Embedded Fiber Optic Sensors for Measuring Transient Detonation/Shock Behavior: Time-of-Arrival Detection and Waveform Determination

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Introduction

The miniaturization of explosive components has driven the need for a corresponding miniaturization of the current diagnostic techniques available to measure the explosive phenomena. Laser interferometry and the use of spectrally coated optical windows have proven to be an essential interrogation technique to acquire particle velocity time history data in one-dimensional gas gun and relatively large-scale explosive experiments. A relatively new diagnostic technique described herein allows for experimental measurement of apparent particle velocity time histories in microscale explosive configurations and can be applied to shocks/non-shocks in inert materials. The diagnostic, Embedded Fiber Optic Sensors (EFOS), has been tested in challenging microscopic experimental configurations that give confidence in the technique's ability to measure the apparent particle velocity time histories of an explosive with pressure outputs in the tenths of kilobars to several kilobars. Embedded Fiber Optic Sensors also allow for several measurements to be acquired in a single experiment because they are microscopic, thus reducing the number of experiments necessary. The future of EFOS technology will focus on further miniaturization, material selection appropriate for the operating pressure regime, and extensive hydrocode and optical analysis to transform apparent particle velocity time histories into true particle velocity time histories as well as the more meaningful pressure time histories.

Methods

Conventionally, laser interferometry is paired with spectrally coated optical windows which are subjected to a dynamic pressure load, sometimes a non-shock or shock event, and measure the apparent particle velocity induced into the window material [1]. The scale of the experiment is typically measured on the order of millimeters or larger for the distance which the dynamic pressure loading, or stress, must traverse. The lateral dimensions for such experiments are on the order of centimeters to achieve one-dimensional loading conditions. EFOS utilizes a 1550nm wavelength laser interferometry system, called photonic Doppler

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velocimetry (PDV), which is coupled with fiber optic sensors. This system was used to measure apparent particle velocity at several locations in spray deposited light sensitive explosives based on the primary explosive called silver acetylide-silver nitrate (SASN). The detonation velocity of SASN based explosives have been historically measured in the same manner as other explosives; with a relatively long strip of the explosive initiated on one end and time-of-arrival (TOA) pins at known distances, usually in inches, from the ignition point [2-5]. Typical measurements ranged from 0.5 to 1.5 mm/µs for areal densities (ρ_{AD}) of SASN explosive ranging from 11.4 to 118.8 mg/cm^2 [2-5] as measured historically and in recent experiments at Sandia National Laboratories (SNL), Light Initiated High Explosives (LIHE) facility.

The original EFOS were manufactured using plane-cleaved Corning SMF-28 9/125 µm diameter fibers. A coating of 4000 Å aluminum was physically vapor deposited to achieve the spectral coating of on the plane-cleaved tip. More advanced EFOS had a coating of 3500 Å thick aluminum spectral surface over a 500 Å titanium layer for adherence to the fiber tip. Over the aluminum was a 1000 Å layer of aluminum oxide to act as a protective coating as seen in Figure 1. The best orientation of the fiber tip is to be perpendicular to the incoming deflagration, detonation, or shock wave as shown in Figure 2. To effectively measure the deflagration/detonation velocity of SASN based LIHEs, four fibers were placed adjacent one another in a rosette arrangement at several positions along the reactive wave front propagation axis.

Additionally, traditional particle velocity, or interface velocity, was captured in adjacent PMMA optical windows with a spectral coating composed of the same materials physically vapor deposited onto the EFOS. The PDV system was used to capture this data for comparison to the EFOS probe at the surface of the rosette.

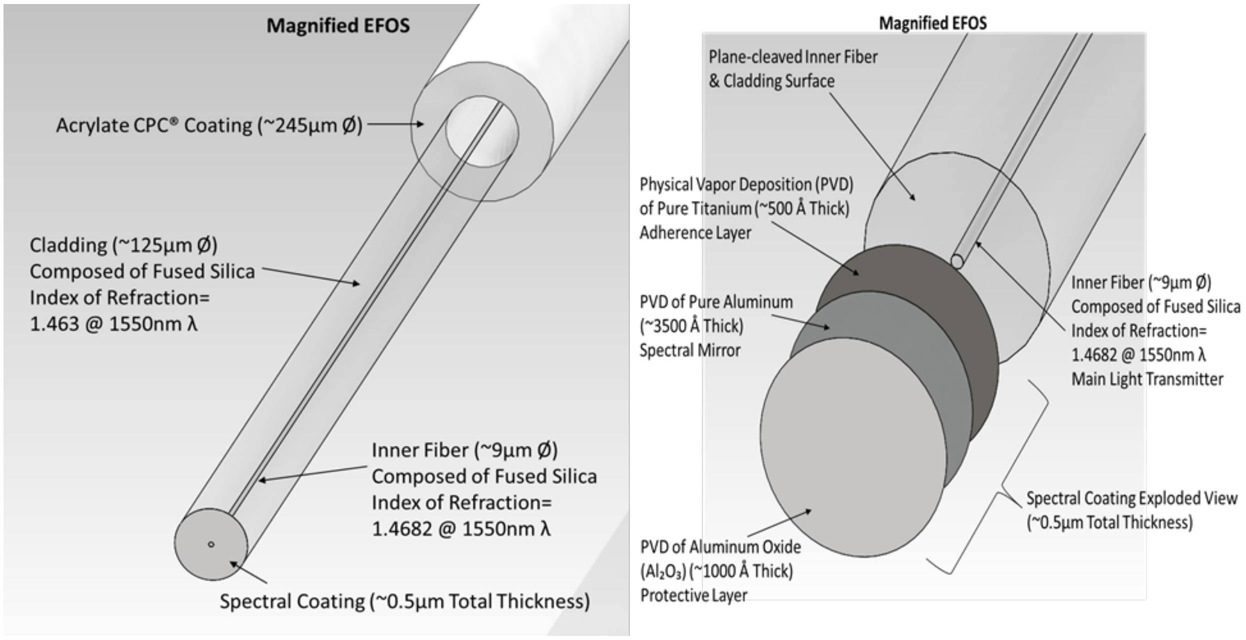

Figure 1. Left: illustration shows detail of the EFOS fiber tip; right: detailed illustration of spectral coating material types, thicknesses, and order of deposition

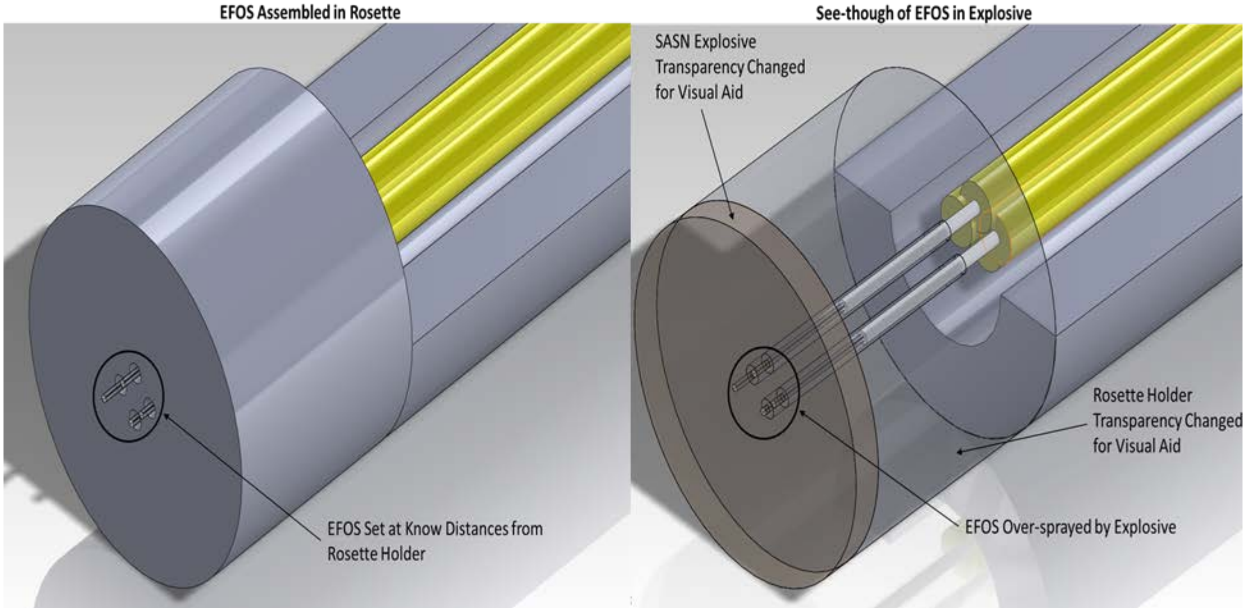

Figure 2. Left: CAD model shows a close-up view of the assembled rosette; right: CAD model allows for a see-through view that illustrates EFOS as they were employed in experiments with SASN explosive spray deposited over the probe tips

Results

A data reduction program developed by SNL called Sandia Infrared Heterodyne Analysis Program (SIHREN) was used to reduce the raw PDV data [6]. Figures 3 and 4 are plots of the data in their final form when reduced in SIHREN. Figure 5 is a distance-time (XT) plot of the apparent particle velocity half max TOA values for each reducable EFOS probe embedded in the explosive and the relative location from the explosive/air surface. The slopes of the lines fitted for the XT plot are used to calculate the reaction wave velocities for SASN. The average reaction front velocity is 0.3 mm/µs for SASN, while the 5%m/m Viton B600/SASN is closer to 0.1 mm/µs. The resulting interface velocity was transformed into the explosive's internal pressure, commonly referred to as the detonation pressure when detonation is in fact occurring. The internal explosive pressure, called P_{spike} in the insets of Figures 3 and 4, was 1 kbar for pure SASN and 0.4 kbar for the Viton B600/SASN mixture.

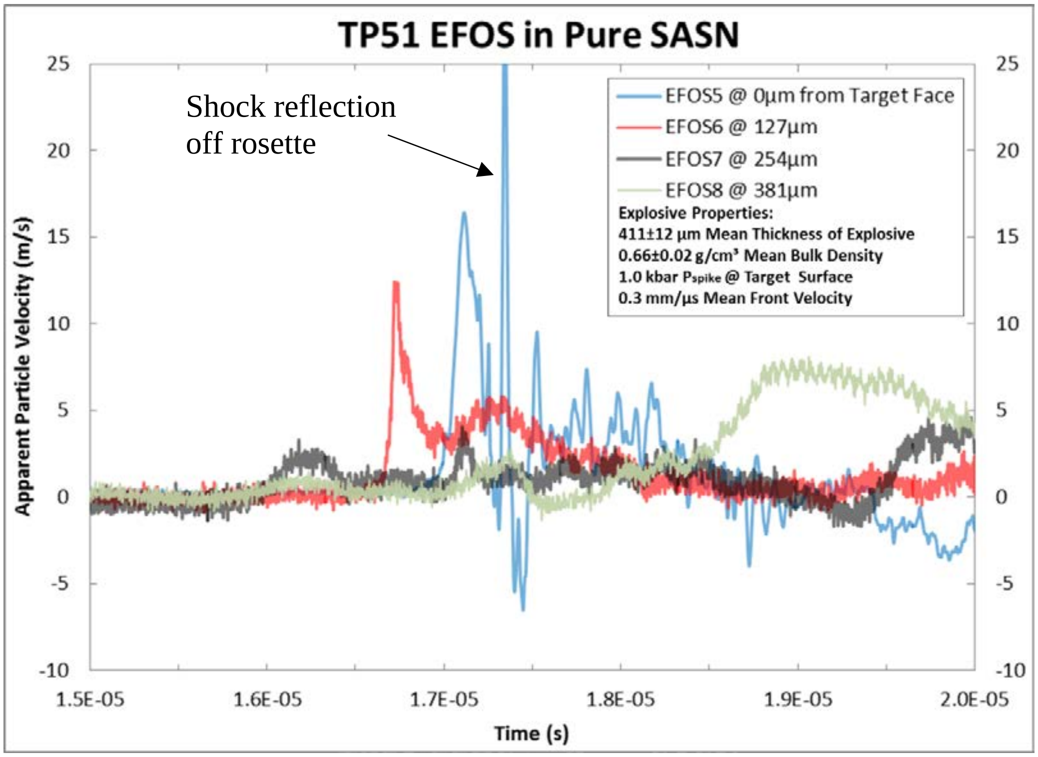

Figure 3. Apparent particle velocity traces from EFOS in the pure SASN

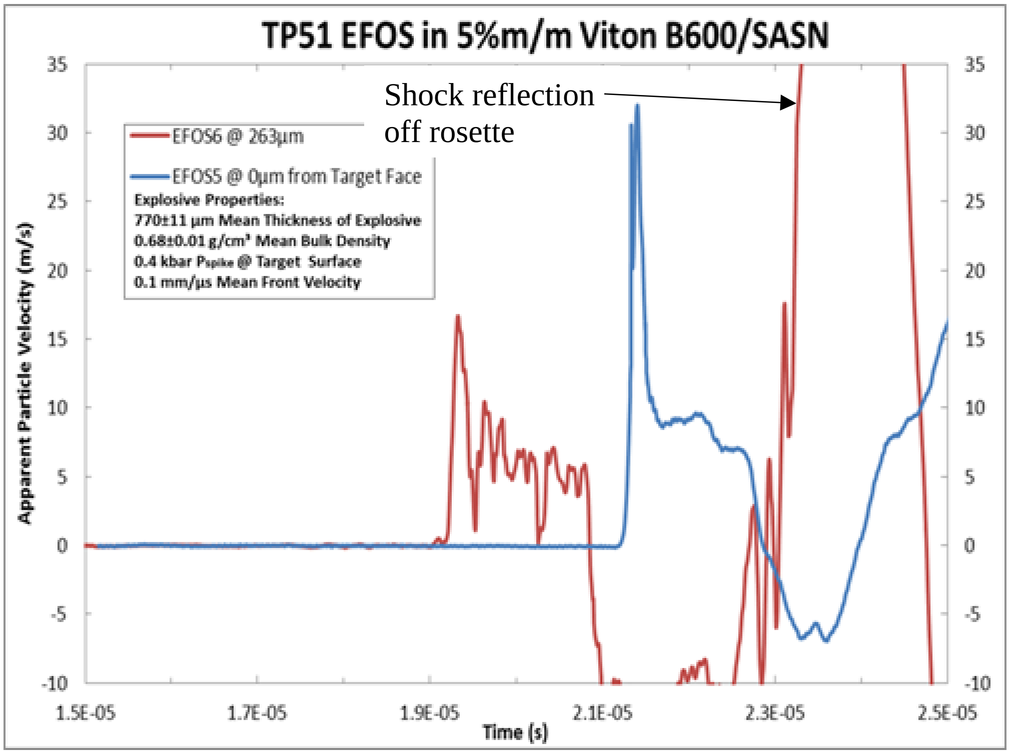

Figure 4. Apparent particle velocity traces from EFOS in the Viton B600/SASN composite explosive

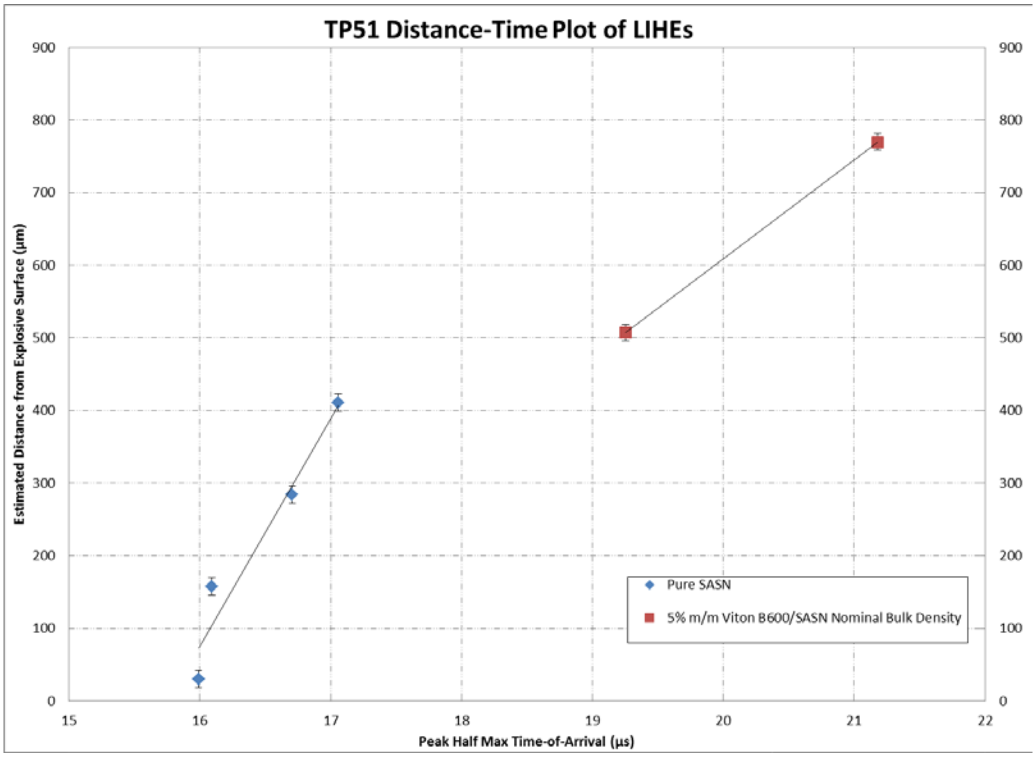

Figure 5. XT diagram of the EFOS from two explosive mixes tested

Discussion

The measured velocity did not match the historical detonation velocity as was expected. Therefore, full steady-state detonation of SASN is most likely not achieved for the thicknesses of SASN in this study. Technically speaking, the reaction front velocity cannot be determined to be a detonation velocity or deflagration velocity without knowledge of the local speed of sound in SASN. However, since this spray deposited SASN is composed of ~90% air because of its extremely porous structure, the speed of sound is likely close to that of air, ~0.34 mm/µs. The planarity of the reaction wave should be considered for these velocity measurements. Non-planarity can change the TOA as well as the apparent particle velocity measured. The orientation of the fiber tips and planarity of the reaction wave should be quantified if feasible.

The measured P_{spike} shows the relative range of pressure in which the EFOS were fielded. However, caution should be exercised to correlate the pressure to the measured apparent particle velocity in this data. Controlled experiments with known input interface velocity (particle velocity) are the best way to correlate the readings of the EFOS.

The measured fiber tip apparent particle velocity time history is indicative of the deflagration/detonation-induced shock strength, rarefaction effects, and the shock-induced change in the index of refraction. The particle velocity trace continues as the combustion products are still under pressure and expand, but the apparent particle velocity changes as a reflected shock from the surface sweeps back up the fiber. As the reflected shock propagates through expanding and probably still chemically condensing combustion products, a second particle velocity jump is induced as seen in Figures 3 and 4. This is supported by hydrocode analysis using another SNL developed code, CTH.

Conclusion

Embedded Fiber Optic Sensors coupled to a photonic Doppler velocimetry system are novel devices used for novel applications in research of transient detonation and shock wave phenomena. These probes were able to produce waveforms similar to those captured with other diagnostics that measure pressure or interface velocity, giving credence to EFOS being capable to generate a transformed version of the interface velocity and pressure. In the pure SASN data traces there is a clear trend of apparent particle velocity growth as a function of distance and time.

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