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On the penetration of high strength steel rods into semi-infinite aluminium alloy targets

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ABSTRACT

Three modes of penetration were observed experimentally in the literature for the penetration of semi-infinite aluminium alloy targets struck normally by high strength steel rods with hemispherical ends and they are, depending upon initial impact velocity, penetration by a rigid penetrator, penetration by a deformable penetrator and penetration by an erosive penetrator. A theoretical study is presented herein to describe these three modes of penetration within a unified framework and the critical conditions for the transition among the three modes are determined by means of two critical velocities, namely, the rigid body velocity (V_R) and the hydrodynamic velocity (V_H). The rigid body velocity is defined as the impact velocity at which the resultant target resistance force is equal to the dynamic strength of the penetrator times the cross-sectional area of the shank and the hydrodynamic velocity as an impact velocity at which a stable mushrooming head is formed on the basis of physical consideration. Furthermore, the secondary penetration by debris tube is also considered. It transpires that the present model predictions are in better agreement with the experimental data for the penetration of 4340 steel rods into 6061-T6511 aluminium alloy targets at impact velocities between 0.5 km/s and 3.0 km/s as compared to the existing analytical and numerical models.

1. Introduction

Long rod penetrators with large length/diameter ratios have been widely used in weaponry industry due to its high specific kinetic energy density and great penetration capability. Much effort has been dedicated to the theoretical, numerical as well as experimental study of long rod penetrators penetrating targets for the past half century or so and a great deal of progress has been made in terms of data collection and analytical and numerical models. Generally speaking, the penetration of a long rod into a semi-infinite target can be divided into two categories depending upon the ratio of the penetrator dynamic strength to the target resistance.

For the scenario where penetrator strength is less than target resistance, many theoretical models have been proposed among which the most widely used theoretical model is the one-dimensional modified Bernoulli equation due to Alekseevskii [1] and Tate [2] (The A-T model). The A–T model assumes that the materials of both penetrator and target near the interface behave as fluid while the rear of the projectile remains rigid and the transition from rigid to fluid is ignored. In the A-T model the penetrator dynamic strength is usually taken to be of the order of magnitude of the Hugoniot elastic limit (*HEL*) of the penetrator material according to Tate [2] and the target resistance (R_t) in the A-T model is assumed to be a constant which is contrary to the finding made by Anderson et al. [3]. They investigated the target resistance (R_t) under various impact velocities by curve fitting the A–T model predictions to the experimental data for tungsten alloy long rod penetration into semi-infinite armor steel targets. It was found that the target resistance is not a constant but a function of impact velocity when impact velocity exceeds 1.5 m/s.

Roisman et al. [5] suggested an analytical model to describe the penetration of an eroding projectile into an elastic-plastic target. The solution does not use any adjustable parameters or functions and it involves only the geometrical and material data known for the experiments taken from the literature which have been used for comparisons. It was shown that the model is capable of predicting the penetration depth, the crater diameter and the residual length and mass of the penetrating projectile. Nonetheless, as acknowledged by Roisman et al. [5] the proposed model is applicable to the scenario where $Y_p < S$ only with Y_p being penetrator dynamic strength and S static target resistance. For the scenario where $Y_p > S$ the model suggested by Roisman et al. [5] is not applicable.

It should be mentioned here that cavity expansion approximation (CEA) models [6–8] show that target resistance is always a function of the projectile-target interface velocity for any velocity greater than zero whilst velocity field approximation (VFA) theories [9–11] demonstrate that target resistance is a constant for penetration

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Nomenclature

A_0	initial area of penetrator shank
A	area of deformed part of penetrator
C	3/2 for incompressible materials
C_H	velocity relative of plane *EP* to the point O, as defined in Fig. 2
DOP_{deform}	depth of penetration by penetrator when it penetrates in a deforming mode
$DOP^{r}{}_{\mathrm{rigid}}$	depth of penetration by residual penetrator in a rigid mode
a, b, c	constants, defined in Eq. (14)
DOP_{primary}	depth of penetration by penetrator in an erosive mode (i.e., quasi-steady penetration)
$DOP^{r}{}_{\mathrm{deform}}$	depth of penetration by deforming residual penetrator
$DOP_{\mathrm{secondary}}$	depth of secondary penetration (i.e., penetration by debris tube)
DOP_{total}	total depth of penetration
E_1	elastic modulus of target material
E_2	plastic modulus of target material in a bilinear model
f	frictional force
$F(r_{0,}\ v)$	resulting axial resistant force
$f(v)$	‘average pressure’ distributed on the cross section of the penetrator
HEL_{t}	Hugoniot elastic limit of target material
HEL_{p}	Hugoniot elastic limit of projectile material
L	initial length of penetrator
L_0	equivalent length of a flat-ended projectile with the same radius and mass
l	length of undeformed part of penetrator
$L^{\mathrm{R}}{}_{\mathrm{residual}}$	length of residual penetrator when $v = V_{\mathrm{R}}$
$L^{\mathrm{H}}{}_{\mathrm{residual}}$	length of residual penetrator when $v = V_{\mathrm{H}}$
L_{residual}	length of residual penetrator
L_{tube}	length of debris tube
M_{rigid}	mass of penetrator when it penetrates in a rigid mode
M_{residual}	residual mass of erosive penetrator
n	constant usually tanken to be 3
p	pressure distributed on the penetrator nose surface
R	radius of deformed part of penetrator
R_{m}	radius of mushrooming nose of penetrator
r_0	radius of residual penetrators
S	target static resistive pressure determined by spherical cavity expansion model
u	penetration velocity
u_{H}	penetration velocity corresponding to V_{H}
U_{F0}	critical penetration velocity, defined as $(HEL_{\mathrm{t}}/\rho_{\mathrm{t}})^{0.5}$
U_{e}	penetration velocity corresponding to V_{e}
v	velocity of rear of penetrator (tail velocity)
v_{n}	normal component of penetration velocity
V_0	impact velocity
V_{R}	rigid body velocity
V_{e}	velocity of ejecting debris
V_{C}	velocity, determined by setting Eq. (14a) equals Eq. (14b)
V_{H}	hydrodynamic velocity
Y	target yield stress
Y_{p}	penetrator dynamic strength
α	square root of the ratio of the average density of the tube to that of the unitary penetrator
θ_c	critical angle at which $v_{\mathrm{n}} = v\cos\theta_c = U_{\mathrm{F0}}$
μ	frictional coefficient
ρ_{t}	target density
ρ_p	penetrator density
φ	ratio of the cross area of penetrator to ejected debris

velocities less than a critical value and for penetration velocities greater than the critical value it is a function of penetration velocity. These two theories are derived based upon different assumptions and, hence, the target resistances obtained are slightly different in mathematical terms. As a matter of fact, the target resistance obtained from CEA model for lower impact velocities is weakly dependent on the impact velocity apart from other factors related to both the projectile and target and, to a first approximation, can be taken as constant for sharp projectiles.

For the scenario where penetrator strength is greater than target resistance, much less research involving deformable and erosive penetrators has been performed so far except for the experimental investigations by Forrestal et al. [4] Piekutowski et al. [12] and Wickert [13]. Forrestal and Piekutowski [4] carried out an experimental investigation into the penetration of semi-infinite 6061-T651 aluminium alloy targets struck normally by 4340 steel long rods at impact velocities between 0.5 and 3.0 km/s. Three modes of penetration were observed experimentally depending on the impact velocities, namely, penetration by a rigid penetrator, penetration by a deformable penetrator and penetration by an erosive penetrator.

For the penetration by a rigid penetrator the depth of penetration (DOP) can be predicted using cavity expansion approximation models [6] whilst for the penetration by an erosive penetrator the DOP can be computed by the A-T model as a first approximation. The penetration by a deformable penetrator is, however, much less discussed than the penetration by a rigid or erosive projectile though it is of great theoretical and practical significance. Based on the experimental observations made by Forrestal and Piekutowski [4], Chen and Li [14] discussed the transition of a penetrator from rigid state to semi-hydrodynamic state. On the other hand, Dekel and Rosenberg [15] performed a series of 2D numerical simulations and, by introducing the failure modes of the penetrator and the target, they obtained similar DOP curve to that reported by Forrestal and Piekutowski [4]. It should be mentioned here that the numerical results were in good agreement with the test data for relatively low impact velocities (i.e., the penetration by a rigid penetrator) and significantly overpredict the DOP for higher impact velocities (i.e., the penetration by a deformable or erosive penetrator).

Recently, Wen and co-workers [16–20] carried out a systematic theoretical investigation into the long rod penetration problem within a unified framework. Long rod penetration can be divided into two categories on the basis of ratio of penetrator dynamic strength (Y_{p}) to target static resistance (S). For $Y_{\mathrm{p}}<S$ the model proposed by Lan and Wen [16] represents an extension of the modified hydrodynamic theory, namely, the A-T model and the target resistance (R_{t}) is no longer a constant but a function of penetration velocity and the thermo-mechanical properties of target material. For $Y_{\mathrm{p}}>S$ depending upon initial impact velocity, there exist three types of penetration, namely, penetration by a rigid long rod, penetration by a deforming non-erosive long rod and penetration by an erosive long rod. For $Y_{\mathrm{p}}<\mathrm{S}$, the model proposed in [16] correlates well with the experimental observations for a combination of penetrator and target materials [21–24], in terms of DOP and crater diameter; for $Y_{\mathrm{p}}>\mathrm{S}$, the model predictions are in reasonable agreement with the test results for the penetration semi-infinite 6061-T651 aluminium alloy targets