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STRAIN RATE AND PRESSURE DEPENDENCE OF ALUMINUM UNDER DYNAMIC LOADING

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ABSTRACT

New experimental results on the strength of aluminum are presented that enhance our understanding of its strain rate dependence. The miniature Kolsky bar is used to bridge the gap between conventional Kolsky and pressure-shear results and show consistency between the two. Magnetic ramp loading can be used to achieve loading rates similar to or higher than pressure-shear, but the measurements occur at a higher pressure than other types of measurements. Accounting for this pressure in ramp and pressure-shear gives significantly reduced rate dependence for aluminum. The apparent discrepancy with shock data, which display negligible rate sensitivity, is explained.

1 INTRODUCTION

The strength of metals is known to be a function of the applied strain rate. For example, 6061-T6 aluminum has been reported to show significant strain rate sensitivity at strain rates over about 10^2 s^{-1} [1]. In determining the strain rate sensitivity of a material, researchers employ multiple techniques such as screw-driven testing machines for the quasi-static regime, Kolsky or Hopkinson bars for the intermediate regime (approximately 10^2 to 10^4 s^{-1}), and pressure-shear loading through oblique impact [2] for higher rates (approximately 10^4 to 10^6 s^{-1}). The first two loading types result in a state of uniaxial stress in compression or tension, but the third yields uniaxial strain with a superimposed simple shear, as well as a mean stress (mechanical pressure) of a few GPa. Note that the highest rates achievable with a conventional Kolsky bar are approximately a factor of five lower than the lowest achievable with pressure-shear, so that no overlap and direct comparison are possible.

Recently, techniques have been developed to augment and extend the experimentally accessible strain rate regime. First, the miniature Kolsky bar [3] bridges the gap between Kolsky bar and pressure-shear results. Second, magnetic [4,5] loading techniques can be used to measure the loading quasi-isentrope under uniaxial strain at rates of 10^5 to 10^7 s^{-1}. By comparison with a hydrostat for the material [6] and making appropriate temperature corrections, it is possible to determine the strength of the material. These ramp loading techniques create significant pressures in the samples due to the uniaxial strain state; the importance of this pressure should be considered when comparing data from different techniques.

Here, we examine the strain rate sensitivity of aluminum in light of recent experiments with the miniature Kolsky bar and through ramp loading techniques. In addition, we examine issues involved with the pressure sensitivity of strength and how this affects strength measurements.

2 EXPERIMENTAL TECHNIQUES

New data for the strength of 6061-T6 aluminum are reported for the miniature Kolsky bar and for ramp loading. The miniature Kolsky bar has been described elsewhere [3]. Ramp loading data from the Veloce [4] and Z [5] machines are considered as well. Finally, we include quasi-ramp loading data generated using a graded-density impactor [7].

Magnetic loading produces smooth ramp waves in the samples; representative velocity measurements from Veloce made using laser interferometry are shown in Fig. 1a. Similar records are obtained for Z [5], albeit to much higher velocities, while records from graded-density impactors [7] are less smooth. The "foot" at the bottom of each record corresponds to the elastic loading of the material; deformation above that includes plastic flow. Because of nonlinearity in the bulk modulus, the loading wave is steeper for the thicker (3.5 mm) sample. The velocity records are analyzed using an iterative characteristics analysis [8] that provides a stress-strain response for the material such as that shown in Fig. 1b (positive in compression). Because the governing equations for plane wave propagation contain only the stress component in the wave propagation direction, the full stress tensor cannot be determined from the experimental loading response alone. However, by subtracting the loading response from an isentropic bulk (P-ρ) response, such as from a theoretical equation of state (EOS) for aluminum [9] shown in Fig. 1b, one can determine the current strength Y. Assuming a von Mises yield function, Y is given as

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$$Y = \tfrac{3}{2}(\sigma - P), \quad (1)$$

with both stress and pressure taken at the same density and temperature. The yield strength thus calculated is also shown in Fig. 1b and is seen to rise steeply in the elastic and initial hardening region. Work hardening seems to saturate and Y increases only gradually over about 0.5 GPa. For comparison with other data, Y is evaluated at a value of density that corresponds to an equivalent strain of 6% (which is a longitudinal strain of 9% for uniaxial strain) as was done for other data by Yadav et al. [1]

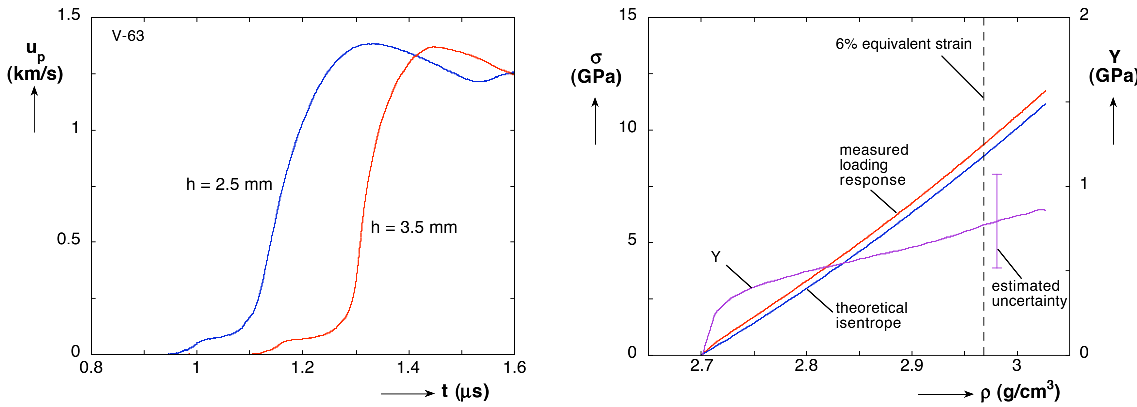

Figure 1 (a) Free surface velocity histories for magnetically loaded samples and (b) derived loading response, a theoretical isentrope, and the strength obtained from their difference.

3 STRENGTH RESULTS AND DISCUSSION

In addition to the ramp loading experiments, new flow stress (strength) data were obtained using the miniature Kolsky bar. These results overlap with conventional Kolsky bar results on the low end and pressure-shear data on the high end, showing good agreement with both as can be seen in Fig. 2. In turn, the pressure-shear results overlap with the ramp loading results, with the ramp loading results about the same or slightly higher, though the results are certainly within the experimental uncertainties for the different techniques. Data in the quasi-static and intermediate strain rate regimes shows no significant difference between compression, torsion, and tension, so the data are lumped together. The results in Fig. 2 appear to show a consistent picture of the strength of 6061-T6 aluminum over strain rates from 10^{-5} to 10^{6} s^{-1}. Previously, an apparent contradiction has been pointed out between rate dependent strengths such as these and measurements of the Hugoniot elastic limit (HEL) from shock loading, which shows little rate dependence even though the strain rate is 10^{7} s^{-1} or higher. However, all the data shown in Fig. 2 are taken at 6% equivalent strain, while the HEL corresponds to the onset of nonlinearity due to plasticity. Thus, it appears that nonlinearity initiates at approximately the same stress for a very wide range of strain rates in aluminum, but hardening increases with strain rate.

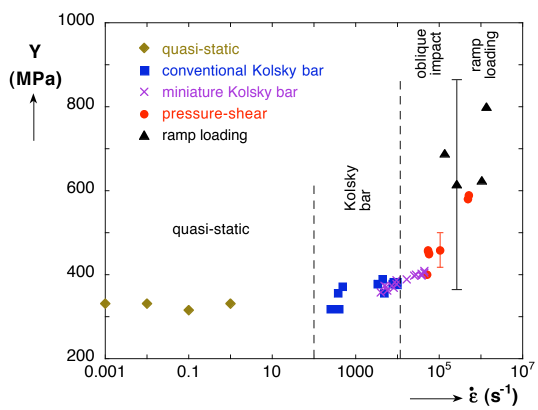

Figure 2 Strength (flow stress) of 6061-T6 as a function of strain rate.

There is a remaining issue in comparing the ramp loading results, which have a pressure of approximately 9 GPa, and the other data, which have negligible or moderate pressure. Existing models for high-pressure strength [10,11] incorporate a scaling of strength with the shear modulus, which increases with pressure. If one assumes a constant Poisson's ratio, then the shear modulus shown in Fig. 3a as a function of density can be calculated directly from the bulk modulus given by the EOS in Fig. 1b. If we scale the ramp and pressure-shear based on the ratio of ambient and current shear moduli, then the strengths at high strain rates are dramatically affected as shown in Fig. 3b. The data here are also largely consistent with one another, but the strain rate dependence is significantly reduced.

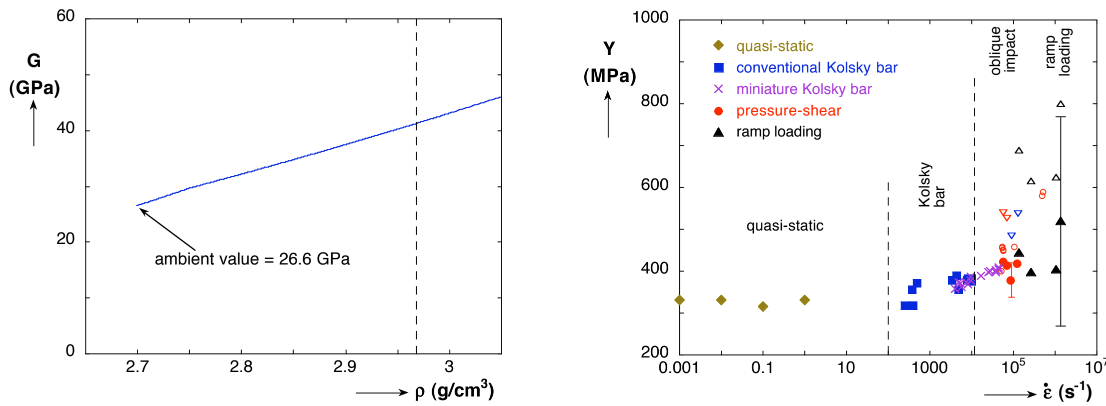

Figure 3 (a) Shear modulus as a function of density based on the assumption of constant Poisson's ratio and (b) strength versus strain rate with strengths from ramp and pressure-shear loading scaled by the ratio of ambient and current shear moduli (empty symbols unscaled values).

4 CONCLUSIONS

The main conclusions of this paper are:

- A cross-technique comparison shows consistency at strain rates of 100-10^6 s^{-1} for 6061-T6 aluminum.
- The effect of pressure must be considered when comparing data obtained by ramp and pressure-shear techniques, though additional work is needed to verify the role of pressure.
- The miniature Kolsky bar is important because it permits Kolsky bar and pressure-shear results to be compared at the same strain rate. Similarly, ramp and pressure-shear results overlap and can be compared provided pressure is taken into account.
- The rate dependence of 6061-T6 is somewhat less than previously reported.
- The rate independence of the HEL of 6061-T6 indicates that the strain rate dependence arises due to different hardening as strain rate varies.

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