“Armaments for the Army Transformation”

NDIA Conference & Exhibition
Parsippany Hilton, Parsippany NJ

# Advanced Penetrator Materials


Dr. Lee Magness*
Lethal Mechanisms Branch
Weapons Materials Division
Phone: 410-278-6022
E-mail: magness@arl.army.mil


20 June 2001

# Report Documentation Page

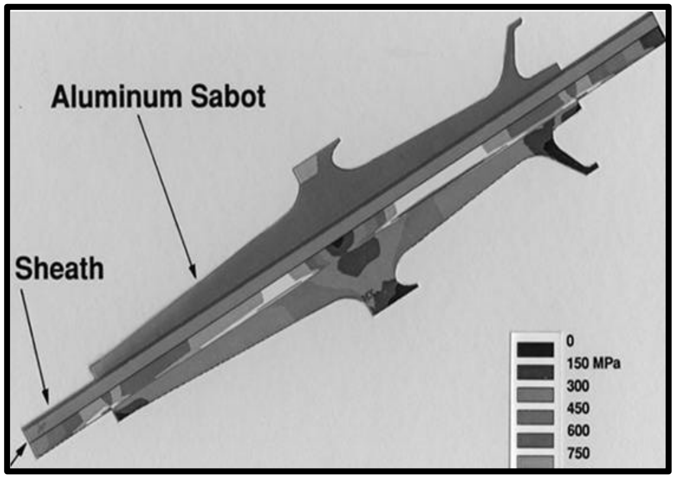
| Report Date | Report Type | Dates Covered (from... to) |
|---|---|---|
| 20JUN2001 | N/A | - |

| | |
|---|---|
| **Title and Subtitle**<br>Advanced Penetrator Materials | **Contract Number** |
| | **Grant Number** |
| | **Program Element Number** |
| **Author(s)**<br>Magness, Lee | **Project Number** |
| | **Task Number** |
| | **Work Unit Number** |
| **Performing Organization Name(s) and Address(es)**<br>Lethal Mechanisms Branch Weapons Materials Division Army Research Laboratory | **Performing Organization Report Number** |
| **Sponsoring/Monitoring Agency Name(s) and Address(es)**<br>NDIA (National Defense Industrial Association 2111 Wilson Blvd., Ste. 400 Arlington, VA 22201-3061 | **Sponsor/Monitor's Acronym(s)** |
| | **Sponsor/Monitor's Report Number(s)** |
| **Distribution/Availability Statement**<br>Approved for public release, distribution unlimited | |
| **Supplementary Notes**<br>Proceedings from Armaments for the Army Transformation Conference, 18-20 June 2001 sponsored by NDIA | |
| **Abstract** | |
| **Subject Terms** | |
| **Report Classification**<br>unclassified | **Classification of this page**<br>unclassified |
| **Classification of Abstract**<br>unclassified | **Limitation of Abstract**<br>UU |
| **Number of Pages**<br>23 | |

# OUTLINE

- Background: Relationships between Properties and Performance of High-Density Materials
  - the adiabatic shear failure of DU
  - general approaches to alloy development
- Uranium (U-V-X) Alloys
- Alternative Matrix (adiabatic shearing) Tungsten Composites
- Amorphous and Nanocrystalline Alloys
- Severe Deformation Processed WHAs
- Jacketed Penetrators
- Conclusions

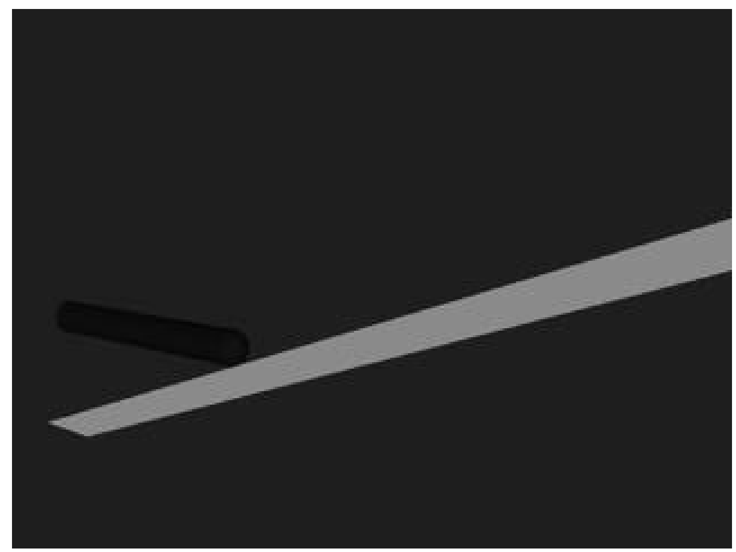
# Properties vs. Performance Relationships/Requirements




- Engineering properties: strength and toughness.
  - Allow more efficient sabots/projectiles.
  - Resist complex armors.
  - Soft-launched projectiles expand options.

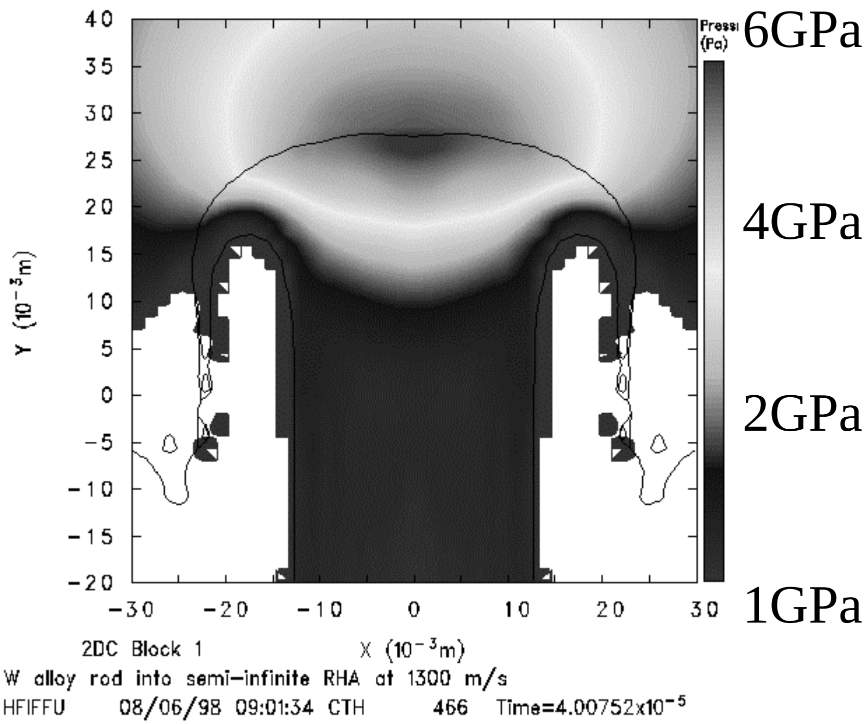
•High-rate, high pressure, deformation.

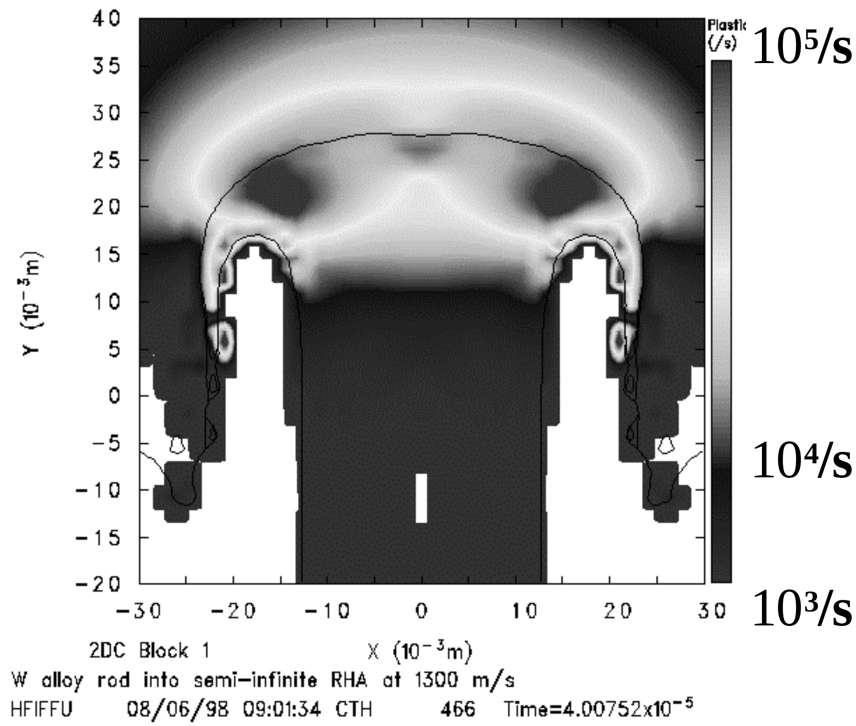
- Controls efficiency during deep penetration.



At the present time, Depleted Uranium alloys provide the best overall combination of structural and high-rate properties.

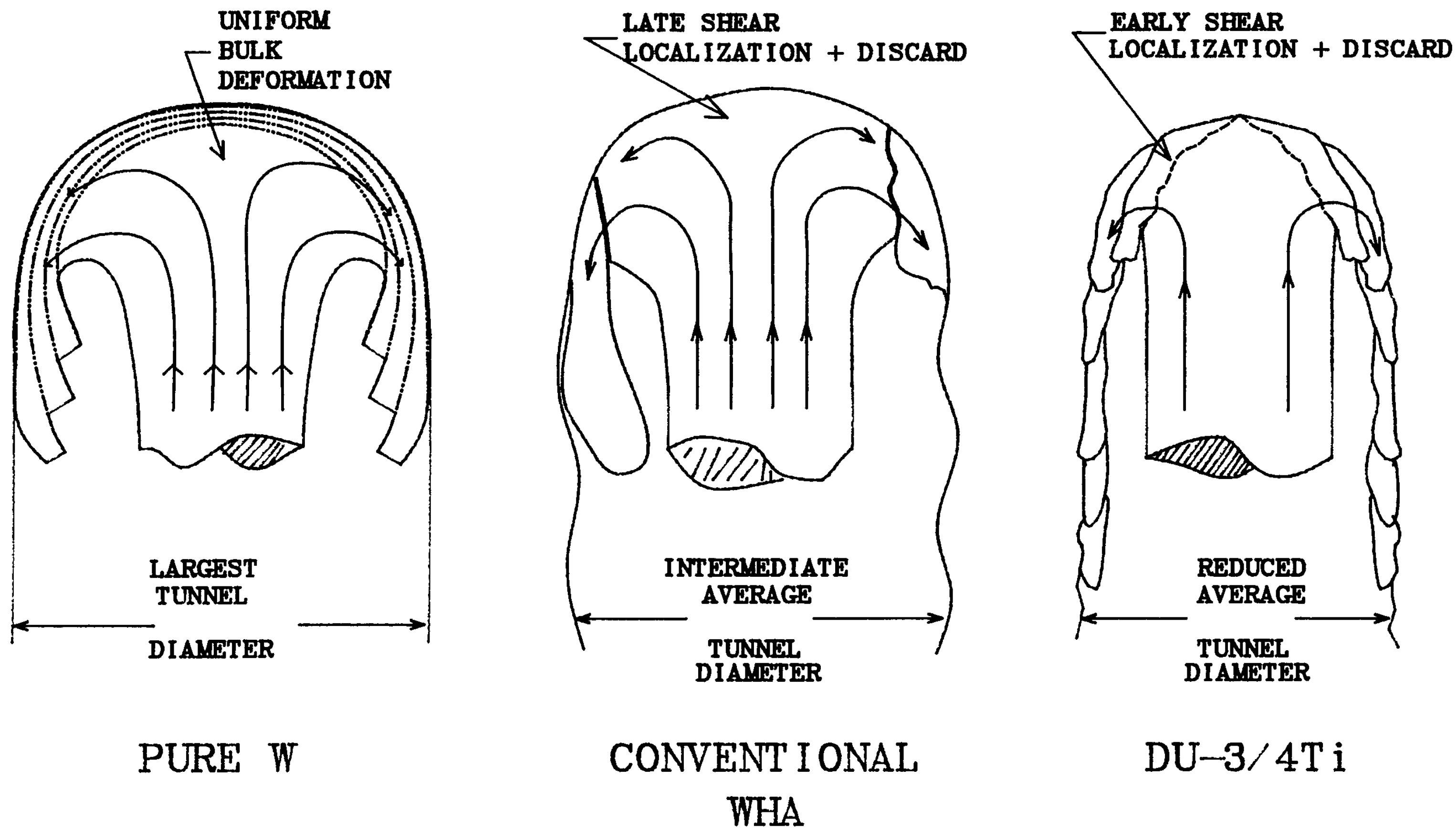
# Pressure & Strain Rate Distributions During Deep Penetration




**Strain-hardening and thermal-softening mechanisms compete during the high rate (adiabatic) deformation.**

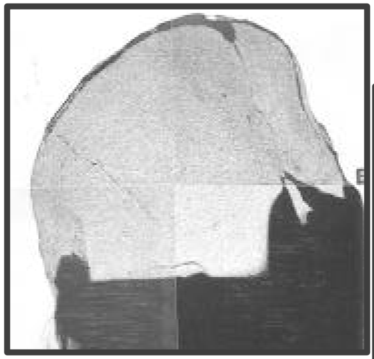
# Flow/Failure of High-Density Penetrator Materials



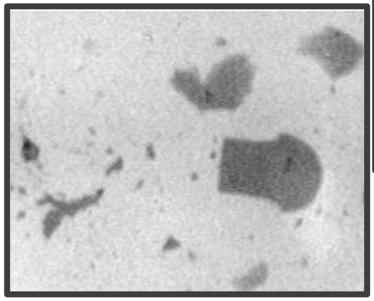

DU failure by adiabatic shear. This reduces the size of penetrator head, burrows narrower & deeper cavity.

# Flow and Failure of High Density Penetrator Materials

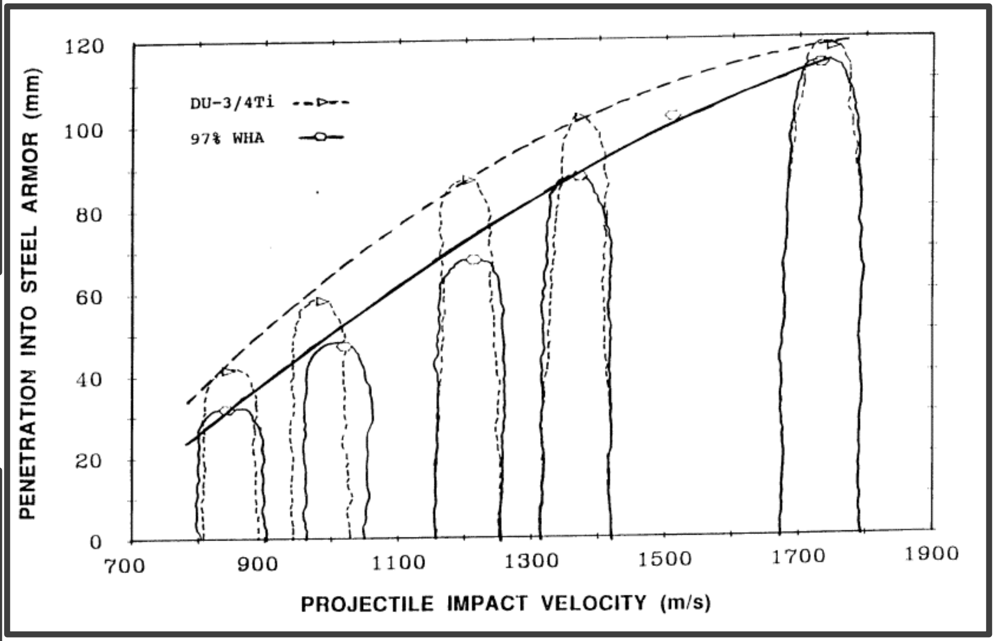
**TUNGSTEN HEAVY ALLOY**



- WIDER CHANNEL
- MUSHROOM NOSE
- LESS DEPTH

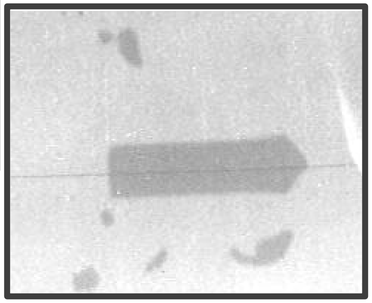


W-Ni-Fe




**U-3/4 Ti ALLOY**

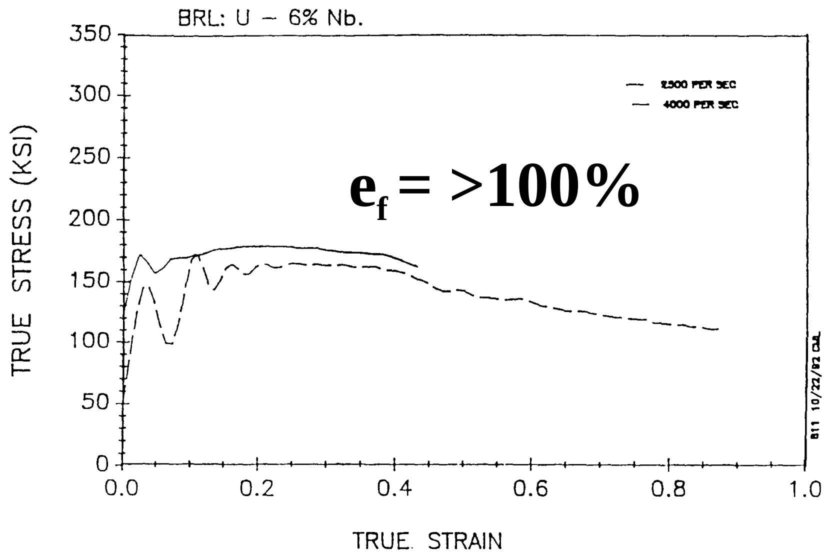
- REMAINS SHARP
- NARROW CHANNEL
- DEEPER CAVITY

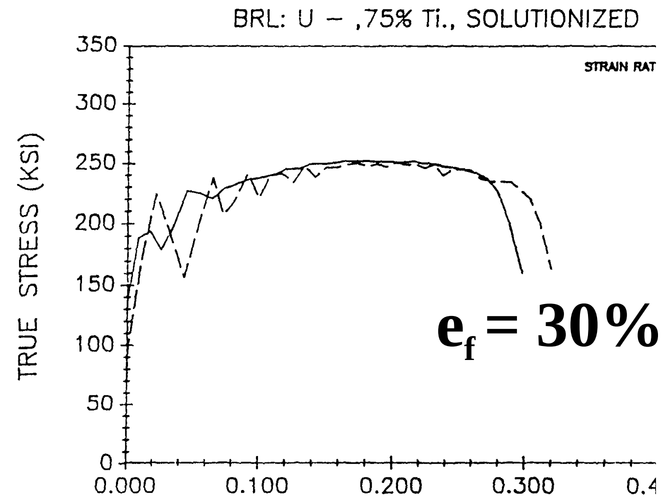


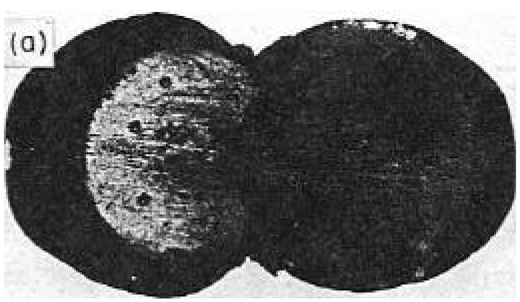
U-8Mo ALLOY

# Dynamic (SHB) CompressionTests

(strain to adiabatic shear failure)



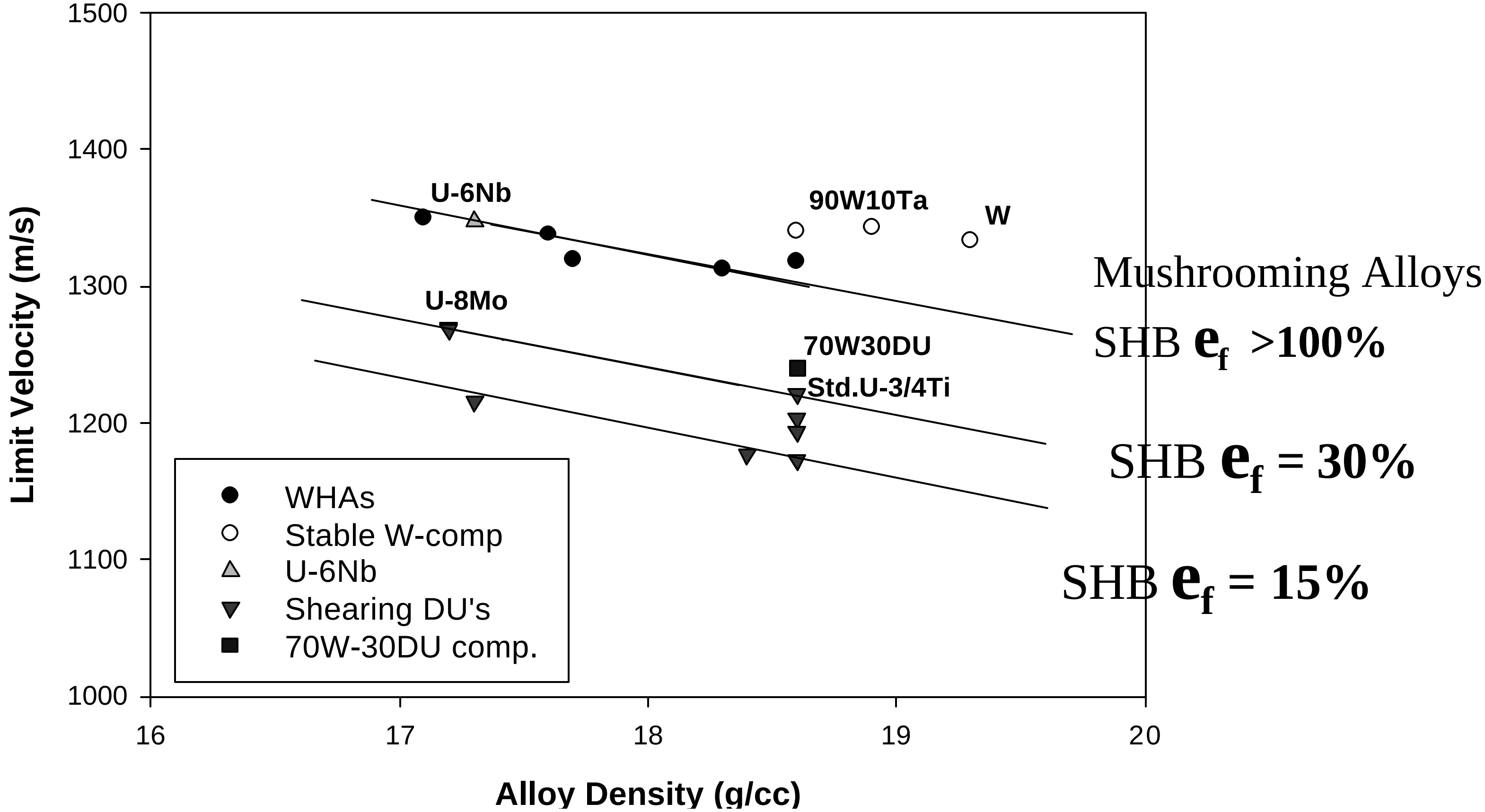




**U-3/4Ti specimen cleaved by shear band**

Dynamic compression experiments provide a means for assessing material failure behavior at high loading rates.

# Comparison of RHA Steel Perforation Capabilities

¼-scale tests, 65g L/D=15 rods vs. 76.2mm RHA

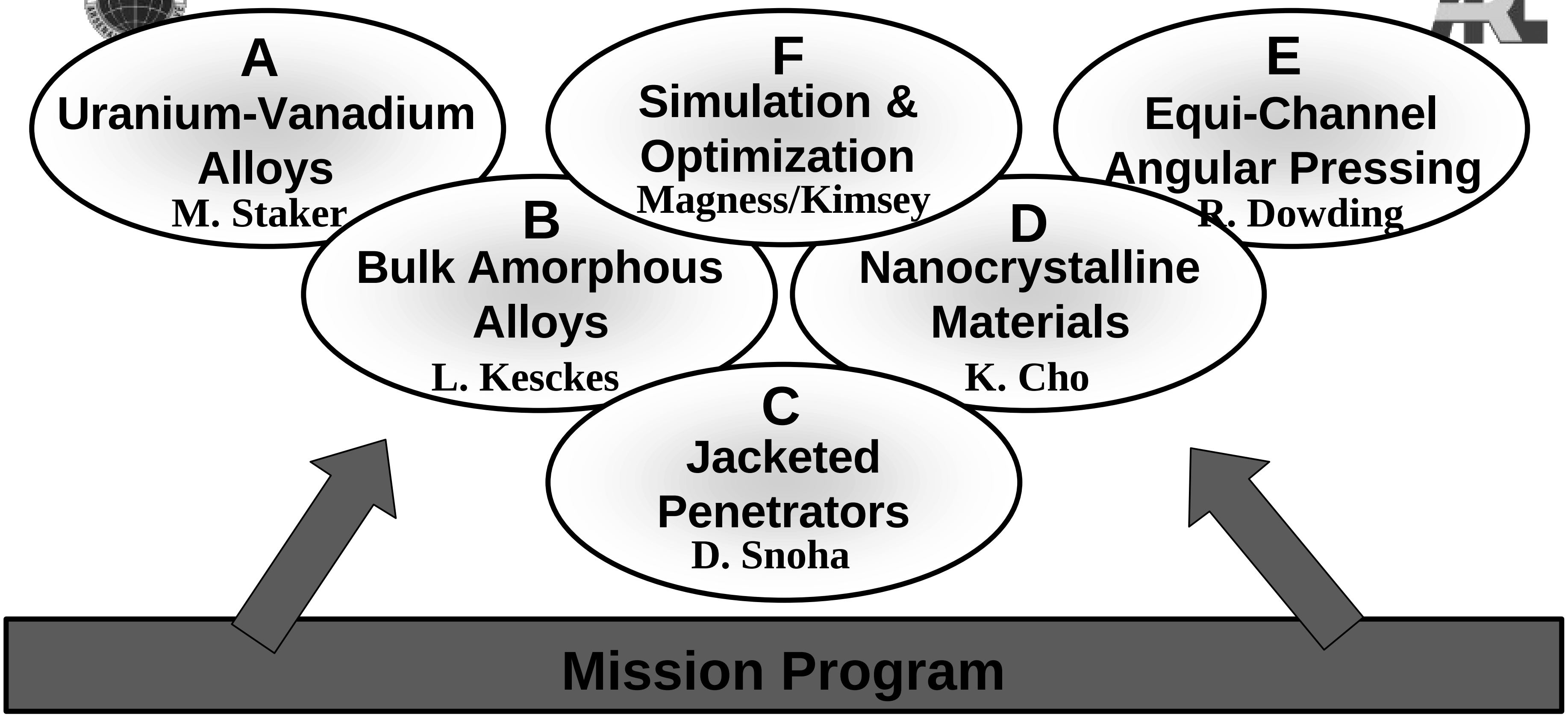



**Deep Penetration performance is a function of alloy density & strain to shear failure.**

# Material Options

- **DU alloys**: Enhance susceptibility to shear failure, while retaining/improving engineering properties.
- **Non-DU materials**: change flow/failure behavior
  - Use alternative matrices, selection based on mechanical <u>and thermal</u> properties that promote high-rate <u>(adiabatic)</u> plastic instability and localization
    - Matrix alloys w/high strength, low work hardening, low strain rate sensitivity, rapid thermal softening
  - Amorphous & nanocrystalline materials as a candidate matrix alloy or entire composite (nano W phase)
    - exhibit localized shear failure in dynamic <u>and quasi-static</u> tests
  - Anisotropic flow/failure of W crystals
- **Jacketed Penetrators**: Systems approach, with materials issues

# CURRENT ANTI-ARMOR MATERIALS DEVELOPMENT PROGRAMS




Center of Excellence Programs

SBIR/STTR Contracts

Congressional Interest Program

ARO University Programs

DARPA

Other Government Agencies

TPA

International Agreements

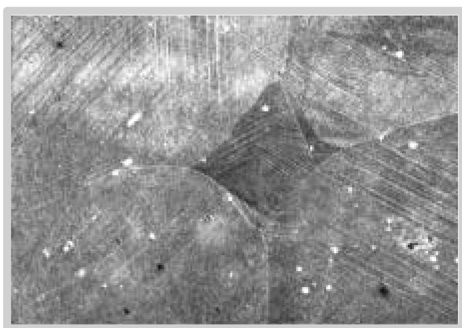
Industry

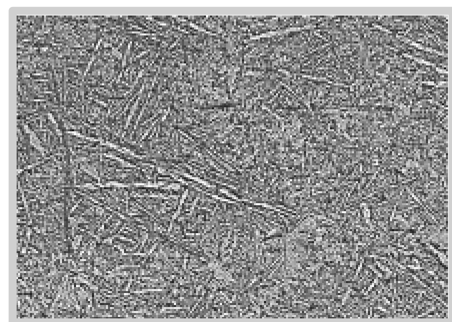
Customer

# Uranium-Vanadium Alloys

| Composition | Density | Hardness | Ult. Tensile Strength |
|---|---|---|---|
| | (g/cc) | HRC | (Ksi/Mpa) |
| U-V (1-4.5%) | 16.7–18.5 | 36-54 | To 310/2140 |
| U-V-X(ternary) | 16-18.5 | 36-55 | To 320/2200 |
| U-3/4Ti | 18.6 | 38-49 | To 250/1720 |

U-2.1%V, banded martensite
(from Staker)

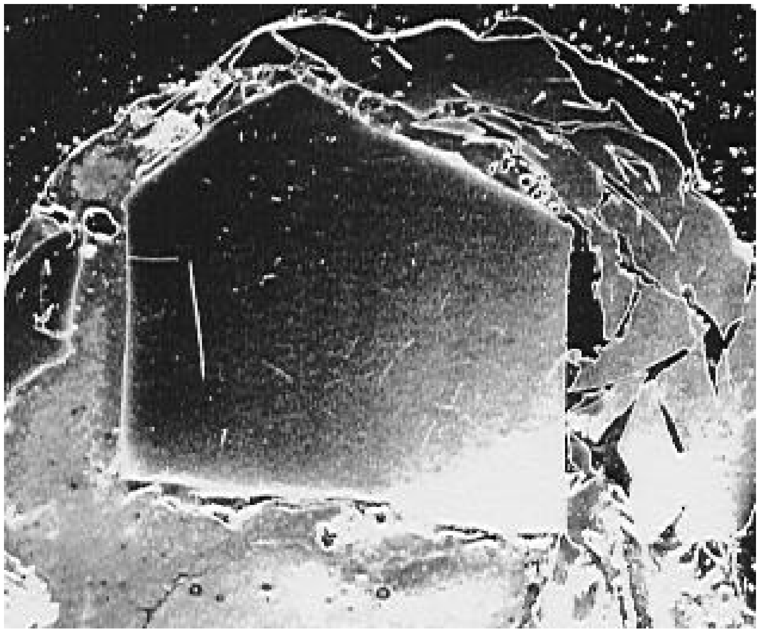




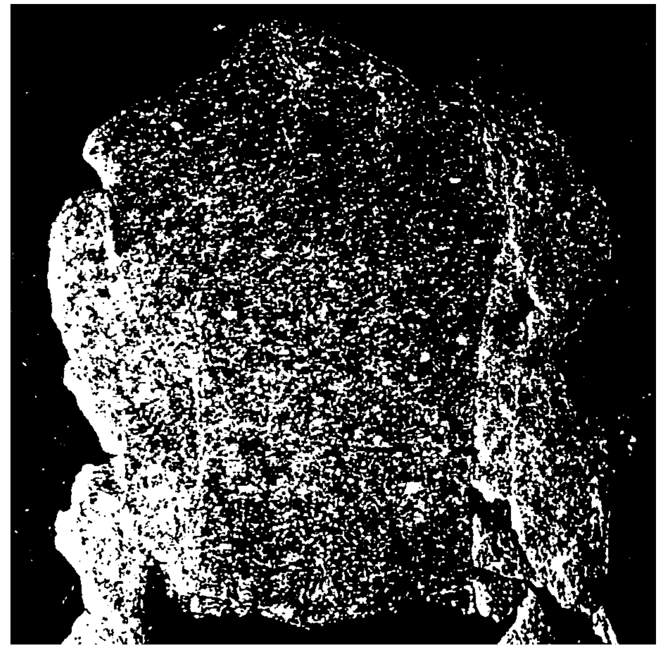
U-.75%Ti, acicular martensite
(from Staker)

• U-V alloys have the potential to maintain penetration capability while reducing penetrator density and mass.

# Tungsten Composites with Adiabatic Shearing Matrix Alloys



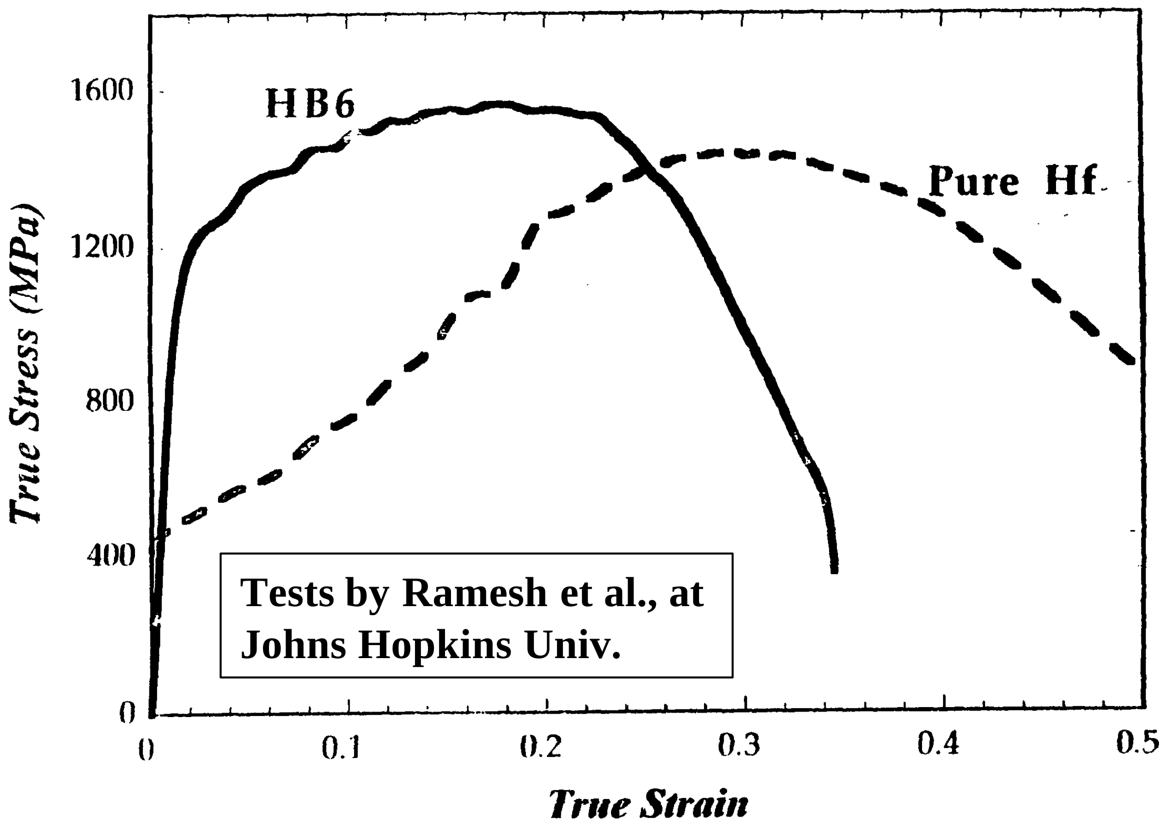
**Residual Ti6Al4V Penetrator**

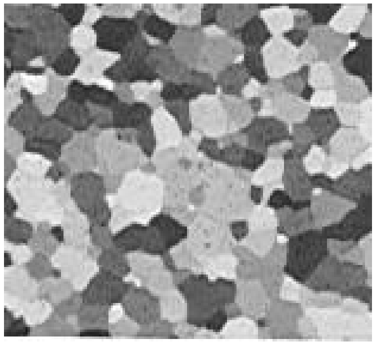


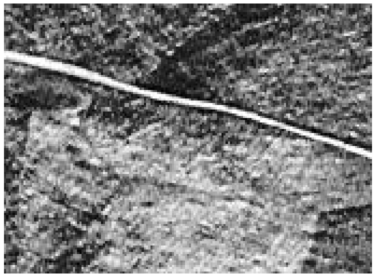
**Residual W-Ti alloy Composite Penetrator**

- Replace conventional Ni-Fe matrix alloy with one more prone to adiabatic shear failure, to enhance plastic instability.

# Dynamic Compression Tests of Hafnium and Hafnium Alloy

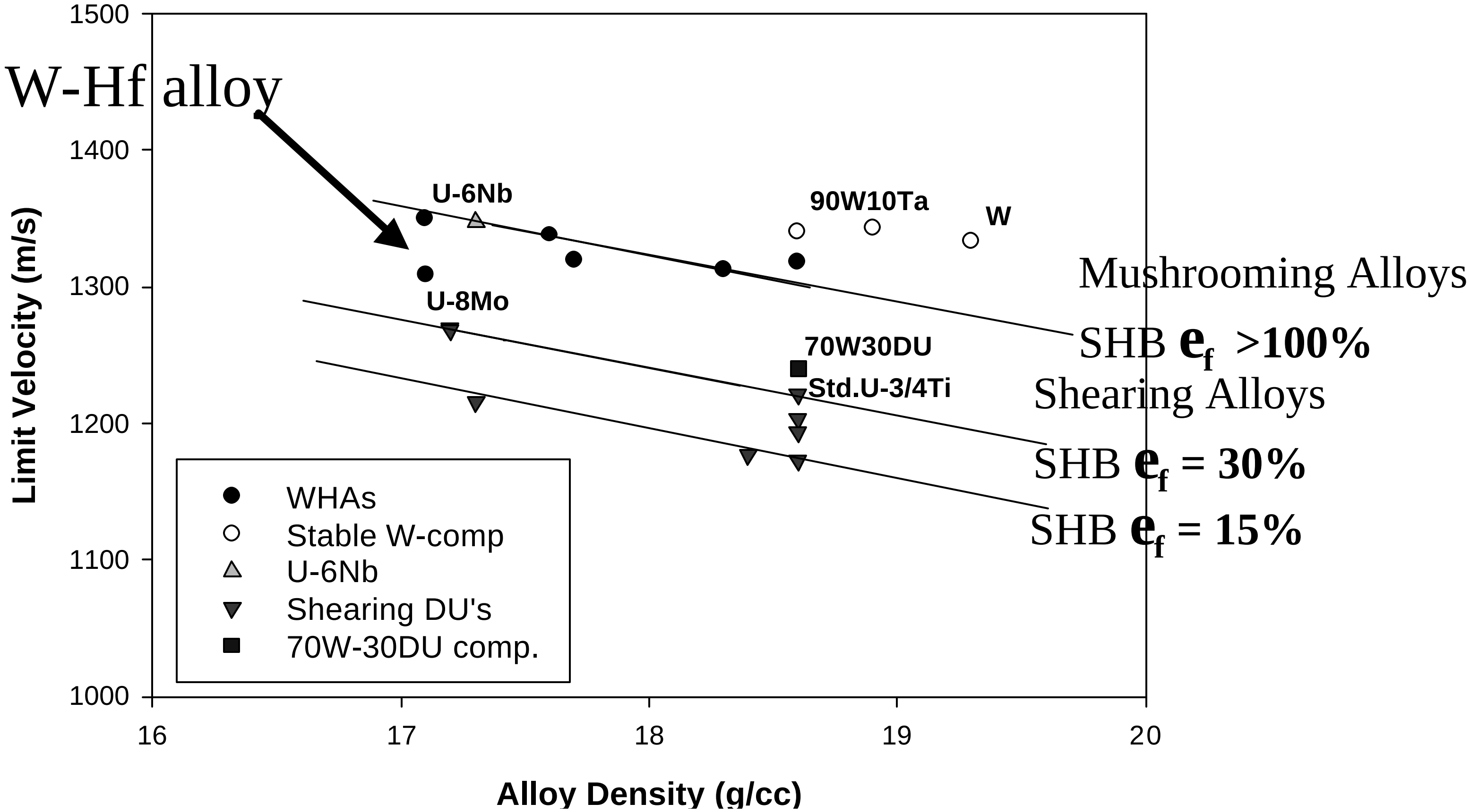




Unalloyed Hf


HB6, Hf10Ti10Ta

• Hafnium alloy HB6 demonstrated the preferred failure behavior in dynamic compression tests.

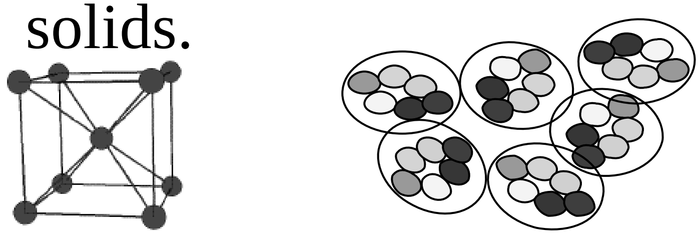
# Perforation of Steel




Performance of W composite with hafnium alloy matrix significantly better than conventional (Ni-Fe)-matrix WHAs, but still short of DU.

# W Composites with Bulk Amorphous Metal (BAM) Matrices

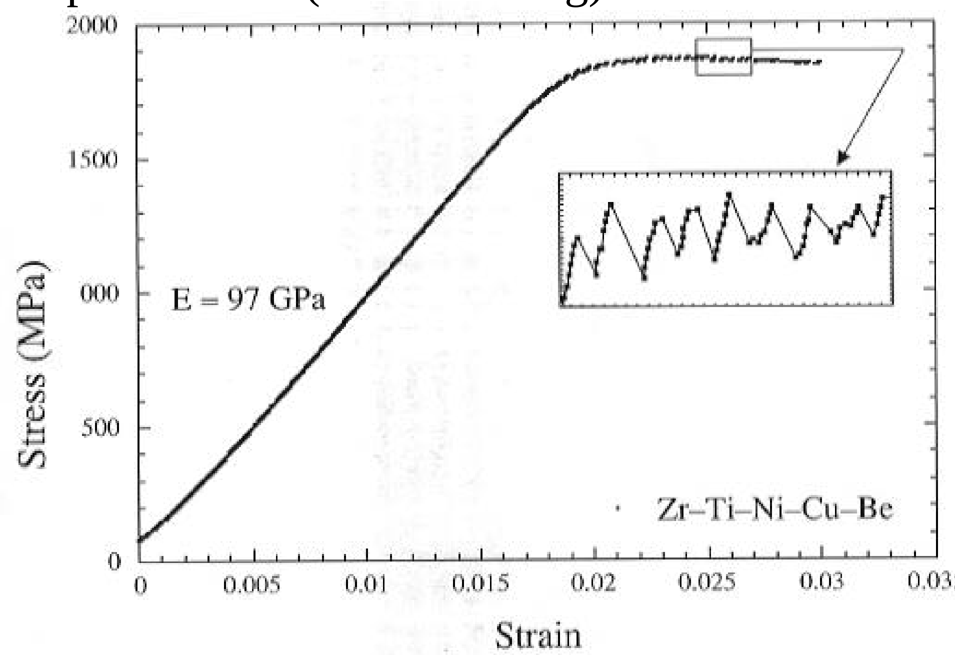
•Amorphous alloys lack long-range structure of crystalline solids.

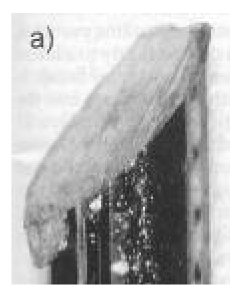



•Unique mechanical properties: high elastic limit (2-3% strain, 1.6GPa Y.S., no work-hardening).

•Recent development of complex, multi-component bulk metallic glass alloys make 1 to 5 cm thick sections possible (low quench rates)

**Typical Mechanical Behavior**: no strain hardening in quasi-static s-e curve, serrated plastic flow (shear banding)



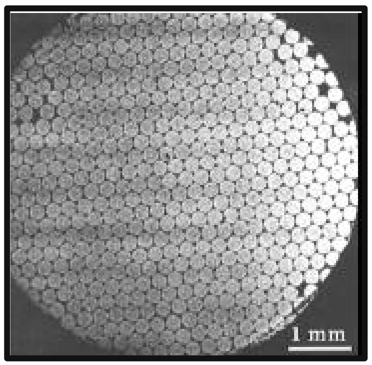




Angled (~ 45°) shear band failure

"Deformation Mechanisms of the ZrTiNiCuBe Metallic Glass", Wright, Saha, & Nix

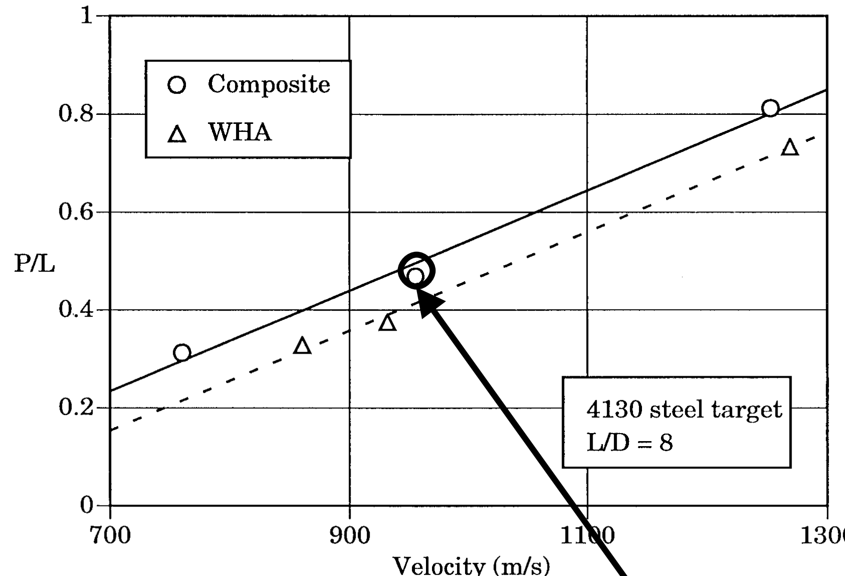
# W Composites with Bulk Amorphous Metal (BAM) Matrices

•ARO-funded CalTech development of W-composite using Z-Ti-Cu-Ni-Be bulk castable amorphous alloy

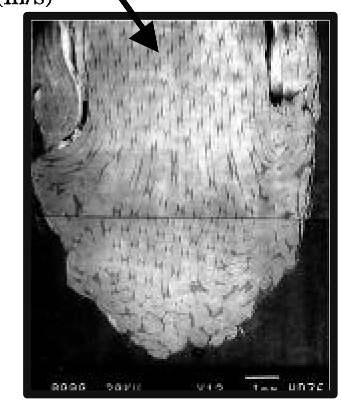



Tungsten wire/ amorphous alloy composite.

80% wire reinforced.



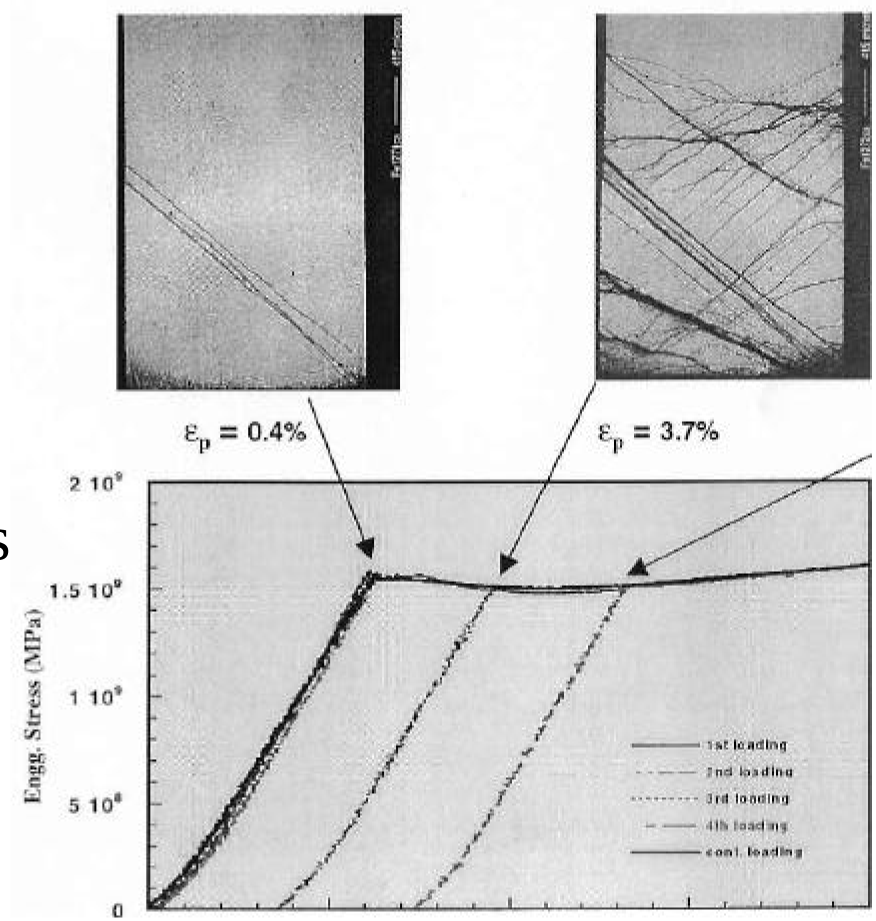

Sub-scale ballistic tests suggest DU-like improvement in penetration performance. From ARO grant to CalTech (W. Johnson)



AMORPHOUS TECHNOLOGIES INTERNATIONAL

# Nanocrystalline Materials

- Like amorphous metals, nanocrystalline (<100 nm GS) metals exhibit little or no work-hardening or bulk plasticity in quasi-static tests
- Shear banding behavior has been observed in materials with GS >250 nm

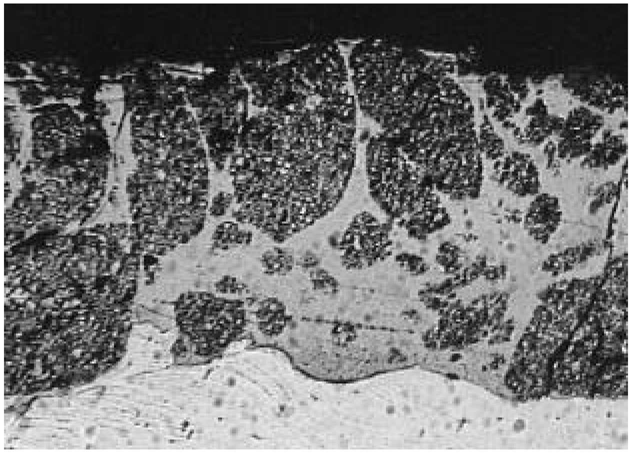



Tests by Dexin Jia, of Johns Hopkins U., aver.GS 268 nm

# Ballistic Tests of Nanocrystalline W-Composite

| Penetrator Type | Material | Density | Limit Velocity |
|---|---|---|---|
| | | (kg/m$^3$) | (m/s) |
| Depleted Uranium | U-3/4 Ti, Rc 40 | 18600 | 1260 |
| Conventional WHA | 90W-9Ni-1Co | 17100 | 1390 |
| Nano W-Composite | W-Cu-Ni-Al | 15200 | 1347 |
| W-Composite w/Hf matrix | 80W-20 HB3 | 17000 | 1350 |

- Performance of nanocomposite surpassed that of conventional WHA or best adiabatic-shearing matrix, despite lower density
- DU vs. WHA performances narrowed, but DU is still superior



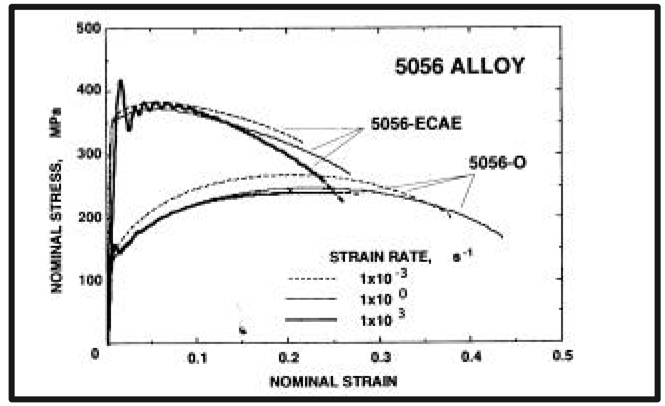
**Nano W-Composite Penetrator Erosion Products Lining Penetrator Tunnel (15X)**

# SEVERE PLASTIC DEFORMATION PROCESSING

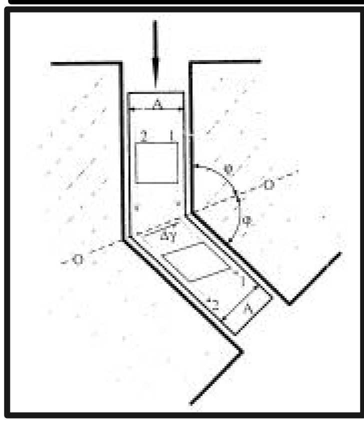
**Equi-Channel Angular Pressing (ECAP)**

- New Mechanical Working Technique
- Developed in FSU

•Path to improved mechanical properties or alternative path to grain size refinement (nano)




5056 Aluminum Alloy
ECAE, >2x strength



**Key Features**

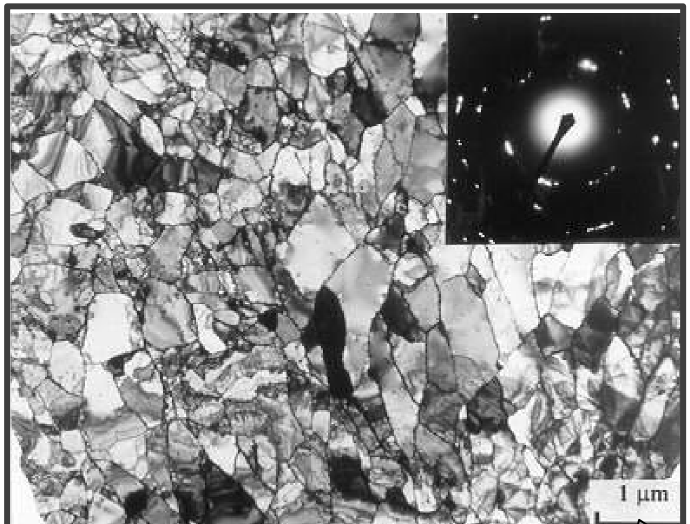
- Cross section in equals cross section out.
- Pure shear deformation
- Imparts cold work (>99% ) with or w/o microstructural changes (reversible).

•Multiple passes increase deformation, refine grain size

| #0f Passes | Equiv. Reduction |
|---|---|
| 1 | 69% |
| 2 | 90 |
| 4 | 99 |
| 8 | 99.99 |

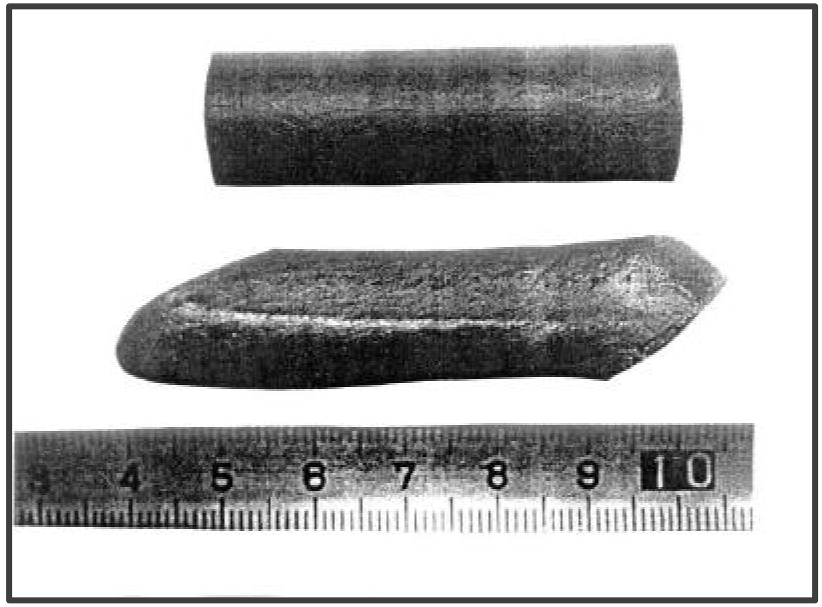
PARTICULATE MATERIALS
PMPT
PROCESSING TEAM

# TEM STRUCTURE AND MICRODIFFRACTION PATTERN 8 PASSES, ROUTE C




Cross Section

1 µm



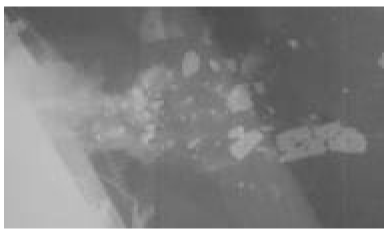

Die Angle of 110°
Route C, 4 Passes

- Ultra Fine Grained (UFG) Structure
- Mean Grain Size Approximately 1 µm, many grains 0.3 to 0.5 µm

PARTICULATE MATERIALS PMPT PROCESSING TEAM

# *Material Bonding for Jacketed Penetrators*

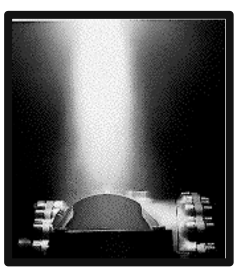
**Goals: Fracture Resistance, Improved Stiffness, Reduced Mass**



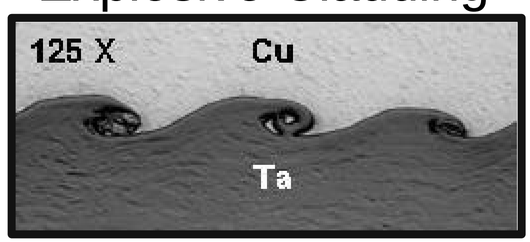
Jacket Material Selection and Bond Strength will be Key to success

**Candidate bonding techniques guided by ballistic experiments and simulations; FOCUS – High Strength Bonds**

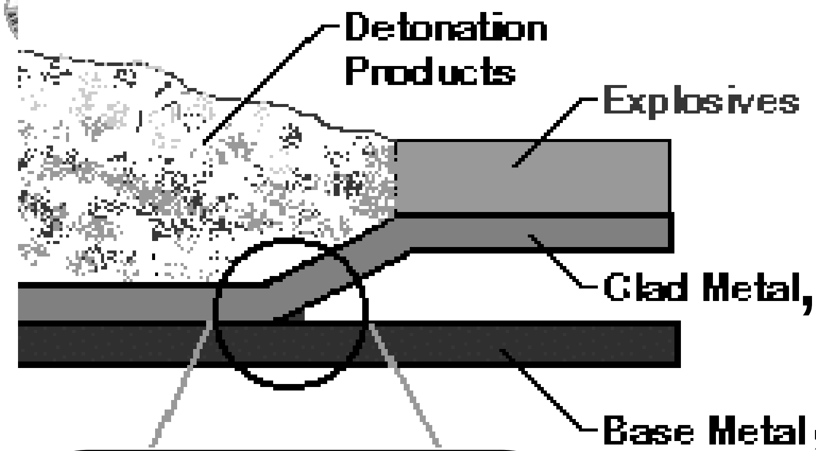
Thermal Spray



Explosive Cladding



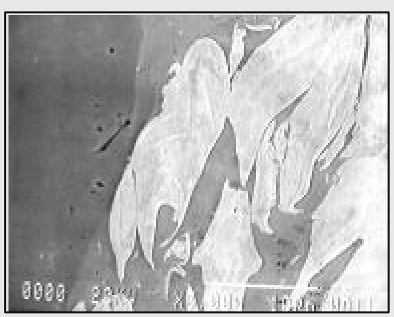
# *Material Bonding for Jacketed Penetrators*




**Clad Metal, 316L Stainless Steel**

**Base Metal, Tungsten Heavy Alloy**

- ✓Metallography
- ✓Centerline Properties
- ✓ High Strength Bond



- ➢ High Strength Bond Achieved!
  - ▪ Subscale Experiments Pending
  - ▪ Reactive & Passive Targets
- ➢ Follow-on contract in place.
  - ▪ Full Scale Processing
- ➢Iterate based on Ballistic Results.
- ➢ Future – Consider alternate bonding.
  - ➢ Swaging
  - ➢ Co-extrusion
  - ➢ Cold Spray

# Conclusions/Summary

- Certain minimum mechanical properties required for launch, for performance vs. complex armors
- Efficient flow & failure behaviors improve penetration performance against thick monolithic armor <u>and</u> individual armor components (e.g. basal armor behind ERA applique)
- Alloy development efforts must meet both goals