1. REPORT DATE (DD-MM-YYYY)  
4/30/14

2. REPORT TYPE  
Interim Research Performance Report (Monthly)

3. DATES COVERED (From - To)  
February 1, 2013 - March 31, 2014

4. TITLE AND SUBTITLE  
Expeditionary Light Armor Seeding Development

5a. CONTRACT NUMBER

5b. GRANT NUMBER
N00014-13-1-0219

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER
FINAL-1

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
875 North Randolph Street
Arlington, VA 22203-1995

10. SPONSOR/MONITOR'S ACRONYM(S)
ONR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for Public Release; distribution is Unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
-Develop Modeling and Simulation tools, use Depth of Penetration (DOP) as metric, 7.62 APM2
-Evaluate SiC tile on Aluminum with material properties from literature
-Develop seam designs to improve performance, demonstrate with DOP experiments (tiles from Supplier, sintered SiC)

15. SUBJECT TERMS
Adhesive Layer Effect, .30cal AP M2 Projectile, 762x39 PS Projectile, SPH, Aluminum 5083, SiC, DoP Experiments, AutoDyn Sim

16. SECURITY CLASSIFICATION OF:
UU

17. LIMITATION OF ABSTRACT
UU

18. NUMBER OF PAGES
20

19a. NAME OF RESPONSIBLE PERSON
Shridhar Yarlagadda

19b. TELEPHONE NUMBER (include area code)
302-831-4941
ONR ARMOR-GRANT FINAL REPORT 2013-2014
Grant No. N00014-13-1-0219
Date: April 30, 2014

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MODELING AND SIMULATION OF CERAMIC ARRAYS TO IMPROVE BALLISTIC PERFORMANCE

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OUTLINE

- Program Overview
- Technical Approach
- Material Properties
- Research Summary February 2013 - August 2013
- Research Summary September 2013 – March 2014
- Future Work
PROGRAM OVERVIEW

TWO PHASE PROGRAM:

- **Grant (15 mos)**
  - Develop Modeling and Simulation tools, use Depth of Penetration (DOP) as metric, 7.62 APM2
  - Evaluate SiC tile on Aluminum with material properties from literature
  - Develop seam designs to improve performance, demonstrate with DOP experiments (tiles from Supplier, sintered SiC)

- **Contract (2 years)**
  - Establish baseline seam and corner performance based on tests with 2 ft x 2 ft panels
  - Tile designs identified in grant – verify performance, provide panels for independent testing
  - Use modeling and simulation tools to assess corner (triple point) performance with seam designs – modifications as needed
    - Evaluate new designs – designs must be manufacturable!
  - Adapt modeling and simulation tools for lightweight backings (composite)
  - Verify designs with DOP and full panel tests
  - Fabricate panels with seam and corner designs and demonstrate improvements
  - Provide panels to Navy for independent verification
TECHNICAL APPROACH

- The University of Delaware Center for Composite Materials (UD-CCM) is developing the next generation of lightweight hybrid ceramic/composite armor kits for Marine Corps tactical and combat vehicles.
- The focus is on simulating and modeling the performance of ceramic/composite lightweight armor at seams and corners, and improving the armor's performance in these regions.
- The ceramic/composite armor is comprised of composite backings, adhesives, ceramics and covers.
- The tiles will be restricted to the sintered ceramics (SiC) due to the ability to fabricate SiC into complex geometries and cost analysis conducted in previous research.
- Model ballistic experiments will validate the modeling done in simulation.
Half-symmetric model is used in AutoDyn to simulate Depth of Penetration (DOP) experiments on SiC tile with and without a gap supported by solid Aluminum (Al5083)

Impacts by .30cal AP-M2 projectile and are modeled using SPH elements in AutoDyn

Center strike model validation runs with SiC tiles are conducted based on the DOP experiments described in reference - ARL-TR-2219, 2000

Tile gap is found to increase the DOP as compared to baseline center impact

Simulations were run on gap sizes 0.508 (20 mil) and 1.061 mm (40 mil) at the standard muzzle speed of 850 m/s

DOP is the main measurement used to determine which geometry and configuration yield the best results.
TECHNICAL APPROACH

Material Models

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>EOS</th>
<th>STRENGTH MODEL</th>
<th>FAILURE MODEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel Core</td>
<td>Polynomial</td>
<td>Johnson &amp; Cook</td>
<td>Johnson &amp; Cook</td>
</tr>
<tr>
<td>Lead Filler</td>
<td>Gruneisen</td>
<td>Piecewise Johnson &amp; Cook</td>
<td>N/A</td>
</tr>
<tr>
<td>Copper Jacket</td>
<td>Linear</td>
<td>Piecewise Johnson &amp; Cook</td>
<td>N/A</td>
</tr>
<tr>
<td>SiC Ceramic</td>
<td>Polynomial</td>
<td>JH-2</td>
<td>JH-2</td>
</tr>
<tr>
<td>Aluminum</td>
<td>Polynomial</td>
<td>Johnson &amp; Cook</td>
<td>Johnson &amp; Cook</td>
</tr>
<tr>
<td>S-Glass/Phenolic</td>
<td>Linear</td>
<td>LS-DYNA MAT162</td>
<td>LS-DYNA MAT162</td>
</tr>
<tr>
<td>Polymeric Foam</td>
<td>Linear</td>
<td>Non-linear Elastic</td>
<td>N/A</td>
</tr>
<tr>
<td>Adhesives &amp; Interlayers</td>
<td>N/A</td>
<td>Cohesive Laws</td>
<td>Cohesive Laws</td>
</tr>
</tbody>
</table>

Smoothed-particle hydrodynamics (SPH) used for all parts
- SPH Size 0.4 used initially
- SPH Size 0.2 used to capture smaller damaged particles
- SiC and SiC 2 are identical in properties and dimensions
- Differentiated to show damage in each tile
- Clamp boundary condition used

.30cal AP-M2 Projectile

<table>
<thead>
<tr>
<th>Component</th>
<th>Material</th>
<th>Weight (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jacket</td>
<td>Gilding Metal</td>
<td>4.2</td>
</tr>
<tr>
<td>Core</td>
<td>Hardened Steel - RC 63</td>
<td>5.3</td>
</tr>
<tr>
<td>Point Filler</td>
<td>Lead</td>
<td>0.8</td>
</tr>
<tr>
<td>Base Filler</td>
<td>Lead</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Total Weight</strong></td>
<td></td>
<td><strong>10.8</strong></td>
</tr>
</tbody>
</table>

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# Material Properties: Al 5083 and SiC

## Experimental Al 5083

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>2.65</td>
</tr>
<tr>
<td>Tensile Strength (MPa)</td>
<td>377.1</td>
</tr>
<tr>
<td>Yield Strength (MPa)</td>
<td>318.5</td>
</tr>
<tr>
<td>Elongation (%)</td>
<td>9.3</td>
</tr>
<tr>
<td>AutoDyn Al 5083</td>
<td></td>
</tr>
</tbody>
</table>

## Experimental SiC

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>3.20</td>
</tr>
<tr>
<td>Elastic Modulus (GPa)</td>
<td>455</td>
</tr>
<tr>
<td>Shear Modulus (GPa)</td>
<td>195</td>
</tr>
<tr>
<td>Longitudinal Wave Velocity (km/s)</td>
<td>12.3</td>
</tr>
<tr>
<td>Poisson's Ratio</td>
<td>0.14</td>
</tr>
<tr>
<td>Hardness (kg/mm²)</td>
<td>2700</td>
</tr>
<tr>
<td>Compressive Strength (MPa)</td>
<td>3410</td>
</tr>
</tbody>
</table>

## AutoDyn SiC

- **Equation of State:** Polynomial
- **Reference density:** 3.21500E+00 (g/cm³)
- **Bulk Modulus A1:** 2.20000E+12 (ubar)
- **Parameter A2:** 3.61000E+12 (ubar)
- **Parameter A3:** 0.00000E+00 (ubar)
- **Parameter B0:** 0.00000E+00 (none)
- **Parameter B1:** 0.00000E+00 (none)
- **Parameter T1:** 2.20000E+12 (ubar)
- **Parameter T2:** 0.00000E+00 (ubar)
- **Reference Temperature:** 2.93000E+02 (K)
- **Specific Heat:** 0.00000E+00 (erg/gK)
- **Thermal Conductivity:** 0.00000E+00 ( )
- **Strength:** Johnson-Holmquist
- **Shear Modulus:** 1.93500E+12 (ubar)
- **Model Type:** Segmented (JH1)
- **Hugoniot Elastic Limit, HEL:** 1.17000E+11 (ubar)
- **Intact Strength Constant, S1:** 7.10000E+10 (ubar)
- **Intact Strength Constant, P1:** 2.50000E+10 (ubar)
- **Intact Strength Constant, S2:** 1.22000E+11 (ubar)
- **Intact Strength Constant, P2:** 1.00000E+11 (ubar)
- **Strain Rate Constant, C:** 9.00000E-03 (none)
- **Max. Fracture Strength, SFMAX:** 1.30000E+10 (ubar)
- **Failed Strength Constant, ALPHA:** 4.00000E-01 (none)
- **Failure:** Johnson Holmquist
- **Hydro Tensile Limit:** -7.50000E+09 (ubar)
- **Model Type:** Segmented (JH1)
- **Damage Constant, EFMAX:** 1.20000E+00 (none)
- **Damage Constant, P3:** 9.97500E+11 (ubar)
- **Bulking Constant, Beta:** 5.96000E+09 (ubar)
- **Damage Type:** Instantaneous (JH1)
- **Tensile Failure:** Hydro (Pmin)

## Ref:

MTL TR-86-14, 1986.

## AutoDyn Al 5083

- **Equation of State:** Linear
- **Reference density:** 2.70000E+00 (g/cm³)
- **Bulk Modulus:** 5.83300E+11 (ubar)
- **Reference Temperature:** 2.93000E+02 (K)
- **Specific Heat:** 9.10000E+06 (erg/gK)
- **Thermal Conductivity:** 0.00000E+00 ( )
- **Strength:** Johnson-Cook
- **Shear Modulus:** 2.69200E+11 (ubar)
- **Yield Stress:** 1.67000E+09 (ubar)
- **Hardening Constant:** 5.96000E+09 (ubar)
- **Hardening Exponent:** 5.51000E-01 (none)
- **Strain Rate Constant:** 1.00000E-03 (none)
- **Thermal Softening Exponent:** 8.59000E-01 (none)
- **Melting Temperature:** 8.93000E+02 (K)
- **Ref. Strain Rate (°/s):** 1.00000E+00 (none)
- **Strain Rate Correction:** 1st Order
- **Failure:** None
- **Erosion:** None
- **Material Cutoffs:** None
- **Maximum Expansion:** 1.00000E-01 (none)
- **Minimum Density Factor:** 1.00000E-05 (none)
- **Minimum Density Factor (SPH):** 2.00000E-01 (none)
- **Maximum Density Factor (SPH):** 3.00000E+00 (none)
- **Minimum Soundspeed:** 1.00000E-04 (cm/s)
- **Maximum Soundspeed (SPH):** 1.01000E+20 (cm/s)
- **Maximum Temperature:** 1.00000E+16 (K)

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Mesh sensitivity analyses were performed to show fracture and determine particle size

Initial AutoDyn Models were developed
MESH SIZE ANALYSIS

Fracture at Varying Mesh Size

- SPH particle size of 0.4 mm determined to be sufficient in capturing the damage of the ceramic tile
- Later simulations SPH size is changed to 0.2 mm to capture more of the damaged particles

0.50-mm  0.40-mm  0.30-mm  0.20-mm

Multiple Mesh Size Failure

- Combining multiple mesh sizes in one simulation fails
  - Due to stress wave propagation causing deflection
  - Softening and damage modes that are occurring differently in the different mesh sizes

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IDENTIFICATION OF THE PROBLEM

MONOLITHIC Al5083

SiC TILE SUPPORTED BY Al5083

- Two projectile IGES geometry files are provided by ONR.
- Quarter-symmetric model is used in AutoDyn to simulate DOP experiments on aluminum targets and ceramic-faced aluminum targets with .30cal AP-M2 projectile using SPH

AUTODYN QUARTER-SYMMETRIC MODEL

- SPH used for all parts
- Particle size = 0.30-mm totaling 351k elements
- Static boundary condition used at end of aluminum to secure the target
- Material strength and damage properties will be varied to validate ARL DOP data in future
SIMULATION OF ARL DOP EXPERIMENTS

MONOLITHIC AI5083

AutoDyn DOP = 37.8 mm
Experimental DOP = 33.8 mm
Difference = 11.8%

SiC TILE SUPPORTED BY AI5083

AutoDyn DOP = 42.4 mm
Experimental DOP = 40.1 mm
Difference = 5.7%

- Simulate DOP experiments in AutoDyn to compare to ARL data
- Conclusion: Reasonable results since yaw and pitch are not considered in AutoDyn or ARL
- Stress wave propagation in the target causes the target to split
  - To control for this a static boundary condition is added to all walls of the target

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- Simulation details
- Baseline monolithic Al5083
- Improved seam design simulations

RESEARCH SUMMARY
SEPTEMBER 2013 – MARCH 2014
Simulations are now incorporating gaps in the tiles to simulate cracks.

Both tiles are SiC but are modeled as two separate materials with the same properties to allow for easy differentiation of the damage.

DOP is calculated by: \( DOP = L - L_{NP} \)

Where \( L \) is the length of the entire target, ceramic tiles and AL5083 backing.

\( L_{NP} \) is the length of the target left unpenetrated when the velocity and kinetic energy of the projectile core have reached zero.
### Monolithic Al5083 DOP

<table>
<thead>
<tr>
<th>Velocity (m/s)</th>
<th>DOP (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>15.0</td>
</tr>
<tr>
<td>450</td>
<td>17.9</td>
</tr>
<tr>
<td>500</td>
<td>20.8</td>
</tr>
<tr>
<td>550</td>
<td>22.2</td>
</tr>
<tr>
<td>600</td>
<td>25.0</td>
</tr>
<tr>
<td>650</td>
<td>28.1</td>
</tr>
<tr>
<td>700</td>
<td>32.1</td>
</tr>
<tr>
<td>750</td>
<td>35.0</td>
</tr>
<tr>
<td>800</td>
<td>37.5</td>
</tr>
<tr>
<td>850</td>
<td>40.0</td>
</tr>
<tr>
<td>900</td>
<td>42.5</td>
</tr>
</tbody>
</table>

- Simulate monolithic Al5083 with the intent to compare to the ARL data and use as a baseline result.
- Simulation results do not show the same trend as the ARL experimental data.
- Simulations will be extended over a larger range of impact velocities.
- Material properties may be edited if the properties do not match the material properties used in the ARL experiments.
SIMULATING EFFECT OF TILE GAP ON DOP

- See DOP of center impacted SiC tiles and effect on DOP of SiC tiles with gap
- Aluminum Backing
  - Length = 35.08 mm
- Ceramic Plate(s)
  - Length ($t_c$) = 5.08 mm
  - Gap size = 1.2 mm
- Total Length = 40.08 mm
- Velocity varying from 700-1000 m/s
- SPH Size 0.4
- As expected tile gap increases the DOP and improvements on this are needed

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EFFECT OF TILE THICKNESS ON DOP AT 850 m/s GAP SIZE 0.508 mm AND 1.016 mm

- When the gap is held at 1.016 mm the baseline DOP of a center impacted tile cannot be effectively achieved.
- A gap size of 0.508 mm allows the baseline to be achieved and gap size of 0.508 mm will be the gap size in use moving forward.
An adhesive layer of Epoxy Resin was added in between the SiC tile and the Al backing

The tile remained 5 mm thick

An adhesive layer of Epoxy Resin was added in between the SiC tile and the Al backing

The tile remained 5 mm thick and the gap size at 0.508 mm to compare when no adhesive was added
An Step Ladders were created according to the schematics with presented specifications.

The tile remained 5 mm thick and the gap size at 0.508 mm to compare to the baseline results.

The DOP results are compare against center impacted single tile and standard 0.508 mm gap between two tiles.

---

### Step Ladder DOP

<table>
<thead>
<tr>
<th>Step Ladder</th>
<th>Step Ladder</th>
<th>No Step Ladder</th>
<th>Baseline</th>
</tr>
</thead>
<tbody>
<tr>
<td>tsi = 0 mm</td>
<td>tsi = 0.2 mm</td>
<td>DOP, Gap Size</td>
<td>Center</td>
</tr>
<tr>
<td>DOP (mm)</td>
<td>DOP (mm)</td>
<td>0.508 mm (mm)</td>
<td>Impacted</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>One Tile</td>
</tr>
<tr>
<td>9.2</td>
<td>11.8</td>
<td>17.2</td>
<td>10.3</td>
</tr>
</tbody>
</table>

---

<table>
<thead>
<tr>
<th>Part</th>
<th>Vo</th>
<th>Hp</th>
<th>tgap</th>
<th>Hc</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>850 m/s</td>
<td>35.31 mm</td>
<td>0.508 mm</td>
<td>5 mm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Part</th>
<th>Vo</th>
<th>Hp</th>
<th>tgap</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>850 m/s</td>
<td>35.31 mm</td>
<td>0.508 mm</td>
<td>5 mm</td>
</tr>
</tbody>
</table>
Angled Seams (a) and Cover plates (b) are proposed seam designs to be tested in the future.

Continued modeling and experimental tests will down select for the best solution and improvement to seam design.

Modeling will move from AutoDyn to LS-DYNA for increased computational power and the ability to model complex geometries.

Baseline performance seam assessment (2 ft x 2 ft panels)

- Sintered 4'sq. SiC (Superior Graphite) on Kevlar/Phenolic with 2-ply cover

(a) Angled Seam

(b) Cover Plate