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Final Report

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13. ABSTRACT (Maximum 200 words) The purpose of this project was to develop improved dynamic failure models for brittle materials (primarily ceramics). The approach to developing these failure models was to establish a database (ACERAM) in which fundamental material properties and processing information could be directly correlated with ballistic performance data. Under this contract, a comprehensive literature search was conducted, many contacts were established in the armor/anti-armor research and development community, and database development was undertaken. A more limited project was also undertaken to assess and compare the effects of material properties and penetration mechanisms on the ballistic performance of depleted uranium and tungsten alloy penetrators.					
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1.0 INTRODUCTION

Failure Analysis Associates, Inc. (FaAA) was funded under the Computational Mechanics Program element of the Balanced Technology Initiative (BTI) to develop improved dynamic failure models for brittle materials (primarily ceramics). Our approach to developing these failure models was to establish a database (ACERAM) in which fundamental material properties and processing information could be directly correlated with ballistic performance data.

1.1 Background

The data collection and database development step was nearly completed under BTI funding, which covered the contract from October 1988 to September 1990. The project was then extended (without funds) to September 1991 and funding was sought to (1) expand data collection activities to complete the database and (2) apply FaAA-developed statistical analysis techniques to critically evaluate the data and to identify those fundamental physical and microstructural properties that control the deformation (if any) and failure of brittle materials during penetration. This planned approach is shown schematically in Figure 1. In fact, however, FaAA's proposal for additional funding was rejected in December 1991. This final report, therefore, documents the contract effort to September 1990 and subsequent publications stemming from this work.

1.2 Problem Statement

The select database of "useful" information on the ballistic performance of ceramics that was to result from this project would have been the most extensive ever constructed in the free world. Existing ballistic data bases (there are at least two other available ceramic armor data bases, AADS [1] and Chicken Little [2]) contain little specific information on materials properties and characteristics, nor are they necessarily structured to permit one-to-one comparisons of the effect of specific materials characteristics on performance under equivalent ballistic test conditions. Because of its size and scope, the comprehensive materials-oriented database for brittle armor materials that was to result from this project would have enabled researchers to determine key properties and processing variables on which to focus their efforts.

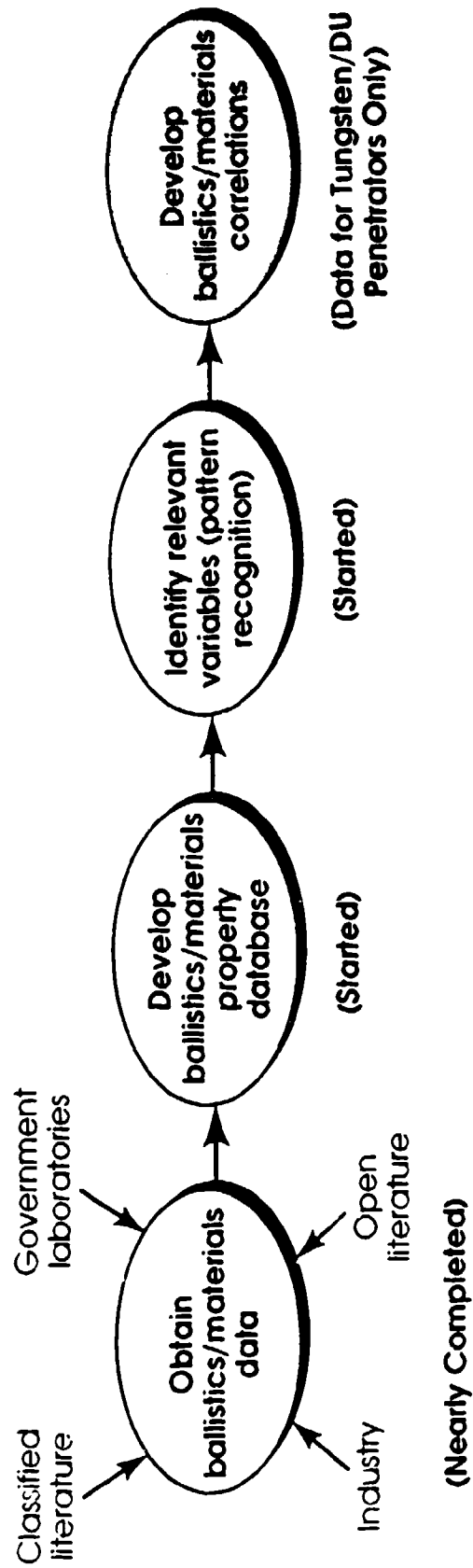


Figure 1: Project Flowchart, Showing Levels of Completion at Project Close

2.0 SUMMARY OF RESULTS

The emphasis of the project in the first two years was to evaluate the literature and survey private industry and government laboratories for appropriate data. Several hundred open literature papers and technical reports were reviewed for usable data, and links were established with available existing databases. A committee -- consisting of representatives from FaAA, the U.S. Army Tank Command (TACOM), the Army Materials Technology Laboratory (AMTL), the Ballistics Research Laboratory (BRL), and Los Alamos National Laboratory (LANL) -- was also formed early in the project to oversee our data collection activities (to prevent duplication) and to develop a standardized list of properties and processing variables to be collected on candidate brittle armor materials.

2.1 Data Collection

Data (both classified and unclassified) was collected from existing databases, from published reports/papers in the open literature, and from unpublished test data from government, university, and industry laboratories on the subjects of (1) ballistic performance of ceramics and (2) ceramic material properties governing impact performance. As a result of these efforts, an extensive collection of useful data was compiled for initial analyses of the material and processing variables that affect the ballistic performance of ceramics. Unclassified reports/papers containing material that contributed significantly to the database include those from Lawrence Livermore National Laboratory (LLNL), the Naval Research Laboratory (NRL), the University of California at Berkeley (UCB), and AMTL, among others. Those unclassified papers that were determined to be most useful are listed in Table 1.

Classified papers that we expected to be useful in this research are identified in Table 2. Appropriate clearance was established with DTIC late in the project, so collection and review of this material never began.

FaAA was also able to establish some important industry and government contacts who agreed to contribute data to this program. A listing of the data that has been

Table 1
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Ferguson, W.J. and Rice, W.J. "Effect of Microstructure on the Ballistic Performance of Alumina," Naval Research Laboratory, NRL Memorandum Report 2302, August 1971.

Landingham, R.L. and A.W. Casey, *Semiannual Progress Report of the Light-Armor Materials Program*, Lawrence Radiation Laboratory, University of California, Livermore, UCRL-51066, June 1971.

Mayseless, M., Goldsmith, W., Virostek, S.P., and Finnegan, S.A., "Impact on Ceramic Targets," *Impact Loading and Dynamic Behaviour of Materials*, editor: Chien, C.Y., Oberursel, Germany: DGM Informationsgesellschaft mit beschränkter Haftung, Vol 1, 1988, pp. 407-414.

Mescall, J.F. and Tracy, C., "Improved Modeling of Fracture in Ceramic Armors," *Army Science Conference Proceedings*, Vol 3, June 17-19, 1986, pp. 41-53.

Rosenberg, Z. and Yeshurun, Y., "The Relationship Between Ballistic Efficiency and Compressive Strength of Ceramic Tiles," *International Journal of Impact Engineering*, Vol. 7, no. 3, 1988, pp. 357-362.

Rosenberg, Z., Bless, S.J., Yeshurun, Y., and Okajima, K., "A New Definition of Ballistic Efficiency of Brittle Materials Based on the Use of Thick Backing Plates," *Impact Loading and Dynamic Behaviour of Materials*, editor: Chien, C.Y., et al., Oberursel, Germany: DGM Informationsgesellschaft mit beschränkter Haftung, 1988, pp. 491-498.

Tracy, C., Slavin, M., and Viechnicki, D., "Ceramic Fracture During Ballistic Impact," *Fractography of Glasses and Ceramics (Advances in Ceramics)*, American Ceramic Society, Westerville, Ohio, Vol 22, 1988, pp. 295-306.

Table 1 Continued

Viechnicki, D., Blumenthal, W., Slavin, M., Tracy, C., and Skeeel, H., "Armor Ceramics-1987," *Third TACOM Armor Coordinating Conference for Light Combat Vehicles*, Vol. 1, February 17-19, 1987, Monterey, California.

Viechnicki, D.J., "Factors Controlling the Ballistic Behavior of Armor Ceramics," *Army Science Conference Proceedings*, Vol 4, June 17-19, 1986, pp. 233-247.

Wilkins, M.L., "Use of Boron Carbides in Lightweight Armor," *Boron and Refractory Borides*, editor: Matkovitch, V.I., Springer-Verlag, Berlin, Germany, 1977, pp. 633-648.

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Wilkins, M.L., R.L. Landingham, and C.A. Honodel, *Fifth Progress Report of Light Armor Program*, Lawrence Radiation Laboratory, University of California, Livermore, UCRL-50980, January 1971.

Wilkins, M.L., *Third Progress Report of Light Armor Program*, Lawrence Radiation Laboratory, University of California, Livermore, UCRL-50460, 1968.

Xavier, C. and da Costa, C.R.C., "A Study of the Mechanical Behavior in Ballistic Impact of Alumina Plates," *Ceramica*, Vol 30, No. 175, July 1984.

Table 2
USEFUL CLASSIFIED LITERATURE DATA SOURCES

Abbott, K.H. and Semple, C.W., "Attributes and Limitations of Lightweight Armor," *Proceedings of Symposium on Lightweight Armor Materials*, AMRA MS-65-01, 326-339, AD 360 764L, U.S. Army Materials Research Agency, March 1965. (Secret Report).

Adams, Hale, and Zwissler, "Advanced Materials Technology Development Project Phase 1," JPL Report No. D-382, Vol. IV, Part 1, January 1, 1983.

Amos, C.W., "Dissemination of Armor Materials Ballistic Performance," *Proceedings of Symposium on Lightweight Armor Materials*, AMRA MS-65-01, AD 360 764L, March 1965, pp. 295-301, (Secret Report).

Askins, D., Bless, S., Hanchak, S., Hartman, D., and Rorleau, R., "Multi-hit Ceramic Armor for 30APM2," *Fourth TACOM Armor Coordinating Conference*, Vol 2, 1988.

Contiliano and Thorpe, "ARAP Activity During Phase 2 of Lightweight Structural Armor Program," ARAP Report #510, December 1, 1983.

Contiliano, R.M. "1982 Annual — DARPA Composite Armor Technology Program," ARAP Report #497, AD-C034-846, May 1, 1983.

Contiliano and Snedeker, "Improved Lightweight Structural Armor," ARAP Report NSWC TR82-48, August 1, 1981.

Contiliano and Snedeker, "Annual Report for 1981 in Composite Armor Technology Program," ARAP Report No. 455, Vol. 2, December 1, 1981.

Table 2 Continued

Florence, A.L. and Ahrens, T.J., "Interaction of Projectiles and Composite Armor," AMRA CR. 67-05 (F), U.S. Army Materials Research Agency, Watertown, Massachusetts, January 1967.

Gooch, W. "30-mm APDS Threat Surrogate," BRL-MR-3568, March 1, 1987.

Mascianica, F.S., "Ballistic Technology of Lightweight Armor," AMMRC TR 81-20, May 1, 1981.

Mascianica, F.S., "Effect of Back-up Thickness of 2024 Aluminum on the Ballistic Efficiency of Al_2O_3 Aluminum Composites," AMRA TA AB1-10, U.S. Army Materials Research Agency, June 1965 (Confidential Report).

Mascianica, F.S., "Effect of Boron Carbide Tile Size on Ballistic Efficiency," AMRA TR AB1-5, U.S. Army Materials Research Agency, April 1965 (Secret Report).

Persh, J., "DOD Armor Materials Programs," *DCIC Current Awareness Bulletin*, Office of the Director of Defense Research and Engineering, Chemical Technology, Materials Division, No. 14, 12-13, January-February 1969.

Reed, E.L., and Kruegel, S.L., "Correlation of Microstructure and Ballistic Properties of Armor Plate," Report 710/261, AD 626 124, U.S. Army Watertown Arsenal, July 11, 1938.

Semple, C.W., "Ballistic Behavior of Ceramic Composite Armors," AD 374 334, U.S. Army Materials Research Agency, June 1966 (Secret report).

Semple, C.W., "Ceramic Composite Armors," AMRA TR -65-26, AD 367 071L, U.S. Army Materials Research Agency, October 1965 (Secret Report).

Table 2 Continued

Semple, C.W., "Fundamental Material Properties Effects on Ballistic Protection of Lightweight Ceramic Composite Armor," AMRA TR-65-06, AD 362 260L, U.S. Army Research Agency, April 1965 (Secret Report).

U.S. Army Tank Automotive Command, *Second TACOM Armor Coordinating Conference for Light Combat Vehicles*, November 1, 1985.

Tarpinian, A., Semple, C.W., and Hannon, F.S., "Ceramic Armor," *Proceedings of the Second Symposium on Lightweight Armor Materials*, AMRA MS-66-07, AD 378 972, U.S. Army Materials Research Agency, Vol.1, October 1966, pp. 215-254 (Secret Report).

Taylor, J.W., "Properties of Materials of Interest for Lightweight Armor," Report LA-3858-MS, Los Alamos Scientific Laboratory, Los Alamos, New Mexico, January 22, 1968 (Confidential).

Wilkins, Herd, and Snowden, "Advanced Armor System to Defeat KE Projectiles and Precision Shaped Charges," UCAL-53268-82, Lawrence Livermore Laboratories, May 1, 1982.

"Representation and Use of Ballistic Limit Data," AB1-65, U.S. Army Materials and Mechanics Research Center, Prototypes Laboratory, January 15, 1967 (Special).

contributed to the analysis effort is presented in Appendix A. Programs and organizations that had promised additional information include:

- **Dow Chemical** — Dow has collected much data on the ballistic performance of ceramic armors over the last few years. They agreed to send us the aluminum nitride data that they have collected as part of the BTI program.
- **W.R. Grace** — W.R. Grace agreed to send us ballistic test data on Al_2O_3 , TiB_2 , SiC , and A•B (Al_2O_3 and B_4C) samples that they have formulated.
- **DARPA Armor program** — Ballistic test data from the participants in the Blue Armor Program [DUPONT, ALCOA, Alliant Tech Systems (formerly Honeywell), and FMC] would have been an important addition to the database.
- **University of Dayton Research Institute (UDRI)** — UDRI agreed to send us draft copies of classified work that they are doing with lightweight ceramic armors for Wright-Patterson Air Force Base.
- **Coors Ceramics Company** — Coors agreed to work with us in identifying material properties and processing techniques for any materials manufactured by Coors that are not reported in available research papers or reports.

The following government laboratories also provided previously unpublished data to the project:

- **Los Alamos National Laboratory** — LANL was completing a test program on the ballistic performance of B_4C and Al_2O_3 ceramics. They agreed to send a copy of the unclassified preliminary report, and a copy of the final report when it becomes available. We were sent a copy of the Phermex photographs of this test program.

LANL was also monitoring a test program to evaluate the ballistic performance of B_4C and SiC ceramics.

- **Ballistics Research Laboratory** — BRL has a significant amount of ballistics data on SiC , B_4C , and Al_2O_3 that had not yet been published.

If a follow-on study is ever funded, it would be worthwhile to pursue these contacts.

2.2 Database Development

The format for the database was established and is shown in Figure 2. The completed database, called ACERAM (Advanced CERamic ArMor), would have used the "4th dimension" relational database software on a Macintosh computer. It was anticipated that this user-friendly database would be the most complete set of "useful" data on the ballistic performance of ceramics that had ever been assembled, and that its data set would be the foundation for the data correlation analysis effort. This is as far as the database development effort progressed under the aborted contract.

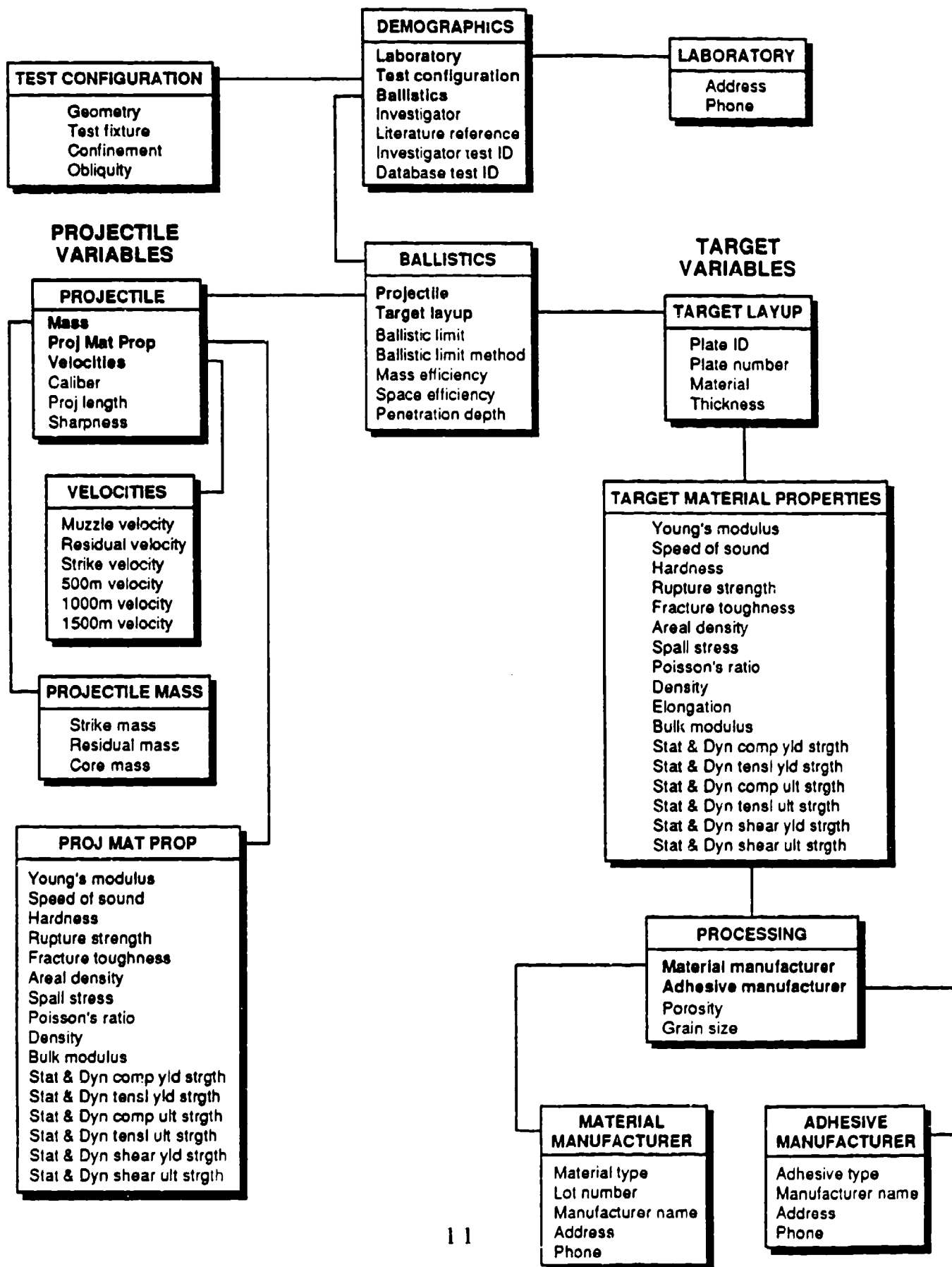
2.3 Tungsten/Depleted Uranium Review

In a related effort, FaAA was asked to review the information available on the dynamic properties of tungsten and DU, and review the mechanisms of penetration and ballistic performance for these two materials. This review, "A Review of High Strain Rate Properties and Penetration Mechanisms of Depleted Uranium and Tungsten Alloys," was presented at the April 1990 ARDEC/ARO workshop on "Metallurgical Aspects of Deformation/Failure Mechanisms in (The Terminal Ballistics of Heavy Metal) Kinetic Energy Penetrator Materials." The purpose of the workshop was to evaluate the current status of properties, penetration mechanisms, and performance of tungsten and DU penetrators. Penetration mechanisms are of particular interest, as it is felt that the differences in these mechanisms may be the reason why DU and tungsten penetrators perform differently.

In support of this effort, FaAA reviewed classified and unclassified literature and contacted government agencies, federal and university laboratories, and private industries. These efforts provided us with over 100 papers/reports on tungsten/DU penetration and over 30 government and industry contracts.

A detailed review paper was submitted to The Minerals, Metals, and Materials Society (TMS) and published by them in 1991. A copy of this paper is included as Appendix B.

Figure 2 Army CERamic ArMor Database Layout



FaAA's conclusions, based on available data, include:

- DU and tungsten alloys respond differently to high rate loading conditions, both in terms of mechanical properties and failure (penetration) mechanisms.
 - Under tensile loading, DU alloys exhibit a higher ultimate tensile strength and a higher strain to failure than do tungsten alloys.
 - Under shear loading, DU and tungsten alloys exhibit similar strengths, but DU exhibits a higher strain to failure.
 - Against steel targets, both DU and tungsten tips undergo ductile flow. However, subsequent penetration results in bulged tip sharpening by shearing (adiabatic or not). This sharpening occurs more readily in DU than in tungsten.
 - Against ceramic composite targets, tungsten alloys penetrate by erosion/localized plastic deformation.
- The ballistic performance of DU and tungsten alloys against monolithic steel targets is similar -- at best a 5 to 10% difference. Current improvements in mechanical properties of DU and tungsten alloys give at best a 5 to 10% improvement in ballistic performance.
- Against oblique spaced arrays, DU alloys significantly outperform tungsten alloys. An increase in ductility/toughness in either alloy can result in a substantial improvement in ballistic performance.
- Based on our preliminary findings, it appears that the best way (in the short-term) to improve the ballistic performance of tungsten alloy penetrators against oblique spaced arrays is to improve their resistance to fracture during penetration.
- Based on our preliminary findings, it may also be ultimately possible to achieve a sharp tip during penetration in tungsten alloys by proper microstructural control.

3.0 OTHER CONTRACT REQUIREMENTS

The following sections present all contract-required information not covered by the summary of contract work.

3.1 List of all Publications and Technical Reports

- Andrew, S.P., R.D. Caligiuri, and L.E. Eiselstein, "Relationship between Dynamic Properties and Penetration Mechanisms of Tungsten and Depleted Uranium

Penetrators," Proceedings of the International Symposium on Ballistics, Stockholm, Sweden (to be presented/published June 1992).

- Andrew, S.P., R.D. Caligiuri, and L.E. Eiselstein, "A Review of Penetration Mechanisms and Dynamic Properties of Tungsten and Depleted Uranium Penetrators," *Tungsten and Tungsten Alloys - Recent Advances*, ed. Andrew Crowson and Edward S. Chen, The Minerals, Metals, & Materials Society, 1991, pp. 141-149.
- Caligiuri, R.D., S.P. Andrew, and T.K. Parnell, "Computational Modeling of Dynamic Failure in Armor/Anti-Armor Materials," Quarterly and Semi-Annual Progress Reports for Contract DAAL03-88-C-0029, Army Research Office Proposal number 26164-MS-A (period covered: October 1988 to September 1991).

3.2 List of All Participating Technical Personnel

Dr. Robert D. Caligiuri

Dr. Lawrence E. Eiselstein

Mr. Stephen P. Andrew

Dr. T. Kim Parnell

No advanced degrees were earned by these participants during the contract effort.

3.3 Report of Inventions

No inventions resulted from this contract effort

3.4 Bibliography

Bibliographic compilations are presented in Appendix A, which is a listing of data sources compiled for this contract, and Appendix B, which contains an extensive tungsten/DU reference listing compiled under this contract. In the interest of brevity, these will not be repeated here.

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APPENDIX A
LISTING OF SOURCES FOR CERAMIC DATABASE

Army Science 1986 Conference: Volume 3 Principal Authors M Through R.
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Washington, DC: Department of the Army, 1986.

Ballistic Coefficients.
In: Sierra Bullets, n.d.: 359-417.

Ballistic Tests of Armor Materials: Final Report.
Aberdeen Proving Ground, MD: Army Test and Evaluation Command, April
6, 1977.

Ballistics 11th International Symposium: Volume 1 Propulsion Dynamics,
Launch Dynamics, Flight Dynamics.
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1989. n.s.: Belgian Royal Military Academy, 1989: v1.

Ballistics 11th International Symposium: Volume 2 Warhead Mechanisms,
Terminal Ballistics.
Ballistics 11th International Symposium. Brussels, Belgium. May 9-11,
1989. n.s.: Belgian Royal Military Academy, 1989: v2.

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1989. n.s.: Belgian Royal Military Academy, 1989: v3.

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Ballistics 9th International Symposium. Shrivenham, UK. April 29- May 1, 1986. n.s., 1986: v2.

DoD/DARPA Coordination Meeting on Advanced Armor/Anti-Armor Materials and Advanced Computational Methods.

DoD/DARPA Coordination Meeting on Advanced Armor/Anti-Armor Materials and Advanced Computational Methods. Alexandria, VA. December 13-15, 1988. Alexandria, VA: Institute for Defense Analyses, March 1989: 2 volumes.

Fiberglass Armor Protects Carrier.

Machine Design, v59 n13, June 11, 1987: 16.

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Watertown, MA: Army Materials and Mechanics Research Center, April 1977.

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Washington, DC: Shock and Vibration Information Center, December 1970.

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APPENDIX B
A REVIEW OF PENETRATION MECHANISMS
AND DYNAMIC PROPERTIES OF TUNGSTEN AND
DEPLETED URANIUM PENETRATORS

A REVIEW OF PENETRATION MECHANISMS AND DYNAMIC PROPERTIES OF TUNGSTEN AND DEPLETED URANIUM PENETRATORS

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Abstract

Kinetic energy penetrators must possess the best possible combination of hardness, stiffness, strength, and fracture toughness characteristics to be effective against modern armor systems. Over the last decade, depleted uranium (DU) and tungsten alloys have been the materials of choice for kinetic energy penetrators. DU and tungsten perform about the same against semi-infinite targets, and DU outperforms tungsten penetrators in oblique, spaced array targets, but because of environmental and subsequent cost concerns, effort has focused on improving the performance of tungsten penetrators over the last few years. However, despite recent improvements in material properties, the penetration performance of tungsten still lags behind that of DU. One possible reason is the difference in deformation mechanisms at the leading edge of the penetrator during the penetration process—DU alloys tend to shear band and sharpen as they penetrate the target material, whereas tungsten penetrators tend to mushroom and blunt. As a first step to determine whether shear banding is truly the reason for superior DU performance, a review and summary of the available information was performed. This paper presents a review of the fabrication, high strain-rate properties, and penetration phenomena of penetrators manufactured from both tungsten and DU alloys. Specifically, the effects of composition, processing, and heat treatment on material properties and penetration mechanisms of these alloys are discussed.

Introduction

As part of an ongoing effort to develop ballistic/materials correlations useful to the armor/anti-armor research and development community, Failure Analysis Associates, Inc. (FaAA) reviewed, assessed, and compared available information on penetration mechanisms of DU and tungsten penetrator alloys. Variables that influence the performance of kinetic energy penetrators include penetrator material properties and geometry, penetration mechanisms, launch dynamics, velocity, and target material properties and geometry. The objective of this phase of the project was to review, to the extent possible, the effect of material properties and penetration mechanisms on ballistic performance of these two materials. Penetration

mechanisms were of particular interest, as it is felt that the differences in these mechanisms may be the reason why DU and tungsten penetrators perform differently. As a first step, FaAA conducted an extensive review of published technical literature, searching the open literature (books, journals, conference proceedings), the DTIC database of unclassified reports, and other government and industry reports. The review and collection process also entailed visits and teleconferences with government and industry personnel.

While numerous recent studies of the differences between penetrator performances have focused on the effects of general penetration mechanics (such as the three penetration phases defined by Wilkins and Reaugh (1)) and on projectile shape differences (2,3,4), the focus of this paper is on the effect of material properties. Data on processing, composition, and heat treatment differences—as reported in studies such as Ekbohm et al.'s (5) investigation of swaged and unswaged 93W-4.5Ni-2.5Fe projectiles and Brooks and Erikson's (6) experimental analysis of varying heat treatments and carbon contents of uranium alloys—were compiled as part of the FaAA review. In all, over 100 literature sources were reviewed and over 30 government and industry contacts were made. To the extent that a comprehensive summary of these diverse studies is possible within the scope of this paper, the conclusions of these researchers are presented herein.

Background

When comparing penetrator performance, two types of targets must be considered: 1) monolithic semi-infinite targets in which the line of flight of the penetrator is normal to the target and 2) spaced array targets—oblique targets with multiple plates in which the line of flight of the penetrator is at an angle to the target. DU is currently the most widely used material in the United States for long rod kinetic energy penetrators. Concerns over environmental problems associated with disposal of materials with residual low-level radiation and the perception that DU kinetic energy research is at the mature stage of the development cycle (further improvements in DU's performance are considered to be incremental) have focused more attention on the continued development of alternative penetrator materials—namely tungsten alloys.

Despite the concerns about DU alloys, however, they continue to be favored for kinetic energy applications because DU alloys are perceived to outperform tungsten alloys. This perception is due primarily to the superior performance of DU penetrators in oblique impacts. Hence, most of the current research in processing is to improve the performance of tungsten penetrators.

Processing

Research into improving performance through processing is being conducted both at the government laboratory and private industry levels. Some of the processing techniques being used are swaging, texturing, chemical vapor deposition (CVD), and alternative matrix formulations. The potential for use of hydrostatic extrusion and hot rolling processing to fabricate composite DU/tungsten penetrators has also been investigated.

The end goal of most advanced tungsten processing research has been to match the dynamic material properties of DU; this goal was based on the belief that improved material properties would increase the ballistic performance of tungsten. Considerable research has been performed along these lines in recent years, and material properties have been improved. However, improved material properties have not directly correlated with improved tungsten penetration performance. This has been demonstrated in both monolithic semi-infinite and oblique spaced targets; despite the improvement in tungsten properties, the performance of the two materials against monolithic targets is still about the same, and DU still outperforms tungsten against oblique spaced targets. New techniques for forming both tungsten and DU/tungsten composite penetrators show the promise of penetrators that will outperform any of those currently in the United States arsenal, and further development of these penetrators is one objective of current research efforts.

DU's penetration characteristics and availability make it an attractive choice for use as a penetrator material (7). It does, however, pose some processing difficulties. The material is sensitive to corrosion (8), to trace levels of impurities (7), and to variations caused by heat treatment (9). In addition, finely divided DU is pyrophoric; therefore, unlike tungsten alloys, DU alloys cannot be easily processed by powder metallurgy techniques, and, although they can be cast and hot-worked by conventional techniques, they require special machining. Some DU powder metallurgy research is being conducted to see whether rapid solidification processing can be used to advantage; however, little work has currently been published in this area.

DU production usually begins with UF_4 (8, 10), which is derived from a nuclear weapons and power industry byproduct, UF_6 . Cast ingots of DU typically retain residual impurities of Fe, Si, Cu, Ni, C, and H_2 from the reduction and vacuum-melt process. Hydrogen embrittlement is a concern for DU alloys, which are also sensitive to re-embrittlement (9, 10). The quality of DU alloys must be carefully controlled to minimize inclusions and mechanical property variations caused by

improper heat treatment. Penrice (9) states that heat treatment after quenching is the single most important step in making quality DU alloy penetrator material. As discussed below, tungsten materials require similar care in processing and heat treatment.

Tungsten Processing

Tungsten alloys used in penetrators are really composite materials. They are composed of hard, brittle tungsten particles embedded in a soft, ductile metal matrix (most often nickel and iron, although copper, cobalt, and other metals have been used for matrix materials to provide ductility to the system). Higher volume fractions of tungsten in the alloy yield heavier penetrators, which in turn have greater kinetic energies for penetration. However, a higher volume fraction of tungsten also yields greater contiguity between tungsten grains (tungsten-tungsten boundaries are fracture initiation sites) and means the alloy must contain less of the ductile matrix which retards cracks and redistributes stresses (11, 12).

Several processes have been used to manufacture tungsten penetrators. Among these are sintering, swaging, extrusion, and CVD processes. Of these, sintering (which is sometimes followed by swaging and annealing to give increased strength and ductility) is the most popular method. Hydrostatic extrusion has also been investigated as a method for making high performance tungsten penetrators. CVD has also been used in some research programs (13), although only to a limited extent and primarily for shaped-charge liner applications.

The sintering process used is liquid-phase and is performed by compacting fine-grained (3-5 micron) tungsten powders and heating them above the eutectic temperature of 1435°C in a hydrogen atmosphere. The resulting composite consists of rounded, tungsten grains (50-90 microns) in a W-Ni-Fe matrix. The tungsten grains retain their BCC structure; however, small amounts of nickel and iron are in solid solution during liquid-phase sintering. Special attention must be paid to ensure complete densification, as small amounts of porosity from entrapped gas or solidification shrinkage will reduce ductility (11, 14).

After sintering, the resulting material must be cooled at a rate that will deter the formation of intermetallics that, along with impurities, can weaken the material by facilitating an intergranular rather than transgranular failure mode across the tungsten grains. Although reports of the effects of cooling rates on observed toughness vary, the consensus appears to be that cooling at slow rates allows the formation of intermetallics and allows impurities (i.e., sulfur, carbon, phosphorous) to segregate to the grain boundaries, resulting in lower fracture toughness (11, 14, 15, 16, 17). German et al. (17) note that the effect of cooling rates lessens as the amount of impurities is reduced. It is also important to prevent hydrogen embrittlement from occurring because it, too, weakens the composite and causes intergranular failure to occur (14, 16, 18). As will be discussed in greater detail below, transgranular failures are preferable to intergranular failures, as they allow a material to achieve higher

strength and toughness before failing in quasi-static mechanical tests.

The nickel-iron matrix material has an FCC structure, the ductility of which is dependent on the amount of post-sintering processing. Even though the matrix is ductile, the mechanical behavior of the W-Ni-Fe penetrators approaches that of pure tungsten, since a low volume fraction of matrix material must be used to maximize overall density. This phenomenon can cause tungsten penetrators to break up after initial impact with oblique targets, making them less effective in penetrating subsequent armor plates. Because of this problem, methods have been sought for increasing the ductility at constant overall density. Ductility may be increased by orienting the grains so that they are parallel to one another and parallel to the longitudinal axis of the penetrator. Two methods for accomplishing this are to swage or hot extrude the W-Ni-Fe composite. The resulting preferential grain orientation produces stronger and harder penetrators. Annealing may also be used to increase ductility; it tends to preferentially soften the matrix. The "cold work" in tungsten grains is not significantly affected due to the higher melting temperature of tungsten relative to that of the matrix material.

To find the most appropriate, ductile, matrix material for penetrators, several alloys have been studied extensively (6, 11, 19, 20, 21, 22); primary among these are W-Co, W-Cu-Fe, and various formulations of W-Ni-Fe.

Most of the reported research has focused on the nickel-iron alloy systems. Iron increases the matrix toughness and ductility (23). The W-Ni-Fe system was chosen over the W-Cu-Fe system for several reasons. The metallurgical reasons include that Cu has been noted to segregate to the boundaries and that the contiguity is about 13% higher in the W-Cu-Fe system than in the W-Ni-Fe system (24); also, a greater amount of transgranular cleavage has been observed in W-Ni-Fe alloys. These microstructural differences contribute to the increased performance of the W-Ni-Fe alloys. Furthermore, the ideal ratio of nickel to iron has been determined to be 7:3, as this avoids the formation of intermetallic phases (11). According to Penrice (9), a major factor in the improvement of the W-Ni-Fe alloys over the last decade has been the control of impurities that segregate to the grain boundaries.

Review of Material Properties

While the exact effects of material properties on ballistic performance have not been established, it has become apparent that harder, stronger materials are preferable for impacts into semi-infinite plates and more ductile materials are preferable for oblique impacts into spaced array armors. Improved material properties also have an effect at launch and allow higher launch speeds to be used. Hence, it is necessary to discuss the effects of material properties in order to assess relative penetrator performance.

As discussed below, there are numerous differences in the material properties of DU and tungsten alloys. For

example, tungsten alloys work harden faster than DU alloys. DU alloys strain harden at a much slower rate, and still work harden after significant swaging (9). Also, Young's modulus for tungsten alloys is twice as large as for DU (9, 25).

Wood and Dini (26) comment that DU's excellent mechanical properties can be significantly improved by alloying and heat treatment. Wood and Dini note that alloying DU with 2 wt% niobium in the over-aged heat treatment condition significantly increases DU's strength without making its material properties sensitive to variations in heat treatment. Compositions containing greater amounts of niobium (in this case, 5.3 and 6.8 wt%) are more resistant to corrosion and hydrogen embrittlement and can be heat treated in larger sections than is possible for DU-0.75Ti. The higher niobium content, however, reduces the strength-ductility relative to that of DU-0.75Ti. In unrelated research, Magness (27) has suggested that DU alloyed with 6 wt% niobium (DU-6Nb) does not shear band (possibly due to its low strength and high work hardening rate), an observation that, if substantiated, could shed new light on the differences in failure mechanisms between tungsten and DU. Because of the current industry focus on improving tungsten properties, the remainder of this discussion centers on that topic.

Tungsten Material Properties

Material properties are sensitive to impurities, microstructure, and processing variations (11, 18, 28) that make it difficult to establish uniform properties. The material properties that have been recorded to date for tungsten alloys vary widely, and the following discussion makes brief note of these as an aid to those who might want to explore the subjects further.

In general, ductility decreases with increased strain rate, as observed by Kaneko (29) and Penrice (15). Bose et al. (30) confirm this observation for 90W-Ni-Fe; Meyer et al. (31) and Kunze and Meyer (32) find that, for 91% tungsten alloys, ductility decreases as strain rate increases for both the as-sintered and the sintered, swaged, and annealed cases.

Elongations up to 25% (15, 16), 29% (33), and 35% (8) have been reported for tungsten alloys. Ekblom (20) reports that elongation decreases as temperature decreases and that tensile strength increases as temperature decreases. As temperature increases, the strain rate sensitivity of the material decreases (20, 30) and Bose et al. (30) report that both strength and ductility appear to be unaffected by strain rates (up to 40s⁻¹) at 600°C.

The strength of tungsten alloys has been a subject for much research, and the general finding is that, in agreement with most metals, strength increases with increased strain rate (15, 29, 30, 34). Penrice (15) also notes that ductility decreases faster than strength increases for 97W-Ni-Fe systems. Kunze and Meyer (32) confirm that strength also increases with increased strain rate for 91% tungsten alloys; Meyer et al. (31) extend this to both the as-sintered and the sintered, swaged, and

annealed conditions, finding the as-sintered condition to be the more strain rate sensitive of the two (by nearly a factor of two).

The effects of swaging were further investigated by Penrice (7), Ekbohm (5), and Kunze and Meyer (32). Penrice (7) found that, as for most metals, as swaging and strain rate increase, tensile strength increases and the percent elongation decreases. Annealing after swaging can increase both ultimate tensile strength and elongation.

Kunze and Meyer (32) show yield strength to be greater in compression than tension for tungsten alloys. Woodward (22) tested 90, 95, and 97% W-Ni-Fe alloys in compression from 0.001 1/s to 1000 1/s and reports that flow stress increases with strain rate. Work softening was observed in these alloys when the strain rate was greater than 2 1/s. This phenomenon is attributed to the effect of temperature rise due to plastic deformation.

Work hardening was found by Rabin et al. (14) to increase with increased tungsten content. Johnson (25) found that 90W-7Ni-3Fe alloys work harden as the shear strain rate increases. He also reports that shear strain at failure decreases as shear strain rate increases, and that tungsten alloys show greater strain rate sensitivity than that measured for DU-0.75Ti. Harding (35) found shear stress to increase as the shear strain rate increases, which parallels Abey and Stromberg's findings (36) for pure DU.

Much of the data on fracture toughness of tungsten alloys comes from Kaneko (37), who investigated W-Ni-Fe alloys with a 2:1 nickel-iron ratio. Kaneko found fracture toughness decreases linearly with the increase in the percent of tungsten (91 to 95.5%). This was found to be true for both as-sintered and 30% swaged material, although the as-sintered showed nonlinear behavior. Values at -40°C and 20°C were about the same.

The most effective ratio of tungsten to matrix materials has also been the object of much research. It is generally accepted that the highest strengths are obtained for tungsten contents from approximately 91 to 93%, corresponding to contiguities from 0.3 to 0.4. Rabin et al. (14) recently performed tests for W-Ni-Fe alloys that support the 93% value; current (unpublished) research seems to support the 91% value.

Another subject for research is to establish hardness, tensile strength, and other mechanical properties for the matrix materials in tungsten alloy penetrators. Woodward (12) has done some work on hardness properties. In measuring the hardness of an alloy that had the same composition as the matrix of a 95% tungsten penetrator, he found that the hardness of the matrix was about 27% that of pure tungsten. He also observed that failure of the low density matrix was characteristic of a ductile failure, confirming the intrinsic ductility of the matrix.

Penetration Mechanisms and Ballistic Performance

The literature indicates that, against monolithic steel targets, improved material properties do not guarantee

enhanced penetration. In fact, against monolithic steel targets, DU and tungsten alloys perform about the same. Against oblique spaced steel targets, increased ductility/toughness seems to enhance penetration. An advantage of DU penetrators is that they can bend when impacting an oblique target and, hence, face a lower penetration area (38). For this reason, DU alloy penetrators (which are more ductile than tungsten) generally outperform tungsten alloy penetrators against these targets. Processing to increase material properties shows varied results against spaced array targets for tungsten alloy penetrators. Note that most of the available literature records performance against monolithic targets. The spaced-array target data is limited and the performance conclusions presented here are expected to evolve as the programs mature and more data is made available.

Failure Modes Under Dynamic Loading

During penetration, very little of the kinetic energy of long rod penetrators is transferred to the target. Depth of penetration is to a large extent determined by projectile length. Penetration is the process of moving material aside that results when the impact stress is greater than the flow stress of the target. When impact stress exceeds projectile and target flow stress, the projectile material deforms, and target penetration occurs at the expense of projectile erosion (1, 39). Large hydrodynamic stresses created by the confinement of the target material are transmitted to the projectile, and the nearby free surfaces of the projectile are accelerated radially. During this process it is important for the projectile to maintain as sharp a point as possible so that the penetration energy is applied to as small an area as possible. Thus it is better for a penetrator to "sluff off" material that has expanded radially (i.e., through shear failure), rather than for it to deform and take on a "mushroom" shape. The projectile in this impact velocity range is actually decelerated by its own material strength.

The mechanisms by which DU and tungsten projectiles penetrate their targets include hydrodynamic deformation, mushrooming/macroscopic plastic deformation, erosion/localized plastic deformation, brittle fracture, adiabatic shear banding, and melting/thermomechanical interaction. The two penetrator material failure modes of most interest are: 1) mushrooming and 2) shear failure. The mushrooming phenomenon occurs when penetrator material flows radially after its first impact with the target. The shear failure phenomenon occurs when shear stresses separate penetrator material from the rest of the penetrator after it impacts the target. The most applicable difference in these two penetration modes is that the mushrooming failure mechanism expends energy to expand the penetration radially, whereas the more pointed shear failure expends energy to achieve greater penetration. Those penetrators that achieve shear failure at the nose also maintain a greater pressure on the target and make a more effective use of the penetration energy.

It has been noted (6, 40) that, at very high velocities, both DU and tungsten penetrators perform the same against thick, ductile targets. This may be because, at these

velocities, both penetrators have essentially broken up and are flat-ended projectiles. Brooks and Erikson (6) also conclude that DU and tungsten perform about the same at intermediate velocities. They note, however, that at lower speeds, superior mechanical properties do not necessarily mean better performance.

Penetration Mechanisms of DU Alloys

The principal penetration mechanism for DU alloys (DU-0.75Ti and DU-2Mo) against steel targets is adiabatic shear banding (21, 41), with some mushrooming. Adiabatic shear banding was first observed by Zener and Holloman (42) in 1944, and was first noted in penetrators by Tardif in 1956 (43). Shear banding occurs during the high loading that a projectile sees upon impact with a target and allows the material to readily fail along the bands. This action creates the sharpened pencil point and sluffing off of material that allows the projectile to achieve greater penetration.

Adiabatic shear is dependent on the localized generation of heat high enough to soften the material (44). During penetration, the penetrator will deform plastically at high rates of strain. This will result in an increase in the flow stress of the material due to work hardening and a competing decrease in the flow stress due to thermal softening (90-95% of the deformation goes into heat). When thermal softening overcomes the increase in flow stress, adiabatic shearing will occur. Adiabatic shear has also been extensively studied analytically (45, 46, 47), and there is general agreement that susceptibility to adiabatic shear increases as strain hardening decreases and thermal softening increases. This adiabatic shear phenomenon is not particular to any crystal structure, as long as the above thermomechanical requirements are met (21, 39, 48, 49, 50). Other penetration mechanisms have also been proposed for DU into steel targets. For instance, Penrice (9) notes that a low melting temperature Fe-U eutectic can form at the penetrator tip, which helps remove target/penetrator erosion products from the target hole. This is an alternate explanation of the target hole being narrower for the DU penetrators than for the tungsten alloy penetrators. Mach (51) has measured the temperature rise of tungsten alloys penetrating steel targets. He was able to determine that the penetrator temperature, at an impact velocity of 1200 m/s, quickly rises to approximately 1480°C. At impact velocities of 1600 m/s, the temperature rises to approximately 1790°C. Gerlach (52) has documented the formation of Fe-W molten material at the bottom of penetrator holes. Gerlach also states the melting point of the Fe-W is lowered to approximately 1650°C. This evidence of molten material appears to be in agreement with Mach's data.

Because of the properties of DU, the adiabatic shear banding failure mode is noted more often in DU penetrators than in tungsten. However, there have been DU alloys that have been noted not to fail due to adiabatic shear. One such material is DU-6Nb (6, 27). This alloy is thought to be too soft to achieve the thermomechanical instability required for shear banding to occur.

Penetration Mechanisms of Tungsten Alloys

Tungsten projectiles show little evidence of adiabatic shear banding against steel targets. In general, tungsten alloys show little evidence of adiabatic shear banding or brittle fracture of tungsten grains when shot into ceramic composite targets; however, Shockey et al. (53), Rogers (48), and Irwin (21) report the repeated formation of shear bands in the mushroomed ends of tungsten penetrators shot into ceramic and metal targets. Irwin offers the following explanation for this phenomenon. During the mushrooming of a penetrator, a fillet occurs as the penetrator flows radially. This creates high strains in the penetrator material and causes it to shear band and break off. This process repeats itself throughout the penetration process, causing the observed periodic appearance of shear bands.

Against steel targets, the principal penetration mechanism of tungsten alloys is mushrooming, with macroscopic plastic deformation followed by erosion. Ekblom (20) suggests that the deformation of the tungsten composite can be broken into two stages: 1) the deformation of the matrix and 2) deformation of the tungsten. The initial strain is localized mainly in the matrix, which rapidly work hardens so that the tungsten composite, acting as a single unit, deforms according to tungsten deformation behavior.

Recent studies have investigated the penetrator/target interaction. Gerlach (52) studied 92W-5Ni-3Fe penetrators shot against steel targets. Residuals of these targets show evidence that the penetrator melts, leaving plumes of projectile material in the target cavity. Gerlach postulates that target and penetrator materials engaged in the interaction and friction weld zones lose their strengths and are extruded in the direction opposite to the direction of penetration. This may be supported by the ongoing work of Caligiuri and Eiselstein (54), who have discovered, in examination of tungsten penetrators fired against ceramic composite targets, ceramic target material intermingled with the material of the recovered projectile.

Composite Penetrators

In addition to the efforts underway to improve the performance of tungsten penetrators, a significant number of researchers are investigating the possibilities for developing composite DU/tungsten penetrators that would combine DU's ductility with tungsten's strength. In the mid-1970s, Brooks (3) and Norris et al. (38) recognized the importance of strength and ductility to penetrators and suggested that these requirements would probably be best met by some kind of composite penetrator. In particular they suggested mounting a uranium-alloy head onto a tungsten shaft to improve the performance of tungsten penetrators in oblique impact situations. Bruchey and Montiel (55) suggested that the performance of a tungsten core would be enhanced against spaced targets if sheathed with DU.

Bruchey et al. (56) discuss tailoring penetrator properties using metal matrix composite fabrication techniques.

They describe seven different types of penetrators manufactured using metal matrix composite manufacturing techniques. These were then shot against an oblique triple-spaced array. The best penetration was achieved by a coextruded DU/tungsten alloy (best in this case being that which had the highest velocity after penetrating three metal plates). This penetrator exhibited less bending and deviation from line of flight than typical DU-0.75Ti penetrators. The DU/tungsten alloy was fabricated by placing tungsten filaments in DU-0.75Ti ingots and heat treating and extruding the composite. The main advantage of this coextrusion technique was that it was done at low temperature, thus minimizing filament/matrix interaction.

As most of the new composite materials development programs are classified, little mechanical property and penetration data is available. Hence the data presented here is culled from only a few studies and may not be representative of the body of information that currently exists. Principal among the programs that offered information to this study is that being conducted by Los Alamos National Laboratory (LANL) to build composite DU/tungsten penetrators consisting of tungsten rods surrounded by DU (57). LANL indicates that thermomechanical working of the microcomposite material appears to offer the best properties of any composite to date. They are currently evaluating all working technologies to deform the tungsten particles in the DU matrix. To date this program has produced penetrators with a 50% increase in strength over kinetic energy penetrators currently in the US arsenal.

The LANL DU/tungsten rods show a yield strength of 133 ksi and total strain to failure of 56% (compression). Failure occurred in the tungsten rod, not at the DU/tungsten interface. Ultimate strength was measured to be approximately 75 ksi with very little ductility. Initial tests shot these penetrators into semi-infinite RHA, and they performed as well as the DU-0.75Ti penetrators.

LANL will continue to investigate technologies that will produce aligned tungsten fibers in the uranium matrix. They have demonstrated the ability to deform tungsten particles using swaging, rolling, or hydrostatic high energy rate forming. To date thermomechanical working of the material has been by rolling. The current approach is to work the tungsten and uranium matrix under two separate conditions to optimize material properties in each material. Since uranium recrystallizes at a lower temperature than tungsten, the uranium matrix is worked and annealed repeatedly without recrystallizing the tungsten. They estimate that very large warm working reductions will be required to adequately deform tungsten particles.

Conclusions

The ballistic performance of DU and tungsten alloys against ceramic composite targets cannot be reliably concluded from available literature, although data may be available from classified sources. The dramatic variation in the performance of the two materials against monolithic steel and oblique spaced steel targets, and the

significant effect that an increase in ductility/toughness can have on the ballistic performance of both materials against spaced arrays indicates that a comprehensive effort should be undertaken to correlate material properties with penetrator performance.

One possible reason for the difference in penetration for the two materials is that DU is more ductile than tungsten and less likely to fracture upon impact. DU also has a greater resistance to bending moments resulting from penetration of spaced arrays. Furthermore, the essentially equivalent penetration performance between DU and tungsten in semi-infinite targets suggests that the facts that DU is more susceptible to adiabatic shearing and that tungsten tends to mushroom have only a secondary effect on penetration.

Conclusions, based on available data, include:

- DU alloys and tungsten alloys respond differently to high-rate loading conditions, both in terms of mechanical properties and failure (penetration) mechanisms.
- Under tensile loading, DU alloys exhibit a higher ultimate tensile strength and a higher strain to failure than tungsten alloys.
- Under shear loading, DU alloys and tungsten alloys exhibit similar strengths, but DU alloys exhibit a higher strain to failure.
- Against steel targets, both DU and tungsten tungsten penetrator tips undergo ductile flow. However, subsequent penetration results in bulged tip sharpening by shearing (adiabatic or not). This sharpening occurs more readily in DU than tungsten.
- Against ceramic composite targets, tungsten alloys penetrate by erosion/localized plastic deformation.
- The ballistic performance of DU alloys and tungsten alloys against monolithic steel targets is similar — at best a 5 to 10% difference. Current improvements in mechanical properties of DU alloys and tungsten alloys give at best a 5 to 10% improvement in ballistic performance.
- Against oblique spaced arrays, DU alloys outperform tungsten alloys. A significant increase in ductility/toughness could result in a substantial improvement in ballistic performance of tungsten penetrators.

It appears that the best way (in the short-term) to improve the ballistic performance of tungsten alloy penetrators against oblique spaced arrays is to improve their resistance to fracture during penetration. It may be ultimately possible to achieve a sharper tip during penetration in tungsten alloys, similar to that which occurs in DU, by proper microstructural control.

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