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RECOMMENDATIONS ON A CONSTITUTIVE MODELING PROGRAM FOR METAL MATRIX COMPOSITE PENETRATORS (U)

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ABSTRACT

An effort to develop improved methods for analyzing the terminal ballistic performance of fiber reinforced, metal matrix composite penetrators in anti-armor applications was initiated several months ago. To date, we have reviewed all pertinent prior work and have developed preliminary plans for our research program. This work was to be pursued as part of a joint DOD-DOE program on anti-armor research and development. Since it is now apparent that this research will not be funded under the DOD-DOE program, we are terminating our effort. We summarize here the background information gathered and present our thoughts on the approach to be taken if such a modeling program were pursued in the future.

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Recommendations on a Constitutive Modeling Program for Metal Matrix Composite Penetrators

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1 Introduction

In order to numerically simulate the terminal ballistic behavior of fiber reinforced, metal matrix composite penetrators for anti-armor applications, it is necessary to have an adequate mathematical model for the response of the penetrator material. Some observations and suggestions relevant to a research effort with the goal of providing such a mathematical model are given here. This work was initiated several months ago at Sandia National Laboratories as part of a DOD-DOE program on anti-armor research and development. The goals of our work were to formulate and pursue a program to develop a continuum model for tungsten fiber-reinforced, depleted uranium composite rods that would be valid for large deformations and to implement this model in a three-dimensional wavecode so that terminal ballistic simulations of anti-armor penetrations could be performed with reasonable accuracy. It is now apparent that this effort will not be funded under the DOD-DOE program, so the work has been terminated.

The following discussion is divided into two parts. The first provides some background information. It provides a short history of the development of fiber-reinforced, metal matrix penetrators as well as a discussion of current activity and fabrication capabilities. A description of previous mechanical characterization studies is also provided. An overview of previous modeling efforts and computational methods for analyzing fiber reinforced composite materials completes the first part. The second part of the discussion focuses on more specific requirements for a modeling effort. In particular, it is recognized that much experimental work is needed to provide data for understanding material behavior and for determining important model parameters. Suggestions are therefore given for appropriate static and dynamic test programs. Some comments on material model development with regards to code limitations are then given. Finally, the methodology for code verification is described, using the case of a tungsten penetrator and steel target plates for the calculational example.

2 Background Information

2.1 Organizations Involved

Three organizations have been involved in the development of long rod penetrators made from fiber-reinforced, metal matrix composites. The early development work was carried out by the Naval Research Laboratory (NRL) in the late 1970's [1]. This was a multi-year DARPA funded program. Several candidate metal matrix composite materials were characterized using static, dynamic, and subscale ballistic test methods. Tungsten fiber-reinforced, depleted uranium composites (W/DU) were identified as best of the composite materials considered for the long rod penetrator application. Ballistic test data, however, revealed that although W/DU rods experience less overall bending than unreinforced DU rods, they are not significantly better in penetrating simple targets.

Development work on W/DU penetrators has been continued, during the past few years, at the U. S. Army Ballistic Research Laboratory (BRL). A variety of sub-scale W/DU penetrators have been tested against complex targets, and a limited number of full scale penetrators were tested recently, as well. The test results seem to be consistent with those of NRL.

Battelle Columbus Laboratories (BCL) has had roughly ten years of experience fabricating W/DU composites. The capability exists at BCL for casting 25 mm diameter by 750 mm long rods, and a hydrostatic extrusion method for fabricating these composites is under development. BCL fabricated W/DU samples for both NRL and BRL, and appears to be the only experienced source for this type of composite material.

2.2 Mechanical Properties of W/DU

NRL characterized unidirectional W/DU composites under quasi-static tension and compression loadings, and also carried out metallographic studies [2,3]. Their data indicate that, when loaded parallel to the fibers, the tensile stress-strain response of the composite is nonlinear. The failure strain of the material is on the order of 1 % , and presumably both fiber and matrix undergo plastic yielding. In contrast, the composite has a very low strain to failure ($\sim$ 0.1 %) and displays little ductility when pulled transverse to the fibers. In compression, the W/DU composite exhibits substantial ductility ($\sim$ 10 %) when tested either along or transverse to the fibers. It is important to note that these test data suggest that there is a significant difference between a W/DU composite and most of the more common metal matrix composites used in aerospace applications (*e.g.,* boron/aluminum and graphite/aluminum). In particular, unlike most metal matrix composites, in which the fiber response can be considered to be linear elastic until failure occurs, both the fiber and matrix yield in W/DU composites. Finally, it should be noted that NRL determined that the fabrication process degrades the tungsten fibers. The fibers are partially recrystallized by thermal exposure above $800^{\circ}C$, and an interfacial reaction zone is created by diffusional processes. The degree to which these phenomena also affect fiber-matrix bonding is not known.

2.3 Modeling Metal Matrix Composites

There is a large number of published papers which investigate methods for modeling the mechanical behavior of metal matrix composites. These works fall into three main categories: anisotropic plasticity models (*e.g.*, [4]), micromechanical analyses (*e.g.,* [5]), and constitutive models based upon concepts from simple mixture theories (*e.g.*, [6,7]). Since uni-directional metal matrix composites often exhibit significant yielding only in shear, an anisotropic plasticity model is appropriate. Such work is usually based upon classical metal plasticity theory, and accordingly, assumes that there is no plastic yielding under hydrostatic pressure. In reality, metal matrix composites do yield under hydrostatic pressure [5]. The fibers act like hard inclusions in a ductile matrix. Note that high hydrostatic pressures might be generated at the point of impact of a metal matrix penetrator and an armor. One other limitation to this approach is that such anisotropic plasticity theories, in general, model the overall response of the composite but do not directly address the manner in which the microstructure (*e.g.*, fiber volume fraction) influences response.

There have been numerous micromechanical analyses of metal matrix composites. Typically, the finite element method is used to calculate the stresses developed within a repeating, fiber-matrix unit cell when it is subjected to either thermal or mechanical loads. As is appropriate for most high performance, metal matrix composites, the fiber is considered to be linearly elastic, while the matrix is an elastic-plastic material. This type of calculation can be used to examine how fiber and matrix properties affect the overall response of the composite. One can also construct a yield surface based upon initial micro-yielding. The principal limitation of this approach is that it does not readily lead to a convenient constitutive relation for structural analyses.

Several researchers have applied a mixture theory approach in an effort to develop a constitutive relation based directly upon fiber and matrix properties. Since a computationally convenient theory is desired, quite simple interaction relations are usually assumed. For example, in Ref. [6] and [7], it is assumed that the fiber and matrix undergo the same axial strain, while the matrix is unperturbed by the fibers when the composite is subjected to transverse tension or shear (this is sometimes called the Vanishing Fiber Diameter model). These are presumably the simplest interaction relations which still define a potentially useful material model.

2.4 Computational Models

The computer codes used to simulate terminal ballistic events for penetrators can be divided into two classes: Lagrangian codes and Eulerian codes (see Ref. [8], Chapters 10 and 11 for detailed descriptions). Lagrangian codes are formulated using a computational mesh that moves with the material in the simulation and, consequently, undergoes a deformation that reflects that of the material. Since it is relatively easy to include extra variables in Lagrangian codes which, say, describe the orientation of a particular material direction or additional state variables in the material models, these codes provide a useful tool when modeling complex material responses. However, in problems where the materials undergo severe deformations, the computational mesh used in a Lagrangian code also deforms severely and degrades the accuracy of the calculation. For severe mesh deformations, the calculation must be rezoned with deformations and appropriate state variables for the materials mapped onto a new mesh. In problems involving penetration, this rezoning process must be performed frequently and, consequently, it becomes extremely difficult to retain accuracy throughout the numerical simulation of the problem. The need for such manual rezoning in problems involving severe deformations can be avoided by using an Eulerian code. In an Eulerian code the calculational mesh is fixed in space and material moves through it. Since the material that occupies a particular computational cell changes during a calculation, it proves difficult to track accurately the many state variables that are required for a description of complex material. In general, Eulerian codes keep track of only the volume fraction and energy of the material that resides in a particular computational cell. Simple methods exist for treating transversely isotropic material with Eulerian codes where the direction of anisotropy is fixed along a particular coordinate axis for the entire simulation. Clearly this method is inadequate if material deformations and rotations change the preferred material direction, for example, when a projectile penetrates a target obliquely.

The use of a code which has a linked Lagrangian-Eulerian capability is one possible option for treating the oblique impact of anisotropic materials. In a linked code, portions of the problem would be modeled as Lagrangian regions while the remaining portions would be modeled in an Eulerian mode. HULL [9] is a code which has a linked option, and has been available to us for use in preliminary studies. In modeling the oblique impact of a transversely isotropic projectile onto a target surface, the anisotropy can be defined within the local Lagrangian coordinate system of the projectile and the target can be represented in an Eulerian system. Large deformations of the target can be easily handled by the Eulerian module; projectile material can be modeled initially in the Lagrangian mesh. As large deformations occur, projectile material would be donated to the Eulerian mesh. The linked Lagrangian-Eulerian option in HULL is currently capable of performing only two-dimensional calculations; however, oblique impact calculations in plane strain geometry can be done as approximations to the three-dimensional problem. Techniques are available [10,11] for recovering information about the three-dimensional problems from plane strain results, and it may be possible to obtain suitable results using one of these methods.

3 Suggestions for W/DU Penetrator Studies

3.1 Static Test Program

A quasi-static test program to characterize the elastic-plastic behavior of W/DU would generate data to guide the development of a suitable model, as well as, provide required model input data. A baseline W/DU composite (*e.g.*, 45 volume %, 12 mil tungsten fiber in a DU-3/4 Ti matrix, using the Battelle Columbus method for casting and heat-treating the composite) should be fully characterized. Tension and compression tests should be conducted for directions both parallel and transverse to the fibers. A torsion test, with fibers aligned axially, could provide insight into the in-situ state of the matrix and also the nature of the fiber-matrix bond. Micro-hardness tests might also provide information on the in-situ matrix yield strength. The unloading behavior of the composite could be characterized by putting the material through a compression-tension cycle (*i.e.*, low cycle fatigue tests). Finally, yielding under a multi-axial stress state (including large hydrostatic components) should be studied.

It would also be desirable to characterize the constituent materials independently. The matrix material should be cast and heat-treated in the same manner as the W/DU composite. To characterize the fiber material, it would be ideal if samples could be extracted from the composite for testing, since it is known that the fabrication process degrades some fiber properties. If this is not possible, virgin fibers could be subjected to a thermal and chemical history similar to that used in the composite fabrication. Note that the full tensile stress-strain relation for the fibers, not just failure load, should be measured.

3.2 Dynamic Test Program

There is a limited amount of data related to the dynamic material response of the W/DU composite. This consists primarily of penetration data from small scale experiments and a few full scale tests. The utility of these data for use in material model development is limited by the complex geometries of the experiments and lack of time resolution in the material response measurements. In general, data of this kind are most useful for exploratory development (the context in which they were obtained) and model verification. Consequently, a set of controlled dynamic tests on the W/DU composite should receive high priority in order to provide some dynamic material response data of use in the modeling effort.

A basic set of plate impact experiments on the W/DU composite should be done. In particular, Hugoniot states and release paths over the range of pressures of interest for this material should be measured. These tests should load the material both along and transverse to the direction of transverse isotropy. Additional experimental measurements of transmitted wave profiles for various sample thicknesses would be useful in determining the length scales for which the microstructure of the composite is significant. Ramp wave experiments and/or Hopkinson bar tests would provide data on the importance of rate effects.

3.3 Model Development and Code Verification

As indicated above, several models for metal matrix composites already exist. It may be possible to use one of these as a basis for a W/DU material model. Model development can vary in complexity depending on the response regime of interest and the type of code in which the model is to be implemented. The preferred approach to model development for a particular material or class of materials is to begin with a general formulation and introduce specific simplifying assumptions appropriate to the problem at hand. Initial modeling efforts were planned using ideas from mixture theory so that the volume fraction of fibers in the composite played an important role in the description of the material response. General kinematical restrictions on constituent motion and volume fraction, which yielded the Vanishing Fiber Diameter approximation as a special case, were to be used as a starting point for model development. Particular attention would be given to both matrix and fiber yielding when developing the plasticity model for this composite.

As a first step in developing an understanding of the impact performance of composite rods, it is important to calibrate and verify our computational capabilities for homogenous projectiles. Because proposed metal matrix composite penetrators will consist of both tungsten and depleted uranium, investigation of each of these materials individually is a logical starting point.

A considerable body of experimental data [12,13] from penetration testing of tungsten projectiles is available. Additionally, theories have been developed to describe the major features of penetration through the use of hydrodynamic models [14,15]. Several normal impact calculations have been done for comparison with available data and theoretical results. As shown in Figure 1, excellent agreement was obtained between experimentally measured penetrator erosion and the corresponding quantity as calculated numerically. Good agreement was also found between hydrodynamic models and the calculations. However, it is clear from these results that the hydrodynamic theory is only valid until the projectile penetrates the back surface of the target. The model fails to account for target material which remains in the projectile path after this time.

Although good data are available for armor penetrating tungsten projectiles, comparable data are difficult to obtain for depleted uranium penetrators. There are apparently several reasons for this. Work with DU is usually classified which reduces the accessibility of published results. Furthermore, the tendency of DU to burn upon impact limits the ability to obtain residual measurements on these projectiles. However, it has been possible to assemble enough information from diverse sources [16,17,18] to obtain a consistent representation of the performance of DU penetrators. Calculations similar to those done for W rods should be done to evaluate existing modeling capabilities for DU penetrators.

The next step is to perform two and three-dimensional calculations of both normal and oblique impacts of homogenous (DU and W) rods against steel plates and RHA plates using independently obtained properties for the penetrator and target materials.

Parameter variations should be done to determine the sensitivity of results to changes in material properties (*e.g.*, yield strength and failure stress) of both target and projectile. These results can be compared with available test data, theoretical models and empirical models. Quantities to be compared include residual velocity, residual length (or mass) and crater volume. The parameter studies should examine the phenomenology over a reasonable range of velocities around the ballistic limit.

Using results of the above comparisons and analysis, it may be necessary to modify existing computational models (or develop new ones) to more accurately describe the penetration of homogenous rods. Phenomena which may be important include work hardening, strain rate effects and temperature dependent yield.

A theoretical description of composite projectiles can be developed in parallel with development of the computational capabilities. When both processes are complete, the model can be incorporated into appropriate multi-dimensional wavecodes for terminal ballistics analyses. This model can then be used to perform parameter studies in which important parameters of the model are varied over an appropriate range of values. Finally, calculational results must be compared with experimental results to demonstrate the predictive capability of the model.

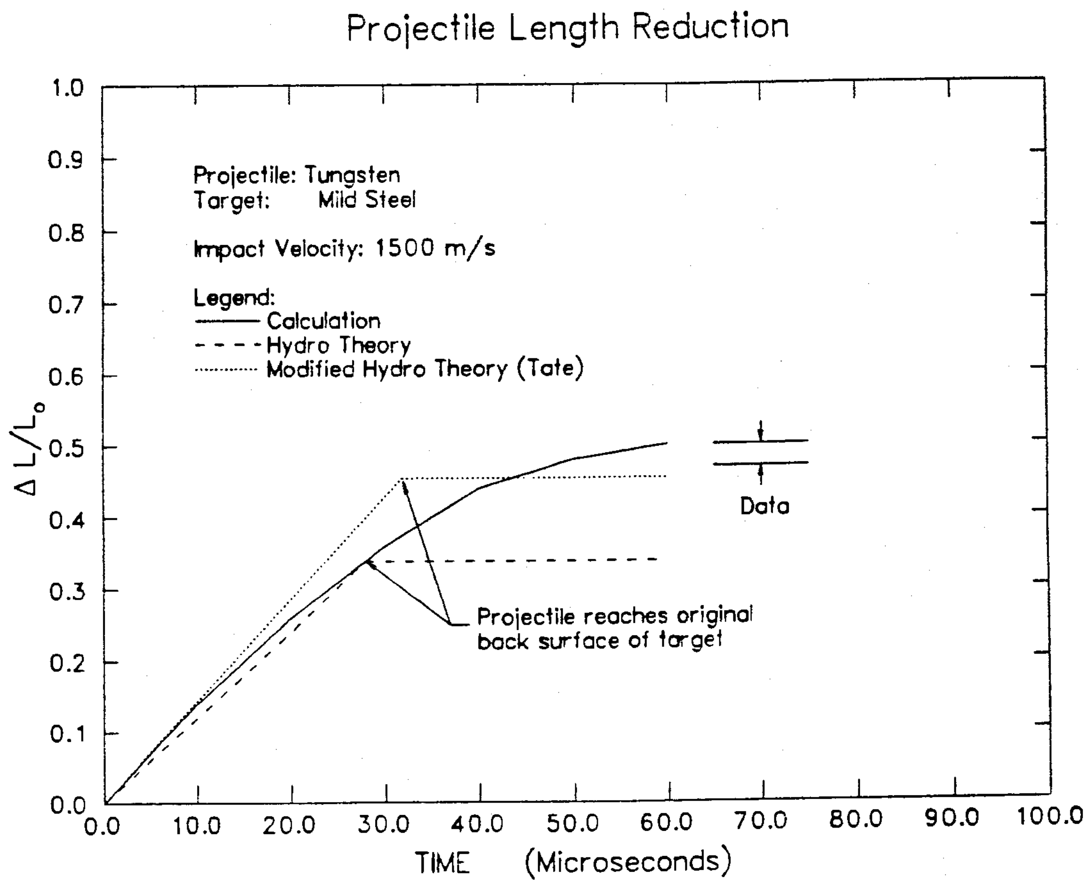

Figure 1: Erosion of tungsten projectile impacting mild steel, as determined from theory, calculation, and experiment.

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