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ANALYTICAL AND EXPERIMENTAL EVALUATION
OF A PROPOSED SELF-FORGING FRAGMENT MUNITION

Dean B. Tuft and Edwin N. Folsom

Advanced Ordnance Development
Lawrence Livermore National Laboratory
Livermore, California

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ABSTRACT

Analytical and experimental tools have been used to study the formation of a proposed self-forging fragment projectile. The primary objective of this study is the determination of the interior and exterior shape of the fully formed fragment, and to determine if the fragment tumbles in flight. In addition, it is of interest to compare computer predictions to experimental results.

An experiment was performed using high speed photography and high-energy flash x-ray radiography to study liner and case motion and projectile formation. Fabrication and assembly tolerances were closely controlled in an effort to eliminate tolerances as a possible source of fragment instability. X-ray film-density contours were analyzed to determine the fully formed fragment interior and exterior shape. Down-range yaw screens showed fragment tumbling in flight.

The computed fragment shape was compared to experimental results and it was found that a retaining ring in the computational model near the liner periphery had a significant effect on the final computed fragment shape. With the retaining ring in the computational model and full two-way sliding between all material interfaces, the final computed fragment showed very good agreement with the experiment on both exterior and interior shapes.

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INTRODUCTION

Self-forging fragments, SFF, (also called explosively formed projectiles, EFP) are currently drawing large interest by weapon designers as potential anti-armor devices. The SFF is particularly interesting because of the potential for attacking targets at very long standoff. In order to achieve suitable performance at long standoff, the fragment must demonstrate stable flight characteristics. Therefore, the designer's goal is to produce a fragment with good penetrator qualities (high aerial density and long length) and aerodynamic stability. The most easily obtainable fragment not susceptible to aerodynamic instabilities is the sphere. A sphere, however, is not an optimum penetrator. The trend therefore has been an attempt to form long rod penetrators with flared tails or wings. The current state of the art in SFF appears to be fragments approaching $L/D \sim 3$, $L \sim 3/4$ caliber and stable flight characteristics.

The design methodology typically employed consists of hydrocode iterations coupled with experimental verification. Often a certain degree of code normalization takes place when mismatches between code and experiment are encountered. The most frequently identified cause for mismatches is the material strength model. Successful material model normalization to produce fragment shape agreement has been obtained by several investigators [1,2,3].

The major goal of this study is to determine, analytically and experimentally, the interior and exterior projectile shapes of a proposed self-forging fragment design and to evaluate the flight stability of the projectile by diagnosing the flight path.

Since flight stability is a function of the relative location of the centers of mass and pressure, both interior and exterior fragment shapes are important. Typically, low energy flash x-ray exposures reveal a plane projection of the outer shape but do not reveal any information about the interior of the fragment. High energy x-ray exposures, on the other hand, can be digitized and evaluated to deduce the interior shape and the presence of voids and low density areas.

The particular design of interest in this study has been tested by others several times prior to this study and has produced fragments that tumbled and veered off course after several hundred feet of flight. Fabrication and assembly precision generally were not well controlled in those prior tests. Consequently, for this study, tolerances were tightly controlled in both fabrication and assembly.

EXPERIMENTAL TEST

A test firing of the proposed munition was conducted. A drawing of the test device is shown in Figure 1. The liner is 99.99% pure OFHC annealed copper. The liner was machined from a rough formed blank in a fully annealed condition. The machined liner varied from nominal thickness by a maximum of 0.013 mm and had a maximum circular runout variation of 0.064 mm.

Metallurgy on a liner blank witness sample revealed a uniform grain size distribution with an average grain size of 0.060 mm. Detonation was achieved with a precision MC1957A detonator, with an internal choke to provide a circular detonation breakout area of 1.52 mm diameter. The detonator was assembled to within ± 0.05 mm true position of the munition centerline. The true position centerline of the liner was assembled to within ± 0.076 mm of the munition centerline.

A schematic of the experiment layout is shown in Figure 2. The line of sight of the linear accelerator was positioned 30 inches from the front face of the munition. Calculations indicate that the fragment would arrive at this location at 300 μ s after detonation and would be fully formed. Several

FIGURE 1. TEST DEVICE.

Fig. 2 Schematic of experiment layout (plan view).

layers of film were exposed in a sandwich in order to bracket the exposure. A 3-inch thick target of rolled homogenous armor was placed 100 feet from the munition.

The primary diagnostic was a 100 MeV (1R at 1 m) linear accelerator flash x-ray for radiographing the fully formed fragment. A copper penetrometer (step wedge) was radiographed prior to the experiment to determine the variation in radiograph film density versus copper thickness. This data was later used to evaluate fragment mass and thickness from the film density contours. High speed framing cameras were used to follow the motion of the liner and the case.

A positive exposure of the radiograph is shown in Figure 3a. A small amount of diffuse material was visible both in front of and behind the fragment on the original radiograph (not shown in the figure). The material in front of the fragment has been identified as possible liner spall. The spalled material shows up in the high speed camera records to be discussed later in this paper. The fragment is 7.5 cm long and 4.3 cm at the widest point. The radiograph was digitized and the resulting isodensity contours (film density) are plotted in Figure 3b. Figure 3b also shows a scan taken across the digitized radiograph to determine film density as a function of position. Decreasing film density indicates increasing fragment mass integrated along the ray path normal to the paper.

By analyzing the film density data, utilizing the penetrometer data as a baseline, we are able to deduce fragment boundaries and the presence of any voids or low density areas internal to the fragment. The result of this analysis is the fragment contour shown in Figure 3c. The figure clearly shows a region of reverse flow (backward jetting) near the rear of the fragment and wings that have folded back and inward around the rear of the fragment. The "Y" shaped region separating the wings from the reverse flow area are most correctly identified as areas of low density material rather than as pure voids.

a) Fragment radiograph

b) Film isodensity contours and film density versus position for a vertical sweep

c) Fragment contour deduced from film density data

Figure 3

High speed framing cameras recorded the early time movement of the case and liner. Two Cordin model-121 (70 mm format) cameras were positioned to capture the early time movement of the liner and case. Interframe time for the model-121 cameras is 1.4 μ s. As a backup, two LLNL model-6 (35 mm format) cameras with interframe time of 1.0 μ s also covered the early motion of liner and case. The positions of the camera ports and turning mirrors with lines of sight (dashed lines) are shown in Figure 2. Light for the framing cameras was provided by four high explosive Argon candles.

A sequence of four photos showing early time case motion is shown in Figure 4. These photos were taken from camera port #4 (see Figure 2). The detonation point is to the right and the direction of projectile motion is to the left in each frame. The grid markings are 22.9 mm squares. Of particular interest in these photos is the evidence of early sideways venting of H.E. reaction products at the locations of arrival pin diagnostics and a plugged hole in the case. Venting at the plugged hole illustrates the effect of case material strength in maintaining a continuous uniform tamping. Though the case appears to have fractured severely at 33 μ s, there is no evidence of venting in areas where the case material was initially continuous. Discontinuities in the case material could result in spatial pressure variations that may affect projectile formation symmetry.

Figure 5 shows a sequence of photos illustrating early time motion of the case and liner taken from camera port #2 (see Figure 2). These photos illustrate the venting of H.E. reaction products around the periphery of the liner beginning at ~ 20 μ s. Also at 20 μ s white spots appear near the center of the liner. These spots are identified as probable liner spall and are most likely associated with material present in the radiograph in front of the main fragment. Early time localized venting at the locations of case discontinuities (e.g. plugged holes, etc.) can be seen at 20 μ s near the top and top right of the case.

Fiberglass screens were placed at 60 and 80 feet down range from the munition. These screens (called Yaw screens) provide data about the orientation of the fragment during flight. Yaw screens are shown in Figure 6. Fragment profiles at both locations indicate a sideways orientation. Damage at the target (located 100 feet down range) was symmetrical indicating an end-on orientation. We conclude, therefore, that the fragment was tumbling in flight.

Four coaxial transducer pins (shorting type) were placed in the case as shown in Figure 7. All pins closed within 162 ns of the average closure time. Because the pins were not all spaced exactly the same distance from the detonation pin, a more reliable measure of detonation symmetry is the wave transit velocity (straight line distance from the detonator divided by the shorting time). All four pins reported wave transit velocities that agreed within 1.1% of the average.

a) $T = 5$ microseconds

Arrival pin
venting

Plugged hole
venting

b) $T = 19$ microseconds

c) $T = 26$ microseconds

d) $T = 33$ microseconds

Figure 4. Sequence showing early time case motion.

a) $T = 5$ microseconds

Arrival
pin venting

H.E. venting

Liner spall

b) $T = 20$ microseconds

c) $T = 27$ microseconds

d) $T = 34$ microseconds

Figure 5. Sequence showing early time case and liner motion.

Figure 6. Hole patterns in yaw screens at (a) 60 feet and (b) 80 feet down range.

Pin	Shock Velocity mm/ μ s	% Difference from Average Velocity
A	7.647	0
B	7.535	1.1
C	7.648	0
D	7.637	0.3

Figure 7. Locations of shorting transducer pins for measuring shock arrival times.

ANALYTICAL MODELING STUDIES

For this study, we used an explicit two-dimensional Lagrangian finite element hydrocode, DYNA2D^[4]. This code utilizes quadrilateral finite element zones and incorporates the JWL high explosive model^[5] and the Steinberg-Guinan (SG) plasticity model^[6]. The SG plasticity model accounts for thermal softening, pressure hardening and strain hardening and is strain rate independent (based on the assumption of strain rate saturation at rates above 10^5 s^{-1}).

A previous study by Werne, et al^[2] used DYNA2D and the aforementioned material model to study an earlier proposed design. That study compared experimental results to computed results and normalized the material model by changing the value of the copper maximum yield strength (Y_{max}) from 0.0064 Mbar to 0.0045 Mbar. This value, obtained from the previous study, was used for calculations in the present study.

The DYNA2D computational mesh (shown in Figure 8a) consists of a copper liner, LX-14 high explosive and a steel case. Two models of the munition were run to evaluate the effect of edge constraints. Figure 8b shows a portion of the mesh where the liner and case meet and Figure 8c shows the same area with a retaining ring added. The mesh shown in Figure 8c more closely matches the actual munition configuration that was tested. Two-way intersecting slide lines were incorporated between all material interfaces giving each part the ability to slide along every interface.

The first calculation we performed did not include the detail of the retaining ring and the resulting sequence of liner deformed shapes is shown in Figure 9a. A second calculation was run to investigate the effect of adding the retaining ring. The results of this calculation are illustrated in the sequence of deformed liner shapes shown in Figure 9b. Both computations show mass flow (rather than pure bending) during the radial convergence of the fragment. Also of interest is the backward jetting produced at the axis due to the radial convergence. Velocity gradients in the fragment are damped to zero by 300 microseconds and only rigid-body motion remains.

a) DYN2D computational mesh.

b) Mesh without retaining ring.

c) Mesh with retaining ring.

Figure 8.

Figure 9a. DYNAB2D computation without retaining ring.

Figure 9b. DYNAB2D computation with retaining ring.

Figure 10 shows a comparison of the final computed fragment shapes for the two calculations. The major difference is the position of the liner periphery elements or "wings". An interesting result is the difference in the overall bulk shape of the fragment on the outside about midway back on the fragment. Apparently the increased folding caused by the retaining ring had an effect on the mass flow process and resulted in a slightly different outer shape.

Figure 11 shows a comparison of the computed fragment shape from the second calculation and the fragment contour deduced from the digitized x-ray exposure. The comparison shows very good agreement on overall fragment shape. The "wings" have folded further around the rear in the experiment than predicted by the computation. The maximum diameter of the experiment fragment is slightly larger than the computation predicts and there is slightly more reverse jetting in the calculation than in the experiment. This difference could be a result of severe element elongation that appears in the mesh near the centerline. Grading the zones through the liner thickness may reduce the extreme zone elongation on the axis and increase the accuracy of the computation.

FIGURE 10 - Computed fully formed fragment shapes resulting from (a) mesh without retaining ring (b) mesh with retaining ring.

Figure 11. Comparison of a) computed fragment shape and b) fragment contour from x-ray.

CONCLUSIONS

An experimental and analytical study of a proposed self-forging fragment has been performed. The primary objective of the study was to determine the final fragment shape and to determine if the fragment tumbles in flight.

A high energy x-ray source was used to obtain an exposure of the fully formed fragment that could be digitized and analyzed to determine interior shape. The experimental results show a fully formed fragment with some reverse jetting and wings that are completely folded back, not forming the desired drag flare. Yaw screens at 60 and 80 feet down range indicate the fragment tumbled during flight.

Computed fragment shape agrees very well with the experimental fragment both on exterior and interior contours. The fragment wings in the calculation fold straight back instead of wrapping around as in the experiment and the calculation predicts slightly more reverse jetting than was seen in the reduced x-ray exposure. This result may be due to extreme elongation of zones along the axis and might be corrected by initially grading zones through the liner thickness.

Computed results also demonstrate the importance of modeling the correct geometry. A small (27 gm) retaining ring, initially thought to have a negligible effect on the fragment formation, was in fact found to have a significant effect on the final shape. Not only did the retaining ring cause the wings to fold further back, but there was also an effect on the bulk shape of the fragment.

These results point to the importance of careful consideration for details which may seem at first to be insignificant. One such possible effect is the occurrence of early venting due to discontinuities in the structure of the weapon case. Another would be non-uniform tamping caused by slots and blind holes in the case. Early venting at plugged hole locations was evident in the high speed photos. Although the mass and tamping was uniform, the discontinuity in material strength allowed early venting. While this is not believed to be a source of fragment asymmetry for this experiment, it is worthy of notice for future design consideration.

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