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LASER-DRIVEN FLAT PLATE IMPACTS TO 100 GPa WITH SUB-NANOSECOND PULSE DURATION AND RESOLUTION FOR MATERIAL PROPERTY STUDIES

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Miniature laser-driven flat plates (<1-mm diam x 0.5-10- μ m thick, typical) of aluminum, copper, tungsten, and other materials are accelerated to ≥ 5 km/s. These miniature plates are used to generate one-dimensional shock waves in solids, liquids, and crystals. Dynamic measurements of spall strength at strain rates $\geq 10^7$ s⁻¹, elastic-plastic shock wave profiles in 10- μ m-thick targets, shocked free-surface accelerations of 10^{12} m/s², and laser-driven plate launch accelerations of 10^{10} m/s² are routinely obtained. The small size of the sample and projectile mass permits recovery of targets without additional unintended damage or energy deposited into the test specimen. These miniature plates can be launched with conventional 1-J laboratory lasers.

1. BACKGROUND

Since the early 1960's, lasers have been used to generate shock waves in condensed matter by directing a high-power laser pulse onto the open surface of a material. Only a small fraction (~4%) of the energy is coupled into the intended target. Although this method can generate high pressures, a laser with high energy (tens of joules) and high power (10^{13} W/cm²) is required.¹ The high energy/power laser pulses are necessary because of the poor optical coupling and/or impedance mismatch between a vacuum or low-density gas and the surface of the condensed matter to be shocked. Sheffield, et al.² transmitted laser pulses through a transparent substrate optically coupled to ≥ 12 - μ m foils with vacuum grease for a better impedance match of the material to be shocked or launched. This method also provided tamping for the laser-induced plasma.

2. EXPERIMENTAL METHOD FOR PLATE LAUNCH

Our experimental method^{3,4,5} involves placing a 0.2-20 μ m plate of metal or composite material to be launched on the output end of an optical fiber. Fiber diameters are typically 0.4 to 2 mm. The resulting plate diameter is that of the optical fiber. A 1.06- μ m, 8-ns Nd:YAG laser pulse is transmitted through the optical fiber at power densities of 0.75 to 3 GW/cm², sufficient to create a plasma of a small

amount of plate material at the interface between the output end of the fiber and the material. Approximately 20 to 90 mJ of laser energy is required to obtain these power densities. Since the optical fiber is typically 0.4 - to 2-mm in diameter and several meters long, many hundreds of internal reflections result in a spatially uniform energy profile at the fiber output, Fig. 1.

FIGURE 1

Experimental method for laser-launched flat plates.

The laser-pulse temporal profile, optical properties of materials, and power density determine the optical coupling efficiency of laser energy to kinetic energy of the launched plate, typically $\geq 30\%$. The laser energy is deposited in only

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a few skin depths, about 15 nm, resulting in the launch of the foil with nearly its original thickness and the diameter of the optical fiber. Plate velocities >5 km/s have been obtained. A modification of this technique is to place an optical fiber in physical and optical contact with one side of a transparent disk with the opposite side coated with the material to be launched.

3. OPTICAL DIAGNOSTICS

For material property studies the impact velocity, plate flatness, and plate integrity are critical. Three optical diagnostic techniques have been used to quantify these: streak photography, stereo photography, and velocity interferometry (VISAR). The synergism of these diagnostics yields a thorough understanding of plate performance.⁴ Streak photography experiments involve placing a quench material, e.g., PMMA, a known distance from the plate to be launched. As the launched plate approaches the PMMA, the compressed ambient air is ionized; on impact the PMMA becomes opaque, quenching the light transmission. A sample of the laser pulse used to launch the plate is also recorded on the streak camera giving a reference fiducial.

Stereo photography of laser-launched plates in flight confirms the streak camera data. To illuminate the plates, part of the Nd:YAG laser output is frequency doubled to 532-nm. The 1.06 μm and 532 nm beams are synchronized in time, and the 532 nm beam is optically delayed. The 532 nm beam is temporally broadened and spatially scrambled by previously developed methods.⁵ A filter is used to pass only the 532 nm beam for photographing the plate.

Velocity interferometry (Fig. 2) has been used to determine plate terminal velocities $>5 \times 10^3$ m/s and accelerations $>10^{12}$ m/s². The optical interference signals from a conventional push-pull VISAR are recorded optically with fiber optics and an electronic streak camera⁶ instead of the more traditional photomultiplier/digitizer techniques. By recording the optical signals directly without converting to electrical signals, the time resolution can equal or exceed the relative time delay of the interferometer,⁷ typically 100-500 ps. Most of our records are recorded with a time resolution of ~ 100 ps/pixel, providing at least a factor of 10 improvement in time resolution over most electrically

recording interferometry systems. Another significant advantage to optical recording is that other optical signals, such as the laser pulse used to launch the plate, can be recorded on the same streak camera, resulting in ~ 100 -ps time correlation between plate acceleration, laser pulse temporal profile and plate impact onto a target. This time correlation is of great value when comparing experiments with computational models.

FIGURE 2

Typical plate velocity profile with ~ 100 ps/pixel resolution.

4. FLYER PLATE CALCULATIONS

Detailed numerical simulations of flyer-plate performance have been carried out using the radiation-hydrodynamics code LASNEX developed by the inertial confinement fusion community. This code provides a comprehensive description of the absorption of laser light by a material system (largely plasma inverse bremsstrahlung, in the present case) and calculates the ensuing dynamical motions of, and radiative emissions from, the system as it subsequently evolves. By virtue of an extensive tabular data base, LASNEX has in-line access to realistic material properties (multigroup radiative opacities, thermal conductivities, equation-of-state, and material-strength data) for a wide range of substances.

Although LASNEX is a fully 2-D code, all of the flyer-plate calculations performed to date have been one-dimensional. Starting from a measured laser power history and known flyer/substrate material and geometric parameters, we have calculated the time of laser-plasma

formation at the flyer-substrate interface, the further heating and additional production of tamped plasma during the remainder of the laser pulse, and the pressure-induced acceleration of the flyer which continues (as a consequence of the plasma confinement) after the end of the laser pulse. The theoretical velocity-time curves are in good agreement with the VISAR measurements described earlier, as are the terminal velocities achieved. As an example, Fig. 3 shows a comparison of the predicted (solid curve) and experimental (open circles) data on flyer terminal velocity with laser energy, for a 5- μm aluminum flyer bonded to a quartz fiber substrate.

FIGURE 3
Comparison of LASNEX model with experiment.

Besides providing detailed time histories of flyer acceleration for comparison with experimental data, the theoretical calculations also furnish useful information on physical conditions within the confined plasma, direct observations of which have yet to be attempted. For example, the simulations indicate that only a minute fraction of the flyer rear surface is vaporized in order to provide the necessary driving pressures, a conclusion which is not inconsistent with measurements of the mass of recovered flyer samples on several representative shots. Finally, the predicted plasma temperatures are in the range 10-15 eV, depending on the incident laser energy. The resulting thermal emission should peak at soft X-ray wavelengths and be readily observable.

5. ONE-DIMENSIONAL PLATE IMPACTS FOR DETERMINING SPALL STRENGTH

To confirm the possible use of these small plates for determining spall strength of materials, we have performed standard dynamic tests on copper and aluminum and compared the results with accepted published values.

In these experiments a 6- μm -thick copper plate was impacted on a 25- μm -thick copper target. The back free-surface velocity of the copper target plate was measured with the subnanosecond resolution VISAR. A similar test was performed with a 10- μm -thick aluminium plate impacting a 25- μm -thick aluminum target, Fig. 4. The tensile spall stresses and strain rates were evaluated by standard methods⁸ and compared with other experimental results. In Fig. 5 the data points at maximum strain rate for aluminum and copper were obtained using laser-driven flyer plates; the other data are from G. Kanel, USSR.^{9,10} These experiments extend the strain rate data to $\geq 10^7 \text{ s}^{-1}$ with relatively good agreement.

FIGURE 4
Free-surface velocity and a spall signal from aluminum.

6. CONCLUSIONS

Miniature laser-launched one-dimensional flyer plates offer several significant advantages for measuring shock wave profiles and dynamic material properties in laboratory experiments but require improved time resolution for

diagnostics. Possible advantages include: 1) ubiquitous <1-J laboratory Nd:YAG lasers can replace conventional plate-launch facilities, e.g. guns and explosives, 2) the small size of the experiments minimizes safety hazards and makes sample recovery easy, 3) small sample size and bench top operation result in significant reductions in experimental and sample costs, and 4) low kinetic energy of the targets makes for easy containment of toxic materials. This miniature plate-launch technique gives any laboratory with a Nd:YAG laser and subnanosecond optical diagnostics the ability to generate and quantify shocks with <1-ns to ~100-ns duration in almost any material.

FIGURE 5

Comparison of standard spall data after G. Kanel and spall data from laser-driven flyer experiments.

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