Metal Matrix Composites for Ordnance Applications

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### Report Title
Metal Matrix Composites for Ordnance Applications

### Abstract
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### Subject Terms

### Report Classification
Unclassified

### Classification of this page
Unclassified

### Limitation of Abstract
UU

### Number of Pages
21
Motivation

Background
- Army History
- 3M DARPA Program

Development of Analysis Methodology
- Lamina or Ply Level
- Laminate Level

Application - Projectile Shell

Conclusions
Motivation

**Outstanding Mechanical and Thermal Properties**
- Specific fiber direction stiffness comparable to carbon/epoxy
- Transverse and shear properties much greater than carbon/epoxy
- Very high compression strength (~500 ksi)

**Useful Physical Properties**
- High thermal conduction (~5 times graphite/epoxy)
- Low CTE
- High melting point

**Objective Force has Critical Need for Lightweight, High Performance Materials**
- Optimized Projectiles
- Lightweight Gun Tubes
Background

- **Metal Matrix Composites** have drawn strong interest from the Army for over 30 years
  - AMMRC, MTL, BRL, and ARL have funded research since 1960’s
  - Over 60 reports in this area

- **Diverse applications have been investigated**
  - Tank track shoes
  - Helicopter transmission casings, landing gears, skids and wear pads
  - Ballistic missile structural components
  - Lightweight assault bridging components
  - .50 caliber machine gun components

- **Widespread use has been limited by**
  - High material costs
  - Lack of a reasonable production base
  - Lack of design tools
3M Production Base

Nextel Alumina Fibers

Low-cost (<$100/lb)
Large production base
Outstanding properties

Electric Power Transmission Line Cores

Flywheels

Automotive Pushrods

3M DARPA Program ($140M)

Defense Advanced Research Projects Agency (DARPA)

Low-cost (<$100/lb)
Large production base
Outstanding properties
**Metal Matrix Composites for Ordnance Applications (STO IV.MA.2001.01)**

Objective: Develop metal matrix composite technology for more lethal projectiles and lighter armaments for FCS

**Pacing Technologies:**
- Artillery Projectile:
  - Joining Technology
  - Processing
- Gun Barrel:
  - Thermal Fatigue
  - Processing

**Warfighter Payoffs:**
- Enhanced Lethality and Survivability
- Lightweight projectiles with greater payload capacity
- Lightweight armament systems

**TOTAL $2150K**

 Projectile shells 50% lighter than steel shells with 67% less parasitic volume than polymer matrix composite shells; Gun barrels 50% lighter than steel
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<td><strong>Material Modeling &amp; Analysis Capability</strong>&lt;br&gt;<strong>METRIC:</strong>&lt;br&gt;Thermal and Mechanical properties validated and modeling capabilities developed</td>
<td><strong>Sub-Scale Testing</strong>&lt;br&gt;<strong>METRIC:</strong>&lt;br&gt;Joining technology developed, non-destructive evaluation and fatigue tests completed</td>
<td><strong>Application Down-select</strong>&lt;br&gt;<strong>METRIC:</strong>&lt;br&gt;Material properties and optimal impact determine application:&lt;br&gt;• lightweight projectile shell or • lightweight barrel component</td>
<td><strong>Prototype Demonstration</strong>&lt;br&gt;<strong>METRIC:</strong>&lt;br&gt;• Projectile shells 50% lighter than steel shells with 67% less parasitic volume than Polymer Matrix Composite technology or Gun barrels 50% lighter than steel &lt;br&gt;• Transition to Multi-Role Armament &amp; Ammunition ATD</td>
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Nonlinear Composite Modeling - Approach

Characterize Lamina Level Properties

Solution Strategy for Laminate

Failure Prediction for Multi-Axial Loading
Composite Mechanics

- **Lamina or Ply Properties**
  - Individual ply or layer
  - Properties dominated by
    - Fiber
    - Matrix
    - Interface
  - Nine failure modes

- **Laminate Properties**
  - Series of lamina
  - Properties dominated by
    - Lamina properties
    - Order and Orientation of lamina
Lamina Properties

- **Tensile Properties**
  - Dominated by fibers
  - Strength and Stiffness are linearly proportional to the fiber volume fraction

- **Compression properties**
  - Stiffness is proportional to fiber volume fraction
  - Strength is dominated by shear yield strength of matrix

\[ \sigma_c = \frac{G}{1 + n} \left[ 1 + \left( \frac{3}{7} \right)^n \left( \frac{\Phi}{(n-1)\gamma_y} \right)^{n-1} \right]^{-1} \]

(from Deve 1997)
Transverse and Shear Lamina Properties

- **Stress-Strain Response**
  - Initial modulus defined by rule-of-mixtures
    \[
    \frac{1}{E_c} = \frac{V_f}{E_f} + \frac{V_m}{E_m}
    \]
  - Overall response is non-linear and dependent on matrix

- **Transverse and shear properties more important in MMCs than PMCs**
  - For MMC $E_T = 138$ GPa
  - For PMC $E_T = 7$ GPa
**Laminate Mechanics**

- Classical laminate mechanics can be used to accurately predict the initial linear-elastic behavior of MMC laminates
- More advanced methodologies are needed to predict full stress-strain curve
  - Non-linear shear and transverse properties
  - Progressive failure of lamina

Predicted and Observed Strength and Modulus for ± 22.5 FP-alumina/Mg

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</table>
Non-linear Progressive Laminate Analysis

**Approach**
- Piecewise Linear Increments
- Superimposed to Form Effective Nonlinear Response
- Individual Ply Stress, Strain and Stiffness
- Ply Stress or Strain Allowables
- FEA for Structure

**Representative Sublaminate**

**Effective Laminate Stress**

**Equivalent Representation (Homogeneous & Anisotropic)**

**Smearing Laminated Composite Structure**

- Apply Lamina Failure Criteria and Ply Stress Unloading
- Calculate Ply-by-Ply Stress and Strain
Non-Linear Laminate Predictions

Compressive stress-strain response of Al with 65% \( \text{Al}_2\text{O}_3 \) fibers with a \([0/90]_{4S}\) architecture

Stress vs. Strain for \([0/90] \text{Al/Al}_2\text{O}_3\)
Thermal Fatigue Testing

Testing done by LTC John Bridge at USMA

- Specimens from 3M's automotive pushrods (commercial product)
- Cycled at 300°C
- Loss of 30% of compression strength after 1000 cycles
- Matrix was Al-2wt%Cu, pure Al may behave better

Compression Strength Degradation

![Graph showing compression strength degradation over cycles](image-url)
Experimental Procedures

- Specimens: 6 inch Long Hollow Rods
  0.375 in. Wall Thickness
- Electro-Pneumatic Piston Cycling Device
  – Timer, Solenoids, Air Compressor, Counter, Air-Conditioner, Thermocouples, Fans
- Specimen “Cage”
- Insulated Convection Furnace
- 0 to 300 Degree C Thermal Range
- 2.5 Minute Cycle Time
- 250 Cycle Intervals up to 1000 Cycles
- Specimens Tested at each 250 Cycle Interval
Lightweight Ordnance
Metal Matrix Composites for
Ordnance Applications

SADARM carrying variant of the XM982 projectile

- Exhibits excessive deformation under setback loading
- Steel shell exceeds weight goal
- Space constraints limit redesign options
- MMC shell necessary for projectile
# Material Impact: Artillery Shell

Comparison of an 18-in 155-mm Artillery Shell made from Steel, Aluminum Metal Matrix Composites, and Graphite/Epoxy.

<table>
<thead>
<tr>
<th>Material</th>
<th>Shell Weight (lbs)</th>
<th>Weight Normalized to Steel</th>
<th>Available Volume (in$^3$)</th>
<th>Internal Vol. Normalized to Steel</th>
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<tbody>
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<td>11.95</td>
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<td>0.83</td>
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MMC 155-mm Shell
Crush Test Results

Failure Strength, 483,000 lbs (25 lbs @ 19,300 g’s)
Conclusions

- **Metal Matrix Composites** have outstanding potential for *Ordnance*
  - Projectile shells 50% lighter than steel, with 67% less parasitic volume than polymer matrix composites
  - Gun barrels 50% lighter than steel

- **Modeling technologies** developed to allow design for *ordnance applications*
  - Lamina-level
  - Gun barrel and Projectile shell components

- **STO Program** will demonstrate technology for *Objective Force*
  - Develop Prototype of gun barrel or projectile shell
  - TRL 5 by 2003