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TERMINAL BALLISTICS OF EFPs – A NUMERICAL COMPARATIVE STUDY BETWEEN HOLLOW AND SOLID SIMULANTS

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A numerical study was undertaken to investigate the penetration and the perforation capabilities at normal incidence of a hollow tantalum EFP simulant against armor steel, within the range of impact velocity between 1500 m/s and 2500 m/s. The results are compared with the performances of a solid tantalum cylinder of the same total length and mass, and with published data relative to an aerodynamically optimized iron EFP simulant, which is 60% longer. Against the semi-infinite target, the difference between the hollow and the solid shape reaches –30% at 1500 m/s and –15% at 2500 m/s. The tantalum hollow projectile retains the advantage over the iron simulant: from 20% at 1500 m/s to 10% at 2500 m/s. As regards to perforation capabilities, the margin is roughly about 10% in favor of the solid shape. Compared with iron, the performances of the hollow tantalum simulant are attractive up to 2300 m/s, with an advantage of 15% at 1500 m/s. At higher velocities, the iron candidate turns its length to account.

INTRODUCTION

Because of its high density combined with a quite high ductility, tantalum is recognized to be a material of choice for Explosively Formed Projectile (EFP) applications. It is used as a liner material in existing systems (BONUS, SADARM, SMArt). To fulfill the aerodynamic requirements, i.e. to hit the target under satisfying impact conditions after a stand-off about 1000-charge-caliber, the projectile must be somewhat hollow with a flared afterbody or fins. Nevertheless, published papers dealing with Terminal Ballistics of EFPs often consider solid shaped projectiles [1,2]. Most of the time there are cylinders with a hemispherical forebody. This paper tries to give an objective evaluation of the penetration and perforation capabilities of a more representative projectile, taking into account realistic parameters of today: degree of slenderness L/D, degree of solidity, impact velocity… For comparison, this study includes results achievable by a solid cylinder of the same total length. Because iron can compete with tantalum under specific conditions

[1,3], results obtained with tantalum are also compared with published data concerning an idealized view of what could be an aerodynamically optimized iron EFP [4].

BASICS

Simulants Investigated

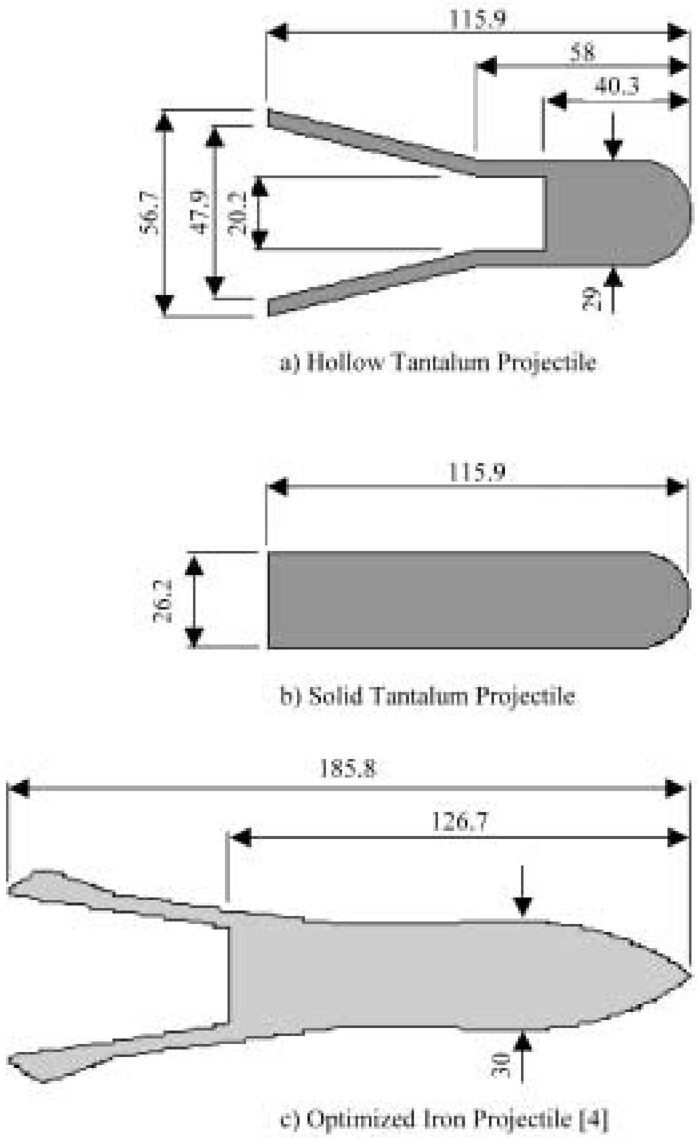

Figure 1. Simulants investigated (axisymmetrical shapes).

The projectiles investigated are presented in Fig 1. They are axisymmetrical. Dimensions are expressed in mm. For convenience, mass of the simulants was fixed at 1 kg. The hollow tantalum projectile (HTP) has a L/D-ratio of 4. The flare diameter is approximately twice the head diameter. The degree of solidity is about 50%. For a same total length, the solid tantalum projectile (STP) shows a L/D-ratio of 4.4. The length of the optimized iron projectile (OIP) takes into account the laboratory state of the art [3]. More details on this geometry can be found in [4]. The original simulant was scaled up for comparison at constant mass. The performances were studied within a velocity range between 1500 m/s and 2500 m/s.

Numerical Simulation Approach

For our purpose, numerical simulations were carried out using the Eulerian capability of OTI*HULL software [5], a multi-material hydrocode featuring a secondorder accurate scheme. Both the projectile and the target were described using the Mie-Gruneisen equation of state and an elastic-plastic constitutive law based on the Von Mises yield criterion. The failure behavior of the target was treated using the "P/Y failure curve" capability of the code. It is recognized that strain to failure of ductile high-strength steels depends markedly on the triaxial stress-state which may be characterized by P/Y, where P represents the mean stress or pressure and Y denotes the effective stress: $Y = \sqrt{3J_2}$, J_2 referred as the second deviatoric stress invariant. Fracture is initiated when the maximum principal strain exceeds the fracture surface $\lambda = f\ (P/Y)$. This critical strain to failure is used as a simple instantaneous failure criterion.

Two types of targets were investigated: a monolithic target, Ø 500 mm and 320 mm thick, to evaluate the penetration performance, and a Ø 500 mm plate of varying thickness to study the perforation capability at normal incidence. The targets are made of "classic" French armor steel MARS 190. Their lateral dimensions are more than 15 times the projectile head diameter. The limit of perforation is determined as the limit thickness above which no fragment is ejected from the rear surface of the plate.

Mesh resolution is clearly an important factor in the successful execution of the simulations. Impact of the various projectiles was simulated using a 1 mm square constant mesh size for the region of most interest. This corresponds to 30 cells across the diameter of the projectile. Beyond this strong interaction region including the entire thickness of the target, zones were increased at an expansion ratio of 2%. Lagrange trace particles were inserted into the projectiles to reveal the material flow. This numerical approach was validated by previous works [6].

RESULTS AND DISCUSSION

Penetration Capabilities

The depth of penetration into the semi-infinite target was firstly reviewed. Examples of crater profiles at 2100 m/s are plotted in Fig 2. A penetration of 121 mm is achieved with the hollow tantalum simulant, while the solid cylinder performs 143 mm. The performance of the iron candidate is limited to 106 mm.

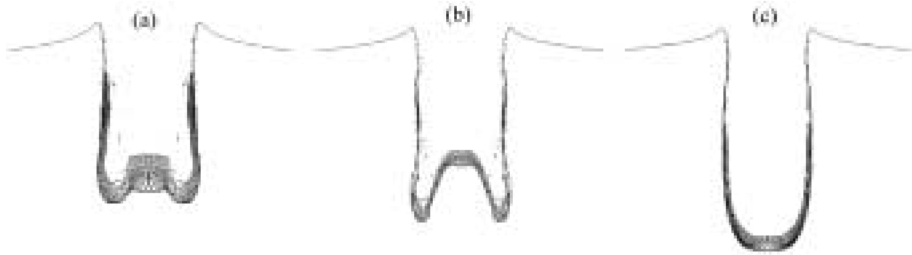

Figure 2. Penetration profiles at 2100 m/s:
(a) Optimized Iron Projectile (b) Hollow Tantalum Projectile (c) Solid Tantalum Projectile.

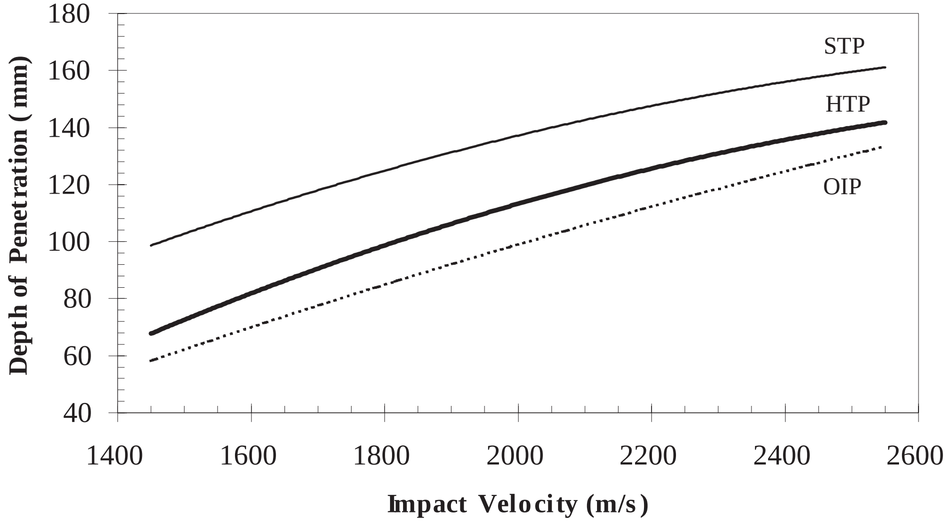

Figure 3. Penetration capabilities against armor steel.

The evolution of depth of penetration versus the impact velocity is shown in Fig. 3. For a same length of projectile, the difference between the solid cylinder and the hollow shape reaches 40% at 1500 m/s and 15% at 2500 m/s. Compared with the iron simulant, which is 60% longer, tantalum hollow projectile retains the advantage over the velocity range investigated: from 20% at 1500 m/s to 10% at 2500 m/s. In other words, to reach the same level of performance as the solid tantalum projectile at 1800 m/s, the hollow simulant should hit the target with an impact velocity around 2200 m/s. To compete with tantalum, the iron projectile should impact at 2400 m/s.

Perforation Capabilities

As it can be seen on Fig. 4, the margin between hollow and solid tantalum simulants is about –10% over the whole velocity range. Compared with iron, the performances of the hollow tantalum projectile are attractive up to 2300 m/s, with an advantage of about 15% at 1500 m/s. At higher velocities, the iron candidate turns its length to account. To give an example: to get the same power of perforation as the solid projectile at 1800 m/s, the impact velocity of the hollow tantalum simulant should be 2000 m/s. To compete, the iron projectile should strike at 2100 m/s. It is worth mentioning that presented results relative to the solid cylinder, STP, are consistent with published data from Weimann [1].

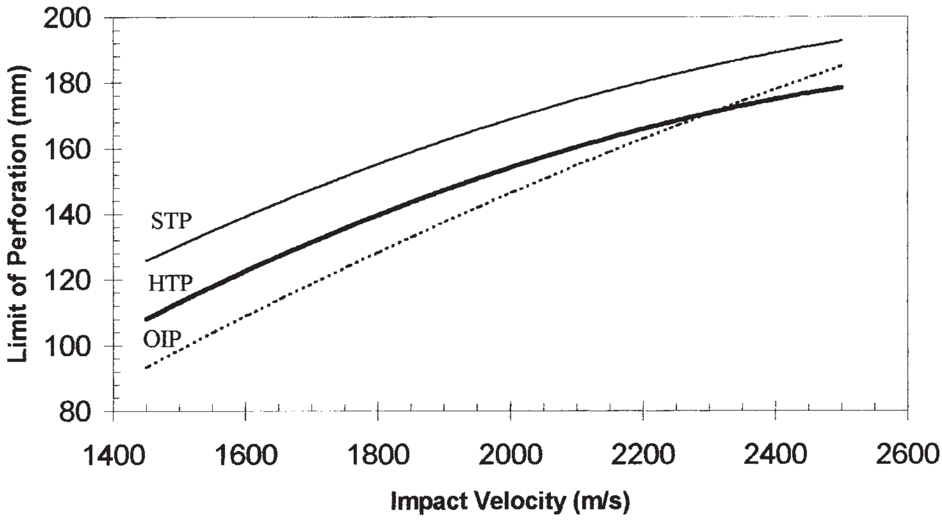

Figure 4. Perforation capabilities against armor steel.

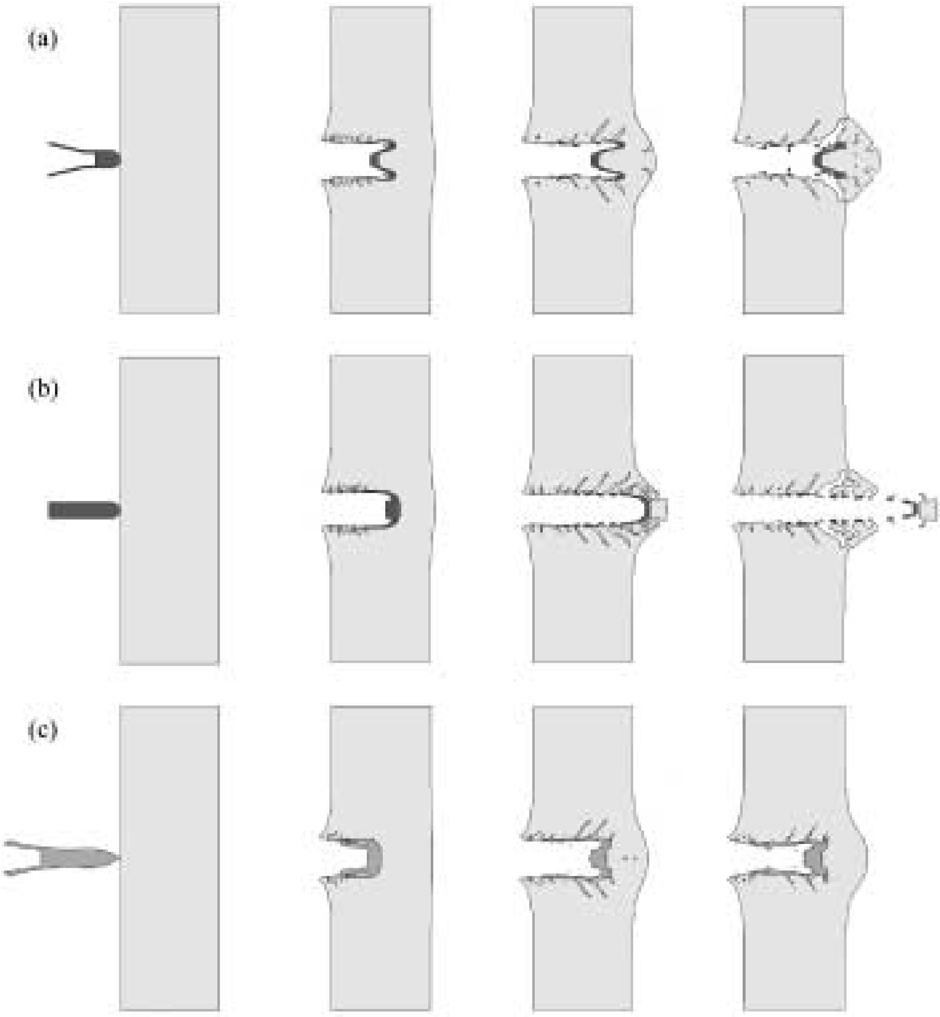

Figure 5. Comparative performances at 2100 m/s against a 160 mm thick armor steel plate. Snapshots at time = 0 µs – 100 µs – 200 µs – 400 µs
(a) Hollow Tantalum Projectile (b) Solid Tantalum Projectile (c) Optimized Iron Projectile.

Fig. 5 illustrates the behavior of the projectiles when impacting a 160 mm thick armor steel plate at 2100 m/s. While the iron candidate is stopped into the target, the hollow tantalum simulant just emerges from the rear side of the plate. Simulations indicate a residual velocity around 50 m/s. The solid cylinder clearly defeats the target. The velocity of fragments approximates 400–500 m/s.

Noteworthy is that none of the formulae in the literature can predict with a satisfying accuracy the performance of EFP-like projectiles over the velocity range investigated. First, because the shape of the projectiles are half-way between the sphere and the rod

(L/D > 10). Then, because even high, the impact velocities do not reach the hydrodynamic regime. Most of the empirical relations proposed to correlate with ballistic data are derived from Jacob de Marre relation (1) where M, D and V denote the mass, the diameter and the velocity of the projectile, and T is the target limit thickness perforated. α, β and C are empirical, best fit parameters. In his original paper [7], de Marre gave the formula with $\alpha = 1{,}4$ and $\beta = 1{,}5$.

$$M\,V^2 = C\;D^\beta\,T^\alpha \qquad (1)$$

CONCLUSIONS

The penetration and the perforation capabilities of a 50%-hollow tantalum EFP simulant against armor steel have been investigated for impact velocities ranging between 1500 m/s and 2500 m/s. Decrease in performance due to hollowness has been evaluated in comparison with a solid shaped projectile of the same total length and mass. A maximum loss of 30% is observed at lowest velocities against the semi-infinite target. With regards to the perforation capabilities, the loss of performance is about 10% over the whole velocity range. Only this order of magnitude should be kept in mind since the semi-infinite configuration is just an academic target, unknown to the battlefield!

To compete with tantalum, iron EFPs should be more elongated and more rapid: 60% longer and with an impact velocity 100 m/s or 300 m/s superior to hollow and solid tantalum projectiles respectively.

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