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THE PENETRATION PROCESS OF LONG RODS INTO THIN METALLIC TARGETS AT HIGH OBLIQUITY

D. Yaziv, M. Mayseless and Y. Reifen

Rafael Ballistics Center, PO Box 2250, Haifa 31021, Israel

Experimental and computational work was conducted in order to study the interaction between long rods and thin metallic plates at high obliquity. A series of ballistic experiments was carried out. The rods were made of tungsten alloy, 135 mm long, with aspect ratio of 17. The targets were high hard steel plates with thickness in the order of the rod diameter. Impact velocities were 1,400 m/sec and the obliquities were around 75° to the normal (NATO). Flash x-ray system was employed to observe the interaction, fracture and deformation processes, as well as the measurement of the residual lengths and residual velocities of the rods. For the computational simulations the AUTODYN 3D hydrocode with the SPH processor was applied. The experimental results are discussed and compared with results predicted by the simulations. Three major phases of the interaction process were observed. The rod head ricochets while shattered into a spray of particles. The central part of the rod perforates the target plate while being eroded and deflected downwards. The tail of the rod keeps moving forward almost undisturbed. All three phases are analyzed and the residual penetration capability is evaluated and discussed.

INTRODUCTION

It is very well known that the ballistic performance of thin targets against short rigid armor-piercing (AP) projectiles is strongly dependent upon the impact obliquity. The higher the obliquity, the better the mass efficiency, for the same target thickness in line-of-sight (LOS). This effect is caused by asymmetric forces acting on the AP projectile during the entrance phase and the exit phase of the perforation process. This effect in short AP projectiles against oblique targets has been demonstrated experimentally and theoretically in many studies (see, for example [1–3]). Several studies have investigated this effect for long rod penetrators at moderate obliquities. Very little effect on the penetration capability was found during the erosion process of the rod [4–6]. Short projectiles as well as long rods penetrating at high impact obliquity might ricochet under certain interaction conditions [1,7,8].

In the present paper, experimental and computational work was conducted in order to study the interaction between long rods and thin steel plates at very high obliquities.

The experimental results are discussed and compared with numerical simulation predictions.

EXPERIMENTS

A series of ballistic experiments was carried out. The rods were made of tungsten alloy, 135 mm long, with aspect ratio of 17. The targets were high hard steel plates 7 mm to 13 mm thick – **t**. Impact velocities were 1,400 to 1,450 m/sec and the obliquities were changed in the range of 70° to 80° to the normal (NATO), keeping constant target thickness in LOS. The schematic view of the experimental setup is presented in Figure 1.

Four channel 150 Kv HP flash x-ray system was employed. The radiographs were used to monitor the interaction, fracture, fragmentation and deformation processes of the rods and the targets, as well as to measure the residual lengths and residual velocities of the rods. To evaluate the ballistic performance of the targets we applied the *depth-of-penetration* (DOP) technique, which was first introduced in [9,10].

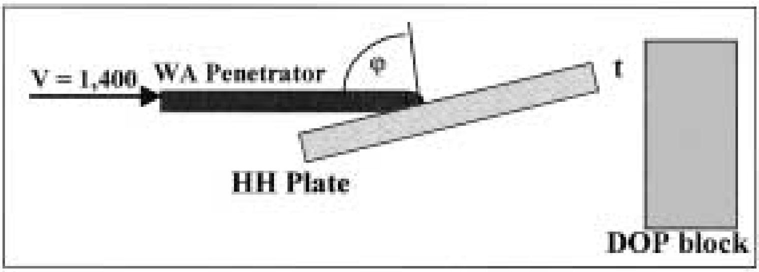

Figure 1. The Experimental Set-up.

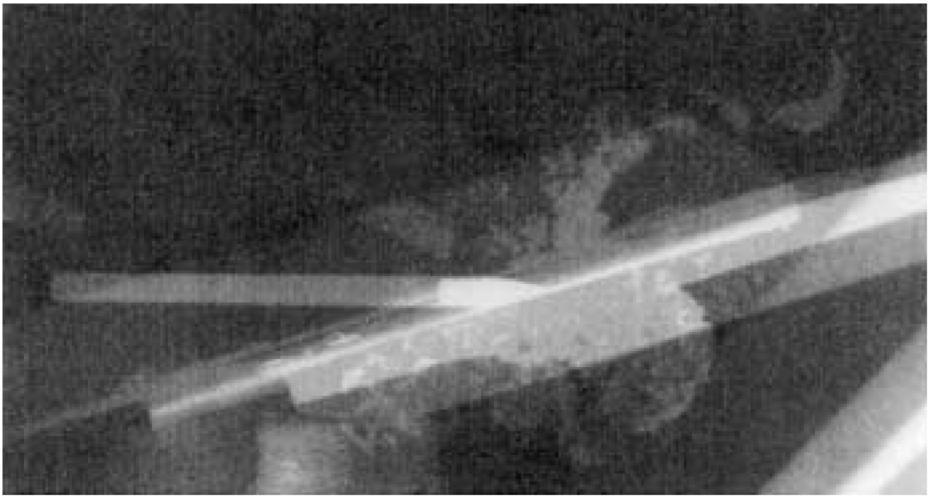

Figure 2. Flash X-ray of Test B, 0 and 100 μsec after impact.

SIMULATIONS

Numerical simulations were conducted employing the Autodyn 3D SPH solver. Two tests were simulated. In the first simulation (Test A) the 135 mm long Tungsten rod perforated a 12.7 mm HH armor plate at 73° inclination. In the second run (Test B) the perforation of a 10 mm HH armor plate at 76° was simulated. The two target configurations have the same thickness in LOS. The impact velocity was the same in both experiments 1407 m/s.

The Tungsten yield point was 1.7 GPa while that of the armor plate was 1.2 GPa. About 200,000 nodes were used for each one of these simulations. The rod and the target are shown in Figure 3 at 0, 50 and 100 μsec after impact.

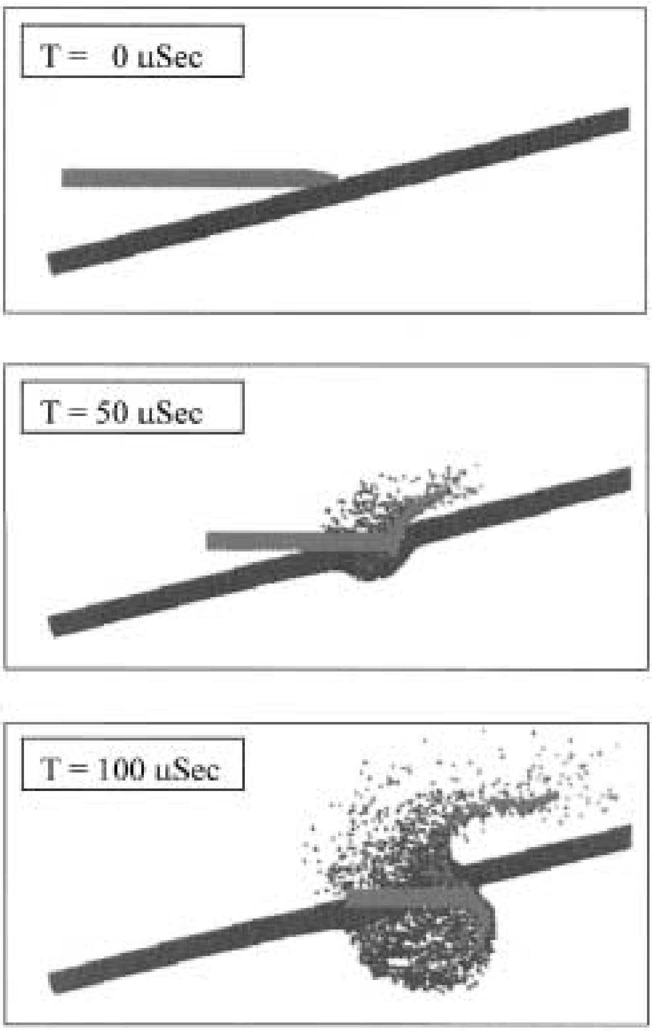

Figure 3: Simulation of Test A, 0, 50 and 100 μsec after impact.

ANALYSIS

Figure 4 compares the X-ray radiograph and the simulation of Test A at 100 µsec after impact. The rod head ricochets while the tip stays intact and the rest of the front part shattered into a spray of particles. The central part of the rod perforates the target plate while eroded and deflected downwards relative to the rear surface of the plate. The tail of the rod keeps moving undisturbed in its original direction.

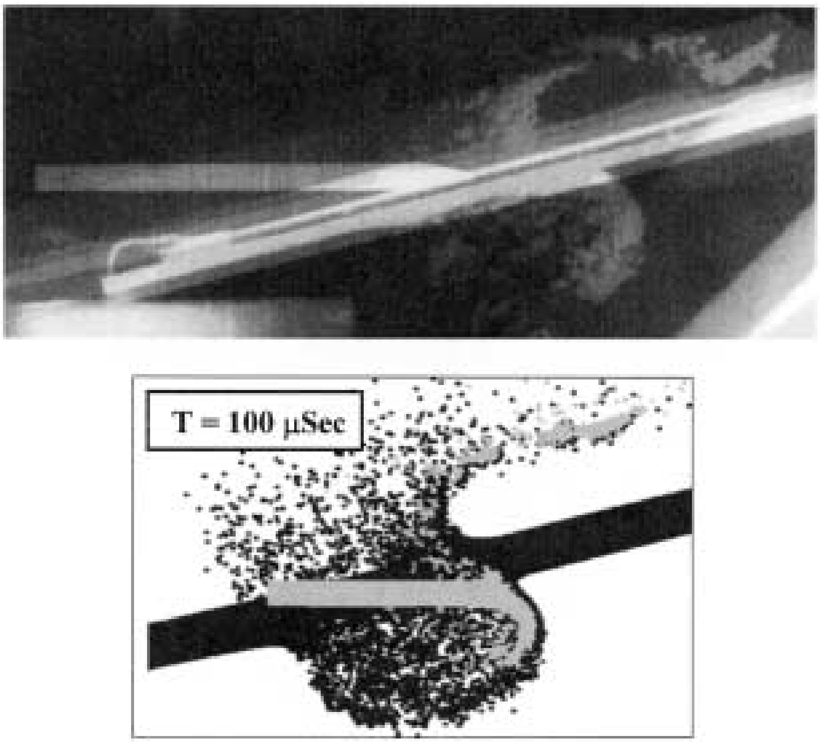

Figure 4: Test A – Top: X-ray Photo (0 and 100 sec after impact). Bottom: Simulation (0 and 100 sec impact).

Examining the numerical simulation results it was found that at the moment of impact the inclined plate pushes up the conical rod nose and a small crater is being created in the plate. This process ends after few tens of microseconds, after a small section of the front part of the rod is eroded and moves upwards. The amount of rod mass being pushed upwards in this test is about 27% of the overall rod mass and it is about the same in both configurations.

As the penetration proceeds, the eroded rod mass is moving forward because of its higher density. The non-uniformity of the crater in the target that has a finite thickness causes this debris to be pushed downwards and to emerge from the backside of the plate with a sideward velocity component. The amount of projectile mass that move downward at the moment the X-ray was taken (100 µsec) is about 8–9 % of the rod mass.

It is interesting to note that the mass loss due to the plate obliquity, the mass that was diverted upwards, is much larger compared with that being eroded during the perforation process. This strong effect is one of the reasons for the *obliquity advantage,* and it is enhanced during the final perforation process while the projectile exits from the back side of the target.

Tracer points were embedded in the simulated projectile and target as presented in Figure 5 (top). In the center part of Figure 5 the calculated axial velocity histories of the rod are presented. As we can see, the projectile is decelerated during the penetration process. The first two shock reverberations are clearly seen in the axial velocity history plot. The axial velocity is decreasing up to the point where the projectile perforates the plate, at about 120 μsec.

The velocity decrease of the rod is very similar in both experiments, and it is about 10% of the impact velocity.

The movement of the back side of the target starts a few tens of microseconds after impact, depending on the location relative to the projectile path. As we can see in Figure 5 (bottom), the material closer to the projectile path moves earlier and faster than that farther away, as expected. Moreover, the material in the upper part of the path (points 5&6) moves earlier and faster compared to that in the lower part of the path. The main reason for this effect is that the upper part in our configuration is located in the upstream direction that is affected by the initial bending of the projectile's front part.

Close to the end of the perforation process, at about 100 μsec, the leading parts of both rods are pushed downwards and the rods start to rotate. This effect is clearly seen in Figure 6 where the history plots of the side velocity of two tracer points located at the back and at the center of the projectiles are presented. The point at the center is pushed sideward strongly at the last twenty microseconds of the perforation process, at the time it gets close to the leading part of the projectile. This side movement (downwards) is the beginning of the rotation process of the residual part of the projectile that moves through the target into the witness plate.

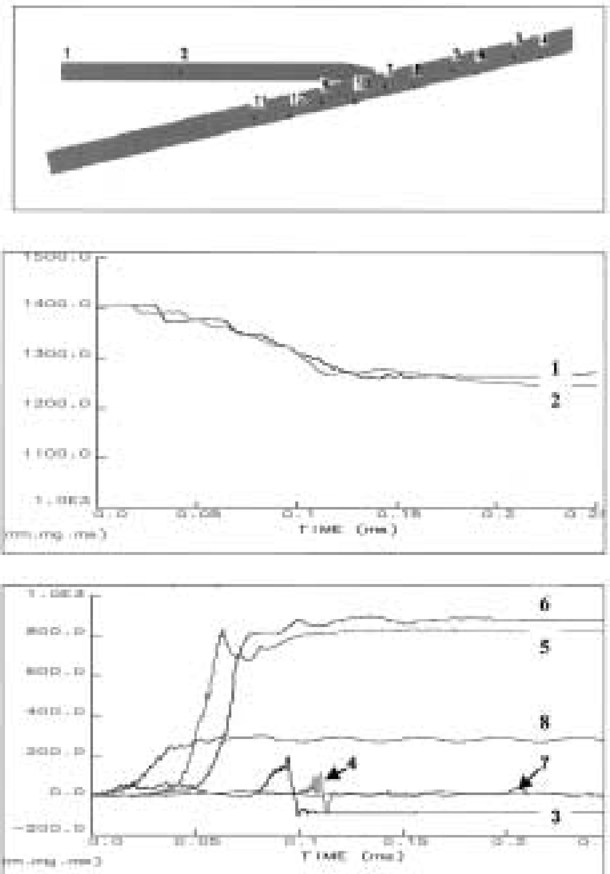

Figure 5: Test B – Axial Velocity Histories.
Top: Tracer points
Center: Rod tracer points 1 and 2
Bottom: Target tracer points 3–8

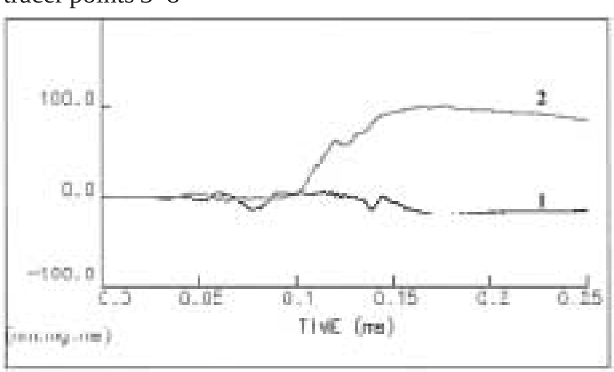

Figure 6: Side Velocity History of tracer points 1 and 2.

The lengths between the rod tails and the front part of the debris clouds in the X-Ray radiograph of the two experiments were compared to that in the simulations and was found to be in a very good correlation. The experimental length of the residual rod is about 72 mm while in the simulation it is 70 mm. The small difference can result from the material model used in the simulation and the inaccuracy in the impact velocity measured (±2%).

The Mass efficiency (E_f) of the target plates was calculated from the DOP results related to the baseline performance of the rod at the relevant impact velocity. The reference penetration is 95 mm in an RHA block at normal incidence. Based on that, the DOP data indicate E_f in the range of 1.07 to 1.09. That efficiency is mainly related to the *obliquity advantage*, described above.

CONCLUSIONS

Three major phases of the interaction were observed during the perforation process of a long rod into a highly inclined target plate:

a. *The head* (~ 27 % of the rod length) ricochets while shattered upwards.
b. *A central part* (~18 % of the rod length) perforates the target plate while eroded and deflected downwards.
c. *The tail* (~55 % of the rod length) is moving almost undisturbed in its original direction.

The residual rod velocity is about 90% of the original rod velocity and its penetration capability is approxirnately 50% of that of the original rod.

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