Studying Ceramic Armor with PHERMEX

by Ed Cort

The ballistic impact of penetrator against armor is a brief moment of violence and shock hidden in a confusion of smoke and debris (Fig. l,). If we are to learn what material properties are relevant to the outcome, we must pierce the veil and freeze in place the key aspects of this event. Large x-ray machines are ideally suited to this task. A short flash of intense x-radiation can penetrate the debris and armor and etch an instantaneous image of deformation and material flow.

Fig. 1, Live fire test of the M1A1 Abrams tank at Aberdeen Proving Ground. (Photograph taken by U.S. Army Combat Systems Teat Activity and provided to Los Alamos by the U.S. Army Ballistic Research Laboratory.)

We are currently using an x-ray machine called PHERMEX (Fig. 2) to study the internal structure of ceramic armor during impact with both penetrating jets from chemical-energy weapons and long-rod kinetic-energy penetrators. The machine uses a 30-MeV high-current linear accelerator to generate very intense but short-duration bursts of x rays from a thin tungsten target. Although built in the early 1960s, PHERMEX is still unequaled at producing high-resolution radiographs of large, fast. objects. We are particularly interested in using PHERMEX to study ceramic armor because the mechanisms by which ceramic armor can defeat a penetrator differ in certain key ways from the defeat mechanisms of more traditional armors. We have only recently begun to

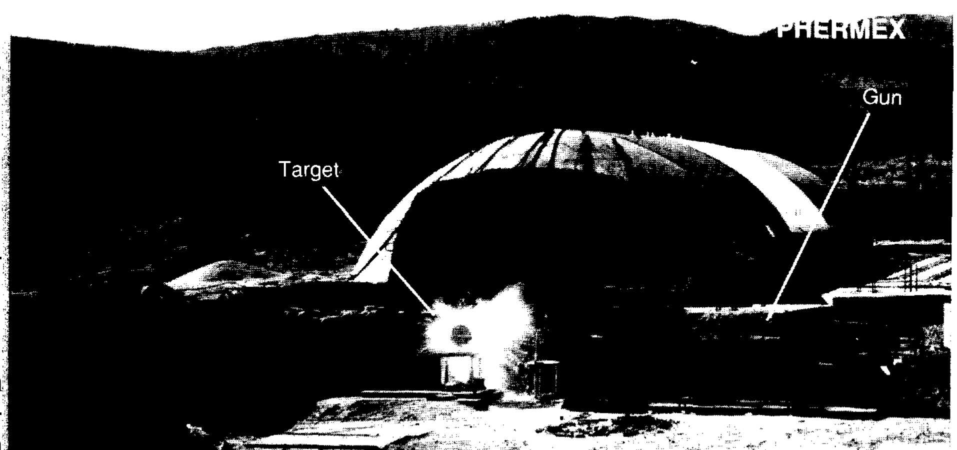

Fig. 2. A flash x-ray machine (in the building behind the target) is currently being used to produce high-resolution radiographs (see Fig. 4) of the ballistic interaction of ceramic targets with long-rod penetrators (fired from the gun at the right).

understand what those differences are.

The long-rod penetrator pierces a target, whether ceramic or otherwise, by depositing large amounts of kinetic energy in a concentrated region," The rod, which may be idealized as a right circular cylinder with a length typically ten or more times greater than its diameter, is intended to strike the target "end on." Any yaw (deviation of the rod's axis from its direction of flight) of more than a few degrees can adversely affect penetration. When the target thickness is greater than a few penetrator diameters—usually the case for problems of interest—penetration is a complex process in which a cavity forms in the target material and the impacting end of the penetrator erodes away. If the incoming rod is yawed, the penetrator may bend or break and lose much of its effectiveness. Heavy armor that is intended to defeat long-rod penetrators is nearly always sloped with respect to the anticipated flight line of the projectile to create oblique impact conditions. Modern armor also tries to induce yaw on impact with reactive sandwiches, tipping plates, and other devices. The combination of obliquity and yaw presents difficult modeling and experimental challenges.

Even non-yawed impact of long-rod penetrators is not well understood when the target is *confined* ceramic armor. One aspect of this problem—the complex way in which the confinement package itself interacts with the ceramic during impact—has not always been well controlled experimentally in the past. We have built targets that are so constrained by steel that confinement is relatively constant from shot to shot and penetration depends on ceramic behavior entirely. We are able to study such thick targets by capitalizing on the penetrating ability of the high-energy x rays of PHERMEX. Although the targets (Fig. 3) do not represent a realistic armor design, their response to penetrator impact is more reproducible and predictable, and the ceramic's behavior is relevant to the general problem.

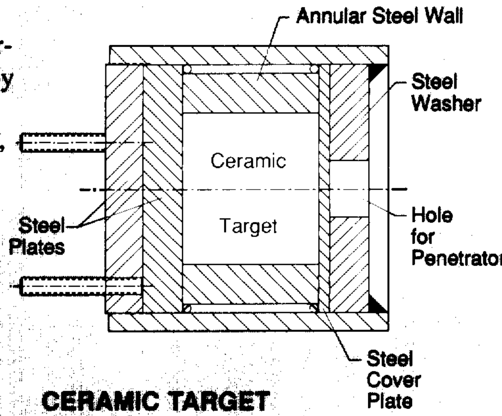

Fig. 3. The targets used to study the response of ceramic to impact by a penetrator rod were designed to keep the ceramic confined during the event. The penetrator rod enters the front of the target through the hole in a steel washer and then strikes a hardened steel cover plate. At a predetermined time after impact, the PHERMEX is pulsed.

To obtain radiographs of a rod or a jet penetrating the ceramic, we pulse the PHERMEX once during each impact. These pictures reveal the residual length of eroded penetrator, the depth and rate of penetration, the material's residual velocity, and whether or not the penetrator is, say, mushroomed at the front, bent, yawed, or broken. The radiographs also reveal the distribution of debris, the shape of the crater, and the presence of large cracks or distortions in the target. However, the radiograph's limits of resolution coupled with strong confinement pressure from the target holder prevent the image of the fracture in the ceramic from being well defined.

We use targets that are thick enough to stop the penetrators in the ceramic and make a radiograph of the target after each shot to show the final penetration depth and the length of any remaining rod or jet material. A sequence of four to six nominally identical shots produces a time-resolved penetration history for one ceramic material and one set of engagement conditions (velocity, obliquity, and yaw) in one plane. In future tests, we hope to flash PHERMEX several times during impact and record a series of dynamic radiographs electronically.

Our current test series ranges over three ceramic materials (boron carbide, aluminum oxide, and titanium diboride), two impact velocities, two obliquities, a number of confinement geometries, and both kinetic-energy rods and jets from chemical-energy weapons. We also look at the flight characteristics of the penetrator (velocity, yaw in two orthogonal planes, rate of change of yaw, and fiducial time at impact).

We are modeling the tests with existing hydrocode models (see "Modeling Armor Penetration"). The code predicts that because the ceramic is relatively incompressible, even when fractured, and because there is no free volume for the rubble to expand into except the penetration hole itself, the ceramic defeats the penetrator. Although the predictions of 'the model are reasonably close to actual events (Fig. 4), our material model for the ceramic, at the moment, is based more on experimental data from prior tests rather than on principles of physics. Consequently, if the rod's velocity, say, were to change significantly, we would not be able to extrapolate with confidence.

At the end of our current series of approximately thirty shots, an advisory panel of experts 'will review the tests and help interpret the data. However, preliminary results confirm that dilatancy (the tendency of the fractured ceramic to expand) is an important gen-@# feature for the defeat of jets fired from chemical-energy weapons. In this mechanism the ceramic rubble refills the impact hole, constantly'fmcing the jet to penetrate new material, and, as the

CERAMIC PENETRATION

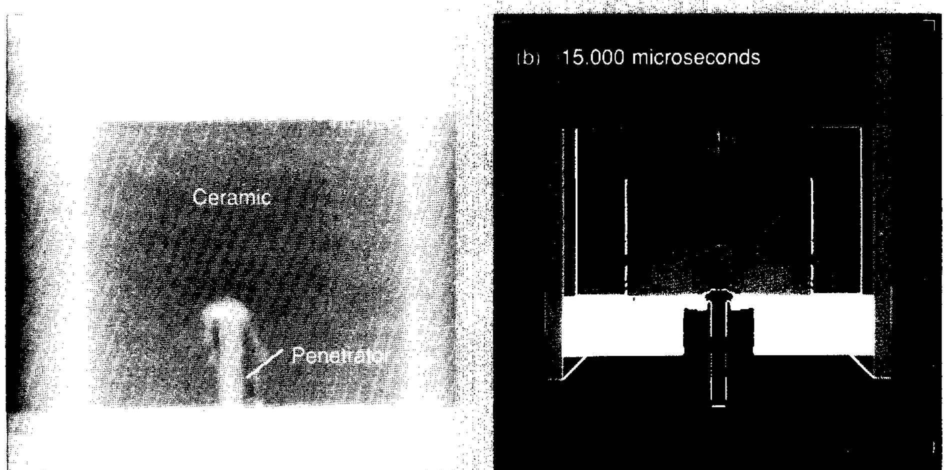

Fig. 4. (a) A PHERMEX radiograph of a tungsten-alloy penetrator colliding with the eeramlc target of Fig. 3. (b) The same event at the same moment in time es simulated with the HULL hydrocodes. (See "Modeling Armor Penetration" for a dlscussion of the hydrocodes.) The iight blue areas in the computer simuiation are regions of faiied ceramic that do not appear in the radiograph because of Iack of resolution and the tight conflnement of the ceramic by the target holder.

rubble flows from the impact hole, it pushes inward and attacks the jet from the sides. In the case of long-rod penetrators, material flows out the hole but does not appear to attack the sides of the penetrator as it goes.

From these experiments, we should obtain radiographs of the dilatancy mechanism in action and accurate materials data on such things as the hardness of the ceramic, One of the main points of the tests is to accumulate more accurate experimental data to validate code-modeling parameters for armor and anti-armor designers.

Although the PHERMEX experiments provide valuable data, several fundamental questions about the dynamic behavior of ceramic armor are more easily addressed in laboratory experiments. One question concerns the *sequence* of events-does fracture occur at the rear of the ceramic (Fig. 4) during the passage of the initial shock wave or later as the penetrator forces its way through the material? In addition, scientists must determine what factors dictate the size and shape of the individual fractured particles and then understand how to model penetration of the resulting pulverized material.

To address such questions, Los Alamos scientists have designed two experiments that complement the PHERMEX ones. The first is a shock-recovery experiment in which a flyer plate propelled by a gas gun impacts a ceramic sample. Elaborate techniques are used to ensure that the specimen is subjected to a *single* shock loading and release of uniaxial strain. Scanning and transmission electron microscopy of the recovered specimen provide insight into the failure mechanisms during shock deformation. A second flyer-plate experiment uses a specimen assembly designed so that tensile waves from the rear of the specimen meet those from the front of the impactor (tensile waves stretch the material and are generated, in this case, as a release of the initial compressive wave). The superposition of these waves creates a large tensile pulse and rapid tensile failure, called spall, of the specimen. Determining spall strength in this way gives a qualitative, in situ measure of the fracture strength of the ceramic *after* the initial compressive shock has passed and caused any potential alterations of material properties. In addition, post mortem characterization of the fracture surfaces provides data on fracture mechanisms.

Although the veil of smoke and confusion has not been totally cleared, PHERMEX is letting us view and identify the major events that occur when a penetrator impacts ceramic armor. ■