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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 (~ 0.1 %) and displays little ductility when pulled transverse to the fibers. In compression, the W/DU composite exhibits substantial ductility (~ 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.

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

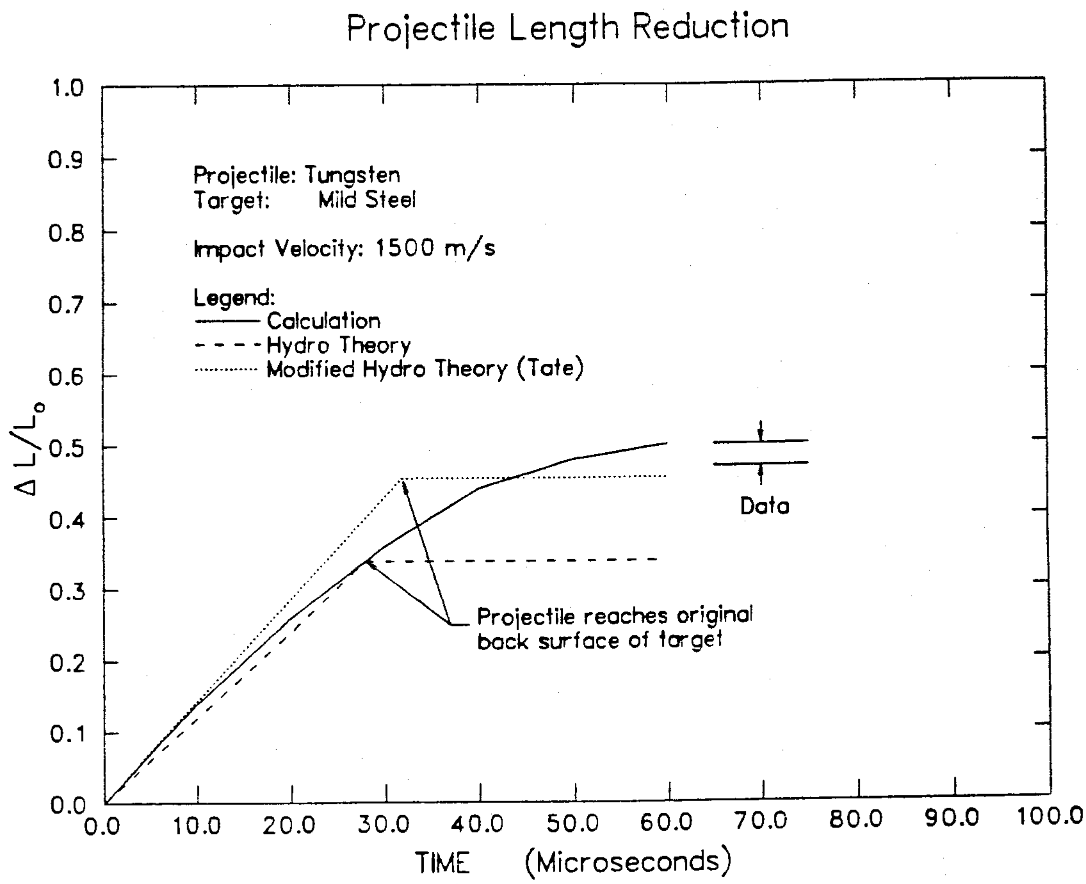

Figure 1: Erosion of tungsten projectile impacting mild steel, as determined from theory, calculation, and experiment.

Bibliography

[1] Sanday, S. C., Weimer, R. J., and Skowronek, C. J., "Development of Metal Matrix Composite Penetrators - Final Report, Part 1 : Program Overview," NRL Memorandum Report 4684, April 1982.

[2] Pattnaik, A., Kim, C., and Weimer, R. J., "Tensile Deformation and Fracture Behavior of Unidirectional Depleted Uranium/Tungsten Composites," *Proceedings of AIME 6th Symposium on Failure Modes in Composites*, Dallas, TX, Feb 1982, pp 15-38.

[3] Pattnaik, A., Kim, C., and Weimer, R. J., "Deformation Behavior of Depleted Uranium/Tungsten Fiber Composites in Compression," *Compression Testing of Homogenous Materials and Composites, ASTM 808*, R. Chait and R. Papirno *Eds.*, American Society for Testing and Materials, 1983, pp 254-275.

[4] Mulhern, J. F., Rogers, T. G., and Spencer, A. J. M., "A Continuum Theory of a Plastic-Elastic Fibre-Reinforced Material," *Int. J. Engng. Sci.* **7** (1969), pp 129-152.

[5] Dvorak, G. J., Rao, M. S. M., and Tarn, J. Q., "Yielding in Unidirectional Composites Under External Loads and Temperature Changes," *J. of Comp. Materials* **7** (1973), pp 194-216.

[6] Dvorak, G. J., and Bahei-El-Din, Y. A., "Plasticity Analysis of Fibrous Composites," *J. of Applied Mechanics* **49** (1982), pp 327-335.

[7] Min, B. K., "A Plane Stress Formulation for Elastic-Plastic Deformation of Unidirectioanal Composites," *J. Mech. Phys. Solids* **29** (1981), pp 327-352.

[8] Zukas, J. A., Nicolas, T., Swift, H. F., Greszczuk, L. B., and Curran, D. R., **Impact Dynamics**, John Wiley and Sons, Inc., 1982.

[9] Durrett, R.E. and Matuska, D.A., "The HULL Code. Finite Difference Solution to the Equations of Continuum Mechanics," AFATL-TR-78-125, Air Force Armament Laboratory, Eglin Air Force Base, Florida, November 1978.

[10] Bertholf, L.D., Kipp, M.E. and Brown, W. T., "Two-Dimensional Calculations for the Oblique Impact of Kinetic Energy Projectiles with a Multi-Layered Target, Sandia Laboratories Report," SAND75-0541, January 1976.

[11] Brown, W. T., "Numerical Modeling of Oblique Hypervelocity Impact Using Two-Dimensional Plane Strain Models," Proceedings of AIP Conference on Shock Waves in Condensed Matter, Menlo Park, CA, June, 1981, pp 529-533.

[12] Hohler, V. , Schneider, E., Stilp, A.J., and Tham, R., "Length and Velocity Reduction of High Density Rods Perforating Mild Steel and Armor Steel Plates," Proceedings of of 4th Int. Symp. Ballistics, Monterey, CA, October 1978.

[13] Tate, A., Green, K. E. B., Chamberlain, P. G. and Baker, R. G., "Model Scale Experiments on Long Rod Penetration," Proceedings of 4th Int. Symp. Ballistics, Monterey, CA, October 1978.

[14] Tate, A., "A Theory for the Deceleration of Long Rods After Impact," *J. Mech. Phys. Solids* **15** (1967), pp 387-399.

[15] Tate, A., "Further Results in the Theory of Long Rods Penetration," *J. Mech. Phys. Solids* **17** (1969), pp 141-150.

[16] Rowe, W. R. and Fibley, G. L., "Quarter-Scale Test Results of a U-3/4 Ti Penetrator Against Steel Targets," Ballistic Research Laboratory Report ARBRL-MR-02904, February 1979.

[17] Hopson, J. W., Hantel, L. W. and Sandstrom, D. J., "Evaluation of Depleted Uranium Alloys for use in Armor-Piercing Projectiles", Los Alamos Report LA-5238, June 1973.

[18] Magness, L. S., "Laboratory Model Scale Ballistic Evaluation of One Tungsten and Four Uranium Projectiles," Ballistic Research Laboratory Report BRL-MR-3406, November 1984.

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