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<td><a href="http://dx.doi.org/10.1063/1.3686590">http://dx.doi.org/10.1063/1.3686590</a></td>
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<tr>
<td>Publisher</td>
<td>American Institute of Physics</td>
</tr>
<tr>
<td>Version</td>
<td>Final published version</td>
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<tr>
<td>Citable Link</td>
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INTERFEROMETRIC ANALYSIS OF CYLINDRICALLY FOCUSED LASER-DRIVEN SHOCK WAVES IN A THIN LIQUID LAYER

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Abstract. We apply time-resolved interferometric imaging to study laser-driven focused shock waves on the microscale. Shock waves are generated in a 10 μm-thick layer of water by sub-nanosecond laser pulses focused into a ring of 100 μm radius. Imaging is performed with a Mach-Zehnder interferometer by time-delayed femtosecond pulses. We obtain a series of images tracing the converging shock wave as it collapses to a focal point and then reemerges as a divergent shock wave eventually leaving behind a cavitation bubble at the focus. Quantitative analysis of interferograms yields density and shock velocity values that match the water Hugoniot data found in the literature. In a separate development, we captured the propagation of cracks in a glass substrate initiated by focused shock waves. The results open the prospect of spatially resolved studies of shock-compressed materials in a small-scale all-optical experiment.

Keywords: Focused shock waves, laser shock, interferometry.

PACS: 47.40.-x, 47.80.Jk, 62.50.Ef

INTRODUCTION

In a typical laser shock experiment [1], a short planar shock wave produced by laser ablation traverses a thin layer of the material of interest that is probed optically from the opposite side. We are exploring an alternative approach to laser shock, in which the shock wave propagates laterally within a thin layer of liquid confined between solid walls [2,3]. The confined layer is amply accessible for optical diagnostics enabling the direct visualization of shock waves. This approach is especially beneficial for studying cylindrically focused shock waves [3]. The next stage in advancing the “in-plane” laser shock experiment is to develop a range of spectroscopic probes for studying material under shock. An interferometric probe for density measurements is the logical first step in this direction. The purpose of this work is to put previously demonstrated interferometric measurements [2,3] on a quantitative basis by developing methodology for measuring density profiles of in-plane propagating shock waves. The method is applied to characterize cylindrically focused shock waves in water.

EXPERIMENT

The experimental set-up is shown in Fig. 1. The shock wave is generated by a 300 ps, 800 nm laser pulse of up to 2 mJ energy delivered by an amplified Ti:sapphire system. The pulse passes through an axicon and is focused by a 3 cm focal...
lens achromatic doublet into a 200 μm diameter and ~10 μm wide ring. The sample is composed of a 10 μm-thick layer of a suspension of carbon nanoparticles in water (India ink diluted to yield ~2 weight % carbon concentration). The shock wave is launched via absorption of the laser shock pulse by the nanoparticles followed by their explosive vaporization. Interferometric imaging was performed in the Mach-Zehnder configuration schematically shown in Fig. 1 using a 180 fs, 400 nm variably-delayed probe pulse derived from the same laser system.

A typical set of interferometric images taken at increasing probe pulse delays at an excitation pulse energy of 0.05 mJ is shown in Fig. 2. The laser excitation ring launches two shock waves: the inward-propagating wave converging towards the center and the outward-propagating diverging wave. At t~60 ns the converging shock wave collapses at the center and re-emerges again as a diverging shock wave.

In addition, we used a configuration with the reference beam blocked to obtained images without interferometry. In this mode, we could make images with large time delays obtained by transmitting the probe-beam through a multimode optical fiber, exemplified by the image at 500 ns delay shown in Fig. 3. Obtaining interferometric images with the fiber delay is challenging due to poor spatial coherence of the probe beam exiting the fiber.

**ANALYSIS OF INTERFEROGRAMS**

We select a narrow strip along a diameter of the image (Fig. 4) and measure the spatial phase of the interference fringes within the strip by fitting the intensity distribution to a sinusoidal functional form. The same analysis is done on an image taken prior to the shock experiment. The reference phase obtained from this reference image is then subtracted from the phase measured on the shock image. There is a constant phase difference between the pre-shock and shock images due to vibrations of mirrors and beam splitters, etc. This phase shift is eliminated based on the fact that outside the outer shock wave front the liquid is undisturbed.

From the phase shift, we calculated the refractive index variation $\Delta n$ which was then translated into the density variation $\Delta \rho$ using an empirical linear relationship [4],

$$\Delta n = b \Delta \rho,$$

where $b=0.0336 \text{ cm}^3/\text{g}$. 

![Figure 1. Experimental setup.](image1)

![Figure 2. Interferometric images of shock waves produced by 0.05 mJ excitation pulse taken at increasing time delays.](image2)
Figure 3. Non-interferometric images taken at 500 ns obtained using an optical fiber and at 5 s delay at the excitation pulse energy 0.05 mJ.

Figure 5 shows calculated density profiles corresponding to 34.6 and 78.2 ns images in Fig. 2. Low density at x=±100 μm corresponds to the laser excitation ring. The inner shock wave is converging in Fig. 5(a) and diverging in Fig. 5(b). In the latter figure, the density change at the center x=0 after the passage of the shock wave is positive; however, the bubble in Fig. 3 indicates that negative pressure eventually develops at the center causing cavitation. In Fig. 5(a), the density jump at the converging shock front amounts to 0.081 g/cm³. According to water Hugoniot data [5], this density jump corresponds to a shock pressure of 0.22 GPa and a shock wave velocity of 1.75 km/s. The average shock wave velocity measured from the image is 1.78 km/s. While this discrepancy is within the uncertainty of the Hugoniot data [5], it should be noted that the uncertainty in the liquid layer thickness in our measurements was ~20%. This uncertainty should be significantly reduced in order to enable obtaining accurate Hugoniot data with our method.

Interferometric images have been obtained at higher excitation energies, up to 2 mJ, as shown in Fig. 6. The quantitative analysis of interferograms taken at high energies is complicated by the fact that between the inner and outer shock fronts the phase can only be determined up to a multiple of 2π. To determine the phase uniquely, the excitation energy should be kept low enough to ensure that the phase jumps at the shock fronts are smaller than 2π, as is in fact the case in images shown in Fig. 2. In order to make a measurement at a large excitation energy it would be necessary to take a series of images with a small excitation energy increment so that the changes in the phase jumps are smaller than 2π at each energy step.

The average shock wave velocity in Fig. 6 is 2.6 km/s which yields a shock pressure of 1.5 GPa.

Figure 4. Interference fringes along a diameter of the pre-shock image (top) and the shock image with the 34.6 ns delay from Fig. 2 used for the analysis.

Figure 5. Diameter profiles of the density change corresponding to (a) 34.6 ns and (b) 78.2 ns images in Fig. 2. The top profile was calculated from interference fringes shown in Fig. 4.

Figure 6. Interferometric image at a high excitation energy.
The shock pressure at the focal point was estimated to be in the tens of GPa [3].

**CRACK PROPAGATION**

At excitation energies ~2 mJ and above, the pressure at the focal point is high enough to damage the glass substrate and launch radial cracks propagating from the focus. Figure 7(a) shows the crack propagation captured at a time delay of 150 ns. In this experiment, one glass plate was thinner than the other (100 μm vs. 300 μm) and cracks were observed in the thin plate only. The estimated velocity of the crack propagation in Fig. 7(a) is ~1.5 km/s. Fig. 7(b) shows the image taken after the shock experiment; here, one can identify all cracks present in Fig. 7(a), albeit relative contrast of different cracks is different in the two images.

**CONCLUSIONS**

Imaging of in-plane propagating shock waves offers an interesting alternative to traditional laser shock experiments. We have demonstrated quantitative interferometric measurements of the density profiles in shock waves which will allow us to obtain density vs. shock velocity Hugoniot data after some improvements such as precise measurement of the liquid layer thickness. Adding spectroscopic probes such as IR/Raman/THz will enhance our capability to characterize shock-compressed materials in this geometry. We believe that the technique can be extended to “soft” solid materials such as polymers that would allow effective confinement of the shock wave between walls of much higher elastic modulus such as glass or sapphire. The question of what takes place in the exact focus is of particular interest; the size of the focal area is expected to be smaller than the optical wavelength which calls for experimental ingenuity. Numerical simulations with high spatial resolution will be helpful in guiding the interpretation. In addition, the capability to capture crack propagation indicates the potential of this method for studying dynamics of brittle fracture.

**ACKNOWLEDGEMENT**

This work was supported by the U.S. Army through the Institute for Soldier Nanotechnologies. Funding was provided by the U.S. Army Research Office, under Grant DAAD19-02-D-0002.

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