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DYNAMIC QUASI-ISENTROPIC LOADING OF TUNGSTEN*

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ABSTRACT

Experiments have been performed on smooth bore guns to obtain quasi-isentropic compression in tungsten to stresses approaching 250 GPa. Quasi-isentropic loading was introduced in the material either by using graded density or layered impactors. Results of these experiments indicate that the quasi-isentrope lies above the Hugoniot up to ~140 GPa, contrary to initial expectations. These results suggest that the dynamic yield strength of the material is higher for the relatively slower rates of isentropic loading.

INTRODUCTION

In this paper, measurements on the quasi-isentropic compression of tungsten to stress levels of 250 GPa are reported. A shock Hugoniot is the locus of end states arrived at from an initial state, under the influence of a single shock wave. An isentrope, however, represents a continuous sequence of thermodynamic states that a material goes through during non-shock compression. Under shock loading to a stress of interest, the strain rates induced in the shock front are controlled primarily by the material viscosity [1], whereas under plane quasi-isentropic loading to that same stress the loading rates may be varied. Under shock loading conditions, the internal energy change of the material is that of the area under the Rayleigh line in the pressure-volume plane, whereas under isentropic compression the internal energy change is that given by the area under the isentropic compression curve. If the dynamic yield strength is similar under both shock loading and quasi-isentropic loading, then the contribution to the internal energy change due to plastic work will be similar in each case. Since the strain rates induced in the material under quasi-isentropic loading are lower than that under shock loading, the contribution to the internal energy change due to viscous work will be relatively smaller for quasi-isentropic loading. Thus, for large compressions, the internal energy change of a material under quasi-isentropic compression will be substantially less than that for shock loading to the same stress, resulting in energy (temperature) states that are lower than those obtained on the shock Hugoniot.

EXPERIMENTAL TECHNIQUE

An impactor disc referred to as a pillow was used in these investigations to obtain quasi-isentropic loading conditions. A pillow [2] is fabricated using powder metallurgical and sedimentation techniques, such that a smooth variation in composition and hence shock impedance occurs across its thickness. The shock impedance of the impact surface of the pillow used in these studies is that of polyolefin, an organic plastic material, and the shock impedance of the back surface of the pillow resembles that of copper. The variation in shock impedance as a function of position through its thickness gives rise to small initial stress jump, followed by a finite rate of loading at the impact interface, when the pillow is used as an impactor. A series of layered materials [2] was also used to impact a buffered-tungsten sample to introduce multiple stair-step loading into the sample. The layered

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impactor consisted of PMMA/aluminum/copper, while PMMA was used as the buffer material in these studies. The input stair-step wave structure generated through the use of a layered impactor gets further conditioned by the buffer material into a series of smaller steps as it enters the target.

An experimental impact configuration used on the Sandia powder gun to obtain quasi-isentropic loading conditions is indicated in Figure 1. The pillow/copper assembly was allowed to impact two samples of different thickness in a single experiment. When these experiments are conducted on the two-stage light gas gun, two different impact experiments at the same velocity are required to obtain the transmitted wave profiles for different thicknessess. For the layered material experiments, the pillow in Figure 1 is replaced by a PMMA/aluminum assembly. The particle velocity profiles shown in Figure 1 were monitored at the interface between the sample and the lithium-fluoride window [2] using velocity interferometric techniques [2].

Measurements of interface particle velocity profiles at two different sample locations are necessary to allow the use of Lagrangian wave analysis techniques [2] to determine the stress-volume loading path under quasi-isentropic loading conditions. This also eliminates the need to know the stress pulse shape at the impact interface. In effect, the analysis considers the pulse measured for the thin sample as the input for the extra thickness of the thicker specimen. Impedance matching techniques are used to determine the in-material particle velocity from interface particle velocity measurements. The equations of motion describing the conservation of momentum and mass are then used to determine the stress-volume loading path [2].

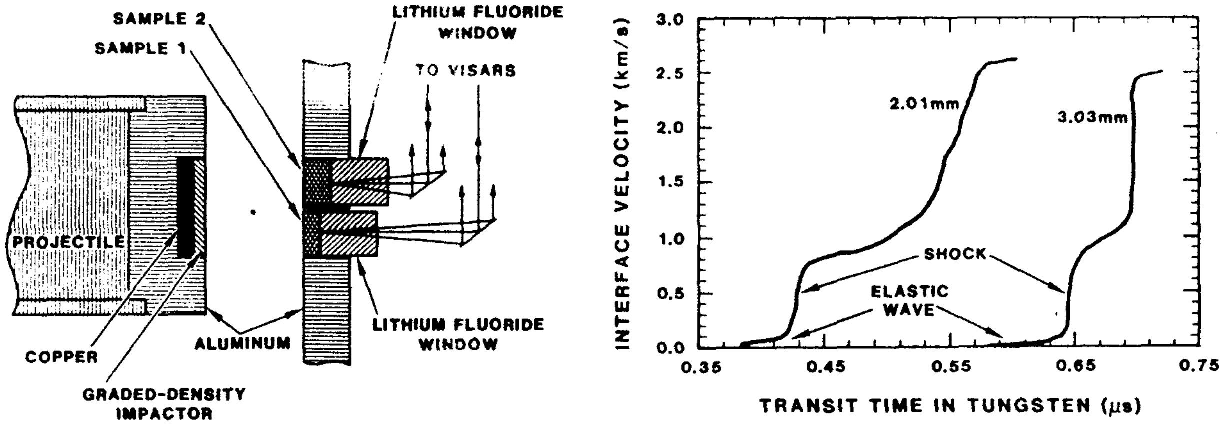

FIGURE 1. **Experimental impact configuration for a pillow impact experiment, and the corresponding interface particle velocity history measurements at two locations. The initial shock results from the impact of the polyolefin side of the pillow upon the sample.**

RESULTS AND DISCUSSION

The composite quasi-isentropic stress-strain loading paths obtained (in three different experiments) to peak stresses of 78, 170, and 250 GPa are shown in Figure 2. This corresponds to a loading rate of $\sim 10^5$ sec^{-1} for the low stress experiments, and is $\sim 10^6$ sec^{-1} for the higher stress experiments., and is at least two to three orders of magnitude slower than those obtained in shock experiments at comparable stresses. Previous results of shock Hugoniot states on tungsten [3] are also indicated in the figure. Like the results for aluminum [4], the shock Hugoniot states for tungsten fall below the experimentally determined isentrope. The quasi-isentrope continues to lie above the Hugoniot up to a stress of ~140 GPa, contrary to expected behavior. This suggests that the strength (stress deviators) of the material is increasing rapidly with pressure under isentropic loading. Beyond 140 GPa, the isentrope crosses over and lies below the shock Hugoniot. Estimates for the dynamic yield strength of tungsten under quasi-isentropic compression can be obtained by comparing the measured isentrope with a calculated *pressure* isentrope. The isentropic *pressure* curve can be determined using the shock Hugoniot as the reference *hydrostat*, and assuming that the material behaves as a Mie-Grueneisen solid, with $\rho\gamma$ being constant (γ is the Gruenisen parameter). These estimates for the dynamic yield strength under quasi-isentropic compression are shown in Figure 2. When compared to the yield strength of tungsten under shock loading, a factor of three increase is noted at a stress of ~250 GPa. The pressure effect on the dynamic yield strength is ascertained in the quasi-isentropic experiments, since the temperature rise resulting from slower rates of loading is much lower than those resulting from shock compression.

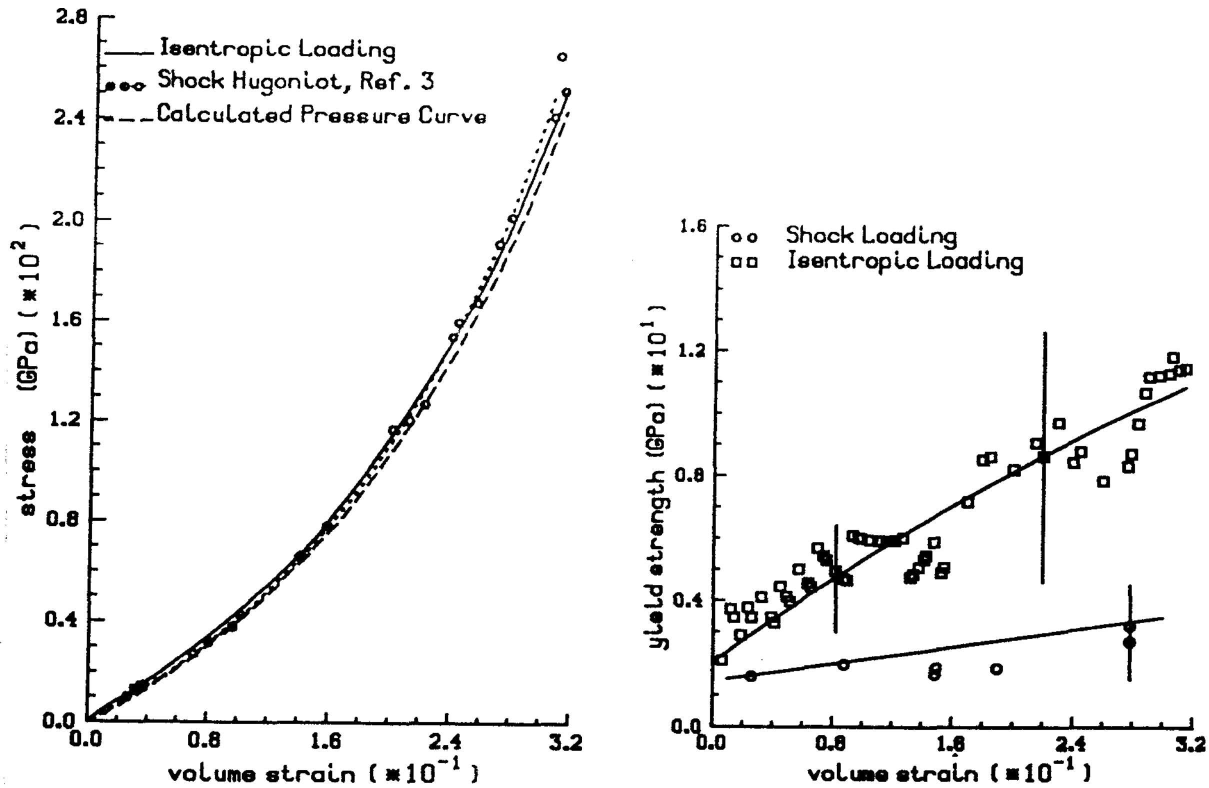

FIGURE 2: Comparison of present experimental isentrope with previous Hugoniot measurements, and the comparison of yield strength determinations under shock and quasi-isentropic loading.

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