19th International Symposium of Ballistics, 7–11 May 2001, Interlaken, Switzerland

CAVITY SHAPE EVOLUTION DURING PENETRATION OF YAWED LONG RODS

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Reverse ballistic experiments were conducted in the IAT Electro-Magnetic launcher to study the effects of yaw in deep penetration. The experiments with copper rods and aluminum targets show that the penetration channel in the target is mostly circular arc shaped with the tip reglon exhibiting a modified shape due to back flow and material accumulation. The presence of yaw destroys the symmetry of flow at the penetrator tip, unlike in normal penetration. The measured value of the cavity curvature is close to the theoretical value for pure circular motion caused by the lateral load due to cavity expansion pressure. The lateral contact surface is not smooth for some cases indicating possible contact instabilities. Target strength has a large effect on the cavity curvature and final penetration depth. All these aspects of yawed penetration, which degrade the penetration efficiency, are discussed in light of the experimental evidences presented.

INTRODUCTION

Presence of yaw can substantially degrade the penetration performance of long rod projectiles. The penetration depth is not much affected for relatively low yaw angles. For yaw angles below the critical value (at which the tail just touches the side wall of the penetration crater,) the penetration is mostly along the length of the long rod. At very large yaw angles, the lateral erosion and deceleration limit the penetration depth to a few times the diameter of the rod. In between these two extremes, the penetration performance degrades progressively as the yaw angle increases above the critical yaw angle. The primary cause of this penetration degradation can be attributed to the re-alignment of the velocity vector due to the lateral load exerted by the target. For example, Fig. 1 shows the result of a hydrocode calculation of a yawed long rod impacting the edge of a thick target. As shown by the enlarged velocity vectors at entree and exit, it is clear that the net effect of the lateral load is to turn the velocity vector into the local length direction, while the long rod cuts a slot into the target due to the lateral velocity component. This velocity reorientation reduces the effective yaw. The amount of local yaw reduction should depend on the length of the rod, its velocity and the initial yaw angle for given material pair. For example, for very high impact velocities the rod may be consumed before the velocity alignment is completed. There have been models [1,2] that quantify the lateral load exerted during slot-cutting by the target material on the yawed rod. It has been shown that plane strain cavity expansion pressure (about 3 times the yield strength of the material for metals) is a good measure of the steady state lateral load. For plate targets this steady state load is modified by transients primarily caused by impact cratering and rod embedment. These models work very well for thin to moderately thick plate targets, for which exit shapes are well matched by the theory. However, for thick targets, as the shape of the rod changes progressively due to turning of the velocity vector, erosion and accumulation of penetrator material in the tip region (which was not important for thin plate cases as perforation occurs rather quickly) becomes equally important. As we shall demonstrate in this paper, a better description of the tip region is required to completely represent the loading on the projectile. In this work the main features of yawed penetration are identified by studying the cavity shape evolution in two different target materials.

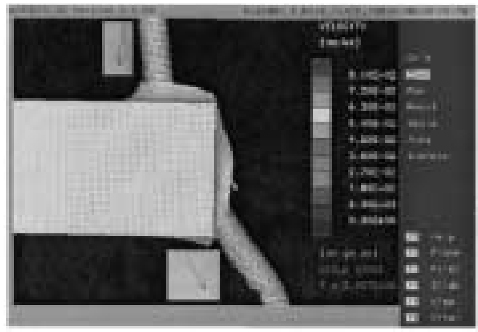

Figure 1. Hydrocode simulation shows that the velocity vector is re-oriented as a long rod cuts a slot into the target. The velocity inserts are enlarged velocity vectors from adjacent cells.

TEST SET-UP

Since it is very difficult to conduct direct ballistic experiments where the yaw in the long rod can be precisely controlled, we chose to conduct the experiments in reverse ballistic. The Medium Caliber Launcher (MCL) at IAT was utilized for this purpose. This is a 7 meters long, 40 mm square bore electromagnetic launcher driven by the pulse power obtained by capacitor banks. Details of this launch facility are described by Parker et al. [3]. Due to the limitation of maximum kinetic energy obtainable by this research launcher, we chose to study penetration behavior of copper rods into aluminum targets. This combination holds similar density and strength ratios as Tungsten/Steel pair, and thus should provide interesting insights for practical applications in addition to being useful for identifying the underlying physical phenomena. The KJ armature commonly used for launcher research was modified (see Fig. 2) to hold a 2" long, 1.5" dia projectile cylinder made of aluminum.

The launch packages consisted of a 7075-T6 Aluminum armature pushing against a lexan fore body which held the target (projectile) cylinder. To study the effect of target strength on cavity evolution, two types of aluminums 1100 and 7075-T6 were used as experimental set up. The penetrators were 2 mm dia by 38 mm long copper pins (except for one test) hung by wires in front of the muzzle from plastic rods attached to the flange of the existing flight tube. To utilize the existing flange holes along with vertical and horizontal X-ray tubes the penetrator was aligned to a plane 30 deg from vertical. As a result, even though two orthogonal radiographs were obtained, none represented the true view. Even though a true view can be obtained by combining the two orthogonal views, no such attempt is done in this paper except for two experiments where cavity curvatures are measured for comparison with theory. The penetrator was aligned to the center of the gun by shining a laser beam from the breech end. The X-rays were triggered simultaneously (except for normal penetration cases) by a contact-shorting pin placed in front of the copper pin, but off set from the centerline to avoid any interference with penetration channel. The simultaneity was required as none of the radiographs produced a true view. The delay time was estimated by projected velocity for the current pulse used. Fiducial wires made of tungsten were placed on the radiographs to act as reference coordinates. To charge the gun for the experiments typically 10 X 1 MJ capacitor banks were used. All yawed tests were conducted at 15-deg yaw and at a nominal impact speed of 1.5 km/s.

Figure 2. Launch package.

TEST RESULTS

Table 1 depicts the test matrix. Fig. 4 summarizes the P/L evolution for all shots. Fig. 5 shows the normal impact pictures from shot #185 for Al-1100 target. For this test alone, a 2 mm X 20 mm copper pin was used to avoid penetration depth getting close to the rear surface. The X-rays delays were set at 20 μs and 55 μs after impact, at which the penetration depths were found to be 18 mm and 38 mm respectively. Using handbook values of 250 MPa and 30 MPa for the flow strengths of Copper and Aluminum respectively in Tate model reproduces the penetration depths at the specified times fairly accurately. Similarly Fig. 6 shows radiographs from shot #168 for normal impact and penetration into 7075-T6 Aluminum.

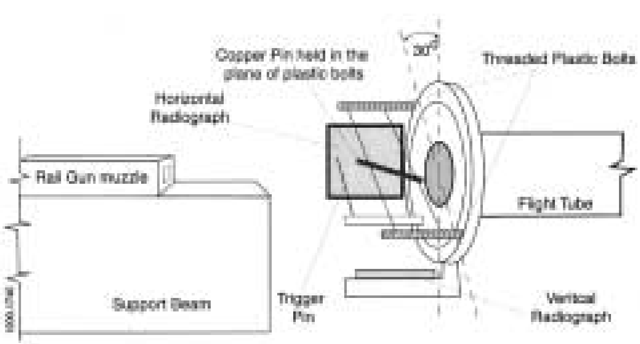

Figure 3. Experimental set up for the reverse ballistic tests in the EM gun.

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t#	Yaw	Target	Delays	V
			micro-sec	km/s
8	0	Al-7075	34,58	1.5
9	15	Al-7075	19.7	1.51
0	15	Al-7075	19.0	1.51
4	15	Pure Al	20.3	1.5
5	15	Al-7075	31.5	1.46
6	15	Al-7075	10.6	1.47
3	15	Pure Al	31.2	1.38
5	0	Pure Al	19.7,54.7	1.5

Table 1. Test matrix

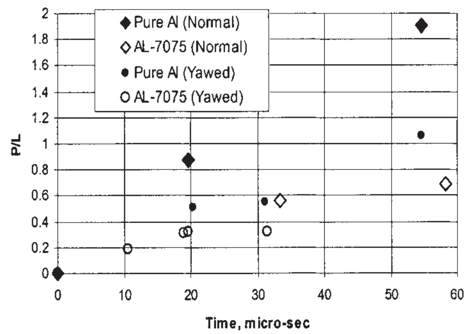
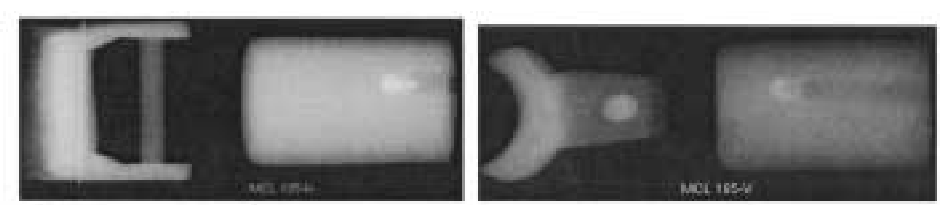


Figure 4. Evolution of penetration for all tests.

Fig. 7 shows the cavity shape evolution in Al-1100, and Fig. 8 shows the radiographs for Al-7075-T6 rounds. From the radiographs the rod does not appear to rotate prior to impacting the target. Examination of the radiographs from yawed experiment reveals that most of the rod bends into somewhat circular shape inside the target except near the tip where the cavity is larger. The symmetry of rod back-flow that was seen for normal impact is clearly lacking in the yawed impacts. The larger cavity near the tip may either be due to relative difficulty of penetrating accumulating debris near the tip, or due to asymmetrical back flow of the mushrooming head. By comparing the radiographs it is evident that 7075-Al exerts a higher lateral load on the rod than pure aluminum, as a result of which the rod experiences larger deformation in the former, leading to reduced cavity curvature and penetration. For the Al-1100 case, the lateral surface is undulated indicating that back flow of the mushrooming material from the head region may be interacting with the in coming material. Of course the possibility of a Kelvin-Helmbotz type instability due to high speed sliding of fluid-type materials cannot be ruled out. This type of undulation is absent for the 7075 Al cases. Thus strength has the effect of either reducing the effects of back flow or suppressing the aforesaid instability.



(a) Vertical X-ray, 19.7 μs after impact. (b) Horizontal X-ray, 54.7 μs after impact.

Figure 5. Normal penetration into pure aluminum (Shot #185).

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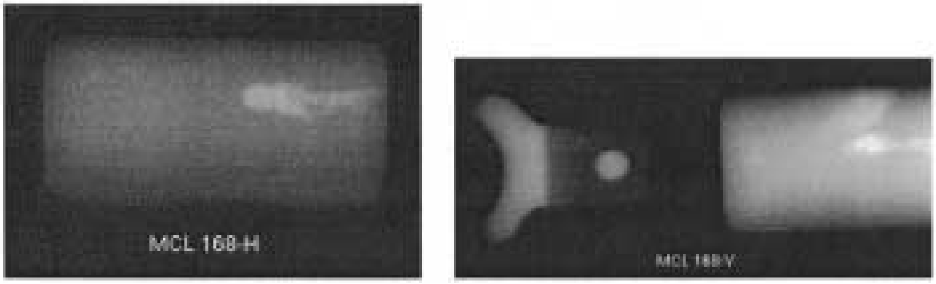

(a) Vertical X-ray, 34 µs after impact. (b) Horizontal X-ray, 58 µs after impact.

Figure 6. Normal penetration into 7075 aluminum (Shot #168).

In Fig. 9, we have plotted the true shape of the curved part of the rod (excluding the tip region) from two identical experiments (#169 and #170) recorded roughly at the same time after impact. A least square method was used to fit a circular arc through the data points. It is clear that the rod does indeed deform into a circular shape. In the slot-cutting model [1] we had assumed that the effect of lateral load on the rod was to reduce the lateral velocity component and provide the centrifugal force to turn the velocity vector. It was shown from computational results and comparison with experimental data [1,2] that the deformation of the rod was primarily inertial. Now, if the deceleration of the lateral component is ignored, and it is assumed that the lateral load causes a circular motion of the rod material, the ensuing radius of curvature can be calculated as follows. Considering a differential element of length dx, the lateral force exerted on it is $F=P_c \cdot D \cdot dx$ where P_c is the cavity expansion pressure typically given by [4] $P_c=a+b\rho_t V_n^2$, where a is quasi-static cavity expansion pressure equal to $(Y/\sqrt{3})[1+\ln(E/\sqrt{3}Y)]$ for a elastic-perfectly plastic type materia with flow stress of Y and Young's modulus of E, and b is a material specific constant which are approximately 1.8 for aluminum, V_n is the normal component of the velocity. The mass of the element is $m=\pi D^2 \rho dx/4$. Thus the radius of curvature is given by $R = mV^2/F = (\pi/4)\rho_P D V^2/(a + b\rho_t V_n^2)$.

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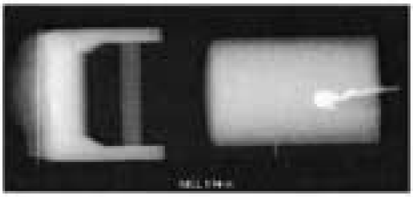
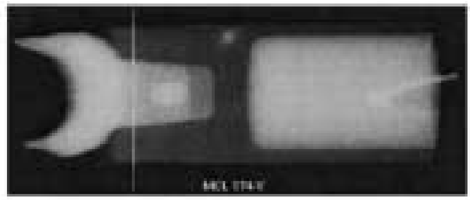
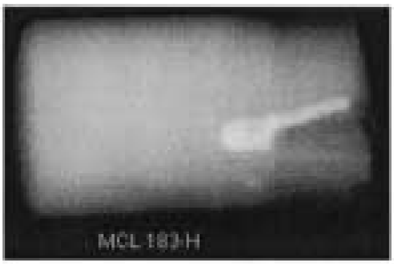


(a) Horizontal X-ray, 20.3 μs after impact.

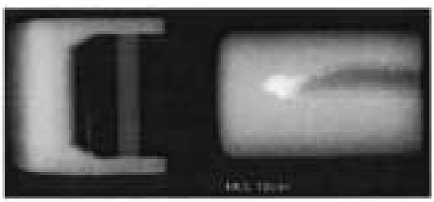


(b) Vertical X-ray, 20.3 μs after impact.

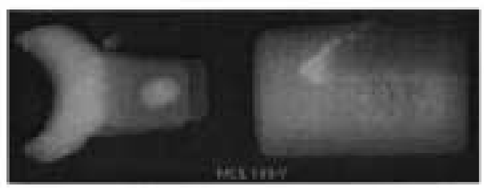


(c) Horizontal X-ray, 31 2 μs after impact.

(d) Vertical X-ray, 31.2 μs after impact.



(e) Horizontal X-ray, 54.6 μs after impact.



(f) Vertical X-ray, 54.6 μs after impact.

Figure 7. Yawed penetration into pure aluminum.

For V = 1500 m/s and yaw angle of 15-deg, R turns out to be 13.7 mm. The experimental values of the curvature are 11–12 mm, which are close to but smaller than the value for pure circular motion. Additionally, the center of the circular arc in Fig. 9 lies at (–2.5 mm, 12.4 mm) for shot # 169, and at (-1.87 mm, 10.7 mm) for shot #170. The line extending from the origin to the center of the circle makes an angle of 9.9 deg, and 11.4 deg for shot # 169 and #170 respectively. Under ideal conditions (pure circular motion) the radius vector to the origin should be perpendicular to the original length vector of the rod, and thus the included angle between the radius vector and the target surface should be equal to the yaw angle (= 15 deg). There are several possible explanations for the differences which could not be ascertained unequivocally using the available data. The rod may stretch as a result of circular motion or the axial velocity may reduce leading to a smaller value of R, and offset the lateral deceleration. Any change in diameter could change the curvature, but any change in diameter could not be positively identified in the radiographs due to lack of enough contrast. For the high impact velocity and the short time of penetration, axial velocity reduction should be extremely small.

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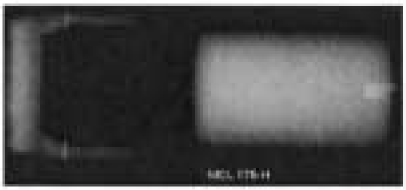
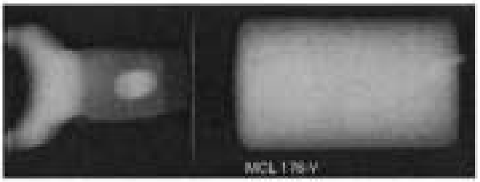
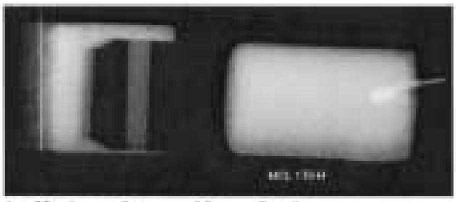
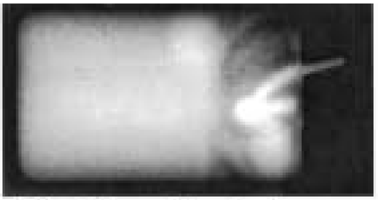
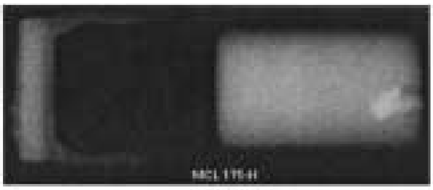

(a) Horizontal X-ray, 10.6 µs after impact.


(b) Vertical X-ray, 10.6 µs after impact.


(c) Horizontal X-ray, 19 µs after impact.


(d) Vertical X-ray, 19 µs after impact.


(e) Horizontal X-ray, 31.5 µs after impact.

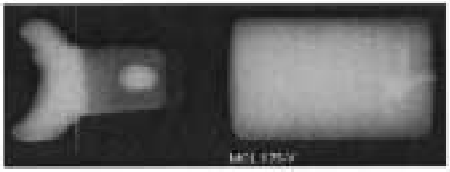

(f) Vertical X-ray, 31.5 µs after impact.

Figure 8. Yawed penetration into 7075 aluminum.

Finally, from the radiographs it appears that for yawed rod case, increase of penetration depth is complete much earlier compared to normal penetration case, even though slot lengthening may continue for a longer period.

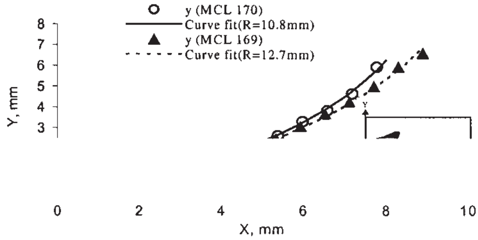


Figure 9. True cavity shape appears to conform a circular shape.

CONCLUSION

The experimental radiographs from the reverse ballistic experiments indicate that most of the cavity is in form of a circular arc, except near the tip region. The radius of curvature measured turned out to be very close to the theoretical value indicated for pure circular motion. The cavity curvature was larger for Al-7075 than Al-1100 presumably due to higher target strength. The contact surface was undulated for Al-1100 targets, which was not the case for Al-7075 targets indicating the fact that higher strength probably suppresses the instability. The portion of the long rod out side of cavity did not appear to rotate with time.

Acknowledgement: This work was supported by the U.S. Army Research Laboratory (ARL) under contract DAAA21-93-C-0101.

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