MEASUREMENTS OF TEMPORAL PROFILES OF PRESSURE IN SHOCKS PROPAGATING IN WATER

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Measurements of the full temporal profile of pressure are important in quantifying energy release rates and shock wave propagation in various media. Current efforts to perform small scale tests have spurred the need for new methods in pressure measurements. Optical –based transducers such as the ruby fluorescence methods have been demonstrated to provide pressure measurements as a function of time. In this paper, we report on improvements to this method that yields stronger signals. Faster time resolutions are thus achieved. Efforts toward faster time resolutions are crucial in quantifying shock fronts that lead to detonation.

INTRODUCTION

The need for accurate measurements of peak pressures, shock speeds and shock arrival times have historically been important in understanding detonation. Through the years this recognition has spurred the development of many piezoresistive and piezoelectric sensors for many shock applications. More recently however, a need for other sensors for many other applications has evolved. Specifically, the full temporal profile of a shock wave is needed to better characterize energy and energy release rates in devices, and the shock propagation and interaction through various media. Moreover, the recent push for scaled down experiments has required the search for non-electric based gauges. Piezoelectric and piezoresistive sensors are rendered ineffective by strong electromotive forces near explosives that are electrically initiated.

Fluorescence from ruby crystals is known to exhibit pressure dependence. In static high-pressure work using diamond anvils, the ruby fluorescence method[1] is the most widely used pressure transducer today. Other researchers have also shown the fast dynamic response of the ruby gauge.[2] Planar shocks can be resolved as fast as 20 ns. The ruby gauge is now transitioned to field experiments where non-laboratory conditions (non-planar shocks, measurements have to be performed at room temperature, existence of interfering stray light from explosives, integrity of the probe) become challenging issues. Recently, these issues were addressed and shocks propagating underwater were measured using the ruby fluorescence.[3] Pressures were inferred from the R1 and R2 lines with a time resolution of 175 ns. CTH calculations gave pressure values that are consistent with the measurements. A need for further improvements in signal collection was raised. In this paper, we show improvements in signal collection that allow faster time resolutions of 70 ns crucial for many field applications. Moreover, pressures on Al targets underwater are now probed.

EXPERIMENTAL METHOD

Ruby hemispheres 0.5 mm in diameter were mounted at the tip of optical fibers as described in Ref.3. The diameter of the optical fiber core and cladding was also 0.5 mm, and the diameter of the fiber sheath was 1.0 mm. 1.1 mm diameter holes were drilled in 10 mm thick Al 6061 plates to accommodate the ruby and fiber. The imbedded ruby was placed 0.5 mm away from the exposed surface of the Al plate. The Al plate with the fiber was then submerged in water. The underwater shock was produced from a standard detonator (RP80, Reynolds) placed 5mm from the Al surface. This detonator produces shocks with longer than 2 μs duration. This is shown in Figure 1.

Figure 2 shows a schematic diagram of the experimental method used to collect time-resolved ruby fluorescence spectra. The principles are similar to those given in Ref. 2, and details to obtain time-resolved fluorescence from minute-sized ruby is provided elsewhere.[4] Briefly, the ruby R-lines are excited with a solid state Spectra Physics continuous-wave laser operating at 532-nm. This yields higher fluorescence intensity than when the exciting wavelength is at 514 nm that is commonly used, because of the higher optical absorbance at 532 nm. The exciting beam then goes through a dichroic beamsplitter that transmits 532 nm and is then focused to the optical fiber that carries the ruby sensor in its other end. The ruby fluorescence is

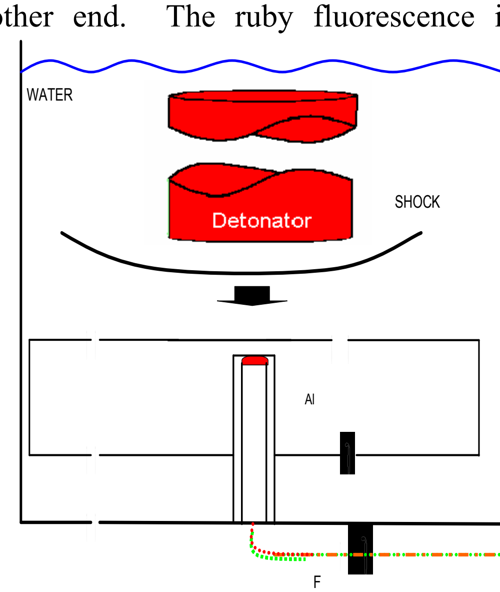

FIGURE 1. SCHEMATIC DIAGRAM OF THE AQUARIUM CONTAINING THE DETONATOR AND THE RUBY SENSOR AT THE TIP OF THE FIBER IMBEDDED IN THE AL TARGET.

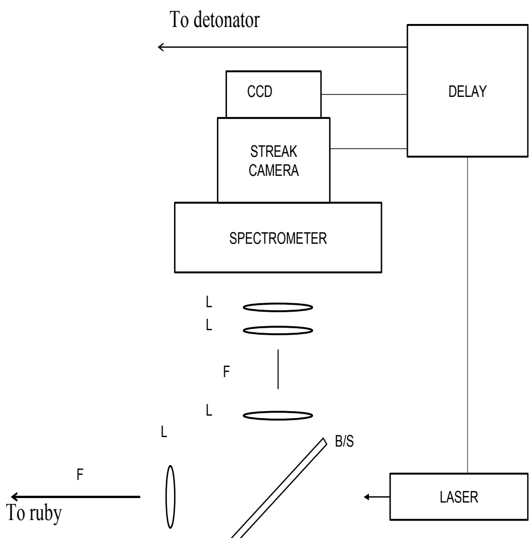

FIGURE 2. SCHEMATIC DIAGRAM OF THE OPTICAL COMPONENTS USED TO COLLECT TIME RESOLVED FLUORESCENCE SPECTRA FROM THE FIBER SENSOR. CCD – CHARGE COUPLED DEVICE DETECTOR, F – OPTICAL FIBER, L – LENS, B/S – BEAM SPLITTER

collected by the same fiber and follows the same optical path backward, until it reflects through the dichroic beamsplitter. The ruby fluorescence is delivered to a transmission monochromator (Holospec f1.8i, Kaiser), which disperses the light in wavelength and has about 5 times the efficiency of f/4 spectrometers such as that used in Ref. 3. This increase in efficiency enables measurements that can be conducted at faster time resolutions. The light is further dispersed in time by a streak camera (Hamamatsu 2830) in a direction orthogonal to the spectral dispersion. The two dimensional output is then recorded in a liquid cooled 2000 X 800 CCD detector (Spex's Spectrum One) to provide time-and-wavelength-resolved spectra of ruby fluorescence intensity as a function of time and wavelength. A delay generator (Stanford Research DG535) controls synchronization of the shock event and the streak spectroscopy system.

Pressure is inferred from the positions of the R_1 and R_2 fluorescence lines using the calibration 0.0366 nm/0.1 GPa valid when no measurable deviatoric stress is present. The R_1 and R_2 peak positions were obtained by fitting the spectra with two lorentzian functions (Origin, CA). Temperature changes in the ruby may affect the fluorescence wavelengths, but are estimated to be negligible.[5] At low shock pressures, the temperature rise in sapphire is low because of its low compressibility. Also heat conduction from the compressed epoxy surrounding the sapphire does not contribute at the time scale of the pressure measurements.

RESULTS

Two experiments were performed where pressure is obtained from the targets. The first experiment was performed with 175 ns resolution similar to those previously conducted. A second experiment was performed with faster (70 ns) time resolution to demonstrate the improvement in signal collection. Figure 3 shows the time-resolved ruby fluorescence spectra from the second experiment. The intensities are plotted as a function of wavelength. Each spectrum is taken over 70 ns duration, and the consecutive spectra are displaced in the vertical axis for clarity. The R1 and R2 peaks are resolved clearly, with much improved signals as obtained previously.[3]

At early times the R1 and R2 lines are at their ambient positions.

When the shock enters the ruby, the R1 and R2 lines shift correspondingly. These lines then slowly shift back toward their ambient values. The R1 and R2 lines are discerned clearly throughout the duration of the experiment.

DISCUSSION

The fluorescence signal obtained in the new configuration provides precise pressure measurements through the passage of the shock. For comparison purposes, previous data

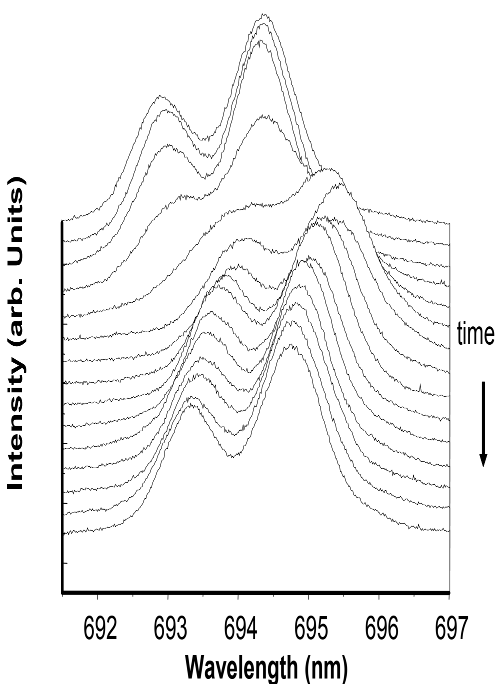

FIGURE 3. TIME-RESOLVED SPECTRA WITH 70 NS RESOLUTION SHOWING MARKED IMPROVEMENT IN SIGNAL COLLECTION. EVEN WITH THE IMPROVED TIME-RESOLUTION, THE SIGNAL TO NOISE QUALITY IS BETTER THAN THAT COLLECTED FROM PREVIOUS SYSTEMS.

from Ref. 3 with longer 175 ns resolution is shown in Figure 4. The signal to noise ratio improvement can be noted from the smoother spectra in Figure 3, despite the faster time resolution used for the measurements.

A second notable advantage the improved signal collection provides can be seen from the spectrum corresponding to shock arrival. In**.** Figure 4, at least four peaks appear in the spectrum when shock arrives at the ruby sensor. The shock traversal and reverberations within 175 ns exposure time reduces the accuracy of the pressure measurement. With improved signal collection, faster time resolutions can be obtained so that the mixing of different pressures that correspond to a shock flow can be avoided. In Figure 3, only two peaks are observed at all times.

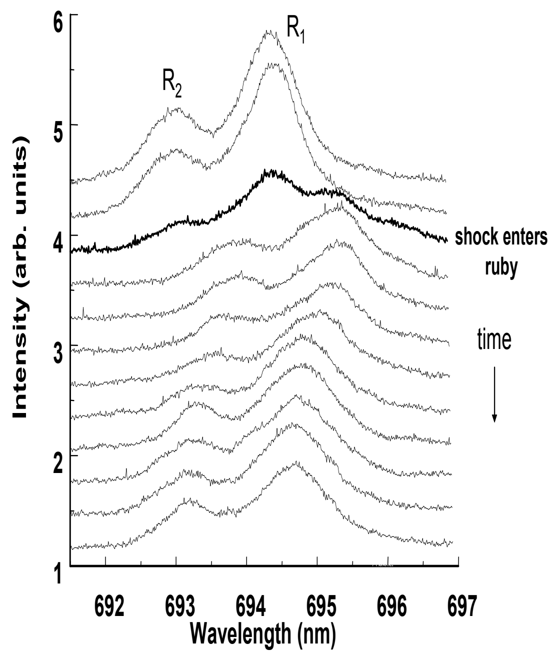

FIGURE 4. TYPICAL SPECTRA WITH 175 NS RESOLUTION FROM PREVIOUSLY REPORTED WORK - THIS IS REPRINTED FROM REF. 3.

Precise pressure measurements can hence be obtained even during the onset of the shock.

CTH calculations modeling the experimental geometry were shown to give predictions in agreement to experimental values.[3] Temporal profiles of pressure measured in a geometry that included both shock propagation in water and reflection off of a nearby surface agreed with CTH results. Figure 5 shows the agreement between pressures measured and CTH predictions.

Figure 6 shows the pressure values inside the Al target inferred from the two experiments. The pressure measured from the two experiments are consistent with each other, falling on a single curve. The longer time coverage is evident for experiments performed with slower time resolutions. However, the advantage of faster time resolutions is seen at the shock front, where the pressure values are more rapidly changing with time. This is evident from the higher peak pressure values that are measured with faster time resolutions. CTH calculations for this new geometry are expected to give predictions consistent with the measured values.

CONCLUSIONS

The temporal profile of shocks propagating underwater have been measured using the ruby fluorescence

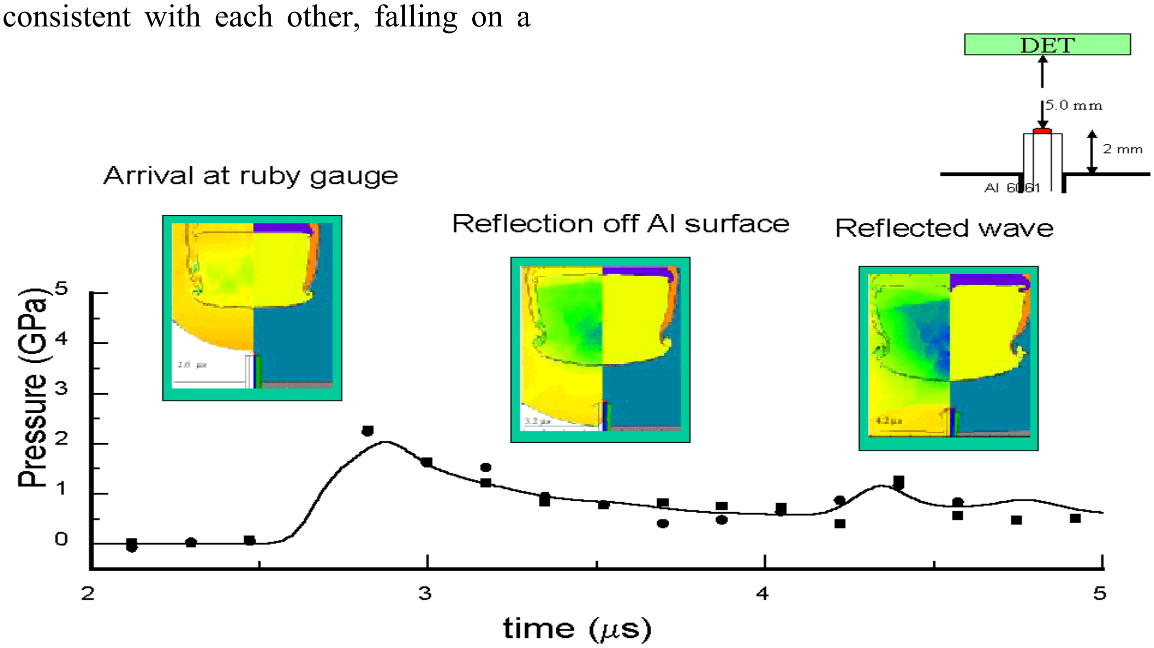

FIGURE 5. PRESSURES DEDUCED FROM SPECTRA TYPIFIED BY FIGURE 4, AND THE AGREEMENT WITH CTH PREDICTIONS. POINTS ARE OBTAINED FROM DATA, WHILE THE CURVES ARE FROM CTH PREDICTIONS. UPPER INSERT SHOWS SPECIFIC GEOMETRY WHERE SENSOR PROBES THE SHOCK FROM THE DETONATOR, AND ITS REFLECTION OFF THE AL TARGET, WHILE PICTURE INSERTS SHOW CTH SNAPSHOTS OF THE SHOCK EVENT AT THE CORRESPONDING TIMES INDICATED BY ARROWS.

method. Shock propagation in water, and its interaction with Al plates have been quantified by pressure measurements in water and inside Al targets. Improved signal collection has allowed for faster time resolutions that are important in measuring shock fronts, and other scenarios where the pressure values are rapidly changing.

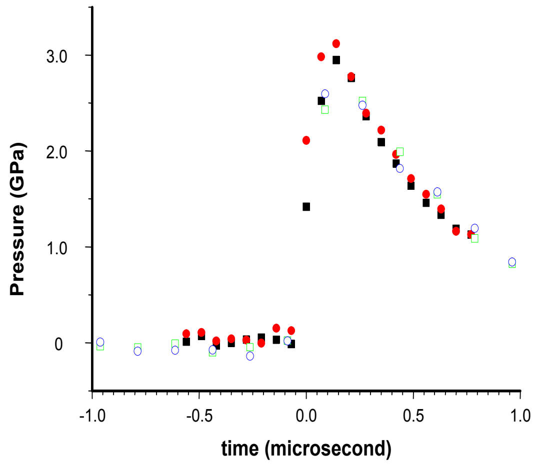

FIGURE 6. PRESSURE INFERRED FROM TWO EXPERIMENTS INSIDE THE AL TARGET. THE OPEN SYMBOLS CORRESPOND TO PRESSURES TAKEN WITH 175 NS RESOLUTION, WHILE THE SOLID SYMBOLS CORRESPOND TO FASTER TIME RESOLUTIONS. THE TWO SETS OF DATA AGREE IN DESCRIBING THE PRESSURE PROFILE. WIDER TIME COVERAGE IS OBTAINED AT LOW RESOLUTIONS, HOWEVER FASTER TIME RESOLUTIONS ARE MORE SENSITIVE TO RAPID CHANGES IN PRESSURE SUCH AS AT TIMES CORRESPONDING TO MAXIMUM PRESSURES. T=0 CORRESPONDS TO SHOCK ARRIVAL ON THE SENSOR.

A better understanding of detonation properties (energy release rates of explosives, and shock wave propagation in various media) requires knowing the full temporal profile of the shock pressure. Pressure sensors to measure shocks as discussed above are essential in developing a theoretical understanding of detonation, and hydrocodes with predictive capabilities.

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