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BALLISTIC PENETRATION OF MULTI-LAYERED CERAMIC/STEEL TARGETS

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The response of multi-layered ceramic/steel targets to high velocity impact and penetration has been investigated through experiments and finite element simulations. Damage quantification and the material stresses and velocity histories provided by experiments are used as constraints to be satisfied by numerical simulations of the ballistic penetration event. Experimental and numerical observations demonstrate that the penetration process does not strongly depend on the ceramic material as usually assumed by most investigators. Instead, local and global effects which are related to material performance and structural features have been found to be very important factors that affect the overall target performance. These findings show that meaningful light weight armor design can only be accomplished through a combined experimental/numerical study in which relevant ballistic materials and structures are *simultaneously* investigated.

INTRODUCTION

There have been several efforts to experimentally design suitable multi-layered ceramic targets (1, 2). The focus of these experiments has been to minimize ceramic damage and flow to maximize penetration resistance. But the challenge of developing effective ceramic armor systems by experiments alone is a difficult task. In general, experiments do not always provide direct information on material behavior. The implementation of an iterative computational/experimental procedure requires reliable material models incorporating microfailure and macrofracture of ceramics and penetrator materials.

Although numerical analyses of high velocity impact and penetration have been carried out for quite some time, their application in analyzing the response of multi-layered ceramic targets is scarce (3). The key issue is the appropriate modeling of the complex constitutive behavior of metals and ceramics in the presence of localized damage.

EXPERIMENTAL AND NUMERICAL APPROACH

Apart from the development of models describing the constitutive behavior of brittle materials, and the numerical simulation of plate and rod impact experiments, not many studies have been carried out to establish the structural performance of multi-layered ceramic targets. In previous work (1, 2, 6) , measurement type and location were decided based on intuition and experience derived from past experiments. Any lack of information was manifested in terms of repeating the experiments, which are very ex-

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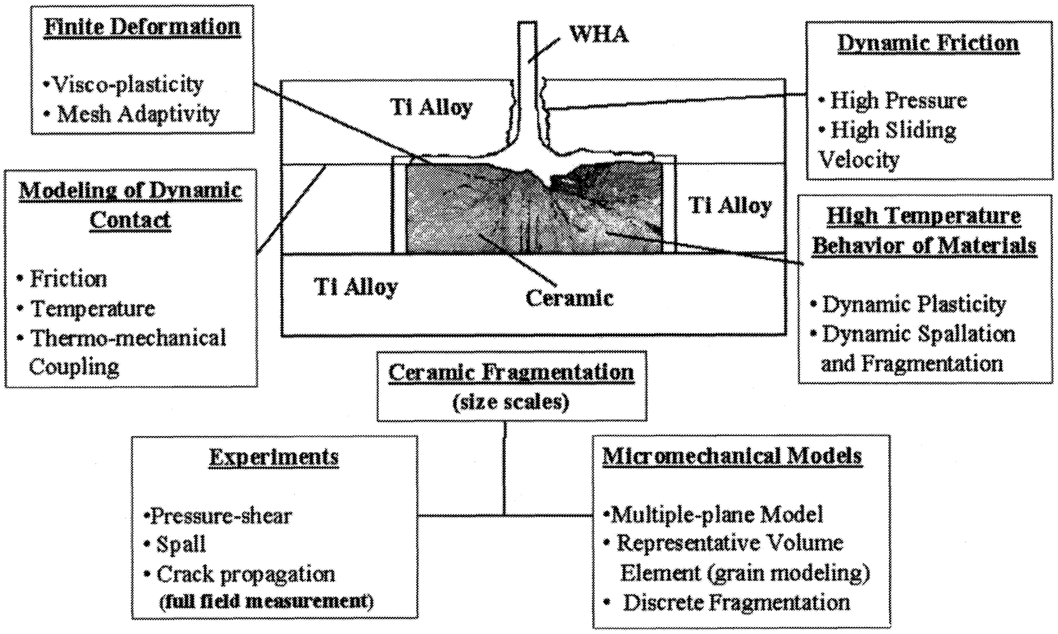

FIGURE 1: Photograph and schematics showing the experimental configuration and main mechanics issues.

pensive and time consuming. There is also the possibility of arriving at inappropriate conclusions if the selected variables are not measured with proper accuracy.

Figure 1 describes the complexity of the physics and engineering involved in impact and ballistic penetration of multi-layered ceramic targets. Each aspect of the problem requires a combined experimental-computational investigation that can lead to physically motivated models. In our Dynamic Inelasticity laboratory, high temperature and high strain rate behavior of materials are studied by means of plate impact experiments (4). Dynamic friction and fracture are investigated by means of a modified Kolsky bar and gas gun experiments (5).

From the computational standpoint, this type of problems constitutes an important challenge in the development of unified computational capabilities. The explicit dynamic finite element code **FEAP-98**, developed at Purdue University, is utilized to investigate the role of fragmentation, shear resistance, ceramic confinement, thermo-mechanical coupling, and finite deformation plasticity in the resistance to penetration of multi-layered targets.

EXPERIMENTS

Impact recovery experiments on confined multi-layered ceramic targets have been performed to identify interface defeat of long rod tungsten heavy alloy (WHA) penetrators (6). Insitu stress measurements have been made, and velocity histories of the target rear surface have been measured using an interferometric technique. Material response to penetration has been examined by considering different hardness of the cover steel plate and two types of ceramics (Al_2O_3 and TiB_2). The combined material-structural response has been examined by changing the thickness of the graphite plate, used to accommodate the deforming WHA penetrator, and by welding top and bottom plates with the middle plate to increase the stiffness of the assembled multi-layered target.

Ceramic damage has been studied by quantifying the size and distribution of fragments in recovered sample. SEM and optical microscopy performed on recovered ceramic plates show that microcracking is the dominant failure mode in multi-layered ceramic targets (See Fig. 2). Quantification of crack surface per unit volume and fragment size, as a function of position, was performed on different region of the ceramic target. Correlation between axial stress and crack density has been also investigated. Examination of the post-shot multi-layered ceramic targets revealed complete and partial interface defeat of long rod tungsten heavy alloy penetrators. Targets with extra stiffness, on account of weld and larger bottom plate thickness, achieved complete defeat of the penetrator.

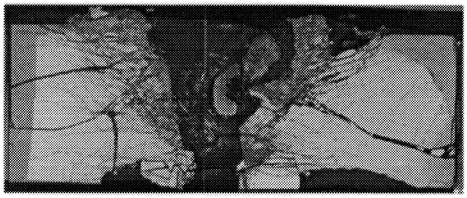

FIGURE 2: Cross-section of a sliced TiB_2 disk showing full penetration of the plate.

The experimental observations show that there are local and global features that affect the overall target performance. Local effects are related to the materials performance, viz., cover plate hardness and shear resistance of the fragmented ceramic. Global effects are related to structural features. Overall stiffness of cover and back plates, as a function of boundary conditions and thickness, appear to play a major role in the transition from interface defeat to ceramic erosion mechanisms. The type of ceramic appears less relevant. In fact, it can be inferred that both Al_2O_3 and TiB_2 demonstrate interface defeat at impact velocities up to 1.5 km/s.

SIMULATIONS

Understanding the relevance of each design parameter can be achieved by performing a series of simulations in which only one parameter is changed in each simulation. In this regard, the damage quantification, the in-material stresses and velocity histories obtained in (6) can be used as constraints to be satisfied by numerical simulations of the ballistic penetration event.

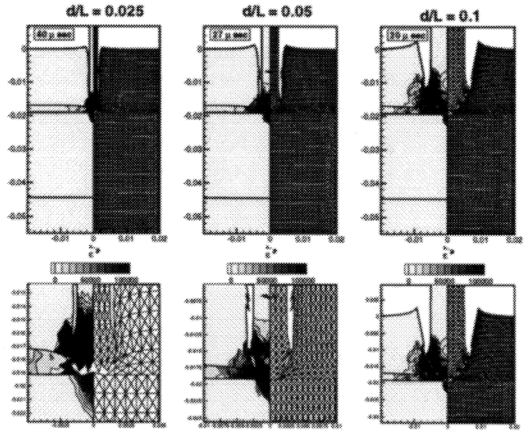

FIGURE 3: Penetration and plastic strain rate for different WHA penetrator d/L ratios.

The multi-plane microcracking damage model, developed by Espinosa, was implemented in **EPIC-95** (7). The objective was to analyze the depth of penetration and interface defeat configurations numerically. Parametric analyses were carried out to establish the effect of ceramic materials, target configuration design for ceramic confinement, diameter/length ratio of penetrator, material erosion threshold levels and the use of a shock attenuator on the response of multi-layered ceramic targets subject to high velocity impact. Figure 3 shows the penetration with the plot of plastic strain rate obtained from analyses for three d/L ratios.

These simulations have demonstrated that the response of multi-layered ceramic targets is relatively independent of the ceramic material but is highly dependent on the multilayered configuration and the target structural design (geometry, and boundary conditions). However, limitations were encountered in the analyses with **EPIC-95**. For example, only one erosion parameter can be selected for all materials, which is not realistic. Interfaces need to be modeled as perfect or frictional interfaces without the possibility of modeling progressive decohesion. Mesh

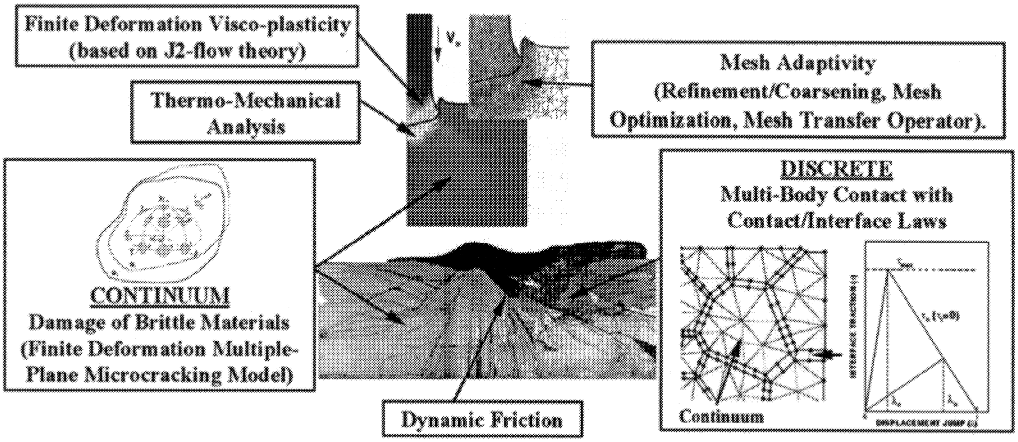

FIGURE 4: Salient features of the explicit finite element **FEAP-98**.

adaptivity to avoid excessive mesh distortion is not available.

Software capable of simulating interface defeat, without all these limitations is currently under development with the explicit finite element **FEAP-98**. An isochoric finite deformation plasticity model for metals, including rate and temperature effects, and a continuum/discrete damage model capable of capturing fragmentation at two size scales is derived by combining continuum damage model and a discrete damage model for brittle failure (8). It is assumed that size and distribution of *potential* fragments are given by crack quantification taken from experiments. The finite deformation continuum multiple-plane microcracking damage model accounts for microcracks within fragments and interface elements, with cohesive strength, between *potential* fragments describe the behavior of macrocracks (See Fig. 4). A versatile adaptive remeshing technique has been implemented to have a well conditioned fine mesh in zones with high rate of inelastic deformation (i.e., when the penetrator flows laterally in the region between the cover plate and the graphite plate).

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