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Author(s): Michael J. Murphy
Steven A. Clarke

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Ultra-high Speed Imaging for Explosive-driven Shocks in Transparent Media

M. J. Murphy, S. A. Clarke
W-6 Detonator Technology, MS-P950, Los Alamos National Laboratory, Los Alamos, NM 87545

ABSTRACT
An ultra-high speed imaging system employing laser backlighting with spoiled coherence is developed to visualize shock waves driven into transparent media, such as air and polymethylmethacrylate (PMMA), through shock and detonation interaction. Resulting time-resolved image sequences yield two-dimensional visualizations of shock geometry as well as quantitative measurements of shock position history. One-dimensional measurements of detonator-driven shock position in both air and PMMA have recently been validated using simultaneous photonic Doppler velocimetry (PDV) measurements and predictive calculations. The imaging system is currently being utilized to visualize shock waves driven into air and PMMA samples through multiple interactions with detonating explosives. System development, implementation, and experimental data are discussed.

INTRODUCTION

With the intent of experimentally characterizing the performance of initiators, detonators, and high explosives (HE), an early version of a laser-backlit schlieren system was introduced in [1] to outline key aspects of the implemented technique critical to successful visualization of explosive events. As presented, the system provided primarily qualitative data that allowed general comparisons to be made between flows generated by different explosive insults. The current shock wave image framing technique (SWIFT) developed in Detonator Technology at Los Alamos National Laboratory (LANL) combines ultra-high speed image recording with spoiled-coherence laser backlighting to directly visualize explosive output directed into transparent media with multi-frame resolution and a much higher image quality than the original system. The qualitative information inherent in SWIFT images as simple flow visualizations provides direct observation of the complex flows under investigation, and data-reduction procedures have been developed to extract numerous quantitative data sets directly from the recorded images.

Implementation of the imaging system, a small range of experimental results, and examples of reduced quantitative data for explosive-driven shocks in both air and polymethylmethacrylate (PMMA) samples are presented in the ensuing discussion. Attention is given to experimental SWIFT data sets and the physical insights that stem from directly observing explosive-driven shock waves as they evolve in both space and time. The main goal of this report is to introduce SWIFT as a means of obtaining unique insights into explosive-drive phenomena, as well as any application involving strong shock waves propagating in transparent media.

EXPERIMENTAL

The optical configuration for SWIFT measurements mirrors an inline lens-based schlieren system, as described in [2]. A schematic is included in Fig. 1 for reference, where the optics have been chosen to investigate length scales relevant to detonators (~ 10 mm field of view). High-quality Nikon lenses are employed to both avoid optical aberrations in the imaging train, as well as to take advantage of precise Nikon F-mount architecture. As a result, every aspect of the imaging system from light collimation to stand-off distance to magnification can be rapidly changed by appropriate lens selection without the need to re-align the inline optical train.

With regard to system magnification (M_0), the physical stand-off distance (primarily defined by the axial dimension of the "boom box" used to contain the explosive events) is chosen to match the infinite-focus focal length of the first imaging lens

(Lens 2 in Fig. 1). As such, dual-lens imaging can be utilized in a manner analogous to infinity-corrected optical systems in microscopy, where the magnification is determined as the ratio of focal lengths of the second imaging lens to the first, i.e. $M_0 = f_3/f_2$. Precise matching of the stand-off distance to f_2 is not critical since the second imaging lens can be manually adjusted via the focusing ring to obtain sharp focus, with the corresponding magnification varying only slightly from f_3/f_2.

There are two critical system components in the SWIFT implementation that directly affect the quality of the recorded data. The first is a high-quality ultra-high speed camera system employing multiple intensified image sensors that are well-aligned such that errors due to perspective, channel registration, and parallax are minimal. Such a camera system allows multi-frame image sequences to be recorded from a single event, which provides visualization of the temporal evolution of the flow. The employment of image intensifiers on the sensors allows ultra-short (5 ns) exposures to be utilized, which provide dual advantages for visualizing explosive events. First, nanosecond-scale exposures are required to freeze the motion of the supersonic shock waves in order to avoid blurring of the shock fronts during recording. Second, such short exposures are required to minimize light-saturation of the sensors due to intense explosive luminance. In current SWIFT experiments, a SIMD camera system (Specialised Imaging) is employed that utilizes eight CCD sensors operating in dual-frame capacity to obtain 16-frame image sequences at frame rates up to 16 MHz, or 8-frame sequences at frame rates up to 200 MHz. Each image has nominally 1.3 Mpixel resolution, a 12-bit bit depth, and is recorded using 5 ns exposures. As depicted in Fig. 1, a precision optical band-pass filter (Andover 532FS02-50) with a bandwidth of 1.0 +/- 0.2 nm is used to block nearly all broadband explosive luminance from entering the camera.

The second critical component in the SWIFT setup is a customized 5 Watt continuous-wave laser (Spectra-Physics Reveal 5) having spoiled coherence and fiber-optic delivery for backlighting the experiments. The absence of coherence in the laser light averts major pitfalls that coherent light introduces into schlieren applications, as summarized in [2] and studied in [3]. The fiber-optic light delivery (SMA connector) provides diverging light from a finite-sized aperture (400 micron), which simplifies light collimation by eliminating the need for either focusing optics or a spatial filter (lack of coherence alleviates diffraction effects). As a result, for schlieren applications the end-user is left with an intense, monochromatic light source of finite-sized aperture that is suitable for backlighting explosive events having high self-luminance and supersonic shock motion.

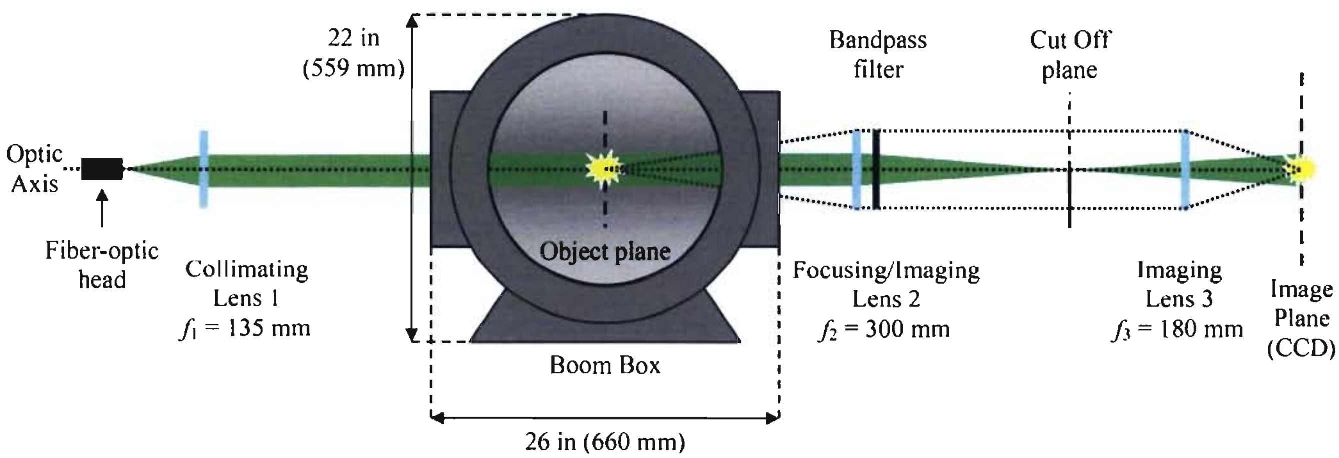

Fig. 1 Schematic of SWIFT optical configuration for detonator/HE investigation

It is important to note that in many SWIFT experiments, where detonators or HE are investigated by driving shock waves into transparent solids, a schlieren cut-off is typically not employed due to the high refractivity of the solid media and the high strength and curvature of the shock waves. In other words, the shock fronts refract the collimated light by such an extent that one visualizes a physical boundary of material density expanding outward, and a schlieren cut-off is not required to visualize this boundary since the refracted light fails to be captured by the aperture of the first imaging lens. Conversely, a conventional schlieren cut-off (typically a knife edge) is commonly utilized for initiators and detonators directed into gaseous media (low refractivity) when the shadowgraph effect due to the large spatial extent of the flow [2] is insufficient to clearly visualize the shock fronts. Recent work by [4] specifically focuses on extending schlieren and shadowgraph methodologies to shock waves in transparent, inert solids in order to extract shock Hugoniot parameters for the solids. Though the authors share a strong interest in this form of analysis for extracting Hugoniot information from SWIFT datasets, the challenges inherent in capturing shock-refracted light in solids resulting from detonation interaction have yet to be overcome.

RESULTS AND DISCUSSION

As a typical detonator functions, a steady detonation wave developed in the detonating explosive interacts with the metal cup that contains the explosive and shock-compresses the metal to pressures exceeding the steady-state detonation condition, i.e. the Chapman-Jouguet (CJ) state [5]. By performing two distinct series of SWIFT experiments, where detonator output is directed into solid PMMA and ambient air, two drastically different flows resulting from the same functioning detonator can be investigated to facilitate understanding of how the detonator performs, as well as to compare with predictive calculations.

Fig. 2 displays image sequences corresponding to the same detonator operated into PMMA and air using the same firing conditions. In PMMA, the images depict the outward expansion of a shock wave that forms at the interface between the metal housing and the PMMA sample due to a mismatch in the shock-compressibility of each material. In air, the SWIFT images depict the outward expansion of the metal cup while it accelerates as an explosively-driven flyer, as well as the transient onset of a detached shock wave that forms ahead of the accelerating metal. Both image sequences suggest the primary output of the detonator has axially symmetric geometry, since no effort was made to key the output to the recording camera. Additionally, the results suggest that secondary shocks and/or wall-effects inside the detonator have little impact on the behavior on the leading flow features.

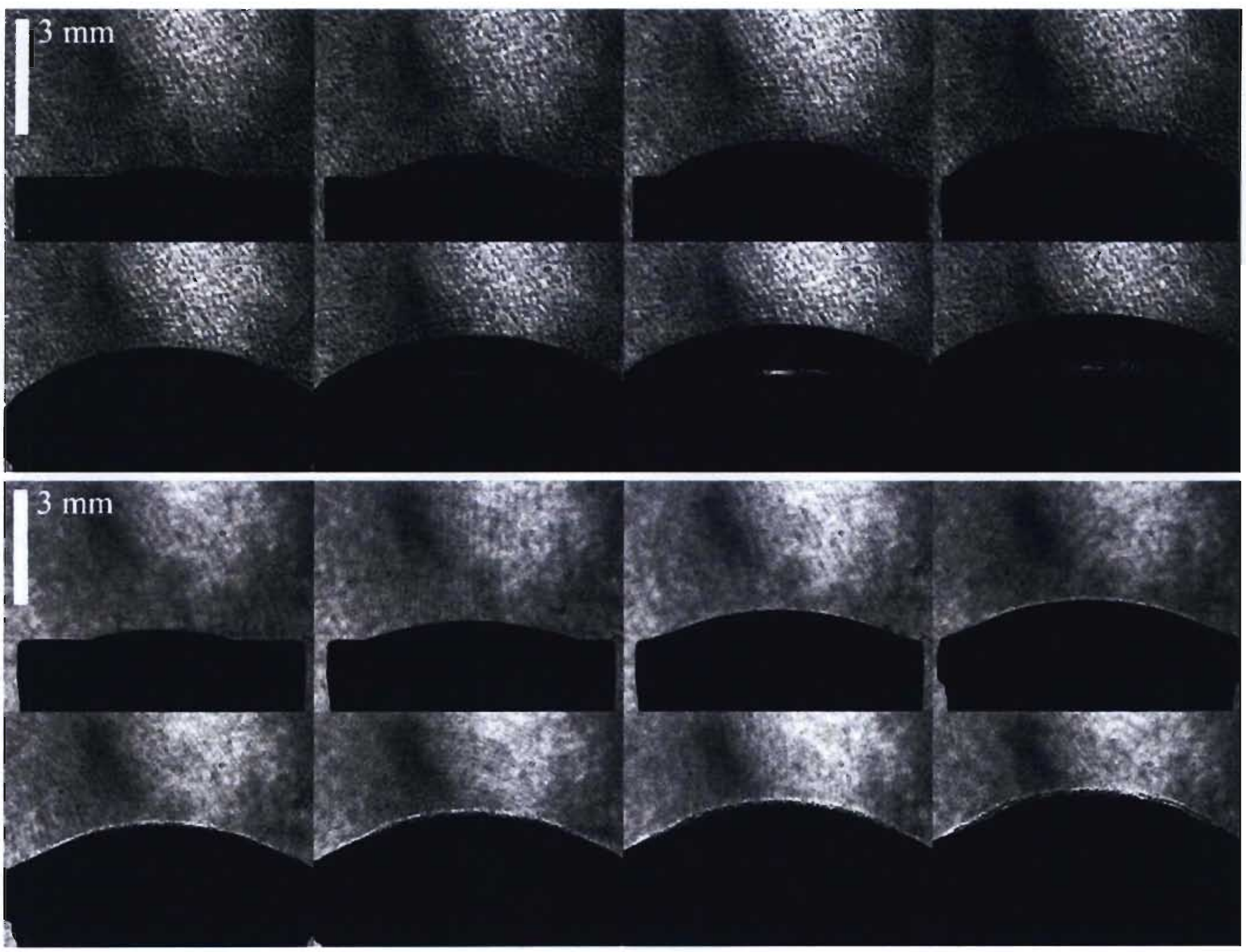

Fig. 2 SWIFT images of detonator output into (top) PMMA and (bottom) air using 70 ns inter-framing

In extracting precise quantitative data from SWIFT images, one-dimensional measurements of vertical shock position in PMMA and flyer position in air have been previously reduced to shock and free-surface velocities and compared to simultaneous photonic Doppler velocimetry (PDV) data with very good agreement [6]. In the same work, mass velocities in the detonator cup and shock velocities in the PMMA samples were converted to shock pressures using well-known velocity-Hugoniot parameters [7] and momentum conservation in order to compare to detonation- and shock-interaction calculations, as well as 1-D numerical simulations.

In this work, a different analysis is presented where 1-D detonator breakout across the surface of the metal cup is measured and compared to streak camera recordings taken across the detonator surface. Fig. 3 includes the first four frames of the SWIFT data for the PMMA experiment displayed in Fig. 2, where red lines are included to track the lateral position of the shock wave driven into the metal cup from the supporting detonation wave. By defining the lateral-position origin as the geometric center of the shock wave and the reference time as the instant of first motion of the metal cup center (obtained from simultaneous PDV data), measurements of lateral shock position are paired with corresponding exposure times and plotted in position-time space as pseudo-streak data. Results from seven different SWIFT experiments are included in Fig. 4 (right), and are plotted to overlay actual streak-camera data measured from the same detonator (Fig. 4 left). Very good agreement is demonstrated that suggests pseudo-streak data reduced from SWIFT images can be used to quickly describe detonator breakout, as well as to validate experimental streak records.

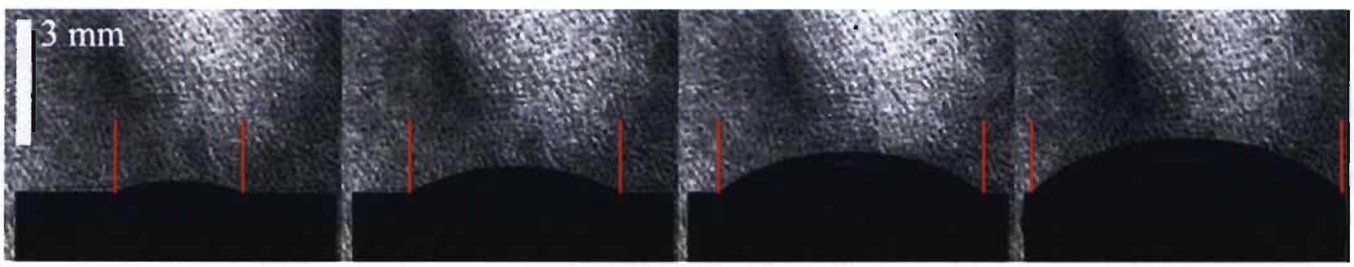

Fig. 3 Subset of SWIFT image sequence for detonator output into PMMA with vertical lines denoting lateral shock position across the detonator surface

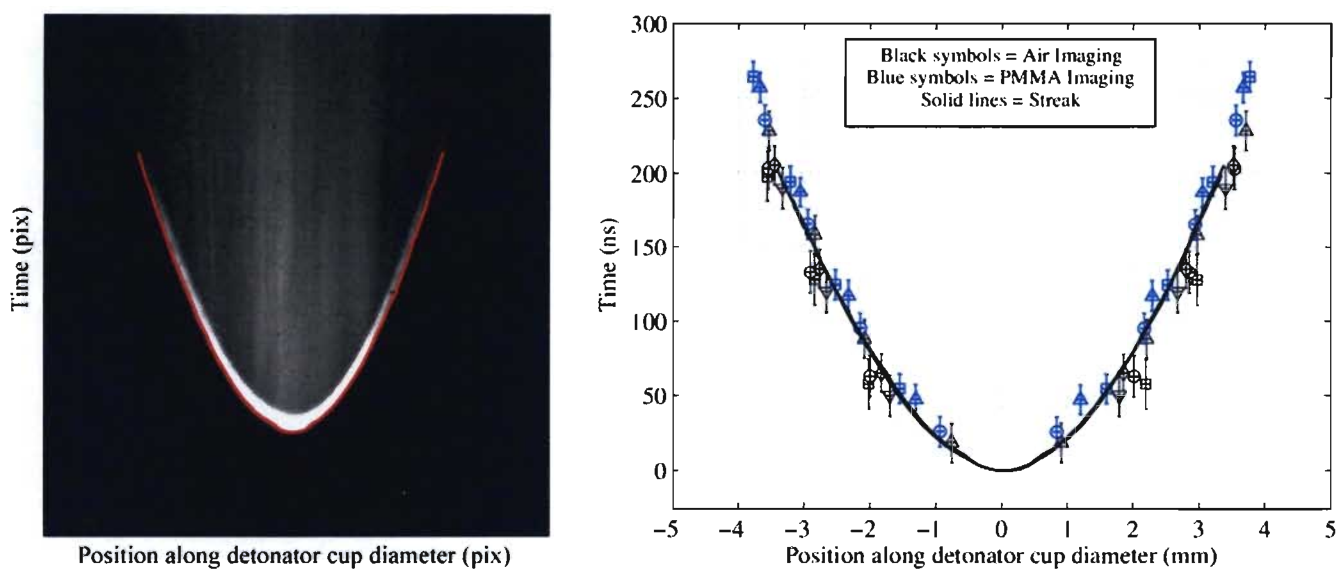

Fig. 4 (Left) Experimental streak-camera data with an edge-detected curve overlay and (right) pseudo-streak data extracted from seven different SWIFT experiments plotted with the actual streak data

To investigate methods in which a detonator can be used to initiate HE through impact loading rather than detonation interaction, an experiment is designed based on the observation in Fig. 2 that a metal detonator cup becomes a thin, explosively-driven flyer plate when the detonator is operated into media with minimal or no impedance, e.g. gas or vacuum. The point of interest is to directly visualize detonator output into both air and PMMA after the cup has interacted with a metal cutter assembly. While this general application of detonators is not novel [ref], and is similar to the small-scale floret test assembly [8], there is scarce literature available on the subject, and the authors have found no previous studies demonstrating direct visualization of the output flow.

A simple cutter is machined out of stainless steel that accepts the detonator of interest on one end and has a 5.75 mm diameter through hole axially aligned with the detonator centerline. Since the aluminum cup of the detonator has a diameter of 7.6 mm, one expects a smaller-diameter flyer to be generated as the detonation wave shock loads the aluminum cup and causes it to shear at the cutter edges. The height of the through hole in the cutter is 2.5 mm, and the thickness of the aluminum cup is 127 microns. Two assemblies are experimentally investigated corresponding to detonator output into air and PMMA, respectively. The corresponding SWIFT images are displayed in Figs. 5 and 6, where the inter-frame time is 135 ns.

Notice in Fig. 5 that the central region of the flow is curved, as is observed in the bottom of Fig. 2, but it is difficult to directly observe a distinct flyer boundary early on. The central region is followed by a flat expansion front that resembles a piston having a lateral geometry consistent with the cutter diameter. As time progresses it becomes clear that the expanding detonation products from the detonator compose the expansion region and partially envelop the central portion of the flow containing the flyer. Since a schlieren cut-off is not utilized, the detached shock waves are visible due to shadowgraphy through the large spatial extent of the flow, and the curvature of the shock fronts. The presence of the lateral detached shock waves supports the observation that the product gases are expanding supersonically, as one would expect. Results from simultaneous PDV verify that not only is a flyer generated through the cutter, but its velocity history is nearly identical to an unaltered detonator having no interaction with a cutter.

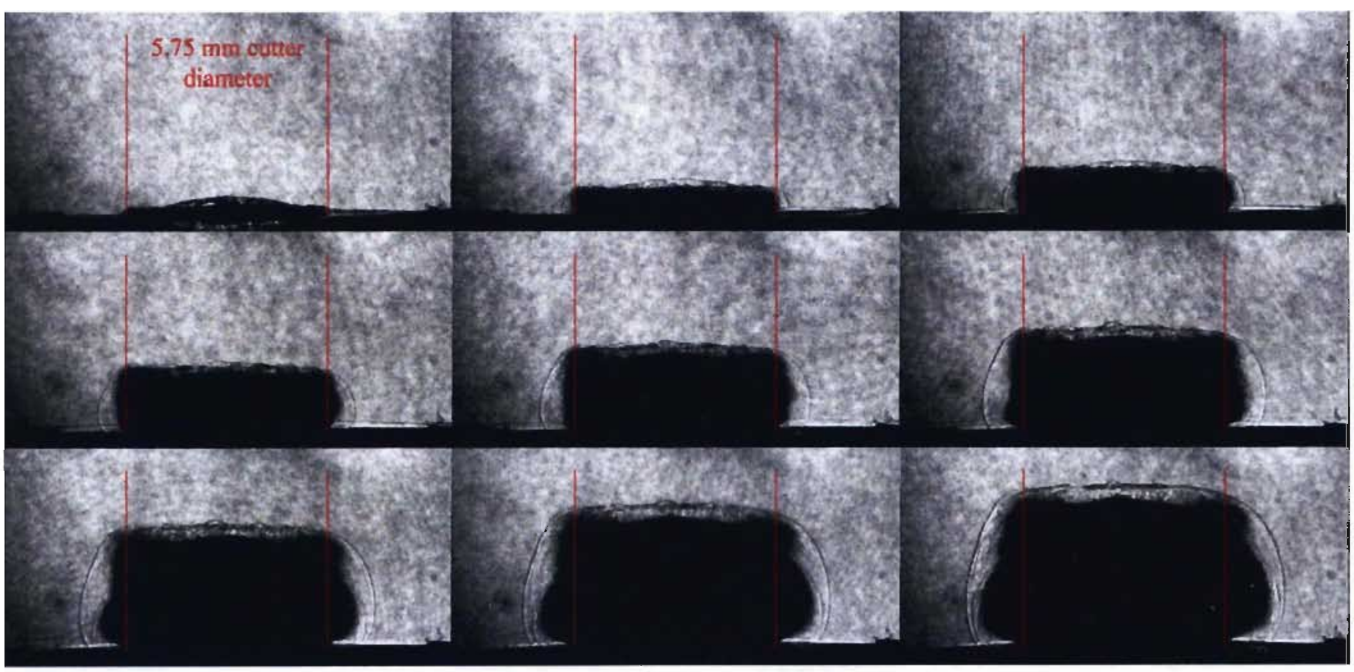

Fig. 5 SWIFT images of the flow in air resulting from the interaction of a standard detonator with a stainless steel cutter assembly (red lines denote lateral locations of the cutter barrel)

Considering Fig. 6, where the output is visualized within PMMA, frames 1 and 2 support the idea that a central flyer initially shocks the PMMA and is promptly followed by a flat expanding piston. Given that the PMMA sample is used here as a surrogate for HE, there is utility in knowing that within a 135 ns inter-frame delay a pellet of HE would incur a double insult that may affect its initiation and subsequent run-to-detonation. Further, frame 5 suggests the shock waves within the stainless steel cutter eventually shock-load the PMMA sample as well. Additional analysis is ongoing to relate the strength of the primary shock driven into PMMA to PDV measurements of the flyer velocity at the instant of impact. Nevertheless, for impact-loading applications, the SWIFT images in Figs. 5 and 6 present a consistent story on which design decisions can be based for an explosively-generated flyer plate using standard detonators.

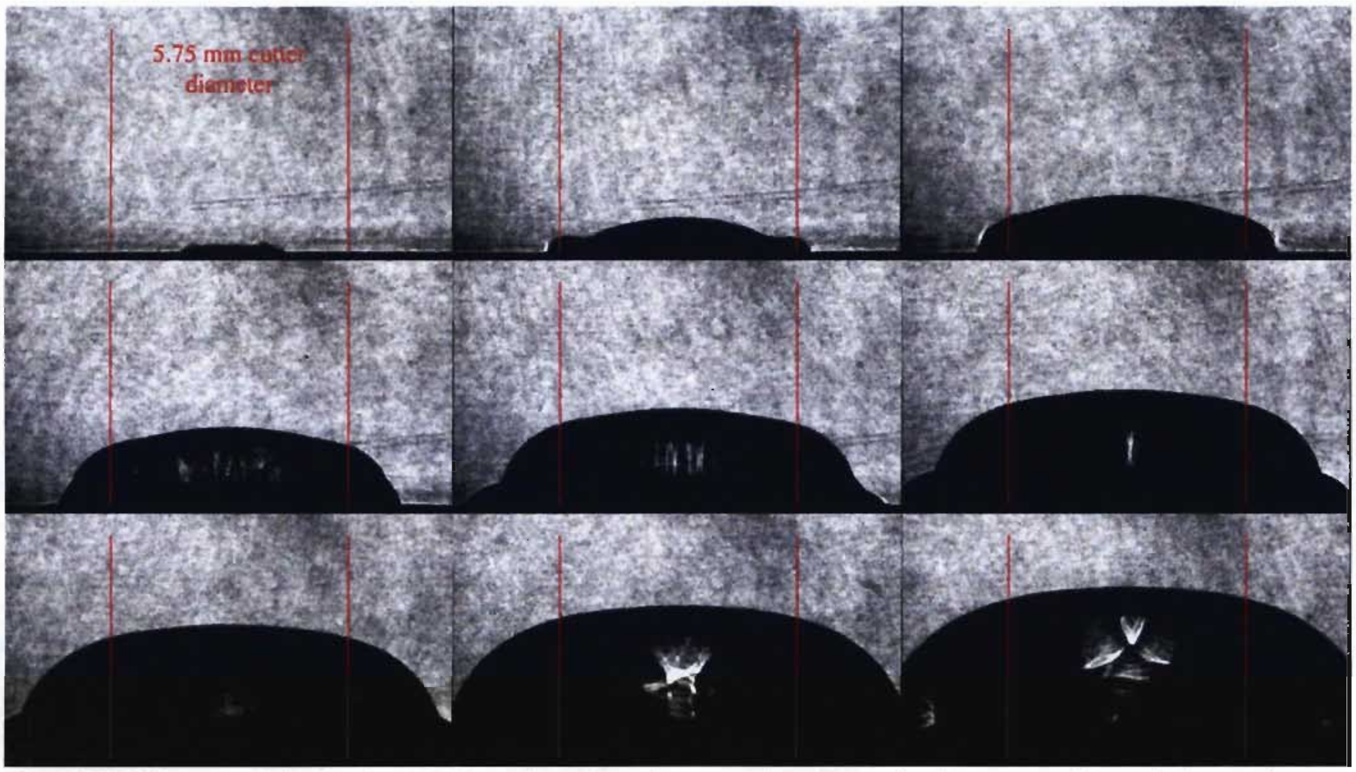

Fig. 6 SWIFT images of the flow in PMMA resulting from the interaction of a standard detonator with a stainless steel cutter assembly (red lines denote lateral locations of the cutter barrel)

As a final experimental example, the SWIFT system is used to visualize a small column of HE as it detonates. A standard detonator is used to initiate a column of XTX 8004 having nominal density, diameter, and height of 1.5 g/cm^3, 3 mm, and 20 mm, respectively. Both the detonator and HE are fully embedded in solid PMMA in order to facilitate visualization of the expected explosive-driven shock waves.

Few detonation parameters are known for XTX 8004 apart from detonation velocity as a function of charge radius [9]. As a result, the SWIFT experiment has been performed as an initial feasibility test to evaluate the usefulness of the method for characterizing HE performance. Since an existing tube of XTX 8004 was utilized for the test, the detonator was made to initiate the HE at an angle to accommodate the end geometry of the tube. Future tests are being designed with an inline HE train, where the detonator is coaxially aligned to the HE column.

The resulting SWIFT image sequence is included in Fig. 7, where the effects of non-coaxial initiation are evident in the first few images. The shock waves expanding outward from the HE column are very clearly visualized, and the quality of the data allows precise measurements of shock position along the HE/PMMA interface to be made with minimal uncertainty. Resulting position measurements are plotted versus corresponding exposure times in Fig. 8, where error bars depicting position uncertainty are smaller than the size of data markers used to plot the measurements. Application of linear least-squares fitting to the position data yields slopes of 7.407 +/- 0.103 mm/μs and 7.536 +/- 0.077 mm/μs, corresponding to the left and right sides of the HE column, respectively.

The published value for the detonation velocity of 1.5 g/cm^3 XTX 8004 at a charge diameter of 3.13 mm is given as 7.30 mm/μs in [9]. Though the velocity values obtained from the SWIFT data fall on the high side of the published values, they deviate by less than 2% and 4%. As initial results from a non-ideal feasibility study, where effects of HE initiation at an angle may play a critical role in the quantitative results, the authors find this agreement very good.

Additional investigation is underway to determine whether the SWIFT data contains sufficient information to extract equation-of-state parameters for the detonation products. The analysis would be based on the current version of LANL's explosive cylinder test [10] and proven data-reduction procedures [11].

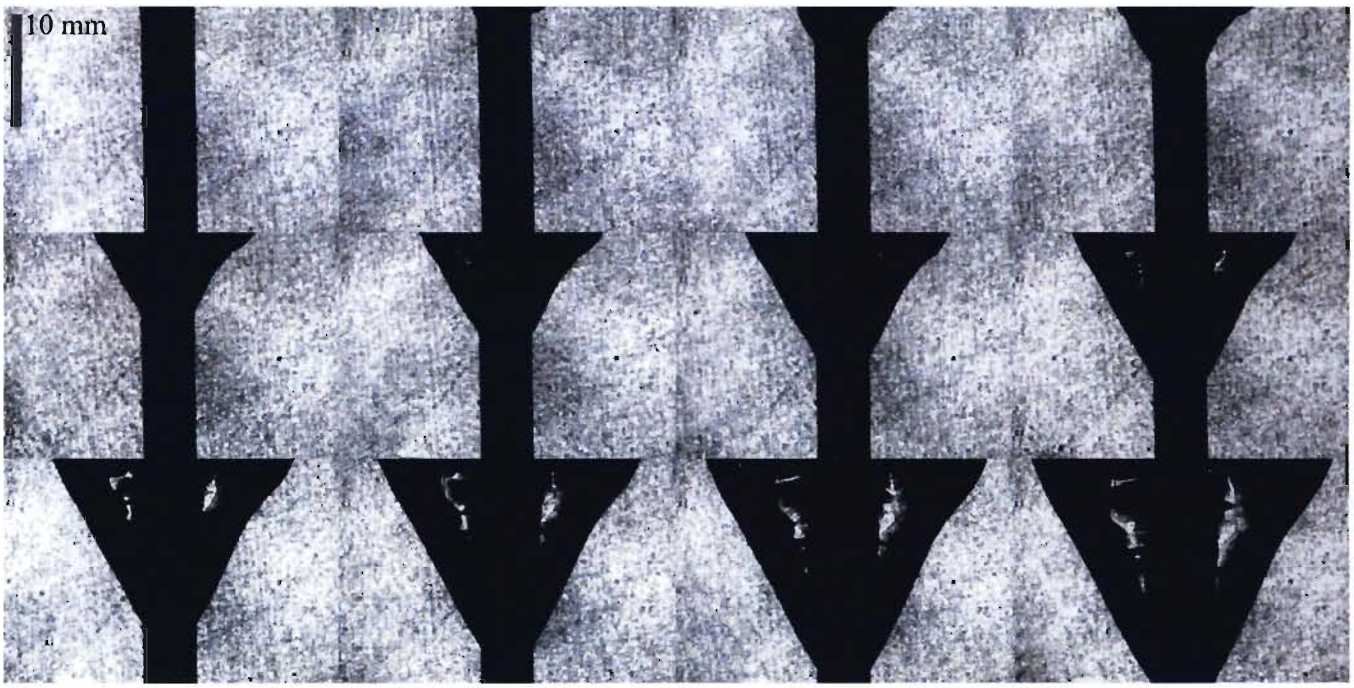

Fig. 7 SWIFT images of the flow in PMMA resulting from the detonation of an HE column (flow is from top to bottom)

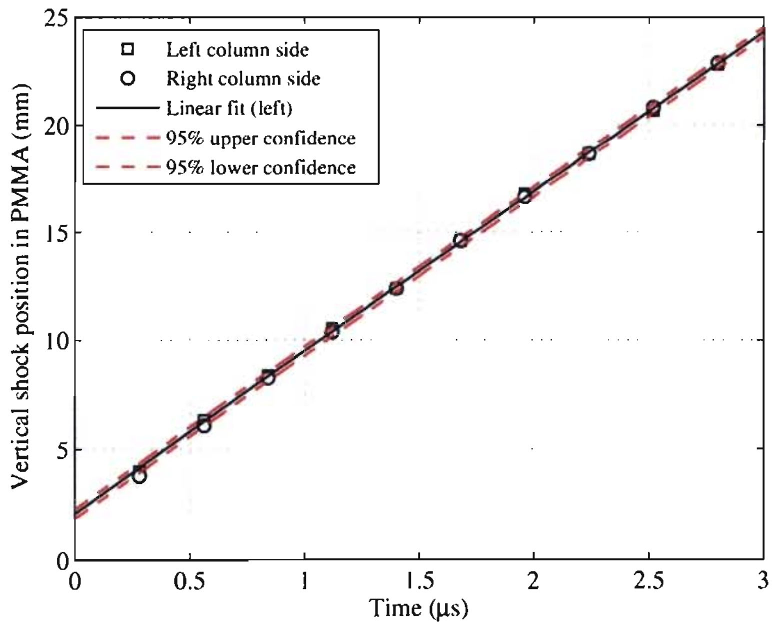

Fig. 8 Extracted measurements of shock position along the HE/PMMA interface with a linear fit and confidence bands

CONCLUSIONS

Current SWIFT implementation is presented to demonstrate a higher quality of achievable data than was possible through its 5-year old predecessor. Improvements in optical configuration, coupled with the use of higher-quality lenses, a laser backlight with spoiled coherence, and a high-performance ultra-high speed framing camera, combine to form an ensemble capable of investigating explosive-drive phenomena with high fidelity. As an example, visualizations of standard detonator output into both air and PMMA are presented as a means of studying output geometry, expected flow physics, and breakout time history. The latter results demonstrate good agreement with streak-camera data, and thus validate an additional data-reduction procedure for extracting quantitative results directly from SWIFT images.

The use of detonator output to generate explosively-driven flyer plates for impact-loading applications is presented, and the results provide unique design information based on the use of PMMA as an HE surrogate. The specific utility of the results emerges from accurate, time-resolved visualization of the complex shock-loading that occurs as a detonator/cutter assembly interacts with the PMMA sample.

Direct visualization of the flow resulting from HE detonation within PMMA provides data that is rich in information directly relevant to the understanding and characterization of how the HE performs. Measurements of shock position along the HE column are extracted from the SWIFT images, and linear least-squares fitting analysis is employed to determine detonation velocity to within 4% of published values in the worst case. Efforts are underway to attempt successful extraction of equation-of-state data for the reaction products of XTX 8004 from the experimental data.

Overall, the SWIFT system offers the experimenter high-resolution images, ultra-high-speed frame rates, time-resolved visualization of a single event, a robust range of magnifications, and the ability to visualize shock waves in the presence of explosive phenomena and high self-luminance. The authors plan to broaden the use of the system to many more scientific flows involving complex shock interactions and initiator-scale events that span fractions of a millimeter.

REFERENCES

1. Clarke, S. A. *et al.*, High-speed multi-frame laser schlieren for visualization of explosives events, *Proc. SPIE*, **6662**, 2007
2. Settles, G. S., *Schlieren and Shadowgraph Techniques*, Springer-Verlag, New York, 2001
3. Oppenheim, A. K., Urtiew, P. A., and Weinberg, F. J., On the use of laser light sources in schlieren-interferometer systems, *Proc. Roy. Soc. A*, **291**, 279-290, 1966
4. Svingala, F. R., Hargather, M. J., and Settles, G. S., Modern optical methods for determining the shock Hugoniot of transparent solids, *Proceedings of 28th International Symposium on Shock Waves*, Manchester, UK, July 2011
5. Cooper, P. W., *Explosives Engineering*, Wiley-VCH, New York, 1996
6. Murphy, M. J. and Clarke, S. A., Simultaneous photonic Doppler velocimetry and ultra-high speed imaging techniques to characterize the pressure output of detonators, *Proceedings of 17th APS Topical Conference on Shock Compression of Condensed Matter*, Chicago, IL, June 2011
7. Marsh, S. P., *LASL Shock Hugoniot Data*, University of California Press, Berkeley, 1980
8. Lee, K.-Y. *et al.*, Synthesis, detonation spreading and reaction rate modeling of fine TATB, *Proceedings of 11th International Detonation Symposium*, ONR 33300-5, 1998
9. Gibbs, T. R., and Popolato, A., *LASL Explosive Property Data*, Univesity of California, Berkeley, 1980
10. Catanach, R. et al., Cylinder Test Specification, Technical Report LA-13643-MS, Los Alamos National Laboratory, 1999
11. Hill, L. G., Detonation product equation-of-state directly from the cylinder test, 21st International Symposium on Shock Waves, Great Keppel Island, Australia, July 1997