Full Paper

Propellants, Explosives, Pyrotechnics

DOI: 10.1002/prep.201400008

Shaped Charge Liner Early Collapse Experiment Execution and Validation

Eric Scheid,*[a, b] T. David Burleigh,[b] Nishkamraj U. Deshpande,[a, b] and Michael J. Murphy[c]

Abstract: A novel experiment developed for researching the initial collapse of an aluminum shaped charge liner was designed, executed, and validated. The experiment evolved from the need to recover shocked liner material to enable the analysis of relationships between microstructure and early liner collapse behavior. The research required material that had been shocked, yet was sufficiently intact to allow for metallurgical examination. Additionally, the experiment was designed to replicate the unique shock loading of shaped charge liners. Practically, the experiment had to be inexpensive to perform. The paper describes the experimental design, execution and validation and presents practical examples of the utility of the output. The experimental design is based on recreating a unique shock front, halting the deformation within a few microseconds and recovering material suitable for examination. Validation of the experiment employs a combination of available hydrocode modeling data and shaped charge liner collapse theory. The data collection supporting the validation was performed with computed tomography (CT) and laser generated 3D imagery. The output is recovered material valid for study.

Keywords: Shaped charge · Explosive testing · Metallurgy · Shock · Aluminum

1 Introduction

This work is associated with researching the relationships between microstructure and early collapse characteristics of an aluminum shaped charge liner. The research required material that had been properly shocked, yet was sufficiently intact to allow for metallurgical examination. The experiment evolved from this need and the requirement to replicate unique shock loading. Practically, the experiment had to be inexpensive to perform.

The paper describes the experimental design, execution, and validation and presents practical examples of the utility of the output. The experimental design is based on recreating a unique shock front, halting the deformation within a few microseconds and recovering material suitable for examination. Validation of the experiment employs a combination of available hydrocode modeling data and shaped charge liner collapse theory. The data collection supporting the validation was performed with laser generated 3D imagery and computed tomography (CT).

Shock loading has been extensively studied. It is known that the behavior of some materials changes with respect to strain rate [1] and that various high strain rate experimental methods are only capable of particular strain regions [2]. In other words, in order to examine high strain rate characteristics, it is necessary to expose the material to representative loads at representative rates.

An obvious problem with generating explosive strain rates is the destructive nature of the event. Associated with this are the safety and logistical demands of explosive testing. The nature of shaped charges further complicates this by introducing complex shock loading, liner convergence, and intensified explosive output.

Metallurgical details are critical to the understanding of early liner collapse and the effects on jet performance. Traditional means include jet capture [3] and flash X-ray experiments supported by extensive hydrocode modeling and on target performance data collection. Jets allowed to fully form before recovery contain the complete deformation history and details of the initial collapse may be lost or become speculative. Flash X-ray experiments are limited in the amount of metallurgical detail available [4]. Hydrocodes represent models of remarkable correspondence with observed performance but do not produce physical material. Many remarkable achievements are associated with these techniques. An apparent gap was a practical ability to cap-

[a] *E. Scheid, N. U. Deshpande*
Naval Surface Warfare Center
Crane Division
300 Highway 361
Crane, IN 47522 USA
**e-mail: eric.scheid@navy.mil*

[b] *E. Scheid, T. D. Burleigh, N. U. Deshpande*
Department of Materials and Metallurgical Engineering
New Mexico Institute of Mining and Technology
Socorro, NM 87801, USA

[c] *M. J. Murphy*
Hydrosoft International
1595 Cross Creek Place
Livermore, CA 94550, USA

 © 2014 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim

ture and recover shaped charge liner material in the initial moments of collapse. This experimental method provides a means to gather additional insight into the study of shaped charge performance.

2 Experimental Design

The experimental design was driven by the need to accomplish two main objectives. The first objective was to maximize the amount of material recovered for study. The second was to replicate the distinctive geometry, loading, and loading rate of the explosive shock and liner interaction of a particular charge.

The research focused on a charge with wave shaper that produces a unique and complex shock front. This front is modeled in Figure 1, a C-language-based Arbitrary Lagrangian-Eulerian (CALE) progression of the shock pressure and liner collapse over the first 3 μs of interaction. The shock front is not planar and is driven towards the apex symmetrically off of the centerline. The modeled images also served as the inspiration behind the experimental concept.

2.1 Hypothesis

The hypothesis driving this experimental concept is that the explosive shock and material interaction can be represented, initially, two dimensionally at all points around the charge. The nascent material reactions of interest are locally two-dimensional as the material deforms uniformly toward the center of the charge. Forces in the tangential direction are in local static equilibrium and strain is planar, assuming isotropic material. This is consistent with the Invariant Direction Concept [5].

2.2 Validation Plan

Proving this hypothesis requires recovering material and some means of assessing the quality of the material against accepted standards. Several interrelated standards are available. The first is the CALE model of this charge. The model is considered validated over years of U.S. Navy on-target experience. For purposes of this experiment, the model will serve as a standard for liner displacement relative to time and was shown in Figure 1.

The possibility was recognized that sufficient material could be recovered to validate the experiment with shaped charge collapse/jet formation theory. Several well established models are available, highlighted by Birkhoff et al. [6], Visco-Plastic Jet Formation and Pugh, Eichelberger and Rostoker (PER) [7] with the Birkhoff et al. theory chosen for this work.

Birkhoff et al. was chosen because the equations are common [8,9] and is the basis of US standard instead of Russian/Soviet visco-plastic jet formation theory [8]. Birkhoff et al. was chosen over PER because this study focused on early collapse and the simplification of assuming constant collapse velocity is appropriate where the PER method accounts for variable collapse velocities [8].

2.2.1 Birkhoff et al. Description

The Birkhoff, MacDougall, Pugh, and Taylor model describes the geometry and velocity of a collapsing shaped charge liner into the central axis and resulting jet. It is the first published fundamental theory of jet formation and recognizes that as the detonation pressure is much greater than the strength of the liner, the liner is treated as an inviscid fluid [10]. The variables are velocities, angles, and locations. The conditions are assumed to be constant and symmetric about the charge axis. The modeled equations and geometry are described in Figure 2.

The relevant information illustrated in Figure 2 are liner velocity (V_0), velocity along the liner axis (V_1), the original angle of the liner (α), the liner collapse angle (β) and the locations associated with the vector equations A to B and P to B. Interrelated with this is liner flow velocity (V_2) as shown in Figure 3. The locations of A, B (and P) along with assumptions on constant, symmetric conditions are consistent with Figure 2.

The relevant equations associated with Birkhoff et al. define V_0 and V_2 as functions of V_1, and liner geometry. Liner velocity (V_o), vector PB, is a component of the velocity along the axis (V_1) as given by Equation (1) [8].

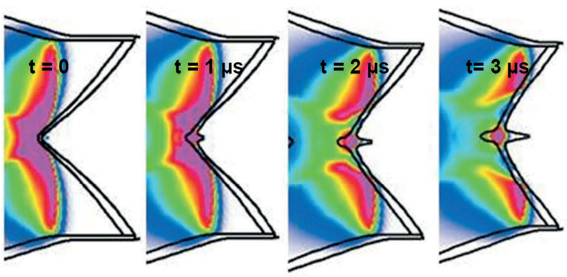

Figure 1. CALE generated model of shock progression and liner collapse over first three μs of shock and liner interaction.

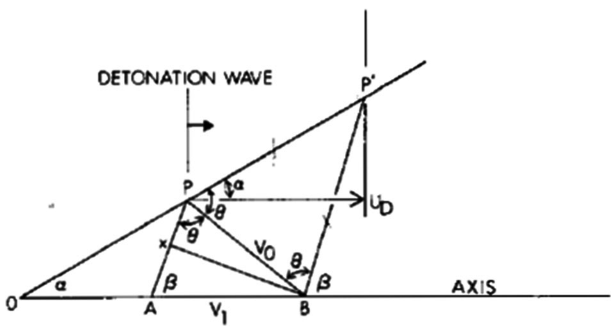

Figure 2. Geometry of the shaped charge collapse process (Birkhoff et al. 1948) [3].

© 2014 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim

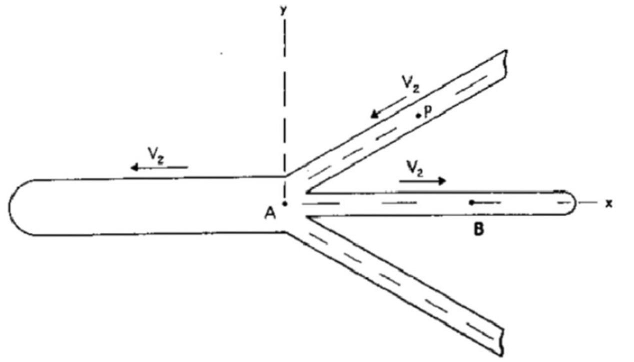

Figure 3. Jet and slug formation associated with liner flow velocity (V_2) (Birkhoff et al. 1948) [3].

$$V_0 = \frac{V_1 \sin\beta}{\cos[(\beta-\alpha)/2]} \quad (1)$$

V_1 is relatable to the jet velocity (V_j) at any consistent location along material moving on the axis. In considering V_1 synonymous with the V_j, it should be noted that some texts set $V_j = V_1 + V_2$ [8], while other do set V_1 to V_j [11]. Regardless, as vector AB is identical with V_1 in the chosen model as $V_1 = 0$.

V_2 is the velocity of the material in the liner wall as if flows into the collapse point and is a function of liner angle (α) liner collapse angle (β), and V_0, (see Equation (2)] [8].

$$V_2 = V_0(\{\cos[(\beta-\alpha)/2]/\tan\beta\} + \{\sin[(\beta-\alpha)/2]\}) \quad (2)$$

2.2.2 CALE Model Validation

The CALE model provides accepted deformation and pressure data relative to time. The displacement data from the hydrocode was used in conjunction with the Birkhoff et al. equations to assess the agreement of the experimental numbers and the model prediction.

2.3 Experimental Development

As the goal was to capture material enabling metallurgical study and it was assumed that testing actual charges would never practically produce material for study, some kind of analog was required. The analog needed to replicate the shock load in actual charge yet minimize explosive weight. Replicating the shock load requires proper attention to the explosive, the shock front, the liner material and the geometry.

2.3.1 Explosive Material

The complete charge consists of a precision pressed LX-14 [12] (95.5% HMX/4.5% polyurethane elastomer) main charge. Therefore the test charge needed to be as homogeneous as possible. This essentially eliminated most practical hand loaded charge options.

2.3.2 Trimming

Trimming implies retaining the scale of the charge but reducing or trimming the charge to the focus area and thus reduce the amount of explosive in the experiment. Even though the focus was on the region near the apex, the CALE model suggests that at least half of the liner would be required to capture the initial shock interface. This is based on the high pressure region observed midway down the liner in Figure 1. As additional liner is included in the experiment, the explosive weight is increased which conflicts with the assumption that an experiment with a full charge would not be successful. The wave shaper introduces another problem with trimming. The wave shaper forces the initiation of the main charge to start at a location near the case wall and any reduction in diameter would artificially manipulate the shockwave and invalidate the experiment.

2.3.3 Scaling

Shaped charge designs can be scaled and the design could simply be miniaturized. However, this would have been associated with an associated reduction in liner thickness. As the research required liner material for study, reducing the thickness would alter liner properties to an unknown degree and this scaled model would necessitate the manufacture of expensive tooling and introduce new manufacturing processes foreign to any performance data.

2.4 Assumptions and Limitations

A number of assumptions have been mentioned or implied thus far. Additionally a number of logistical and other limitations had to be respected. They are summarized along with supporting rational. Accordingly, the experimental analog design is now constrained by these assumptions and limitations.

(i) The explosive weight of the complete charge is over four pounds and the charge is capable of penetrating well over a foot of solid material. Arresting this process was assessed as impractical from research standpoint and was functionally impossible given the available resources. Accordingly, the explosive mass of the experiment had to be minimized.

(ii) Hand loaded explosives would not properly replicate the homogeneous shock front.

(iii) Trimming would introduce invalid changes in the shock front and complicate.

(iv) Scaling would introduce an invalid change in liner metallurgy.

 © 2014 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim

(v) Use of the Birkhoff et al. model assumes isentropic material, consistent (symmetric) pressure and a locally constant collapse velocity.

2.5 Experimental Analog Design

The CALE model images served as the inspiration behind the experimental concept that evolved from these assumptions and limitations. The model images are two-dimensional (2D), cross-sectional representations of a symmetric, three-dimensional (3D) event. A 2D cross-sectional model could potentially meet all of the above requirements. Thus a 3 mm thick, planar, section of the cylindrical charge was considered for study. This concept evolved into an analog consisting of a thin piece of explosive sheet, cut to the vertical cross-sectional dimensions of and in place of the pressed explosive load. The explosive sheet assembly was supported with an acrylic form which included the cross-section of the wave shaper. The structure was placed across the center line of the shaped charge liner. The design and execution of experimentation with this analog is described in this section.

2.5.1 Explosive Weight

The net explosive weight (NEW) of a 2D model, including the booster, was nominally 42 g. The full charge NEW is over 2000 g. This is almost a 98% reduction in NEW. Therefore the chances of recovering material are significantly improved. The logical challenges of the experiment are also reduced accordingly.

2.5.2 Explosive Material

Explosive sheet (63% PETN, 28% acetal tributylcitrate, 8% nitrocellulose, 1% dye) [13] is provided as a factory extruded product and was available to the research. It is accepted to be homogeneous and produces a satisfactory shock front and has been used in shaped charge shock experiments [14]. While a high explosive, the energetic output is less than that of LX-14. Shock pressure calculations were performed using Chapman-Jouget (CJ) condition and Hugoniot equations [11]. The result is a measure of the tensile stress in the target material from the shock pressure. The shock pressure equations are listed as Equation (3) and Equation (4).

$$P = 2.412P_{CJ} - (1.731P_{CJ}/\mu_{CJ})\mu + (0.3195P_{CJ}/\mu^2{}_{CJ})\mu^2 \tag{3}$$

$$P = \rho_o C_o \mu + \rho_o s \mu^2 \tag{4}$$

Shock pressure (P) is a function of CJ pressure (P_{CJ}) and particle velocity (μ_{CJ}), target density (ρ_o), the bulk sound speed of the target (C_o), target particle velocity (μ) and an empirical constant of the target material (s).

Table 1. CJ condition for LX-14 and explosive sheet.

Explosive	P_{CJ} [GPa]	Particle velocity [m s^{-1}]
LX-14 @ 1.83 g cm^{-3}	34.190	2.130
Explosive sheet @ 1.42 g cm^{-3}	15.08	1.456

Table 2. Material constants.

Material	Density [g cm^{-3}]	Bulk Sound Speed [km s^{-1}]	"s"
1100 Aluminum	2.714	5.392	1.341

The explosive constants from *Cheetah* [15] for LX-14 and explosive sheet are found in Table 1. The material constants for Al 1100 [16] are in Table 2.

Solving the system of the two Equation (3) and (4) yields shock pressures of 39.654 GPa for LX-14 and 21.118 GPa for explosive sheet [17]. While reduced by nearly half the difference was considered acceptable considering there are no better alternatives. Without hydrocode modeling accounting for explosive sheet, validation will need to keep in mind that sheet generated deformation will slightly under perform due to the reduced pressure. Regardless of any faults, the fact that it is a sheet and easily cut to shape and detonates completely and steadily in spite of a thin cross-section makes it an ideal choice in a 2D analog model.

2.5.3 Scaling and Trimming

Neither was necessary in the 2D model. The size and scale are exact to the actual cross-section. While the explosive is reduced to nearly two dimensional, actual liners can be used. The 2D analog charge is simply placed over the centerline of the liner. This eliminates concerns associated with a scaled, trimmed, or otherwise replicated liner material.

2.5.4 Birkhoff et al. Assumptions

The 2D concept assumes that local, initial shock interactions are essentially two dimensional in nature. The Birkhoff et al. equations are two dimensional and shaped charge collapse, under symmetric, isotropic conditions is modeled in 2D. This is also consistent with the invariant direction concept [5] described by Hirsh. Validation will demonstrate the degree of correlation between the experimental results, the hydrocode and these equations and assess the appropriateness of this assumption. These assumptions are also consistent with modeling associated with bi-explosive or double-layer shaped charge (DLSC) collapse [18].

2.5.5 Test Charge

The innovation [19] is the creation of the 2D test fixture. The design precisely replicates the cross-sectional area of

© 2014 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim

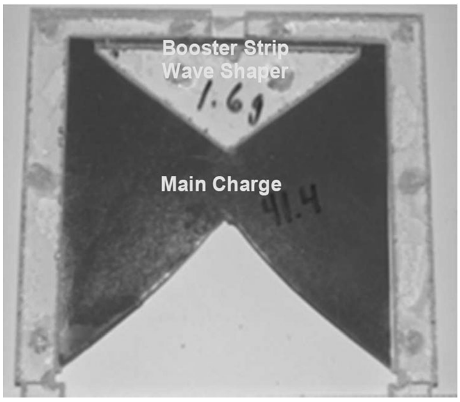

Figure 4. Test assembly with explosive sheet profile.

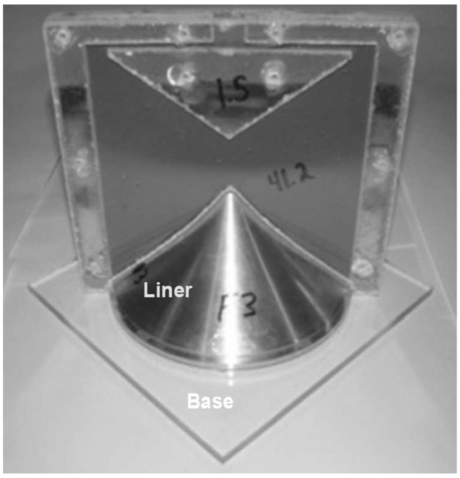

Figure 5. Assembled test charge with liner.

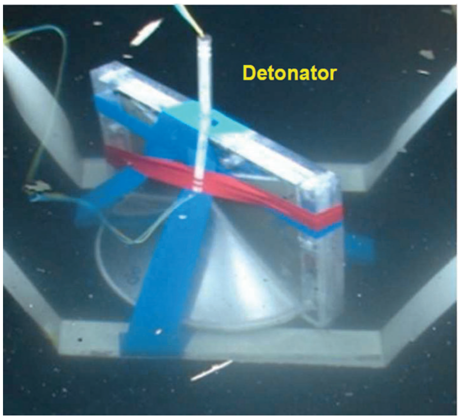

Figure 6. Submerged assembly primed for detonation.

the charge. The fixture was constructed from three layers of $^{1}/_{4}''$ thick precision cut acrylic. The center sheet consists of a location replicating the wave shaper and voids for the main charge and booster. The explosive sheet was cut from a precision template designed to match the profile of the actual charge and booster and inlayed (Figure 4) into the glued assembly aligned with steel pins. The pins were removed after the adhesive cured. The shaped charge liner was positioned and centered in the fixture. An acrylic base completes the assembly (Figure 5). For testing the completed assembly is submerged just below the surface of the water in a tank (Figure 6) with the air evacuated from under the liner. A standard detonator is inserted in the cap well to initiate the charge.

2.6 Experimental Design Summary

The results achieved as seen in Figure 8 proved the feasibility of the experimental method. The NEW was reduced by nearly 98% and symmetrically deformed and complete material was achieved. Logistically, the act of recovery was simply "fishing" the sample from the bottom of the tank with a net. The tank was reusable. Only the addition of few gallons of water and replacement of the wooden support structure was required between shots. Ultimate validation of the method would come upon analyses of complete liners with assessment in accordance with the plan.

3 Experimental Execution

Actual liners were mounted, exploded, and recovered (Figure 6). An example is shown in Figure 7.

3.1 Observations

Two initial observations were encouraging. First, the deformation of the underside indicates that the jet attempted to form (Figure 8). Next was the resemblance to the backside and mid-liner portion of the liner as seen in the frames in the CALE model. A cross-section of the recovered liner further highlights the correspondence (Figure 9).

3.2 Data Collection

To assist in quantifying the deformation, the liner was imaged by laser scanning and computed tomography (CT). Before and after laser imagery allowed for the development deviation maps. A deviation map is an inspection technique that displays measured differences between a part and an accepted baseline. The scanned images of the liners are provided in Figure 10.

The deviation maps of the surfaces are shown next (Figure 11 and Figure 12). The top contour is the original liner surface. The deformed surface is the lower and the distance between them is illustrated with the colored connecting lines.

Images from the (CT) scan are shown in Figure 13 below.

This imagery shows a void along the charge axis that is just below the sectioned surface. The formation and elon-

 © 2014 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim

Figure 7. Full liners shock deformed and recovered upper (a) and lower (b) surface.

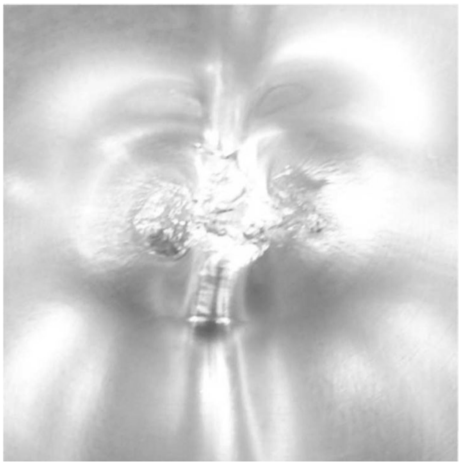

Figure 8. Deformed liner lower surface close up suggesting early jet formation.

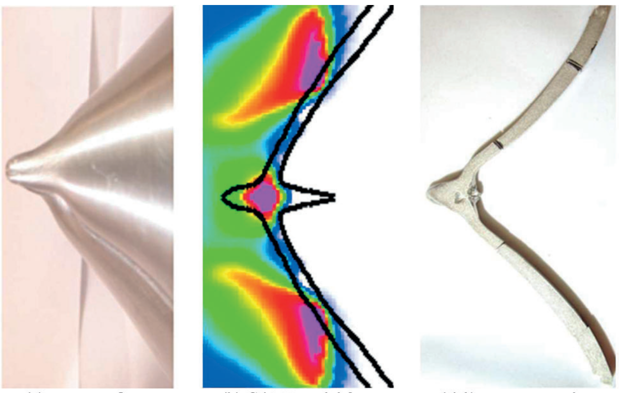

Figure 9. Correspondence of experimental liners with CALE model.

gation of these voids copper shaped charge jets in flight has been observed [20]. This is potentially a unique observation in an aluminum liner.

3.3 Validation

The validation plan incorporates a combination of hydrocode modeled deformation and shaped charge liner collapse equations. Birkhoff et al. defines V_0 and V_2 as functions of V_1, which relates to V_j at any location along the charge axis. Jet velocity is simply a change in location over time.

$$V_1 = V_j = \frac{(B - A)}{t} \tag{5}$$

It is also possible to observe V_0 or the change in location of a point P along the charge liner to point B.

$$V_0 = \frac{(B - P)}{t} \tag{6}$$

3.3.1 Determination of Experiment Birkhoff et al. Variables and Coefficients

Resolving the Birkhoff et al. equations requires determining the variables and coefficients described in Figure 5. The use of either Equation (5) or Equation (6) above and any validation based on displacement and velocity requires an assessment of time t. Time estimates are resolvable by comparing the CALE images with the observed deformation and utilizing the bending angle (δ). The bend angle is an estimate of the difference between the collapse angle (β) and the liner angle (α).

$$\beta = \alpha + \delta \tag{7}$$

The angle is proportional to the sweep velocity along the liner and V_0. Accordingly, it is the change in the liner angle as deformation occurs and shown with respect to the CALE images from $t = 0$ to 2 μs in Figure 14.

The bend angles in Figure 15 are approximately 28° and 39°, respectively. The liner angle (α) is associated with the original profile. While the angle of the overall liner is varia-

© 2014 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim

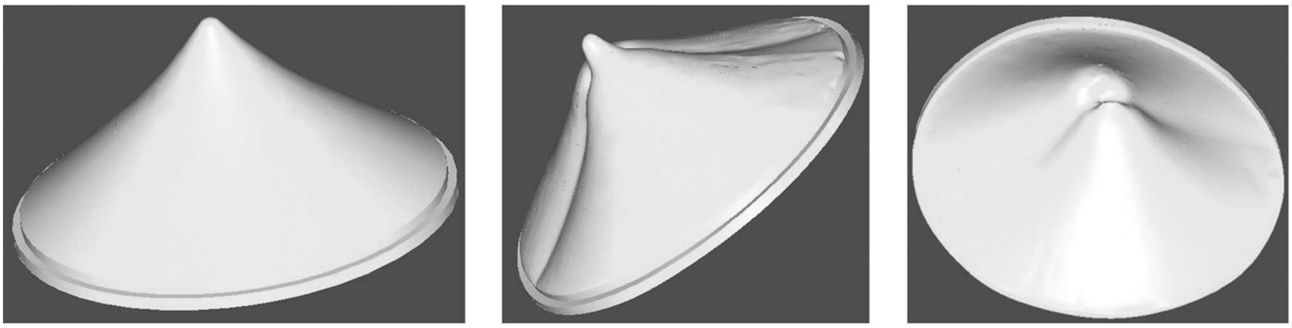

Figure 10. Laser scanned images (a) baseline, (b) upper surface, (c) lower surface.

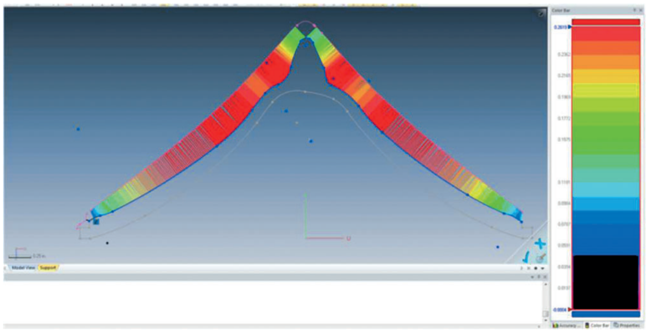

Figure 11. Deviation map upper liner surface.

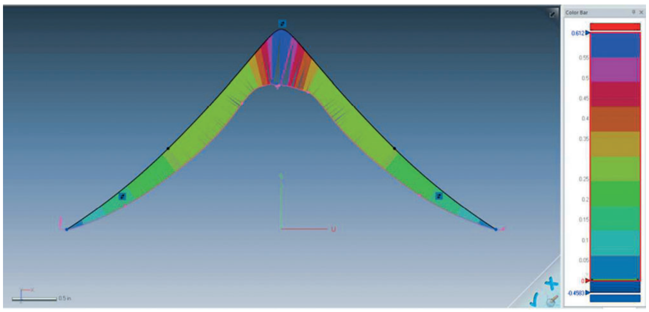

Figure 12. Deviation map lower liner surface.

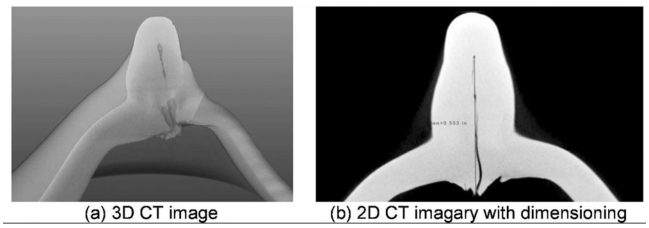

Figure 13. CT Images of a deformed liner apex.

ble, this is an early collapse study and the angle at the apex (42°) was selected accordingly. Using Equation (7) then resulting angles of β would be 70° and 81°. Figure 16(a) shows α and (b) angles of β superimposed over a cross-section of the deformed apex.

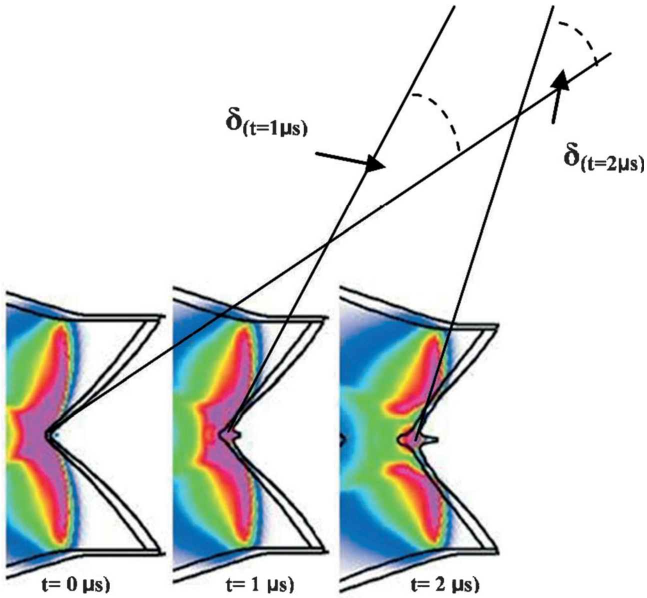

Figure 14. Liner bend angle (δ).

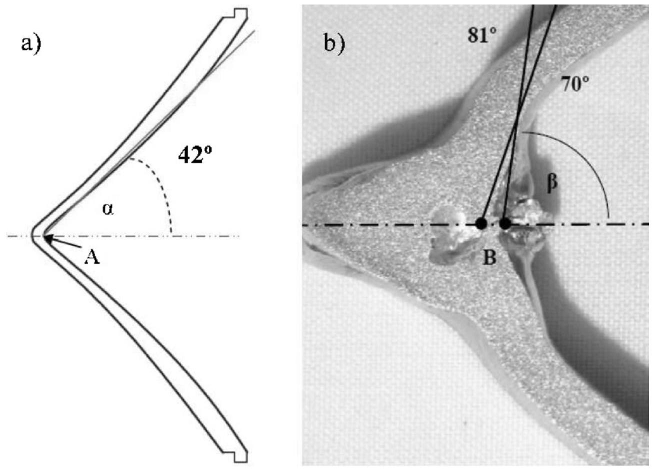

Figure 15. (a) Liner angle α and (b) estimated collapse angle β agreement with recovered shocked material.

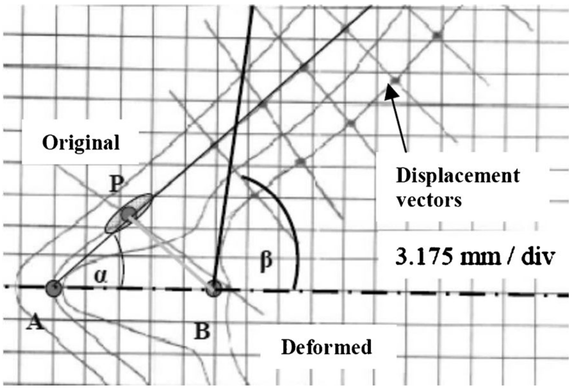

Figure 16. Original and deformed liner profiles developed from laser scanning with corresponding locations A, liner angle α, estimated locations B and P and angle of collapse β.

Figure 15(b) shows the detonation sweep from the apex to moment the deformation ceased. The close agreement of the material and the collapse angles estimated from the CALE image support a time estimate of 2 μs. Figure 15 also shows the chosen location of A, the lower surface of the apex, and potential locations of B based on β. The locations of A, B, and angles α and β are translated onto laser imaged, original and deformed liner profiles in Figure 16. Location P is along the bottom surface of the liner wall where this surface flows into the liner jet extrusion [5].

The location of P is arbitrary. There are no material markers but the deviation map (Figure 12) and the overlay (Figure 16) show very little strain along the under surface until the region that has collided. With α, β, A, B, and P located, the overlay of the laser scanned cross-sections were utilized to determine the distance P to B as 12.1 mm. The CT image in Figure 13(b) provides an additional opportunity to locate B in the sense of a shocked position of material from A. The location of the top of the linear void is the likely location of material from directly under the apex or distance A to B of 3.42 mm. Applying the Birkhoff et al. coefficients and equations for the shocked liner provides the results in Table 3.

3.4 Experiment Correspondence with Hydrocode

These results are in agreement with the expected values. The model predicts jet tip velocity (V_{tip}) in the range of

Table 3. Birkhoff et al. velocities generated from experimental input.

Input variable	Value	Output	Value
P	0	V_1	5.80 mm μs^{-1}
B	12.1 mm	V_2	2.86 mm μs^{-1}
α	42°	V_0	6.05 mm μs^{-1}
β	80°		
t	2 μs		

13 ± (0.6) mm μs^{-1} at 2 to 3 μs range. When vector PB are used calculated $V_{tip}(V_1)$ values are nearly half the hydrocode results.

3.5 Validation Summary

Upon successful execution of the experiment and the application of sophisticated spatial data collection techniques, suitable, representative shocked material was produced for analyses. The recovered material corresponds with accepted hydrocode predictions and satisfies the Birkhoff et al. shaped charge collapse equations. The experiment includes explosive and liner material interaction, and is an enhancement over the method described by Zernow and Chapyak [14] with respect to recovering shocked jet material. The correspondence is high; essentially half of the predicted value. The lower output explosive and the presence of the water backing would have an effect. Also, the choice of time was arbitrary. However, the fact that the results are certainly will within an order of magnitude validates the experimental method. Again, the validation was to show that the material was subjected to a representative shock.

3.6 Output

As the purpose of this experiment was to produce material suitable for research, sample generated output generated are presented. Optical microscopy is an obvious application of the material. Figure 17 is a 50× image at the transition point in the collapsing liner.

4 Conclusions

An experimental method to efficiently produce quantifiable liner material associated with early shaped charge collapse was developed and validated. The method had to replicate

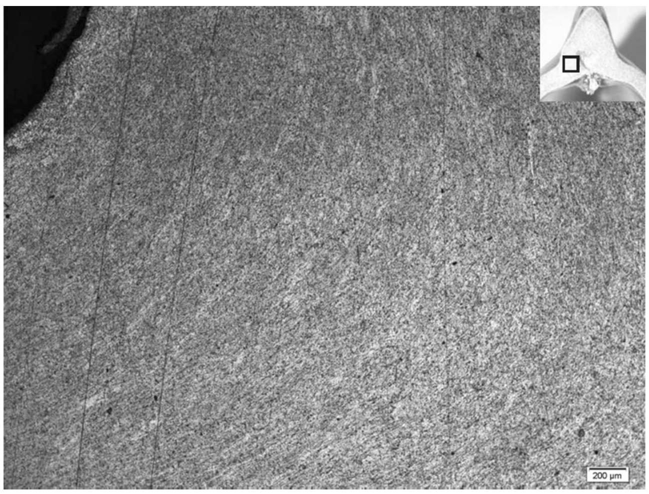

Figure 17. 50× optical microscopy examination of aluminum liner.

 © 2014 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim

the geometry of the shock load, the rate of the loading, recover material and be practical to perform. To achieve this, the original charge geometry was replicated precisely as any adjustments in size and scale would have introduced artificial conditions in shock front geometry or material properties. The innovation was the use of an exact, "two-dimensional" cross-section of the actual charge. This would satisfy the dimensional requirements and drastically reduce the explosive weight.

The 2D experimental analog consisted of a thin piece of explosive sheet, cut to the vertical cross-sectional dimensions of and in place of the pressed explosive load. The explosive sheet assembly was supported with an acrylic, form which included the cross-section of the wave shaper. The structure was placed across the center line of the shaped charge liner. With care to insure that no air was trapped in the liner apex, the test charge was fired just under the surface of a large (approximately 90 gallon) water tank. After the shot, the deformed liner was recovered from the bottom of the tank and available for study. The tank remained reusable. Preliminary experiments attempted to produce and capture material with sectioned liners detonated in open air above the tank. Even with the reduced explosive, the deformation of the material was too great for study. Once the charge was placed under the surface of the water, the experiment generated material for research, filling a gap [14,21].

Accordingly, the method introduced a hypothesis that the interaction between explosive shock and material in a shaped charge can be replicated in a 2D experiment. A means to validate the experiment was also required. The use of local 2D equations in shaped charge characterization is established [5,8,22].

The validation methods used herein served to assess the agreement with the observed deformation and those projected by established hydrocode modeling and shaped charge collapse theory. This was performed with a combination of a CALE model and Birkhoff et al. theory equations. Deformation observations were performed with CT and 3D laser imagery.

Most importantly, the method produced shocked material relevant to the research it was developed to support. Without this experiment, the research would have been left with attempting to draw analogous conclusions from material loaded with other than an explosive shock, in a generalized geometry. Or (and likely both) the research would have been limited to representative materials adapted to an achievable shock experiment. As this research was focused on liner microstructure associated with production history, use of actual liner material was highly preferred.

With this method, the research was able to recover and study actual liner material, shocked by direct explosive contact. Furthermore, the geometry of the shock front was replicated. While the validity of the experiment is only believed to match the first few microseconds of the event, this limitation was a perfect match for this research as other interrupted or soft catch shaped charge experiments were believed to carry the deformation process beyond the focus of this research and were beyond the practical limits available. While designed to research a specific charge, the experiment would be applicable in researching other systems with complex shock and material interactions.

Acknowledgments

Thanks to Naval Surface Warfare Center Crane Division for the opportunity and environment permitting such research and in particular the following individuals for their tangible or inspirational contributions towards this research; Mr. Matt Alley, Mr. Pat Bruner, Mr. Phil Erler, Mr. Jeff Fuller, Mr. Paul Hurst, Ms. Nancy Maloy, Mr. Brad Moan, Mr. Jason Miller, Dr. Sara Pliskin, Mr. Travis Sipes, Mr. Jeff Thompson and Mr. Barry Welch. Thanks to Dr. Gillian Bond, Dr. Bhaskar S. Majumdar, Dr. Brian Melof and Dr. Van Romero for New Mexico Institute of Mining and Technology for their continued patience. Special individual thanks to Mr. Kevin Hovden and Mr. Kevin Stewart for their assistance and encouragement as well.

References

[1] A. S. Khan, S. Huang, Experimental and Theoretical Study of Mechanical Behavior of 1100 Aluminum in the Strain Rate Range 10^{-5}–10^{4} s^{-1}, *Int. J. Plasticity* **1992**, *8*, 397–424.

[2] H. Huang, J. R. Asay, Compressive Strength Measurements in Aluminum for Shock Compression over the Stress Range of 4–22 GPa, *J. Appl. Phys.* **2005**, *98*, 16.

[3] D. H. Lassila, W. P. Walters, D. J. Nikkel Jr., R. P. Kershaw, *Analysis of "Soft" Recovered Shaped Charge Jet Particles*, Report UCRL-JC-123850, Lawrence Livermore National Laboratory, Livermore, CA, USA, **1996**.

[4] F. Jamet, Investigation of Shaped Charge Jets Using Flash X-ray Diffraction, *8th International Symposium on Ballistics*, Orlando, FL, USA, October 23–25, **1984**, p. 6.

[5] E. Hirsch, Internal Shearing During Shaped Charge Jet Formation and Break-Up, *Propellants Explos. Pyrotech.* **1992**, *17*, 7.

[6] G. Birkhoff, D. P. MacDougall, E. M. Pugh, G. I. Taylor, Explosives with Lined Cavities, *J. Appl. Phys.* **1948**, *19*, 563 – 582.

[7] E. Pugh, R. Eichelberger, N. Rostoker, Theory of Jet Formation by Charges with Lined Conical Cavities, *J. Appl. Phys.* **1952**, *23*, 5.

[8] W. P. Walters, J. A. Zukas, *Fundamentals of Shaped Charges*, CMC Press, Baltimore, **1989**.

[9] M. A. Meyers, *Dynamic Behavior of Materials*, John Wiley & Sons Inc., New York, **1994**.

[10] P. C. Chou, W. J. Flis, Recent Developments in Shaped Charge Technology, *Propellants Explos. Pyrotech.* **1986**, *11*, 16.

[11] P. W. Cooper, *Explosives Engineering*, Wiley-VCH, New York, **1996**.

[12] MIL-H-48358, *HMX/Resin Explosive Compostion LX-14*, U.S. Army, Washington, DC, USA, **1977**.

[13] SW010-AG-ORD-010 Rev 7, *List of Explosives for Navy Munitions*, Naval Sea Systems Command, Washington, DC, USA, **2011**.

[14] L. Zernow, E. J. Chapyak, Analysis of Strains, Strain Rates and Temperature During Early Stages of Shaped Charge Liner Collapse, *Propellants Explos. Pyrotech.* **1994**, *19*, 13.

[15] L. E. Fried, *Cheetah 6.0*, Lawrence Livermore National Laboratory, Livermore, CA, USA, **2010**.

© 2014 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim

[16] S. P. Marsh, *LASL Shock Hugoniot Data*, Los Alamos Data Center for Dynamic Material Properties, University of California Press, Berkeley, CA, USA, **1980**.

[17] E. Scheid, *Characterization of Explosive Foam and Development of an Associated Evaluation Process, in Mechanical Engineering*, Rose-Hulman Institute of Technology, Terre Haute, IN, USA, **1998**.

[18] X.-F. Zhang, Q. Liang, Studies on Jet Formation and Penetration for a Double-Layer Shaped Charge, *Combust. Explos. Shock Waves (Engl. Transl.)* **2011**, *47*, 9.

[19] E. Scheid, *Shaped Charge, Novel Test Method*, United States Navy Case 120264, Naval Surface Warfare Center, Crane, IN, USA, **2012**.

[20] D. H. Lassila, W. P. Walters, D. J. Nikkel Jr., R. P. Kershaw, *Evidence of Melt in "Soft" Recovered Copper Jets, in: Metallurgical and Materials Applications of Shock-Wave and High-Strain-Rate Phenomena* (Eds.: L. E. Murr, K. P. Staudhammer, M. A. Meyers), Elsevier Science, Amsterdam, **1995**, p. 7.

[21] F. I. Grace, *Shaped Charge Jetting of Metals at Very High Strain Rates, in: Shock-Wave and High-Strain-Rate Phenomena in Materials* (Eds.: M. A. Meyers, L. E. Murr, K. P. Staudhammer), Marcel Dekker, New York, **1992**, p. 9.

[22] A. J. Schwartz, M. J. Busche, R. Becker, M. Kumar, D. J. Nikkel, *Role of Texture in Spin Formed Cu Shaped-Charge Liners*, Report UCRL-JC-139810, Lawrence Livermore National Laboratory, Livermore, CA, USA, **2001**.

Received: January 9, 2014

© 2014 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim