The Relation between Initial Yaw and Long Rod Projectile Shape after Penetrating an Oblique Thin plate

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ABSTRACT

The effect of yaw on the ability of an eroding long rod projectile to penetrate oblique thin targets was investigated. Numerical simulations of an eroding long tungsten rod projectile penetrating an oblique thin steel plate target were conducted using the LS-DYNA code with a user-written subroutine. The numerical results were found to agree with the experimental data.

From the simulation results it may be concluded that following penetration of a thin target, for non-zero initial yaw values, the projectile nose bends toward the velocity vector, while for zero yaw the bending is negligible.

In addition, for a non-zero initial yaw angle, the side of the projectile pointing in the direction of its velocity is damaged (this side is in greater contact with the target because of the velocity vector direction).

INTRODUCTION

The performance of thin targets against long rod projectiles is strongly dependent upon the impact obliquity. Depending on the material, geometry and impact conditions (obliquity, pitch, yaw), a projectile can be deflected from its original flight path, lose its nose, break, erode, bend, and pick up additional yaw (see figure 1, taken from Zukas [1]).

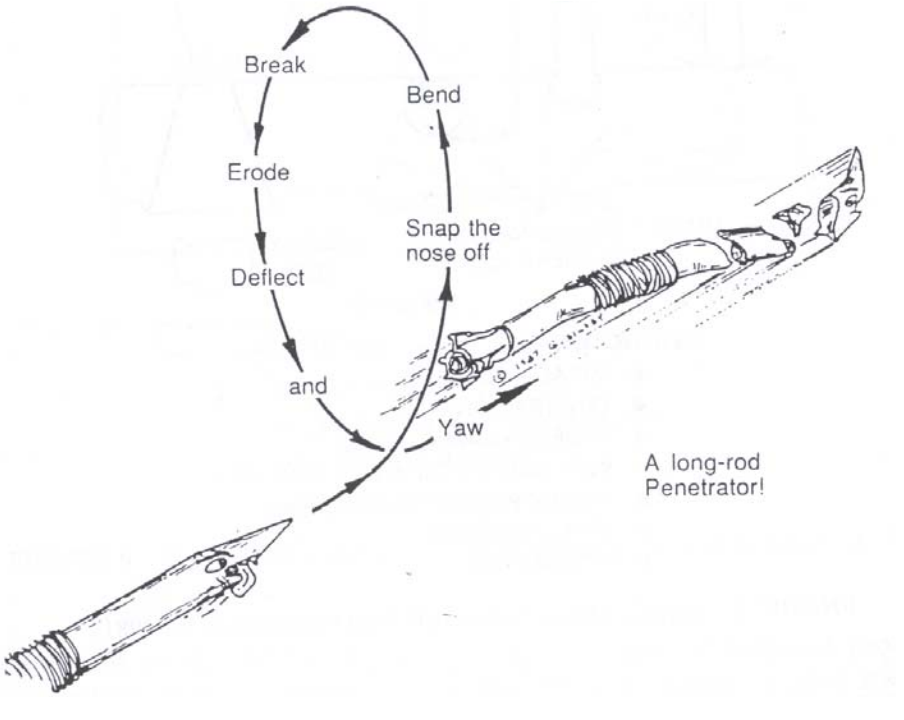


Figure 1 Effects of obliquity (Zukas [1])

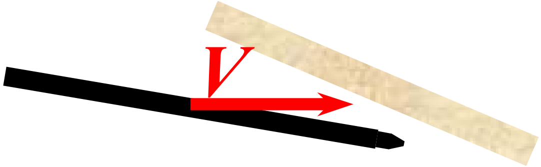
Long rod projectiles seem to erode excessively while perforating thin steel plates. In comparison, the penetration of a semi-infinite thick target at comparable impact velocity is achieved with significantly higher penetration efficiency. To gain insight into this phenomenon, a numerical study was undertaken on the perforation of a stationary, finite thickness, oblique steel plate target by tungsten-alloy long rod projectiles.

The study of the impact of projectiles on thin plates has long been of interest, and several studies on the subject are available in literature. Comprehensive surveys on the subject have been published by Backman and Goldsmith [2]; Corbett et al. [3] and Goldsmith [4] which discuss various features of the phenomena involved.

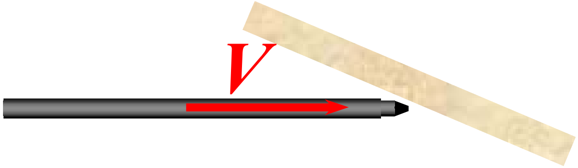
The decrease in penetration of reduced scale rods on normal and oblique semi-infinite RHA target with increasing yaw angle has been investigated for tungsten sinter alloy rods with blunt and conical noses by Hohler and Behner [5] and Behner et al [6]. Walker et. al [7] compiled a series of analytical expressions that predict the penetration of tungsten alloy projectiles into armor steel as a function of impact velocity, projectile aspect ratio (L/D), and yaw angle.

A numerical study of the perforation of stationary, finite thickness, oblique steel plates (one- or two- plate spaced target configurations) by hypervelocity tungsten-alloy cylindrical rod projectiles was carried out by Gee [8].

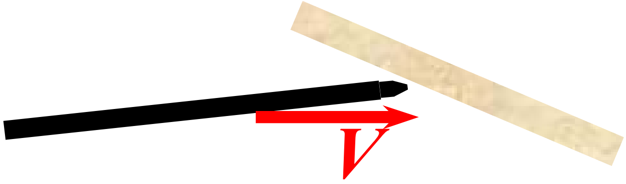
In this paper the effect of initial yaw on the ability of an eroding long rod projectile to penetrate an oblique thin target is investigated numerically. Yaw is defined as the angular difference (in degrees) between the velocity vector direction and the projectile direction (see figure 2 for yaw sign).



a) Negative initial yaw angle



b) Zero initial yaw angle



c) Positive initial yaw angle

Figure 2 initial yaw sign

NUMERICAL SIMULATIONS

The penetration process of a long rod projectile while penetrating a thin and oblique target is characterized by erosion at the nose of the projectile, large plastic strain and material flow, rotation and bending of the projectile, projectile breakage and interaction between the broken parts of the projectile and the target.

A three-dimensional time-dependent finite element numerical simulation using LS-DYNA was performed in order to emulate the penetration process of a tungsten-alloy projectile during penetration of a thin and oblique steel target. The target and the projectile were modeled with Lagrangian solid elements. Because in this kind of problem plasticity is both strain and temperature sensitive, the strain rate varies over a large range of values. Adiabatic temperature increases due to plastic heating cause material softening for which we use the Johnson-Cook material model [9]. The model for von Mises flow stress, σ , is expressed as

$$\sigma = [A + B\varepsilon^n][1 + C\ln\dot{\varepsilon}^*][1 - T^{*m}]$$

where ε is the equivalent plastic strain, $\dot{\varepsilon}^* = \dot{\varepsilon}/\dot{\varepsilon}_0$ is the dimensionless plastic strain rate for $\dot{\varepsilon}_0 = 1.0s^{-1}$ and T^* is the homologous temperature. The five material constants are *A, B, n, C, m* and are summarized in Table 1.

Table 1. Johnson-Cook material constants.

	A (MPa)	B (MPa)	n	C	M
Tungsten	1506	177	0.12	0.016	1.0
Steel	792	510	0.26	0.014	1.03

The material equation-of-state used in the simulation is the linear polynomial equation-of-state which is linear in internal energy. The pressure is given by:

$$p = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3 + \left(C_4 + C_5\mu + C_6\mu^2\right)E.$$

where $\mu = \frac{\rho}{\rho_0} - 1$, and $\frac{\rho}{\rho_0}$ is the ratio of current density to initial density. The terms $C_2\mu^2$ and $C_6\mu^2$ are set to zero if $\mu < 0$.

Adaptive Contacts were used to model the interaction between the tungsten-alloy projectile and the steel target.

We replaced the Johnson-Cook failure model in the LS-DYNA code by a failure model more suitable to our problem. The failure criterion in our model is based upon the maximum value of effective plastic strain in each element and depends upon two types of material failure:

- Erosion failure
- Static maximum plastic strain failure

The failure criterion is activated on each element and depends upon the state of the material in the element (stress, strain, pressure …). When the failure criterion is satisfied, the material loses all of its strength.

The tungsten-alloy projectile and the steel target used in the simulation are shown schematically in figure 3.

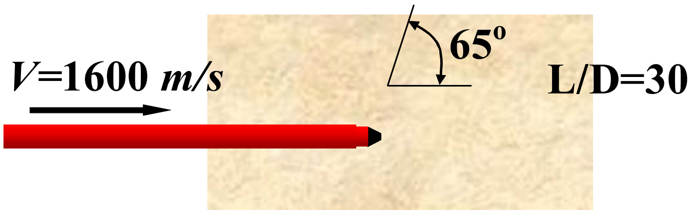


Figure 3 Schematic drawing of the tungsten-alloy projectile and the steel target.

The simulated shapes of the projectile during and after target penetration, with initial yaw angles of -1° and 0°, respectively, are presented in figures 4-5.

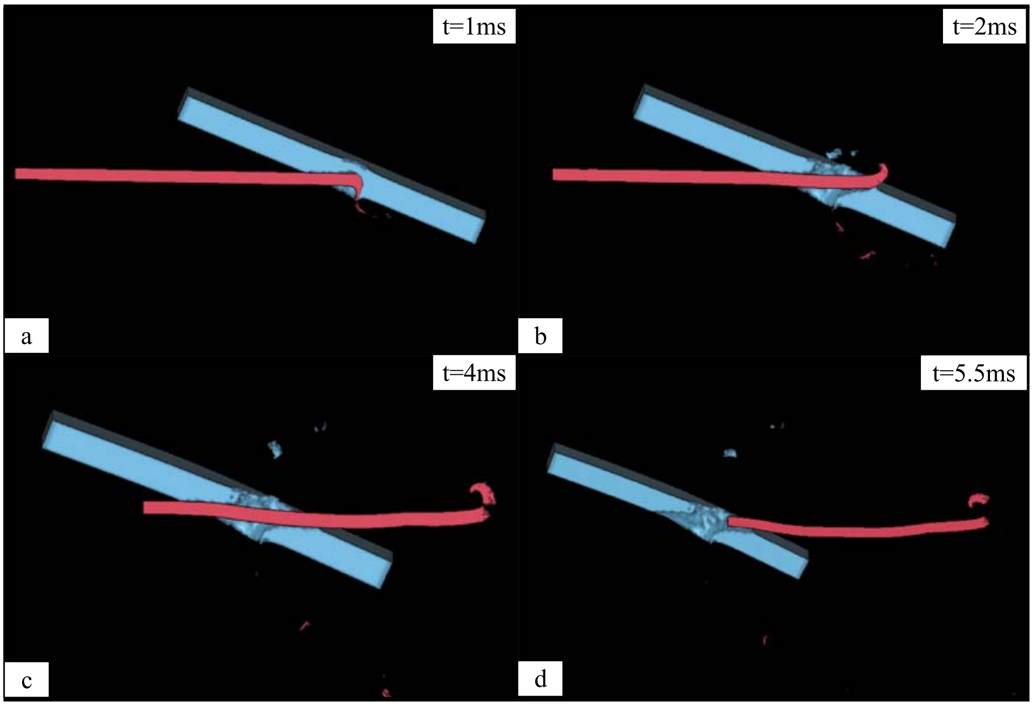


Figure 4 Simulated impact of a tungsten-alloy projectile into a steel target with initial yaw angle of -1°

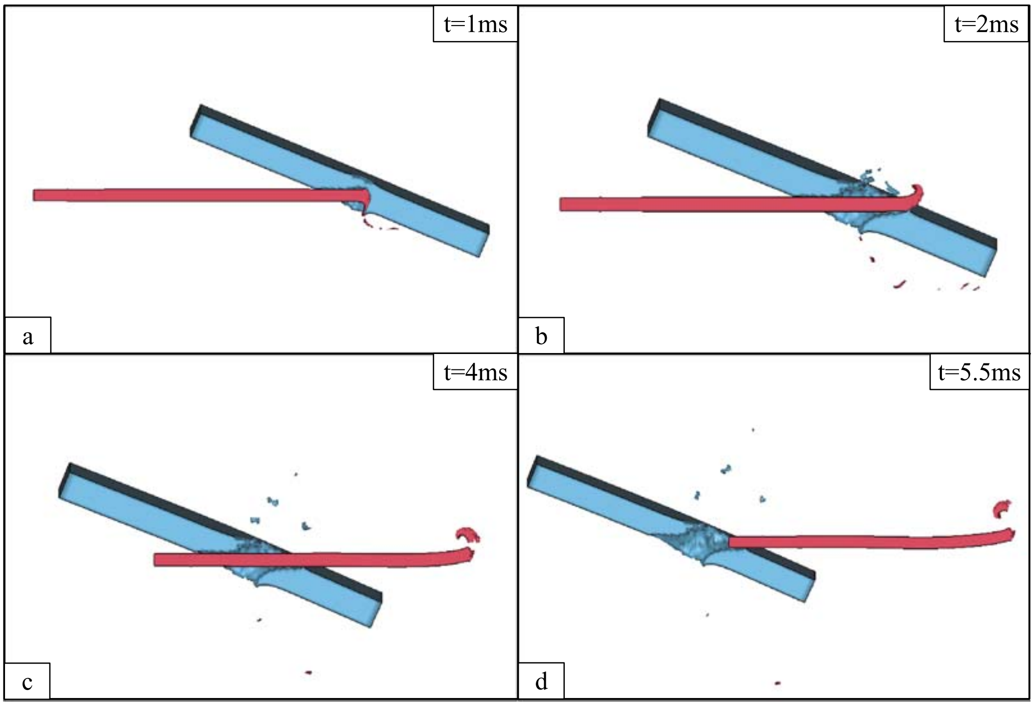


Figure 5 Simulated impact of a tungsten-alloy projectile into a steel target with initial yaw angle of 0°

It is apparent that following penetration of a thin target, for non zero initial yaw values, the projectile bends toward the velocity vector, while for zero yaw the bending is negligible.

This phenomenon was also observed in the experimental results (see appendix). The bending, which is created during penetration, enlarges the crater in the plate, thus decreasing the projectile's velocity and also diverting its direction. The overall results are a weakening of the projectile and a decrease in its ability to penetrate additional plates placed behind the target.

For large yaw angles the bending of the projectile will cause it to break into several pieces.

In addition, for a non-zero yaw, the side of the projectile pointing in the direction of its velocity is damaged (this side is in greater contact with the target because of the velocity vector direction). This damage also weakens the projectile and decreases its performance for a series of plate penetrations.

The numerical model was used to redesign the projectile in order to improve its penetrative capability and to decrease the adverse influence of yaw. We studied the influence of initial yaw numerically on many parameters during and after penetration.

In figures 6 and 7 we can see the influence of the initial yaw on the diversion (inclination angle) and the inclination angular velocity, respectively, of the projectile during and after penetration of the thin target for the three initial yaw angles.

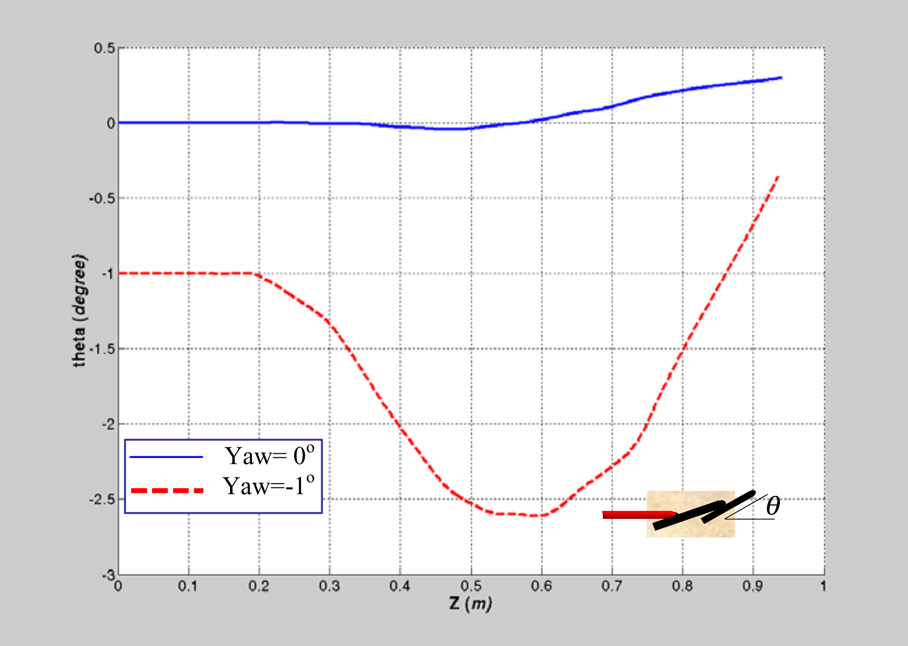


Figure 6 Penetrator Inclination angle during and after penetration

We can see that for a negative initial yaw of -1°, the inclination of the projectile axis becomes more negative during the penetration than at the end of the penetration process when its inclination angle approaches -0.4°. The rate of change of the penetrator's inclination angle is negative at the beginning and it becomes positive during the penetration. For a zero initial yaw the projectile changes its inclination by a slight positive amount. Notice that for an initial yaw of -1°, the simulated interaction plots and the impact angle graphs (figures 6 and 7) show that early time interaction includes the formation of a slot cut into the front face of the plate which tends to impart a counter-clockwise pitching moment to the rod. Once the lateral interface moves behind the long rod's center-of-gravity, it tends to convey a clockwise pitching moment to the rod. At later times, rod rotation tends to re-align the rod axis along the original trajectory.

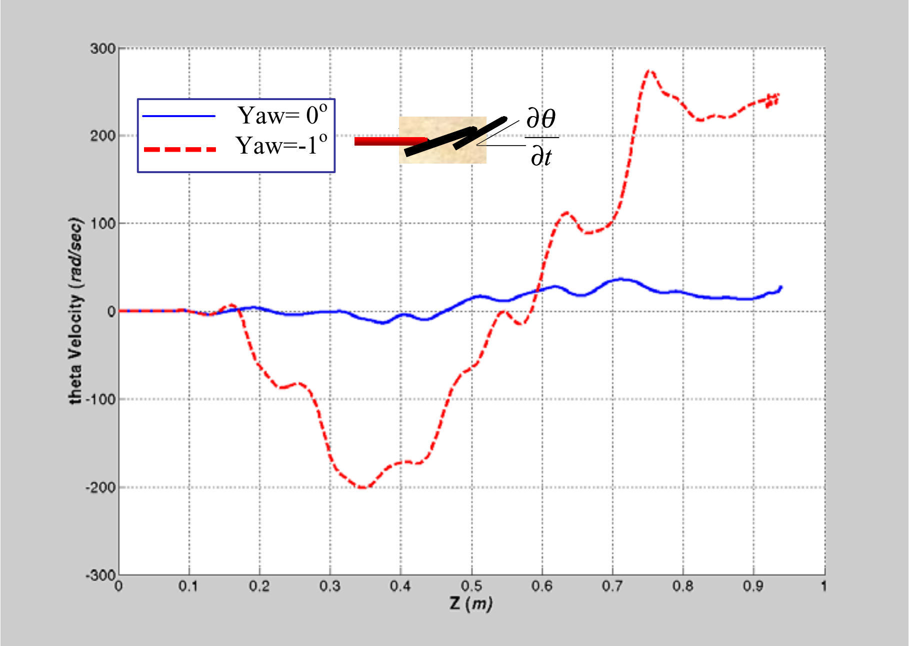
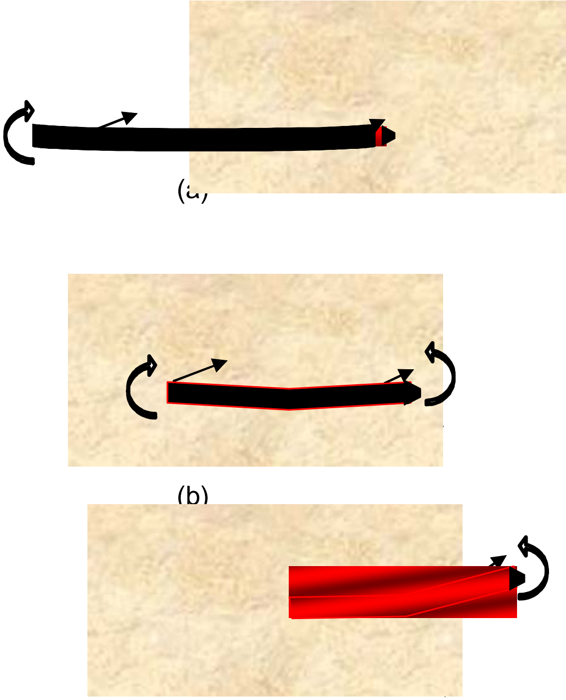


Figure 7 Penetrator Inclination angular velocity during and after penetration

The reasons for the bending can also be explained by examining the sketch in figure 8.


(a)

(b)

(c)

Figure 8 Moments due to negative initial yaw

From the sketch in figure 8a it is apparent that, initially, only the nose of the rod is in direct interaction with the target and decreases its velocity. Because of the velocity difference between the tail and the nose of the rod, and because of the negative yaw angle between the rod and its velocity, a moment is created which acts on the rod and causes it to bend up and change its inclination in a clockwise direction. When the nose of the rod has left the target (figure 8b), while its tail has not yet penetrated, the velocity differences between the tail, the mid section and the nose of the rod coupled with the negative yaw angle, creates a moment which further increases the bending of the rod. At the target's exit point, the moment further increases the bending and changes the penetrator's inclination to the counter-clockwise direction (figure 8c). This phenomenon is also noticeable in figure 4, 6 and 7.

SUMMARY AND CONCLUSIONS

In this paper we examined the effect of yawing on the ability of an eroding long rod projectile to penetrate an oblique thin target by means of numerical simulations.

A three-dimensional time-dependent finite element numerical simulation using LS-DYNA was performed in order to emulate the penetration process of a long rod tungsten projectile during and after penetration of a thin and oblique steel target, with initial yaw angles of -1^{o} and 0^{o}.

From the simulation results it may be concluded that following penetration of a thin target, for non zero initial yaw values, the projectile bends toward the velocity vector, while for zero yaw the bending is negligible.

For large yaw angles the bending of the projectile will cause it to break into several pieces.

One can also see that for non-zero yaw, the side of the penetrator pointing in the direction of its velocity is damaged, with consequent weakening of the projectile and a decrease in its performance for a series of plate penetrations following the original thin plate target.

One way of improving the ability of the projectile to penetrate a thin plate is to decrease its initial yaw angle as much as possible. When this not possible, one must find ways of decreasing the influence of the initial yaw angle on the bending and subsequent weakening of the projectile, hence decreasing its ability to penetrate additional target plates placed after the original thin plate target.

APPENDIX: EXPERIMENTAL RESULTS

In order to improve the ability of a projectile to penetrate several thin plates (target capable of breaking the projectile) several instrumented experiments were carried out. The resulting X-ray images will now be presented. The projectile and the target are shown schematically in figure 3 and the experimental results are shown in figures 9 -10 for yaw $\approx 0^{o}$ and yaw $\approx -1^{o}$, respectively.

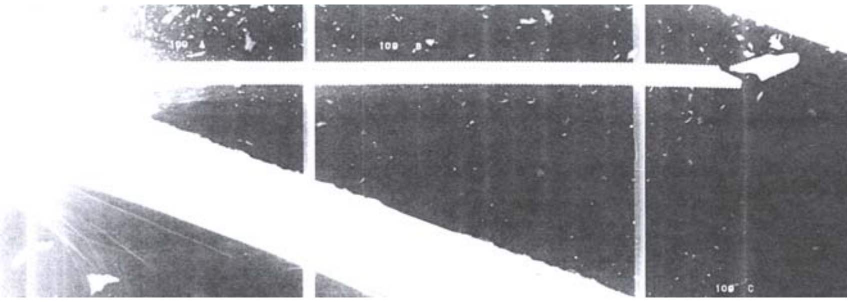


Figure 9 X-Ray image of a projectile after it penetrates a thin plate with an initial yaw angle of 0°.

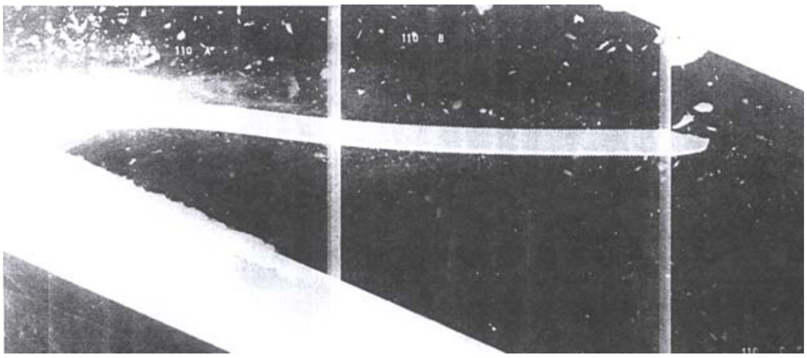


Figure 10 X-Ray image of the projectile after it penetrates a thin plate with an initial yaw angle of -1°.

From these figures it is apparent that following penetration of a thin plate target, for non zero initial yaw values, the projectile bends toward the velocity vector, while for zero yaw the bending is negligible.

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