantly higher than under shock loading, even before melt occurs. Of course, isentropic loading is really quasi-isentropic loading due to elastic–plastic behavior and other irreversible deformation mechanisms in solids and viscous dissipation in fluids. See Ding and Asay (2009) for a discussion of the degree to which ramp loading differs from isentropic conditions.

Several techniques are available to achieve quasi-isentropic loading experimentally as discussed by Asay (2000). The current investigation includes experiments using both magnetic loading and layered impactors. We will refer to both of these as quasi-isentropic loading to distinguish them from shock loading; the degree to which the two differ from isentropic is discussed above and in Section 2.3.

Although results in the literature for strength of materials under shock loading are fairly limited, there are far fewer results for isentropic loading. Two investigations using lateral gauges have been reported: one with aluminum and copper (Bat'kov et al., 1999), the other with copper, iron, and mild steel (Rosenberg et al., 2002). In the former study, the difference in principal stresses was found to be 2–3 times that found in shock loading, but these results appear to be erroneous (Vogler and Chhabildas, 2006).

Another means for determining strength is through comparison of a loading response with an isentrope for a material without strength. The difference in stress between the two at a constant density is then four-thirds of the maximum shear stress (two-thirds of the yield strength). This approach has been used for tungsten (Chhabildas and Asay, 1992), molybdenum (Reisman et al., 2001), and aluminum (Smith et al., 2007). The principal difficulty with this approach lies in the accuracy of the calculated isentrope. While either a theoretical EOS (Reisman et al., 2001; Smith et al., 2007) or thermally corrected Hugoniot or isothermal data can be used (Chhabildas and Asay, 1992), the accuracy of the hydrostatic isentrope depends upon the accuracy of the EOS used for comparison or to make thermal corrections. Further, we note that proper comparison requires that heating due to plastic work be included, which has not been done to date.