LLNL-PROC-426362

LAWRENCE LIVERMORE NATIONAL LABORATORY

Dynamic Characterization of Mock Explosive Material Using Reverse Taylor Impact Experiments

Louis Ferranti, Jr., Franco J. Gagliardi, Bruce J. Cunningham, Kevin S. Vandersall

March 26, 2010

SEM Annual Conference & Exposition on Experimental and Applied Mechanics
Indianapolis, IN, United States
June 7, 2010 through June 10, 2010

Disclaimer

Dynamic Characterization of Mock Explosive Material Using Reverse Taylor Impact Experiments

*Louis Ferranti, Jr., Franco J. Gagliardi, Bruce J. Cunningham and Kevin S. Vandersall

*Engineering Technologies Division, Materials Engineering Group
Physical and Life Sciences Directorate, Chemical Sciences Division, Energetic Materials Program Element

Lawrence Livermore National Laboratory
7000 East Avenue, Livermore, CA 94550
ferranti@llnl.gov

ABSTRACT

The motivation for the current study is to evaluate the dynamic loading response of an inert mock explosive material used to replicate the physical and mechanical properties of LX-17-1 and PBX 9502 insensitive high explosives. The evaluation of dynamic material parameters is needed for predicting the deformation behavior including the onset of failure and intensity of fragmentation resulting from high velocity impact events. These parameters are necessary for developing and validating physically based material constitutive models that will characterize the safety and performance of energetic materials.

The preliminary study uses a reverse Taylor impact configuration that was designed to measure the dynamic behavior of the explosive mock up to and including associated fragmentation. A stationary rod-shaped specimen was impacted using a compressed-gas gun by accelerating a rigid steel anvil attached to a sabot. The impact test employed high-speed imaging and velocity interferometry diagnostics for capturing the transient deformation of the sample at discrete times. Once established as a viable experimental technique with mock explosives, future studies will examine the dynamic response of insensitive high explosives and propellants.

INTRODUCTION

The safety and performance characteristics of insensitive high explosive and propellants are desirable for developing and validating computational models. Therefore, a systematic method for evaluating dynamic material parameters is needed for predicting the deformation behavior including the onset of failure and intensity of fragmentation resulting from impacts. Damage as a result of a sufficient insult alters the material's combustion response. This may range from a mild deflagration reaction to a violent explosion. The characterization of cumulative material damage and the threshold of these reaction extremes are needed for predicting energetic materials response to a variety of insults. These may include low-level insults, such as accidental handling impacts to more intense bullet and fragment impacts. A quantitative method for characterizing the damage evolution of explosive and propellant materials is necessary for constructing and validating physically based material models that predict fracture initiation and intensity of fragmentation.

The Taylor test [1] has become a customary method for developing and evaluating the constitutive behavior of materials. The average dynamic yield strength of a material is estimated as the consequence of an impact and based on the overall deformation imparted to the test specimen. The traditional experiment is performed with a rod-shaped specimen of a length, L_0 colliding against a rigid anvil at a velocity, U and making post impact measurements of the deformed shape. However, modified versions of Taylor impact experiments have been conducted in conjunction with velocity interferometry techniques to measure the material's response throughout dynamic loading up to and including fragmentation. [2] Taylor's original theory assumed an ideally rigid-plastic material model that exhibits rate-independent behavior and simple one-dimensional wave propagation concepts that neglect radial inertia. Upon impact, an elastic compression wave propagates through the axial length of the rod followed by a much slower plastic wave. The deformed region propagates away from the contact surface, and the stress in this region is assumed to be constant and equal to the average yield stress of the material at a constant strain rate. The elastic wave continues to propagate the length of the specimen until it is reflected from the rear free surface and returns toward the propagating plastic wave. Upon reflection, the elastic wave interacts with the plastic wave and reduces the stress within the region to zero, thus bringing the deformation process to a conclusion.

Taylor's analysis was based on the behavior of metallic materials and neglects the minor elastic strains from a predominantly rigid-plastic material response. However, many energetic materials such as polymer bonded explosives (PBX) and propellants exhibit significant elastic strains prior to yielding. Energetic materials also behave non-linearly and are moderately dependent on both strain rate and temperature.[3] Additionally, PBX's contain an energetic component combined with a small quantity of a polymeric binder, generally 5-20 % by weight. [4] The addition of polymeric binder provides several potential advantages for the processing, performance and safety of PBX materials. These include making energetic materials mechanically rigid with better dimensional control and tolerance, improved pressing densities, the ability to machine complex geometries, and less sensitivity to accidental detonations such as a sudden shock.

Modified Taylor impact experiments have been successfully used to study the deformation behavior of polymer-bonded materials containing relatively hard inclusions. [2] Hutchings used a one-dimensional elastic/plastic wave propagation analysis and modified Taylor's rigid-plastic theory to account for the significant elastic strains encountered by polymeric materials prior to yielding. [5] Theories for the deformation of metallic materials predict some plastic deformation in the specimen at any finite, nonzero impact velocity. In contrast, Hutchings analysis accounts for an experimentally measured critical impact velocity where polymeric materials exhibit permanent deformation. Above this critical velocity, the change in specimen length increases as a function of impact velocity. The average dynamic yield stress can be calculated with knowledge of the specimen's length following impact and the critical velocity below which no plastic deformation occurs.

A complimentary version of the Taylor test uses a reverse configuration where the specimen of interest is held stationary and a rigid anvil impacts the specimen at a high-velocity. [2] This configuration makes it possible to probe the specimen's free surface for obtaining a velocity-time signal to characterize the elastic wave behavior throughout the experiment. Furthermore, combining this analysis with transient deformation measurements using high-speed photography techniques provides a method for developing and validating constitutive models at discrete times throughout the deformation process.

In the present study, dynamic impact experiments were performed on mock explosive material using a reverse Taylor impact configuration. The mock explosive is an inert formulation used to replicate the density, mechanical and thermal properties of LX-17-1 and PBX 9502 insensitive high explosives. [6] The use of a mock explosive is advantageous, from a safety standpoint, for conducting initial experimental studies where specimen preparation techniques, experimental methods and design are still being developed. It is also of interest to characterize and eventually compare the mock explosive response with the actual explosive material. This work provides initial insight into the dynamic behavior of this class of materials.

The response of this material to dynamic loading was completely unknown and the mechanical behavior was characterized using a combination of diagnostics that include high-speed photography, to capture the transient deformation of the specimen, and photonic Doppler velocimetry (PDV), to measure the free surface velocity. [7] Digital image correlation (DIC) techniques [8] were also utilized for characterizing the mock explosive's response to an impact. The elastic wave speeds obtained from the DIC diagnostics were measured and compared to those obtained from the arrival of the wave at the free surface indicated from PDV. Insight into the critical fracture velocity for the mock was additionally revealed.

EXPERIMENTAL DETAILS

Reverse Taylor impact experiments were conducted on mock explosive specimens over an approximate 6-70 m/s impact velocity range. The specimens had a cylindrical geometry with a nominal diameter of 6.35 mm and 25.40 mm length. The experimental setup is shown schematically in Figure 1. For this configuration, the specimen of interest was held stationary while a rigid anvil plate, mounted on the face of a polycarbonate sabot, was fired from a compressed-gas gun and collided with the specimen. The transient deformation of the specimen was observed throughout the entire deformation process up to the point of fragmentation using high-speed digital photography and PDV. Information regarding the experimental design and execution are described in the following section.

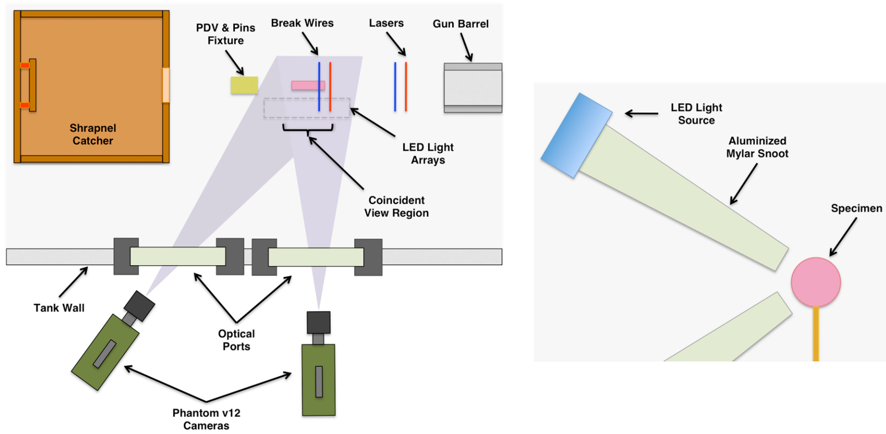

Figure 1. Top view schematic diagram of the reverse Taylor impact experiment (*left*) showing the cameras' orientations with respect to the specimen. The LED lighting system is also shown schematically in a vertical downrange orientation (*right*). Note both diagrams are not to scale.

EXPERIMENTAL SETUP

Reverse Taylor impact experiments were conducted using a newly acquired portable single-stage light compressed-gas gun (DEMII gun) that has three 1.8 m long interchangeable barrels with 25.4, 50.8 and 76.2 mm diameters. [9] The gun was operated within a large enclosed firing tank with a 5 kg explosive limit (TNT equivalent). An existing 100 mm diameter propellant-driven gun, in use mainly for studies on initiation and detonation of high explosives, operates over a velocity range (0.3-2.5 km/s) that exceeds the lower regime required for the reverse Taylor impact experiments. The 100 mm gun barrel was removed and the DEMII gun was placed in the firing tank for these experiments. Although the current work studies the dynamic response of an inert mock explosive, future experiments will be performed on energetic explosives and propellants in this firing tank.

The DEMII gun uses a simple ball valve breech design that incorporates an expendable shear pin with a gas actuator. The breech includes a 2 L accumulator volume with a 2.1 MPa maximum operation pressure that is sufficient for the approximate 10-100 m/s desired velocity regime. The 50.8 mm diameter barrel was used for these particular experiments and the gun was fired using dry air.

A shrapnel catcher was fabricated from two thick steel plates (25.4 mm) secured on either side of a steel pipe with an approximate diameter and length of 91.4 and 96.5 cm, respectively. The front of the shrapnel catcher, pictured in Figure 2, had a 17.8 cm hole that allowed the sabot and specimen debris to pass through the outer plate. A steel deflecting plate (30.5 cm square and 25.4 mm thick) was secured inside the vessel at the back with four heavy-duty springs. The plate was slightly angled for deflecting the debris downwards and bringing the materials to rest in the sand located at the bottom of the vessel.

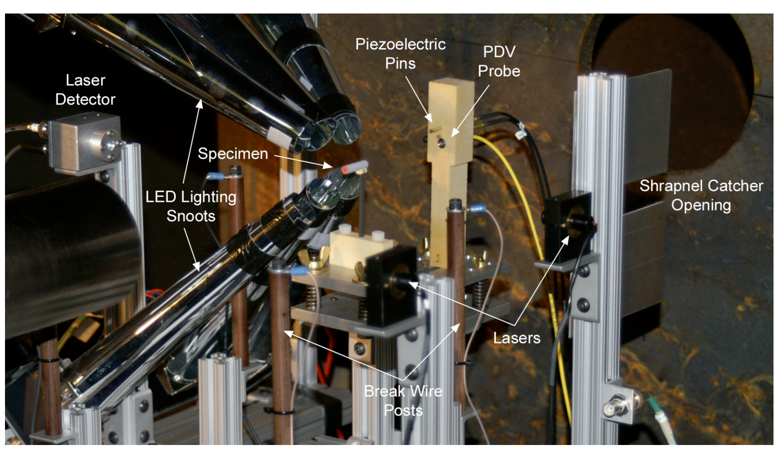

Figure 2. Image of the experimental setup featuring the specimen and associated diagnostics.

The sabot body was approximately 50.8 mm in diameter and made from polycarbonate. A steel anvil made from AISI 4140 steel (hardened to R_C 54-55) was attached to the front. The anvil was 10 mm thick with a slightly undersized diameter compared to that of the sabot. The back of the sabot had a medium density polyethylene obturator to form a tight seal with the barrel and two Viton® o-rings placed along the length. The complete assembly has a mass of approximately 500 g each and is shown in Figure 3.

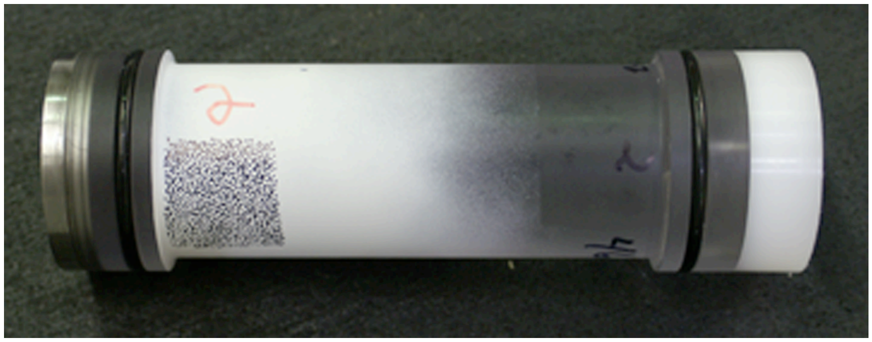

Figure 3. Image of the 50.8 mm diameter polycarbonate sabot assembly showing the AISI 4140 hardened steel anvil, polyethylene obturator and Viton® o-rings.

Since these experiments were the first use of the new gun, several redundant velocity-measuring techniques were utilized to obtain a precise impact velocity. The first technique used a laser-interrupt detection design with two laser/detector stations mounted down range from the gun muzzle. The system recorded the time interval between the two stations for computing the velocity. The laser/detector station closest to the specimen impact face (approximately 5 mm) was also used for triggering all of the diagnostics. The second method used a series of fine tungsten break wires (25.4 μm diameter) placed in the path of the sabot such that the wire breaks when contacted at the bottom edge of the anvil plate (approximately 5 mm). The break wires operated in a similar manner as the laser-interrupt system in that the distance between the two wires was measured and the arrival times of the sabot were detected for computing the velocity. The final technique used two piezoelectric crush pins with the impact faces offset approximately 10 mm and the arrival of the anvil at each provided a timed signal for computing the velocity. The piezoelectric pins were located behind the specimen and measured the velocity following the sabot's interaction with the target.

Two Vision Research® Phantom v12 high-speed digital cameras were used for the DIC measurements. The cameras were located outside the explosive firing tank and viewed the axial length of the specimen through two separate windows (3.81 cm thick quartz glass). The specimen was located in the center of the firing tank, which has an inside diameter of approximately 3.5 m. The camera's fields of view were approximately 32 by 16 mm and the cameras were fit with Nikon® 80-200 mm zoom lenses with Tamron® 2x teleconverters for imaging the specimen from a distance of approximately 2 m. The framing rate was approximately 120,000 fps (or 8.32 μs interframe time) with a 7.75 μs exposure time and the corresponding best available resolution of 256 x 128 pixel images.

The amount of light required for imaging the transient deformation of the specimen is related to the image acquisition rate. The DIC system additionally requires highly uniform light intensity over the entire surface to be measured. For these experiments, a total of six low voltage Lamina Titan® LED light sources were used to illuminate the specimen. Each light source is populated with multiple LED's to deliver approximately 1800 lumens of light. The light was focused on the specimen using reflective snoots, shown in Figure 2, made from rolling aluminized mylar sheets. The ends of the snoots were positioned approximately 10 mm from the specimen, while the LED light sources were located approximately 40 cm from the specimen. This provided sufficient light to image the specimen and sufficient standoff distance to protect the lights from specimen fragmentation debris.

An adjustable three-point mounting fixture was used to secure the specimen perpendicular to the barrel, ensuring a normal impact with the anvil. A laser located at the up-range end of the barrel was focused toward the down-range direction through an optical collimator onto a small mirror placed on the impact face of the specimen. The three-point fixture was used to adjust the specimen's orientation and, once the laser reflected off of the mirror and projected a spot through the center of the barrel, the fixture was securely fastened.

SPECIMEN PREPARATION

The mock explosive material (RM-03-AG) was prepared from a mixture of 45 *wt.%* cyanuric acid, 44.5 *wt.%* magnesium silicate, and 10.5 *wt.%* PIBBMA binder, a copolymer of isobutyl and butyl methacrylate. The mock constituents were combined and isostatically pressed at approximately 138 MPa and 105 °C for three cycles of one minute each. The final mock explosive billet had a cylindrical geometry with approximately 24.1 cm diameter and 16.5 cm tall. Additional details regarding the development of mock explosive materials are available elsewhere. [10]

Several right-circular cylindrical specimens with a nominal aspect ratio (*L/D*) of four-to-one were machined from the bulk billet of material. The specimens were measured at several locations and had an average length, *L* and diameter, *D* of 25.401 ± 0.001 mm and 6.342 ± 0.034 mm, respectively. The average density measured from eight specimens was 1.887 ± 0.020 g/cm^3 and corresponded to 97.2 %TMD.

Each specimen was hand lapped using a lightly weighted fixture in preparation for the impact experiments. Lapping was conducted in two stages, first using 15 μm and then 1 μm silicon carbide sandpaper. The sandpaper was placed on a flat piece of glass and the specimens were lapped using a figure eight motion until the impact and rear surfaces were both parallel and planer to each other. The specimens were checked regularly during the lapping process until the desired overall length and surface finish was achieved. An aluminum reflector of approximately 5 mm diameter and 12.7 μm thick was attached to the rear surface of the specimen using RTV silicon adhesive (Dow Corning®). The laser light from a PDV probe was reflected from the surface and used to measure the free surface velocity during the impact experiment.

The specimens were prepared with speckle pattern for DIC measurements. A thin layer of flat white Rust-Oleum® paint was applied to the radial surface of each specimen. The front and back surfaces of the rod-shaped specimens were masked with tape to prevent paint from adhering to these surfaces. After the white paint was allowed to dry, a flat black Rust-Oleum® paint was applied with a misting technique to form the fine black speckle pattern. An example of the final speckle pattern applied to each specimen is shown in Figure 4.

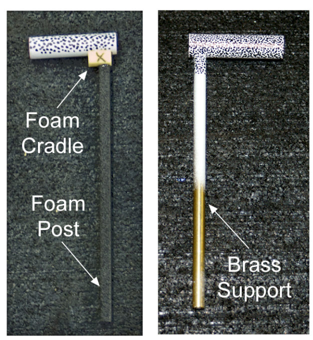

Figure 4. Examples of reverse Taylor specimens shown with a foam support assembly (*left*) and brass rod (*right*). Both support systems were attached approximately 1 mm from the free surface using a small amount of epoxy.

Two methods were used to secure the specimen and hold it aligned to the muzzle end of the barrel. Both attempt to hold the specimen adequately for handling and positioning purposes, but were designed to break away and provide the least amount of resistance during the impact experiment. The first assembly used a light foam cradle that had the same radius of curvature as the specimen and was secured to an upright foam rod as shown in Figure 4. The second method used only a 3.2 mm brass rod that was machined at one end with the same radius of curvature as the specimen. Figure 4 also shows an example of a specimen attached with a brass support rod. The foam cradle assembly and the brass rod were each located towards the rear surface of the specimen, approximately 1 mm from the edge and secured with a small amount of epoxy.

RESULTS AND DISCUSSION

Reverse Taylor impact experiments were performed on a mock explosive material at several impact velocities listed in Table 1. The experiments were performed in a light vacuum level of less than 20 torr to eliminate the possibility of an air blast interacting with the specimen before the anvil arrived. A total of seven experiments were completed for measuring the transient deformation and calculating the elastic wave speed of the material. In each experiment, great care was given to aligning the impact face of the specimen with the rigid anvil exiting the compressed-gas gun barrel using a laser alignment system. An indication of good alignment was observed from high-speed camera images acquired for each experiment. The planarity of impact was additionally measured, from an independent experiment with no target specimen in place, using a circular array of eleven piezoelectric contact pins. The array was aligned to the anvil in the same manner as the specimen using the laser alignment system. The planarity of impact had a measured tilt of 3.1 mrad and is expected to be similar for each reverse Taylor test conducted in this work.

Table 1 Summary of reverse Taylor impact experiments conducted for mock explosive material at several different impact velocities. Specimens fractured for shot numbers RT-001, RT-002, and Q-003.

Shot Number	Impact Velocity U [m/s]	Elastic Wave Velocity C_L [mm/μs]		*Free Surface Velocity U_{fs} [m/s]	
		PDV	DIC	PDV	DIC
RT-003	6.39	2.37	2.60	6.02 (11.16)	5.74 (9.91)
Q-001	8.79	2.52	2.47	15.52 (16.54)	14.47
RT-004	10.37	n/a	2.57	17.59 (20.49)	17.48
RT-005	10.73	2.44	2.59	18.81 (21.12)	18.56 (19.69)
RT-001	32.84	2.49	2.28	31.04 (36.10)	30.61
RT-002	47.46	n/a	2.56	n/a	27.18
Q-003	72.26	n/a	n/a	n/a	22.49 (60.71)

*Peak free surface velocities are shown in brackets.

The mock explosive had a highly brittle response to dynamic loading. This was expected since quasi-static measurements have shown similar behaviors for flexural three-point bend fracture toughness tests. [11] The specimens were observed to fracture for impact velocities of 32.84, 47.46, and 72.26 m/s corresponding to shots RT-001, RT-002, and Q-003, respectively. Selected images from experiment Q-003 are shown in Figure 5. Fracture initiation was observed 21.64 and 22.88 μs following impact for experiment RT-002 and Q-003, respectively. Both showed a typical double-frustum shape at the impact face. [12] However, experiment RT-001 exhibited a different behavior with essentially no radial deformation close to the impact face. This particular specimen fractured approximately 10 mm from the impact face at 31.18 μs following impact. It does not appear that the fracture was initiated as a result of the impact (32.84 m/s), but rather the foam specimen support deflected significantly during the experiment. The deflection caused a bending moment on the specimen and was constrained at the impact face by the anvil. This was clearly observed from the high-speed camera images. Therefore, the actual critical fracture initiation velocity falls approximately between 32.84 and 47.46 m/s. The support deflection was also observed for shot Q-003 and illustrated in Figure 5. However in this case the specimen began to fracture at the impact face prior to appreciable deflection of the beam and does not appear to influence the overall response of the mock. Axial and areal strain measurements quantify these observed differences in deformation behavior.

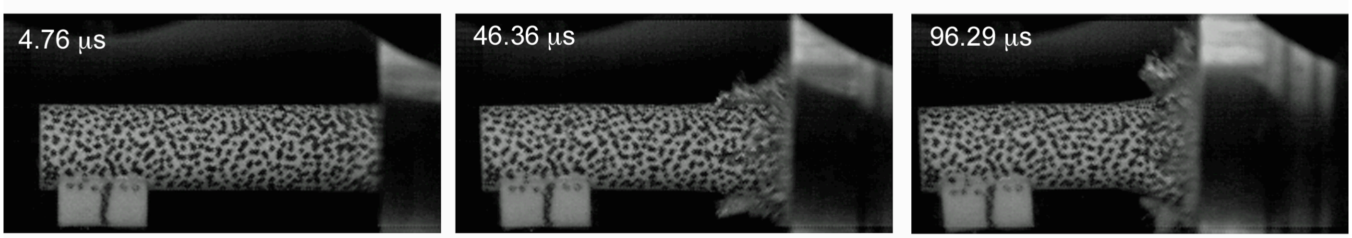

Figure 5. Select images from a reverse Taylor test showing the anvil impacting the specimen from the right at 72.26 m/s (shot Q-003). Images were taken (*left to right*) at 4.76, 46.36 and 96.29 μs following impact. The specimen begins to fracture almost immediately at approximately 13.08 μs.

Axial strain was calculated using $\varepsilon_L = ln(L_0/L)$, where L_0 and L are the initial and incremental specimen lengths, respectively. Similarly, areal strain was calculated using $\varepsilon_A = 1-(A_0/A)$, where A_0 and A are the initial and incremental cross sectional areas of the specimen, respectively. Areal strain measurements were taken at the impact face where the maximum deformation was typically observed. Shots RT-002 and Q-003 had areal strains measured at the moment of fracture and corresponded to 23.4 and 20.3 %, respectively. These represent the approximate maximum strain that the material could support before failure. However, shot RT-001 had a significantly lower areal strain of 9.3 %, thus indicating that the specimen did not have the characteristic deformation localized to the impact face of the specimen. All of these specimens had relatively small axial strains of 1.5, 2.0 and 4.1 % for RT-001, RT-002 and Q-003, respectively.

Specimens that were impacted at the lower velocities did not fracture and were observed to rebound from the anvil surface. These specimens were additionally recovered following the experiment and physically measured. All the specimens completely recovered elastically and had unchanged dimensions. The measured axial strains obtained during the experiment from high-speed camera images were typically less then 1%, while the specimens' diameters were unchanged.

The free surface velocity, U_{fs} was measured using PDV and DIC for each experiment. The PDV system detects a velocity rise once the elastic wave reaches the free surface of the specimen. For a purely elastic collision, the free surface velocity is expected to be twice that of the impact velocity. However, energy was typically consumed by the specimen deformation (elastically in this case) and breaking away from the support. Other energy dissipation mechanisms may also contribute, such as friction between the impact surfaces. The measured free surface velocities for specimens that did not fracture had an average coefficient of restitution of 0.893 ± 0.01. The coefficient of restitution, C_R is a fractional value that represents the ratio of velocities following an impact. A perfectly elastic collision has a C_R = 1, while a C_R = 0 represents a perfectly inelastic collision. Impact experiments with velocities that resulted in the specimen fracturing had an average C_R of 0.130 ± 0.01.

The average velocity of the specimen following impact was also determined using DIC measurements. These are comparable to the free surface velocity measurements obtained from PDV. Figure 6 compares the PDV and DIC velocities for two representative experiments with impact velocities of 6.39 and 10.37 m/s (shots RT-003 and RT-004, respectively). The figure shows that PDV has a significantly better response time and captured a much quicker rise to peak velocity for both experiments. This was typically observed for all the experiments performed in this study. Notice that the initial peak value for shot RT-003 was slightly greater from the PDV measure, but both measurements decay at the same rate to a similar terminal velocity of 5.74 and 6.02 m/s for the DIC and PDV curves, respectively. The overall measured terminal velocity values from both types of measurements compare well and are listed in Table 1.

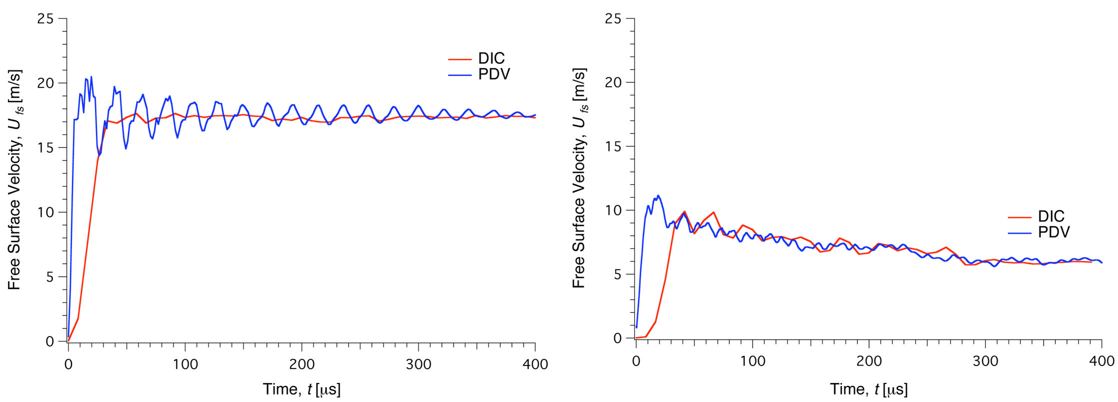

Figure 6. Comparison of PDV and DIC free surface velocity measurements for two experiments (shots RT-004 and RT-003, respectively) with impact velocities of 10.37 m/s (*left*) and 6.39 m/s (*right*).

The arrival of the wave at the free surface also permits the calculation of the elastic wave velocity. Knowing the impact time and the specimen length, the elastic wave velocity was computed for each experiment. These values are also listed in Table 1. The average elastic wave velocity can also be obtained from the DIC measurements as depicted in Figure 7 for shot RT-003. The anvil was just out of sight, to the right of the image and moving at a velocity of 6.39 m/s. The color contour scale range was 0.01 to -0.02 mm of displacement, U. Each image was at the same scale and the negative displacement direction was to the left. The first image shows the displacement contour just following impact at 0.03 μs. Most of the specimen was within the middle range of the scale, which indicates zero displacement. The next image taken at 8.35 μs following impact shows the elastic wave moving towards the free surface. The front of the wave at this point was approximately 3.6 mm from the back surface. The color contour indicates that the free surface has not yet moved. The image shows the front of the wave was fairly dispersed and possibly reflects the resolution limits of the measurement. The next image taken at 16.67 μs indicates the entire specimen was moving at this point. The DIC measured elastic wave velocity was 2.601 mm/μs and compares fairly well with 2.371 mm/μs obtained from the PDV measurement. The average elastic wave velocity obtained from six experiments using DIC was 2.51 ± 0.13 mm/μs and was not calculated for shot Q-003 due to a problem with the trigger timing that prevented the determination of the impact time. The average elastic wave velocity using PDV was 2.46 ± 0.07 mm/μs. This value was obtained from only five experiments due to triggering problems for shots Q-003 and RT-002, which missed the arrival of the elastic wave at the free surface.

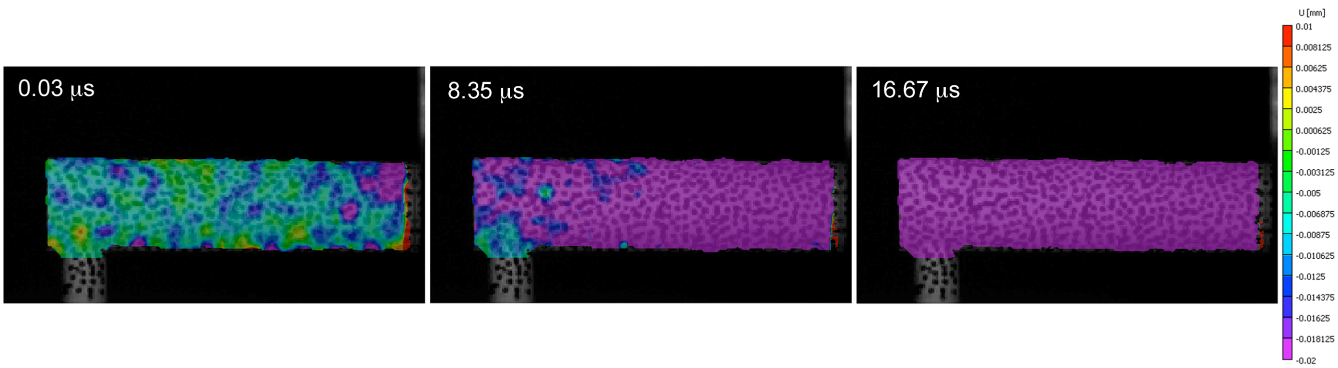

Figure 7. Select images from a reverse Taylor test showing the elastic wave propagating from right to left within the specimen using DIC calculated displacements, *U*. The anvil impacts the specimen from the right side and is moving at a velocity of 6.39 m/s (shot RT-003). The images were taken (*left to right*) at 0.03, 8.35, and 16.67 μs following impact. The middle image shows the elastic wave reaching approximately 3.6 mm from the free surface.

Ultrasonic elastic wave velocities were independently measured from an 8.76 mm thick rectangular plate obtained from the same batch of material used in the impact experiments. The measured ultrasonic velocity or bulk sound speed, C_0 was 2.92 ± 0.04 mm/μs. The elastic wave travels at a slightly higher velocity through an unbounded medium than through a thin bar or rod. [13] The bulk sound speed was adjusted to account for this using elastic relations and a Poisson's ratio of 0.3, to give C_0 = 1.16 C_L. After correction, the ultrasonic elastic wave velocity was 2.51 ± 0.04 mm/μs and compares extremely well with the DIC and PDV measured values.

SUMMARY AND CONCLUSION

This paper reports on the details regarding reverse Taylor impact experiments conducted for a mock explosive material. The motivation comes from the need for a quantitative method to measure the fracture and fragmentation behavior of explosives and other energetic materials. In doing so, it is important to measure the transient deformation state of the material up to and including its associated mechanical breakup. Once established, this capability will provide a method for developing and validating constitutive material models at discrete times throughout the entire deformation process.

The mock explosive has shown a highly brittle response to dynamic loading above a critical impact velocity. In contrast, sufficiently low impact velocities have also shown a visceoelastic material response that exhibited a small axial strain of less than 1 % and virtually no radial deformation. Experiments conducted at impact velocities of 32.84, 47.46 and 72.26 m/s have resulted in fracturing. The two highest velocity experiments showed the characteristic double-frustum deformation geometry before fracture initiation. However, the lowest velocity experiment exhibited a different response to loading with essentially no radial deformation upon impact. High-speed camera images show the specimen fracturing approximately 10 mm from the impact face due to a bending moment. For this particular experiment, a foam support assembly was used to hold the specimen aligned with the gun barrel. Upon impact, the beam deflected and caused the specimen to fracture. Therefore, it is possible this is not the critical impact velocity for specimen fragmentation. Additional impact experiments over the approximate 33 to 48 m/s velocity range are planned to determine the actual critical velocity for the mock explosive material.

The reverse Taylor experimental configuration also provided useful data that was obtained from PDV and DIC diagnostics. Both techniques showed good agreement for measured free surface velocities of the specimen throughout the deformation process. However, PDV had a much faster response time to capture the specimen's acceleration than compared to the DIC measurements. This was evident by directly comparing free surface velocity-time plots for both techniques. The DIC measurements successfully captured the elastic wave propagating the length of the specimen and was used for computing the elastic wave speed of 2.51 ± 0.13 mm/μs. This value compared well with 2.46 ± 0.07 mm/μs obtained from the PDV measurements. Both techniques additionally compared extremely well with the ultrasonically measured elastic wave speed of 2.51 ± 0.04 mm/μs.

Future reverse Taylor impact experiments will be designed for measuring the response of energetic materials to include explosives and propellants. Further refinement of this technique will permit the incremental measure of elastic/plastic transient deformation throughout the entire impact event, to characterize the elastic and plastic waves interactions within the specimen and measure mechanical properties for generating dynamic stress-strain response curves for energetic materials. Directly measuring the strain using DIC techniques is currently the largest challenge since significantly small deformations are taking place rapidly in a dynamic experiment. These effects require capturing the transient deformation of the specimen with high-speed cameras operating at significantly high framing rates and maximum resolution under ideal lighting conditions.

ACKNOWLEDGEMENTS

Many people have been essential for their technical support and assistance in this study. The authors would like to thank Randy Bonner, Tony Whitworth and Ted Strand for providing PDV support, Micha Gresshoff and Don Hoffman for their technical support working with Physics Application, Inc., John Scott, Adrian Godinez, Thomas Vi and Brian Cracchiola for HEAF facility support, Jan Batteux, Paul Chiao, Adriano Salamanca, Greg Silva and Jeff Wardell for mechanical support, Dan Greenwood for lighting design and camera operation, Frank Garcia for target design and assembly and the gas gun firing operations team James Jones, Rich Villafana and Jim Van Lewen. This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

REFERENCES

[1] G.I. Taylor, "The Use of Flat-Ended Projectiles for Determining Dynamic Yield Stress: I Theoretical Considerations," *Proc. R. Soc. Lond. A*, **A194**, 289-299 (1948).

[2] L. Ferranti, Jr. and N.N. Thadhani, "Dynamic Mechanical Behavior Characterization of Epoxy-Cast Al+Fe_2O_3 Thermite Mixture Composites," *Met. Trans. A*, **38A**, [11] 2697-2715 (2007).

[3] W.R. Blumenthal, G.T. Gray III, D.J. Idar, M.D. Homes, P.D. Scott, C.M. Cady and D.D. Cannon, "Influences of Temperature and Strain Rate on the Mechanical Behavior of PBX 9502 and Kel-F 800," *Shock Compression of Condensed Matter* – 1999, Vol. 505, 671-674 (2000).

[4] P.W. Cooper and S.R. Kurowski, Introduction to the Technology of Explosives; Wiley-VCH, New York (1996).

[5] I.M. Hutchings, "Estimation of Yield Stress in Polymers at High Strain-Rates Using GI Taylor's Impact Technique," *J. Mech. Phys. Solids*, **26**, 289-301 (1979).

[6] D.M. Hoffman, B.J. Cunningham and T.D. Tran, "Development of a Replacement Mock for the Insensitive High Explosives LX-17 and PBX 9502," LLNL Report, UCRL-JRNL-223040 (2006).

[7] O.T. Strand, D.R. Goosman, C. Martinez, T.L. Whitworth, and W.W. Kuhlow, "A Novel System for High-Speed Velocimetry Using Heterodyne Techniques," *Rev. Sci. Instrum.*, **77**, 083108 (2006).

[8] M.A. Sutton, J.J. Orteu and H.W. Schreier, Image Correlation for Shape, Motion and Deformation Measurements: Basic Concepts, Theory and Applications; Springer Press, New York (2009).

[9] K.S. Vandersall, A. Behn, M. Gresshoff, L. Ferranti, Jr., and P.I. Chiao, "New Gun Capability With Interchangeable Barrels to Investigate Low Velocity Impact Regimes at the Lawrence Livermore National Laboratory High Explosives Application Facility," Proceedings of the 60th Aeroballistic Range Association, Baltimore, MD, September (2009).

[10] D.M. Hoffman, B.J. Cunningham and T.D. Tran, "Development of a Replacement Mock for the Insensitive High Explosives LX-17 and PBX 9502," LLNL Report, UCRL-JRNL-223040 (2006).

[11] L. Ferranti, Jr., F.J. Gagliardi, B.J. Cunningham and K.S. Vandersall, "Measure of Quasi-Static Toughness and Fracture Parameters for Mock Explosive and Insensitive High Explosive LX-17," Proceeding of the 14th International Detonation Symposium, Coeur d'Alene, Idaho 11-16 April (2010).

[12] R. Balendra and F.W. Travis, "An Examination of the Double-Frustum Phenomenon in the Mushrooming of Cylinderical Projectiles Upon High-Speed Impact with a Rigid Anvil," *Int. J. Mech. Sci.*, **13**, 495-505 (1971).

[13] M.A. Meyers, Dynamic Behavior of Materials; John Wiley & Sons, Inc., New York, 23-65 (1994).