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S.C. SCHMIDT, R.D. DICK, J.W. FORBES, D.G. TASKER (editors)

LASER GENERATION OF 100-kbar SHOCK WAVES IN SOLIDS

Craig T. WALTERS
Battelle Memorial Institute, 505 King Avenue, Columbus, Ohio 43201

Neodymium-glass laser pulses (1.06-μm wavelength, 25-ns pulse width) have been used to generate shock waves with peak pressures in the 5- to 120-kbar range at the front surface of solids. Relatively uniform irradiance levels were employed with circular beam areas in the 0.4- to 1.5-cm^2 range and single pulse energy up to 800 J (fluences ranged from 200-2000 J/cm^2). At 1000 J/cm^2, the resulting peak shock pressure is about 35 kbar. By confining the plasma with a transparent glass overlay, this peak pressure was raised to 120 kbar. The nature of the plasma initiation process has been revealed through careful simultaneous temporal resolution of the beam-power, temperature, and stress-wave details.

1. INTRODUCTION

High-power laser pulses have been used to produce stress waves in materials for more than two decades. Most of the measurements of stress wave amplitude have been performed with pulse fluences less than 100 J/cm^2. Laser exposures with fluences many orders of magnitude greater than this have been conducted, but pressures have not been directly measured in these cases. We report here measurements of stress-wave amplitudes in laser interactions with fluences in the range 200-2000 J/cm^2 with and without plasma confinement (transparent overlays). A map of pressures that may be achieved with single laser pulse interactions is presented in Figure 1 in terms of peak power density. The dashed line at high intensity follows the set of ablation pressures estimated by Cottet et al.[1,2] in the correlation of thin aluminum foil spallation data. These estimates follow a 0.7 power dependence on intensity. Similar estimates made by Eliezer et al.[3] and Gilath et al.[4] are shown in Figure 1 by the dotted line for aluminum and the chain dashed line for carbon/epoxy at lower intensity. The open circles are peak pressures measured recently with 20- to 30-ns pulses at Battelle[5,6] at the front surface of stress gage packages coated

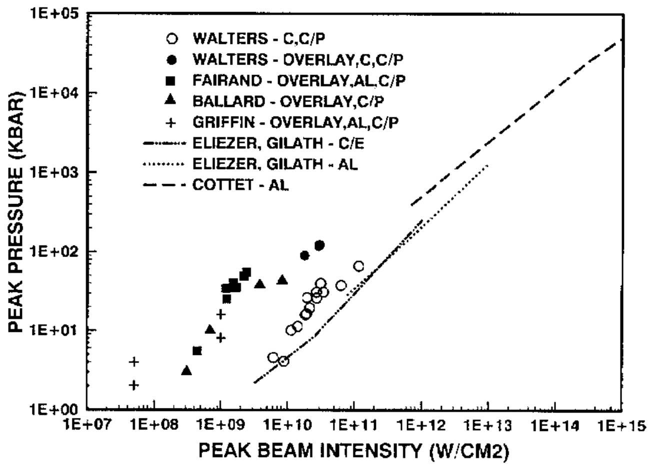

FIGURE 1
Peak laser-generated pressures

with either graphite or carbon/polymer (black paint). These data agree with the estimate of Reference 3 at low intensity, but rise nearly linearly up to 5 x 10^{10} W/cm^2 in contrast to the model. The solid circles show the effect of confining the plasma at these intermediate intensities with a transparent overlay. These pressures were in the 90 to 120 kbar range and are believed to be the highest directly recorded pressures generated in laser interactions with solids. The solid squares and triangles present the measurements of confined interactions by Fairand and Clauer[7] and by Ballard et al [8] for 30-ns pulses. These data are highly consistent up to about 3 x 10^9 W/cm^2 (90 J/cm^2). For fluences in the 100- to 1000-J/cm^2 range, the detailed nature of the transparent overlay probably takes on increased importance as breakdown processes interfere with energy delivery to the absorbing interface. Our data indicate that some benefit in increased pressure from a correctly designed overlay may be possible at even higher fluences than those investigated, contrary to the plateau seen in the Ballard data. Careful examination of the pressure histories with different coatings and with and without overlays has also revealed some detail of the plasma initiation process as discussed below.

2. EXPERIMENTAL APPROACH

The laser exposures were conducted in Battelle's Laser Effects Center using a neodymium-doped glass laser. The laser power signal was detected with a biased PIN photodiode viewing a reflection from the vacuum chamber entrance window. The digitizer system was capable of responding to 500 Mhz signals, but no such modulation was normally present. The spatial irradiance pattern was circular with a near flat-top fluence profile as detected with an EG&G

solid-state array camera. The temperature history of the front surface was measured on most tests using a fast silicon photodiode-based radiometer operating at 0.48 μm. Both quartz and polyvinylidine fluoride (PVDF) stress gages were used to record laser-generated pressures. The quartz gages used in this program were of a basic Sandia design manufactured by Valpey-Fisher. They employ an "x"-cut circular quartz crystal disk 7.0 mm in diameter by 1.0 mm thick with an active electrode 3.0 mm in diameter surrounded by a 2-mm wide shorted guard ring electrode. Standard PVDF gages that were already poled and characterized were purchased from Ktech Corporation. The gages were 25-μm thick and had a square 2-mm x 2-mm active area defined by thin film electrodes, one on each side of the polymer film. The PVDF gages were read out in the current mode wherein the current was inferred from voltage recorded across the 50 ohm termination at the digitizer. The gage current records were integrated numerically to produce pressure time histories.

The majority of the pressure data reported in References (5) and (6) were acquired with the PVDF gages embedded in composite material sandwiches or with quartz gages attached to the rear surface of the samples. Several experiments were conducted, however, with the laser beam exposing a thin coating placed directly on the pressure gage to assess the front surface stress. These latter data are reported herein and were acquired for coatings applied directly on quartz gages and for coatings on PVDF gages mounted on the front surface of quartz gages. The coatings were necessary to protect the gages from direct ablation and thermal damage and were representative of the type of materials under study. The coatings included carbon black in an acrylic matrix (flat black paint) and graphite particles sprayed on with a volatile vehicle.

3. EXPERIMENTAL RESULTS

The timing of the plasma heating relative to the incident irradiance is illustrated for a pure carbon (graphite coating) surface in Figure 2. Great care was taken in calibrating the cable delays and optical transit times so that the relative timing in the figure is believed to be accurate to about 1 ns. Plasma initiation (T >10,000 K) occurs about 8 ns into the pulse for the case shown in the figure. The front surface pressure history for the same test is also presented in Figure 2. The pressure rises sharply at 37 ns with only a small precursor pulse at earlier time (< 20 ns) for this surface. The delay between the temperature rise and the main pressure has not been understood until now. Some of the delay (about 5-10 ns) may be attributed to the shock transit time through the 25-μm thick graphite coating on the front of the quartz pressure gage used for the measurement. It is believed that the plasma actually initiates at a small distance off the graphite surface and cuts off ablation. The remaining delay is introduced by the propagation time for the shock wave moving against the gas flow from the ablating surface.

In previous work,[5] measurements of pressures generated under the same conditions with black paint coatings (carbon particles in acrylic resin) revealed significant precursor pressures that did not scale in magnitude with the main (delayed) plasma pressure pulse, but correlated in timing with laser irradiance. At that time, it was concluded that the precursor pulse was due to surface ablation pressures prior to plasma initiation. The present work appears to confirm this conclusion. Several graphite-coated pressure gages were exposed with the intent to demonstrate that the precursor would be gone or greatly reduced for this material. This was found consistently to be the case. In the case of a pure carbon surface, the ablation pressures are expected to be much lower than for a surface containing resin. The ablation pressure is approximately equal to the rate of mass removal, dm/dt, times the average flow speed, $< v >$, where m is the mass per unit area. Since the temperatures are similar for the two surfaces, the expansion speeds are about the same and the dominant factor is the mass flow rate, dm/dt. This rate may be estimated as $dm/dt=I/Q^*$, where I is instantaneous irradiance and Q^* is the effective heat of ablation. It turns out that Q^* values for resins are about 3-5 kJ/g, while for a pure carbon surface, they are about 60 kJ/g. Thus, for the same irradiance, ablation precursor pressures would be expected to be more than a factor of ten lower for pure carbon than for a carbon resin mixture. A comparison of the pressure histories for a graphite and a carbon particle/acrylic (black paint) surface is presented in Figure 3. While the main pressure pulse shapes and timing are very similar for the two cases, the ablation precursor is almost in the noise for the carbon surface and is clearly evident in the carbon/acrylic surface case.

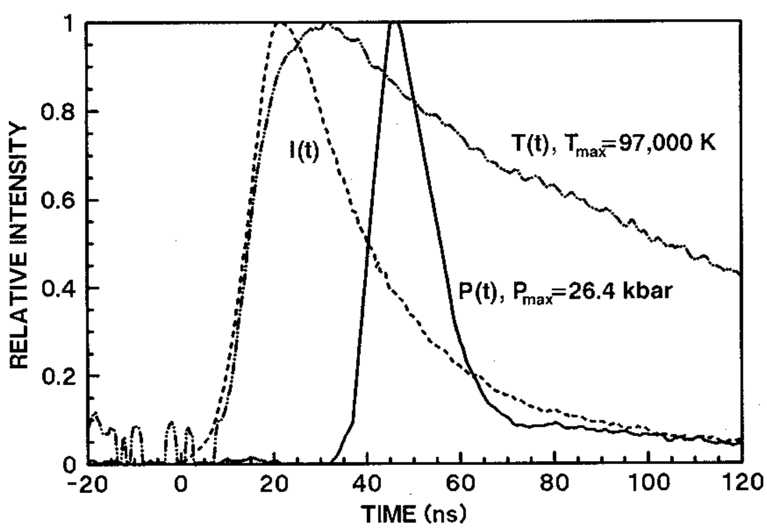

FIGURE 2
Pure carbon (graphite coating) response data

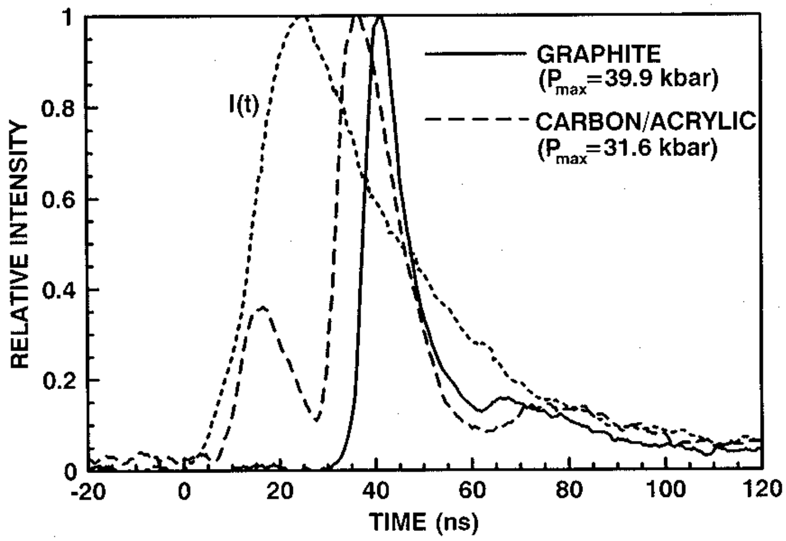

FIGURE 3
Ablation precursor pressure timing

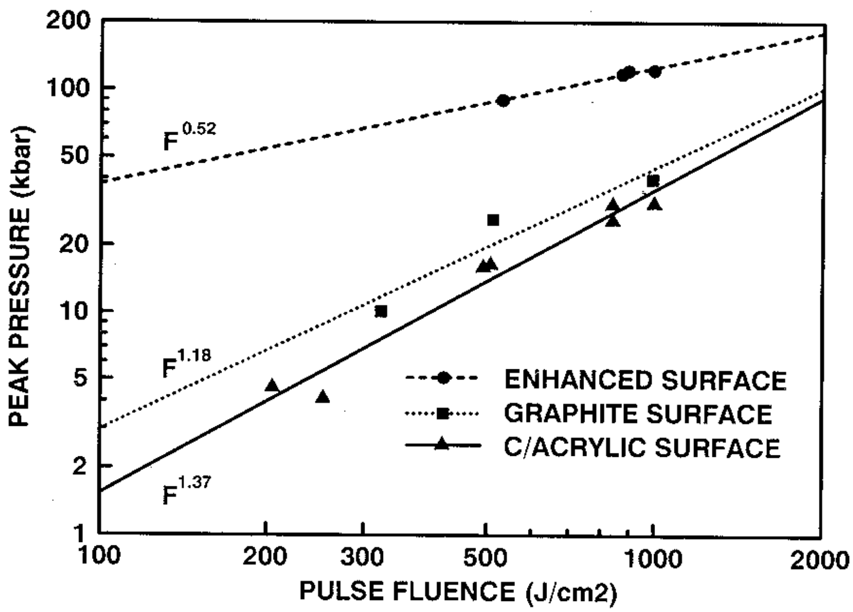

FIGURE 4
Overlay effect on pressure (enhanced surface)

The peak front surface pressure measurements taken in the current work are summarized on a finer scale in the graph in Figure 4. The data for the carbon/ polymer surface (triangles) agree fairly well with previous results. The graphite data (squares) are new and appear to show a significantly greater (30-50 percent) peak pressure for a pure carbon surface than for the resin bearing surface. The circles show four data points for enhanced surfaces wherein a transparent glass overlay (210-μm thick) was bonded to the front surface to act as a mechanical tamp on the plasma expansion and increase the shock pressures. Peak pressures achieved by this method exceeded 120 kbar as shown in the figure. The pressure confinement time corresponds to a round-trip shock transit time in the overlay (about 80 ns). While these are the highest pressures yet measured directly in laser interactions, the trend indicates that damage in the overlay has not yet saturated the pressure level achievable. The fluence dependence is consistent with the model of Griffin et al.[9] The detailed time histories of the pressure for the confined cases show the pressure rising sharply at the time of plasma ignition with no ablation precursor, which is in strong contrast to the unconfined interaction as expected.

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