Recent Representative IAT Studies in Hypervelocity Penetration Mechanics with Bibliographies

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The Institute for Advanced Technology (IAT) has conducted, and continues to conduct, a broad program to investigate the penetration characteristics and lethality of rod penetrators. The IAT's investigations are experimental, analytical, and numerical and are concerned primarily with slender rods impacting armor steel and ceramic targets at hypervelocity — that is, above about two km/s. This report summarizes the results developed in representative examples of these studies that supported the U.S./UK Project Arrangement. The work accomplished supports items a), b), and c) of the agreed-upon SOW. Each summary is accompanied by a bibliography listing relevant publications generated at the IAT and elsewhere.

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Recent Representative Studies in Hypervelocity Penetration Mechanics with Bibliographies

William G. Reinecke

INTRODUCTION

The Institute for Advanced Technology (IAT) has conducted, and continues to conduct, a broad program to investigate the penetration characteristics and lethality of rod penetrators. The IAT's investigations are experimental, analytical, and numerical and are concerned primarily with slender rods impacting armor steel and ceramic targets at hypervelocity — that is, above about two km/s. Below are summarized the results developed in representative examples of these studies that supported the U.S./UK Project Arrangement. The work accomplished supports items a), b), and c) of the agreed-upon SOW. Each summary is accompanied by a bibliography listing relevant publications generated at the IAT and elsewhere.

SCALING EFFECTS IN PENETRATION

The effect of test scale in penetration experiments has recently been examined by a number of authors (see Bibliography) with seemingly contradictory results. To the extent that penetration phenomena depend on test scale, strain rate effects have appeared to be a likely cause. In particular, while it has been shown in calculations that logarithmic rate hardening would result in barely perceptible effects, if there is a transition to linear rate hardening at a small enough scale, then scale effects might become more evident. Considering the difficulties of interpreting penetration experiments, we have conducted "zero penetration" tests; i.e., Taylor tests using common armor steel (RHA). Tests were conducted in the reverse ballistic mode at 215 to 280 m/s. To examine scale effects, two L/D = 5 rod sizes with diameters of 1 cm and 0.2 cm were used.

Taylor tests were performed on common armor steel in the reverse ballistic mode at 215 to 280 m/s to examine scale effects on yield strengths using L/D = 5 rods of 1 cm and 0.2 cm diameter. AUTODYN-2D calculations showed that strain rate scales inversely with size and directly with velocity in agreement with dimensional analysis. Yield strengths (Y_d) of RHA were determined to be 1.46 to 1.79 GPa using the Wilkins-Guinan formula. It was found that the strength of the smaller specimens was 7 to 9%

more than the larger specimens. This is nearly what would be expected from a logarithmic dependence of strength on scale (strain rate), which predicts an increase of 12%.

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CAVITY MODELS FOR ERODING PENETRATORS

The goal here is to explain the diameter of craters in metal targets that are penetrated by eroding projectiles. At high velocity, craters can be two to three times larger than the penetrator diameter. It is shown in numerical calculations [Kivity and Hirsch, 1987] that the radial motion of target material penetrated by long projectiles occurs in two stages. In the first stage, the radial flow of eroded penetrator elements plays the dominant role in opening a cavity. In the second stage, the radial inertia deposited in the target is responsible for the further cavity expansion (cavitation) until the strength of the target forces it to come to rest.

There have been several previous attempts to explain cavity diameters made by high speed penetrators. An early analytical study based upon a momentum balance argument was presented by Szendrei [1984]. Using an energy balance argument, Tate provided an approximate formula for the crater diameter [Tate, 1986]. In more recent experiments, Bjerke et al., 1992, presented an empirical equation for the channel diameter versus impact velocity for sintered tungsten-nickel-iron penetrators impacting thick and normal incidence steel targets. By accounting for the first stage with a proper choice of initial conditions, Shinar et al., 1995, modeled the second stage and determined the final crater size. However, there are some difficulties associated with the initial conditions since it is assumed that the inertia phase starts when the cavity radius is equal to the initial penetrator radius. Miller, 1990, presented a complete engineering description of the jet erosion front and kinematics in the absence of material strengths. Szendrei, 1995, reformulated his previous model to explicitly include target strength. For the case of non-eroding projectiles, Hill, 1980, investigated the cavitation produced by an axisymmetric projectile traveling through an infinite medium at constant velocity, although the entire physics is different for hypervelocity attack, where the projectile itself deforms.

Cavity formation during hypervelocity penetration of slender hollow cylinders was modeled by Franzen, 1987, based on hydrodynamic theory. Even though many simplifications were made, the model can provide a criteria for choking of flow on the tube axis. This condition, in which no significant amount of projectile material passes through the axial projectile cavity, occurs for a ratio of the inner diameter to the outer diameter that is less than 0.7.

The IAT developed two analytical models for the crater diameter generated by long-rod and thick-walled tube projectiles. The first, Lee and Bless [1996], is based on energy; in a steady-state penetration, the kinetic energy loss of a penetrator is related to the total energy deposited in the target. This simple approach provides an upper bound for the crater size. The second approach, Lee and Bless [1997], is based on the observation that two mechanisms are involved in cavity growth due to long penetrators: flow of penetrator erosion products, which exerts radial stress on the target and opens a cavity, and radial inertia of the target as it flows around the penetrator nose (cavitation). This analysis includes the centrifugal force exerted by the penetrator, radial inertia of the target, and the strength of the target. Thus it can estimate the extent of cavity growth due to penetrator mushrooming, which cannot be predicted by other analyses. This model was shown to be in good agreement with experimental data. Models have also been extended to account for finite targets [Normandia et al., 1996] and brittle targets [Satapathy and Bless, 2000].

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FAILURE IN CERAMICS

Al_2O_3 (alumina and sapphire) is the most common ceramic material used for impact protection. Alumina is the most widely used armor material mainly due to the fact that it is the cheapest high-grade ceramic.

There has been a great effort to characterize alumina's dynamic properties, and there are several different computer models for it [Simha, 1998]. Although many features of the response of alumina are felt to be understood, one of the most important behavior patterns is not presently described by any model — the time-dependent degradation of strength in both thick and thin tiles [Rajandran, 1999; Bless, et al., 1993]. Hence, research on this material continues. Sapphire is a poorer armor material [Rosenberg, et al., 1987], but is commonly used for shock windows and some transparent armor applications. Recently, there has been a growing interest in the polycrystalline ceramic aluminum oxynitride (AlON, $Al_{23}O_{27}N_5$, or transparent alumina).

AlON first came to prominence as a possible replacement for MgF_2 as an IR transparent dome for missiles [Hartnett, Gentilman, 1984.] Currently, AlON is regarded as the best transparent armor material [Brar, 1998]. AlON has spinel crystal structure (i.e., cubic symmetry) which results in isotropic optical and mechanical properties. Consequently, if the ceramic is 100% dense with no voids, inclusion, or grain boundary phases, it will be transparent. For reference, polycrystalline alumina has hexagonal symmetry, with voids, inclusions, and grain boundary phases.

Aside from applications, AlON, because it is transparent, seems to offer the potential of greatly improved understanding of the development of impact damage in alumina. AlON might also surpass sapphire as a shock window.

Since it is transparent, AlON also raises comparisons with glass. Glass is a poor shock window material because of failure waves. Its use as an armor material is mixed. It is remarkably effective against shaped charges, but is poor against ballistic impact. The good performance against shaped charges is usually attributed to the dilatent behavior of glass which interferes with the jet, although we have recently shown that it also exhibits high strength against ballistic penetration if the penetration velocity is higher than the failure wave velocity [Zilberbrand, et al., 1998].

The series of experiments conducted by the IAT [Cazamias and Bless, 1999; Cazamias et al., 2001 (a, b)] consisted of bar impact tests, which provide a good way to study failure under no or partial confinement and over relatively long time scales. It also allows optical diagnostics to determine damage intensity and morphology, and gauge measurements to determine strength. Plate impact tests are currently being performed at Lawrence Livermore National Laboratory, measuring the Hugoniot Elastic Limit (HEL), spall strength, release wave speeds, and failure wave properties.

The IAT performed bar impact experiments on aluminum oxynitride (AlON), a transparent polycrystalline ceramic, measuring the peak stress and taking high-speed photographs. The peak stress measured in the AlON bars is 4 GPa, about 10% higher than that measured in AD-99.5 bars. Failure was observed propagating up the center of the bar, leaving the outer part intact at relatively late times. There was anomalous damage to the witness bar, similar to what happens with glass bars, indicating either retained strength in the center column or explosive fracture of the AlON bar.

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YAWED ROD PENETRATION

Many practical problems in terminal ballistics require predictions of penetration from yawed long rod penetrators. In recent years there have been analytic treatments of yaw effects in thin plates [Yatteau, Recht, Edquist, 1998; Bless, Satapathy, Normandia, 1998], but the effects of yaw on long rod penetration of thick targets still must rely on empirical descriptions.

Yaw effects are usually assumed to scale with yaw (γ) divided by critical yaw (γ_c). Critical yaw is the yaw angle at which the rear of the rod contacts the entrance lip of the crater, and it is given by:

$$\gamma_c = \sin^{-1}\left(\frac{H/D - 1}{2\,L/D}\right), \tag{1}$$

where H = hole diameter, D = rod diameter, and L = rod length.

There exist several empirical models [Yaziv, Rosenberg, Riegel, 1990; Bjerke, Silsby, Scheffler, Mudd, 1992], but they present penetration only as a function of critical yaw angle, γ_c. However, the existing empirical models are only appropriate for restricted ranges of L/D ratio, γ/γ_c ratio, and impact velocity. At the IAT, we are especially interested in relatively high L/D ratios and higher than ordnance velocity. So, we have developed a new empirical equation to describe yaw effects in order to have more accurate predictions for the fineness ratios and velocities of most interest to us. An empirical study of the effects of yaw on thin plates was reported in Bless et al., 1991a.

The effect of yaw on penetration of high L/D ratio tungsten rods striking RHA was examined on the velocity range 1.5 to 3 km/s. An improved empirical equation was developed that fits both data and CTH calculations and was calibrated for the velocity and L/D range of interest [Bless et al., 1999b]. The form of this equation is:

$$\frac{P}{P_n} = \begin{cases} 1 & \gamma \le \gamma_c \\ \max\left(X\left(\frac{L}{D}\right)^a \left(\frac{\gamma}{\gamma_c}\right)^b (\cos\gamma)^c, \frac{\sqrt{\frac{\rho_p D^2 V^2}{2R_t}}}{P_n} \right) & \gamma > \gamma_c \end{cases} \tag{2}$$

where P_n is the penetration of an unyawed rod, L = rod length, D = rod diameter, γ = yaw angle (in radians), R_t is the target penetration resistance, r_p is the penetrator density, X = 1.221, a = -0.099, b = -0.077, and c = 3.844. An analytic model for yaw effects based on slot cutting forces was reported in Bless et al, 1998.

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FAILURE WAVE EFFECTS

Dynamic resistance to penetration, R_t, is conventionally computed from the Alekseevski-Tate equation (see, for example, Vlasov et al., 1997). It has been noted that whereas R_t for metals is several times the compressive strength, for brittle materials R_t is generally about equal to the compressive strength. R_t values for metals can be derived from cavity expansion analysis assuming elastic-plastic behavior (see, for example, Chocron et al., 1998). R_t values for brittle materials can also be computed from cavity expansion analysis, but it is necessary to make some assumptions about the properties of the fractured material ahead of the penetrator (see, for example, Satapathy and Bless, 1995).

In order to understand the relationship between R_t and the fundamental strength of brittle materials, two different penetration modes should be distinguished, depending on whether the penetration velocity, U, is below or above the failure wave velocity, V_f, which can be crudely defined as the ultimate rate of propagation of brittle fracture. In general, V_f is assumed to range between the single crack propagation rate (lower limit) and the shear wave speed (upper limit). It should be noted, however, that precise measurements of single crack propagation rates are rare, and that sometimes fracture travels along with the shock front.

Investigations of brittle materials performed at penetration velocities below V_f (impact velocities up to about 2 km/s) show the penetration parameters to depend primarily on the fracture kinetics (for example, Vlasov et al., 1997, and Satapathy and Bless, 1995). These kinetics govern the target strength degradation in a zone ahead of the penetrating projectile and, consequently, the penetration resistance. The fracture kinetics, in turn, depend on the target and projectile geometry, impact pressure, and material properties. For this reason, no direct correlation between the impact behavior of brittle materials and their initial strength properties has been found at $U < V_f$.

For brittle materials at $U > V_f$, the projectile interacts with an intact material, and impact behavior of brittle materials should thus be determined by initial strength properties rather than by the fracture kinetics [Lazarev et al., 1993]. This type of penetration is similar to indentation. A study performed at the Ioffe Physico-Technical Institute at $U > V_f$ shows brittle materials to exhibit strength resistance to penetration comparable to their microhardness; i.e., about one order of magnitude higher than most hard metals and alloys [Kozhushko et al., 1991].

The data reported by Lazarev et al., 1993, for $U > V_f$ were obtained in experiments using shaped charge jets. The jets exhibit a velocity gradient along the axis which is difficult to account for in calculations. As a rule, R_t is estimated with an error of about 15-20%. One should also keep in mind a possible interaction of the jet with crater walls, resulting in a reduction of the jet's effective length, which is considered by some authors to be responsible for the high ballistic performance of brittle materials against shaped charge jets.

To obtain more reliable data of R_t and demonstrate unambiguously the high-strength state of brittle materials at $U > V_f$, experiments using tungsten long-rod projectiles were performed against glass. Glass is a common armor material, and it is also often treated as a prototypical brittle solid. More importantly, sound speeds in glass are about half of those in ceramics, allowing easier access to the supersonic penetration regime. Two sets of experiments were conducted:

1. Penetration at velocities $U < V_f$ to demonstrate the degradation of the strength of a brittle target when the target material is comminuted ahead of the penetrator.

2. Penetration at velocities $U > V_f$ to determine the true strength of the glass. It should be noted that eventually the target material ahead of the projectile undergoes failure due to the reflection of stress waves from side and rear surfaces.

Experimental data for penetration into glass may be classified into two groups.

1. *Data obtained at penetration velocities below 2.4 km/s.* The observations that the projectile consumption rate in Al and glass is the same, and that the ratio of U/V for WA projectiles penetrating glass targets corresponds to the hydrodynamic prediction, are indicative of purely hydrodynamic phenomena in the glass. In other words, the penetration resistance is of an inertial nature, and high-velocity strength effects may be neglected. Physically, it means that the projectile penetrates into comminuted glass since the failure wave travels ahead of the projectile-target interface.

2. *Data obtained at penetration velocities above 2.6 km/s.* In this regime, U/V is approximately equal to 0.66, which is markedly less than the hydrodynamic U/V ratio. This gives an R_t for the glass on the order of 8 to 9 GPa. This agrees with that found in experiments with shaped charge jets [Lazarev et al., 1993.]

The gap between these two regimes allows an estimate of the failure wave velocity on the order of 2.4 to 2.6 km/s for soda-lime glass. This estimate is in line with data reported by Bless et al., 1992.

We may conclude, then, that normal penetration may be represented as a two-stage process. The first stage involves penetration with a low velocity that increases as the target material is being fractured. The resistance of brittle materials to penetration decreases with time and is determined by the fracture kinetics. The second stage consists of quasi-steady penetration into comminuted material of very little strength, and the penetration is essentially hydrodynamic. A high value of the penetration resistance, R_t = 5 GPa, exceeding inertial resistance, is observed during the first stage. It is this stage that is responsible for the high ballistic performance of ceramics as armor materials. For glass, this normal penetration sequence is observed at penetration velocities up to 2.4 km/s.

At a higher impact velocity providing a penetration velocity over 2.6 km/s, a significant deviation of penetration parameters from the hydrodynamic predictions has been found. Under these conditions, the glass shows even greater resistance to penetration, R_t, of about 8 to 9 GPa. This value is in good agreement with data obtained in experiments with shaped charge jets at Ioffe Institute [Kozhushko et al., 1991]. The above result indicates that a projectile travels ahead of the failure wave in the target and interacts with intact material. Under these conditions, the strength resistance to penetration is determined by fundamental strength properties of the intact target material rather than by the fracture kinetics.

The available data also enables an estimate of the failure wave velocity in soda-lime glass. It lies in the range 2.4 to 2.6 km/s. These results are reported in two joint IAT-Russian papers: Zilberbrand et al., 1999; and Satapathy et al., 1999.

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