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TITLE: QUASI-ELASTIC HIGH-PRESSURE WAVES IN 2024 Al AND Cu

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QUASI-ELASTIC HIGH-PRESSURE WAVES IN 2024 Al AND COPPER*

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ABSTRACT

Release waves from the back of a plate slap experiment are used to estimate the longitudinal modulus, bulk modulus and shear strength of the metal in the state produced by a symmetric collision. The velocity of the interface between the metal target and a window material is measured by the axially symmetric magnetic (ASM) probe. Wave profiles for initial states up to 90 GPa for 2024 Al and up to 150 GPa for Cu have been obtained. Elastic perfectly-plastic (EPP) theory cannot account for the results. A relatively simple quasi-elastic plastic (QEP) model can.

INTRODUCTION

States of solids along shock loci have stresses more complicated than the simple fluid pressure that has been assumed for simplicity in the high pressure regime. In the past decade three techniques have become available that can record continuous wave profiles at very high pressures which can be used to study elastic-plastic flow in solids at these extreme conditions. They are the VISAR[1], the ASM probe[2], and the use of radiation from shock fronts in transparent materials[3]. In this brief communication we shall give some preliminary results obtained from use of the ASM probe on plate slap experiments where the driver has been accelerated by high explosive systems. Asay and Chhabildas[1], in their work on 6061Al, describe similar experiments and analysis. Because of the brevity of this communication, we rely heavily on their paper for discussion of the concepts involved and references to previous work.

EXPERIMENTAL, SIMPLISTIC RESULTS

Figure 1 shows the ASM probe assembly and driver before impact. Fringing lines from the magnet are pinned to the front face of the target. Motion of the front face is taken on by the magnetic field lines, resulting in a loss of flux in the coil. The induced signal in the coil can be analyzed to give u(t) of the target front face.

Figure 2 shows the interactions of interest in our experimental system. Impact at 1 and outgoing shock waves, release at 2 and 3, the extended interaction of these release waves 4567, and the extended interaction of the foward moving release with the window 8910. The probe records the velocity of the interface, i.e., along the path 3, 8, 10..... An ideal window material would match the metal in impedance everywhere, have low (and independent of pressure) wave velocities, and have a sufficiently low conductivity to be transparent to a diffusing magnetic field. Such does not exist. In these high pressure experiments it was necessary to design in a large

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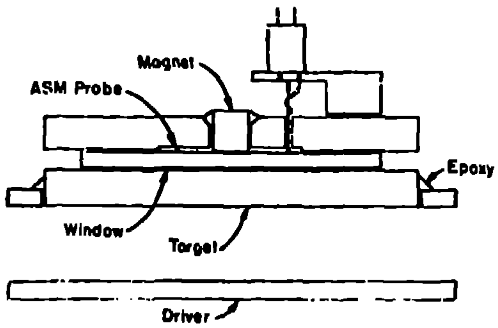

Fig. 1 Experimental Assembly

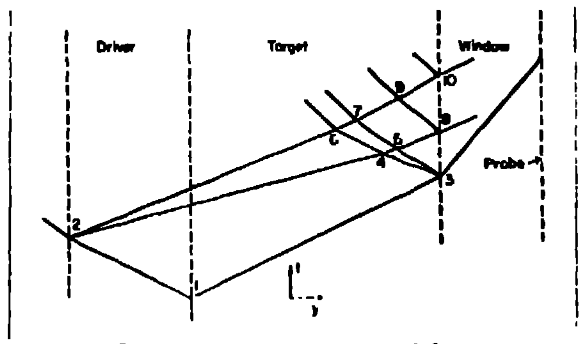

Fig. 2 Lagrangian y-t Diagram

plateau time, t_8-t_3, so that the wave from the interaction 8 would not overtake the initial shock in the window, interact and come screaming back to confuse the information recorded between t_8 and later. This causes the 4567 interaction to be buried more deeply in the target, which makes the change in slope of the characteristics of the foward facing release a non-neglectable correction. If the window does not match the metal in impedance (and it is the match of small waves around the high pressure states that we must be concerned with) a further untangling of the 8910 interaction must be done. The goal of this analysis is the $\sigma_n(\eta)$ path ($\eta = 1-\rho_0 V$) in a simple wave (also $\sigma_n(u)$ for impedance matching). Given the symmetric impact, time independent flow, uniqueness of the release path (i.e. experimental design is such that no hysterises occurs), and a complete EOS of the window material, a characteristic code analysis could be done that would give $\sigma_n(\eta)$ from the measured $u(t)$. It would not be a simple forward analysis nor a simple backward one, since unscrambling 4567 depends on the information at 8910, which in turn depends on 4567. A characteristics code would be useful whose elementary steps are solved by integral rather than difference equations. It is however, a determined problem (aside from a necessary extrapolation of the $\sigma_n(\eta)$ curve) and amendable to an iterative analysis. In lieu of such an analysis we have utilized concepts from EPP theory to analyze the results. This amounts to treating the characteristics in Fig. 2 as "shocks" carrying discontinuous waves, the earliest being the elastic release, and later, the bulk release, or an appropriate fraction of it. This results in the interaction diagram shown in Fig. 3. The striking feature of this is the large fraction of the release that is accomplished "elastically".

A typical analyzed experimental record is shown in Fig. 4 for a mid range 2024 Al shot. The u_p of the plateau is used to determine a point on the window Hugoniot and, with an impedance match, the initial metal state. The time difference, t_8-t_3, primarily determines the longitudinal velocity in this metal state and hence the initial slopes in the σ_n-u diagram. The velocity difference, u_3-u_{10} determines the size of the structure in the interaction diagram, and hence determines the change in shear stress[1], $\tau_0+\tau_c$, that the material would support. Complete use of EPP concepts in this scheme would result in a shear strength too large by a factor of

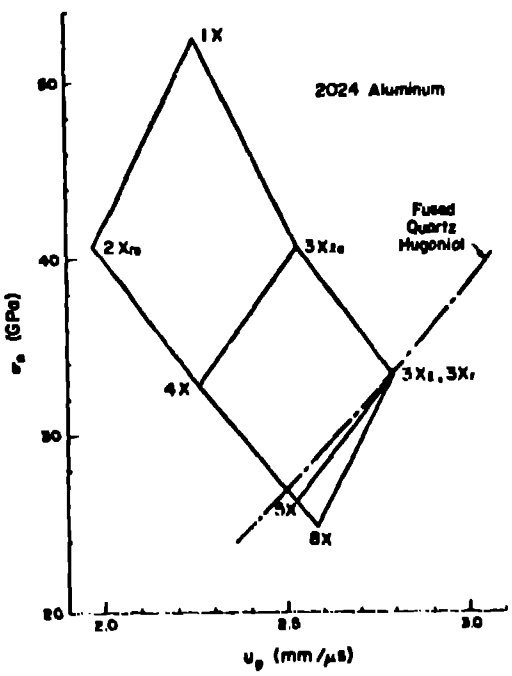

Fig. 3 Simplified EPP σ-u Diagram

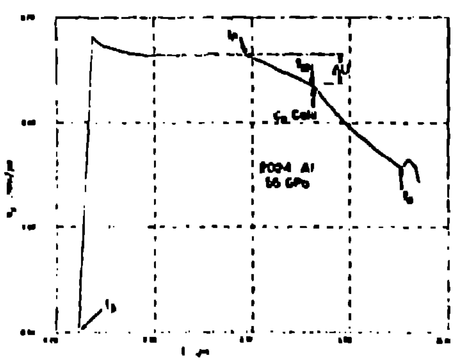

Fig. 4 Exp. u(t) Record

two. Sufficient dispersion in the wave velocities (curvature in the $\sigma_n(n)$ plane) was included to match the ramp in the u(t) curve. The knowledgeable reader will recognize the corrections and interactions necessary in these procedures. Figure 3 was for a fused quartz window while Fig. 4 was for a teflon window. They are close enough for illustrative purposes, but the data we shall now present was taken using teflon as a window material. Further characterization of fused quartz and a high density leaded glass needs to be done before we can rely on our results for these windows.

Figures 5 and 6 show C_L for the two metals studied here. We

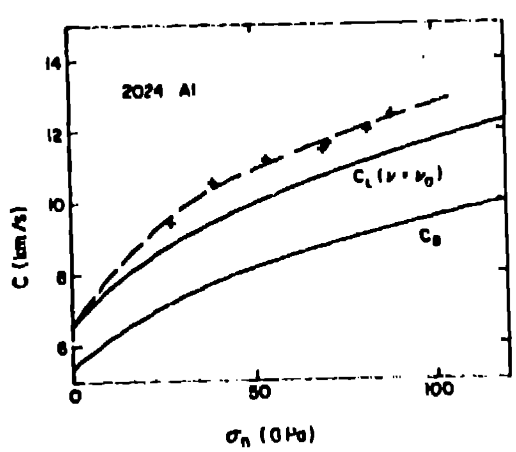

Fig. 5 Sound Speed, 2024 Al

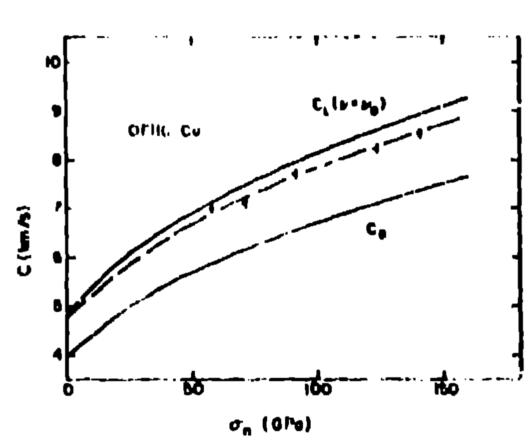

Fig. 6 Sound Speed, OFHC Cu

observe that the longitudinal sound speed lies above and below the curve where Poisson's ratio equals a constant. This behavior for these two metals agrees with the systematics inferred by Roman et.al.[4] from lower pressure data. The disappearance of the longitudinal velocity indicating the onset of melting has not been observed at the highest pressures we have obtained with our explosively driven drivers.

Figure 7 shows the shear strengths we have obtained for these two metals. We have clearly gone past the maximum value for both of these metals. It is tempting to use an extrapolation of these curves to estimate the melting transition, but it is not clear that a 'reasonable extrapolation' of these curves would necessarily give even an upper bound to the melting transition.

DISCUSSION

We must add several caveats to the data as we have presented them here. Most of the uncetainty arises from explosively driven drivers. Wave traversal time through the driver is quite important in our experiments and hence a stretching of the driver could cause us to overestimate C_L. A 1% thinning of the driver could cause a 1.8% (in 2024 at 55 GPa) and a 1.1% (in Cu at 70 GPa) overestimate. Our experiments have a self calibrating feature in that the time from initial plate motion to magnet distruction gives the shock velocity through the window material. Since these two events are not at the same radius, bow in the driver would cause this shock velocity to be overestimated. We have used the window shock velocity to estimate the pressure of the interaction. This has yielded pressures 2-10% higher than those obtained from the plateau u(t) associated with the interface. Elimination of a positive bow effect and a suspected ~2-3% error in magnet calibration due to a probe misalignment would bring these pressures into agreement. Framing camera studies on drivers have been performed but are as yet unanalyzed. Many of these problems will be eliminated and higher pressure will be achieved by transferring these experiments to our two-stage light gas gun. A better knowledge of the 8910 target-window interaction must be

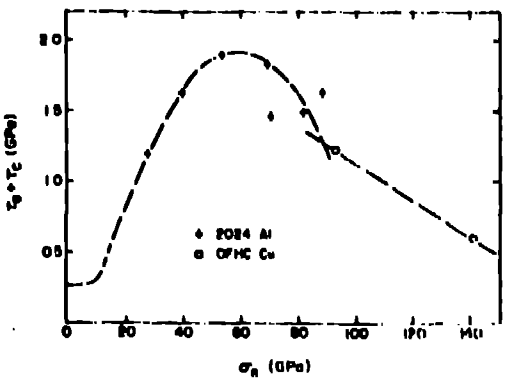

Fig. 7 Shear Strength vs Initial σ_n in the Metal. These data are not in agreement with Al'tshuler, et al.[5]

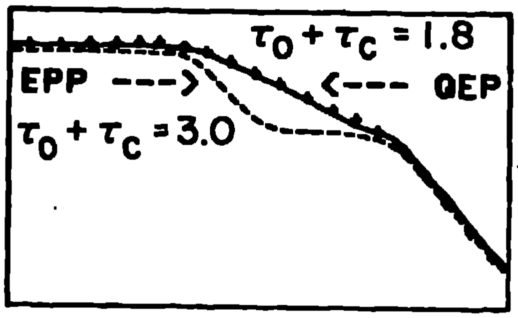

Fig. 8 EPP-QEP Comparison

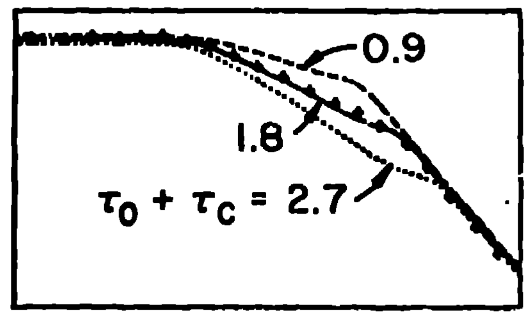

Fig. 9 QEP with Various $\tau_0+\tau_c$

obtained. A series of experiments investigating release waves in suitable window materials is underway.

In order to verify our simplistic method of calculating C_L and $\tau_0+\tau_c$ we have performed some 1D Lagrangian hydrodynamic calculations for the 55 GPa 2024 Al record. Figures 8 and 9 show these calculations. The EPP model requires 3.0 GPa for $\tau_0+\tau_c$ and does not fit the data. Our QEP local model is characterized by the following expression for the rigidity modulus:

$$\mu(\sigma_n) = \mu_0 + \mu_0' \ (\sigma_n - \tfrac{4}{3}\tau) \ (\tau_c+\tau)/(\tau_c+\tau_0)$$

The dimensionless quantity μ_0' was chosen to give the right C_L at pressure and is in excellent agreement with the ultrasonic data of Thomas[6]. A global model such as that of Steinberg et.al.[7] would incorporate the dependence of μ_0' on pressure and temperature to a greater extent. From Fig. 9 one can see that $\tau_0+\tau_c$ is fairly well determined within the assumptions of the model and agrees with our earlier simplistic method of estimating it. Nothing profound is implied by this model other than it gives a $\sigma_n(\eta)$ curve close to the experimental one.

For this analysis to be complete, reloading waves need to be introduced into the driver-target. This is almost impossible to do with explosively driven flyers. This will also be done on the gas gun.

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