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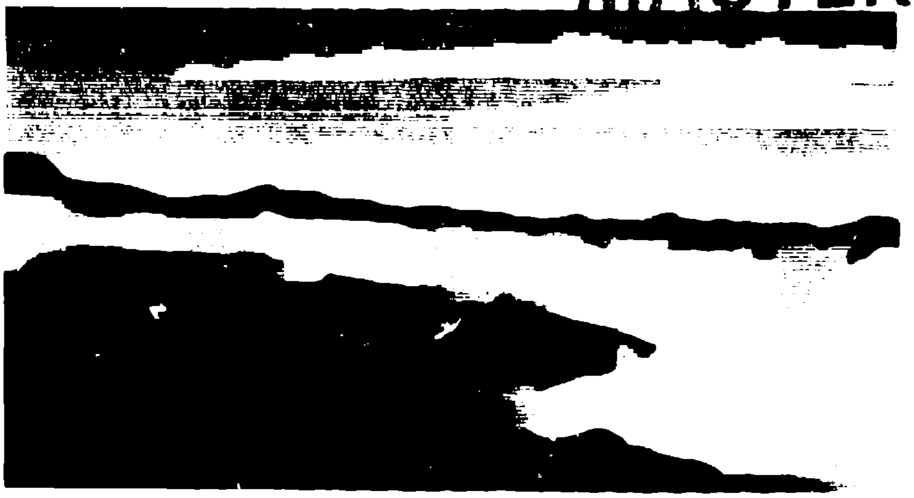

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HUGONIOT AND SPALL DATA FROM THE LASER-DRIVEN MINIFLYER

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The laser-driven miniflyer has been developed as a small-sized complement to the propellant- or gas-driven gun with which to make material property measurements. Flyer velocities typically range from 0.5 to 1.5 km/s, depending on the energy of the launching laser and the flyer dimensions. The 10–50 µm-thick flyers, 1–3 mm in diameter, and comparably small targets require very little material and are easy to recover for post-experiment analysis. To measure and improve the precision of our measurements, we are conducting an extensive series of experiments impacting well-characterized Cu, Al, and Au on several transparent, calibrated, windows (PMMA, LiF, and sapphire). Measurement of the impact and interface velocities with a high-time-resolution velocity interferometer (VISAR) gives us a point on the Hugoniot of the flyer material. These are then compared to published Hugoniot data taken with conventional techniques. In the spall experiments, a flyer strikes a somewhat thicker target of the same material and creates a spall in the target. Measuring the free-surface velocity of the target gives information on the compressive elastic-plastic response of the target to the impact, the tensile spall strength, and the strain rate at which the spall occurred. Volumetric strain rates at spall in these experiments are frequently in the 10^6–10^8 s^{-1} range, considerably higher than the 10^3–10^4 s^{-1} range obtainable from gas gun experiments.

INTRODUCTION

The Laser-driven Miniflyer has been developed over the last several years to measure the dynamic properties of materials under shock-wave conditions. A pulsed Nd:YAG laser is focused through a transparent substrate onto a thin multilayer that has been deposited on the substrate, Fig. 1. A thin foil (the flyer) is placed on the multilayer. The laser pulse is absorbed in the multilayer and creates a plasma, which in turn accelerates the flyer to its terminal velocity within three or four pulse widths of the laser. The nearly perfectly flat flyer then impacts a target and the response of the flyer and target after the impact are measured with a high-time-resolution laser velocity interferometer (VISAR) (1–2). Many of the material properties that are routinely determined with propellant- or gas-driven guns or explosives can be obtained with the Miniflyer.

Because the flyers and targets are very small (10-50 µm thick and 1 to 3 mm in diameter), recovery of the samples for post-shot analysis is straightforward. The amount of material needed for an experiment is also quite small—a definite advantage if the material being studied is toxic and/or expensive.

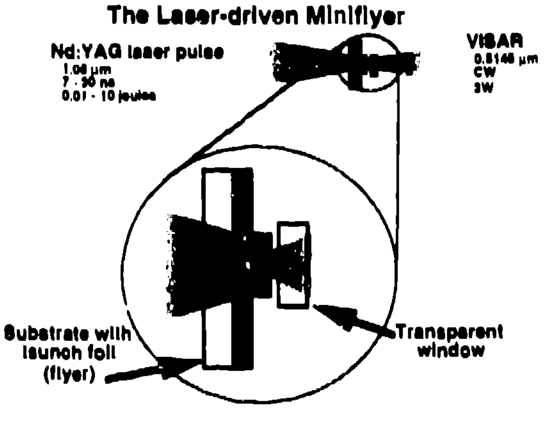

FIGURE 1. A schematic of the Laser-driven Miniflyer. The launching laser enters from the left, and the diagnostic laser enters from the right

Some details of the Miniflyer launch and the direct optical recording of the VISAR data have been presented previously (3–4). The purpose of this paper is to describe the data analysis and to compare the results with data obtained by conventional techniques. The experiments discussed here are just the first few of many scheduled to determine if the assembly and alignment procedures and the precision of the measurements are adequate to determine accurate Hugoniots and spall-related properties. In addition we hope to determine the effect of scaling, if any, on the properties being measured.

HUGONIOT EXPERIMENTS

In these experiments the material to be studied, the "unknown", is the flyer—a 25-µm-thick foil of OFHC Cu in the as-received state of hardness. The target is one of several transparent window materials of known Hugoniot and calibrated for use with the VISAR in shock-wave experiments (5–6). PMMA, LiF, and sapphire are used. The VISAR is focused through the window and onto the flyer, Fig. 1. Before impact the velocity history of the flyer is recorded; after impact the flyer/target interface velocity is recorded, Fig. 2. From these two measurements, a point on the Hugoniot of the "unknown" flyer can be calculated.

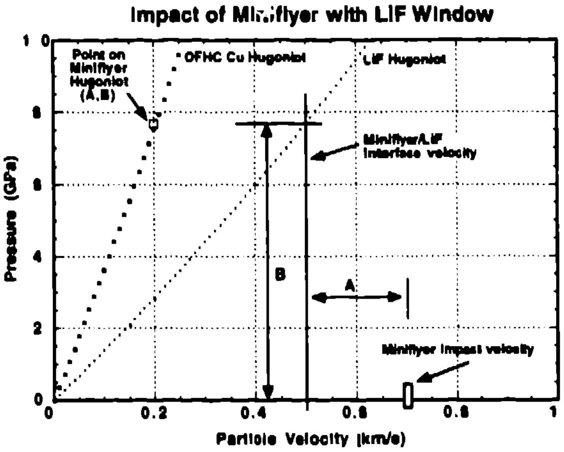

FIGURE 3. Graphical representation of the data analysis. From the flyer and interface velocities, a point on the flyer Hugoniot may be determined.

Figure 3 shows graphically how a point on the flyer Hugoniot is determined from the impact and interface velocities. The measured impact velocity is shown as a rectangle on the particle velocity axis at 0.7 km/s. The measured interface velocity is corrected for the window effects (5–6) and then shown in Fig. 3 as the vertical line at a particle velocity of 0.5 km/s. The pressure at the flyer/target interface, B, is determined by the intersection of this vertical line and the window (in this case, LiF) Hugoniot. If the impact velocity minus the actual interface velocity is A, the coordinates of a point on the flyer Hugoniot are (A,B).

The measured Hugoniot of the flyer material is

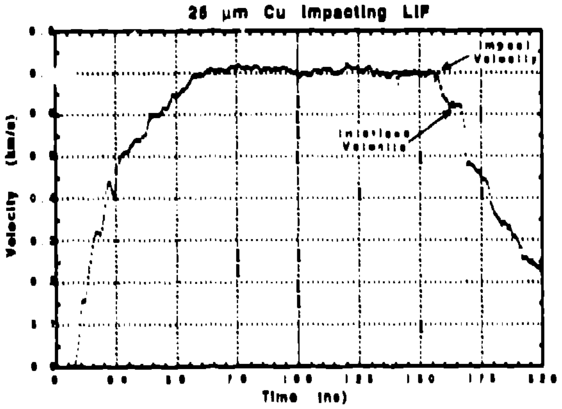

FIGURE 2. Velocity data from the VISAR. The data required are the impact and the flyer/window interface velocities.

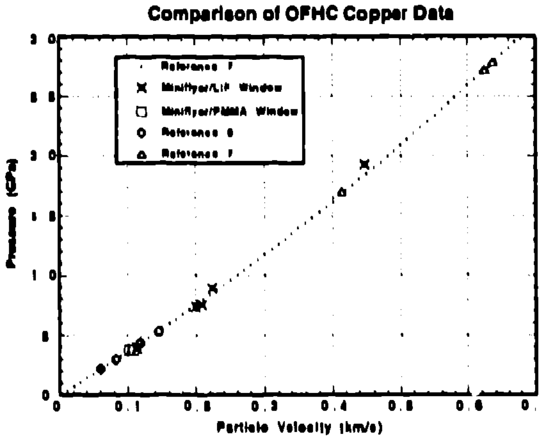

FIGURE 4. Comparison of Miniflyer data on OFHC copper with published data. LiF and PMMA windows were used in these experiments

TABLE 1. Miniflyer Experiments, Calculations, and Comparisons

Experiment No.	Window Material	Impact Velocity (km/s)	Interface Velocity (km/s)	CTH Interface Velocity (km/s)	Measured Hugoniot u_p, P (km/s, GPa)	OFHC Cu Hugoniot u_p, P (km/s, GPa)	Difference in Pressure %
1	LiF	0.679	0.480	0.483	0.200, 7.341	0.200, 7.556	2.9
2	LiF	0.793	0.570	0.563	0.223, 8.907	0.223, 8.507	4.5
3	LiF	0.382	0.269	0.273	0.113, 3.918	0.113, 4.146	5.8
4	LiF	0.697	0.490	0.496	0.208, 7.511	0.208, 7.894	5.1
5	LiF	1.547	1.099	1.087	0.448, 19.25	0.448, 18.431	4.3
6	PMMA	0.930	0.821	0.827	0.109, 3.735	0.109, 3.993	6.9
7	PMMA	0.921	0.819	0.818	0.102, 3.724	0.102, 3.735	0.3

compared to published OFHC Hugoniot data in Fig. 4 (7–8). The parameters that can be varied to get a range of pressures and particle velocities on the Hugoniot of the flyer material are the impact velocity of the flyer (adjusted by changing the flyer thickness and the energy in the Nd:YAG laser pulse) and the impedance of the window used for the target.

The CTH code (9) has been used to model the flyer/target interaction. Table 1. gives some details of the small but representative set of experiments plotted in Fig. 4 and shows the agreement between the measured and calculated interface velocities.

SPALL ANALYSIS

The miniflyer wave profile data can be analyzed by wave code computer simulation. Information about the plasticity in the shock rise and release, as well as spall strength, can be extracted. To demonstrate this process, we present a simulation result of an early miniflyer experiment on aluminum.

Figure 5 shows the particle velocity data taken by a VISAR on the free surface of a sample foil of Reynolds aluminum nominally 50 µm thick. The flyer plate was launched from a substrate coated with a layer of vapor-deposited Al nominally 25 µm thick. The metallurgical properties of both foils are not well known.

Figure 5 also shows the result of a simulation using the characteristics wave code CHARADE (10). The materials modeling included the Johnson-Barker model for the plastic strain rate in the plastic rise (11), a backstress model for the reverse plastic flow in the release (12), and a pressure threshold spall model. The EOS used was a Mie-Grueneisen type with a pressure dependent bulk modulus and constant Poisson's ratio (13). The equation of state material parameters used were roughly appropriate for 6061-T6Al. Using parameters for 2024 Al and 1100 Al produced little change in the calculated free surface velocity profile.

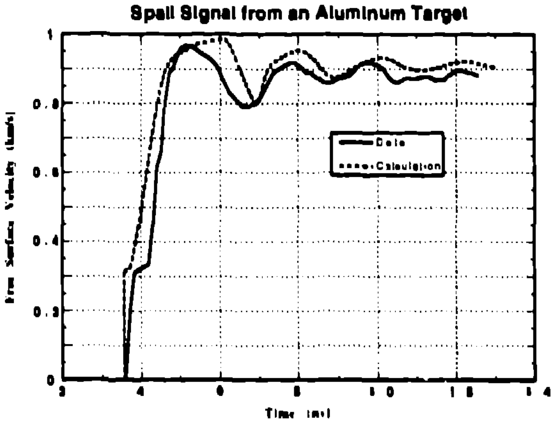

Figure 5. Comparison of free surface velocity data from a spalled aluminum target with a CHARADE wave code simulation.

The volumetric tensile spall strength was found to be 1.8 GPa. This value, because it was obtained from a full hydro calculation in CHARADE, takes into account the wave evolution between the spall plane and the free surface. A calculated value of 2.8 GPa was found for a gas gun experiment on 6061-T6Al (13).

In the calculation, the flyer plate impact velocity was taken to be the observed free surface peak particle velocity, since the impact velocity was not measured independently. This velocity produced a fairly good overall comparison with the free surface velocity data, as seen in Fig. 5.. The fit of calculation to data was done only on a qualitative basis since the experiment is not well characterized. The various materials models were adjusted to demonstrate that the general features in the data are reproducible with CHARADE, as seen in the figure.

It is of interest to compare the materials parameters arrived at in the fitting with their counterparts from a simulation of gas gun data on 6061T6 Al at a shock strength of about 4.3 GPa and involving much larger plate dimensions (13). In the miniflyer fit, the plastic strain rate multiplier had to be increased ten fold and the dislocation multiplication right after the precursor had to be decreased by about 7 fold from the gas gun fits. In the backstress model, the miniflyer fit required about a seven fold smaller dislocation viscosity and a twenty fold increase in pinned dislocation density. The miniflyer fitting seems consistent with the sample foil being in a strongly work hardened state from its rolling preparation, and, therefore, having a large initial dislocation density.

The calculated volumetric strain rate for the miniflyer spall was about 7.6 x $10^7 s^{-1}$, many orders of magnitude above that of gas gun experiments. The high spallation strain rate obtainable in the miniflyer experiment is another example of the advantages this technique has to offer.

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